Modeling melt ponds in Global Circulation Models

CR6.2 Rapid changes in sea ice: processes and implications
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J. Sterlin, T. Fichefet, F. Massonnet, O. Lecomte, M; Vancoppenolle

UCLouvain / Earth and Life Institute, ELIC, Louvain-la-Neuve, Belgium

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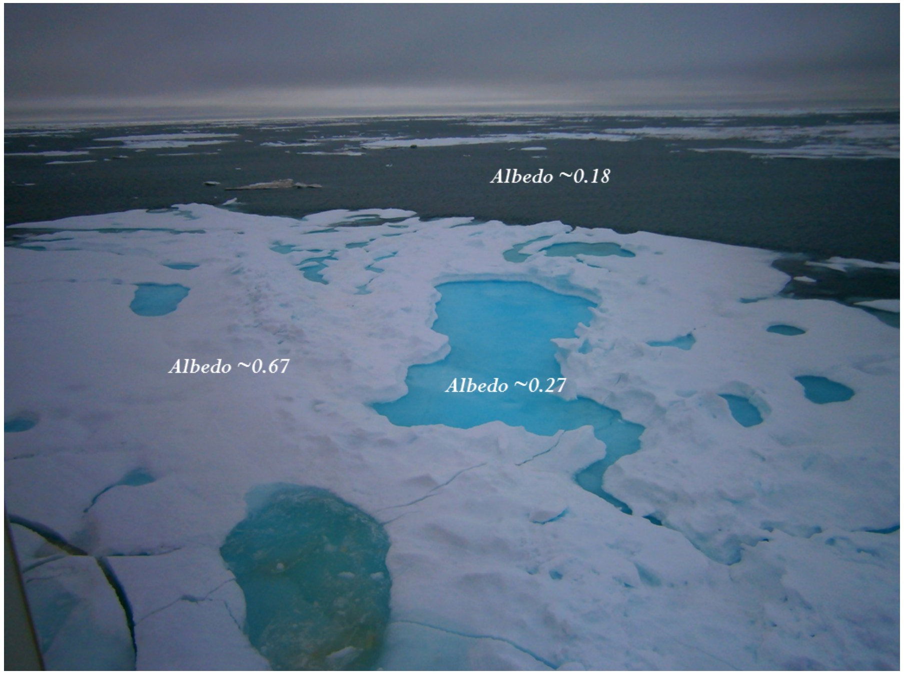
Melt ponds and the Arctic climate

Melt ponds

Melt ponds are pools of freshwater forming on sea ice during summer months in the Arctic. The freshwater takes it source from snow and ice melts as well as precipitation. Melt ponds occupy 30 to 50% of sea ice area on flat ice.



Melt ponds on Arctic sea ice, credit: I. Sudakov

Effect on the Arctic climate:

Ice-Albedo Feedback

Pond albedo is lower than the snow or ice
More ponds → lower albedo → more melts

Freshwater redirection between the ocean or the ice systems

Delays the re-stratification of the ocean surface layer, by acting as a temporary reservoir
Parts of the melt ponds refreeze and incorporate into the ice cover

Neutral Drag coefficients

The edges of the ponds contribute to the form drag, in the same manner as floe edges, leads, and ridges on the ice surface. They impact the heat and momentum fluxes

=> there is a need of including the effects of melt ponds in sea ice models

Melt ponds and Global Circulation Models (GCM)

Several schemes have been developed for GCM to estimate the melt pond characteristics. They differ notably by their definition of the aspect ratio between the melt pond area and depth.

Lüthje et al. (2006)
Mathematical model solved by finite difference method

Pedersen et al. (2009)
Polynomial fit of results from Lüthje et al. (2006)

SHEBA

Holland et al. (2012)
Linear fit of depth against melt pond area fraction from SHEBA expedition

Zhang et al. (2018)
Increased water capacity on thicker ice

Flocco and Feltham (2007)
Ice Thickness Distribution to infer the ice surface topography

Flocco et al. (2010, 2012)
Further refinement into CICE ice model

Schröder et al. (2014)
Melt pond fraction and September minimum

Lecomte et al. (2015)
Implementation in LIM3 + blowing snow

Hunke et al. (2013)
Level ice based definition

Define explicitly the melt ponds aspect ratio: from models or observations

Theoretical considerations to define the melt pond aspect ratio

Melt pond aspect ratio

The manner the scheme defines the aspect ratio has a strong influence on how they are represented

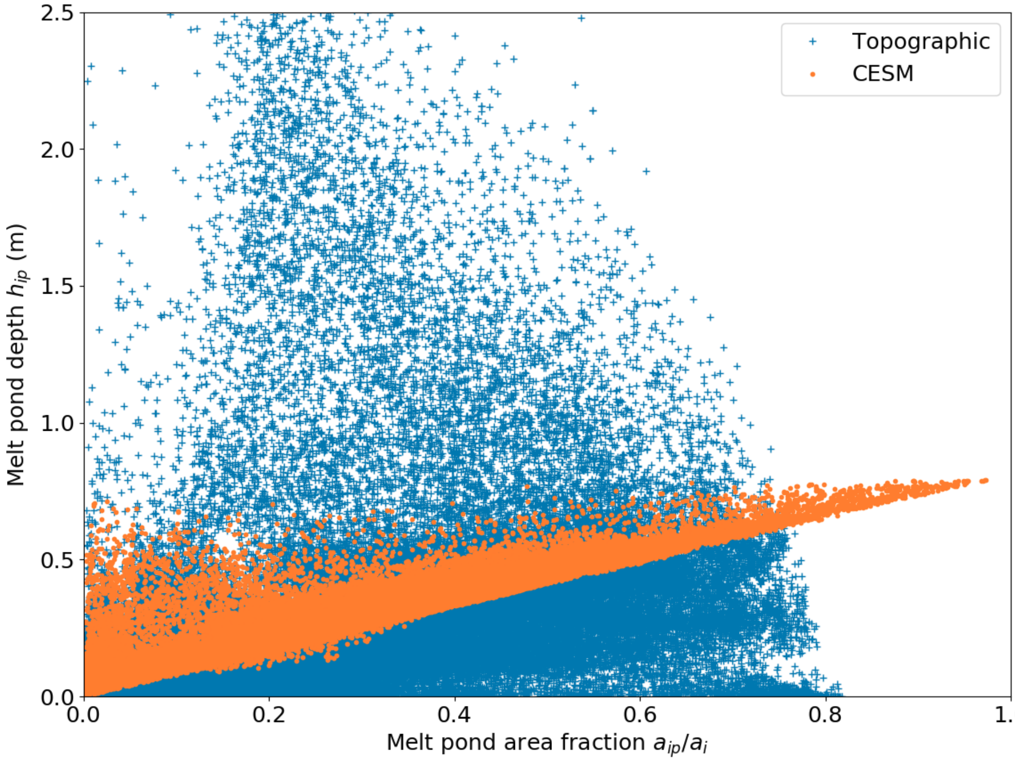


Figure: melt pond depth against the area fraction of sea ice from NEMO-LIM3 simulations. The CESM scheme follows the linear relation from SHEBA, whereas the topographic simulations are less constrained

<u>CESM scheme</u>

- **Based on Holland et al (2012)**
- **The depth in the ponds is a linear function of the melt pond area fraction of sea ice**
- **strongly bounded by the SHEBA relation**
- **Melt ponds can reach up to 100% of sea ice area**

<u>Topographic scheme</u>

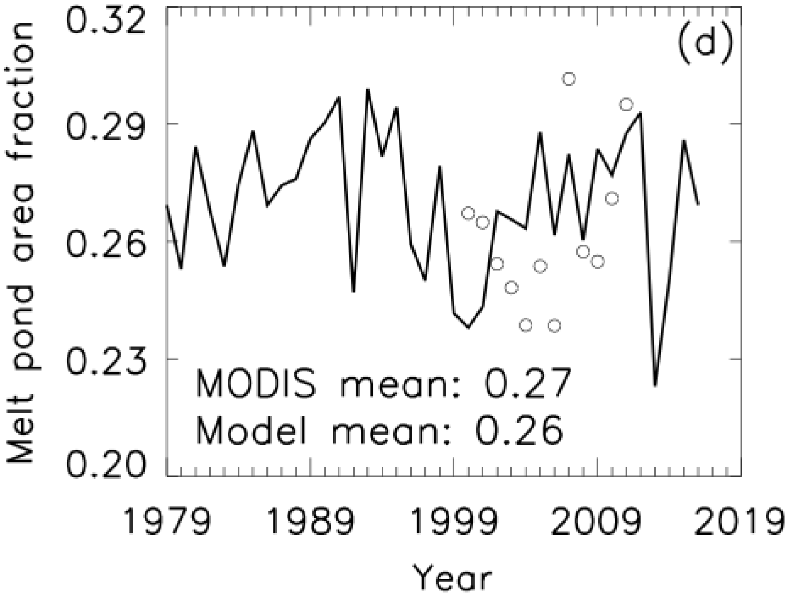
- **Flocco et al. (2010, 2012)**
- **The melt ponds are calculated from the Ice Thickness Distribution (ITD)**
- **wider range of melt pond depths and areas**
- **Most of the ponds are less than 0.5m deep, but can reach unphysical depth**

The aspect ratio is one of the driver of differences between the schemes

Trends over the last decades

The studies of Zhang et al (2018) and Schröder et al. (2014) found different trends in melt pond area fraction, over the last decades.

Zhang et al. (2018)

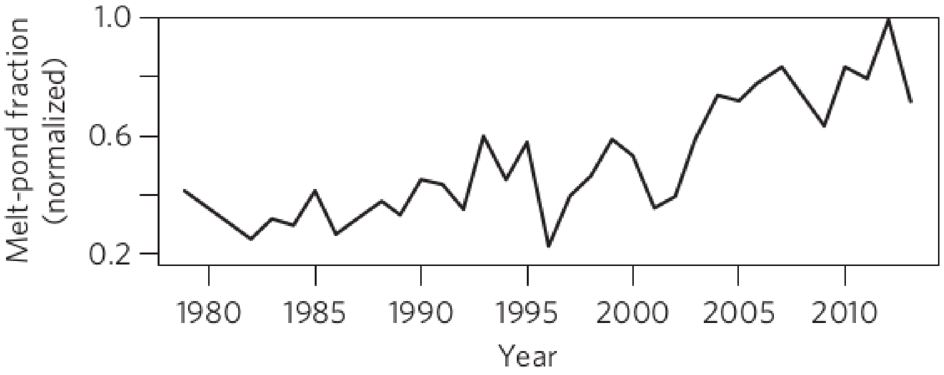


June-August mean melt pond area fraction, averaged over the Arctic Ocean

No trend in melt ponds area fraction

Scheme:	CESM improved
Model	MIZMAS (Ocean-ice)
Refreezing:	Exponential formulation
Surface forcing sets:	CFSR/CFSv2

Schröder et al. (2014)



Time series of normalized pond fraction (mean over the period from 25 June to 25 July)

Positive trend in melt ponds area fraction

Scheme:	Topographic
Model	CICE (stand-alone)
Refreezing:	Ice lid formulation
Surface forcing set:	NCEP_Reanalysis-2

Structure of the presentation

From the studies of Zhang et al (2018) and Schröder et al. (2014), we can list three factors that could explain the difference of trends: the formulation of the refreezing of melt ponds; the atmospheric surface state; the melt pond aspect ratio

What we want to know

1) the conceptual difference of the aspect ratio definition in melt pond schemes;
2) the role of the refreezing of the melt ponds;
3) the impact of the uncertainties in the atmospheric forcing on the simulations.

What we have:

- CESM (Holland et al., 2012) + Topographic (Flocco et al. 2010, 2012) in LIM3
- Holland et al. (2012) refreezing mechanism in both schemes
  → K: threshold to trigger the refreezing of melt ponds
- DFS5.2 and JRA-55 reanalyzes to define the atmospheric surface state

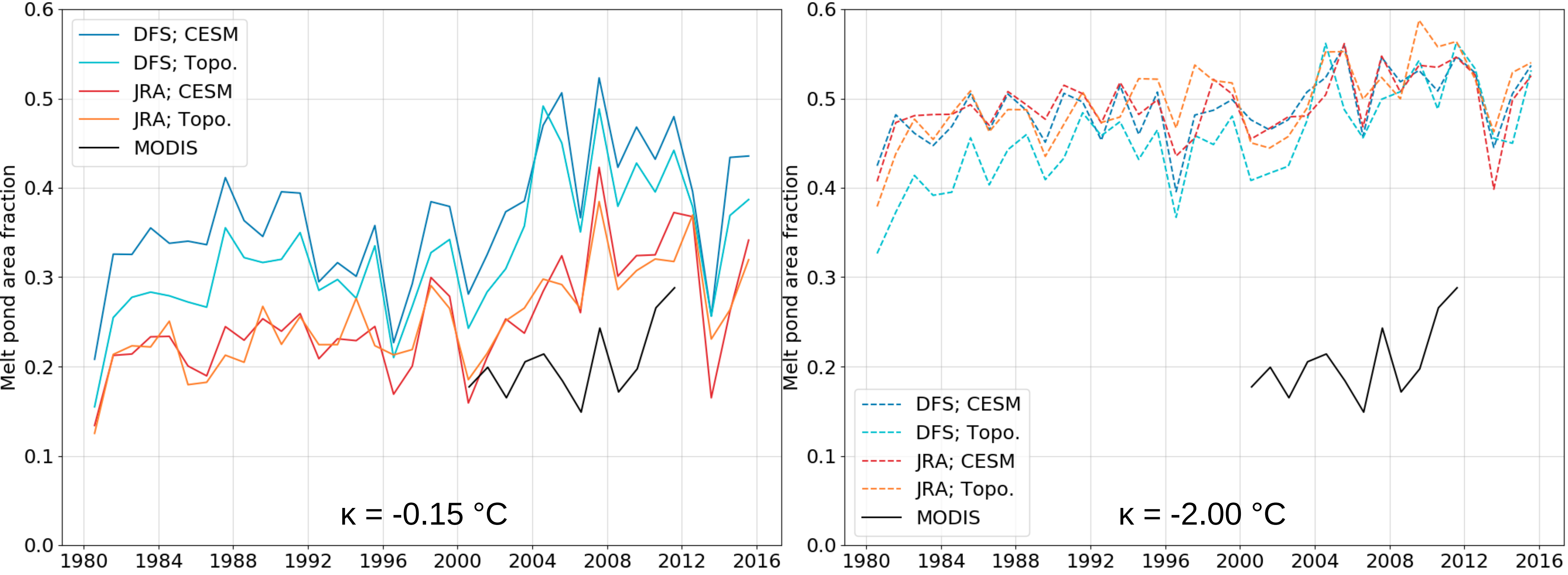
Method

Run NEMO 3.6 + LIM3 on ORCA1 grid for 58 years, in combination with:
CESM or Topographic schemes; κ = -2.00°C or κ = -0.15°C ; JRA-55 or DFS5.2

Results & discussions

Impact on the representation of the melt ponds and the sea ice
Inclusion of melt ponds schemes in GCM

Trends in melt pond area fraction (of sea ice) in August



K is the temperature threshold of melt ponds. The volume in melt ponds decreases exponentially when the surface air temperature is below κ (see next slide).

When κ = -0.15 °C:
- larger trends in ponded ice area
- larger variability
- lower melt pond area fraction

When κ = -2.00 °C:
- Smaller trends in ponded ice area
- lower variability
- larger melt pond area fraction

=> The temperature threshold κ has a strong impact on the trends in melt pond area fraction

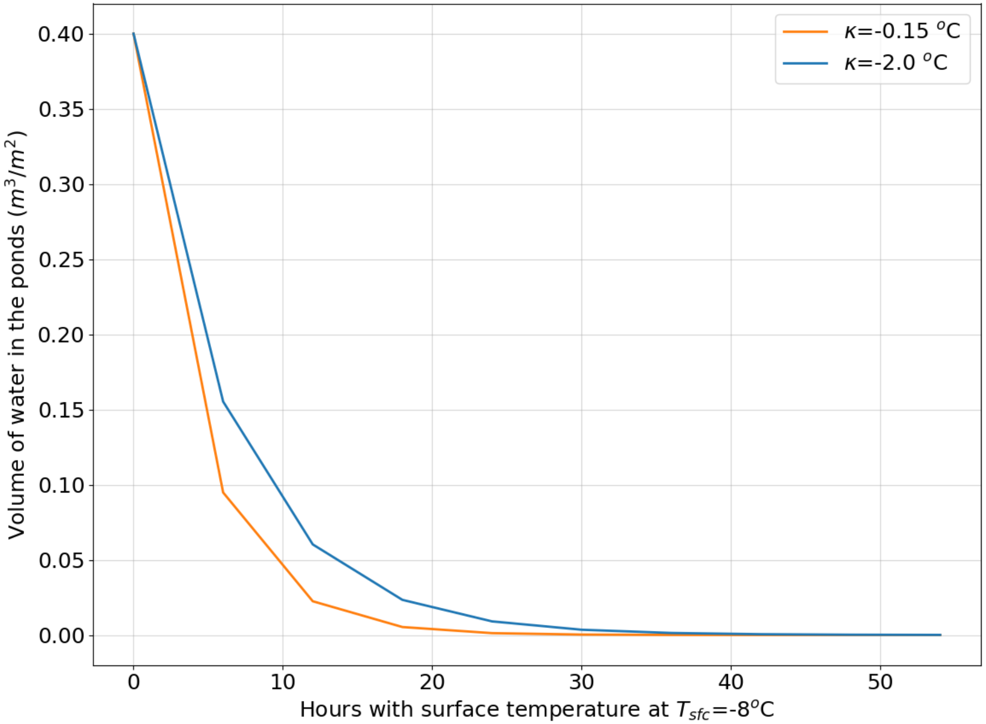
Holland refreezing melt pond mechanism

When the surface air temperature T_{sfc} is lower than the threshold κ, the volume in the ponds decreases exponentially:

$$V_{pnd}^{t+1} = V_{pnd}^{t} \exp\left(-0.01\frac{T_{sfc} - \kappa}{\kappa}\right)$$

Where:

V_{pnd}^{t}	volume in the ponds at time step “t”
K	refreezing threshold temperature
0.01	freezing rate of melt ponds

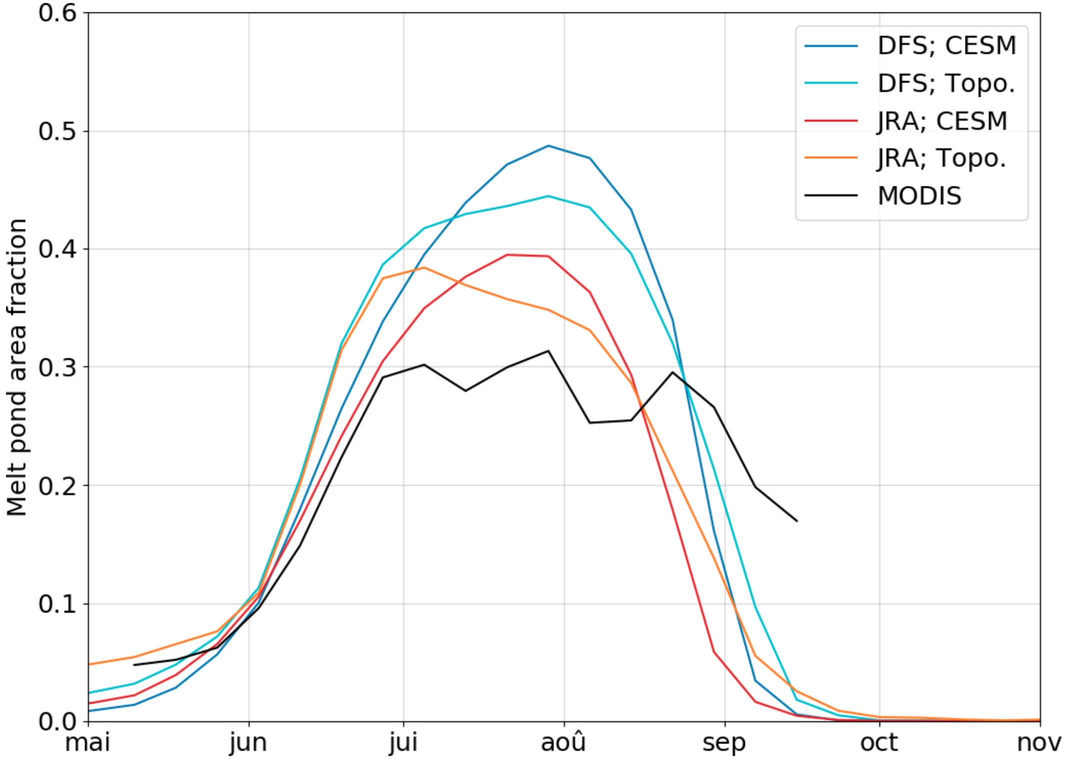


- The refreezing is more efficient with -0.15 °C as threshold temperature

- There are more days with surface air temperature below -0.15 than -2.00°C
  - 7 to 15 days below -0.15°C in August in average
  - 1 to 5 days below -2.00°C

=> -2.00 °C delays strongly the refreezing of the melt ponds

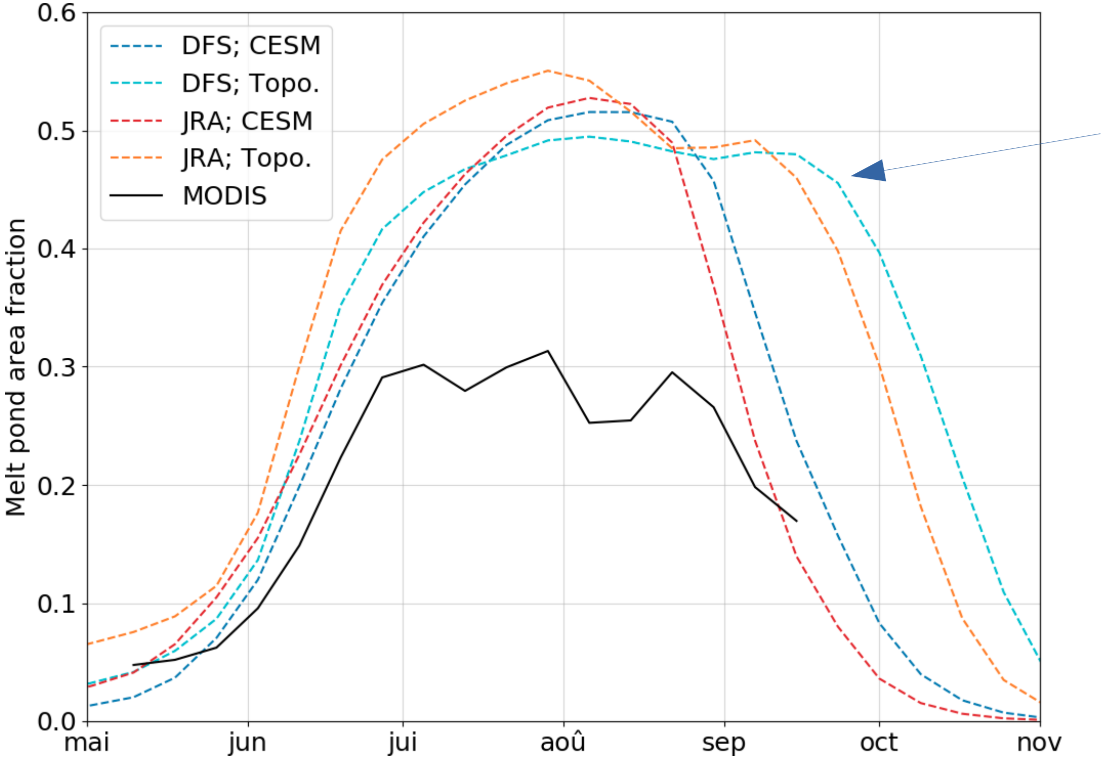
Mean seasonal cycle in melt pond area fraction



<u>κ = -0.15 °C:</u>

The summer maximums show greater sensitivity to the reanalyzes and the schemes
The refreezing occurs in advance to MODIS
CESM scheme gives larger ponded ice area than the topographic
DFS5.2 gives larger ponded ice area than JRA-55

Mean seasonal cycle in melt pond area fraction



Formation of sea ice
→flattening of the ITD

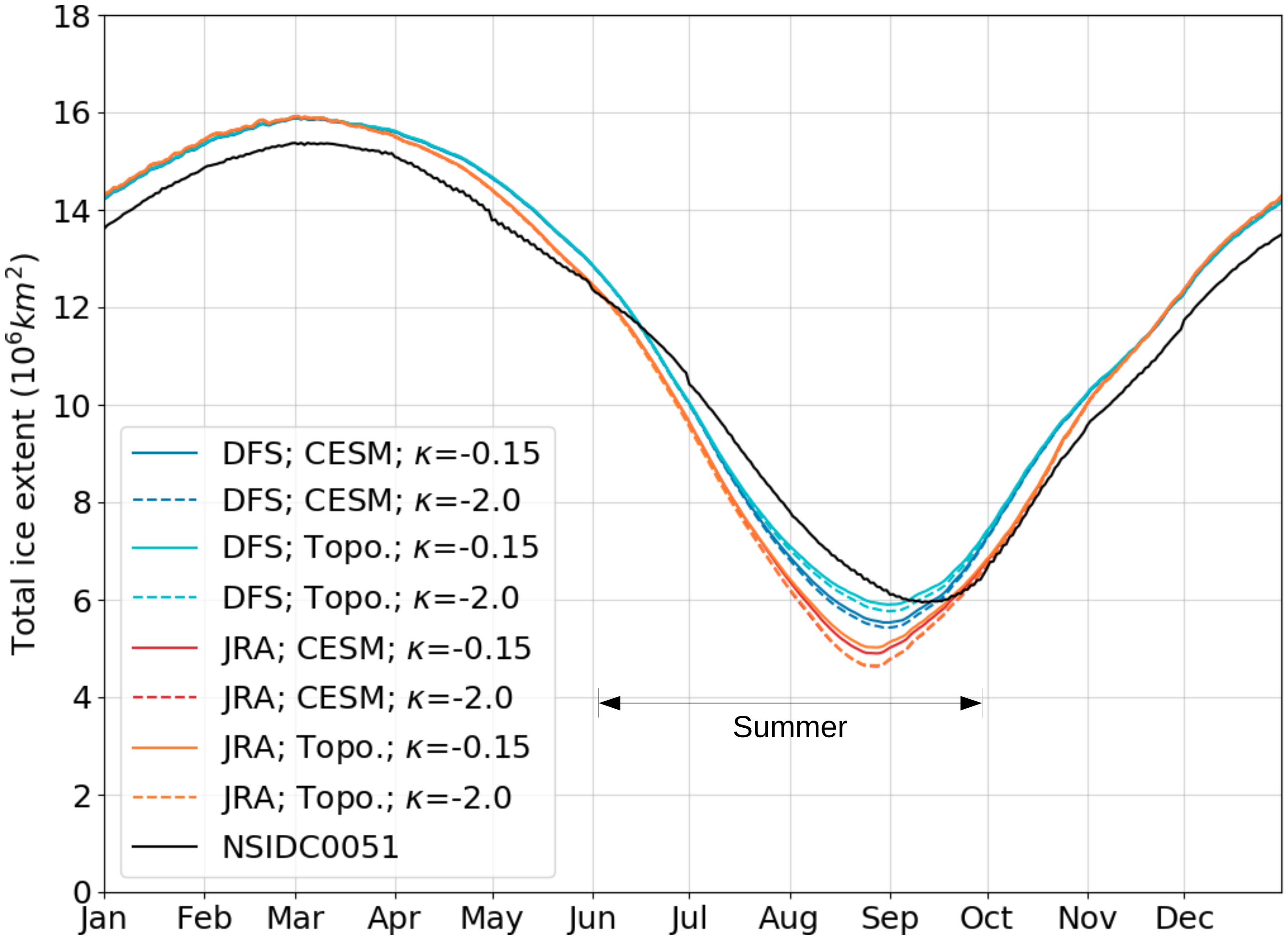
Topo. redistributes the melt water over the newly formed thin ice categories

=> shallow but extended melt ponds over the sea ice

<u>κ = -2.00 °C:</u>

Less differences between the simulations in July
When using the topographic scheme, second maximum in September
Differences between CESM and Topographic schemes unclear
DFS5.2 gives lower ponded ice area than JRA-55

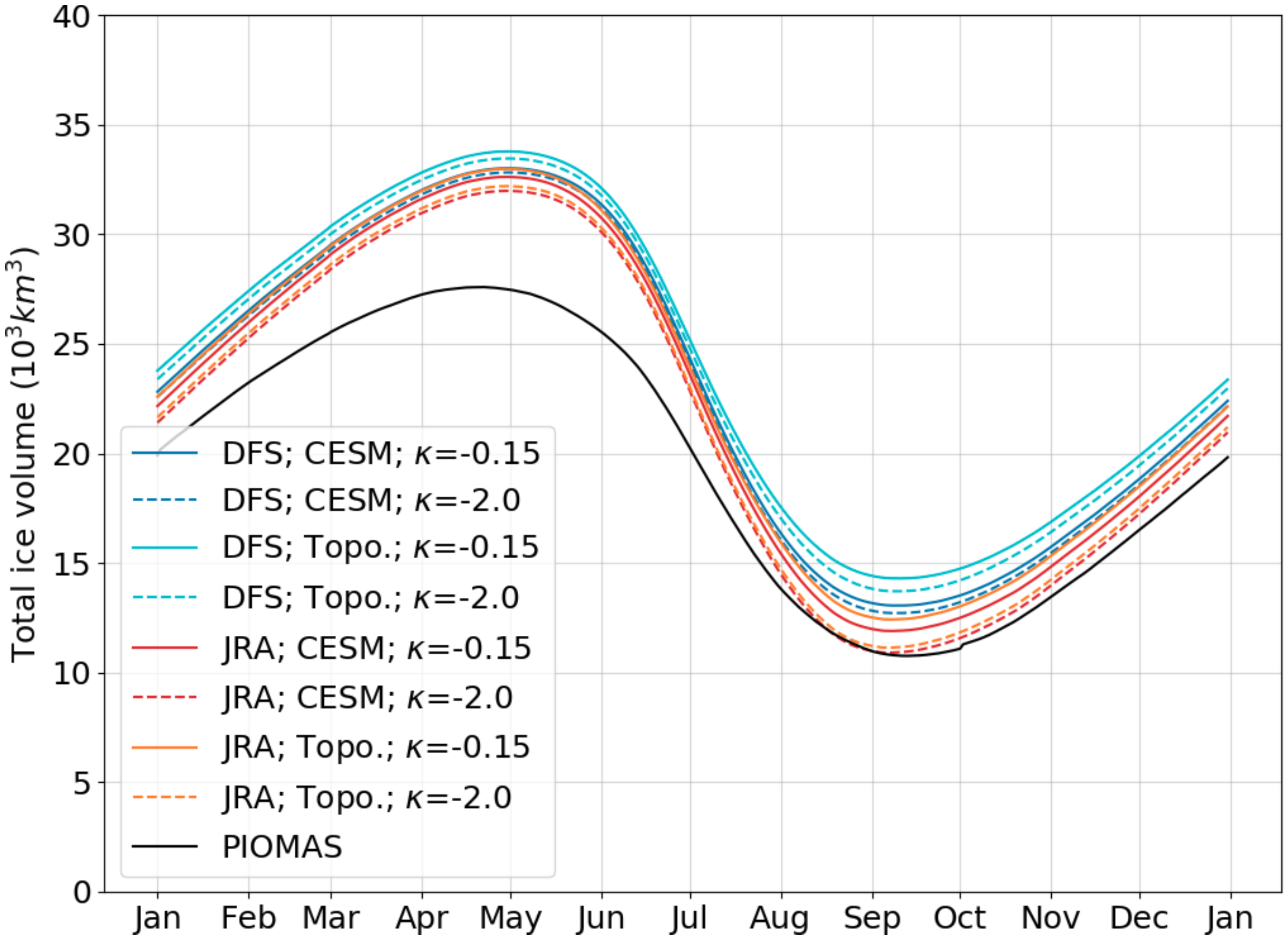
Impact on the Arctic sea ice



The effect of the ponds on the total sea ice extent is restricted to summer months.

- DFS5.2 > JRA-55
- K = -0.15°C > K = -2.00°C
- Topographic > CESM

Impact on the Arctic sea ice



The total sea ice volume is offset by a near constant amount between the simulations. The shape of the seasonal cycle is preserved.

- DFS5.2 > JRA-55
- K = -0.15°C > K = -2.00°C
- Topographic > CESM

Mean absolute difference between the simulations

The simulations are paired representations of the same climate system.

The differences between the simulations express the disagreement of the model on the climate state.

We can select paired simulations and express the difference between the simulations

$$D_s = \frac{1}{4} \sum_{f} \sum_{\kappa} \left\| X_{\{s=CESM\}} - X_{\{s=Topo\}} \right\|$$

$$D_f = \frac{1}{4} \sum_{s} \sum_{\kappa} \left\| X_{\{f=JRA\}} - X_{\{f=DFS\}} \right\|$$

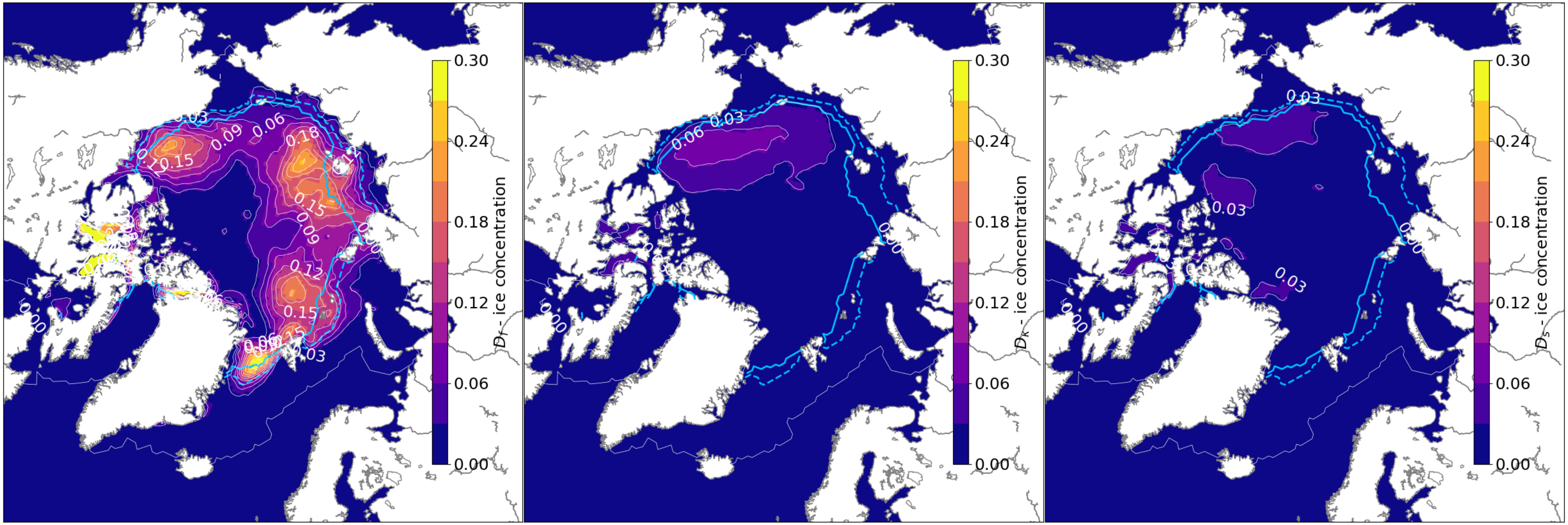
$$D_\kappa = \frac{1}{4} \sum_{s} \sum_{f} \left\| X_{\{\kappa=-0.15\}} - X_{\{\kappa=-2.00\}} \right\|$$

Where:

X is a variable of the model, such as the ice concentration, volume, etc
f is the forcing, either DFS or JRA
k is the refreezing temperature, -0.15°C or -2.00°C

Ds, Df, Dk are the mean absolute difference between the simulations.

Mean absolute difference - ice concentration - August



D_forcing

D_freezing

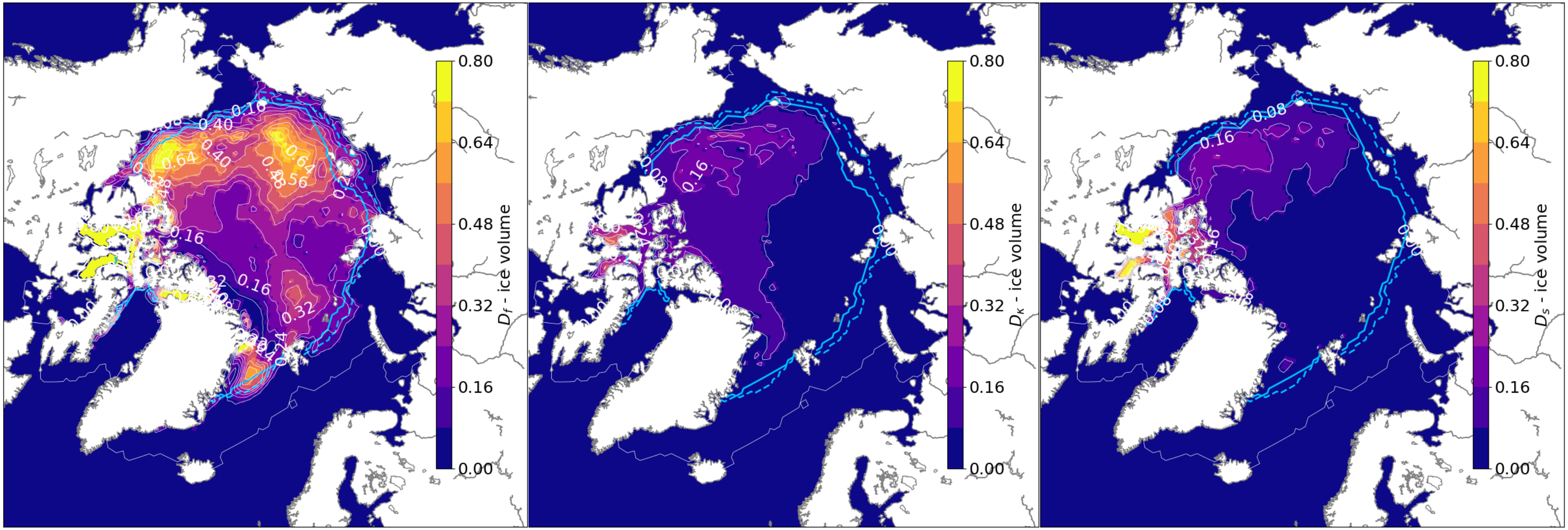
D_scheme

The atmospheric forcing method explains most of the differences in ice concentration between the simulations.

The choice of the refreezing temperature has an effect in August, in the Pacific sector of the Arctic: Beaufort, Chukchi, and the East Siberian seas.

The melt pond schemes result in differences in specific places of the Arctic, where the forcings has less impact: north of Greenland and the Arctic Archipelago

Mean absolute difference - ice volume - September



D_forcing D_freezing D_scheme

The uncertainties in the atmospheric states are the main driver of the differences in ice volume. However, the differences associated to κ and the schemes are non negligible.

The numerical schemes give differences of the same order of magnitude than the atmospheric forcing in the Chukchi sea and the Arctic Archipelago.

The effect of the refreezing parameter on the ice volume extends to large areas of the Arctic. The influence is reduced in the Arctic Archipelago.

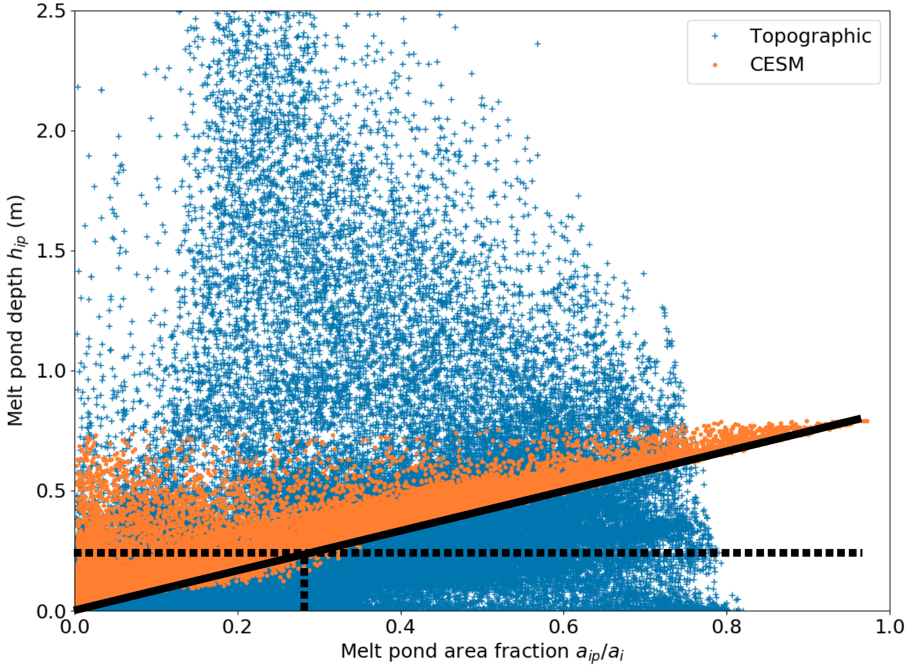
In winter, the differences between the simulations are less important and concentrate in the Arctic Archipelago.

Discussion

As presented before, the aspect ratio of the CESM scheme is strongly bounded to the SHEBA linear relation (continuous black line).

The albedo α_{pnd} of melt ponds is a function of the effective depth h_{pnd} in the ponds:

$$\alpha_{pnd}\left(h_{pnd}\right) = \alpha_{ice}^{dry} + (\alpha_{ice}^{dry} - \alpha_{pnd}^{ref})\exp\left(\frac{h_{pnd}}{\omega}\right)$$



The albedo of melt ponds quickly converges to a minimum as the water depth increases

A melt pond depth greater than 0.23 meter results in more than 99% of decrease in albedo. The horizontal black dotted line shows the 0.23 meter. Points above the line have an albedo nearly equal to α_{pnd}^{ref}

Surface type	Name	Value
Dry bare-ice albedo	α_{dry}^{ref}	0.72
Ponded ice albedo	α_{pnd}^{ref}	0.25
Characteristic depth	ω	0.05

=> the CESM scheme is less sensitive to the melt pond depth than the topographic scheme. In our set of simulation using CESM, the water depth in the ponds quickly becomes greater than 0.23 meter and gives the reference ponded ice albedo value.

Discussions and conclusion

As implemented in our model, the melt pond refreezing mechanism has a strong influence on the behavior of the melt pond area fraction seasonally and on the trends over the last decades. The onset of melt ponds is sooner with κ set to -2.00°C and the refreezing of melt ponds is delayed to September.

The refreezing mechanism is turned on when the surface air temperature is below the threshold temperature κ. It occurs in Autumn when the ice starts to grow, but also in spring, when the surface of the ice cover is melting.

There are more days with temperatures below -0.15°C than -2.00°C. Thus, the refreezing acts longer with -0.15°C. Secondly, the freezing rate is greater with higher κ. Consequently, the value of -0.15°C shortens the life span of melt ponds during summer.

Concerning the impact on the trends in melt pond area fraction, we need to investigate further the role of the surface air temperature: one explanation is that with Arctic warming, the melt ponds life time is more impacted when κ is set to -0.15°C. The refreezing of the ponds happens too late with the lower value of -2.00°C.

Lastly, the differences of ice concentration and volume between the simulations are mainly explained by the uncertainties in the atmospheric reanalyses. It indicates that although the formulation of the melt ponds scheme are different, the impact is limited. The differences of ice volume due to the aspect ratio and refreezing parameter κ lie in the Arctic Archipelago, Beaufort, Chukchi, and East Siberian Seas.