NEED

The Northern European Enclosure Dam for if climate change mitigation fails

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ABSTRACT

It might be impossible to truly fathom the magnitude of the threat that global-mean sea level rise poses. However, conceptualizing the scale of the solutions required to protect ourselves against global-mean sea level rise, aids in our ability to acknowledge and understand the threat that sea level rise poses. On these grounds, we here discuss a means to protect over 25 million people and important economical regions in northern Europe against sea level rise. We propose the construction of a Northern European Enclosure Dam (NEED) that stretches between France, the United Kingdom and Norway. NEED may seem an overwhelming and unrealistic solution at first. However, our preliminary study suggests that NEED is potentially favorable financially, but also in scale, impacts and challenges compared to that of alternative solutions, such as (managed) migrations and that of country-by-country protection efforts. The mere realization that a solution as considerable as NEED might be a viable and cost-effective protection measure is illustrative of the extraordinary global threat of global-mean sea level rise that we are facing. As such, the concept of constructing NEED showcases the extent of protection efforts that are required if mitigation efforts fail to limit sea level rise.

Capsule Summary

If climate change is left unmitigated the construction of a 637 km long Northern European Enclosure Dam (NEED) might be the most viable solution to protect Northern Europe against sea level rise.

1. Scaling a solution to the problem

Current global mean temperature is about 1°C above pre-industrial levels (Haustein et al. 2017), while implemented policies imply a further global warming up to 2.6-3.1 °C by 2100 (Rogelj et al. 2016) or 2.0-4.9 °C overall (Raftery et al. 2017). Global-mean sea level rise (SLR) lags behind global-mean temperature rise, but is accelerating and has risen over 21 cm since 1880 (Church and White 2011). It is virtually certain that global mean SLR will continue beyond 2100 (Church et al. 2013). A baseline of 2.3 m global mean SLR per °C is predicted (Levermann et al. 2013), suggesting an unavoidable 5 – 11 m rise over the next centuries to millennia. High-end scenarios predict over 10 m global-mean SLR by 2500 (DeConto and Pollard 2016; Edwards et al. 2019), with a possible 1 – 2 m by 2100 (Jevrejeva et al. 2014; Kopp et al. 2014; Bars et al. 2017). In short, global-mean SLR may pose an unprecedented threat to society as we know it.

The magnitude of the threat that SLR may pose demands a response with a solution that reflects the scale of the problem. On these grounds, we propose the construction of the Northern European Enclosure Dam (NEED) that disconnects the North and Baltic Seas from the Atlantic Ocean, to protect 15 Northern European countries from global-mean SLR. This can be achieved by constructing two enclosure dams (Fig. 1). The southern part of NEED connects France (near Brest) to the south-west coast of England and measures 161 km in length with an average depth of about 85 m and a maximum depth of 102 m. The Northern part of NEED extends from the north-east tip of Scotland, via the Orkney and Shetland Islands to Bergen in Norway. The northern part has

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a total length of 476 km and average depth of 127 m with a maximum of 321 m in the Norwegian Trench. The two components together are referred to as NEED and have a total length of 637 km. The construction of NEED would protect coastal communities that under current population density consist of about 25 million people below 2 m SLR while 55 million live below 15 m SLR (inset Fig. 1). If constructed, NEED would be one of the largest civil-engineering challenges ever faced. Alternative configurations of NEED are considered less effective (Appendix A).

NEED may seem an overwhelming and unrealistic solution at first. Regardless, we here present preliminary quantification and thoughts on the financial feasibility, social-political considerations, environmental impacts and technological challenges of NEED compared to that of alternative solutions, such as (managed) migrations and that of country-by-country protection efforts. In doing so, we arrive at an alarming conclusion; a solution as considerable as NEED might be a viable and cost-effective protection measure for even a few meters of SLR. For northern Europe, NEED may therefore be preferred over the alternative solutions. This conclusion reflects the magnitude of the threat that society is facing as a result of global-mean SLR. We here do not and cannot conclusively determine if NEED could and should be constructed. Yet, we do emphasize that the conclusions of our preliminary findings advocate for immediate action to intensify and further climate mitigation efforts, so that solutions with a scale and impact such as NEED are not going to be required.

Alternative Solutions

In order to place NEED in context of alternative solutions, we compare with other strategies to cope with (local) SLR. These can be categorized into 1) no action, 2) protection, or 3) managed retreat. Based on monetary value alone, the cost of no action exceeds that of protection and managed retreat by a factor 5 to 10 (Aerts et al. 2008; Kabat et al. 2009; Diaz 2016; Hinkel et al.

2014, 2018). Due to the additional non-monetary losses and associated possible social-political instabilities of no action (Adger et al. 2009), we only consider protection and managed retreat as practical solutions.

Managed retreat could potentially be less expensive than protection in certain locations (Diaz 2016) and may theoretically be a good solution when implemented over long periods of time, well before a potential disaster occurs (Nicholls and Klein 2005; Dronkers et al. 1990a). In the case of SLR this requires immediate implementation. However, managed retreat leads to intangible costs such as large social and psychological difficulties in displacing people from their homes as well as cultural-heritage loss. Related migration can lead to national and international social-political instability, forcing decision-makers to shy away from spurring processes to facilitate managed retreat (Hino et al. 2017). Consequently, managed retreat is currently not widely implemented and arguably not a viable solution to timely address the threat of SLR.

If we accept the reasoning provided above, we are left with protection as the most realistic solution. With economic and population growth in coastal areas, protection also becomes increasingly more worthwhile, while encouraging a proactive rather than reactive attitude to the threat of global-mean SLR (Nicholls 2011). Current protection measures are implemented on a country-by-country (national) basis. Instead, NEED could offer a concerted effort to address protection of coastal zones across Europe against SLR (Tol et al. 2008).

From the forgoing discussion we conclude that to understand how NEED compares to other solutions, we only have to compare NEED against national-based protection, as that seems to be the most viable ongoing measure. In what follows we will therefore provide a preliminary discussion on the technical challenges, financial feasibility and environmental, social and political impacts of NEED, with respect to that of national-based protection. To our surprise, NEED can sometimes be conceived as a better solution than continuing future upgrades of ongoing efforts.

That a solution as radical as NEED has the potential to be preferred over ongoing protection measures, is a direct reflection of the magnitude of the threat that SLR poses.

Technical considerations for constructing NEED

There is substantial expertise available with regards to engineering of dikes, enclosure dams, and land reclamation projects. The largest constructed enclosure dams to date are the Afsluitdijk (Netherlands) and the Saemangeum Seawall (South Korea, Fig 2). The Afsluitdijk[1] is 32 km long, about 11 m in height and 90 m wide. The Saemangeum Seawall[2] is 33 km long, 36 m height on average (maximum of 54 m) and 290 m wide. These dimensions are not far off those required for the construction of NEED-south and NEED-north near the Orkney and Shetland islands. However, we expect a substantial but surmountable technological challenge for the part of NEED-north that crosses the Norwegian Trench with depths over 300 m. Fixed oil rigs are feasible in depths over 500 m, while moored oil rigs operate in waters over 2000 m depths, indicating that having fixed constructions over 300 m depths is possible. Although dams have different requirements than oil rigs, this is encouraging for the possibility of constructing NEED.

River Discharge

Enclosing the North and Baltic Seas will yield a net freshwater discharge of 40.000 m^3 s^{-1} into the basin (Appendix B). The discharge would lead to a SLR of 0.9 m $year^{-1}$ within the enclosure and must therefore be pumped out into the Atlantic Ocean (Appendix B). Recently, a pumping station with a capacity of 550 m^3 s^{-1} was taken in operation in New Orleans (Orleans 2015), while the Dutch Afsluitdijk will install two new pumping stations with a capacity of 400 m^3 s^{-1}

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[1] `https://deafsluitdijk.nl/wp-content/uploads/2014/06/Startdocument-planuitwerking-Afsluitdijk_tcm174-355254.pdf`

[2] `http://www.korea.net/NewsFocus/policies/view?articleId=89560`

each[3]. As such, the discharge can be accounted for with less than 100 of such pumping stations, while we may expect more efficient and higher capacity pumps likely to become available in the future. The discharge will also lead to freshening of the basin and reduce the salinity by a factor 10 in about 100 years (Appendix B). The freshening is expected to affect ecosystems, biodiversity and the fishing industry (discussed later).

Effects on the Maritime Industry

The construction of NEED would significantly impact the maritime industry. The busiest trading ports in Europe (Rotterdam, Antwerp, Hamburg, Bremerhaven) lie within the enclosure. Without a proper solution to reduce the impact of NEED on the maritime industry, NEED would be a less viable solution for protection against SLR. Solutions are available, as NEED could for example incorporate sluice gates to allow for a continuation of ongoing shipping traffic. Sluice gates allowing for some of the largest ships in the world are already operational in the Netherlands and Belgium. Alternatively harbours could be build on the ocean-side of NEED from where goods could be transferred to trains or to vessels operating within the enclosure.

Regardless, the effect of NEED on the maritime industry will remain uncertain, both economically and technically. However, it is certain that without the construction of NEED, the maritime industry will also be economically affected and technically challenged as SLR will force ports to relocate, or adopt and continuously upgrade their protection measures.

Remaining technical challenges

Assuming a dam with a middle width of 50 m, two sloping sides with a 1:2 (height:width) ratio (Jonkman et al. 2013), and adding 20 m to the ocean depth to take into account future global-mean

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[3] `https://www.deafsluitdijk.nl/wp-content/uploads/2014/05/DNA-druk-30april.pdf`

SLR, the volume of NEED-south and NEED-north are 4.6 and 31.6 km^3, respectively. With most dams made out of a sand- or clay-like material, building NEED would require about 51 billion tons of sand (using a density for sand of 1400 kg m^{-3}), which is equal to about one year worth of global sand use (Peduzzi 2014). With sand becoming an increasingly scarcer material (Torres et al. 2017), the availability, sourcing and transport of building material and related energy cost to build and maintain the enclosure could pose limitations on the ability to construct NEED. However, we argue that constructing new coastal defenses and maintaining, upgrading and expanding the thousands of kilometers of coastal defense that are already in place to protect Northern European coastal communities will also provide complex technological challenges that may not be easy to overcome. As such, these challenges could well exceed those that arise when constructing NEED, showcasing that no solution will be straightforward when dealing problems as complex as SLR. As such, solutions of the extent as NEED are to be considered in shaping our future protections measures against global SLR.

Financial Feasibility of NEED

We here provide a back-of-the-envelope estimate of the costs of constructing NEED. We do so by scaling up the construction costs of several existing projects.

The most recent and comparable construction to NEED is that of the 33.9 km long Saemangeum Seawall[4]. Using the ratio of the volume of the Saemangeum Seawall (0.34 km^3) and of NEED (36.1 km^3), multiplied by the cost of the Saemangeum Seawall (1.83 billion Euro, 2018 value), we find an estimate of 192 billion Euro to construct NEED. The Maasvlakte 2, is a 20 km^2 extension of the Rotterdam harbour that includes hard and soft flood protection and basic infrastructure such as quays, rail track and roads[5]. Land was reclaimed from 17 m depth to 5 m above sea level, using

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[4] `http://www.korea.net/NewsFocus/policies/view?articleId=89560`

[5] `https://www.maasvlakte2.com/en/index/`

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0.24 km^3 of sand at a total cost of 3.38 billion Euro (2018 value). When we use volume to scale up the total cost (including infrastructure) we estimate a cost of 508 Billion Euro to construct NEED. Finally, by assuming that dike-height and construction costs scale linearly and with an upper estimate of 42 million Euro per km for an enclosure dam at depths of 10 meters (Dronkers et al. 1990b; Jonkman et al. 2013), we estimate 313 billion Euro for the construction of NEED.

In addition to the construction of the dam itself, several discharge pumping stations must be included. When considering the total discharge scaled with the cost and capacity of the pumps of either the Afsluitdijk (200 million Euro) or New Orleans (500 million Euro), this would add an additional 20-33 billion Euro. If the construction of sluices is required, this would add additional costs.

Combining all the above, we estimate the total costs to be roughly [250-550] billion Euro. When assuming a 20-year construction time over which to spread the costs, this gives an annual expense of [0.07 - 0.16] % of the combined Gross Domestic Product (GDP) of the 15 involved countries[6]. The UK, Netherlands, Germany, Belgium and Denmark would likely drive the construction of NEED because of their awareness of SLR, vulnerability or both (Tol et al. 2008). For these 5 countries alone, the total expenses would amount to [0.15 - 0.32] % of their GDP, annually for 20 years. These numbers are achievable and pose no financial limitation, even when fewer countries contribute.

Comparing NEED to ongoing national protection measures

With about a third of the country and 4 million people already below sea level, the Netherlands currently has about 3600 km of flood protection in place against flooding from rivers and SLR

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[6] using 2019 GDP rates, downloaded from `https://www.imf.org/external/datamapper/PPPGDP@WEO/OEMDC/ADVEC/WEOWORLDon22-11-2019`

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along the coast (Kok et al. 2008). The protection consists of hard protection (dikes, enclosure dams), soft protection (beaches nourishment, dunes) and managed flooding (van Staveren et al. 2014). Although the Netherlands may be able to continue current protection measures for 2-3 m SLR (Hinkel et al. 2018; Stronkhorst et al. 2018), over 5 m of SLR leads to protection costs up to 18 billion Euro a year (Olsthoorn et al. 2008; Stolwijk and Verrips 2000) and exceed the cost of evacuation (Hinkel et al. 2018), while also reaching technical limitations (Tol et al. 2006).

A low-end estimate suggests Dutch protection will increase from 0.35 to possibly 1.5 billion Euro per year in 2200 for 2 m SLR, with a total cost of over 100 Billion Euro (Kok et al. 2008). Other estimates suggest that continuing ongoing protection measures in the Netherlands for SLR up to 1.5 m in 2100, the cost range from 1.6 to 3.1 billion Euro per year until 2050 with an integrated costs of 32-140 billion Euro in 2100 (0.1 to 0.5 % of the GDP annually) (Aerts et al. 2008; Kabat et al. 2009; Hinkel et al. 2018). In short, for only 1.5 m SLR, protecting the Netherlands is about 1/3 of the costs of NEED. For more SLR, protection quickly becomes technically and financially challenging and possibly unsustainable. Therefore, we argue that integrated over the next 100-200 years, even for the Netherlands alone, NEED may both technically and financially be a better solution than scaling up existing protection measures.

For countries other than the Netherlands, there are fewer estimates available that detail costs of protection against SLR, but we here discuss a few. In Germany, a SLR of 1 m would put more than 300,000 people at risk in the coastal cities and communities, and economic values endangered by flooding and erosion would amount to more than 270 billion Euro (Sterr 2008). With 3700 km of German coast, ongoing improvements of SLR protection measures may become too costly and alternative measure may have to be found (Sterr 2008). In 1990 it was estimated that 80 billion USD (140 billion Euro in 2018 values) of protection cost were needed to protect Western and

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Northern Europe and the Baltic coast against a 1 m SLR (Dronkers et al. 1990b). As SLR may already reach 1 m in 2100, actual costs are likely to quickly become much higher.

NEED as the optimal financial solution

Based on the discussion above, we conjecture that protection of other coastal areas and cities against SLR exceeding 2 m, will quickly become multi-billion euro investments. For SLR of even a few meters, we expect that the integrated cost of individual protection of all 15 countries together far exceeds the costs of constructing NEED. For protection against long term SLR projection (> 10 m), NEED is almost certainly the least costly option.

Furthering the debate

Technical and financial consideration on constructing NEED have so far not excluded NEED as a possible solution to address the threat of SLR to Northern Europe. Regardless of the initial reluctance to construct NEED, this motivates to further progress the debate and provide our preliminary view on the possible impact of NEED on the environment, society and politics.

We do so by focusing on the impact of NEED on ocean dynamics, which describes fundamental changes that feed into higher order changes such as that of biodiversity. To remain within the scope of this study, we only roughly extrapolate the dynamical results to gain some preliminary insight of other major impacts that may be expected.

Impact on ocean dynamics and the environment

The impact of NEED on ocean circulation is quantified using simulations with a version of the numerical ocean model NEMO that explicitly resolves tides (details in Appendix C). The computational domain covers the North-East Atlantic including the North Sea. The results are shown for simulations with and without NEED constructed (Fig. 3).

Under current circumstances, a tidal Kelvin wave propagates around the North Sea basin in an anti-clockwise manner, leading to large tidal amplitudes (> 1 m) and velocities (> 2 m s^{-1}) (Otto et al. 1990) (Fig. 3a). This sets up a circulation in which water is entering the North Sea between the Orkney and Shetland Islands and exiting along the Norwegian coast. Due to the construction of NEED, the Kelvin wave is obstructed from entering the basin and the tidal amplitude inside the basin becomes very small (Figs. 3b and C3). Instead, the new geometry causes the tidal amplitude to increase by about 0.7 m along the coasts of South-Western England and Wales and about 0.4 m for North-Western England (Figs. 3 and A1). With NEED constructed, an anti-clockwise circulation is set up inside the North Sea basin that is driven by wind, baroclinic circulation from freshwater discharge and very small tidal motions excited within the basin itself. Furthermore, with the changes in tides and circulation due to the construction of NEED, there should also be an associated change in the location of tidal energy dissipation and mixing. This could, for example, influence overturning circulation outside of the basin.

As such, constructing NEED will unquestionably have a large impact on the circulation and exchange of nutrients, sediment and small marine life within the enclosure and possibly outside of the enclosure in the Atlantic ocean and along the European Shelf. Changes in atmospheric circulation and rain patterns could also occur. Finally we note that it remains unclear if the freshening of the enclosed basin can be compensated for. Such compensation could require hundreds of desalinisation plants and/or a drainage system. The later would require additional pumps. Without compensation for the freshening however, wholesale ecosystem changes will occur.

In short, NEED will heavily impact both marine and terrestrial ecosystems inside and outside of the enclosure and as such also have social and cultural implications and impact the tourism and fisheries industries. Although the exact details and extent of the consequences for the environment are beyond the scope of this study, certain consequences will oppose people to the idea of constructing NEED. Alternative solutions however, will undoubtedly also lead to irreversible environmental changes that may be equally undesirable as those associated with the construction of NEED. Therefore the only way to limit any such impacts is to limit global-mean SLR itself. This can only be achieved by immediate implementation of climate change mitigation efforts such as that of reducing cumulative carbon emissions (Clark et al. 2018).

Social and cultural implications

The impact of social and individual factors such as loss of places and culture are difficult to quantify and often subjective, but are real for those experiencing them (Adger et al. 2009). Therefore such less-quantifiable impacts are important and can limit viability of adaptation measures and warrant a discussion (Stern et al. 2006).

Forced migration leads to loss of property, cultural heritage (Marzeion and Levermann 2014) and can cause mental and physical health problems (Schwarz 1997; Oliver-Smith 1991), and a large burden on the economical, social and cultural values in the host area (Wood 1994; Dadush and Niebuhr 2016). Accumulated over a large population (>25 million people for only 2 m SLR (inset Fig. 1), this can significantly disrupt and destabilize societies and cause (inter)national tension and conflict, beyond the directly affected coastal communities (Hauer et al. 2016; Hauer 2017; Aerts 2017). We therefore take the approach that the adaptation measure with the least disruption of the established society is the least limiting adaptation measure with respect to social and cultural values. In that view, protection is generally preferred over (managed) migration.

Unfortunately, even protection measures may lead to conflicts and can impact human rights (Robinson and Shine 2018). An important example is forced relocation to make space for new constructions or enlargements of existing protection structures such as dikes. NEED however, would significantly reduce the total length of required protection measures and place them in areas with a low population density or in the sea. This minimizes the number of people that are negatively affected and in that regard NEED could be a preferred solution. The conglomeration of all social and cultural advantages and disadvantages of NEED will have to be compared and contrasted against that of alternative solutions.

We hope that the mere suggestion of NEED as a solution, and associated protest, may instigate a thought process that sparks public awareness of the threat that SLR poses, possibly clearing a path for global scale action to address long-term climate change related threats.

Political Considerations

Because SLR is a slow but unstoppable process, there is a central role for long-term coastal adaptation strategies (Döös 1997; Hinkel et al. 2014). Adaptation efforts require substantial institutional, structural and cultural change, while ongoing impacts are already evident (Hugo 2011; Church et al. 2013). Therefore, an immediate response is required to reduce the negative social, economical, political and cultural impacts of SLR (Dawson et al. 2005). Unfortunately, large uncertainty in quantifying emission scenarios and limited understanding of the Antarctic ice sheet dynamics (DeConto and Pollard 2016; Kingslake et al. 2017; Spence et al. 2017; Bell et al. 2017; Bronselaer et al. 2018), make it near impossible to construct a cost-benefit analysis (Hallegatte et al. 2016). This leads to divergent views among policy makers that delays the implementation of adaptation measures (Adger et al. 2009). Whether policy makers are capable of delivering a timely response that limits the negative impacts of SLR, is heavily contested (Olsthoorn et al. 2008; Biesbroek et al. 2011).

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Without new policy however, SLR will lead to unavoidable and irreversible loss of physical places, cultural heritage and environmental and ecological systems. In addition, landlocked European countries will also suffer from global-mean SLR as a result of changes in trade, migration and social-political instabilities (Bosello et al. 2012). Therefore the question is not if we should start adaptation efforts, but which adaptation measures we should start to implement right now. We take the stand that a policy that has the least direct impact on peoples daily life, at reasonable costs, has the largest potential to be implemented with the required urgency to be effective. As NEED would be constructed mostly in the sea (reducing direct impact on peoples lives) and may have financial advantages over individual protection measures, it could become a solution with which policy makers can concur.

A solution such as NEED requires individuals and policy makers to think in terms of a collaborative and pro-active approach that spans across political parties, countries, and generations. That is, an European-wide endeavor that reduces financial costs, improves quality of protection measures, reduces local impacts and boost international political and economical ties. As such, NEED represents a solution of the scale that is required to counter the threat we are facing.

Other Mega-Enclosures

Around the world we have identified various other regions in which Mega-Enclosures such as NEED could serve as a solution to protect against regional SLR. These are the 1) Irish Sea, 2) Japanese Sea, 3) Mediterranean Sea, 4) Baltic Sea alone (unless covered by NEED), 5) Red Sea, and 6) the Persian Gulf (Fig. 4). All these cases require future studies to asses if their potential construction is worthwhile. Furthermore, it has recently been suggested to build sea-walls around melting glaciers in Greenland and Antarctica (Moore et al. 2018). Such a construction may potentially reduce the global mean SLR due to melting, but there are many uncertainties related to the

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concept (as with NEED) and there would still be some SLR due to thermal expansion. Due to technical, geographical or financial limitation, many countries will not be able to protect themselves with large enclosures, such that their coastal communities remain unprotected. Hence, limiting future SLR by taking precautions now, remains the most effective way forward.

Mitigation now, or NEED later

It is perhaps impossible to truly fathom the magnitude of the threat that global-mean SLR poses. However, by conceptualizing the scale of the solutions required to protect ourselves against global-mean SLR, we aid our ability to understand this impending danger. The example we provide here is the construction of a 637 km long Northern European Enclosure Dam (NEED) to protect 15 Northern European countries against global-mean SLR. As immense as this solution may seem, our preliminary study suggest that NEED is comparable or sometimes favoured in scale, impacts and challenges to any existing alternative solutions, therefore warranting further investigation. This realization thus illustrates the extraordinary global threat of global-mean SLR that we are facing. However, solutions such as NEED are symptomatic treatments of the effects of climate change. The best solution will always be treatment of the cause: human-caused climate change. If however climate change is left unmitigated, only solutions as impact-full as NEED, or worse, will remain. We therefore advocate for immediate action to further intensify climate mitigation efforts so that global-mean SLR can be limited and there will be no need for NEED.

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Data availability

The output data from the numerical simulations that have been used in this study have been deposited at GEOMAR and are publicly available at `https://thredds.geomar.de/thredds/kjellsson_et_al_2019_review/catalog.html`. The Gridded Population of the World (GPW), v4.10 data (CIESIN 2017) that support the findings of this study are available from `http://sedac.ciesin.columbia.edu/data/set/gpw-v4-population-density-rev10/data-download`. The 2-Minute Gridded Global Relief Data (ETOPO2v2) data (Smith and Sandwell 1997) that support the findings of this study are available from `https://www.ngdc.noaa.gov/mgg/global/etopo2.html`. The Common Ocean Reference Experiment (CORE.2) Global Air-Sea Flux Dataset (Yeager and Large 2008) that support the findings of this study are available from `https://rda.ucar.edu/datasets/ds260.2/\#!description`. TPXO9 tidal data set is available from `https://www.tpxo.net/global/tpxo9-atlas`

Code availability

The scripts used to generate figures and statistics that support this study are available at `https://git.geomar.de/joakim-kjellsson/nemo-scripts/tree/need`.

APPENDIX A

Alternative Configurations

Alternative configurations at different locations would decrease the length and depth of NEED. For example, NEED-south could be moved to be parallel to the French-English Channel Tunnel. Numerical simulations show that such a configuration would reduce the tidal amplitudes at the west coast of England compared to the configuration in Fig. 1. However, it would increase the tidal amplitudes in the English Channel and also leave many of the cities along the English channel unprotected (Fig. A1). In a similar way, NEED-north could be moved south, allowing for various possible combinations to connect the UK to Norway, possibly even via Denmark. This move mostly reduces dam-height but not length of the enclosure, while it may also amplify the tidal amplitude north of the enclosure and will reduce the number of people protected. Therefore, we think that the presented form of NEED is probably the optimal balance between financial and technical feasibility and population protection.

APPENDIX B

Freshening of the basin

Using both the CORE2 atmospheric data (Large and Yeager 2009) and ERA-Interim reanalysis (Dee et al. 2011), the net freshwater input into the enclosure is estimated to be at most 40.000 m^3 s^{-1}, of which -24 000 m^3 s^{-1} is due to evaporation E, 35.000 m^3 s^{-1} due to precipitation P and

29.000 $\mathrm{m}^3\ \mathrm{s}^{-1}$ due to river runoff R. The enclosure has an area of about $1.0 \times 10^6\ \mathrm{km}^2$ (Smith and Sandwell 1997) which, combined with the net freshwater flux $D = P + R + E$, would lead to a SLR within the basin of ~ 0.9 m year^{-1}. Therefore the 40.000 $\mathrm{m}^3\ \mathrm{s}^{-1}$ of seawater would need to be pumped out of the basin into the Atlantic Ocean. The net input of freshwater would also cause a freshening of the basin. A freshening timescale can be calculated using the equivalent salt flux (Huang 1993; Nurser and Griffies 2019) and assuming that the amount of freshwater discharge D is pumped out with a salinity S. The change in salinity of the basin is then given by $d\ S/d\ t = -DS/V$, where $V \approx 5.8 \times 10^{13}\ \mathrm{m}^3$ is the volume of the North Sea basin and English Channel combined. The solution $S(t) \sim \exp(-t\ D\ /\ V)$ can be used to infer the time it takes to reduce the salinity by a factor 10, which is $\Delta t = VD^{-1}\ \ln(0.1) \approx 106$ years.

APPENDIX C

Numerical Model Details

The ocean circulation of the European shelf is simulated using the AMM7 configuration (O'Dea et al. 2017; Graham et al. 2018) of the NEMO ocean model v3.6 (Madec et al. 2017). The AMM7 grid has a 7 km horizontal resolution with 51 vertical $z-\sigma$ levels and explicitly simulates 15 tidal components (Q1, O1, P1, S1, K1, 2n2, Mu2, N2, Nu2, M2, L2, T2, S2, K2, M4) inside the model domain, including boundary conditions from the TPXO 7.2 Global Tidal Solution (Egbert and Erofeeva 2002) and the inverse barometer effect. Lateral boundary conditions of baroclinic velocities and temperature and salinity are taken from a global simulation at $1/4°$ horizontal resolution (without tides) to the north, south and west (Graham et al. 2018). Boundary conditions of the Skagerrak basin are taken from a regional Baltic Sea simulation at $1/60°$ that resolves the Arkona basin flow. Atmospheric forcing is taken from ERA-Interim reanalysis (Dee et al. 2011). The model time step is 300s and a 10s subcycle for barotropic modes and uses a bi-Laplacian lateral viscosity of $A_{\mathrm{h,m}} = -1.25 \cdot 10^{10}$ m^4 s^{-1} and a Laplacian lateral diffusion of $A_{\mathrm{h,t}} = 125$ m^2 s^{-1}. Vertical mixing is parametrized by the GLS scheme with settings equivalent to a $k-\varepsilon$ scheme.

We perform three simulations of the year 1981, a control run (AMM7-CTRL), a run with NEED as proposed in Fig. 1 (AMM7-NEED), and a run with NEED but NEED-south placed between Dover and Calais (AMM7-TUNNEL). Amplitudes and phases for 15 tidal components in the AMM7 simulation are calculated using the built-in harmonic analysis diagnostics in NEMO. We compare and contrast the amplitudes and phases of the tidal components in our control simulation AMM7-CTRL, to the TPXO9 tidal solution which is based on a global barotropic model at $1/6^\circ$ horizontal resolution and assimilates data from various satellite altimeter sources (Egbert and Erofeeva 2002). The AMM7-CTRL simulation accurately simulates the amplitudes and phases of the major tidal components on the European shelf (Figs. C1 and C2) as previously found by other studies (O'Dea et al. 2017; Graham et al. 2018). Constructing NEED leads to distinct modifications of the major tidal components (Fig. C3).

The barotropic stream function is calculated using the 5-daily meridional velocity as

$$\Psi(x,y) = \int_0^{H(x,y)} \int_{x_W}^{x_E} v \, dx \, dz, \tag{C1}$$

where $H(x,y)$ is the bathymetry, and x_W, x_E are the western and eastern boundaries of the domain.

The velocities shown in Fig 3c are computed by taking the time mean velocity over the 5-daily output for the subsurface velocities and rotating them to be positive out of the North Sea, i.e. approximately positive westward for SED and north-westward for NED. The velocities have been interpolated from the $z-\sigma$ vertical grid used in the model to fixed depth levels using the time-mean depths of each model level.

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Fig. 1. The proposed location of the Northern European Enclosure Dam (NEED, thick black lines) superimposed on the topography (Smith and Sandwell 1997), combined with areas where the population density exceeds 200 persons km^{-2} in the year 2020 (CIESIN 2017) (pink dots). We use the combination of this data to provide the number of people within the enclosure that will be submerged for a certain amount of sea level rise (inset). NEED-south runs from France (Ploudalmézeau, $\sim$ 25 km north from Brest) to England (The Lizard Heritage Coast, $\sim$ 100 km west from Plymouth) and measures 161 km in length and has an average ocean depth of about 85 m and a maximum depth of 102 m. NEED-north runs from northern Scotland (John o' Groats, $\sim$ 200 km north of Aberdeen), via the Orkney Islands to the Isle of Noss (part of the Shetlands Islands) from where it crosses the North Sea to Bergen in Norway. Making use of the islands, the part from Scotland to the Isle of Noss is only 145 km length and averages 49 m depth. The crossing from the Isle of Noss to Norway measures 331 km length and has an average depth of 161 m, with a maximum depth of 321 m in the Norwegian Trench. The construction of NEED would protect coastal communities of 15 countries, namely Belgium, Denmark, England, Estonia, Finland, France, Germany, Latvia, Lithuania, Poland, Netherlands, Norway, Russia, Scotland, Sweden. This includes capital cities of Amsterdam, Copenhagen, Edinburgh, Helsinki, London, Oslo, Riga, Stockholm and Tallin, and major cities such as Bremen, Hamburg, Rotterdam, St. Petersburg and The Hague. 32

Fig. 2. Shown here are aerial views of the the Saemangeum Seawall in South Korea (Source: https://structurae.net/en/photos/252428-saemangeum-seawall) and the Afsluitdijk in the Netherlands (Source: https://beeldbank.rws.nl), which are both over 30 km long. 33

Fig. 3. The circulation and Sea Surface Height (SSH) for a scenario without and with NEED constructed (Panel A and B, respectively). The SSH is assessed by taking the 95th percentile of the hourly SSH output from the numerical model run and given by the blue colors (Appendix C). Orange contours show the 0.2, 2, and 20 Sv contours of the barotropic stream function (1 Sv = 10^6 m^3 s^{-1}). Solid contours indicate anti-clockwise flow. Panel C shows the bathymetry of the cross section traversed by NEED, split into its southern and norther components. Superimposed is the mean velocity as computed by the numerical simulation (described in Appendix C). Note that tidal velocities are averaged out, but could locally reach values over 1 m s^{-1}. 34

Fig. 4. Various other regions in which Mega-Enclosures such as NEED could serve as a solution to regional sea level rise. These are the Irish and Mediterranean Sea (A), Red Sea (B), Japanese Sea (C) and Persian Gulf (D). 35

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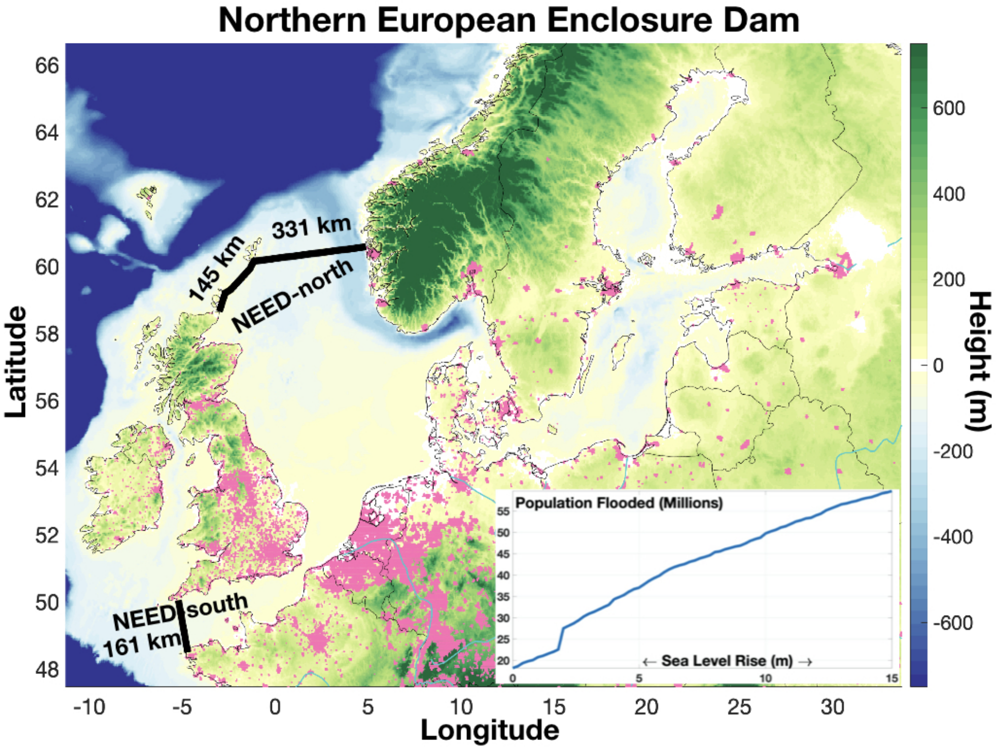

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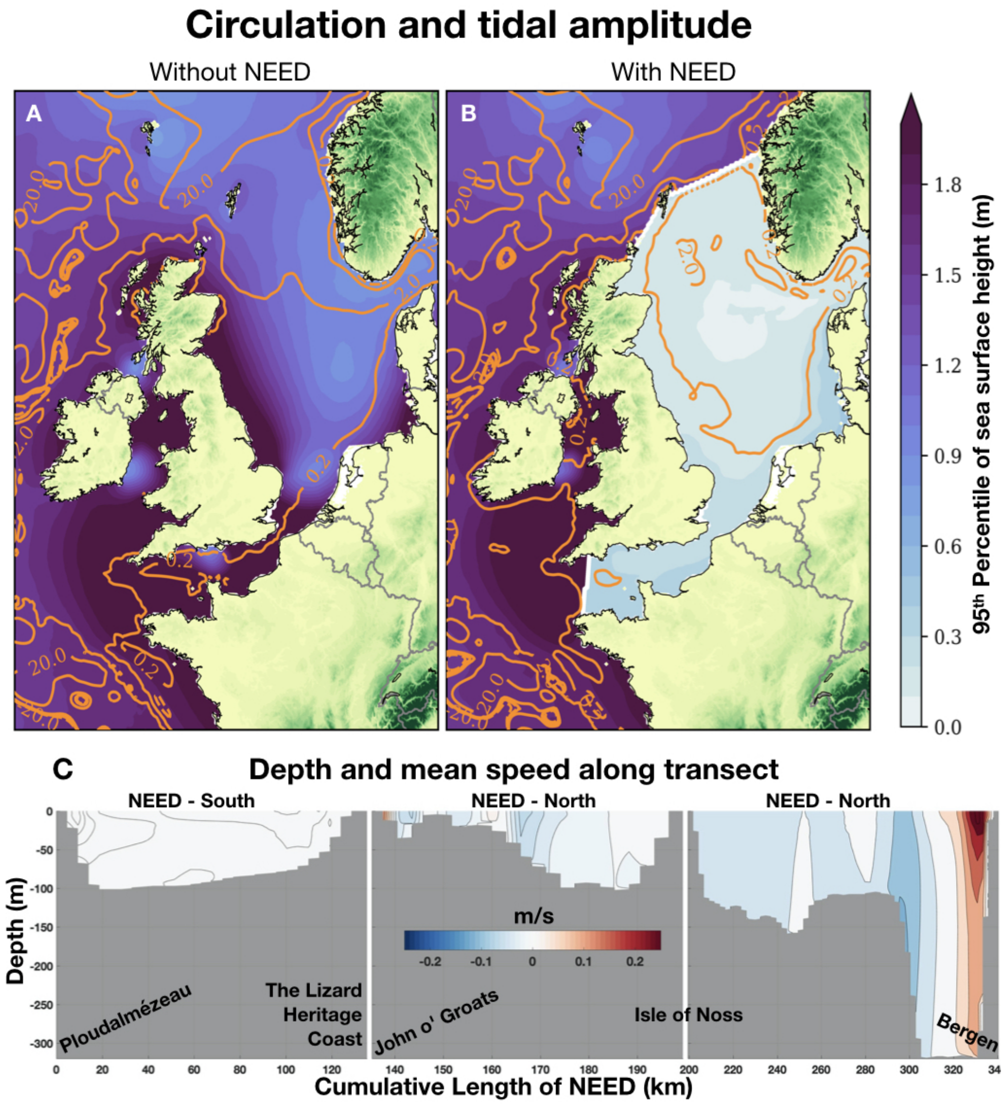

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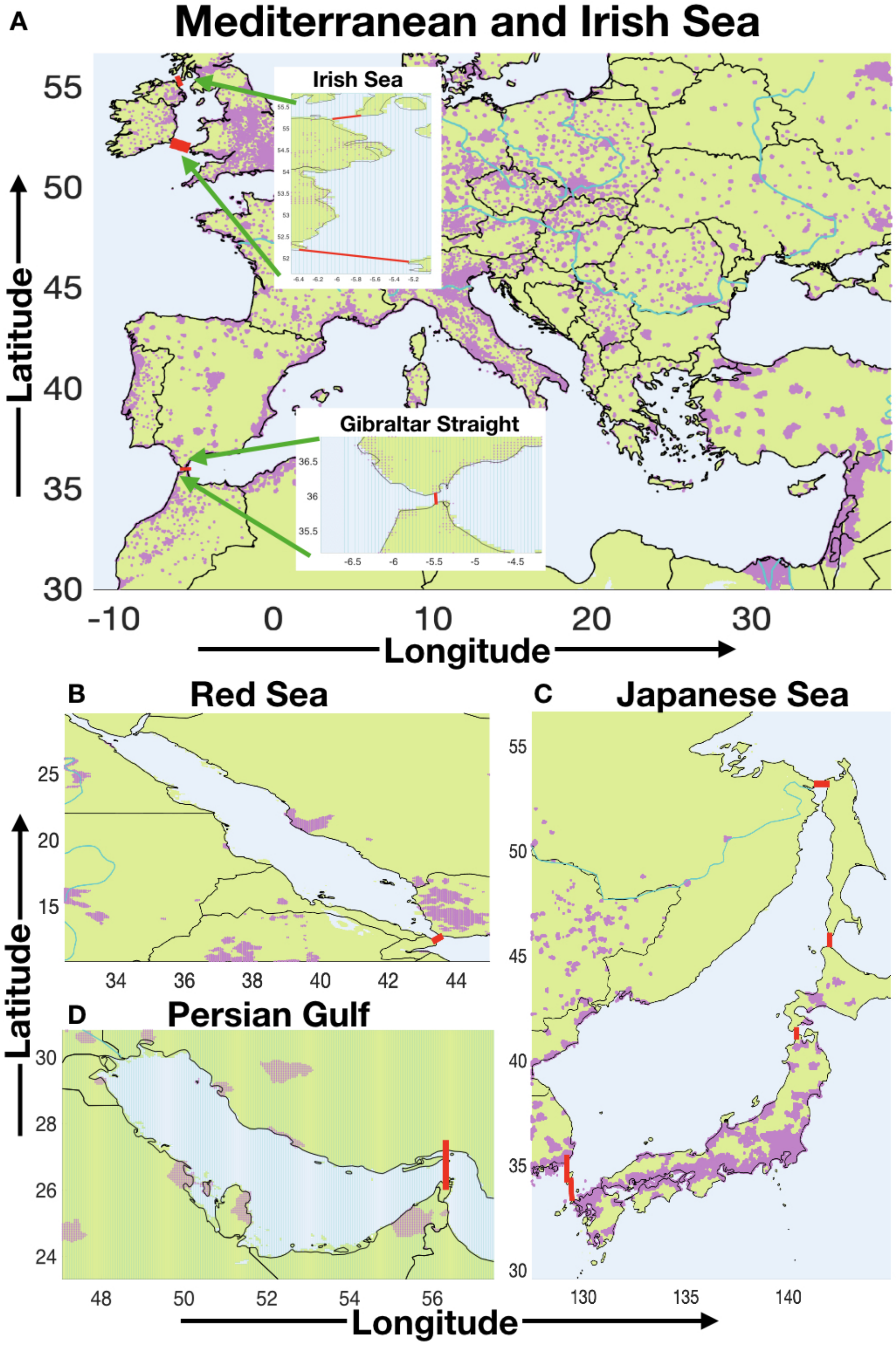

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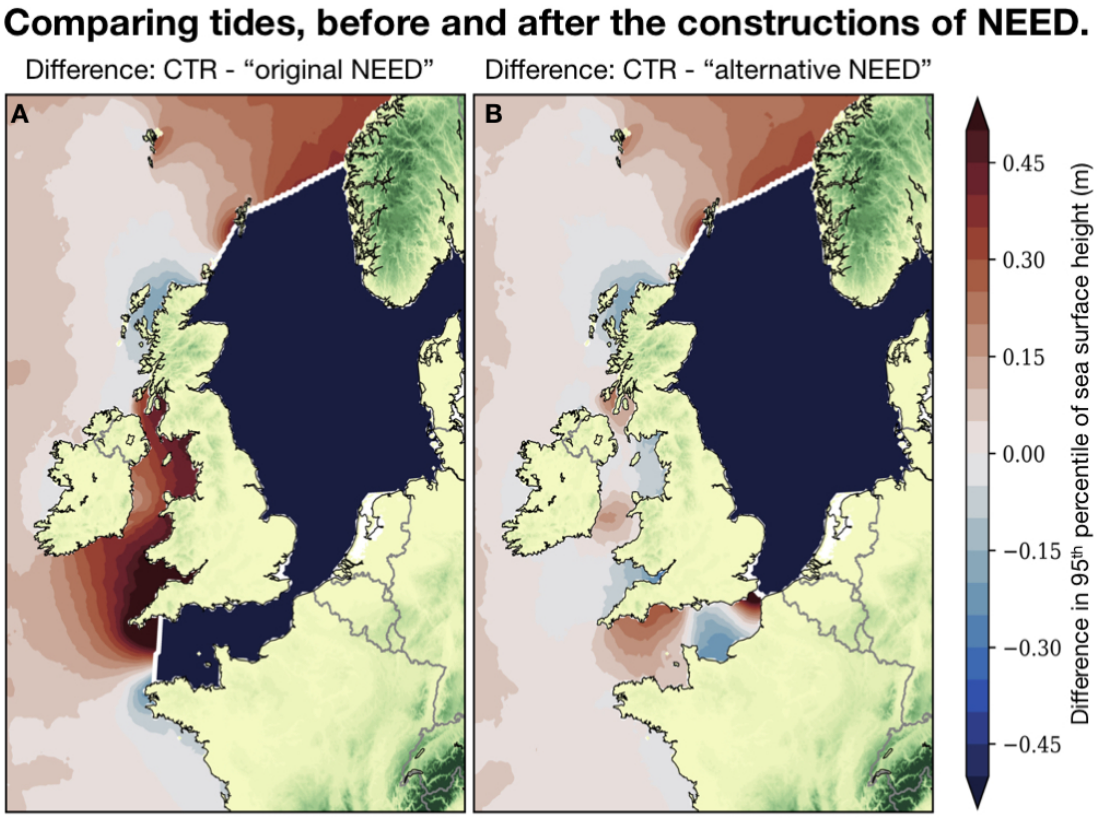


Fig. A1. The difference in 95th percentile of hourly Sea Surface Height (SSH) output in model runs with and without NEED. The difference between normal circumstances and the "original" version of NEED (as Fig. 1) shows a strong increase in the 95th percentile SSH along the Western UK (left panel). The difference between normal circumstances and the "alternative" version of NEED (with NEED-south along the Channel Tunnel) shows a strong increase in the 95th percentile SSH along the French-English channel, and less so along the Western UK (right panel).

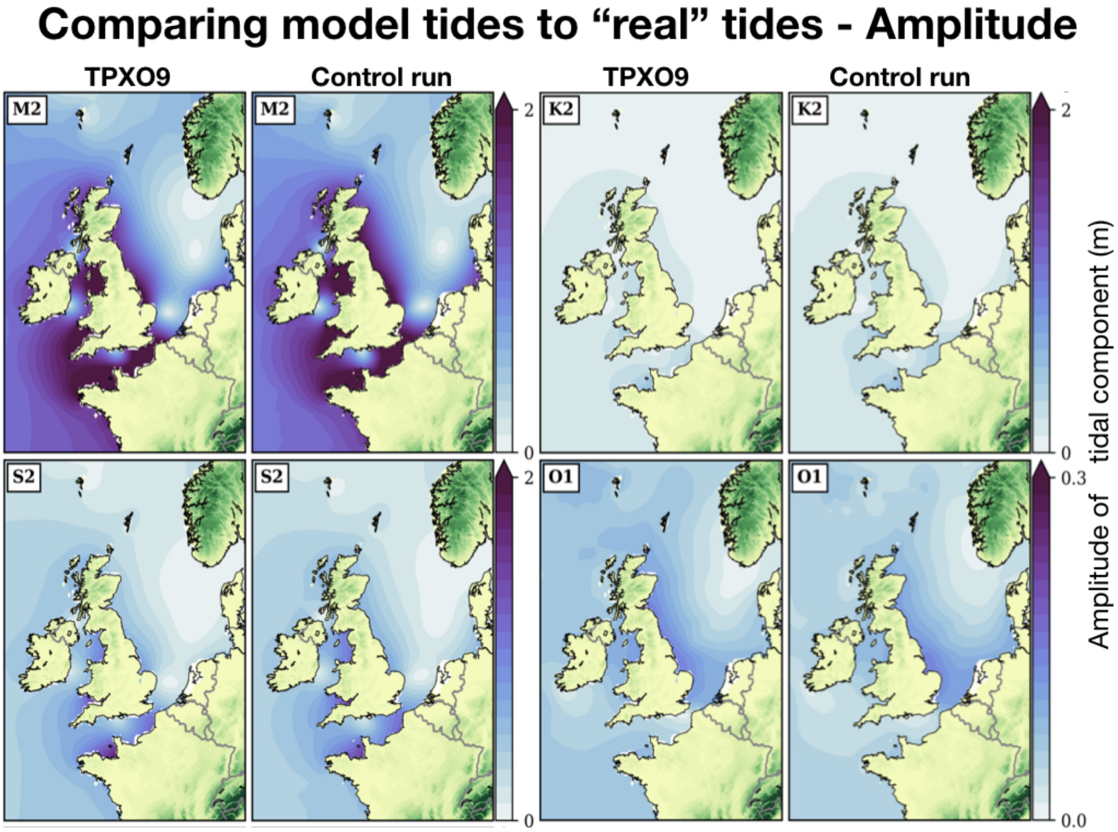


Fig. C1. Amplitudes of the major tidal components in TPXO9 tidal analysis and the AMM7-CTRL simulation.

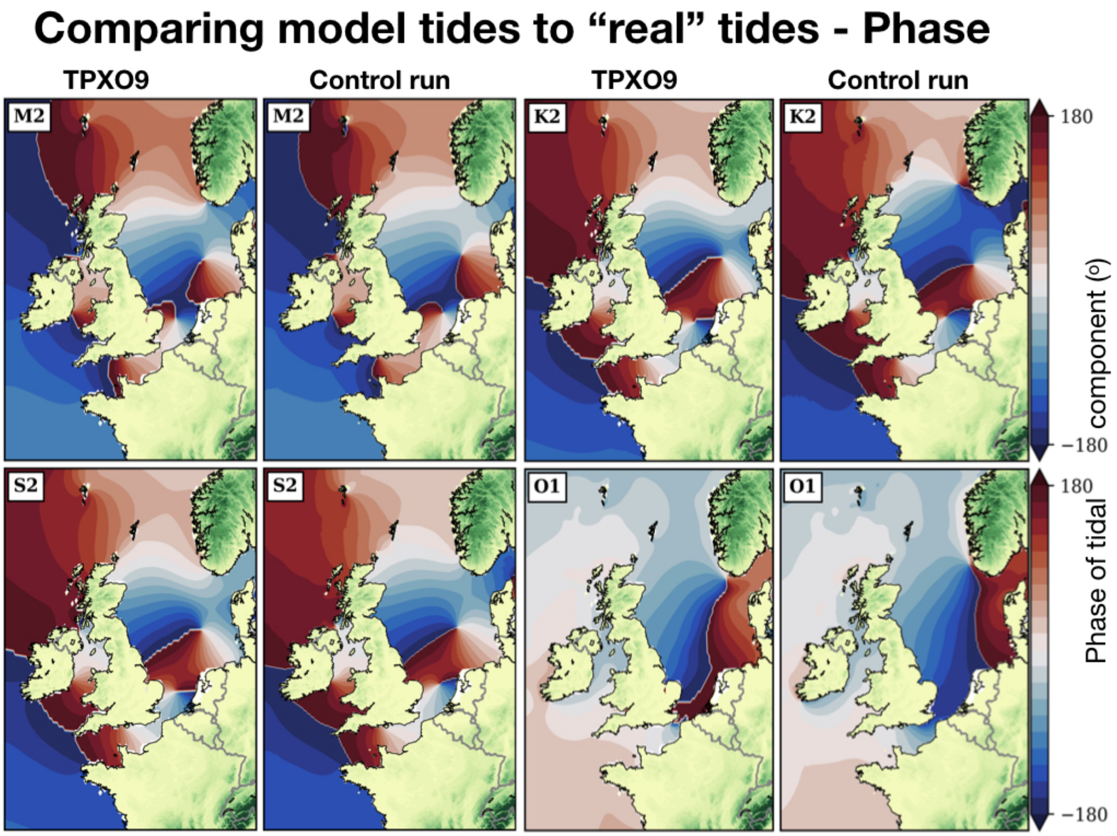
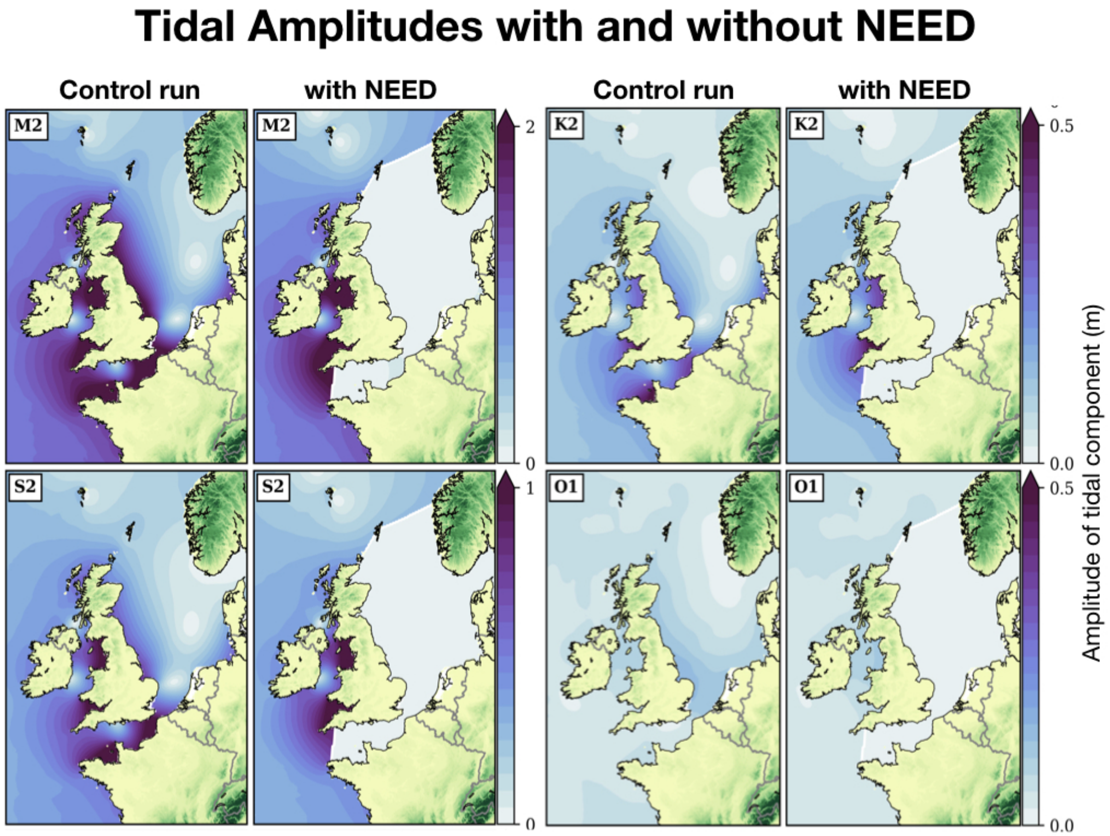


Fig. C2. Phases of the major tidal components in TPXO9 tidal analysis and the AMM7-CTRL simulation.



696 Fig. C3. Amplitudes for the major tidal components in AMM7-NEED (with NEED constructed) and
697 AMM7-CTRL (control run). Note the slight increase in tidal amplitudes of M2 and S2 along the west coast of
698 England and Wales.