Angular Effect of Residual Clouds and Aerosols in Clear-Sky IR Obs

Nicholas R. Nalli [1,2]

and

Christopher D. Barnet,[2] **Antonia Gambacorta,**[3,2] **Eric S. Maddy,**[3,2]
H. Xie,[1,2] **T. King,**[1,3] **E. Joseph,**[4] **V. R. Morris**[4]

[1] *I.M. Systems Group Camp Springs, Maryland, USA*
[2] *NOAA/NESDIS/STAR, Camp Springs, Maryland, USA*
[3] *Riverside Technology, Inc., Camp Springs, MD, USA*
[5] *NCAS, Howard University, Washington, DC, USA*

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Outline

- Part 1: Angular Effect of Residual Cloud and Aerosol Contamination
  - IR Window Channel Radiance Sensitivity
- Part 2: Satellite Experimental Analyses
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  - MetOp-A AVHRR/3 Cloud Mask
- Part 3: Aircraft Analyses (TBD)
  - NAST-I spectra

Introduction and Background

- Accurate satellite **observations (obs)** and **calculations (calc)** of top-of-atmosphere (TOA) infrared (IR) spectral radiances are required for the accurate retrieval of **environmental data records (EDRs)** such as atmospheric vertical temperature and moisture profiles.

- Ideally, it is desired that systematic differences between observations and calculations (calc − obs) under well-characterized conditions be minimal over the sensor's scanning range of zenith angles.

- A fundamental problem with **"clear-sky"** (i.e., cloud and aerosol free) **analyses** of **calc − obs is** the **assumption of perfect clear-sky obs**, when **in reality** we only have access to **cloud-cleared** or **cloud-masked** obs, **these being the products of algorithms**, both of which are subject to errors and not designed to mask aerosols.

- This presentation summarizes work (*Nalli et al.* 2012a,b, *JGR-Atmospheres*) **investigating the impact of the "clear-sky" observations commonly used in such analyses**, which include **cloud-cleared radiances** (i.e., from hyper/ultraspectral sounders), as well as **cloud-masked data** (i.e., from imagers).

Angular Effect of Residual Clouds/Aerosols in Clear-Sky IR Obs

PART 1: ANGULAR EFFECT OF CLOUD AND AEROSOL CONTAMINATION

Angular Effect of Clouds and Aerosols

- Idealized approximations for assessing the impacts of single layer clouds and aerosols on window channel radiances are derived in this work for various scenarios, including
  - Broken opaque clouds
  - Aerosol layer
  - Aerosol layer overlying or underlying broken opaque clouds
  - Broken semitransparent clouds

- To achieve this, we rely on a statistical model for predicting the **probability of a clear line of sight (PCLoS)**, which assumes idealized opaque clouds, Poisson-distributed within a plane-parallel, horizontally unbounded layer (e.g., *Kauth and Penquite* 1967; *Taylor and Ellingson* 2008).
  - We assume that the ensemble probability of a cloudy FOV mischaracterized as "clear" behaves as 1 − PCLoS with a very small absolute cloud fraction.

Modeled Impact of Broken Opaque Clouds: Probability of Clear Line of Sight (PCLoS) Model

(e.g., *Kauth and Penquite* 1967; *Taylor and Ellingson* 2008)

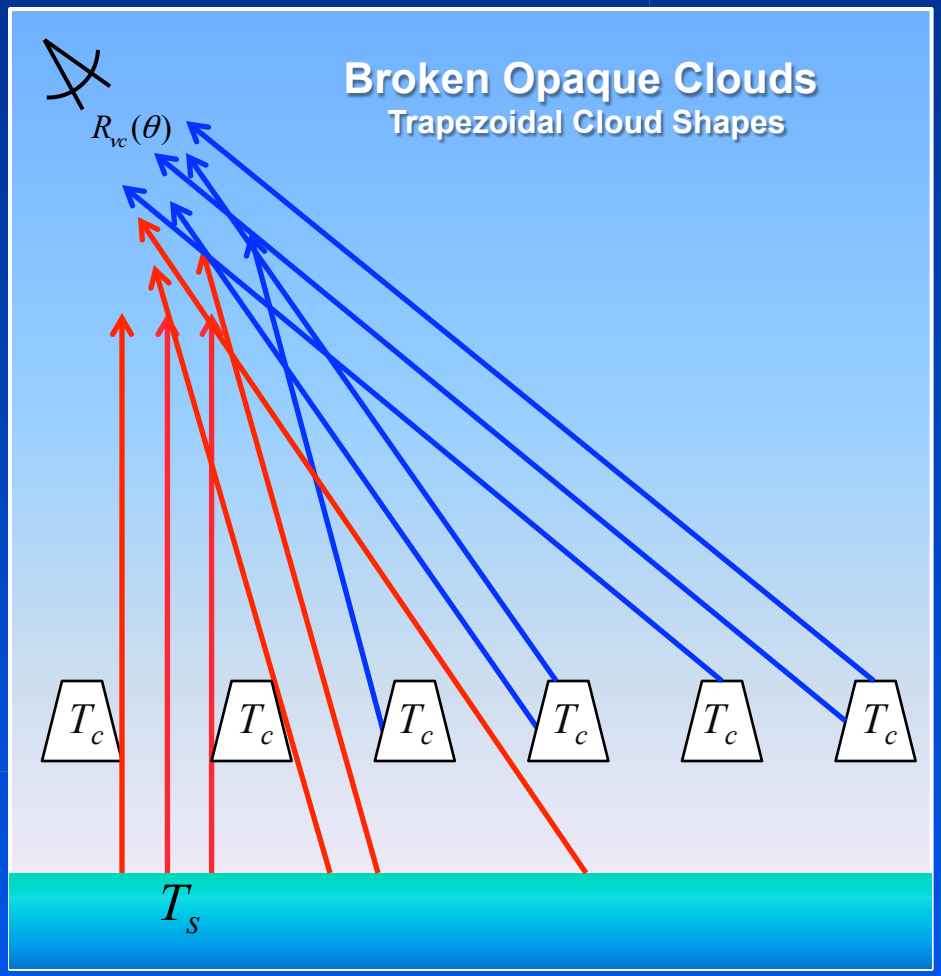
- **Clouds** are idealized as blackbodies in a plane-parallel atmosphere Poisson-distributed over a blackbody sea surface
- Given **absolute cloud fraction *N***, the expression for **PCLoS** is

$$P(\theta,\alpha,\ldots) = P(0)^{f(\theta,\alpha,\ldots)},$$

$$P(0) = 1 - N,$$
$$f(\theta,\alpha,\ldots) \equiv \text{shape factor},$$
$$\alpha \equiv \delta z / \delta x, \text{ the cloud vertical aspect ratio}$$

- **Cloud shapes** for $f(\theta,\alpha)$ used in this work are **ellipsoid**, **semiellipsoid**, **isosceles trapezoid**
- For the special case of **opaque clouds**, the variation of **ensemble "superwindow" radiance with** θ is approximated by

$$R_{vc}(\theta) \approx P(\theta,\alpha)\,B_\nu(T_s) + \left[1 - P(\theta,\alpha)\right]B_\nu(T_c).$$



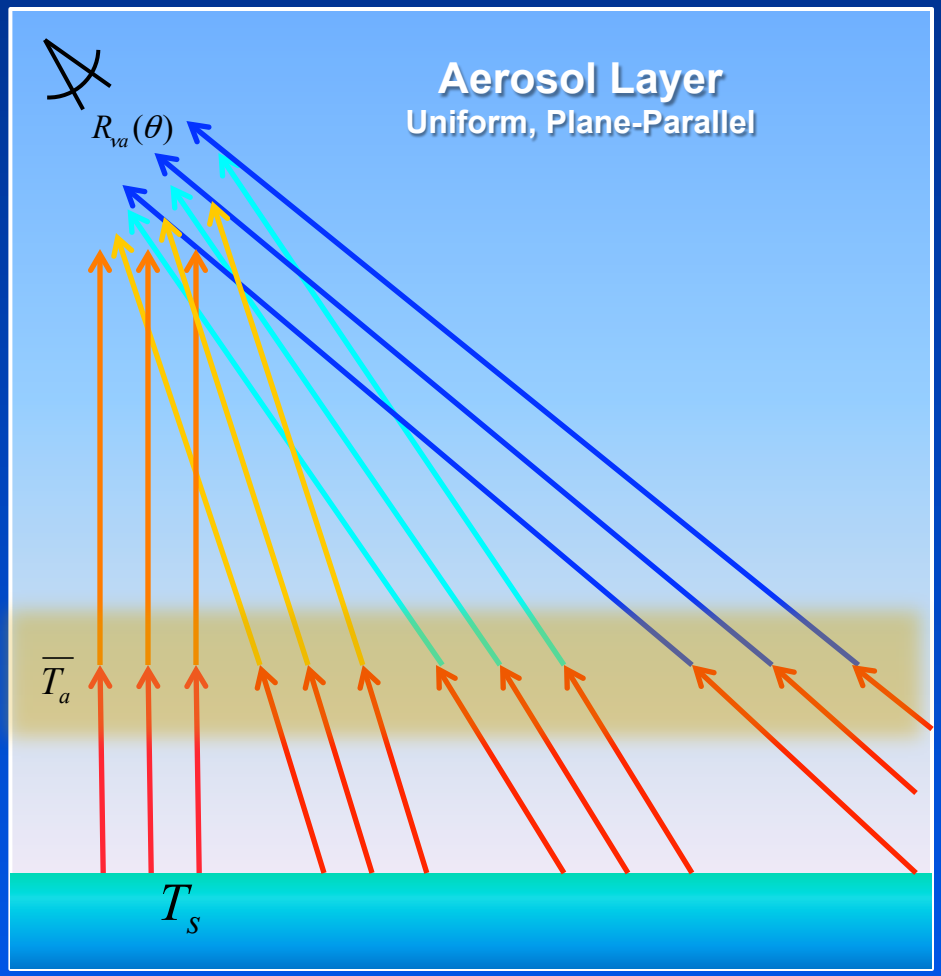
Modeled Impact of Aerosols

- Assuming a uniform, plane-parallel **aerosol layer** (e.g., Saharan dust) over a blackbody sea surface, the variation of **FOV superwindow radiance with** θ is approximated by

$$R_{\nu a}(\theta) \approx B_\nu(T_s)\mathsf{T}_{\nu a}(\theta,\tau_{\nu a}) + B_\nu(\overline{T_a})\left[1-\mathsf{T}_{\nu a}(\theta,\tau_{\nu a})\right],$$

where

$$\mathsf{T}_{\nu a}(\theta,\tau_{\nu a}) \equiv \exp[-\tau_{\nu a}\sec(\theta)].$$



Modeled Impact of Opaque Clouds + Aerosols, and Semitransparent Clouds

- More sophisticated superwindow radiative transfer equations are likewise derived for
  - **Aerosol layer over or under broken opaque clouds**
  - **Broken semitransparent clouds**
    - **Analytical expressions are derived** for **mean slant-paths** through idealized shapes

IR Window Channel Radiance Sensitivity (1/2)

- **Sensitivity equations** for the angular impact on superwindow channel radiance for various scenarios are derived as follows

$$\delta T_B(\nu,\theta,\alpha) \approx \begin{cases} \left[1-P(\theta,\alpha)\right]\dfrac{\left[\partial B_\nu/\partial T\right]_{\overline{T_{sc}}}}{\left[\partial B_\nu/\partial T\right]_{\overline{T_B}}}\delta T_{sc}\ , & \text{broken opaque clouds} \\ \left[1-\exp(-\tau_{\nu a}\sec\theta)\right]\dfrac{\left[\partial B_\nu/\partial T\right]_{\overline{T_{sa}}}}{\left[\partial B_\nu/\partial T\right]_{\overline{T_B}}}\delta T_{sa}\ , & \text{uniform aerosol layer} \\ \left[1-P(\theta,\alpha)\exp(-\tau_{\nu a}\sec\theta)\right]\dfrac{\left[\partial B_\nu/\partial T\right]_{\overline{T_{sc}}}}{\left[\partial B_\nu/\partial T\right]_{\overline{T_B}}}\delta T_{sc}, & \text{opaque clouds over aerosol layer} \\ \varepsilon_{\nu c}(\theta,\tau_{\nu c})\left[1-P(\theta,\alpha)\right]\dfrac{\left[\partial B_\nu/\partial T\right]_{\overline{T_{sc}}}}{\left[\partial B_\nu/\partial T\right]_{\overline{T_B}}}\delta T_{sc}, & \text{broken semitransparent clouds ,} \end{cases}$$

where

$\delta T_{sc} \equiv T_s - T_c$, $\delta T_{sa} \equiv T_s - \overline{T_a}$, $\overline{T_{sc}}, \overline{T_{sa}}$ are means of surface and cloud/aerosol temperatures

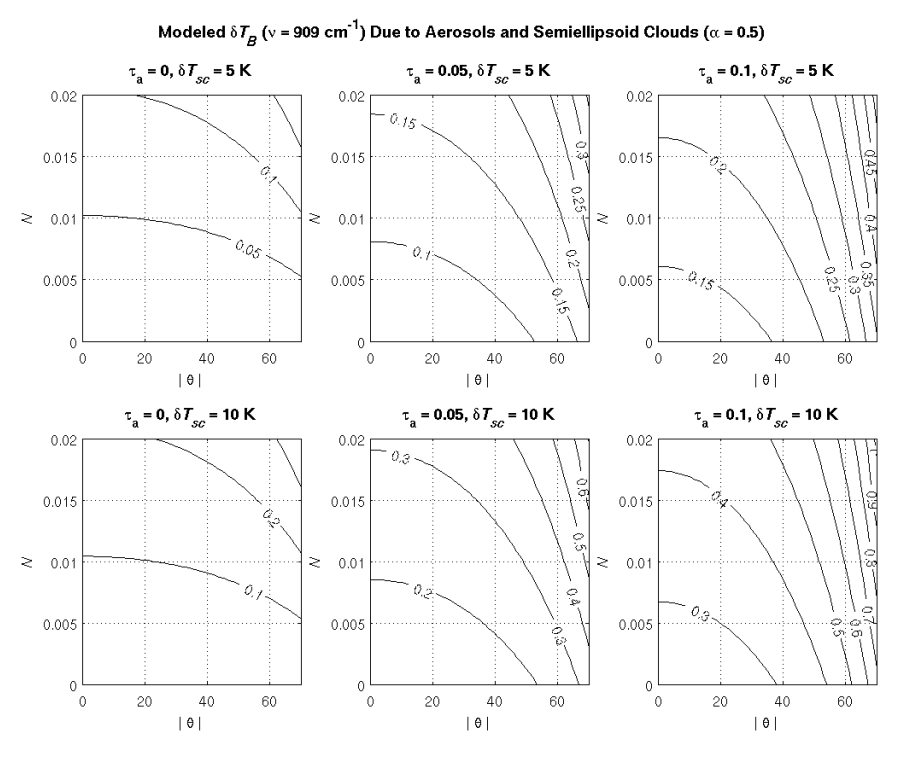
$\varepsilon_{\nu c}(\theta,\tau_{\nu c}) \equiv 1-\exp\left[-\tau_{\nu c}\overline{S}(\theta,\alpha)\right]$, $\overline{S}(\theta,\alpha)$ is the mean slant-path through the cloud shape.

Note that

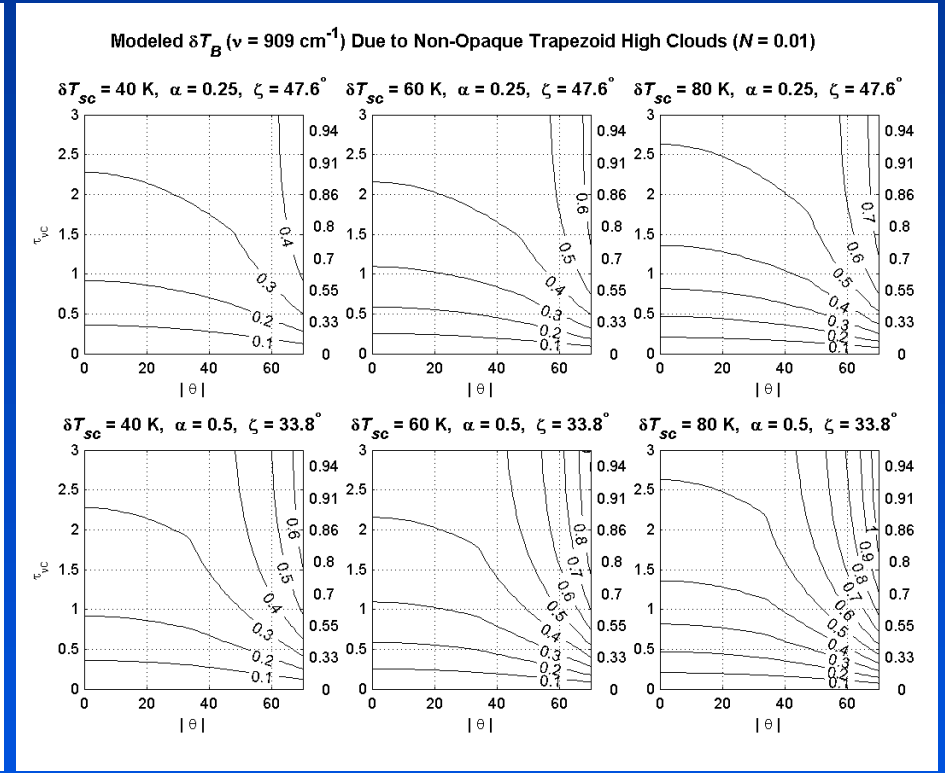
$\varepsilon_{\nu c}(\theta,\tau_{\nu c})\left[1-P(\theta,\alpha)\right]$ is the "effective cloud fraction," a parameter retrieved by satellite sounders.

IR Window Channel Radiance Sensitivity (2/2)

Aerosols and Broken Opaque Clouds



Semitransparent Broken Clouds



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PART 2: SATELLITE EXPERIMENTAL ANALYSES

Experimental Analyses

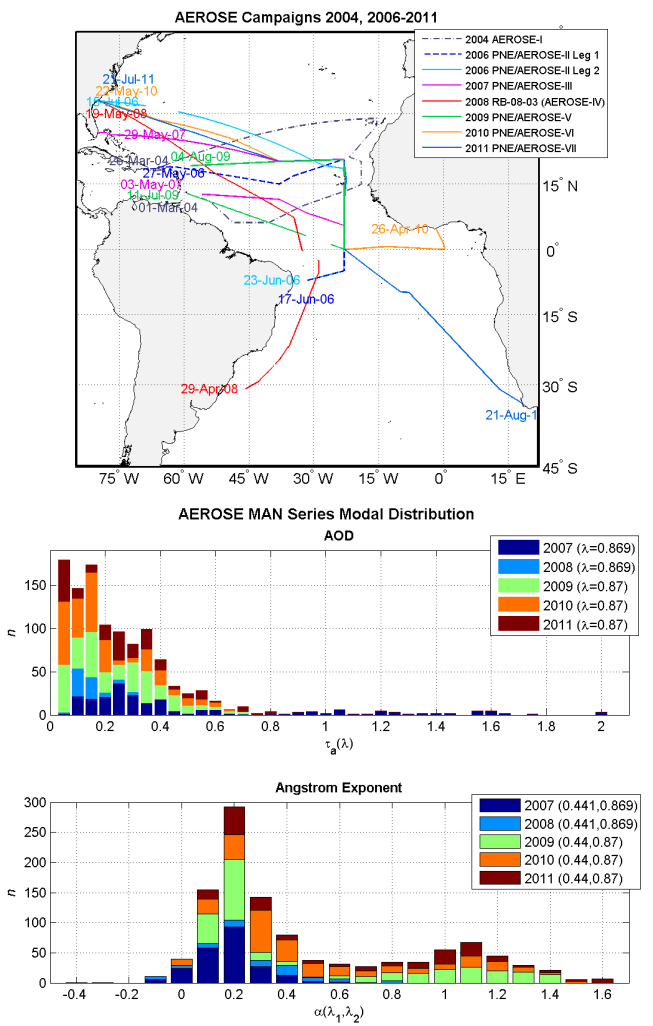
- **Analyses of calc − obs as a function of** θ are performed using **MetOp-A NOAA-unique IASI Level 2 cloud-cleared radiance (CCR)** granules produced by NESDIS/STAR
  - Sample granules have been matched with ocean-based **dedicated RAOBs** obtained from the **NOAA Aerosols and Ocean Science Expeditions (AEROSE)** (*Nalli et al.* 2011, *BAMS*)
  - To minimize uncertainties arising from gas absorption deviating from atmospheric state parameter inputs, **spectral microwindows** minimally impacted by absorbing species in the IR are selected.

- Corollary analyses of **satellite cloud products** are also conducted
  - MetOp-A **IASI effective cloud fraction**
  - MetOp-A **AVHRR/3 cloud mask (not shown here)**

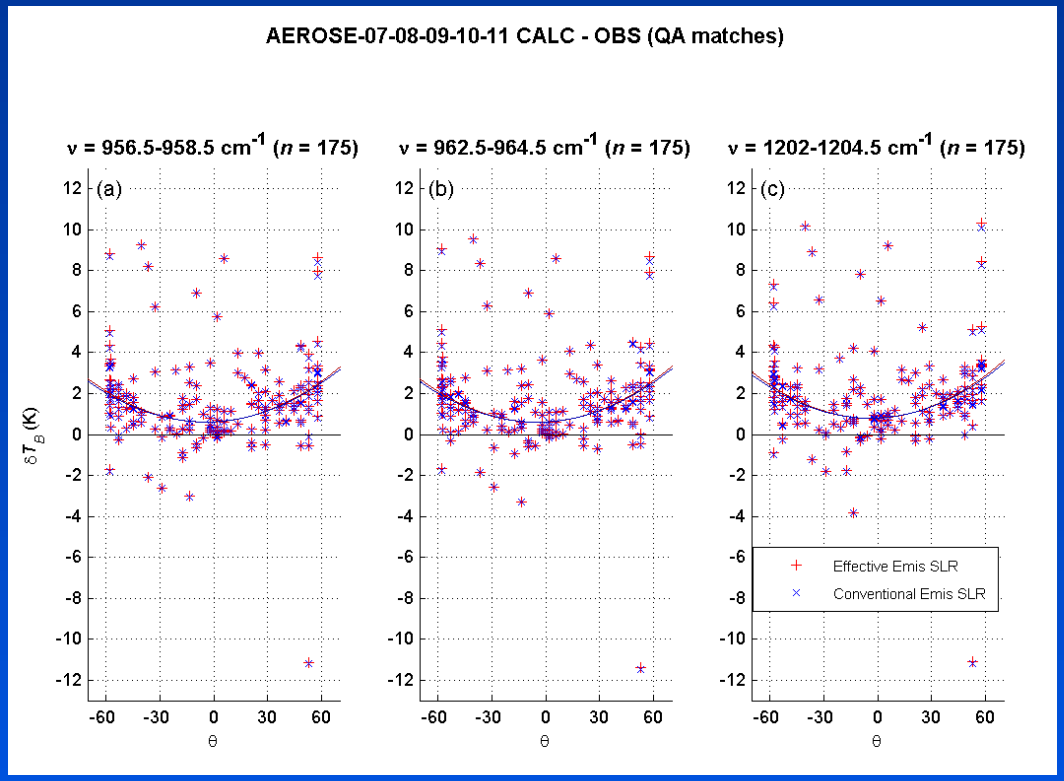
- Analyses using radiance spectra (without cloud-clearing) obtained from NAST-I during the 2007 Joint Airborne IASI Validation Experiment (JAIVEX) over-flight of the Gulf of Mexico, is the subject of ongoing research.

Satellite Analysis Using Cloud-Cleared Radiances

- **NOAA Aerosols and Ocean Science Expeditions (AEROSE)** 2007–2011
- Calculation (calc)
  - Atmosphere – **LBLRTM v11.7**
    - *T* and H_2O profiles obtained from **Vaisala RS92 RAOBs** launched over open ocean ≈ 30 min prior to MetOp overpasses
  - Surface
    - RAOB lowest level measurements
      - Wind speed used for emissivity models
      - Skin SST proxy given by the air temperature
- Observation (obs)
  - **NOAA Unique Infrared Atmospheric Sounding Interferometer (IASI) CCRs**
    - Nearest IASI field-of-regard (FOR) within 200 km of RAOB
    - Ascending (day) and descending (night) overpasses
  - **Microwindow channels**
    - 956.5–958.5 cm^{-1}, 962.5–964.5 cm^{-1}, 1202.0–1204.5 cm^{-1}



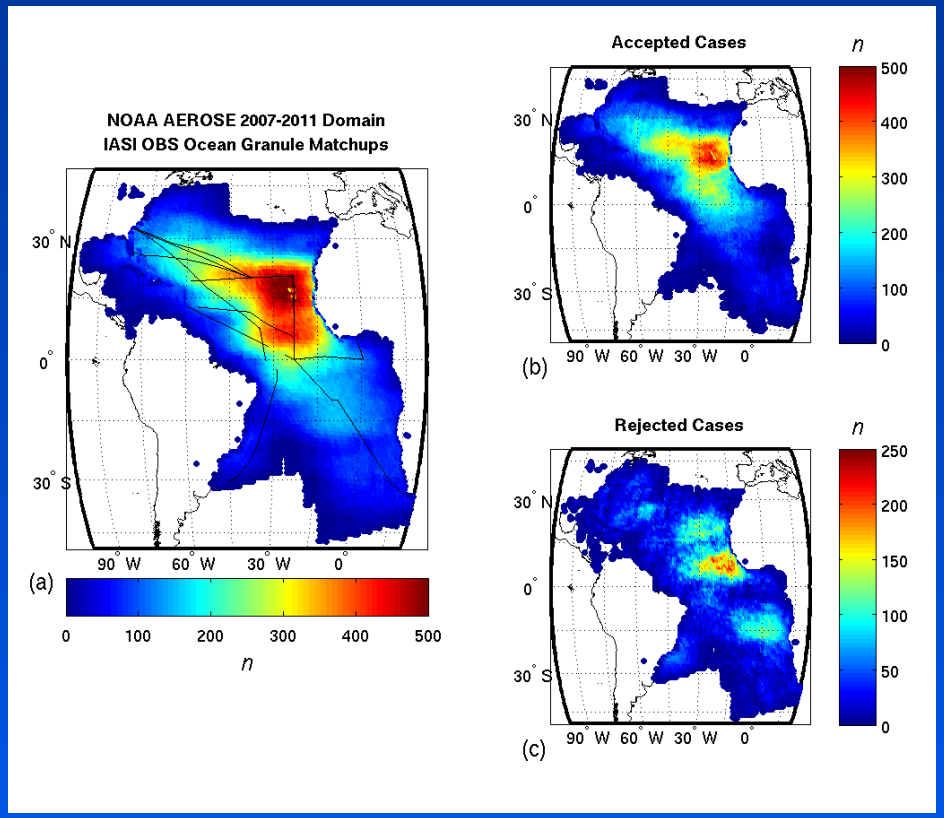
AEROSE IASI-RAOB calc – obs Results



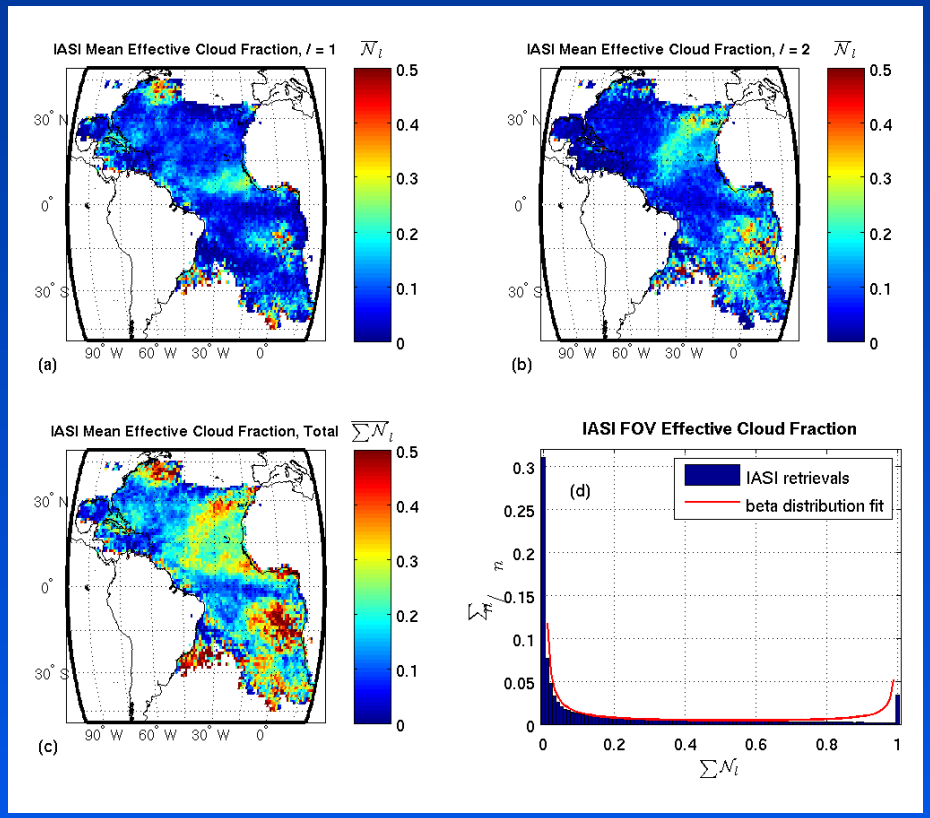
- A **strong concave-up signal is observed**
- This *cannot* be attributed to the forward model
  - Selected channels are minimally impacted by gas absorbers
  - The sfc emissivity model difference is an order of magnitude smaller than the observed variation
- Thus, the **concave-up variation** is an **indicator of cloud contamination in the cloud-cleared radiances**, a known issue (e.g., *Maddy et al.* 2011)

AEROSE IASI Effective Cloud Fraction Retrievals (1/2)

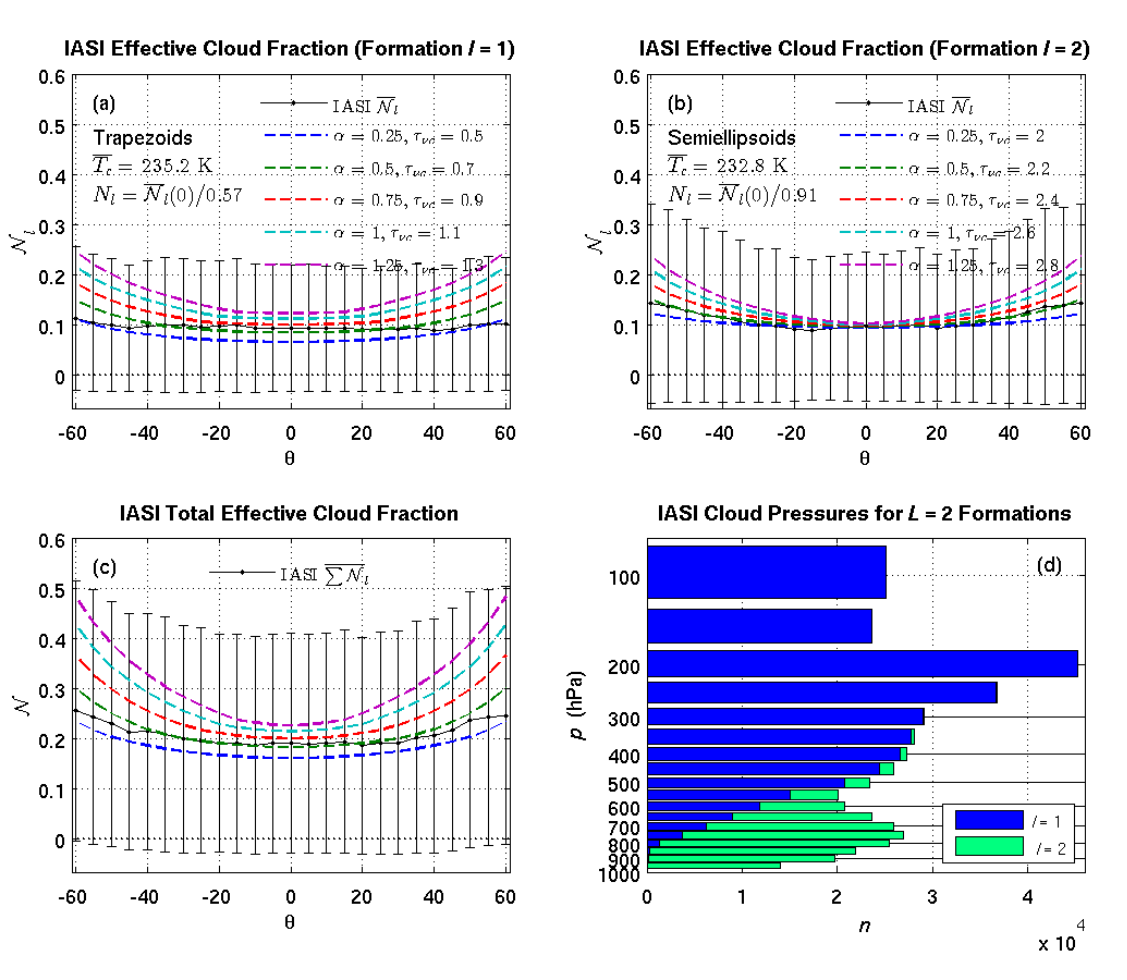
AEROSE IASI Granule Sample



Mean IASI Retrieved Effective Cloud Fraction



AEROSE IASI Effective Cloud Fraction Retrievals (2/2)



- Shown are NOAA IASI **effective cloud fraction** retrievals for the upper and lower atmosphere (AEROSE domain, *n* = 525,843) as a function of angle (5° binned means)
- Overlaid are hypothetical calculations based upon our cloud and aerosol models for various assumed scenarios, assuming IASI effective cloud fractions near nadir
- The IASI retrievals exhibit a small degree of concave-up angular dependence for the lower formation
- However, it appears that the upper formation (*l* = 1) retrievals may be underestimating effective cloud fraction at larger angles
  - IASI retrieval s assume blackbody clouds
  - This corroborates that cloud contamination is a probable culprit in the observed concave-up calc − obs

Summary and Conclusion

- In typical analyses of clear-sky TOA window channel calc − obs, the **"clear-sky" observations (obs) themselves are the product of an algorithm** that is subject to uncertainties.

- This work has presented idealized models and satellite data that indicate that residual clouds and aerosols remaining in "clear-sky" window radiances can lead to colder obs with greater angles, and therefore a **concave-up calc − obs variation with zenith angle.**

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EXTRA SLIDES

Radiative Transfer Model (RTM)

- Assuming a plane-parallel, non-scattering (IR), clear-sky, azimuthally symmetric atmosphere, the RTE is given by:

$$R_\nu(\theta) = I_{\nu s}(\theta)\mathrm{T}_{\nu s}(\theta) + I_{\nu a}^{\uparrow}(\theta).$$

- Where the **surface-leaving radiance (SLR)** is modeled as

$$I_{\nu s}(\theta) \approx \varepsilon_\nu(\theta,\bar{u})B_\nu(T_s) + \left[1-\varepsilon_\nu(\theta,\bar{u})\right]I_{\nu a}^{\downarrow}(\theta).$$

- Atmospheric transmittance and radiance terms are calculated using the AER **Line-By-Line Radiative Transfer Model (LBLRTM)** (*Clough et al.* 2005) Version 11.7.
  - LBLRTM calculations performed in this work take into account absorbing species H_2O, CO_2, O_3, N_2O, CH_4, CFC-11, CFC-12 and CCl4.