Environment and Climate Change Canada

Canada

ECMWF/EUMETSAT NWP SAF Workshop on the treatment of random and systematic errors in satellite data assimilation for NWP: 4 November 2020

Pragmatic approaches for treating spatial error correlations: thinning, inflation, gradient observations

Joël Bédard[1,2], Mark Buehner[1] and Alain Beaulne[2]

[1] Data Assimilation and Satellite Meteorology Research Section

[2] Data Assimilation and Quality Control Development Section

Motivation

Even though satellite brightness temperature is the observation type with the biggest impact on atmospheric analyses and ensuing forecasts, they are still underused (e.g. ECCC does horizontal thinning at 150 km).

- Brightness temperature errors can have significant spatial correlations:
  - Correlated instrument noise and representativeness error.
  - Correlation from background state used in the observation operator.
- Assimilation algorithms assume spatially uncorrelated obs. errors:
  - Methods to account for spatially correlated observation errors can be impractical if the number of correlated observations is large or if the observations are non-uniformly distributed.
  - Difficult to estimate the real error correlations.
- It is common practice to spatially thin obs. to reduce error correlation between remaining obs., resulting in a loss of small-scale information.
- **Goal:** Develop a practical assimilation approach to extract more information from observations with spatially correlated errors, while still assuming spatially uncorrelated observations in the assimilation.

Part I: Idealized experiments

- Testing and understanding practical approaches (thinning, inflation and gradient observations) using idealized experiments (*Bédard and Buehner*, 2019).

Experimental framework

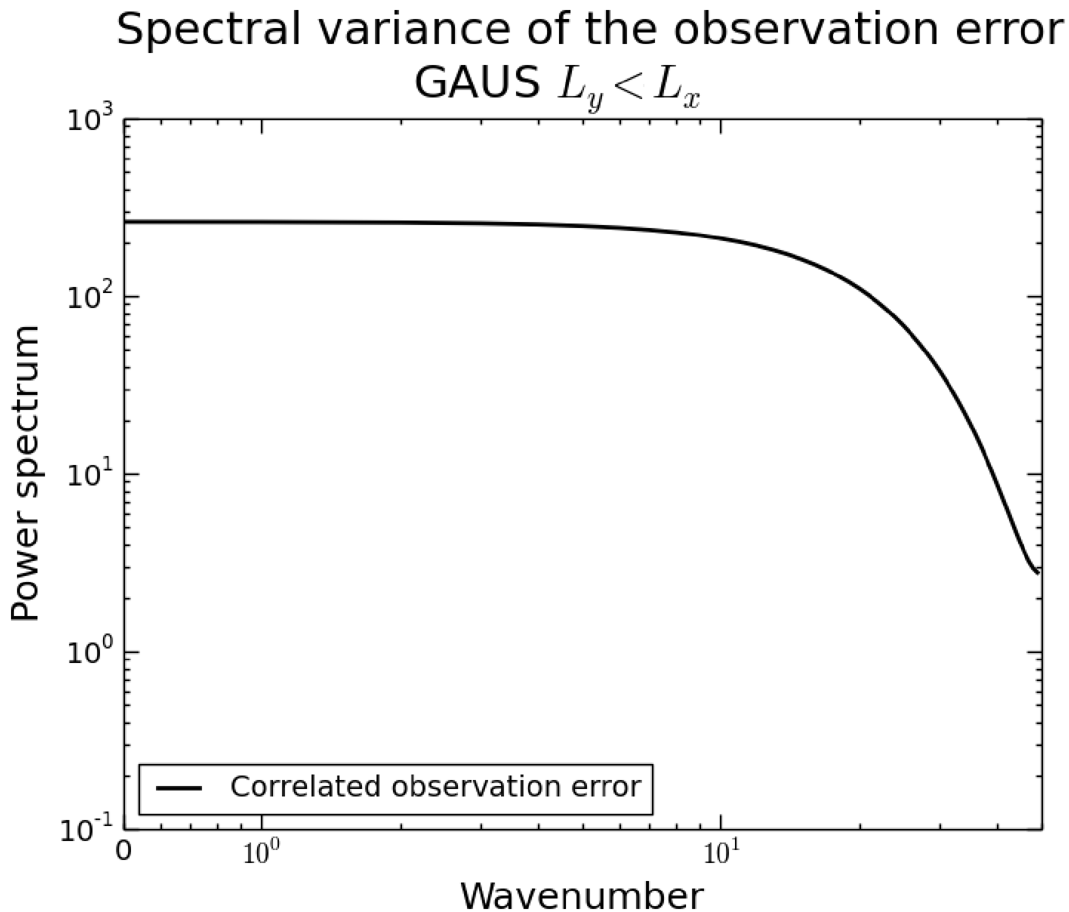
Assimilation experiments are performed in a simplified context to assess the impact of observations with spatially correlated errors on analyses:

- Unidimensional periodic domain with 100 grid points.
- Single dimensionless variable.
- Observations are available at every grid point (no interpolation, $\mathbf{H} = \mathbf{I}$).
- Background and observation error variances are set to 1.0.
- Tests performed with several correlation functions (GAUS, SOAR, FOAR) and correlation length scales are defined w.r.t. the e-folding scale:
  - Background (prior) error correlation length scale (L_x): 3 grid points.
  - Obs. error correlation length scale (L_y): 0.0, 1.5, 3.0, and 4.5 grid points.
- The true analysis error covariances (**A**) is computed as:

  $\mathbf{A} = (\mathbf{I} - \mathbf{K})\mathbf{B}(\mathbf{I} - \mathbf{K})^T + \mathbf{KRK}^T$ where $\mathbf{K} = \mathbf{B}\,(\mathbf{R}_{est} + \mathbf{B})^{-1}$
  - **B** and **R** are the true background and obs. error covariance matrices.
  - $\mathbf{R}_{est}$ is the estimated obs. error covariance matrix used (typically diagonal).
- All assimilation tests using diagonal observation error covariance matrix employ optimally inflated variances.

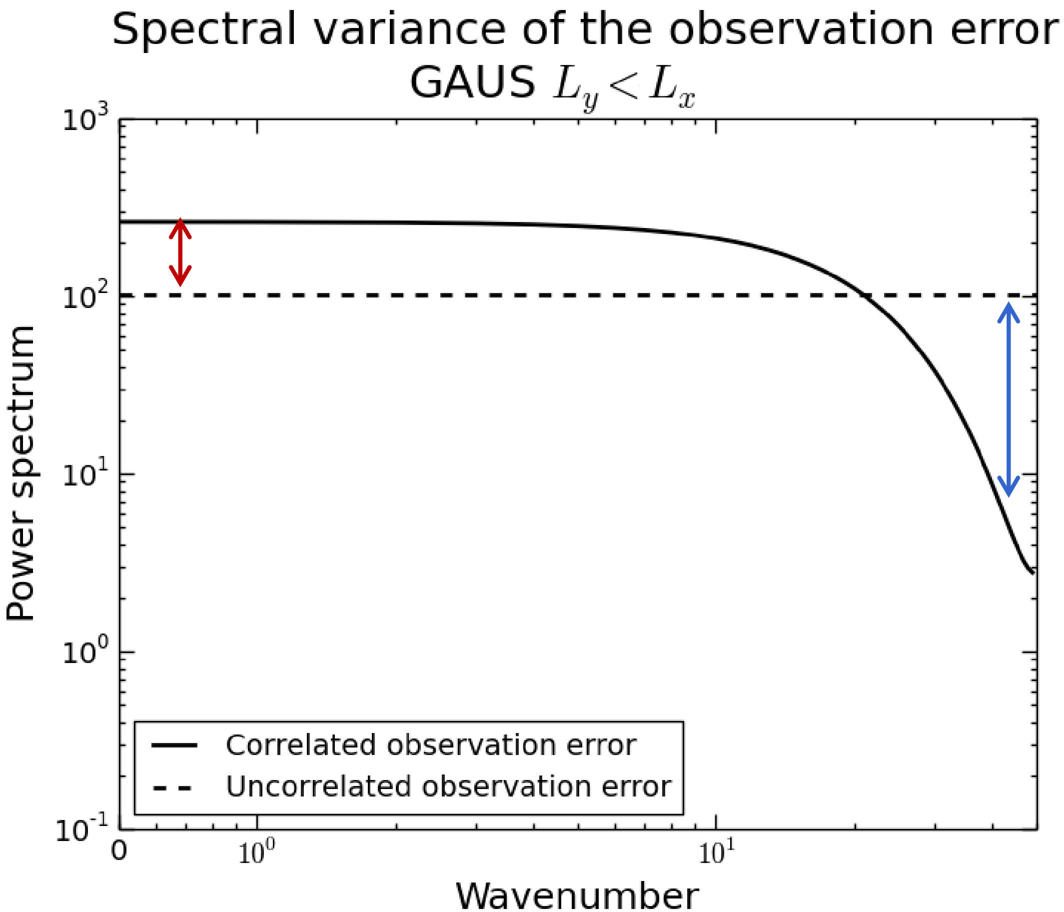
Correlated observation error

- Positively correlated errors have more energy at the large scales.
- The spectrum is similar to red noise.



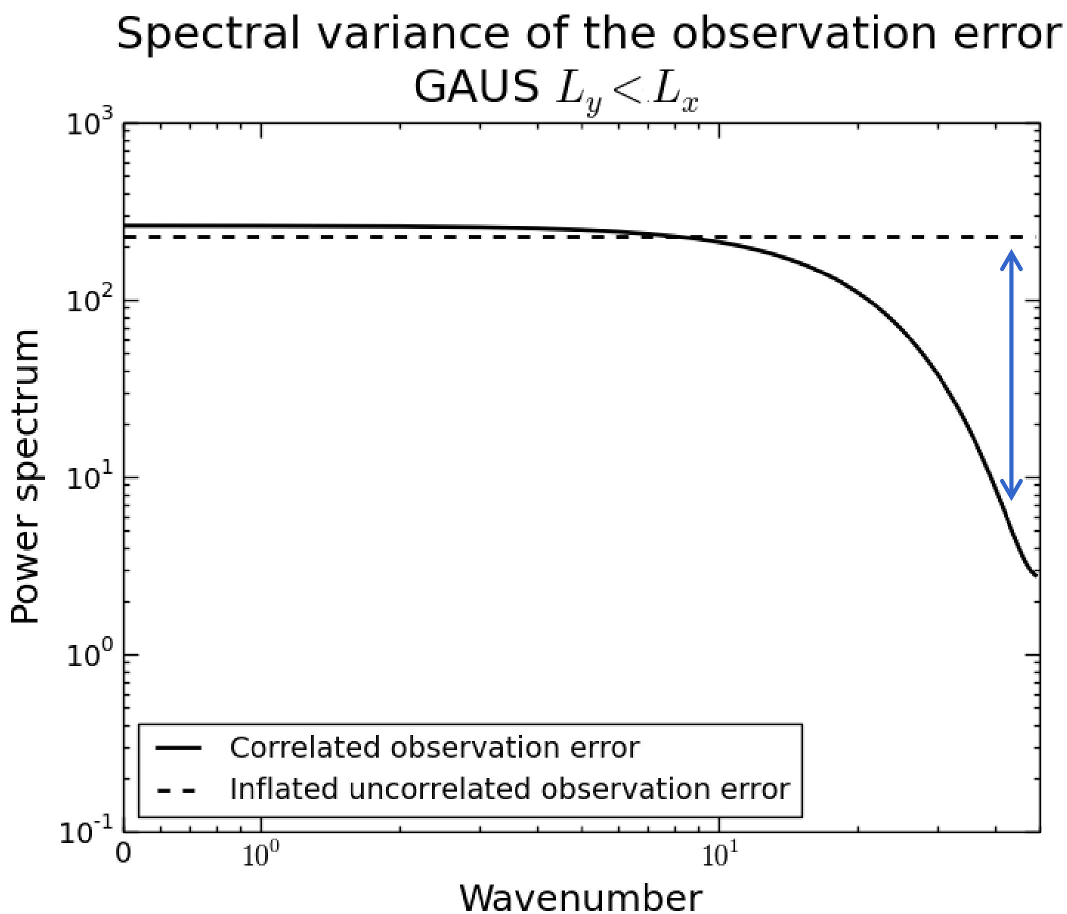
Correlated observation error

- Simply neglecting the error correlations can degrade the resulting analysis by overfitting large scales and underfitting the small scales.



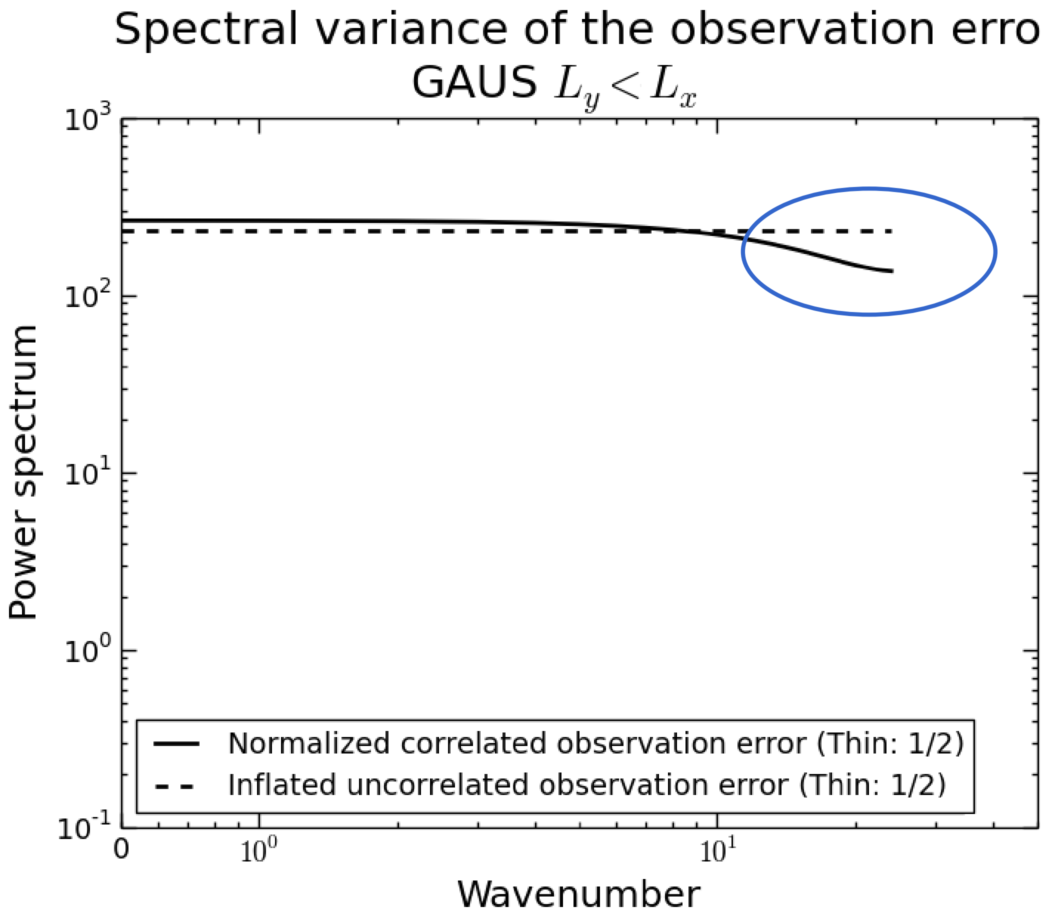
Correlated observation error

- Inflation allows correctly fitting the scales at which background error has the most energy (large scales), but further neglects small scales.



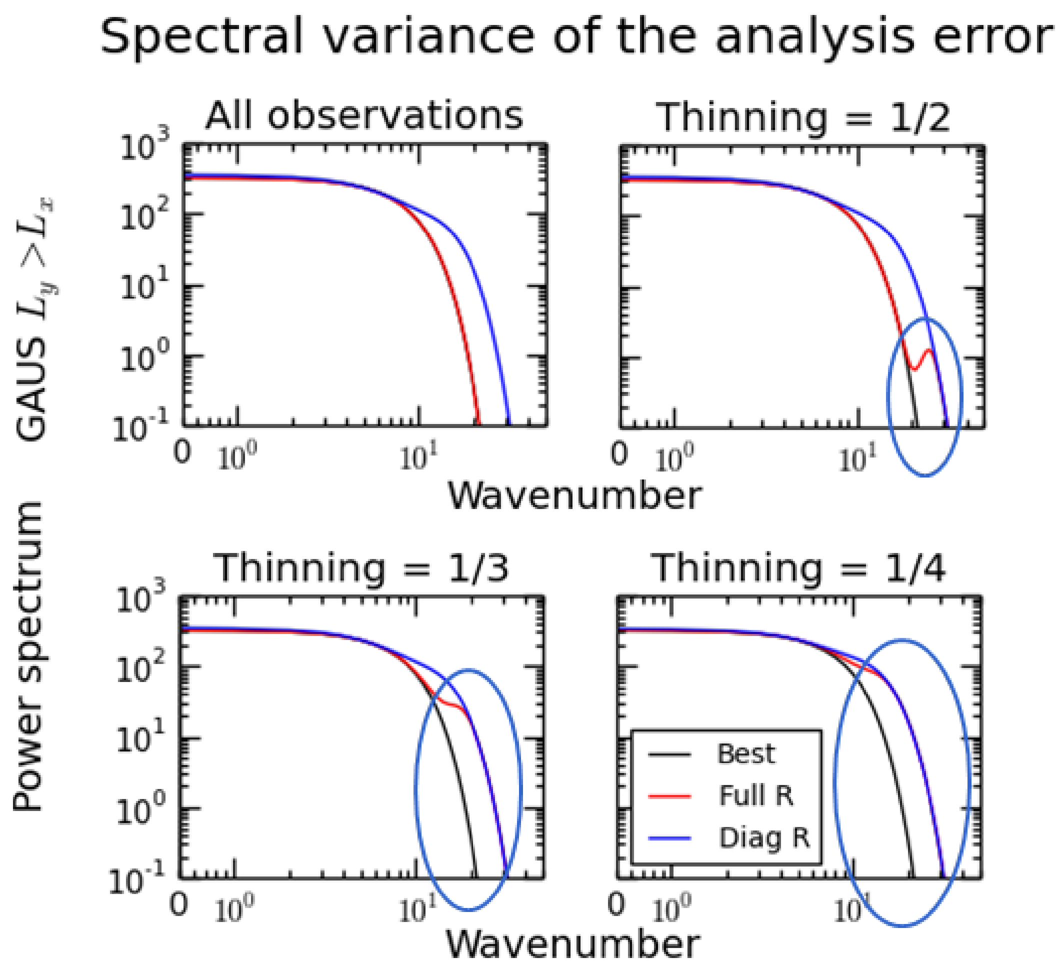
Correlated observation error

- Thinning reduces spatial error correlation between the remaining obs. (spectrum more flat), but information on the small scales is lost.



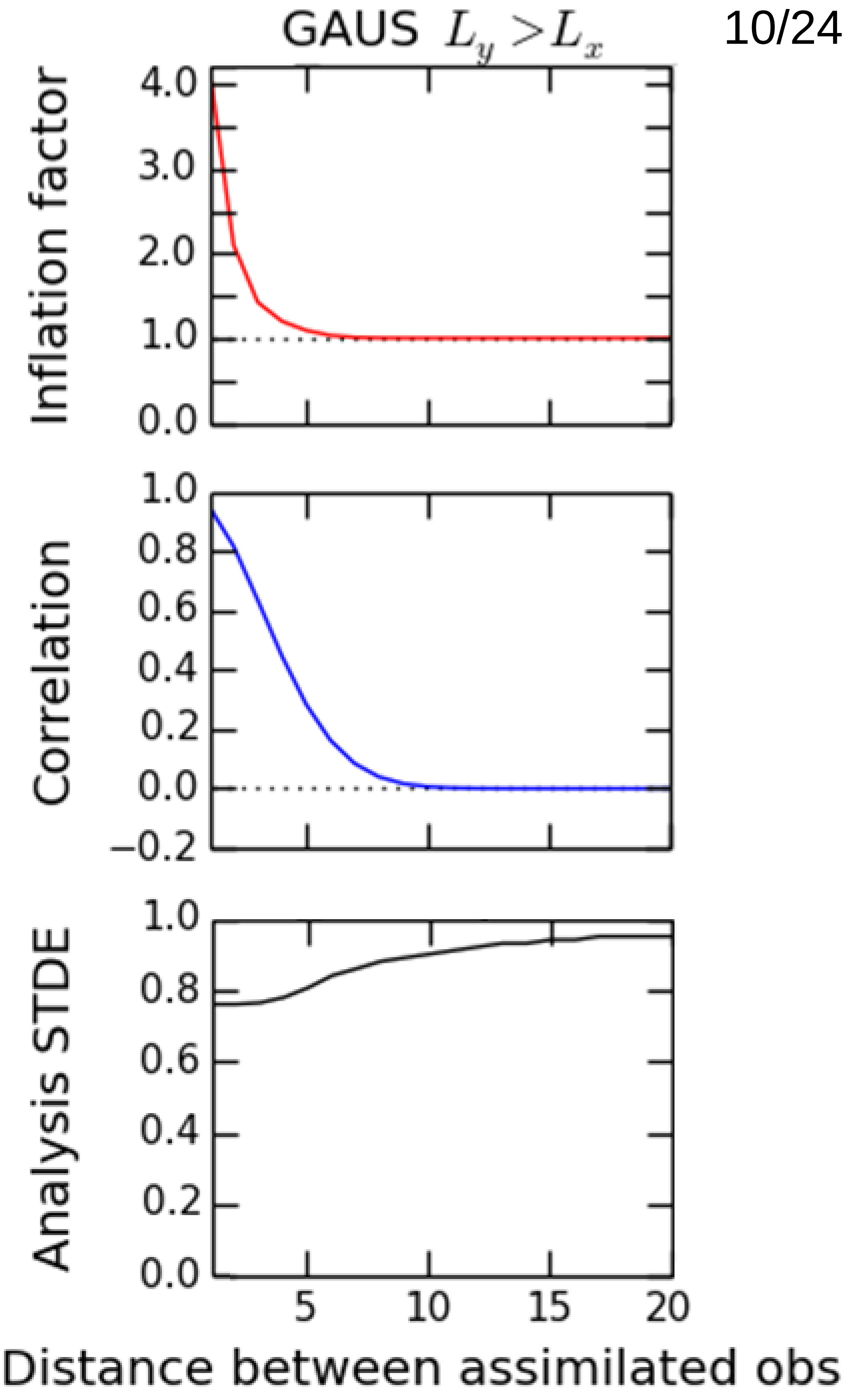
Impact of thinning on analysis error

- With more thinning, the impact of neglecting correlations is reduced, at the expense of losing any potential skill for an increasing number of wavenumbers at the small scales.



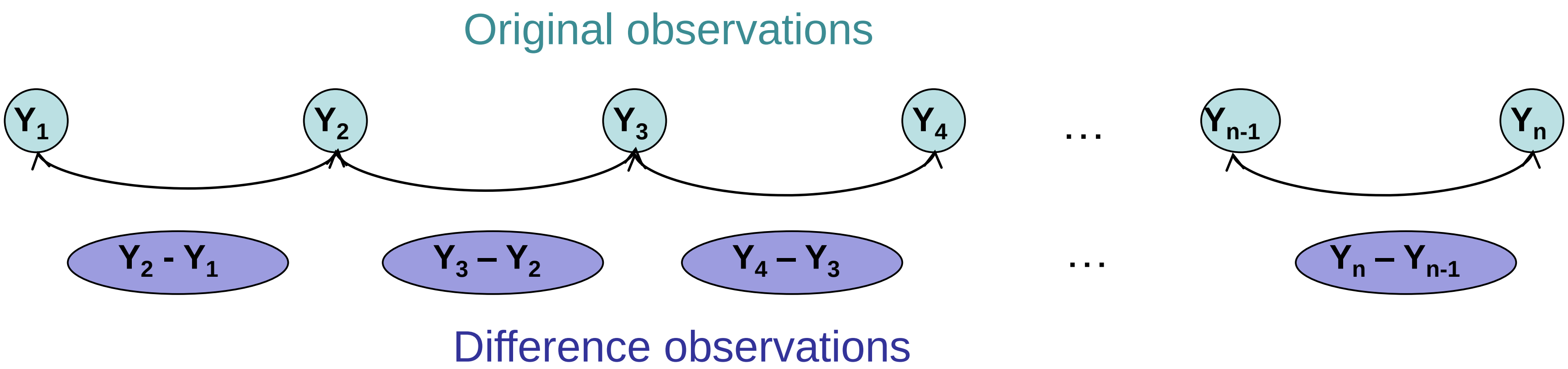
Thinning impact with inflated diagonal R

- Optimal inflation ≈ 1 when correlation ≤ 0.2 (Liu and Rabier, 2002).
- When correlation > 0.2, the analysis would be degraded without inflation (not shown).
- With optimally inflated diagonal R, the analysis error is smallest when using all obs. (no thinning).



Difference-observations

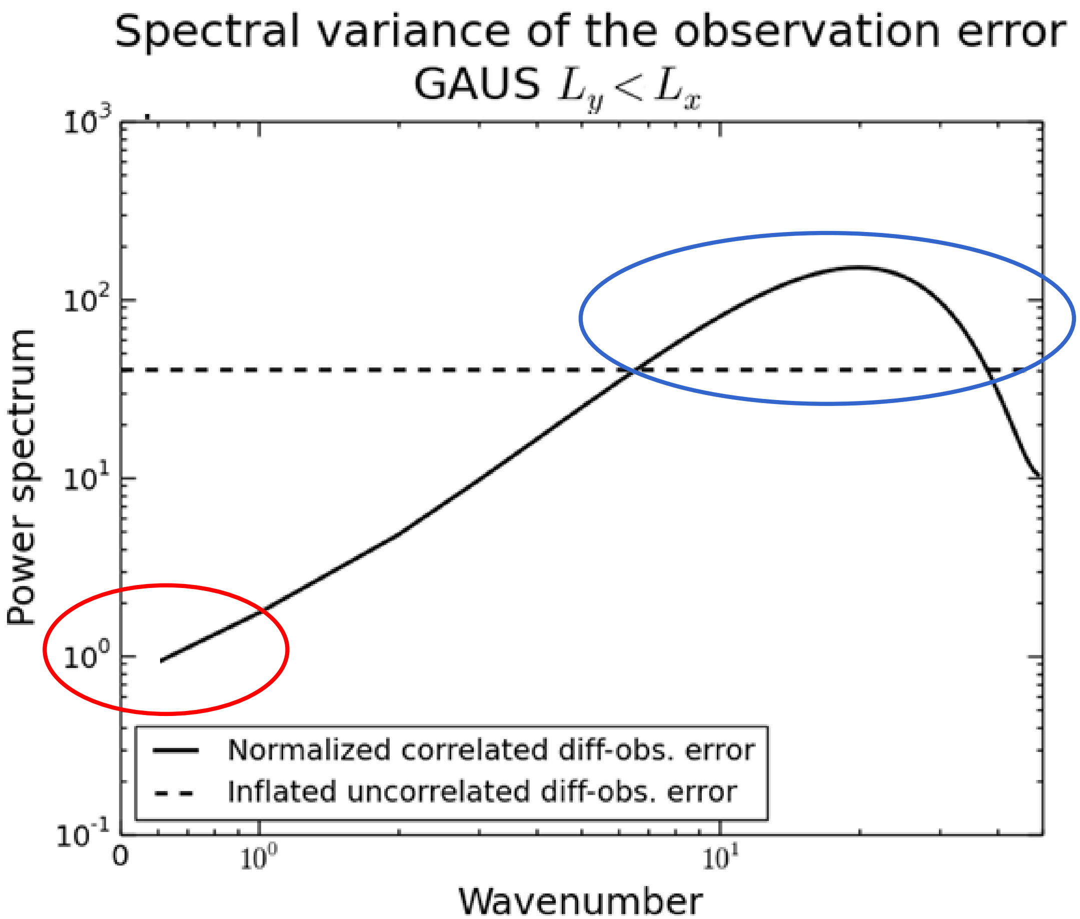
- Similar to other studies that use spatial transformations to reduce error correlations (Ruggiereo *et al.*, 2016), spatial differences of neighboring observations (difference-obs.) can be used to increase the weight on small scales (inspired from Anderson's presentation at the Australia data assimilation workshop in 2016).



- Combining thinned obs. (as they are currently used in operational NWP) with spatial difference-obs. (both with their own tuned diagonal R) may allow introducing complementary information at small scales.

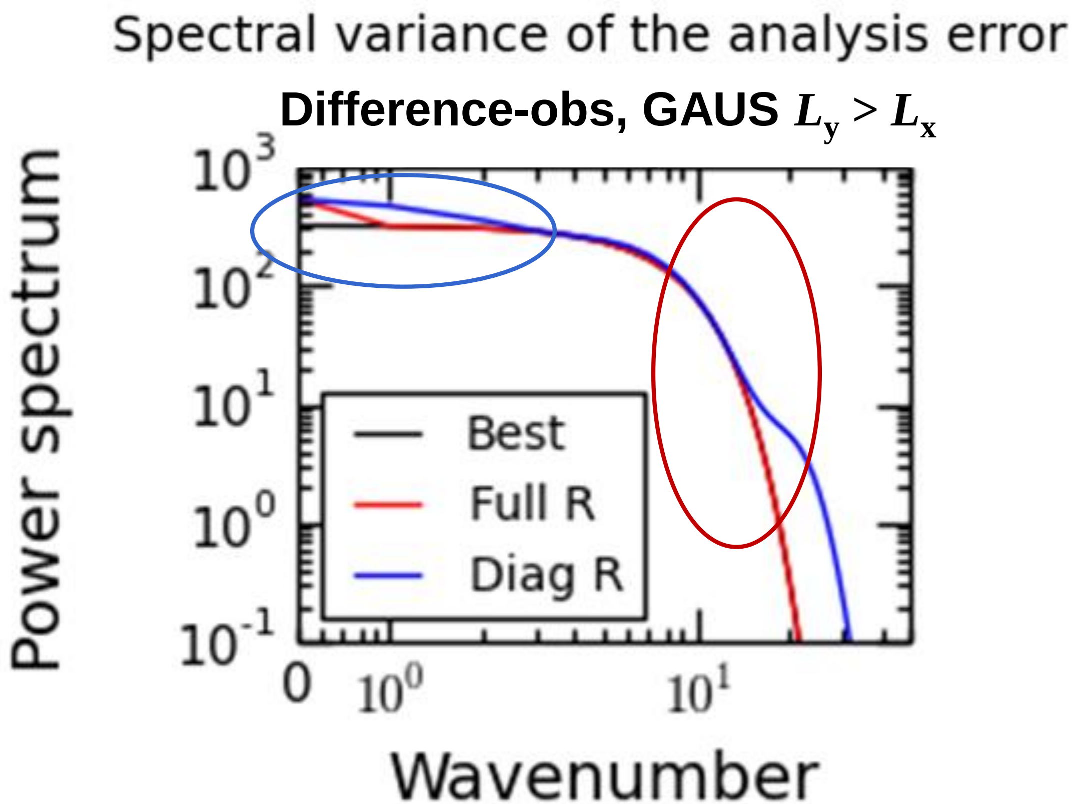
Difference-observations

- Spatial differential operator = multiplying spectrum by wavenumber.
- More weight is given to "intermediate" scales and the information at wavenumber 0 is lost.



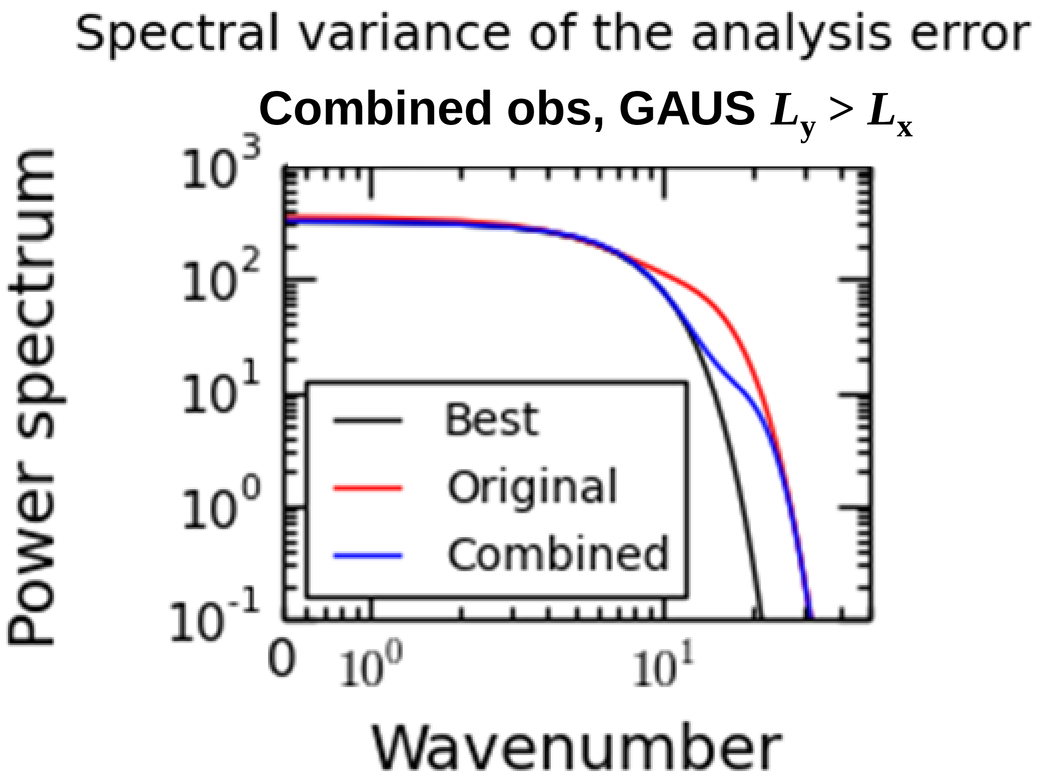
Difference-observations

- Difference-obs. have low skill at the large scales.
- Using difference-obs. with diagonal R improves "intermediate" scales.



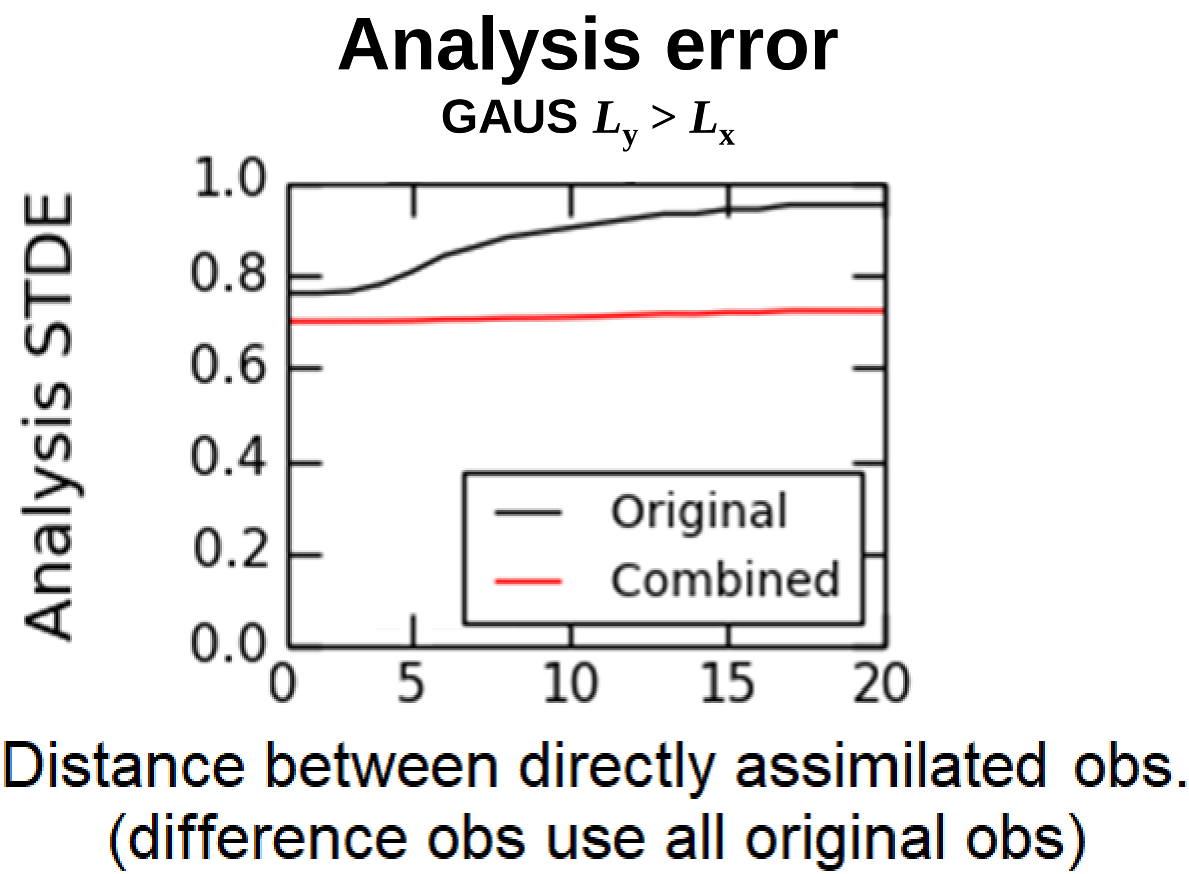
Combining original and difference-obs

- The analysis benefits from both the large scales of the original observations and the intermediate scales from difference-obs.
- The combine approach is equivalent to assimilating obs. available at every grid point using non-diagonal obs. error covariances based on a first-order autoregressive (FOAR) correlation function (not shown).



Combining original and difference-obs.

- The analysis error is reduced when using the combined approach.
- The analysis error is now less sensitive to thinning.
- Optimal inflation has to be computed for both thinned and diff-obs.



Part II: Near-Operational Context

- Thinning and inflation tests based on experiments performed in a near-operational context.

Experimental framework

Assimilation experiments are performed in a near-operational context to assess the impact of reducing thinning applied to brightness temperature observations.

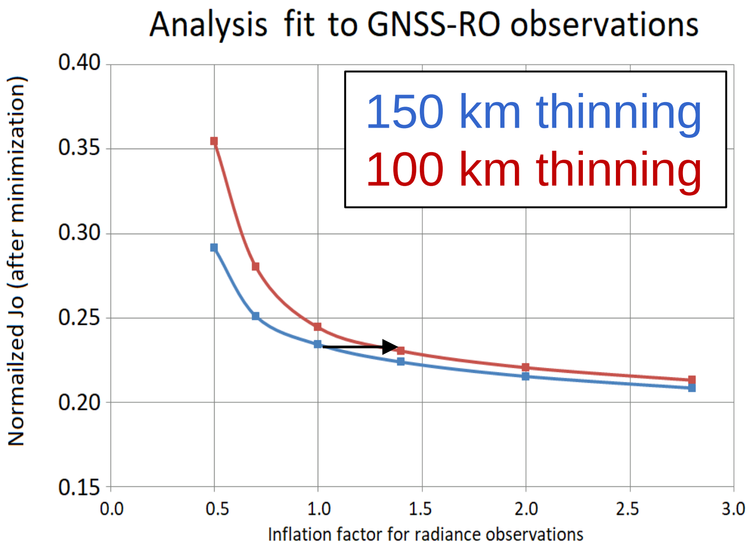
- 39 km global deterministic prediction system:
  - 3D-EnVar data assimilation algorithm using 256 ensemble members.
  - Spatially diagonal observation error covariance matrix (R).
- Tests performed on radiance obs. (MW and IR imagers and sounders):
  - Different thinning (150 km vs 100 km).
  - Different observation error variance inflations (0.5, 0.7, 1.0, 1.4, 2.0, 2.8).
- Tests performed over 2.5 months period (2016/06/15 to 2016/08/31):
  - All operationally assimilated observations are used.
- Forecasts are evaluated against Era5 analyses:
  - Evaluation against radiosondes not statistically significant.

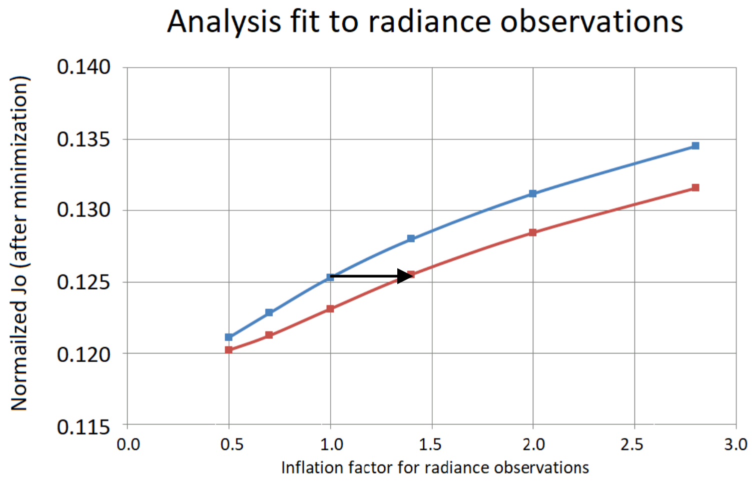
Impact of reduced thinning

- With reduced thinning, the number of assimilated radiance obs. is increased.
- With reduced thinning, observation error variance has to be inflated to keep a similar analysis fit to assimilated obs. (radiances and other obs. families).

# profile / cycle	150km	100km	% Increase
AIRS	10.5k	15.8k	51%
CRIS	11.4k	18.3k	61%
IASI	23.2k	34.7k	50%
CSR	57.2k	97.3k	70%
AMSU-A	65.5k	110.2k	68%
MHS	33.6k	69.8k	108%
ATMS	15.9k	35.1k	120%
SSMIS	16.6k	36.8k	122%

* Some families of observations are sensitive to the thinning algorithm geometry.



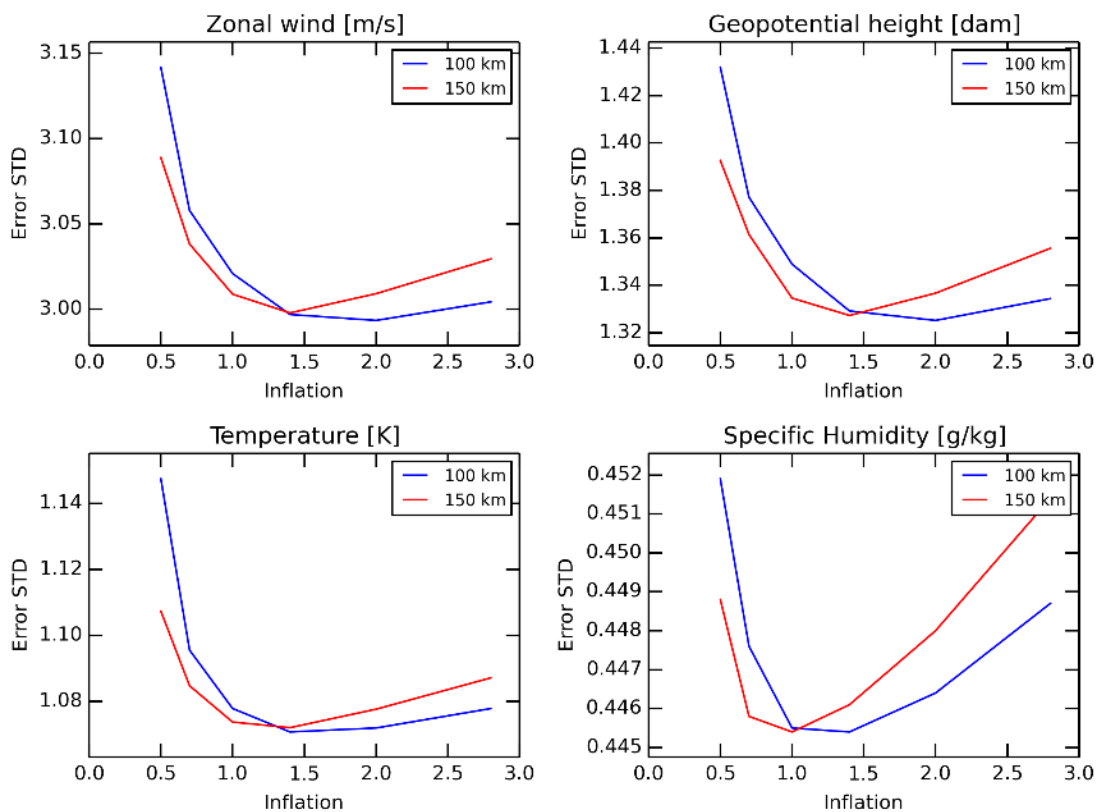


Impact from thinning and inflation

Forecast evaluation against Era5:

- Vertically averaged scores (from 1000 to 1 hPa) @ 48 h (world):

  - Operational system with current thinning could benefit from more observation error variance inflation (for winds, GZ and temperature).
  - Reduced thinning, without obs. error variance inflation can degrade forecasts.
  - Reduced thinning experiments can provide improved forecasts if obs. error variance is inflated accordingly.
  - Separate tuning for humidity sensitive channels may be useful.

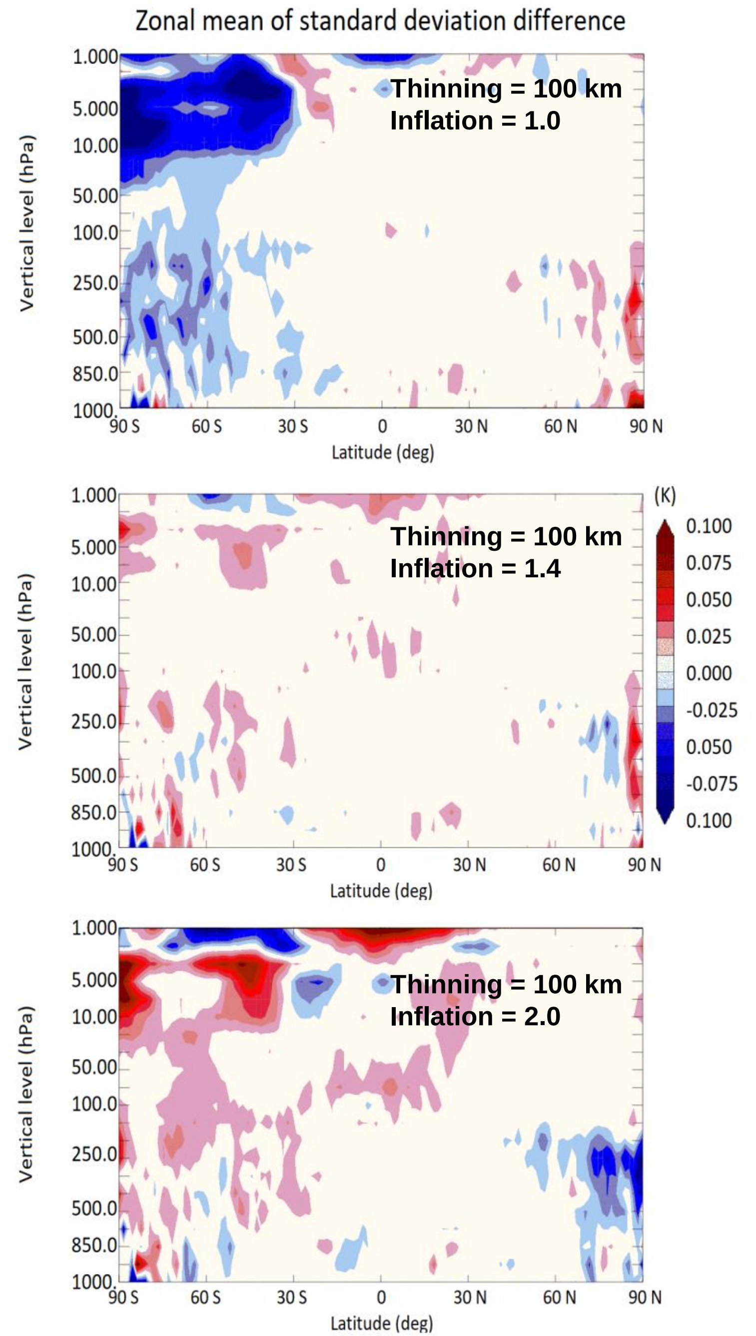


Impact on forecasts: zonal distribution.

Forecast evaluation against Era5:

(ref: Thinning = 150 km, Inflation = 1.0)

- Temperature @ 48 h (World):
  - Reducing spatial thinning without further inflating observation error variance degrades the forecasts (blue contours).
  - Small improvements (≤ 0.1 K) are achieved when reducing spatial thinning while inflating the obs. error variances (red contours).
  - **Impacts mostly noticeable in the Southern extratropical and tropical regions.**

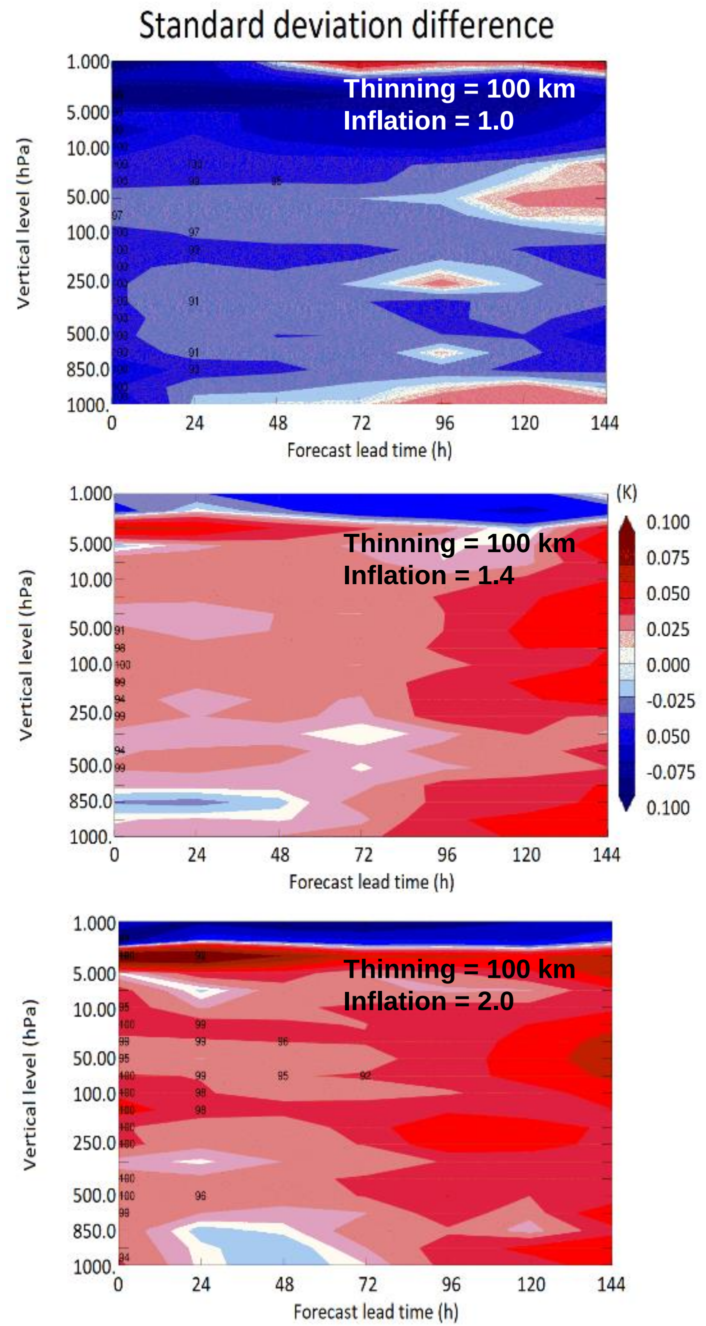


Impact on forecasts as a function of lead time

Forecast evaluation against Era5:

(ref: Thinning = 150 km, Inflation = 1.0)

- Temperature (Southern extratropics):
  - Reducing spatial thinning without further inflating observation error variance degrades the forecasts (blue contours).
  - Small improvements (≤ 0.1 K) are achieved when reducing spatial thinning while inflating the obs. error variances (red contours).
  - **Differences are statistically significant for forecasts up to 72 h.**
  - Deteriorations in upper levels:
    - Potentially need to re-assess inflation for AMSU-A channels 13-14 and ATMS channels 14-15.



Environment Canada Environnement Canada

Part III: Ongoing investigation

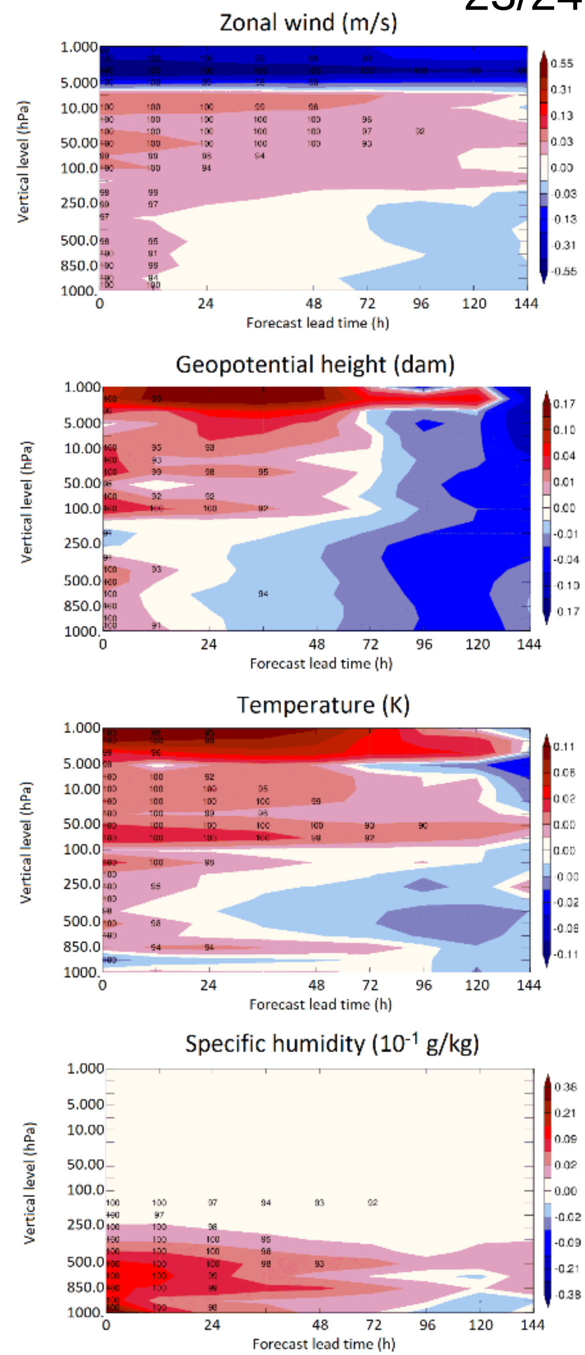
- Re-assess observation error variance inflation for high-peaking channels (AMSUA 13-14 / ATMS 14-15) and humidity sensitive channels independently.
  - Final inflation factor reduced to 1.4 for those channels.
- Tests based on experiments performed in a near-operational context during winter 2020 (similar results were obtained during summer 2019 period).

Impact on forecasts as a function of lead time

Forecast evaluation against ECMWF analyses (ref: Thinning=150 km, Inflation=1.0).

- World scores (thinning=100km, inflation=2.0*)
  *After fine tuning high-peaking and humidity sensitive channels (inflation set back to 1.4):
  - Humidity scores significantly improved throughout the troposphere (up to 48-72h).
  - Wind, geopotential height and temperature significantly improved in the stratosphere up to 48-96h, and in the troposphere up to 12-24h.
- Outstanding issues:
  - Significant wind degradation above 7 hPa.
  - Potential (not stat. significant) tropospheric degradation past 24-48h for UU, GZ and TT.
  - Degradation of upper level temperature above 7 hPa in the tropics (not shown).

STD differences



Take Home Messages

Inflation and thinning can be used to give correct weight to large scales, but underweights the small scales (when obs. error is correlated).

- With optimally inflated diagonal R, the analysis is degraded with thinning.
- Observation error variance inflation needs to be increased when reducing spatial thinning distance to avoid overfitting large scales.

Near operational results are consistent with idealized ones.

- Small (but statistically significant) improvements can be achieved by reducing spatial thinning of satellite radiance observations from 150 km to 100 km, although a few outstanding issues still has to be addressed.
- Fine-tuning error variance inflation for specific channel groups appears useful.

Combining thinned observations with difference-obs.

- Is equivalent to assimilating obs. at every grid-point using non-diagonal obs. error covariances based on a first-order autoregressive correlation function.
- Provides good fit to observations at both large and finer scales and reduces overall analysis error as compared with thinned obs. alone.
- Two parameters (inflation factors) would need to be tuned experimentally.

ECCC to pursue work on **difference-obs in near-operational context**.