Worksheet

Using idealized models to understand the impact of sea ice on climate change

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** Based on notes from Ian Eisenman (UCSD) and work by Nicole Feldl (UCSC) and Tim Merlis (Princeton)*

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This worksheet provides a hands-on exercise to explore the impact of sea ice on climate change. We will use an idealized model of the climate system based on the work of Feldl and Merlis, (2021) and Wagner and Eisenman, (2015). The goal is to demonstrate the usefulness of simple conceptual models in understanding climate processes. Details of the model can be found in the papers below:

- Feldl, N., & Merlis, T. M. (2021). Polar amplification in idealized climates: The role of ice, moisture, and seasons. Geophysical Research Letters, 48(17), e2021GL094130.
- Wagner, T. J., & Eisenman, I. (2015). How climate model complexity influences sea ice stability. Journal of Climate, 28(10), 3998-4014.

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1. Start by accessing the model code in the folder. You will see a Jupyter notebook titled:

   `idealized-models-Sikumiut-field-school.ipynb`

   and a Python file titled:

   `SCM_MEBM.py`

   You do not need to change anything in the `SCM_MEBM.py` file, but feel free to poke around and look at how the idealized model is constructed. You will see similar equations as described in the introductory slides. You will also see a number of physical and numerical parameters and code that numerically solves the partial differential equation.

2. Run the idealized model by running each block of code in the `.ipynb` file. This can be done by clicking on each block and pressing `Shift + Enter`. For this exercise, we will focus on the Northern Hemisphere. There is some code to post-process the model output and generate initial plots of surface temperature and sea ice thickness. The plots show the surface temperature and sea ice thickness fields during the final year of the simulation as well as zonal-mean profiles of surface temperature and sea ice thickness for the annual-mean and summer and winter seasons.

   You can see that the idealized model *qualitatively* reproduces some features of the real world, such as the seasonal cycle of surface temperature and the growth and melting of sea ice. However, the idealized model *quantitatively* fails when considering specific regions. For example, just for fun, we can note that April 7-11 in Utqiagvik (71.3°N) corresponds to ($t = 0.27$; $x = 0.95$). There is some code to generate values and plots for Utqiagvik around April 7.

- What does this idealized model predict the surface temperature and sea ice thickness to be right now in Utqiagvik?
- When does this model predict the surface melt season will begin in Utqiagvik?
- Does the seasonal cycle of surface temperature and sea ice thickness at 71.3°N in this model accurately represent conditions in Utqiagvik?

3. Have a look through the setup of the idealized model. The code begins by defining a series of numerical parameters for the spatial grid (e.g., n), as well as other definitions that impact the timestepping of the idealized model. The code then integrates the idealized model in time and saves the last year of data. To understand how some of these parameters affect the interpretation of the model output, try varying the length of the simulation by changing the duration `dur = 100` to `dur = 5`. Here, 100 refers to 100 years.

   - How long do you need to run the model for it to approximately reach equilibrium?

   You can examine this by looking at the "Global-mean top-of-atmosphere energy imbalance". A world in equilibrium should have a value close to zero.

4. Now that you have a good grasp of how the idealized model works, let's explore the impact of sea ice on climate change. First, make sure to set `dur = 100` (the default value).

   To examine the impact of sea ice on climate change, we need to simulate the radiative effects of greenhouse gases such as carbon dioxide. If atmospheric carbon dioxide were doubled from pre-industrial values, the radiative forcing (F) on Earth's climate system would be approximately 4 W m^{-2}. Thus, by prescribing `F = 4` in the model, we can simulate the effects of increased carbon dioxide levels.

   To conduct climate change simulations, we want to compare simulations with and without increased carbon dioxide concentrations. First, run a simulation in which `F = 0` and label the model output as a control run (e.g., `Ts_ctrl`). Next, run a simulation in which `F = 4` and label the model output as an experiment run (e.g., `Ts_exp`). To examine how surface temperature and sea ice thickness change under increased carbon dioxide concentrations, take the difference of each variable and generate some plots.

   - How does surface temperature respond to increased carbon dioxide concentrations?
   - What is the magnitude of 'Arctic amplification'?
   - What changes occur in sea ice thickness under higher carbon dioxide levels?
   - Do any notable seasonal patterns emerge in the response?

5. Now, suppose that sea ice did not exist on Earth. One could imagine this as an extremely warm climate, similar to those seen during the early Eocene (approximately 50 million years ago). Evidence suggests that the Arctic was so warm that crocodiles thrived in the high latitudes.

   We can simulate a climate with no sea ice by turning off the thermodynamic effects of sea ice and removing its influence on the albedo at Earth's surface. In the idealized model, this can be done by setting `sea_ice_albedo = 'off'` and `sea_ice_thermodynamics = 'off'`.

   To examine how sea ice impacts climate change, we now need to run a new control simulation where both the effects of sea ice albedo and thermodynamics are turned off, as well as a new climate change simulation (i.e., `F = 4`) with the same modifications. For both experiments, save the model output and generate the same plots as above.

- How does surface temperature respond to increased carbon dioxide concentrations when there is no sea ice?
- What is the magnitude of 'Arctic amplification'?
- Do any notable seasonal patterns emerge in the response?

6. Now, let's summarize our conclusions. As discussed in the introductory slides, Arctic amplification is a well-established feature of climate change. In this exercise, we used an idealized model to explore how sea ice influences climate change and Arctic amplification. Specifically, we asked:

   - How does sea ice influence climate change?

   Based on your results from #4 and #5, how would you answer this question? What role does sea ice play in Arctic amplification?

   Idealized models are widely used in climate science as they provide a first-order understanding of the climate system.

   - Do you think this model overestimates or underestimates the effect of sea ice on climate change?
   - What key processes might be missing from this model, and how could their absence impact your conclusions?

7. If you finish early or want to explore further, here is another exercise. As mentioned above, idealized models like this are often used to develop first-order understandings of what controls Earth's climate. For example, the parameter `B = 1.8` represents the efficiency of radiation to space. This parameter can be thought of as Earth's climate feedback, which either amplifies or dampens warming. If `B` is larger, Earth emits more radiation to space; if `B` is smaller, Earth emits less radiation to space. Try changing `B` by 10%. What happens to the magnitude and pattern of warming under increased carbon-dioxide with a weaker or stronger climate feedback (`F = 4`)? Remember to run a control and experiment for each parameter.