Optimal trade off between spectral and radiometric resolution in order to optimize the performances of a radiometer in the far infrared region

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Introduction

Current observations used in numerical weather prediction systems come mostly from spaceborne thermal infrared sounders such as AIRS, IASI and CrIS. However, the thermal infrared only constitutes half of the Earth's emitted radiance, the other half being the far infrared (far-IR), ranging from 15 to 100 µm. In recent years, some theoretical studies have shown the added-value of far-IR observations for remote sensing of water vapor and clouds, especially in dry and cold regions. Satellite missions sounding in the far-IR, such as TICFIRE, FORUM and PREFIRE, are also emerging from various space agencies.

In this study, the objectives were to evaluate the potential of far-IR spaceborne measurements to provide information for temperature and humidity and to analyze the optimal trade-off between spectral and radiometric resolution. A radiometer was used since it allows to have bands with different spectral widths, which means that the bands can be selected where the Jacobians are strongest. A simple 1D framework was used to compare the impact of far-IR and mid-IR measurements through the reduction of the analysis error variance obtained by assimilating those. Information content (or Degrees of Freedom per Signal, DFS) was used as the metric to examine synthetic measurements for different number and widths of spectral bands, and measurement error.

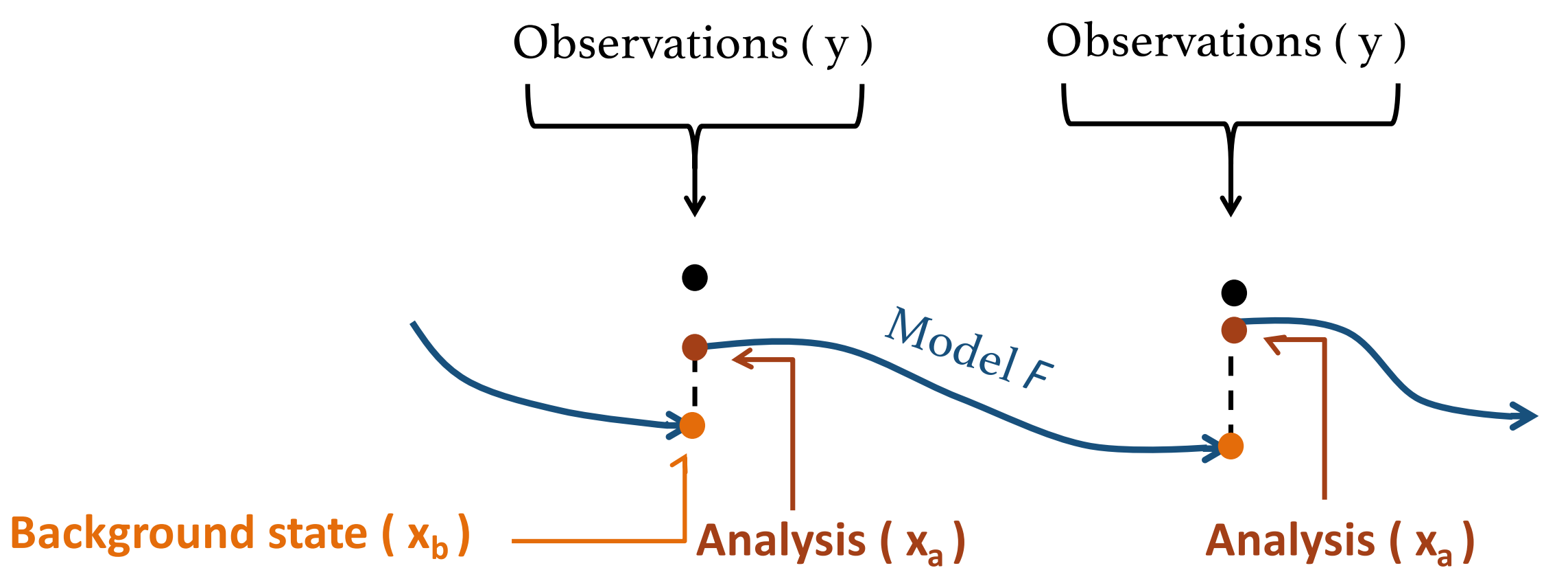
Objectives

To determine the added-value of assimilating F-IR radiances in NWP systems

- Explore the trade-off between spectral and radiometric resolution for a radiometer in the F-IR (15 to 100 µm)
- Evaluate the potential of far-IR spaceborne measurements to provide information for temperature and humidity

Theory and instruments

- **Data assimilation**



$$x_a = x_b + \mathbf{K}(y - \mathbf{H}x_b)$$

Where $\mathbf{K} = \mathbf{B}\mathbf{H}^T(\mathbf{R} + \mathbf{H}\mathbf{B}\mathbf{H}^T)^{-1}$ is the gain matrix which gives a statistical weight to measurements and observations [6]

$$H = \left.\frac{\partial F(x)}{\partial x}\right|_{x_b}$$ is the Jacobian which gives the sensitivity of TOA radiance to small changes in atmospheric properties where F(x) is the radiative transfer model MODTRAN 5.4

- The humidity Jacobian (ln q) is obtained by finite difference taken around a background state [2], which is taken from a radiosonde profile at Eureka, Canada. This was done for 48 atmospheric profiles through the Arctic region

- **B** is the background error covariance matrix, which is the stationary components of the background term in the ECCC system [1]

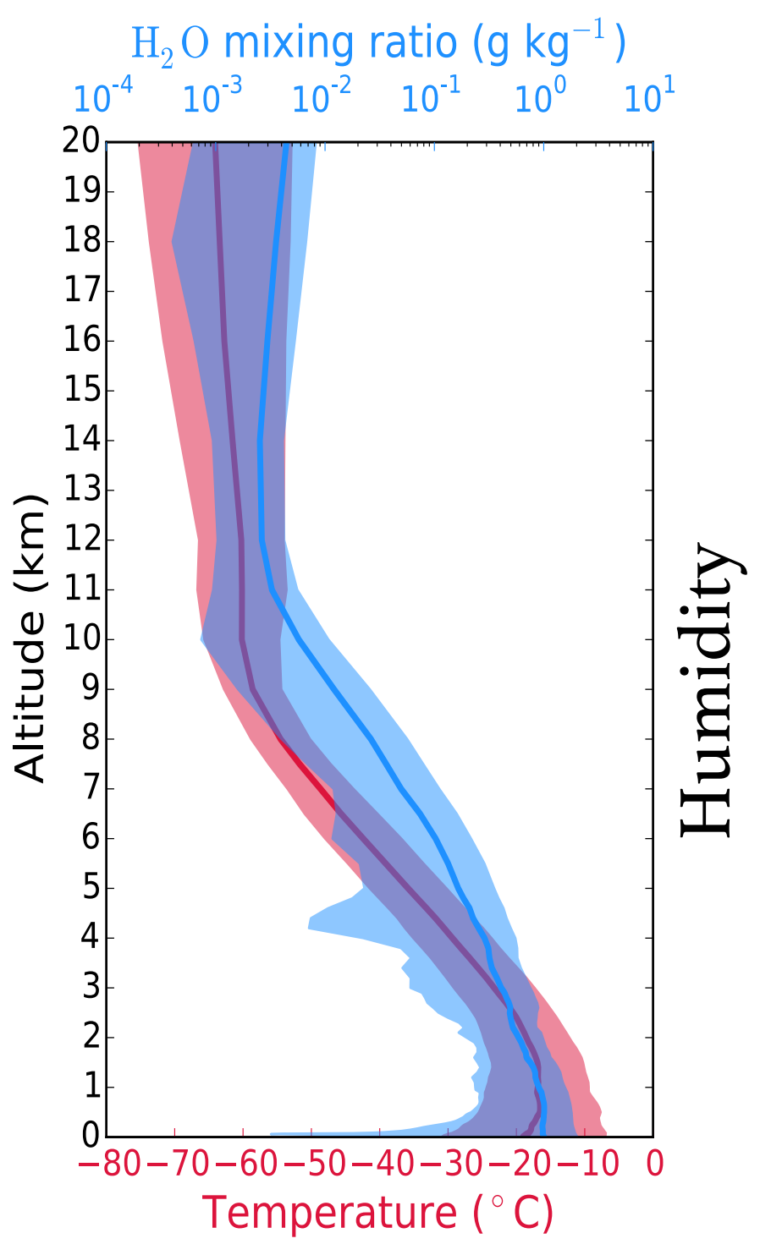


Figure 1 : Temperature and humidity profiles averaged for the 48 radiosoundings at eight Arctic stations shown with the red and blue lines, respectively. The shaded area shows the standard deviation associated with the variables.

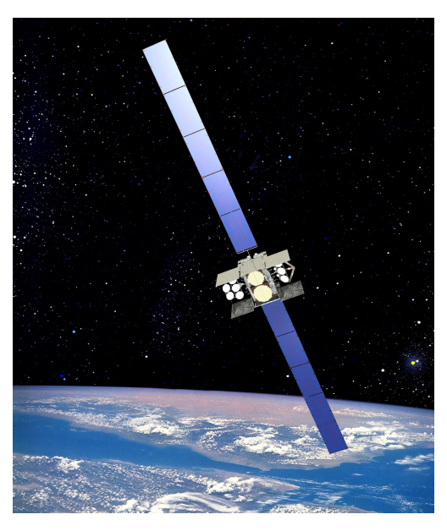
- **Degrees of freedom per signal (DFS)**

$$DFS = tr(\mathbf{HK}) = tr(\mathbf{HBH}^T(\mathbf{HBH}^T + \mathbf{R})^{-1})$$

- Quantify the added-value of a set of observations

- **F-IR Radiometer**

- Synthetic spaceborne F-IR radiometer
- Measures radiation in the F-IR with a spectral coverage of 16.5 100 µm
- Fixed detector noise of 0.01 $Wm^{-2}sr^{-1}$, value taken for the diagonal of the error covariance matrix **R**. This NER value corresponds to the F-IR radiometer FIRR. [4] A target NER of 0.002 $Wm^{-2}sr^{-1}$ is also considered.
- **Multiples configurations considered**
  - Equi-energetic bands
  - Constant wavelength bands
  - Constant wavenumber bands



- **AIRS**

- Measures radiation in the M-IR (3.75 – 15.4 µm) with 2378 channels
- Subset of 142 channels taken

References

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F-IR radiometer configurations

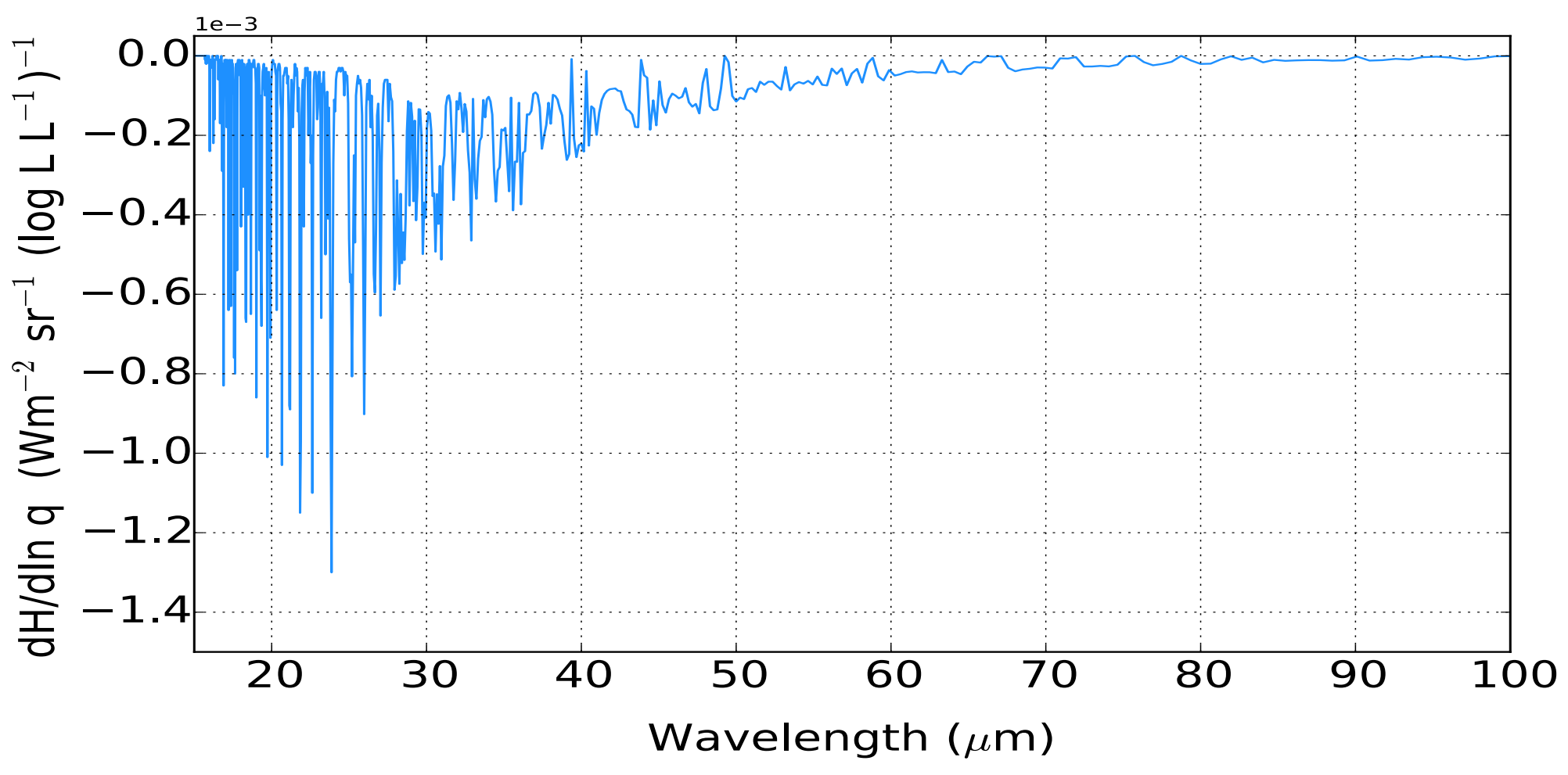

Figure 2 : Humidity Jacobians at 300 hPa as a function of the wavelength for a bandwidth of 1 cm^{-1}.

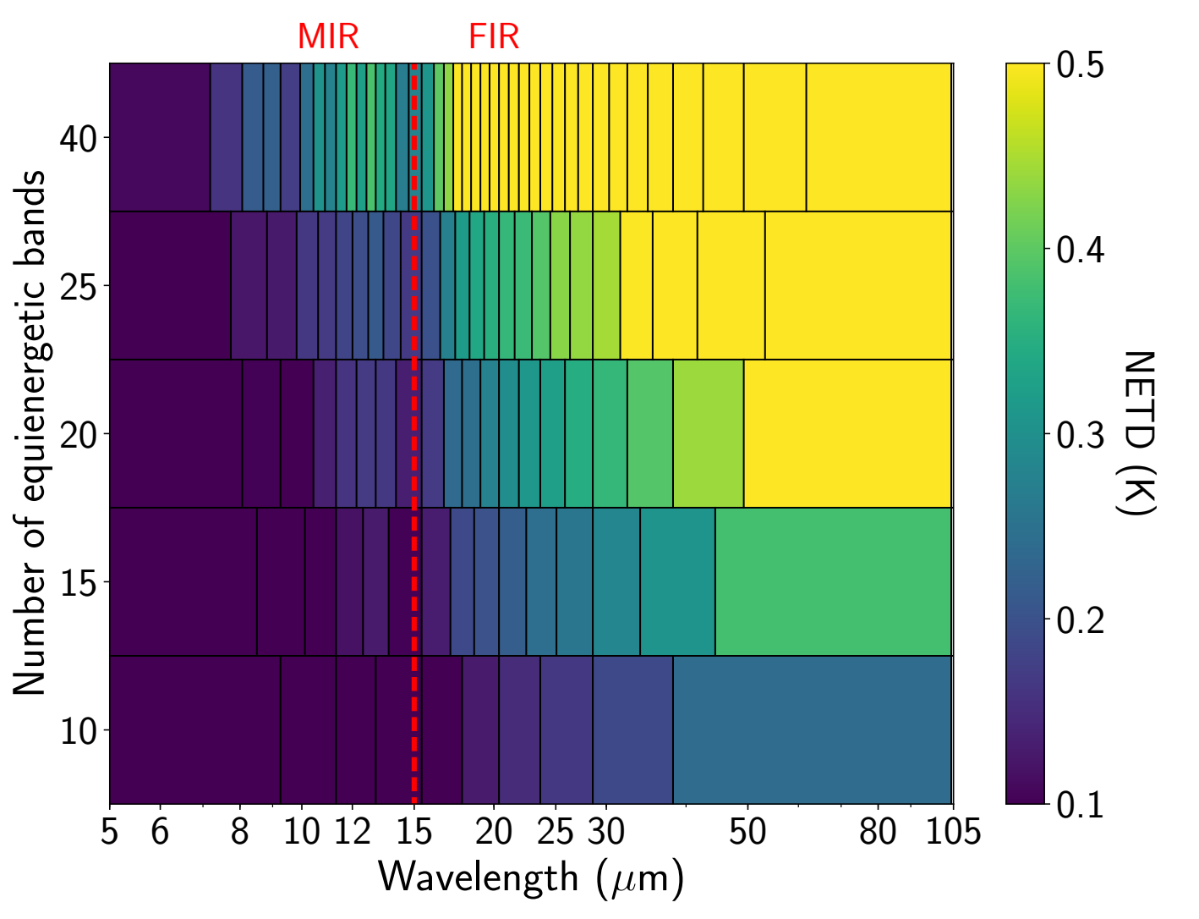

Figure 3 : NETD for different configurations of equi-energetic bands for a blackbody at 250 K with a constant NER of 0.01 W/m^2sr.

- Noise-equivalent temperature difference (NETD) not constant for a configuration with a noise-equivalent radiance (NER) of 0.01 W/m^2sr
- Spectral widths vary for equi-energetic bands

➢ Strong wavelength dependence of the Jacobians

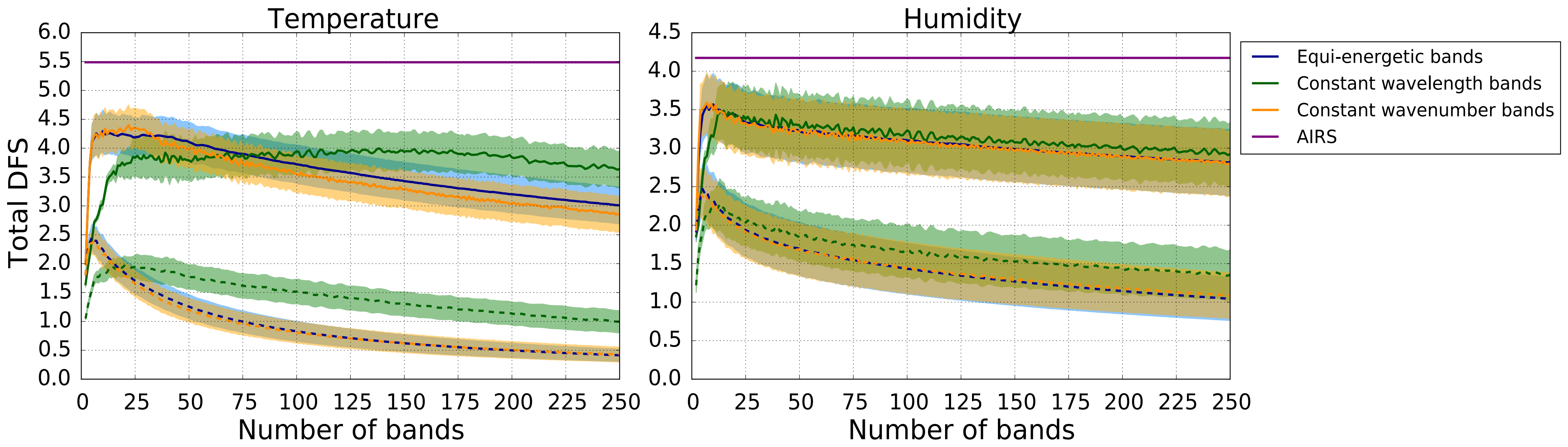

Figure 4 : The averaged total DFS as a function of the total number of bands for three configurations which are equienergetic bands (blue line), constant bandwidths in terms of wavelength (green line) and wavenumber (orange line) for temperature (left) and humidity (right). The dashed lines are for a NER of 0.01 $Wm^{-2}sr^{-1}$, whereas the full lines are for the target NER of 0.002 $Wm^{-2}sr^{-1}$. The purple line represents the averaged total DFS of AIRS for the 48 atmospheric profiles. The shaded area represent the standard deviation of the 48 atmospheric profiles which are shown for all configurations except for AIRS. The standard deviation of AIRS is equal to 0.53 and 0.67 for temperature and humidity, respectively.

Configuration	Total DFS (Number of bands)	
	Temperature	Humidity
Equi-energetic bands	4.294 (10)	3.569 (10)
Constant wavenumber bands	4.399 (22)	3.594 (7)
Constant wavelength bands	3.996 (138)	3.482 (15)

- For the three cases, as the number of bands increases the total DFS decreases. This is due to the constant NER, which results in less energy when the bandwidth is reduced
- The highest DFS is with the constant wavenumber bands configuration for both temperature and humidity with 22 and 7 bands respectively for the NER error of 0.002 $Wm^{-2}sr^{-1}$
- When compared to AIRS, the DFS for the optimal configuration with constant wavenumber bands is smaller than the DFS of AIRS

Sensitivity to sensor noise

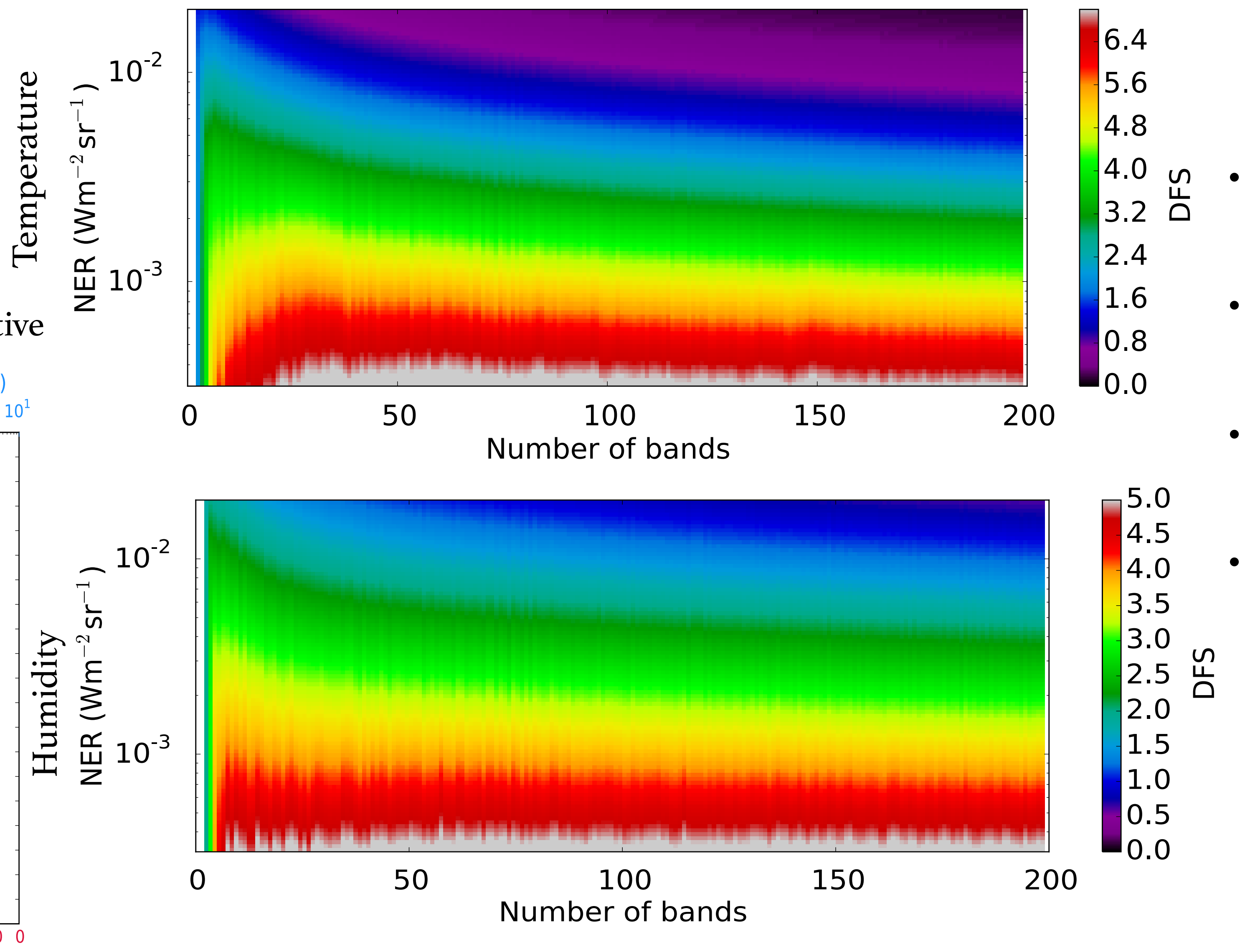

Figure 5 :The averaged total DFS is shown for variations of the NER level (y- axis) and variations of the total number of bands for humidity of the constant wavenumber bands for temperature (top) and humidity (bottom). The DFS for each configuration is shown with the colorbar.

- For a fixed NER, the DFS increases and then decreases as the number of bands increases
- The maximum DFS is always obtained with a configuration which has less than 55 bands
- It has variability in the DFS for an horizontal, which is partly due to spectral features of transmittance
- This figure can be useful when there are technological constraints for example. If the NER is imposed by the available technology, taking a horizontal line highlights the available spectral configurations

Analysis error variance

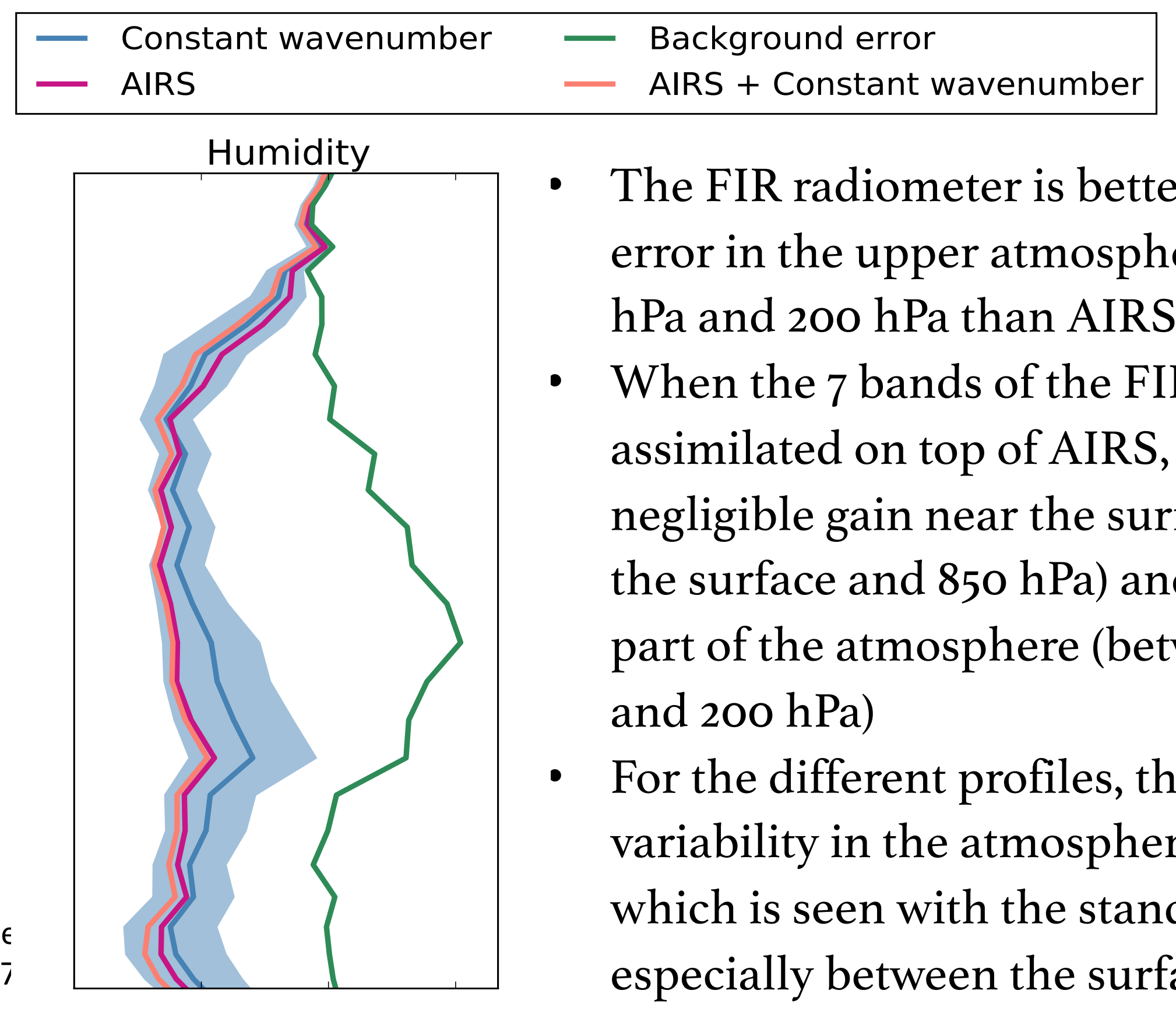

Figure 6 : Analysis error variance profile for humidity for the optimized FIR radiometer. The shaded area represents its associated standard deviation.

- The FIR radiometer is better at reducing the error in the upper atmosphere, between 400 hPa and 200 hPa than AIRS
- When the 7 bands of the FIR radiometer are assimilated on top of AIRS, there is a non negligible gain near the surface (between the surface and 850 hPa) and in the upper part of the atmosphere (between 400 hPa and 200 hPa)
- For the different profiles, there is some variability in the atmospheric conditions which is seen with the standard deviation, especially between the surface and 600 hPa which is expected

Instruments	Total DFS Target NER
AIRS	4.173
Constant wavenumber bands	3.594
AIRS + Radiometer	4.714

Conclusions

- ➢ The position and width of the bands have a big impact on the DFS
- ➢ The optimal configuration for the synthetic FIR radiometer is with 22 and 7 constant wavenumber bands for temperature and humidity respectively
- ➢ With a few bands, it was possible to get a DFS similar to AIRS when compared individually
- ➢ There is a complementarity in assimilating measurements in the F-IR and in the mid-IR, since the DFS increases when F-IR measurements were assimilated on top of AIRS
- ➢ Between 400 hPa and 200 hPa, taken individually, the FIR radiometer is better at reducing the humidity analysis error variance than AIRS
- ➢ There is a non negligible gain near the surface (between the surface and 850 hPa) and in the upper part of the atmosphere (between 400 hPa and 200 hPa) in assimilating the FIR radiometer over AIRS for humidity

For more information: Coursol, Laurence, et al. "Optimal Configuration of a Far-Infrared Radiometer to Study the Arctic Winter Atmosphere." *Journal of Geophysical Research: Atmospheres* 125.14 (2020): e2019JD031773.