Horizon 2020

Societal Challenge: Improving the air quality and reducing the carbon footprint of European cities

Project: 690105 – ICARUS

Full project title:

Integrated Climate forcing and Air pollution Reduction in Urban Systems

MS12: Atmospheric modeling results for the whole of Europe and for the participating cities

WP 3: Integrated atmospheric modelling for connecting pressures to the environment to concentrations at the regional and urban scales

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1. Introduction

In compliance with WP3 requirements a computational environment has been created in terms of software and hardware to be able to predict meteorological and air quality conditions in regional and local urban scale in Europe under give climatic conditions in the future, present and past. Particularly, this study provides high space and time resolution ground concentrations reflecting climatic trends for the period 2001-2050.

- on major air pollutants (PM_{10}, $PM_{2.5}$, NO_2, O_3, BaP)
- on major Greenhouse Gases (CO_2, CH_4)

in Europe, focusing on nine (9) cities i.e. Thessaloniki, Athens, Madrid, Stuttgart, Ljubljana, Brno, Milan, Basel and Copenhagen/Roskilde using

- appropriate climatic and emission scenarios and
- appropriate air modelling and statistical tools.

2. Methodology

2.1. The Strategy

Trying to follow climatic changes on local meteorology and air quality is a very demanding effort in terms of computational capability and computational time.

Thus, the present methodological strategy is based on the following principles:

1. Minimize the required CPU time and be at the same time adequately reliable.
2. Provide a methodological approach to avoid unnecessary additional computational runs.

Based on the above principles and taking into consideration the modeling state of the art and the available resources the following decisions have been made:

1. Provide the necessary meteorological input for the future years following the IPCC scenarios based on the Fifth Assessment Report (AR5) and on the Representative Concentration Pathways (RCP);
2. Investigate the possibility to provide air quality future trends and representative detailed results following the concept of weather clustering/classification;
3. Produce the abovementioned detailed results by using WRF-Chem methodology to provide hourly concentrations of air pollutants in both regional and local scale on the selected representative days.

2.2. The Platform

The computational system has been upgraded with partial support of ICARUS Project. A short system description is given below

No.	Description
1.	**<u>Server:</u> DELL PE R530** **CPU: 2 x Intel Xeon Processor E5-2630 v3 (8 cores, 20M Cache, 2.40 GHz, 8 GT/s QPI)** **HDDs: 6 x 4TB 7.2K 3.5''** **RAM: 48 GB RDIMM**
2.	**<u>Server:</u> DELL PE R530** **CPU: 2 x Intel Xeon Processor E5-2630 v3 (8 cores, 20M Cache, 2.40 GHz, 8 GT/s QPI)** **HDDs: 2 x 300Gb 10K SAS** **RAM: 48 GB RDIMM**
3.	**<u>Server:</u> DELL PE R530** **CPU: 2 x Intel Xeon Processor E5-2630 v3 (8 cores, 20M Cache, 2.40 GHz, 8 GT/s QPI)** **HDDs: 2 x 300Gb 10K SAS** **RAM: 48 GB RDIMM**

The Platform functions as integrated environment for hosting and executing Prediction Models on demand. Installing, configuring and running models such as WRF is a very costly process, as far as resources are concerned, in the sense that it that entails overheads for finding and installing third party tools (compilers, software libraries etc.), handling and maintaining dependencies, as well as updating software packages that function either within the operating system or the computational models themselves. Furthermore, all software components need automation up to a great degree for initialization, configuring and scheduling runs and extracting, categorizing, storing, managing and presenting the results. Our approach aims to unify as many aspects of the aforementioned models as possible and provide a graphical tool for using WRF consistently, taking out of the picture as many issues as possible that would otherwise require special technical staff.

2.3.The Models

2.3.1. The WRF and WRF-Chem Models

The Weather Research and Forecasting (WRF) Model is a next-generation mesoscale numerical weather prediction system designed for both atmospheric research and operational forecasting applications. It features two dynamical cores, a data assimilation system, and a software architecture supporting parallel computation and system extensibility. The model serves a wide range of meteorological applications across scales from tens of meters to thousands of kilometers.

For researchers, WRF can produce simulations based on actual atmospheric conditions (i.e., from observations and analyses) or idealized conditions. WRF offers operational forecasting a flexible and computationally-efficient platform, while reflecting recent advances in physics, numerics, and data assimilation contributed by developers from the expansive research community. WRF is currently in operational use at NCEP and other national meteorological centers as well as in real-time forecasting configurations at laboratories, universities, and private companies.

The ARW has been developed in large part and is maintained by NCAR's Mesoscale and Microscale Meteorology Laboratory. The NMM core was developed by the National Centers for Environmental Prediction, and is currently used in their HWRF (Hurricane WRF) system.

- **Physics**

Since the model is developed for both research and operational groups, sophisticated physics schemes and simple physics schemes are needed in the model. The objectives of the WRF physics development are to implement a basic set of physics into the WRF model. The WRF physics options fall into several categories, each containing several choices. The physics categories are (1) microphysics, (2) cumulus parameterization, (3) planetary boundary layer (PBL), (4) land-surface model, and (5) radiation. Since the WRF model is targeted at resolutions of 1-10 km, some of physics schemes might not work properly in this high resolution (e.g. cumulus parameterization).

WRF-Chem is the Weather Research and Forecasting (WRF) model coupled with Chemistry. The model simulates the emission, transport, mixing, and chemical transformation of trace gases and aerosols simultaneously with the meteorology. The model is used for investigation of regional-scale air quality, field program analysis, and cloud-scale interactions between clouds and chemistry.

The WRF-Chem model package consists of the following components

- Dry deposition, coupled with the soil/vegetation scheme

- Four choices for biogenic emissions:
  - No biogenic emissions included
  - Online calculation of biogenic emissions as in Simpson et al. (1995) and Guenther
  - et al. (1994) includes emissions of isoprene, monoterpenes and nitrogen
  - emissions by soil
  - Online modification of user specified biogenic emissions such as the EPA
  - Biogenic Emissions Inventory System (BEIS) version 3.14. The user must
  - provide the emissions data for their own domain in the proper WRF data file
  - format
  - Online calculation of biogenic emissions from MEGAN
- Three choices for anthropogenic emissions:
  - No anthropogenic emissions Global emissions data from the one-half degree RETRO and ten-degree EDGAR data sets
  - Specified anthropogenic emissions such as those available from the U.S.
  - EPA NEI-05 and NEI-11 data inventories. The user must provide the emissions data for their own domain in the proper WRF data file format
- Several choices for gas
  - phase chemical mechanisms including:
  - RADM2, RACM, CB4 and CBM-Z chemical mechanisms
  - The use of the Kinetic Pre-Processor, (KPP) to generate the chemical
  - mechanisms. The equation files (using Rosenbrock type solvers) are currently available for RADM2, RACM, RACM-MIM, SAPRC-99, MOZART and NMHC9 chemical mechanisms
- Three choices for photolysis schemes:
  - Madronich scheme coupled with hydrometeors, aerosols, and convective parameterizations. This is a computationally intensive choice, tested with many setups
  - Fast-J photolysis scheme coupled with hydrometeors, aerosols and convective parameterizations

    - F-TUV photolysis scheme. This scheme, also from Sasha Madronich is faster than the previous Madronich scheme option.

- Five choices for aerosol schemes:
    - The Modal Aerosol Dynamics Model for Europe - MADE/SORGAM
    - The Modal Aerosol Dynamics Model for Europe with the Volitity Basis Set aerosols – MADE/VBS
    - The Modal Aerosol Module (MAM) 3 or 7 bin schemes closely coupled to the CAM5 physics
    - The Model for Simulating Aerosol Interactions and Chemistry (MOSAIC-4 or 8 bins) sectional model aerosol parameterization
    - A bulk aerosol module from GOCART
- Aerosol indirect effect through interaction with atmospheric radiation, photolysis, and microphysics routines.
- An option for the passive tracer transport of greenhouse gases
- Two options for a 10-bin volcanic ash aerosol scheme based upon emissions from a single active volcano. One scheme includes SO2 degassing from the volcano while the other ignores SO2 degassing. Volcanic ash emissions can also be coupled to some aerosol modules (bulk and modal)
- A tracer transport option in which the chemical mechanism, deposition, etc. has beenturned off. The user must provide the emissions data for their own domain in the proper WRF data file format for this option. May be run parallel with chemistry
- A plume rise model to treat the emissions of wildfires

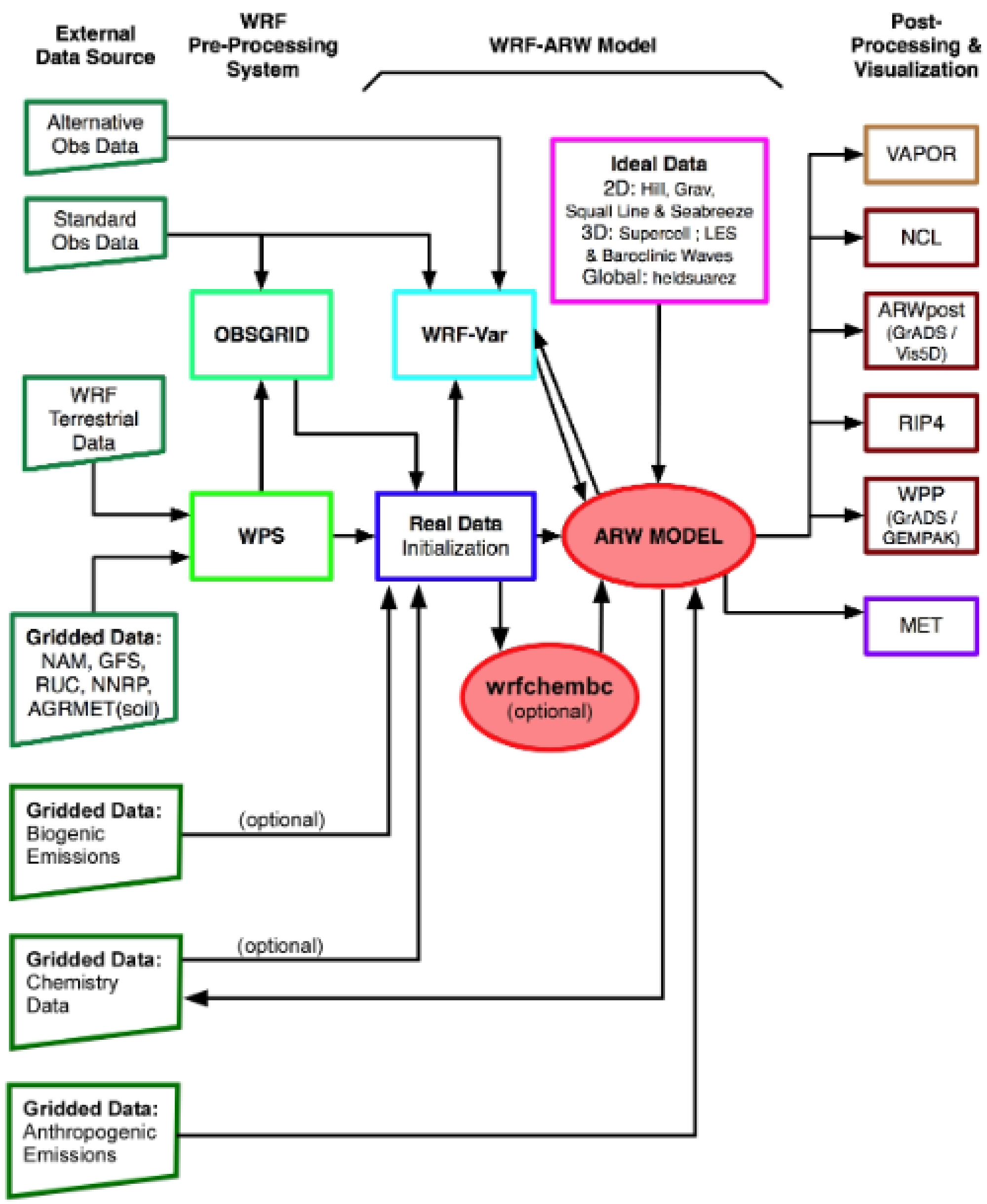

Figure 1. The WRF-Chem modeling system overview

- **Initial Conditions**

The ARW may be run with user-defined initial conditions for idealized simulations, or it may be run using interpolated data from either an external analysis or forecast for real-data cases. The initial conditions for the real-data cases are pre-processed through a separate package called the WRF Preprocessing System (WPS)

The WPS is a set of programs that takes terrestrial and meteorological data (typically in GriB format) and transforms them for input to the ARW pre-processor program for real-data cases (real).

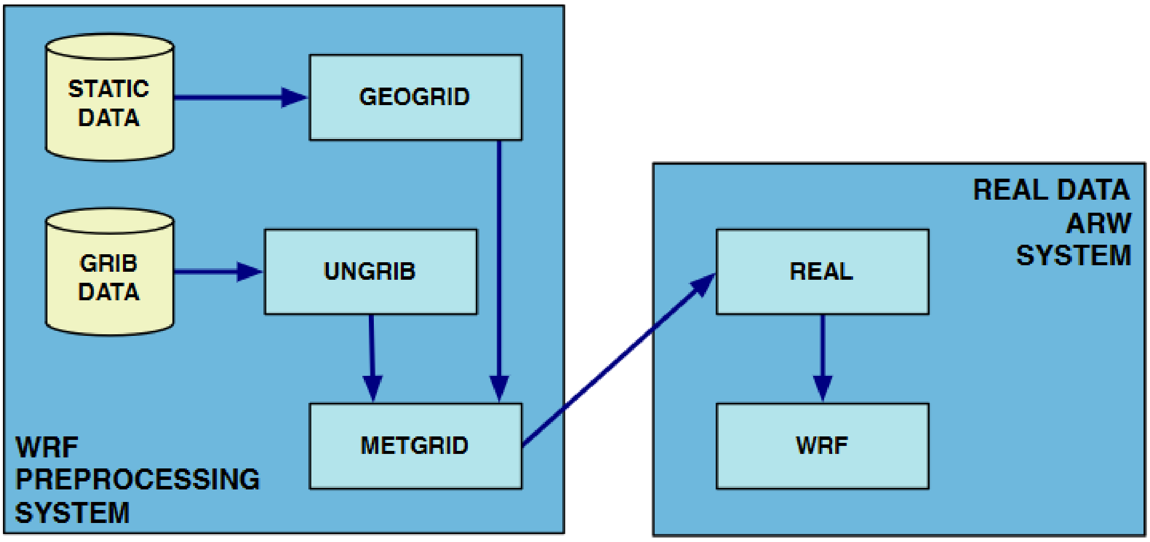

Figure 1 WPS and WRF Schematic

The input to the ARW real-data processor from WPS contains 3-dimensional fields (including the surface) of temperature (K), relative humidity (and the horizontal components of momentum (m/s, already rotated to the model projection). The 2-dimensional static terrestrial fields include: albedo, Coriolis parameters, terrain elevation, vegetation/land-use type, land/water mask, map scale factors, map rotation angle, soil texture category, vegetation greenness fraction, annual mean temperature, and latitude/longitude. The 2-dimensional time-dependent fields from the external model, after processing by WPS, include: surface pressure and sea-level pressure (Pa), layers of soil temperature (K) and soil moisture (kg/kg, either total moisture, or binned into total and liquid content), snow depth (m), skin temperature (K), sea surface temperature (K), and a sea ice flag.

The programs that generate the specific initial conditions provide the ARW with input data that is on the correct horizontal and vertical staggering, hydrostatically balanced reference state and perturbation fields and metadata specifying such information as the date, grid physical characteristics, and projection details.

For neither the idealized nor the real-data cases are the initial conditions enhanced with observations.

- **Lateral Boundary Conditions**

Several lateral boundary condition options exist for the ARW that are suitable for idealized flows, and a specified lateral boundary condition for real-data simulations is available. For nesting, all fine domains use the nest time-dependent lateral boundary condition where the outer row and column of the fine grid is specified from the parent domain The remaining lateral boundary options are exclusively for use by the most coarse/parent domain.

- **Nesting**

The ARW supports horizontal nesting that allows resolution to be focused over a region of interest by introducing an additional grid (or grids) into the simulation. In the current implementation, only horizontal refinement is available: there is no vertical nesting option. The nested grids are rectangular and are aligned with the parent (coarser) grid within which they are nested. Additionally, the nested grids allow any integer spatial (Δxcoarse / Δxfine) and temporal refinements of the parent grid (the spatial and temporal refinements are usually, but not necessarily the same). This nesting implementation is in many ways similar to the implementations in other mesoscale and cloudscale models (e.g. MM5, ARPS, COAMPS). The major improvement in the ARW's nesting infrastruture compared with techniques used in other models is the ability to compute nested simulations efficiently on parallel distributed-memory computer systems.

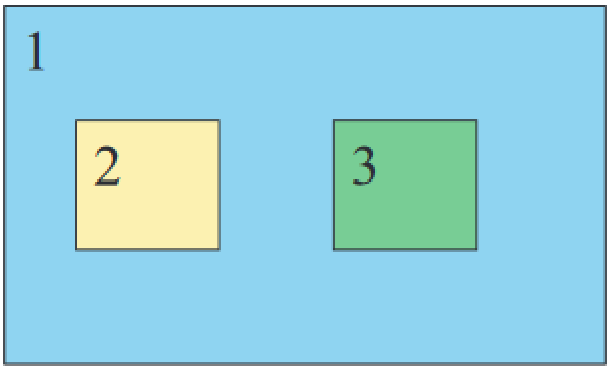

Figure 2 Nest example

2.4. The Databases

The databases with free data that are used for WRF and WRF-Chem simulations are provided at the tables below

NCEP FNL Operational Model Global Tropospheric Analyses, continuing from July 1999 (used for year 2015)			
Description	Included variables	Web Link	Used in Model
These NCEP FNL (Final) Operational Global Analysis data are on 1-degree by 1-degree grids prepared operationally every six hours. This product is from the Global Data Assimilation System (GDAS), which continuously collects observational data from the Global Telecommunications System (GTS), and other sources, for many analyses. The FNLs are made with the same model which NCEP uses in the Global Forecast System (GFS), but the FNLs are prepared about an hour or so after the GFS is initialized. The FNLs are delayed so that more observational data can be used. The GFS is run earlier in support of time critical forecast needs, and uses the FNL from the previous 6-hour cycle as part of its initialization. [National Centers for Environmental Prediction/National Weather Service/NOAA/U.S. Department of Commerce, (2000)]	Air Temperature , Cloud Liquid Water/Ice , Convection , Evaporation , Geopotential Height , Humidity , Hydrostatic Pressure , Ice Extent , Land Use/Land Cover Classification , Planetary Boundary Layer Height , Potential Temperature , Sea Level Pressure , Sea Surface Temperature , Skin Temperature , Snow Water Equivalent , Soil Moisture/Water Content , Soil Temperature , Surface Pressure , Surface Winds , Terrain Elevation , Total Precipitable Water , Tropopause , Tropospheric Ozone , Upper Air Temperature , Upper Level Winds , Vertical Wind Velocity/Speed , Vorticity	https://rda.ucar.edu/datasets/ds083.2	WRF

NCAR CESM Global Bias-Corrected CMIP5 Output to Support WRF/MPAS Research (used for future year implementing RCP 4.5 scenario)			
Description	Included variables	Web Link	Used in Model
This dataset includes global bias-corrected climate model output data from version 1 of NCAR's Community Earth System Model (CESM1) that participated in phase 5 of the Coupled Model Intercomparison Experiment (CMIP5), which supported the Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC AR5). The dataset contains all the variables needed for the initial and boundary conditions for simulations with the Weather Research and Forecasting model (WRF) or the Model for Prediction Across Scales (MPAS), provided in the Intermediate File Format specific to WRF and MPAS. The data are interpolated to 26 pressure levels and are provided in files at six hourly intervals. The variables have been bias-corrected using the European Centre for Medium-Range Weather Forecasts (ECMWF) Interim Reanalysis (ERA-Interim) fields for 1981-2005, following the method in Bruyere et al. (2014). Files are available for a 20th Century simulation (1951-2005) and three concomitant Representative Concentration Pathway (RCP) future scenarios (RCP4.5, RCP6.0 and RCP8.5) spanning 2006-2100. [Monaghan et al. (2014)]	Air Temperature, Boundary Layer Winds Geopotential Height , Humidity, Sea Ice Concentration, Sea Level Pressure Sea Surface Temperature , Skin Temperature, Snow Water Equivalent , Soil Moisture/Water Content , Soil Temperature Surface Pressure ,Surface Winds , Upper Air Temperature , Upper Level Wind	https://rda.ucar.edu/datasets/ds316.1/	WRF

Other Databases Used		
Name	Web Link	Used In Model
MOZART-4 output data	https://www.acom.ucar.edu/wrf-chem/mozart.shtml	WRF-Chem
WPS geographical input data	http://www2.mmm.ucar.edu/wrf/users/download/get_sources_wps_geog.html	WRF
EDGAR-HTAP	http://edgar.jrc.ec.europa.eu/htap_v2/index.php	WRF-Chem
USTUTT Emission Inventories		WRF-Chem

2.5. Emission Inventory Data

For the present simulation runs, USTUTT emission inventory data have been utilized as follows:

- For the years 2001-2019: USTUTT 2015 baseline scenario;
- For the years 2020-2029: USTUTT 2020 baseline scenario;
- For the years 2030-2050: USTUTT 2030 baseline scenario.

In the frame of QA/QC, results were compared using the EDGAR HTAP V2 inventory.

2.5.1. Description of the Emission Inventories

- **The University of Stuttgart (USTUTT) High Resolution Emission Inventory Data**

The developed emission inventories are based on activity-emission-factor-databases comprising all major anthropogenic emission sources for EU28 plus Norway and Switzerland on national level. The general approach follows the EMEP/EEA Air pollution emission inventory guidebook (EMEP/EEA 2016). Overall the baseline scenario considers the years **2015, 2020 and 2030** and comprises policies addressing energy efficiency, power generation and energy markets, cross-sectoral climate policies such as the EU ETS directive(s), transport related policies, policies related to infrastructure and innovation and environmental policies on EU-level. Furthermore, national measures, such as national subsidy schemes for renewable energy, ban of nuclear power plants in some countries or the ban on landfill of biodegradable waste in Austria, Germany, Denmark, Netherlands and Sweden are taken into account.

With regard to projections of future air pollutant and greenhouse gas emissions different models have been used for the construction of the emission inventory; namely the Eclipse V5a Scenario [1] as

[1] http://www.iiasa.ac.at/web/home/research/researchPrograms/air/ECLIPSEv5a.html

implemented in the GAINS model (IIASA)[2] and the baseline dataset from the TRANSPHORM project[3] for road transport and railway. The chosen scenario represents a business-as-usual case reflecting current legislation and agreed-on future policies as of 2013. With respect to climate mitigation on European level this means that all policies in context of the *2020 Climate & Energy Package*[4] from the European Commission, which sets a 20% cut in greenhouse gas emissions compared to 1990 levels for 2020, are included while the *2030 climate and energy framework*[5] which was set into place in 2014 is not considered explicitly. This policy package strives for a 40% reduction of greenhouse gas emissions in 2030. In principal, the constructed baseline scenario is rather conservative including no further attempts on climate mitigation. Thus, the 2020 targets are met, while the 2030 targets are slightly missed, which is also in line with the latest EU Reference Scenario 2016 (Capros 2016). Similarly, the market penetration of electric vehicles is assumed to stagnate on today's level, i.e. the share of vehicle kilometres for electric vehicles in 2020 and 2030 is the same as 2015. With regard to air pollution mitigation policies, national emission control legislations as well as EU-wide legislations are taken into account. Hence, considered policies comprise *the Clean Air Policy Package 2013*[6], including the new *National Emission Ceilings Directive,* on European level as well as national legislation and practices, e.g. the ban on landfill of biodegradable waste or special subsidy schemes for renewables in some European countries (see also TSAP Report #11, Amann et al. 2014)

The projected greenhouse gas reduction (CO_2 equivalents) from 2015 to 2030 is about 9 % for the whole EU. The emission reduction of classical air pollutants varies from 37 % for NO_x and 35 % for SO_2 to 1 % for NH_3. Particulate matter emissions are reduced by about 13 % for PM10 and 19 % for PM2.5. Emissions of NMVOC are reduced by 12 % compared to 2015 levels. If emission reduction is analysed on country level, reduction levels vary significantly between different countries with some countries even increasing less regulated emissions such as NH_3. This is also true for total greenhouse gases. Huge emitters in 2015 such as Germany and the United Kingdom are reducing their emissions constantly over time, while others such as Poland are increasing them in 2020 before finally decreasing emissions in 2030. Other countries like Spain are even increasing their greenhouse gases in absolute terms. This can be partly explained by the applied burden sharing within the EU28 to reach their overall reductions targets, allowing individual countries to still increase greenhouse gases to enable better economic growth while others have to decrease even more.

- **EDGAR HTAP V2**

It includes annual data for the year 2010 with 0.1x0.1 deg spatial resolution over Europe. It covers the pollutants NOX, NH3, PM10, PM2.5, SO2, CO and NMVOC. HTAP V2 uses nationally reported emissions combined with regional scientific inventories in the format of sector-specific gridmaps. The gridmaps are complemented with EDGARv4.3 data for those regions where data are absent. The global gridmaps are a joint effort from US-EPA, the MICS-Asia group, EMEP/TNO, the REAS and the EDGAR group to serve in the first place the scientific community for hemispheric transport of air pollution. The static version is available on this EDGAR website, but also the GEIA data portal and the ECCAD server.

The data were downloaded from ftp://aftp.fsl.noaa.gov/divisions/taq/global_emissions/

according to WRF-Chem manual guidance.

More details can be found in http://edgar.jrc.ec.europa.eu/htap_v2/

[2] http://gains.iiasa.ac.at/gains/EUN/index.login
[3] http://transphorm.eu/
[4] https://ec.europa.eu/clima/policies/strategies/2020_en
[5] https://ec.europa.eu/clima/policies/strategies/2030_en
[6] http://ec.europa.eu/environment/air/clean_air_policy.htm

3. Simulations and Results

The detailed results will be presented in Deliverable D3.3 : Report on AQ and GHGs concentration at the ground level in the ICARUS cities

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