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Climate tipping point interactions and cascades: a review

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Possible example of nonlinear climate component interactions: Arctic sea ice loss leading to coastal permafrost erosion

In this section, we discuss a recent example of a potential tipping cascade between parts of tipping elements, where the decline of Arctic sea ice deteriorates coastal permafrost through increased erosion. As even regional tipping elements can have substantial spatial extent it is possible that only a part of a tipping element or nonlinearly behaving region is affected. Here we discuss an example of such nonlinear climate component interaction, namely the impact of accelerating Arctic sea ice loss on coastal erosion in Siberian and North American permafrost regions.

Relic carbon-rich coastal shelf ice in Siberia and Alaska is exposed to the ocean and atmosphere (Irrgang et al., 2022). Currently, Arctic coastal erosion rates are of 4 m a^{-1}, peaking at 25-50 m a^{-1}, an order of magnitude higher than elsewhere in the world (Philipp et al., 2022). The shortened sea ice season exposes the ocean to winds and increases ocean wave fetch, leading to higher ocean waves that accelerate erosion levels (Nielsen et al., 2022; Meucci et al., 2023; Hošeková et al., 2021; Casas-Prat and Wang, 2020). The Siberian and Alaskan coasts transition to a higher erosion state, with a total retreat of 500-1000 m since the 1950s, and an accelerated retreat since the mid 2000's (Fig. 5) (Grigoriev, 2019).

The shelf primary production sustains about a third of Arctic production; coastal erosion provides the majority of nitrogen and phosphorus and a third of carbon (Terhaar et al., 2021). These fluxes can be much higher in the future, changing marine food-webs. Summer sea ice disappearance increases seasonal bloom and nutrient depletion in the ocean, nutrient inputs from rivers and coastal erosion alleviate the nutrient limitation (Oziel et al., 2022). The erosion is a risk to infrastructure, settlements and economy (Clare et al., 2022). The impact of erosion on ecosystems is medium to high with the medium to high uncertainty.

Change in sea ice is gradual (Notz, D. and SIMIP Community, 2020), however, storms can abruptly change sea ice on the shelves (Lukovich et al., 2021), leading to high waves and a destabilization of parts of the permafrost coast (Casas-Prat and Wang, 2020). The impact of coastal erosion on ecosystems is irreversible, as are socioeconomic impacts (Fritz et al., 2017). Furthermore, coastline collapse and permafrost degradation can release large amounts of carbon to the ocean and atmosphere (Vonk et al., 2012; Tarnocai et al., 2009).

In summary, this cascade operates as follows: (1) abrupt changes (a tipping point) in summer-autumn sea ice retreat from the coast leads to (2) increase in the waves, resulting in (3) abrupt increases in erosion rates (2-4 times higher) due to a wave undercut mechanism. Thus, (4) there is a cascading risk of large carbon releases to the Arctic ocean and atmosphere due to the coastal collapse. At the same time, Arctic coastal ecosystems would be impacted through increased nutrients and other terrigenous matter fluxes as well as local communities and economies (fisheries and infrastructure collapse) (Irrgang et al., 2022; Nielsen et al., 2022).

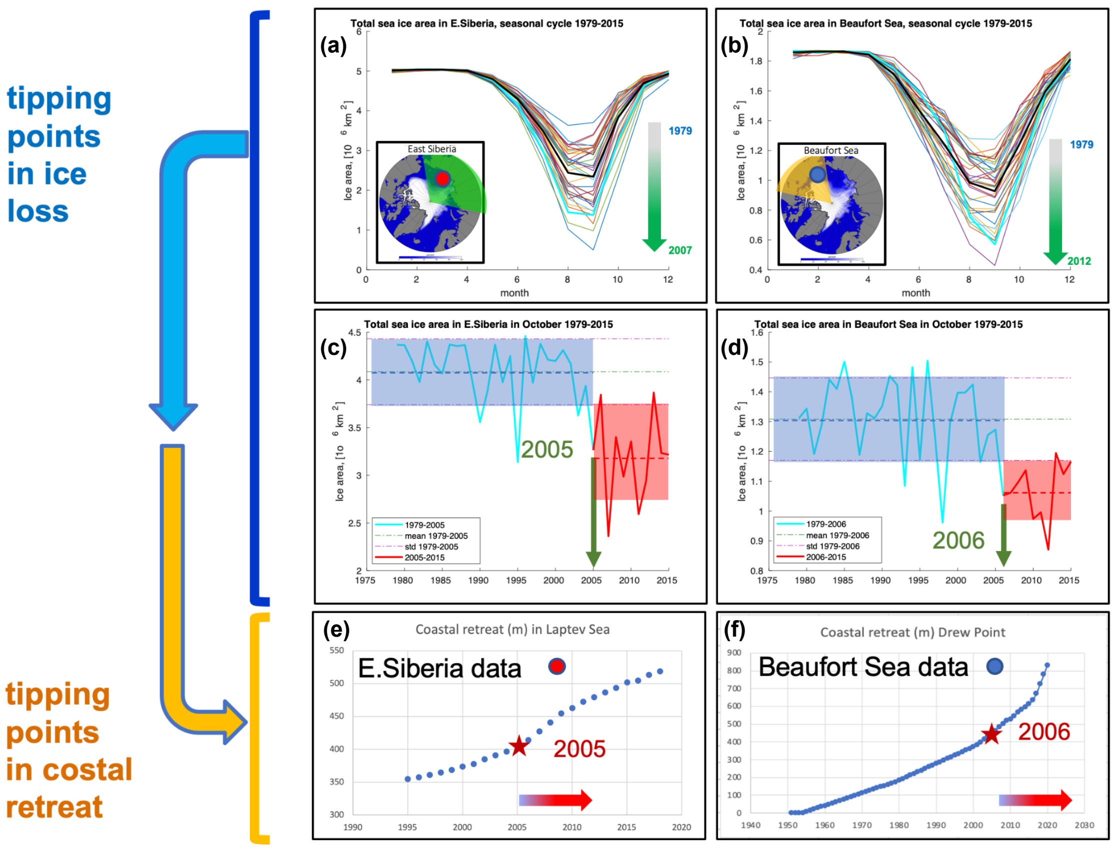

Figure S 1. Cascade between different elements of the Arctic climate system: sea ice and coastal permafrost erosion. (a,b) Sea ice area seasonal cycle for the 1979-2015 in Siberia and Beaufort Sea. (c,d) Time series of the October sea ice area with a tipping point, defined through changes in the mean, standard deviation and linear trends; the two ice states are marked by the cyan and red lines. (e,f) Coastal retreat in these regions. Stars show potential tipping points. The mechanism of transition, linking the sea ice retreat to the increased waves and accelerated coastal erosion, suggests a cascade, acting from the abrupt changes in the ocean and cryosphere to the changes of state in the coastal retreat and ecosystem.

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