Temperature Dependence in IR Sea Surface Emissivity (IRSSE): CRTM Model Upgrade

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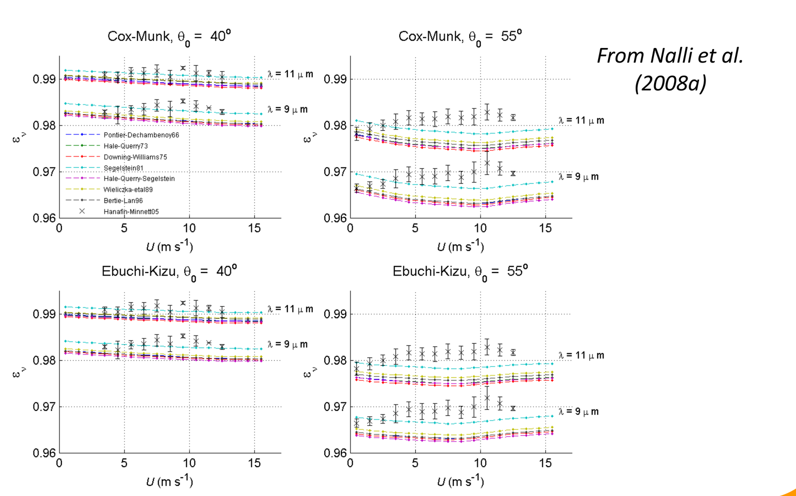
Background

- For satellite IR remote sensing applications, the **surface emissivity/reflectance** spectrum must be specified with a high degree of absolute accuracy
  - **0.5%** uncertainty results ≈**0.3–0.4 K** systematic error in **LWIR window channels**
- Conventional **IR sea-surface emissivity models** have gained widespread acceptance (e.g., *Masuda et al.* 1988; *Watts et al.* 1996; *Wu and Smith* 1997), **but only after they were validated**
  - **Masuda's model** was published in **1988**, **but nobody used it** because it was *never validated* against observations
  - The **Marine Atmospheric Emitted Radiance Interferometer (MAERI)** (*Smith et al.* 1996; *Minnett et al.* 2001) led to acceptance and application of emissivity models
- In these models, **emissivity** is calculated as the ensemble-mean of **one minus Fresnel reflectance** of surface wave facets

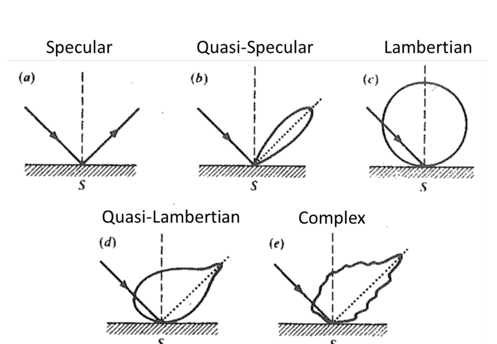
$$\overline{\epsilon}_\nu(\theta_0, N_\nu) = 1 - \int_{\theta_n}\int_{\varphi_n} \rho_\nu(\theta_n, \varphi_n; \theta_0; N_\nu)\, P(\theta_n, \theta_0; \sigma_s^2)\, d\varphi_n\, d\mu_n = 1 - \overline{\rho}_\nu(\theta_0, N_\nu)\,,$$

- The emissivity is modeled as a function of **wavenumber *ν***, **zenith view angle θ**, and **surface wind speed *U***
- The latter models were improved to agree reasonably well with observations, but **residual systematic discrepancies** (0.1–0.4 K) are still present at higher wind speeds and view angles ≥40° (*Nalli et al.* 2001, 2006; *Hanafin and Minnett* 2005)



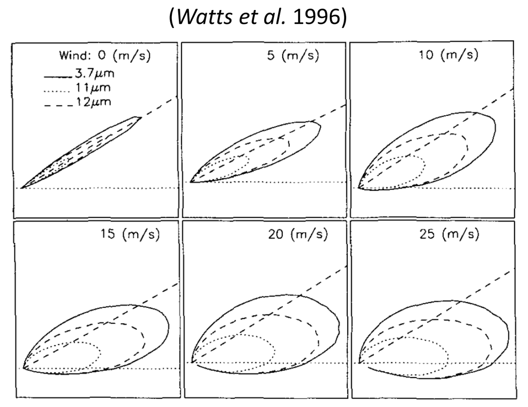
From Nalli et al. (2008a)

Quasi-Specular Ocean Reflection in the IR



From Stephens (1994)

Modeled Reflection Lobes (*Watts et al.* 1996)



- Ocean reflected downwelling radiance is **quasi-specular**, i.e., diffuse with a large specular component (*Nalli et al.* 2001; *Watts et al.* 1996)
- However, because of the impracticality associated with a hemispheric double integral, *radiative transfer models typically treat the reflectance as **either specular** or **Lambertian***

JCSDA, STAR and JPSS Support for IRSSE Model Development

- **JCSDA and STAR** supported in-house **FY05-06** research to find a workable solution for application to the CRTM
  - This research culminated in the **CRTM IRSSE model** (*Nalli et al.* 2018a,b; *van Delst et al.* 2009)
  - Notably, the IRSSE model uses the **effective emissivity principle** to account for quasi-specular reflection in a practical manner
- **JCSDA** has agreed to support (beginning Sep 2019) an **upgrade** to the **CRTM IRSSE model** as part of their **2019 Annual Operating Plan**
- **JPSS provided in-kind support** up until Sep 2019

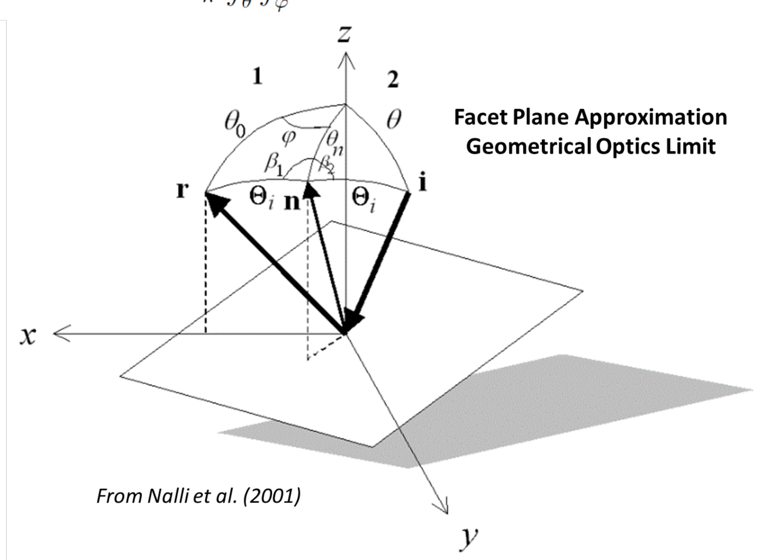
Radiative Transfer-Based Effective Emissivity (after *Nalli et al.* 2018a,b)

The **directional emissivity** of a terrestrial surface is defined as

$$\epsilon_\nu(\theta_0) \equiv \frac{I_{\nu s}(\theta_0)}{B_\nu(T_s)}\,,$$

where the **surface-emitted radiance** (numerator) is separated from the **surface-leaving radiance** (as measured by a detector) by subtracting the **surface-reflected radiance**

$$I_{\nu s}(\theta_0) = R_{\nu s}(\theta_0, \varphi_0) - \frac{1}{\pi}\int_\theta\int_\varphi r_\nu(\theta, \varphi; \theta_0, \varphi_0)\, I_\nu^{\downarrow}(\theta, \varphi)\cos(\theta)\sin(\theta)\, d\varphi\, d\theta$$



From Nalli et al. (2001)

The **conical-directional reflectance for non-isotropic incident radiation** (*Nicodemus et al.* 1977) for the **sea surface reflectance** may be written as

$$\rho_\nu(\theta_0, \sigma_s^2) = \frac{\iint \rho_\nu(\theta_n, \varphi_n; \theta_0)\, P(\theta_n, \theta_0; \sigma_s^2)\left[B_\nu(T_s) - I_\nu^{\downarrow}(\theta)\right] d\varphi_n\, d\mu_n}{\iint P(\theta_n, \theta_0; \sigma_s^2)\left[B_\nu(T_s) - I_\nu^{\downarrow}(\theta)\right] d\varphi_n\, d\mu_n}\,,$$

which, from the mean value theorem is equivalent to

$$\rho_\nu(\theta_0, \sigma_s^2) \equiv \rho_\nu(\overline{\theta}_n, \overline{\varphi}_n; \theta_0; \sigma_s^2) = \rho_\nu[\overline{\Theta}_i(\theta_0), \sigma_s^2]$$

The denominator simplifies as

$$\iint P(\theta_n, \theta_0; \sigma_s^2)\left[B_\nu(T_s) - I_\nu^{\downarrow}(\theta)\right] d\varphi_n\, d\mu_n = B_\nu(T_s) - I_\nu^{\downarrow}(\overline{\theta})\,,$$

where $\overline{\theta} = \overline{\theta}(\nu)$ is a diffusivity angle, thus allowing **simplification of the surface-leaving radiance RTE** as

$$\begin{aligned} R_{\nu s}(\theta_0) &= B_\nu(T_s) - \rho_\nu(\overline{\Theta}_i, N_\nu)\left[B_\nu(T_s) - I_\nu^{\downarrow}(\theta_0)\right] - \rho_\nu(\overline{\Theta}_i, N_\nu)\,\Delta I_\nu^{\downarrow}(\overline{\theta}) \\ &\approx B_\nu(T_s) - \rho_\nu(\overline{\Theta}_i - \Delta\Theta_i, N_\nu)\left[B_\nu(T_s) - I_\nu^{\downarrow}(\theta_0)\right] \\ &\equiv B_\nu(T_s) - \rho_\nu(\Theta_e, N_\nu)\left[B_\nu(T_s) - I_\nu^{\downarrow}(\theta_0)\right] \end{aligned}$$

Then, defining an **effective emissivity** as

$$\mathcal{E}_\nu(\theta_0) \equiv 1 - \rho_\nu[\Theta_e(\theta_0)]\,,$$

where Θ_e is an **effective emission angle**, $\Theta_e \equiv \overline{\Theta_i} - \Delta\Theta_i \lesssim \overline{\Theta_i}$, compensates residual diffuse reflectance. This leaves a **simplified quasi-specular RTE for the SLR**

$$R_{\nu s}(\theta_0) = \mathcal{E}_\nu(\theta_0)\, B_\nu(T_s) + \left[1 - \mathcal{E}_\nu(\theta_0)\right] I_\nu^{\downarrow}(\theta_0)\,.$$

The effective emissivity as defined is equivalent to

$$\mathcal{E}_\nu(\theta_0) = \frac{R_{\nu s}(\theta_0) - I_\nu^{\downarrow}(\theta_0)}{B_\nu(T_s) - I_\nu^{\downarrow}(\theta_0)}$$

The effective emission angle Θ_e iteratively via **least-squares spectral minimization** of RMSE

$$\mathrm{RMSE}(\Delta\nu) = \sqrt{\frac{1}{n-1}\sum_\nu \left[T_{\nu s}(\Theta_e) - T_s\right]^2}\,,$$

where $T_{\nu s}(\Theta_e)$ is the radiometric skin temperature given by

$$T_{\nu s}(\Theta_e) = B_\nu^{-1}\left(\frac{R_{\nu s}(\theta_0) - \rho_\nu(\Theta_e, N_\nu)\, I_\nu^{\downarrow}(\theta_0)}{1 - \rho_\nu(\Theta_e, N_\nu)}\right)$$

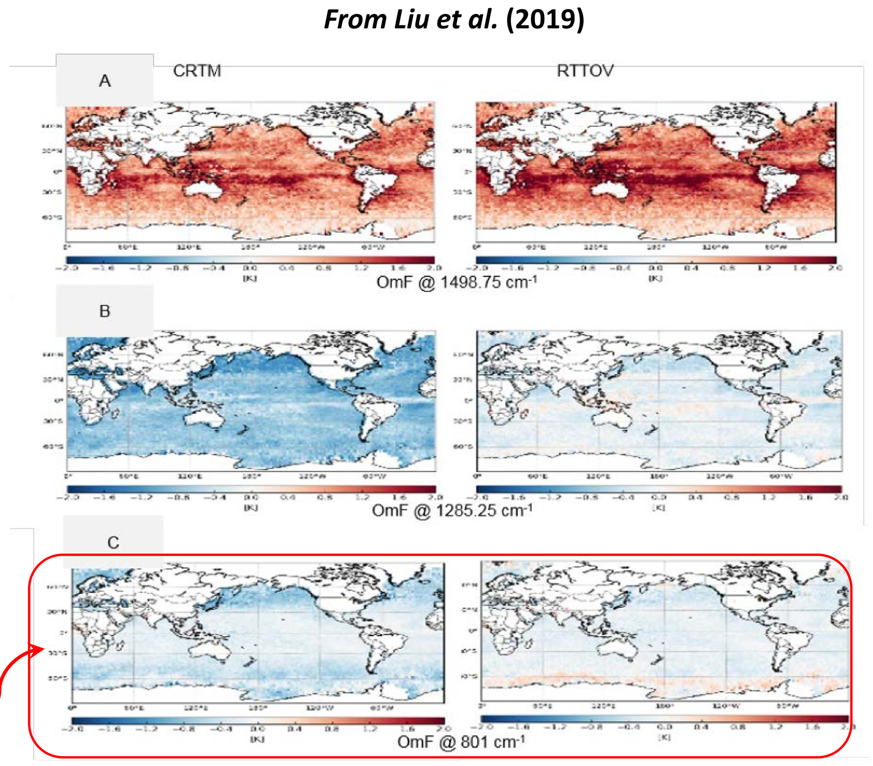
The retrieved Θ_e can then be used to derive the entire effective emissivity spectrum.

IRSSE Temperature Dependence

Temperature Dependence Found in Global Data

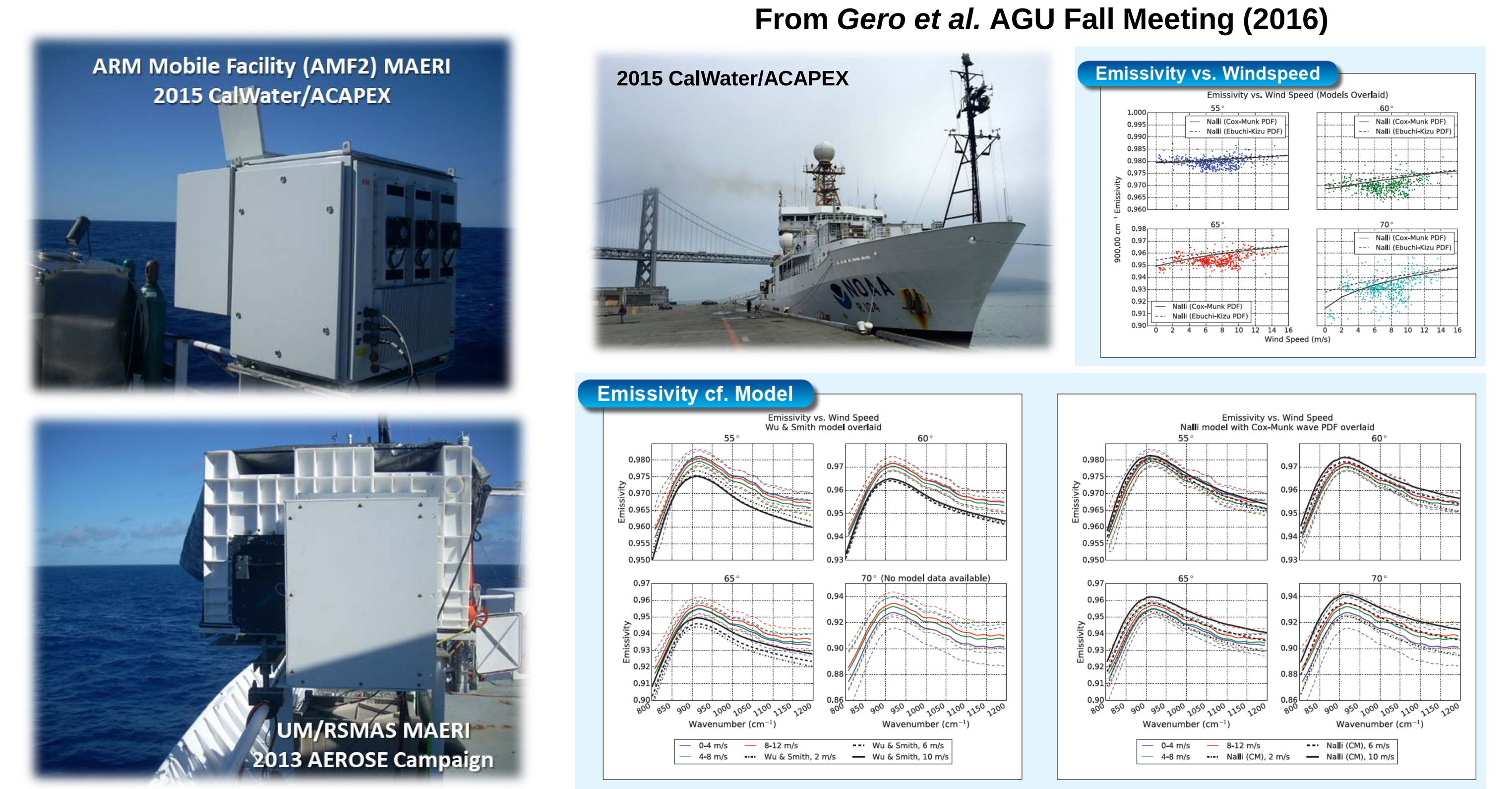
- **We were aware in 2008** of the **temperature dependence** of the **IR optical constants on IRSSE**
  - *Nalli et al.* (2008b): "In agreement with other recent work on the subject, we found a significant temperature dependence, which, if unaccounted for, can lead to spectral SLR errors of the same order of magnitude as those we have sought to correct. Therefore, additional work is desirable to derive an optimal seawater refractive index dataset…"
  - Unfortunately, however, this work was **not supported** at the time
- However, **recent findings of *Liu et al.* (2019)** have shown a significant **systematic bias** (on the order of **0.5 K**) on a **global scale**, thus bringing this issue back into focus for support

From *Liu et al.* (2019)



IRSSE Model Validation Plan

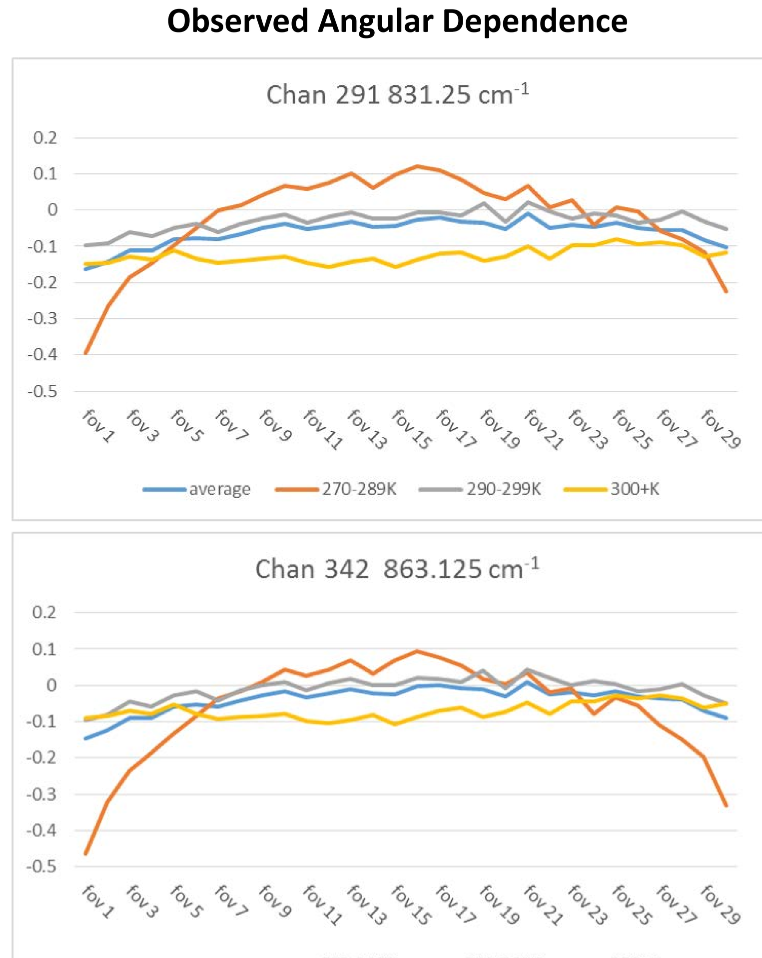
From *Gero et al.* AGU Fall Meeting (2016)



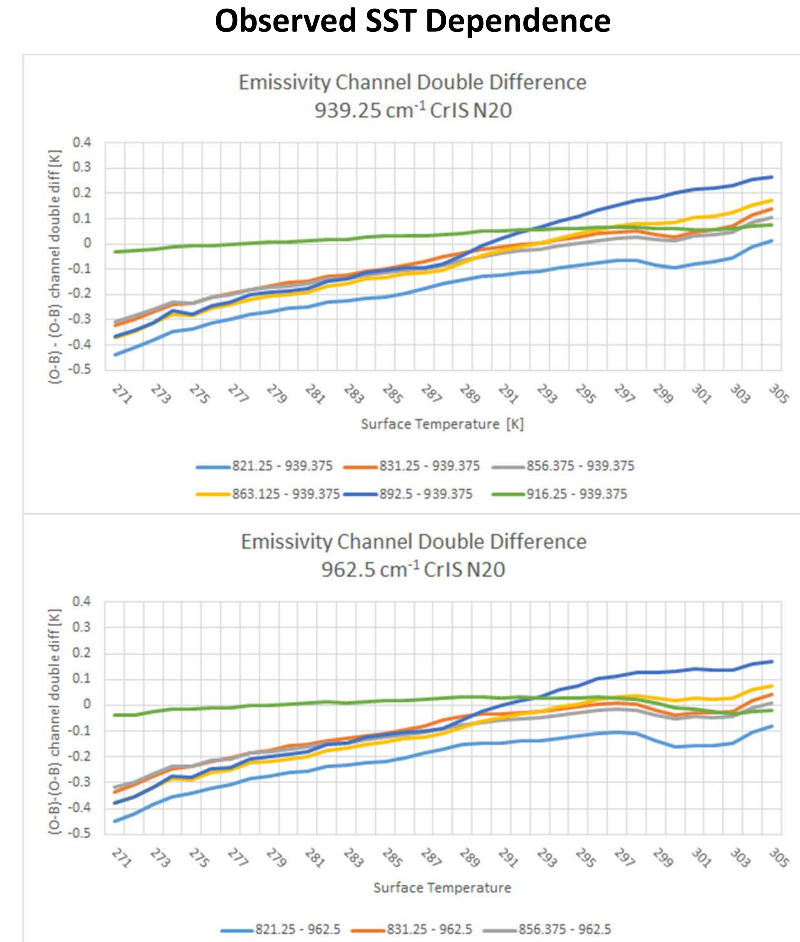
Observed and Modeled Global Scale Impact of Temperature: Global Double Differences

- **2-weeks global NOAA-20 CrIS data (OBS) versus CRTM model calculations (CALC)**
- Shown are microwindow-channel double-differences of OBS – CALC in regions of varying surface temperature dependence observed in the IR spectrum
- The **double-differences** serve to place control on the unknown atmospheric path uncertainties (e.g., model bias, cloud contamination, H_2O errors, etc.)
- **Significant surface-temperature dependence** is clearly visible **on the order of >0.5 K**
  - This is of **first order significance** within the context of the total forward model uncertainty

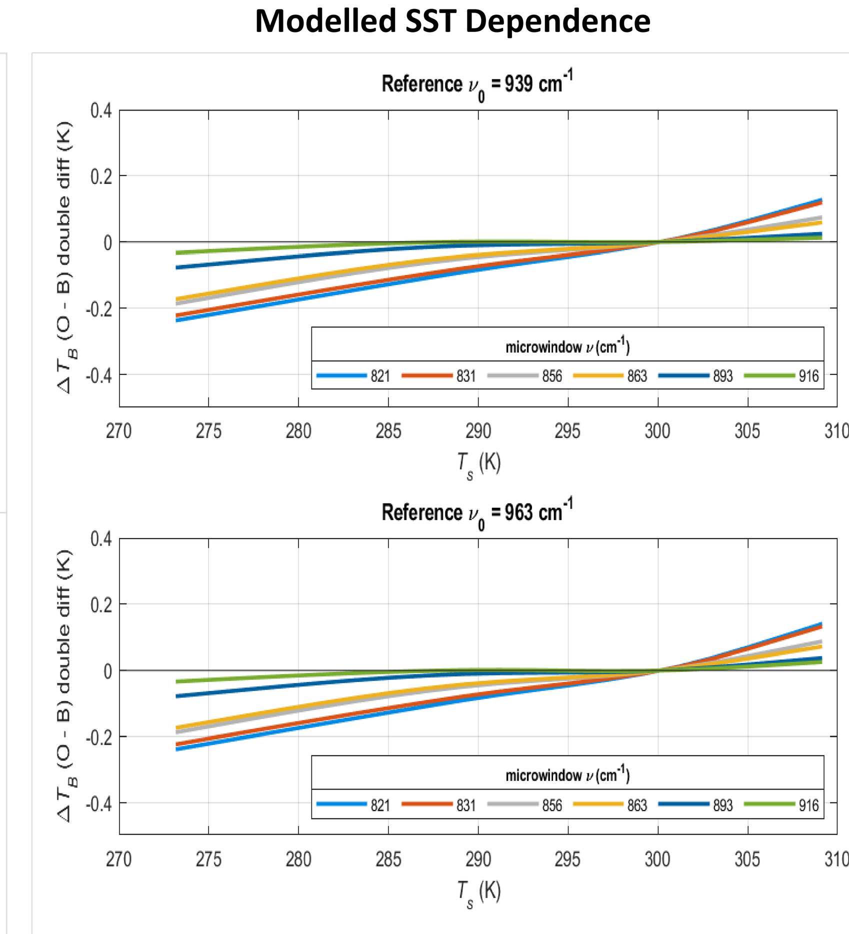
Observed Angular Dependence



Observed SST Dependence



Modelled SST Dependence



Potential SARTA Implementation

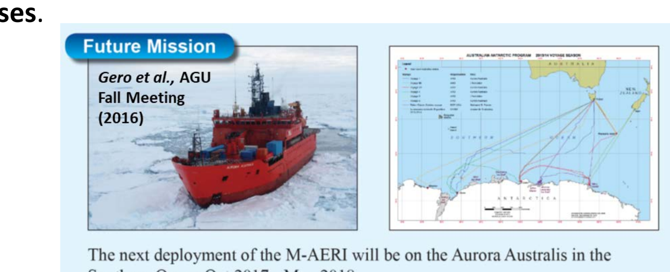
- We plan to **extend this effort toward an upgrade of the ocean emissivity used by SARTA.**
  - We will explore implementing the IRSSE model within an offline experimental SARTA version in collaboration with UMBC.
- **SARTA** implementation would require modification of the "Reflected Downwelling Thermal Radiance" term.
  - According to *Strow et al.* (2003), an **approximation** is used (based on *Kornfield & Susskind* 1977) that may "require further improvements":

    $$r_\nu(\theta) \approx \pi\rho_\nu^F B_\nu(T_\nu)\left[1 - \mathcal{T}_{\nu s}(\theta)\right] F_\nu(\theta)$$

  - It should be reasonably straightforward to conduct a test replacing this Lambertian approximation within SARTA for the "Reflected Downwelling" over oceans to implement the effective-emissivity (with temperature dependence) upgrade.

Summary and Future Work

- Ocean surface IR emissivity depends on wavenumber, zenith angle, surface wind speed, and **surface temperature.**
  - Temperature dependence arises from changes in the **IR refractive indices**
- Most models incorporate only the first 3 variables
- Furthermore, most models do not explicitly treat the **quasi-specular reflected** downwelling atmospheric radiance.
- We are currently working on upgrading the **CRTM IRSSE (effective emissivity) model** to **include temperature dependence**
  - The model will be conveniently rendered as **4-D** (instead of 3-D) **lookup tables (LUT)** (NetCDF or MATLAB format)
  - We plan to have the **preliminary test model** ready this fall, with testing to commence after that
  - Pending successful results, the theoretical model will then be **parameterized and implemented within CRTM release version**
  - We will continue our collaboration with UW/CIMSS and UM/RSMAS **using MAERI data**, including **cold-water cruises**.



The next deployment of the M-AERI will be on the Aurora Australis in the Southern Ocean Oct 2017 - May 2018.

Acknowledgements

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- The **STAR NUCAPS Soundings Team** (C. Tan, K. Pryor, et al.)

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