Assimilating thermodynamic information in cloudy skies from hyperspectral IR sounders for improving tropical cyclone forecasts

Jinlong Li, and Jun Li

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Outlines

- Motivation and current status on IR sounder radiance assimilation in cloud skies;
- Imager-based IR sounder cloud-cleared radiances (CCRs);
- Impact CrIS CCRs on recently hurricanes;
- Summary and future work.
Q: Is direct assimilation of cloudy IR radiances in NWP realistic?

A: Very challenging because:

(1) Both NWP and RTM have larger uncertainty;

(2) Big change of Jacobian at cloud level;

(3) In consistency between NWP and satellite observations on cloud presence.
Current status

• Hole hunting for clear pixels;
• Assimilating radiances not affected by clouds;
• Direct radiance assimilation;
• Cloud-clearing for assimilation
  – Imager-based (keeps single IR footprint)
  – MW-based (degrades to MW footprint)
  – Background-based (background dependent)

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Using high resolution imager measurements to assist hyperspectral IR sounder radiance assimilation

1. Both instruments (sounder and imager) have good signal-to-noise ratio, have overlap spectral coverages;
2. They are comparable through convolving sounder to imager spectrally and averaging imager to sounder spatially.

Using imager for assisting IR sounder radiance assimilation:
1. IR sounder sub-pixel cloud-detection and QC for radiance assimilation;
2. Cloud-cleared radiances (CCRs) in cloudy skies for assimilation.
Current status on using imager for sounder radiance assimilation

- IR sounder sub-pixel cloud characterization has been demonstrated and recommended by ITWG to operational centers at ITSC20;
- Using collocated imager data (IR band radiances and cloud mask) to derive the sounder cloud-cleared radiances
  - AIRS/MODIS demonstrated (Wang et al. 2016);
  - Algorithm implemented for CrIS/VIIRS, demonstrated with CIMSS SDAT for recent hurricanes; Started test in HWRF;
  - VIIRS-base CrIS CCRs tested in GFS by EMC (Dr. Collard and Dr. Liu) (9p.09 - Liu et al.);
  - VIIRS-based CrIS CCRs tested in RAP by ESRL;
  - Test by NRL planned (Dr. Ruston).
ITSC20 Recommendation DA/NWP to Data Providers
Consider including a map of the sub-pixel information derived from imager pixels within hyperspectral sounder FOVs, should bandwidth allow.
(http://cimss.ssec.wisc.edu/itwg/itsc/itsc20/itsc20_wg_report_final.pdf)
AIRS/MODIS cloud-clearing (Li et al. 2005)

\[ J(N^*) = \sum_i \frac{1}{\sigma_i^2} [(R_{M_i}^{clr} - f_i(R_v^{cc}))]^2 = \min \]

\[ J(N^*) = \sum_i \frac{1}{\sigma_i^2} [(R_{M_i}^{clr} - f_i(\frac{R_v^1 - R_v^2 N^*}{1 - N^*}))] = \min \]

\[ \sigma_i \] is NEdR for MODIS band

solve \[ \frac{\partial J(N^*)}{\partial N^*} = 0 \]

\[ N^* = \frac{\sum_i \frac{1}{\sigma_i^2} [f_i(R_v^1) - R_{M_i}^{clr}] [f_i(R_v^1) - f_i(R_v^2)]}{\sum_i \frac{1}{\sigma_i^2} [f_i(R_v^2) - R_{M_i}^{clr}] [f_i(R_v^1) - f_i(R_v^2)]} \]

\[ R_v^{cc} = \frac{R_v^1 - R_v^2 N^*}{1 - N^*} \]
(1) For each cloudy AIRS FOV, 8 pairs are used to derive 8 AIRS CC radiance spectra;
(2) Compare AIRS CC radiances with MODIS clear radiance observations within the AIRS FOV, find the best pair and the corresponding CC radiance spectrum.
CrIS/VIIRS cloud clearing for CrIS radiance assimilation

- The CC method (Li et al., 2005);
- VIIRS cloud mask identifies partially cloudy FOVs (black circle);
- VIIRS radiances help quality control cloud cleared CrIS radiances;
- Only three VIIRS bands (4.05, 10.763, and 12.013 um) used (overlapped with CrIS);
- Cloud cleared radiances very close to VIIRS clear sky radiances;
- 12.5% of partially cloudy FOVs are successfully cloud cleared for Hurricane Sandy (2012) case.
CrIS clear radiances:
(clear FOVs + radiances not affected by clouds)

CrIS CCRs:
(clear + CC coverage)

Example of 1 day CrIS coverage
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120 h forecast track plots of the OFCL, HWRF model, AVNO, and UKM global model for the forecast cycles between 0600 UTC on 29 September and 1800 UTC on 1 October 2015 for Hurricane Joaquin. The best track of Joaquin is indicated by the black lines with six-hourly tropical cyclone positions. The dots for HWRF, AVNO, and UKM forecasts represent 6 h intervals, and OFCL represent 12 h intervals.
Analyzing 120hr forecasts from 18 UTC 09-30 2015

How do CrIS CCRs improve tropical cyclone forecast?

**CrIS original radiances** assimilated at 18 UTC 09-30 (channel 130)

**CrIS CCRs** assimilated at 18 UTC 09-30 (channel 130)
Hurricane Joaquin is merged with the low pressure center over CONUS with assimilation of CrIS radiances (left).
Hurricane Joaquin is separated from the low pressure center over CONUS with assimilation of CrIS CCRs (right), which is verified with GOES Imager.
Experiments on Hurricane Harvey (2017)

**WRF-ARW v3.6.1:** 12 km horizontal resolution (400*300), 52 vertical layers from surface to 10hPa

**GSI v3.3:** 3D-Var Data Assimilation Method
- NAM background error covariance matrix
- Conventional Data (GTS)
- AMUS-A radiances onboard NOAA-15, NOAA-18, NOAA-19, and Metop-A
- IASI onboard Metop-A and Metop-B
- ATMS onboard Suomi-NPP
- CrIS radiances onboard Suomi-NPP
- Updated bias correction for each cycling, enhanced bias correction method in GSI
- Background and initial conditions: NCEP FNL (BG: GFS)

**Hurricane Harvey (2017)**
- Assimilation: Aug 23 00z to Aug 25 18z, 2017
- Forecasts: Aug 23 12z to Aug 28 18z, 2017
- Assimilation every 6 hour, 10 groups in statistics

**Data:**
- **Conv** from GTS;
- **POES:** AMSU-A, IASI, ATMS and CrIS;
- **CCRs:** CrIS cloud-cleared radiances (CCRs) in cloudy skies;
- **GOES-16:** Three layered precipitable water (LPW) from ABI at: 0.3 - 0.7, 0.7 - 0.9, and 0.9 – 1.0 in sigma level.

**Experiments**
- **CNTRL:** Conv+AMSUA+IASI+ATMS+CrIS (Conv + POES)
- **CNTRL+CCRs:** adding radiances in cloudy skies
- **CNTRL+LPW:** adding GOES-16 moisture information
Statistics (RMSE) from the experiments

Forecast Time (hour)

HT RMSE (km)

SLP RMSE (hPa)

- CNTRL
- CNTRL+CCRs
- CNTRL+LPW
Better moisture distribution
HWRF cloud-cleared radiance test on hurricane Irma
2017090418-207091000

- HWR v3.9a
- Ocean coupled
- No hybrid ensemble
- Vortex correction and relocation
- Conventional and satellite radiance
- CrIS data from NCEP for control
- CrIS cloud-cleared radiance from CIMSS for experiment (cc)
Summary and future work

- Assimilating VIIRS-based CrIS CCRs show positive impact on recent hurricane forecasts;
- QC is important, since atmosphere might be inhomogeneous within IR sounder sub-pixel in cloudy condition, and high resolution VIIRS can help CrIS assimilation in cloudy skies;
- Future work will focus on full spectral resolution CrIS from NOAA-20, improve QC on assimilating CrIS CCRs, collaborate with users on more experiments in NOAA and other models for potential operational applications.