EU grant
No. 773421

Representing Arctic Coastal Erosion in the Max Planck Institute Earth System Model

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05 May 2020, 10:45h–12:30h
CR4.2 Permafrost: Open Session

Max-Planck-Institut für Meteorologie

International Max Planck Research School on Earth System Modelling

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Arctic coastal erosion in Earth system models

Can we quantify how Arctic coastal erosion will evolve with the future climate, and its role in the Arctic carbon cycle?

The ice-rich sedimentary Arctic coast suffers direct impacts from climate change. Increasing air temperatures and decreasing sea-ice cover cause permafrost to thaw and the open-water season to extend. Consequently, increasing the vulnerability of Arctic coasts to erosion. In turn, Arctic coastal erosion releases substantial amounts of carbon to the ocean and atmosphere (Tanski et al. 2019), potentially contributing to further warming in a positive feedabck loop. The Arctic coasts are retreating at 0.5 m/year (Lantuit et al. 2012) and releasing about 14 Tg of particulate organic carbon per year (Wegner et al. 2015), on average, at the present climate. In the future, these rates are likely to increase – to which extent remains unknown.

Earth System Models (ESMs) have not yet considered the important role that Arctic coastal erosion plays in the carbon cycle. Here, we present the ongoing development of a semi-empirical Arctic coastal erosion model and its coupling with the Max Planck Institute Earth System Model (MPI-ESM).

Northeast coast at Muostakh Island, Laptev Sea, where ground ice is estimated at 87% volume (Günther et al. 2015). The mean organic carbon content at the Laptev Sea coast is estimated at 1.63 % weight (Wegner et al. 2015).

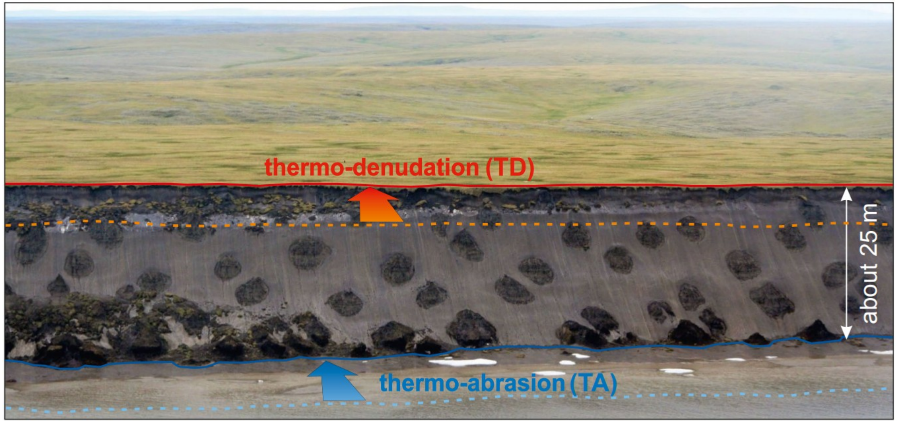
Physical drivers

The rates of coastal erosion are represented as a combination of thermal and mechanical drivers

The erosion of unconsolidated Arctic coasts can be represented as a combination of two processes:

- **Thermo-denudation (TD):** the thermal component, associated with the thawing of the sediment and ground-ice melt;
- **Thermo-abrasion (TA):** the mechanical component, associated with the abrasion of the coastal cliffs by the action of ocean waves, in combination with the thawing of sub-sea permafrost.

These terms were first coined by Aré (1988), and are now often used to describe the retreat rates by aerial thawing of cliff tops (TD), and the retreat rates at cliff bottoms by the opening of notches and the subsequent removal of the eroded blocks and thawed sediment by ocean waves (TA) (e.g. Günther et al. 2013, 2015).



Aerial photo of an ice-complex deposit at the western Laptev Sea coast. **Figure from Günther et al. (2013)** https://doi.org/10.5194/bg-10-4297-2013

The **duration of the open-water season (OWS)** has been pointed first-order driver for coastal erosion (Banhart et al. 2014). Indeed, Nielsen et al. (2020) showed that the first mode of interannual coastal erosion variability at the Southern Laptev sea responds to low-frequency changes in OWS duration, modulated by sea ice. While TA is limited by the presence of sea ice, TD may take place before the coastal margin is ice-free, as soon as surface air reaches above-freezing temperatures.

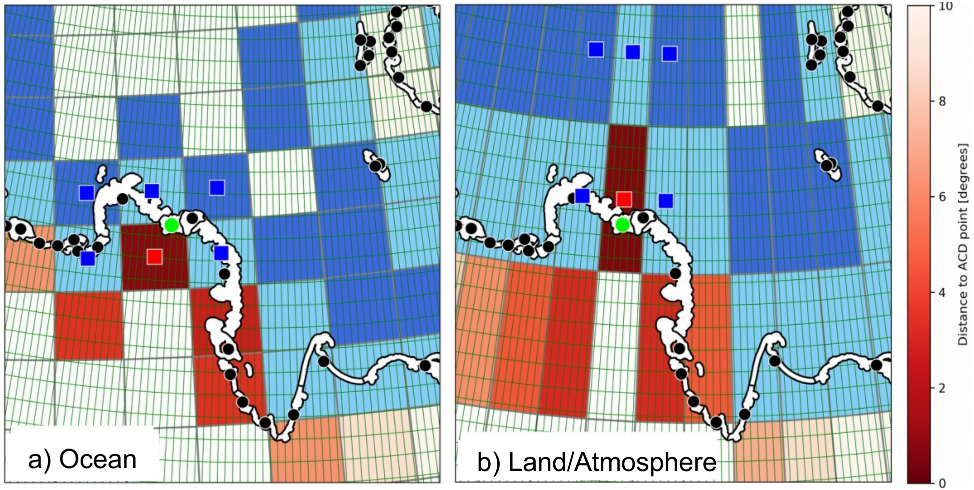
Data

We use ERA5 reanalysis, remapped to the MPI-ESM grid, to adjust our erosion model. Each coastal segment is attributed to the closest land coastal grid cell in MPI-ESM

From **ERA5 Reanalysis,** we use annual sums of positive surface air temperatures *T*, and annual sums of significant wave heights squared H_S^2, as a proxy for wave energy, to represent the thermal and the mechanical terms, respectively.

From the **Arctic Coastal Dynamics (ACD) database** (Lantuit et al. 2012), we take **long-term coastal erosion mean rates** estimates, ground-ice and organic carbon content, distances to isobaths and cliff height information. These data are provided for 1314 coastal segments, comprehending an extensive portion of the Arctic coast. From this total, 319 coastal segments are classified as erosive and unlithified.

Each coastal segment is attributed to land and ocean grid cells in the components of **Max Plank Institute Earth System Model (MPI-ESM) version 1.2** (Giorgetta et al. 2013). ERA5 data are remapped to the MPI-ESM grid.



Example of data harmonization. The ACD coastal segment (mouth of Tumatskaya channel, Lena Delta, green marker) is attributed to the closest land coastal grid cell (red marker) and to the surrounding ocean coastal grid cells (blue markers) in the MPI-ESM components. In this configuration, MPIOM **(a)** has 1.5^0 mean horizontal resolution. ECHAM and JSBACH **(b)** have and 1.875^0 mean horizontal resolution. The ERA5 grid has about 0.28^0 resolution and is overlaid in green lines. Black circles show coastal segments centers, to which distances are calculated.

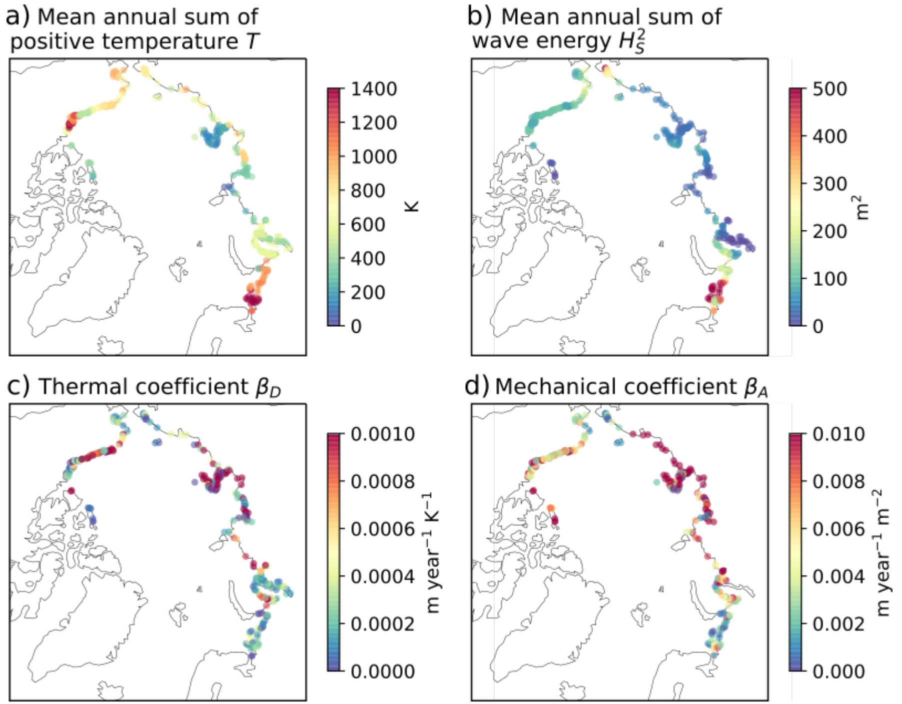
Coastal Erosion Model

Erosion rates are calculated as a simple linear combination of the thermal and mechanical components at each coastal segment

A simple coastal erosion model is given by:

$$E(t) = \beta_D T(t) + \beta_A H_S^2(t)$$

Where β_D and β_A are coefficients that scale the annual sums of thawing temperatures and wave energy into coastal erosion rates. The scaling coefficients are functions of the ground-ice content and local long-term means of the two drivers, and are therefore specific for each coastal segment. Most of the spatial variability in the scaling coefficients is explained by the large variability in the mean drivers. Locally, the differences also account for geomorphologial characteristics, such as orientation of the shoreline, cliff height and bathymetric profile, which make neighboring coastal segments respond differently to similar environmental conditions.



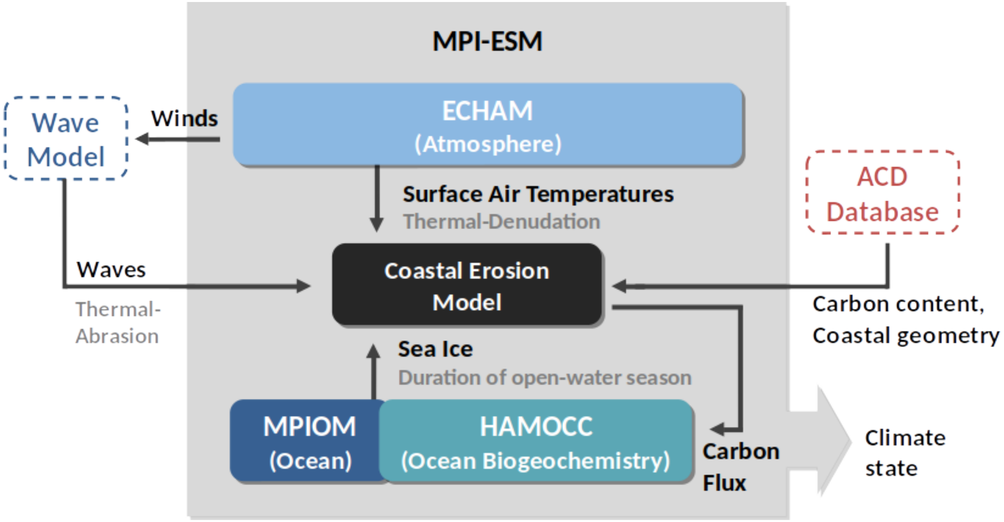
Mean thermal (a) and mechanical (b) drivers from ERA5 at each erosive and unlithified ACD coastal segments, and associated thermal (c) and mechanical (d) coefficients to reproduce the long-term coastal erosion mean estimations.

Coupling with the MPI-ESM

Coastal erosion rates and associated organic carbon fluxes are calculated within the MPI-ESM, allowing transformations into oceanic and atmospheric CO_2

Annual coastal erosion rates are calculated for each coastal segment, given MPI-ESM simulation outputs. From the calculated coastal erosion rates, organic carbon (OC) fluxes are calculated, given the coastal segment geometry and OC content data from the ACD database. This approach allows us to estimate historical and future climate OC fluxes due to coastal erosion.

The annual OC fluxes are then given to the MPI-ESM as particulate organic matter at the coastal ocean shelves during the simulations, which may be converted into CO_2 and interact with the other model components. This step will allow us to assess the role of coastal erosion on changing ocean biogeochemical properties, on atmospheric CO_2 concentration, and its climatic impact.



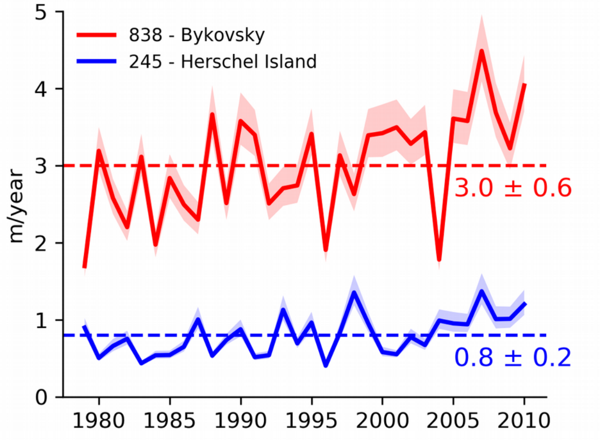
Schematic representation of the exchange of variables between different models and within the MPI-ESM.

Conclusion

We can estimate future scenarios of Arctic coastal erosion and its role in the climate system by applying a simple coastal erosion model, compatible with the scale and resolution of ESMs

A model for Arctic coastal erosion is developed to reproduce the long-term coastal erosion mean rates available at a circum-Arctic scale. The model assumes that erosion is explained by a simple linear combination of the thermo-denudation and thermo-abrasion components, which are represented by annual sums of positive air surface temperatures and wave heights. The coastal erosion model translates the spatial and temporal variability of its main drivers into annual time series of coastal erosion rates. However, calculated erosion rates at individual years should not be compared with annual observations. Our approach is intended to capture changes in long-term means of the coastal erosion drivers.

The physical representation of Arctic coastal erosion is not compatible with the relatively coarse resolution of ESMs. However, most of the variability of coastal erosion rates measured at the southern Laptev Sea, for example, can be explained by large-scale mechanisms, normally well-captured in modern ESMs (Nielsen et al. 2020). **Our approach allows us to bridge changes in long-term coastal erosion mean rates with long-term changes in Arctic surface air temperatures and wave heights, which directly respond to climate change.** In a next step, organic carbon fluxes due to coastal erosion will be considered in historical and future climate simulations.



Examples of modelled time series of coastal erosion rates for two key coastal segments (full lines), calculated from ERA5 data. The time series reproduce the long-term mean rates from the ACD database (dashed lines).

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