Using information in satellite passive microwave radiances, with or without geostationary IR, to improve analysis and forecasting of convective storms

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Original motivation:
express observed microwave radiances in terms of
1) the 3D spatial distribution of condensed water in the clouds, especially in upper levels (because of direct sensitivity), rather than to near-surface rain (indirect correlation, if any)
and
2) the water vapor inside the cloud

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1) the vertical distribution of condensed water in the clouds:
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(out of beam) scattering

absorption/emission
2) the water vapor inside the cloud:
Simulations confirm that the microwave radiances are sensitive to the vertical distribution of condensed water and water vapor in the cloud, especially above freezing:

MHS, deep clouds (TRMM radar top > 12 km)

Blue curves ("CC1") represent combination with maximum correlation (and coefficients peak between 5 km and 8 km AMSL)

Red curves ("CC2") represent coefficients of 2nd-best combination (and coefficients peak near 8 km AMSL)
Simulations confirm that the microwave radiances are sensitive to the vertical distribution of condensed water and water vapor in the cloud, especially above freezing:

MHS, deep clouds (TRMM radar top > 12 km)

- Coefficients of best combo of RH(H) for each MHS channel
- Coefficients of top 5 combos of RH(H) for top 5 combos of 5 MHS channels
- Coefficients of top 2 combos of RH(H) for combos of MHS channels 1 & 2
- Coefficients of top 3 combos of RH(H) for combos of MHS channels 3,4,5

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The problem with “single-shot” forward radiative transfer calculations

1st EOF of \{\text{radiance1}, \ldots, \text{radiance5}\}

2nd EOF of \{\text{radiance1}, \ldots, \text{radiance5}\}

\mu\text{physics 1}

\mu\text{physics 2}

\mu\text{physics 3}

\mu\text{physics 4}

empirical
The problem with alternate “assimilation by proxy” approaches:

Activating SAPHIR in all-sky assimilation

Philippe Chambon & Alan Geer

Given observed swath:
1) Calculate synthetic obs $T'(x(p))$
2) For location $p_o$, with obs $T$:
   a) Find $T'$ in the swath whose value is “closest” to $T$
   b) Assimilate $x(p')$ as if they were the variables observed at $p_o$
The problem with “single-shot” forward radiative transfer calculations

Ideally, need to find $H$ so that, if $x$ are the control variables and $\mu$ the (myriad) parameters,

$$\text{Obs} = E_\mu \{ H( x ; \mu ) \} + \text{gaussian noise}$$

“variable” $x$ = have modeled dynamics
“parameter” $\mu$ = assumed constant (or ignored) by the model
One way to find the expectation of observed radiances given state variables:

Write \[ H(\mathbf{x} ; \mu ) = H_e(x_{\text{precip}}; \mu ) + H_s(x_{\text{vapor}}) \] and determine first the Expectation of the 1st term

For the 1st term: Using a coincidence set of radar + radiometer data, estimate

\[ \mathbb{E}\{H(x_{\text{precip}})\} \]

empirically.

In this step, \( x_{\text{precip}} \) is given by the radar, and the observations are observed (note: this effectively removes bias)
Single shot:

Empirical:
One way to find the expectation of observed radiances given state variables:

Write $H(x; \mu) = H_e(x_{\text{precip}}; \mu) + H_s(x_{\text{vapor}})$ and determine first the Expectation of the 1st term.

For the 1st term: Using a coincidence set of radar + radiometer data, estimate $E\{ H(x_{\text{precip}}) \}$ empirically.

In this step, $x_{\text{precip}}$ is given by the radar, and the observations are observed (note: this effectively removes bias).

For the 2nd term: Using forward simulations, fit

Observation - $E\{ H(x_{\text{precip}}) \}$

to

$x_{\text{vapor}}$
Test:

No-assimilation control run

“truth”

Analysis using $H_e + H_s$
Furthermore, in addition to the observation operator:

The approach produces an objective “retrieval” of
- condensed-water structure and
- 1\textsuperscript{st} order water vapor
in the cloud, for every radiometer, regardless of channel combination or viewing geometry.

In fact, one can estimate
- Heights of condensed water concentration at different thresholds: $H_{0.05}, H_{0.1}, H_{0.2}$
- $vPC_1(CW)$ (condensed water above freezing), $vPC_2(CW)$ (cw above 9km – below)
- $vPC_1(RH)$
i.e. a single set of geophysical variables (with different uncertainty for different radiometers, but nevertheless a common set of descriptors, regardless of source)
Example: TC Winston “cloud heights” – 3 comparisons

2016/02/11 11:50 #11107 5 km - 0.2 g/m³

2016/02/22 8:30 #11284 5 km - 0.2 g/m³

2016/02/22 8:30 #11284 5 km - 0.05 g/m³

GMI (89, 166, 183.3 x2)

SAPHIR (~183.3 x6)

vPC₂ ~ (CWM>9km) – (5<CWM<9km)
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Applications:
1) Sample storm heights, and track their evolution over decades (climate)
2) Merge the storm-structure information with geo-IR for nowcasting (weather)
Application 1:
Observation of the Hadley circulation
(from ocean-surface wind)

Zonal Component - 10 year mean

Zonal Component; Zonal Averages – means for 10 years
QSCAT; 12km; Global Oceans: 000 < LON < 360

U (m/s)

Latitude (degrees)

Hadley; QSCAT; 12km; Region 000–360

number of fortights starting 1 November 1999

Application 1:
Observation of the Hadley circulation (from ocean-surface wind)

What about precipitation?
Application 1: Cloud-top stats with TRMM radar

North Pacific

Mostly positive trends JJA & SON

(N. Utsumi et al)
Application 1: Cloud-top stats with TRMM radar

South Pacific - East

Moderate trends

Positive trends

(N. Utsumi et al)
Application 1: Cloud-top stats with TRMM radar

South Pacific - East

Cloud Top Height – total count

Radar sample size is very small!
Application 2: analysis and nowcasting of severe convection

» IR detection and classification

Example 1: Mali / Burkina Faso, 11 September 2006

“seed and grow”

“image overlap”
Application 2: analysis and nowcasting of severe convection

**IR detection and classification**

- **History**: Williams & Houze (1987) detect using a single IR threshold, then track evolution using overlap between consecutive images


- **Operational at Cemaden** (Natural hazards monitoring and warning)

- **Issues**: single threshold, combined with overlap tracking, creates split/merge artifacts during evolution and can misrepresent size because of missing segmentation and/or misattribution of anvils

- **1997**: Boer & Ramanathan proposed “Detect And Spread” using “region growing”, not tied to a single threshold, and consecutive spreading from one IR threshold to the next

  ➤ Fiolleau+Roca: Try using “region growing” with multiple thresholds
Application 2: analysis and nowcasting of severe convection

- IR detection and classification

Example 2: NE Brasil (~Belem), 2 November 2006
In practice: with Geo-IR only

At storm-resolution:
For each storm, from the history of the storm over the past 6 hours, using the latest microwave obs, along with ...

\[
\text{Size}(\text{IR}_{t+nDt}) \sim F(\text{IR}_t, \text{IR}_{t-Dt}, \text{IR}_{t-2Dt}, \ldots)
\]

... along with past 6 hours of geoIR, ...

forecast the next 6 hours of geoIR information

...
In practice: with Geo-IR and microwave

At storm-resolution:
For each storm, from the history of the storm over the past 6 hours, using the latest microwave obs, along with ...

\[
\text{Size}(\text{IR}_{t+nDt}) = H(\text{IR}_t, \text{IR}_{t-Dt}, \text{IR}_{t-2Dt}, \ldots ; \mu\text{wave}_t)
\]

... along with past 6 hours of geoIR, ...

forecast the next 6 hours of geoIR information
We have already verified that merging microwave with IR forecasts better than IR alone:

ForTraCC quadratic-regression nowcasting without or with microwave (SAPHIR only)

**Correlation** between forecast ellipse and actual

**Error** between forecast ellipse area and actual

Future time from present
Summary + opportunities for (collaborative) research and development:

1) It is possible to formulate an objective semi-empirical representation of satellite passive microwave radiances as an approximate function of the 3D distribution of condensed water content and water vapor.

2) The resulting observation operator performs reasonably even when tested on a humidity sounder (SAPHIR) – but can (and should) be improved using Machine Learning (instead of linear correlations).

3) The approach has broader applications, as it allows the generation of a 4D storm-structure descriptor – which can (and should) be applied retrospectively to monitor climatology of convective storms.

4) Injecting this microwave information into geo-IR nowcasting improves the accuracy of the forecast (correlation with actual storm size) and appears to suppress growth of error with time – systematic implementation should improve nowcasting of convection.