Multi-Model Analysis of Artic Sea Ice using Thermodynamic Models

Augustin Lambotte and Amaury Laridon
Université Catholique de Louvain, École de Physique,
Chemin de Cyclotron 2, 1340 Louvain-la-Neuve, Belgique[*]

In the context of current global warming, producing relevant sea ice simulations and projections for the following century is crucial. In this paper we perform a multi-model analysis of uni-dimensional thermodynamical sea ice models. Using this ensemble simulation, we discuss two main topics. The long term behavior at the end of the century of sea ice and its seasonality.

INTRODUCTION

Sea ice is a crucial element of the climate system. Although it's quite thin - barely never more than 5 meters - its high albedo has a determinant impact on the energy budget of the highest latitude, affecting the whole climatic system. The global warming, which is at least twice as fast as the rest of the planet in the Arctic[1] - a phenomenon known as polar amplification - has lead to a rapid decline of Arctic sea ice. A recent paper of Guarino and al[2] strongly supports the hypothesis that Arctic summers will be completely ice-free by 2035. An overall decrease in the thickness and extent of sea ice is a phenomena that will seem to last during the XXI centuries due to an increasing greenhouse forcing. In addition to its central place and its interactions in the climate system, there are also major socio-economic issues related to the state of sea ice in the Arctic, whether for the more than 4 million people who live there or for maritime transport.[3] Therefore being able to perform relevant sea ice evolution projection is an important topic in order to understand the consequences of climate change and adapt mitigation policies.

In this paper, we perform a multi model analysis over 15 thermodynamics uni-dimensional sea ice models. three scenarios are investigate, each ones relates a different forcing magnitude. They are `PR03`, `PR06` and `PR12`, for a maximum forcing of 3, 6 and $12W/m^2$ at the end of the century. Using these simulations as well as a control run (`CTL`) for comparing all members of the ensemble, we will investigate two main questions. *How sea ice will evolve over the century, are we going to face an acceleration of the current decrease or will it stop ?* Secondly, *over which season in a year will the melting rate be the largest ?*

We will start by a short presentation of the materials and methods we used in Part I, in Part II we will present our results and discuss the skills of the models face to real data. The part III will give way to a discussion of these results and the possible implications.

MATERIALS AND METHODS

This multi-model analysis of sea ice is based on 15 *Thermodynamic Sea Ice Model* (`TSIM`) all based on the *Semtner 0-layer model*[4]. Here we explain briefly what are this model made off and how we will use them using ensemble technique as well as the different simulations. [9]

TSIM Model

All the `TSIM` models are composed of a vertically dynamic layer of ice coupled to a free surface temperature and an ocean mix layer. Nine of the 15 models also have a dynamic layer of snow implemented. All models have a daily time resolution and are able to simulate first-year and multi-year sea ice regimes.

The `TSIM` models are able to simulate a full seasonal cycle of sea ice growth and melt. They are based on a thermodynamic equilibrium computation between energy from the atmosphere and an ocean heat flux. The atmospheric solar heat flux Q_{sol} and non solar Q_{nsol} (such as downwelling longwave, latent and sensible heat fluxes) are converted into SI units from Fletcher[5]. The surface temperature changes according to the different fluxes from the atmosphere where the incoming atmospheric fluxes and the outgoing longwave flux form the ice are balanced by the conduction flux in the ice. The temperature gradient in the ice is assumed to be linear all the time and the surface temperature T_{su} is computed each iteration from this energy budget relation [10],

$$Q_{sol}(1-\alpha) + Q_{nsol} - \epsilon\sigma T_{su}^4 = k.\frac{T_{su} - T_f}{h} \qquad (1)$$

where α is the surface albedo, T_f the bottom temperature of the ice [11] and k the heat conductivity coefficient that will depends on whether there is also a layer of snow on top of the ice and their relative thickness. If $T_{su} > 0°C$ the net surface flux is positive [12] and this energy is used for melting. A gain of sea ice may happen because there can be a congelation heat loss due to conduction (based on Fourier-Fick's law) of heat from the sea ice base.
For the nine models that have it, the snow layer has an input distribution of snowfall following Maykut and Untersteiner[6] and snow melting is simply parameterized using surface energy budget when the temperature reach and exceed $0°C$.
The ocean mix layer acts as a heat reservoir with a temperature T_w especially when the sea ice melts completely in summer. In that case the net positive surface energy flux warms the ocean mix layer which is assumed to have a fixed depth of $h_w = 50m$. At the end of the ice-free season, once the temperature drops below freezing, the ocean temperature is reset to freezing temperature and the excess heat is used to grow some new ice.

All models have been first tuned on the basis of the twelve monthly mean values from `MU71` simulation of ice thickness of Maykut and Untersteiner[6] which provides a typical Arctic perennial ice thickness distribution before the recent effects of climate change. The simulated ice thickness being strongly depended of the parameterization of thermal conductivity and albedo used, those where the two major axes investigated to approach as close as possible the `MU71` data set.

In order to do that, a multiplicative coefficient $\gamma^{SM} \approx 1.1$ has been implemetend to artificially enhance ice growth to balance the inhability of the `TSIM` models to store negative heat in winter. Then, a more elaborate representation of the albedo with a linear variation between the dry snow albedo $\alpha_s = 0.83$ and the bare ice albedo $\alpha_i = 0.64$ depending on the thickness of snow and ice has also been added. Lastly, because in summer radiation penetrates below the surface, which is a phenomena not explicitly implemented in `TSIM`, a reflect back to space fraction $\beta^{SM} \approx 0.4$ of the radiation that should be stored into brine inclusions is perform.

Control Simulation and Projections

The first experiment for all models (15) has been a control run of fifty years (`CTL`) with parameters tuned in order to achieve a model equilibrium seasonal cycle as close as possible to the `MU71` simulation. For all models, the output used is the daily values of the last year of simulation of T_{su}, the ice thickness h_i, the snow thickness h_s and the ocean mix layer temperature T_w.
Then projection simulations (`PR`) has been made with the same parameters values for each model as in the `CTL` run. [13] The `PR` are hundred years simulation starting from the equilibrium state i.e the last day values of the variable of the `CTL` run but with this time a progressively increase downwelling longwave radiation over the 100 years to emulate the effect of the increasing greenhouse effect. Three different scenarios has been run, `PR03`, `PR06` and `PR12`. For each, a linear increasing extra forcing is apply from $0W/m^2$ in the first year to a maxima longwave perturbation $\Delta Q^{lw} = 3, 6, 12W/m^2$ at the end of the century, respectively. The data output are this time the annual value for each of the 100 years of the minima in ice thickness hi_{min}, its mean hi_{mean}, its maxima hi_{max}, the snow thickness maxima hs_{max} and the surface temperature minima Tsu_{min}. The data for the `CTL` and the `PR` experiment are available in the Annexe.

Ensemble technique

Ensemble simulations and analysis are very common in scientific research especially in climatology because they allow to reduce uncertainties associated with imperfect model physics and understanding by using multiple models coded by different individuals. The method used in this report in order to answer the two scientific question is a ensemble analysis from the `CTL` and `PR` experiment. Indeed, the first question about the evolution of sea ice thickness in the Arctic over the century will be investigated with the ensemble `PR` simulations. For the seasonal anomaly in melting rate over a year, again, the `PR` will be very useful once a comprehensive understanding of the behavior of the models will be achieved after studying the `CTL` experiment. As we will see, the ensemble behavior allows us to distinguish the divergence in the individual behavior of the models, particularly those that implemented snow and those that did not.

DESCRIPTION OF THE RESULTS

Multi-Model CTL Performance with MU71

First we compare the multi-model behavior face to observations in the CTL experiment. The mean ice thickness of the ensemble (ENS) in one year at equilibrium in the CTL experiment is $\mu_{ENS} = 2.952m$ where for the MU71, $\mu_{MU} = 2.884m$. Hence there is a relative error of $\epsilon_r = 2.36\%$ of overestimation of the ENS. For exemple if we look at SIGUS it has an $\epsilon_r = -1\%$ where TSIMAL has $\epsilon_r = 0.047\%$ to illustrate that some models overestimate with regards to MU71 and/or ENS where it may be the opposite for other. Nevertheless we can see from the right frame of Fig.(1) that the ENS globaly fit well the MU71 target data with the latter beeing almost always in the uncertainty range of ENS except in the sea ice growing period where MU71 has a noticable smaller growing rate than ENS. In contrast, the melting in the ENS simulation is faster than MU71.

As we have see, each model has its own identity and we can divide them in two big categories. The ones which simulates snow and the one who don't - hereafter called SM and SFM for *Snow Models* and *Snow Free Models*, respectively. We have plotted on Fig.(1) the results of the multi-model control run (ENS-CTL) face to observed data MU71. We see that SFM are more than twice dispersed than SM ($\sigma_{SM} = 0.1m$ where $\sigma_{SFM} = 0.24m$). During the winter season, SM simulate quite well the ice growth when SFM grows way more than MU71. This is due to the isolating power of the snow, without it the heat exchange is bigger and ice can grow more. We can see a clear distinction in the transition of the growth and melt regime of sea ice between SM and SFM. For the SM they have to first completely melt the layer of snow before starting to melt the ice layer which explains this more smooth behavior in the SFM and the observed delay of the melting until this treshold. During the melting, SM and SFM have more or less the same mean behavior but SFM are way more dispersed. We note that both of them overestimate the melting rate during the melting season but then overestimate the ice grow rate after the summer especially for the SFM. On Fig.(1) the BRAILLE_ANE and YBLAIRE models are explicitly represented. Those two models are in fact distinct in their design from the other TSIM. [14]
BRAILLE_ANE can be considered as an SFM that underestimate a lot the mean ice thickness and act as a pronounced variability creator for the SFM ensemble but has globally a similar shape that the ensemble SFM with nevertheless a more noticeable melt.
YBLAIRE is an SM with a really similar trend as the other SM except that it has a strong negative bias in its mean and produces hence marked variability in the SM ensemble.

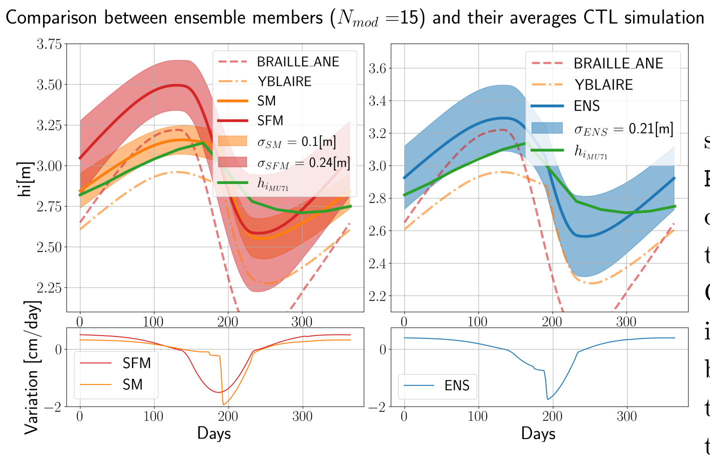

FIGURE 1: *Multi-Models simulation of ice thickness in the CTL experiment. Models simulating snow (SM) are colored in orange and models who don't (SFM) in red. The ensemble mean distribution (ENS) is in blue. The $\pm\sigma$ interval is displays by the shadow. The green line represent MU71 data. BRAILLE_ANE and YBLAIRE are models different in their design from the TSIMAL.*

Projection of Artic Sea Ice cover the next century

We have mapped out on Fig.(2) the ENS distribution of sea ice thickness for the three scenarios PR03, PR06 and PR12. We also displays on Table 1 the mean and standard deviation of each variables for each projection. We see that all scenarios are facing to a sea ice thickness decrease. Only the PR12 scenario includes a possibility of reaching ice free condition, with the minimum sea ice thickness box including $hi_{min} = 0m$. Even the maximum sea ice thickness distribution includes zero value, but in the long tail and therefore, with low probability. The PR06 scenario doesn't reach ice free condition, the minimum thickness is around a bit more than one meter while the maximum are sparse around $hi_{max} \approx 2m$. For the PR03 experience, the minimum ice thickness ensemble median is between $1.5m \leq hi_{min} \leq 2m$ while the ensemble median for the

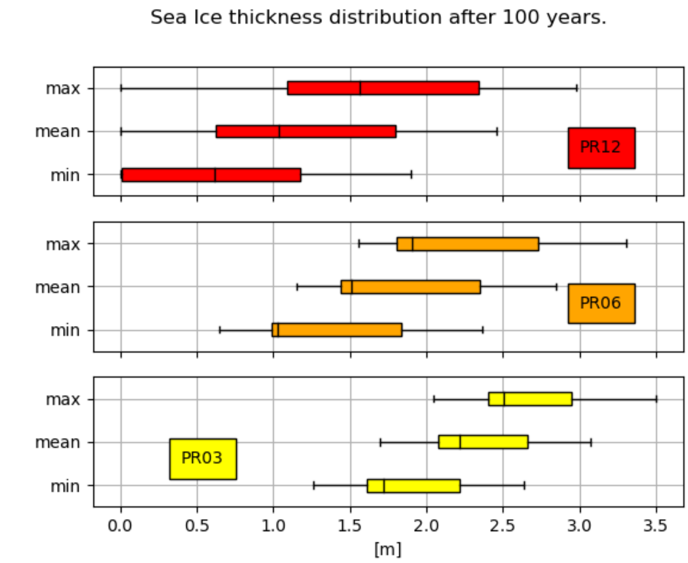

FIGURE 2: *Boxplot of Multi-Model maximum, minimum and mean ice thickness under the different* PR *scenarios.*

	CTL	PR03	PR06	PR12
h_{min}	$\mu = 2.51m$ $\sigma = 0.22m$	$\mu = 1.89m$ $\sigma = 0.37m$	$\mu = 1.38m$ $\sigma = 0.54m$	$\mu = 0.72m$ $\sigma = 0.69$
h_{mean}	$\mu = 2.9m$ $\sigma = 0.17m$	$\mu = 2.33m$ $\sigma = 0.37m$	$\mu = 1.87m$ $\sigma = 0.53m$	$\mu = 1.25m$ $\sigma = 0.71m$
h_{max}	$\mu = 3.24m$ $\sigma = 0.19m$	$\mu = 2.7m$ $\sigma = 0.41m$	$\mu = 2.28m$ $\sigma = 0.57m$	$\mu = 1.7m$ $\sigma = 0.79m$

TABLE I: *Mean and std values for the three variables h_{min}, h_{mean} and h_{max} and for the three Projection scenarios* PR03, PR06 *and* PR12*. The values for the* PR *scenarios are given for the end of the simulation.*

maximum thickness is around $hi_{max} \approx 2.5m$. We can note from Table 1 that larger is the forcing, the more sparsed are the models results.

Seasonal anomaly

In order to understand in which season the Arctic sea ice decrease will be the largest we have display on Fig.(3) for each PR scenario the seasonal anomaly by plotting the trend of hi_{min} and hi_{max}. Why does those values gives us insight of the seasonal distribution ? Because we can under good approximation consider that for the Arctic we have only two season [15], summer and winter where the maxima of the ice thickness happens in winter due to coldest temperature and the minima during summer for opposite reason. [16] Therefore difference in the slope of the trend line for hi_{min} and hi_{max} under projection scenarios gives us information about which season suffer the most of sea ice decrease.

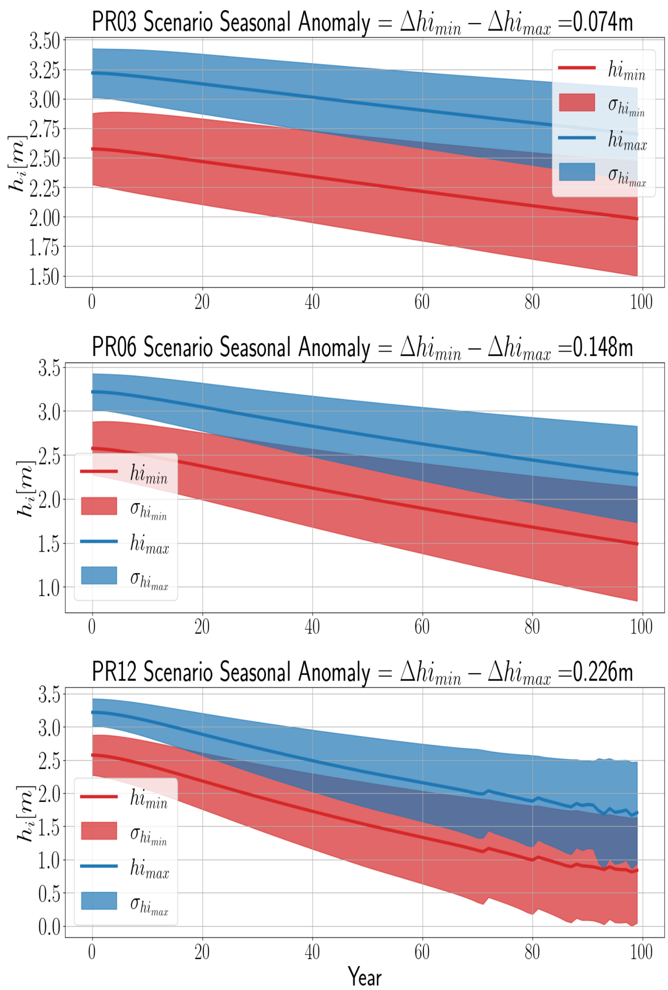

FIGURE 3: *Multi-Model mean value of hi_{max} and hi_{min} and their associated uncertainty during the* PR *experiments for the three different scenarios.*

The difference between the difference of the value of the sea ice thickness at the beginning of PR and at the end of it for hi_{min} and hi_{max} is computed and show in the title of Fig.(3). As we can see this difference is always positive hence the variation during the experiment for the minima is bigger than for the maxima i.e the sea ice thickness decrease is bigger during summer (the melting period) than during winter. An other interesting behavior from the simulations is that this anomaly between the two seasons increase as the emulation of the greenhouse radiative forcing is higher. However, even in the PR12 simulation the seasonal anomaly $\Delta SA = 0.226m$ which remains a small but though noticeable value. Compared to the CTL mean sea ice thickness ($\mu_{CTL} = 2.9m$) this represent a seasonal anomaly at the end of the century of 7.79%. The abrupt variations at the end of the PR12 scenario in the ice thickness are due to four members of the ensemble that reach faster than the other moments in the year where there is no longer sea ice.

DISCUSSION OF THE RESULTS

More or less sea ice at the end of the century ?

So, will there be more or less sea ice at the end of the century ? If we follow the simulations we performed, all projections simulate a decrease in sea ice thickness during the following century, leading to less sea ice in the end. We could expect this behavior due to the nature of the experiment, the forcing applied increase the surface temperature which in turn thin more the ice layer due to more energy available for melting. Even in the scenario with the smallest forcing, a clear decrease is notable with the mean sea ice thickness lowered by almost $70cm$. However, only the most extreme scenario - PR12 - face to the possibility of ice free condition in the end of the century (five models over the 13-ensemble are reaching ice free condition during at least one day of the century).

What does these results tells us ? We have shown that an increasing forcing would results to a thinning of sea ice. And for some particularly strong forcing, ice free conditions couldn't be excluded. However, the forcing we applied in these projections were highly idealized and are only rough estimation of the future anthropologically driven forcing we will face. Moreover, we do not initialize the simulations here on the last observed data of the sea ice thickness, which underlines once again that the goal of these simulations is not to provide a quantified projection of the sea ice evolution in the future but rather to understand its trend.

Nevertheless, these simulations have unanimously showed that we will face a thinning and a reduction of Arctic sea ice in the following century if the forcing increasing isn't stop. It has also showed that the ensemble model deviation is increasing with the magnitude of the forcing applied. It tells us that the more heavily we continue to disrupt the Earth system the more we will face uncertainties in the projections and the less able we will to prepare useful adaptation policies that are based on those projections.

In which season the Artic sea ice decrease will be the largest ?

Obtaining a prediction of the average decrease value of the ice thickness in the Arctic is one thing, but like any average it does not give information on the shape of its distribution in this case during a year. Based on our multi-model analysis we can conclude that the decrease of the average ice thickness in the Arctic will be stronger during the boreal winter than during the summer. This seasonal anomaly appears to be stronger the more intense the radiative forcing representing the increase of greenhouse gases is.

Limitations

However, whether it is in the case of projections of the sea ice trend thickness or its seasonal distribution, we must not lose sight of the fact that the analysis presented here has its limits and is mainly qualitative. The first major limitation of the TSIM models is their lack of sea ice dynamics and feedback loops with the ocean and atmosphere. Those simplifications reduce the sensibility of the models to radiative forcing. This limitation is particularly noticeable in the radiative forcing projections where we have to reach insane values of $12W/m^2$ before modeling even a punctual disappearance of the ice thickness at any time of the year. As a comparison, the anthropogenic radiative forcing between 1750 and 2011 was estimated at $2.29W/m^2$ in 2011.[7]

CONCLUSION

In conclusion, we were able to use ensemble simulations based on simple thermodynamic model of sea ice thickness in aim to answer two important scientific questions.

Not surprisingly, our models simulate well a decrease in the sea ice thickness due to a more important radiative forcing. The radiative forcing associated with greenhouse gases has indeed produced this effect on sea ice for several decades and many other models confirm this trend for the end of the century.[1] However, the exact value of this decrease cannot be captured in a relevant way by our models, which are far too simplified in their representation of radiative forcing and in their design. The absence of ice dynamics and atmosphere and ocean feedback loops are the first limiting factor.

Something more complex to grasp a priori is to know which season will be more strongly impacted by this decrease. Our results show that the impact on ice thickness will be strongest during the summer. Again, the quantitative information from our simulations only gives an order of magnitude, but it underlines once again the importance of continuing to develop our understanding of the physics of sea ice and to develop increasingly reliable models to predict its evolution.

Annexe : Script and Data

A GitHub repository has been made in order to store the python script `data_analysis.py` used for this report, the simulation's data and more interesting figures which are not shown here. The Multi-Model Analysis repository is at the following adress : https://github.com/AmauryLaridon/LPHYS2265-TSIM-Multimodel-Analysis.
The directories corresponding to `TSIMAL` is also available at https://github.com/AmauryLaridon/LPHYS2265-TSIMAL

* Electronic address: augustinlambotte@student.uclouvain.be, amaurylaridon@student.uclouvain.be

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[8] M Vancoppenolle and T. Fichefet. *LPHYS2265 - Sea ice ocean atmosphere interactions in polar regions.* UCLouvain, 2023.
[9] This section only briefly summarizes the design of the `TSIM` model. For more informations go on the GitHub repository and read the *TSIM Report.pdf* as well as the *Exercise_part_1.pdf*, *Exercise_part_2.pdf*
[10] The temporal dependency of each flux is not explicitly noted here to simplify the notations. Nevertheless as explained below only ϵ the emissivity coefficient remains constant during the simulations.
[11] When there is a sea ice layer above the ocean, the bottom temperature of the ice will remains at $T_f = -1.8°C$ in all simulations corresponding to the freezing point of sea water with a salinity of $34g/kg$.
[12] The sign convention is that all downward fluxes are positive.
[13] On the fifteen models used for the simulation only fourteen have projection and we did not retain the `DOUGLACE` model because we noted irregularities in the data ($hi_{min} > hi_{max}$). So finally we used a 13 models ensemble for projections.
[14] In `BRAILLE_ANNE` the falling snow is converted directly into ice without being stored in a specific tank. In `YBLAIRE` the ocean heat flux is related to a form of solar radiation absorption. Again the script of those two models is available on the GitHub in the Annexe.
[15] This is due to the fact that at those latitude we have polar night for roughly 6 months of the year and then 6 months with the Sun above the horizon.
[16] In reality the maxima and minima are a bit shifted. The maxima comes in March and the minima in September for the Arctic.[8]