Development and Implementation of a Physical Thermal-to-Far Infrared (TIR-FIR) Emissivity Model for Uniform Snow Surfaces within CRTM

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  - Field data from polar and winter campaigns to be used in validation are provided by **UW/CIMSS** (*M. Loveless, Jon Gero et al.*)
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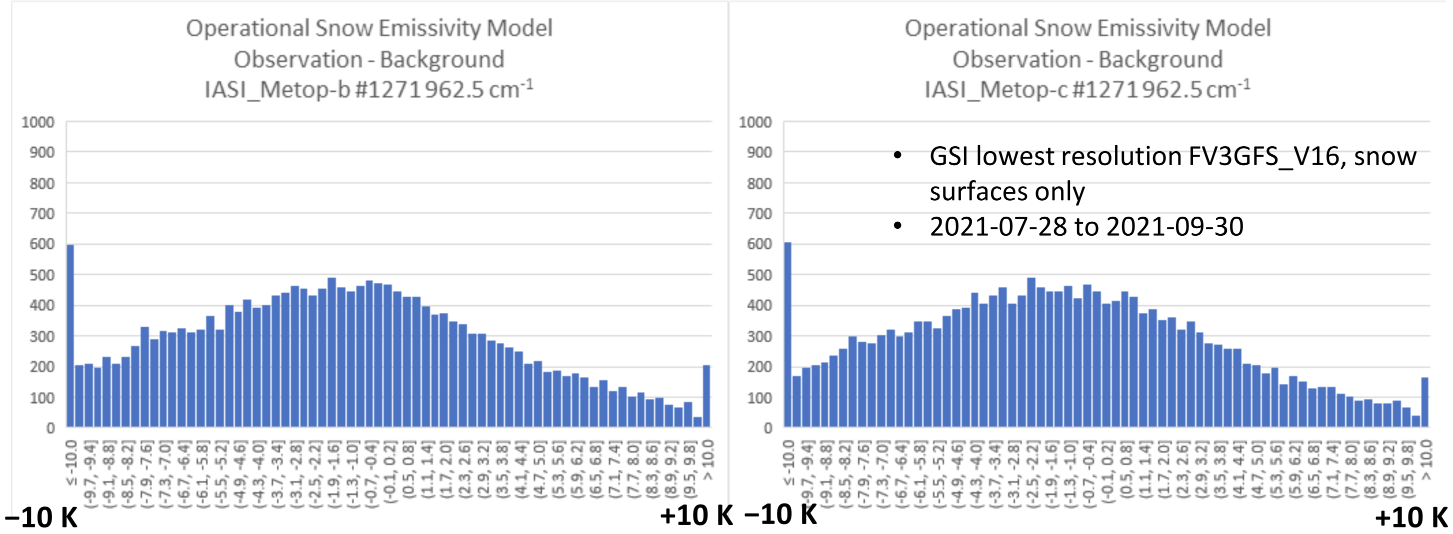
Outline

- **Background and Motivation**
  - Discrepancies in global obs − calc
  - Discrepancies in NUCAPS retrievals
- **TIR-FIR Snow/Ice Emissivity Models**
  - Physical Models
  - Empirical Models
- **Model Selection, Development, and Testing**
  - *Wiscombe & Warren* (1980) Physical Model for Snow Albedo (*WW80*)
  - Research code implementation
  - Problem at larger particle sizes
  - CRTM implementation and preliminary results: Improvement of global obs − calc
- **Improving the Size Dependency at Larger Snow Grain Sizes**
  - Problem at larger particle sizes
  - Observed particle size dependence
  - Hybrid Physical Model for CRTM upgrade
    - *Hori et al.* (2013) Semi-Empirical Model (*H13*)
  - Model results vs laboratory and field measurements
- **Summary and Future Collaborative Work**
  - Additional validation
  - CAMEL database merge
  - Implementation

Background and Motivation

- Accurate **thermal IR (TIR)** fast-forward RT calculations (**calc**) are fundamental for radiance assimilation and operational retrieval algorithms (e.g., NUCAPS)
- **Information about the lower troposphere and surface** are derived from semi-transparent spectral window channels, which require *a priori* information about both the surface emissivity and BRDF
- **NCEP GFS assimilation studies** have revealed significant discrepancies **±5 K RMSE** in clear-sky CRTM calculations (calc) versus CrIS/IASI observations (**obs**) over snow/ice surfaces
- **NUCAPS temperature retrievals** exhibit similar biases associated with these factors
    - Lower-tropospheric temperatures exhibit positive bias of **≈1-2 K** relative to RAOBs

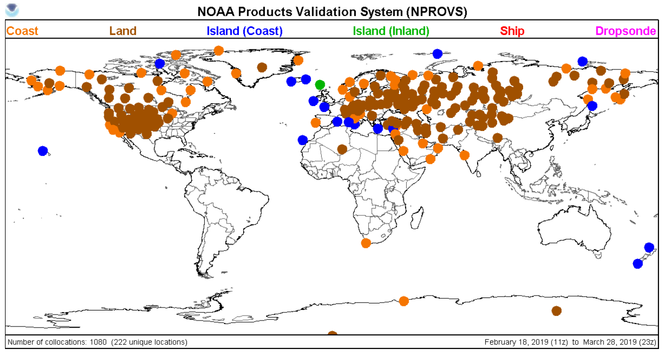
Global Snow obs (IASI) − calc (CRTM) GSI Control Run

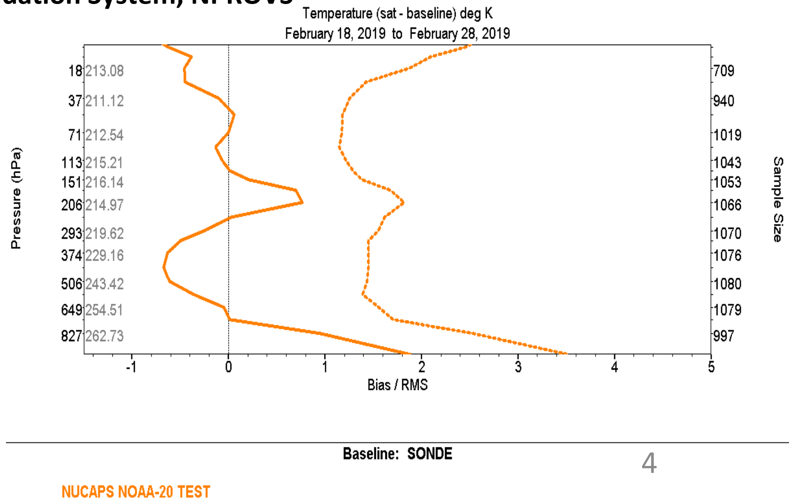


- GSI lowest resolution FV3GFS_V16, snow surfaces only
- 2021-07-28 to 2021-09-30

NUCAPS Temperature Profile Statistics: Snow

NOAA Products Validation System, NPROVS





Courtesy of Bomin Sun (IMSG at NOAA/STAR)

TIR-FIR Snow Emissivity Physical Model for CRTM

TIR-FIR SNOW/ICE EMISSIVITY MODELS

Thermal IR (TIR) Snow/Ice Emissivity Models

Physical Models

- Based upon first-principles and simplifying assumptions for spectral regimes (e.g., the geometrical optics limit, etc.)
- Notable examples include
  - *Berger* (1979) model, based on geometrical optics
  - *Wiscombe &Warren* (1980) model (*WW80*), based on Mie scattering
  - *Wald* (1994) Mie correction based on "diffraction-subtraction" method

Empirical Models (Atlases/Databases)

- Based on empirical data, including both laboratory and field-measurements
- Notable examples include
  - **Combined ASTER MODIS Emissivity over Land (CAMEL)** database (*Borbas et al.* 2018; *Feltz-Loveless et al.* 2018), used by RTTOV
  - *Zhou et al.* (2011) hyperspectral IR derived global database

TIR-FIR Snow Emissivity Physical Model for CRTM

MODEL SELECTION, DEVELOPMENT, AND TESTING

Wiscombe & Warren (1980) Model (*WW80*) for Snow Albedo (1/2)

- After an extensive literature review, we chose to implement the ***WW80* snow albedo model** to calculate spectral albedo, α_ν
  - Ideal in terms of both **theoretical basis** and **practical application**
  - Valid for **VIS-TIR spectrum**
  - Used by the SNICAR-ADv3 community model (*Flanner et al.* 2021)
  - Based on **Mie scattering theory** for single-scattering and **Delta-Eddington approximation** for multiple scattering in (*Joseph et al.* 1976)
  - From Kirchhoff's law, the **directional emissivity** may be computed as

$$\epsilon_\nu(\theta_0) = 1 - \alpha_\nu(\theta_0)$$

- **Delta-Eddington Approximation**
  - Assumes the Eddington approximation, which assumes a truncated two-term Henyey-Greenstein (H-G) phase function
  - To account for the strong forward scattering peak of snow, **a Dirac delta function term** is included
  - The **phase function** is approximated as

$$P^*(\cos\Theta) \approx 2f\,\delta(1-\cos\Theta) + (1-f)(1+3g^*\cos\Theta)$$

where *g** is the D-E scaled asymmetry parameter

Wiscombe & Warren (1980) Model (*WW80*) for Snow Albedo (2/2)

- From the D-E phase function, a simplified **scaled layer RTE** may be derived as

$$\frac{dI(\theta_0,\tau_\nu^*)}{d\tau_\nu^*}\,\mu_0 + I(\mu_0,\tau_\nu^*) = \frac{\varpi^*}{2}\int_{-1}^{1}(1+3g^*\mu_0\mu)\,I_\nu(\mu,\tau_\nu^*)\,d\mu\,,$$

where the asterisks denote D-E scaled quantities

- The scaled RTE is then used for deriving upward and downward fluxes for deriving **albedo***, $\alpha_\nu(\theta_0)$ (i.e., **hemispherical-directional BRDF**)

*After considerable derivation; "the Devil is in the details…"

- Assuming **quasi-infinite optical depth for TIR-FIR** (e.g., *Dozier & Warren* 1982) the albedo is then shown to be

$$\alpha_\nu(\theta_0) = \varpi^*\left(\frac{1}{1+\zeta}\right)\left(\frac{1-\gamma\,\xi\cos\theta_0}{1+\xi\cos\theta_0}\right),$$

Intermediate Parameters

$$\xi \equiv \sqrt{3\,(1-\varpi^*g^*)(1-\varpi^*)}\,,$$

$$\gamma \equiv \frac{g^*}{1-\varpi^*g^*}\,,$$

$$\zeta \equiv \frac{2\xi}{3\,(1-\varpi^*g^*)}\,.$$

DE-Transformed Mie Scattering Parameters

Single-scattering albedo:

$$\varpi^* = \frac{(1-f)\,\varpi}{1-f\varpi} = \frac{(1-g^2)\,\varpi}{1-g^2\varpi}\,,$$

Asymmetry Parameter:

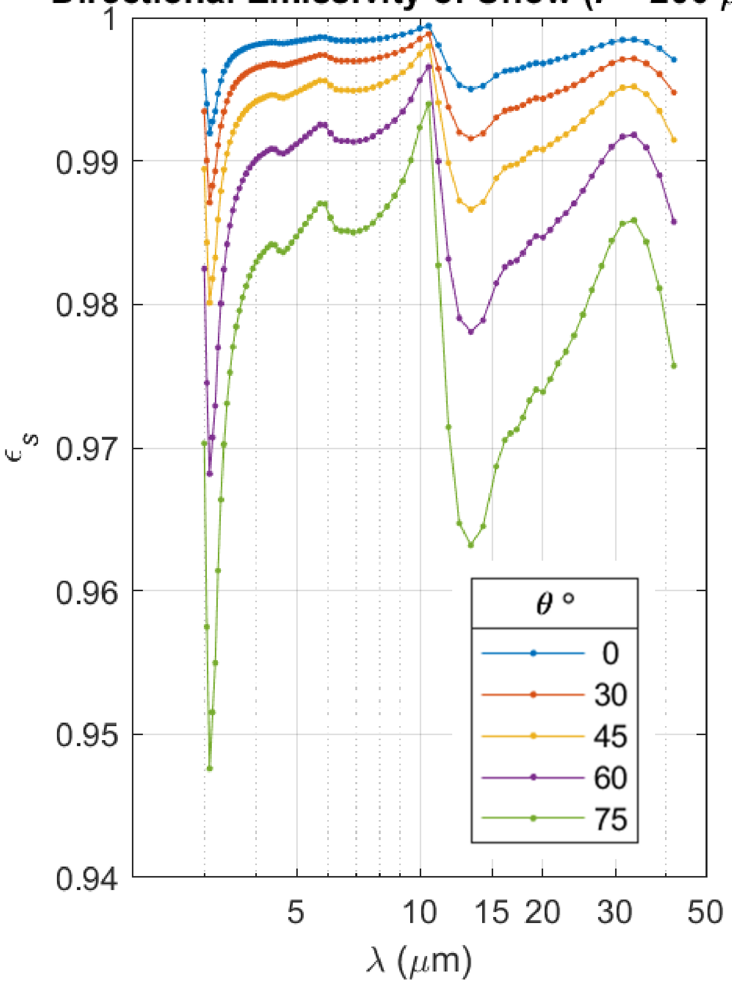
$$g^* = \frac{g}{1+g}\,.$$

Research Code Implementation and Sanity Check

- Developed **MATLAB research-code** for performing Mie calculations
  - MATLAB is extremely well suited for performing Mie calculations, while retaining direct correspondence with theory
  - Full-scattering *WW80* model was implemented
    - Includes solar spectrum (VIS) wavelengths
- Researched the latest published **optical constants of ice in the TIR-FIR,** and implemented the **temperature-dependent dataset** by *Iwabuchi & Yang* (2011)
- Tested output of research codes against those from earlier publications and confirmed that they are functioning correctly
- **Version 1 physical model** for CRTM output as **4-D LUT** $\boldsymbol{\epsilon(\nu,\theta,T_s,r)}$

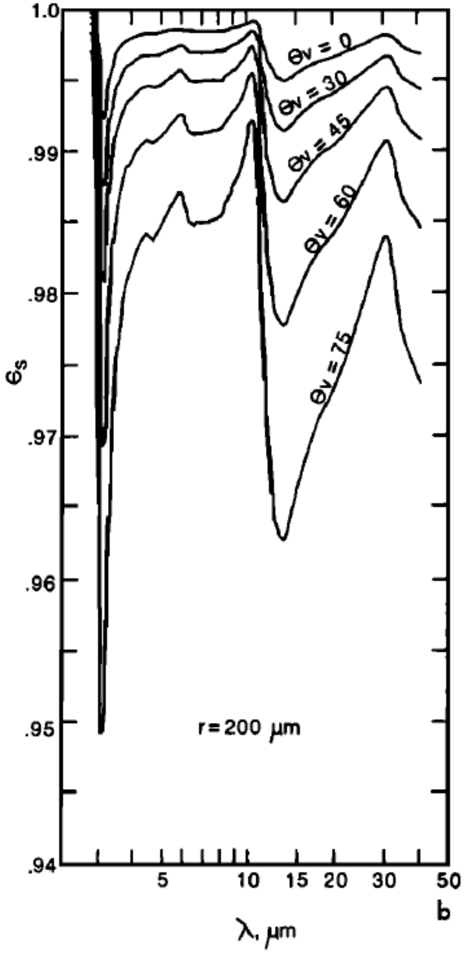
Research Code Implementation

Directional Emissivity of Snow (r = 200 μm)



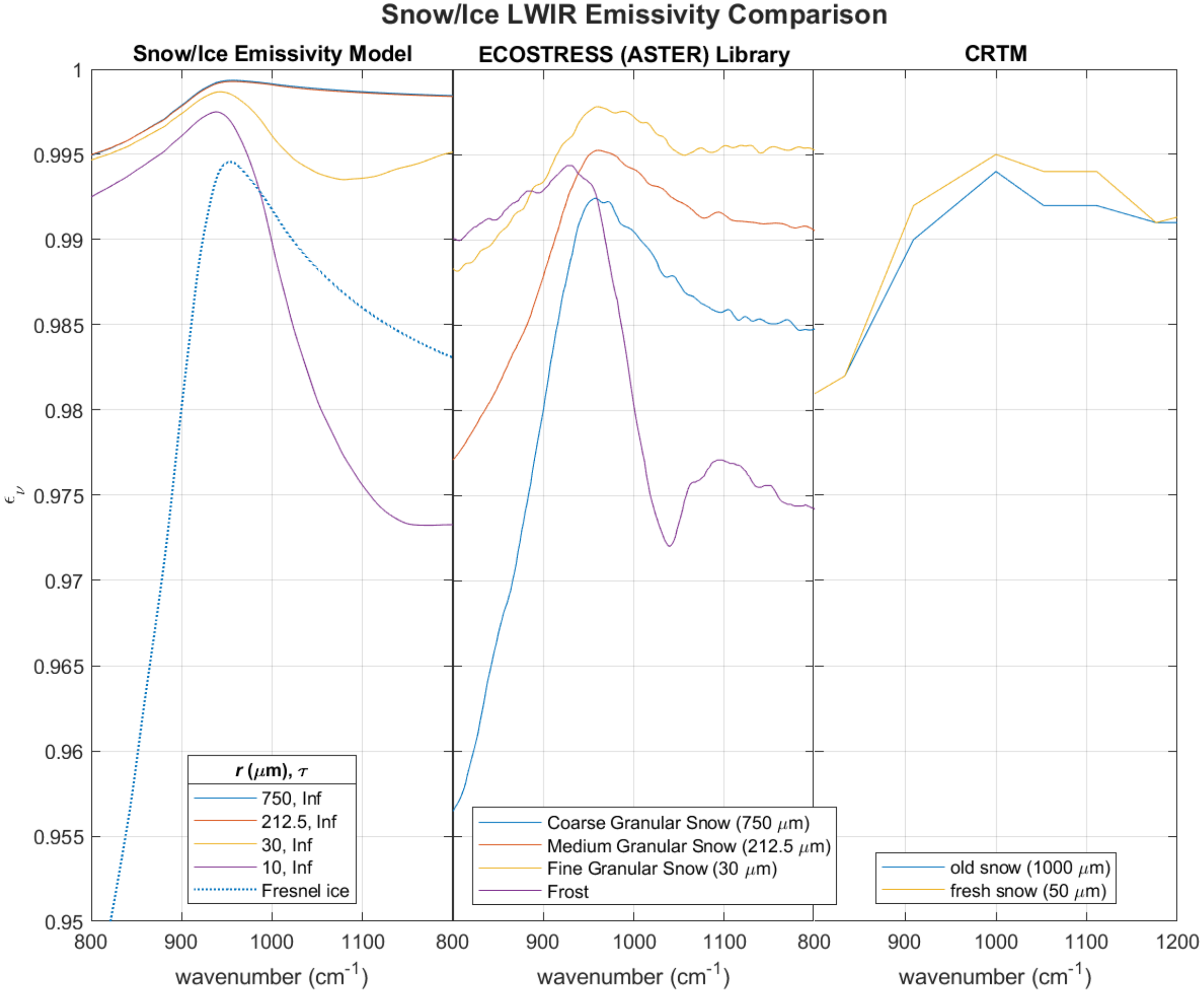
Dozier & Warren **(1982)**

Fig. 1b



Size Dependence Problem at Larger Snow Grain Sizes

- **Preliminary validation** against field measurements by *Salisbury et al.* (1994) from the ECOSTRESS (ASTER) Library (*Meerdink et al.* 2019)
- **Magnitudes are reasonably comparable**, but problems have been identified
  - Significant discrepancies seen in the **spectral dependence on particle size**
  - **Model breaks down** for **larger snow grain sizes** (for ***r* ≥ 25;** e.g., *Warren* 2019)
  - There is also discrepancy and ambiguity between the sizes reported in the ECOSTRESS files versus those reported in the *Salisbury et al.* (1994) paper



CRTM Implementation and Preliminary Results (1/2)

Version 1 Physical Model

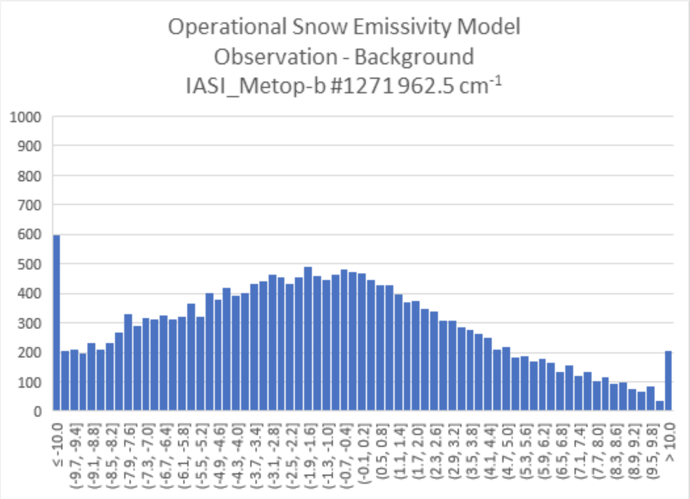
- **NCEP GSI obs – calc experiments** are being conducted testing the offline CRTM implementation (v3.0) and impact (J. Jung)
  - GSI lowest resolution FV3GFS_V16; snow surfaces only
  - **Metop-B,-C IASI**, and **NOAA-20, SNPP CrIS**, 28 July to 30 Sep 2021
  - Reset all satellite bias corrections; 5 week spin-up

- Results of **global obs – calc (O–B)** are shown in histograms (next slide)
  - Scales are −10 to +10 K
  - **Control run (Ctrl)** using the previous CRTM snow emissivity model
  - **Experimental test run (Test)** using v1 physical snow emissivity model

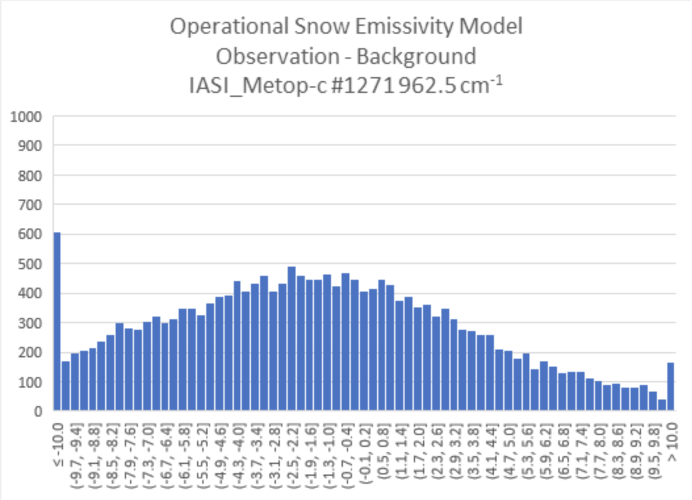
CRTM Implementation and Preliminary Results (2/2)

Version 1 Physical Model

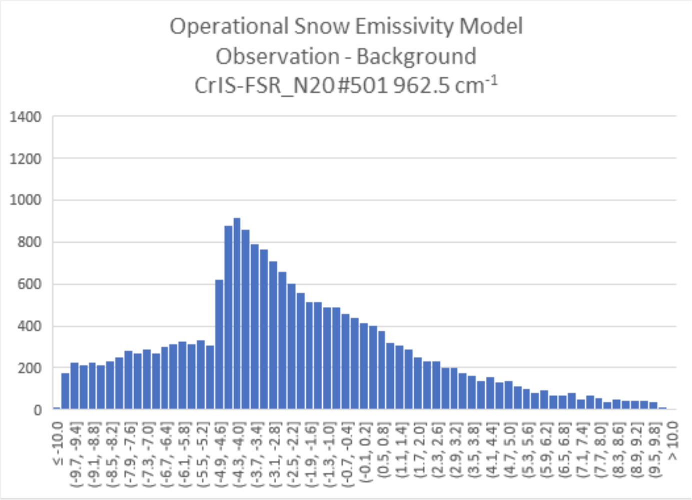
Metop-B IASI (962.5 cm^{-1}) CTRL



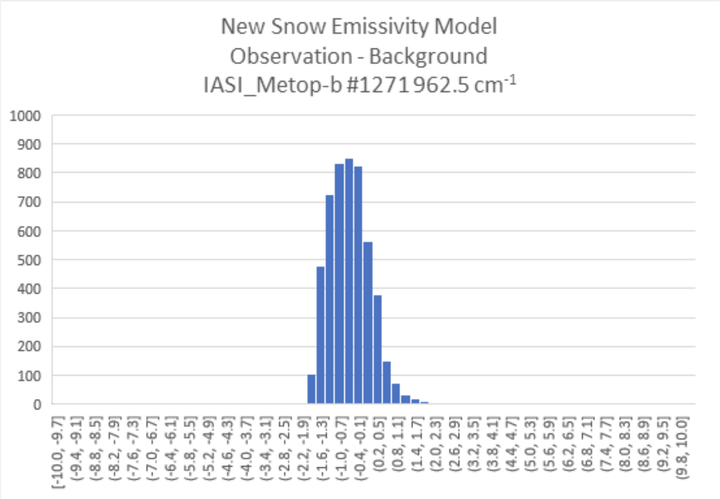
Metop-C IASI (962.5 cm^{-1}) CTRL



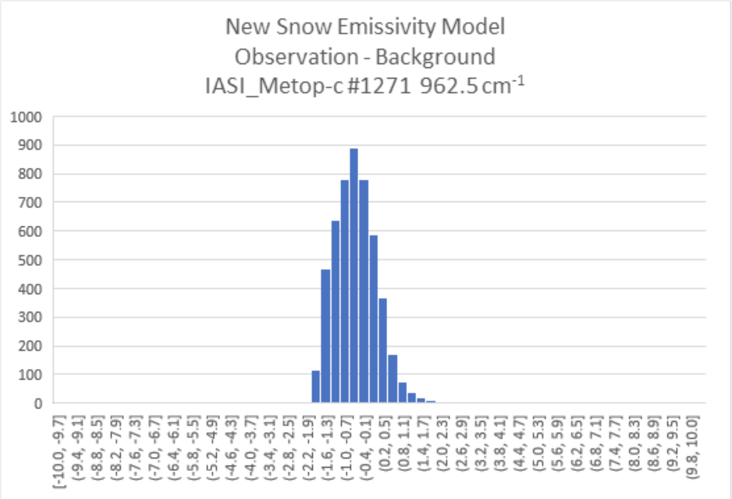
NOAA-20 CrIS (962.5 cm^{-1}) CTRL



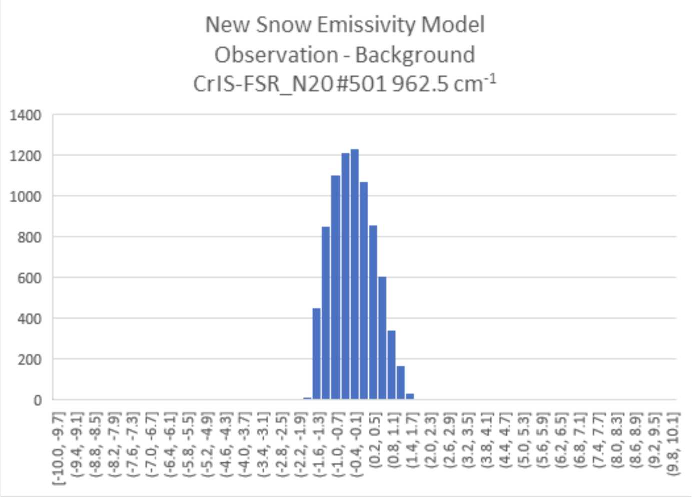
Metop-B IASI (962.5 cm^{-1}) TEST



Metop-C IASI (962.5 cm^{-1}) TEST



NOAA-20 CrIS (962.5 cm^{-1}) TEST



TIR-FIR Snow Emissivity Physical Model for CRTM

IMPROVING THE SIZE DEPENDENCY AT LARGER SNOW GRAIN SIZES

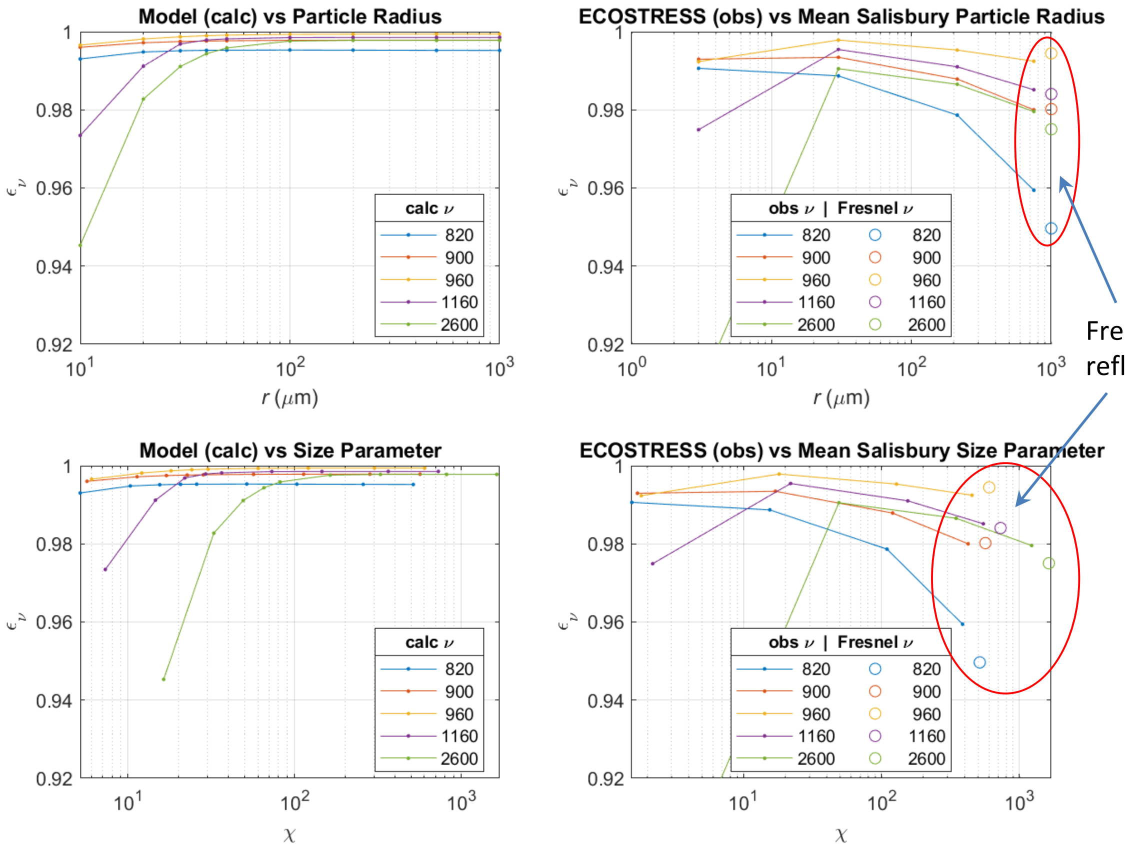
Problem At Larger Particle Sizes

- The *WW80* model was found to agree reasonably well for smaller particle sizes (< 30 µm), but **did not capture the size dependence for larger sizes**
- It was later learned that this is a known problem with the *WW80* model (*Wald* 1994, *Hori et al.* 2013), but the particle size dependence was a lesser concern compared to the spectral and angular dependencies
- The improvement in global obs – calc is believed to be due to the **improved angular and spectral dependencies** afforded by the physical model
- However, **snow grain sizes are known to increase as snow ages,** so size dependency ultimately should not be ignored

Observed Particle Size Dependence

- Additional research into this problem has led to the observation that the albedo of snow surfaces **gradually become more specular** as snow ages (i.e., becomes coarser grained)
- We directly noticed this ourselves when studying the field and laboratory data, but we subsequently learned that others had also noted this previously
- As the snow ages, the particle sizes not only grow larger, but they also tend to **"weld" together** (*Wald* 1994) into an "ice-like" surface as opposed to a scattering layer
- Examination of the particle size dependence seemed to reveal a **linear transition** from the layer scattering regime (*WW80*) to a Fresnel surface reflectance regime

Snow Model v1 (calc, θ = 10°, T_s = 260 K) and ECOSTRESS (obs) vs Particle Size



Fresnel reflectances

Hybrid Physical Model for CRTM Upgrade

- These previous results suggested that **snow/ice surface “effective emissivity”** could be modeled such that

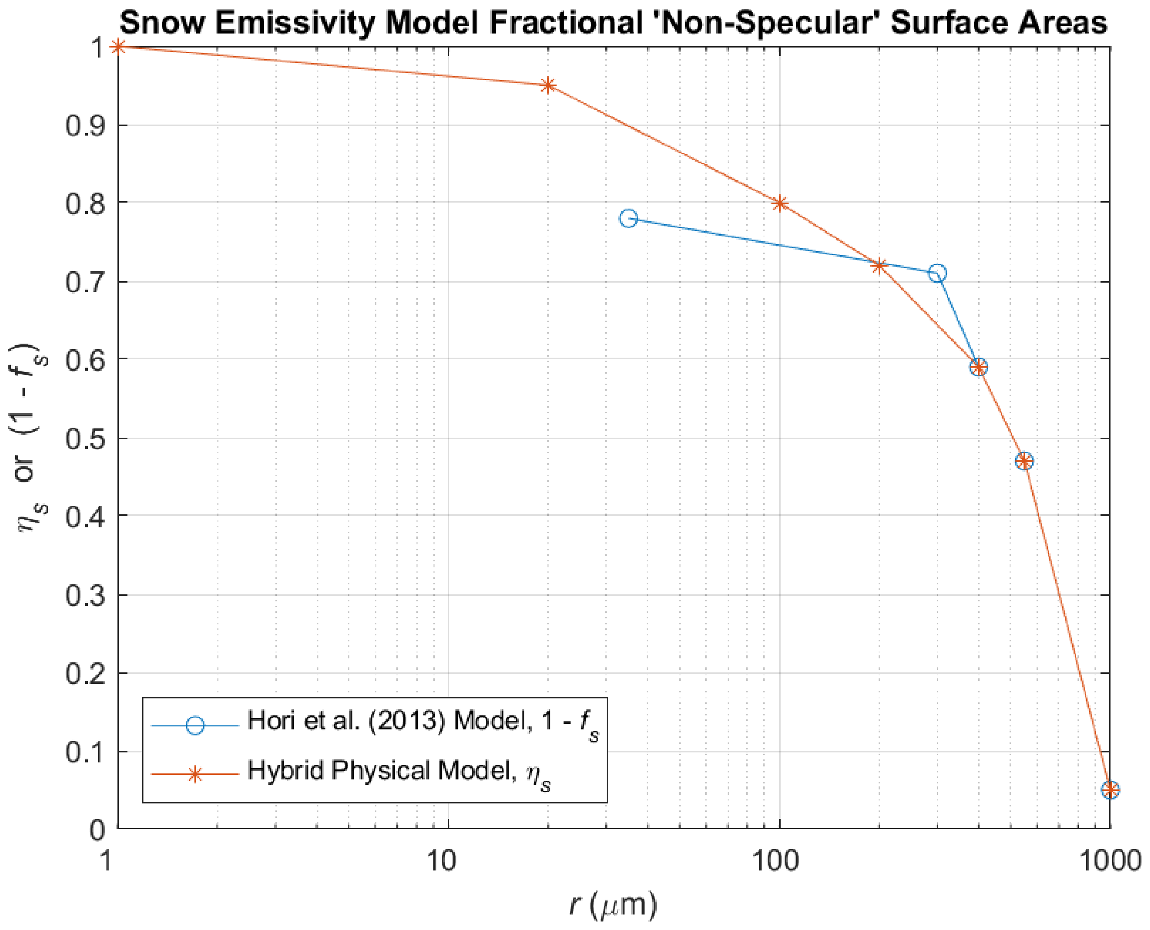
$$\epsilon^*_\nu(\theta_0, r) = \eta_s \, \epsilon_\nu(\theta_0, r, N_\nu) + (1 - \eta_s) \left[1 - \rho_\nu(\theta_0, N_\nu)\right],$$

  where η_s is the fractional surface area that behaves as a multiple-scattering layer, and $1 - \eta_s$ is the area of specular (Fresnel) reflectance

- In a similar vein, *Hori et al.* (2013) had proposed a **“semi-empirical” model** as a linear combination of an isotropic blackbody component and an “apparent” emissivity of the specular fraction, $f_s \sim 1 - \eta_s$
  - Empirically determined the specular fractions, f_s, for various snow samples from field observations of *Hori et al.* (2006)

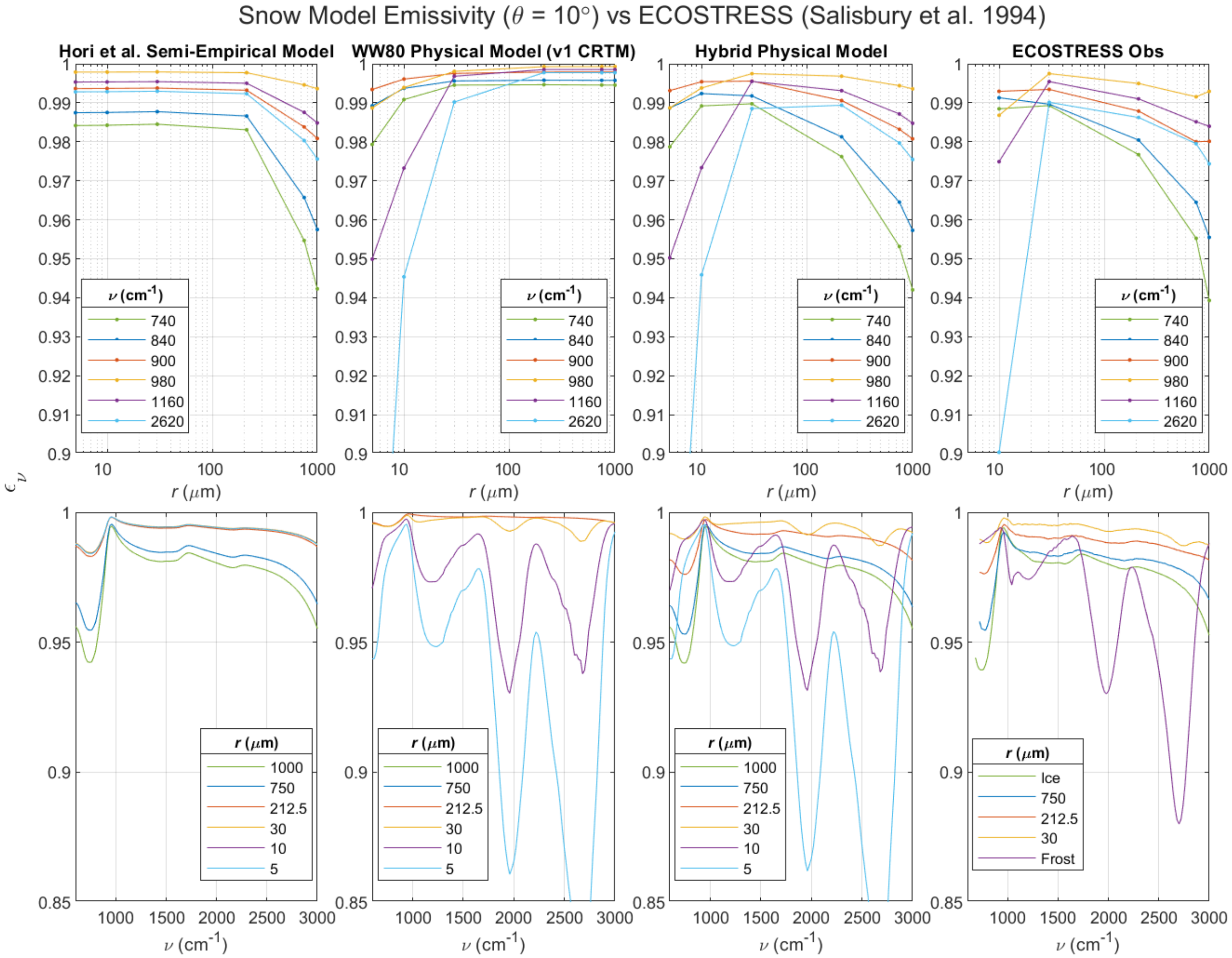
$$\varepsilon^*_\nu(\theta_0, r) = (1 - f_s) + f_s \cdot \left\{f_s \left[1 - \rho_\nu(\theta_0, N_\nu)\right] + (1 - f_s)\left[1 - \rho_\nu(45^\circ, N_\nu)\right]\right\},$$

- The ***Hori et al.* (2013) (*H13*) model** compares favorably for larger particle sizes, but **not** for small particle sizes
- We thus chose to adopt the “effective emissivity” approach proposed above, using specular fractions similar to *H13*, but optimized to accommodate better the smaller particle sizes treated by the *WW80* model



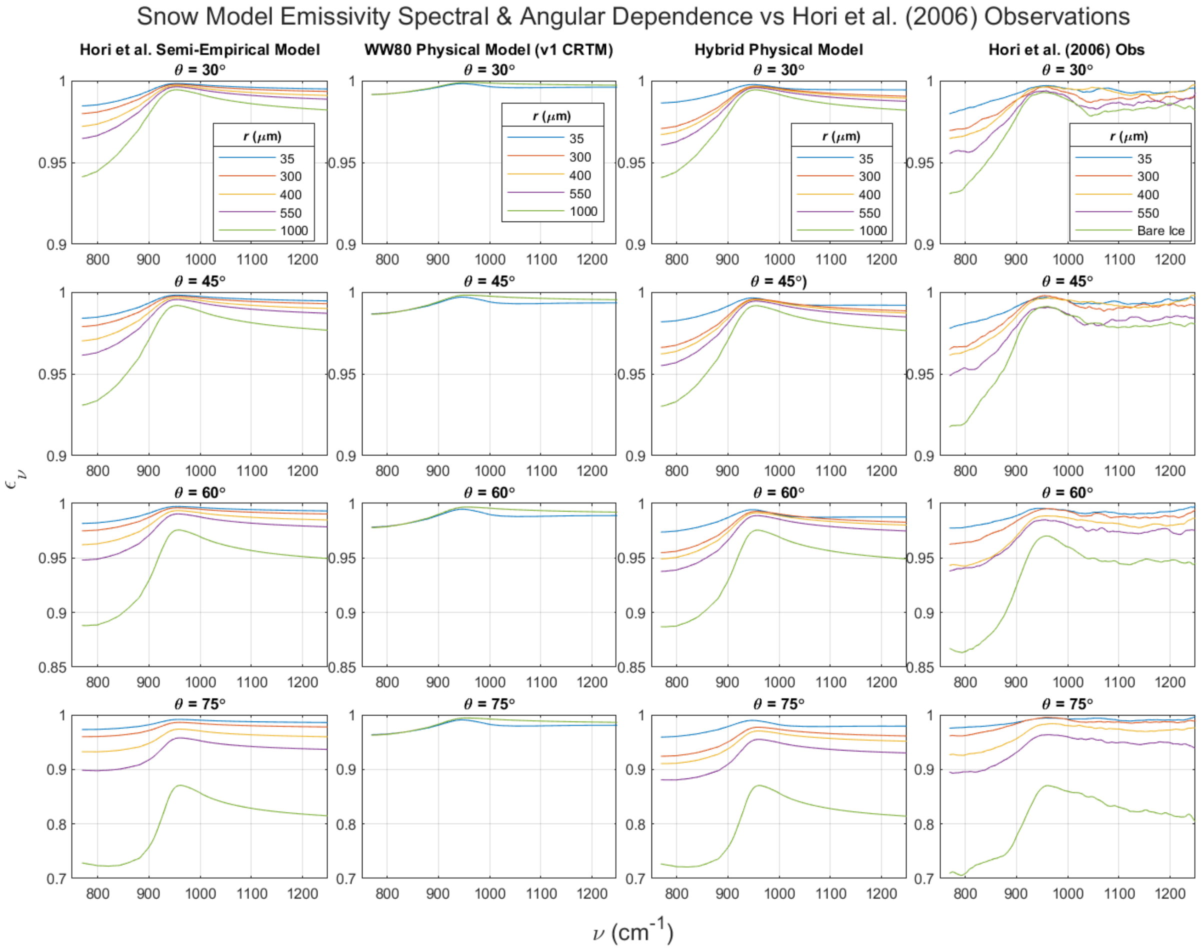
Model Results vs Laboratory Measurements
from ECOSTRESS Library

- **ECOSTRESS library** (*Meerdink et al.* 2019) includes measurements of snow albedo spectra taken at $\theta = 10°$ (*Salisbury et al.* 1994)
  - **Frost** (*r* ≈ 3.25 µm)
  - **Granular snow**
    - **Fine** (*r* ≈ 30 µm)
    - **Medium** (*r* ≈ 212.5 µm)
    - **Coarse** (*r* ≈ 750 µm)
  - **Ice** (*r* ≥ 1000 µm, flat)
- *WW80* and *H13* models perform well for small and large particle sizes, respectively
- The hybrid physical model captures both regimes, including the prominent low-emissivity spectral features known as **reststrahlen bands**

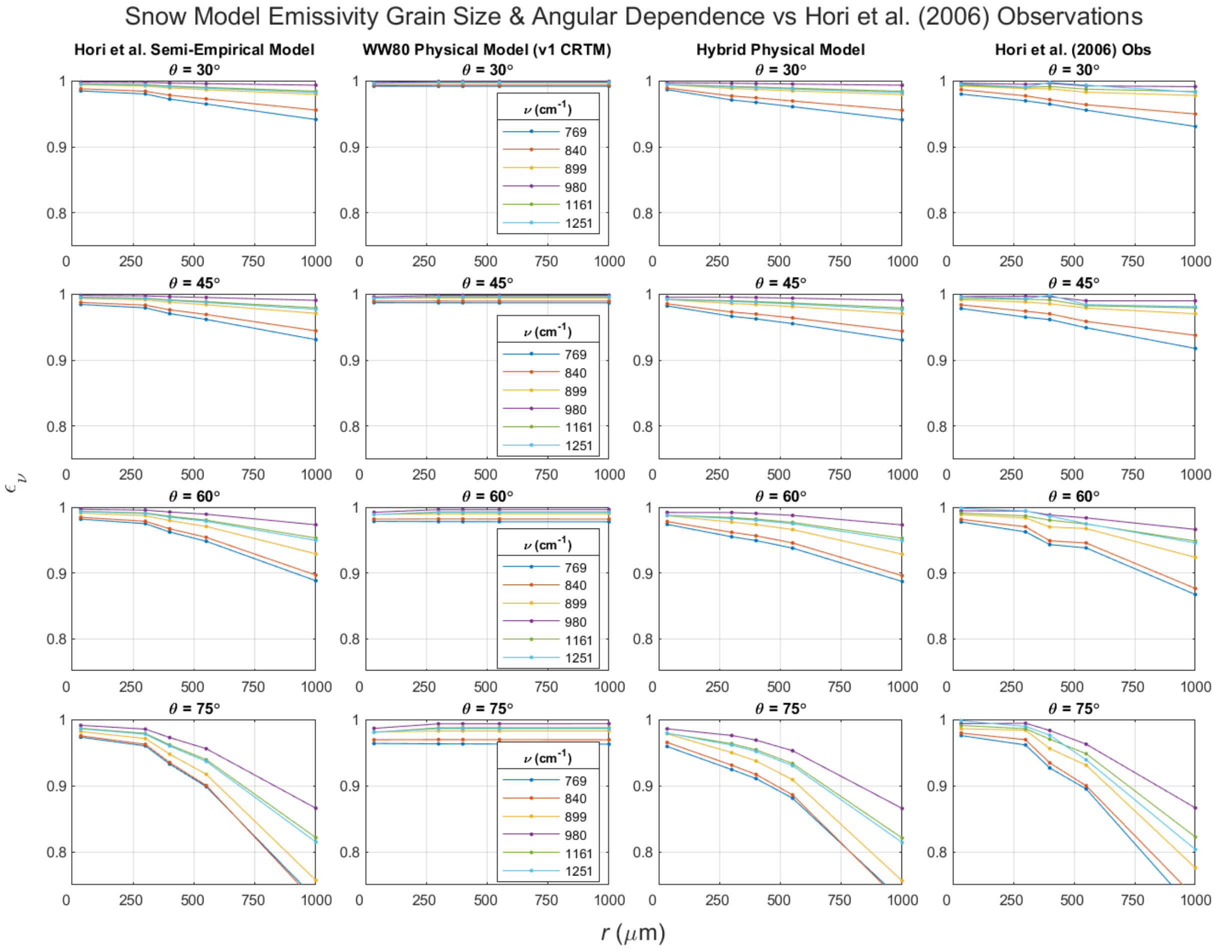


Model Results vs Multi-Angular Field Measurements
from *Hori et al.* (2006)

Spectral Dependencies



Grain Size Dependencies



Summary and Future Collaborative Work

- A **physical TIR-FIR snow emissivity model** based on Mie scattering and D-E approximation (*WW80*) was developed (as research code) and implemented within CRTM (v1 physical model)
  - The albedo model itself is valid to VIS wavelengths
- Preliminary analyses of global obs − calc are encouraging, **nearly an order of magnitude improvement** over snow surfaces
  - The v1 physical model improvement in global obs − calc is believed to be due to the improved angular and spectral dependence afforded by the physical model
- A **hybrid physical model** (similar to *H13*) was developed to extend the v1 (*WW80*) physical model to larger particle sizes
- The **optical constants** used in the hybrid physical model include *T*-dependence and **span the TIR-FIR spectral range**
  - FIR is of interest for polar remote sensing (Loveless et al.)
- **Additional validation** of hybrid physical model against MAERI/ARI field/laboratory data
  - Polar MOSAIC campaign
  - SSEC "rooftop" laboratory (Loveless, Knuteson, Taylor, Revercomb, et al.)
- **Merge with CAMEL** to account for non-uniform surfaces (Borbas et al.)
- **Implementation within CRTM/GSI** and global obs − calc experiments (Jung, Dang, Johnson, et al.)
- **Implementation within NUCAPS** (Pryor, Divakarla, Zhu, Zhou, DeSouza-Machado, et al.)

TIR-FIR Snow Emissivity Physical Model for CRTM

THANK YOU! QUESTIONS?

TIR-FIR Snow Emissivity Physical Model for CRTM

BACKUP SLIDES