



Reducing sea level rise with submerged barriers and dams in Greenland

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Received: 11 September 2018 / Accepted: 26 November 2018 / Published online: 21 December 2018
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Abstract

Sea levels have been rising at an increasing rate in the past decades, due to the increased ocean temperatures and glacier melt caused by global warming. The continued increase in sea levels will result in large-scale impacts in coastal areas as they are submerged by the sea. Locations not able to bear the costs of implementing protection and adaptation measures will have to be abandoned, resulting in social, economic, and environmental losses. The most important mitigation goal for sea level rise is to reduce or possibly revert carbon dioxide (CO₂) emissions. However, given the magnitude and long time lag between emissions and impacts, new adaptation measures to reduce sea level rise should be proposed, developed and if possible, implemented. This paper suggests that submerged barriers or dams built in front of ice sheets and glaciers would contribute to reducing the ice melt in Greenland. The ten proposed barriers or dams in this paper could prevent the contribution to sea level rise by up to 5.3 m at a cost of US\$ 0.275 billion a year. This is much lower when compared to adaptation measures to sea level rise around the world estimated to be US\$ 1.4 trillion a year by 2100.

Keywords Sea level rise · Climate change · Greenland · Ice sheet melt

1 Introduction

Glaciers and ice caps have retreated worldwide during recent decades. This has resulted in sea levels increasing 20 cm over the last century (Meyssignac and Cazenave 2012), with a significant acceleration since the early 1990s. Natural and human induced global warming is the main contributor to sea level rise (Church et al. 2011), and melting of the cryosphere will continue long after emissions of greenhouse gases have stopped (Nauels et al. 2017; Mengel

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et al. 2018). Moreover, the Arctic has seen the fastest warming globally (Arctic Climate Impact Assessment 2004), and melting of the Greenland ice sheet could add up to 7.3 m to sea levels (Solomon et al. 2007).

Recent adaptation measures have been implemented to reduce the impact of sea level rise. For example, United States of America (USA) dollars (US\$) 14.5 billion is the budget allocated to protect New Orleans, Louisiana, USA against category 5 hurricanes (Burnett 2015), the Modulo Sperimentale Elettromeccanico (MOSE) project built to protect Venice, Italy against flooding is estimated at € 5.5 billion (Giovannini 2017), and The Netherlands spent € 8.9 billion from 1954 to 2008 in flood infrastructure (Aerts et al. 2008). At a regional scale, sea level rise adaptation strategies have also been applied in Europe (Hinkel et al. 2010), Brazil (Lacerda et al. 2014), United States of America (USA) (Ashton et al. 2008; Song et al. 2018), Saudi Arabia (Babu et al. 2012), Egypt (Frihy and El-Sayed 2013), Australia (Lin et al. 2014), and Bahrain (Al-Jeneid et al. 2007). If sea levels were to increase 5.3 m by 2300, assuming a Representative Concentration Pathway 8.5 (RCP8.5) emissions scenario, 700 million people are expected to suffer from flooding events every year (Nicholls et al. 2018). In particular, low-lying developing countries such as Bangladesh would be heavily impacted.

The most important mitigation measure to reduce sea level rise is the reduction of carbon dioxide (CO₂) emissions or even the removal of CO₂ in the atmosphere with biomass-based carbon capture and storage and other proposed measures (Haszeldine et al. 2018), with the intention of reducing, stopping, or reverting global warming and its impacts. However, given the complexities involved in mitigating climate change, new adaptation measures should also be considered for the resulting impacts from global warming, for example, droughts, flooding, heat waves, animal extinction, migration, agriculture, desertification, etc. Focusing on mitigating sea level rise, methods have been used to estimate the impact of groundwater storage in sea levels (Ramillien et al. 2008). Other projects to reduce sea level rise have also been proposed (Battersby 2010).

Recent work has shown the implementation of dams in front of glaciers to reduce the melting of glaciers in Antarctica (Moore et al. 2018; Wolovick and Moore 2018). The proposals to reduce sea levels rise presented in these articles, particularly the construction of a submerged dam, are similar to this article's proposal. In addition, these papers include important discussions regarding the impact of submerged dams to Greenland society, the continuing need for reducing CO₂ emissions, and other issues.

This paper suggests that submerged barriers and dams built in front of ice sheets could contribute to reducing the ice melt in Greenland and, thus, reduce sea level rise.

2 Methodology

Most of the ice melting in Greenland results from the contact of seawater underneath ice shelves (Fenty et al. 2016), where seawater is in contact with the ice sheet above. Figure 1 presents a schematic diagram explaining how ice melting occurs under ice shelves (DeConto and Pollard 2016). The mechanism behind ice shelf melting is mainly driven by warmer and saltier water that enters under the ice self in the direction of the grounded ice. When the warmer water enters in contact with the ice, it results in melting part of the shelf. This melting contributes to reducing the density of the salty water. The amount of warmer water flowing under the ice shelf is much larger than the amount of

ice melted. The heat and mass balance estimates were taken from a case study on the Amundsen Sea (Jourdain et al. 2017).

Figure 1 presents the overall horizontal flow of water under the ice shelf. However, as the flow of warmer water is much higher than the ice melt flow, horizontal flows of water within the different thermal layers of water are much more expressive than the overall vertical flow presented in Fig. 1, which results from melting the ice. The warm seawater inflow ratio to melt $1000 \text{ m}^3/\text{s}$ of ice varies from 100,000 to 500,000 m^3/s , due to the changes in temperature, if the inlet temperature is high, the flow ratio will be closer to 100, if the inlet temperature is low, the flow ratio will be closer to 500. There are several factors involved in the melting process. These can be divided into two main processes, the heat exchange process between the warm seawater and the ice, which melts the ice, and the mass transfer process (melting the water is essential to reduce the density of the water so that it can rise).

As can be seen in Fig. 2, the interior of Greenland has an absolute bathymetry lower than sea level. Thus, if seawater continues to melt the Greenland ice sheet, the seawater could penetrate inside the island and potentially melt the entire ice sheet. However, there is a chance that the land surface might rise as a response to ice melt and the release of the ice overburden.

With the intention to reduce the flow of seawater in contact with ice shelves in Greenland and therefore the amount of ice melting below it, submerged barriers and dams are proposed. The restriction of the seawater flow in contact with the ice shelves will reduce the melting of ice in the Greenland glaciers. With less melting, the glacier will stop losing mass reducing or even increase, and therefore, the ice will remain frozen and more ice will be stored on the continental shelf, reducing sea level rise.

Figure 3a shows a schematic diagram of the proposed submerged ice sheet barrier. The barrier should be located in front of the ice shelf cavity, where the sea depth is the smallest,

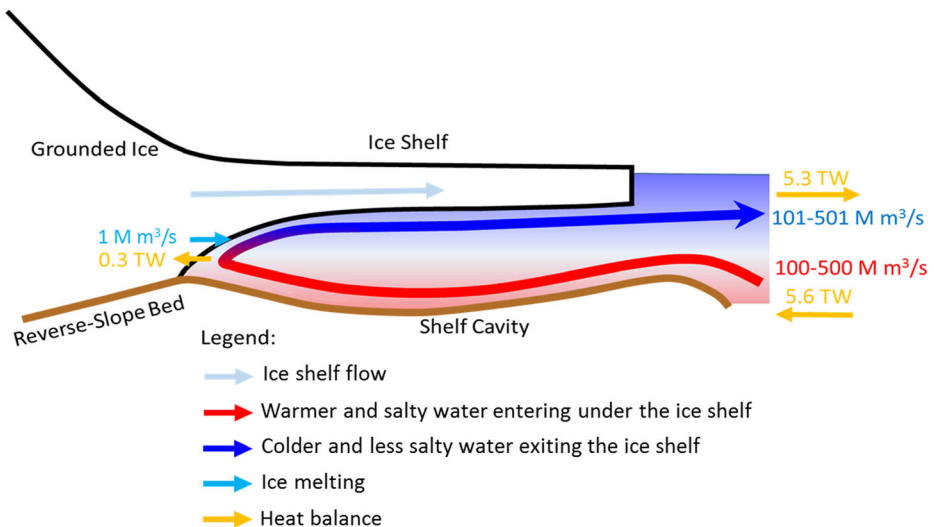


Fig. 1 Schematic diagram of the melting under an ice shelf. The heat and mass balance is taken from a case study on the Amundsen Sea (Jourdain et al. 2017) (adapted from (DeConto and Pollard 2016))

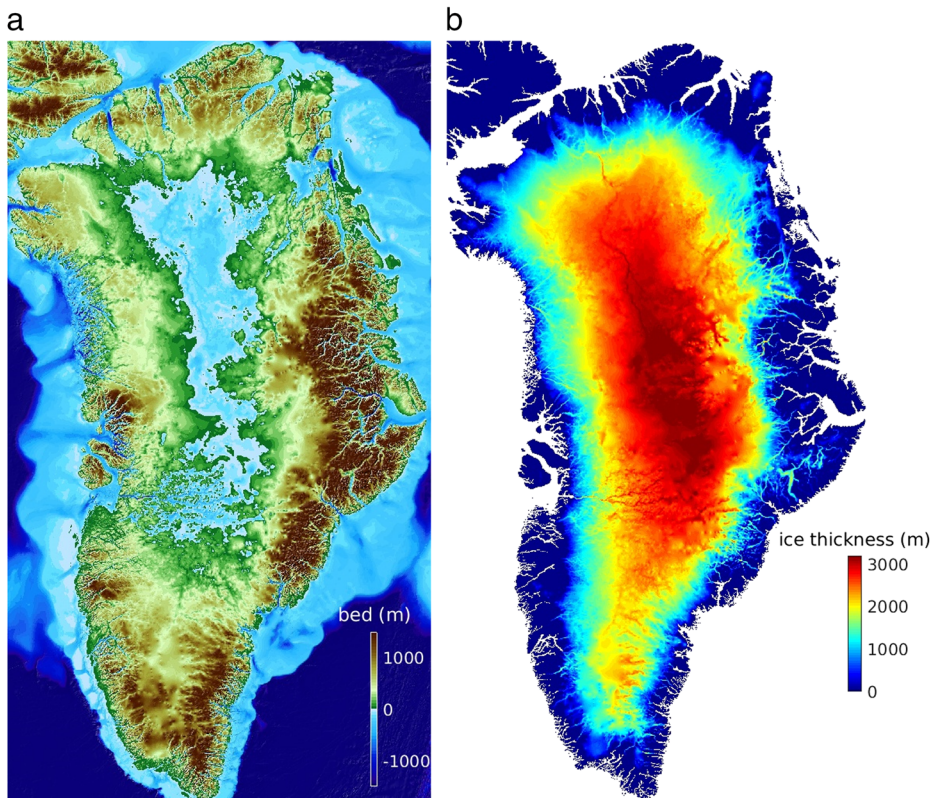


Fig. 2 Greenland maps showing **a** land topography and **b** ice bed thickness (Morlighem 2017)

as shown in Fig. 3a. The barrier consists of a 200 cm thickness, marine grade steel plate. The steel plates are connected to the steel cylinders with air inside to create enough buoyancy so that the barrier floats in seawater. Ropes are used to maintain the barrier positioned in the right location. The barrier is slightly inclined into the open sea with the intention to minimize the effect of waves and icebergs on the barrier as shown in Fig. 3b. Another alternative is to build a submerged dam as shown in Fig. 3c. This alternative has been firstly proposed in Moore et al. (2018) and Wolovick and Moore (2018). The dam could be built using underwater rocks and sediments carried by the glacier where the dam should be located. These rocks would then be used to build a submerged rock-filled embankment dam as shown in Fig. 3c. Depending on the project, there might not be the need for the dam to reach the top of the sea surface. At the surface, the dam will have to withstand stronger forces from waves. Additionally, the glacier will constantly release icebergs, which might end up damaging the dam. Thus, a small gap between the sea surface and the top of the dam might be a better design.

Analyzing the construction of the submerged barrier, in order to reduce the pressure differences between both sides of the barrier and, thus, the chances of barrier failure, the density of the water on both sides should be the same. This can be provided by allowing a controlled amount of saltier and denser water to enter the bottom of the barrier and a release of fresher and less dense water from the top of the barrier. As no

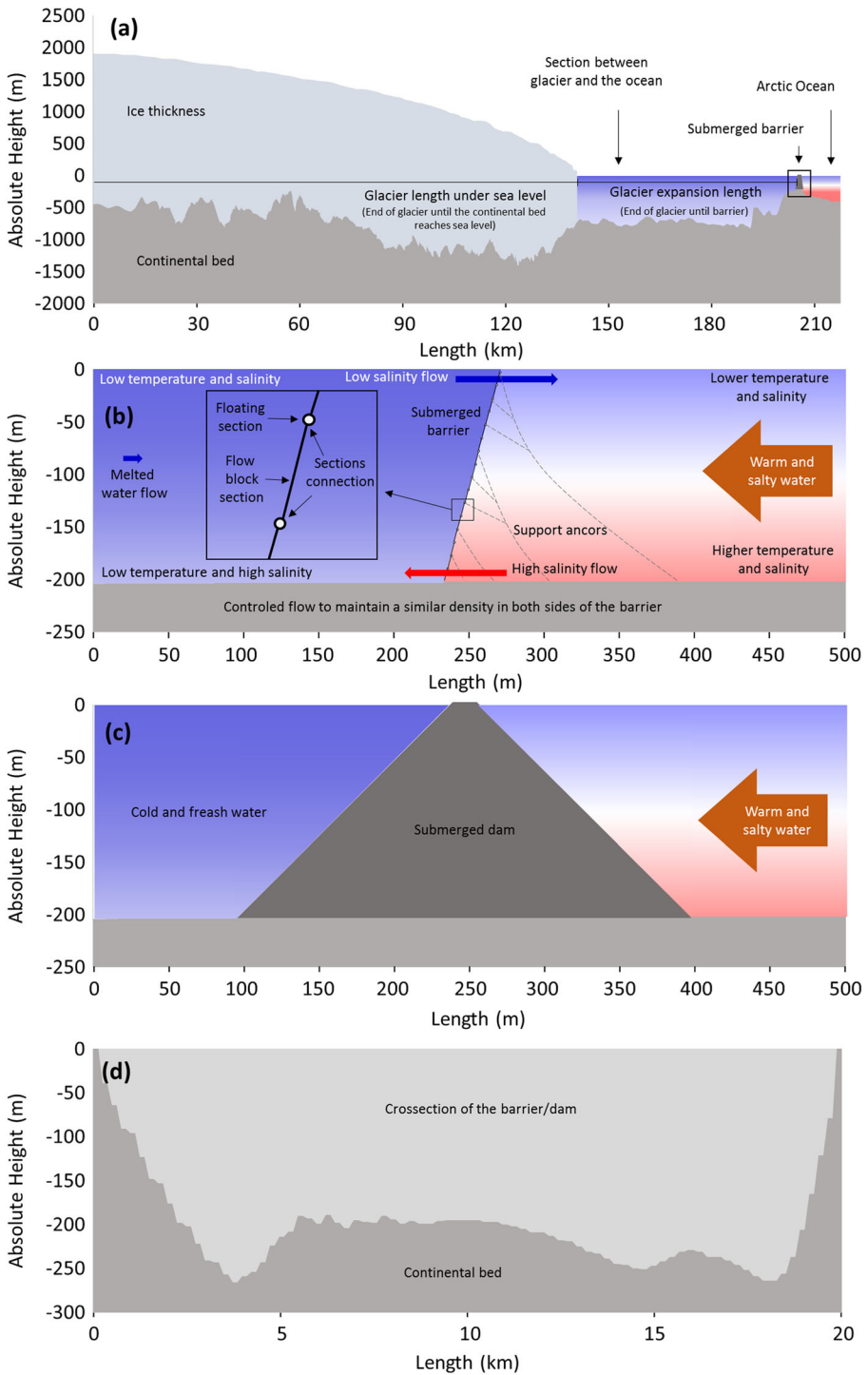


Fig. 3 Proposed a location of the submerged barrier or dam, **b** submerged barrier, **c** submerged dam, and **d** cross-section of dam or barrier

such barrier has been developed before, three main steps for the construction of the barrier are proposed below:

- (1) The barrier components should be transported to its designed location during the summer, when there is no ocean ice cover and the access to the location of the barrier is less challenging. Also during the summer, mooring structures should be added where the barrier will be installed.
- (2) During the winter, the barrier is assembled where it would be placed, over the frozen ice cover.
- (3) During the next summer, the ice cover will melt again and the barrier will float right above the place where it is should be fixed. The chains attached to the barrier will pull the barrier into place, using the mooring structures in the ground.

The submerged dam has a much more complex construction process. Its construction is considerably different to conventional hydropower dams. This is mainly because it should be implemented underwater and dams have to support very high pressures from the water head. The submerged dam proposed in this article is not required to sustain high pressure differences; however, it has to resist strong underwater currents. A similar process for the creation of the dams has been implemented in the out-wall of the Palm Jumeirah Island in Dubai (Omi et al. 2010; Martín-Antón et al. 2016). Recent work shows the implementation of dams in front of glaciers to reduce the melting of glaciers in Antarctica (Moore et al. 2018; Wolovick and Moore 2018). The proposals to reduce sea level rise presented in these articles, particularly the construction of a submerged dam, are similar to this article's proposal.

Table 1 presents the advantages and disadvantages of the submerged barriers and dams. The cost of building submerged dams is one or two orders of magnitude higher than the cost of submerged barriers. However, submerged dams have a longer lifespan than submerged barriers. In addition, barriers are reversible and can be removed at a low cost should the need arise. Dams are on the other hand not reversible and their removal would require an effort similar to the construction of the dam.

The methodology applied to find the length, height, cross-section, cost, and contribution to sea level rise of the barrier and dam is presented in Fig. 4. This framework is divided into two major steps. Step 1 has the objective to draw the cross-section of the major glaciers in Greenland, including the seabed, seawater, and ice cover. In this step, the bathymetric, ice thickness, and topographic data are loaded into the model. The most relevant glaciers, which could have a barrier or dam with a maximum depth of 500 m, are selected. Glaciers with a depth higher than 500 m were not included because the construction of the barrier/dam would be considerably challenging. With the bathymetric data, the cross-section of the glacier is drawn and plotted. The location of the barrier/dam is then proposed with the intent of reducing its width and depth. Then, the characteristics of the glaciers are analyzed to estimate their contributions to sea levels rise as explained in Fig. 3a. Step 2 intends to find the cross-section of the barrier or dam required to stop the flow of warm seawater. Several barriers/dams are proposed and the one with the smallest cross-section area is selected and plotted. Then, the length, height, area, and costs for the barrier and dams are estimated. More details on the data utilized in the paper can be found in Table 2.

Table 1 Advantages and disadvantages of submerged barriers and dams

	Barrier	Dam
Advantages	<p>Reversibility: The submerged barrier is made of modular sections which can be removed or reduced in size. This is appropriate because there might be a need to remove the barrier, due to unexpected impacts, or even an overall reduction in sea levels, larger than expected. The cost of removing the barriers is relatively small.</p> <p>Costs of Construction: The submerged barrier has a lower cost than the submerged dam. This is because the barrier requires much less construction material and the construction is simpler.</p>	<p>Lifetime: The submerged dam is built to last for centuries or more.</p> <p>Robustness: Dams are appropriate for locations with 1 to 10 m deep. Shallow locations need a robust solution to withstand the destructive power of breaking waves.</p>
Disadvantages	<p>Lifetime: The submerged barrier is expected to have a lifetime of 20 to 30 years, depending on the quality of the material used in its construction and the costs of maintenance. This is because the barrier suffers from considerable wear and tear, and chemical and biological corrosion.</p>	<p>Irreversibility: Once the dam is constructed, it is designed to stay in the same location for a century or more. If there might be a need to remove the barrier, due to unexpected impacts, the costs of removing the dam are substantial, similar to the costs of building the dam.</p> <p>Costs of Construction: The dam is estimated to be one or two orders of magnitude more expensive than the barrier. This is because the construction requires much more material for construction and the construction is much more complicated. Another issue with submerged dams, is that the width of the dam considerably increases with the height of the dam.</p>

3 Results

This article analyzes ten major glaciers in Greenland and proposed possible barriers or dams to stop the contact of seawater with the ice shelves, this is presented in Fig. 5. The proposed barriers intend to have the smallest cross-section area as possible to stop the seawater flow in the ice sheets. The barriers are usually proposed after the ice shelf cavity because they consist of the shallowest and narrowest section of the glacier as presented in Fig. 5a, b, c, i, j, k.

The proposed barriers/dams in Fig. 5 are compared in Table 3. The main parameters considered when comparing the effectiveness of each barrier/dam are the barrier cost, which varies with the barrier's cross-section, the dam's cost, which varies with the dam's length and height, and the contribution of the barrier/dam to reducing ice melting. The contribution of the barrier to reducing ice melt is difficult to estimate. It involves the flow of the glacier, the melting rate, the temperature of the seawater, etc. These values are difficult to predict and are not available for all the glaciers considered in this study. Thus, this paper estimates the contribution of the barrier with three main parameters, the length of the glacier that could be melted by the seawater if no barrier is built and the possible expansion for the glacier if the barrier is built, which is equivalent to the distance from the barrier to where the ice sheet is touching the ground. The glaciers, which would allow seawater to reach the middle of Greenland, are given a value of 1000 km.

Submerged Barrier and Dam Model Framework

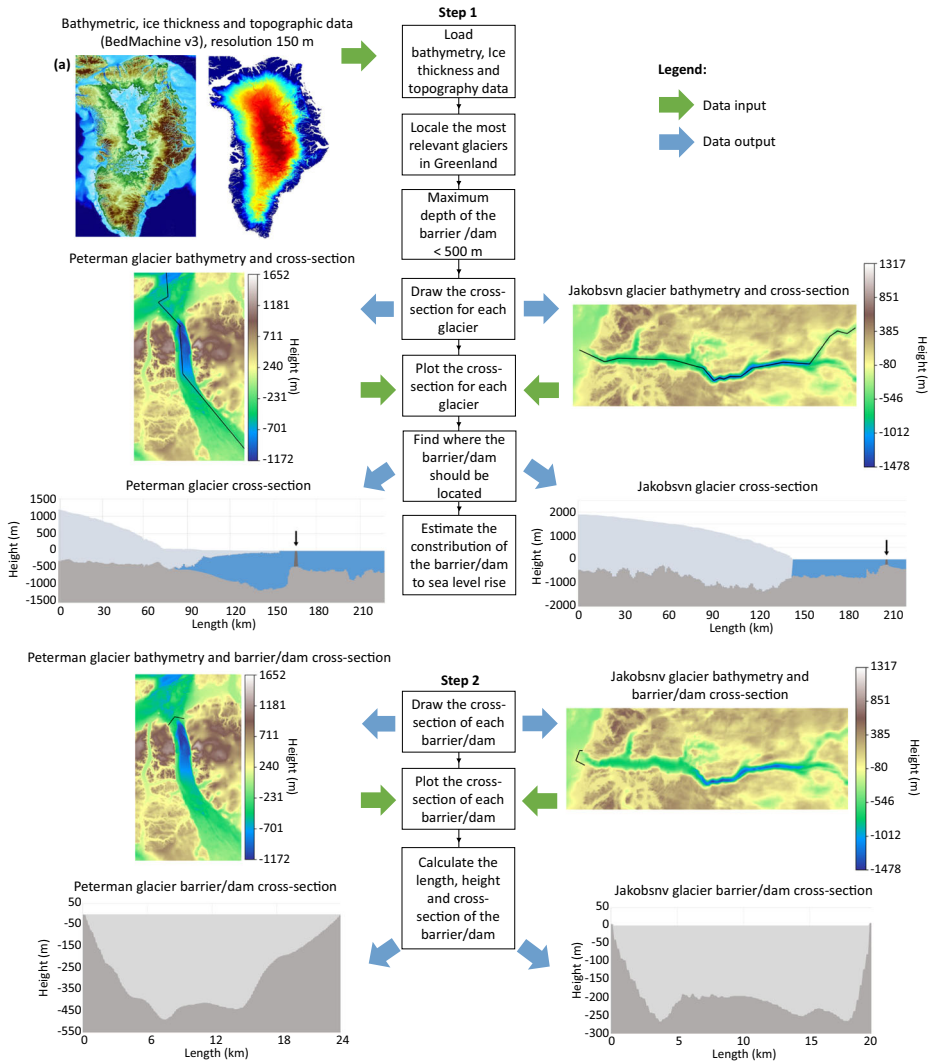


Fig. 4 Submerged barrier and dam model framework (a from (Morlighem 2017))

The cost estimate of the submerged barrier assumes that the barrier has 200 mm thickness, the area presented in Table 3, material costs of US\$ 2000 per ton of marine grade steel (Alibaba 2018) and that the cost of the material of the barrier constitute about 30% of the total project cost, which includes investment, operation, and maintenance costs. It is assumed that the barriers and anchors have a lifetime of 20 years, and that they will have to be replaced after 20 years. The cost estimate of the submerged dam is assumed to be the same cost of a conventional hydropower dam (Slapgard 2012). Submerged dams have different construction methodologies when compared with conventional hydropower dams and serve for a completely different reason. This cost estimate is just to give an order of magnitude of costs.

Table 2 Data used in the submerged barrier and dam model framework

Data	Description	Resolution	Purpose	References	Fig.4 Steps
BedMachine v3	Bathymetry, ice thickness and topographical data.	150 m	Draw the glacier and barriers cross-sections.	(Morlighem 2017)	1 and 2

In calculating the estimated volume of ice, which will be prevented from melting or accumulate in the continent for each barrier/dam, and, thus, their contribution to reducing sea level rise, we assume the sum of the glacier length under the sea level and the glacier expansion length, a width of the ice cover around the glacier of 150 km and an average thickness of 1000 m. This paper assumes that the impact of the barrier/dam in the width and thickness of the glacier does not vary in different glaciers and are set at 150 km and 1000 m, respectively. This is not the case, given that the amount of ice stored or melted will depend on the bathymetry of the glacier, the flow of ice, the distance from other glaciers, the temperature of the region, and a lot of other reasons. A glacier with a narrow and steep bathymetry will allow less ice to be stored than a glacier with a broad and plain bathymetry, and thus have a smaller impact on sea level rise. However, this aspect was not included in this paper due to the complexity of ice flows in Greenland. For example, a reduction in flow in one glacier might increase the flow in another glacier. Given the high complexity of ice flow in Greenland, a detailed analysis was not included in this study and it is proposed for future work.

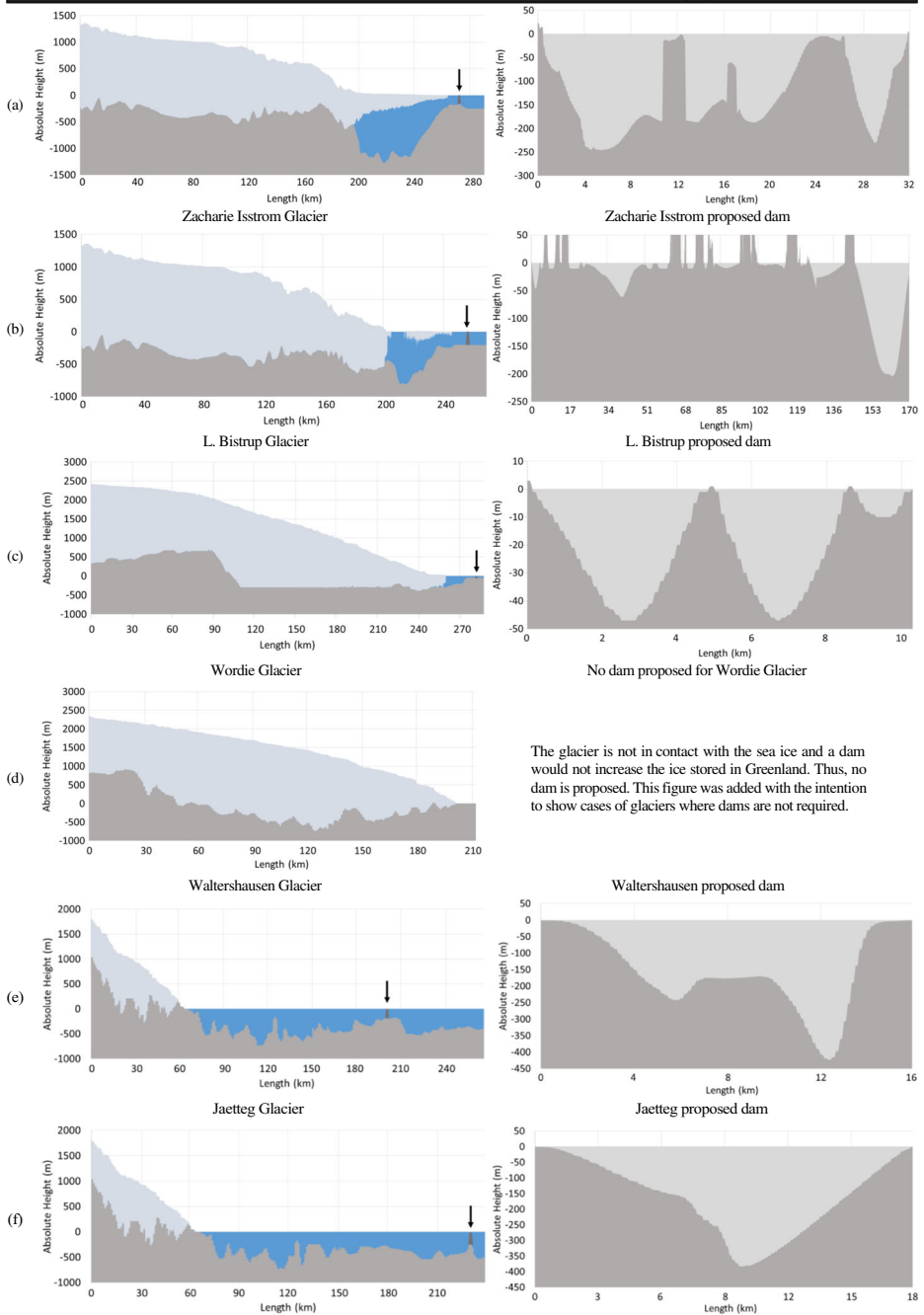
The Intergovernmental Panel on Climate Change estimated that if the Greenland ice sheet (2,600,000 km³ of ice) melted, it would contribute to an increase of 7.3 m to sea levels (Solomon et al. 2007). Using the same ratio, the additional ice sheet storage volume is used to estimate its impact on sea levels.

Assuming that the barrier will contribute to a reduction in sea level rise of 5.3 m from 2040 until 2300, the dam costs are estimated to be US\$ 5.3 billion per 20 years, no return on the investment, and negligible inflation the final cost of the project would be US\$ 68.9 billion. The same sea level reduction could be achieved with submerged dams built at a cost of US\$ 337.1 billion, but it would last for several hundred years.

4 Discussion

Given that the width of the submerged dam increases with the height of the dam, the ratio between the cost of the dam and the costs of the barrier varies with the overall height of the dam. The higher the dam, the more expensive the dam becomes.

Considering a submerged dam will last for much longer than a barrier. It could be the case that it is appropriate to build a dam instead of a barrier. But this might be limited to dams with small heights, such as, for example, in waters 1 to 10 m deep, particularly because shallow locations need a robust solution to withstand the destructive power of breaking waves. For locations with larger depths, submerged barriers are the preferred solution, even considering that smaller life cycle of the submerged barrier. It turns out that the costs for building a dam in front of a deep glacier far exceed the costs of barriers. Thus, it is suggested that dams are appropriate alternatives for locations with depths smaller than 10 m. However, in location where the depths are higher than 10 m, barriers are the best alternative.



The glacier is not in contact with the sea ice and a dam would not increase the ice stored in Greenland. Thus, no dam is proposed. This figure was added with the intention to show cases of glaciers where dams are not required.

Fig. 5 Glaciers and proposed dams to contain the contact of seawater with the glacier ice

This article assumes that all cross-section is blocked with either the barrier or the dam. It might be more appropriate to allow some free space between the sea surface and the top of the barrier or dam, as proposed in Moore et al. (2018) and Wolovick and Moore (2018). This is

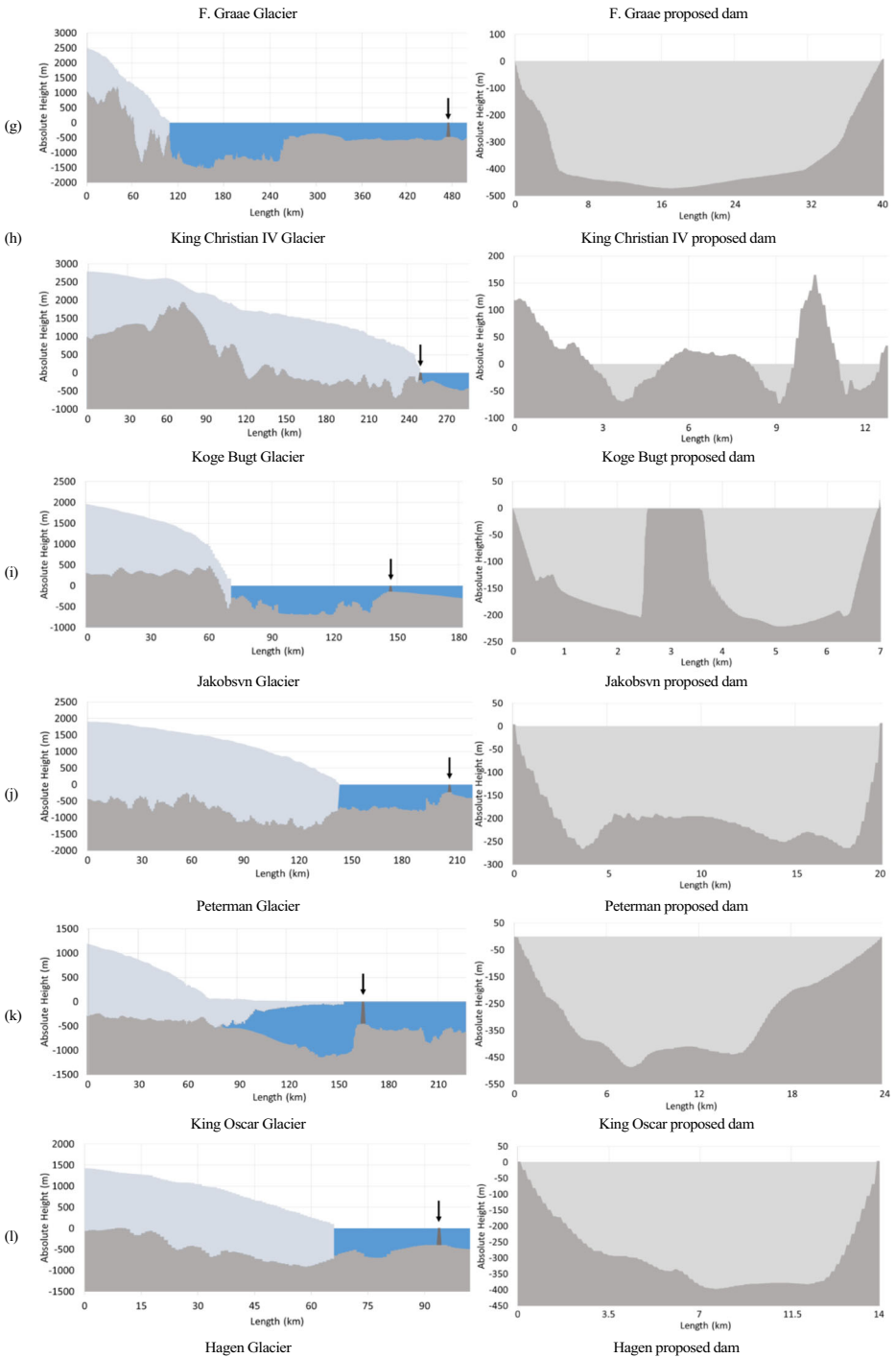


Fig. 5 continued.

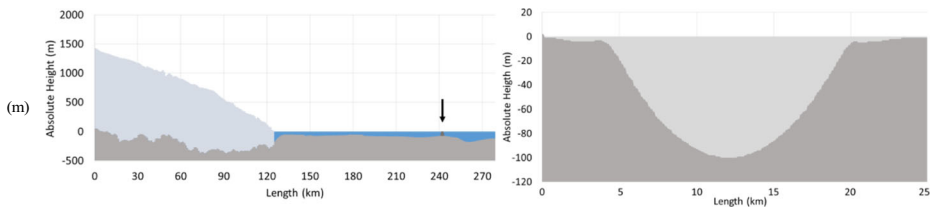


Fig. 5 continued.

especially appropriate for animals to pass through the barrier/dam and for ice bergs released from the ice shelf not to damage the barrier/dam. However, the reduction in ice melting in Greenland will increase the temperature of the upper layer of the Arctic Ocean. Thus, the glacier should be insulated as much as possible from the ocean seawater.

This paper showed that barrier or dams could be used to reduce sea level rise in 5.3 m with investments of US\$ 5.5 billion/per 20 years with submerged barriers or US\$ 337.1 billion with submerged dams. Assuming that the costs of construction of the barriers and dams do not vary significantly, and that the money invested is free from interest rate, the selection of the dams as the solution to reduce sea levels in 5.5 m would pay back if the dams remained intact for 37,000 years. However, given that there is no interest free investment and that the investment costs of the dam are much higher than the costs of the barrier, the construction of the barrier makes sense if a 1% interest rate is applied. Thus, it is concluded that a submerged barrier would be the most appropriate solution for reducing the ice melting in Greenland and thus, to reduce sea level rise.

Scientists predict that sea level rise will have an economic impact of around US\$ 1.4 trillion per year by 2100, if the world temperature remains between 1.5 and 2 °C above current temperatures (Jevrejeva et al. 2018). It would therefore justify to the spending of US\$ 0.275 billion a year to construct and maintain the submerged barriers in Greenland. Even though the proposed dams have environmental impacts, the resulting environmental impact of adaptation measures around the world's coast would substantially exceed the impact of the proposed barriers. In addition, a location that does not have adaptation measures will be flooded by the ocean, further increasing the environmental impact.

This article presents a proposal to reduce sea level rise and presents an initial consideration of the challenges involved in its implementation. The paragraphs below highlight some of the possible impacts resulted from this proposal:

- The reduction of ice melt in Greenland glaciers will contribute to an increase in seawater temperature around Greenland. This increase in seawater temperature will increase the melting potential of glaciers that does not have a barrier.
- The reduction in ice melting will result in an increase in salinity and temperature of the top layer of the Arctic Ocean. This will considerably affect the formation of the seasonal ocean ice cover in the Arctic Ocean, which would increase the Alberto effect of the region, contributing to ocean warming. However, oceanic ice sheets work as a powerful thermal insulator, keeping the heat in the ocean and the atmosphere cold. The reduction of the ice cover during the winter will considerably increase the temperature of the atmosphere and increase the heat radiated from the Arctic Ocean into space cooling the Arctic Ocean.

Table 3 Comparison of proposed dams and barriers

Glacier	Barrier and dam details					Contributions to sea level rise				
	Length (km)	Max height (m)	Cross-section (km ²)	Barrier cost (B US\$/20 years)	Dam cost (B US\$)	Dam/barrier cost Ratio	Glacier length under sea level (km)	Glacier expansion length (km)	Sea level impact (m)	
79 North	32	246	3.98	0.42	24.41	58.12	1000	73	0.98	
Zacharie Isstrom	125	204	4.50	0.47	27.07	57.60	1000	55	0.96	
L. Bistrup	10	47	0.26	0.03	1.48	49.33	180	34	0.20	
Wordie	0	0	0	0	0	-	0	0	0	
Waltershausen	16	423	2.48	0.26	15.61	60.04	0	135	0.12	
Jaetteg	18	383	2.97	0.31	18.74	60.45	0	165	0.15	
F. Graac	40	472	13.90	1.45	92.94	64.10	50	375	0.39	
King Christian	5.4	73	0.20	0.02	1.18	59.00	110	0	0.10	
Koge Bugt	70	221	9.70	1.01	60.04	59.45	5	75	0.07	
Jakobsvn	19	266	2.76	0.29	17.23	59.41	1000	65	0.97	
Peterman	23	486	6.91	0.72	45.59	63.32	1000	90	0.99	
King Oscar	14	397	4.06	0.42	26.40	62.86	55	88	0.13	
Hagen	25	100	1.08	0.11	6.41	58.27	120	128	0.23	
Average	30.6	255.2	4.1	0.43	24.41	56.77	348	99	0.41	
Total				5.5	337.1	61.29			5.3	

Additionally, the increase in ice free Arctic Ocean surface will allow more CO₂ to be stored in the world's ocean, reducing the overall CO₂ in the atmosphere, particularly because of the low temperature of the Arctic Ocean.

- The increase in temperature in the Arctic region with the removal of the ice cover and the continuing warming of the globe could end up melting the Greenland ice sheets from the top of the ice sheet.
- Other benefits will result from the reduction in sea ice cover in the Arctic Ocean, such as the possibility for navigation through the Arctic Ocean. However, the changes in world currents could increase the intensity and frequency of hurricanes in the Atlantic.
- Further research is required to predict how the proposed barriers would affect the regional biosphere, climate, ocean currents and how these impacts will affect the global climate and ocean currents. Ideally, there would first be a “demonstration project” that would help evaluate the effect of the barrier or dam and allow a better cost estimate to be made.

5 Conclusion

Climate change is increasing the melting rate of the Greenland ice sheet, which is contributing to sea level rise. This paper has proposed the construction of submerged barriers or dams in front of Greenland glaciers with the objective of reducing the free flow of warmer seawater under ice shelves, thus, reducing the melting of the Greenland ice sheet. It was estimated that the ten proposed barriers would cost around US\$ 68.9 billion and contribute to reducing sea level rise by up to 5.3 m from 2040 to 2300 with submerged barriers or US\$ 337.1 billion for several hundreds of years with submerged dams.

Comparing the proposed alternatives to reduce sea level rise with the current solutions to adapt to the rise in sea levels, barriers would be around four orders of magnitude cheaper than adaptation and submerged dams would be around three orders of magnitude cheaper than adaptation.

This paper provides an initial cost assessment of the use of submerged barriers and dams to mitigate the impact of sea level rise. It mainly focuses on the required barrier area to restrict the flow of seawater under the ice shelves. Future work will involve the creation of a dynamic computational fluid mechanics model to predict the impact of the barrier/dam on the flow of ice in Greenland with the intent of better analyzing the contributions of the barrier/dam to sea level rise. Changes in ice melting in Greenland are expected to have a considerable impact in the Arctic Ocean ice cover, the temperature of the Arctic region, and in global currents. These impacts will also be studied.

The mitigation of CO₂ emissions might not be enough to prevent dangerous impacts from climate change. New strategies to reduce sea level rise should be further studied and implemented to buy us time for a smoother transition to a more sustainable world.

Acknowledgments Open access funding provided by International Institute for Applied Systems Analysis (IIASA). We would like to thank the IIASA for the postdoctoral research fellowship, Joeri Rogelj and Matthias Mengel for their contributions to the paper.

Funding information This study received research grant from CAPES/Brazil.

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References

- Aerts J, Bannink B, Sprong T (2008) IVM Report - Aandacht voor Veiligheid, Amsterdam
- Al-Jeneid S, Bahnassy M, Nasr S, El Raey M (2007) Vulnerability assessment and adaptation to the impacts of sea level rise on the Kingdom of Bahrain. *Mitig Adapt Strateg Glob Chang* 13:87–104. <https://doi.org/10.1007/s11027-007-9083-8>
- Alibaba (2018) SS316L marine grade steel plate price
- Arctic Climate Impact Assessment (2004) *Impact of a warming Arctic: highlights*. Cambridge University Press, Cambridge
- Ashton AD, Donnelly JP, Evans RL (2008) A discussion of the potential impacts of climate change on the shorelines of the northeastern USA. *Mitig Adapt Strateg Glob Chang* 13:719–743. <https://doi.org/10.1007/s11027-007-9124-3>
- Babu DSS, Sivalingam S, Machado T (2012) Need for adaptation strategy against global sea level rise: an example from Saudi coast of Arabian gulf. *Mitig Adapt Strateg Glob Chang* 17:821–836. <https://doi.org/10.1007/s11027-011-9346-2>
- Battersby S (2010) Think or swim: can we hold back the oceans? York, New
- Burnett J (2015) Billions Spent On Flood Barriers, But New Orleans Still A “Fishbowl.” In: *Natl. Public Radio Church JA, White NJ, Konikow LF, Domingues CM, Cogley JG, Rignot E, Gregory JM, van den Broeke MR, Monaghan AJ, Velicogna I (2011) Revisiting the Earth’s sea-level and energy budgets from 1961 to 2008. Geophys Res Lett* 38. <https://doi.org/10.1029/2011GL048794>
- DeConto RM, Pollard D (2016) Contribution of Antarctica to past and future sea-level rise. *Nature* 531:591–597
- Fenty I, Willis JK, Khazendar A et al (2016) Oceans melting Greenland: early results from NASA’s ocean-ice mission in Greenland. *Oceanography* 29:72–83. <https://doi.org/10.5670/oceanog.2016.100>
- Frihy OE, El-Sayed MK (2013) Vulnerability risk assessment and adaptation to climate change induced sea level rise along the Mediterranean coast of Egypt. *Mitig Adapt Strateg Glob Chang* 18:1215–1237. <https://doi.org/10.1007/s11027-012-9418-y>
- Giovannini R (2017) Venice and MOSE: story of a failure. *La Stamp, In*
- Haszeldine RS, Flude S, Johnson G, Scott V (2018) Negative emissions technologies and carbon capture and storage to achieve the Paris agreement commitments. *Philos Trans R Soc A Math Phys Eng Sci* 376: 20160447. <https://doi.org/10.1098/rsta.2016.0447>
- Hinkel J, Nicholls RJ, Vafeidis AT, Tol RSJ, Avagianou T (2010) Assessing risk of and adaptation to sea-level rise in the European Union: an application of DIVA. *Mitig Adapt Strateg Glob Chang* 15:703–719. <https://doi.org/10.1007/s11027-010-9237-y>
- Jevrejeva S, Jackson L, Grinsted A et al (2018) Flood damage costs under the sea level rise with warming of 1.5 °C and 2 °C. *Environ Res Lett* 13
- Jourdain N, Mathiot P, Merino N et al (2017) Ocean circulation and sea-ice thinning induced by melting ice shelves in the Amundsen Sea. *J Geophys Res Ocean* 122:2550–2573
- Lacerda GBM, Silva C, Pimenteira CAP, Kopp RV, Grumbach R, Rosa LP, de Freitas MAV (2014) Guidelines for the strategic management of flood risks in industrial plant oil in the Brazilian coast: adaptive measures to the impacts by relative sea level rise. *Mitig Adapt Strateg Glob Chang* 19:1041–1062. <https://doi.org/10.1007/s11027-013-9459-x>
- Lin BB, Khoo YB, Inman M, Wang CH, Tapsuwan S, Wang X (2014) Assessing inundation damage and timing of adaptation: sea level rise and the complexities of land use in coastal communities. *Mitig Adapt Strateg Glob Chang* 19:551–568. <https://doi.org/10.1007/s11027-013-9448-0>
- Martín-Antón M, Negro V, Del Campo JM et al (2016) Review of coastal land reclamation situation in the world. *J Coast Res* 1:667–671. <https://doi.org/10.2112/SI75-133.1>
- Mengel M, Nauels A, Rogelj J, Schleussner C-F (2018) Committed Sea-level rise under the Paris agreement and the legacy of delayed mitigation action. *Nat Commun* 9:601. <https://doi.org/10.1038/s41467-018-02985-8>
- Meyssignac B, Cazenave A (2012) Sea level: a review of present-day and recent-past changes and variability. *J Geodyn* 58:96–109. <https://doi.org/10.1016/j.jog.2012.03.005>
- Moore J, Gladstone R, Zwinger T, Wolovick M (2018) Geoe engineer polar glaciers to slow sea-level rise. *Nature* 555:303–305

- Morlighem M (2017) BedMachine v3: complete bed topography and ocean bathymetry mapping of Greenland from multibeam Echo sounding combined with mass conservation. *Geophys Res Lett* 44:11051–11061
- Nauels A, Rogelj J, Schleussner C-F, Meinshausen M, Mengel M (2017) Linking sea level rise and socioeconomic indicators under the shared socioeconomic pathways. *Environ Res Lett* 12. <https://doi.org/10.1088/1748-9326/aa92b6>
- Nicholls R, Brown S, Goodwin P, et al (2018) Stabilization of global temperature at 1.5°C and 2.0°C: implications for coastal areas. *Philos Trans R Soc A Math Phys Eng Sci* 376:
- Omi H, Ohno S, Horikoshi N (2010) Design & build for palm jumeirah monorail infrastructures in Dubai, U.A.E. In: 3rd International fib Congress and Exhibition, Incorporating the PCI Annual Convention and Bridge Conference: Think Globally, Build Locally, Proceedings
- Ramillien G, Bouhours S, Lombard A, Cazenave A, Flechtner F, Schmidt R (2008) Land water storage contribution to sea level from GRACE geoid data over 2003–2006. *Glob Planet Change* 60:381–392. <https://doi.org/10.1016/j.gloplacha.2007.04.002>
- Slapgard J (2012) Cost base for hydropower plants: with a generating capacity of more than 10,000 kW. **Oslo**
- Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (2007) Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge
- Song J, Fu X, Wang R, Peng ZR, Gu Z (2018) Does planned retreat matter? Investigating land use change under the impacts of flooding induced by sea level rise. *Mitig Adapt Strateg Glob Chang* 23:703–733. <https://doi.org/10.1007/s11027-017-9756-x>
- Wolovick M, Moore J (2018) Stopping the flood: could we use targeted geoengineering to mitigate sea level rise? *Cryosph* 12:2955–2967