Temperature dependence in IR sea surface emissivity (IRSSE): Model upgrade plans

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Outline

- **Ocean Reflectance and Emissivity**
  - Conventional Ocean Emissivity Models
  - Observed Underestimation of Surface-Leaving Radiance
- **Radiative Transfer Based Effective Emissivity**
  - Quasi-Specular Reflectance
  - IR Sea-Surface Effective-Emissivity (IRSSE) Model
- **Temperature Dependence**
  - Planned Upgrades to IRSSE Model
  - Validation Plan
    - MAERI Campaigns
    - Global Double-Differences
  - Possible application to SARTA?
- **Summary and Future Work**

Temperature dependence in IR sea surface emissivity

OCEAN REFLECTANCE AND EMISSIVITY

Ocean Reflectance and Emissivity

- 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

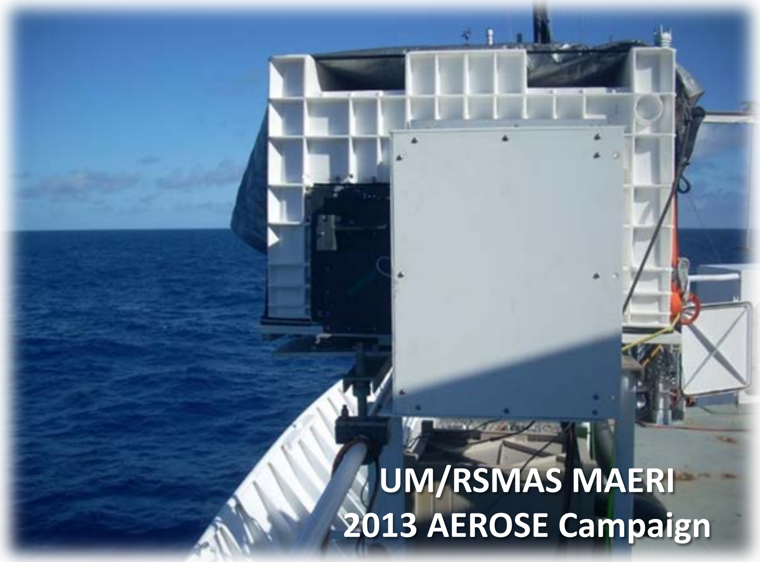
$$\begin{aligned}\overline{\epsilon}_\nu(\theta_0, N_\nu) &= 1 - \int_{\theta_n}\int_{\varphi_n} \rho_\nu(\theta_n, \varphi_n; \theta_0; N_\nu)\, P(\theta_n, \theta_0; \sigma_s^2)\, d\varphi_n\, d\mu_n \\ &= 1 - \overline{\rho}_\nu(\theta_0, N_\nu)\,,\end{aligned}$$

- 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)

Marine Atmospheric Emitted Radiance Interferometer (MAERI)

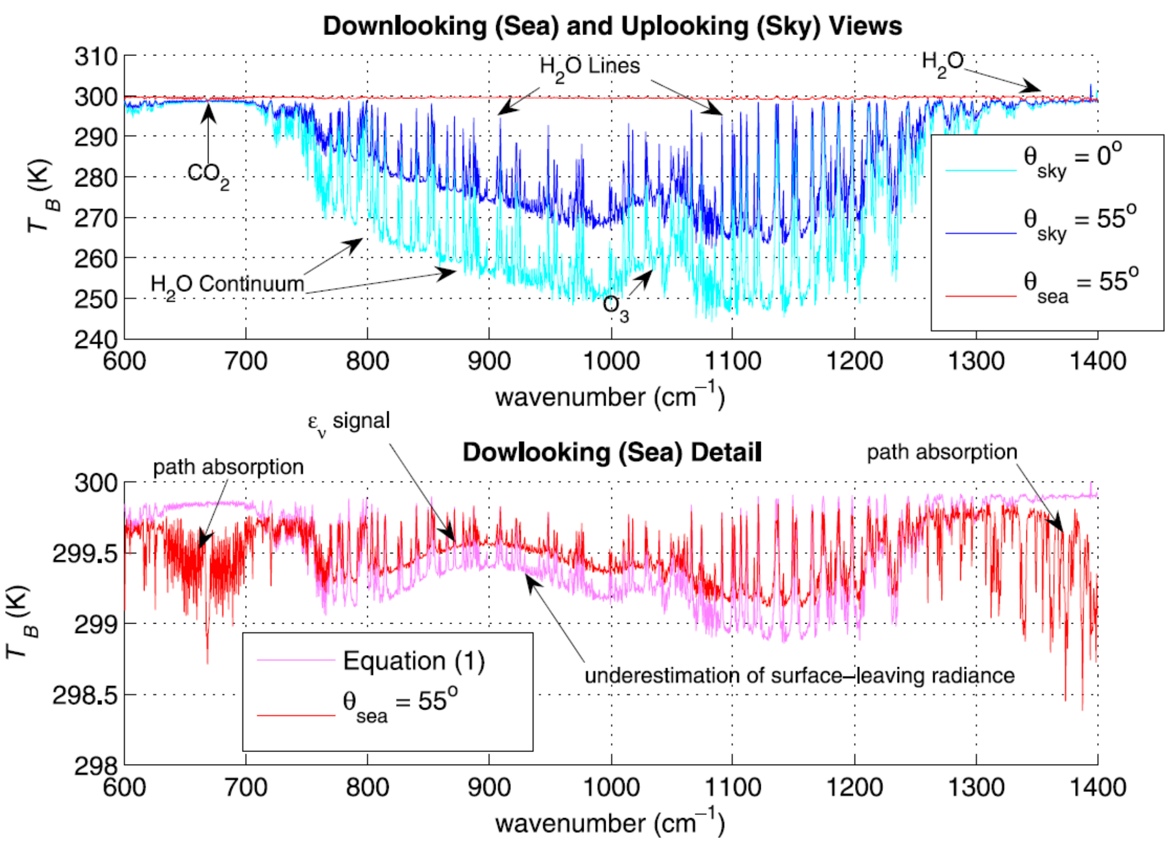
- **Ship-based FTS** designed to sample downwelling and upwelling IR high-resolution spectra near the surface (*Minnett et al.* 2001)
  - **High accuracy calibration** (e.g., *Revercomb et al.* 1988) is achieved using 2 NIST-traceable blackbodies
  - Original prototypes designed at **UW/SSEC**
  - First generation MAERIs were supported and deployed by UM/RSMAS
  - Second generation MAERIs have recently been developed and deployed by both UM/RSMAS and the **ARM Mobile Facility 2 (AMF2)**

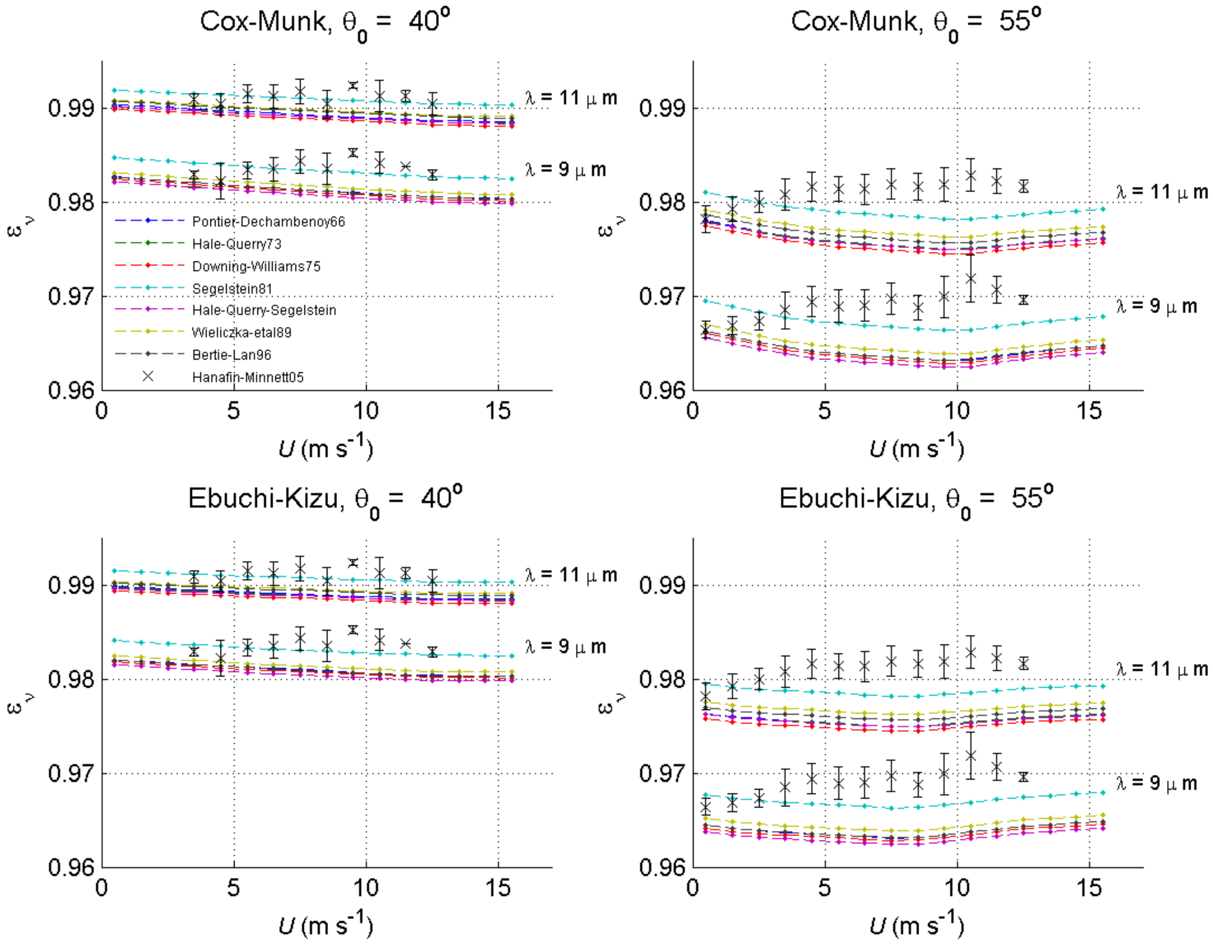
- Derived products include
  - **Radiometric skin SST** (0.1 K accuracy) derived from semi-opaque spectral region (≈7.7 µm) (*Smith et al.* 1996)
  - **Spectral emissivity**: the effective emission angle is iterated until the T_s spectral variance is minimized (*Smith et al.* 1996; *Hanafin and Minnett* 2005).



Observed Underestimation of Surface-Leaving Radiance

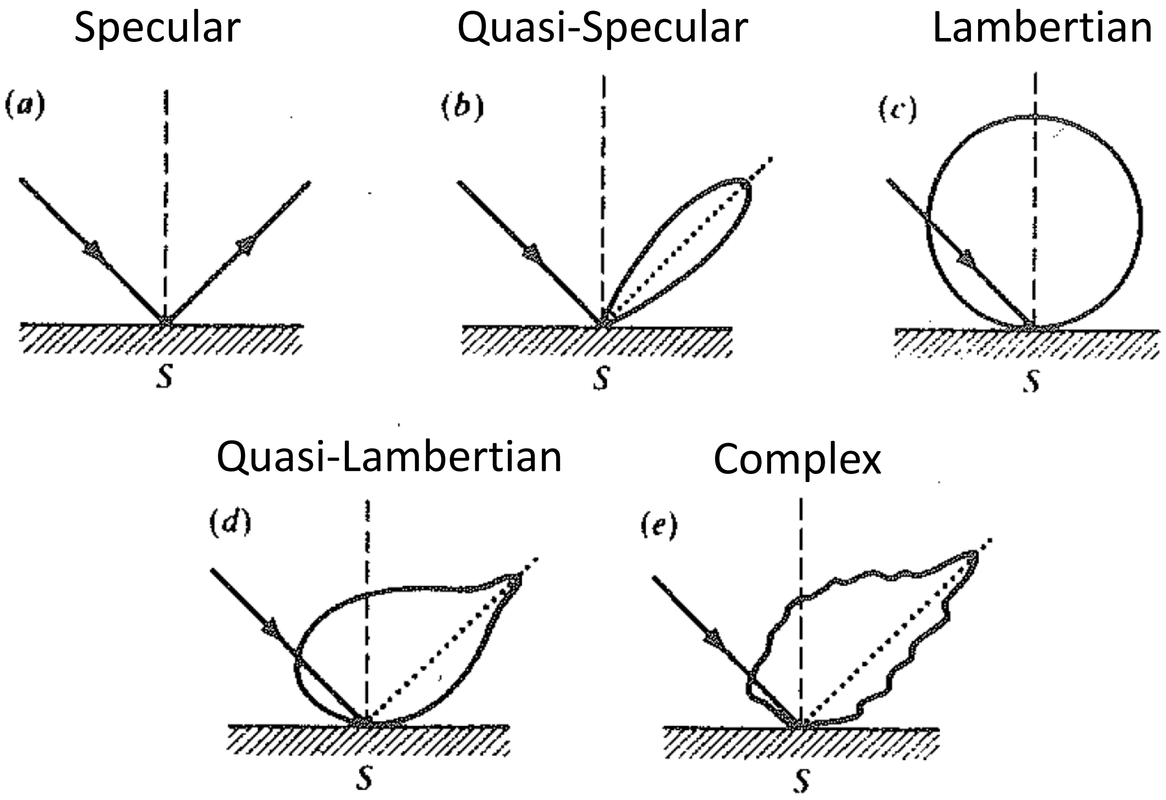
NALLI ET AL.: SHIP MEASUREMENTS FOR IR VALIDATION





Emissivity models are theoretically sound, so where's the culprit?

- **Approximation of multiple reflections**
  - Enhancement of emissivity in well-known analytical models includes only SESR radiation
  - Accounted for in Monte Carlo models (e.g., *Henderson et al.* 2003), but less convenient to implement
  - A second order effect ≈O(0.05) K, but today's hyperspectral IR sensors approach this accuracy
- **Incorrect specification of reflected atmospheric radiation**
  - 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***



From Stephens (1994)

$$[1 - \bar{\epsilon}_\nu(\theta_0)]\, I_\nu^{\downarrow}(\theta_0) \equiv \bar{\rho}_\nu(\theta_0)\, I_\nu^{\downarrow}(\theta_0) \;<\; \iint \rho_\nu(\theta_n, \varphi_n; \theta_0)\, I_\nu^{\downarrow}(\theta)\, P(\theta_n, \theta_0; \sigma_s^2)\, d\varphi_n\, d\mu_n$$

Quasi-Specular Ocean Reflection in the IR (1/2)

From *Cox and Munk* (1954)

November 1954 MEASUREMENT OF THE SEA SURFACE

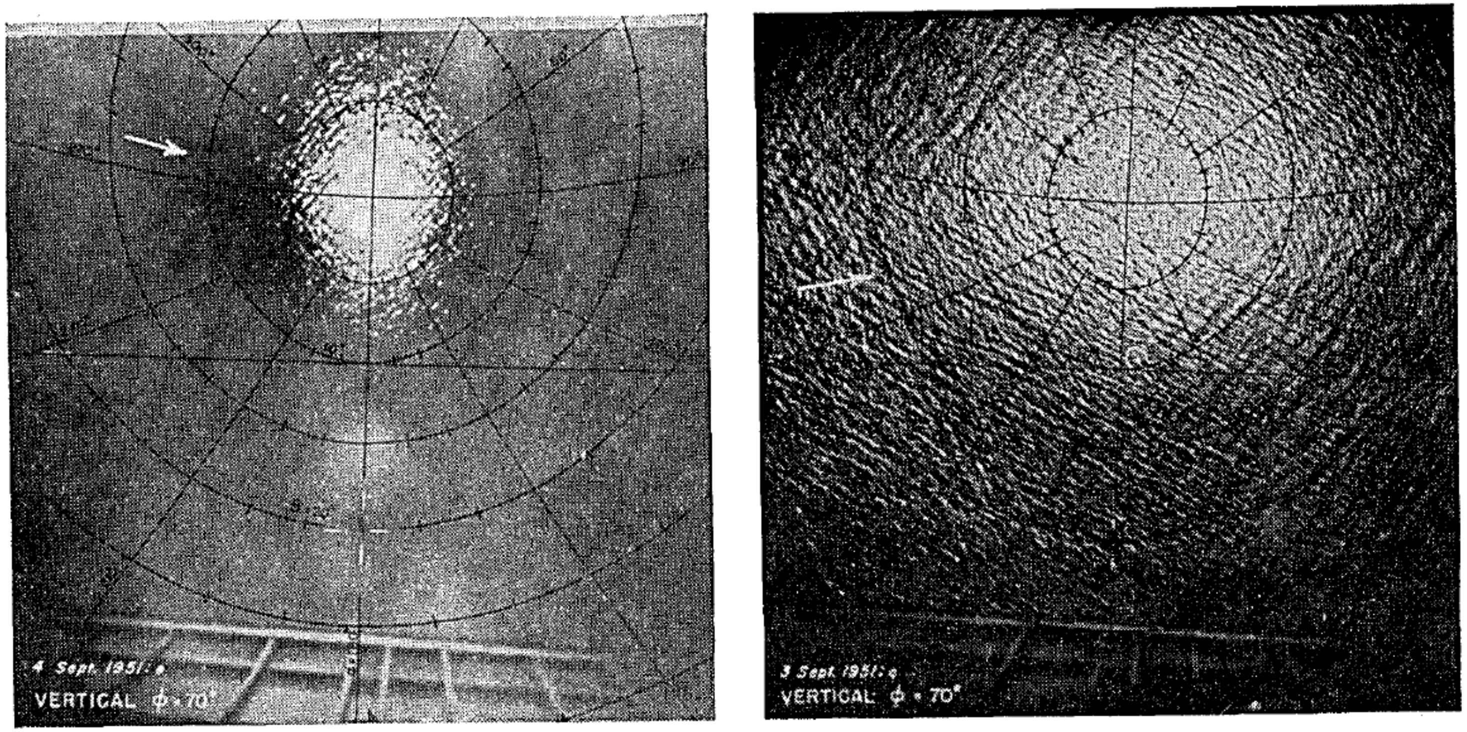
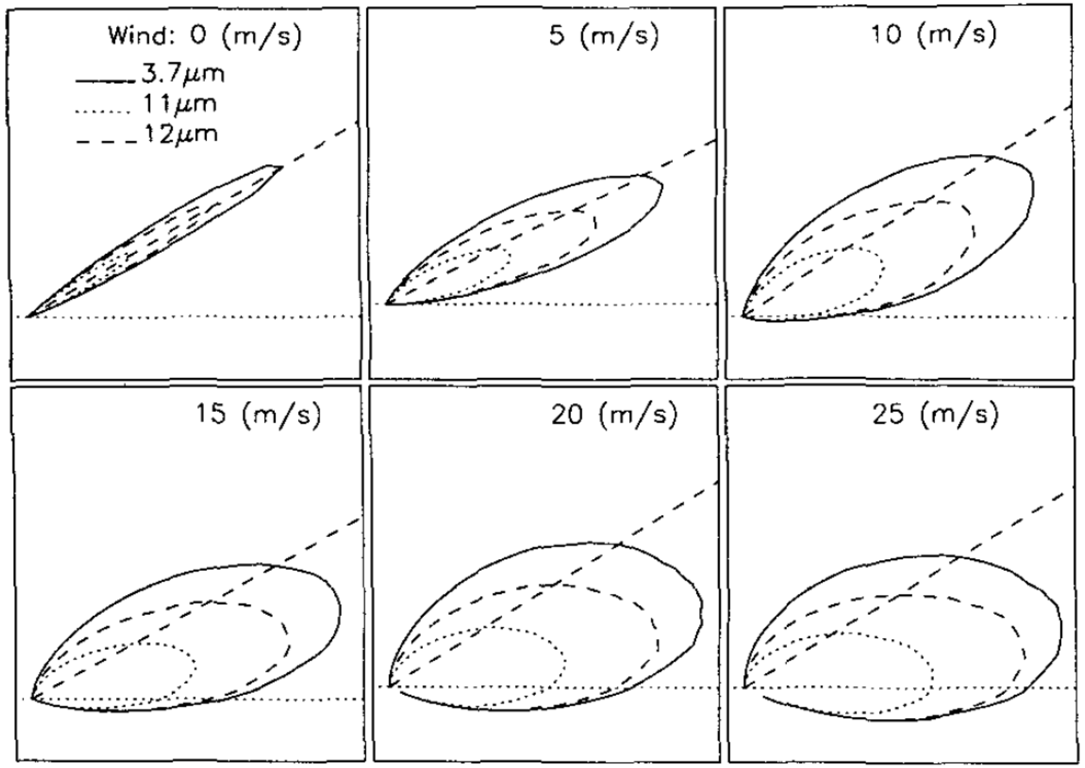


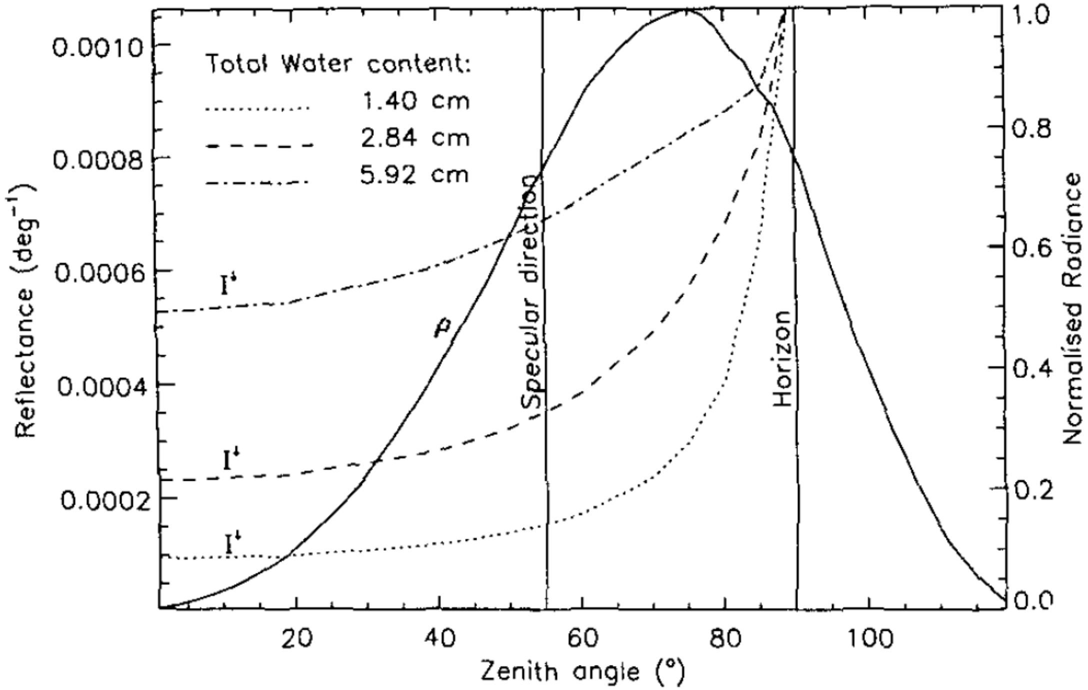
FIG. 1. Glitter patterns photographed by aerial camera pointing vertically downward at solar elevation of $\phi = 70°$. The superimposed grids consist of lines of constant slope azimuth α (radial) drawn for every 30°, and of constant tilt β (closed) for every 5°. Grids have been translated and rotated to allow for roll, pitch, and yaw of plane. Shadow of plane can barely be seen along $\alpha = 180°$ within white cross. White arrow shows wind direction. *Left:* water surface covered by natural slick, wind 1.8 m sec^{-1}, rms tilt $\sigma = 0.0022$. *Right:* clean surface, wind 8.6 m sec^{-1}, $\sigma = 0.045$. The vessel *Reverie* is within white circle.

Quasi-Specular Ocean Reflection in the IR (2/2)

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



Surface Reflectivity and Downwelling Atmospheric Radiance as Function of Zenith Angle
(*Watts et al.* 1996)



Figures from Watts et al. (1996)

Temperature dependence in IR sea surface emissivity

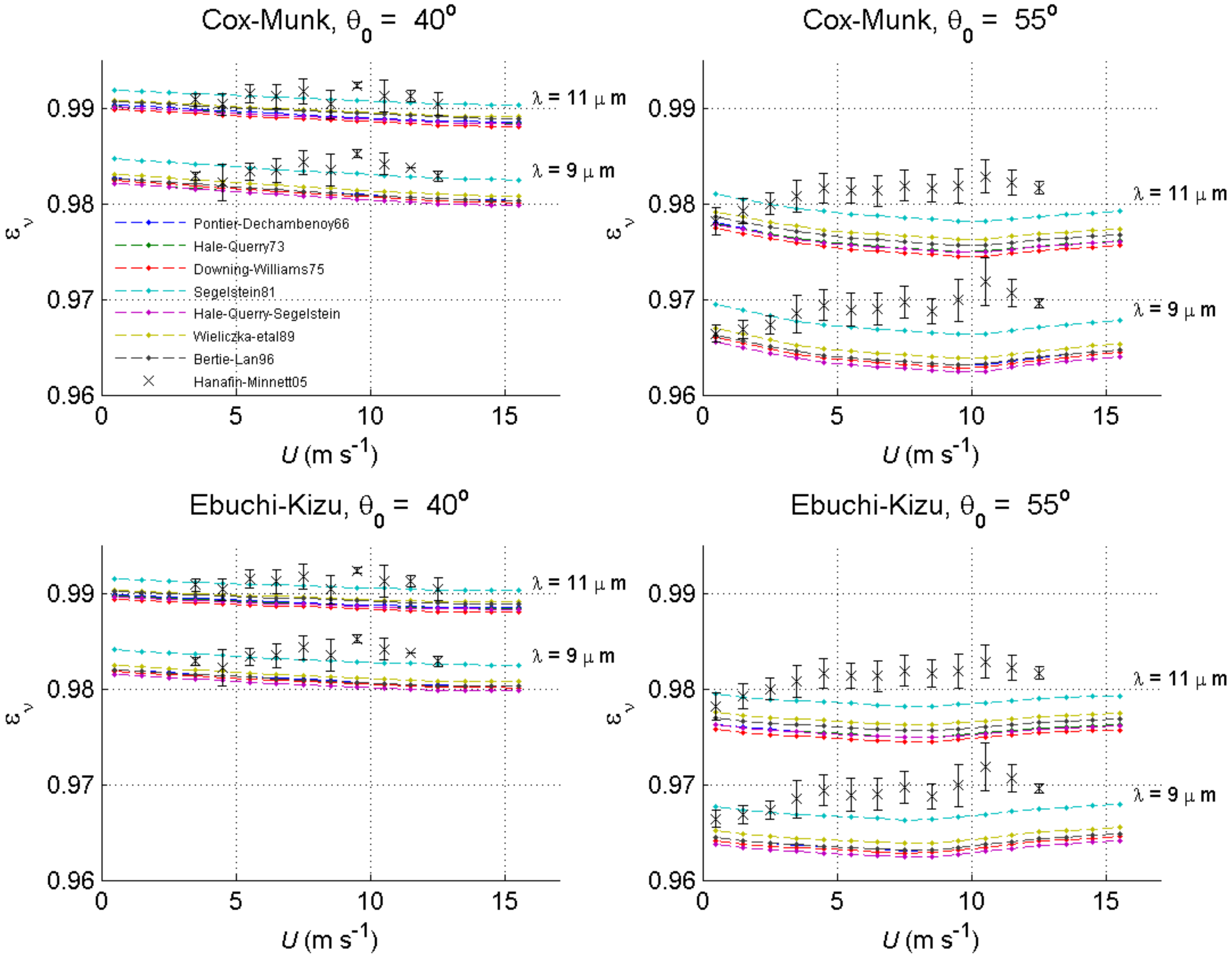
EFFECTIVE EMISSIVITY

Radiative Transfer-Based Effective Emissivity

- **Effective emissivity** is the guiding principle behind **cavity blackbodies** (e.g., *Prokhorov* 2012) commonly used for calibration of IR sensors.
  - A cavity's surface is **not** inherently black
  - However, it is the cumulative effect of emission and reflection off the surface that **enhances** the ***effective emissivity*** of the cavity
    - Thus, while the "optical emissivity" of the cavity is non-black, it nevertheless **appears black to the sensor**, which is ultimately all we care about
    - The sensor does **not** discriminate between directly emitted or multiply reflected contributions to the radiance
  - The **same principle holds for any natural rough surface**, including the sea surface — **reflection of radiance effectively enhances the apparent emissivity of the surface**
- A handful of previous investigators sought **practical solutions** to the **quasi-specular problem** (*Watts et al.* 1996; *Nalli et al.* 2001), but these ultimately were not satisfactory for existing operational algorithms and models (e.g., CRTM)
- **JSCDA and STAR** thus supported in-house FY05 and FY06 research to find a workable solution for application to the CRTM
- This JSCDA-funded 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 the quasi-specular reflection problem in a practical manner

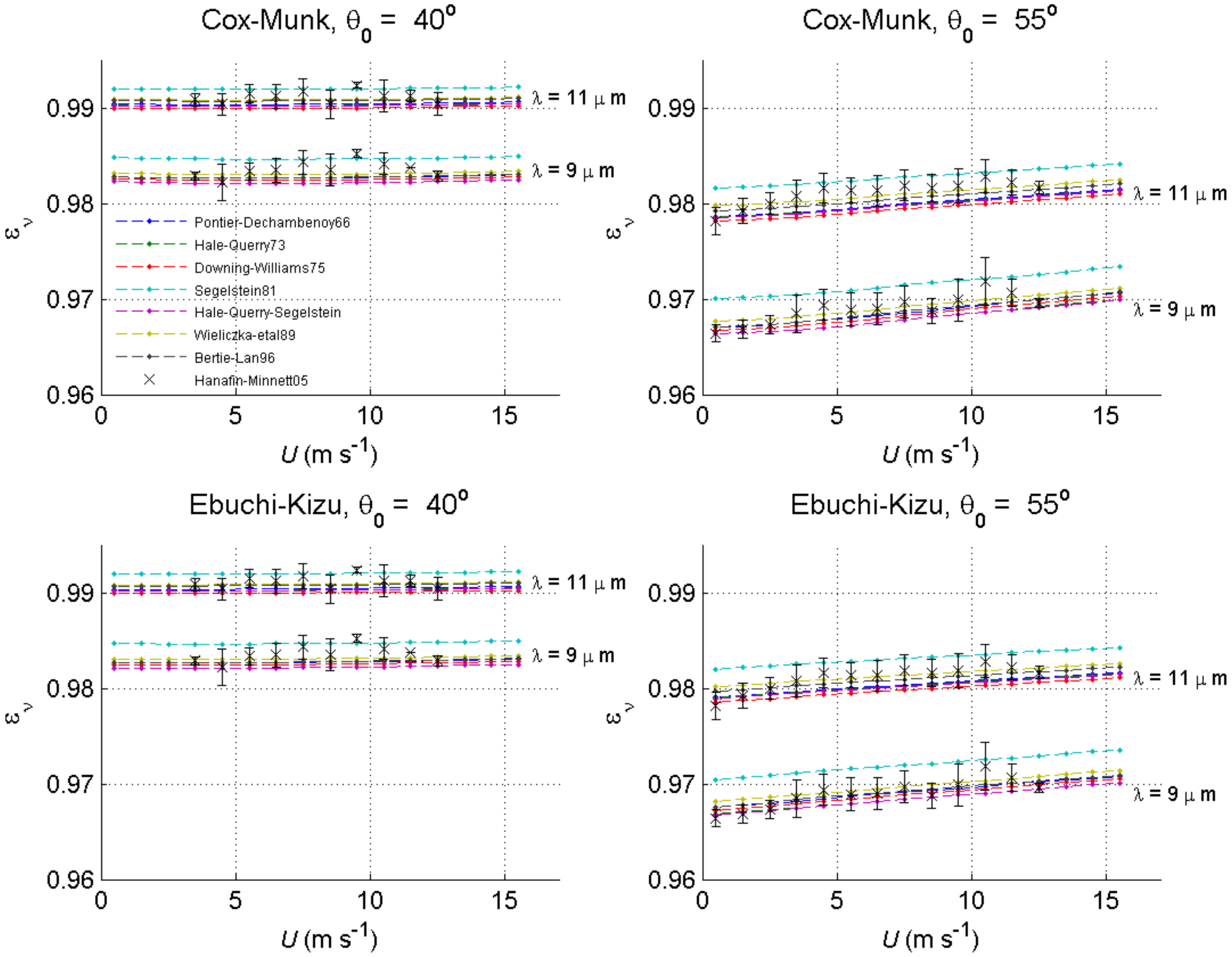
Calculated Emissivity versus MAERI-1 Observation

***Masuda* (2006) Model vs *Hanafin and Minnett* (2005) MAERI observations**



Calculated Effective Emissivity MAERI-1 Observation

Nalli et al. **(2008) IRSSE Model vs *Hanafin and Minnett* (2005) MAERI observations**



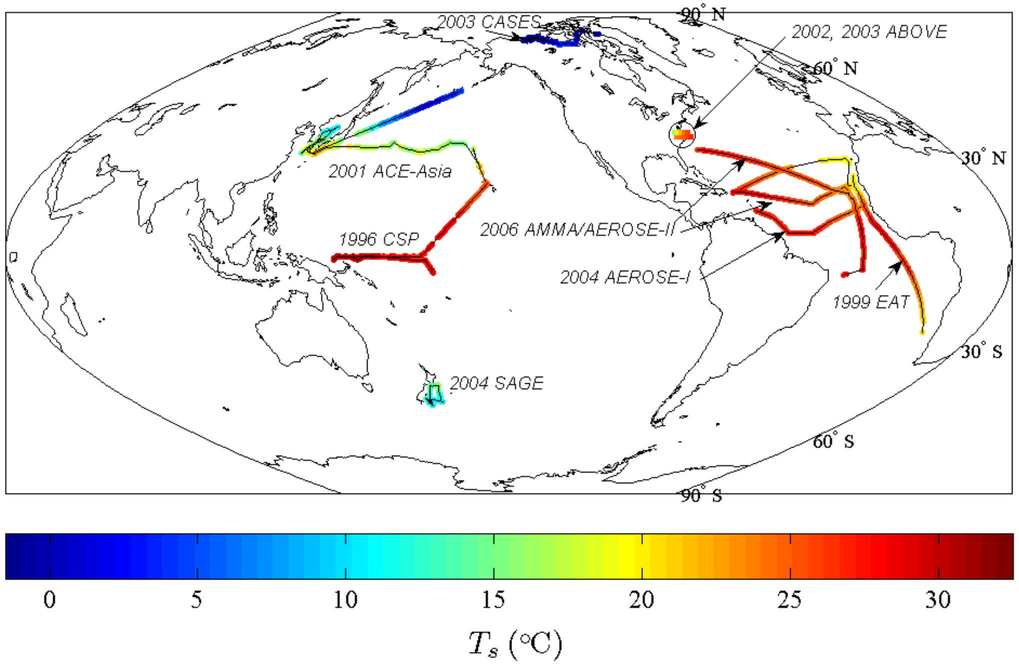
Temperature dependence in IR sea surface emissivity

TEMPERATURE DEPENDENCE

MAERI Surface-Leaving Radiance Measurements

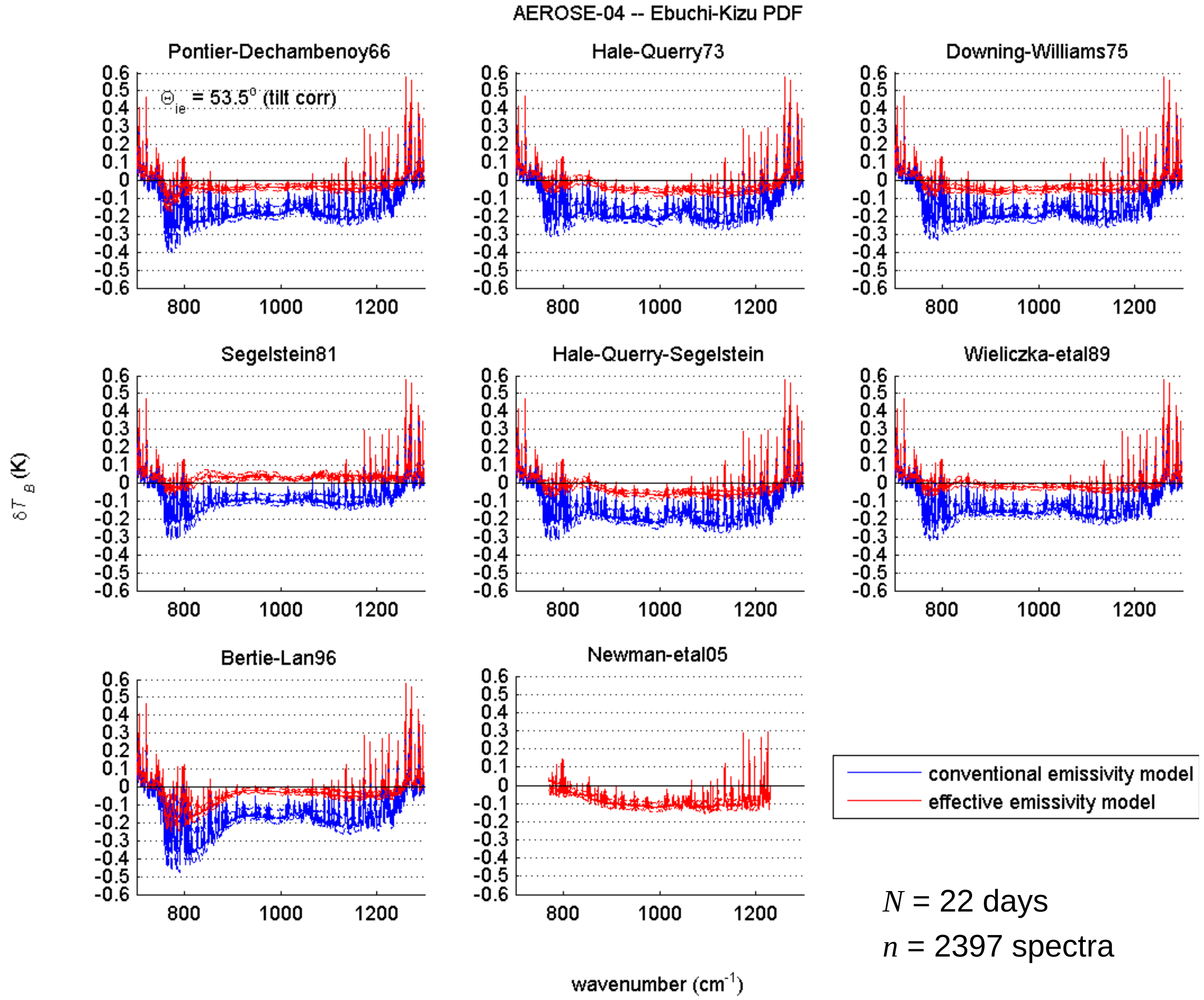
- For model validation, an exhaustive sample of **MAERI** and **BBAERI** radiances were used from several intensive field campaigns:
  - 1996 Combined Sensor Program (CSP) (*Post et al.* 1997)
  - 1999 East Atlantic Transect (EAT)
  - 2001 Asian Pacific Regional Aerosol Characterization Experiment (ACE-Asia)
  - 2002, 2003 AIRS BBAERI Ocean Validation Experiment (ABOVE)
  - 2003 Canadian Arctic Shelf Exchange Study (CASES)
  - 2004 Aerosol and Ocean Science Expedition (AEROSE-I) (*Nalli et al.* 2006)
  - 2004 Surface-Ocean Lower-Atmosphere Studies Air-sea Gas Experiment (SAGE)
  - 2006 African Monsoon Multidisciplinary Analysis (AMMA) AEROSE-II (*Morris et al.* 2006)

- Unlike prior limited studies, these data included varying **all-sky atmospheric conditions** (clear, cloudy and dusty), with **regional samples** from the **tropics**, **midlatitudes** and **high latitudes**.



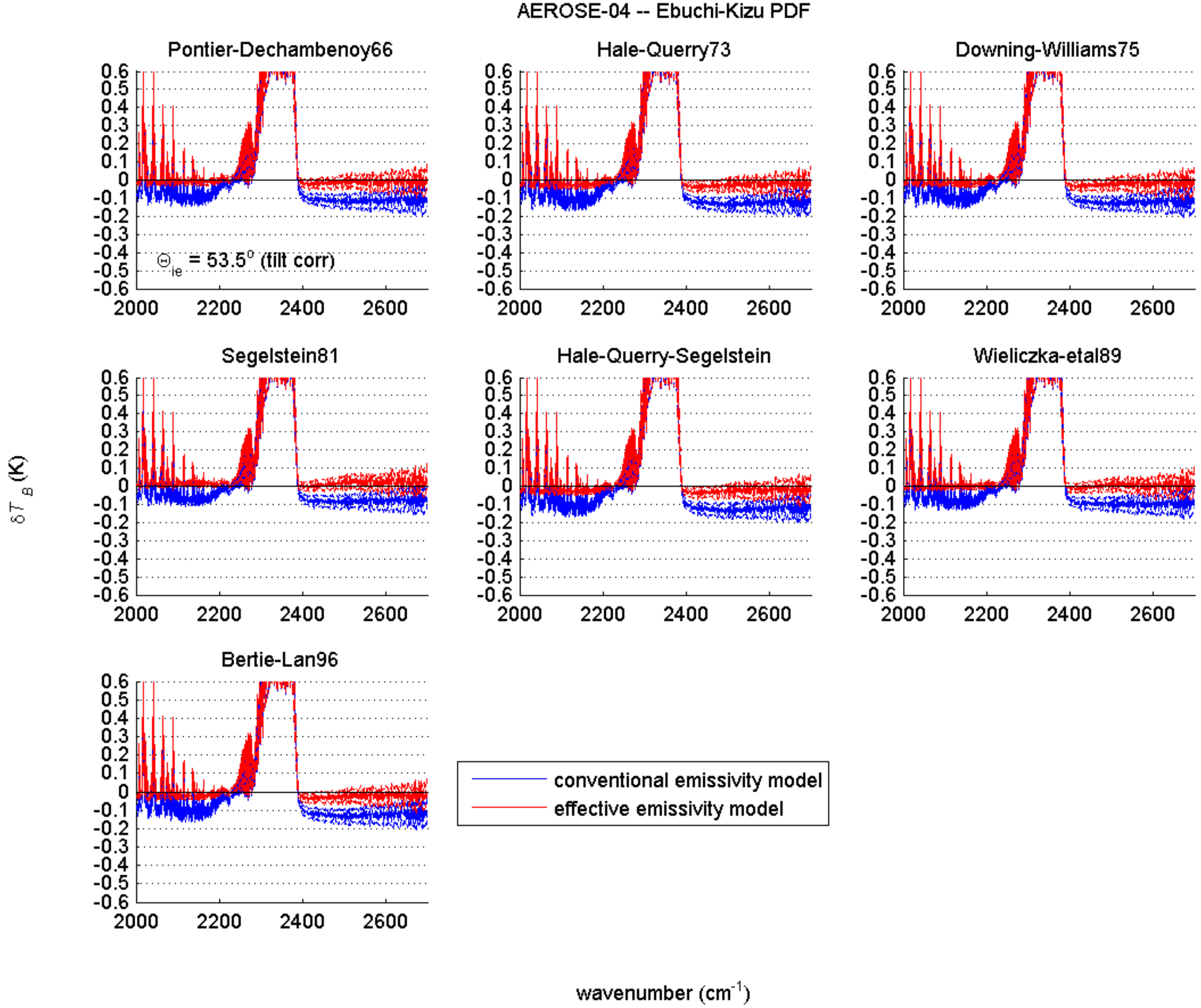
AEROSE 2004 (UM/RSMAS MAERI-1)

LWIR 55°

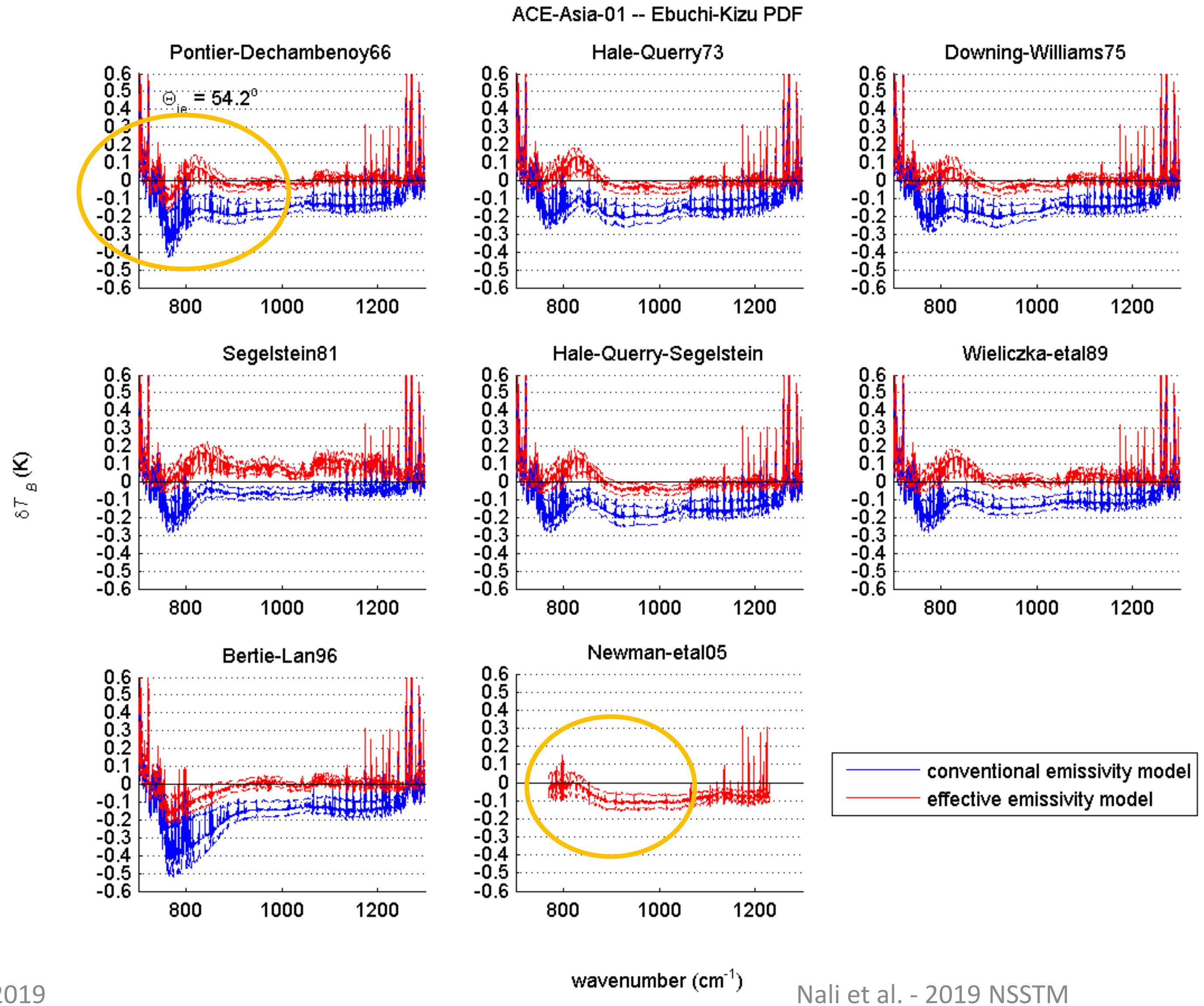


N = 22 days
n = 2397 spectra

SWIR 55°



ACE-Asia 2001 (UM/RSMAS MAERI-1)

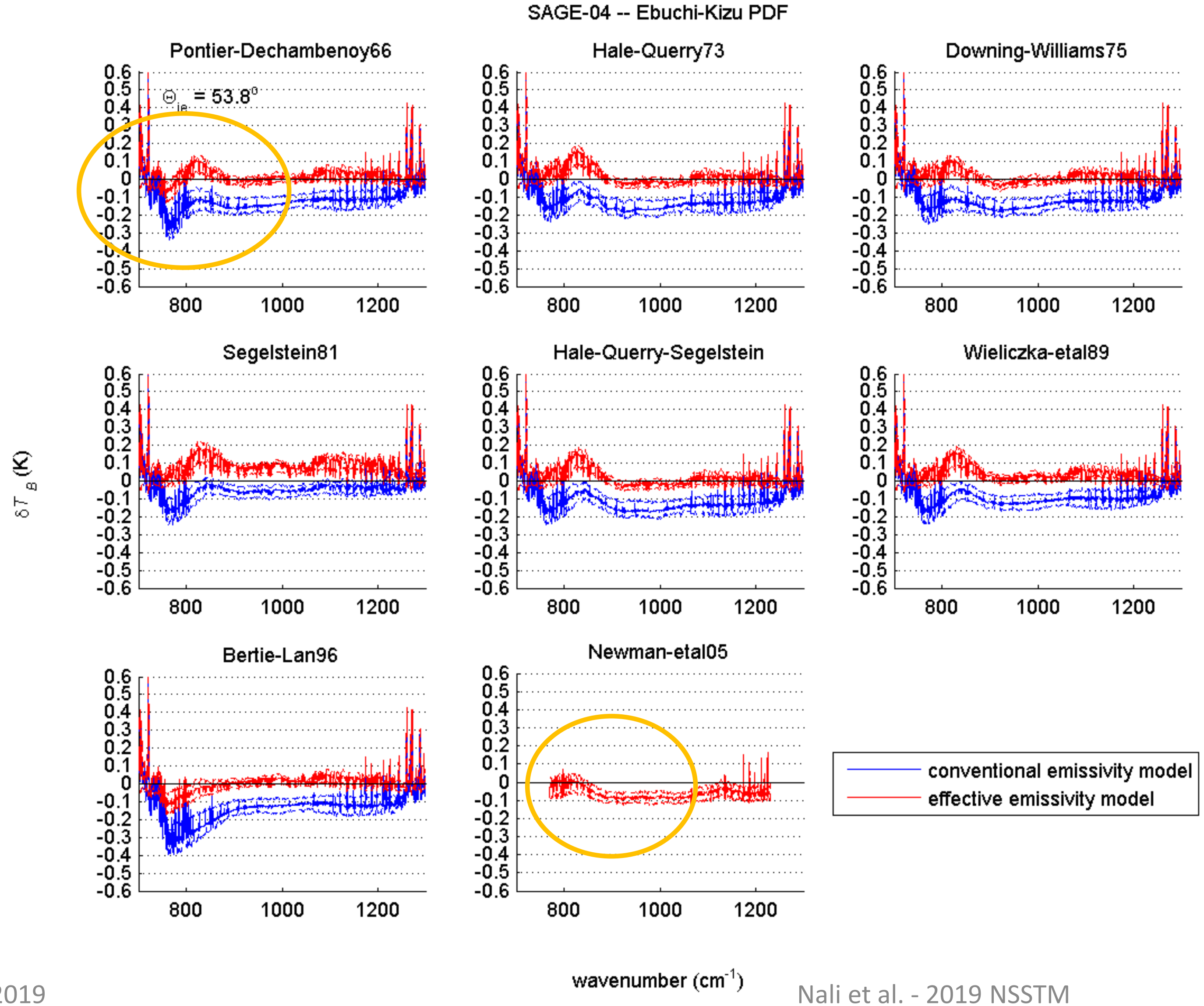


LWIR 55°

N = 38 days

n = 4434 spectra

SAGE 2004 (UM/RSMAS MAERI-1)

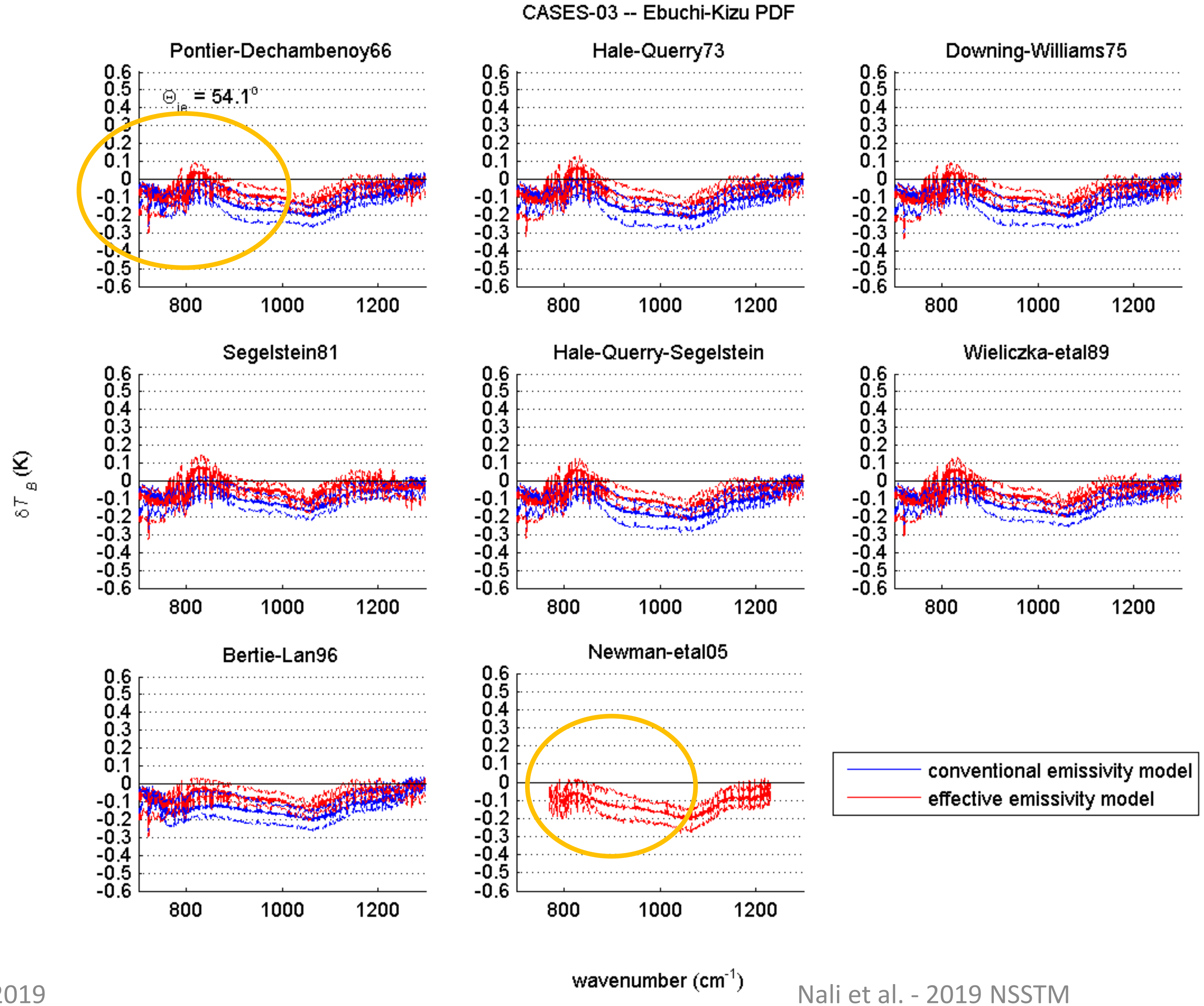


LWIR 55°

N = 25 days

n = 2293 spectra

CASES 2003 (UM/RSMAS MAERI-1)



LWIR 55°

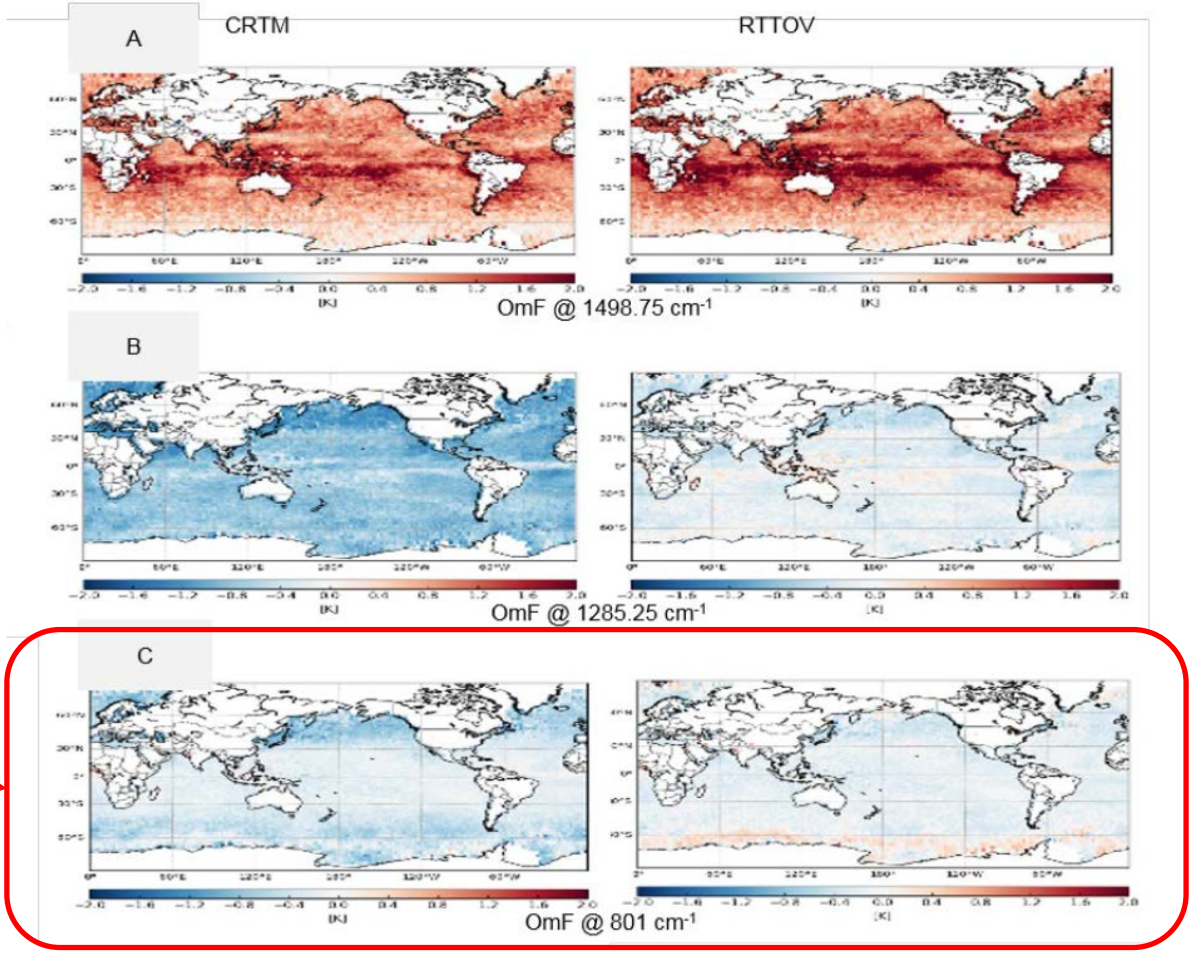
N = 8 days

n = 643 spectra

Temperature Dependence Found in Global Data

- **We were thus 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

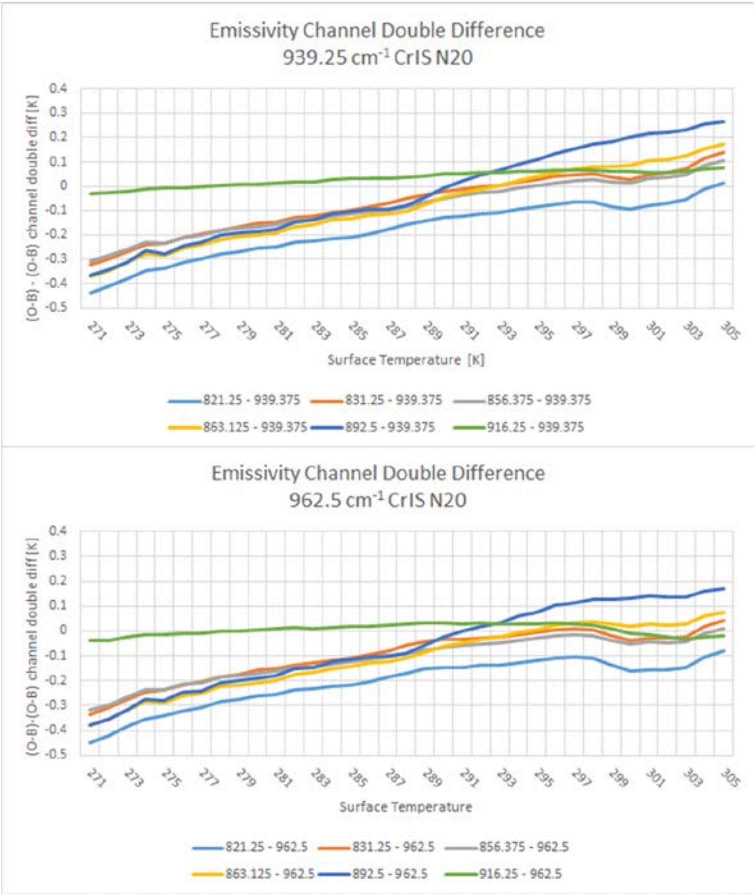
From Liu et al. **(2019)**



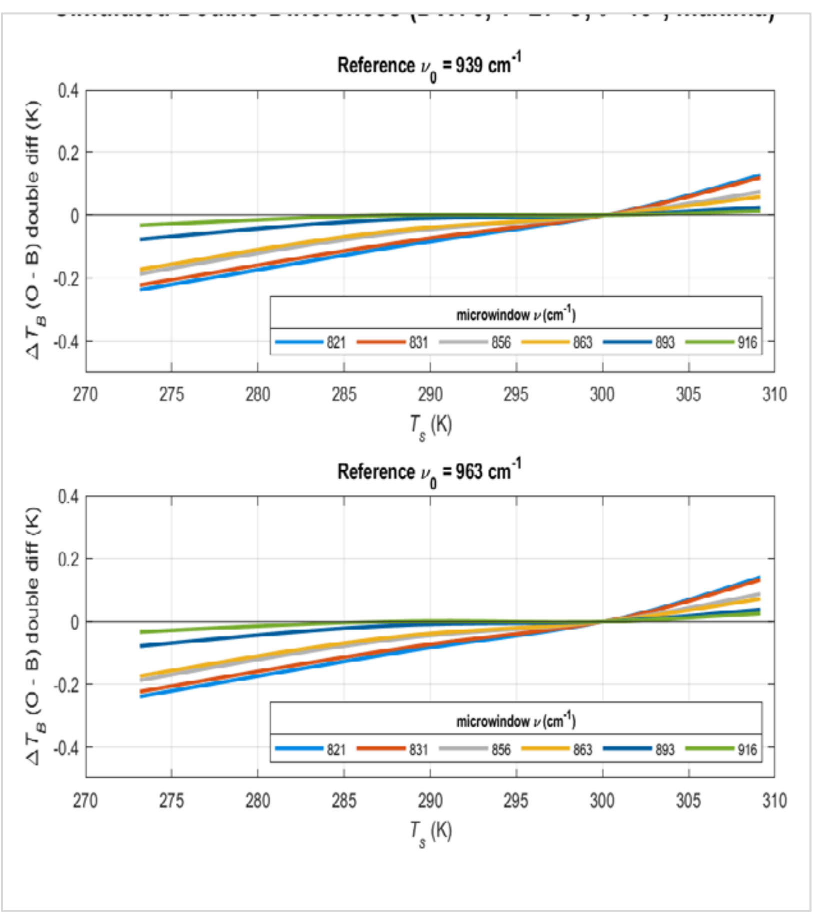
Observed and Modeled Global Scale Impact of Temperature

- **Global OBS – CALC 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 Global Double-Differences



Simulated Global Double-Differences



IRSSE Model Upgrade

- **JCSDA** has agreed to support an **upgrade to the CRTM IRSSE model** as part of their **2019 Annual Operating Plan** to include **surface temperature dependence** along with some other misc upgrades.
- After further discussions, it was realized that there would be an opportunity to **extend this effort toward an upgrade of the ocean emissivity used by SARTA.**
  - **Tong Zhu is a CRTM developer** who has been familiar with the IRSSE model upgrade plans and is now on the NUCAPS team.
  - **Scott Hannon** had expressed interest when I presented the model at the 2007 AIRS Science Team Meeting
    - To my knowledge the SARTA IRSSE model hasn't been modified significantly since before 2003

- **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”:

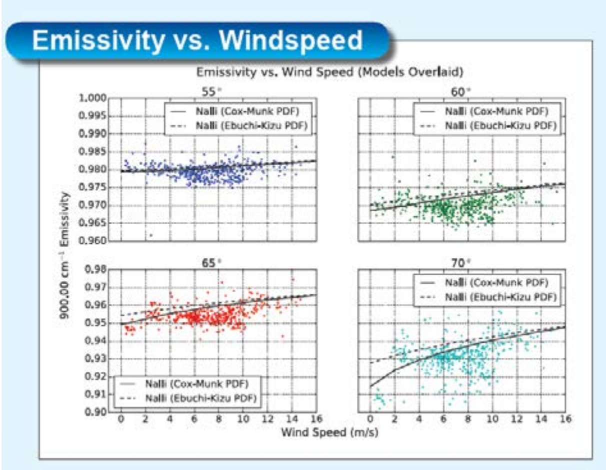
$$r_\nu(\theta) \approx \pi \rho_\nu^F B_\nu(T_\nu)[1 - \mathcal{T}_{\nu s}(\theta)]F_\nu(\theta)$$

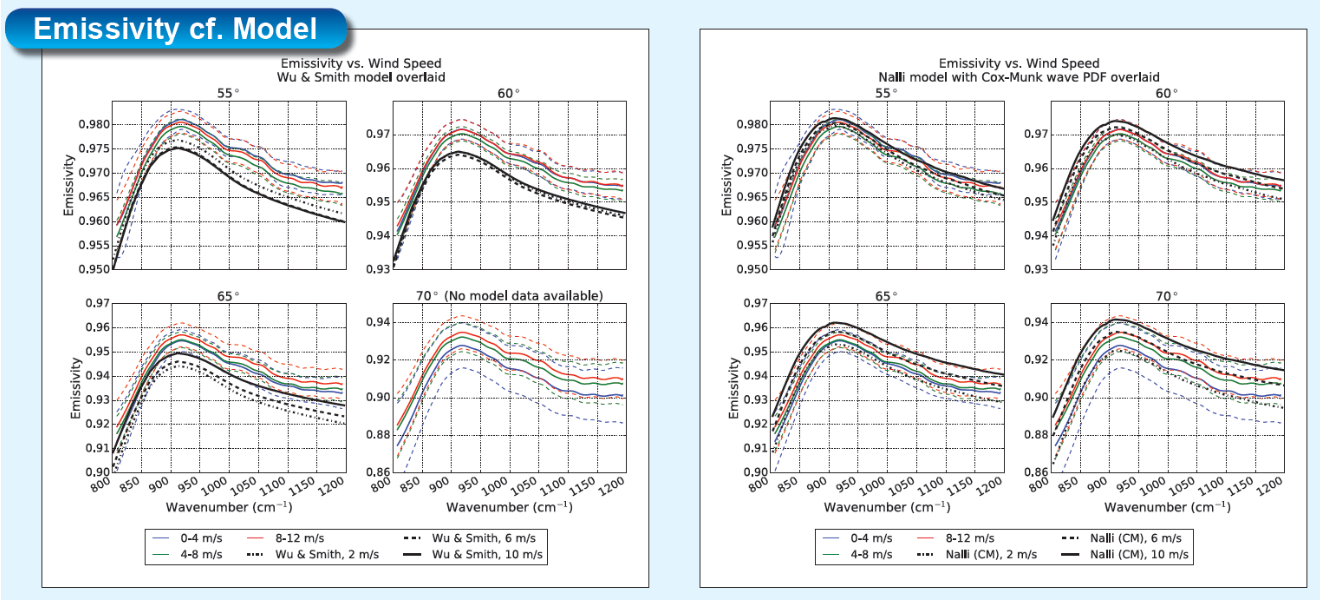
  - It should be reasonably straightforward to conduct a test replacing this Lambertian approximation within SARTA for the “Reflected Downwelling” over oceans to implement the effective-emissivity (with temperature dependence) upgrade.

Validation Plan (1/2): MAERI Campaigns

2015 CalWater/ACAPEX

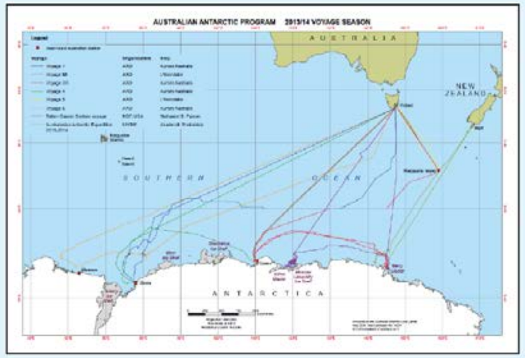
NOAA Ship *Ronald H. Brown*





From *Gero et al.*

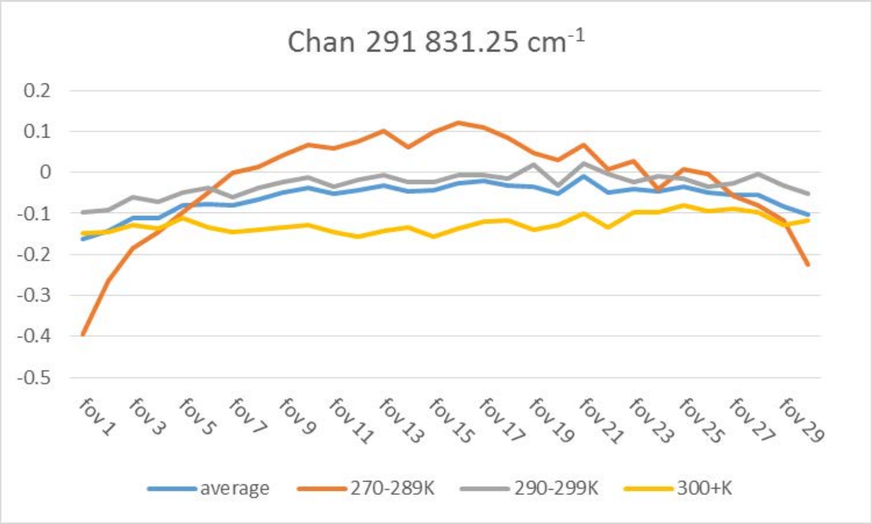
AGU Fall Meeting (2016)

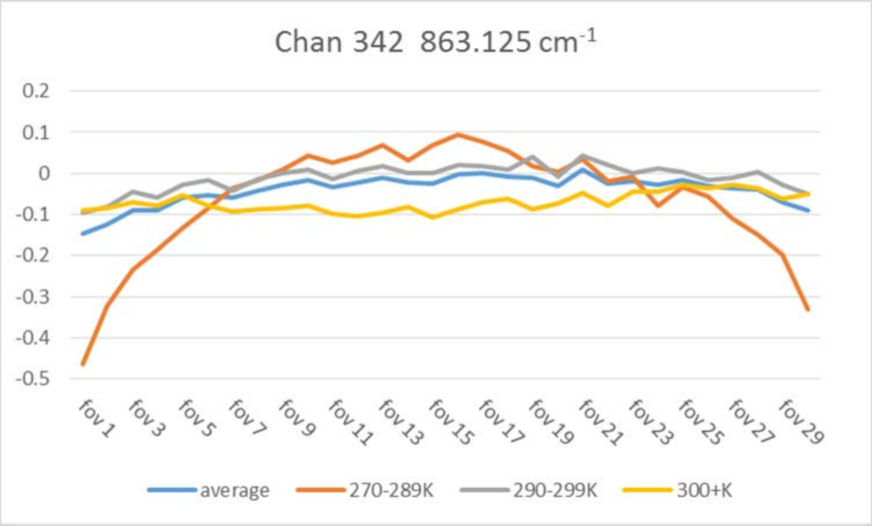


The next deployment of the M-AERI will be on the Aurora Australis in the Southern Ocean Oct 2017 - May 2018.

- We will continue our collaboration with UW/CIMSS and UM/RSMAS using MAERI data, including cold-water cruises.

Validation Plan (2/2): Global Simulation and Observed Double-Differences





- **Observed Angular Impact**
  - 17 March – 30 March 2019
  - CrIS-FSR NOAA-20
    - 8 channels from 431 subset
    - 275 (821.25), 291 (831.25), 332 (856.375), 342 (863,125), 389 (892.5), 427 (916.25), 464 (939.375), 501 (962.5)
  - Clear profiles derived from VIIRS cloud amount in CrIS BUFR
  - Observations – Background (6 hour fcst)
    - Values are residuals using current operational IRSSE
  - Observations grouped into 3 categories
    - 270K – 289K
    - 290K – 299K
    - 300K +
  - Colder SST tend to have larger scan angle residuals.

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**
  - We will also explore implementing the model within an **offline experimental SARTA version** with UMBC

Acknowledgements

- This work is supported by **JCSDA** Annual Operating Plan 2019 (Kevin Garrett) and the **JSTAR** Cal/Val Program (Arron Layns and Lihang Zhou).
- **MAERI** data are provided to us by UM/RSMAS (Peter Minnett et al.) and UW/CIMSS (Bob Knuteson, Jon Gero, et al.)

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THANK YOU! QUESTIONS?

Temperature dependence in IR sea surface emissivity

BACK-UP SLIDES