Danish Meteorological Institute
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DMI Report 25-07

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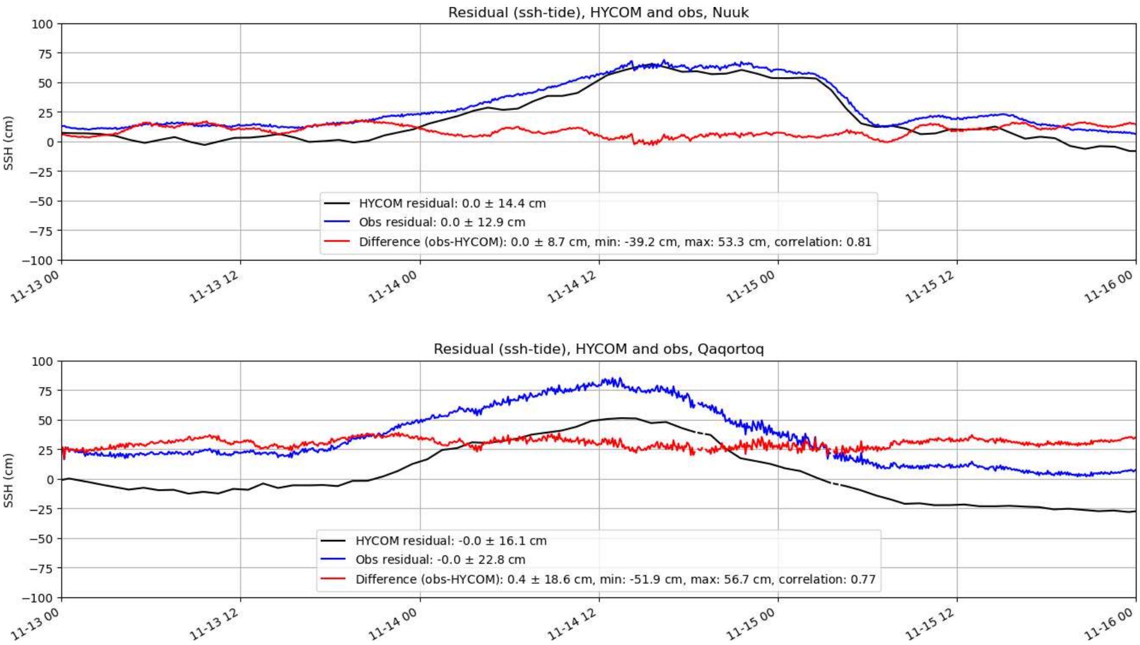
Mia Nørholm and Mads Hvid Ribergaard



Copenhagen 2025

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Colophone

Serial title:
DMI Report 25-07

Title:
Validation of HYCOM-CICE sea surface height simulations using tide gauge observations in Greenland

Subtitle:

Authors:
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Other Contributors:

Responsible Institution:
Danish Meteorological Institute

Language:
English

Keywords:
sea level, Greenland waters, HYCOM, CICE, storm surge, tides

Url:
www.dmi.dk/publikationer/

ISSN:
2445-9127 (online)

ISBN:

Version:
1.0

Website:
www.dmi.dk

www.dmi.dk/publikationer/

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Authors: Mia Nørholm and Mads Hvid Ribergaard

January 30, 2025

Abstract

Storm surge events poses a potential threat to the population living close to the coastline in Greenland, but a storm surge warning system for Greenland does not exist. This report investigates the potential to apply the operational ocean-sea-ice model HYCOM-CICE as a forecast for storm surges in Greenland. This is done by comparing HYCOM-CICE simulated sea surface height with observed sea surface height recorded by tide gauges at five locations in Greenland. Tides have been calculated for the two time-series using Utide in order to evaluate the correlation between the simulated and observed residual sea surface height. Except for areas of the time-series where there is a potential observational bias, the mean standard deviation on the difference between the simulated and observed residual sea surface height generally don't exceed 10 cm, except at Qaqortoq where a bias correction might be relevant to apply. By investigating histograms of the distributions of sea surface height, it is clear that HYCOM-CICE is able to simulate all sea surface heights well. There is a seasonal fluctuation in correlation, where HYCOM-CICE slightly overestimates sea surface height in the summer and underestimates sea surface height in the winter. Finally, HYCOM-CICE is able to simulate the residual sea surface height increase followed by the November storm along the West Coast in 2019 in Nuuk and Qaqortoq. This report underlines the potential to apply the operational HYCOM-CICE model as an early warning system for storm surges in Greenland. To make a definitive conclusion on the suitability of the model it is necessary to perform further analysis of the model performance in other extreme events, and preferably also on longer time-series.

Contents

1 Introduction

Storm surge events in Greenland poses a threat to the population living close to the coastline, but a storm surge warning system for Greenland does not exist. Without a forecast system, preventative initiatives such as evacuation are delayed and thus increasing the chance of materialistic or personal damage.

In mid-November 2019, a passage of a strong low pressure system moving northward along the West Coast of Greenland resulted in elevated sea surface height (Ribergaard and Eriksen, 2020). In Paamiut parts of the harbor area was flooded and in Ilulissat 3 houses were evacuated due to a combination of high water levels and strong waves. The driving force behind both incidents was the powerful low pressure, which also laid down most of the aviation. The water levels became extraordinarily high, because the wind driven surge, and especially the waves for Ilulissat, unfortunately coincided with high tides at spring tides. It was thus the combination of strong tides, a storm surge and high waves, which resulted in strongly increased water levels locally in the towns of Paamiut in Southwest Greenland and Ilulissat in Disko Bay one day after. The storm surge observed in Paamiut and Ilulissat on the 14-15th November 2019, is an example of the potential dangers a storm surge event might pose on the Greenlandic society (Ribergaard and Eriksen, 2020).

1.1 Objective

This report briefly evaluates the ability of the ocean-sea-ice model HYCOM-CICE (Ponsoni et al. (2023)) to simulate sea surface heights (SSH) at locations around Greenland by comparing modelled SSH to observed SSH measured using tide gauges. The purpose of this comparison is to initially evaluate the HYCOM-CICE models applicability as a storm surge warning system. The models ability to simulate SSH is evaluated by investigating correlation between modelled and observed SSH, and compare the de-tided residual modelled and observed SSH. By de-tiding the time-series, it is possible to focus on, and validate other SSH-controlling parameters than tide, mainly wind. Histograms for each location provides insight into the distribution of observed and simulated HYCOM-CICE SSH and residual SSH, in order to compare the two. Residual SSH in Nuuk and Qaqortoq during the 2019 November storm on the West coast are investigated in closer detail to evaluate the models performance at this specific event.

2 Data and model

2.1 Observational SSH-data

Observational data is provided by DTU Space, who maintain tide gauges located in Nuuk, Qaqortoq, Ittoqqortoormiit, Upernavik, Pituffik. The stationary tide gauges provides a continuous SSH time-series, going back to 2005 for some locations (Table 1). At Upernavik, tide-gauge data is only available for August 2023. The longer data-series provides the potential for a statistical analysis of sea surface height around Greenland, including mean periodicity and investigation of extreme events such as storm surges. Observational data has a time-step of 5 minutes.

Table 1: Tide gauge stations in Greenland, coordinates and length of time-series.

Location	Longitude	Latitude	Obs. start time	Obs. end time
Nuuk	-51.72	64.17	2014-07-01	2023-08-31
Qaqortoq	-46.04	60.72	2005-10-01	2023-12-31
Ittoqqortoormiit	-21.96	70.48	2007-10-01	2023-12-31
Upernavik	-56.15	72.79	2023-08-01	2023-08-31
Pituffik	-68.84	76.54	2005-09-01	2023-12-31

Given that continuous simulated SSH data from a consistent model run is only available since January 2019, the time series analyzed in this report is from January 2019 to August 2023. This limits the possibility for extreme events or statistical analysis on a longer time scale, and the report thus focus on correlation and phase lag between observed and modelled SSH, and the specific storm surge event in November 2019 instead.

2.2 HYCOM-CICE simulations

HYCOM-CICE is an ocean-sea-ice model with an approximate horizontal resolution of averagely 5 km around Greenland. The model is forced by weather forecasts provided by the European Centre for Medium-Range Weather Forecasts (ECMWF). Furthermore, satellite based sea surface temperature and sea ice concentration are assimilated (Ponsoni et al., 2023).

Point location SSH time series from the model is extracted for each location based on the closest ocean-grid cell to the coordinates of the DTU tide gauges. The location of the nearest grid cell along with their distance (from the center point of the grid cell) to the tide gauges is reported in Table 2. Continuous HYCOM-CICE SSH-data from the same model run is available from January 2019 to August 2023 with a 1 hour time-step. The simulated SSH time series is interpolated linearly onto the same time-step as the observed SSH (5 minutes), in order to ease comparison and investigate phase lag and correlation.

Table 2: Coordinates of nearest grid-cell and the distance between tide gauge location and nearest grid-cell center, along with phase lag between observed and simulated SSH. The phase lag at Upernavik is based on 1 month of data and therefore not necessarily representative. *The 95th percentile difference is the difference between observed SSH and simulated SSH without phase shifting of the time series.

Location	Nearest grid-cell lon	Nearest grid-cell lat	Distance to obs	Phase lag	95th pct diff*
Nuuk	-51.79	64.16	3.45 km	35 min	57 cm
Qaqortoq	-46.19	60.71	8.33 km	30 min	45 cm
Ittoqqortoormiit	-22.09	70.46	5.69 km	5 min	15 cm
Upernavik	-56.22	72.79	2.48 km	50 min	26 cm
Pituffik	-68.96	76.52	3.76 km	25 min	35 cm

All nearest grid cells are reasonably located in a proximal ocean-grid cell close to the observation point as is evident when zooming in on Nuuk (Figure 1, b). The distance between the center of the grid cell to the location of the tide gauge is maximum 8.33 km at Qaqortoq. The phase lag between the observed and simulated SSH time series is for most stations approximately 30 minutes, but for Ittoqqortoormiit it is 5 minutes. At Upernavik the phase lag is 50 minutes, but this is not robust as it is only based on 1 month of data. The 95th percentile difference between observed SSH and simulated SSH is calculated for each station before phase shifting the simulated SSH to be in phase with the observed. The maximum 95th percentile difference is found at Nuuk (57 cm), while the minimum is found at Ittoqqortoormiit (15 cm).

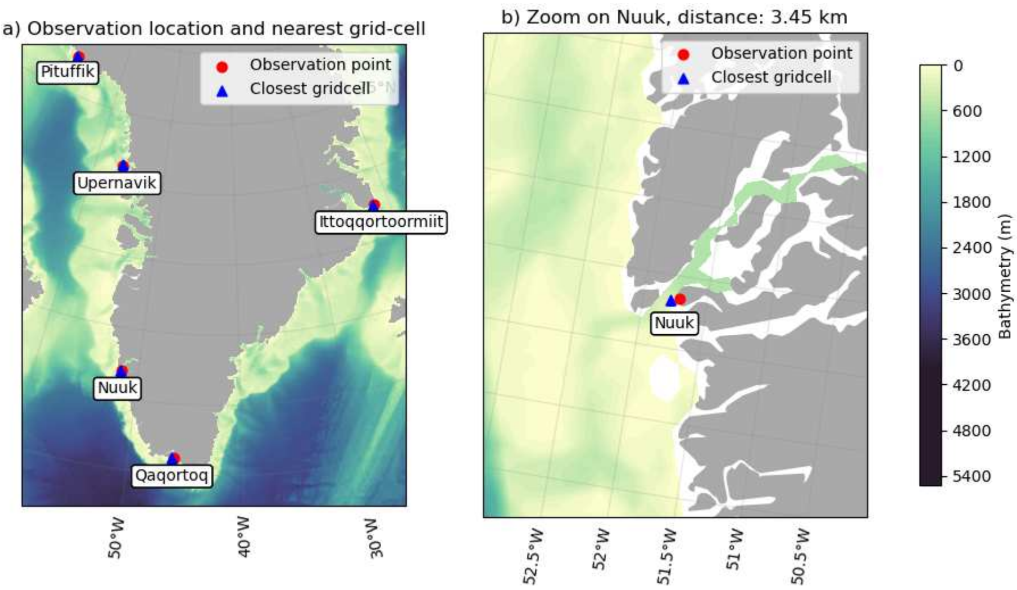


Figure 1: a) Locations of observational data (red dot) and closest grid cell (blue triangle). Notice they almost overlap in all cases. b) Zoom in on Nuuk location, to visualize distance between observation point and nearest grid cell.

2.3 Data processing

DTU Space has performed quality control on the observed SSH time-series they have provided. This includes a visual evaluation and correction for outliers exceeding mean ± 3.5 std. dev, which are set to NaN. Following interpolation of HYCOM-CICE data to observed data time-step, all SSH data is further corrected by removing data where time between datapoints exceeds 30 minutes, in order to remove areas of incorrectly interpolated data-points. The two time-series are normalized by subtracting each data-point with the mean of the entire data-series. The difference between the two time-series is found by subtracting observational SSH with HYCOM-CICE SSH.

2.4 Correlation, tide and phase lag

After interpolating HYCOM-CICE modelled SSH to observed SSH time-step, the linear correlation between the two is tested using Pearson correlation coefficient. The test reveals a generally very high linear correlation between observed and modelled SSH for all locations, as is expected with SSH time-series that are highly dependent on a tidal signal.
Modelled and observed SSH was up to 50 minutes out of phase at Upernavik, and only 5 minutes out of phase at Ittoqqortoormiit (Table 2). The phase correlation at Upernavik is only based on 1 month of data, and should be interpreted with caution. For further analysis, modelled HYCOM-CICE SSH has been shifted by the corresponding time-steps to be in-phase with observed SSH with the highest correlation. Tidal signal from both observed and modelled SSH has been calculated using UTide based on the observed SSH from tide gauge observations, and on HYCOM-CICE SSH without interpolation or phase shift. The tidal signal calculated for HYCOM-CICE has afterwards been interpolated to observed SSH time-step, phase shifted in accordance with the original lag found by investigating correlation of the full SSH signal, and normalized by subtracting each data-point with the mean of the entire time-series. Residual SSH is then found by subtracting the full interpolated and phase shifted SSH-signal with the tidal signal for each time-series, and the difference between observed and modelled residual SSH is found by subtracting observed residual SSH with modelled residual SSH.

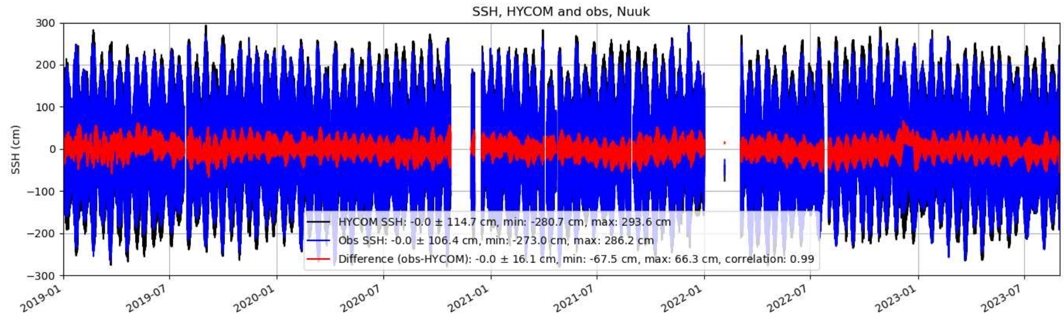
3 Results

3.1 Comparison of simulated and observed SSH

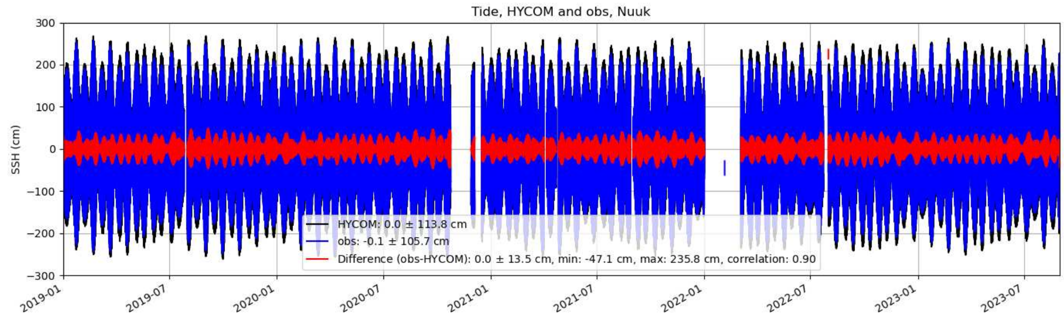
3.1.1 Nuuk

Observed SSH in Nuuk varies from -273 cm to 286 cm between January 2019 and August 2023 (Fig. 2a). HYCOM-CICE simulates SSH that varies between -281 cm and 294 cm, indicating that simulated SSH varies slightly more than observed SSH. This trend is also reflected in the larger std. dev. for HYCOM-CICE (± 115 cm) compared to observed SSH (± 106 cm). The standard deviation between the two time series is ±16 cm, and the difference is minimum -67 cm and a maximum 71 cm. The correlation between the two time series is 0.99. Tidal signal std. dev. are approximately equal to the full SSH signal std. dev. (Fig. 2b). The difference between the two tidal signal varies from -52 cm to 43.9 cm. The corresponding residual signal, obtained by subtracting calculated tide from complete SSH signal, for both observed and simulated SSH is relatively similar, with a std. dev. of ± 13 cm and ± 14 cm, respectively. The standard deviation of the difference between the two residuals is ± 9 cm, minimum -39 cm and maximum 53 cm, and the correlation is 0.8. There is a relatively short period of bad correlation until approximately May 2019, from where the time-series correlate better, except in a short time period around December 2023, where HYCOM-CICE simulates a significantly lower residual SSH (Fig. 2c). The reason is likely due to instrumental service and new fixation depth for the latter case. The reason for the initial noise part is unknown, but could be due to problems with the tube or fixation of the instrument.

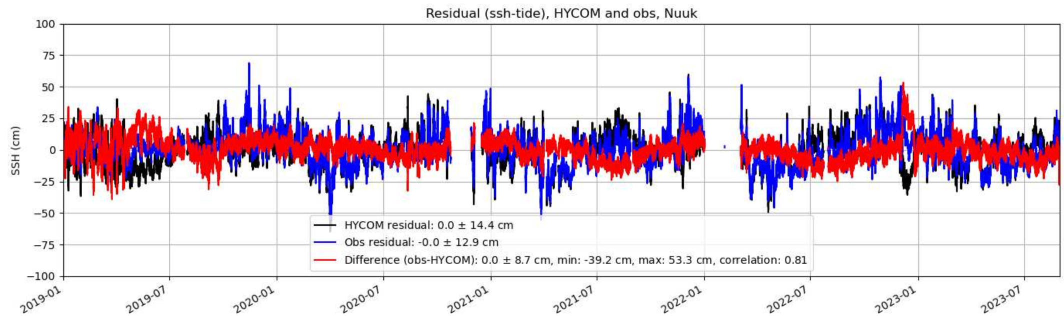
In August 2023, the model performs best compared to observed SSH just after neap tide, where the tide is increasing, around 08/01, 08/14 and 08/27 (Fig. 3). The model seems to perform worst after spring tide, as tide is decreasing. A zoom on the residual signal in August 2023 underlines the good correlation. From approximately the 21st to the end of the month, observed residual SSH is generally higher, something that is also resolved by HYCOM-CICE (Fig. 3c).



(a) Observed SSH (blue line), simulated SSH (black line), difference (red line)

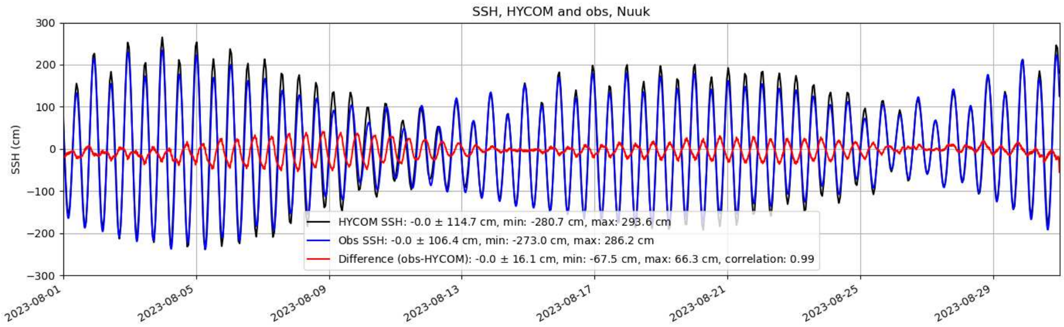


(b) Tide, calculated using UTide for observed (blue line), simulated (black line) and difference (red line)

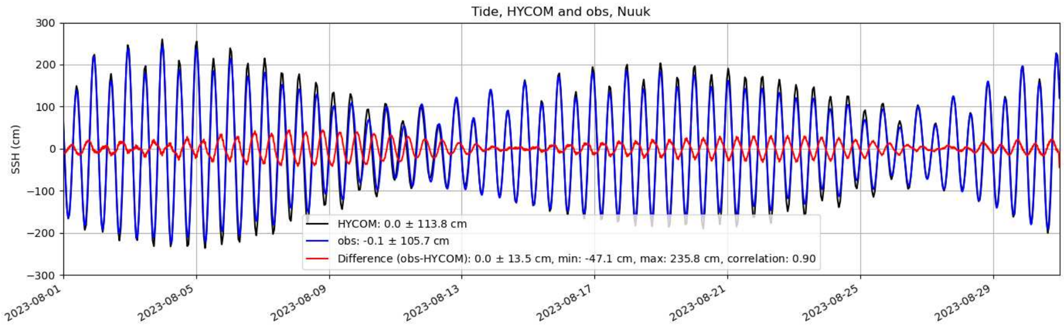


(c) Residual (SSH-tide) for observed (blue line), simulated (black line) and the difference (red line)

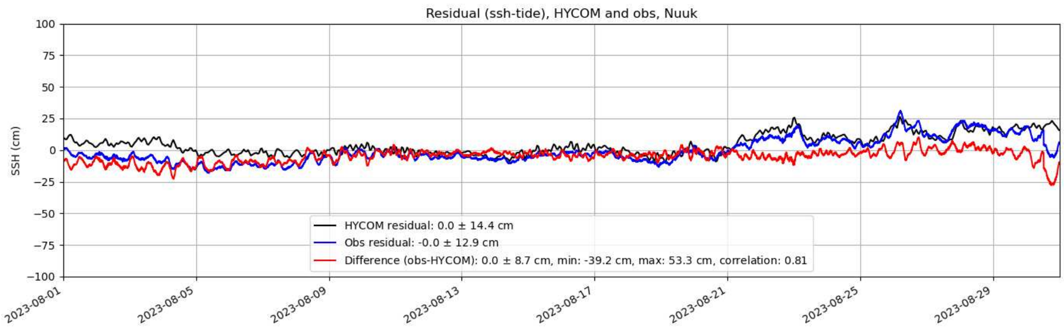
Figure 2: SSH in Nuuk between January 2019 and August 2023



(a) Observed SSH (blue line), simulated SSH (black line), difference (red line)



(b) Tide, calculated using UTide for observed (blue line), simulated (black line) and difference (red line)

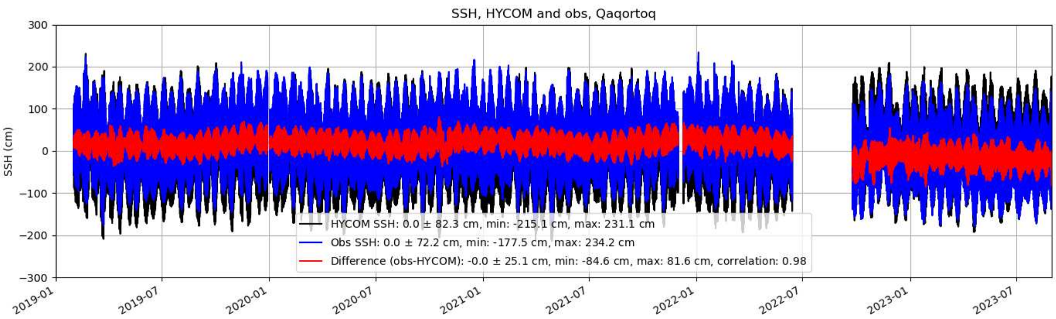


(c) Residual (SSH-tide) for observed (blue line), simulated (black line) and the difference (red line)

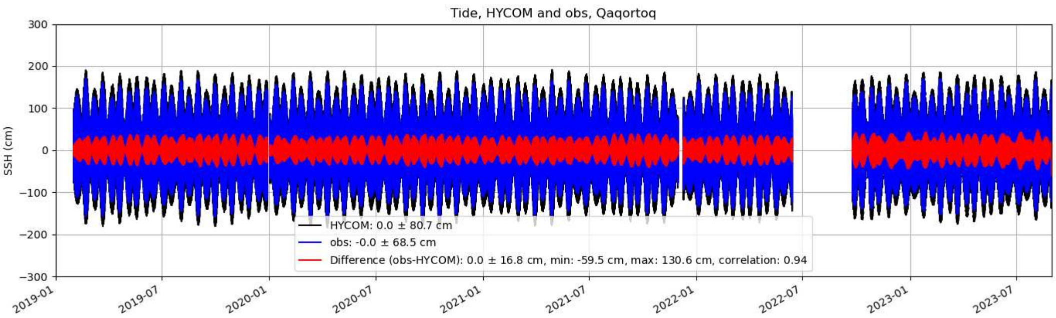
Figure 3: SSH in Nuuk in August 2023

3.1.2 Qaqortoq

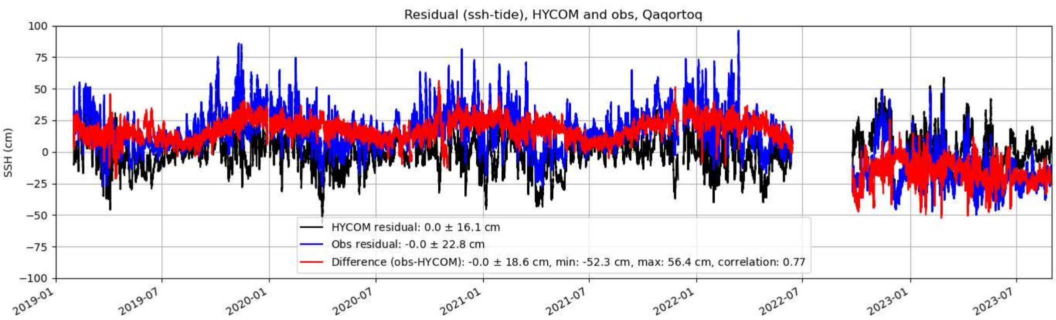
Observed SSH in Qaqortoq varies between -178 cm and 234 cm between January 2019 and August 2023. HYCOM-CICE simulates SSH that varies between -215 cm and 231 cm for the same time-period. The HYCOM-CICE SSH time-series varies more (std. dev.: $\pm$ 82 cm) compared to observed SSH (std. dev.: $\pm$ 72 cm). The standard deviation on the difference between the two time-series is $\pm$ 25 cm, and the difference varies from -85 cm to 82 cm. The correlation between the two time-series is 0.98. Mean observed SSH appears to be higher up until a gap in the time-series around July 2022, from where it appears that the mean observed SSH shifts to be lower (Fig. 4a). The residual SSH underlines this trend, mean observed SSH appears higher up until the data-gap in Autumn 2022, from where observed SSH in general is lower (Fig. 4c). The difference in trends following a data-gap might be credited to observational bias such as a slight change in the physical location of the tide gauge etc., and conclusions from this should be drawn with that in mind.



(a) Observed SSH (blue line), simulated SSH (black line), difference (red line)



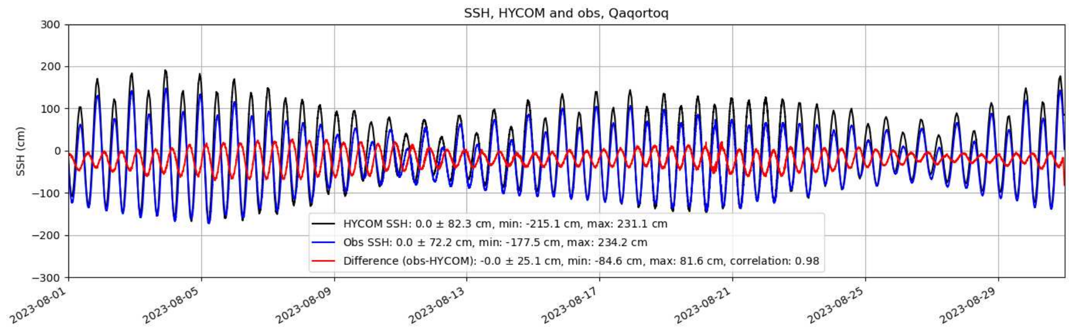
(b) Tide, calculated using UTide for observed (blue line), simulated (black line) and difference (red line)



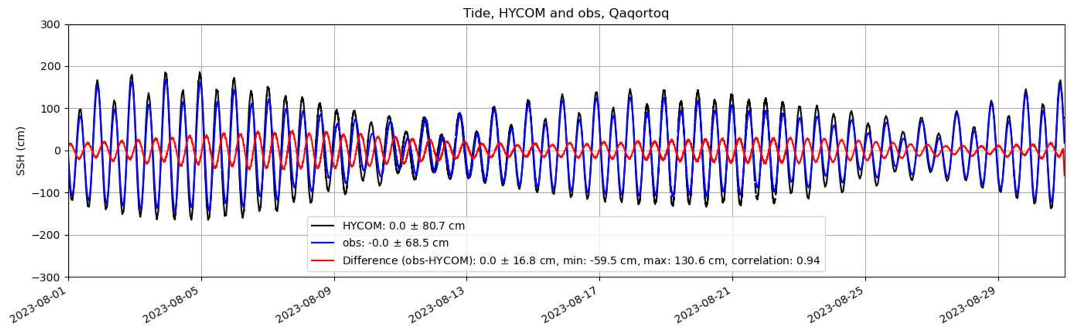
(c) Residual (SSH-tide) for observed (blue line), simulated (black line) and the difference (red line)

Figure 4: SSH in Qaqortoq between January 2019 and August 2023

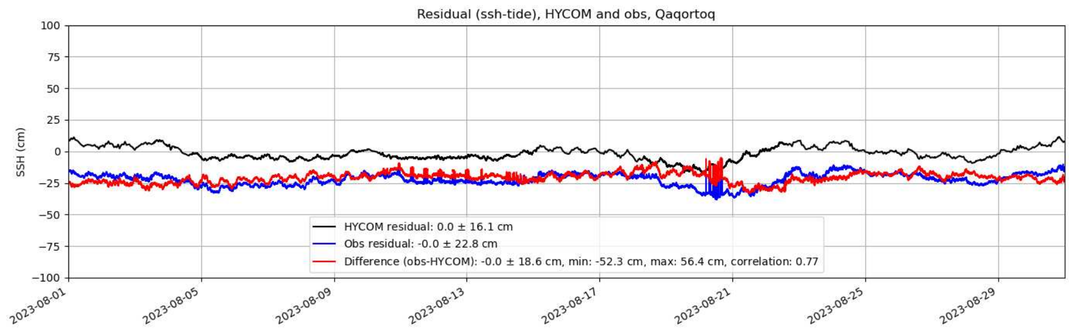
A zoom on August 2023 at Qaqortoq makes the observational bias clear, as observed SSH is generally lower compared to modelled SSH (Fig. 5). Except for this bias, changes in SSH appear relatively well resolved, and the difference between observed and modelled residual SSH is relatively stable throughout the month, with a standard deviation of ± 25 cm and a correlation of 0.98 (Fig. 5c). It does appear that the model performs best as the tide is increasing just after neap tide, and worst as the tide is decreasing after spring tide in August 2023 (Fig. 5a). Zooming in on August, irregularities in observed SSH appear (Fig. 5c, around 2023-08-21).



(a) Observed SSH (blue line), simulated SSH (black line), difference (red line)



(b) Tide, calculated using UTide for observed (blue line), simulated (black line) and difference (red line)

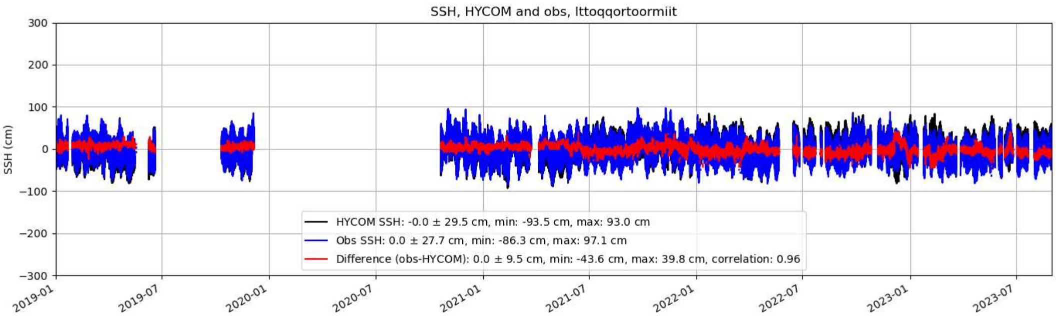


(c) Residual (SSH-tide) for observed (blue line), simulated (black line) and the difference (red line)

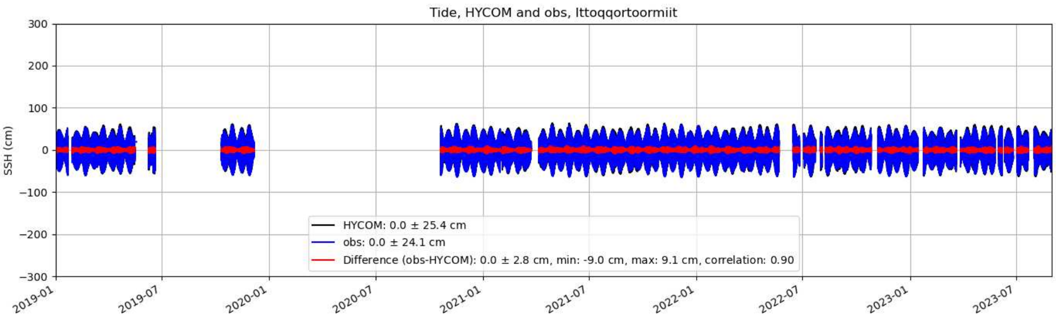
Figure 5: SSH in Qaqortoq in August 2023

3.1.3 Ittoqqortoormiit

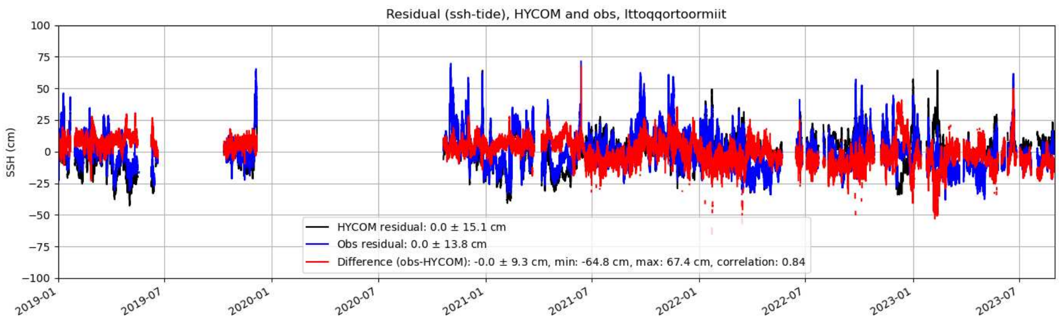
Observed SSH in Ittoqqortoormiit varies from -87 cm to 97 cm between January 2019 and August 2023, while modelled SSH varies from -93 to 93 cm (Fig. 6a). HYCOM-CICE simulated SSH varies slightly more (std. dev. = ± 29 cm) compared to observed SSH (std. dev. = ± 28 cm). The difference between the two is minimum -64 cm and maximum 76 cm and the correlation is 0.96. Sea surface height generally varies less in Ittoqqortoormiit compared to the other stations, as the east coast generally is less affected by tides (Fig. 6b). The difference between the modelled and observed residual SSH is minimum 65 cm and maximum 67 cm, with a standard deviation of 9 cm and a correlation coefficient of 0.84. (Fig. 6c)



(a) Observed SSH (blue line), simulated SSH (black line), difference (red line)



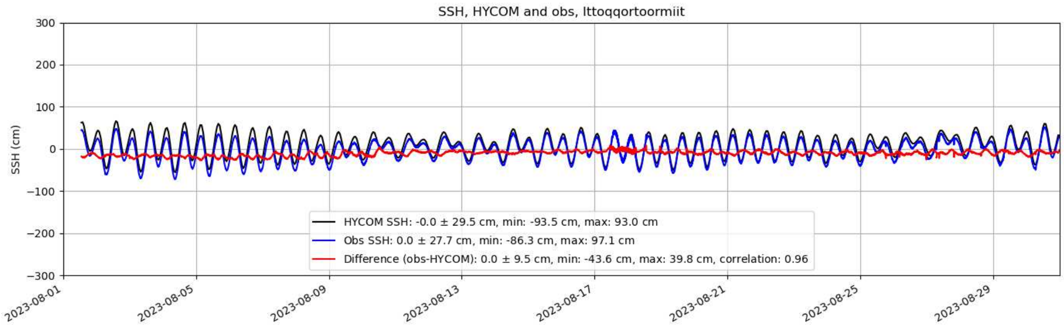
(b) Tide, calculated using UTide for observed (blue line), simulated (black line) and difference (red line)



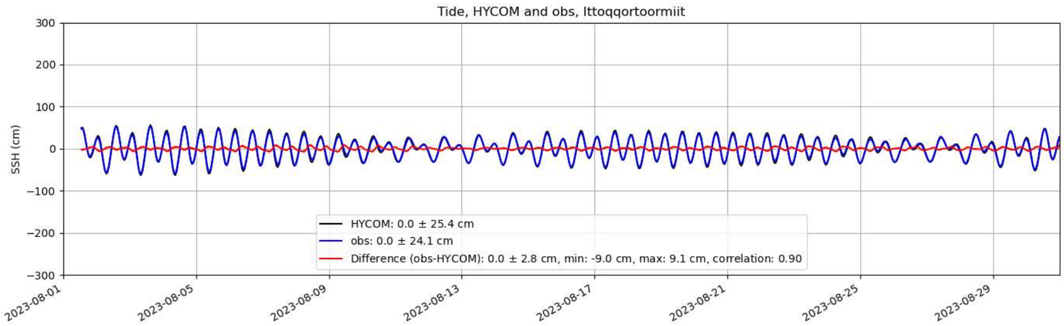
(c) Residual (SSH-tide) for observed (blue line), simulated (black line) and the difference (red line)

Figure 6: SSH in Ittoqqortoormiit between January 2019 and August 2023

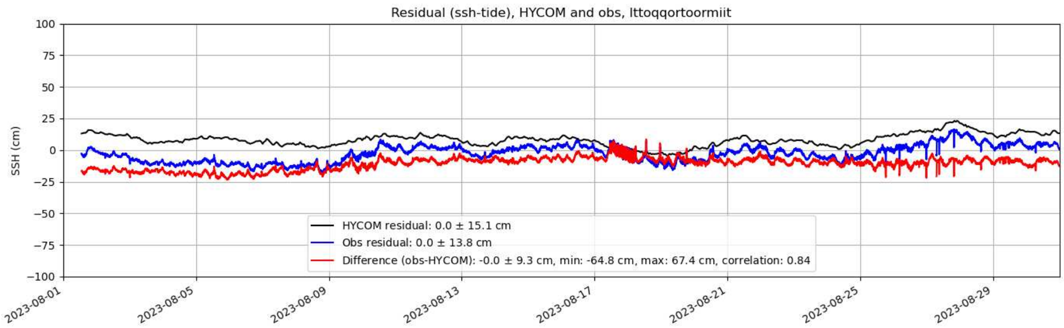
In August 2023 the difference between the modelled and observed SSH is close to constant (Fig. 7). Again, observational bias appears as we zoom in on the residual signal in August (Fig. 7c).



(a) Observed SSH (blue line), simulated SSH (black line), difference (red line)



(b) Tide, calculated using UTide for observed (blue line), simulated (black line) and difference (red line)

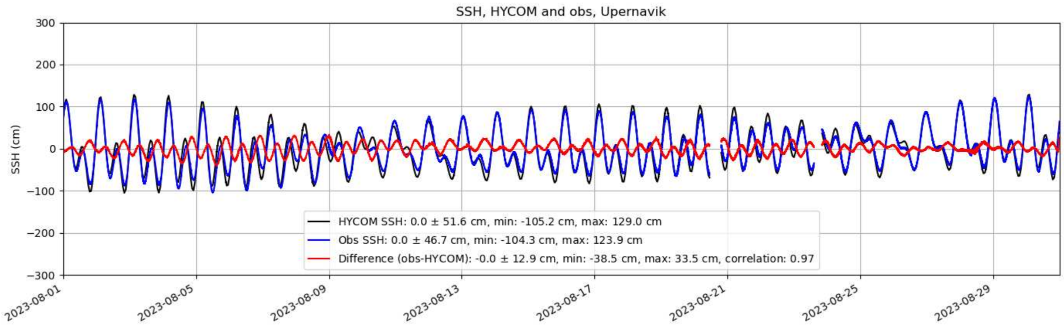


(c) Residual (SSH-tide) for observed (blue line), simulated (black line) and the difference (red line)

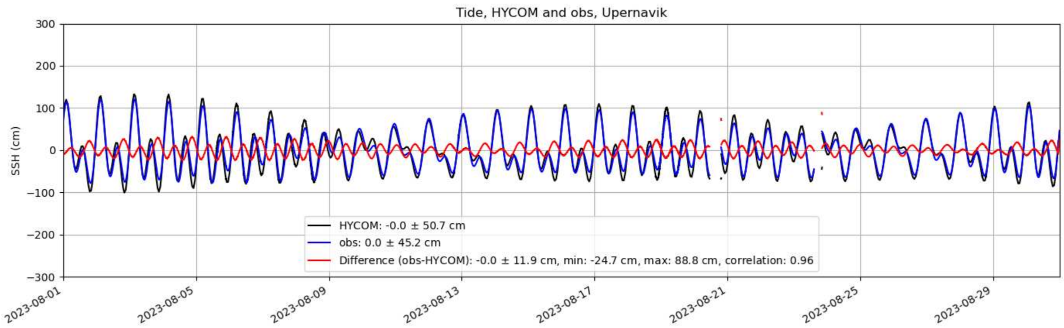
Figure 7: SSH in Ittoqqortoormiit in August 2023

3.1.4 Upernavik

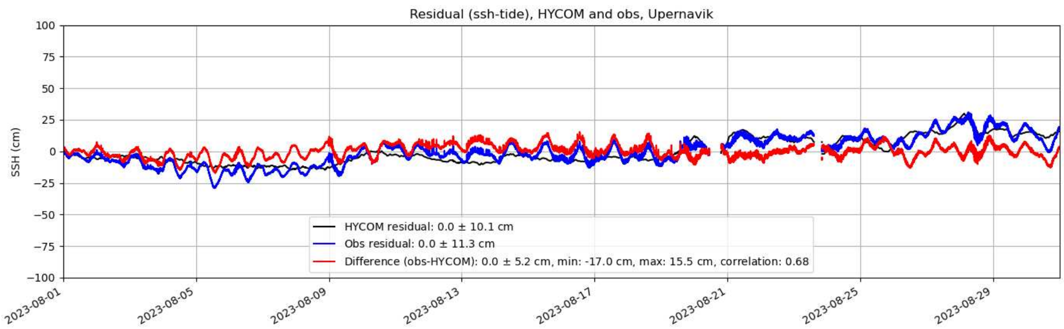
Observational data from Upernavik only exists for August 2023, so analysis is done based on an insufficient amount of data. The tidal analysis (Fig. 8b) is thus equally not confident. The minimum observed SSH in Upernavik in August 2023 is -104 cm and maximum is 124 cm. Simulated SSH for the same time period is minimum -105 cm and maximum 129 cm, reflecting that HYCOM-CICE simulated SSH varies slightly more compared to observed. The standard deviation of the mean difference is ± 13 cm, with minimum of -38 cm and maximum of 36 cm. The residual signal reveal a relatively good fit between the two time series, with HYCOM-CICE SSH generally reflecting the trend of observed SSH with the exception of small short-time variations in observed residual SSH.



(a) Observed SSH (blue line), simulated SSH (black line), difference (red line)



(b) Tide, calculated using UTide for observed (blue line), simulated (black line) and difference (red line)

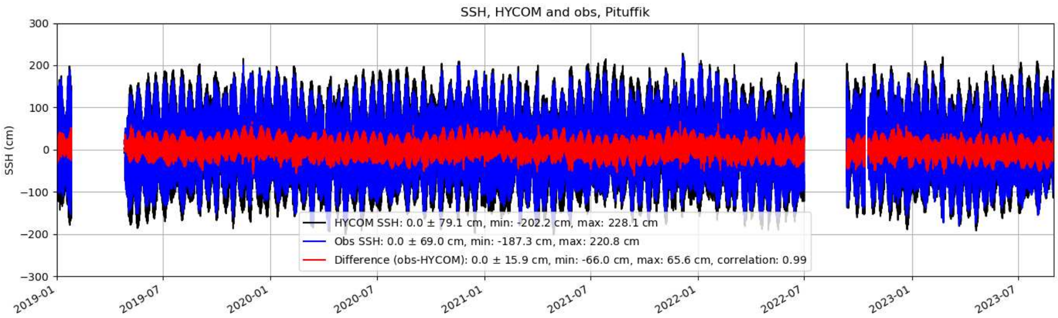


(c) Residual (SSH-tide) for observed (blue line), simulated (black line) and the difference (red line)

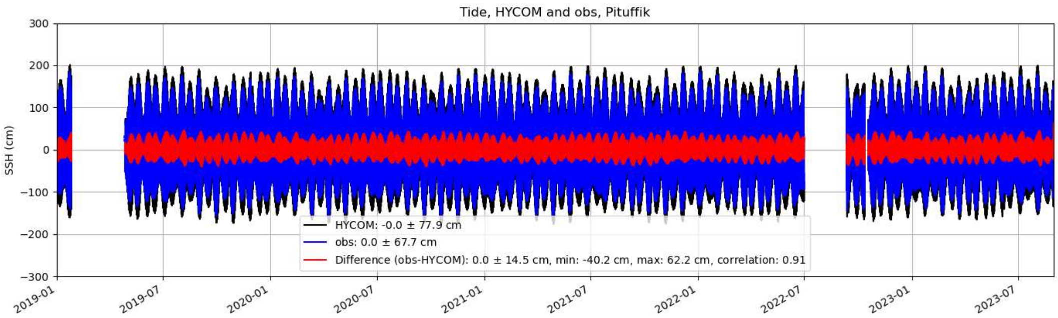
Figure 8: SSH in Upernavik in August 2023

3.1.5 Pituffik

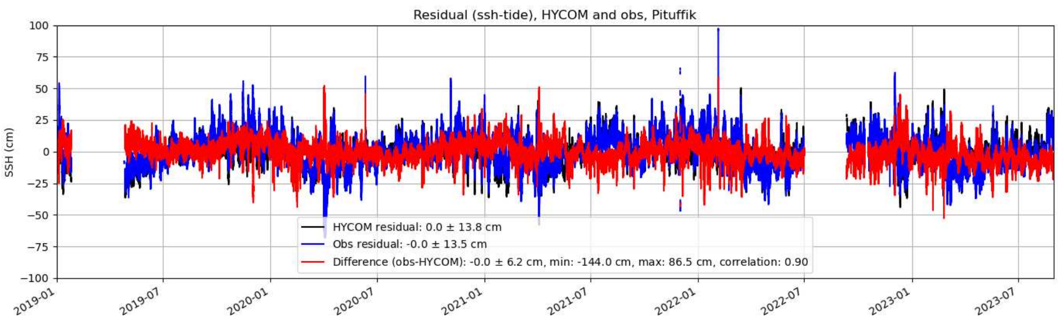
Observed SSH in Pituffik varies between -187 cm and 221 cm from January 2019 to August 2023. For the same period, HYCOM-CICE simulates minimum SSH of -202 cm and maximum SSH 228 cm (Fig. 9). The std. dev. for observed SSH is ± 69 cm and for HYCOM-CICE simulated SSH is ± 79 cm, which reflects the larger variation in simulated HYCOM-CICE SSH. The standard deviation of the difference between the two time-series is ± 16 cm, with minimum -66 cm and maximum 72 cm. Comparison of the residual signal after removal of tides reveal a standard deviation of the difference of ± 6 cm. In general, the model seems to simulate SSH according to the observed SSH rather well, as the residual SSH signals correlate by 0.90.



(a) Observed SSH (blue line), simulated SSH (black line), difference (red line)



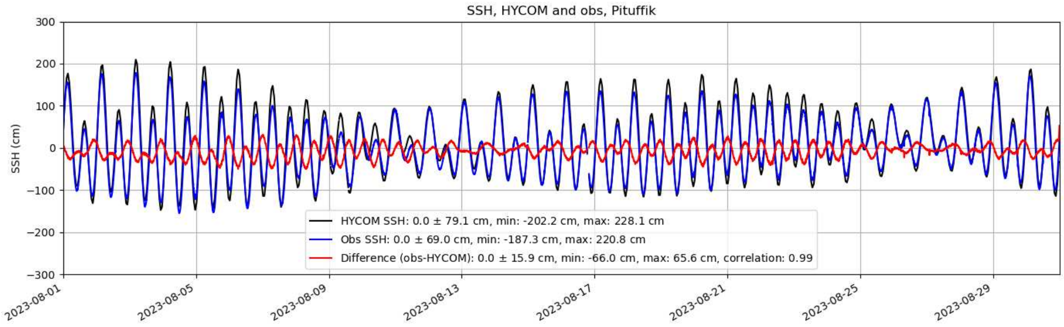
(b) Tide, calculated using UTide for observed (blue line), simulated (black line) and difference (red line)



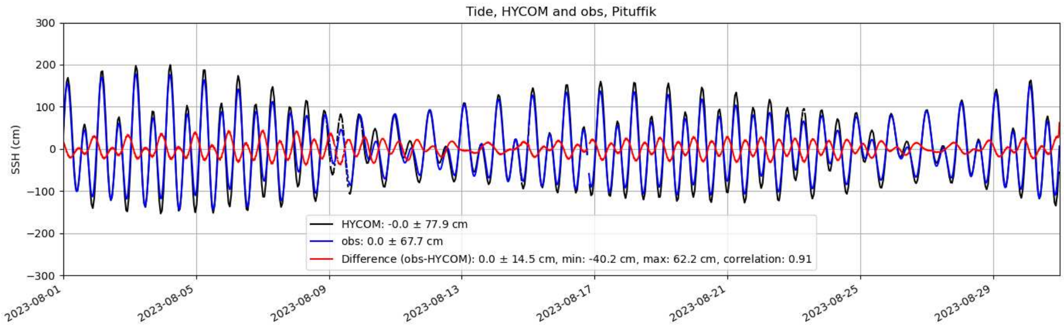
(c) Residual (SSH-tide) for observed (blue line), simulated (black line) and the difference (red line)

Figure 9: SSH in Pituffik between January 2019 and August 2023

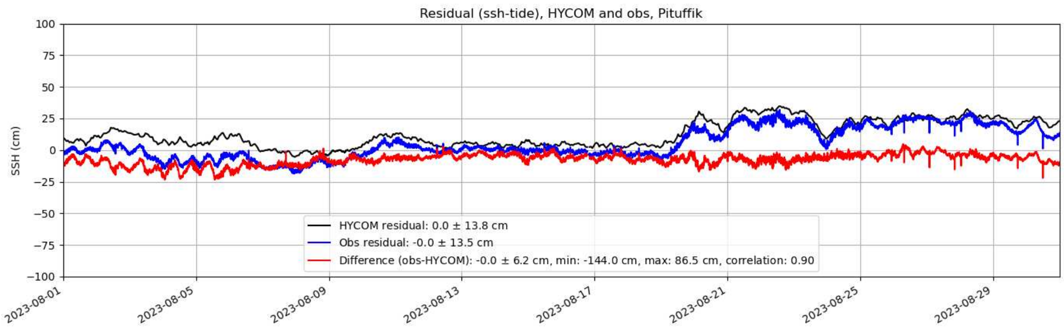
Similar as for Nuuk and Qaqortoq, the model seems to perform slightly better just after neap tide, where the tide range is increasing, and slightly worse just after spring tide, where the tidal range is decreasing, in August 2023 (Fig. 10a). Visual investigation of the residual signal in August 2023 reveal relatively well performance by the model. HYCOM-CICE simulates an increase in SSH from approximately 0 cm to approximately 25 cm around the 19th, a trend that is equally observed (Fig. 10c). The difference between the two time-series is relatively stable throughout the month.



(a) Observed SSH (blue line), simulated SSH (black line), difference (red line)



(b) Tide, calculated using UTide for observed (blue line), simulated (black line) and difference (red line)

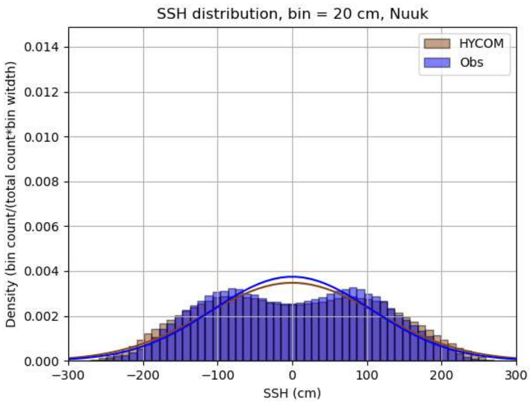


(c) Residual (SSH-tide) for observed (blue line), simulated (black line) and the difference (red line)

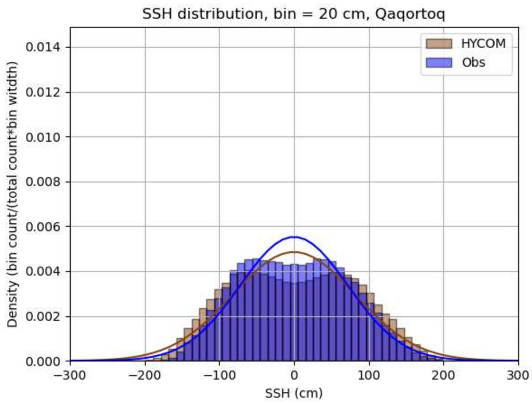
Figure 10: SSH in Pituffik in August 2023

3.2 Data distribution

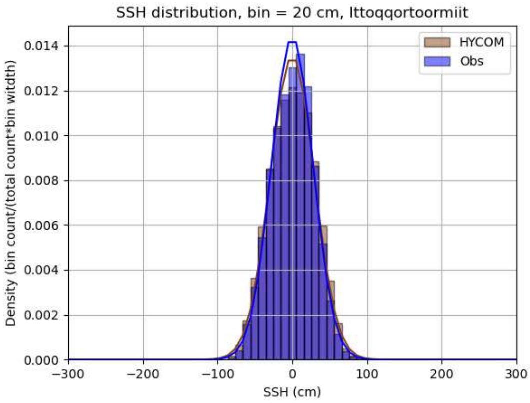
The distribution of observed and simulated SSH is investigated for all location through histograms showing the density of SSH intervals. The bin-size for the histograms is 20 cm for histograms with the full SSH signal, and a fitted normal distribution is plotted along with the histogram for comparison. For Nuuk, the spread is highest compared to the other locations, as SSH-fluctuations are highest here (Fig. 11a). The histograms reveal that HYCOM-CICE data density is slightly higher at the more extreme water levels (above/below approximately $\pm$ 150 cm, whereas the opposite is the case at smaller water level-fluctuations. This confirms the notion that HYCOM-CICE slightly overestimates SSH fluctuations compared to observed. At Qaqortoq, the spread and thereby SSH fluctuations are smaller, but the over-representation of extreme SSH-values by HYCOM-CICE is more pronounced. The smallest SSH fluctuation, of the stations included in this report, is found at Ittoqqortoormiit, reflected in the high data-density close to SSH = 0 cm. The observed and simulated extreme SSH values are in better agreement here. Upernavik should be interpreted with caution as it is based on data from only 1 month. At Pituffik, the models over-representation of extreme SSH values is again evident.



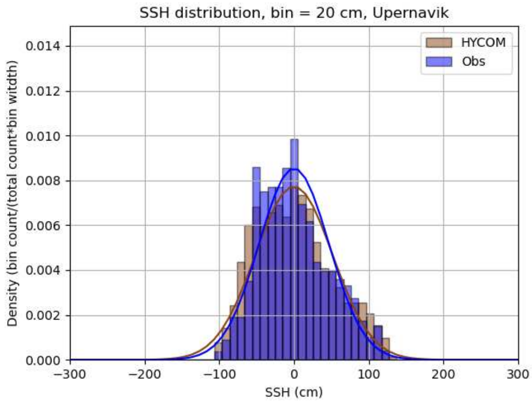
(a) Nuuk



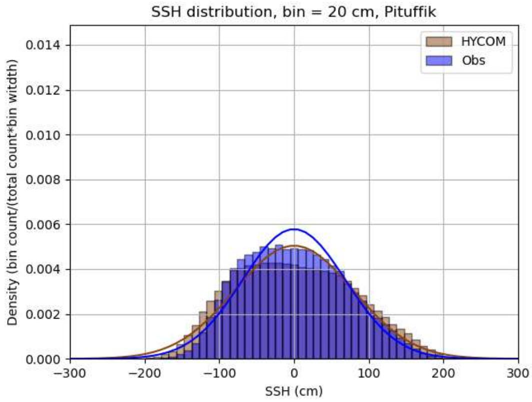
(b) Qaqortoq



(c) Ittoqqortoormiit



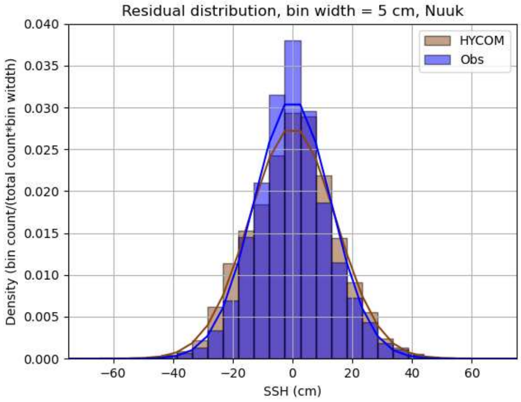
(d) Upernavik



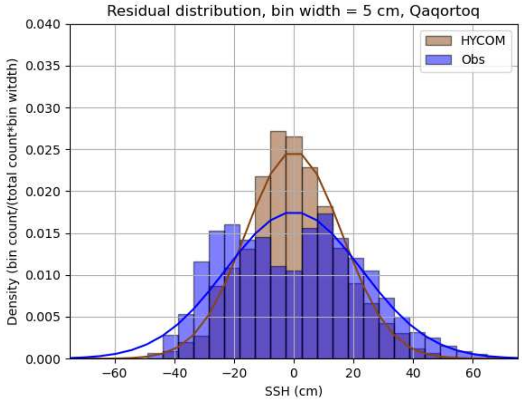
(e) Pituffik

Figure 11: Distribution of observed and modelled SSH at the five locations

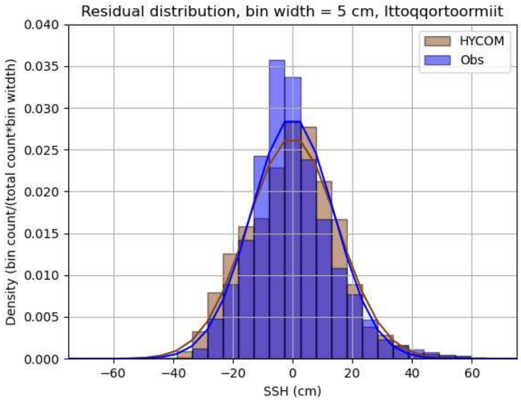
The distribution of residual observed and simulated SSH is equally presented through histograms showing the density of observed and modelled residual SSH in bin sizes of 5 cm.



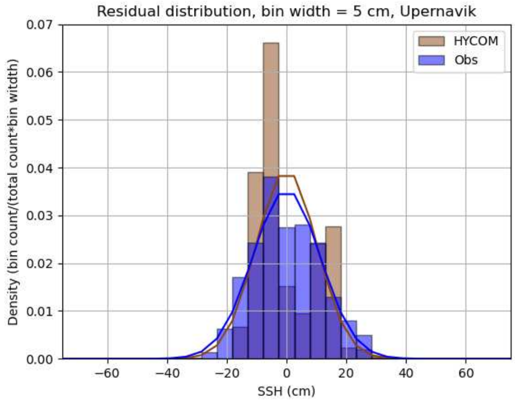
(a) Nuuk



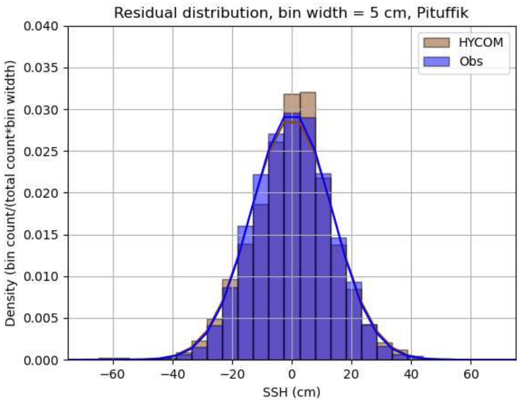
(b) Qaqortoq



(c) Ittoqqortoormiit



(d) Upernavik, notice the different y-axis



(e) Pituffik

Figure 12: Distribution of observed and modelled residual SSH at the five locations

3.3 Seasonal bias

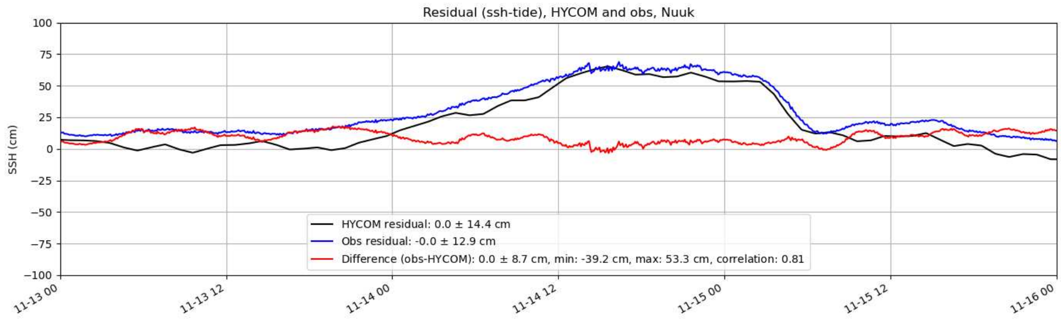
Visual investigation of the difference between observed and modelled SSH for the full time-series indicate potential seasonal fluctuations (Fig. 4a for an example). By locating the seasonal mean difference between observed and modelled SSH, it becomes evident that SSH on average, by HYCOM-CICE is overestimated in summer and underestimated in winter, compared to observed SSH. This trend is evident for all locations (Table 3). By investigating seasonal bias in the residual SSH it is also clear that the majority of the seasonal bias is in the residual signal, and for Ittoqqortoormiit that is less influenced by tides, it is fully explained by the residual SSH signal.

Table 3: Winter and summer mean difference between observed and modelled residual SSH at the locations. Seasonal means for Upernavik are not available as Upernavik only contains observed data from August 2023. Summer months are June, July and August, and winter months are December, January and February. Difference is observed SSH - HYCOM SSH, and residual difference is observed residual SSH - HYCOM-CICE residual SSH.

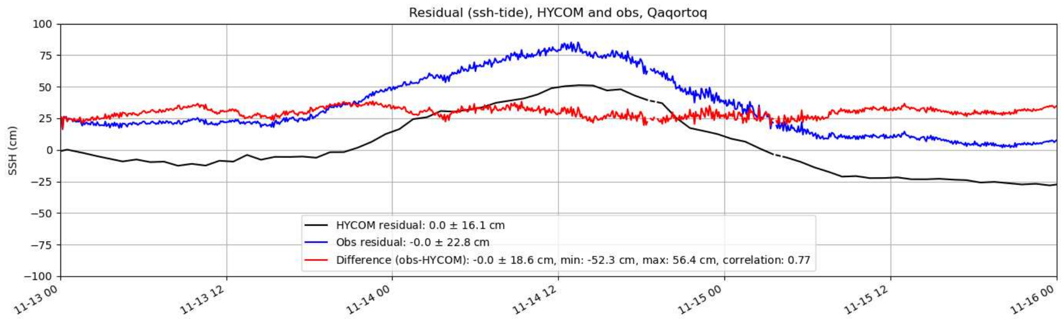
Location	Winter mean difference	Summer mean difference	Residual winter mean difference	Residual summer mean difference
Nuuk	5.1 cm	-5.4 cm	5.2 cm	-5.3 cm
Qaqortoq	3.9 cm	-7.9 cm	4.3 cm	-7.6 cm
Ittoqqortoormiit	0.9 cm	-5.8 cm	0.9 cm	-5.8 cm
Upernavik				
Pituffik	3.6 cm	-3.5 cm	3.5 cm	-3.1 cm

3.4 West coast storm, 14-15th November 2019

On the 14-15th November 2019, a storm system caused especially high SSH in Paamiut and Ilulissat, causing three households in Ilulissat to be evacuated. While elevated SSH was observed in these cities, there are no tide gauge measurements from this event available, but the storm system affected SSH on the entire southwestern coast of Greenland. By investigating the residual SSH signal these days in Nuuk and Qaqortoq, from where tide gauge measurements are available, we can evaluate the models performance in this specific event. Residual SSH in Nuuk increased steadily from approximately 15 cm just before midnight, before the 14th November (Fig. 13a). It peaked just after noon on the 14th at approximately +65 cm, and declined rapidly again the morning of the 15th November. The magnitude of the SSH increase and decline is relatively well simulated by HYCOM-CICE. In Qaqortoq, observed water levels increase from approximately 25 cm in the evening of the 13th November, to approximately 75 cm at noon the 14th November, from where it steadily decreases again until reaching approximately 10 cm just before noon the 15th November. HYCOM-CICE generally underestimates SSH by approximately 25 cm, but equally to Nuuk, the magnitude of the increase and decrease is very similar to the observed, and the difference between observed and simulated SSH remains almost constant (Fig. 13b).



(a) Nuuk



(b) Qaqortoq

Figure 13: Residual SSH (obs-tide) in the time-period 13th-16th November 2019 in Nuuk (a) and Qaqortoq (b) for observed SSH (blue line), modelled HYCOM-CICE SSH (black line) and the difference (obs residual - HYCOM-CICE residual, red line). The min, max and correlation reported on the figure refer to the full time-period (01/01-2019 to 08/31-2023).

4 Discussion

4.1 Phase lag

The observed phase lag for each of the locations has been corrected for by moving the modelled sea surface height the corresponding time-steps in order to be in maximum correlation with observed sea surface height, which is mainly guided by tides. As the consequence of this, the model predicts the arrival of the tidal wave too late. This will impact the models applicability in a forecast situation, although this lag is mainly with regards to tides and by knowing, and correcting for the phase lag, it is still possible to predict large relative sea level fluctuations. The largest phase lag between observed and simulated SSH is 50 minutes and occurs at Upernavik. This lag comes with some uncertainties, as there is only one month of data from Upernavik. Otherwise the phase lag ranges between 35 min and 5 min. To assess the consequences of the phase lag, the 95th percentile of the difference between the observed SSH and the simulated SSH has been calculated. This shows that at Nuuk where the phase lag was 35 minutes, 95% of the simulated SSH are less than 57 cm off from the observed SSH. At Ittoqqortoormiit where the phase lag was only 5 minutes, the 95th percentile difference is 15 cm. Given that the tidal range is high at Nuuk in the order of 5-6 meters, even a minor phase lag will result in a relative high absolute error. This is evident from figure 2a, where the standard deviation of the differences of the phase-corrected series is only 16 cm.

In general, the higher tidal range, the faster does the water level changes between high and low waters. Thereby, even a minor phase lag can result in high deviation of water levels. Despite the overall good model performance with relative small phase-lags and almost correct amplitudes, there are still rooms for local improvements by tuning the model against tides. This has not been done for the presented model simulation, but it is an obvious next step for improvement.

4.2 Tide gauge data

Quality control of the observed data has been limited and thus some observational bias might impact the results of this report. As an example, at Qaqortoq mean observed SSH time series appears to shift after a gap in the data (Fig. 4). For a forecasting system, it will be relevant to investigate and correct sources for error in the observed data where necessary. Here, all datasets have been normalized in order to avoid offsets and more easily compare sea level fluctuations timing and magnitude rather than absolute values. For a forecasting system, it will be important to report the absolute water levels at the same reference point for both observed data and model data. In Greenland you have significant land uplift, and the data should be corrected for this on a regular basis ideally by installing a GNSS receiver on the tide gauge station or nearby it.
The validation of the report is limited by the number of tide gauge stations as additional stations would substantiate the validation. Using more tide gauge stations, it will make it possible to fine tune the model against tides and lowering the phase lag and amplitude error. This will result in a more precise storm surge forecasts valid for more cities.

4.3 Model physics shortcomings

The HYCOM-CICE models ability to recreate local SSH in cities might be limited first of all by the resolution of the model. Especially in cities located within narrow fjords such as Kangerlussuaq, the model will struggle to simulate the true oceanographic dynamics. The fjord is less than 10 km wide in most places, and as the grid-cell size of HYCOM-CICE is approximately 5 km, at best only two grid-cells will resolve the fjord. The lower resolution also means, that bathymetry contours are not resolved in the high detail that might be necessary to correctly predict magnitude and timing of storm surges. Local details of the coastline are equally not well resolved, which further contributes to issues with timing of the arrival of a surge and partly from which direction. The resolution of the atmospheric forcing from the ECMWF-HRES model is approximately 8 km, which might also contribute to local topographic limitations. It does not resolve fjords as well as coastal winds, which are normally underestimated in strength. These are much better resolved using a higher resolution atmospheric forcing model like the DMI-HARMONIE IG model with 2.5 km horizontal resolution (DMI, 2024).

Furthermore, as was evident in the November 2019-storm, the severity was the combination of a wind driven surge, high tide during spring tide and, especially for Ilulissat, also waves. The HYCOM-CICE model does not simulate waves, and will therefore not be able to predict this part of a storm surge event. However, a wave model (WAM) runs operational for the Greenlandic waters in 5 km horizontal resolution, and is obvious to use in a storm surge prediction system, as was suggested by Ribergaard and Eriksen (2020).

5 Conclusion

In general, HYCOM-CICE simulates sea surface height (SSH) very similar to observed SSH at the locations of the tide gauges in Nuuk, Qaqortoq, Ittoqortoormiit, Upernavik and Pituffik. In Nuuk, the model only simulates a slightly larger varying SSH compared to observed. Observed and modelled residual SSH has a correlation of 0.81. The model also resolves the storm surge that accompanied a storm system on the Southwestern coast of Greenland on the 14th-15th November 2019 in Nuuk. In Qaqortoq, there appears to be a bias in observational data since Autumn 2022. The timeseries has been normalized, but before Autumn 2022, the model generally underestimates SSH, whereas after, the model generally overestimates SSH, which might indicate observational bias such as the maintenance of a tide gauge that is then not put back at the exact same place etc. Observed and modelled residual SSH has a correlation of 0.77 at Qaqortoq. In Ittoqqortoormiit, the tidal signal is weaker and therefore SSH fluctuates less. The model replicates observed SSH fairly well in Ittoqqortoormiit, with a residual SSH correlation of 0.84. In Upernavik, there is not enough data for a confident analysis and tidal calculation. For the month of August 2023 where there is data, the model generally reflects the trend of observed SSH. Observed and modelled residual SSH has a correlation of 0.68. At Pituffik, the model slightly overestimates high and low SSH compared to observed high and low SSH, but otherwise it performs well, with modelled and observed residual SSH with a correlation of 0.90.

At locations with long time-series and a pronounced tidal component (Nuuk, Qaqortoq and Pituffik), the model appears to perform better just after neap tide as tides are increasing, and slightly worse just after spring tide as tides are decreasing. Furthermore, there are seasonal variations in the residual SSH difference between the two models. In winter, the residual mean difference is positive, indicating that in winter, HYCOM-CICE underestimates observed SSH. In summer the opposite is the case where residual mean difference is negative, indicating that HYCOM-CICE overestimates residual SSH.

A storm event on the 14-15th November 2019 was observed in Ilulissat and Paamiut, and the same residual SSH increase is observed at tide gauges in Nuuk and Qaqortoq. The model is able to simulate the increased residual SSH well in Nuuk and Qaqortoq, although HYCOM-CICE generally underestimates residual SSH at Qaqortoq, a trend that is evident at Qaqortoq for the time-period January 2019 to July 2022. This might be an effect of observational bias. The timing of the residual SSH increase along with the magnitude of the residual increase on the other hand is very well reflected in the model.

In order to confidently conclude the applicability of the model for forecasting of storm surge events, longer model-runs are necessary. With longer modelled SSH time-series it will be possible to do extreme value analysis of both observed and modelled SSH, and thereby compare the modelled and observed return-times of same-magnitude events. Additional tide gauge stations providing continuous SSH measurements would allow for assimilation in more cities, thus improving performance of the model.
Furthermore, for a storm surge warning system in Greenland we want to underline the necessity to include local experience and conditions in order to determine local warning criteria for each city. It will benefit the validity of the model to explore its performance in additional storm surge events, but to do that it will be necessary to talk to specific communities and learn about additional storm surges and their severity. This effort is worth exploring, as the results of this report indicate that the readily available and already operational HYCOM-CICE model-setup is able to simulate storm-surge events in Greenland.

6 Acknowledgements

This work was supported by the GrønSL project, funded by Jens Smeds Oceanografiske Fond. Tide gauge data was kindly provided by Ole Bjerregaard Hansen, DTU Space, who continuously maintain and collect data from the stations in Greenland. Jian Su, DMI, has reviewed and provided important feedback on the report.

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