CLIMATE SYSTEM II
COURSE 2023/2024

CLIMATE DATA ANALYSIS

LECTURE OF JANUARY 23 2024

CHRISTIAN STEPANEK

ALFRED WEGENER INSTITUTE

DEPARTMENT FOR CLIMATE SCIENCES

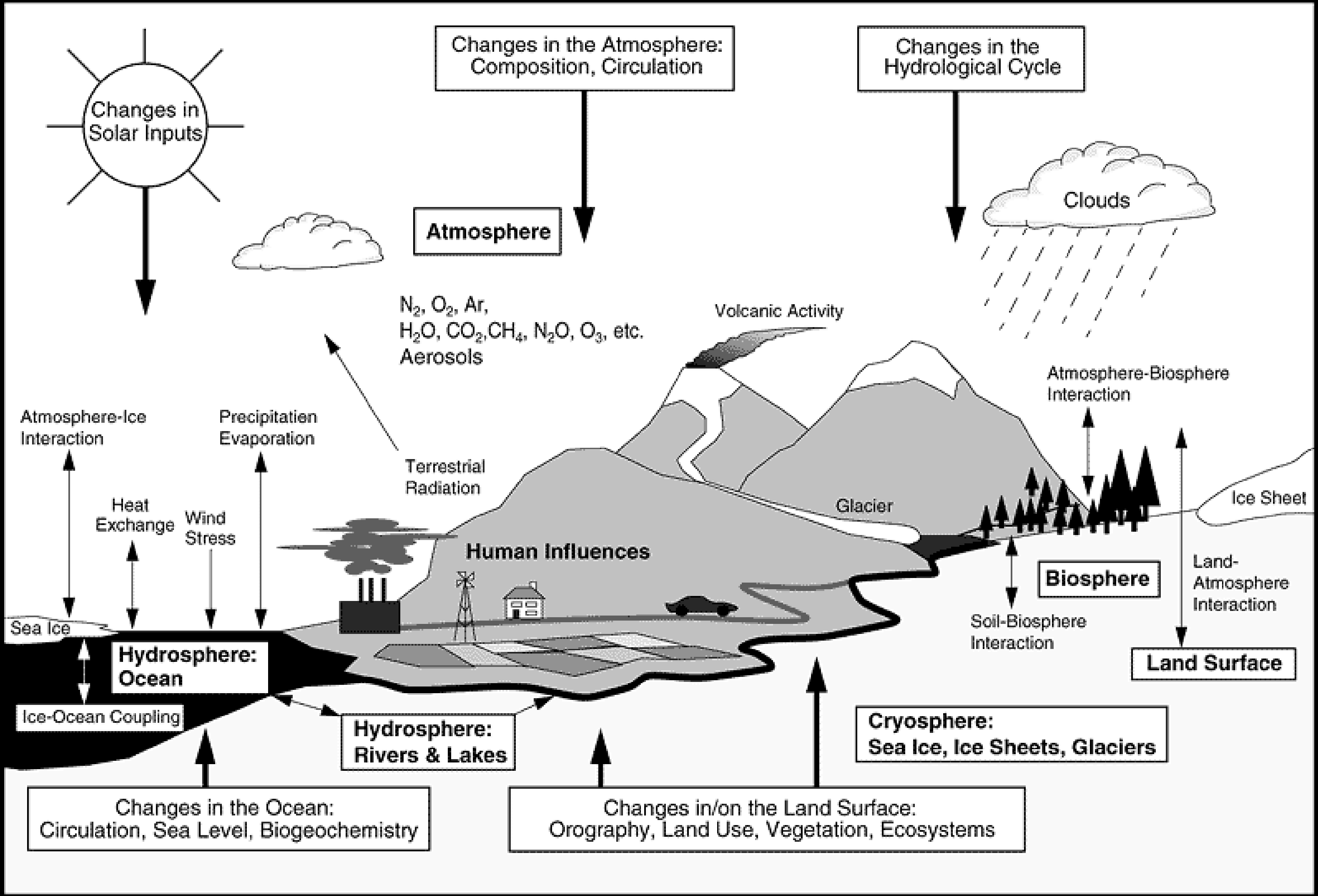
PALEOCLIMATE DYNAMICS

OUTLINE / MOTIVATION

- The climate system – complex coupled subsystems interacting in complicated ways
- Coupled models of atmosphere-ocean circulation as a laboratory for scientific studies
- The mid-Pliocene as a case study for analyzing a past state of warmer climate
  (⇨ Beyond models, we cannot study the future – but we can study the past)
- Understanding climate dynamics in coupled climate models difficult (many simultaneous changes)
  - Solution: take a step back, analyze model results in simpler climate models
  - Tutorial: five sets of simulations by the Community Earth System models (COSMOS) are further analyzed in a zero-dimensional energy balance model
  - Five assignments, each one to be solved by a group of students
  - Collaboration between groups explicitly supported (and necessary for some tasks)
  - Focus of the problems is on understanding the analysis and discussing some implications of results
  - All analyses already coded in Python/CDO and formulated in jupyter-notebooks
  - You are of course very welcome to modify example code for further analyses

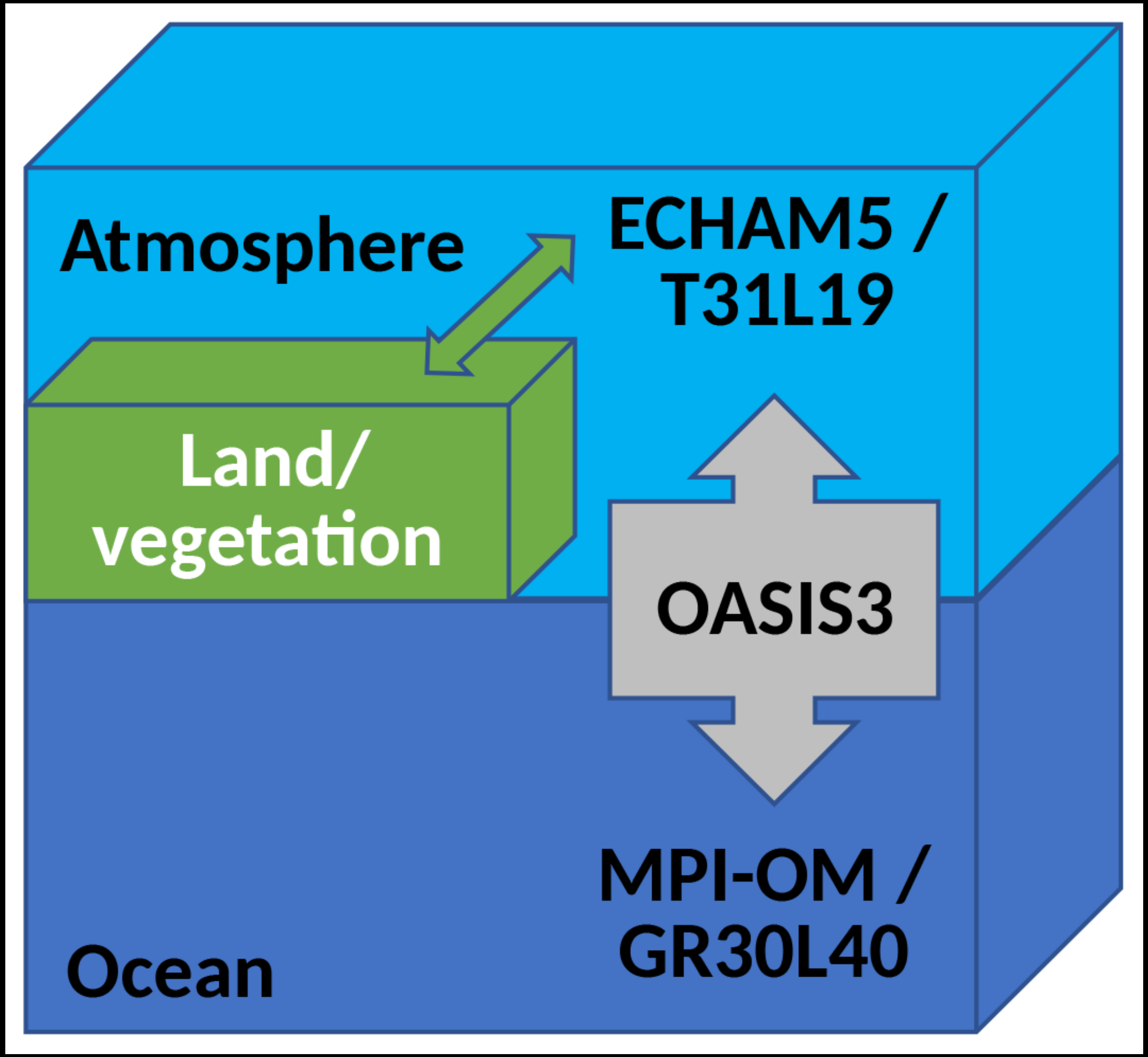
THE COUPLED CLIMATE SYSTEM

- Complex interactions of the various subsystems generate an integrated climate signal
- Unraveling causal chains in the climate system that follow a change in a specific climate driver is complicated
- Separation of cause and effect is difficult
- Use climate models as a controlled laboratory



THE COSMOS

- One submodel per climate system compartment (atmosphere / ocean / sea ice / land)
- Not all climate subsystems explicitly represented (e.g. no ice sheet dynamics)
- Model couples fluxes of energy / mass / momentum between submodels
- Studying the climate system by analyzing effects of controlled perturbations

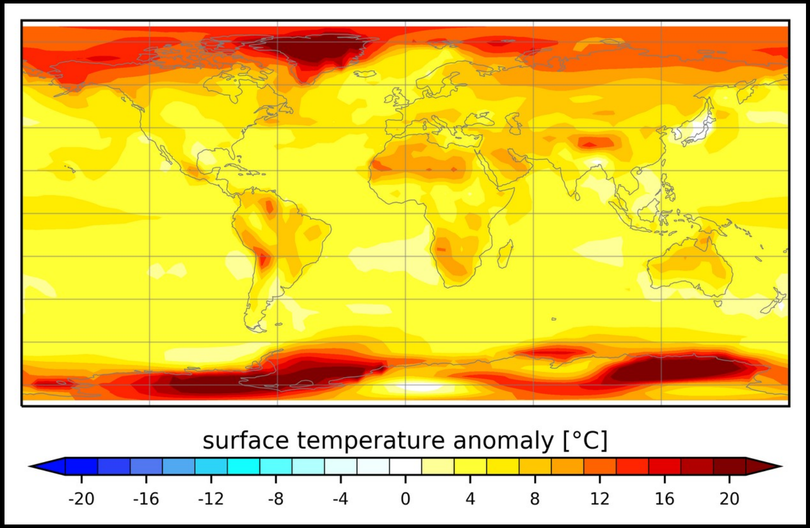


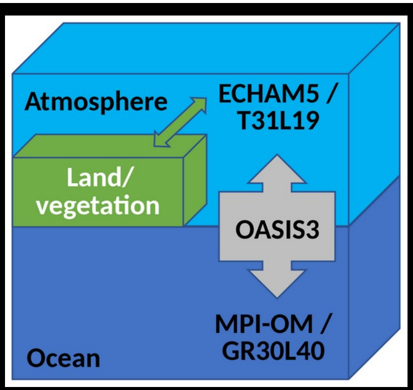
THE MID-PLIOCENE

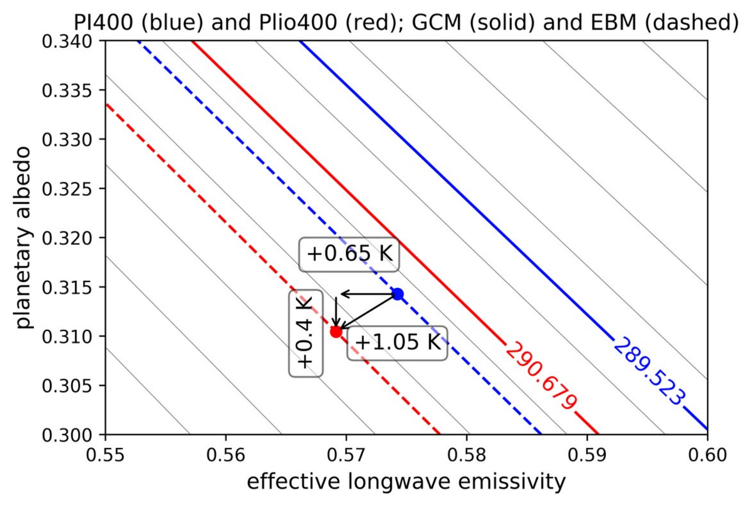
- About 3 Million years before present
- Similar greenhouse gases as today, but much warmer (globally +2-3°C above modern)
- Much smaller ice sheets and much higher sea level (~25 m higher than today)
- Considered as one potential analog for future climate (CO_2 similar to today!)
- ⇨Focus of intense research (reconstructing and modeling of climate)

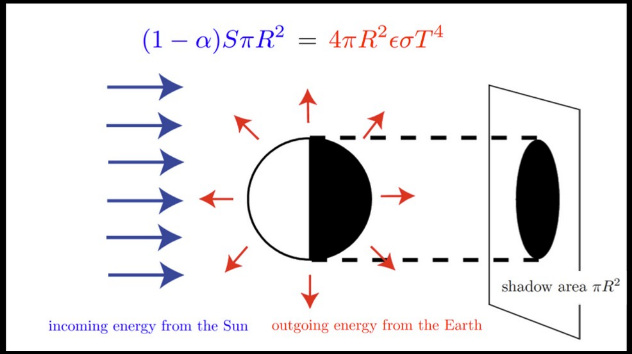
THE SCIENTIFIC PROBLEM

- Complex climate models are valuable tools to derive the state of climate for a specific forcing (e.g. carbon dioxide)
- Unraveling the dynamics, that lead to a specific climate pattern based on a specific forcing, is difficult in a complex climate model
- ⇨ After deriving a climate pattern in a complex model, we may study the dynamics behind it in a simpler model
- Example: Zero-dimensional Energy Balance Model (EBM)



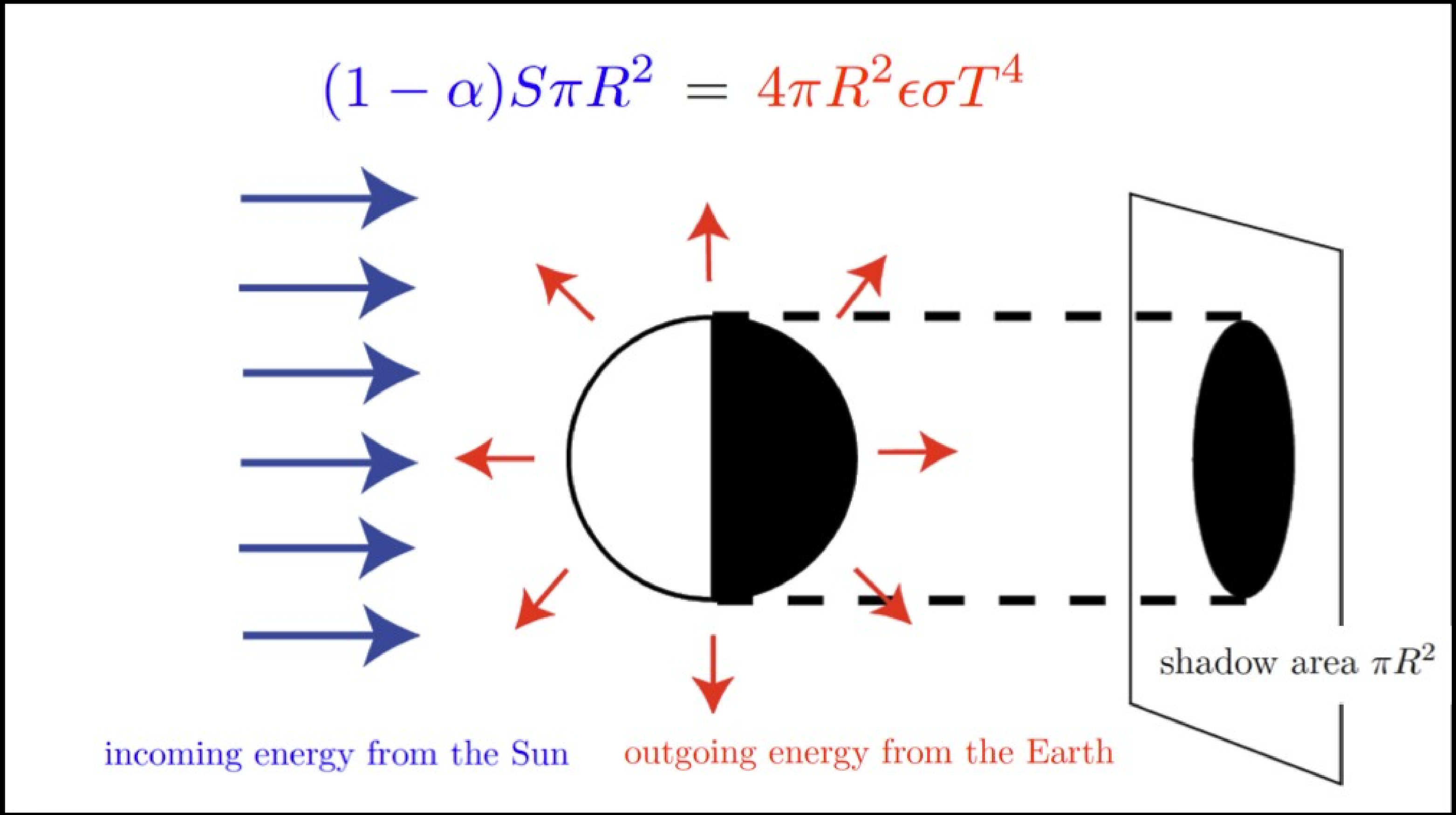






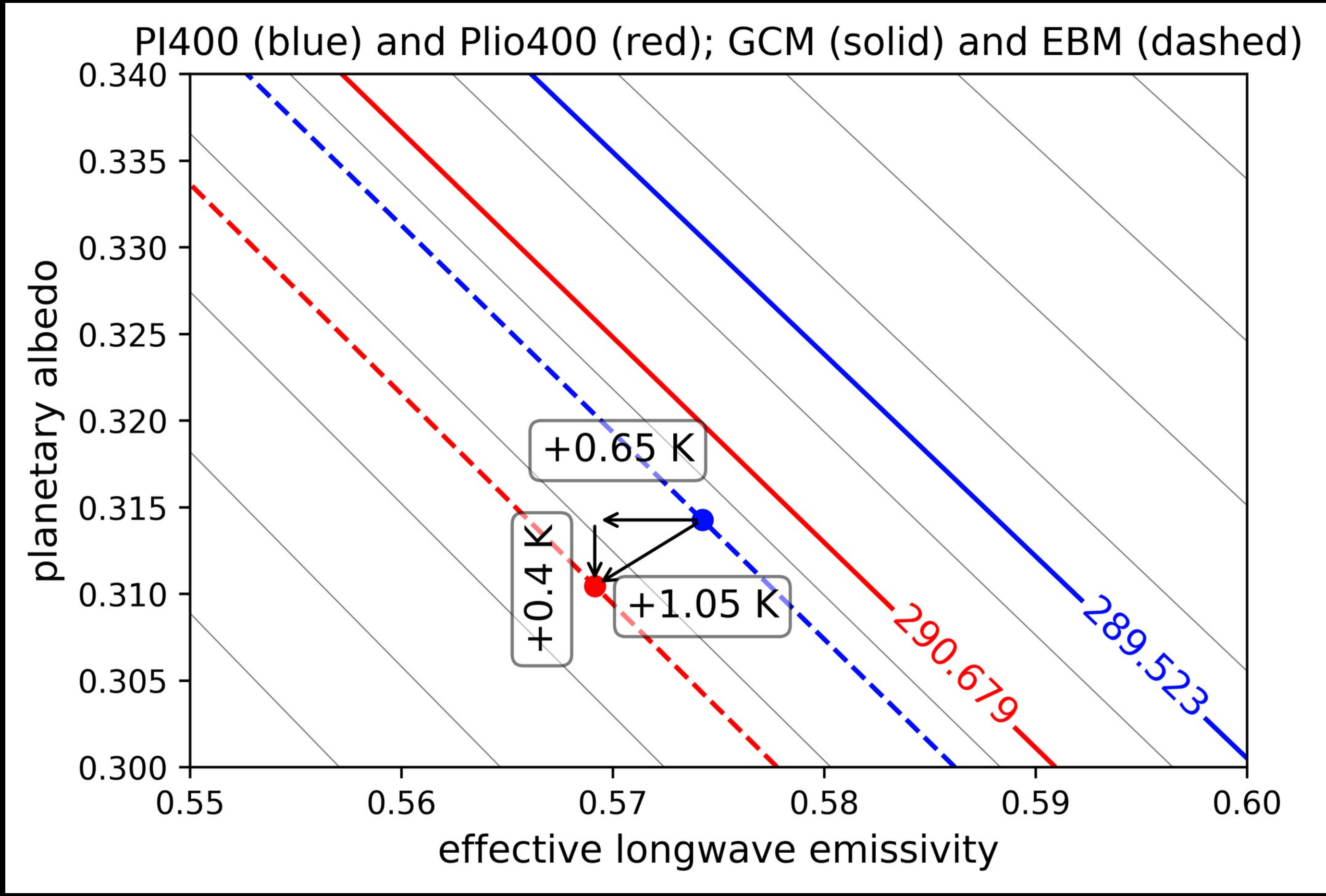
ANALYZE COSMOS CLIMATE IN EBM

- Climate (T, radiation, ...) simulated with COSMOS
- Compute planetary albedo α and effective longwave emissivity ϵ from COSMOS climate output based on their physical definitions (see tutorial notebooks)
- Recompute T in EBM from α and ϵ for reference
- Compute contributions of α and ϵ to T
- Visualize results in phase space of α and ϵ



ANALYZE COSMOS CLIMATE IN EBM

- Climate (T, radiation, ...) simulated with COSMOS
- Compute planetary albedo α and effective longwave emissivity ϵ from COSMOS climate output based on their physical definitions (see tutorial notebooks)
- Recompute T in EBM from α and ϵ for reference
- Compute contributions of α and ϵ to T
- Visualize results in phase space of α and ϵ



TUTORIAL BASED ON PYTHON3 / JUPYTER-NOTEBOOK

- Five assignments
- Two COSMOS simulations per assignment, study impact of a change in climate forcing / parameters
- Analysis of climate anomalies, "experiment" (perturbed simulations) vs. "reference" (simulated reference climate)
- Quantification of global average quantities in COSMOS, further analysis in a zero-dimensional EBM
- Visit https://jupyter.org/ for infos on jupyter-notebooks

notebook	reference	experiment	perturbation
1	Pre-Industrial (PI), with: ➯modern geography ➯280 ppmv CO_2 ➯standard ocean mixing	as PI, but with: ➯modern geography ➯560 ppmv CO_2 ➯standard ocean mixing	doubling CO_2 for modern geography
2	PI, with: ➯modern geography ➯280 ppmv CO_2 ➯standard ocean mixing	mid-Pliocene (mP), with: ➯mP geography ➯560 ppmv CO2 ➯standard ocean mixing	doubling CO_2, implementing mP geography
3	as PI, but with: ➯modern geography ➯400 ppmv CO_2 ➯standard ocean mixing	mP, with: ➯mP geography ➯400 ppmv CO_2 ➯standard ocean mixing	implementing mP geography at 400 ppmv of CO_2
4	mP, with: ➯mP geography ➯280 ppmv CO_2 ➯standard ocean mixing	mP, with: ➯mP geography ➯560 ppmv CO_2 ➯standard ocean mixing	doubling CO_2 for m P geography
5	mP, with: ➯mP geography ➯400 ppmv CO_2 ➯standard ocean mixing	mP, with: ➯mP geography ➯400 ppmv CO_2 ➯increased ocean mixing	increasing ocean vertical mixing for mP geography and 400 ppmv CO_2

TUTORIAL BASED ON PYTHON3 / JUPYTER-NOTEBOOK

- Download tutorial from: https://1drv.ms/f/s!AnZSDMNwdkDMgccDeuhjFFrmQHaqvw?e=RTWVOa
- Study notebooks and accompanying literature
- Answer problems outlined at the end of your notebook, work in groups
- Interact with other groups where necessary (as outlined in the notebooks)
- Prepare a presentation of your solutions for the lecture on 30th of January 2024

Assignments

This tutorial is split over five different assignments. Each of the assignments may be processed by a group of students. The assignments will be rather simple from the viewpoint of devising an analysis method, as all equations, methods and analyses are already available in the notebooks and results have been precomputed. The task is rather to interpret and discuss the findings based on some guidelines that will be provided towards the end of this notebook.

Assignment 1 - Analysing climate warming in a 2xCO2 world (modern land surface conditions, carbon dioxide doubled to 560 ppmv with respect to the pre-industrial value (280 ppmv))

Analysis of the global average temperature change due to a rise of carbon dioxide from pre-industrial conditions (280 ppmv) to 560 ppmv (that means a doubling of carbon dioxide from pre-industrial conditions). Reference simulation (pre-industrial climate) is COSMOS simulation E280. Target simulation (that will be analyzed in reference to simulation E280) is COSMOS simulation E560. Particular tasks fulfilled by this notebook:

- computing the global average equilibrium temperature change from a 100 year annual mean
- splitting the warming into contributions from changes in planetary albedo and effective longwave emissivity by means of an energy balance model
- computing Equilibrium Climate Sensitivity from the simulated equilibrium climate for modern land surface conditions

Assignment 2 - Analysing climate warming in a mid-Pliocene 2xCO2 world (mid-Pliocene land surface conditions, carbon dioxide doubled to 560 ppmv with respect to the pre-industrial value (280 ppmv)) in comparison to the Pre-Industrial.

Analysis of the global average temperature change due to a doubling of carbon dioxide and modification of land surface conditions from modern to mid-Pliocene (see Stepanek et al., 2020 for details). Reference simulation (pre-industrial climate with 280 ppmv) is COSMOS simulation E280. Target simulation (that will be analyzed in reference to simulation E280) is COSMOS simulation Eoi560. Particular tasks fulfilled by this notebook:

- computing the global average equilibrium temperature change from a 100 year annual mean
- splitting the warming into contributions from changes in planetary albedo and effective longwave emissivity by means of an energy balance model
- computing Equilibrium Earth System Sensitivity from the simulated equilibrium climate under the assumption that the mid-Pliocene earth surface, implemented into the mid-Pliocene climate simulation, is in equilibrium with the 560 ppm of carbon dioxide in that simulation

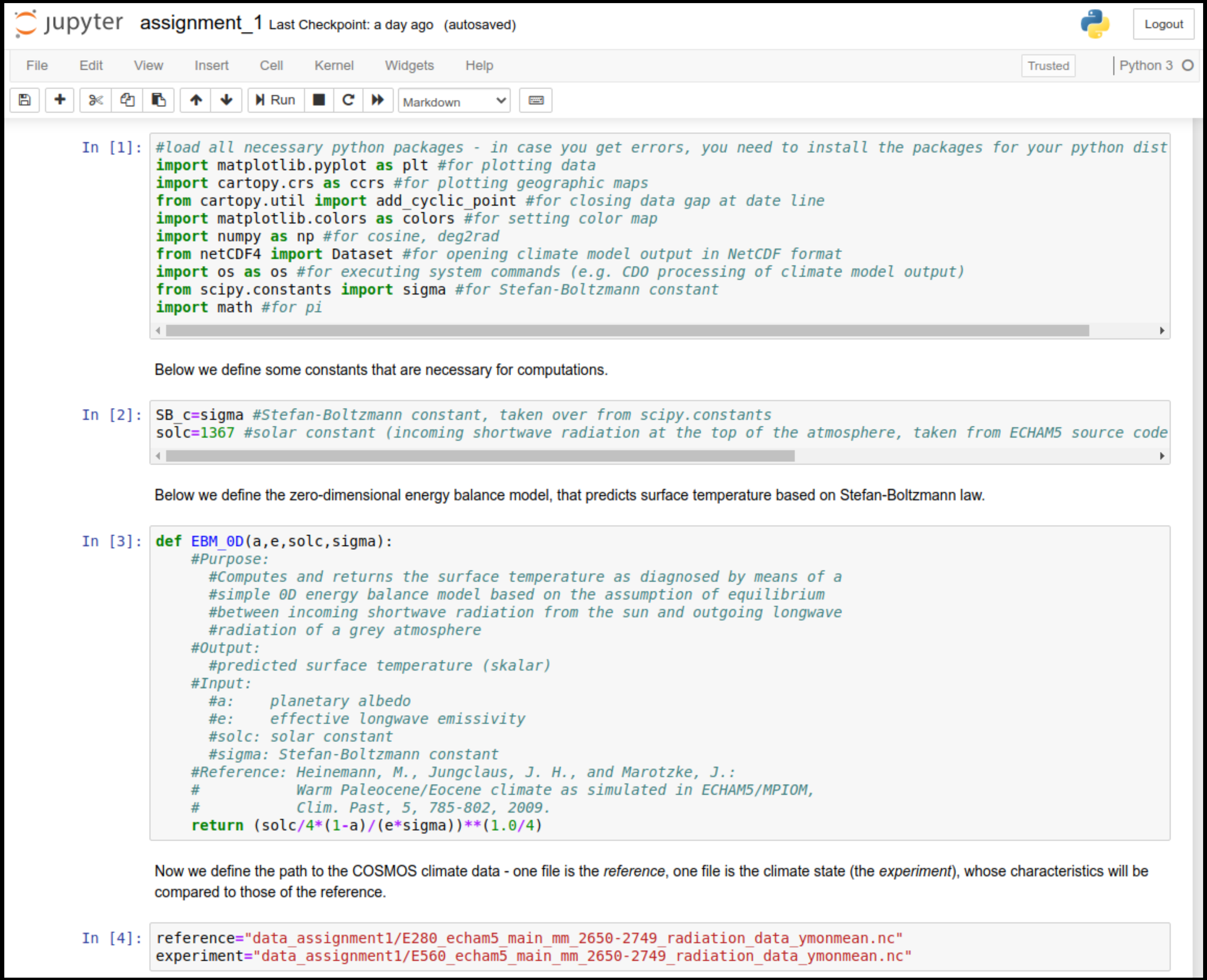
Assignment 3 - Analysing climate warming caused by mid-Pliocene geography (mid-Pliocene land surface conditions and carbon dioxide of 400 ppmv, compared to a simulation with modern geography and 400 ppmv of carbon dioxide)

Analysis of the global average temperature change due to adjustment of the land surface to mid-Pliocene conditions (see Stepanek et al., 2020 for details). In contrast to assignment 2, here we will quantify the impact of only changing the land surface to Pliocene conditions, excluding any effects of carbon dioxide. To this end we compare the mid-Pliocene simulation Eoi400, that is characterized by 400 ppmv of carbon dioxide, to a simulation with modern land surface conditions that has the same amount of carbon dioxide in the atmosphere. Reference simulation (a climate state with modern land surface and carbon dioxide of 400 ppmv (a bit less than the modern value)) is COSMOS simulation E400. Target simulation (that will be analyzed in reference to simulation E400) is COSMOS simulation Eoi400. Particular tasks fulfilled by this notebook:

- computing the global average equilibrium temperature change from a 100 year annual mean
- splitting the warming into contributions from changes in planetary albedo and effective longwave emissivity by means of an energy balance model
- computing the global warming caused by adjustment of land surface conditions to a mid-Pliocene setup at a carbon dioxide level of 400 ppmv

TUTORIAL BASED ON PYTHON3 / JUPYTER-NOTEBOOK

- Download tutorial from: https://1drv.ms/f/s!AnZSDMNwdkDMgccDeuhjFFrmQHaqvw?e=RTWVOa
- Study notebooks and accompanying literature
- Answer problems outlined at the end of your notebook, work in groups
- Interact with other groups where necessary (as outlined in the notebooks)
- Prepare a presentation of your solutions for the lecture on 30th of January 2024



In [1]:
```
#load all necessary python packages - in case you get errors, you need to install the packages for your python dist
import matplotlib.pyplot as plt #for plotting data
import cartopy.crs as ccrs #for plotting geographic maps
from cartopy.util import add_cyclic_point #for closing data gap at date line
import matplotlib.colors as colors #for setting color map
import numpy as np #for cosine, deg2rad
from netCDF4 import Dataset #for opening climate model output in NetCDF format
import os as os #for executing system commands (e.g. CDO processing of climate model output)
from scipy.constants import sigma #for Stefan-Boltzmann constant
import math #for pi
```

Below we define some constants that are necessary for computations.

In [2]:
```
SB_c=sigma #Stefan-Boltzmann constant, taken over from scipy.constants
solc=1367 #solar constant (incoming shortwave radiation at the top of the atmosphere, taken from ECHAM5 source code
```

Below we define the zero-dimensional energy balance model, that predicts surface temperature based on Stefan-Boltzmann law.

In [3]:
```
def EBM_0D(a,e,solc,sigma):
    #Purpose:
      #Computes and returns the surface temperature as diagnosed by means of a
      #simple 0D energy balance model based on the assumption of equilibrium
      #between incoming shortwave radiation from the sun and outgoing longwave
      #radiation of a grey atmosphere
    #Output:
      #predicted surface temperature (skalar)
    #Input:
      #a:    planetary albedo
      #e:    effective longwave emissivity
      #solc: solar constant
      #sigma: Stefan-Boltzmann constant
    #Reference: Heinemann, M., Jungclaus, J. H., and Marotzke, J.:
    #           Warm Paleocene/Eocene climate as simulated in ECHAM5/MPIOM,
    #           Clim. Past, 5, 785-802, 2009.
    return (solc/4*(1-a)/(e*sigma))**(1.0/4)
```

Now we define the path to the COSMOS climate data - one file is the *reference*, one file is the climate state (the *experiment*), whose characteristics will be compared to those of the reference.

In [4]:
```
reference="data_assignment1/E280_echam5_main_mm_2650-2749_radiation_data_ymonmean.nc"
experiment="data_assignment1/E560_echam5_main_mm_2650-2749_radiation_data_ymonmean.nc"
```

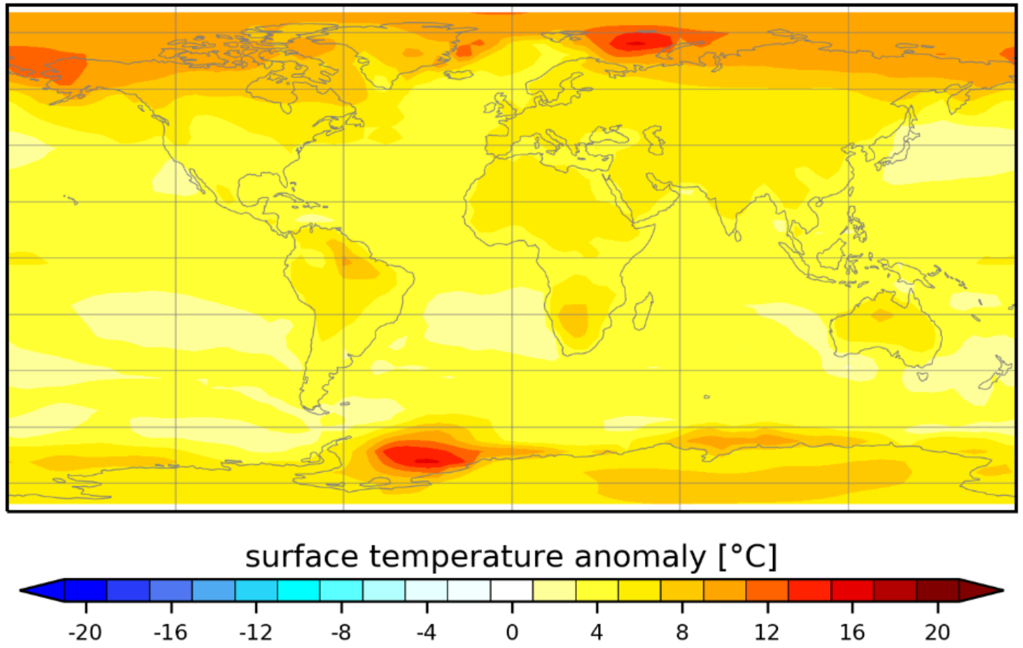
TUTORIAL BASED ON PYTHON3 / JUPYTER-NOTEBOOK

- Download tutorial from: https://1drv.ms/f/s!AnZSDMNwdkDMgccDeuhjFFrmQHaqvw?e=RTWVOa
- Study notebooks and accompanying literature
- Answer problems outlined at the end of your notebook, work in groups
- Interact with other groups where necessary (as outlined in the notebooks)
- Prepare a presentation of your solutions for the lecture on 30th of January 2024

```
#plot a colorbar for the heat flux anomaly data
print("adding a colorbar ...")
cax=plt.colorbar(cf, ticks=np.arange(level_min,level_max+stepsize,stepsize*2), drawedges=True, orientation='horizon
                      label=r"surface temperature anomaly [°C]",pad=0.10,shrink=.95,aspect=40)
cax.ax.xaxis.set_ticklabels([label.get_text().replace("−", "-") for label in cax.ax.xaxis.get_ticklabels()])
cax.ax.tick_params(labelsize=7)
cax.ax.xaxis.set_label_position('top')

#export the figure to PNG
print("exporting figure to PNG file " + outfile + "...")
plt.savefig(outfile,dpi=600,bbox_inches='tight')
```

```
executing cdo command: cdo timmean data_assignment1/E280_echam5_main_mm_2650-2749_radiation_data_ymonmean.nc data_
assignment1/E280_echam5_main_mm_2650-2749_radiation_data_ymonmean_timmean_tsurf.nc
executing cdo command: cdo timmean data_assignment1/E560_echam5_main_mm_2650-2749_radiation_data_ymonmean.nc data_
assignment1/E560_echam5_main_mm_2650-2749_radiation_data_ymonmean_timmean_tsurf.nc
generating map of surface temperature anomaly, experiment minus reference ...
adding a colorbar ...
exporting figure to PNG file assignment1_tsurf_anomaly_map.png...
```



We define a file name for the phase space diagram that will be produced below. Furthermore, we define labels for simulations reference and experiment, that will indentify major characteristics of the simulations in annotations in the analysis below.

```
outfile="assignment1_phase_space.png"
ref_name="PI280"
exp_name="PI560"
```

TUTORIAL BASED ON PYTHON3 / JUPYTER-NOTEBOOK

- Download tutorial from: https://1drv.ms/f/s!AnZSDMNwdkDMgccDeuhjFFrmQHaqvw?e=RTWVOa
- Study notebooks and accompanying literature
- Answer problems outlined at the end of your notebook, work in groups
- Interact with other groups where necessary (as outlined in the notebooks)
- Prepare a presentation of your solutions for the lecture on 30th of January 2024

```
In [13]: print("percentage of temperature change explained by change in planetary albedo:           "+str(abs(np.round(10
         print("percentage of temperature change explained by change in effective longwave emissivity: "+str(abs(np.round(10
```

```
percentage of temperature change explained by change in planetary albedo:              31.6%
percentage of temperature change explained by change in effective longwave emissivity: 68.4%
```

Finally, we compute Equilibrium Climate Sensitivity from the difference between experiment (modern geography with 560 ppmv of carbon dioxide) and reference (pre-industrial with 280 ppmv of carbon dioxide).

```
In [14]: print("equilibrium climate sensitivity for a modern land surface is: "+str(np.round(tsurf_exp-tsurf_ref,2))+"°C")
```

```
equilibrium climate sensitivity for a modern land surface is: 4.48°C
```

Guidelines for discussing results of assignment 1

1. Based on your results, is the climate warming due to a doubling of carbon dioxide more impacted by effects in the longwave or shortwave range of radiation?
2. Is the climate model COSMOS, for which we have computed the climate sensitivity above, rather sensitive or rather insensitive to changes in carbon dioxide in comparison to other climate models? Please answer this question based on information from the carbonbrief.org, https://www.carbonbrief.org/explainer-how-scientists-estimate-climate-sensitivity#:~:text=Climate%20models%20provide%20a%20wide,average%20sensitivity%20of%203.1C, and based on information by the study by Meehl et al. (2020; https://advances.sciencemag.org/content/6/26/eaba1981.abstract).
3. Your simulations differ in carbon dioxide by a factor of two (280 ppmv vs. 560 ppmv). At the moment, the real climate system is exposed to about 410 ppmv of carbon dioxide (https://keelingcurve.ucsd.edu/) - note though, that the modern climate system is much less in equilibrium with the ever-changing level of greenhouse gases than your two simulations, that have been conducted over a long period of time with fixed levels of carbon dioxide. Yet, by means of some simple estimates, and based on the equilibrium climate sensitivity derived from your analysis: Do you expect that we can still keep the 1.5°C warming target (https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement) if we immediately stop any further carbon emissions and keep the atmospheric composition stable? Consider the climate on the long term rather than over the next view years only - that means, we consider the 1.5°C target at a time when climate has reached an equilibrium with the current levels of carbon dioxide.
4. Please get in touch with colleagues solving assignment 4 and ask them for the value of Equilibrium Climate Sensitivity that they derive in a similar simulation setup employed by you, but based on a mid-Pliocene land surface rather than a modern land surface as employed in your simulations. Is the value of Equilibrium Climate Sensitivity larger for mid-Pliocene or for modern land surface conditions? Which differences in land surface conditions between the mid-Pliocene and modern could contribute to a difference in Equilibrium Climate Sensitivity? Figure 2 by Stepanek et al. (2020, https://cp.copernicus.org/articles/16/2275/2020/cp-16-2275-2020.html) may be helpful in this respect. Please think in particular about the two land surface characteristics *albedo* and *elevation*. These may in particular be influenced by differences in ice sheet extent and ice sheet height between modern and mid-Pliocene.

QUESTIONS?

- contact Christian.Stepanek@awi.de

Further Reading

1.) Applications of the COSMOS climate model (e.g. Stepanek, C., Samakinwa, E., Knorr, G., and Lohmann, G.: Contribution of the coupled atmosphere–ocean–sea ice–vegetation model COSMOS to the PlioMIP2, Clim. Past, 16, 2275–2323, https://doi.org/10.5194/cp-16-2275-2020, 2020.)

2.) Application of an Energy Balance Model towards unravelling contributors to differences in global mean temperatures (Chapter 4 of Heinemann, M., Jungclaus, J. H., and Marotzke, J.: Warm Paleocene/Eocene climate as simulated in ECHAM5/MPI-OM, Clim. Past, 5, 785–802, https://doi.org/10.5194/cp-5-785-2009, 2009.)

3.) The relevance of past (warm) climates for humankind, e.g.:

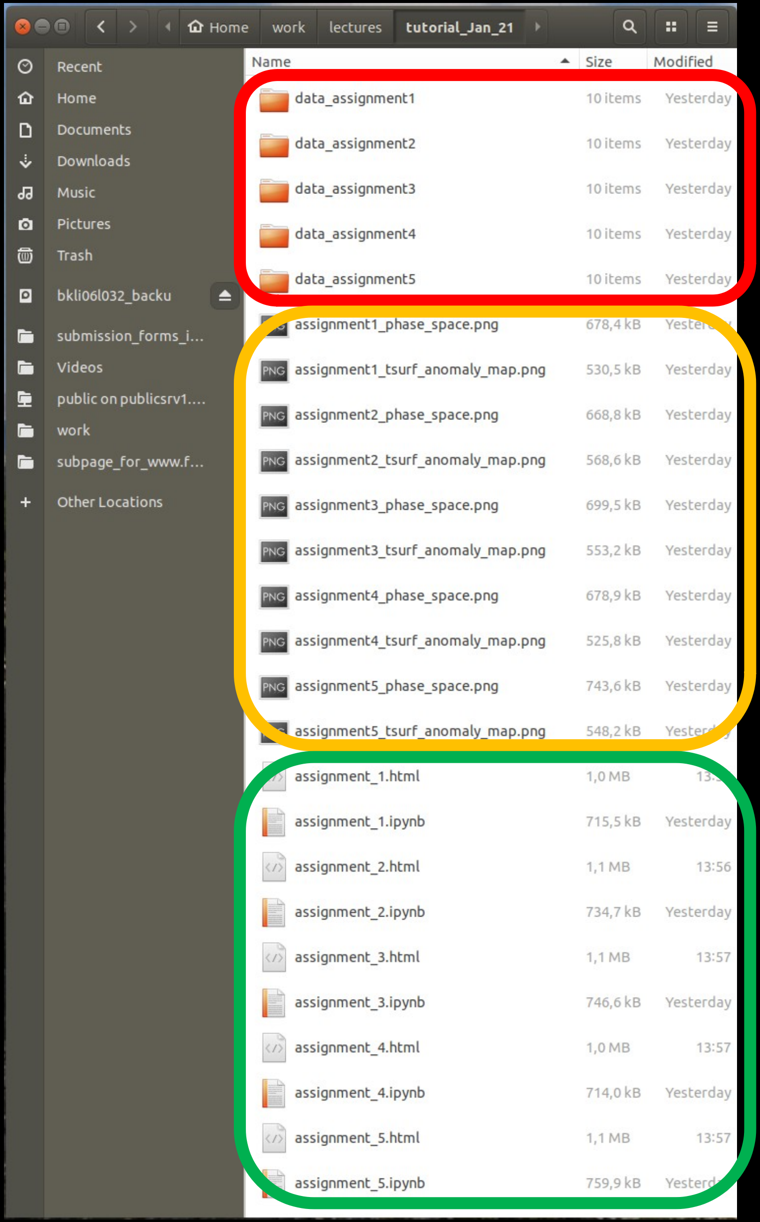
- Burke, K. D., Williams, J. W., Chandler, M. A., Haywood, A. M., Lunt, D. J., and Otto-Bliesner, B. L.: Pliocene and Eocene provide best analogs for near-future climates, P. Natl. Acad. Sci. USA, 115, 13288–13293, https://doi.org/10.1073/pnas.1809600115, 2018.
- Haywood, A. M., Valdes, P. J., Aze, T., Barlow, N., Burke, A., Dolan, A. M., von der Heydt, A. S., Hill, D. J., Jamieson, S. S. R., Otto-Bliesner, B. L., Salzmann, U., Saupe, E., and Voss, J.: What Can Palaeoclimate Modelling Do for You?, Earth Syst. Environ., 3, 1–18, https://doi.org/10.1007/s41748-019-00093-1, 2019.

Glossary for some terms employed in the assignments

- **greenhouse gases** as contributors to climate variations
  Beyond carbon dioxide, that is currently a major driver of ongoing climate change, there are other contributors that may be already known to you from general information on physics of climate change. There are further greenhouse gases, including water vapor that is actually the most important greenhouse gas in the Earth System. As formulated by the Clausius-Clapeyron equation, increasing temperature of the Earth System (e.g. via increasing carbon dioxide) will lead to an increase in the amount of water vapor in the atmosphere. This, in turn, will further increase the temperature (due to an increase in the greenhouse effect). This interplay of temperature and water vapor changes represents a positive feedback loop, where the initial climate signal is reinforced by internal dynamics of the climate system.
- **land surface conditions** as a contributor to climate variations
  Even in the absence of changing carbon dioxide or other greenhouse gases, temperature change of the Earth System may occur via adjustments to land surface conditions; reducing the extent of ice sheets, for example, will decrease the surface albedo, leading to less sunlight being reflected back towards space and increasing the conversion of sunlight into heat. Reducing the height of ice sheets, for example, will reduce the height of the land surface, and lead to a warming via lapse rate. As another example, that will be touched in this exercise: By increasing the effectivity of the ocean to mix down heat into the deeper ocean, one can create a larger heat sink in the ocean, which will cause more heat to be trapped in the Earth System.
- **Equilibrium Climate Sensitivity**
  Equilibrium Climate Sensitivity is defined as the equilibrium change in global average temperature due to a doubling of carbon dioxide from pre-industrial conditions - that is a change from 280 ppmv to 560 ppmv. In this context, only short-term climate feedbacks are considered. This means, for example, that it is implicitly assumed that ice sheets are not (yet) responding to a change in temperatures.
- **Equilibrium Earth System Sensitivity**
  Equilibrium Earth System Sensitivity is defined as the equilibrium change in global average temperature due to a doubling of carbon dioxide from pre-industrial conditions - that is a change from 280 ppmv to 560 ppmv. In this context, also long-term climate feedbacks are considered. This means, for example, that it is implicitly assumed that ice sheets are responding to a temperature change, meaning that ice-sheet related climate feedbacks are able to increase temperatures above the initial warming created by short term feedbacks alone.
- **Planetary Albedo**
  Planetary albedo is the reflectivity of the Earth System for shortwave radiation from the viewpoint of space. An increase of planetary albedo will have the tendency to cool the climate via increasing reflection of shortwave radiation (that is incident sunlight) back into space.
- **Effective Longwave Emissivity**
  Effective longwave emissivity quantifies the amount of longwave radiation emitted by the Earth System as a result of its temperature. The physical foundation for this behavior is the well-known Stefan-Boltzmann law.

QUESTIONS?

- contact
  Christian.Stepanek@awi.de



Folders containing data used and produced by individual jupyter-notebooks

Graphics produced by individual jupyter-notebooks as a result of the data analysis

Notebooks (*.ipynb-files) of the five different assignments. These can be opened with a jupyter-notebook server and interactively executed. You can modify the program code towards further exploration of model data. As a backup, there are also *.html-files that contain all contents of the *.ipynb-files and that can be opened with any web-browser

OUTLINE / MOTIVATION

- The climate system – complex coupled subsystems interacting in complicated ways
- Coupled models of atmosphere-ocean circulation as a laboratory for scientific studies
- The mid-Pliocene as a case study for analyzing a past state of warmer climate (⇨ Beyond models, we cannot study the future – but we can study the past)
- Understanding climate dynamics in coupled climate models difficult (many simultaneous changes)
- Solution: take a step back, analyze model results in simpler climate models
- Tutorial: five sets of simulations by the Community Earth System models (COSMOS) are further analyzed in a zero-dimensional energy balance model
- Five assignments, each one to be solved by a group of students
- Collaboration between groups explicitly supported (and necessary for some tasks)
- Focus of the problems is on understanding the analysis and discussing some implications of results
- All analyses already coded in Python/CDO and formulated in jupyter-notebooks
- You are of course very welcome to modify example code for further analyses