On the Angular Effect Of Undetected Clouds In Infrared Window Radiance Observations: Aircraft Experimental Analyses

Nicholas R. Nalli[1,2], William L. Smith[3], and Quanhua (Mark) Liu[2]

[1]IMSG, Rockville, Maryland, USA
[2]NOAA/NESDIS/STAR, College Park, Maryland, USA
[3]Hampton University, Hampton, Virginia, USA

NASA Sounder Science Team Meeting
Greenbelt, Maryland, USA
October 2015

Outline

- **Modeled Angular Effect of Cloud Contamination: Recap**
  - PCLoS Model
  - LWIR Window Channel Radiance Sensitivity

- **Aircraft Campaign LWIR Microwindow Analysis**
  - JAIVEX 29 April 2007 Gulf of Mexico Case
    - Data: NAST-I spectra, dropsondes and all-sky camera
    - Fair Weather Cumulus (FWC) clouds
    - Systematic scan-dependent sun-glint
  - Cloud-Cover Information from GOES Aerosol EDR
  - Angular Effect of Opaque FWC Clouds
    - Estimating cloud aspect ratios from cloud shadows
  - calc – obs Results
    - Double Differences versus Cloud Sensitivity Equation
  - Discussion and Summary

On the Angular Effect Of Undetected Clouds In Infrared Window Radiance Observations

MODELED ANGULAR EFFECT OF CLOUD CONTAMINATION: RECAP

Background

- Accurate satellite **observations (obs)** and **calculations (calc)** of top-of-atmosphere (TOA) infrared (IR) spectral radiances are required for retrieval of **environmental data records (EDRs)**.
  - It is important that systematic differences between obs and calc (calc − obs) under well-characterized conditions be minimal over the sensor's scanning range.

- A fundamental difficulty in **clear-sky 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.
  - For example, *Wong et al.* (2015) found cloud contamination biases in lower troposphere temperature profile EDRs (AIRS version 6) based on a thorough analysis against global RAOBs and MODIS cloud pressure and optical depth estimates.

- This presentation continues previous work (*Nalli et al.* 2012, 2013, *JGR-Atmospheres*) investigating the impact of the clear-sky observations commonly used in such analyses.
  - In the current work we utilize aircraft-based Fourier transform spectrometer (FTS) data obtained during the 2007 **JAIVEX** campaign **(*Nalli et al.* 2015, manuscript submitted to *JAS*)**

Angular Variation of Apparent Cloud Cover

- Idealized approximations for assessing the impacts of single layer clouds and aerosols on IR window channel radiances were derived by *Nalli et al.* (2012) for various scenarios, including
  - Broken opaque clouds
  - Aerosol layer
  - Aerosol layer overlying or underlying broken opaque clouds
  - Broken semitransparent clouds
- This was achieved using a statistical model for predicting the **probability of a clear line of sight (PCLoS)**
  - Clouds are assumed to be uniform Poisson-distributed within a plane-parallel, horizontally unbounded layer (e.g., *Kauth and Penquite* 1967; *Taylor and Ellingson* 2008).
  - The ensemble probability of a cloudy FOV mischaracterized as "clear" (i.e., false negatives) is assumed to behave as 1 − PCLoS (e.g., a cloud-mask algorithm having a small, angularly independent fraction of false-negatives in regions consisting of broken, sub-pixel clouds with small absolute cloud fractions).

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

(e.g., *Kauth and Penquite* 1967; *Taylor and Ellingson* 2008; *Nalli et al.* 2012)

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

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

$$P(0) = 1 - N,$$

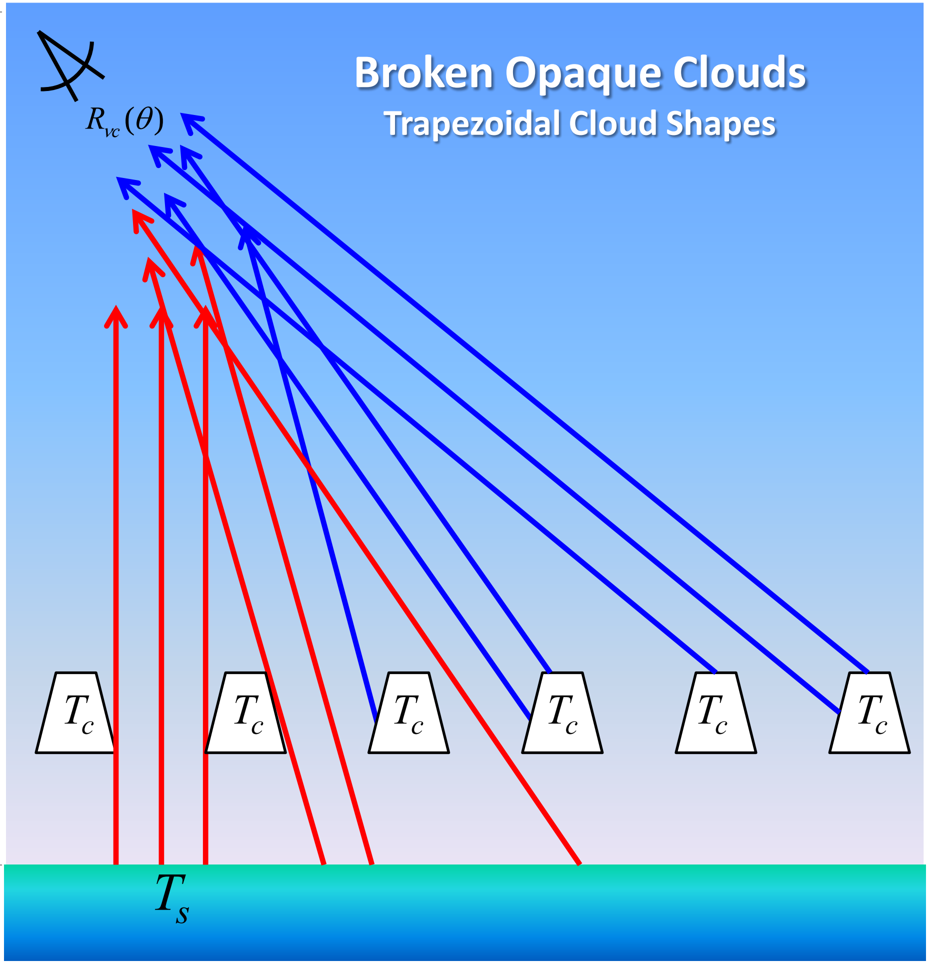
$$f(\theta,\alpha_c,\ldots) \equiv \text{shape factor},$$

$$\alpha_c \equiv \delta z / \delta x, \text{ the cloud vertical aspect ratio}$$

- **Cloud shapes** for $f(\theta,\alpha_c)$ 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

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

$$\Rightarrow \delta T_B(\nu,\theta,\alpha_c) \approx \left[1 - P(\theta,\alpha_c)\right] \frac{\left[\partial B_\nu / \partial T\right]_{\overline{T_{sc}}}}{\left[\partial B_\nu / \partial T\right]_{\overline{T_B}}}\, \delta T_{sc}.$$



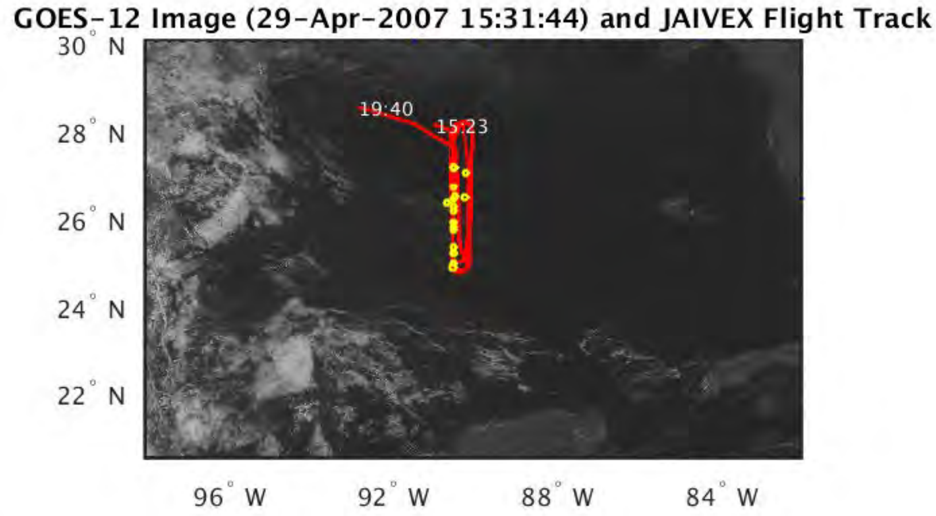
On the Angular Effect Of Undetected Clouds In Infrared Window Radiance Observations

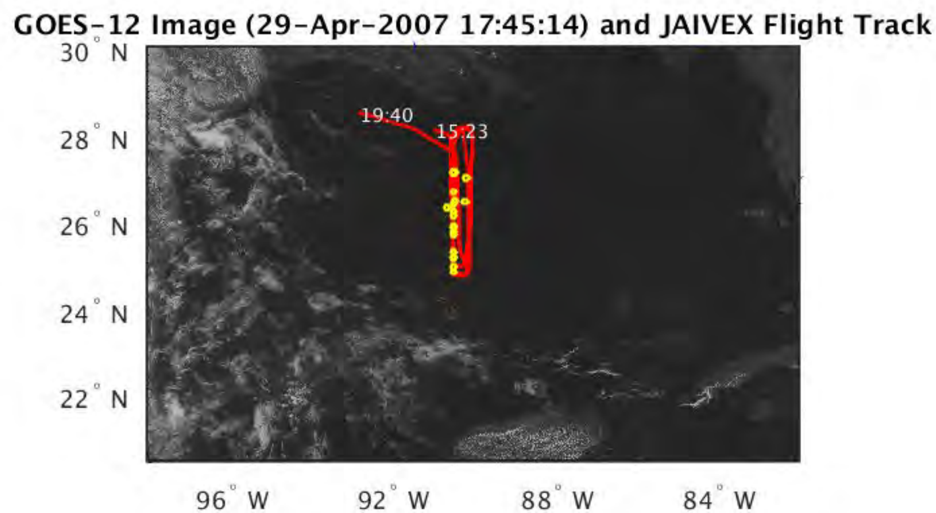
AIRCRAFT CAMPAIGN LWIR MICROWINDOW ANALYSIS

Joint Airborne IASI Validation Experiment (JAIVEX)
(*Newman et al.* 2012)

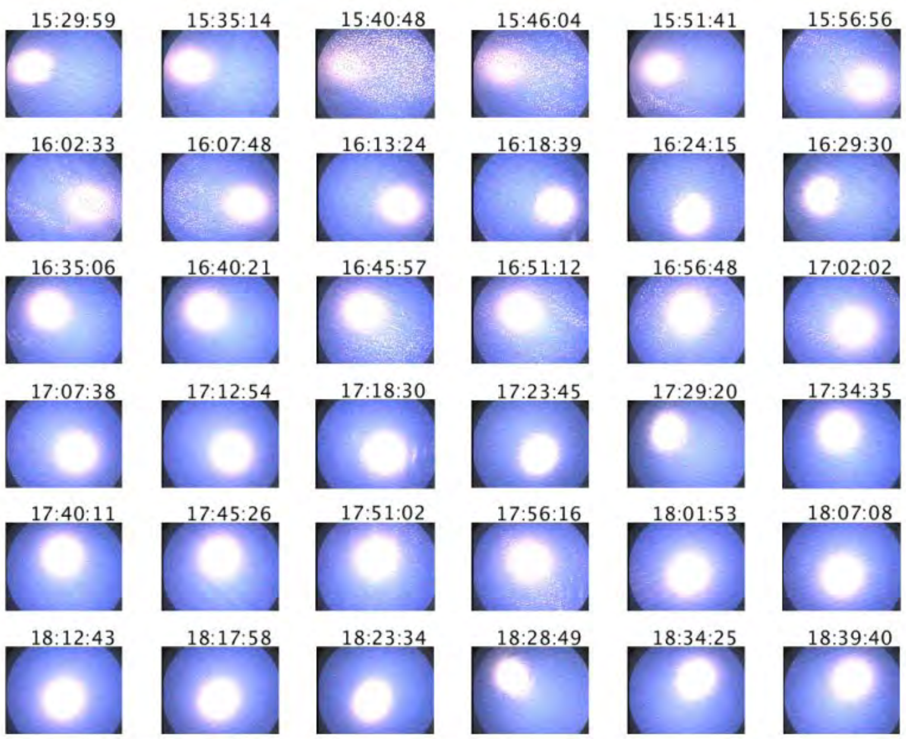
- **29 April 2007 clear-sky overflight of the Gulf of Mexico** (e.g., *Larar et al.* 2010) , 15:23–19:40 UTC (09:23–13:40 LST).
  - High resolution radiance spectra from the NPP Atmospheric Sounder Testbed Interferometer (**NAST-I**) (*Smith et al.* 2005)
    - NASA WB-57 aircraft ≈16–18 km
    - Nadir FOV "footprint ≈2.08–2.34 km
  - **20 Vaisala dropsondes** launched from FAAM BAe 146 aircraft at ≈7–8 km.
  - **Hemispherical camera** mounted on WB-57 main fuselage for all-sky imagery

- **GOES imagery (right)** shows the appearance of a **nearly ideal "clear-sky" field experiment** given that the percentages of cloud-free FOV for a IR sounder such as CrIS or IASI are small (e.g., ≤10%; *Maddy et al.* 2011).





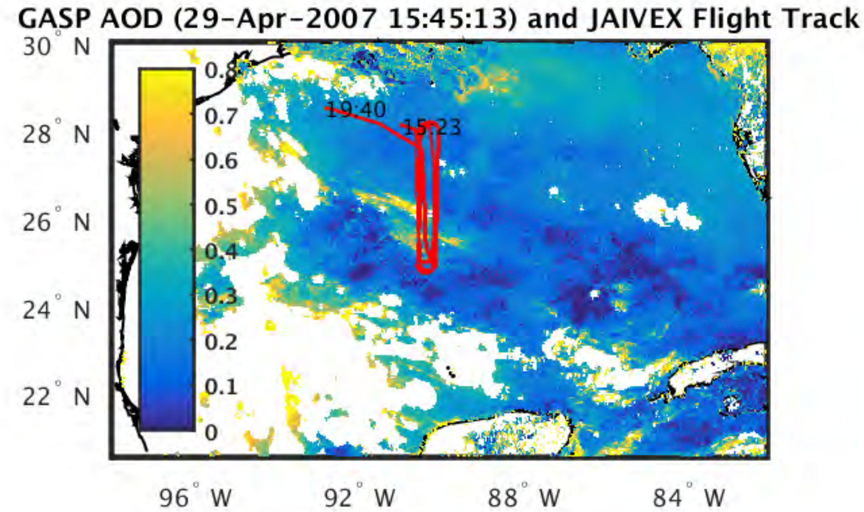
Insidious Case: Microscale Fair Weather Cumulus (FWC) Clouds and Sun Glint!

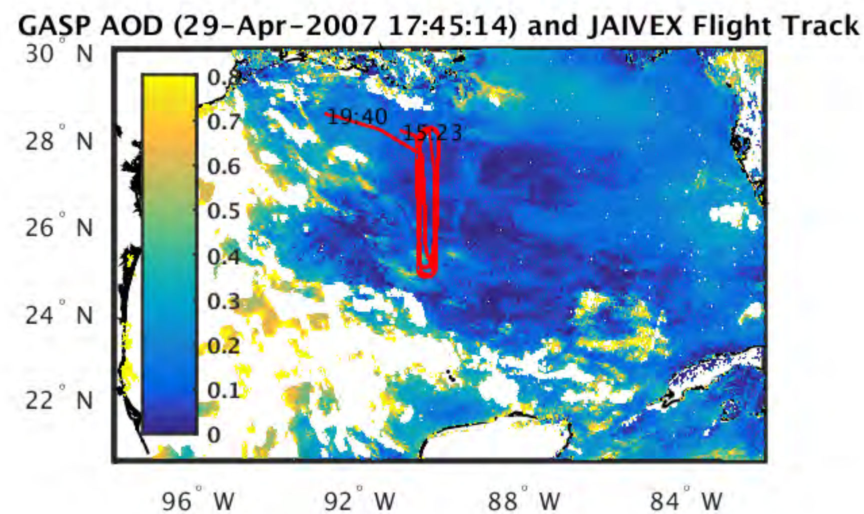


- Closer examination of the sky conditions using the hemispheric camera reveals the presence of **marine boundary layer (MBL) fair weather cumulus clouds (FWC)** (e.g., *Stull* 1985)
  - These were found to be persistent at the mid-to-south end of the flight track. Only a small hint of their presence is barely noticeable in the GOES-12 images (Slide 8).
  - Thus, JAIVEX 29 April 2007 provides a fortuitous case of a broken field of sub-pixel FWC clouds (as well as cirrus and haze) that can be very difficult to clear or mask completely (e.g., *Benner and Curry* 1998).
- Another problem evident in these images to be dealt with is **systematic sun glint contamination** near nadir.

Cloud-Cover Information from GOES Aerosol EDR (NOAA GASP Product)

- To obtain quantitative characterizations of the MBL FWC (as well as aerosols/haze), we realized that visible data from GEO orbit is the best option. However, an algorithm designed for detecting very small backscatter signals would be necessary.
- This prompted us to utilize the **GOES Aerosol/Smoke Product (GASP)** developed at STAR (*Knapp et al.* 2002; *Prados et al.* 2007).
  - Retrieves **aerosol optical depth** (AOD) by removing invariant "background" solar reflectance using an image composite, thereby allowing small transient anomalies (i.e., backscatter due to aerosol, sub-pixel cloud) to be detected (*Knapp et al.* 2002).
  - GASP thus provides quantitative measurements of low-signal, atmospheric backscattering as AOD.
- The FWC observed by the hemispheric camera appear as intermittent regions of high AOD (≥0.25); there are other regions of elevated AOD (≥0.15) that presumably correspond to the haze and/or cirrus reported in the Flight Summary Document.

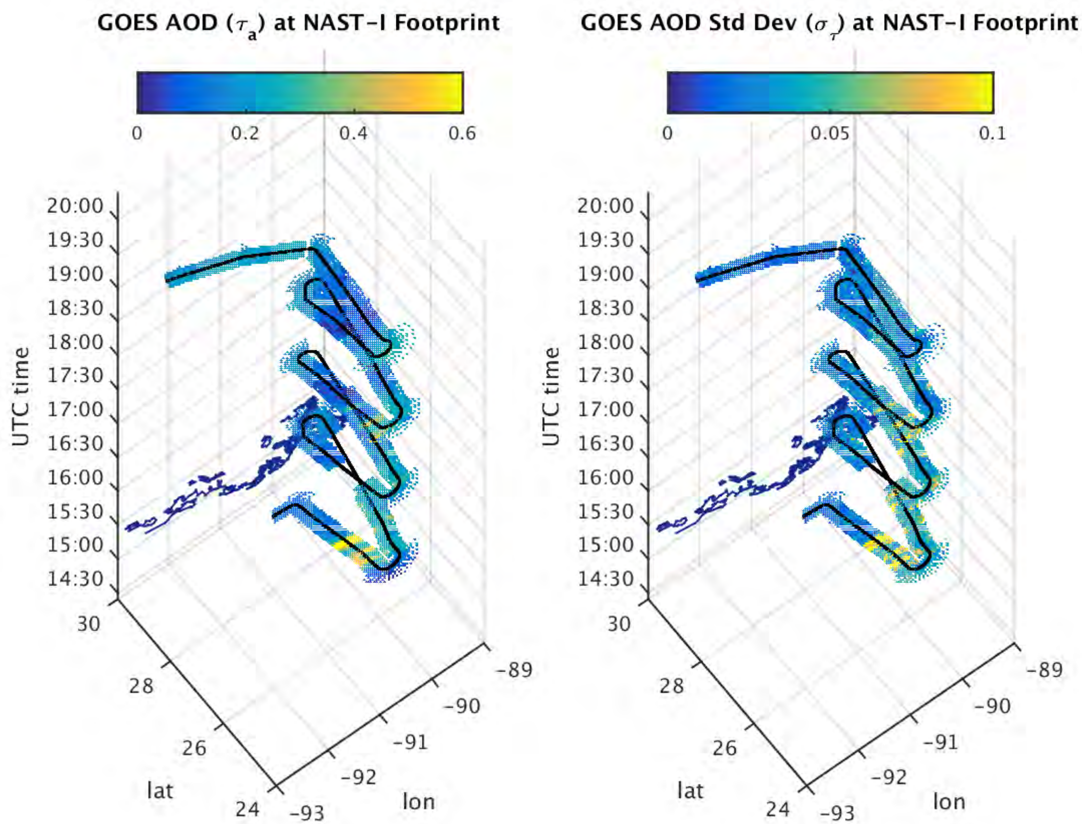




Space-Time Interpolation of GOES AOD to NASI-I FOV

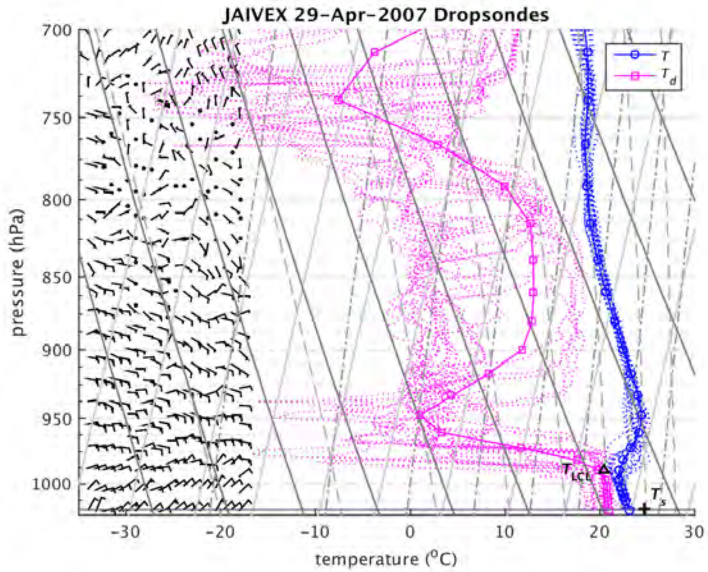
- The GASP EDRs are derived from the FOV of the GOES-12 Imager located at (0°N, 75°W*)*. Therefore, the atmospheric paths measured within the GOES FOV strictly speaking do not correspond to those of the NAST-I FOV.
  - To deal with this, the would-be coordinates of clouds/aerosols within NAST-I FOV are estimated given their estimated altitude.
  - The "footprints" (i.e., FOV at the surface) where they would be observed by GOES are then determined.

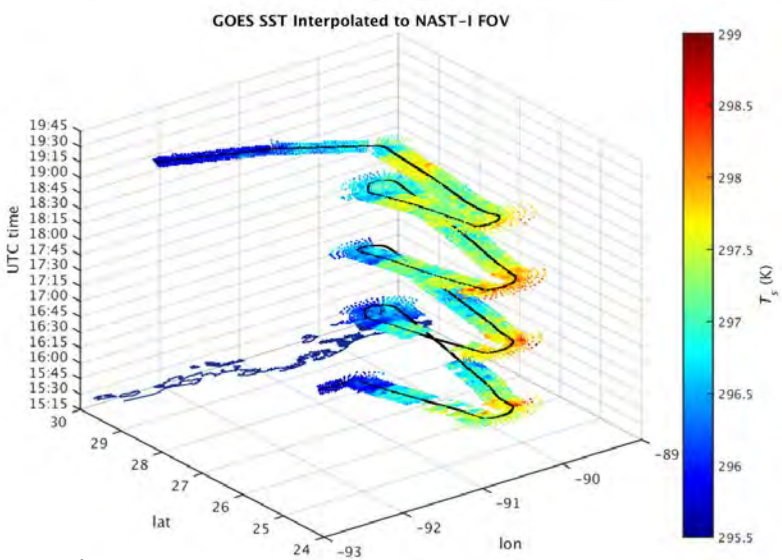
- After performing this remapping of FOV, we can then use a space interpolant for each half hourly GASP AOD (and AOD standard deviation) field to interpolate to the lat/lon coordinates. This is followed by a linear interpolation in time to the NAST-I times.



Methodology for calc – obs

- Forward model calculations (calc) for the individual NAST-I FOV are conducted based upon
  - ***In situ* dropsonde** profiles along with **ECMWF** (18:00 UTC analysis, 15:00, 21:00 UTC forecast)
  - Satellite SSTs: GOES IR and RSS GHRSST MW-IR blended SST
- The radiative transfer equation (RTE) includes **CRTM effective surface emissivity** (*Nalli et al.* 2008) as well as **sun-glint (≈0.05 K)**
- Atmospheric radiance calculations valid for the NAST-I viewing geometry (including aircraft roll/pitch) are obtained using **LBLRTM v12.2** for **LWIR microwindows** defined by [899.5,901.8], [956.5,958.5], [962.5,964.5] cm^{-1} (and others)





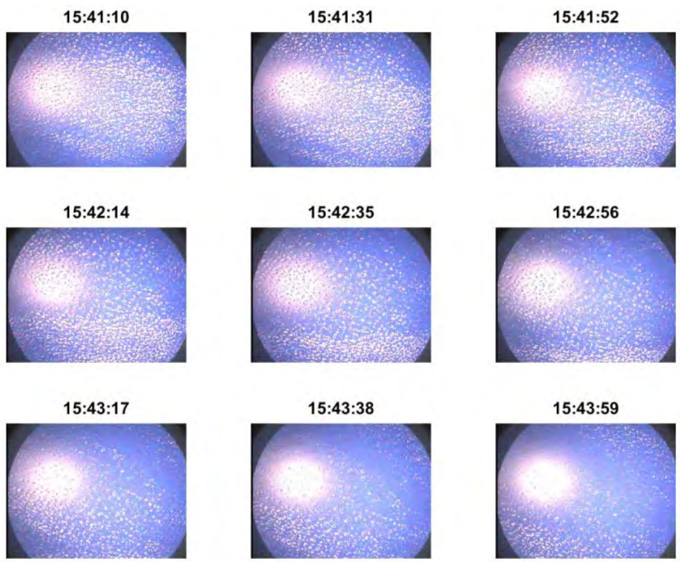
Angular Effect of Opaque FWC Clouds

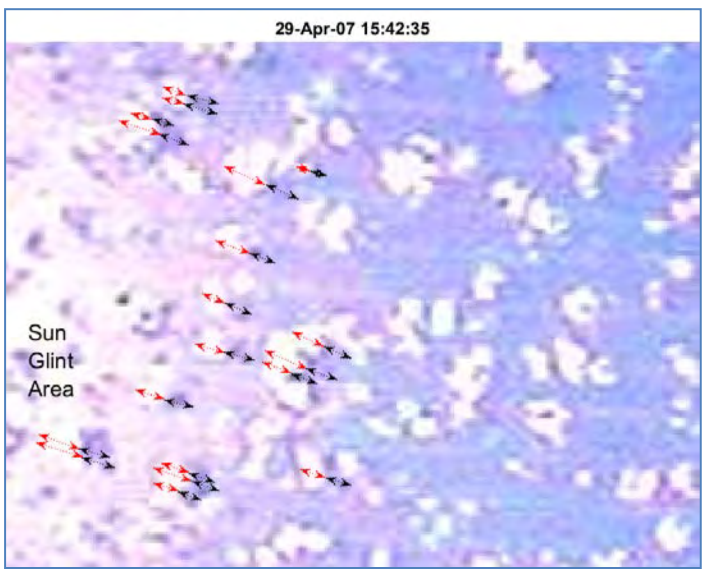
- To ascertain the angular impact of FWC clouds on clear-sky calc − obs, we utilize the **sensitivity equation for broken opaque clouds** (*Nalli et al.* 2012)

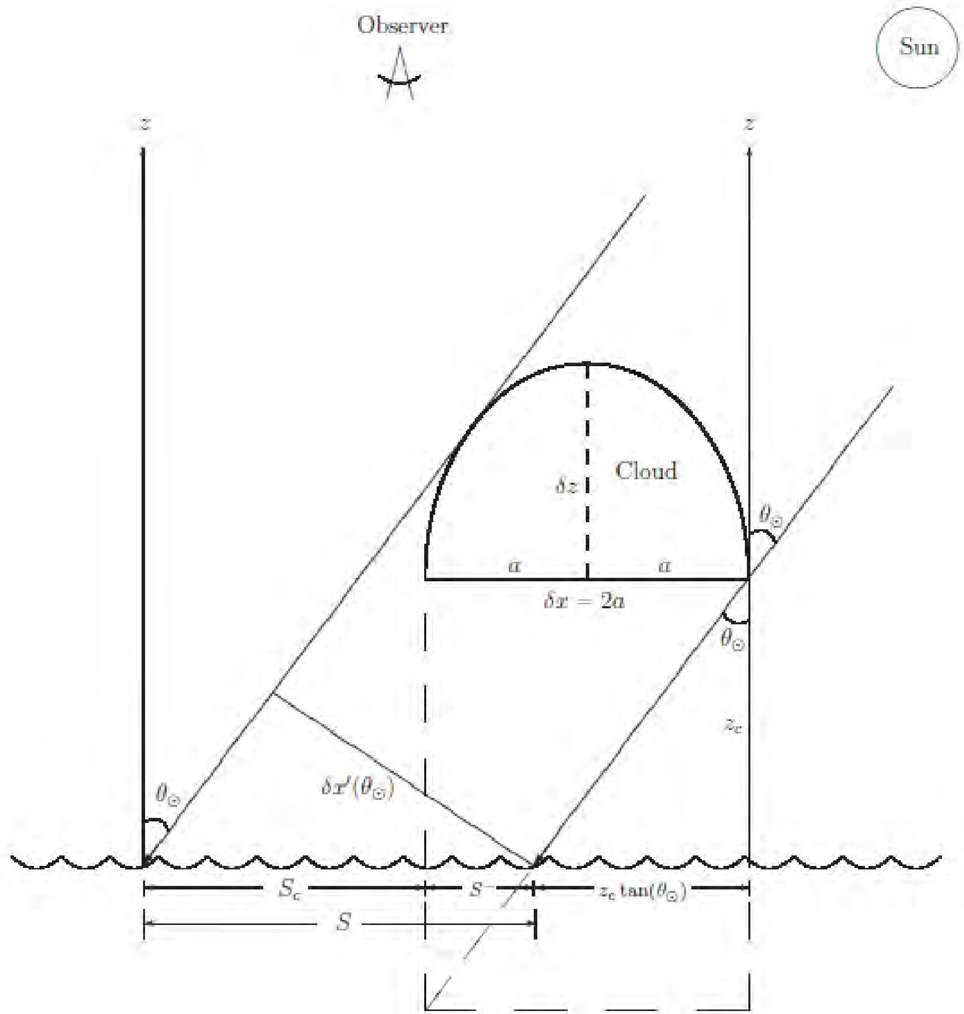
$$\delta T_B(\nu,\theta,\alpha_c) \approx \left[1 - P(\theta,\alpha_c)\right] \frac{\left[\partial B_\nu / \partial T\right]_{\overline{T_{sc}}}}{\left[\partial B_\nu / \partial T\right]_{\overline{T_B}}} \delta T_{sc}$$

- The lifted condensation level (LCL) for each NAST-I FOV is calculated given the dropsonde/ECMWF profiles
  - LCL temperature from *Inman* (1969) → cloud temperature
  - LCL height from the Espy approximation → cloud base height
- However, to calculate *P,* it is *also* necessary to obtain an estimate of the cloud aspect ratios, α_c.
  - Using expressions for cross-sectional widths of clouds originally derived for calculating mean cloud slant paths, δx (*Nalli et al.* 2012), **we can estimate α_c using the all-sky camera imagery by analyzing the shadows cast by the FWC onto the sun-glint region**.

Estimating Cloud Aspect Ratios From Cloud Shadows (1/2)







Estimating Cloud Aspect Ratios From Cloud Shadows (2/2)

- Isosceles trapezoid shadow

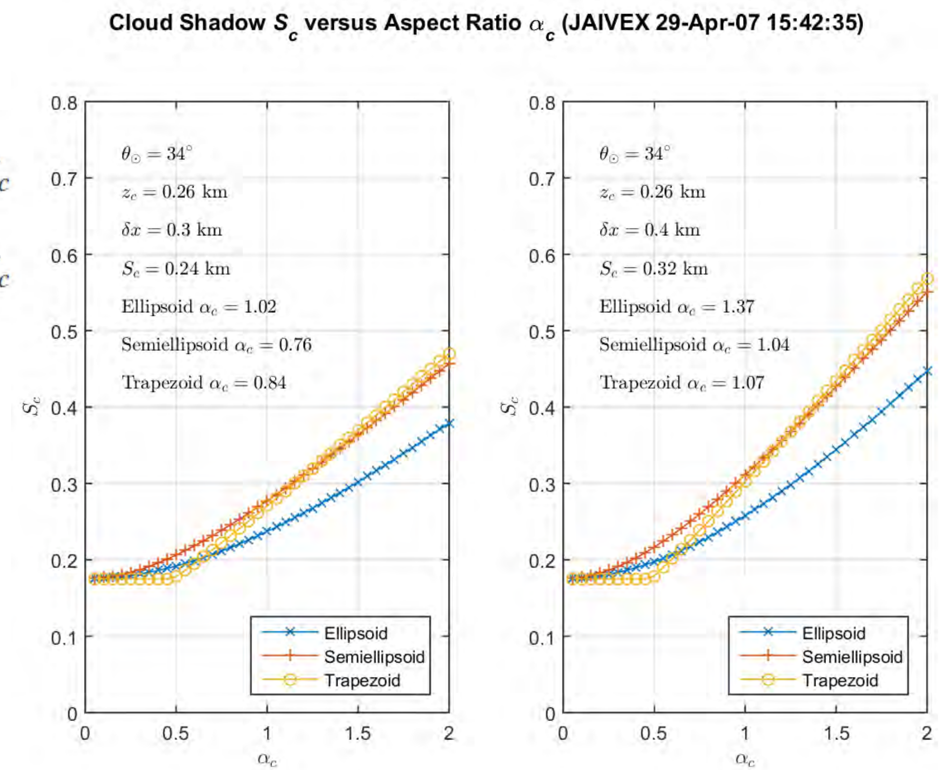
$$S(\theta_\odot, \alpha_c, \zeta_c, \delta x) = \begin{cases} \delta x & , \quad |\theta_\odot| < \zeta_c \\ \delta x \sec(\theta_\odot)\, \alpha_c \dfrac{\cos(\theta_\odot - \theta_d)}{\sin(\theta_d)} & , \quad |\theta_\odot| \geq \zeta_c \end{cases}$$

- Ellipsoid shadow

$$S(\theta_\odot, \alpha_c, \delta x) = \delta x \sec(\theta_\odot) \sqrt{(1 - \alpha_c^2)\cos^2(\theta_\odot) + \alpha^2}$$

- Semiellipsoid shadow

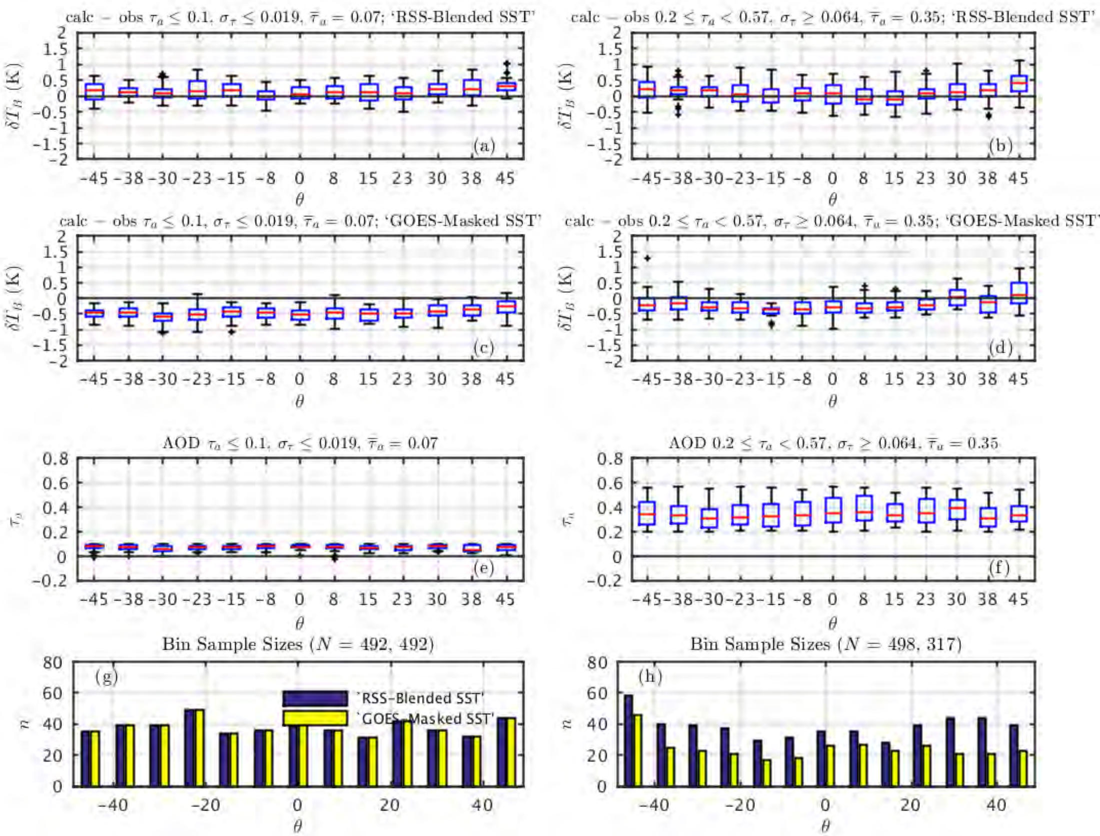
$$S(\theta_\odot, \alpha_c, \delta x) = \delta x \sec(\theta_\odot) \frac{1}{2} \left[\cos(\theta_\odot) + \sqrt{(1 - 4\alpha_c^2)\cos^2(\theta_\odot) + 4\alpha_c^2}\right]$$



Results (1/2)

- **To examine the impact of the observed FWC clouds** (and residual ambient aerosols) on the angular variation of calc obs analyses, we place data in **angular bins** centered on the NAST-I nadir scan angles.
- We further **bin data according as "clear" or "cloudy"** using the **GOES AOD EDR** (τ_a), and 3×3 pixel AOD standard deviation (σ_τ), to eliminate or isolate cloudy FOV.
  - Binned as "clear" for $\tau_a \leq 25^{th}$ percentile and $\sigma_\tau \leq 20^{th}$ percentile.
  - Binned as "cloudy" for $75^{th} \leq \tau_a \leq 99^{th}$ percentiles and $\sigma_\tau > 95^{th}$ percentile.
  - These thresholds mitigate limitations inherent in the FOV interpolation scheme
    - FOV remapping
    - Linear interpolation in time from 30 min GOES sampling to boundary layer time scales (≤10 min).

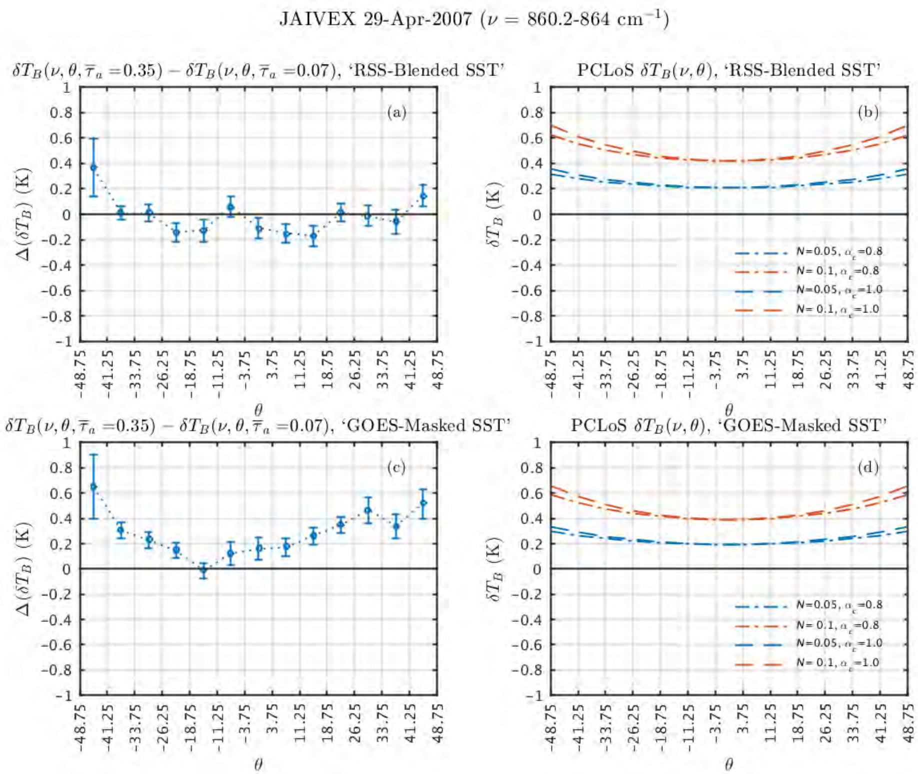
Box Plot Summary Microwindow ν = [956.5,958.5] cm^{-1}



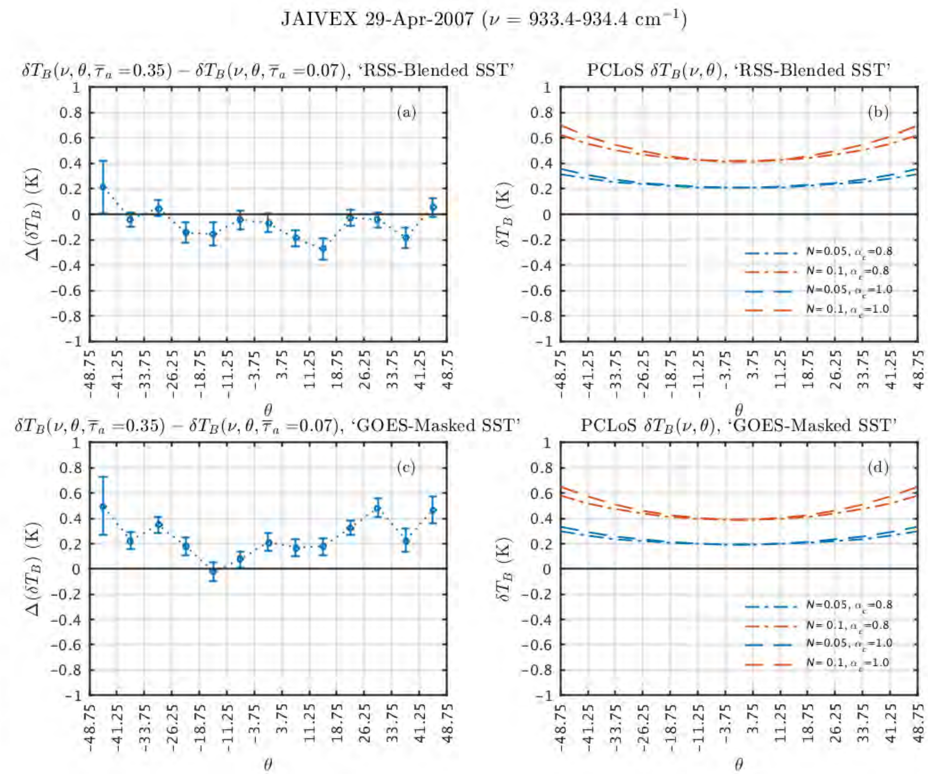
Results (2/2)

Double Differences Versus Sensitivity Equation (Slide 13)

ν = [860.2,864] cm^{-1}



ν = [933.4,934.4] cm^{-1}



Discussion and Summary

- **These results**, based upon observations totaling N = 492 “clear,” and N = 498 (317 using GOES cloud-masked SST) “cloudy,” FOV indicate that contamination by residual clouds and/or aerosols within clear-sky observations can have a **small, but measurable, concave-up impact** (i.e., an increasing positive bias symmetric over the scanning range) **on the angular agreement of observations with calculations**.
  - The cloudy FOV consisted of **broken subpixel FWC cloud fields that are undoubtedly difficult to detect**.
  - Results for different LWIR microwindows are very similar, thus providing us greater confidence in our calculations.
  - Based on the estimated T_s and T_{lcl}, the results suggest an average absolute cloud fraction of $N \leq 0.05$ and aspect ratio $\alpha_c \geq 1.0$.
  - Regardless of the SST dataset, there are **distinct concave-up signals** in the double-difference plots (subplots a, c) **ranging from ≃0.2–0.4 K**.
  - These magnitudes are consistent in magnitude (albeit somewhat larger) than the δT_B predicted by the sensitivity equation, that is ≃ 0.1–0.2 K.

Acknowledgments

- This research was supported by the **NOAA Joint Polar Satellite System (JPSS-STAR) Office** and the NOAA/NESDIS/STAR Satellite Meteorology and Climatology Division (SMCD) (M. Goldberg and F. Weng).
- We are grateful to the following individuals for their contributions in support of this work:
  - **V. Leslie** (MIT Lincoln Lab) for providing the all-sky camera images and for discussions pertaining to the image timestamp offset.
  - **S. Kondragunta** and **C. Xu** (NESDIS/STAR) for providing the NOAA GASP aerosol EDR product for April 2007.
  - **A. Ignatov** and **X. Liang** (NESDIS/STAR) for bringing our attention to the possibility of sun-glint contamination in LWIR channels.
  - **C. Barnet** (STC, formerly STAR) for his support of our earlier related papers.