ASSESSMENT OF FUTURE REGIONAL CYCLONE AND EXTREME WAVE CLIMATE IN THE BALTIC SEA

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INTRODUCTION

Cyclonic activity in the mid-latitudes during the winter months (i.e. extratropical cyclones; ETCs) are the main hazard drivers in the Baltic Sea region. Aside from wind damage, they are known for causing significant changes to coastlines through surge and high energy wave impacts (Mäll et al. 2020). Changes in the future ETC climatology in Europe has been the subject of many studies, though findings by the end of 21st century still retain a level of uncertainty. Most recent studies suggest that the North Atlantic storm track is projected to extend further into Europe (e.g. Priestly & Catto, 2022). While shifts in future ETCs have been widely researched, there are not many that utilize bias-corrected general circulation model outputs (although use of cyclone compositing and ensemble approach have increased). In addition, the future storminess characteristics have found little direct translation into regional and local coastal risk assessment, which is made difficult by the relatively coarse resolution of climate models. This study aims to further elaborate on the potential future pathways based on downscaled bias-corrected general circulation models and numerical wave model.

STUDY AREA

The study area includes the Baltic Sea and its surrounding countries. This area experiences frequent winter cyclones approaching from southwest. Due to the cyclone propagation angle, historically most of the extreme surge and wave events have concentrated towards the eastern side of the Baltic coast. For instance in 2005 January 9 an ETC named „Gudrun" in the Nordic countries, caused a 2.75 m storm surge in the Pärnu Bay, Estonia and caused substantial changes in the coastal geomorphology, especially along the coasts that were exposed to winds and waves (Tõnisson et al. 2008).

DATA AND METHODS

The core datasets include the sea level pressure data from ERA5 (1981-2010) and from 18 bias-corrected general circulation models (bGCMs; hist: 1981-2010, future: 2041-2100). The bGCM includes two future scenarios: SSP245 and SSP585 with a 1.25deg x 1.25deg horizontal resolution, while temporal resolution is 6-hourly. The future data was split to 30 year segments (2041-2070 and 2071-2100). Historical ERA5 was regridded to match the resolution of bGCMs and include only every 6th hour. This is to analyse the historical performance of bGCMs and have a more standard baseline for objective comparisons. For both datasets cyclone tracks were detected and tracked by following Flaounas et al. (2023; M02). Only cyclones that reached minimum sea level pressure (MSLP) 980 hPa or less and had a lifetime longer than 1 day, were considered. The analysis focused on the colder half of the year (start of October to end of March) to include a wider range of possible ETC event occurrences (for instance some notable recent events occurred in the months of October, November and February/March; Mäll et al. 2020). The second part includes direct downscaling of bGCMs with the Weather Research & Forecasting model (WRF). The target horizontal resolution for Baltic Sea (child domain) is 4 km at 1-hourly temporal resolution. These results will be used to drive select extreme events from the future scenarios with a Simulating WAves Nearshore (SWAN) numerical wave model.

RESULTS AND DISCUSSIONS

The results shown in Fig.1 consider only cyclones that were tracked between the months of October and March (including) for all the sea level pressure readings between 961-980 hPa. Other ranges with 20 hPa segments include up to 1000 hPa, and as low as 921 hPa (not shown here) to further distinguish between different intensity levels and their respective shifts within the Baltic Sea region. In this area the 961-980 range is relatively good indicator of cyclones impact. For instance, the more recent extreme ETC events in the region, 2005 Gudrun and 2013 St. Jude had central pressure levels around 961 and 970 hPa, respectively, during their passage over the Baltic Sea. The SSP 30-year segments are relative to bGCM historical (1981-2010) track data. Notably all the tracks crossing the region had a significant increase in pressure readings within the specified range, where 3 of them had a 24-27% increase, while the SSP585 (2071-2100) had a 35.3% increase. While most had some slight variations in the spatial density shifts, the results indicate a density increase in most of the Baltic Sea region (higher density increase in the central region).

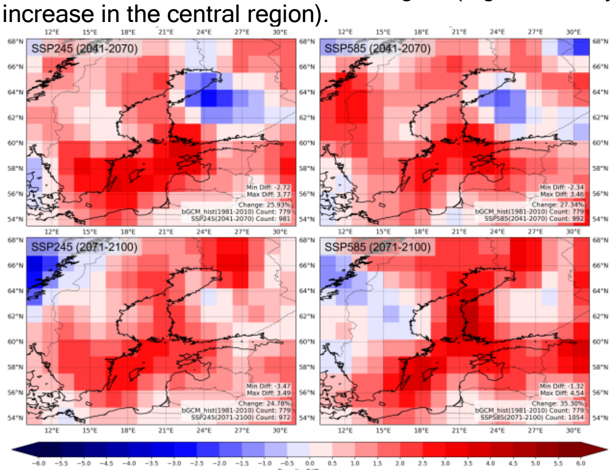

Figure 1 - ETC track pressure range (961-980 hPa) density differences between bGCM historical (1981-2010) and future SSPs (2071-2100) over the Baltic Sea region during Oct-March.

Notably the density increase of such occurrences in the SSP585 (2071-2100) is the highest around Southwest Finland (location around where also the 2005 ETC Gudrun passed), a cyclone location with high potential for destructive storm surge and wave action along the Estonian coast. Similarly, as noted by previous studies (e.g. Mäll et al. 2020, Priestly & Catto, 2022) it is possible that under the most severe future scenario (RCP8.5/SSP585) strong wind fields of extreme cyclones can elongate their area of effect. Fig. 2 on the other hand shows the changes in MSLP location and spatial intensity for bGCM historical track data and SSP585 (2071-2100). For instance, in general there is a 6.4% increase in cyclone events reaching the study area, and 3% increase in the intensity (that is, lower MSLP) in the strongest 10% of cyclone events (see also Table 1). These findings indicate that more extreme events will reach their pressure minima (within the study domain) over the Baltic Proper. However, in all the SSP scenarios more cyclones reach the area and tend to have a slight increase in their pressure minima. Further, the increase in the density of lowest pressure timings over the Baltic Proper have the potential to increase the frequency of events such as the 2005 Gudrun and 2013 St. Jude.

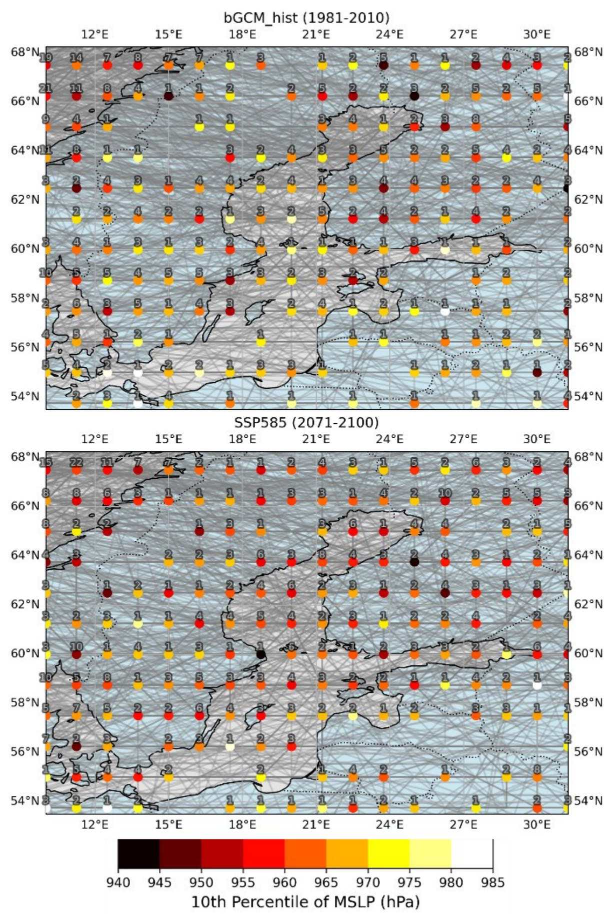

Figure 2 – 10th percentile maps of minimum sea level pressure (MSLP) of ETCs within the study area. The inside circle shows the MSLP 10th percentile value, while the number count shows how many tracks reached their MSLP in that location.

Table 1. Unique cyclone events and their statistics within the study domain. Percentiles are based on MSLP (hPa) values inside the domain only (not full track). SSP changes are relative to bGCM historical, while latter is relative to ERA5 coarse.

Case	Events	Change (%)	10th %ile	25th %ile
ERA5_coarse	616	-	967.9	973.8
bGCM_hist	560	-9.1	964.8	973.4
SSP245 (2041-2070)	615	9.8	963.0	971.1
SSP585 (2041-2070)	586	4.6	963.6	972.1
SSP245 (2071-2100)	606	8.2	963.3	970.9
SSP585 (2071-2100)	596	6.4	961.8	970.3

CONCLUSIONS

The marked shifts in ETC spatial intensity distributions would have large impacts on the extreme wave climate and increase in the frequency of high risk storm surge events in the Baltic Sea region. The low-pressure event occurrence increase (941-960 hPa range) in the Baltic Proper also suggests that the wave extremes are likely shifted towards more central and southern sections of the Baltic Sea coasts. This in conjunction with the relative sea level rise (higher in southern sections) can pose increased coastal risk management implications along the southeast coastlines which are mainly characterized by low-lying fine sediment beaches. Further research is being carried out to elaborate on such implications.

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