Angular Effect of Undetected Clouds in Infrared Window Radiance Observations: Aircraft Experimental Analyses

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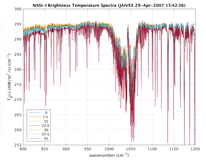
Introduction and Background

- 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.* 2016, manuscript accepted in *JAS Special Section***)



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)** (e.g., *Kauth and Penquite* 1967; *Taylor and Ellingson* 2008).
  - Clouds are assumed to be uniform Poisson-distributed within a plane-parallel, horizontally unbounded layer.
  - 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).

Infrared Window Sensitivity to Undetected Clouds and Aerosols

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

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

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

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

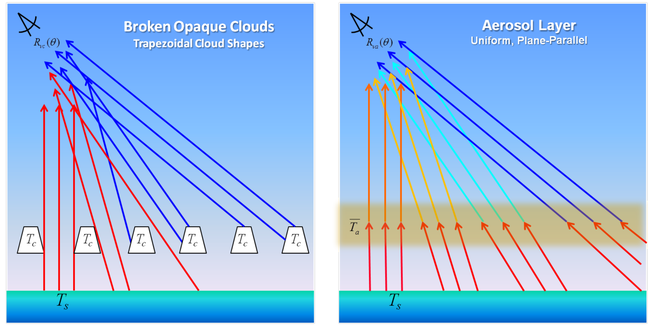
$$f(\theta,\alpha_c,\ldots)\equiv\text{shape factor},$$

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

- **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

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

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



IR Sensitivity Equations (*Nalli et al.* 2012)

$$\delta T_B(\nu,\theta,\alpha)\approx\begin{cases}\left[1-P(\theta,\alpha)\right]\dfrac{\left[\partial B_v/\partial T\right]_{\overline{T_{sc}}}}{\left[\partial B_v/\partial T\right]_{\overline{T_B}}}\delta T_{sc}, & \text{broken opaque clouds}\\[2ex] \left[1-\exp(-\tau_{va}\sec\theta)\right]\dfrac{\left[\partial B_v/\partial T\right]_{\overline{T_{sc}}}}{\left[\partial B_v/\partial T\right]_{\overline{T_B}}}\delta T_{sa}, & \text{uniform aerosol layer}\\[2ex] \left[1-P(\theta,\alpha)\exp(-\tau_{va}\sec\theta)\right]\dfrac{\left[\partial B_v/\partial T\right]_{\overline{T_{sc}}}}{\left[\partial B_v/\partial T\right]_{\overline{T_B}}}\delta T_{sc}, & \text{opaque clouds over aerosol layer}\\[2ex] \varepsilon_{vc}(\theta,\tau_{vc})\left[1-P(\theta,\alpha)\right]\dfrac{\left[\partial B_v/\partial T\right]_{\overline{T_{sc}}}}{\left[\partial B_v/\partial T\right]_{\overline{T_B}}}\delta T_{sc}, & \text{broken semitransparent clouds},\end{cases}$$

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

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

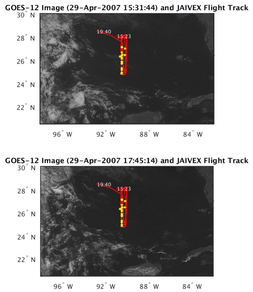
Note that

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

Aircraft Campaign LWIR Microwindow Analysis

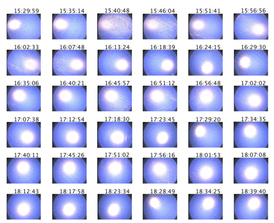
Joint Airborne IASI Validation Experiment (JAIVEX) (*Newman et al.* 2012)

- **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).



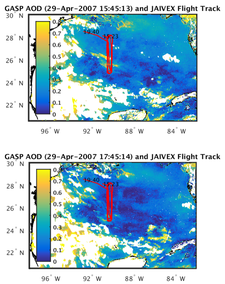
Insidious Case: Microscale Fair Weather Cumulus (FWC) Clouds and Sun Glint!

- 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.
  - Thus, JAIVEX 29 April 2007 provides 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.



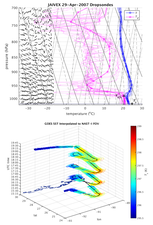
Cloud-Cover Information from GOES Aerosol EDR (NOAA GASP Product)

- 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 appear as intermittent regions of high AOD (≳0.25); there are other regions of elevated AOD (≳0.15) that correspond to the haze and/or cirrus reported in the Flight Summary Document.



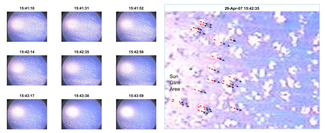
Methodology

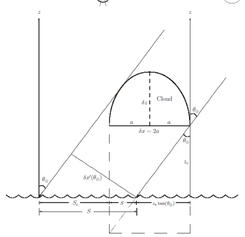
- **Forward model calculations (calc)** for the individual NAST-I FOV are conducted based upon
  - ***In situ* dropsonde** profiles along with **ECMWF** (18:00 UTC analysis, 15:00, 21:00 UTC forecast)
  - Satellite SSTs: GOES IR and RSS GHRSST MW-IR blended SST
- The radiative transfer equation (RTE) includes **CRTM effective surface emissivity** (*Nalli et al.* 2008) as well as **sun-glint (≈0.05–0.1 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)



Modeled LWIR Impact of Broken FWC Clouds

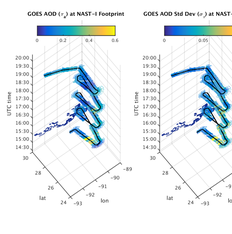
- The lifted condensation level (LCL) for each NAST-I FOV is calculated given the dropsonde/ECMWF profiles
  - LCL temperature from *Inman* (1969) → cloud temperature
  - LCL height from the Espy approximation → cloud base height
- However, to calculate P, it is *also* necessary to obtain an estimate 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**.





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

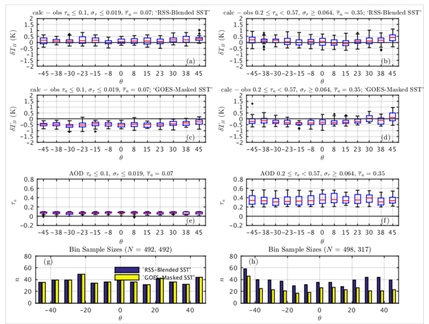
- The GASP EDRs are derived from the FOV of the GOES-12 Imager located at (0°N, 75°W). Therefore, the atmospheric paths within the GOES FOV do not correspond to the NAST-I FOV.
- To account for this, coordinates of clouds/aerosols within NAST-I FOV are estimated given their estimated altitude.
- The "footprints" where they would be observed by GOES are then determined.
- After performing this remapping of FOV, we perform linear interpolation for each half hourly GASP AOD field to the NAST-I lat/lon coordinates, followed by linear interpolation in time to the NAST-I times.



Results

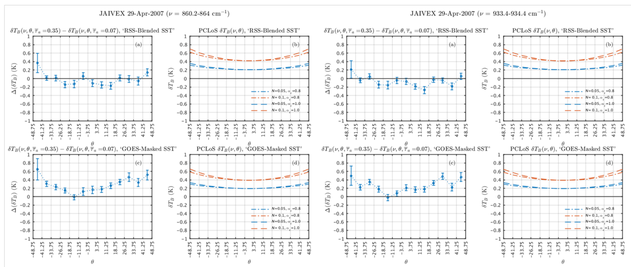
- **To examine the impact of the observed FWC clouds** (and residual ambient aerosols) on the angular variation of calc obs analyses, we place data in **angular bins** centered on the NAST-I nadir scan angles.
- We further **bin data according as "clear" or "cloudy"** using the **GOES AOD EDR** (τ_a),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



Double Differences Versus Sensitivity Equation

ν = [860.2,864] cm^{-1} ν = [933.4,934.4] cm^{-1}



Summary and Discussion

- **These results support the hypothesis** 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 \le$0.05 and aspect ratio $\alpha_c \ge$ 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.
- We also found the impact of **sunglint in LWIR microwindows** can reach magnitudes of ≃+0.05–0.1 K in brightness temperature.
  - Future aircraft-based daytime satellite cal/val campaigns focused on high-accuracy SDR cal/val involving forward calculations (e.g., *Newman et al.* 2012), may consider accounting for sunglint in LWIR, as it can introduce angularly systematic radiance contributions.
- Our work on the angular effect of clouds has methodically extended the application of the PCLoS model, including three general cloud shapes, from visual based remote sensing and radiative flux applications to passive IR remote sensing applications.

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