Lessons learned from the assimilation of RO in large volumes at ECCC

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Included commercial data supplied by

- NOAA (Spire, GeoOptics)
- PlanetIQ

11-Jun-2024

Preamble I

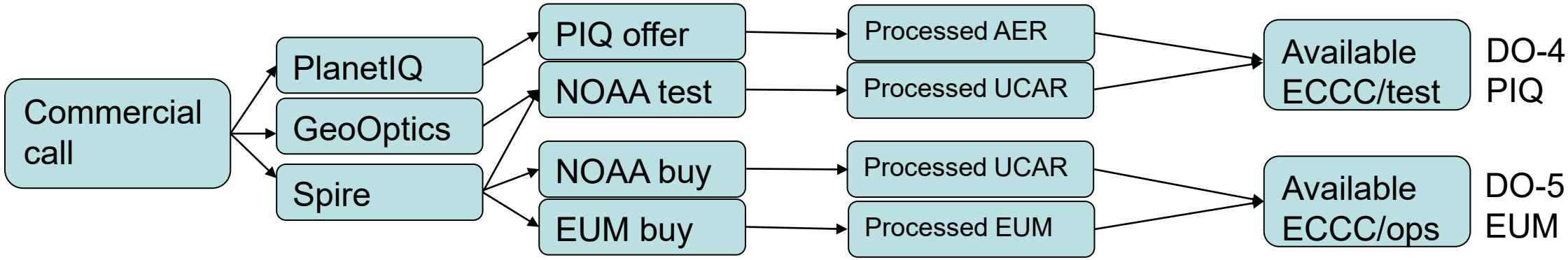
- We present a study adding a large amount of RO Data to the operational base at ECCC (2022)
- Objectives at the time were
  - Deciding if those sources were technically ready to become operational
  - Identify any technical limitations yet unknown
  - Overview and quantification of impact
  - Basis for decision making
- Summary of results
  - Some data identified as ready
  - Some identified as requiring some review
  - Issues with the system were identified, which required some attention
    - Review N vs BA
    - Review PBL
    - Review anchors
- These lessons being relevant, we will discuss them here

Preamble II Adding 20k prof/day

- **RO Data that was operational at ECCC in the study period**
  - METOP-B & C (~1200 prof/day, polar, GPS, rise & set)
  - COSMIC-2 (~5000 prof/day, |lat| <~ 40 deg, GPS+GLO, rise & set)
  - FY-3D (~500 prof/day, polar, GPS, rise & set)
  - KOMPSAT-5 (~300 prof/day, polar, GPS, set)
  - TERRASAR-X (~200 prof/day, polar, GPS, set)
  - TANDEM-X (~150 prof/day, polar, GPS, rise)
  - PAZ (~200 prof/day, polar, GPS, set)
  - GRACE-A,B (~500 prof/day, polar, GPS+GLO, 1 rise, 1 set)
- **Upcoming at the time** (available, waiting final decision)
  - Sentinel-6A (~800 prof/day, polar, GPS+GLO, rise & set)
- **Massive addition**
  - Research licenses through NOAA, EUMETSAT, and agreements
    - **Spire** (~6000 prof/day, polar, GPS+GLO+GAL, set)
      - 6000 from NOAA
      - 1500 from EUMETSAT
    - **GeoOptics** (about 500 prof/day, polar, GPS+GLO+GAL, NRT irregular delivery)
    - **PlanetIQ** (about 3300 prof/day, polar, GPS+GLO+GAL+BEI, received offline, direct agreement ECCC/PIQ)
  - Spire had even more (not part of this study)

Preamble III

- **License**:
  - All current operational data are available under **open and free use** policy (standard WMO-40)
  - Recent Sentinel-6A also open, free
  - Commercial providers: GeoOptics, Spire, PlanetIQ. For tests described here we had only a **non-operational test** license.



  - This commercial pool contained ~10000 profiles/day from an existing commercial pool ***estimated*** at about 24000 profiles/day, tens of micro/nanosatellites

Preamble IV

- **Operational GPSRO data at ECCC at the time** ~ 8500 prof/day
  - 2500 polar orbits
  - 6000 low incl orbits
- **Experiments here** ~ 15000 (Spring22) and 19000 (Summer22)
- **Estimate existing pool (std+comm)** ~ 32000 prof/day

Preamble V

- ECCC uses two base atmospheric systems (then several regional, local, ocean, ice, waves, coastal, hydrologic… here outside the scope)
  - Global Deterministic (filter & QC of obs, provides **OBS** to ensemble)
  - Global Ensemble (background covariance, provides **B-matrix** to deterministic) B-matrix is dynamic, ensemble based

- Thus they are (weakly) **coupled**.
- Tests shown are deterministic-only (**stored ensemble**). Coupling (B-matrix) was later verified to be small <10% impact**.**

- **Deterministic TEST+B from Ensemble OPS** **(uncoupled)**
- Deterministic **TEST+B from (own) Ensemble TEST** (coupled)

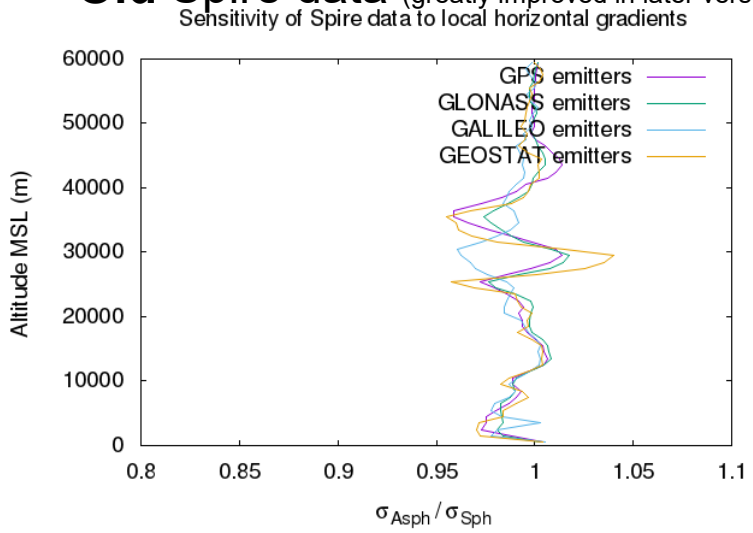
Preamble for Evaluation

- Large added volumes, potentially leading to impacts that may be *challenging to verify*. **Affects radiance bias correction**.
  - **Against-external-analysis**: These data were not yet operational at ECMWF. Careful when comparing against ECMWF analysis (otherwise std practice).
  - **Against-external-data**: We chose
    - RS: To check impact in data-dense regions
    - RO METOP-B&C: To check impact against homogeneous global high-quality reference of the ***same kind***
    - ATMS: To check impact against homogeneous global high-quality reference (***different kind, near-nadir***)
    - MLS: (Temperature) Against global limb profiler (***different kind, limb geometry****, T not assimilated*)

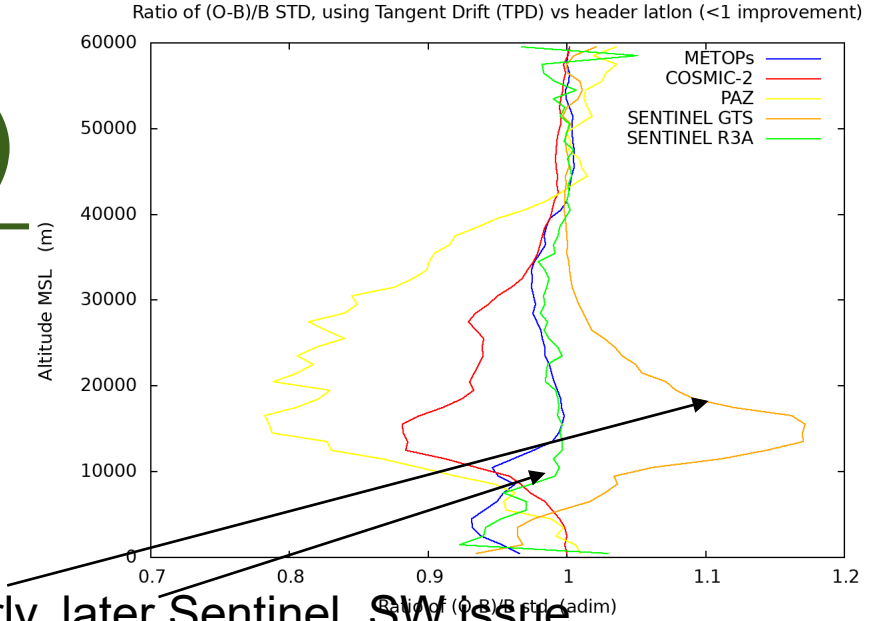
Threshold to add value (Contrast)

- Do data notice model's skill?
  - Model has very high skill at large scale, progressively less at smaller scales.
  - Data able to discriminate model **intermediate** value?
    - No value at too large scale, skill **too good to improve**
    - No value at too small scale, skill **too bad to help**
  - **Test intermediate scales (10-100 km)** (use 2 different H(x): the **best** and a slightly **degraded**)
    - Here "best" contains eg TPD, plane rotation, "degraded" does not apply these
    - Preliminary data of most sources often not sensitive
    - UCAR, EUMETSAT software ok.
  - Check if data can identify best vs degraded
  - **Data unable to discriminate intermediate skill, unlikely to add skill.**
  - Example of contrast here, others possible

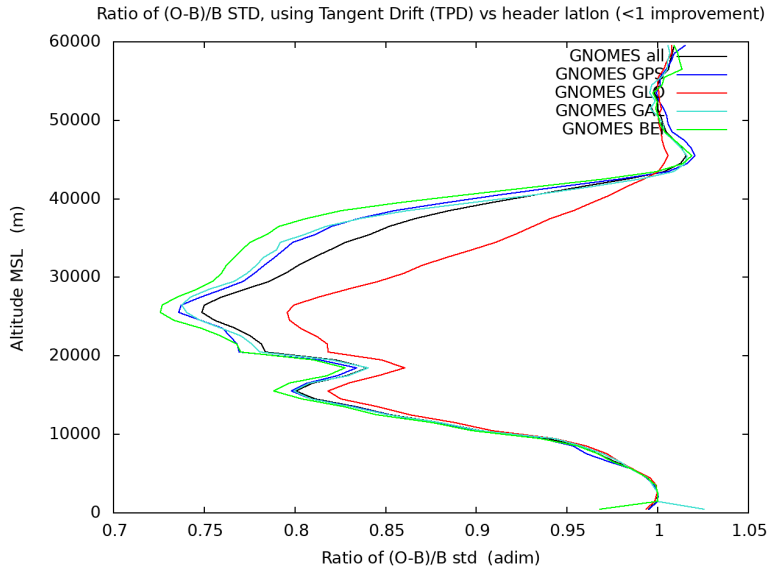
Old Spire data (greatly improved in later versions)



Contrast test heuristically found to be necessary and nearly sufficient



Early, later Sentinel, SW issue



Several GNOMES, HW/signal issue

Some details about RO in ECCC

- Observation used is refractivity
  - Many tests/reimplementations tried: Best performing always **refractivity**
- Error estimation
  - Dynamic (based on **vertically sliding window** of O-B). Smaller error if column of O-B small.
  - Self-adjusting.
  - Highly tolerant to temporary glitches, like transient orbit errors
  - Highly tolerant to different hardware/sources (providers)
  - Highly tolerant to ECCC system evolution (new models, assimilation systems, vertical and horiz resolution, etc)
- Interesting:
  - Refractivity is naturally “smoothed” (integral produces correlations)
  - O-B naturally narrower in N (~0.5%) than BA (~1%)
  - Most of the impact 300 < p < 50 (hPa)
  - Refractivity naturally inferior low tropo (below prime RO region)
  - N also inferior in upper strato (initialization) (above prime region)
  - Prime region not immediately N-inferior

$$Z_i = \frac{O_i - B_i}{B_i}.$$

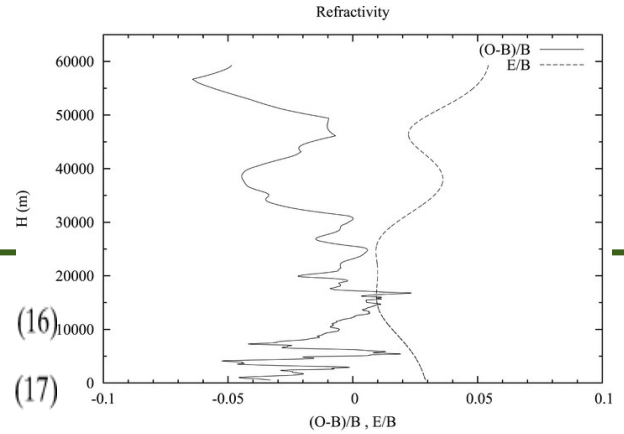
$$w_{ij} = \exp[-(h_j - h_i)^2/H^2],$$

$$z_i^2 = \frac{\sum_j w_{ij} Z_j^2}{\sum_i w_{ij}}.$$

$$\varepsilon_i = z_i B_i.$$

Sliding window

(16)



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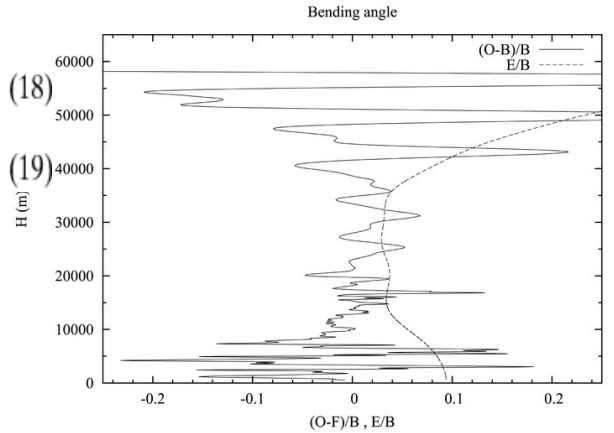

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Experiments

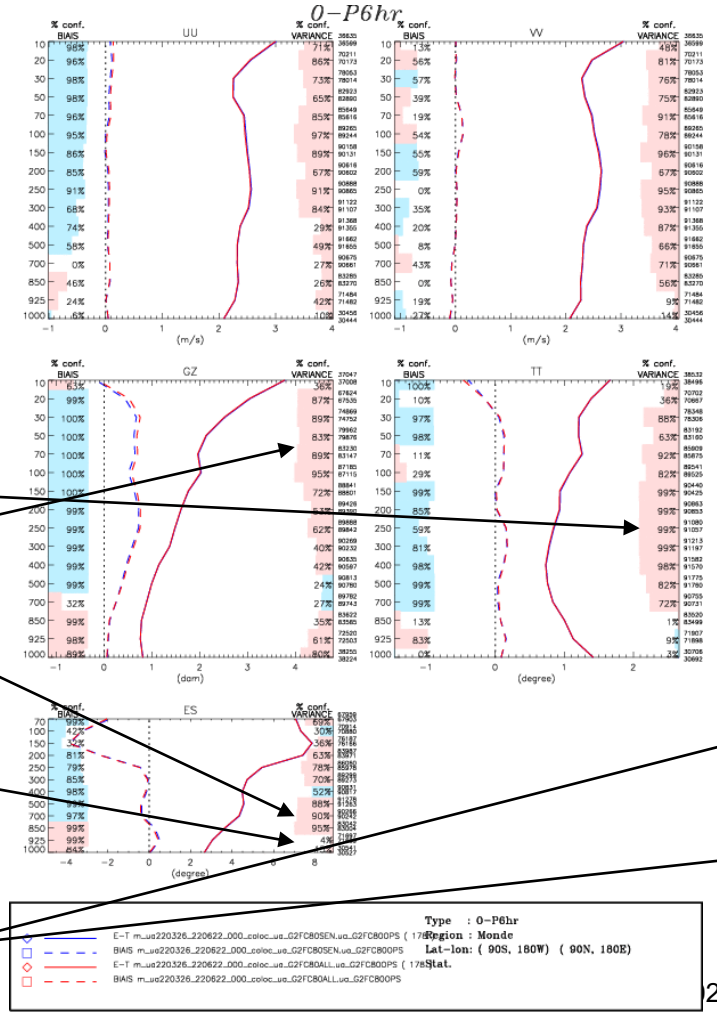
- **NRT**:
  - 1 experiment
    - As OPS + Sentinel-6A + (**GeoOptics+Spire**). Nearly 3 months: 2022032600 to 2022062200 (Spring22)
  - GPSRO data sources:
    - Wait for the creation of each 6h batch of OPS-RO data (derialt).
    - Within **10 min** of OPS-RO creation, close ALL-RO, adding available Sentinel-6A and commercial
    - **Nearly identical latency** cutoff for added data, all operational data strictly identical.
  - Scheduled to run 12h behind Global Deterministic OPS
    - Could have been just 10 min behind
    - Test **reliability as NRT source**, not just data impact (got well above 99% before G2 cutoff)
- **Offline**
  - 2 experiments (Summer22)
    - **ALL**: As OPS + Sentinel-6A + (**GeoOptics+Spire**). Additional test 2022061400 to 2022083100
    - **COM**: As OPS+Sentinel-6A+(**GeoOptics+Spire+PlanetIQ**). 3.5 months: 2022061400 to 2022093018 (Fiona)
  - COM ~20000 profiles/day, more than **2xops**, and about 4xops at higher latitudes, **10x early 2020!**
    - License was test-only, not for ops
    - **Test above expected available** (ops-licensed) volume in H1 2023 (~1.5-2x)
      - Useful to check for any form of saturation, anomalous behavior, resource overflow…

Verifications I: RS (high data density areas)

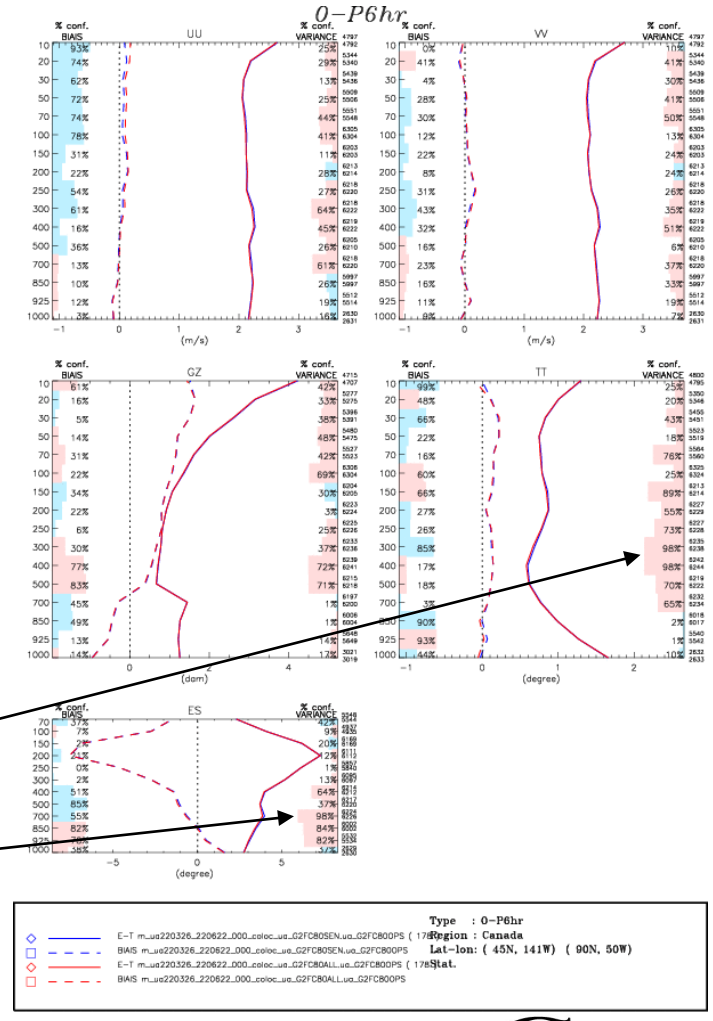
Spring NRT test (Mar-Jun)

- Thermodynamic, wind, moisture
- High data density regions
  - not exactly global, but interesting to see if there is a **benefit when sampling is already dense**
- General positive tendency. Two items to note:
  - Peak T impact at 300 hPa
    - GZ impact derives from T
  - Noticeable q impact in upper PBL/ low free troposphere
    - This signature is weak at lower data densities
  - But neutral **below** PBL
- Limited to Canada:
  - Same signatures, with weaker significance
  - Yet, some T, q, above 90%

Northern Hemisphere

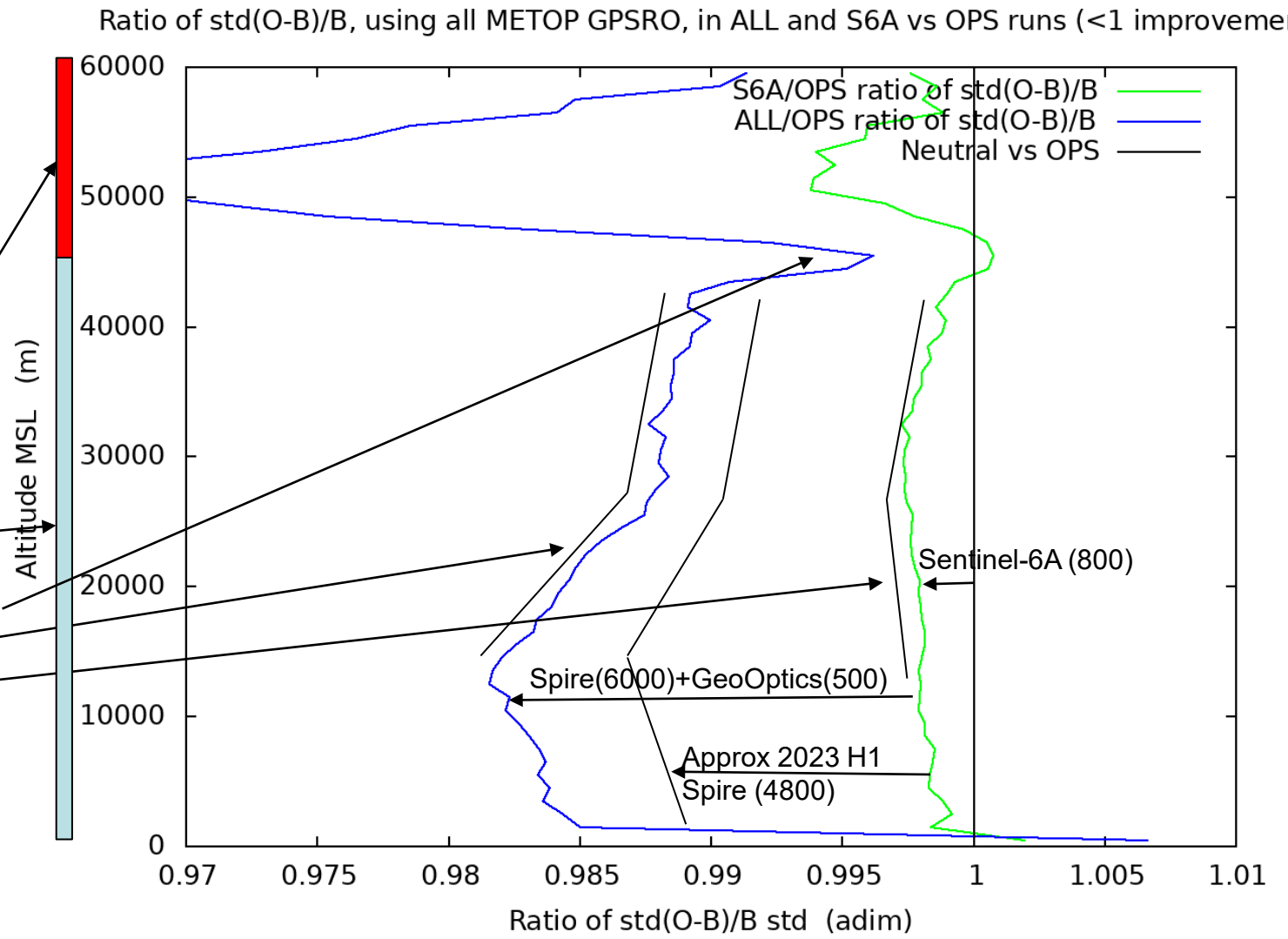


Canada



Verifications II: RO from METOPs

- Thermodynamic, also RO
- Global sampling, very uniform land/ocean, populated/not.
- Not uniform in latitude: **denser sampling at high latitudes** (7x poles vs equator)
- Not uniform in local time
- None of the RO data (neither METOP/RO, nor S6A, Comm, …) are bias corrected.
- Global profiles/day in (parethesis)
- Prime results:
  - Most column sees benefit (<1 hPa, <45 km MSL)
    - Above 1 hPa probably not meaningful
    - Weakness ~1hPa related to anchoring of radiance bias correction (to be addressed IC4)
  - More impact below 20 hPa (25 km MSL)
    - Not seen in current Sentinel-6A
    - Note that Sentinel has a bug (suboptimal <25 km MSL)
  - Near surface (< 1 km MSL): probably not meaningful
    - RO not designed to measure the surface layer
    - and these data are in fact rejected in assimilation



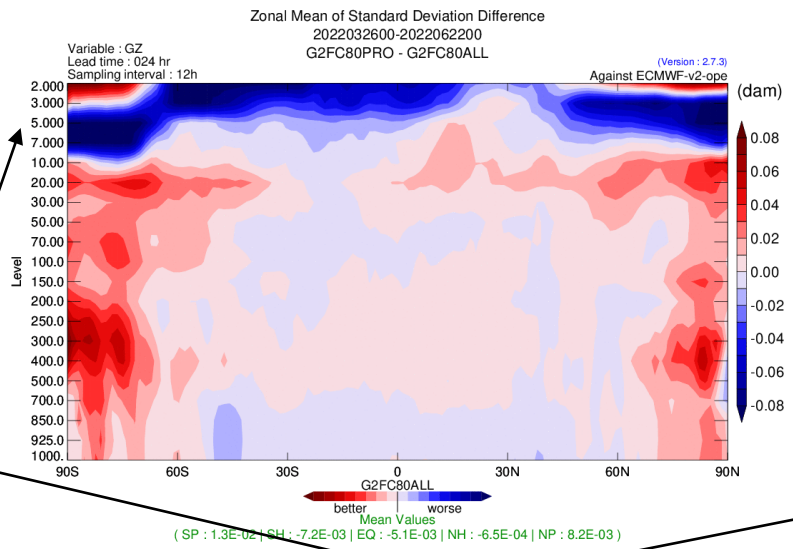
Verifications III: Against ECMWF analysis

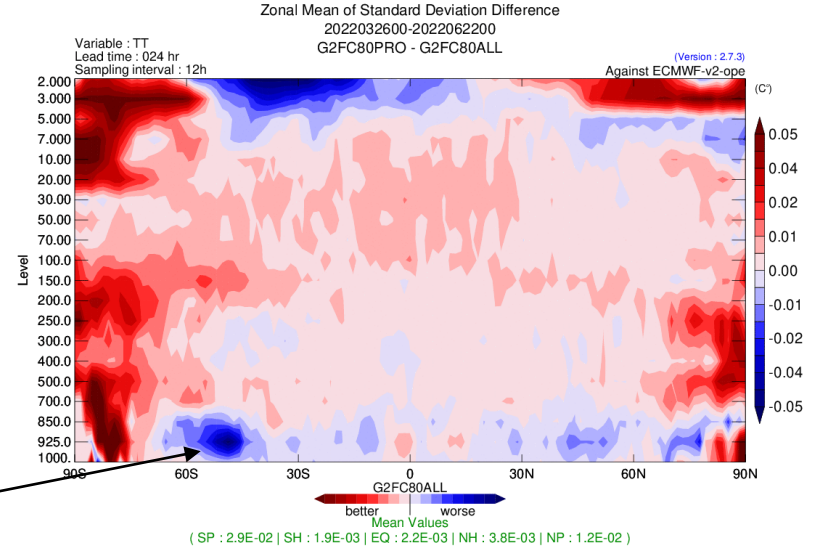
Generally positive

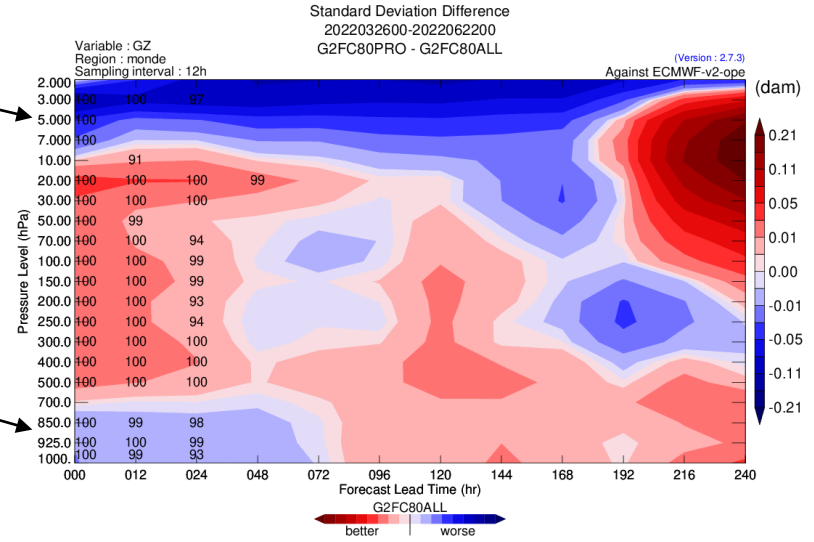
- Typical structure of polar satellites (higher impact at high lat)

But there are some negative effects identified

- Anomalous negative impact upper stratosphere
  - **Already Identified** as anchoring clash during radiance bias correction (ro against static channels). **To be addressed in IC4.**
  - Not problematic below 10hPa
- Some TT, HU negative impact at low alt **(PBL?)**
  - Coherent with RS weak response at low altitude
  - Fine just above PBL
  - Not yet critical, but statistically significant
  - Must be addressed before increasing data further
  - Likely IC4

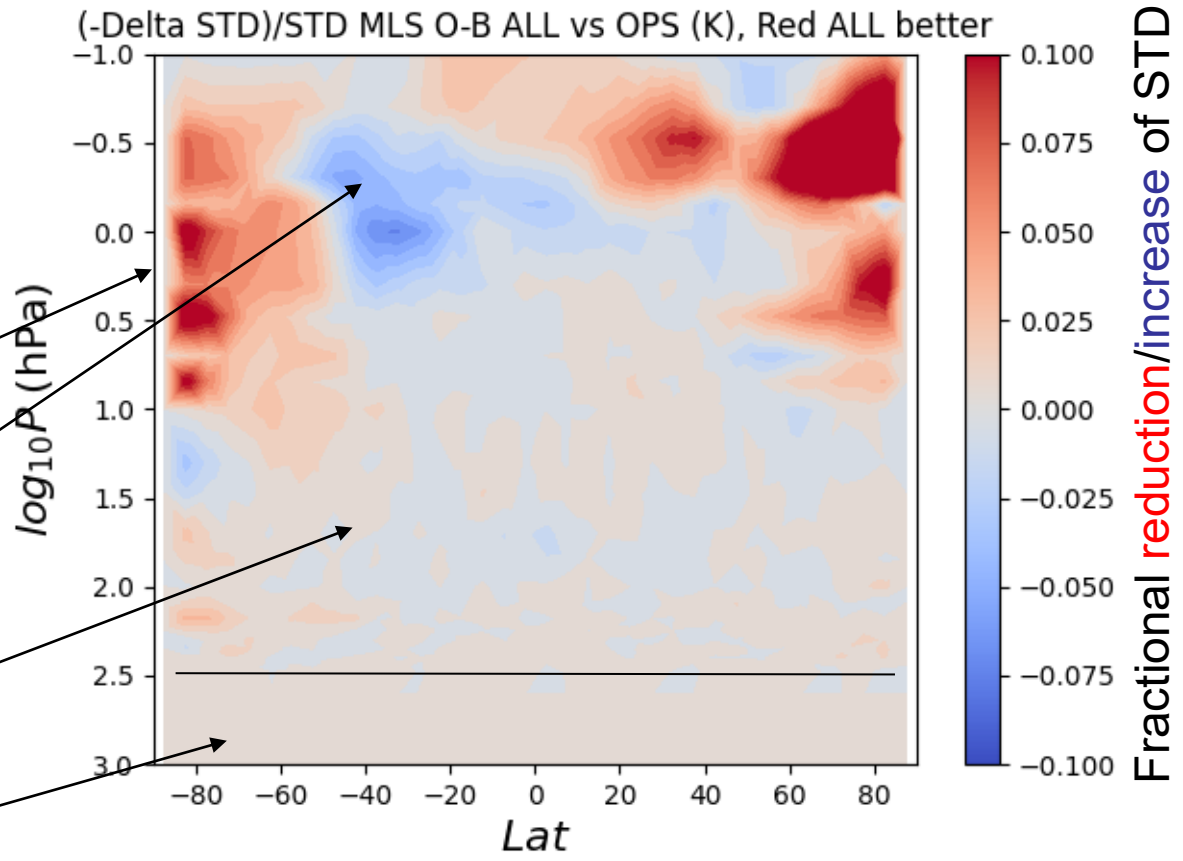






Verifications IV: MLS (Microwave limb sounder)

- Thermodynamic, but not RO
- Global, uniform weight by latitude
- Not uniform local time
- Not assimilated
- Limb geometry, moderately high vertical resolution. **Reaches model's lid.**
- As radiances, subject to bias. To simplify relative radiometer_vs_model bias, we mostly ignore bias here, look **only to STD**.



- Large mid-upper stratosphere improvements in the poles
- Degradation in upper stratosphere (later identified as collision of radiance anchors, ro against static channels). No impact below. **TBA in later research**.
- Generally positive elsewhere
- MLS **not sensitive below 300 hPa**

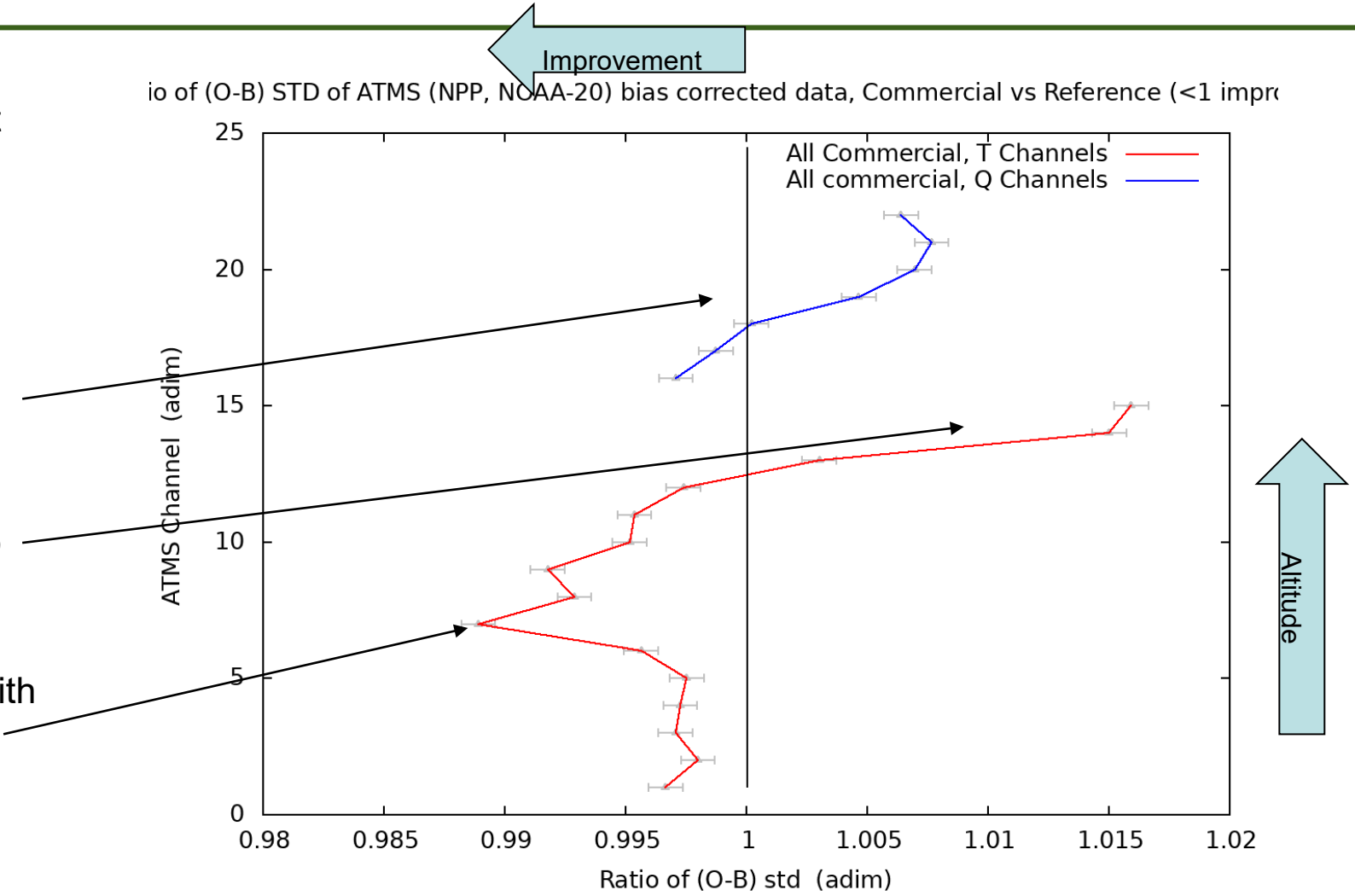
Verifications V: ATMS (NPP & NOAA-20)

- Thermodynamic, profiled, but not RO
- Global, also weigthed towards higher lat
- Not uniform local time
- Subject to bias, under bias correction
  - This may be non-trivial

- Moisture channels confirm some mixed behavior TBA

- Upper 2 static channels clash against ro anchoring (and drag the third upper)

- Other temperature channels coherent with general improvement, particularly upper tropo, low strato



Verifications VI: 24h FSOI, Global weighted, dry norm

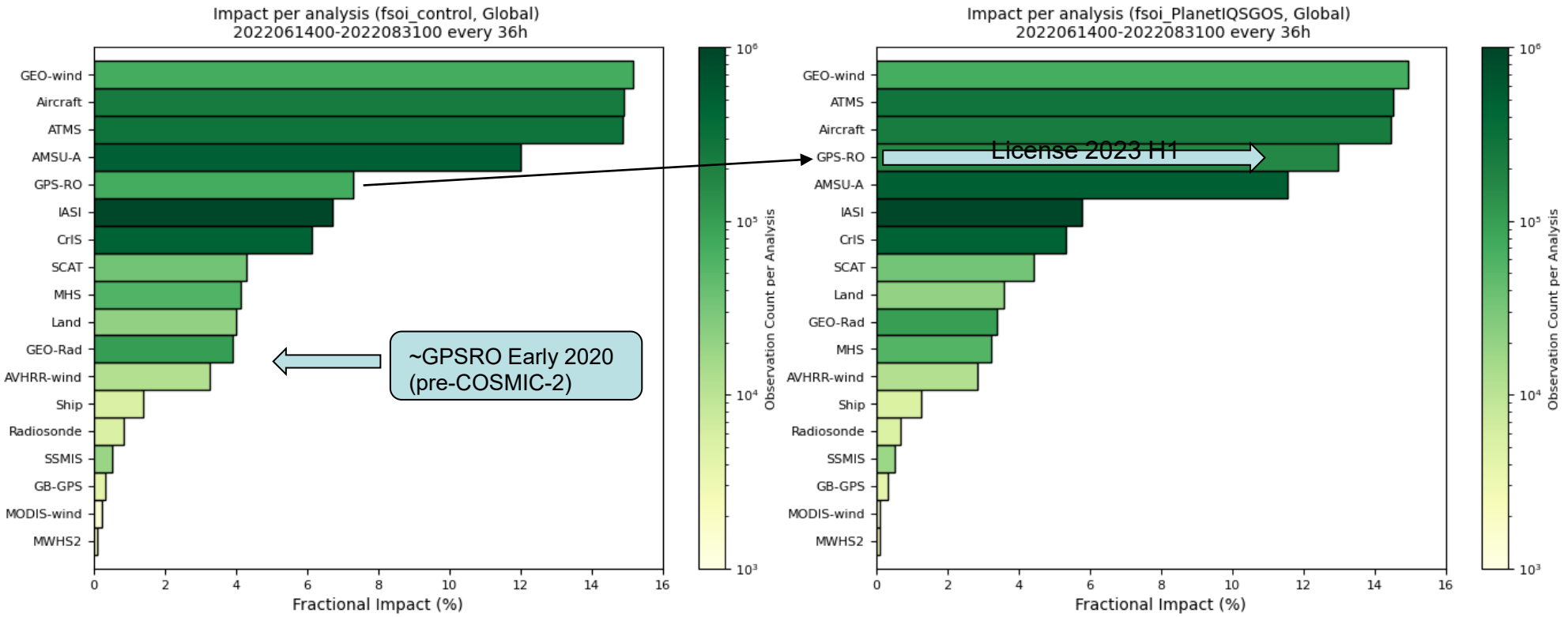
Test with all available data included

GPSRO advanced **ahead of AMSU-A**

Note: only 2/3 of the **new data** here will be available (licensed) in Jan-Jun 2023

Ballpark estimation for operationally available in 2023 H1 marked in the arrow

In late 2023, volume may be higher than test shown here. To follow.



Added Sentinel-6A (since approved), GeoOptics, Spire, PlanetIQ

Verifications VII: Global-weighted FSOI (only RO)

Test with all available data included

GPSRO advanced **ahead of AMSU-A**

Note: only 2/3 of the **new data** here will be available (licensed) in Jan-Jun 2023

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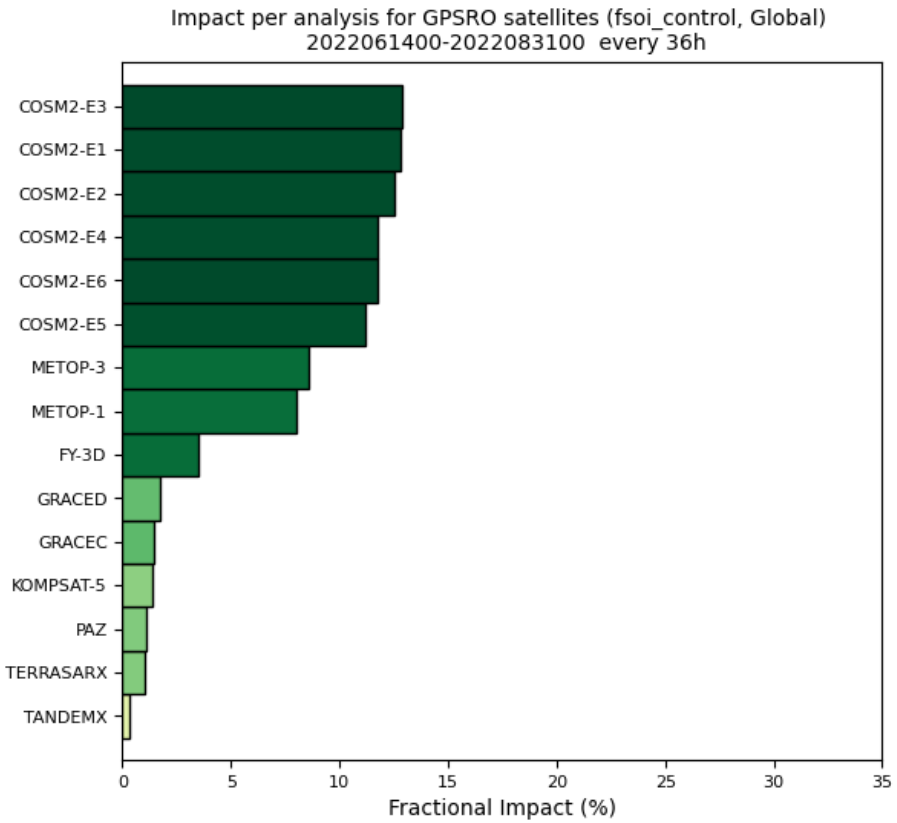
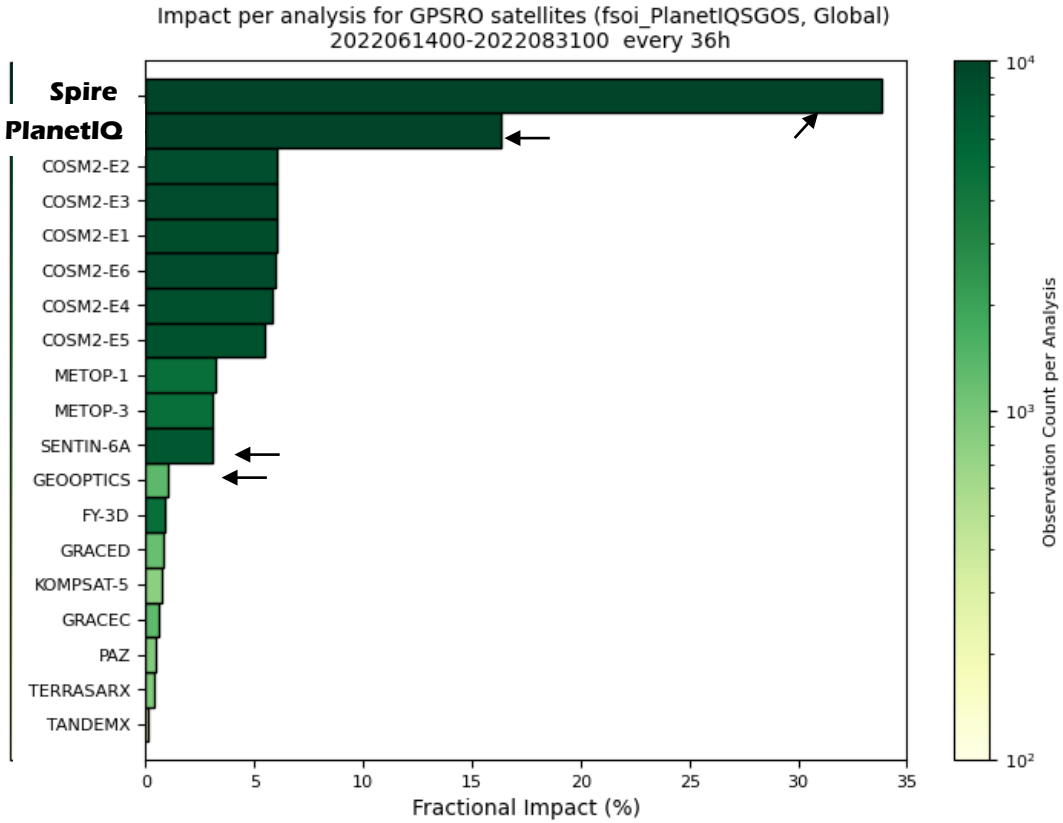


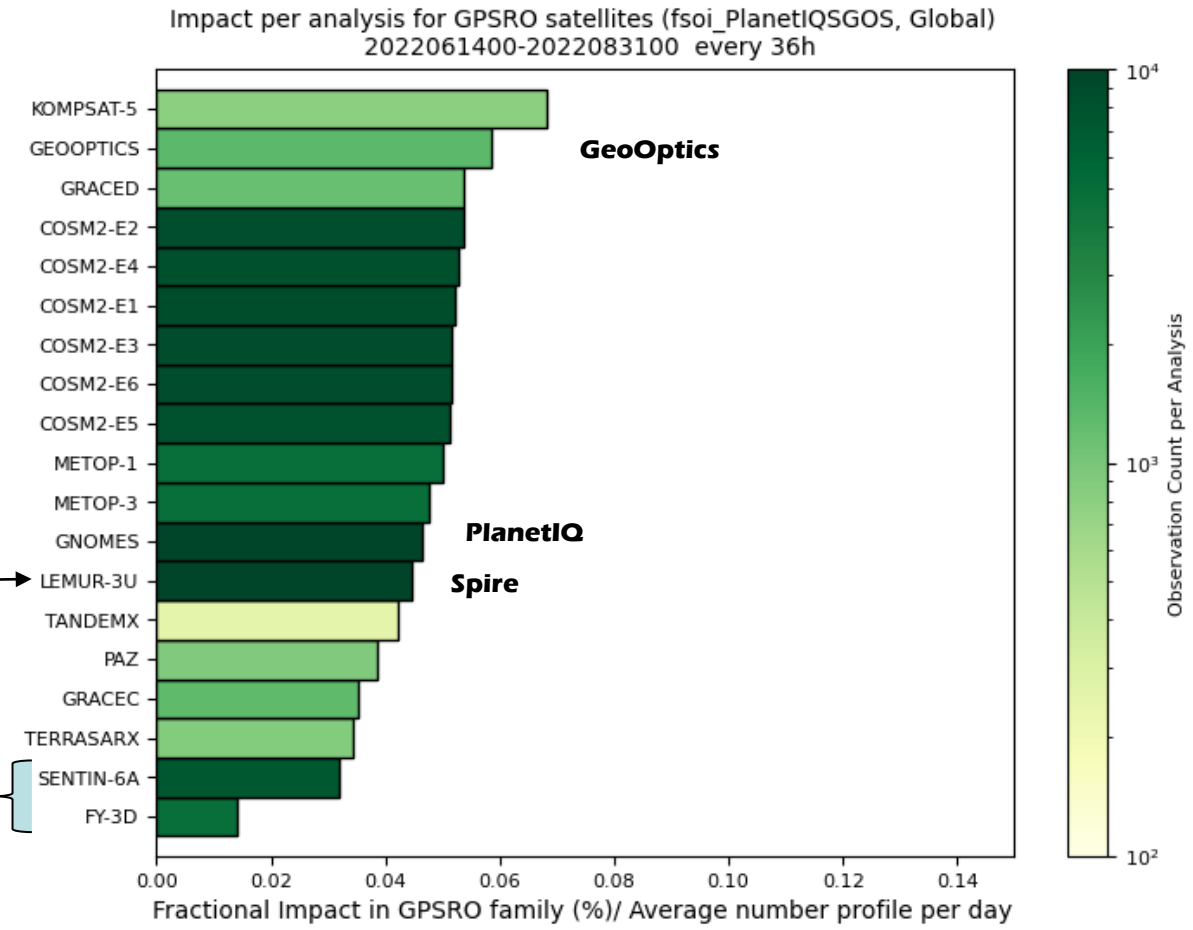


Added Sentinel-6A, GeoOptics, Spire, PlanetIQ

Verifications VIII: FSOI
Number of profiles as a quantitative measure

Comparison of FSOI impact/profile, for several missions/satellites

- Very similar across satellites
- New data proposed here good, but mostly due to **volume** (otherwise in the low average)
- Some ~outliers (known issues)

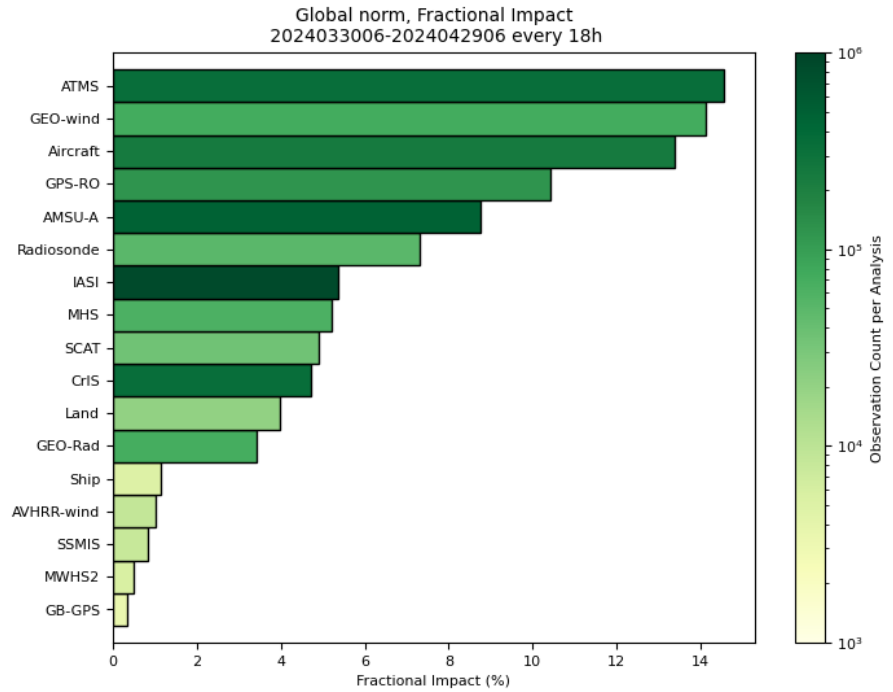


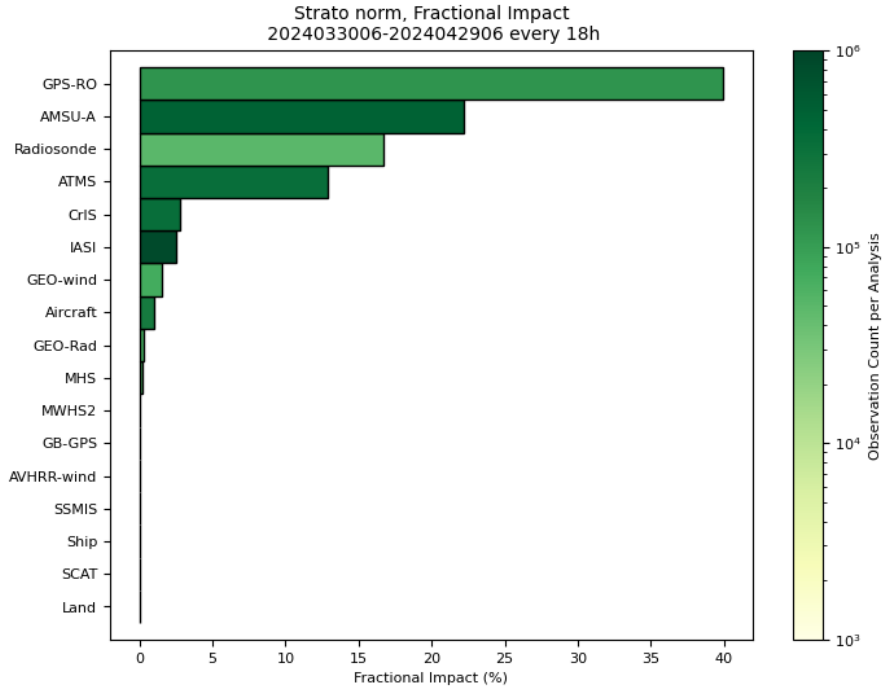
Verifications IX: FSOI strato

Comparison of FSOI (wet norm)

- all atmosphere
- only 100 hPa < p

- RO among best for entire atmosphere
- RO best 100 hPa <p
  - ~40% impact
  - Plus anchoring or radiances





Brief

- Commercial data in general particular show **improvement at short-mid range**
  - At 6h, in the (Spire+GeoOp), thermo fcst error reduced by **2.5%**, entire column, max at 8-10 km above MSL. Not improved above 2 hPa.
    - Good processing (by UCAR) of GeoOptics, Spire. Above 2hPa, known issues with **radiance bias correction**.
  - At 6h, in the (Spire+GeoOp+PlanetIQ), thermo fcst error reduced by **3.5%**, similar properties
    - **Approx: 0.4% per 1000 occultations/day reduction in background uncertainty**
    - Note that there is an additional pool of ~10-15 kocc/day, of which this is but a sample. **Potential of 8% reduction** at 6h field with already flying assets
  - Statistically significant impacts to METOP/RO, RS (UTLS/T, PBL/Q, midtropo/wind), ATMS.
  - Very large impact strato both poles.
- Compatible signature against ECMWF
- Compatible signature against ATMS/T channels
- Apparently weak signature against ATMS/Q channels
  - But bias correction is an issue. Substantial bias adjustments seen in mid strato. Unclear if bias settled even after 3 months.
  - Compatible with issue below PBL
- Net result, good, generally compatible with our understanding
  - Upper troposphere, low and mid stratosphere, apparently able to accept even higher volume.
  - But radiance bias correction issues to be understood better (**clash of anchoring in upper strato**, cause identified and being adressed towards IC4)
  - Expected more from **below-PBL**. Cause TBD, to be further researched until IC4, and **before any further increase in volume**.
- All tested data would lead to a net benefit
- FSOI shows that all data are positive.
  - Some differences between emitters & receivers, in agreement with our understanding of their hardware (atomic clock stability, antennae SNR)
    - E.g. GLONASS somewhat more noisy
  - Known issues with FY-3D and Sentinel-6A, cause identified (detaiiled latlon, net positive but underperforming).
  - Homogeneous data across missions (**well tested EUMETSAT and UCAR software**)

Caveats

- Net benefit, but there were **issues identified**.
- Not necessarily data's fault, most likely our system
  - Clash of **anchoring** (upper static radiance channels)
  - **PBL** numeric response to assimilated data (filtering PBL RO data **did not help**)
  - Choice of N vs BA at low altitude

- Potential future growth of data must be progressive, with time to fix any issues
- Hardware was **not** the limiting factor (some minor details through SNR)
- **Provider software appeared critical**:
  - **Earlier versions** received from SP, GO were **not ready for OPS or even test** (trivially verified)
  - Well-tested software by EUMETSAT, UCAR appears ok (**critical for this test**: UCAR software).
- Now system tested robust until 20k prof/day
- Free atmosphere (700-10 hPa) ready to accept more, but hints of localized issues
  - Midlatitude PBL

- **Not recommended to exceed 20k/day before issues adressed.**
- **Likely ready to exceed 20k/day within 1-3 yr. Progressive ramp-up recommended.**

Approach now being followed

- Success of N in prime region implies **we will keep it** in the core region
- Limitations in low tropo, upper stratosphere
  - **Hybrid** N, BA is under research
  - BA to be preferred for low tropo, upper strato
  - Exact hybrid strategy TBD
- N, BA cross-related by integral relationships
  - They are approx. derivative/integral relationships
  - Background matrix may not contain all subtleties of integral/derivative relationships
  - Some obs may better fit with relationships that do exist in the background representation
    - Some atmospheric features are better represented through **values** (eg pres, temp, dens)
    - Some are better represented through **gradients** (eg PBL, tropopause)
    - Despite they may even appear equivalent, their convergence may differ considerably
  - We **do not assume** that one single expression of the profiles may be universally the best