Assimilation of IASI & CrIS sounder for O_3 & CO in MOCAGE CTM

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1) The MOCAGE Chemistry Transport Model (CTM) at Météo-France

- **Main processes** : Meteorological forcing, Sources, Transformations, Transport, Sinks
- **Chemical schemes** : REPROBUS (stratosphere) [**Lefevre et al., 1994**], RACM (troposphere) [**Stockwell et al., 1997**]
- **MOCAGE simulations** : 118 gaseous species, 434 chemical reactions, primary aerosols, secondary inorganic aerosols

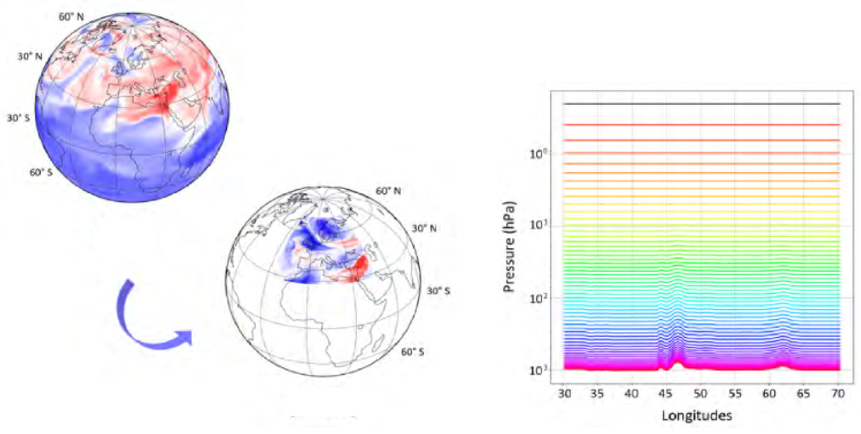

Fig.1 Illustration of the MOCAGE global model at 0.5° (GLOB05) and regional model at 0.1° (MACC01) and representation of the 60 hybrid pressure levels. [by Vittorioso, 2023]

2) Atmospheric composition enhancement methods

- **Modeling** :
  - → Reduced horizontal and vertical resolution
  - → Process improvement
  - → Use of new emission registers
- **Data assimilation** :

  Assimilation of conventional or remote sensing observations
  What does MOCAGE currently assimilate?

  - → AOD MODIS (L2)
  - → AOD VIIRS (L2)
  - → SO_2 TROPOMI (L2)
- **Objective** :
  - → Assimilate radiances (L1) for ozone (O_3) and carbon monoxide (CO) field enhancement in MOCAGE CTM
  - → IASI & CrIS infrared sounders

3) IASI and CrIS

- IASI and CrIS are respectively on board the polar satellites (Metop-B and C) and (NOAA-20 and 21)
- IASI is sensitive in the infrared between 645 and 2760 cm^{-1} (8461 channels) with a spectral resolution of 0.5 cm^{-1}
- CrIS-FSR is sensitive in the infrared between 650–1095, 1210–1750 and 2155-2550 cm^{-1} (2211 channels) with a spectral resolution of 0.625 cm^{-1}
- Channels currently available in operational selections :
  - → IASI : 15 channels sensitive to ozone
  - → CrIS : 35 channels sensitive to ozone and 5 channels sensitive to carbon dioxide

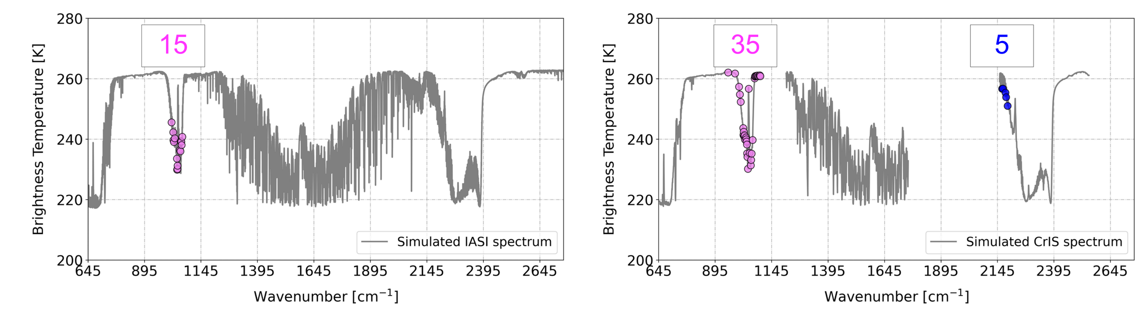

Fig.2 Typical spectrum at 280 K for IASI (left) and CrIS (right) with channel selections for O_3 (violet) and CO (blue)

4) Sensitivity of the observations

- Jacobians Represents the sensitivity of observations to a geophysical parameter in the atmosphere, here O_3 and CO
- Ozone-sensitive channels are mainly sensitive in the troposphere and middle stratosphere, and carbon monoxide-sensitive channels are sensitive in the troposphere.

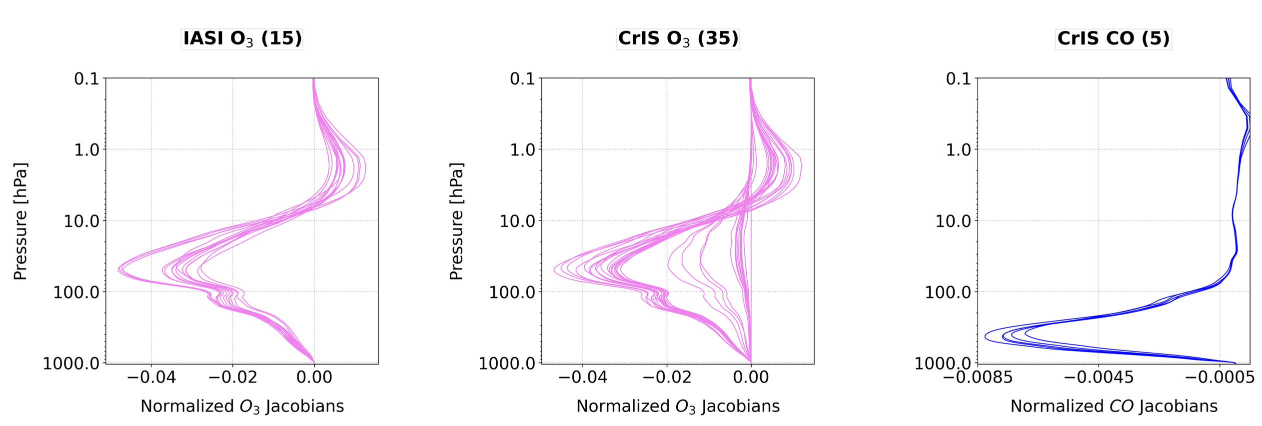

Fig.3 Normalized jacobians for 15 IASI ozone-sensitive channels (left), 35 CrIS ozone-sensitive channels (middle) and 5 carbon monoxide-sensitive channels (right)

5) 3D-Var assimilation experiment in MOCAGE

Period	05/2023 → 04/2024
Model	MOCAGE global (0.5 °)
Instruments	IASI + CrIS
Channels	IASI O3 (15), IASI Tskin (1), CrIS O3 (35), CrIS CO (5), CrIS Tskin (1)
Bias correction	NO
Control variable	O3, CO and Tskin
Tskin retrieved	YES
B errors	Estimated background error covariance matrix
R errors	Diagnosed observation error covariance matrix
Thinning	Only over sea and clear sky condition

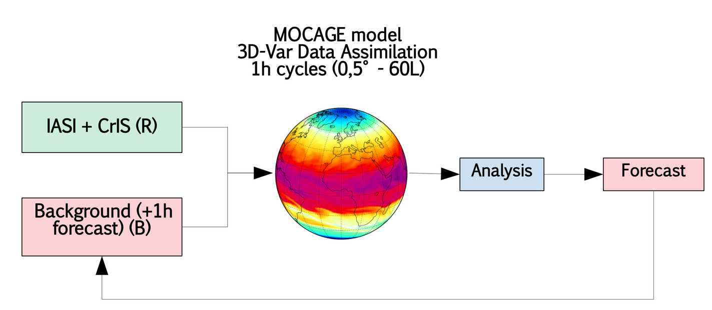

Fig.4 Scheme of the 3D-Var data assimilation experiment in MOCAGE

6) Background error covariance matrix

- In order to be as accurate as possible for the data assimilation system, we chose to use background error covariance matrices including vertical correlations for ozone and carbon monoxide. These matrices were estimated using the NMC method on one year's data and calculated using the forecast difference (+36h - +12h).

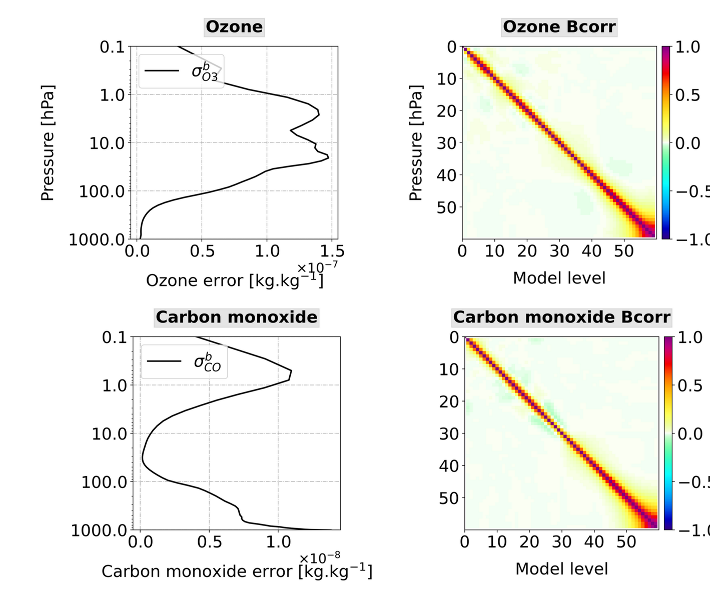

Fig.5 Background error standard deviation of ozone on the atmospheric vertical (pressure) and associated vertical error correlations (levels) (top) and same for carbon monoxide (bottom).

7) Observation error covariance matrix

- Observation errors were diagnosed using the so-called top-down method, based on an initial assimilation experiment using a fixed observation error value, then at the end of this experiment, a [Desroziers, G., (2005), https://doi.org/10.1256/qj.05.108] diagnosis was performed. These diagnosed errors are then used in turn in a new assimilation experiment, and so on until convergence is achieved.
- Observation error standard deviation values are highly variable for O_3 channels, with strong correlations, whereas for CO channels the values are very low.

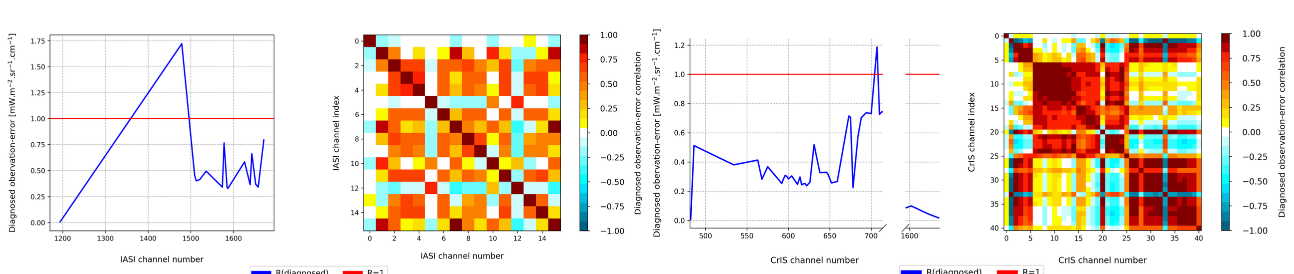

Fig.6 Diagnosed observation error standard deviation (blue) and associated error correlation for IASI (left) and the same for CrIS (right)

8) Scores wrt. radiosondes for O_3

- Forecast scores between the MOCAGE experiment without and with assimilation of IASI and CrIS wrt. to ozone radiosondes for the summer period (June 01 to August 31, 2023) and the winter period (December 12, 2023 to February 29, 2024). Here, we show the statistics in the form of CRMSE (Centered Root Mean Squared Error), which represents the RMSE minus the bias error. These experiments have not yet included variational bias correction.

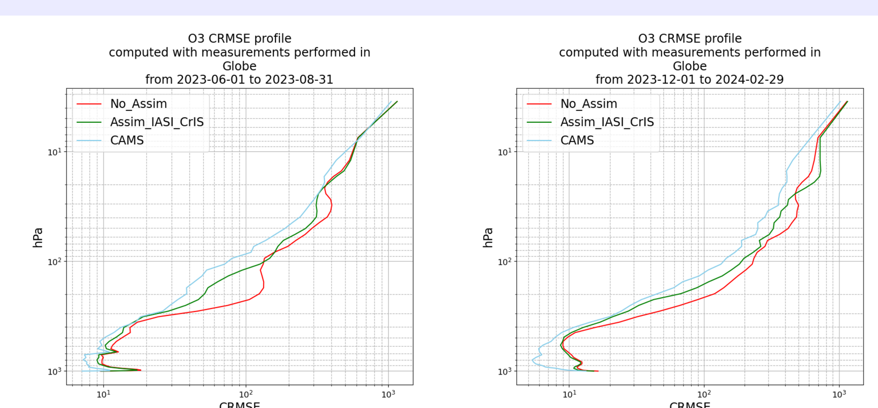

Fig.7 CRMSE on the globe for experiments without assim (red) with assim (green) and for CAMS (blue) wrt. ozonesondes for 3 summer months (left) and 3 winter months (right).

9) Temporal scores wrt. OMI for O_3 total column

- Same scores as in section 8, but in temporal evolution and wrt. level 2 products from the OMI (Ozone Monitoring Instrument), for the 3 experiments and the two periods.
- Assimilation of the ozone-sensitive IASI and CrIS channels significantly reduces the CRMSE with respect to the MOCAGE experiment without assimilation. We also note that the improvement is stable over time, and this error reduction is close to the values obtained from CAMS forecasts.

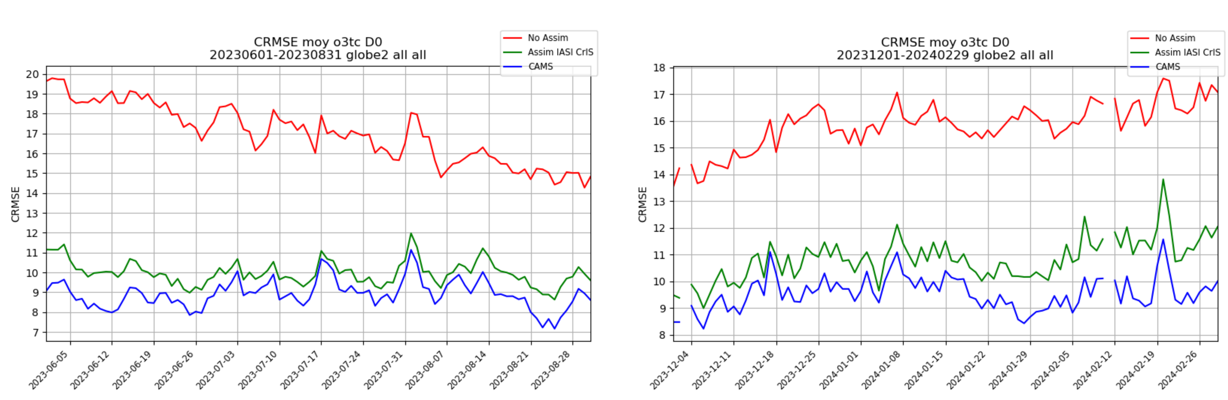

Fig.8 Temporal CRMSE on the globe for experiments without assim (red) with assim (green) and for CAMS (blue) wrt. OMI ozone total column for 3 summer months (left) and 3 winter months (right).

10) Map scores wrt. OMI for O_3 total column

- Same scores as in section 9 but in map representation.
- Assimilation of the ozone-sensitive IASI and CrIS channels reduces the CRMSE compared with the MOCAGE experiment without assimilation, mainly in the tropics and mid-latitudes over the 2 study periods. We also note that CRMSE values with assimilation are close to CAMS values.

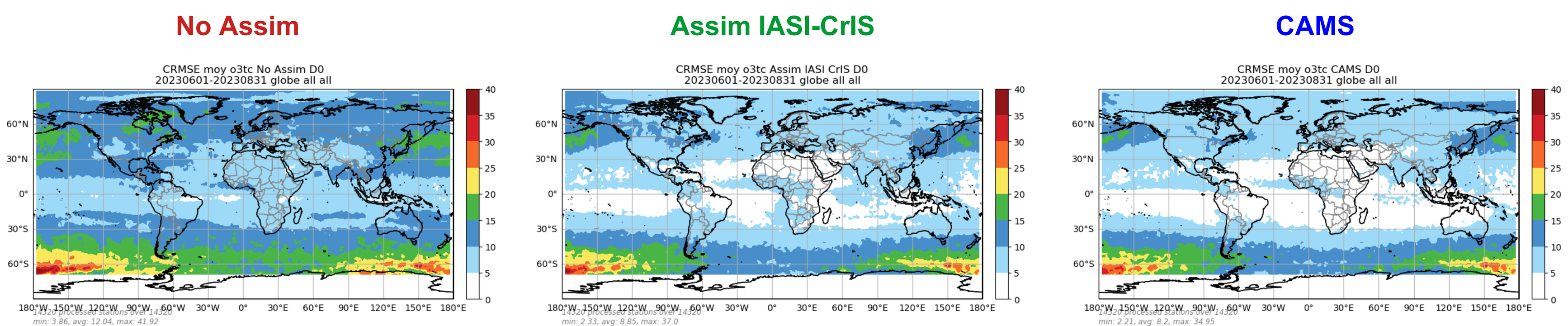

Fig.8 Representation of the CRMSE for ozone total column for experiments without assim (left) with assim (middle) and for CAMS (right) for 3 summer months.

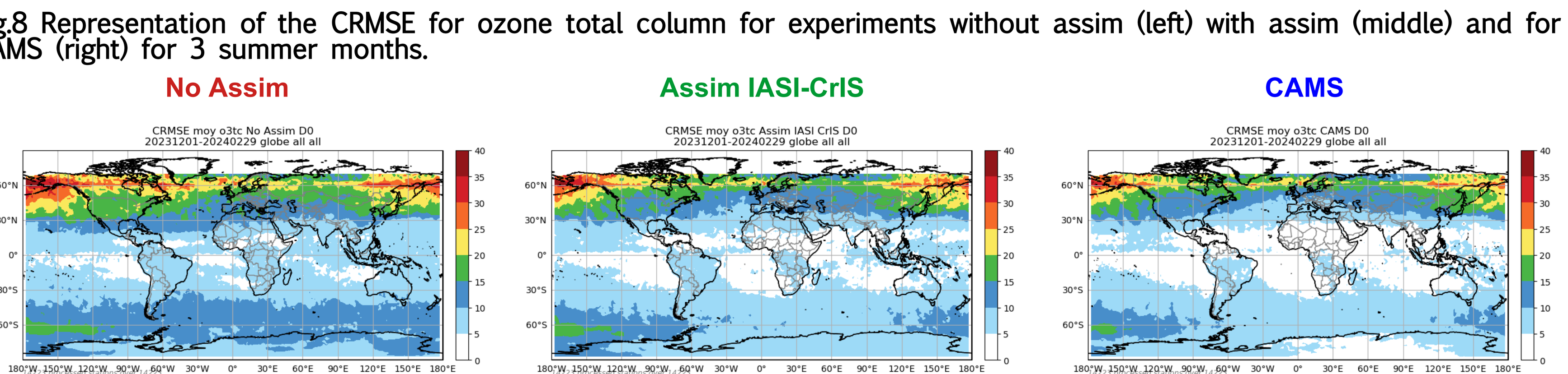

Fig.9 Representation of the CRMSE for ozone total column for experiments without assim (left) with assim (middle) and for CAMS (right) for 3 winter months.

11) O_3 & CO forecast scores

- These Figures show the forecast error reduction (RMSE) by latitudinal slice (at 0° longitude) for ozone and carbon monoxide from the CTL and IASI-CrIS assimilation experiments compared with CAMS forecasts for the summer period (JJA).
- We note that assimilation of the ozone-sensitive IASI-CrIS channels reduces the ozone forecast error of MOCAGE (using CAMS fields as reference) compared with the control experiment, mainly in the troposphere and stratosphere up to 30 hPa.
- In the same lighter vein, the assimilation of CO-sensitive CrIS channels has enabled us to get closer to the CAMS forecasts, mainly in the troposphere in the northern hemisphere, using only 5 channels, which represents a positive impact with so few observations. Similar results were obtained for the winter period.

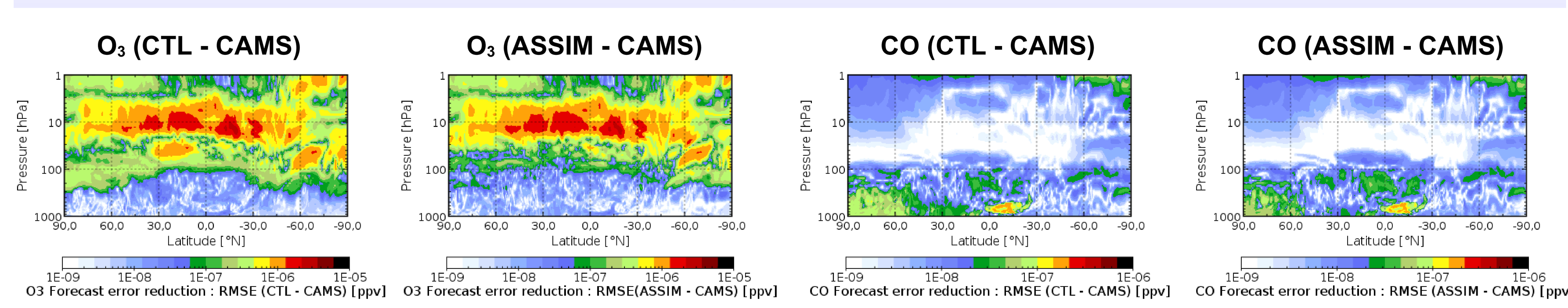

Fig.10 Forecast error reduction (RMSE) on the atmospheric vertical as a function of latitude (at 0° longitude) for the 3 months of summer period (JJA) for the ozone (left) and carbon monoxide (right) fields of the control experiment and the IASI-CrIS assimilation experiment compared with the CAMS forecasts.

12) O_3 & CO forecast error reduction

- The figures below show the forecast scores for ozone (left) and carbon monoxide (right) on the atmospheric vertical as a function of the forecast range up to +24h for the summer period (JJA). These are RMSEs of the relative differences between the CTL and ASSIM experiments compared with the CAMS reference field. Blue isolines indicate a positive impact of IASI-CrIS assimilation, red indicates a negative impact, grey a neutral impact, and yellow indicates the significance of these results at 95%.
- IASI-CrIS assimilation has significantly improved ozone forecasts up to +24h between 700 and 30 hPa, with error reductions of up to 72%. We also note that assimilation of the 5 CrIS channels improves CO fields, also over all forecasting ranges in the troposphere from the surface down to 400 hPa, with reductions of up to 21%. Negative impacts on forecasts are mainly due to the lack of assimilated observations in these atmospheric regions, and certainly to the failure to correct observation biases.

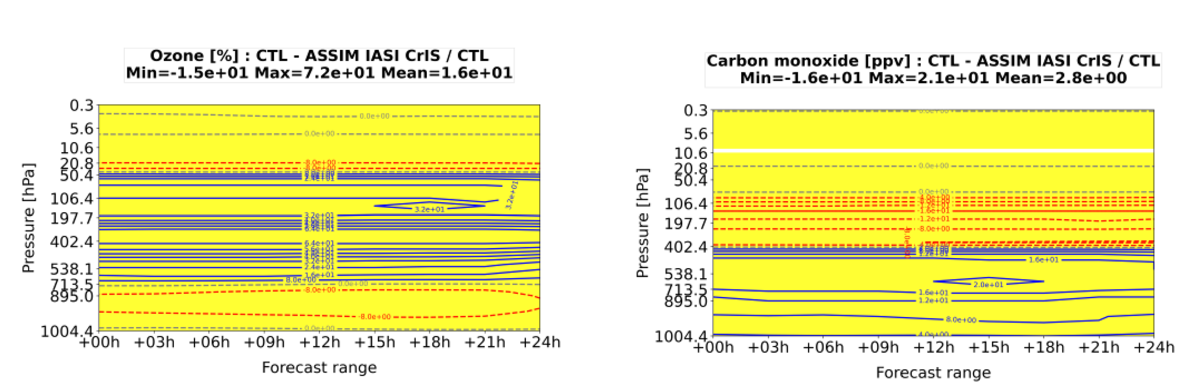

Fig.11 Forecast scores for ozone (left) and carbon monoxide (right) over the summer period. The graphs represent the reduction in forecast error (RMSE) of the relative differences between the two experiments compared with the CAMS forecasts.

13) Conclusions

- For the first time, we tested the direct assimilation of radiances (15 IASI channels for O_3, 35 CrIS channels for O_3 and 5 CrIS channels for CO) in the global chemistry transport model MOCAGE at Météo-France.
- These experiments carried out over more than one year (2023 - 2024) showed significant improvements in ozone and carbon monoxide forecasts compared to independent data (ozonesondes, OMI total ozone column) over a summer and winter period. These results were also compared to the MLS product (O_3 and CO) and IAGOS observations (not shown here).
- Additionally, comparisons were made using forecasts from CAMS as a reference model and also show significant improvements in the MOCAGE ozone (up to 72%) and carbon monoxide (up to 21%) fields.
- A new version of the MOCAGE global model including the assimilation of these IASI and CrIS radiances became operational at the beginning of November 2024.

14) Future prospects

- Requests are underway to have real-time access to more IASI and CrIS channels sensitive to ozone and carbon monoxide.
- A similar experiment is being evaluated for the MOCAGE regional model.
- Work to add variational bias correction to the 3D-Var MOCAGE assimilation system is currently being considered.
- In order to enrich the assimilation for ozone and carbon monoxide mainly in atmospheric levels not sensitive to radiances, we are evaluating the possibility of combining with the assimilation of radiances, the use of geophysical product (UV and Visible).
- An article on this study is being written.