Project Title: Upgrading a climate model to improve regional climate projections

Acronym: UpClim

Deliverable 2.6
Report assessing the impact of model aerosol developments on European regional climate

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Technical References

Project Number	014696
Principal Investigator	KATRAGKOU ELENI
Sub-action	Sub-action 2. Funding Projects in Leading-Edge Sectors – RRFQ: Basic Research Financing Horizontal Support for all sciences
Acronym	UpClim
Proposal Title (EN)	Upgrading a climate model to improve regional climate projections
Proposal Title (ΕΛ)	Αναβάθμιση ενός κλιματικού μοντέλου για τη βελτίωση περιοχικών κλιματικών προβολών
Thematic Area	ThA1. Physical Sciences, Engineering Sciences and Technology, Environment and Energy
Thematic Field	1.13 Development of high resolution earth system models for global and regional climate change projection
Host Institution (HI)	ARISTOTLE UNIVERSITY OF THESSALONIKI
Department	SCHOOL OF GEOLOGY
Beneficiary- Collaborating Organization	FOUNDATION FOR RESEARCH AND TECHNOLOGY-HELLAS (FORTH)
Starting Date	01/02/2024
Duration (in months)	23

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Terms, definitions and abbreviated terms

The following acronyms have been used across this document:

ACRONYM	FULL TERM
AOD	Aerosol optical depth
WRF	Weather Research and Forecasting model
CORDEX	Coordinated Downscaling Experiment
CMIP6	Coupled Model Intercomparison Project (Phase 6)
ARW	Advanced Research dynamic solver
IFS	Integrated Forecasting System
ECMWF	European Center for Medium-Range Weather Forecast
MYNN2	Mellor-Yamada Nakanishi and Niino Level 2.5
ERA5	ECMWF reanalysis data
Nt_c	Cloud droplet concentration

1 Introduction

The purpose of this document is to describe Deliverable 2.6 (D2.6) of Task 2.3, *"Assessing the impact of model aerosol developments on regional climate,"* under Working Package 2 (WP2), *"Implementation of time-evolving aerosol forcing,"* within the framework of the UpClim project. One of the primary objectives of UpClim is the implementation of improved aerosol forcing in climate models. This improved forcing accounts for both direct aerosol effects (aerosol–radiation interactions) and indirect aerosol effects (aerosol–cloud interactions). Particular emphasis is placed on the indirect aerosol effect and its impact on regional climate over Europe. To this end, we employed the Weather Research and Forecasting (WRF) model, incorporating a state-of-the-art aerosol dataset into the parameterization of direct effects. More importantly, we modified the representation of aerosol indirect effects within the microphysics scheme to better reflect the characteristics of the updated aerosol data. Two five-year simulations over Europe were conducted, one including the improved representation of aerosol indirect effects and one without it. In this report, we analyse and compare the results of these simulations to assess the impact of the implemented model developments.

2 Modelling experiments

The modifications in the model and the methodology of incorporating a more accurate aerosol indirect effect are described in detail in Deliverable 2.4 ("*Model source code modifications to include the indirect aerosol effect*"). The regional climate simulations conducted to assess the indirect effect over Europe are described in detail in Deliverable 2.5 "*Two 5-year simulations (with and without the aerosol indirect effect* including the new aerosol forcing". Below we present a summary of the climate simulations conducted.

2.1 The Regional Climate Model WRF

For the regional climate simulations of Task 2.2 "*Implementation of a new state-of-the-art aerosol forcing and test simulations*" we use the WRF model, a very popular climate and weather forecasting model. WRF has been widely used as a regional climate model (Katragkou et al. 2015; Fita et al. 2019; Ban et al. 2021) and is an official model-member of the Ensemble Desing Matrix of Coupled Model Intercomparison Project (CMIP6)/EURO-CORDEX (Katragkou et al. 2024). We use the non-hydrostatic WRF model with the Advanced Research dynamic solver (WRF-ARW, v4.5.1) has been utilized. More specifically, the selected model version is 4.5.1.4 (WRF451Q) which includes some additional modifications and improvements in NoahMP land use model (Yang et al. 2011), available from the CORDEX WRF community fork (git clone --recursesubmodules -b v4.5.1.4 https://github.com/CORDEX-WRF-community/WRF.git).

2.2 Model configuration and simulations

To assess the impact of the enhanced description of aerosol indirect effect we have conducted two 5-year regional climate simulations over Europe spanning the period 2000-2004 with an additional initial year as a spin-up period (1999). Both are conducted over the official EURO-CORDEX domain at 0.11° resolution (EUR-11) and are driven by ERA5 reanalysis data (Hersbach et al. 2020). Both simulations share the same set-up and parameterizations that follow the official WRF-EURO-CORDEX CMIP6 simulations and differ only regarding the treatment of aerosol indirect effect. For the aerosol direct effect both simulations incorporate aerosol optical depth (AOD) derived by the MERRA-CORDEX dataset (Solmon et al. 2022).

The reference simulation (Eval) is performed using the MERRA-CORDEX aerosol dataset to describe only the aerosol-radiation interactions (direct effect), while the aerosol indirect effect is crudely described by a parameter that describes the cloud droplet concentration (Nt_c). This parameterization is part of the Thompson microphysics scheme (Thompson et al. 2008) used by both simulations. In Eval simulation we use the default Nt_c value (100 x10^6 /m^3) that remains constant throughout the simulated period.

The second simulation (NTC) also uses the MERRA-CORDEX AOD for aerosol-direct effect. However, for the aerosol indirect effect (aerosol-cloud interactions) it updates the Nt_c parameter monthly to better reflect the MERRA aerosol input. The Nt_c is derived by the MERRA-CORDEX AOD based on the methodology of Stevens et al. (2017).

Table 1: The two simulations and their treatment of aerosol

Simulation	Aerosol direct effect	Aerosol indirect effect
Eval	MERRA-CORDEX dataset	Default Nt_c value fixed in time
NTC	MERRA-CORDEX dataset	Nt_c value calculated based on MERRA-CORDEX, monthly update

2.3 Methodology

The current analysis includes four variables: temperature at 2m (tas), precipitation(pr), downward shortwave radiation at the surface (rsds) and cloud fraction (clt). We focus on comparing the two simulations and thus assessing the impact of the enhanced aerosol indirect effect. Temperature and precipitation were evaluated against the most recent version (v32 – November 2025) of the E-OBS gridded observational dataset. This is a state-of -the-art dataset at high resolution (0.1 degree) (Cornes et al. 2018). We present maps of the results as well as averaged values over and the Prudence subregions (Christensen et al. 2007) and the European domain as we define it in (Figure 1 and Table 2).

Table 2: Boundaries of the original Prudence regions and the European domain as we have defined it.

Subregion	West	East	South	North
1 (BI) British Isles	-10	2	50	59
2 (IP) Iberian Peninsula	-10	3	36	44
3 (FR) France	-5	5	44	50
4 (ME) Mid-Europe	2	16	48	55
5 (SC) Scandinavia	5	30	55	70
6 (AL) Alps	5	15	44	48
7 (MD) Mediterranean	3	25	36	44
8 (EA) Eastern Europe	16	30	44	55
9 (EU) Europe	-10	30	36	70

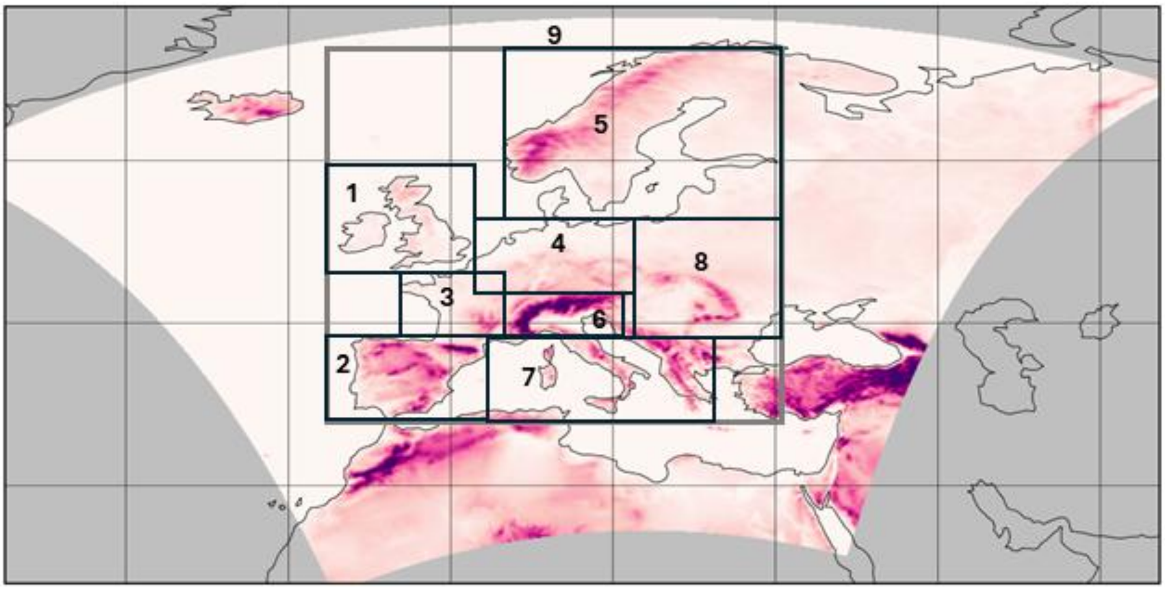

Figure 1: The original Prudence regions (black boxes and 1 to 8 numbering) and the European domain region that outlines them (grey box – number 9) as we have defined it.

Metrics used
For model comparison with observations we use the following metrics:

Bias = Simulation – Observation

Relative Bias = 100(Simulation – Observation)/Observation*

For comparison between model simulations to assess the impact of indirect effect representation*:*

Difference = NTC – Eval

Relative Difference =100(NTC – Eval)/Eval*

Absolute Difference = Absolute (NTC – Eval)

Relative Absolute Difference = Absolute (100(NTC – Eval)/Eval)*

When discussing the absolute impact of indirect effect we use the absolute difference (relative or not) between NTC and Eval while when discussing the sign of impact we use the plain difference.

3 Results

3.1 Temperature

Simulation comparison
Overall, the impact on temperature is rather limited, typically below 0.1 °C in terms of absolute differences and not spatially widespread across the domain. However, notable effects emerge over specific regions and seasons. Substantial temperature responses are identified over central and western Europe and parts of the Balkans during winter, the Iberian Peninsula in spring and summer, France in summer, and parts of eastern Europe in autumn. In these areas, temperature differences at individual grid points can exceed 0.5 °C, while mean absolute differences over selected subregions can surpass 0.2 °C. The largest overall impact occurs in winter, with an absolute mean temperature difference of 0.15 °C over the EU domain. For several subregions (FR, ME, SC, AL, and EA), wintertime mean differences are also pronounced, ranging from approximately 0.2 to 0.3 °C. On average, the NTC simulation is colder than Eval during winter over the EU domain, with a mean

difference of −0.1 °C, as well as across most subregions. In the remaining seasons, mean differences over the EU domain are generally small, while regional responses vary. Some subregions exhibit consistent behavior throughout the year, such as the Iberian Peninsula, where NTC is systematically colder, and the mountainous regions of the Balkans, where NTC tends to be warmer.

Biases against E-OBS

Overall, the temperature biases against the E-OBS dataset have very similar patterns for both simulations. Biases are usually constrained, for all seasons, remaining below 1.5 ^{o}C, while there are exceptions over specific areas. During winter and spring both simulations are colder than observations over most of the domain. In summer, there is an overall warm bias while in autumn there is a small underestimation with most areas being sightly colder than observations.

In **winter**, domain averaged (EU domain) biases are around -0.6 to -0.7^{o}C and all averaged biases over the subregions are also negative for both simulations indicating an underestimation over most areas. Averaged biases for most subregions range between -0.5 to -0.8^{o}C. Northern Scandinavia and mountainous areas over the Balkans are some limited exceptions to the overall underestimation, presenting warm biases. **Spring** presents also a widespread cold bias that is however slightly smaller than that of winter. Domain averaged (EU domain) biases are close to -0.5^{o}C for both simulations, while the mean biases over all the subregions are also negative and range between -0.3 to -0.6^{o}C. **Summer** is the only season that is warmer than the observations. Both simulations exhibit a positive mean bias of approximately +0.6 °C over the EU domain. Similarly, most subregions show positive mean biases, typically ranging from +0.4 to +0.7 °C, except for Britain and Ireland (BI), where biases are smaller or near neutral. **Autumn** presents a slight underestimation with a small cold mean bias (EU domain) of around -0.1^{o}C for both simulations. Most subregions also present mainly small negative mean biases (usually between -0.1 to -0.3 ^{o}C) except for the Alps (AL) and Eastern Europe (EA).

As described above, the biases in the two simulations are very similar in both spatial pattern and magnitude. The NTC simulation exhibits a slightly larger mean bias in winter (−0.73 °C) compared to Eval (−0.57 °C), while biases during the other seasons are very close. Consequently, both simulations demonstrate comparable overall performance. The implementation of the enhanced aerosol indirect effect in NTC does not alter the general bias pattern or magnitude; however, it can substantially modify the biases over specific regions and during particular seasons.

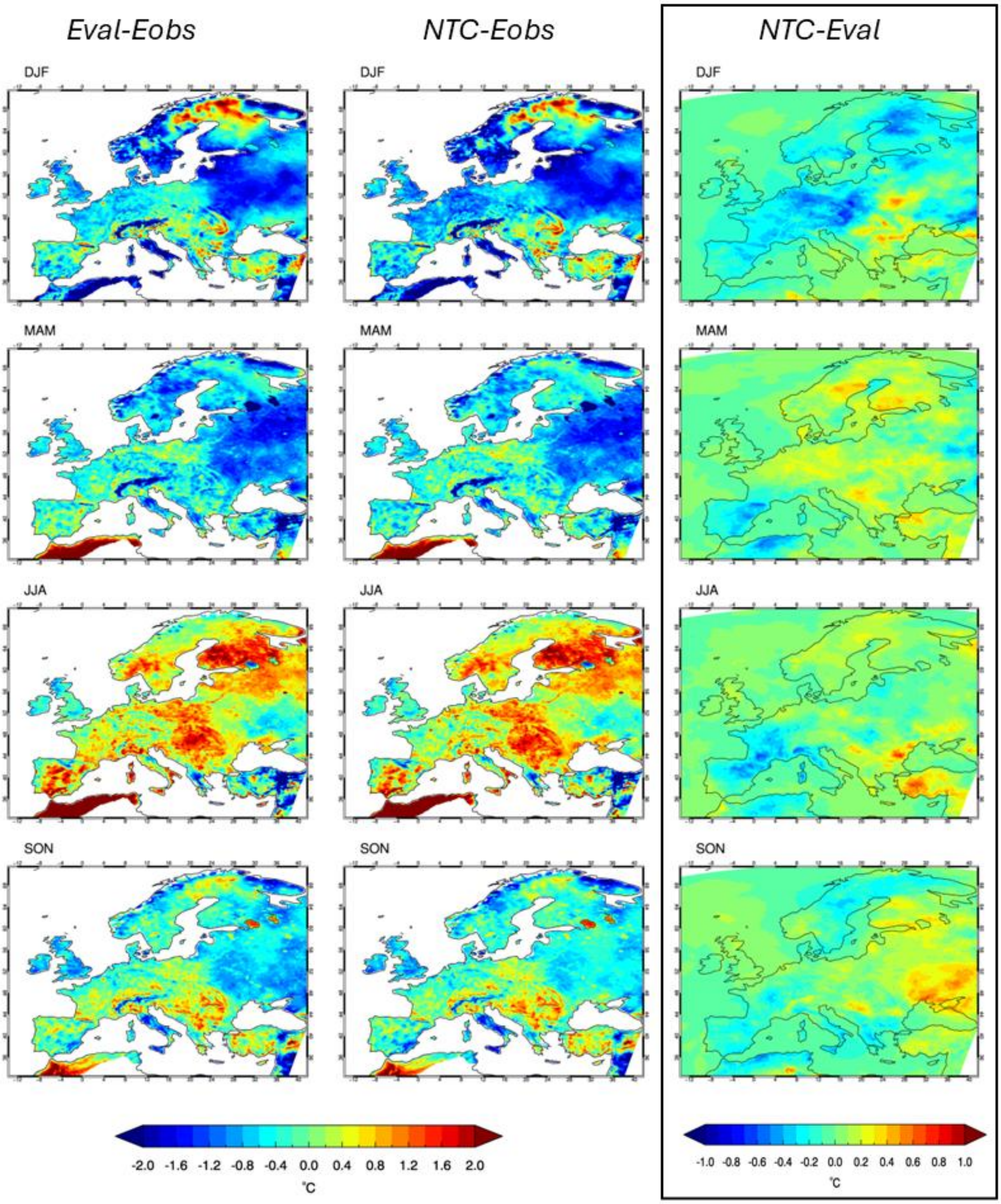

Figure 2: Temperature analysis. Bias of Eval simulation against E-OBS (first column), bias of NTC simulation against E-OBS (second column), difference between Eval and NTC simulations (third column). For all seasons (rows).

Table 3: Temperature analysis in winter. Averaged values per subregion as well as over the EU domain regardinng biases agaist E-OBS of Eval (first row) and NTC (second row) simulations, as well as the absolute difference between Eval and NTC simulations and within parenthesis the difference between the simulations (third row).

Winter (DJF)									
°C	BI	IP	FR	ME	SC	AL	MD	EA	EU
Eval - EOBS	-0.65	-0.33	-0.53	-0.51	-0.75	-0.51	-0.78	-0.53	-0.57
NTC - EOBS	-0.77	-0.54	-0.79	-0.84	-0.96	-0.78	-0.75	-0.57	-0.73
Absolute (NTC - Eval)	0.08 (-0.08)	0.16 (-0.16)	0.21 (-0.21)	0.29 (-0.29)	0.16 (-0.16)	0.26 (-0.26)	0.07 (0.01)	0.22 (-0.05)	0.15 (-0.10)

Table 4: Temperature analysis in spring. Averaged values per subregion as well as over the EU domain regardinng biases agaist E-OBS of Eval (first row) and NTC (second row) simulations, as well as the absolute difference between Eval and NTC simulations and within parenthesis the difference between the simulations (third row).

Spring (MAM)									
°C	BI	IP	FR	ME	SC	AL	MD	EA	EU
Eval - EOBS	-0.54	-0.09	-0.25	-0.34	-0.76	-0.58	-0.31	-0.63	-0.49
NTC - EOBS	-0.55	-0.33	-0.24	-0.16	-0.63	-0.56	-0.29	-0.52	-0.44
Absolute (NTC - Eval)	0.04 (-0.02)	0.16 (-0.16)	0.07 (0.00)	0.14 (0.13)	0.11 (0.09)	0.08 (0.02)	0.07 (0.00)	0.12 (0.11)	0.09 (0.03)

Table 5: Temperature analysis in summer. Averaged values per subregion as well as over the EU domain regardinng biases agaist E-OBS of Eval (first row) and NTC (second row) simulations, as well as the absolute difference between Eval and NTC simulations and within parenthesis the difference between the simulations (third row).

Summer (JJA)									
°C	BI	IP	FR	ME	SC	AL	MD	EA	EU
Eval - EOBS	-0.30	0.74	0.39	0.42	0.63	0.66	0.67	0.81	0.58
NTC - EOBS	-0.26	0.55	0.12	0.40	0.68	0.53	0.67	0.84	0.57
Absolute (NTC - Eval)	0.03 (0.02)	0.15 (-0.13)	0.20 (-0.20)	0.08 (-0.01)	0.07 (0.04)	0.14 (-0.12)	0.08 (0.00)	0.11 (0.03)	0.09 (0.00)

Table 6: Temperature analysis in autumn. Averaged values per subregion as well as over the EU domain regardinng biases agaist E-OBS of Eval (first row) and NTC (second row) simulations, as well as the absolute difference between Eval and NTC simulations and within parenthesis the difference between the simulations (third row).

Autumn (SON)									
°C	BI	IP	FR	ME	SC	AL	MD	EA	EU
Eval - EOBS	-0.72	-0.06	0.08	-0.07	-0.31	0.16	-0.10	-0.01	-0.12
NTC - EOBS	-0.69	-0.22	-0.03	-0.08	-0.34	0.13	-0.26	0.09	-0.14
Absolute (NTC - Eval)	0.04 (0.03)	0.12 (-0.12)	0.10 (-0.10)	0.06 (-0.01)	0.12 (-0.03)	0.09 (-0.02)	0.10 (-0.10)	0.11 (0.10)	0.09 (-0.03)

3.2 Precipitation

Simulation comparison

The enhanced aerosol indirect effect has a considerable impact on precipitation, since differences between NTC and Eval can be substantial. Spatially the differences are patchy and varying in sign. However, there are multiple areas, such as southern Scandinavia in spring and central Europe in summer, where widespread impacts of a specific sign are present. In many cases, over specific grid points, impacts greater than 30% can be seen.

Overall, the largest impact is seen in summer, with domain averaged (EU) absolute relative difference is around 14%. For the Mediterranean region (MD) the impact is around 29% during summer. This elevated impact, however, can be somewhat inflated due to the small precipitation amount over this region in summer. During spring and autumn, domain (EU) averaged absolute relative differences are similar, around 9%, while for most subregions the impact is close to 10%. In winter, impact is slightly smaller with a 6% domain (EU) averaged absolute relative difference. For the various subregions, impact is also more constrained, being less than 10% regarding subregional averages.

Pronounced spatial variability in the differences is evident in all seasons. Overall, however, the NTC simulation is wetter than Eval during winter, spring, and summer, with EU domain–averaged differences of approximately +2 to +3%. In contrast, autumn exhibits a slightly negative mean difference over the EU domain (−0.5%), along with considerable variability across subregional averages.

Biases against E-OBS

Overall, precipitation biases against the E-OBS dataset are substantial for all seasons with both simulations being more wet than the observations throughout the year. It is characteristic that almost all subregions also present a wet mean bias for all seasons. Domain (EU) averaged biases range from around 25% in autumn to over 80% in summer, with winter (around 35%) and spring (around 50%) also presenting large overestimation. Subregional mean biases usually range above 20% while particularly in summer, there are subregions such as the Iberian Peninsula (IP) and Mediterranean (MD) with very high mean biases, close to 200%, which correspond though, to small absolute precipitation amounts.

The spatial pattern of the precipitation biases is very similar for both simulations while mean biases are quite close is several subregions. However, they are not identical, and substantial differences in bias are seen between the two simulations over several regions and seasons. Some examples are the Alps (AL) and Middle Europe (ME) in spring, Eastern Europe (EA) in autumn and spring, France and the Alps in summer. Thus, the enhanced representation of aerosol indirect effect in NTC does modify the bias against the E-OBS data compared to the Eval simulation. Finally, the Eval simulation has a slightly better (lower) overall bias in winter and spring, while NTC has a slightly better bias in summer and autumn. Therefore, no simulation clearly demonstrates superior performance for precipitation.

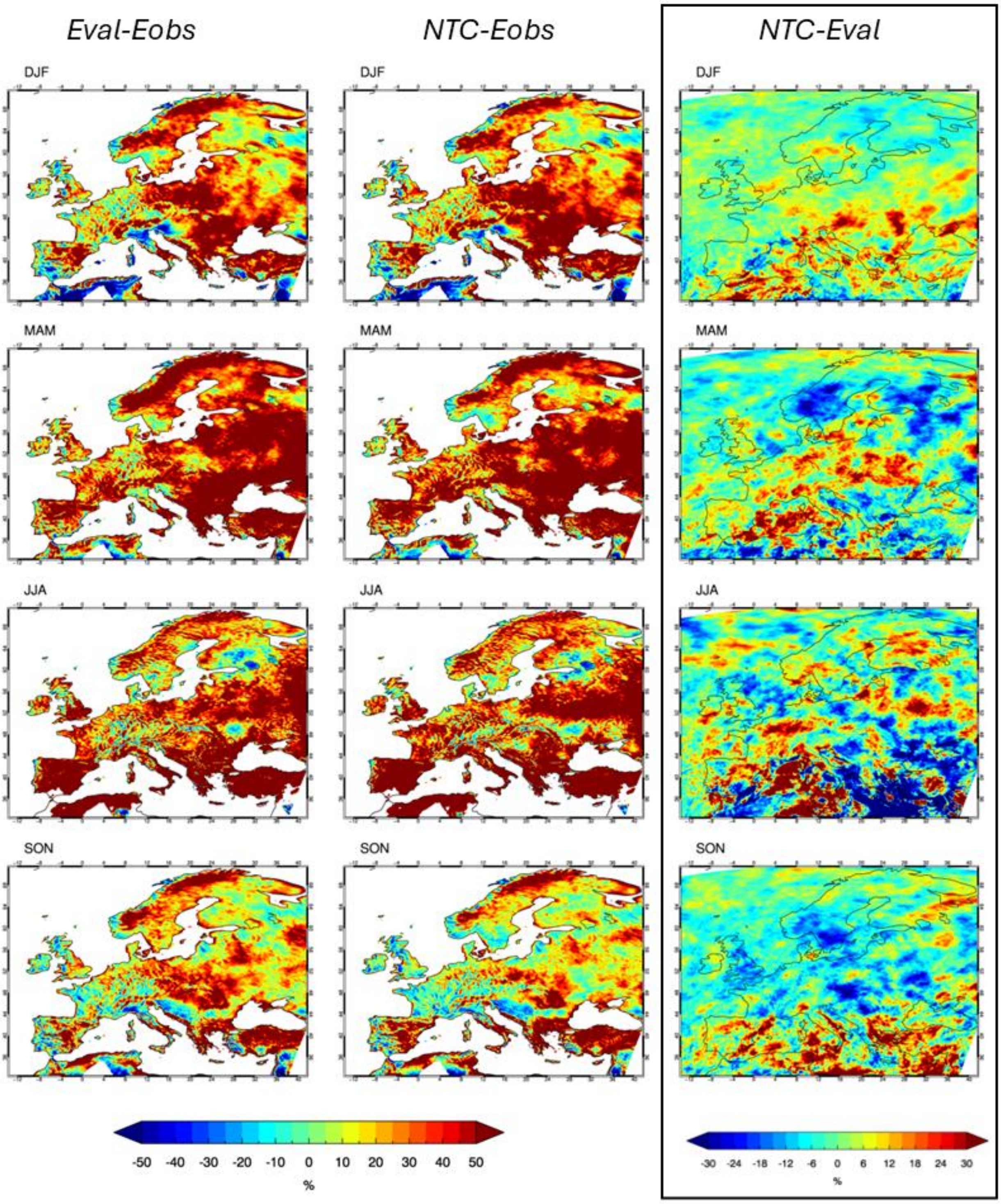

Figure 3: Precipitation analysis. bias of Eval simulation against E-OBS (first column), bias of NTC simulation against E-OBS (second column), relative difference between Eval and NTC simulations (third column). For all seasons (rows).

Table 7: Precipitation analysis in winter. Averaged values per subregion as well as over the EU domain regardinng biases agaist E-OBS of Eval (first row) and NTC (second row) simulations, as well as the absolute relative difference between Eval and NTC simulations and within parenthesis the difference between the simulations (third row)

Winter (DJF)									
	BI	IP	FR	ME	SC	AL	MD	EA	EU
Eval – EOBS %	15.2	23.4	16.0	21.8	29.4	24.4	43.0	53.9	32.9
NTC - E-OBS %	15.9	25.2	16.8	27.7	27.8	33.1	51.9	67.4	38.4
Absolute % (NTC - Eval)	3.0 (0.5)	7.2 (1.9)	3.0 (0.6)	5.7 (5.2)	4.1 (-0.8)	8.7 (7.8)	9.7 (6.9)	9.4 (8.9)	6.3 (3.4)

Table 8: Precipitation analysis in spring. Averaged values per subregion as well as over the EU domain regardinng biases agaist E-OBS of Eval (first row) and NTC (second row) simulations, as well as the absolute relative difference between Eval and NTC simulations and within parenthesis the difference between the simulations (third row)

Spring (MAM)									
	BI	IP	FR	ME	SC	AL	MD	EA	EU
Eval – EOBS %	24.0	41.5	35.3	28.8	45.1	39.0	81.1	63.7	49.8
NTC - E-OBS %	25.1	49.7	44.0	38.2	35.8	52.4	81.7	77.3	53.0
Absolute % (NTC - Eval)	5.2 (-0.1)	11.2 (9.4)	6.7 (4.8)	9.5 (5.1)	8.6 (-3.9)	10.1 (8.5)	12.4 (4.6)	12.6 (8.8)	9.4 (2.4)

Table 9: Precipitation analysis in summer. Averaged values per subregion as well as over the EU domain regardinng biases agaist E-OBS of Eval (first row) and NTC (second row) simulations, as well as the absolute relative difference between Eval and NTC simulations and within parenthesis the difference between the simulations (third row)

Summer (JJA)									
	BI	IP	FR	ME	SC	AL	MD	EA	EU
Eval – EOBS %	34.1	195.7	33.3	27.8	23.4	34.6	204.2	50.0	87.4
NTC - E-OBS %	33.1	192.1	45.6	34.9	26.5	46.5	199.2	44.7	81.2
Absolute % (NTC - Eval)	7.9 (-1.9)	16.0 (5.7)	10.8 (7.7)	12.5 (4.1)	8.3 (1.8)	11.5 (7.9)	28.6 (9.3)	12.5 (-2.4)	14.2 (2.4)

Table 10: Precipitation analysis in autumn. Averaged values per subregion as well as over the EU domain regardinng biases agaist E-OBS of Eval (first row) and NTC (second row) simulations, as well as the absolute relative difference between Eval and NTC simulations and within parenthesis the difference between the simulations (third row)

Autumn (SON)									
	BI	IP	FR	ME	SC	AL	MD	EA	EU
Eval – EOBS %	10.9	24.0	4.6	19.7	25.1	8.5	51.7	33.5	26.9
NTC - E-OBS %	3.0	34.4	-1.9	12.2	18.8	6.4	66.2	22.4	24.7
Absolute % (NTC - Eval)	7.0 (-5.4)	11.4 (9.4)	7.5 (-5.1)	7.3 (-5.6)	6.6 (-4.5)	7.6 (-1.7)	13.5 (9.1)	10.6 (-8.2)	8.9 (-0.5)

3.3 Cloud Fraction

Cloud fraction amount is also impacted when the enhanced aerosol indirect effect is implemented in NTC. Over large parts of the domain differences between the simulations are constrained, usually less than 1.5%, however extensive areas with considerable differences, in some cases exceeding 10%, are present during all seasons. Some examples are: southern Scandinavia in spring, central Mediterranean in winter and spring, eastern Mediterranean in autumn and the Iberian Peninsula in summer.

As was the case with precipitation, the largest impact is seen during summer. Domain averaged (EU) absolute relative difference is around 3.4% while for several subregions mean absolute differences range between 3 to 4%. Especially for the Mediterranean subregion (MD) impact is the largest with 6.3% mean absolute relative difference during summer, while over specific grid points the difference can exceed 15%. This strong impact during summer, however, could be inflated due to the small cloud fraction amount over this region, especially over southern Europe. During spring and autumn, domain (EU) averaged absolute relative differences are similar, around 2.4%, while for most subregions mean absolute relative differences range between 1.5 to 3%. Winter presents a slightly smaller impact with 1.7% domain (EU) averaged absolute relative difference.

The Mediterranean (MD) and the Alps (AL) are the two subregions that present the most persistent impact on cloudiness, since the mean differences (>2%) are considerable throughout the year. A similarly persistent impact during all seasons, but to a lesser extent, is also seen over the Iberian Peninsula (IB) and Eastern Europe (EU).

Overall, the NTC simulation exhibits a slightly larger cloud cover than Eval during winter over the EU domain, with a mean increase of approximately +0.9%, and similar behavior across most subregions. During the remaining seasons, no consistent pattern emerges, and the sign of the subregionally averaged differences varies. Focusing on the Mediterranean region, Eval shows higher cloud cover in winter, spring, and autumn, whereas in summer a pronounced spatial variability with both positive and negative differences is observed across the subregion.

Table 11: Cloud fraction absolute relative difference and within parenthesis the relative difference between the simulations. Averaged values per subregion as well as over the EU domainfor all seasons.

Absolute % (NTC - Eval)									
	BI	IP	FR	ME	SC	AL	MD	EA	EU
Winter (DJF)	0.9 (-0.6)	2.2 (-1.5)	1.2 (0.1)	1.0 (0.5)	0.7 (0.1)	4.0 (4.0)	3.5 (3.4)	2.1 (2.1)	1.7 (0.9)
Spring (MAM)	1.6 (-1.3)	2.8 (0.3)	1.2 (0.5)	1.5 (-0.4)	3.1 (-3.0)	3.0 (2.7)	3.2 (2.3)	1.8 (1.3)	2.3 (-0.1)
Summer (JJA)	1.2 (0.14)	4.2 (2.5)	2.6 (2.0)	3.0 (0.7)	2.0 (-1.4)	4.4 (4.1)	6.3 (0.7)	3.4 (-2.4)	3.4 (-0.2)
Autumn (SON)	1.6 (-1.4)	2.2 (-1.9)	1.4 (-1.1)	2.7 (-2.5)	1.3 (-0.6)	2.1 (-1.1)	4.8 (3.5)	2.9 (-2.6)	2.4 (-0.3)

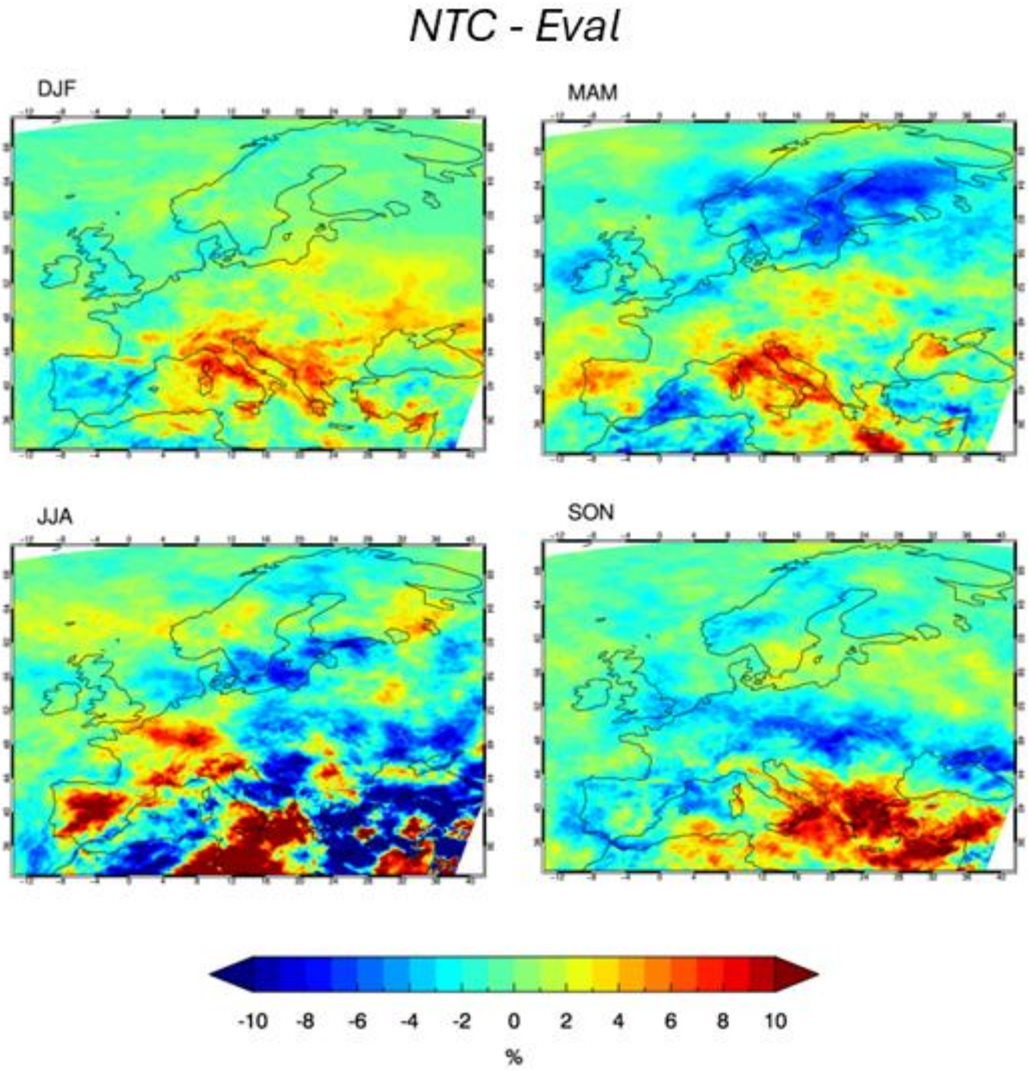

Figure 4: Cloud fraction relative difference between Eval and NTC simulations. For all seasons.

3.4 Shortwave radiation

The two simulations present differences regarding downward shortwave radiation at the surface (rsds). Extensive areas with considerable impact are seen throughout the year. Some examples are: eastern Europe in autumn and spring, western Europe in winter and the Mediterranean subregion (MD) during winter and spring. In many cases, over specific grid points differences can exceed 5%. Cloud fraction changes are certainly a significant driver of the changes in rsds, even though these two fields are not always spatially correlated.

Largest impact is seen during autumn with the domain averaged (EU) relative absolute difference being 2.2%. Winter and spring present a slightly smaller impact (1.6%) while summer presents the lowest domain averaged relative absolute difference (1%).

Scandinavia (SC) and the British Isles (BI) are the two subregions that present the most persistent impact on rsds with mean differences being above 1.5% throughout the year. Finally, the largest impact regarding subregionally averaged differences is present in Middle Europe (MD) in autumn (3.7%).

Overall, the NTC simulation exhibits higher downward surface shortwave radiation than Eval in all seasons when considering EU domain–averaged differences, ranging from 0.7 to 1.7%. The largest positive impact occurs in autumn (+1.7%). Increased surface shortwave radiation in NTC is also evident across most subregions, with a few notable exceptions: the Alps (AL) in winter, spring, and summer; the Mediterranean (MD) in winter and autumn; and Eastern Europe (EA) in spring.

Table 12: Shortwave radiation at the surface absolute relative difference and within parenthesis the relative difference between the simulations. Averaged values per subregion as well as over the EU domainfor all seasons.

Absolute % (NTC - Eval)									
	BI	IP	FR	ME	SC	AL	MD	EA	EU
Winter (DJF)	2.2 (2.2)	1.2 (0.9)	2.5 (2.5)	2.5 (2.4)	1.9 (1.7)	1.0 (-0.3)	0.9 (-0.3)	1.2 (0.6)	1.6 (1.1)
Spring (MAM)	1.6 (1.0)	0.8 (0.1)	0.9 (0.2)	0.7 (0.1)	3.1 (2.9)	0.9 (-0.6)	0.9 (0.1)	1.1 (-0.6)	1.6 (0.9)
Summer (JJA)	1.4 (1.3)	0.5 (-0.1)	0.7 (0.0)	1.0 (0.5)	1.6 (1.4)	0.6 (-0.4)	0.4 (0.0)	0.8 (0.7)	1.0 (0.7)
Autumn (SON)	3.4 (3.3)	0.7 (0.2)	1.2 (0.9)	3.7 (3.7)	2.9 (2.5)	1.4 (0.6)	0.7 (-0.4)	3.3 (3.2)	2.2 (1.7)

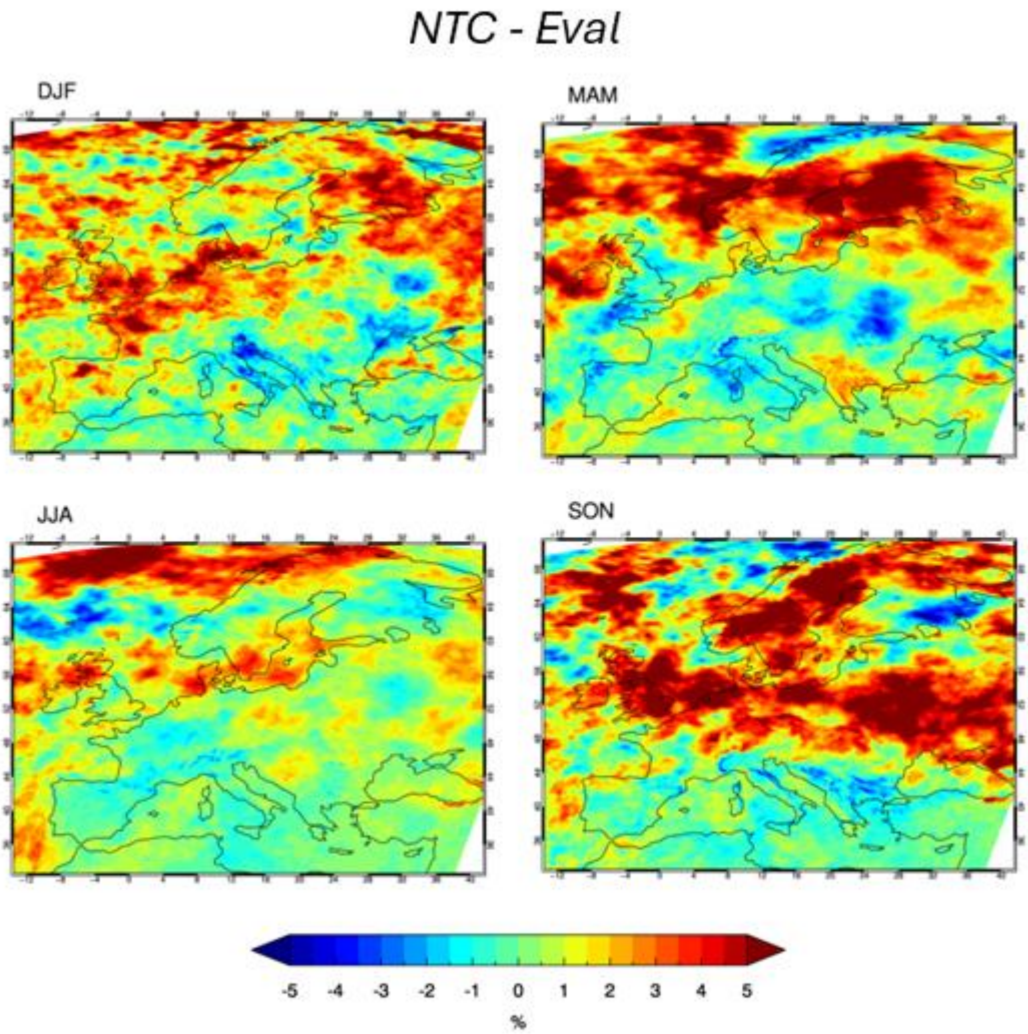

Figure 5: Shortwave radiation at the surface relative difference between Eval and NTC simulations. For all seasons.

3.5 Conclusions

In this section we present a synthesis of the results across all variables to provide a provide a comprehensive assessment of the impacts of aerosol indirect effect representation. Figure 6 up to Figure 9 display the seasonal difference maps between the NTC and Eval simulations for all variables.

Modifications in the aerosol indirect effect representation (changes in the Nt_c parameter) in the Thompson microphysics scheme can clearly impact both precipitation and cloud fraction. Over specific grid points, changes in precipitation can exceed 30% while changes over 10% are seen in cloudiness. Precipitation changes exhibit a patchy spatial structure, while cloud fraction shows more spatially cohesive changes. These two fields are not very well spatially correlated (coefficient ~ 0.3 for all seasons). Overall, there does not seem to be a specific tendency towards cloud fraction changes with a given change in precipitation over the entire domain. However, over specific areas precipitation and cloud fraction changes can be either strongly positively or strongly negatively correlated.

Downward shortwave radiation at the surface is also clearly impacted with changes over 5% seen over many specific grid points during all seasons. One of the major drivers of shortwave radiation change is definitely the change in cloudiness. Overall, radiation and cloud fraction changes have a decent negative spatial correlation, as expected, that is around -0.6 for most seasons except in winter where it drops to a mediocre -0.4. Therefore, in many cases the impacts in cloud fraction do seem to cause considerable collocated impacts in shortwave radiation.

Temperature is also impacted. Changes are modest, usually less than 0.5^{o}C however, over specific limited cases can reach 1^{o}C. Interestingly, the changes in temperature are not very well spatially correlated with the changes in shortwave radiation. Coefficients are quite small, below 0.2 for all seasons and only in autumn reach 0.3.

We must note that there are some cases over specific areas where collocated impacts are seen in all examined variables. A nice example is central Europe and Iberian Peninsula during summer; a strong precipitation increase is accompanied by a clear increase in cloudiness (positive correlation) that leads to a considerable decrease in shortwave radiation and finally a decrease in near surface temperature. Another example is the central and eastern Mediterranean in autumn.

The Mediterranean showcases a strong sensitivity in indirect effect representation, since it is among the most impacted regions regarding all seasons and all examined variables.

When compared to the E-OBS dataset, the simulations showcase an overall decent performance regarding temperature where even at grid point level biases rarely exceed 1.5 ^{o}C. Precipitation biases are usually positive and in most cases relatively constrained (<30%), however considerably larger values can exist over specific areas and seasons. Finally, both simulations present a similar performance for both temperature and precipitation. Even though the introduction of an enhanced aerosol indirect effect in simulation NTC can modify the biases compared to Eval, the overall performance does not change drastically.

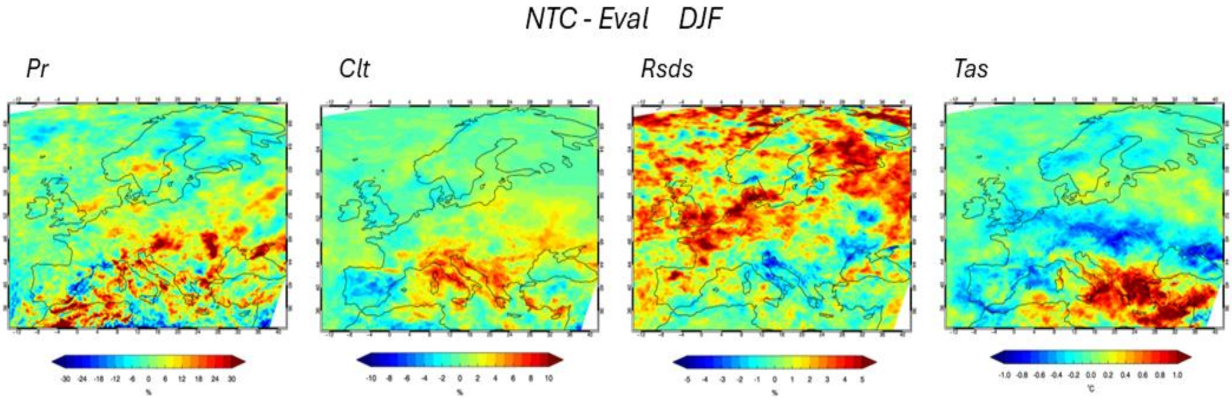

Figure 6: Difference between Eval and NTC simulations in winter. For precipitation (pr), cloud fraction (clt), shortwave radiation at the surface (rsds) and temperature (tas).

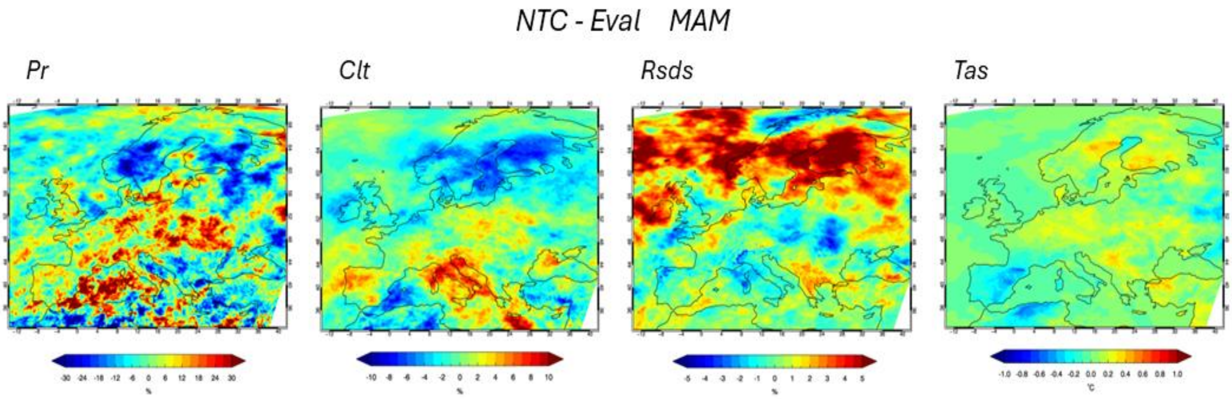

Figure 7: Difference between Eval and NTC simulations in spring. For precipitation (pr), cloud fraction (clt), shortwave radiation at the surface (rsds) and temperature (tas).

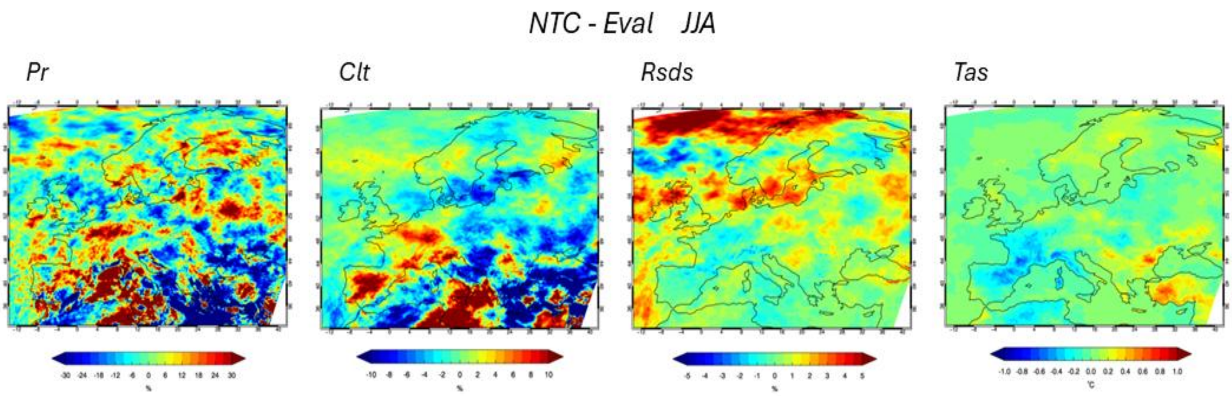

Figure 8: Difference between Eval and NTC simulations in summer. For precipitation (pr), cloud fraction (clt), shortwave radiation at the surface (rsds) and temperature (tas).

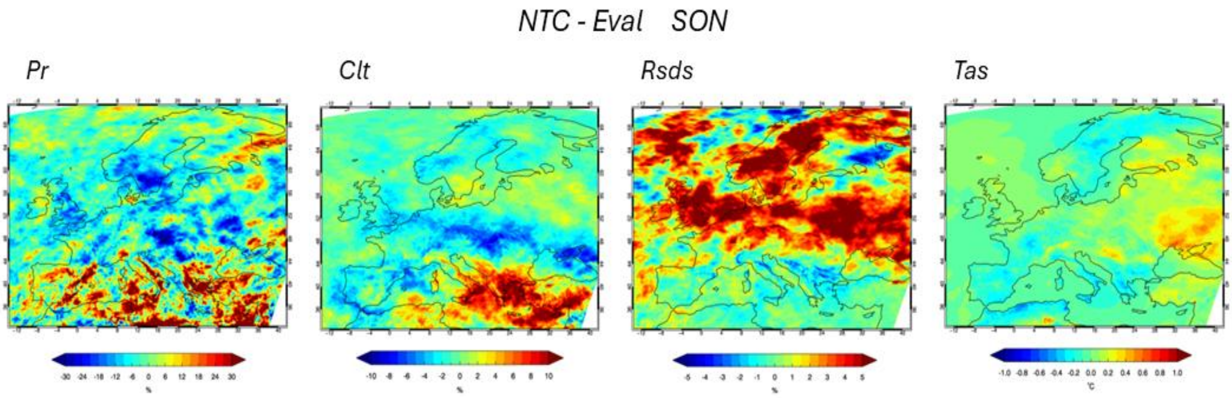

Figure 9: Difference between Eval and NTC simulations in autumn. For precipitation (pr), cloud fraction (clt), shortwave radiation at the surface (rsds) and temperature (tas).

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H.F.R.I. Hellenic Foundation for Research & Innovation
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Funded by the European Union NextGenerationEU