ON THE USES OF COMPUTER MODELING FOR IMPROVED UNDERSTANDING OF CLIMATE

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WE LIVE IN A CHANGING WORLD!

from IPCC report (2021), WG1
IN OUR BACKYARD!

Observed U.S. Precipitation Change
WHY IS IT HAPPENING?

from IPCC report (2021)
FAQ 3.1: How do we know humans are causing climate change?

Observed warming (1850-2019) is only reproduced in simulations including human influence.

From IPCC report (2021)
Conclusions and predictions for the planet are obtained using climate models.

Climate models are deterministic models that represent all the geophysical processes that contribute to determine climate on Earth.

The are based on systems of partial differential equations representing the laws that govern the motion of fluids, also called the governing equations of the atmosphere. The number of equations vary depending on the complexity of the model.

The equations are solved using numerical approximations.
CLIMATE MODELS

Aerosols
- SWR

Natural Fluctuations in Solar Output
- SWR, LWR

Clouds
- SWR, LWR

Ozone
- SWR, LWR

Greenhouse Gases and Large Aerosols
- LWR

Outgoing Longwave Radiation (OLR)

Chemical Reactions

Latent Heat Flux
- Sensible Heat Flux

Back Longwave Radiation (LWR)

LWR Emitted from Surface

Emission of Gases and Aerosols

Ice/Snow Cover

Ocean Color Wave Height

Vegetation Changes

Surface Albedo Changes

from Rose (2022)
from McGuffie and Henderson-Sellers (2014)
CLIMATE MODELS

- Land Biogeochemistry
  - Land
  - CLM5
- River Runoff
  - MOSART
- Surface Waves
  - WW3
- Marine Biogeochemistry
  - MARBL
- Atmosphere
  - CAM6 / WACCM6
- Coupler
  - CIME5
  - POP2
- Ocean
- Sea Ice
  - CICE5
- Land Ice
  - CISM2

from Rose (2022)
# Climate Models: Then and Now

![Diagram of climate models evolution](image)

The evolution of climate models from the mid-1970s to AR5 highlights advancements in understanding the Earth's climate system. Each model iteration has incorporated additional components and processes, as indicated by the bars representing different elements such as the atmosphere, land surface, ocean and sea ice, aerosols, carbon cycle, dynamic vegetation, atmospheric chemistry, and land ice. The progression shows an increase in complexity and accuracy, reflecting the models' ability to simulate and predict climate changes more effectively.

*From Rose (2022)*
MY WORK WITH CLIMATE MODELS

• Have been working with climate models, or related models (numerical weather prediction models), since my PhD days.

• My work has been focused on:
  • assessing and evaluation the output of the models
  • postprocessing the output of the models
  • studying the inputs of the models
  • coming up with strategies for improving the inputs of the models
• Outputs of global climate model (GCMs) are provided over large spatial domains at a coarse spatial resolution.
• Regional climate models (RCMs) operate over a smaller spatial domain and can capture local processes better.
Assessing a climate model is not a trivial task. Climate, being the distribution of weather and other climatic factors over long periods of time, cannot be measured directly. Usually, long-term observational averages are compared to the climate model output. But the spatial resolution of the two is not the same!

When assessing an RCM there are two sources of discrepancies:
- inadequacy in the model itself (the equations, the methods used to solve them, etc);
- inadequacy in the initial and boundary conditions provided to the model.

In our study, we control for the second so that we can make statements about the model itself.
• Output from an RCM run at the Swedish meteorological center

• 2-m daily average temperature, averaged to yield quarterly average temperature. Period: December 1, 1962 to November 30, 2007.

• Output available at 12.5km x 12.5km resolution
• Observations of daily temperature available from 17 stations over the same period, December 1, 1962 to November 30, 2007.

• We used 15 stations to develop our statistical models and 2 stations to validate the model out-of-sample.
The RCM output and observations have different spatial resolution.

Perform the comparison addressing the difference in spatial scale explicitly via **downscaling** the corrected RCM output to point level and **upscaling** the observations to the RCM grid box.
A FIRST COMPARISON
DOWNSCALING MODEL

RCM output: DJF 2002

Observation data: DJF 2002
DOWNSCALING MODEL

RCM output: DJF 2002

Observation data: DJF 2002
The weights are estimated from the data and they vary spatially and temporally.
RESULTS

- Assessment of predictions at the two hold out sites: Borlange and Stockholm.

- **Black line**: observation
- **Red line**: RCM output
- **Magenta line**: Upscaling model
- **Blue line**: Downscaling model
RESULTS

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RESULTS

- Spatial differences between predictions of quarterly average temperature generated by the upscaling and downscaling model, generated as averages over gridboxes, and the RCM output.
CONCLUSIONS

• Predictions from the downscaling model agree more with the RCM output than predictions generated from the upscaling model.

• Upscaling predictions are warmer than the RCM output in the North and colder in the South.

• In the extreme quarters, both the downscaling and the upscaling model tend to predict warmer temperatures than the RCM.
ANOTHER RCM ASSESSMENT: LOOKING FOR SYSTEMATIC PATTERNS

• In a different project, we looked at whether we could detect systematic patterns in the differences between the RCM output and the predicted average temperature by our downscaling model.

• We still considered quarterly average temperature for the same period: December 1, 1962 to November 30, 2007.
• For each year $t$, we looked at the differences between the RCM output and the predicted average temperature by our downscaling model. We call this the RCM spatial error for year $t$.

• We clustered the RCM spatial errors.
• **Probability** that the RCM errors for average temperature in **Winter** for two specific years **cluster together**, e.g. are very similar.
• Probability that the RCM errors for average temperature in Spring for two specific years cluster together, e.g. are very similar.
• **Probability** that the RCM errors for average temperature in **Summer** for two specific years **cluster together**, e.g. are very similar.
• **Probability** that the RCM errors for average temperature in **Fall** for two specific years **cluster together**, e.g. are very similar.
Examining the RCM spatial error for Fall 2002.
CONCLUSIONS

• The type of errors made by the RCM were more similar in the last 12 years in the period 1962-2007.

• The probability that the RCM spatial errors were similar was particularly high in Summer and Fall.

• Examining the pattern, we determined that the RCM systematically underestimated average temperature in the North and overestimated average temperature in the South in the last 12 years.
• Global climate model represent various geophysical processes and the evolution in time of these processes.
• They need to be initialized with information of the initial state of the system.
• Often there is not enough amount of information available on the state of the system. This is particularly true for variables for which collecting information is time-consuming (e.g. soil variables).
A variable that is very important to describe the carbon cycle is soil organic carbon.

Soil organic carbon (SOC) refers to the fraction of carbon in the soil that is exclusive of non-decomposed plants and animal residues.

SOC is a very important variable used as input in climate models.

However, since collecting soil organic carbon is time consuming not much data is available.

We want to determine where to concentrate sampling efforts for soil organic carbon.
• We used data collected on SOC in 2010-2012 by the US Department of Agriculture.

• We developed a spatial model to learn about variations in the spatial dependence structure of SOC.
Future sampling efforts should be concentrated in the region in (b) with a blue boundary.
OVERALL CONCLUSIONS

• Climate models are fundamental and necessary to study future climate, understanding the impact of climate change on the ecosystem and humans and determining adaptation measures.

• Climate models are complex deterministic mathematical models that rely on an incredible amount of information.

• Assessing the reliability of climate models is important for future projections.

• Understanding the sources of inadequacy in climate models is of vital importance.

• Improving the quality of input data to climate models is necessary to reduce the uncertainty and errors of climate models.