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Assimilation of IASI radiances in the MOCAGE CTM to improve dusts fields

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1) Desert aerosols

- Dusts are primary aerosols, emitted directly into the atmosphere, driven mainly by wind saltation. The main places of emission are deserts (Figure 1), and the diameters of these dusts range from 0.2 to 20 μm .
- Good forecast of dust fields is important for weather and climate, with direct and indirect effects on radiative impact. Also for human activities, with effects on air quality, energy and civil aviation.
- To model aerosol fields, chemistry transport models (CTM) such as MOCAGE at Météo-France are used.

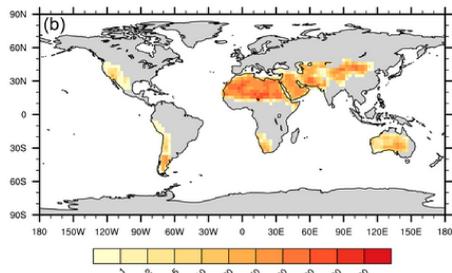


Fig.1 Annual desert aerosol emissions (2020) [Beer, 2020, <https://doi.org/10.5194/gmd-13-4287-2020>]

2) MOCAGE CTM

- In this study, we use the global MOCAGE CTM, which represents the processes of emission, transport, transformation and sedimentation. It models gases and different types of aerosols with a horizontal resolution of $0.5^\circ \times 0.5^\circ$ and a vertical resolution of 60 levels from the surface to 0.1 hPa. Aerosols are represented by 6 size groups (bins).
- CTMs can provide realistic fields of desert aerosols in the atmosphere, but there are limits to the accuracy of forecasts. The assimilation of satellite observations could improve the representation of dusts.

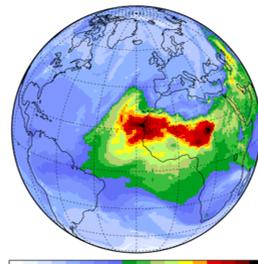


Fig.2 Total dust column on January 24, 2024 at 12 UTC

1) The IASI instrument

- The IASI instrument needs no introduction! It has enabled us to make major advances not only in Numerical Weather Prediction, but also in atmospheric composition and climate monitoring. Currently aboard Metop-B and C, it continues to provide us with a huge quantity of observations essential to atmospheric science. In addition to gases, it is also sensitive to desert aerosols in atmospheric windows. Currently, IASI observations are used to generate geophysical products of desert aerosol fields, but no model directly assimilates IASI radiances to analyze dusts.
- This is the subject of this study, carried out as part of an internship supported by a PNTS project.

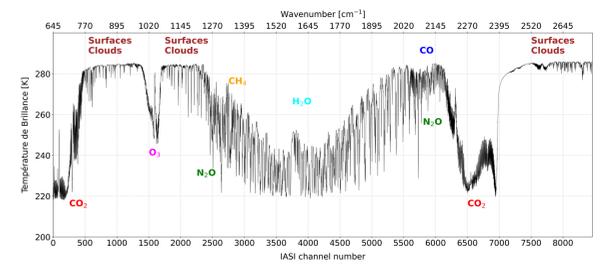


Fig.3 IASI brightness temperature spectrum

4) Objectives

- Currently, only total Aerosol Optical Depth products (L2 MODIS & VIIRS at 550 nm) are assimilated into the MOCAGE 3D-Var system. The aim of this study was to prepare for the assimilation of IASI radiances into the MOCAGE global ($0.5^\circ - 60\text{L}$) chemistry transport model in order to improve dust fields.
- To achieve this, a sensitivity analysis and selection of dust sensitive channels was carried out. Tools were then implemented in the model to identify IASI pixels contaminated by desert aerosols. Finally, assimilation experiments were performed and the results compared with independent data and geophysical products.
- The study period is around January 24 and 25, 2024, when a strong advection of dust from West Africa over the Atlantic Ocean reached Europe.

5) Channel selection by sensitivity analysis

- The aim is to identify the IASI channels most sensitive to dusts in the atmospheric window, excluding channels sensitive to ozone and water vapour.
- We used the method using the radiative transfer model RTTOV which consists in evaluating the brightness temperature response ΔBT to a perturbation for each atmospheric constituent separately (O_3 , H_2O & dusts).
- Typical perturbations:
 - $\text{O}_3 \rightarrow 10\%$
 - $\text{H}_2\text{O} \rightarrow 10\%$
 - Dusts \rightarrow with and without vertical profiles
- Figure 5 shows the average brightness temperature differences over 2365 pixels in and around the aerosol plume. For ozone (red), water vapour (blue) and desert aerosols (green).
- This sensitivity analysis using RTTOV allows us to select 196 channels sensitive to dusts (in yellow).

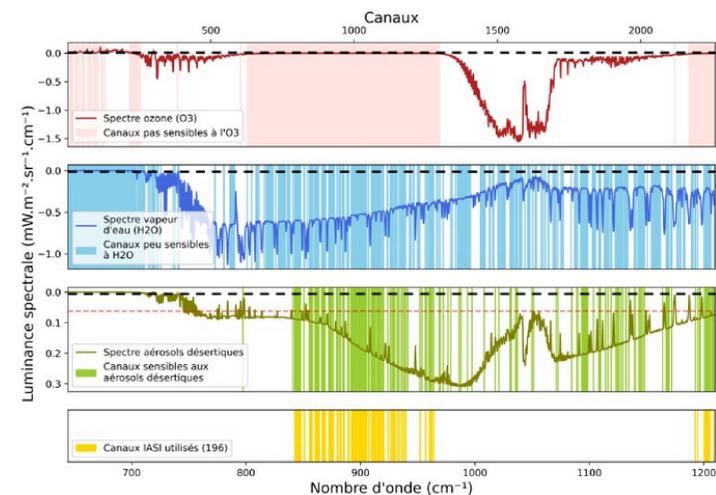


Fig.5 Differences in IASI brightness temperatures between raw and perturbed simulations for O_3 (red), H_2O (blue), Dusts (green) and channel selection (yellow) over 2365 pixels.

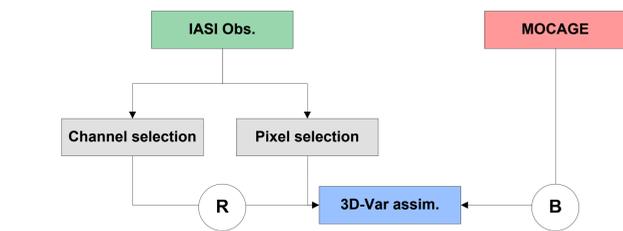


Fig.4 Scheme of this study

6) Selecting pixels for assimilation

- For assimilation, a test on IASI pixels must be carried out to identify pixels contaminated by clouds and desert aerosols. To identify desert aerosols in the pixels, we used the dust-index, which provides a value per radiance difference between 4 dust-sensitive channels on either side of the typical "V" signature in the atmospheric window. An empirical threshold (0,75) on this value gives an initial indication of the presence or absence of desert aerosols.
- For clouds, we use the AVHRR instrument, which provides information on the percentage of cloud contamination of an IASI pixel. However, we have found that AVHRR can identify aerosols for clouds, which drastically reduces the number of pixels required for assimilation.
- To precisely identify dust-contaminated IASI pixels, we used the CADS algorithm (NWPSAF) to determine whether pixels contain desert aerosols (on land or at sea), volcanic ash and unclassifiable aerosols.
- As can be seen in Figure 6, using these 3 tests for the night of January 25, 2024 identified 84% of cloudy pixels (in grey), 15% of clear pixels (in red) and only 1% of dusty pixels (in yellow). For the assimilation experiment, only clear and dusty pixels will be assimilated.

$$\text{Dust-Index} = [\text{Tb}(737) - \text{Tb}(1311)] - [\text{Tb}(2231) - \text{Tb}(1805)]$$

From [El Aabariboune, 2022] Thesis

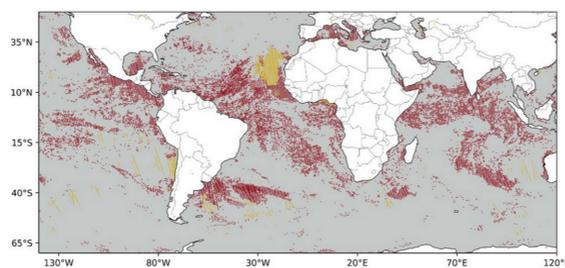


Fig.6 Map of IASI pixels identified as cloudy (grey), clear (red) and dusty (yellow) for the night of January 25, 2024, using the 3 tests: AVHRR, dust index and CADS.

7) IASI observation errors

- Multiple assimilation experiments were specifically carried out to diagnose the observation errors of the 196 channels selected up to convergence. In Figure 7, observation error standard deviations and correlation matrices have been separated using all data (clear and dusty), only clear and only dusty. In the following, only the R matrix with all data was used for the assimilation experiment.

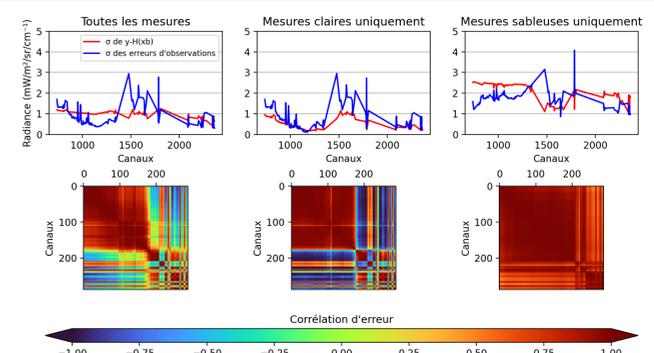


Fig.7 Standard deviations of First-Guess departures (in red) and diagnosed observation errors (in blue) (top) and correlation matrix (bottom) for all data (left), clear-sky (middle) and in dusty sky (right)

8) Summary of experimental set-up

XP	Assim. experiment
Period	2024-01-24 \rightarrow 2024-01-25
Obs. assimilated	196 IASI channels
Control variable	Dust (6 bins)
R error	Full & diagnosed R matrix
B error	Standard deviation background error for dust calculated from 30% of the profile
Verification	AEROIASI & LMD-AOD (AOD-Dust at 10 μm) VIIRS & MODIS (AOD at 550 nm)

- The geophysical product AEROIASI, produced by LISA, provides the vertical profile of the extinction coefficient and the AOD of the desert aerosols for each IASI observation in the absence of clouds [Cuesta et al. 2015, doi:10.1002/2014JD022406].
- The method developed at LMD to derive dust characteristics from IASI observations is a three-step algorithm based on a "Look-Up-Table" (LUT) approach [Capelle et al., 2014, doi:10.5194/acp-14-9343-2014]. The first step determines the atmospheric state observed; the second step determines simultaneously the 10 μm AOD and the aerosol layer mean altitude while the dust coarse mode effective radius is determined in the third step.

9) Results

- Figure 8 shows the MOCAGE AOD at 10 μm with and without assimilation compared to the AEROIASI and LMD-AOD products.
- We notice that our assimilation experiment makes it possible to increase the AOD concentration compared to the experiment without assimilation.
- We also notice differences between the 2 geophysical products, which marks a limit on these data as a source of verification.
- All of the scores including the comparison to MODIS and VIIRS are summarized in the table below. All of the comparisons show an improvement thanks to the assimilation of the 196 IASI channels for dusts.

Data	Correlation Without \rightarrow with assim.	Standard-deviation Without \rightarrow with assim.
VIIRS (AOD 550 nm)	0,82 \rightarrow 0,86	0,30 \rightarrow 0,28
MODIS (AOD 550 nm)	0,84 \rightarrow 0,88	0,40 \rightarrow 0,37
LMD-AOD (Dust-AOD 10 μm)	0,77 \rightarrow 0,81	0,13 \rightarrow 0,12
AEROIASI (Dust-AOD 10 μm)	0,80 \rightarrow 0,82	0,038 \rightarrow 0,037

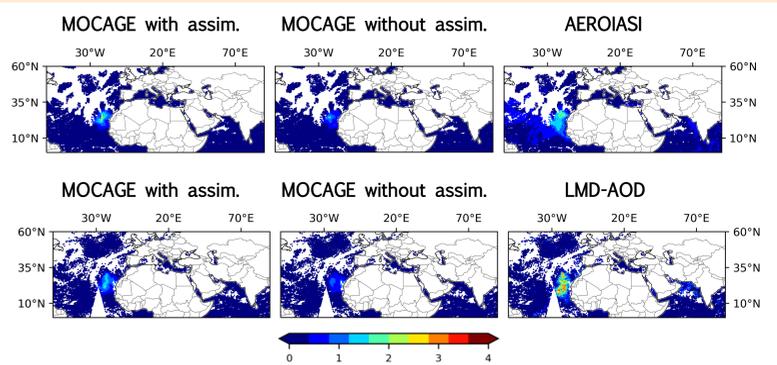


Fig.8 10 μm AOD from MOCAGE with (left) and without assimilation (middle), AEROIASI (top right) and LMD-AOD (bottom right) for 25 January 2024

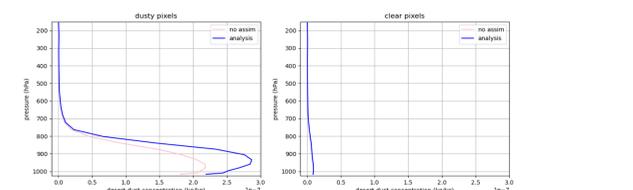


Fig.9 Average profiles of desert dust concentration, with no assimilation (pink) and IASI assimilation (blue), for dusty pixels (left) and clear pixels (right), for 25 January 2024

10) Conclusions

- Direct assimilation of IASI radiances in MOCAGE for the representation of desert aerosols seems to be a success because it allows to improve the correlation between MOCAGE and validation data (independent and from IASI). However, we saw that we were still very far from the measure (whether independent or not), except at some places where we exceed it

11) Perspectives

- In the short term: fine-tune the assimilation settings (ozone, T_{skin}), accurately estimate the dust background errors (NMC method), find the adequate control variable and carry out these experiments over a long period
- In the medium term: prepare for the arrival of the future infrared sounders IASI-NG and IRS. This work will be the subject of a PhD thesis that will begin at CNRM in October 2024.