Impact of the sea ice friction on ocean tides in the Arctic Ocean: modelling insights at various time and space scales

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Introduction

The ocean tides are one of the major contributors to the energy dissipation in the Arctic Ocean. In particular, barotropic tides are very sensitive to friction processes, and thus to the presence of sea ice in the Polar regions. However, the interaction between the tides and the ice cover (both sea ice and grounded ice) is poorly known and still not well modelled, although the friction between the ice and the water due to the tide motions is an important source of energy dissipation and has a direct impact on the ice melting. The variations of tidal elevation due to the seasonal sea-ice cover friction can reach several centimeters in semi-enclosed basins and on the Siberian continental shelf. These interactions are often simply ignored in tidal models, or considered through relatively simple combinations with the bottom friction.

In the frame of the Arktalas project funded by the European Space Agency, we have investigated this aspect through a sensitivity analysis of a regional pan-Arctic ocean tide hydrodynamic model to the friction under the sea ice cover, in order to generate more realistic simulations. Different periods of time, at the decadal scale, were considered to analyze the impact of the long-term reduction of the sea ice cover on the ocean tides in the region, and at global scale. Tide gauge and satellite altimetry observations were specifically processed to retrieve the tidal harmonic constituents over different periods and different sea ice conditions, to assess the model simulations.

Improving the knowledge on the interaction between the tides and the sea ice cover, and thus the performance of the tidal models in the Polar regions, is of particular interest to improve the satellite altimetry observation retrievals at high latitudes, as the tidal signals remain a major contributor to the error budget of the satellite altimetry observations in the Arctic Ocean, but also to generate more realistic simulations with ocean circulation models, and thus contribute to scientific investigations on the changes in the Arctic Ocean.

Tidal modelling setup

Tidal modelling strategy based on the TUGO-m hydrodynamic model, previously used for the development of global models such as FES2014 (Lyard et al., 2021) and regional tidal models (Cancet et al., 2018).

- High-resolution unstructured mesh grid
- Careful definition of the model extent and inputs (bathymetry, coastline)
- Regional/local tuning of the model parameters (bottom friction mainly)
- Under-sea-ice friction – exploration of several approaches:
  - Multiplying factor of the bottom friction value in polygons or in a map defining the sea ice extent
  - Friction proportional to the sea ice concentration, considering or not the distance to the coast as a confinement index (fast ice close to the coast, moving ice in the open ocean)

Validation datasets

Tide gauge tidal harmonic constituents (amplitude and phase lag):

- Computed from time series over different periods (from the 1940s to the 2020s), depending on availability in GESLAv3 (Haigh et al., 2021) and UHSLC (Caldwell et al., 2015) databases
- Directly extracted from databases and publications (time series not available at high frequency)

CryoSat-2 tidal harmonic constituents computed:

- From ESA GOP Baseline C products (LRM, SAR and SARin modes)
- In bins of 1° x 1°
- Over 2010-2020

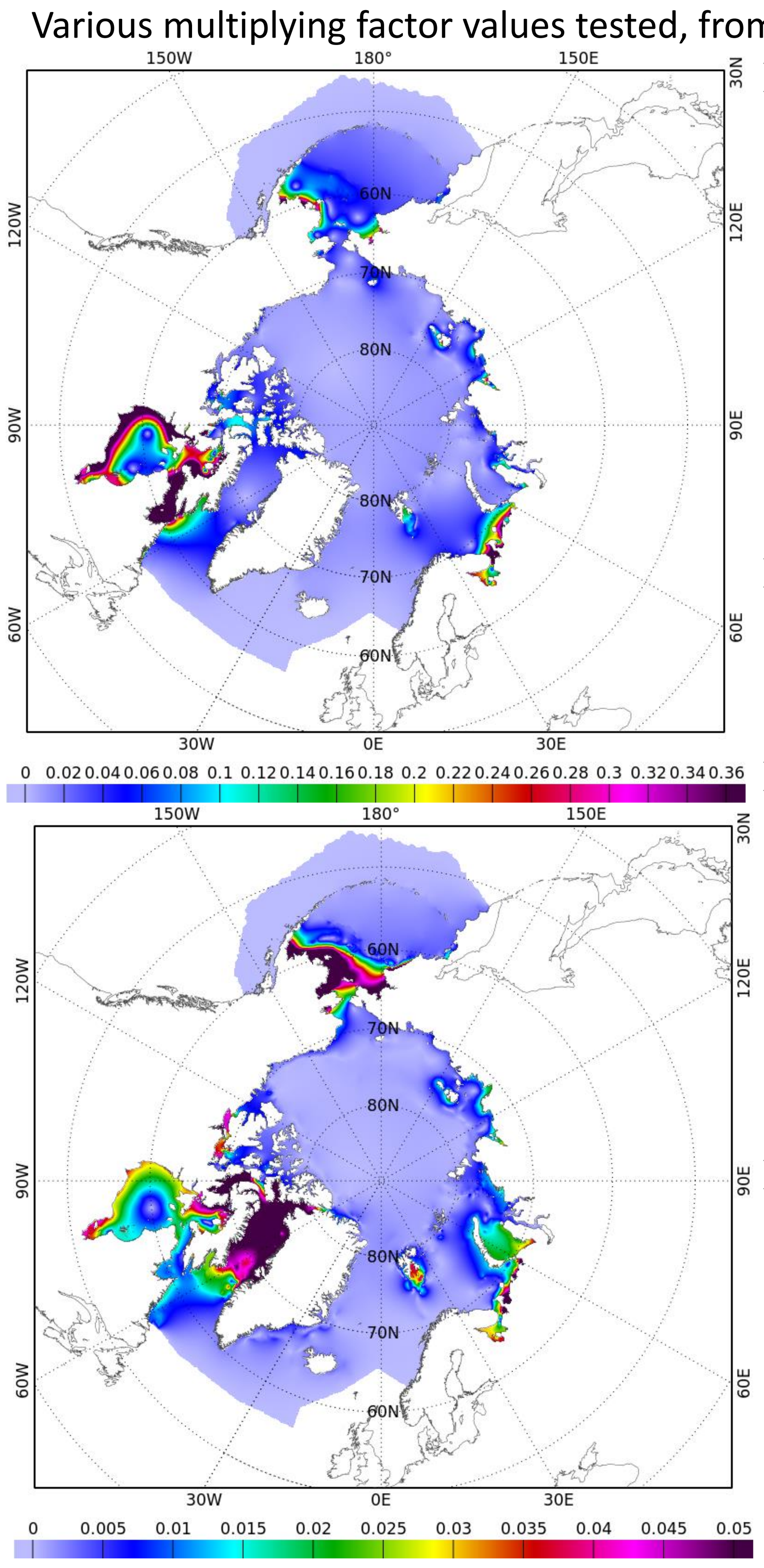
Exploration of the sea ice friction impact on tides

Multiplying factor of the bottom friction value in a polygon

Assumption: the friction is of the same type at the bottom and at the top of the water column, under the ice.

Sea ice polygons: median sea ice extent for the months of March (Winter configuration) and September (Summer configuration) computed over the period 1981-2010 (NSIDC product)

Various multiplying factor values tested, from 2 to 5.



- **Strong seasonal variability of main tidal components, linked to the sea ice cover** (tens of cm for M2), in the Hudson Bay and Canadian Archipelago, in the Baffin Bay (K1 mainly), in the Barents Sea, along the Siberian coasts and in the Bering Strait (Fig. 1).
- **Amplification of the tides in Summer**, due to less friction dissipation as the sea ice extent is smaller.
- Similar features obtained whatever the multiplying factor values, with **stronger sensitivity of the model to the friction increase in Winter** than in Summer (expected, due to more sea ice in Winter).
- **Basic approach** providing a first estimate of the Arctic Ocean tides sensitivity to the presence of sea ice. Does not consider any specificities of the sea ice (concentration, thickness, type, bottom roughness…)

Fig. 1: Vector differences (m) between the tidal simulations for Summer and Winter sea ice configurations, with a bottom friction multiplying factor of 4. Upper plot: M2 tidal component. Bottom plot: K1 tidal component.

Long-term seasonal impact of sea ice concentration

Assumption: Dissociation of the ocean floor friction and the sea ice friction in the model, now proportional to the sea ice concentration. If the sea ice is dense to a certain point, it can be considered fixed, and thus induces friction, contrary to less dense ice that moves with the tides (threshold on sea ice concentration).

Sea ice concentration:

- Seasonal maps computed from NSIDC monthly sea ice concentration maps, for each year of the period 1980-2020.
- Threshold on sea ice concentration arbitrarily set to 0.7.

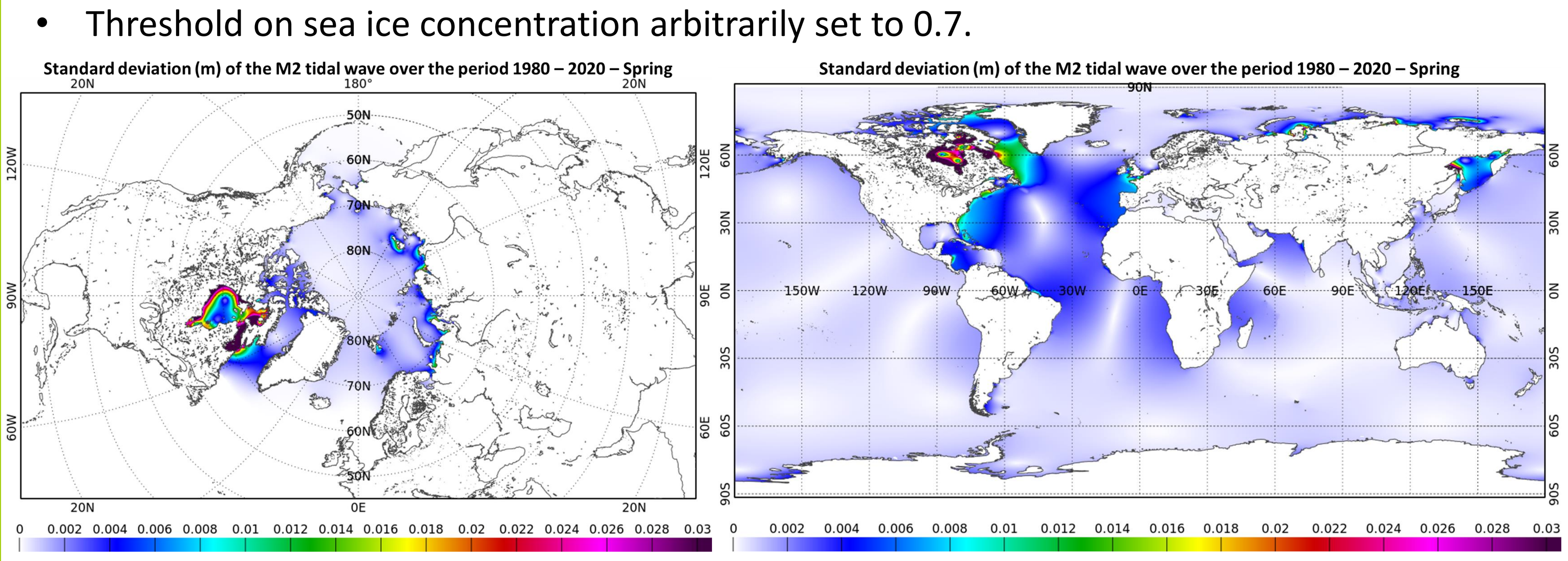


Fig. 2: Standard deviation (m) of M2 tidal simulations over the period 1980-2020, with sea ice friction based on Spring seasonal sea ice concentration maps. Regional Arctic model (left) and global model (right).

- Largest long-term variability observed in Spring, lowest in Summer.
- Several centimeters of variability on M2 in particular in the Hudson Bay.
- Long-distance connections at global scale.

Evaluation of the seasonal variations of the tides in tide gauge observations and model simulations:

Tide gauge data processing

- Long time series (1980-2020) of GESLAv3 and UHSLC hourly data (quite rare)
- Located in areas where model shows long-term variability (even more rare)
  - ➔ 10 stations, some with gaps, some measuring very local dynamics (e.g. Churchill station, see Ray, 2016)
- Time series split in 3-month subsets, harmonic analysis to obtain seasonal tides

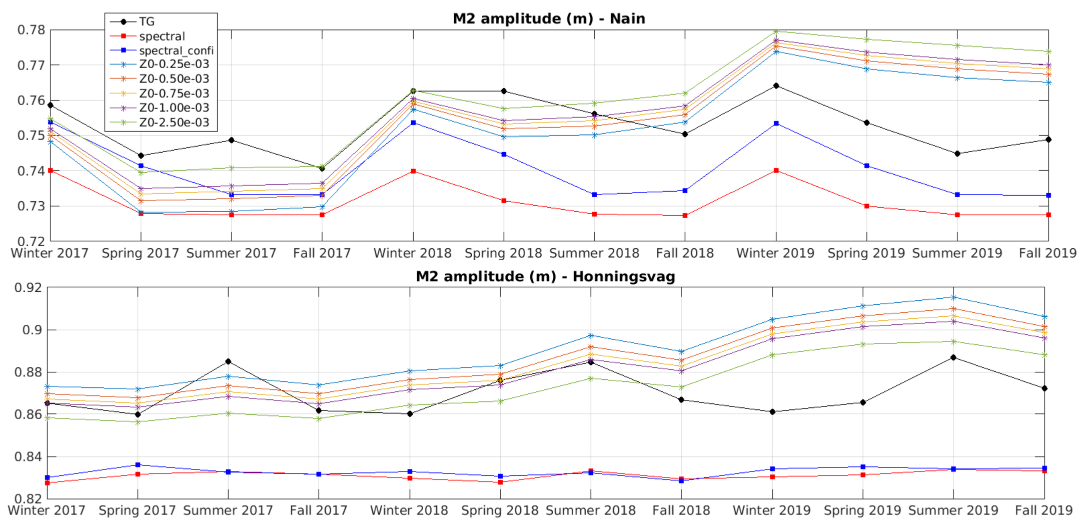


Fig. 3: Seasonal M2 amplitude (m) at the Nain (top) and Honningsvåg (bottom) tide gauges (in black), and from model simulations (in colors) using various under-sea-ice friction configurations, for the period 2017-2019.

- The tidal seasonal variations are well represented by the model at some stations, not so well at others. Further analyses underway.

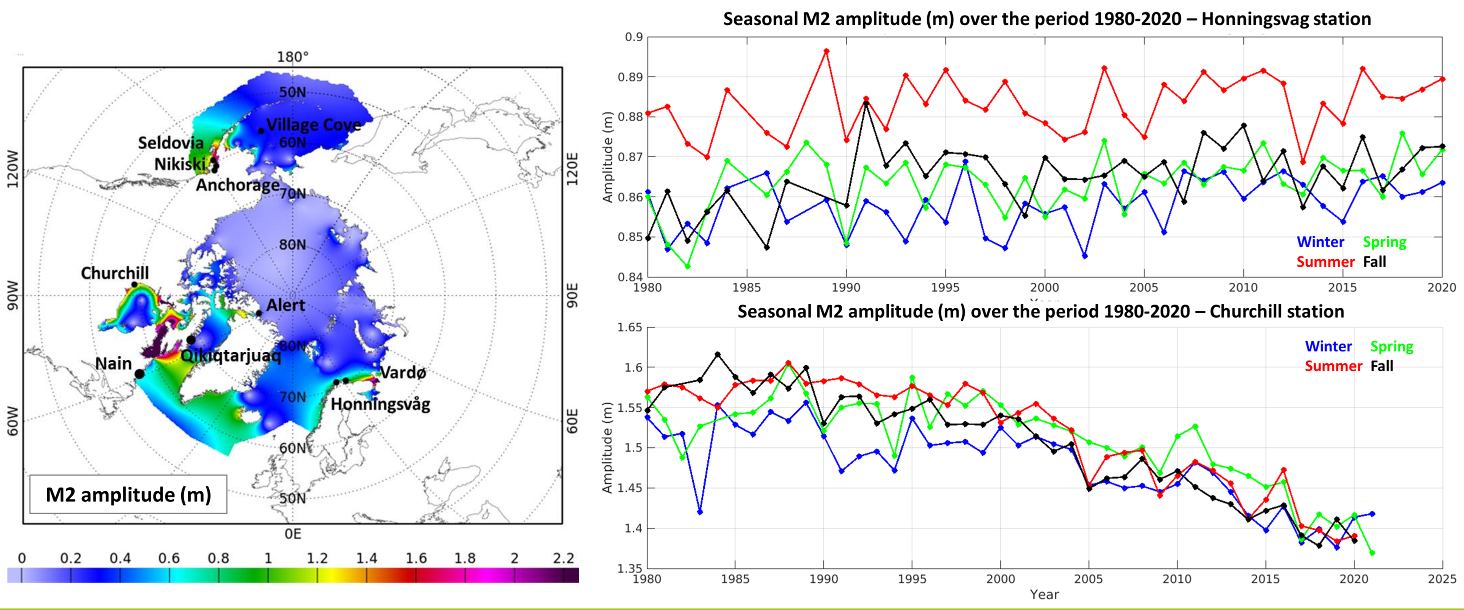


Fig. 4: Seasonal amplitude (m) of M2 over the period 1980-2020 at the Honninsvåg and Churchill tide gauge stations.

CONCLUSIONS AND PERSPECTIVES

- Clear impact of the sea ice friction highlighted in the tidal model simulations, with strong seasonal variability in semi-enclosed basins like the Hudson Bay and on the Siberian continental shelf.
- Very little information about the sea ice bottom roughness, which implies strong and rather basic assumptions to define the related friction in the hydrodynamic model. Further work is underway.
- The scarcity of long time series of high-frequency tide gauge observations (with variable accuracy) makes it difficult to estimate long-term seasonal tidal variations in the Arctic Ocean, with many questions arising from the data. CryoSat-2 satellite altimetry data provide invaluable tidal information, but only as an average of the 2010-2020 period, to be continued with the CRISTAL mission.

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