A GLOBAL VIEW OF THE IMPLICATIONS OF WAVE CLIMATE EXTREMES ON SUSTAINABLE SHIP DESIGN AND OPERABILITY: A REVIEW

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SUMMARY

Under a changing climate, with the potential for increased storminess and the likelihood of more extreme atmospheric temperatures, it will become increasingly prudent to consider the implications of extreme wave and weather conditions on maintaining safe and effective operations for the required lifespan of a vessel. In this paper, we explore the current status of operational design versus oceanographic and meteorological variables within ship design and operability, with a focus on wave characteristics and cyclones as these are of concern for a ship's stability, structural integrity, operations and manoeuvrability. We then illustrate the latest IPCC (AR6) projections and provide evidence from scientific literature for oceanic extremes (significant wave height, extreme wave height, wave power, storm intensity, storm frequency, storm tracks and wind speeds) across the globe for the typical lifespan of a vessel. By comparing existing approaches to the use of oceanographic variables in ship design criteria, with how these variables may change under future climates, we will provide recommendations for continued development and further research towards maintaining safe (structural and stability) and effective (energy efficient/economical) operations within the context of the physical effects of climate change.

NOMENCLATURE

ρ	Density of water (kg m^{-3})
H_s	Significant Wave Height (m)
T_z	Mean wave period (s)
T_{sd}	Standard deviation of wave period (s)
H_x	Extreme design wave height (m)
E	Wave energy (Nm^{-2})
g	Acceleration due to gravity ($9.81ms^{-2}$)
h	Water depth (m)
k	Wave number ($\frac{2\pi}{L}$) where L = wave length (m)
RCP	Representative Concentration Pathway
SSP	Shared Socioeconomic Pathway
IPCC	Intergovernmental Panel on Climate Change

1. INTRODUCTION

In the face of a changing climate, the maritime industry must adapt to the weather conditions of the future to ensure the safety and efficiency of ship operations. This paper explores the current status of ship design and operability in relation to oceanographic and meteorological variables, highlighting the importance of integrating climate resilience into naval ship design. By examining the latest projections from the Intergovernmental Panel on Climate Change Sixth Assessment Report (IPCC AR6) and reviewing scientific literature on oceanic extremes, we aim to contribute to the wider understanding of how future climate scenarios may impact ship design criteria and operational limits.

The rationale for this paper stems from the need to address the implications of climate extremes on sustainable ship design and operability. With the potential for increased storminess and more variable atmospheric temperatures, how these conditions will affect the safe and effective operations of vessels throughout their lifespan warrants consideration. As western economies are actively seeking to modernise their naval fleets to address evolving security challenges and maintain maritime superiority, there are opportunities to enhance the durability and performance of naval assets in the face of potentially changing environmental conditions.

1.1 CURRENT STATUS OF SHIP DESIGN IN THE CONTEXT OF WAVE CLIMATE PROJECTIONS

The United Kingdom Royal Navy has announced a three-phase approach to climate change and sustainability, with plans since 2022, to build 150 vessels over the next 30 years (Ashbridge and Beard, 2022). The Ministry of Defence (MoD) Defence Equipment and Support (DE&S) organisation has three key environmental commitments. The first being 'Mitigating and Adapting to Climate Change' which includes 'Implementing interventions to reduce greenhouse gas emissions and enable operation in a climate changed environment.' (Defence Equipment and Support, 2024). The three commitments are to be delivered and assessed against multiple outcomes, the most relevant being Outcome 4: ensure changing environmental conditions resulting from, for example, climate change and environmental degradation are recognised, and due diligence is applied when procuring, designing, and supporting Products Systems and Services (PSS) to ensure that it is resilient to changing environmental conditions and can therefore maintain operational capability (Defence Equipment and Support, 2024). Other Navies are also seeking to modernise; under the United States Navy's 2025 shipbuilding plan, total fleet size will increase from 295 today to 390 in 2054 (Congressional Budget Office, 2025), and in 2024 the Australian Government announced plans for 55 new vessels (Australian Government, 2024). Importantly, these modernisation processes offer many opportunities to incorporate climate resilience, ensuring that ships are suitable for their entire lifespan.

Operational ship design describes the process through which ships can be designed for efficient and safe operation for their lifespan, currently a period of typically 25 to 50 years. Severe weather events can contribute to loss of life, injury and damage to ships and in extreme cases, loss of the vessel. During a study of naval accidents during the 1945 to 1988 period, it was determined that there had been 65 publicly available documented accidents involving adverse weather conditions, impacting 107 different ships (Arkin and Handler, 1989). To ensure ships are sufficiently resilient, naval architects and marine engineers design for specific operational requirements and to a specific range of environmental conditions. This process has become more regulated as design standards have changed with time, evolving through operational experience, lessons learned, and technological advancements. For example, prior to the 1980s, the consideration of environmental conditions in United States Naval ship design was quite limited (Bales, 1983). Technological advancements have understandably had a significant impact on the ship design process. Since the 1990s, the testing of ship resilience has been increasingly aided by computer analysis and can be carried out throughout the design process (Ashe *et al.,* 2006). However, as the maritime domain is particularly susceptible to the effects of climate change, there is a level of uncertainty regarding the suitability of the existing environmental conditions used for design criteria. There is concern regarding rising sea levels, storm frequency, storm severity and altered wave patterns, which may pose threats to naval infrastructure and operations (Mihailov and Ichim, 2024). The effects of climate change may be compensated for by adjusting routes based on improved weather forecasts (Bitner-Gregersen *et al.,* 2018). For naval ships it is not always possible to adjust routes or operations based on forecasts, which still hold levels of uncertainty (Petacco and Gualeni, 2023). In fact, naval ships are often required to operate in locations outside of shipping routes and in areas where limited ship operations are conducted.

The standards for operational ship design are set by a variety of organisations. Environmental loads do not substantially differ between the naval and commercial sectors, but the operational profiles do (Ashe *et al.,* 2006), with the requirement for military vessels to be capable of withstanding higher sea states without compromising their military or support capabilities. Globally, the International Maritime Organisation (IMO), a specialised agency of the United Nations, are the standard-setting authority for the safety, security and environmental performance of international shipping. Every commercial ship should have a registered flag state which enacts the IMO regulations, which can authorise Classification Societies to act on their behalf, carrying out statutory survey and certification duties. Additionally, individual Classification Societies develop and apply technical standards for the design, construction and survey of ships. There are currently more than 50 of these societies worldwide (IACS, 2025). Lloyd's Register is one example of these societies, which published the first set of naval rules for the design, construction and classification of ships in 1998 (Ashe *et al.,* 2006). Reference to climate change is not systematically included in Classification Societies rules, most likely due to uncertainties associated with climate change projections (Bitner-Gregersen *et al.,* 2018), yet to enable improved design and operational criteria, these uncertainties need to be quantified, and updates made to current guidance (Bitner-Gregersen *et al.,* 2018).

Currently, many navies rely on external organisations for ship design and construction, making the regulation of design through Classification Societies even more important (Ashe *et al.,* 2006). The North Atlantic Treaty Organisation (NATO) is a key organisation, who act as an intergovernmental transnational military alliance and publish the Naval Ship Code. The Naval Ship Code, developed by the International Naval Safety Association (INSA), is applicable to all surface naval craft, coastguard, and other vessels operated by a government which are not for commercial purposes. It provides a consistent framework to parallel the IMO and process of flag states for commercial ships. Each commercial ship should have a registered flag state which can authorise Classification Societies to act on their behalf, carrying out statutory survey and certification duties. The goal-based framework within the Naval Ship Code allows for ships to be certified as safe to operate (International Naval Safety Association, 2019). Individual naval administrations also set their own standards, often building upon NATO frameworks. These present an opportunity to implement specific protocols and personalised approaches. In the United Kingdon, the Defence Standards, a set of technical specifications, are published by the MoD (UK Defence Standardization, 2025).

Key guidelines for ship design in the context of wave climate are the Allied Naval Engineering Publication 77 Part 1 Edition G Version 3 (ANEP 77), the NATO Standardisation Agreement No. 4194 (STANAG 4194) Edition 1 and the Lloyd's Register Rules and Regulations for the Classification of Naval Ships (NSR 2024). ANEP 77 is part of the Naval Ship Code, outlining goals, functional objectives and performance requirements, dated July 2019. The Naval Ship Code has been developed in consideration of risks and issues that may impact on safety (International Naval Safety Association, 2019). This includes the development of high-level goals that need to be addressed through the application of technical standards (International Naval Safety Association, 2019). For example, Regulation 3 in Part 1 Chapter II 'Structural Design' outlines the following goals:

> *3.13 As a minimum it is mandatory to assess the structural capacity of all ships when subjected to the following demands:*
> *3.13.1 Above water: Wind, air temperatures (high and low), ice accretion, solar radiation.*
> *3.13.2 Sea surface: Waves, green seas, ice navigation, ship motions (including slamming).*

STANAG 4194, a longstanding document, is aimed to establish a common source of wave and wind data for NATO operational areas. It also provides NATO sea state summaries (Table 1) to categorise sea conditions for the North Atlantic Ocean (North Atlantic Treaty Organization and Military Agency for Standardization, 1983). These values were produced using a 20 year hindcast climatology database that was in development by the United States Navy from 1976 (North Atlantic Treaty Organization and Military Agency for Standardization, 1983).

Table 1. NATO sea state numeral table for the open ocean North Atlantic (North Atlantic Treaty Organization and Military Agency for Standardization, 1983)

Sea State Number	**Significant Wave height (m)**		**Sustained Wind Speed (Knots)**		**Percentage probability of sea state**	**Modal Wave Period (sec)**	
	Range	Mean	Range	Mean		Range	Most probable
0 -1	0 – 0.1	0.05	0 - 6	3	0.7	-	-
2	0.1 – 0.5	0.3	7 - 10	8.5	6.8	3.3 – 12.8	7.5
3	0.5 – 1.25	0.88	11 - 16	13.5	23.7	5.0 – 14.8	7.5
4	1.25 – 2.5	1.88	17 - 21	19	27.8	6.1 – 15.2	8.8
5	2.5 - 4	3.25	22 - 27	2.5	20.64	8.3 – 15.5	9.7
6	4 - 6	5	28 - 47	37.5	13.15	9.8 – 16.2	12.4
7	6 - 9	7.5	48 - 55	51.5	6.05	11.8 – 18.5	15.0
8	9 - 14	11.5	56 - 63	59.5	1.11	14.2 – 18.6	16.4
>8	>14	>14	> 63	> 63	0.05	18.0 – 23.7	20.0

NSR 2024, dated January 2024, Volume 1 Part 5 Chapter 2 outlines the environmental conditions including wind, wave, currents, ice and thermal conditions that should be applied in the derivation of loads (Lloyd's Register, 2024). Oceanographic conditions are particularly important for use in calculations of ship structural strength and stability. Waves have the largest impact on load and response calculations in ship design (Bitner-Gregersen *et al.,* 2013). The environmental conditions used are derived from hindcast data, long term measurements and theoretical studies complemented with service experience (Lloyd's Register, 2024). The sea state definitions match that of STANAG 4194 (Table 1). Wave environmental data depends on the service area (SA) that the ship will operate in (Table 2). For example, SA1 refers to ships that have unrestricted global operations and SA2 is primarily for ships that will operate in tropical and temperate regions, these extents are shown in Figure **1** (Lloyd's Register, 2024).

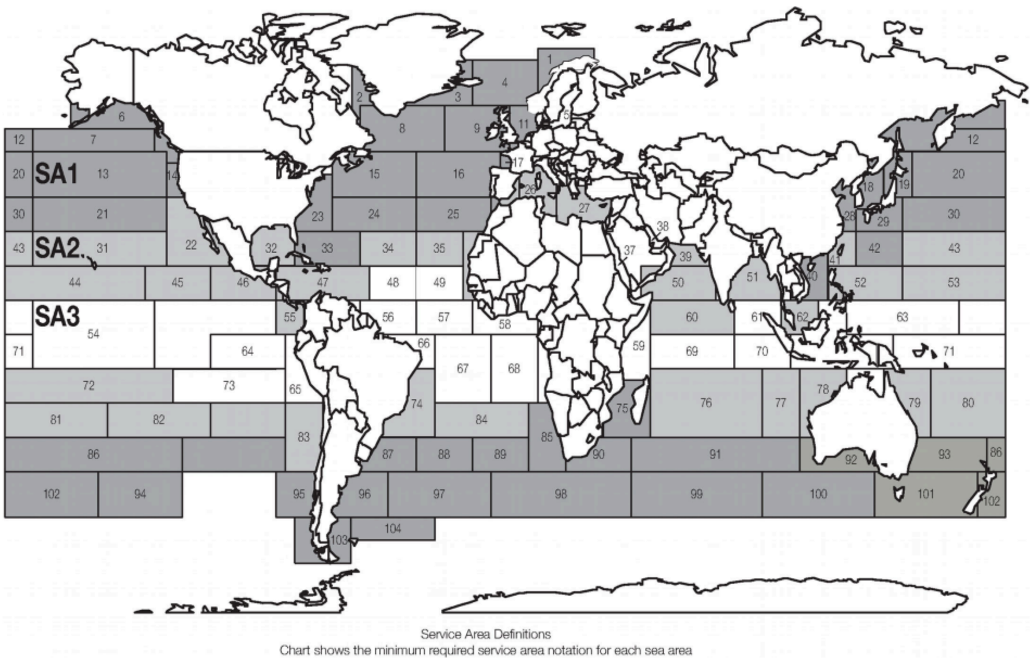

Figure 1: Map showing sea areas (numbers) and corresponding Service Areas (SA) (Lloyd's Register, 2024)

Table 2. Environmental wave data for each service area (Lloyd's Register, 2024)

Service Area Notation	**Wave height for the service area, m**	**Mean wave period, seconds**	**Standard deviation of wave period, seconds**	**Extreme design wave height, m**
	H_s	T_z	T_{sd}	H_x
SA1	5.5	8.0	1.7	18.5
SA2	4.0	7.0	1.7	13.5
SA3	3.6	6.8	1.7	9.5
SA4	2.5	6.0	1.5	6.0
SAR	*To be specially considered*			

1.2 CURRENT STATUS OF OPERATIONAL LIMITS AND THRESHOLDS IN THE CONTEXT OF WAVE CLIMATE PROJECTIONS

In the context of naval ships, operational limits are the predefined thresholds that define the boundaries within which a ship can safely operate. These limits can include environmental conditions, vessel motion and structural stresses. When these thresholds are exceeded, the ship may be unable to maintain its stability, performance, and its overall integrity may be at risk. These limits are usually set during the design phase and then used onboard to guide operational processes, linking the two phases. Ship design criteria assume that the crew possesses a predetermined level of expertise (Bačkalov *et al.,* 2016). Additionally, during the design phase, assessments on ship stability are carried out to fulfil requirements set by design rules (Petacco and Gualeni, 2023). Traditionally, these assessments are often based on static equilibrium conditions, and investigations on ship motion in waves focus primarily on the vertical motions (Petacco and Gualeni, 2023).

One example of guidelines on the operational limits and thresholds for vessels are the Second-Generation Intact Stability Criteria (SGISC), which were approved by the IMO in 2020. This second generation of guidelines were required due to advancements in computer technology which had occurred following the 2008 Intact Stability Code (International Maritime Organization, 2020). The SGISC includes information on vulnerability criteria, direct stability failure assessment and operational measures (limitations and guidance) (International Maritime Organization, 2020). Operational guidance (sitting within operational measures) is particularly relevant to the current status of limits and thresholds. To summarise, it identifies a set of assumed dangerous situations for each sea state (Petacco and Gualeni, 2023). These assumed situations are defined by the combination of environmental parameters such as wave height and the vessel condition (Petacco and Gualeni, 2023). It is important to note that within the SGISC, this concept is covered in more detail and has various approaches.

The implications of climate change go beyond the physical design of the ship, as vessel safety also depends on the operational processes in place. These operational processes guide crew in their decisions and actions when faced with extreme conditions. Modern technology enhances these processes. Decision support systems can be integrated with extreme weather warning criteria to offer timely, actionable advice, enabling crews to react quickly and appropriately during challenging scenarios (Bitner-Gregersen *et al.,* 2013; Bačkalov *et al.,* 2016). Real-time sensor inputs further enhance onboard safety and operability by continuously measuring key environmental factors such as wave height, wind speed, and the ship's motion. These sensors provide immediate feedback that informs crew decisions but can be used to adjust operational strategies if required (Ferrier *et al.,* 2022). Consequently, operational processes can be adjusted dynamically based on real-time environmental conditions and predictive analytics. This capability is critical in the face of extreme weather or changing climate conditions.

1.3 GLOBAL WAVE CLIMATE PROJECTIONS

When considering sustainable ship design and operability in the context of how oceanic states are and will become altered under a changing climate, we can consider a number of different oceanic variables and parameters that enable us to quantitatively and qualitatively describe changes to wave characteristics. Due to the influence wave climate has on the fate of the coastal zone, infrastructure, offshore energy, global transport and operations, numerous global and regional studies have been conducted in the last few decades since AR5 (IPCC, 2014), and the recent AR6 (IPCC, 2023), attempting to forecast how wave characteristics are likely to alter with climate change. Here, we assess how the literature (mostly since IPCC AR5 and the recent AR6) has influenced our understanding of global wave climate.

Some global wave climate studies have focussed on changes to significant wave height as a measure of changing wave climate (the average height from trough to crest, of the highest-one third of the waves (H_s)), for extreme wave climate and average wave climate, including return values. Others have characterised how wave energy flux or wave power (the rate at which wave energy is carried by moving waves) and the intensity, frequency and tracks of tropical cyclones have varied over the last few decades and how they are projected to vary in the future. The IPCC reports provide recommendations in terms of large-scale global adaptation and resilience for a wide range of climate related risks across a variety of different sectors. The IPCC AR6 also provides recommendations for the transport and shipping sector (Jaramillo *et al.,* 2022), which we refer to here, as no recommendations are made for the Defence sector.

The latest Intergovernmental Panel on Climate Change, Physical Science Basis Sixth Assessment Report highlighted how anthropogenic climate change has altered a range of observed oceanic variables over the last 30-40 years (IPCC, 2023). In the context of intensity of extreme wave climate changes, extreme wave heights have been found to have increased in the Southern and North Atlantic Oceans by around 1.0 $cmyr^{-1}$ and 0.8 $cmyr^{-1}$ (Young and Ribal 2019) since the mid- 1980's (Collins *et al.,* 2019). It was found with high confidence that observed extreme sea level events associated with tropical cyclones has increased the intensity of multiple extreme events and associated cascading impacts. The report found with low confidence that a poleward migration of maximum tropical cyclone intensity in the North Pacific has been related directly to anthropogenically-forced tropical expansion. Under RCP 8.5 (Representative Concentration Pathway high emissions scenario) the report projects, with high confidence, an increase in significant wave height (H_s) across the Southern Ocean, tropical eastern Pacific and Baltic Sea (with medium confidence), yet a decrease in the North Atlantic and Mediterranean Sea. A global and regional scale wind-wave review study (Morim *et al.,* 2018) found there was a general consensus across 91 different sources, that H_s would increase over the Southern Ocean, tropical eastern Pacific and Baltic Sea and decrease in the North Atlantic and Mediterranean. Sea ice loss was also found to lead to a positive trend in significant wave height in the Arctic between 1994-2014 (Stopa *et al.,* 2016; Thompson *et al.,* 2016). Overall, there is general agreement in the literature on how significant wave height is projected to change with climate change.

1.3 (a) Mean and significant wave height

There are clear regional dependencies of annual averaged and extreme wave hight changes from present to future (Mori *et al.,* 2010). It is anticipated that generally, the Southern Ocean, Eastern Tropical Pacific and Arctic Oceans will face the greatest changes in wave height. Mean wave height is projected to increase by 1-3 $cmyr^{-1}$ in the Southern and Arctic Oceans with extremes increasing by >10 $cmyr^{-1}$ in the Arctic (Casas-Prat *et al,* 2024; Jaramillo *et al.,* 2022; Morim *et al.,* 2018). By 2100, the mean wave height is projected to rise by 5-10% in the Southern Ocean and Eastern Tropical Pacific and by >100% in the Arctic Ocean. Wave heights are projected to increase at mid-latitudes and in the Antarctic Ocean, decreasing at the equator (Mori *et al.,* 2010). There is also overall agreement in the literature that reductions in mean wave height are projected, by up to 10% in North Atlantic and North Pacific with regional variability and uncertainty (Casas-Prat *et al.,* 2024). Analysing changes in H_s return values compared with annual mean H_s values, enables a view on how extreme waves undergo changes that may be linked to climate change (Lobeto *et al.,* 2021). Return values for H_s reflect the same pattern globally. Under the RCP8.5 scenario, the highest increase in extreme H_s is projected in the Southern Ocean with local increases in over 2 m regardless of return period. In the tropical North Pacific, a decrease in extreme H_s with local decreases of 1.5 m. In the SE Indian, NW Atlantic and NE Pacific Oceans and increase in extreme H_s return values, however a decrease in annual mean H_s was also projected (Lobeto *et al.,* 2021). A detailed study (Mori *et al.,* 2010) predicting future wave climate based on the atmospheric general circulation model and global wave model focuses on present and future climate for both average and extreme wave conditions. Exploring smaller scale regional patterns, they found that wave heights are likely to increase at mid-latitudes and in the Antarctic Ocean, decreasing at the equator. They also project that using the normalised difference between the future and present climate (future minus present divided by present), the future mean *Hs* for the Pacific Ocean will decrease along the equator by 7%, corresponding to a 0.1 m decrease in average *Hs.* In the latitude range of 30˚N – 40˚N in the North Pacific and North Atlantic will decrease by 7%, corresponding to a 0.15 m decrease in average *Hs*. Conversely, in the Antarctic, there is likely to be an increase in average *Hs* by 6-9%, corresponding to a 0.2 m increase (Figure 2). The results showed a latitudinal dependence in the future daily wave climate, where mid-latitudes will experience lower mean wave heights and higher wave heights at higher latitudes.

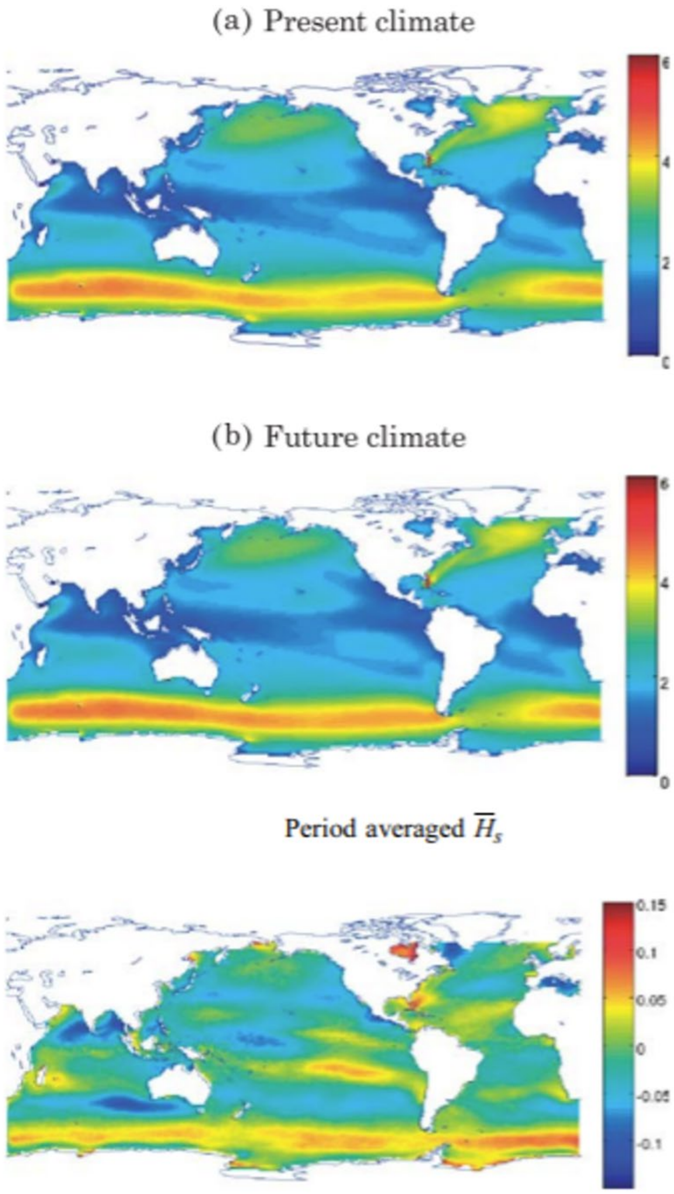

Figure 2: Present climate H_s *(m)*, Future Climate H_s *(m)*, and the difference of the mean H_s *(m)* between future minus present climate normalised by present climate (Mori *et al.,* (2010)).

1.3 (b) Wave energy Flux/ Wave Power

Using wave power or wave energy flux, as opposed to significant wave height alone, has been suggested as being a more appropriate means of characterising long term wave behaviour (Reguero *et al.,* 2019) as it measures the transport of energy by air-sea exchanges and therefore takes into account factors that employ wave motion, for example sea surface temperature. Wave power is a function of the square of the wave height (eqn 1), therefore a 1% annual increase in significant wave height will translate to a 2% increase in wave power per year. For example, multi-model ensemble of wave climate projections indicates changes in mean H_s of 7.1% globally, 10% in the Southern Ocean, which equates to an increase in wave power of 20%. Another example, using W10 (wind speed measured at 10 m height above surface) an observed 0.54% annual increase in upper ocean warming over the past 70 years has led to a 0.5 m increase in H_s causing a boost in wave power by 32.8 kWm^{-1} (Chen, 2024). This implies if current warming trends continue, this will lead to greater energy levels in the world's oceans.

$$P = EC_n \qquad \textit{eqn 1}$$

where wave energy E is given by

$$E = \frac{1}{8}\rho g H^2 \qquad \textit{eqn 2}$$

And wave group velocity (C_g) is related to the speed of individual waves C_n by

$$C_g = C_n \qquad eqn\ 3$$

Where the parameter *n* increases from 0.5 to 1 in deep to shallow water and is given by

$$n = \frac{1}{2}\left[1 + \frac{2kh}{\sinh{(2kh)}}\right] \qquad eqn\ 4$$

The parameter *n* describes how deep-water waves travel at twice the speed of the wave group (*n=0.5)* and shallow water waves propagate at the same speed as the wave group (*n=1*) (Masselink and Hughes, 2003).

As wave power measures the transport of energy (EC_n), upper ocean warming: a consequence of anthropogenic global warming is creating waves with greater power. It is therefore a valuable climate change indicator, and the long-term signal of systematic sea surface temperature increase behaves similarly to the increase in global wave power, yet a global time series of such a valuable variable is undetermined (Reguero *et al.,* 2019). Wave climate projections for the end of century indicate that sea surface temperature warming in the tropical Pacific will lead to increases in wave heights and wave energy levels at mid-high latitudes over Southern Ocean and Central North Pacific as SAM ENSO and NAO intensify. Measuring wave energy flux also requires information on wave period and as wave periods have also been increasing over the period of 1985-2008, this will influence the measure of global wave power, which was found to increase globally by 0.4% per year over this period (Figure 3). Similar results were found by Chen (2024) where an increase of 0.54% annually in global wave power was found between a 70-year period between 1957-2020. Looking forward, this study projects a 30% increase in wave energy flux at a 100-year return level for the majority of coastal areas in the southern temperate zone and higher in the open ocean, by the end of the century.

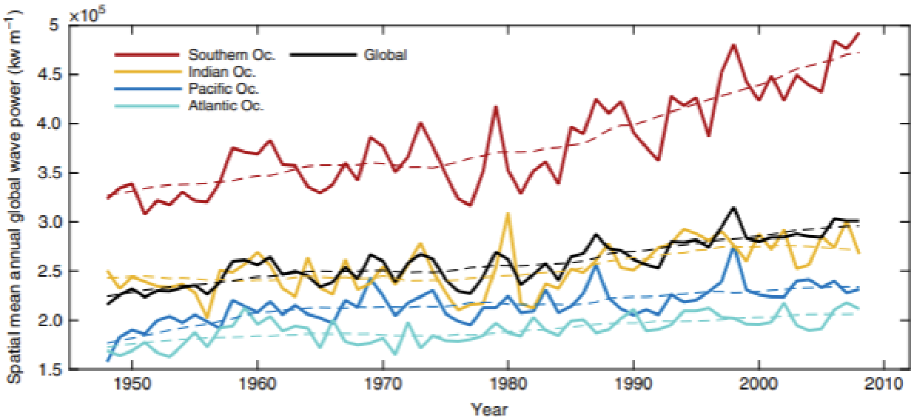

Figure 3: Spatial mean annual wave power (kwm^{-1}) calculated globally and by ocean basin. Dashed lines show 10-yr moving average, solid lines indicate each time series (Reguero *et al.,* 2019).

Using the longest reanalysis available 1940-2022 (ERA5) taken from multiplatform satellite altimeters, Lui *et al.,* (2024) evaluate the long-term variability of global wave power and the underlying mechanisms. They highlight, as others, a consistent increase in global wave power over this period, stemmed from the influence of global climate change and the intensification of Antarctic Oscillation events. This study highlights the increases projected in the southern hemisphere, where low pressure systems moving southwards are likely to generate an increase in global wave power 2.6 times larger than the global average increase in wave power. Interestingly, examining the wind-wave and swell contributions to wave power, they find the wind-waves are more important in the Southern Ocean than in low and mid-latitude regions, whereas the swell component of the wave power is less important.

1.3 (c) Tropical Cyclone Intensity and Frequency

As well as general global wave climate, variability in tropical storm tracks and intensity play a crucial role in an understanding of sustainable ship design and operability. Warming of the ocean surface by human causes is likely to lead to more powerful tropical cyclones (Knutsen *et al.,* 2021). Along with precipitation rates increasing with more moisture content in the atmosphere due to global warming, rapid intensification, the poleward migration of the latitude of maximum intensity and the slowing of forward motions of tropical cyclones have been observed. Although most climate models however project a decrease in the total number of tropical cyclones per year, the proportion of category 4 and 5 tropical cyclones is too likely to increase (Knutsen *et al.,* 2021). Under RCP 8.5, global atmospheric trends, which drive such changes were found to show that the northern hemisphere mid latitude jet has migrated polewards since the 1980's leading to poleward migration of TC's as well as poleward migration of storm tracks seen in the southern hemisphere over the last few decades. There is high likelihood that the mid latitude jet will continue to shift polewards and strengthen, leading to subsequent strengthening of storm tracks in the southern hemisphere by 2100. There has been a marked increase in the proportion of intense tropical cyclones (TC's) over the last 40 years and there is high confidence that this proportion is likely to continue to increase, yet the global number of TC's is likely to decrease or remain the same. The proportion of major TC's (Cat 3-5) and the frequency of rapid intensification has increased over the last 40 years. The average location of the peak TC wind intensity, which has consequences for wind-wave interaction, has likely migrated polewards in the western North Pacific since the 1940's. There is high confidence that as average TC peak wind speeds will increase with global warming, the peak wind speeds of the most intense TC's will increase, leading to growth of larger waves. (IPPC, 2023). In a first attempt to quantify the magnitude of expected changes in extreme wave heights generated by tropical cyclones, Grossman-Matheson *et al.,* (2024) explore how historical and future tropical cyclone tracks generate wind fields and use this to force a model to estimate global H_s as a result of tropical cyclones across all tropical cyclone basins. They estimate 1–100-year return periods for *Hs* for historical and future changes under SSP 585 high emissions scenario. They project that in the next 25 years (by 2050) there will be an increase in the 100 yr H_s by up to 1.5 m (10%) in the Eastern and Western Pacific, Southern Indian and South Pacific Ocean basins, yet no consistent trend of increase in the North Atlantic and a decrease in the North Indian Ocean, largely the Bay of Bengal (Figure 4).

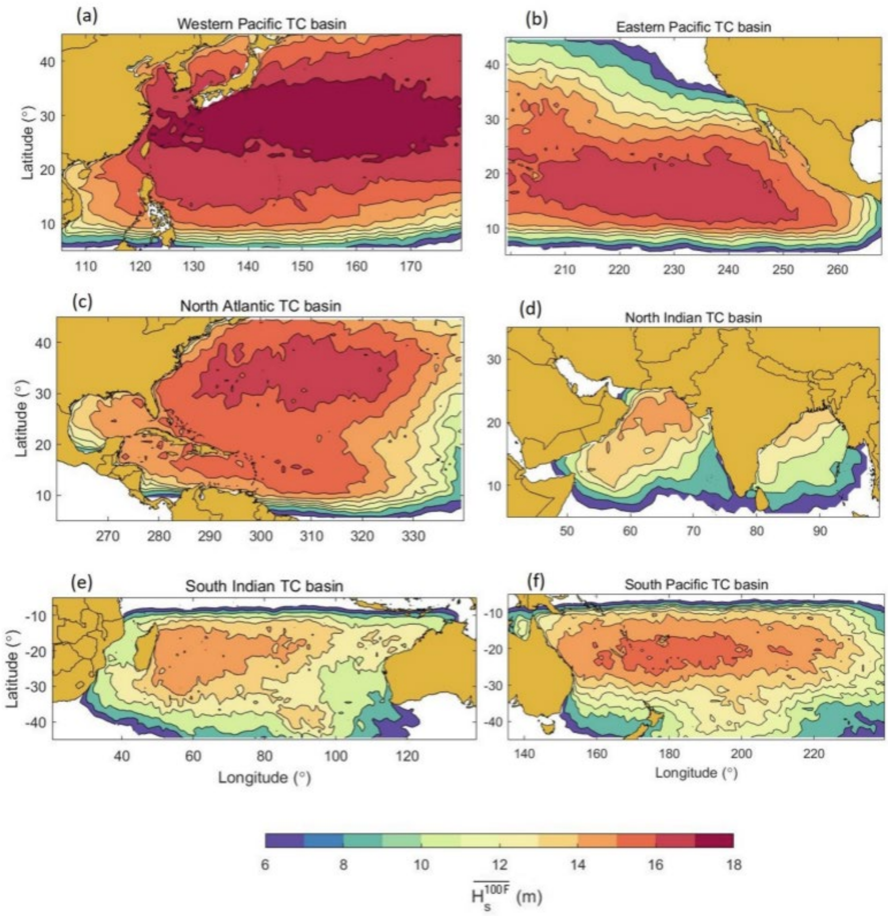

Figure 4: Contour values of projected future tropical cyclone ensemble median, 100-yr significant wave height (by the end of 2050 for SSP585) for each tropical cyclone basin (Grossmann-Matheson *et al.,* 2024).

2. DISCUSSION

Overall, there tends to be agreement within the literature that wave climate will increase and/or decrease in the same regions/oceanic basins (Table 3). Taking a global view on how wave climate is likely to alter under climate change naturally comes with a degree of uncertainty and generalisation. That said, it is understood, broadly speaking that average significant wave height and as a result, wave power are on the increase and will continue to increase in certain regions, i.e. Southern Ocean, Tropical and North Eastern Pacific and the Arctic Oceans. The degree of which varies regionally, but the greatest increase is likely to occur in the Southern Ocean (1-3 $cmyr^{-1}$). Conversely, it is agreed that a decrease in annual/average significant wave height is likely in the North Pacific, North Atlantic, Mediterranean Sea and Indian Ocean, however extreme significant wave heights in these regions will increase. Increases in extreme significant wave heights will be seen in all basins, apart from the North Pacific, where a decrease in 1.5 m is projected. The region facing the greatest extreme significant wave heights is again the Southern Ocean, where an increase in over 2 m is projected. Global wave power is likely to increase across all ocean basins with climate change, with the greatest increase 2.6 times more than any other basin, seen in the Southern Ocean.

Table 3. Summary of how wave climate is likely to change under climate change across different literature sources.

Oceanic Basin	Sea State Variables	Key findings	Reference
North Pacific	Future Mean H_s	Decrease closer to equator of 7% (0.1 m) 30˚N-40˚N Projected to decrease by up to 10 % / 1.5 m	Mori *et al.,* 2010; Casas-Prat *et al.,* 2024
	Extreme H_s	Projected to decrease by up to 1.5 m	Lobeto *et al.,* 2021
	North Eastern Pacific Extreme H_s	Projected to increase	Lobeto *et al.,* 2021
	Annual H_s	Projected to decrease	Lobeto *et al.,* 2021
South Pacific	Tropical Eastern Pacific H_s	Projected to increase By 2100 mean wave height projected to rise by 5-10%	IPCC; Morim *et al,* 2018; Mori *et al.,* 2010
North Atlantic	Extreme wave heights (over the last 30-40 years)	Increased by 0.8 $cmyr^{-1}$	Young and Ribal 2019; Collins *et al.,* 2019
	H_s	Projected to decrease by up to 10 %	IPCC; Morim *et al,* 2018; Casas-Prat *et al.,* 2024
	Extreme and Annual H_s	Projected to increase	Lobeto *et al.,* 2021
Mediterranean Sea	H_s	Projected to decrease	IPCC; Morim *et al,* 2018
Southern Ocean	Extreme wave heights over the last 30-40 yrs	Increased by 1 $cmyr^{-1}$	Young and Ribal 2019; Collins *et al.,* 2019
	H_s	Projected to increase	IPCC; Morim *et al,* 2018
	Mean wave height	Projected to increase by 1-3 $cmyr^{-1}$ By 2100 mean wave height projected to rise by 5-10%	Casas-Prat *et al.,* 2024; Jaramillo *et al.,* 2022; Morim *et al.,* 2018; Mori *et al.,* 2010
	Extreme H_s	Projected to increase by over 2 m	Lobeto *et al.,* 2021
	Wave power	Increase in wave power since 1948 Projected to increase 2.6 times larger than average global wave power increase	Reguero *et al.,* 2019

Arctic	H_s	Projected to increase	IPCC; Morim *et al,* 2018
	Mean wave height	Projected to increase by 1-3 cmyr^{-1}	Casas-Prat *et al.,* 2024; Jaramillo *et al.,* 2022; Morim *et al.,* 2018
	Extreme mean wave height	Projected to increase by >10 cmyr^{-1} By 2100 mean wave height projected to rise by >100%	Mori *et al.,* 2010
Indian	South East Indian Ocean Extreme H_s	Projected to increase	Lobeto *et al.,* 2010
	Annual mean H_s	Projected to decrease	Lobeto *et al.,* 2010

Both wave height and wave power are of concern for a ship's structural stability and integrity, operations and manoeuvrability. As noted previously, NATO Standardisation Agreement No. 4194 (STANAG 4194) among others, set out guidelines for design and operation standards for vessels. These are based on sea states as a function of wave height, wind speed and wave period. As wave power incorporates parameters such as wave speed and wavelength, not only significant wave height, it accounts for wave period, which has been increasing in line with wave height and is projected to continue to do so. Wave power is therefore a key indicator of climate change and is likely to be the predominant influence on propulsion and manoeuvrability and therefore efficiency and resilience and has a greater influence on the long-term maintenance and lifespan of a vessel. In light of this, and the projected global increase in wave power, these authorities may need to, in the future, address the influence of not only wave height and period but wave power, to determine guidelines for ship design (hull design and integrity, propulsion and stabilisation systems) and operations. The bending of a ship's hull on a wave has over time become updated to our increased understanding of waves. With the potential for more powerful and more frequent extreme waves to occur in the future, it will therefore be necessary for the characteristics used in global strength to be revisited. This will fall most likely to the classification societies that publish such rules. It may also be necessary to consider the characteristics used in the fatigue life assessments, where changes in the wave period and potentially wave power may impact. As well as considering future designs by adapting the rules sets, where current vessels are expected to remain in service for significant periods with operations that expose them to these more extreme conditions, it may be necessary to re-evaluate their strength and fatigue lives to derive any further restrictions that may be necessary, if these changes are realised.

Tropical cyclones and extreme sea states play a crucial role in ship operations and planning, as well as feeding into the limitations of ship design and materials. From a stability assessment point of view, the assessments and particularly those conducted on naval vessels (i.e. deterministic rather than probabilistic) do not directly utilise wave data. However, the use of wave and wind heeling moments to assess some criteria indirectly includes characteristics which have a historical basis. Whilst the conditions considered are not the extreme, the potential for vessels to operate within higher sea state conditions on a more frequent basis would be a matter to consider. Globally, it is agreed that warming of the ocean surface as a result of anthropogenic causes is likely to cause more destructive and powerful storms. Global models however, demonstrate that the overall number of tropical cyclones is projected to reduce, yet the frequency and intensity of more powerful category 4 and 5 tropical cyclones are likely to increase. A general poleward migration of storm tracks, particularly in the Southern Hemisphere has been observed over the last 40 years and is likely to continue. In addition to this, the peak wind speeds associated with tropical cyclones in this region are projected to increase, leading to growth of larger waves. In light of this, as such extreme events will tend to evolve in the future, it will become vital to review structural design codes, for example NATO Standardisation Agreement No. 4194 (STANAG 4194), equipment, materials and redundancy. In terms of operational shifts, factors which will need reviewing in the near future include operational routing and planning, training protocols, intelligent systems and models for forecasting conditions to be able to deal with the potential for more severe events globally.

Sea state requirements for launch and recovery from Naval assets has led to the advancement of techniques such as the MoD/University of Exeter's Quiescent Period Prediction (QPP) program, where technologies are in development to use ship deployed wave sensors to measure the sea surface several hundred metres in advance of the vessel. These measurements can feed into short-term deterministic wave models which pre-propagate the wave field to the ship's location (Ferrier *et al.,* 2022). The development of such technology will become more and more vital to a ship's operations as wave climate potentially alters. In addition to *in situ,* short-term forecasting techniques, longer term predictions of extreme events and more robust quantification of wave climate projections will become crucial. That said, such predictions at regional scales are limited in the response of global climate models to greenhouse gas emissions and other forcing. Improving resolution of climate models may reduce some uncertainties as well as ensembles or much longer climate model runs to incorporate extreme events, and nonlinear changes (IPCC, 2023).

A study in 2021 by Losada *et al.,* exploring climate change related risks to ports worldwide identified that under a high-end warming scenario, Ports in the Pacific Islands, Caribbean Sea and Indian Ocean are likely to be at extremely high risk by 2100, whereas those in African and Arabian Peninsula are expected to experience very high risk. This however takes into account coastal risks associated with climate change in terms of sea-level rise and coastal flooding, not only wave overtopping and potential erosion. An investigation into the Marine Casualties and Incidents Reports issued by the IMO concluded that over 30% of the commercial shipping accidents from 2001 to 2010 were caused by poor weather, with an additional 25% being unexplained (Zhang and Li, 2017). As satellite earth observation technological advancements are made, along with global models and machine learning and AI approaches (Juan and Valdecanos, 2024), vast improvements in more accurate predictions of wave and weather patterns are in development. A recent study by Casas-Prat *et al.,* (2024) makes recommendations for resolving global scale climate change impacts on wave climate including improving modelling capabilities, enhancing spatio-temporal resolution and coverage of observations, for data products to be more homogenous and a better sampling of uncertainty with larger ensembles. It is also recommended that integration of real-time monitoring of weather conditions, wave heights, and ship performance with decision support systems are developed further, to provide actionable recommendations to the crew during extreme weather events. The importance of these processes becomes even more pronounced when considering that performance requirements vary by ship type. For example, combat vessels must be able to withstand environmental conditions without any decrease in the operational ability (Ashe *et al.,* 2006). Maintaining operational readiness in the face of climate change is a relatively new challenge but there has already been a shift in naval operations from the use of static design limits towards adaptive thresholds which may better capture changing environmental hazards.

3. CONCLUSIONS

In this paper we explore the current status of ship design and operability in relation to oceanographic and meteorological variables, highlighting the importance of integrating climate resilience into naval ship design. Following the latest IPCC AR6 (IPCC, 2023) report and subsequent scientific literature exploring the premise of an increasingly changeable global wave climate, we re-visit the current international military vessel design standards and specifications and operational criteria and provide a review of these in light of potentially increasing global wave heights, wave power and tropical cyclone intensity as a result of anthropogenically influenced climate change. Current design standards tend to account for extreme significant wave heights and periods according to the wave climate over the last 30-40 years. Looking towards the future however, it is understood that average significant wave height and wave power have been increasing and will continue to increase in certain regions, i.e. Southern Ocean, Tropical and North Eastern Pacific and the Arctic Oceans. The greatest increase is likely to occur in the Southern Ocean (1-3 $cmyr^{-1}$) where the greatest extreme significant wave heights is likely to increase by over 2 m and wave power will increase by 2.6 times more than the global wave power increase in any other ocean basin. Warming of the ocean surface as a result of anthropogenic induced climate change is likely to cause more destructive and powerful storms and although the overall number of tropical cyclones is projected to reduce, the frequency and intensity of more powerful category 4 and 5 tropical cyclones is likely to increase. Such storms are likely to experience a general poleward migration in terms of storm tracks, particularly in the Southern Hemisphere. In addition to this the peak wind speeds associated with tropical cyclones in this region are projected to increase, leading to growth of larger waves. The potential for such changes to global wave conditions in the future calls for further research and review of current naval ship design standards, codes and operational requirements. It is recommended that as climate change continues to affect maritime conditions into the future, the use of adaptive processes, enhanced by real-time data and innovative technology will be essential in ensuring that naval ships remain resilient.

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