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EUMETSAT

Evaluating the impact of the CMIM satellite constellation on NWP using an OSSE framework

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CNRM

cnes

CMIM Constellation

Constellation of MIni sounders for Meteorology

Phase 0 at CNES.

Objective → Improving short and medium range Numerical Weather Prediction (NWP) by 2030 – 2035.

Means → **Densifying temperature and water vapor observations in lower layers** of the atmosphere by **increasing revisits** of Infra-Red (IR) and/or Micro-Wave (MW) instruments.

Assessing NWP impact → Observing System Simulation Experiments, **OSSE methodology**.

CMIM Constellation

Baseline constellation architecture :

- 8 satellites with sun-synchronous orbits (SSO). 1 instrument per satellite.
- 4 orbital planes (2 sats/plane), altitude : 630km
- **Revisit time 3H30** between latitudes 35° to 60° (95% of cases)

3 CMIM reference scenarios :

1. CMIM-IR : 1 IR hyperspectral sounder per satellite
2. CMIM-MW High-Frequency (HF) : SAPHIR-like instrument, 6 channels centered around 183GHz, sensitive to water vapour (HU)
3. CMIM-MW Low-Frequency (LF) : 8 channels, more sensitive to the surface. 3 temperature channels (54GHz), 1 HU channel (22GHz)

OSSE Framework

OSSE = replica of a NWP system, but entirely simulated.

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ARPEGE Nature Run

OSSE Framework

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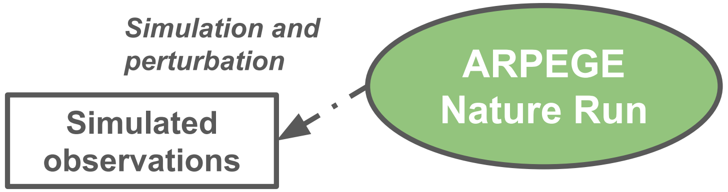
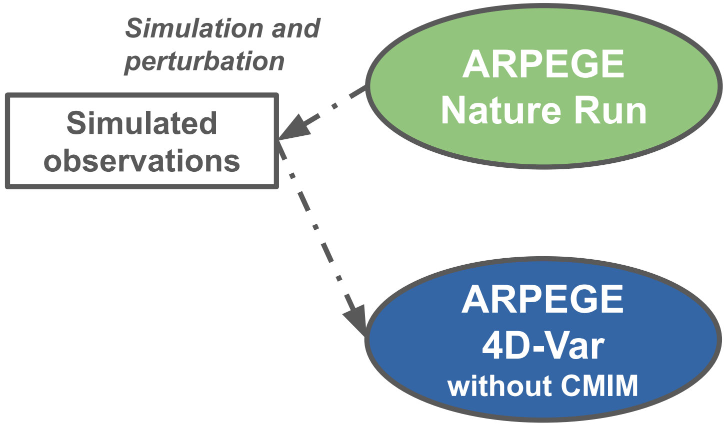


OSSE Framework

OSSE = replica of a NWP system, but entirely simulated.



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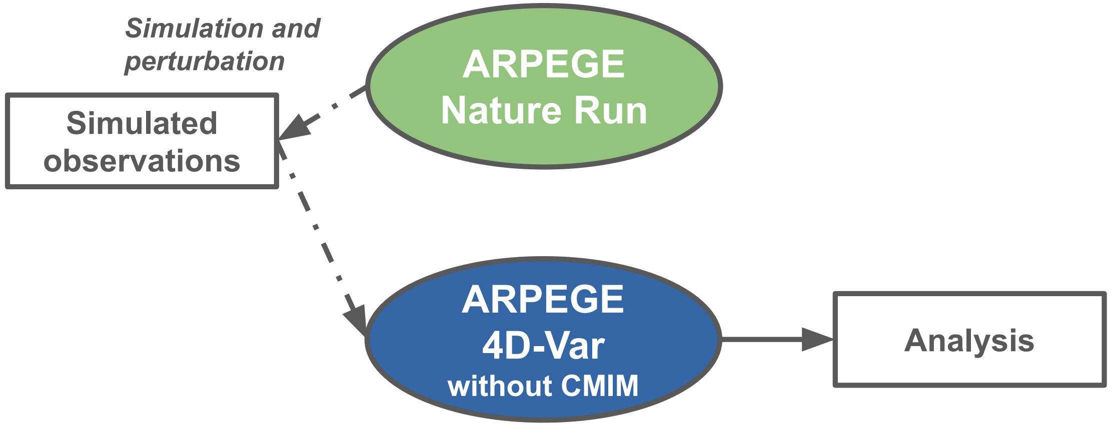

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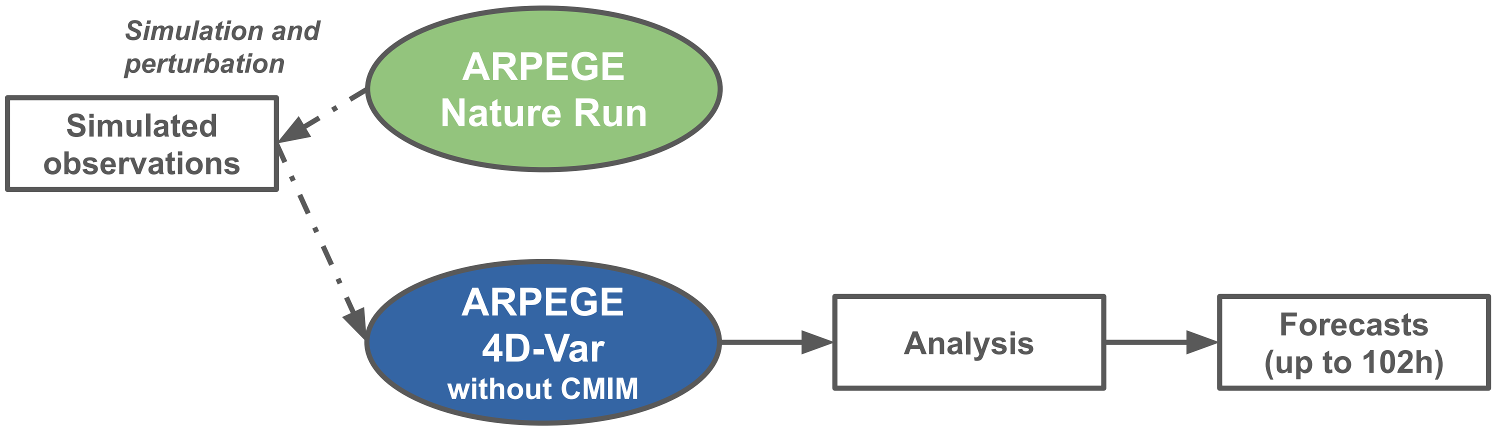

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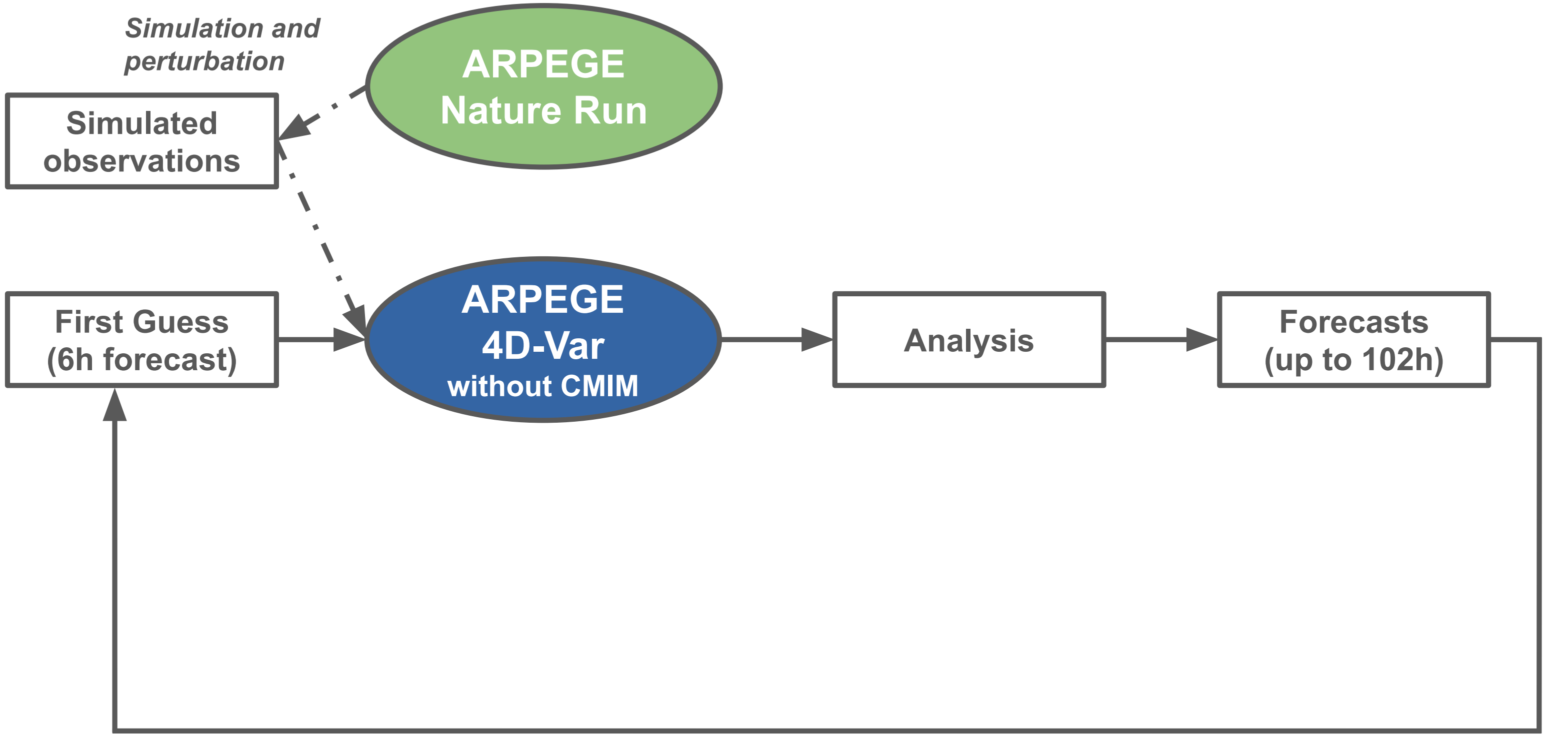

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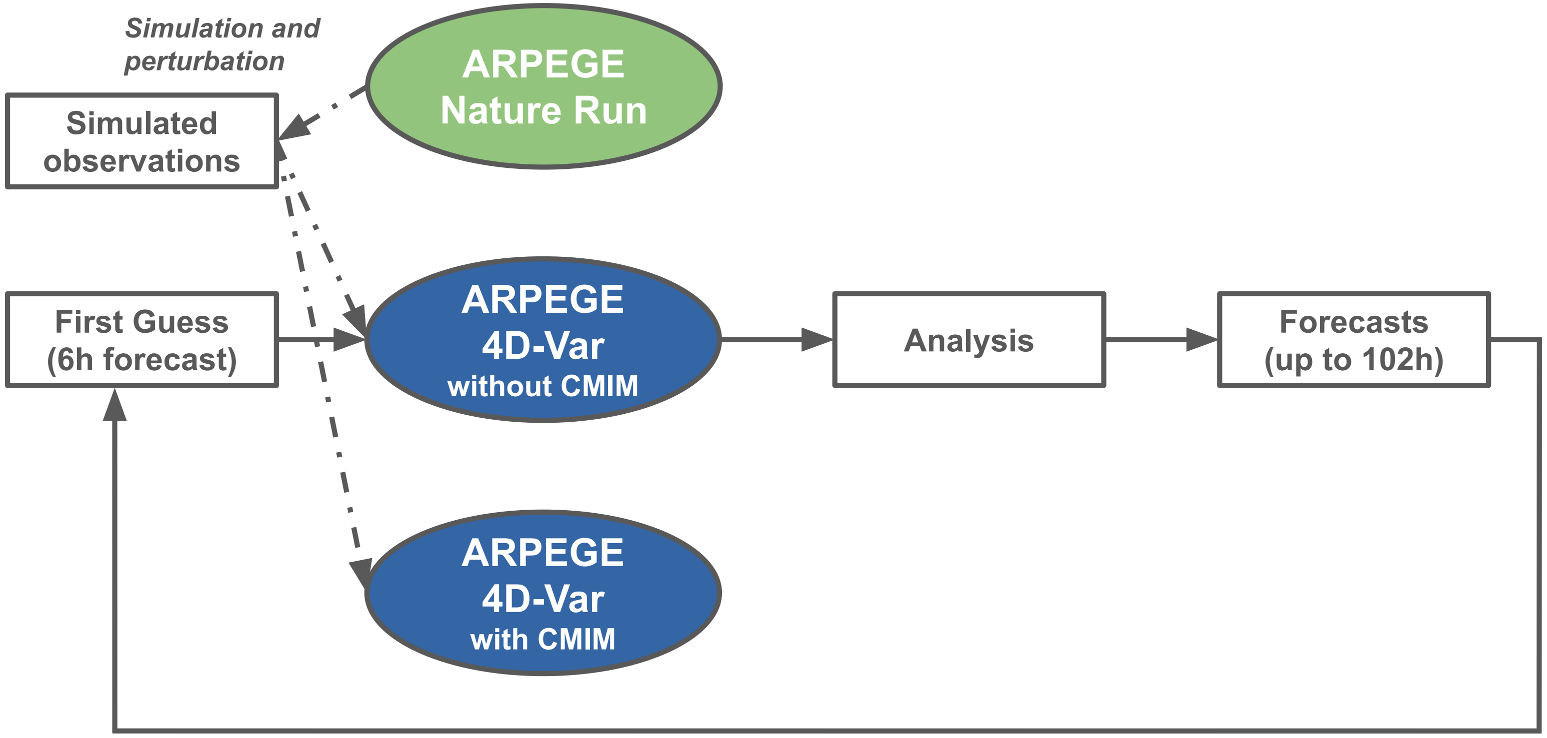

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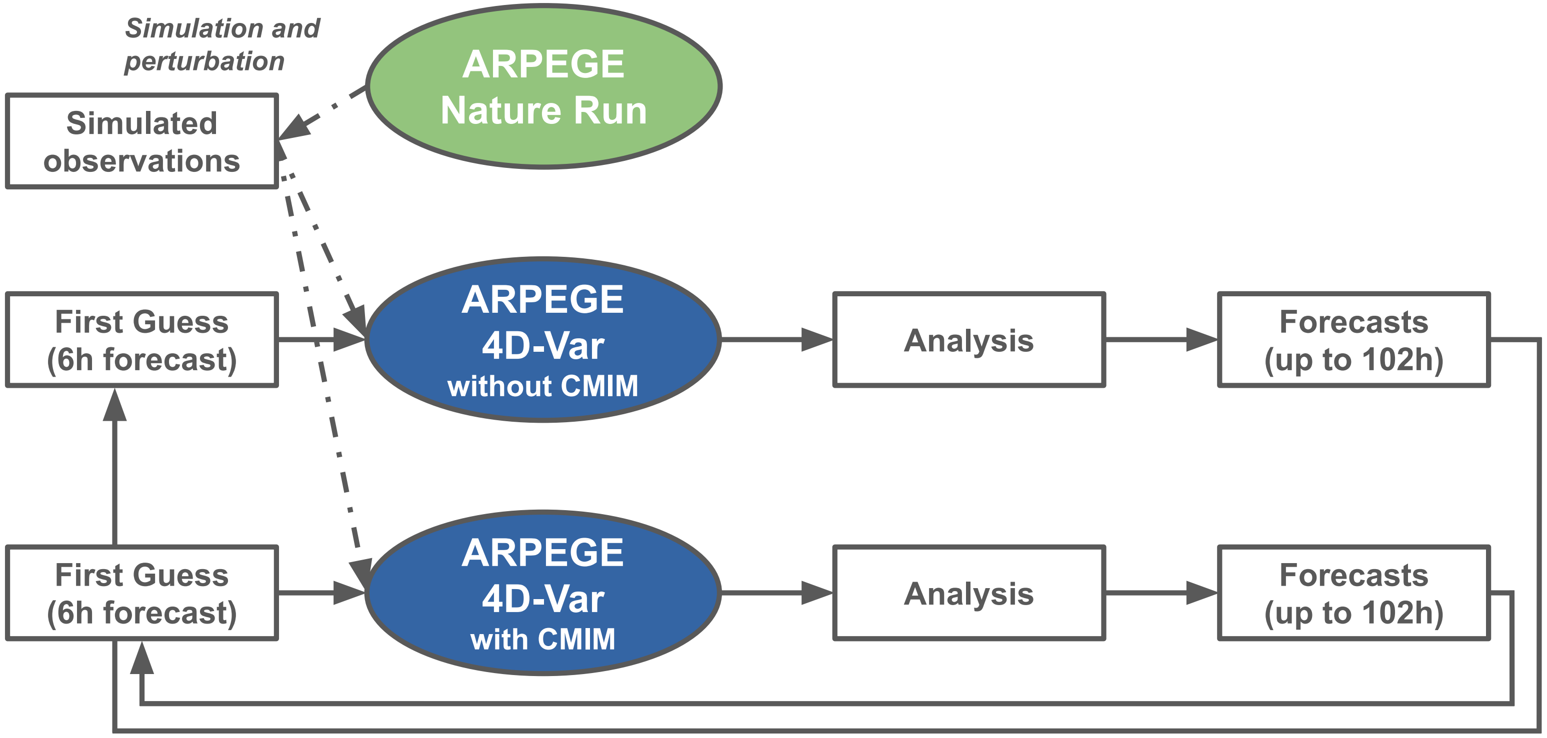

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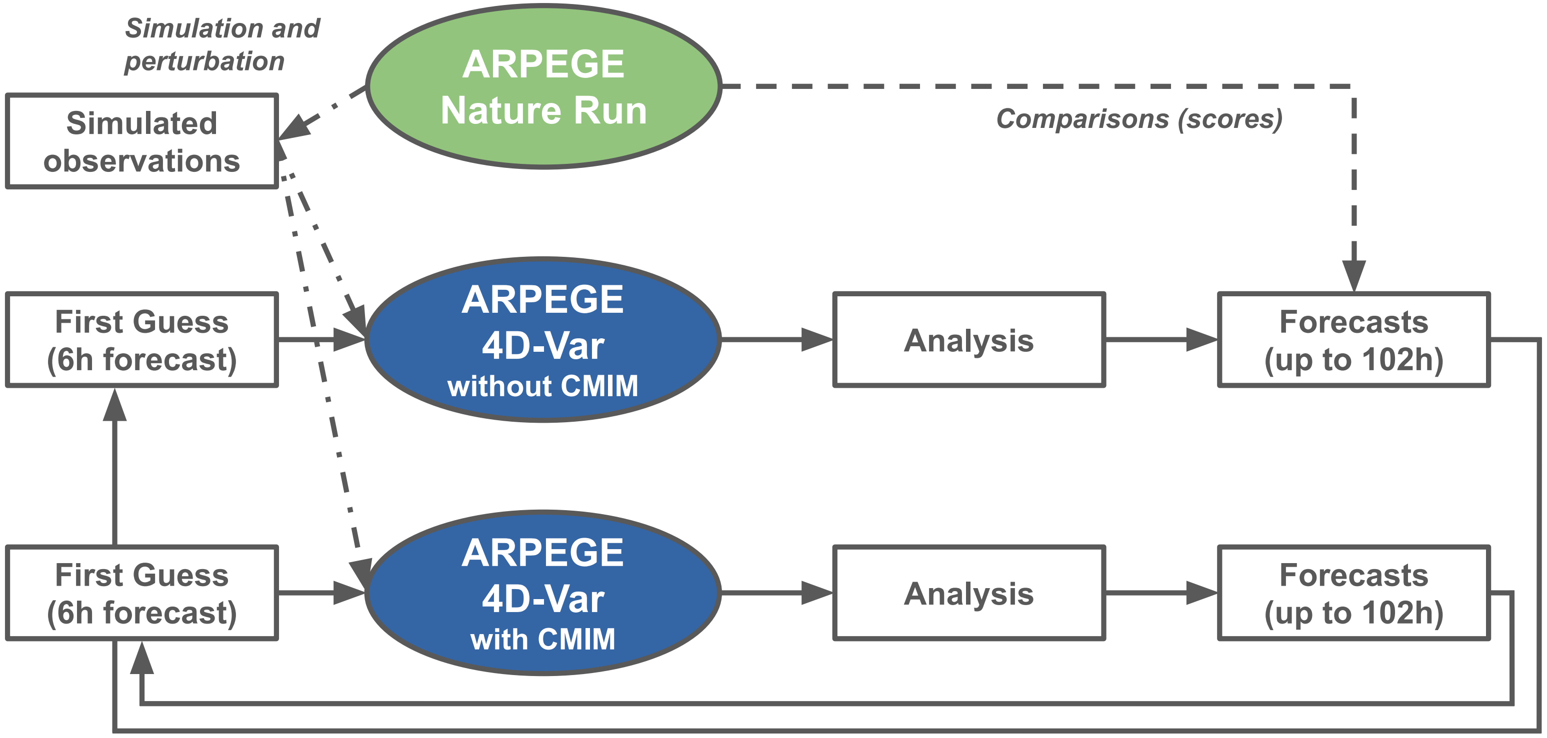

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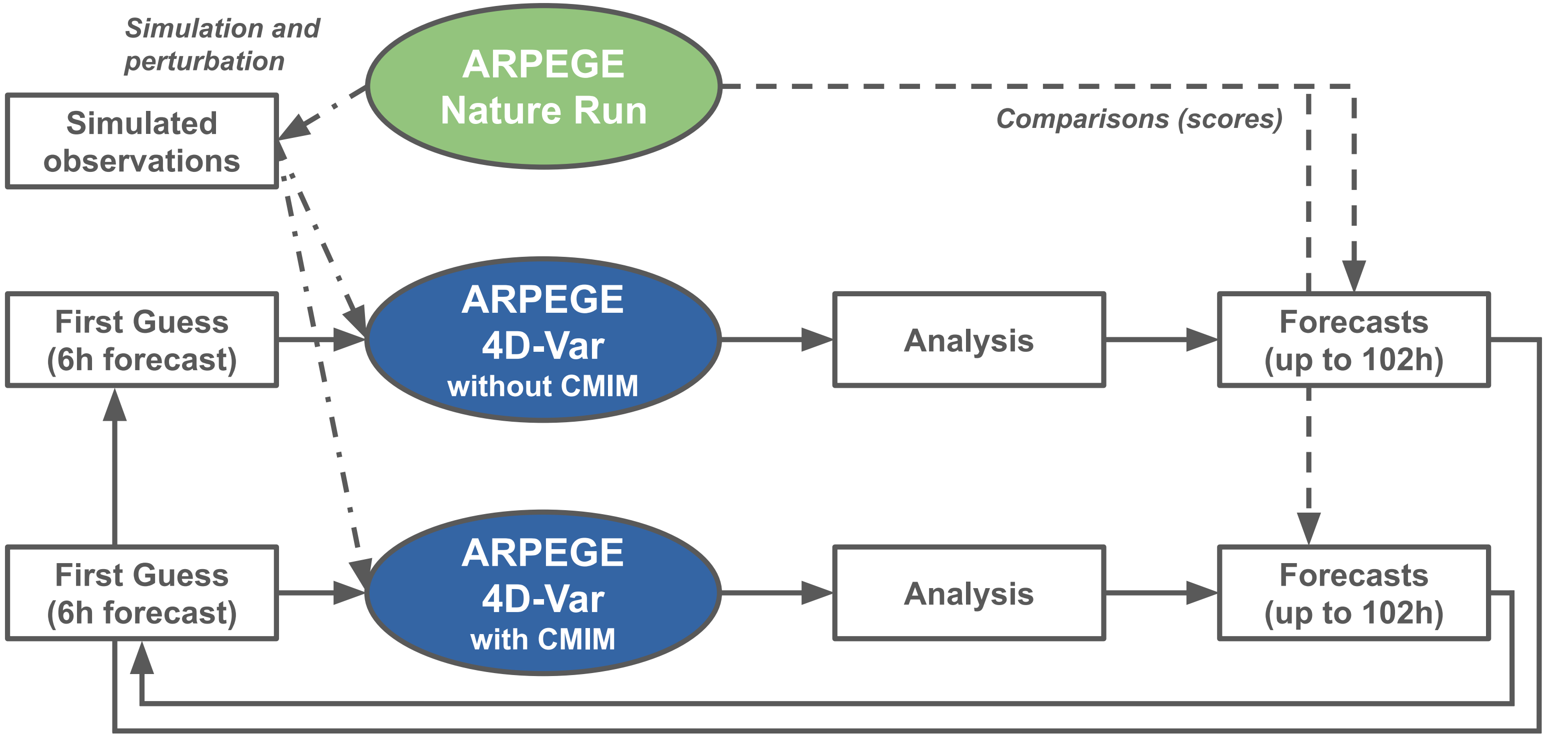

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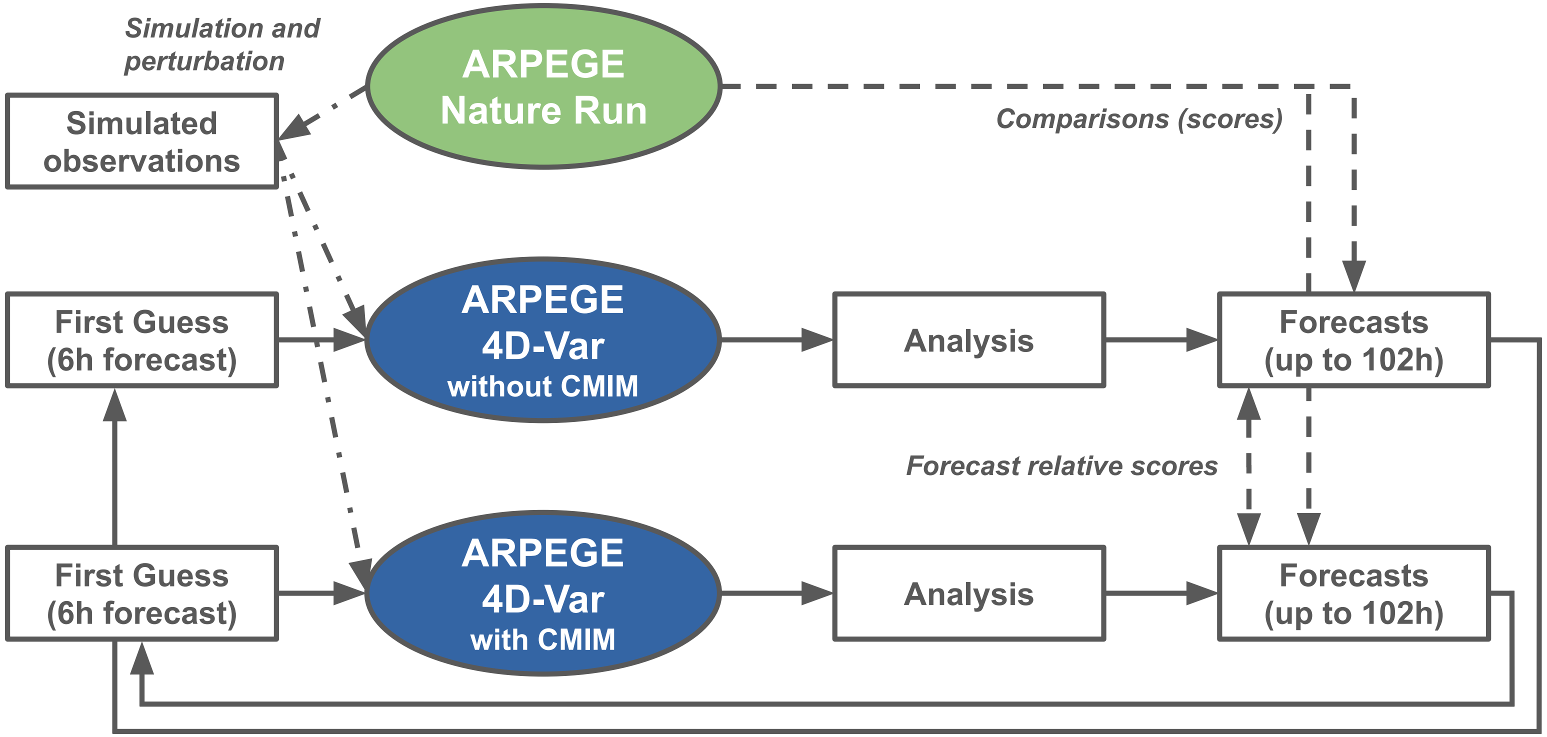


Figure 1. Description of the framework of the OSSE, with and without the CMIM constellation

Infrared Scenario
Presentation

CMIM-IR reference scenario :

- 1 IR instrument per sat, 8 total
- Pixel resolution : between 3 and 8km
- Spectral resolution : ~1cm^{-1}
- NeΔT CMIM = 3 x NeΔT IASI
- 113 assimilated channels (85 in B1, 28 in B2). 200 channels for cloud detection.

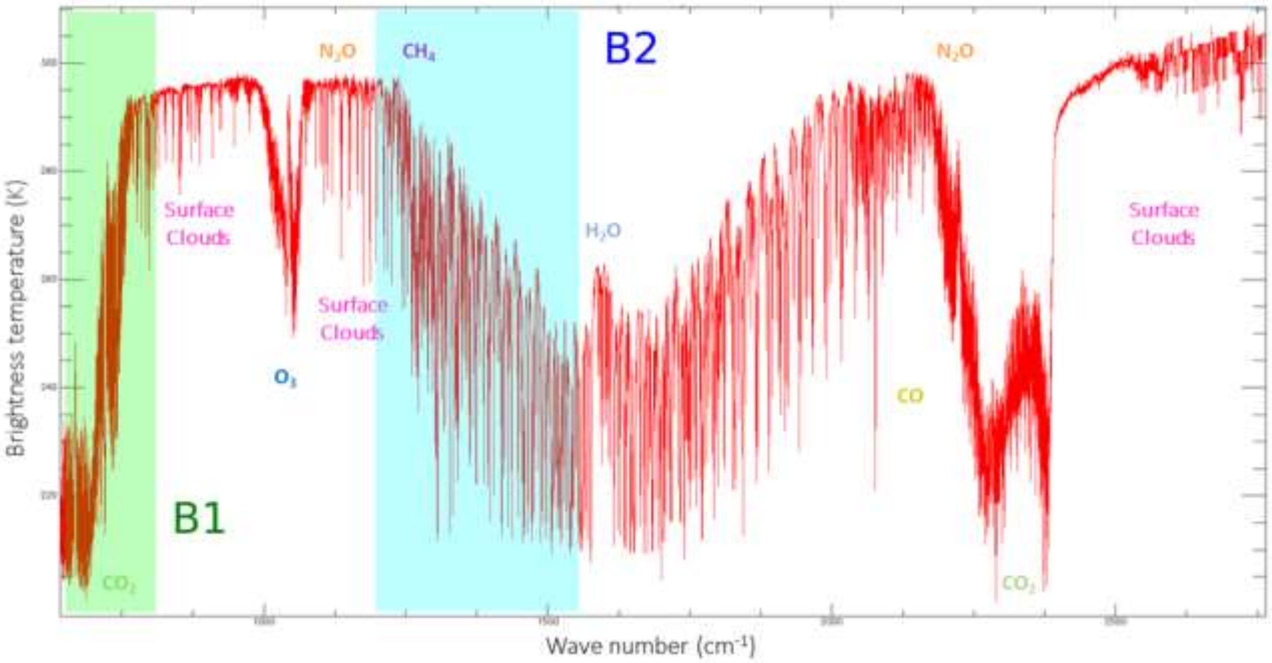


Figure 2. Spectrum produced by IASI aboard Metop-C, generated on 12/12/2018. The green frame represents the spectral band B1 = [645, 800] cm^{-1} and the blue frame the spectral band B2 = [1200, 1550] cm^{-1} of CMIM-IR. Source : EUMETSAT (2018)

Infrared Scenario

Scores (146 days, Aug 21 to Feb 22)

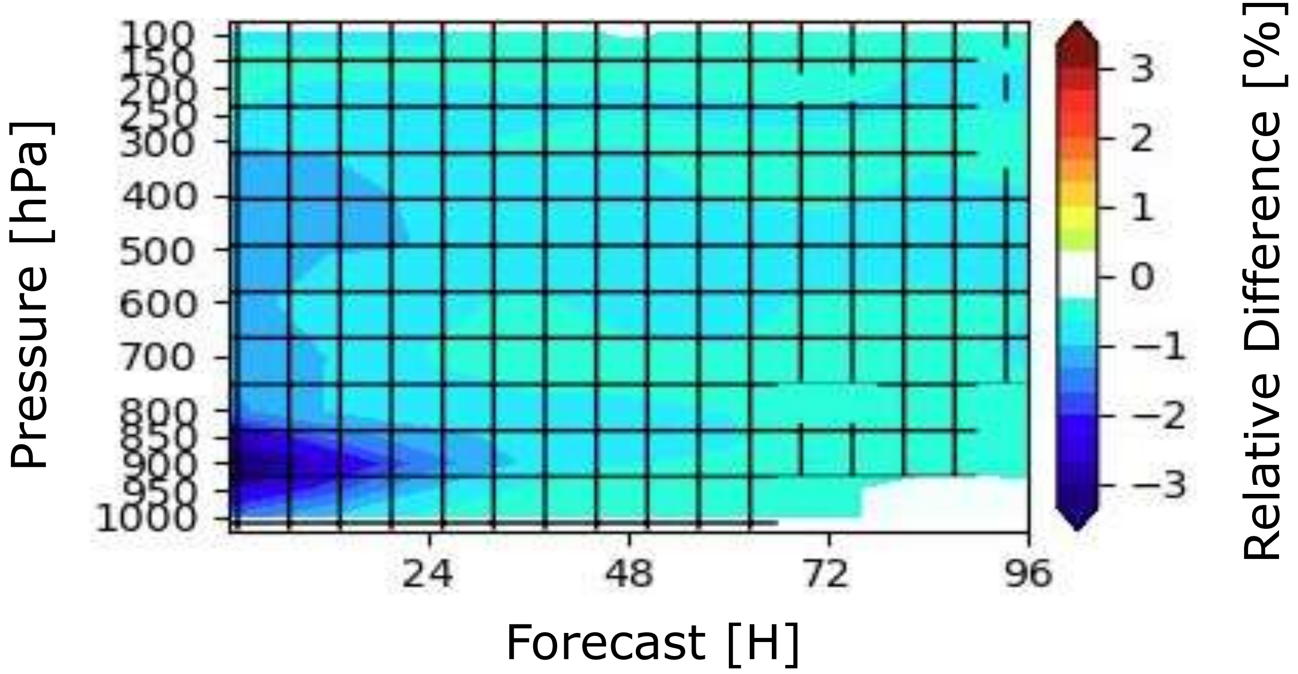
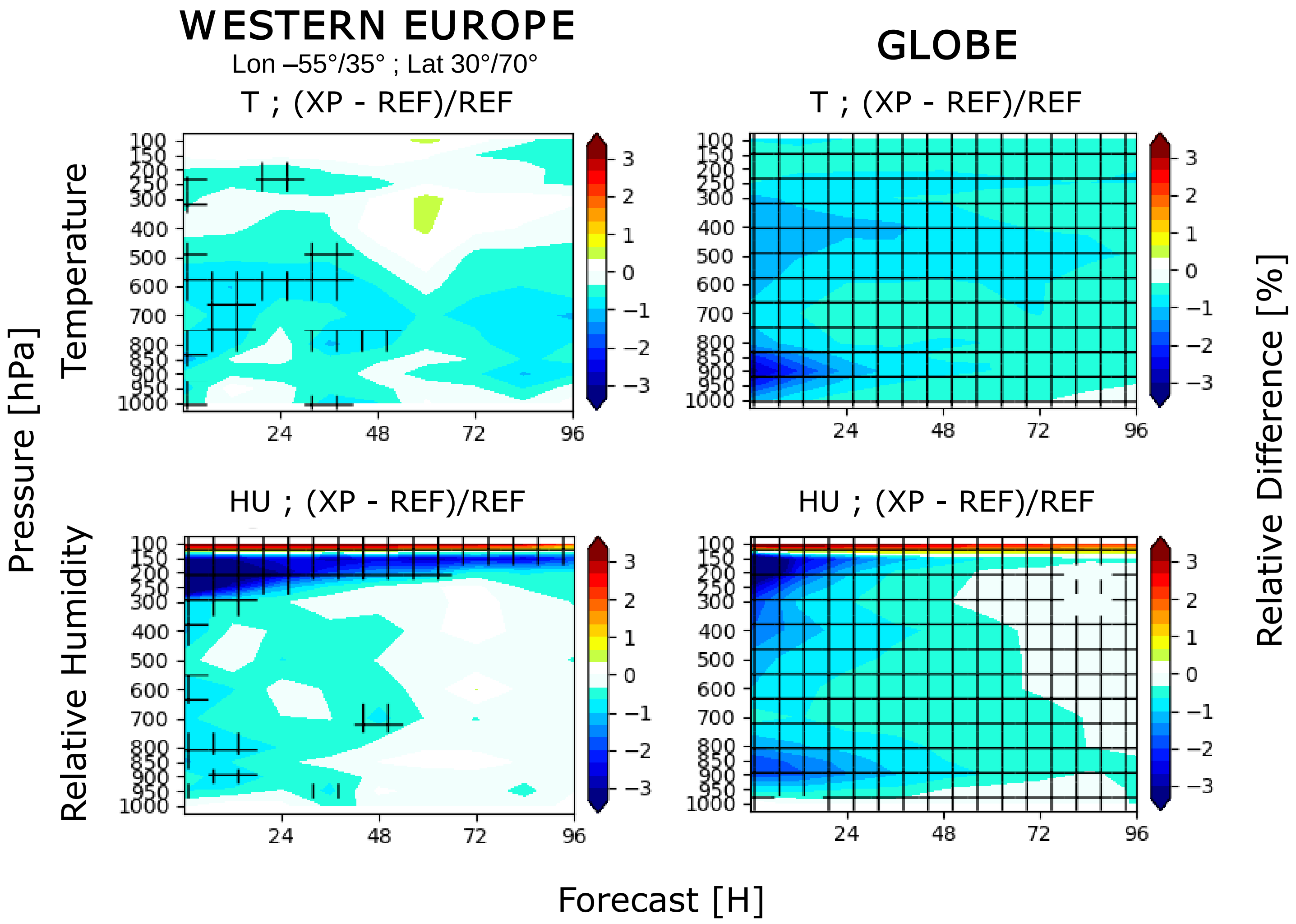


Figure 3. Relative difference of standard deviation of the forecast error for a CMIM-IR scenario (XP) compared to the a reference scenario (REF), in percent.

- Blue = reduction of forecast errors
- Red = increase of forecast errors
- = statistical significance at 99% confidence level
- For different model variables : T, HU, Wind,...

Infrared Scenario

Scores (146 days, summer + winter)



- Reduction in the forecast errors observed for temperature (T) and relative humidity (HU), <u>for all regions</u>.
- On the Globe, reduced forecast errors for T and HU, <u>along all vertical levels</u>.
- For T, strongest improvements near the surface.

Figure 4. Relative difference of standard deviation of the forecast error for the CMIM-IR scenario (XP) compared to the scenario without CMIM (REF), in percent.

Micro-wave Scenarios

Presentation

CMIM-MW High-Frequency (HF) reference scenario :

- 1 MW HF instrument per satellite, 8 total
- Pixel resolution : 7km
- All-sky assimilation for observations, super-obbed

Channel Number	Frequency [GHz]	Bandwidth [MHz]	NeΔT [K]
1	183.31 +/- 0.2	200	1.6
2	183.31 +/- 1.1	350	1.2
3	183.31 +/- 2.7	500	1.0
4	183.31 +/- 4.2	700	0.9
5	183.31 +/- 6.6	1 200	0.7
6	183.31 +/- 11	2 000	0.5

Table 1. Channel Selection for the CMIM HF Scenario

CMIM-MW Low-Frequency (LF) reference scenario :

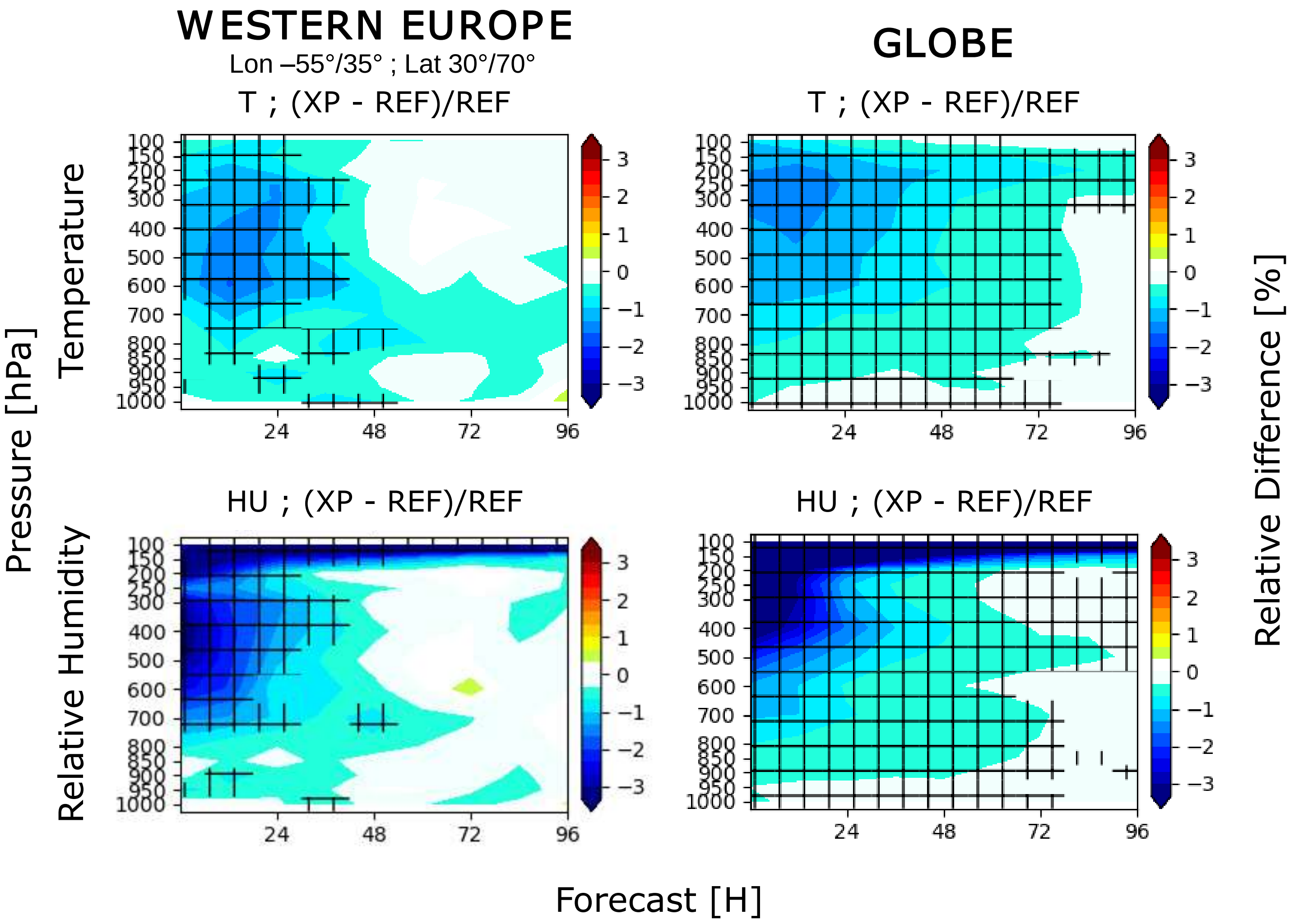
- 1 MW LF instrument per satellite, 8 total
- Pixel res : 20km for 50-54GHz
- All-sky assimilation for obs, super-obbed

Channel Number	Frequency [GHz]	NeΔT [K]
1	19.3	0.1
2	22.2	0.1
3	36.7	0.1
4	50.3	0.4
5	52.8	0.3
6	53.6	0.3
7	54.4	0.3
8	89	0.1

Table 2. Channel Selection for the CMIM LF Scenario

Micro-wave Scenarios

High-Frequency Scores (146 days)

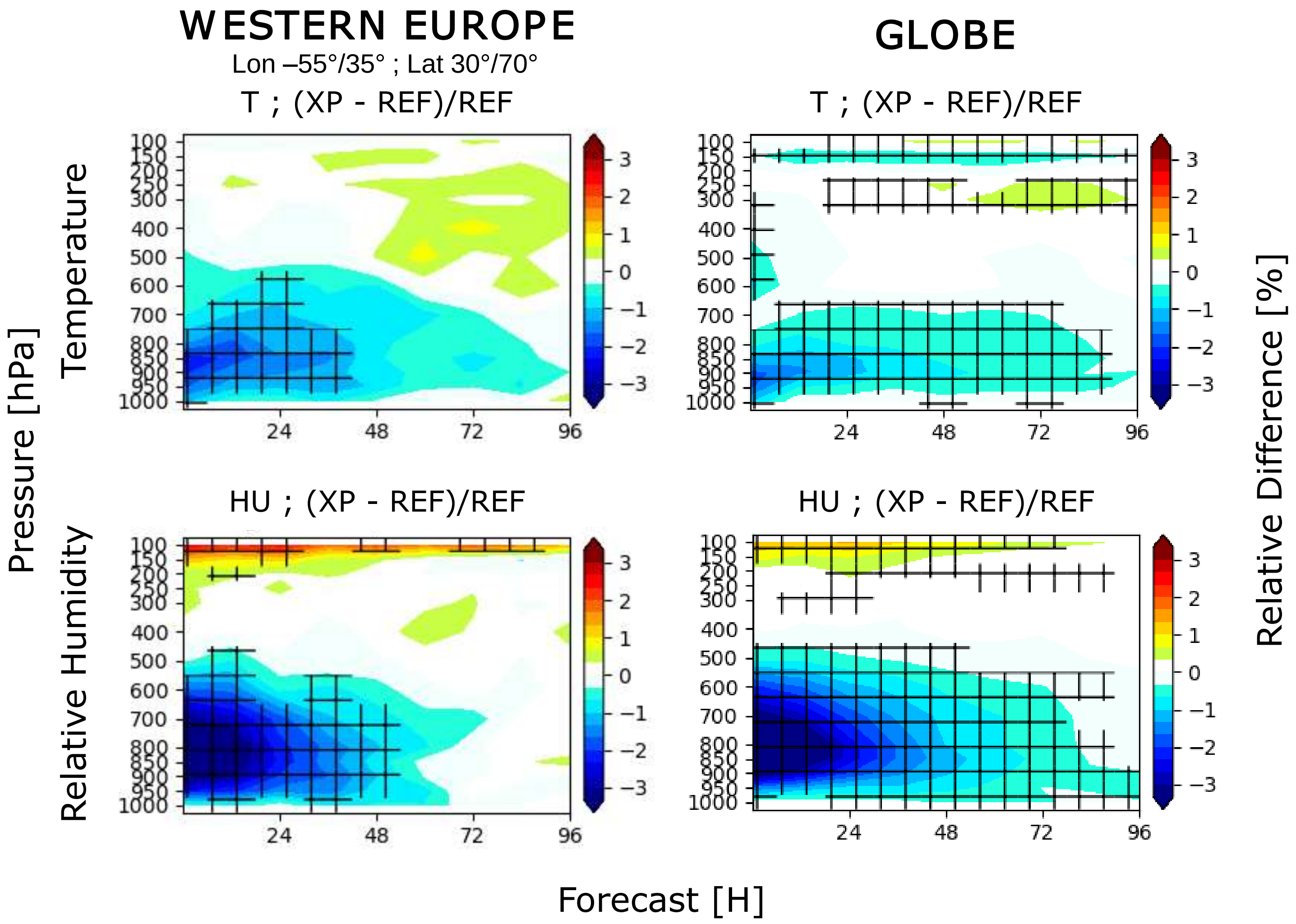


- Significant reduction in forecast errors for both T and HU.
- Strongest improvements observed for HU, expected.
- Strongest improvements in mid to high troposphere, above 600hPa, expected.

Figure 5. Relative difference of standard deviation of the forecast error for the CMIM-MW High-Frequency scenario (XP) compared to the scenario without CMIM (REF), in percent.

Micro-wave Scenarios

Low-Frequency Scores (146 days)



- Significant reduction in forecast errors for both T and HU.
- Strongest improvements observed for HU -> 22GHz.
- Strongest improvements for surface levels, expected.

Figure 6. Relative difference of standard deviation of the forecast error for the CMIM-MW Low-Frequency scenario (XP) compared to the scenario without CMIM (REF), in percent.

NWP Impact Comparisons
Energy Norms over the Globe (146 days)

Moist Energy Norm = integrated forecast score, used for FSOI scores. Computed from the formula proposed by Ehrendorfer et al. (1999)

- Negative bar = reduction of forecast errors
- Whisker = uncertainty on the mean at 95% confidence level
- **All 3 CMIM reference scenarios improve NWP up to 48H forecasts (96H for IR) on the Globe**

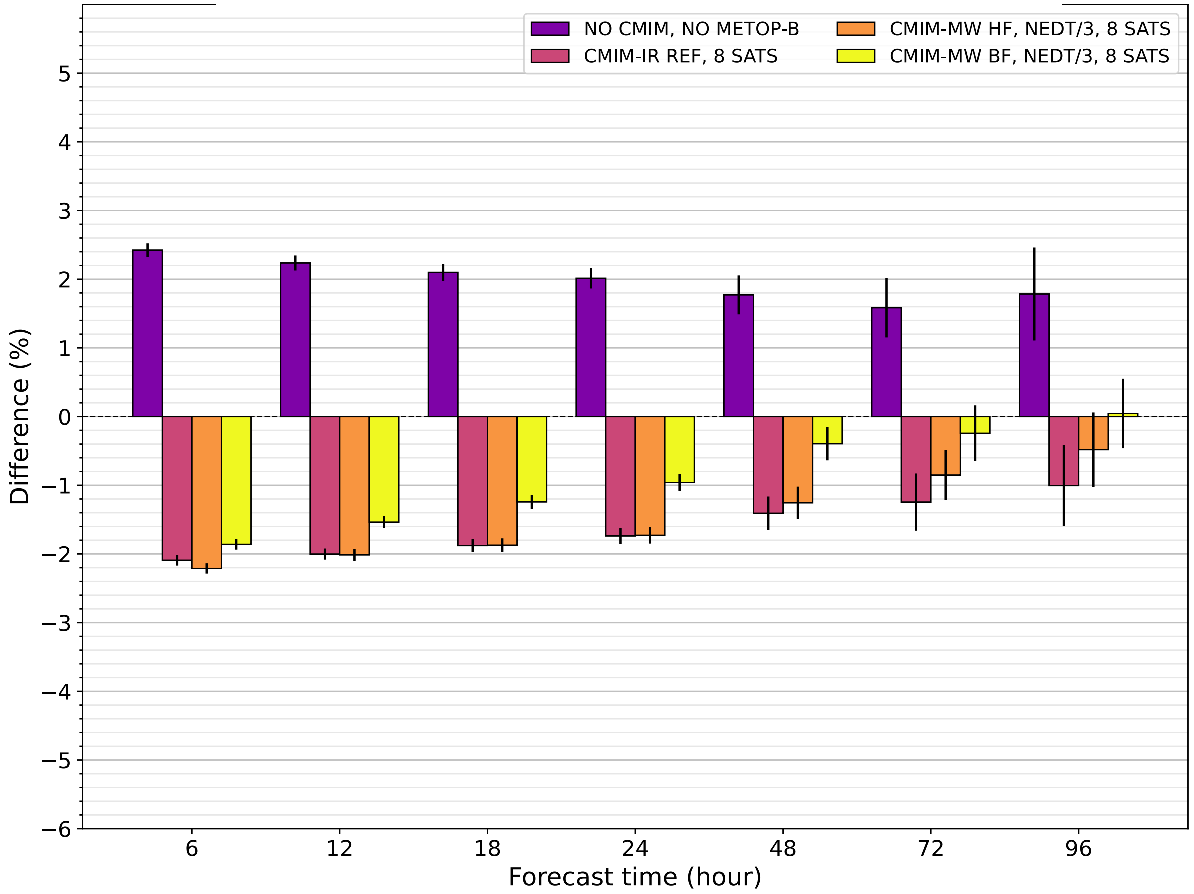


Figure 7. Relative diff in energy norms of the forecast error for CMIM reference scenarios. Relative differences computed using the scenario without CMIM as the ref.

Conclusions

1. All 3 CMIM reference scenarios show promising results, Temperature (T) and Relative Humidity (HU) forecast errors reduction, globally.
2. No saturation observed in forecast error reduction when revisit is increased.
3. CMIM-MW Low-Frequency : best configuration to improve HU surface forecast => importance of the 22GHz channel.

Many other scenarios were tested :

- **Constellation parameter sensitivity** : revisit time, bandwidth reduction, NeΔT variation
- **Mixed scenarios combining IR and MW instruments (poster!)** in the same constellation
- Impact of a MTG-IRS proxy on CMIM performance

Thank You for your attention

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Ehrendorfer, M., Errico, R. M., & Raeder, K. D. (1999). Singular-Vector Perturbation Growth in a Primitive Equation Model with Moist Physics [Publisher: American Meteorological Society Section: Journal of the Atmospheric Sciences]. Journal of the Atmospheric Sciences, 56 (11), 1627-1648.

Eumetsat. (2018). L’instrument IASI embarqué sur Metop-C produit son premier spectre. Consulted February 14, 2024, on https://www.eumetsat.int/fr/linstrument-iasi-embarque-sur-metop-c-produit-son-premier-spectre

Rivoire, L., Marty, R., Carrel-Billiard, T., Chambon, P., Fourrié, N., Audouin, O., Martet, M., Birman, C., Accadia, C., & Ackermann, J. (2024). A global Observing System Simulation Experiment for the EPS-Sterna microwave constellation.

Complementary Slides

CMIM Constellation

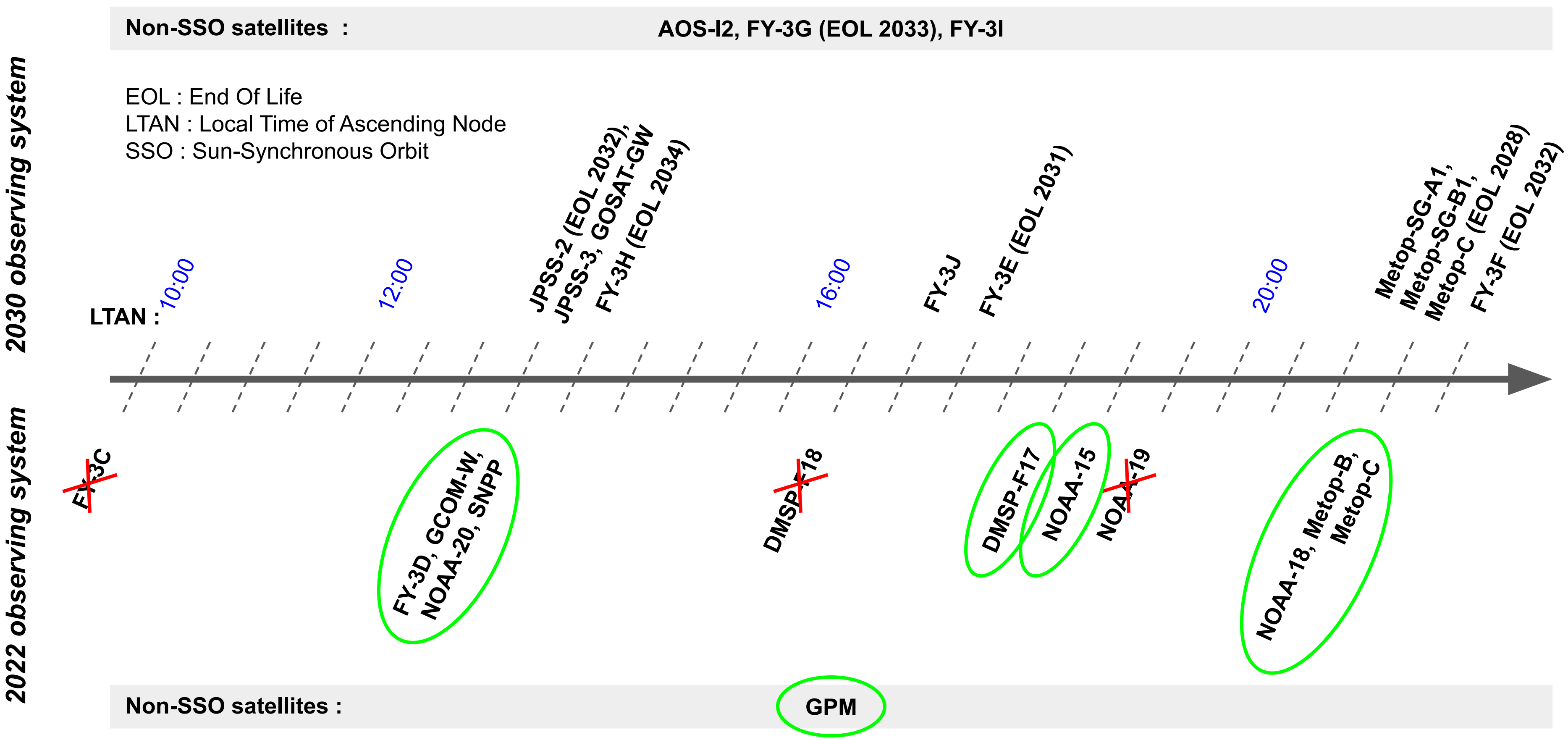


Figure 8. 2030-2035 Observing System used to determine the NWP impact of CMIM

At the start of the study, no satellite was announced at the local time of ascending node for the following instruments : MWHS-2 aboard FY-3C, SSMIS aboard DMSP-F18, AMSU- A and MHS aboard NOAA-19. Therefore, there observations were not assimilated in the study.

Green circles indicate satellites already part of the 2022 observation system, expected to still be operating by 2030.

CMIM Constellation

Measurement Type	Instrument	Satellite
Surface	Ground stations, boats, buoys, wind profilers, GNSS ground receivers	
Altitude	Radiosonde, aircraft data	
Satellite	Atmospheric Motion Vectors (AMVs)	Meteosat, GOES, Himawari
Satellite	Advanced Technology Sounding Unit (ATMS)	NOAA-20, SNPP
Satellite	Advanced Microwave Sounding Unit (ATMS)	NOAA-15, NOAA-18, Metop-B, Metop-C
Satellite	MicroWave Humidity Sounder 2 (MWHS-2) *(all-sky DA)*	FY-3D
Satellite	Special Sensor Microwave - Imager/Sounder (SSMIS)	DMSP-F17
Satellite	Microwave Humidty Sounder (MHS) *(all-sky DA)*	Metop-B, Metop-C *(proxy for Metop-SG A and B)*
Satellite	Microwave imagers, with emphasis on precipitation, such as GMI, AMSR2 *(all-sky DA)*	Respectively aboard GPM, GCOM-W
Satellite	Advanced Himawari Imager (AHI)	Himawari-8
Satellite	Hyperspectral infrared data from IASI	Metop-B, Metop-C *(proxy for Metop-SG A and B)*
Satellite	Hyperspectral infrared data from CrIS	NOAA-20
Satellite	Spinning Enhanced Visible Infra-Red Imager (SEVIRI)	Meteosat-8, Meteosat-11 *(MSG proxy for FCI on MTG-I)*
Satellite	Scatterometers winds	Metop-B, Metop-C *(proxy for Metop-SG A and B)*
Satellite	GNSS radio occultation data	

Table 3. Summary of complete 2030-2035 Observing System used to determine the NWP impact of CMIM

OSSE Framework

Model Parameter	Nature Run	OSSE Framework for NWP
Geometry	TL1798 (ARPEGE)	TL798 (ARPEGE)
Horizontal Resolution Europe	Approx. 5km	Approx. 10km
Horizontal Resolution New-Zealand	Approx. 24km	Approx. 61km
Convective Scheme	Tiedtke	Bougeault
Observations	No injected observations	
Data Assimilation	No DA	Atmospheric and surface DA
Date Range	From July to August and from November to February (with 1 month spin-up), between 2021 and 2022	From August to October (summer) and from December to February (winter)

Table 4. Comparison of model parameters between the Nature Run and the DA assimilation system used for the OSSE framework

CMIM Reference Constellation

Baseline constellation architecture :

- 8 satellites with sun-synchronous orbits (SSO)
- 4 orbital planes (2 sats/plane), alt. 630km
- Revisit time 3H30 between latitudes 35° to 60° (95% of cases)
- To complete Metop series and JPSS
- 1 instrument per satellite, IR or MW

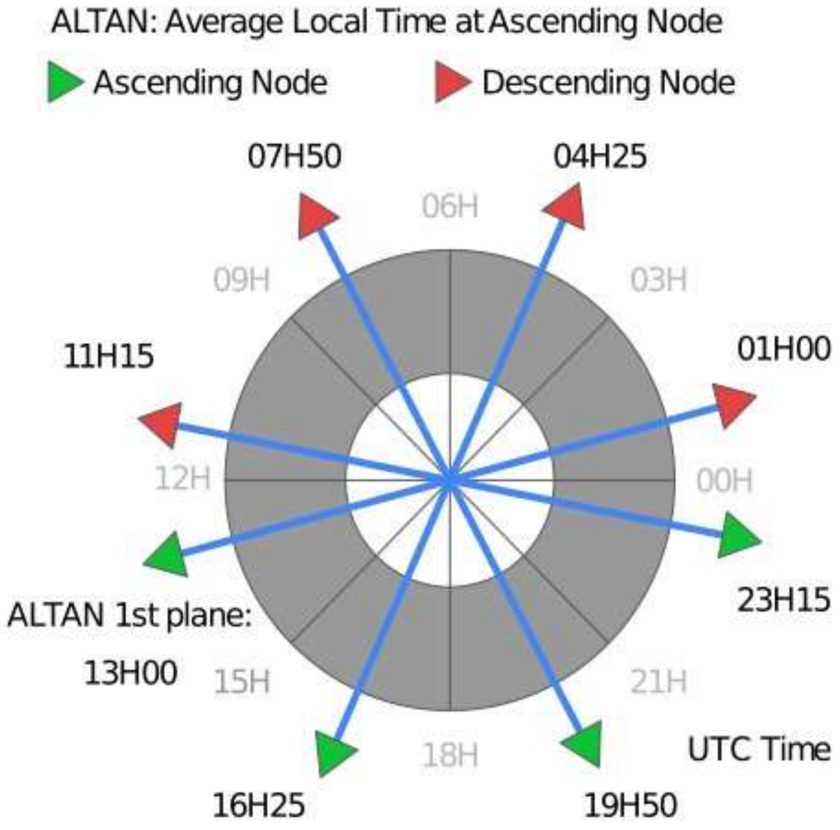


Figure 9. Equatorial cross-sectional plane of the nodes for the reference CMIM constellation : 8 satellites, 4 orbital planes, with a revisit time lower than 3H30 for 95% of cases between 35 and 60 degrees of latitude. Source : CNES (2023)

CMIM-IR
Instrumental Noise

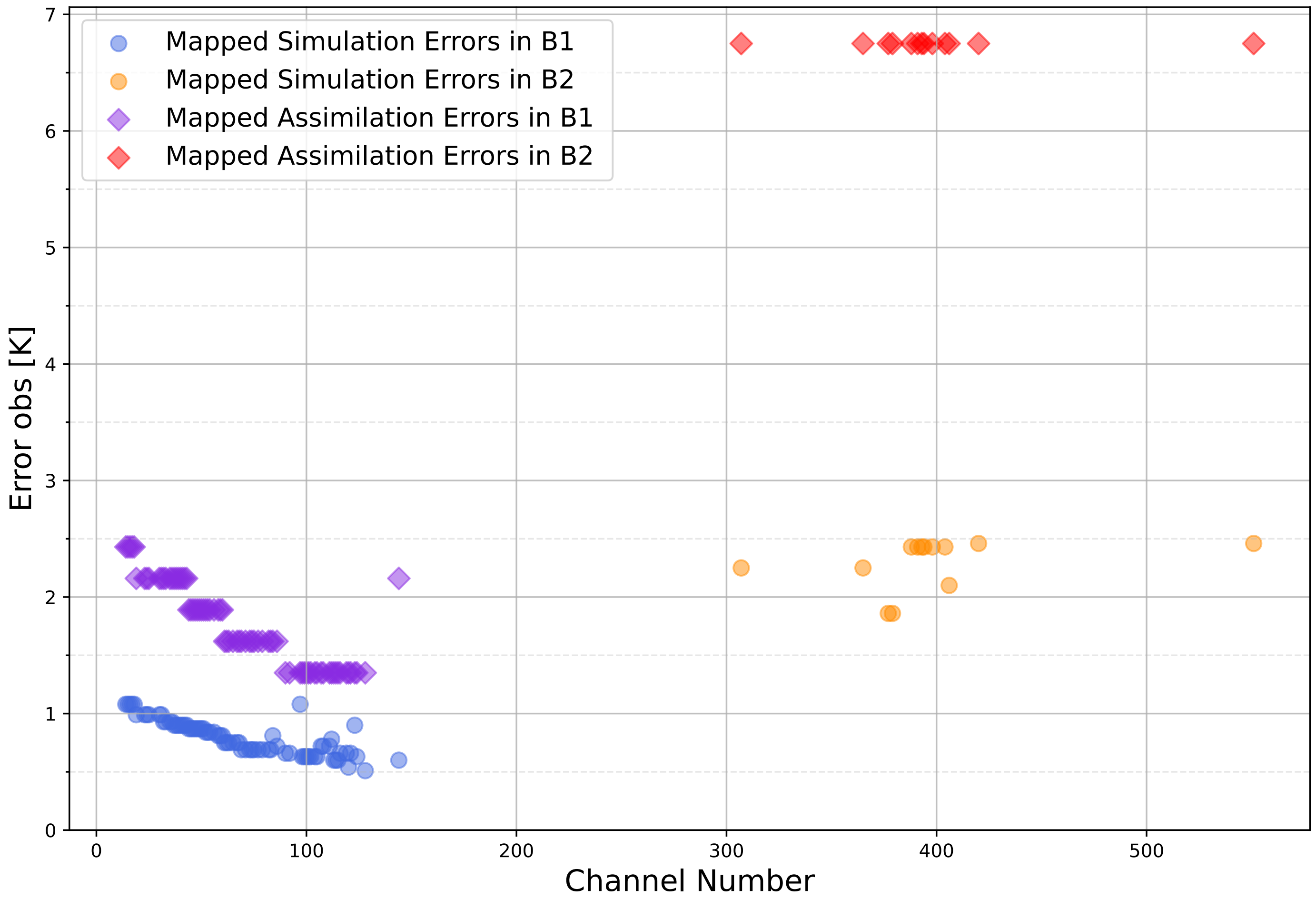


Figure 10. Comparaison of instrumental noise applied to the CMIM-IR reference scenario, mapped from the instrumental noise applied to IASI in Kelvin

CMIM-IR

Complete Score Results – 146 days – 5 zones

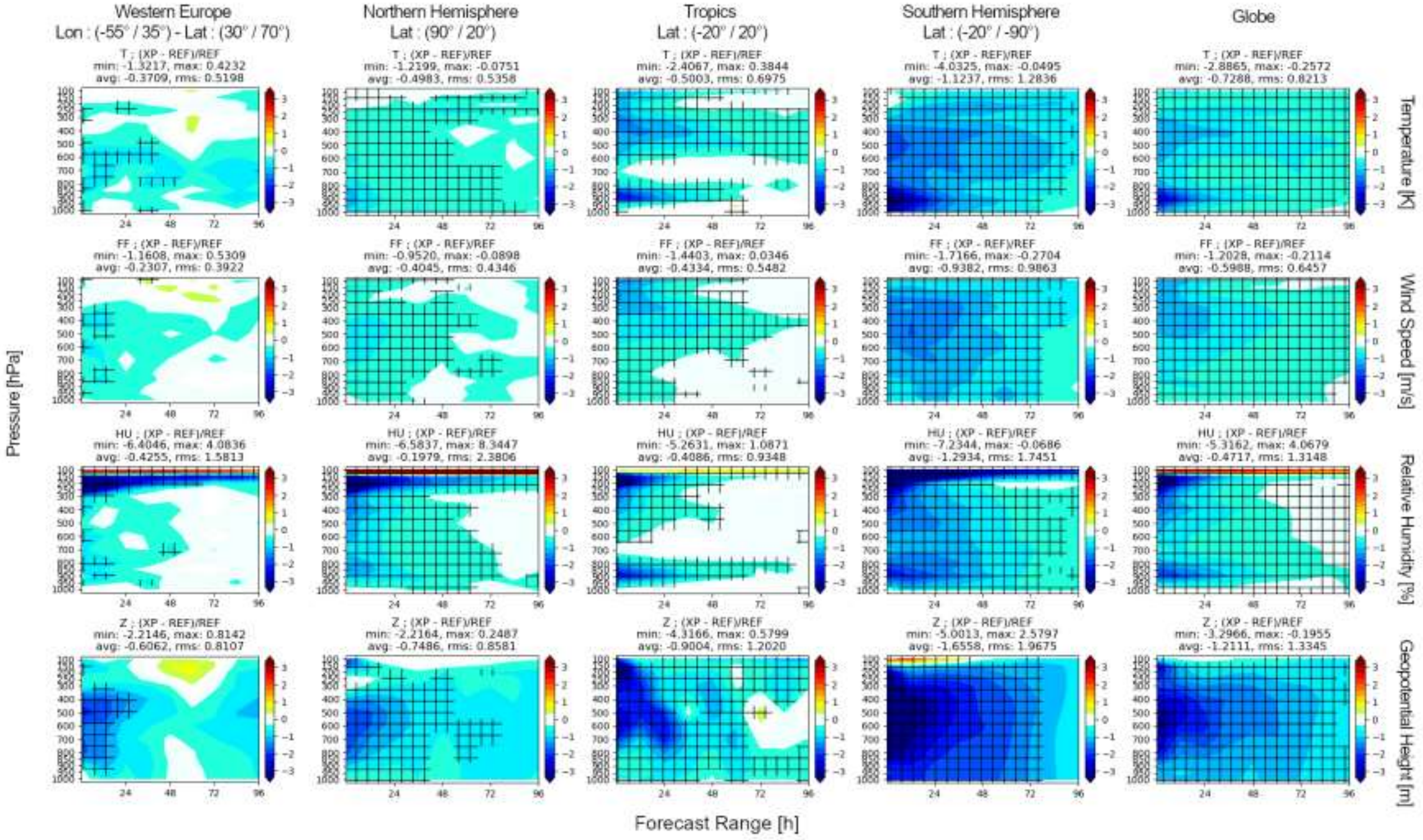


Figure 10. Relative difference of standard deviation of the forecast error for the CMIM-IR scenario (XP) compared to the scenario without CMIM (REF), in percent. Results are shown for 4 parameters and 5 geographical zones.

CMIM-MW High-Frequency

Complete Score Results – 146 days – 5 zones

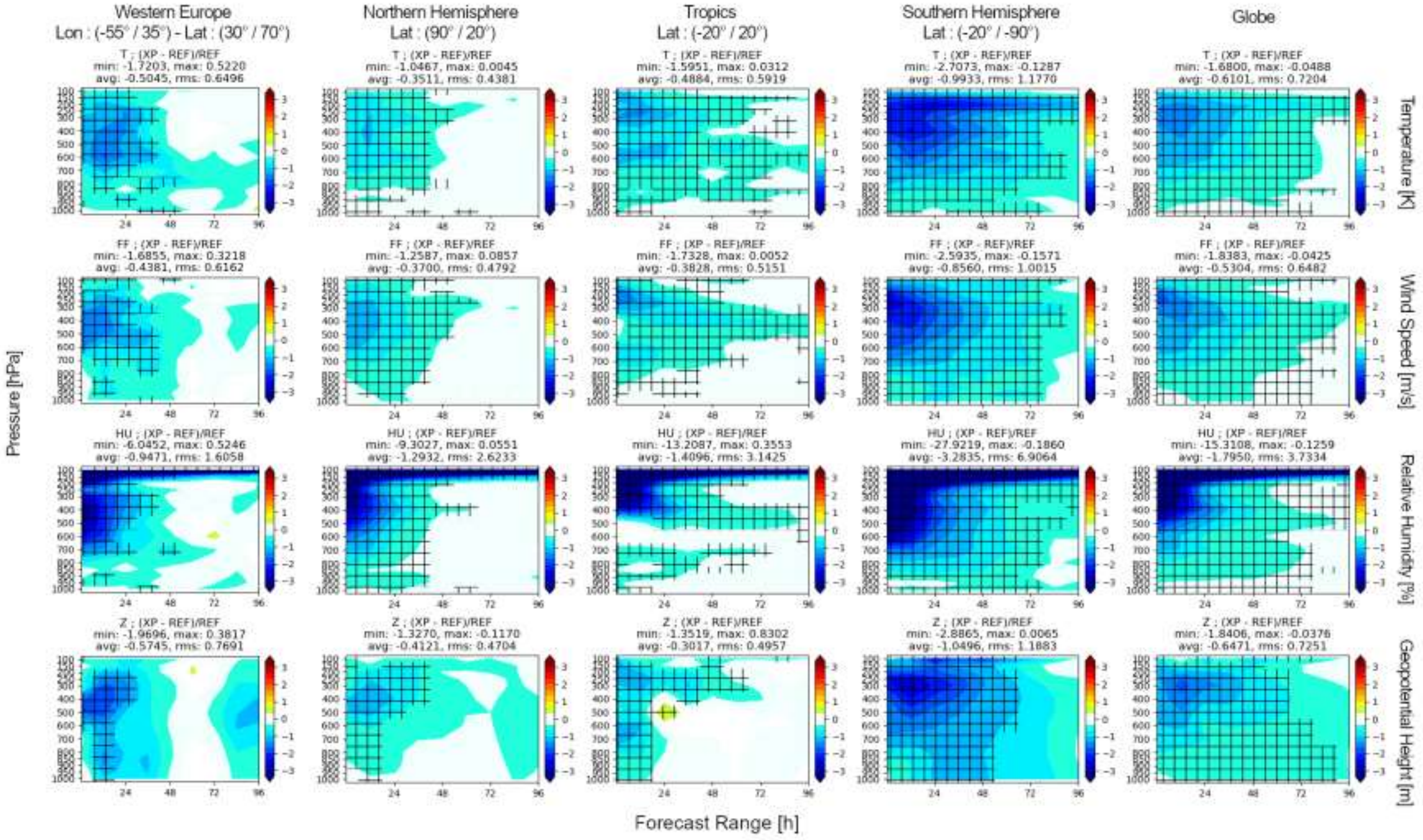


Figure 11. Relative difference of standard deviation of the forecast error for the CMIM-MW High Frequency scenario (XP) compared to the scenario without CMIM (REF), in percent.

CMIM-MW Low-Frequency

Complete Score Results – 146 days – 5 zones

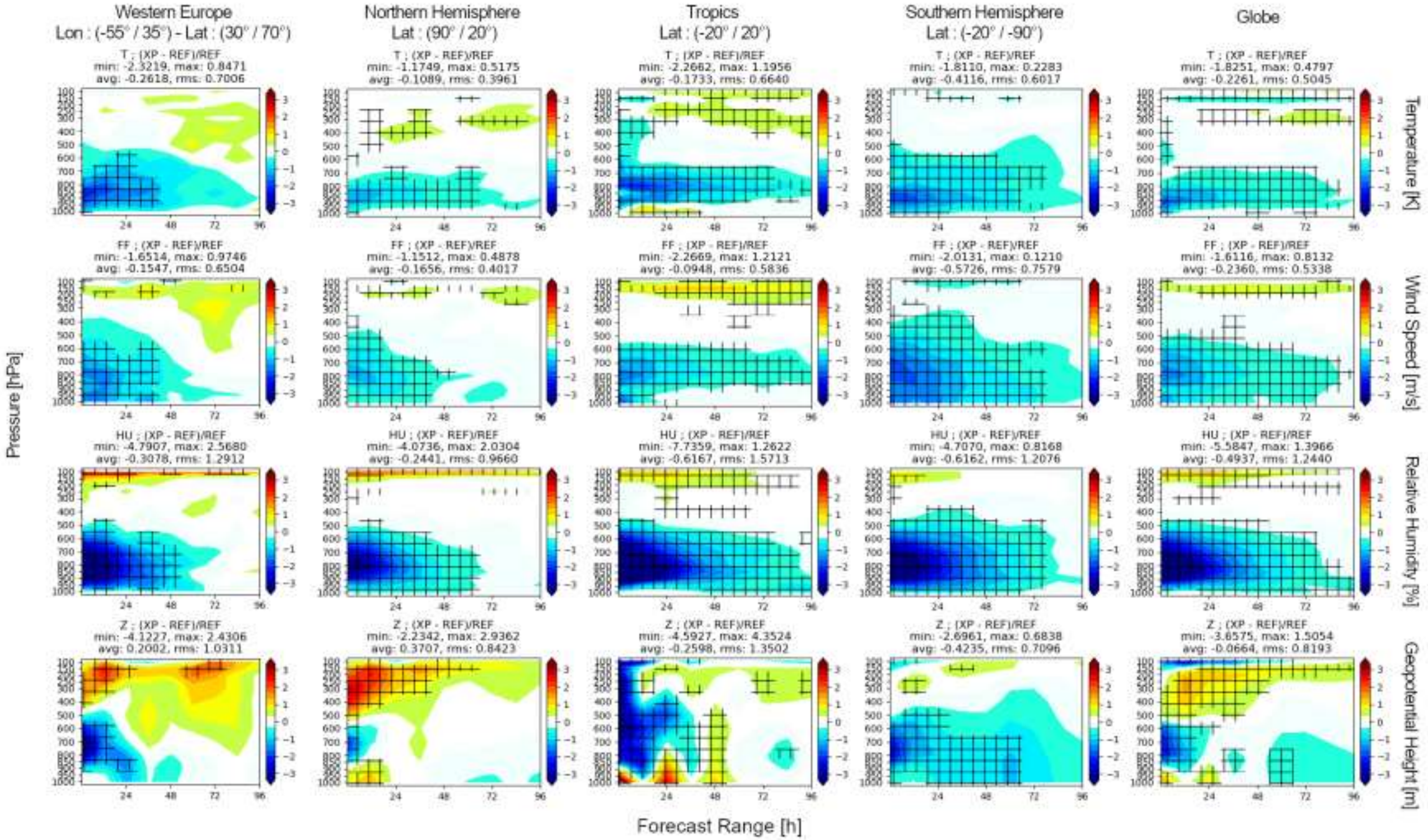


Figure 12. Relative difference of standard deviation of the forecast error for the CMIM-MW Low Frequency scenario (XP) compared to the scenario without CMIM (REF), in percent.

CMIM-IR – Revisit 2H – 18 sats

Complete Score Results – 146 days – 5 zones

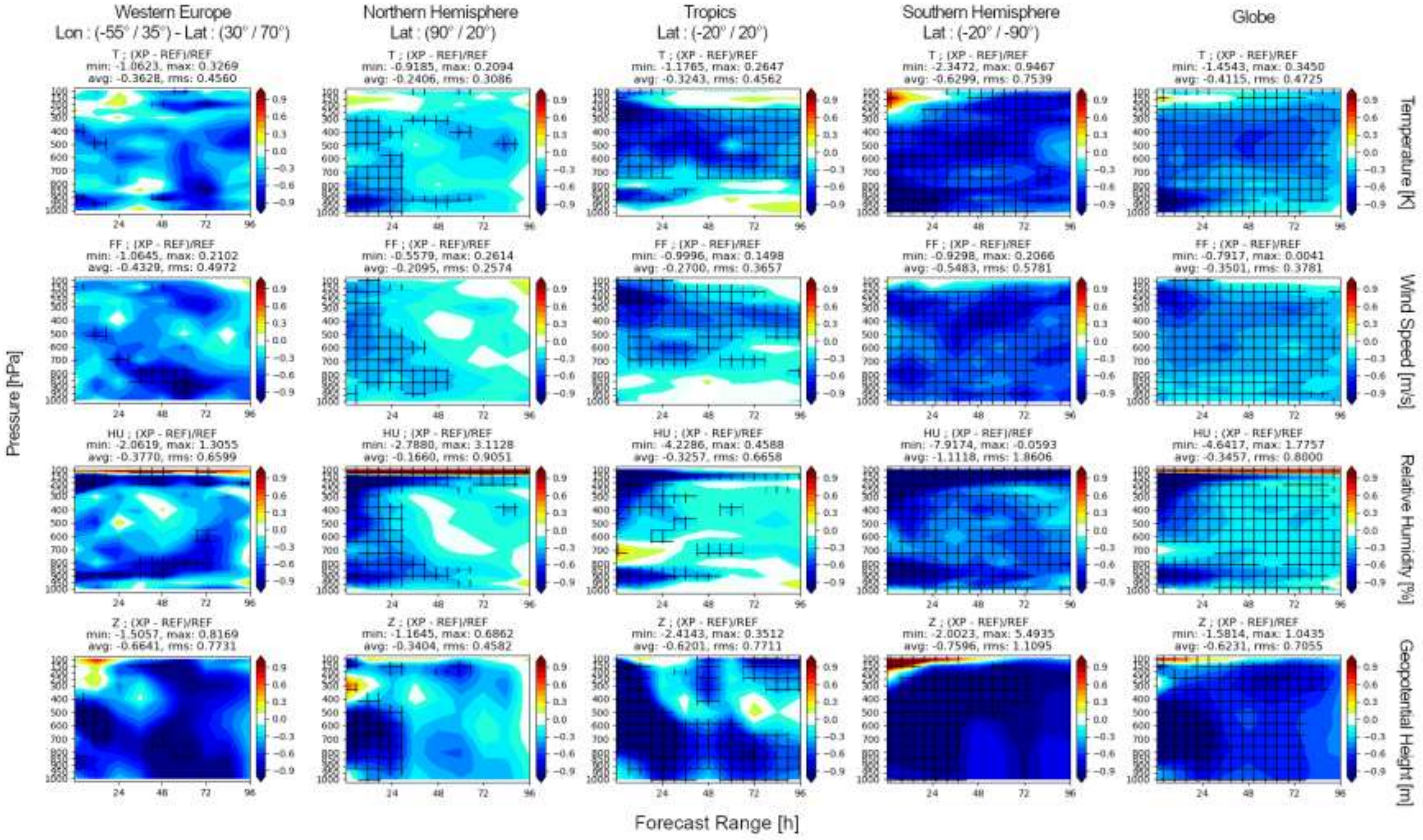


Figure 13. Relative difference of standard deviation of the forecast error for the CMIM-IR 2H revisit scenario (XP) compared to the reference CMIM-IR scenario with 3H30 revisit (REF), in percent.

No obs saturation

CMIM-IR – NEDT 1 x IASI

Complete Score Results – 146 days – 5 zones

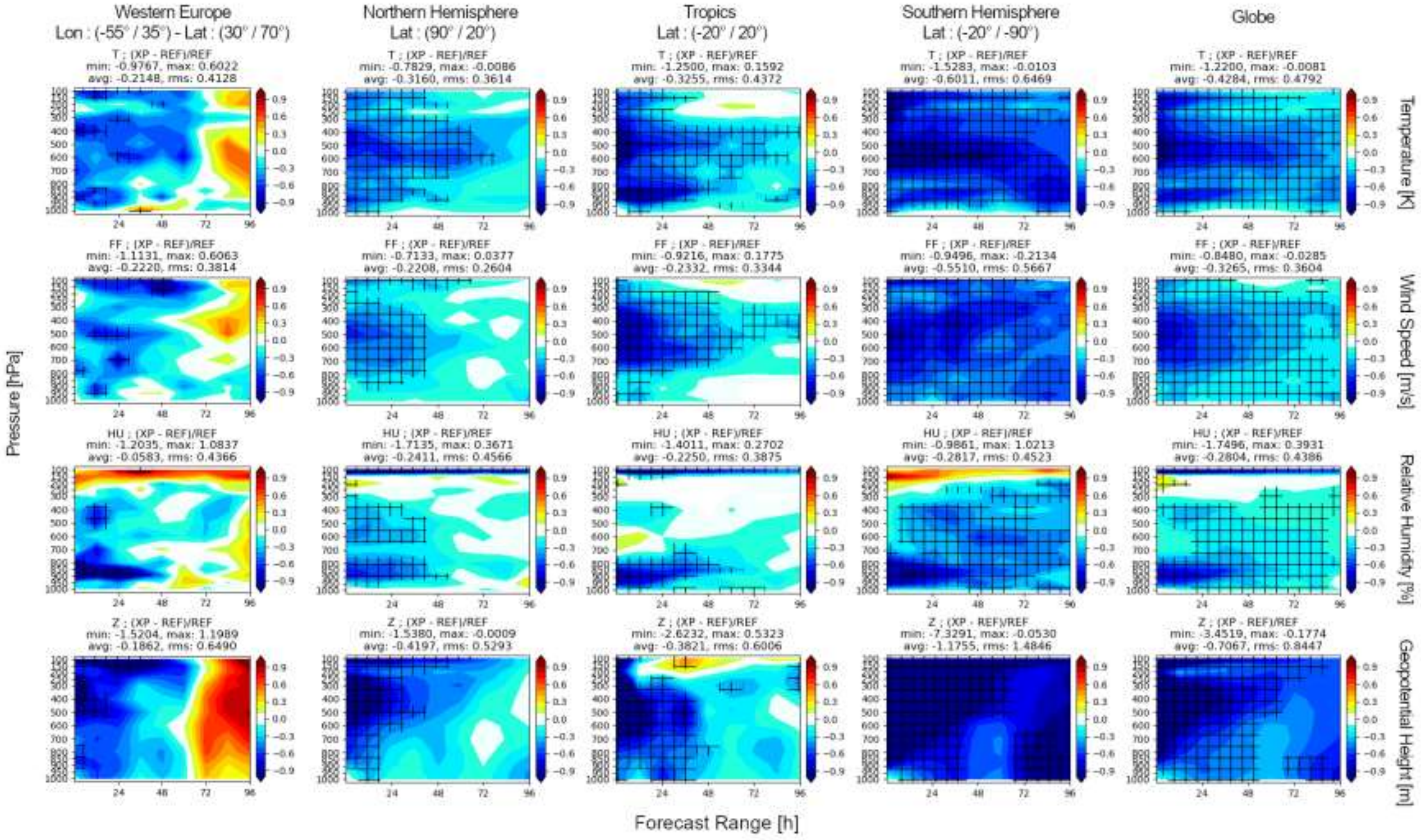


Figure 14. Relative difference of standard deviation of the forecast error for the CMIM-IR 1 x IASI NEDT scenario (XP) compared to the reference CMIM-IR scenario with 3 x NEDT IASI (REF), in percent.

Importance of low-noise instrument

CMIM IR + MW HF

Complete Score Results – 146 days – 5 zones

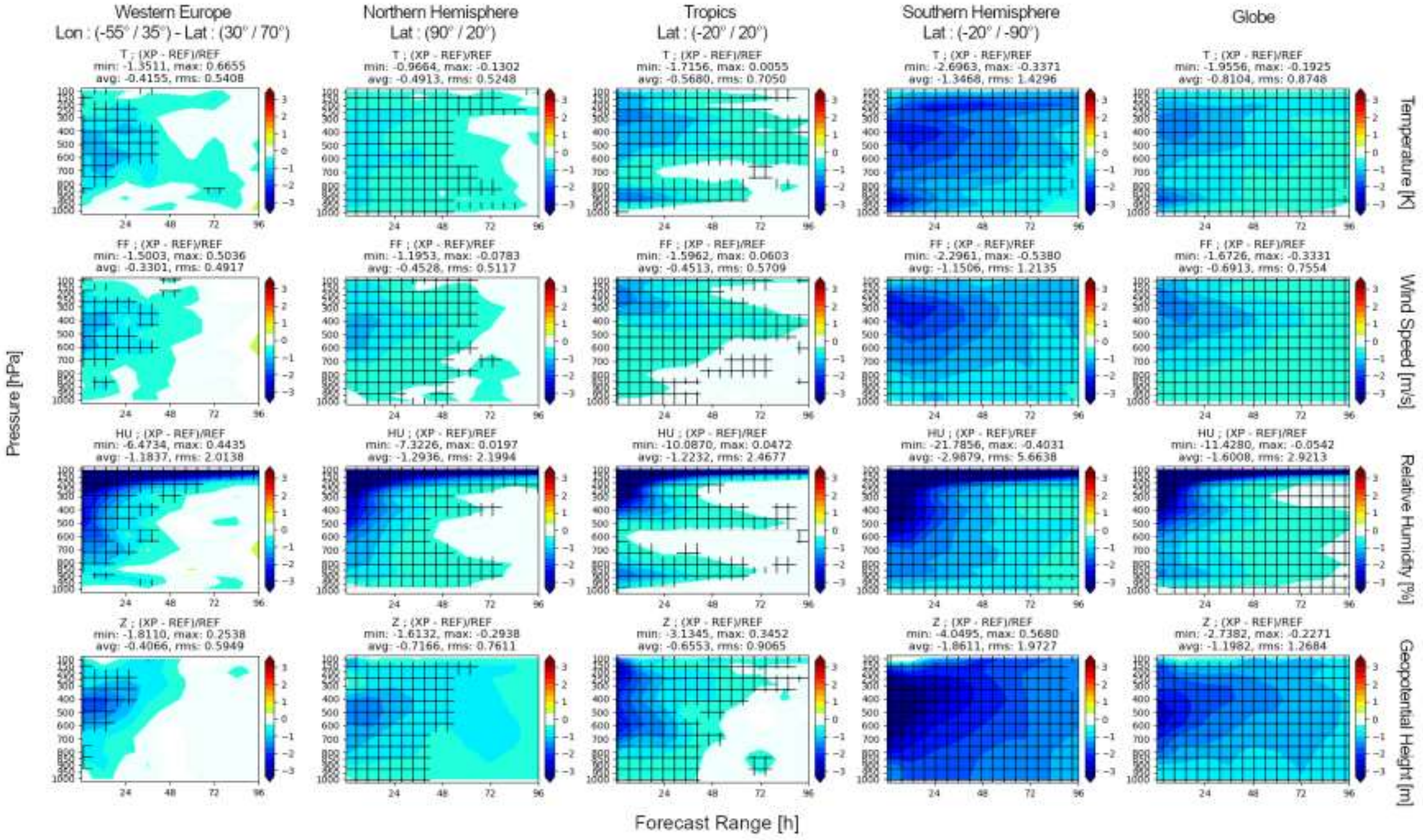


Figure 15. Relative difference of standard deviation of the forecast error for the CMIM IR + MW HF scenario (XP) with 4 IR instru and 4 MW instru, 1 instru per sat. Compared to the scenario without CMIM (REF), in percent.

CMIM IR + MW LF

Complete Score Results – 146 days – 5 zones

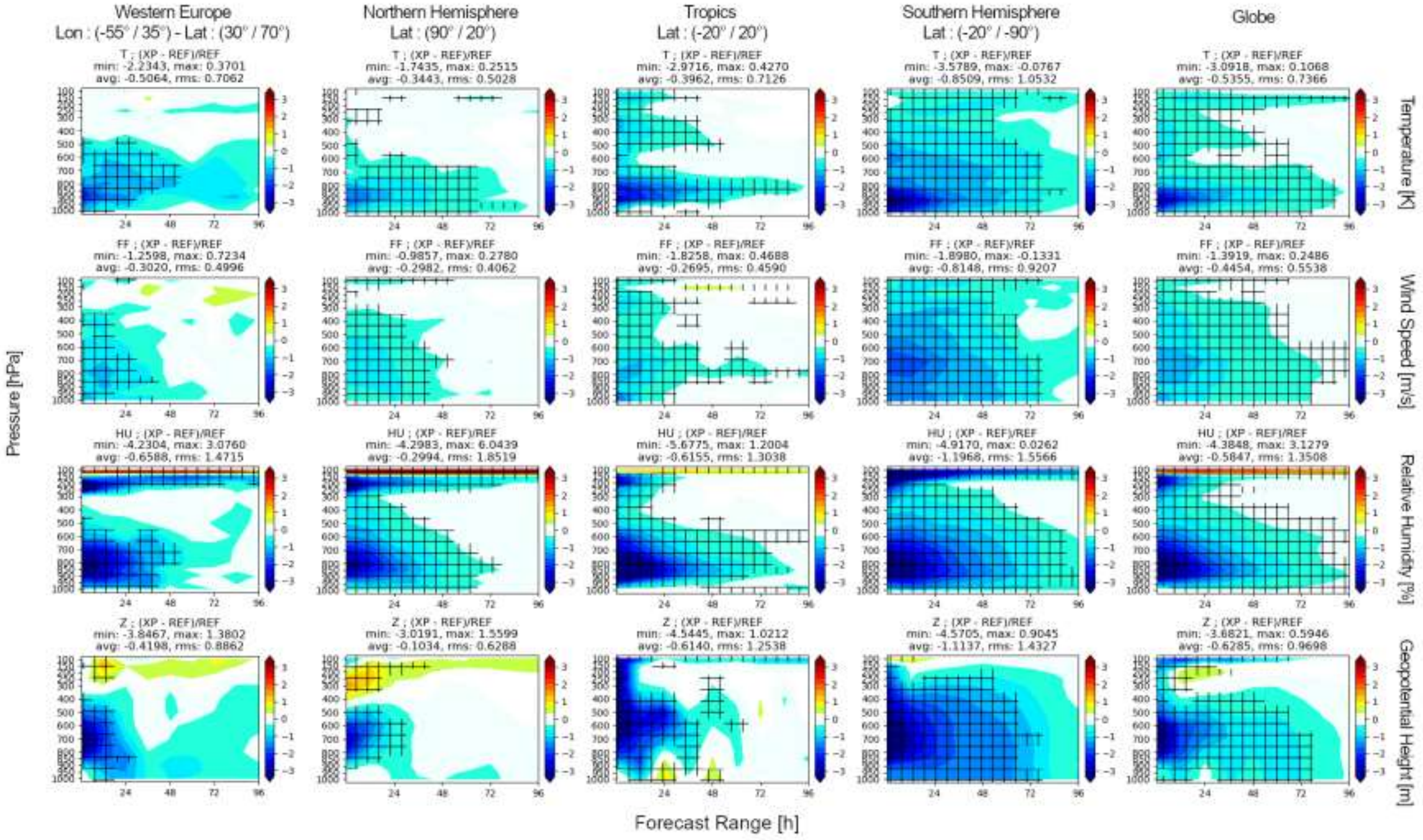


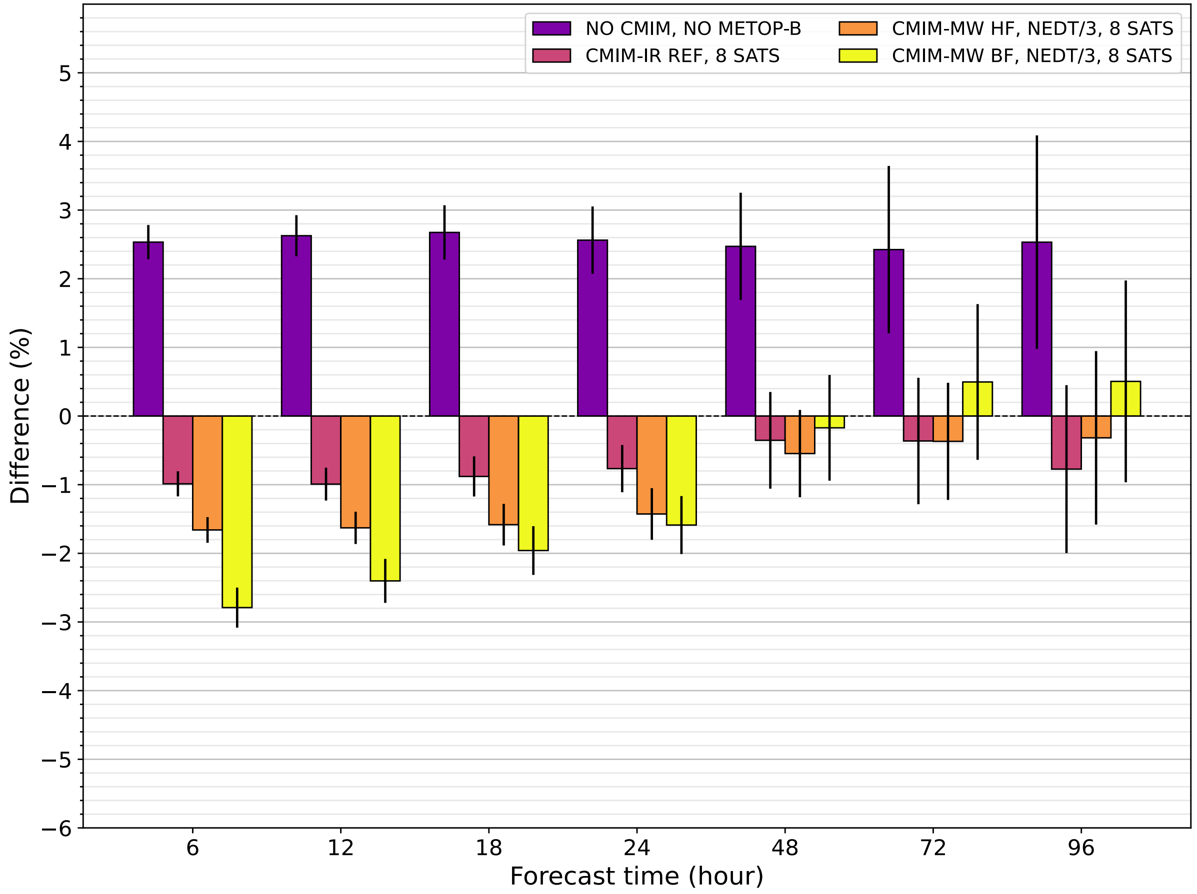
Figure 16. Relative difference of standard deviation of the forecast error for the CMIM IR + MW LF scenario (XP) with 4 IR instru and 4 MW instru, 1 instru per sat. Compared to the scenario without CMIM (REF), in percent.

IR + MW synergy

NWP Impact Comparisons
Energy Norms on Western Europe

Figure 17. Relative differences in energy norms of the forecast error for the CMIM IR and MW reference scenarios at different forecast times. Norms are averaged over 146 days, between 08/14/2021 and 02/27/2022, and over the Western Europe region (EURATL). Relative differences are computed using the scenario without CMIM as a reference. The error bars correspond to uncertainty on the mean at the 95% confidence level.

- **All 3 CMIM reference scenarios improve NWP up to 24H forecasts on Western Europe.**
- On Western Europe, Micro-wave scenarios perform better than the IR one, coherent with results from scores.
- For this metric and on Western Europe, CMIM-MW Low-Frequency improves NWP the most.



NWP Impact Comparisons

Energy Norms on Western Europe

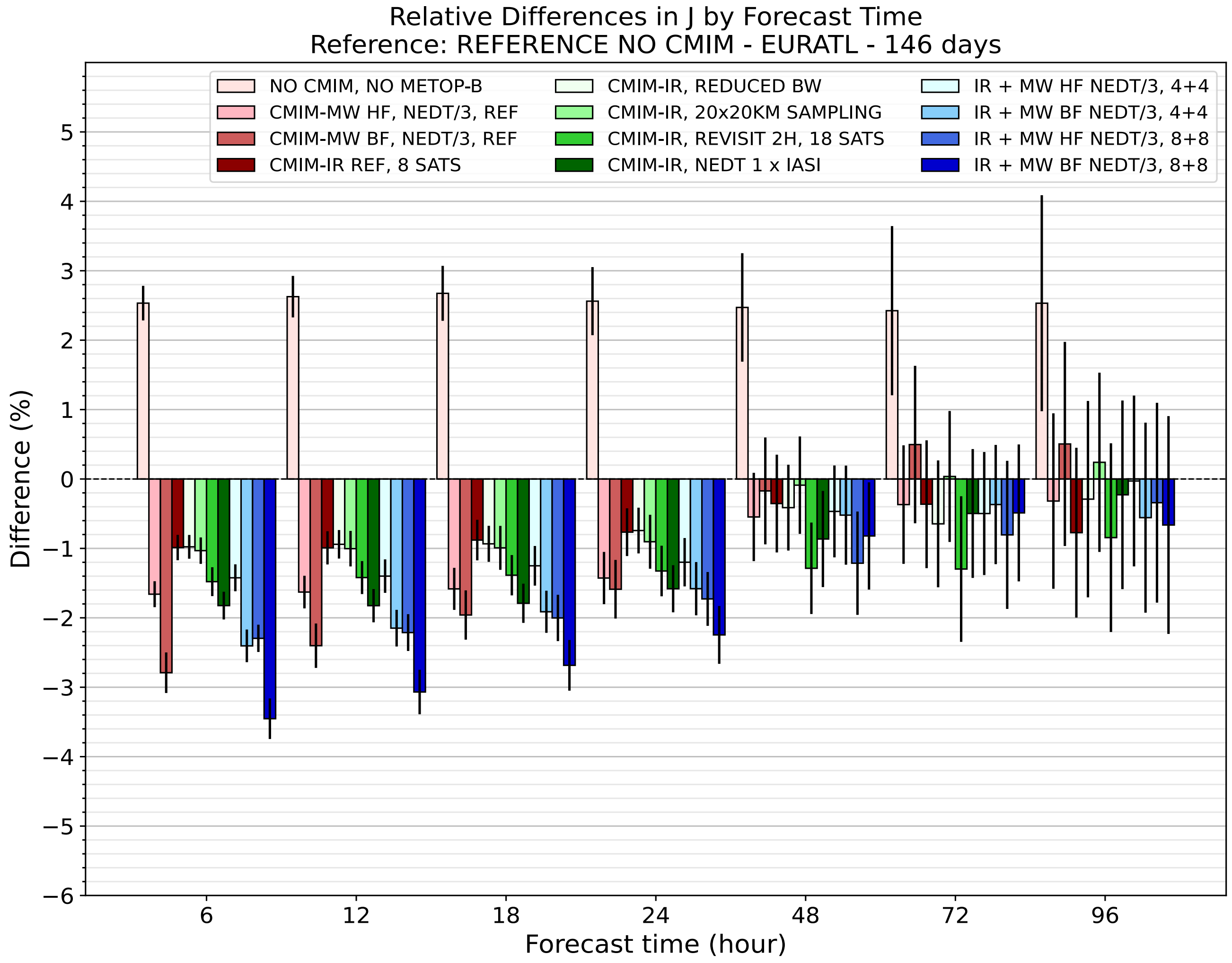


Figure 18. Relative differences in energy norms of the forecast error for the several CMIM scenarios at different forecast times. Norms are averaged over 146 days, between 08/14/2021 and 02/27/2022, and over the Western Europe region (EURATL). Relative differences are computed using the scenario without CMIM as a reference. The error bars correspond to uncertainty on the mean at the 95% confidence level.

NWP Impact Comparisons

Energy Norms over the Globe

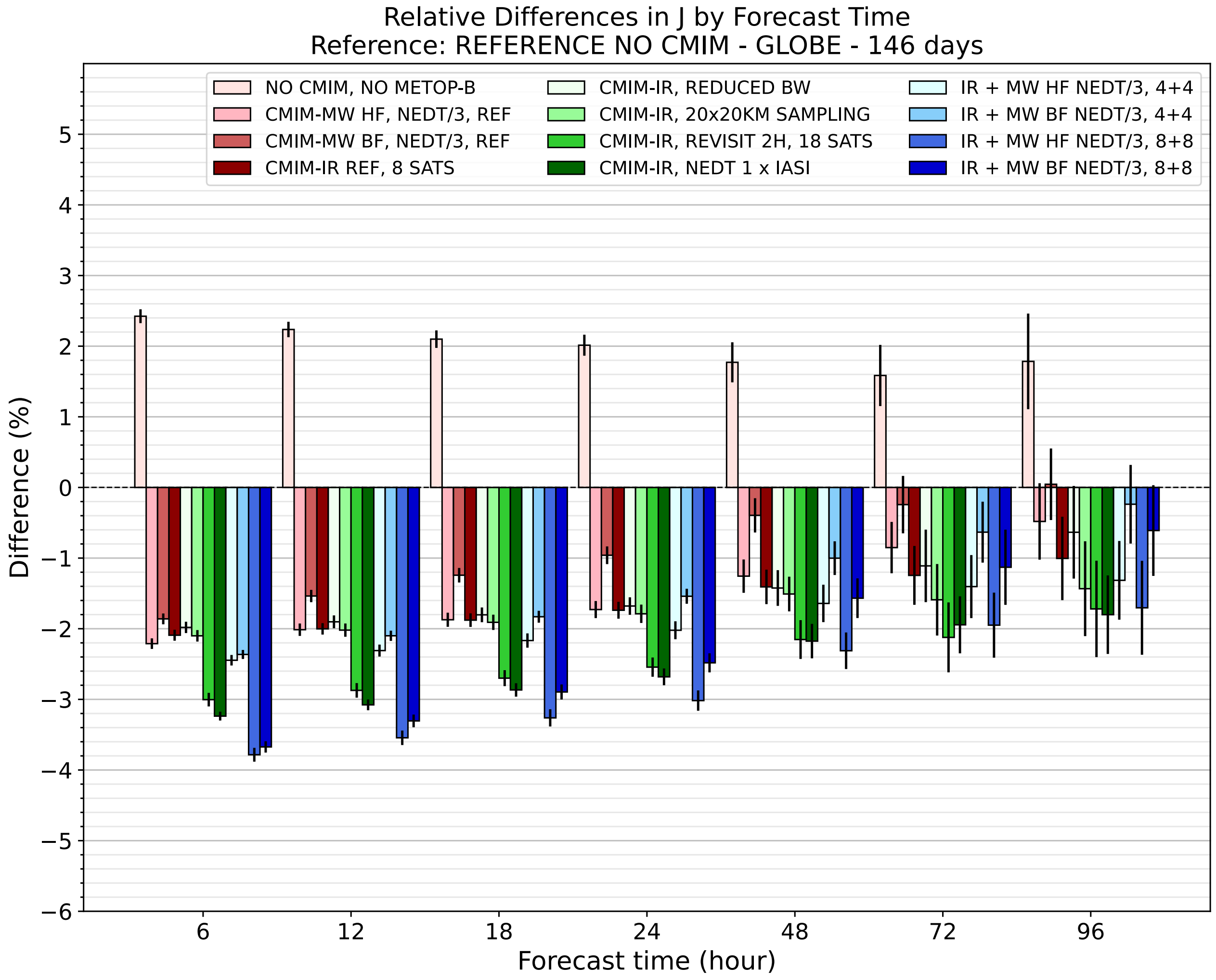


Figure 19. Relative differences in energy norms of the forecast error for the several CMIM scenarios at different forecast times. Norms are averaged over 146 days, between 08/14/2021 and 02/27/2022, and over the Globe (GLOBE). Relative differences are computed using the scenario without CMIM as a reference. The error bars correspond to uncertainty on the mean at the 95% confidence level.