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

Acronym: **UpClim**

Deliverable 2.5

Two 5-year simulations (with and without the aerosol indirect effect) including the new aerosol forcing

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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	Meteorology and Climatology
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 Centre 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 2.5 (D2.5) of Task 2.2 ("Implementation of a new state-of-the-art aerosol forcing and test simulations"), under Working Package 2, "Implementation of time evolving aerosol forcing") in the framework of the UpClim project. One of the primary objectives of the UpClim project is the implementation of improved aerosol forcing, both the direct (aerosol-radiation interactions) and indirect (aerosol-cloud interactions) aerosol effects, into a regional climate model. Emphasis is given on the aerosol indirect effect, in order to assess its impacts on regional climate over Europe. For this purpose, we use the Weather Research and Forecasting (WRF) model and incorporate a state-of-the art aerosol dataset into the aerosol direct effect parameterization but most importantly, we modify the aerosol indirect effect in the microphysics parameterization to better describe the aforementioned aerosol data. These steps are described in detail in Deliverable 2.4 ("Model source code modifications to include the indirect aerosol effect").

2 Numerical simulations

2.1 Regional Climate Model utilized

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. 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 (Sobolowski et al., 2025). 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 as EURO-CORDEX ensemble member) 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 numerical experiments

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. The MERRA-CORDEX is a dataset of monthly aerosol optical properties with global coverage that has recently been published specifically to be used in climate model simulations (Solmon et al. 2022). It is used as the reference aerosol dataset for the EURO-CORDEX evaluation simulations (Katragkou et al., 2024).

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

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described by a parameter that describes the cloud droplet concentration (Nt_c). This parameterization is part of the Thompson microphysics scheme 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 on a monthly basis 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).
As stated, the rest parameterizations and set-up are identical for both simulations. These include: the Thompson microphysics scheme (mp_physics = 8) (Thompson et al. 2008), the RRTMG scheme (Iacono et al. 2008) for the shortwave and longwave radiation, the Mellor-Yamada Nakanishi and Niino Level 2.5 (MYNN2) scheme (Nakanishi and Niino 2006; 2009) for representation of boundary layer properties, the Kain-Fritcsh scheme (Kain 2004) for the parameterization of sub-grid convection, the Nakanishi and Niino PBL's surface layer scheme for surface layer processes and Noah-MP Land Surface Model (Niu et al. 2011; Yang et al. 2011) for land-atmosphere interactions. For the vertical model set-up we used 54 sigma levels reaching up to 20hPa.
Both simulations used the ERA5 reanalysis data (Hersbach et al. 2020) as initial and boundary conditions. The ERA5 is produced by the European Center for Medium-Range Weather Forecasts (ECMWF), and it is based on the Integrated Forecasting System (IFS) Cy41r2 with horizontal resolution of 31 km, 137 vertical layers and hourly output. The ERA5 is available from the Copernicus Climate Change Service (C3S) (Thepaut et al. 2018) at a horizontal grid-spacing of 0.25°x 0.25° (latitude-longitude).

Table 1: Monthly values of cloud droplet concentration values (Nt_c) derived by the MERRA-CORDEX dataset and used in simulation NTC for the period 1999-2004.

year	month	Nt_c	year	month	Nt_c	year	month	Nt_c
1999	1	71,1	**2000**	1	68,2	**2001**	1	71,3
1999	2	71,5	**2000**	2	69,5	**2001**	2	73,6
1999	3	75,5	**2000**	3	75,7	**2001**	3	75,2
1999	4	75,9	**2000**	4	77,4	**2001**	4	77,2
1999	5	76,5	**2000**	5	78,7	**2001**	5	77,5
1999	6	77,6	**2000**	6	77,2	**2001**	6	77,3
1999	7	78,7	**2000**	7	76,9	**2001**	7	78,7
1999	8	77,0	**2000**	8	78,7	**2001**	8	79,8
1999	9	76,6	**2000**	9	76,3	**2001**	9	75,3
1999	10	71,4	**2000**	10	74,4	**2001**	10	73,2
1999	11	71,2	**2000**	11	72,2	**2001**	11	68,6
1999	12	67,9	**2000**	12	70,3	**2001**	12	68,7
year	month	Nt_c	year	month	Nt_c	year	month	Nt_c
2002	1	69,3	**2003**	1	69,9	**2004**	1	69,6
2002	2	70,3	**2003**	2	74,5	**2004**	2	70,0
2002	3	73,7	**2003**	3	78,7	**2004**	3	75,3
2002	4	79,5	**2003**	4	80,6	**2004**	4	79,0

2002	5	76,8
2002	6	78,0
2002	7	80,9
2002	8	83,0
2002	9	79,4
2002	10	71,7
2002	11	71,2
2002	12	71,4

2003	5	80,7
2003	6	82,7
2003	7	79,5
2003	8	80,5
2003	9	76,1
2003	10	70,7
2003	11	71,8
2003	12	68,2

2004	5	77,0
2004	6	75,6
2004	7	81,3
2004	8	78,4
2004	9	73,5
2004	10	71,7
2004	11	69,3
2004	12	67,9

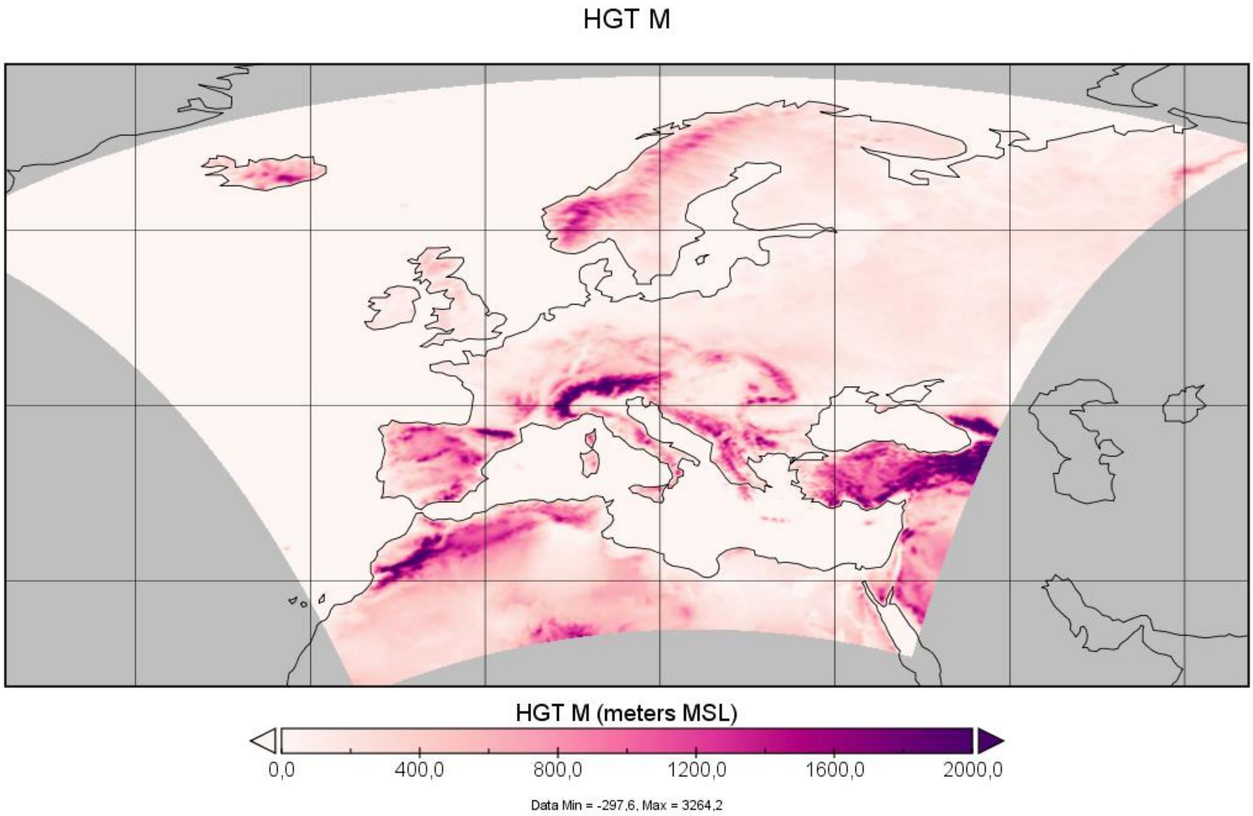

Figure 1: Surface altitude over the entire domain that is common for both Eval and NTC simulations.

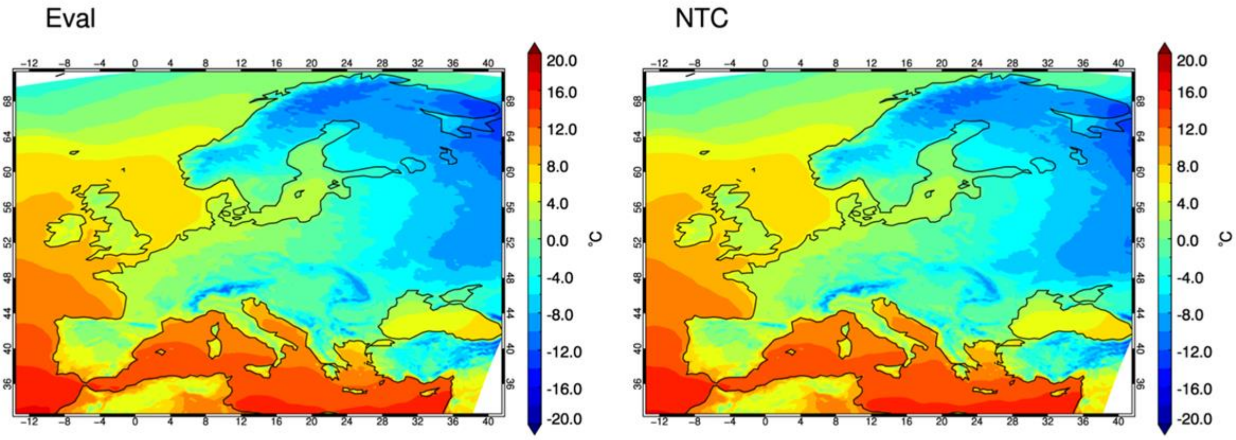

Figure 2: Monthly mean near surface temperature for simulations Eval (left) and NTC (right) for January 2000.

3 Data availability and simulated variables

The raw output data of both simulations has been extensively post-processed to produce a number of climate variables that cover all aspects of the climate system in easy to access form. In total, 159 variables are available in NetCDF format. All variables are available on monthly resolution while also hourly, six-hourly or daily resolution is available depending on the given variable (Table 1). The total amount of data for both simulations is approximately 2 TB. The data are stored in the Aristotelis Data Centre of AUTH, in the following path:"/mnt/meteo_i/WRF_EURO-CORDEX_CMIP6/cmorized/Fully_cmorized/ECMWF_runs/" and are available upon request (mailto: katragou@geo.auth.gr). In the Appendix, we present the structure of a typical NetCDF file.

Table 2: List of all extract variables for the two simulations

Output variable name	units	long_name	Frequency
clivi	kg m^{-2}	Ice Water Path	1hr
clt	%	Total Cloud Cover Percentage	1hr
clwvi	kg m^{-2}	Condensed Water Path	1hr
evspsbl	kg m^{-2} s^{-1}	Evaporation Including Sublimation and Transpiration	1hr
hfls	W m^{-2}	Surface Upward Latent Heat Flux	1hr
hfss	W m^{-2}	Surface Upward Sensible Heat Flux	1hr
hurs	%	Near-Surface Relative Humidity	1hr
huss	1	Near-Surface Specific	1hr

		Humidity	
mrsos	kg m^{-2}	Moisture in Upper Portion of Soil Column	1hr
pr	kg m^{-2}	Precipitation	1hr
prc	kg m^{-2}	Convective Precipitation	1hr
prsn	kg m^{-2} s^{-1}	Snowfall flux	1hr
prw	kg m^{-2}	Water Vapor Path	1hr
ps	Pa	Surface Air Pressure	1hr
psl	Pa	Sea Level Pressure	1hr
rlds	W m^{-2}	Surface Downwelling Longwave Radiation	1hr
rlus	W m^{-2}	Surface Upwelling Longwave Radiation	1hr
rlut	W m^{-2}	TOA Outgoing Longwave Radiation	1hr
rsds	W m^{-2}	Surface Downwelling Shortwave Radiation	1hr
rsdt	W m^{-2}	TOA Incident Shortwave Radiation	1hr
rsus	W m^{-2}	Surface Upwelling Shortwave Radiation	1hr
rsut	W m^{-2}	TOA Outgoing Shortwave Radiation	1hr
sfcWind	m s^{-1}	Near-Surface Wind Speed	1hr
tas	K	Near-Surface Air Temperature	1hr
ts	K	Surface Temperature	1hr
uas	m s^{-1}	Eastward Near-Surface Wind	1hr
vas	m s^{-1}	Northward Near-Surface Wind	1hr
zmla	m	Height of Boundary Layer	1hr
hus at various pressure levels*	1	Specific Humidity at level	6hr
mrro	kg m^{-2} s^{-1}	Total Runoff	6hr
mrros	kg m^{-2} s^{-1}	Surface Runoff	6hr
mrso	kg m^{-2}	Total Soil Moisture Content	6hr
snc	%	Snow Area Percentage	6hr
snd	m	Snow Depth	6hr

snm	kg m^{-2}	Surface Snow Melt	6hr
ta at various pressure levels*	K	Air Temperature at level	6hr
ua at various pressure levels*	m s^{-1}	Eastward Wind at level	6hr
va at various pressure levels*	m s^{-1}	Northward Wind at level	6hr
wa at various pressure levels*	m s^{-1}	Upward Air Velocity at level	6hr
zg at various pressure levels*	m	Geopotential Height	6hr
tasmax	K	Daily Maximum NearSurface Air Temperature	day
tasmin	K	Daily Minimum NearSurface Air Temperature	day
orog	m	Surface Altitude	-
sftlf	%	Percentage of the Grid Cell Occupied by Land	-

*Available pressure levels: 1000, 925, 850, 750, 700, 600, 500, 400, 300, 250, 200, 150, 100, 70, 50, 30, 20

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APPENDIX

```
netcdf tas_EUR-11_ERA5_evaluationECMWF_r1i1p1f1_AUTH-MC-WRF451_v1-
r1_1hr_1999010100-1999020100 {
dimensions:
	rlon = 424 ;
	rlat = 412 ;
	height = 1 ;
	time = UNLIMITED ; // (745 currently)
variables:
	double lon(rlat, rlon) ;
		lon:standard_name = "longitude" ;
		lon:long_name = "Longitude" ;
		lon:units = "degrees_east" ;
		lon:_CoordinateAxisType = "Lon" ;
	double lat(rlat, rlon) ;
		lat:standard_name = "latitude" ;
		lat:long_name = "Latitude" ;
		lat:units = "degrees_north" ;
		lat:_CoordinateAxisType = "Lat" ;
	double rlon(rlon) ;
		rlon:standard_name = "grid_longitude" ;
		rlon:long_name = "Longitude in rotated pole grid" ;
		rlon:units = "degrees" ;
		rlon:axis = "X" ;
	double rlat(rlat) ;
		rlat:standard_name = "grid_latitude" ;
		rlat:long_name = "Latitude in rotated pole grid" ;
		rlat:units = "degrees" ;
		rlat:axis = "Y" ;
	char rotated_pole ;
		rotated_pole:grid_mapping_name = "rotated_latitude_longitude" ;
		rotated_pole:grid_north_pole_latitude = 39.25f ;
		rotated_pole:grid_north_pole_longitude = 18.f ;
	double height(height) ;
		height:standard_name = "height" ;
		height:long_name = "Height" ;
		height:units = "m" ;
		height:positive = "up" ;
		height:axis = "Z" ;
	double time(time) ;
		time:standard_name = "time" ;
		time:long_name = "Time" ;
```

time:units = "days since 1949-12-01T00:00:00Z" ;
time:calendar = "standard" ;
time:axis = "T" ;
float tas(time, rlat, rlon) ;
tas:standard_name = "air_temperature" ;
tas:long_name = "Near-Surface,Air,Temperature" ;
tas:units = "K" ;
tas:cell_methods = "time: point" ;
tas:coordinates = "lon lat height" ;
tas:grid_mapping = "rotated_pole" ;
tas:missing_value = 1.e+20f ;
tas:_FillValue = 1.e+20f ;

// global attributes:
:activity_id = "DD" ;
:contact = "Eleni Katragkou, katragou@geo.auth.gr" ;
:Conventions = "CF-1.4" ;
:creation_date = "2025-07-25-T11:48:52Z" ;
:domain_id = "EUR-11" ;
:domain = "Europe" ;
:driving_experiment_id = "evaluationECMWF" ;
:driving_experiment = "evaluation: reanalysis simulation of the recent past" ;
:driving_institution_id = "ECMWF" ;
:driving_source_id = "ERA5" ;
:driving_variant_label = "r1i1p1f1" ;
:frequency = "1hr" ;
:grid = "Cylindrical Equidistant with 0.11 degree grid spacing" ;
:institution = "Aristotle University of Thessaloniki, Dept. of Meteorology & Climatology, Thessaloniki, Greece" ;
:institution_id = "AUTH-MC" ;
:license = "https://cordex.org/data-access/cordex-cmip6-data/cordex-cmip6-terms-of-use" ;
:mip_era = "CMIP6" ;
:product = "output" ;
:project_id = "CORDEX" ;
:source = "Weather Research and Forecasting model version 4.5.1" ;
:source_id = "AUTH-MC-WRF451" ;
:source_type = "ARCM" ;
:tracking_id = "55ba4aa2-694d-11f0-afee-080038b98cf3" ;
:variable_id = "tas" ;
:version_realization = "v1-r1" ;
:references = "http://www.auth.gr" ;
:title = "Run at ECMWF, AUTH-MC-WRF451 model output prepared for EU CORDEX evaluation run, forcing from ERA5 reanalysis" ;
:comment = "postprocessing: WRF_CMORizer.f90 v0.4; excl. 10 grid point boundary

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```
relaxation zone" ;
		:conventionsURL = "http://www.cfconventions.org" ;
```