



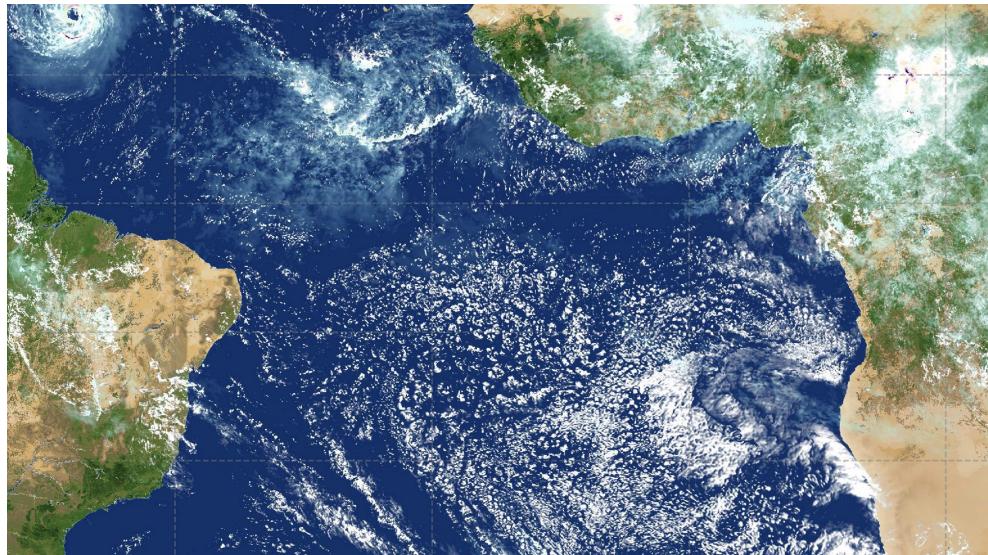
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Scientific Visualisation of High-resolution Climate Simulations

Semester Project

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Abstract

In this thesis a scientific visualisation program was developed to produce realistic looking pictures from the output data of the COSMO model [1]. This software imitates satellite images to help visualize the complex weather conditions over the globe. It is highly customisable and gives satisfying results during different seasons and in most climate regions.

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Chapter 1

Introduction

Climate and weather simulations are becoming very important as climate change progresses and extreme weather events occur more frequently(Carvalho 2020 [2], Luiz-Silva 2020 [3], Walsh et al. 2020 [4]). This thesis presents a visualisation program based on Python 3 to create animations for high-resolution climate simulations, specifically for output of the non-hydrostatic limited-area atmospheric model COSMO (Steiger 2020) [1]. Animations are extremely useful on the kilometre scales (spatial resolution), since convective clouds can be explicitly resolved and therefore better represented (Leutwyler 2017 [5]).

1.1 Motivation

When picturing weather and climate visualisations, satellite images come to mind at first. Even non-scientists are used to seeing them on the news and in weather forecasts. This leads to an intuitive understanding of satellite imagery by a broad group of people. Even though satellites provide images over large areas at high temporal resolution, they cannot barely cover a single large area at the same time. Therefore, it is necessary to create a program that is able to reproduce satellite-like images that cover huge areas without temporal interruption. This would be useful for at least two reasons. Firstly, it helps in scientific communication. The visualisation is intuitive and self-explanatory, instead of overwhelming the audience with many labels. This has the additional benefit that various variables can be shown on the same visualisation. This thesis considers up to 15 variables for creating a single visualisation depending on the chosen configuration. Secondly, it also helps climate and weather scientists assessing the simulated variables. Namely, using this program facilitates the comparison of model output against satellite images, i.e., it functions as a qualitative tool to visually validate simulations.

During previous work, a python program was developed to create realistic

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looking figures of climate and weather simulations for the Atlantic region. This thesis aims at improving this program in terms of ease of use and applicability for various regions worldwide.

1.2 Outline

This thesis is structured as follows: Section 2 presents the methodology of the program and its application, Section 3 and 4 show discuss and results of the program, respectively, and section 5 discusses future improvements.

Chapter 2

Methods

This chapter explains the program that creates the visualisation; moreover, it introduces the variables and parameters that are used. Furthermore, this chapter presents a guideline about how to use the program, which includes the set up and the corresponding source code. The figures shown in this thesis were created by running the program on the ETH Piz Daint super computer [6] where the data used by this program was created by the COSMO model.

2.1 How the code works

This section shows the code's structure and describes in detail how the plots are generated.

2.1.1 Structure

The source code is structured into three parts. Firstly, the Visualization class (vis) which is run by the main method. Secondly, there are the Visualization parameter class (VisParam) and the JSON configuration file which work similarly to a namelist in climate and weather simulations. These concepts are explained in more detail below.

2.1.2 Visualization class

The Visualization class is the class which generates the visualisations. It is initialised with the JSON-file 2.1.4 and the VisParam-class 2.1.3. Listing 2.1 shows how the main visualisation loop works, also called pseudo code. It begins by reading in all the parameters specified in VisParam 2.1.3 and the JSON file 2.1.4. Next, it checks how often every variable should be read in and how often plots should be generated. This distinction is made since typically, some variables are written out with higher temporal resolution

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than others, e.g., precipitation, hail and lightning. Note that in this work the term precipitation refers to the total precipitation, i.e., liquid and solid precipitation.

2.1.3 Visualization parameter class

This class is used for the visualisation parameters. This class should be used by users who want to change the variable plotting bounds if there is for example precipitation happening in the simulation, but not showing visible enough in the visualisation. Users can also colour maps, toggle grid lines, change font sizes of the grid lines and the datetime. It is also possible to change the parameters of the land surface function and to define special markers for hail and lightning according to 2.6.

2.1.4 JSON config file

The JSON config file is the file that a user has to change most often. It is strongly recommend creating a new JSON config file for every new visualisation. The reason to use the JSON type is because it can be directly read in as an object into python. This means the user is not required to edit a python file directly and structural error are easily caught due to the strict JSON syntax. The listing 2.3 shows an example JSON file. Enable_plotting is a container of booleans in which the user can toggle to plot the surface, clouds, snow, hail and lightning. Const_path is the direct path to the file containing the constant values for this simulation. Paths is a container of strings which should contain the paths of the folders where the NetCDF-files are where those specific variables are stored. Namely, those variables are TQI, TQC, W_SNOW, TOT_PREC, W_SO, LPI, DHAIL_MX and TQV. Instead of strings one can write null if the variable does not exist or is not used. Data_time_stepping is used to decide how often new data should be read in. The durations can be written in different formats, because the string will be interpreted nicely by the django library, but it is recommend sticking to the example below. Vis_duration and vis_start_time are used to determine how long the visualisation should take and when it should start. Output_Path is the path where pictures are stored. Plotting_time_step is how often in simulation time you want to generate a new picture.

```
1 read_in_all_the_visualisation_parameters(JSON file, Visualization  
Parameter class) # initialise the Visualisation class  
2  
3 dt = find_min_timestep() # timestep of the visualisation / the  
# minimum data read time  
4 timesteps = anim_duration / dt # number of time steps for data  
# reading  
5 data_read_intervals = data_read_intervals() # array of data  
# reading intervals for each specific variable
```

2.1. How the code works

```
6 plotting_frequency = plotting_interval / dt # determines at which
    time steps a new picture gets generated
7
8 loop over timesteps:
9
10    loop over every variable:
11        o read data if there is new data available and:
12            o in first timestep
13            o it is not plotting time
14                o concatenate multiple data reads together ( used
                    for hail, lightning and precipitation)
15                o skip to next time step and update time
16
17    update time
18    plot_all() # function that plots all variables in the correct
        order
19
20    loop over every variable:
21        o read data if there is new data available
```

Listing 2.1: Pseudo code: main visualisation loop

The pseudo code (Listing 2.2) shows how the visualisation is built up: (i) It starts drawing surface features such as land, oceans, elevation, ice and snow, (ii) the cloud water components, such as cloud water and ice are superposed, (iii) the weather phenomena rain, hail and lightning are visualised on top of the figure, (iv) the figure is saved in a jpg format and afterwards deleted internally to prevent memory leaks. The jpg format is used, since it is a portable format and storage efficient. The next sections go into detail on how the different layers are built up. Each section provides a visualisation on what is added.

```
1 plot_all():
2     o define figure, axis and grid lines
3
4     o check for every variable if it needs to be plotted
5         plot_land_ocean
6         plot_elevation
7         plot_ice
8         plot_snow
9         plot_TQV
10        plot_TQC
11        plot_TQI
12        plot_TOT_PREC
13        plot_DHAIL_MX
14        plot_LPI
15
16    o save figure as .jpg
17    o delete figure
```

Listing 2.2: Pseudo code: plot all function, all functions called here are explained in detail in their respective sections

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2.1.5 Figure Initialisation

The figure is initialised in the following manner. The figure's size is inferred by the underlying data. This is done by reading in the dimensions of the NetCDF-files. It is also possible to specify this manually. The axes are adjusted by the rotated pole transformation which are used by all the COSMO simulations used in this work, thus the program reads in the rotated pole automatically from the COSMO output files. Further, grid lines can be displayed which show longitude and latitude. The cartopy library is used for these two features [7].

2.1.6 `plot_land_ocean`

This function plots the earth's surface using only the information from the COSMO-model, i.e., constant and simulated fields. Note that some of the initial conditions of the COSMO-model come from satellite-based observations. This was the most involved section and required a lot of tweaking, in order to work in multiple climate regions with one single configuration. The original idea was developed by C. Heim and further elaborated in this project. Fundamentally, the idea is to modulate the land-surface color depending on the soil moisture content. More specifically, the following variables stored in the nc-files are considered: soil moisture content of soil levels, the fraction of evergreen and deciduous forest, the diffuse albedo and the location of the oceans. These variables are combined in the code of the `plot_land_ocean()` and `load_const_data()` functions in the `Visualization` class. With the result of this calculation, it was possible to colour the land surface from very dry, beige, sand colours to moist, green, forest colours. The ocean is coloured in blue uniformly. The result of this can be seen in Figure 2.1.

2.1.7 Plotting standard variables

Most work for plotting is being done by the `plot_var()` function. The function takes the variable to be plotted, a corresponding colour map and variable plotting bounds as arguments. These are then given to the `pcolormesh` function which plots the variable. Another argument is whether to plot the variable over the the whole domain which is the default or only over land or ocean. This is useful for land-surface variables that should not be plotted over the ocean.

In the following subsection I will go into detail which functions called in Listing 2.2 invoke this function.

`plot_elevation`

One issue that was visible was that mountains were too green. Thus it was necessary to create a function which considers the elevation information and

2.1. How the code works



Figure 2.1: Surface plot of Europe in summer with the corresponding colour map for the surface

applies drier colours to the areas with higher elevation. (Shown in Fig. 2.2)



Figure 2.2: Surface plot of the Alps in summer without and with the elevation map

plot_ice

The program also plots the permanent ice cover such as glaciers which are present in the constant files as a soil type, as illustrated in Figure 2.3.

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Figure 2.3: Permanent ice cover of the Alps

plot_snow

The simulated snow is also visualised. (Fig. 2.4)



Figure 2.4: The Alps in winter with snow cover, clouds are also visible

Clouds

Clouds consist of cloud water (TQC) and cloud ice (TQI) which are visualised in white and light-blue-to-white color, respectively. Note that the vertical integral of these quantities is plotted instead of the three-dimensional field. In principal, any other two-dimensional variable can be added effortlessly, since the plotting methods are already implemented i.e. the `plot_var()` function 2.1.7. Figure 2.5 shows the added TQC and TQI.



Figure 2.5: Europe in summer with clouds (TQC and TQI)

plot_TOT_PREC

As mentioned in section 2.1.2, precipitation information can be read more often than being plotted; therefore, depending on the temporal resolution of plotting the pictures, the precipitation information can be summed up in between plotting time steps to show an accumulated value. Note that precipitation falls within and below clouds and therefore being barely distinguished in the visible range (human eye's range) from satellites. To show the precipitation intensity, the precipitation is coloured from yellow over red to blue (Fig. 2.6)

2.1.8 plotting marker variables

The plotting_marker_variables-function is the second plotting method. It is used for variables that are plotted as a marker when occurring like hail or lightning. This is done regardless of the hail sizes or lightning intensity. Here a scatter plot with custom markers is used to visualise lightning and hail. The lightning marker was designed by me. The hail marker was taken from The Comprehensive LATEX Symbol List [8] and generated an svg-format picture and converted it to a matplotlib path according to an

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online tutorial [9].

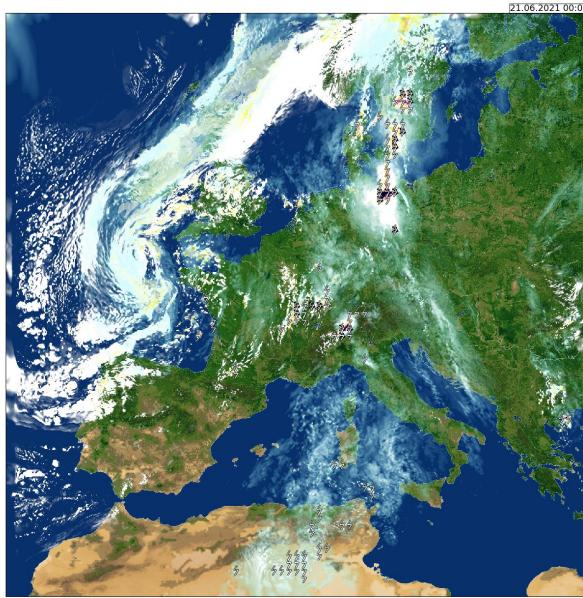


Figure 2.6: Europe in Summer with rain (here TOT_PREC), lightning and hail added.

2.1.9 Additionally used software

There are other libraries heavily used in the program: matplotlib [10], xarray [11] and Django [12]. Matplotlib is the plotting library for python and thus used for my visualisation. Xarray permits to easily deal with the large number and size of the NetCDF-files. It even has some light wrappers to matplotlib which make plotting the data set really simple. Django has a method to read in durations and transform them into python datetime objects. The EOSDIS Worldview website [13] shows current and past satellite pictures which played a key role in tweaking the colour maps and validating the visualisation, e.g., when Europe was covered by snow. The last software is ffmpeg which creates videos out of the generated pictures. [14]

2.1.10 Important notes

Note that the program assumes that the NetCDF-files are named in the following way: "lffd" + YYYYmmddHHMMSS + ".nc". Additionally the data time steppings should have to have a common divisor, because otherwise

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the program might skip some files, since the program takes the smallest data time step as the plotting time step. Thus if the smallest data time step is 10 min and another one is 15 min, the 15 min one will only be updated every 30 min. Furthermore the data time steppings should be smaller than the plotting frequency for precipitation, hail and lightning, because it produces a smoother video.

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```
1  {
2      "enable_plotting": {
3          "TQI": true,
4          "TQC": true,
5          "W_SNOW": true,
6          "TOT_PREC": true,
7          "W_SO": true,
8          "LPI": true,
9          "DHAIL_MX": true,
10         "TQV": false
11     },
12     "const_path": "~/atmosthesis/lffd20210522000000c.nc",
13     "paths": {
14         "TQI": "~/atmosthesis/lightning",
15         "TQC": "~/atmosthesis/lightning",
16         "W_SNOW": "~/atmosthesis",
17         "TOT_PREC": "~/atmosthesis/hail",
18         "W_SO": "~/atmosthesis",
19         "DHAIL_MX": "~/atmosthesis/hail",
20         "LPI": "~/atmosthesis/lightning",
21         "TQV": null
22     },
23     "data_time_stepping": {
24         "TQV": null,
25         "TQI": "01:00:00",
26         "TQC": "01:00:00",
27         "W_SNOW": "1 day, 00:00:00",
28         "TOT_PREC": "00:5:00",
29         "W_SO": "1 day, 00:00:00",
30         "DHAIL_MX": "00:5:00",
31         "LPI": "01:00:00"
32     },
33     "vis_duration": "00:05:00",
34     "vis_start_date": "2021-06-21 00:00:00",
35     "plotting_interval": "00:01:00",
36     "outputPath": "./pics",
37
38 }
```

Listing 2.3: JSON config file example

2.2 How to use the program

Five pieces of software are needed to use the program.

- visualize_climate_simulation.py
- YourJSONFile.json
- Visualization.py
- VisParam.py
- a python environment with the necessary libraries installed

2.2.1 Setting up the environment

To set up the environment files described above need to be downloaded. These files can be found at [15]. Put all the files in a new folder. Alternatively there is github repo linked there aswell.

Next, a conda environment shoud be set up [16]. In the git repository, there are two .yml files for daint and macOS. To create a new environment use the following command.

```
conda env create -f NAME_OF_YML_FILE.yml
```

Next one needs to create a JSON-file and to fill in the variables pertaining to your simulation (explained in 2.1.4). This determines what would be visualised.

2.2.2 Running the code

The next step is running the program itself with this command:

```
python3 visualize\_climate\_simulation.py YourJSONFile.json
```

After the program has finished running, one creates an animation from the created pictures. This can be done by running the following command in the folder where the pictures are created. This should work cleanly, since the files are inherently sorted by their time step as a file name. Alternatively, you can also download the pictures to your local computer as the pictures do not exceed 1MB per file. Thus one needs ≈ 500 MB storage for an animation of 20 days with hourly frames.

```
ffmpeg -framerate 20 -pattern_type glob -i '*.jpg' \
-c:v libx264 -pix_fmt yuv420p -vf "pad=ceil(iw/2)*2:ceil(ih/2)*2" \
ANIMATION_NAME.mp4
```

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Here the frame rate is set to 20 frames per seconds, but this can easily be changed by changing the number after “-framerate”.

2.2.3 Additional information

The run time is strongly dependent on the size of the data provided by the COSMO-model. For example the pictures for Europe shown above took approximately 60s on Piz Daint per picture. Note that if this program is submitted as a job on Piz Daint it does not have access to the \$PROJECT-folder. Thus NetCDF-files and generated pictures need to be in \$SCRATCH. Further, many tweaks can be made to the visualisation itself by changing the VisParam 2.1.3 or even the Visualization 2.1.2 class. Two examples of this are shown in Fig. 2.7. One option is to enable grid lines for latitude and longitude. If one does not need this option, turning it off is recommended to increase realism. There is also the option to change the plotting range boundaries of your variables. For instance, this needs to be done if the plotting range does not match the precipitation rate, which could happen when the setup was previously done for a region with higher precipitation rates.

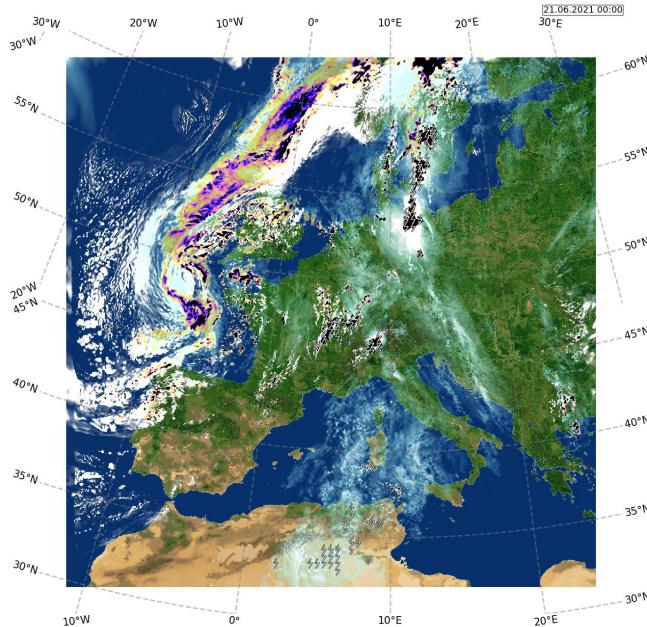


Figure 2.7: Europe in Summer with rain being plotted more visibly and added latitude and longitude grid lines.

Chapter 3

Results

This chapter shows five examples of the visualisation in different regions. The goal here is to show the application of the program on different climate regions. There are animated visualisations stored online at Zenodo [15]. These videos are in the examples folder. The corresponding JSON-files is in the json-files folder. For all these examples the presets were not changed, except the turning on or off the grid lines for different regions. The first example is the Arabian Peninsula which is a very arid region (Fig. 3.1). The second example shows a large part of Asia covering the Himalayas (Fig. 3.2). Next, Figure 3.3 and 3.4 show Europe for summer and winter conditions, respectively. Lastly, the Tropical Atlantic is shown which includes large parts of Africa and Brazil (Fig. 3.5).

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Figure 3.1: Visualisation of the Arabian Peninsula

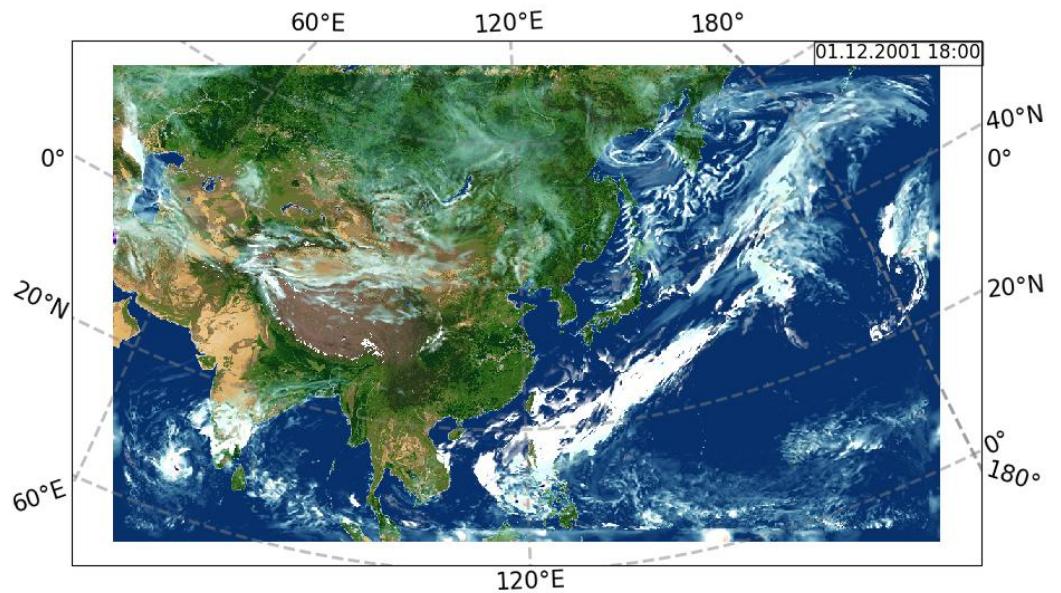


Figure 3.2: Visualisation of Asia

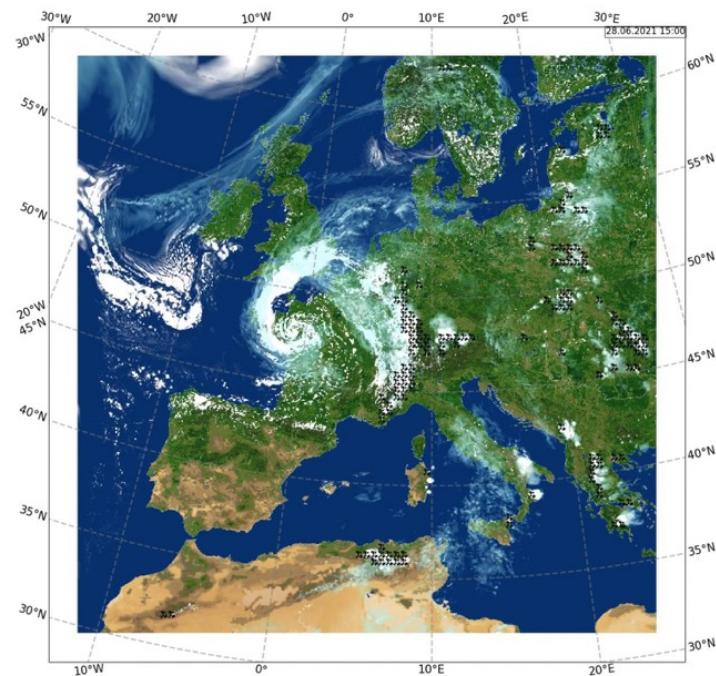


Figure 3.3: Visualisation of Europe in summer with a hail storm

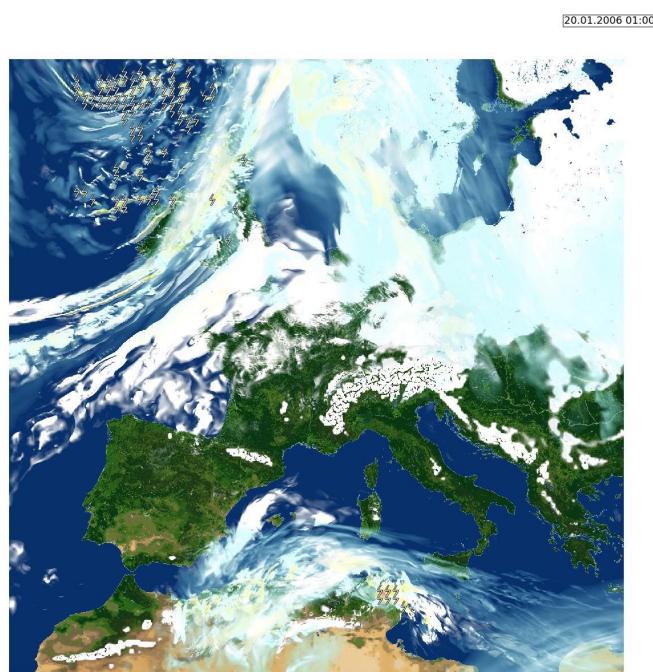


Figure 3.4: Visualisation of Europe in winter

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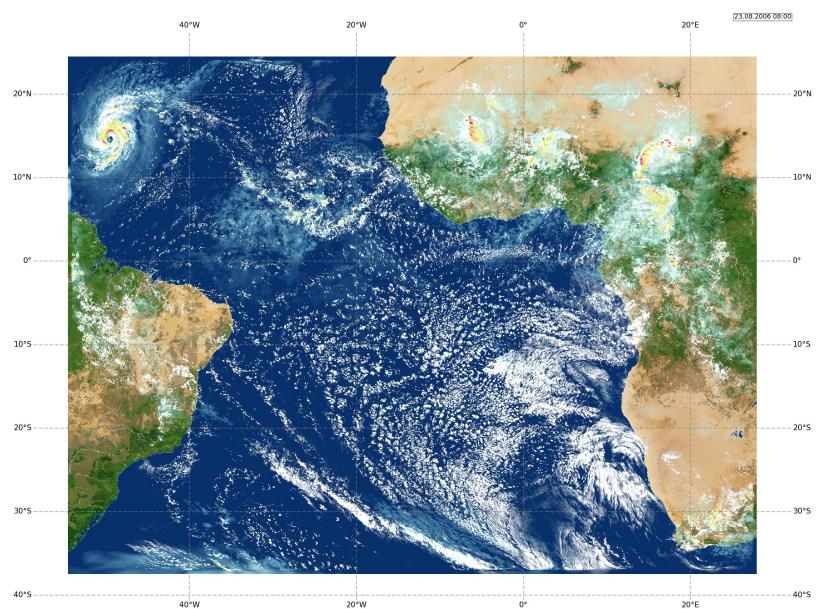


Figure 3.5: Visualisation of the tropical Atlantic region

Chapter 4

Discussion and summary

This thesis aims at providing a program to create satellite-like visualisations using high-resolution climate simulations. The created visualisations look realistic (chapter 3). Therefore, the program's application on different climate regions works properly and does not need to be further adapted. Moreover, the original program made by C. Heim was improved, which was able to produce realistic visualisations only for the Atlantic region (Fig. 4.1). The current program is more user-friendly, and it renders the surface across different climate regions more accurately.

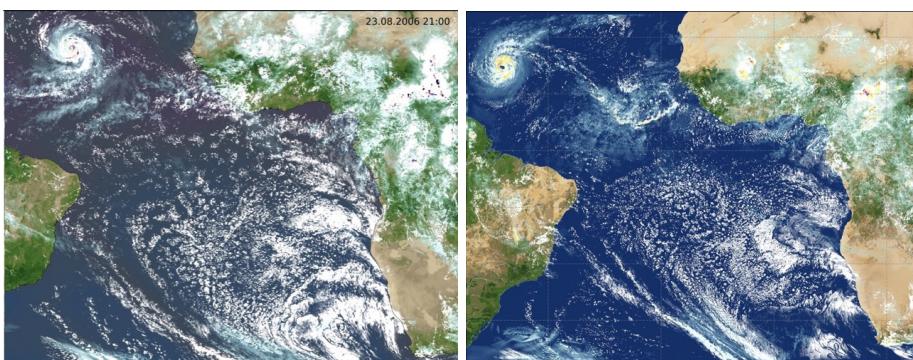


Figure 4.1: The original version of the visualisation by Christoph Heim (left) compared to my visualisation (right). Note that in the left panel, vertically integrated water vapor content over oceans is colored in purple, which is not done in the right panel.

When comparing the visualisation of Brazil with satellite pictures on the same day (Fig. 4.2) we can see that the pictures match reasonably well, particularly surface conditions. It is arid where it is supposed to be and green where there is vegetation. Rivers also show up even though they are not explicitly modelled. Additionally, since the visualisation tries to be applicable to the whole globe a few limitations can be seen in this figure, as

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well. One is that the hue of the surface is not correct. Brazil's desert regions have a darker and redder hue in reality. Another one is that the ocean are just a single colour without any gradient as is usually observed in satellite images.

Figure 4.3 compares satellite pictures provided by [13] and a visualisation. We observe that the pictures and the visualisations look very similar. The limitations for the gulf are the same as for Brazil. Another issue arises when plotting for Europe. In satellite images the colours of the vegetation are less saturated. This makes the winter surface greener in the visualisation compared to satellite images. This could be due to the fact that temperatures (soil and near-surface temperature) are not considered in this program.



Figure 4.2: Brazil. Comparison between satellite picture [13] and surface visualisation

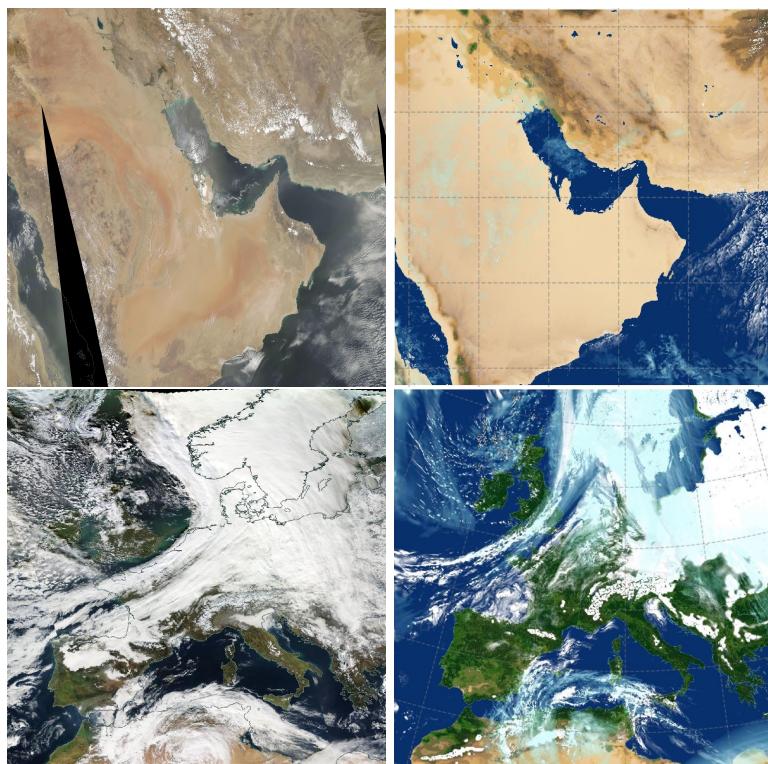


Figure 4.3: Arabian Peninsula (04.07.2015) / Europe (20.01.2006) . Comparison between satellite pictures [13] and visualisation

Chapter 5

Future improvements

There is still room for further improvements of the program. The following steps are left to future work due to time constraints in this project:

Finding a method to improve the visualisation of surfaces with redder hues. This could possibly be done by adding an additional parameter to the surface calculation that is already present in the NetCDF-files, or by manually creating a map where these kinds of surface colours occur. During winter, particularly in mid latitudes, the surface conditions could be more pale. A further step would be to consider the effects of temperature. With this addition the lessened growth of plants in winter could probably be visualised. Additionally, the ocean looks bland in the visualisation because it is just a single colour everywhere. This issue could be improved by displaying the ocean in different shades of blues depending on ocean temperature, near-surface wind velocity, and solar zenith angle.

Furthermore, a testsuite could be added to the code. In this testsuite, a NetCDF-file and a JSON file are provided to test if the environment is set up correctly. It could also be used to debug the program during future developments and to conveniently test the outcome of such developments (e.g., when changing the colour maps).

Lastly, the most impactful fix would be to improve performance of the visualisation. The bottleneck is the rendering of the pictures in matplotlib, whereas the reading of data is comparably faster. Thus having the rendering done in parallel would improve the performance. A first version of this has been implemented in the Visualization-class, but it ran into race conditions (a common bug in multi-core programs with parallel threads trying to access the same data simultaneously). Thus, to implement this change, one would need to inspect the program variables and prevent processes of changing each others data.

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