Are thermal infrared measurements of CO$_2$ from GOSAT and IASI over the Arctic Ocean in summer able to detect climatic change?

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Outline

• Using the thermal infrared region (TIR) covered by TANSO-FTS in B4 (GOSAT) and IASI (MetOp) for ice free Arctic Ocean studies in summer

• Retrieval scheme and sensitivity study as a function of $T(z)$

• Comparison for coincidences between GOSAT and IASI-A/IASI-B for $T_{\text{surf}}$ and $\text{XCO}_2$

• Monthly climatology of $T_{\text{surf}}$ and $\text{XCO}_2$ for the 3 summer months for GOSAT/IASI-A (2010 to 2015) and GOSAT/IASI-B/IASI-A (2013-2015) → only this 3 years period presented during this talk

• Impact of TIR sounders for climate studies
Why using TIR for Arctic Ocean studies?

• The Arctic Ocean is a key region where the effect of climate change can be detected

• Two similar instruments covering the thermal infrared region TIR can be used over an extended period: GOSAT (7 years) and IASI (10 years)

• Other sounders (for CO₂ or CH₄) are dwelling on the SWIR region (GOSAT and OCO-2 currently) using solar reflected/backscattered light

• Hence only daytime observations are possible with an additional constraint on the solar zenith angle (SZA ≤ 70° usually, meaning poor coverage of the sub-polar regions)

• TIR sounders (GOSAT TANSO-FTS in B4, IASI, AIRS and CrIS) are achieving a daily global coverage (usually one daytime and one night time overpass) → no night above the Arctic circle during July/Aug, however

• Their sensitivity to near surface concentrations is limited by the thermal contrast, but TIR sounders provide essential information in particular for the diurnal/nocturnal cycle and at high latitudes where models are poorly constrained by lack of observations
Why and how to compare GOSAT, IASI-A and IASI-B?

- It is important to compare spectra and retrieved geophysical parameters from three TIR sounders to check their consistency → IFOVs over ice free open water are most favourable for this comparison (retrievals over ice pack are more complicated)
- IASI-A and IASI-B on MetOp-A and MetOp-B can view the same IFOV in the same geometry within a time difference between 40 min and 50 min
- IASI-A and IASI-B can have quasi-coinciding IFOVs with GOSAT within the chosen criterion of 30 km and 1 hr
- Comparisons can be done for off-nadir observations and the choice of the polar summer period (July, August, September) lead mostly to daytime only observations in the latitude region [68N ; 80N]
- The retrieved products $T_{surf}$ and $CO_2$ will be considered here
Window fitted and state vector

• Window: 940 - 980 cm$^{-1}$, "CO$_2$ laser band region"
• State vector: $x = (T_{surf}, XCO_2, \text{coeff}_H_2O, \text{coeff}_O_3)$
• For IASI-A and IASI-B Carmine Serio instrument full covariance matrix $S_y \rightarrow$ needed because IASI spectra are “Gaussian” apodised
• For GOSAT diagonal covariance matrix $S_y$ (L1B unapodised spectra)
• No a priori for $T_{surf}$ and $XCO_2 \rightarrow$ constant mixing ratio profile
• $T(z)$ extracted from ECMWF ERA-Interim analyses
• $H_2O(z)$ profile scaled from ECMWF ERA-I
• SF$_6$ fixed (including trend between 2010 and 2015)
• The retrieval sensitivity to the shape of the actual $T(z)$ profile has been checked and used for pre-selecting the IFOVs
Retrieval scheme

• The line-by-line LARA radiative transfer model (RTM) and its associated retrieval model (package developed by J. Bureau and S. Payan) has been used

• Even though LARA can be configured for OEM, in the present study spectra where “least squares fitted” with a state vector containing $T_{surf}$ and XCO$_2$ as well as multiplicative scaling factors for the vertical mixing ratio profiles of H$_2$O and O$_3$

• The temperature profile is taken from ECMWF product (and fixed)

• The emissivity of Masuda for sea water is used/fixed
Temperature profile

lapse rate

isothermal

T(z) inversion
Pre-selection (or pre-filtering)
→ keep only IFOVs
with normal lapse rate \( T(z) \) profiles

\[ T(z) \text{ inversion} \]
Inversion configuration

Config xxx  

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<table>
<thead>
<tr>
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<tbody>
<tr>
<td>230</td>
<td>no SF\textsubscript{6}, 1 scaling factor for H\textsubscript{2}O(z), inflate S\textsubscript{y} around 948 cm\textsuperscript{-1}</td>
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<tr>
<td>231</td>
<td>with SF\textsubscript{6} values and trend fixed from GAW, idem for H\textsubscript{2}O</td>
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<td>232</td>
<td>idem for with SF\textsubscript{6}, 2 scaling factors for H\textsubscript{2}O(z)</td>
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<td>233</td>
<td>variable SF\textsubscript{6}, 2 scaling factors for H\textsubscript{2}O(z), nominal S\textsubscript{y}</td>
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<tr>
<td>238</td>
<td>scaled SF\textsubscript{6} values, 2 scaling factors for H\textsubscript{2}O(z), nominal S\textsubscript{y}</td>
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- **TANSO-FTS:** L1B v201.202, spectrally calibrated, 201 spectral samples
- **IASI-A and IASI-B:** standard L1C product (EPS or BUFR), 161 spectral samples
- months: mm=[07, 08, 09]
- Uncorrelated L1B TANSO-FTS noise (diagonal S\textsubscript{y} matrix)
- Full covariance S\textsubscript{y} matrix from C. Serio, App. Opt., 2015 for IASI-A and IASI-B
- T(z) and shape of H\textsubscript{2}O(z) from ECMWF ERA-Interim
- **pre-selection** before retrieval: standard lapse rate for T(z), sea, clear IFOV
- definition of "clear"
  - controlled level and slope on both sides of the O\textsubscript{3} band
  - apparent background brightness temperature BT > 272 K
  - contrast of the CO\textsubscript{2} lines in the 940-980 cm\textsuperscript{-1} region > 4.2
  - contrast of the H\textsubscript{2}O lines in the 820-940 cm\textsuperscript{-1} region > 4.0
  - contrast = rms\{\Delta BT(absorption lines)\}/rms\{\Delta BT(emission lines)\}
Typical TANSO-FTS grand average spectrum

- **H$_2$O**
- **CO$_2$**
combined variability of $\text{H}_2\text{O}/\text{CO}_2/\text{SF}_6$

$\text{NEdT (K)}$

$\text{SF}_6$
- P Branch
- R Branch
- Q branch

$\text{wavenumber (cm}^{-1}\text{)}$

<Tobs-Tcalc>

rms[Tobs-Tcalc]

TANSO-FTS

yyyy=[2010;2015], m=[07;09]
n=6668

$\text{SF}_6$ not included, with post-filtering, xxx=230
Residual variability reduced in rms[\text{Tobs-\text{Tcalc]} by varying the H\textsubscript{2}O scaling factor in the 0-0.8 km
Distribution of the solar local time at the pre-selected IFOVs

IASI-A [2010;2015] mm=[07,08,09]

IASI-B [2010;2015] mm=[07,08,09]

GOSAT [2010;2015] mm=[07,08,09]

Distribution of the solar local time at the pre-selected IFOVs
Distribution of coincidences of GOSAT with IASIA or IASIB
Distribution of coincidences of IASIA with GOSAT
Distribution of coincidences of IASB with GOSAT
Comparison of $T_{\text{surf}}$ for IASI/GOSAT coincidences, $xxx=238$
$\Delta L < 30 \text{ km}, \Delta t < 1 \text{ hr}$

Full Arctic ocean

1 slide for IASIA/GOSAT and 1 slide for IASIB/GOSAT

The number of pairs of spectra (one for each sounder) used in the covered period is given above each figure

For GOSAT several consecutive spectra (with $dt \sim 4.6 \text{ s}$) pertain to almost the same location (3 IFOVs mode)
Aug 2015 missing
Because cryocooler
Problems in GOSAT
Aug 2015 missing
Because cryocooler
Problems in GOSAT
Comparison of $T_{surf}$ for IASI/GOSAT coincidences in the period [2013;2015], mean differences, $xxx=238$

\[
< T_{surf}(\text{GOSAT}) - T_{surf}(\text{IASIA}) > = 0.105 \pm 0.012 \text{ K} \quad n=191
\]
\[
< T_{surf}(\text{GOSAT}) - T_{surf}(\text{IASIB}) > = 0.193 \pm 0.020 \text{ K} \quad n=143
\]

**Conclusion**: The absolute radiometric calibration in the [940;980] cm\(^{-1}\) region is critical. The statistics of the coincidences is not high enough to make a final statement on the difference between GOSAT and the two IASI.

Note that version v201.202 of TANSO-FTS L1B spectra have been used. The new non-linearity correction applied for version v203.203 will probably change the results. There is probably a small absolute radiometric calibration difference between IASI-A and IASI-B in this specific spectral region.
Comparison of $\text{XCO}_2$ for IASI/GOSAT coincidences, $\text{xxx}=238$

$\Delta L < 30 \text{ km}, \Delta t < 1 \text{ hr}$

Full Arctic ocean

1 slide for IASIA/GOSAT and 1 slide for IASIB/GOSAT

The numbers for each sounder are the total numbers of IFOVs used in the covered period (not the monthly ones)

For GOSAT several consecutive spectra (with $dt \sim 4.6 \text{ s}$) pertain to almost the same location (3 IFOVs mode)
Aug 2015 missing because cryocooler problems in GOSAT
Aug 2015 missing because cryocooler problems in GOSAT
Comparison of $\text{XCO}_2$ for IASI/GOSAT coincidences in the period [2013;2015], mean differences, $\text{xxx}=238$

\[
\langle \text{XCO}_2(\text{GOSAT}) - \text{XCO}_2(\text{IASIA})\rangle = 6.41 \pm 0.16 \text{ ppmv} \quad n=191 \\
\langle \text{XCO}_2(\text{GOSAT}) - \text{XCO}_2(\text{IASIB})\rangle = 6.29 \pm 0.24 \text{ ppmv} \quad n=143
\]

**Conclusion**: the bias in $\text{XCO}_2$ (derived from TIR) between GOSAT and IASI is probably due to the difference between the absolute radiometric calibration of the Japanese and French/European instruments.

The same type of absolute radiometric calibration differences in other spectral regions may explain some of the bias observed by other groups for $\text{XCH}_4$ retrieved from GOSAT and IASI in the 7.8 $\mu$m region.

The exact impact of the **ILS knowledge** on the retrieved values has to be assessed.
Summary (1/2)

- This exercise was done to compare the capabilities of retrievals of $T_{\text{surf}}$ and CO$_2$ from GOSAT, IASI-A and IASI-B in one “surface window” i.e. 940-960 cm$^{-1}$ (~10.4 μm) for obtaining “climate quality records” at a regional scale in the summer months of the Arctic Ocean for a period for 3 years common to GOSAT, IASI-A and IASI-B (2013 to 2015) in the latitude region [68N ; 80N]

- The individual $T_{\text{surf}}$ precision of GOSAT is $\sim 0.10$ K 1σ and of IASI is $\sim 0.16$ K 1σ for clear IFOVs, homogeneous, over sea and with a normal atmospheric lapse rate $T(z)$ profile (from ECMWF)

- The individual XCO$_2$ precision of GOSAT is $\sim 6$ ppmv 1σ and of IASI is $\sim 10$ ppmv 1σ for clear IFOVs, homogeneous, over sea and with a normal lapse rate

- There is no a priori constrain on the XCO$_2$ value except a constant mixing ratio profile $x_{\text{CO2}}(z)$. The exact shape of the profile in the oceanic boundary layer is not very well constrained by the models due to the complicated sea-air exchanges

- The variation of $T_{\text{surf}}$ with latitude and between July/Aug/Sept is significant

- The interannual variability does not show a trend in $T_{\text{surf}}$ at the regional scale

- The overall trend in the CO$_2$ column averaged VMR is well captured over the 6 years period for GOSAT and IASI-A and 3 years period for IASI-B
Summary (2/2)

- There is a significant interannual variability in XCO₂ over the ice free Arctic Ocean, to be correlated to large anomalies as the year 2012 when an absolute minimum in the ice pack area was observed (by other instruments).
- More work is needed to refine the analysis and get a better statistics on identified Arctic Ocean basins using more IFOVs (a “thinning” of IASI-A and IASI-B IFOVs was performed in the present work, all useful IFOVs have been used for GOSAT).
- The zonal average of XCO₂ over ice free Arctic waters between 68N and 80N for the 3 months of July, August and September and the 6 years between 2010 and 2015 show the expected overall geophysical behaviour, with significant zonal and interannual variations, however.
- With these characteristics TIR measurements at high latitude can constrain CO₂ flux inversion models through the ocean-land contrast and latitudinal as well as monthly variations especially in summer.
- A longer time frame analysis will consolidate these conclusions using IASI-A data before 2010, more data of IASI-A and IASI-B in 2016, 2017, 2018, and with the operational and backup IASI after the launch of IASI-C.
- The GOSAT and IASI mission are not yet providing a fully consistent time series of “climate quality variables” for Tsurf and CO₂ due to remaining inter-instrument absolute radiometric calibration differences which still need to be carefully examined.
- Using the newly available TANSO-FTS version v203.203 including an improved non-linearity correction in B4 (TIR) will reduce the bias between GOSAT and IASI-A/IASI-B.
Acknowledgements

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• Mesocentre IPSL and French atmospheric data base

• Access: EUMETSAT products of Ether
Backup slides
Forward model uncertainties near 948 cm\(^{-1}\)

- \(\text{SF}_6\) Q branch in the vicinity of one \(\text{CO}_2\) line and one \(\text{H}_2\text{O}\) line \(\rightarrow\) need better T/P dependence of the \(\text{SF}_6\) cross-sections and better line parameters (temperature dependence for the foreign and self-broadening for this \(\text{H}_2\text{O}\) line)

- This leads to an additional spectral variability around 948 cm\(^{-1}\)

- Inflating the measurement error near 948 cm\(^{-1}\) (3 spectral samples for GOSAT, 2 samples for IASI) is a way to handle the problem

- A more effective solution has been to vary separately the \(\text{H}_2\text{O}(z)\) scaling factor in the range 0.0-0.8 km and in the range 0.8-14.0 km (ensuring continuity). This is correcting for the error of ECMWF in the lowermost layers/levels.

- This is reducing the bias in \(<\text{T}_{\text{obs}} - \text{T}_{\text{calc}}\>\) and loweringing the \(\text{rms}[\text{T}_{\text{obs}} - \text{T}_{\text{calc}}]\), correcting for the impact of the knowledge of the shape of the \(\text{H}_2\text{O}\) profile on the retrieved values of \(\text{T}_{\text{surf}}\) and \(\text{XCO}_2\)