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A decision support system for accident prevention using wave field analysis.

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The input data and products of this thesis Decision Support Tool have been **generated using E.U. Copernicus Marine Service Information (https://doi.org/10.48670/moi-00017)**

This Master Thesis has been unanimously approved by the examining committee as appointed by the program steering committee of the Master's program according to the rules and regulations of "Marine Science and Technology Management".

The members of the examining committee were:

- Ass. Professor Ioannis Lagoudis (Suprevisor)
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Abstract

This thesis presents a Decision Support System based on wave field analysis aimed at accident prevention for those mishaps attributed to parametric rolling phenomena. The DSS is created under a Java environment and aims at producing a NetCdf formatted geo referenced data of wave field ship specific risk index. The basic methodology for DSS creation is the relevant IMO guide to the master for rough seas ship handling. Colored risk index thematic maps are produced, plotting in a time space georeferenced grid, wave risk levels, across the area of interest. As a proof of concept, the case of a widely published mishap of MV APUS ONE in NE Pacific Ocean is analyzed, under the notion of wave field interactions between the sea surface and ship hull. The user-friendly approach via the production of colored risk indexed thematic maps, allows the personnel involved to passage planning, to take operational decisions in order to avoid high risk areas of the ocean, even away from the obvious high wave height areas. These sectors present a danger zone for parametric rolling phenomena to occur. The locate and avoid principle, alleviates the safety factor, and procures risk minimization for the ship and the company alike. All these parameters are discussed thoroughly in this dissertation.

Keywords

Decision Support System, Operational Oceanography, METOC support tool

Table of contents

List of Tables

List of figures

Abbreviations

ABS: American Bureau of Shipping

CMEMS: Copernicus Marine Environmental Monitoring Service

DSS: Decision Support System

ECMWF: European Centre for Medium-Range Weather Forecasts

EEDI: Energy Efficiency Design Index

GHG: Green House Gazes

GM: Metacentric Height

IMO: International Maritime Organization

IOC: Intergovernmental Oceanographic Commission of UNESCO

MCA: Multi Criteria Analysis

METOC: Meteorological and Oceanographic

MVR: Monetary Value at Risk

NK: Nippon Kaiji Kyokai

NTSB: National Transportation Safety Board

RAM: Random Access Memory

SAR: Synthetic Aperture Radar

STCW: International Convention on Standards of Training, Certification and Watchkeeping for Seafarers

SWH: Significant Wave Height

VTM10: Variance Spectral Density inverse frequency moment

WMO: World Meteorological Organization

Chapter 1 – Introduction

The aspect of maritime trade is one of the cornerstones of our modern society. The diversification of natural resources and raw materials, combined with the great range and geographical spread of industrial production centers, presents a unique environment for the transportation of goods. Both primary resources and industrialized final products are spaced on a planetary scale.

As our planet, with its natural environment, is a blue planet, sea is covering more than 2/3 of the total surface area. Therefore, our current globalized economies, standing strong on their productivity basis, would be impossible to develop if the world oceans were deemed as an obstacle and not as a mean to trade.

This infinite movement across the world seas, presents a unique operational environment for maritime companies to thrive. The need for high capital-intensive assets, as the current day megaships, especially conceived under the aspect of economies of scale for productivity maximization, has led to the development of travel capabilities considered as impractical not so many years ago. For example, based on contemporary data more than 255k vessels of all types and sizes are crisscrossing the world seas at any given moment (*MarineTraffic: Global Ship Tracking Intelligence | AIS Marine Traffic*, accessed 03/04/2022).

The sheer number of vessels underway, especially when correlated to the carrying capacity of the global fleet, gives a unique picture of the societal structuring on a global scale. It is not improbable for most of our daily used artifacts, to be constructed with parts and raw materials originating from 3 different continents. This unlimited flow is primarily based on ships. These ships are to be operated in a highly dynamic and potentially dangerous environment. The world seas, with their never-ending dynamic phenomena form the stage on which the ships are designed to operate.

This stage exhibits a unique array of sea and atmosphere interactions. The chaotic interconnection of fluid dynamics at the sea – atmosphere boundary, the effect of winds dynamic energy potential upon the sea surface is the main mechanism behind the wave field genesis. The same wave field that constantly mixes the surface layers of the global ocean, is also the natural area of ships operations.

Despite the mind-blowing technological innovations implemented at a more than rapid pace in ships construction, design and capabilities, maritime accidents occur due to the intricate interaction between the ship's hull and the wave field. A prime example of the profound effects of a simple software miscalculation of metacentric height (GM), originating from human error and lack of proper procedures is, the capsizing event of car carrying vessel Golden Ray that occurred September 9, 2019 near Brunswig Victoria (NTSB, 2021). This accident happened in calm seas during port exiting maneuvering. Obviously, the complexity of the user interface of the stability tool used by the ship, played a significant role for the accident. Therefore, simple, user-friendly tools are needed to mitigate the inherit risk of maritime mishaps to occur.

The current thesis presents a Decision Support System (DSS), based on relevant International Maritime Organization (IMO) guidelines for wave field attributed accident-avoidance measures. The severity and gravity of such mishaps are identified for at least the last 20 years. For instance in a 2003 paper, an investigation of parametric rolling effects on head seas is made, examining also its influence on container lashing systems (France *et al.*, 2003). Studies like this, have led to the creation of the relevant IMO guidelines for parametric rolling phenomena avoidance. The herein proposed DSS is designed for operational use by the maritime company, aspiring to present in a graphical and user-friendly way thematic maps of risk index based on the wave field characteristics, on a ship specific basis. It is therefore a DSS resting on an Operational Oceanography basis, combined to the maritime guidelines of IMO. My current experience as an Operational and Military Oceanographer (Hellenic Navy Officer), engaged to duties related to Meteorological and Oceanographic (METOC) Support for the Hellenic fleet, provided me the opportunity to access *in vivo* all the practical decision-making steps for an operational commander. The need to provide with a suitable, easily comprehended, and user-friendly tool for safety at sea reasons is the main force that drives this thesis. The basis for ship handling in rough weather is already provided by the relevant IMO technical publications, but few (if any) relevant DSS are found in the literature.

In chapter 2, a literature review of relevant proposed DSS for all levels of commands is presented. The basic definitions of any DSS are set and some user cases for different tools are critically examined. The vast array of proposed methodologies for decision support is identified and a classification attempt for the included DSS is made. Additionally, the subject of ship stability at rough seas is examined from the classification societies perspective.

In chapter 3, the methodological base for the tool creation is presented. The breakdown of the relevant IMO guidelines to the master for rough weather ship handling, allows (allied with the initial assumptions made), the creation of the needed software steps to be defined. The tool is made in a Java environment and uses several third-party open-source libraries. As the basic wave input is provided in a Netcdf format, the tool is used to create a new datafile, of the same format, with the exact time-space dimensions as the original wave data. The definition of input wave data is chosen based on the wave modelling capabilities. An added parameter taken into consideration for the suitability of the wave model, besides its accuracy, is data availability. Afterall, the very best wave model cannot claim any operational value if its output is not made publicly available with ease.

In chapter 4, the proposed DSS is used to assess a highly publicized maritime mishap. The loss of about 1850 containers from APUS ONE that took place 1800nm NE of Hawaii, due to large amplitude rolling on the night of 30 Nov 2020, is an accident to be reckon with. The loss of property combined with the long off hire time for the ship, makes this accident one of the larger losses in liner shipping to date. It is an accident proving the power of nature. It is also bringing to the spotlight, the much-needed wave field analysis (compared to ship stability behavior), for safety at sea. This wave field analysis is present to a plethora of relevant research papers, but it has never been observed to be implemented on a ship specific basis (besides some generic examples).

In Chapter 5, the results obtained from the DSS implementation, are examined on a correlation basis to the wave field characteristics. The identification of small perturbating danger zones for ship stability is achieved. These danger zones are of an elusive nature. The procurement of easily identifiable color-coded thematic maps allows for the people involved in route planning, to reach decisions upon the safest possible route the ship should follow. The safety margin is therefore alleviated due to the informational enrichment to the environmental knowledge of the wave field, for all involved in shipping operations. Notations for further study are also made in line with the proof of concept.

Lastly in the Appendices, both the input wave data and the relevant results are presented in an expanded view, organized as a thematic maps inventory. The relevant short description of the wave model is presented along with a DSS functional diagram, indicative data structuring for input and output data files and headers, combined also with a user interface representation of the system.

Chapter 2 – Literature review

The frame under which any decision support system (DSS) is, as the name implies, the decision-making process. A definition of the *decision* is therefore needed. Based on the work done in a 2001 paper (Bohanec, 2001), any decision can be considered as a sum of sequential logical steps in order to choose one out of many alternative courses of action. The term of Decision Support is defined as an entity / system helping *humans to decide*.

To create a DSS, the core question that must be addressed is the definition of decision support. As a broad initial consideration, a generic term given to the process of decision making, is any kind of organized set of activities in order to meet objectives. Obviously, there is not a unified model of decision making nor such a model will ever be invented. The huge expanse of different scenarios, informational structuring, informational availability and even the vast importance of core intellectual properties and diversity of the people involved, makes any attempt to generalize destined to failure.

Across the full spectrum of decision making 3 basic levels are generally accepted. Strategic, operational, and tactical. The demands from a DSS, are totally different between levels, even if the core decision making remains the same. For instance, Mladineo et al. presents "a Multi-Criteria-Analysis (MCA)-based Decision Support System (DSS) developed for the management of incidents in maritime traffic". The system is created to organize a large quantity of information derived / collected, addressing different aspects in relation to incidents related to emergency management, spatial data and live data (e.g. radar data, weather forecasting data). The ultimate goal is to make all these information available to decision makers via an end user friendly way (Mladineo N, Mladineo M and Knezic, 2017). At the core of this study, the quality and graphical representation of spatial information plays an important role to decision making, an approach followed also on the current dissertation.

The development of DSS for accident prevention is a relatively new area of research within the maritime domain. The basic guidelines for the need of such systems development, are primarily derived from the Marine risk assessment research, which in turn is attracting extensive research efforts as all ships are considered to operate in a high risk environment (Adland et al., 2021). Among other high-risk scenarios, heavily trafficked basins and the related navigation challenges for collision avoidance is leading to the development of shipborne DSS to help the crew, by enhancing the situational awareness of the bridge watch keepers. The developed and broadly operated existing anti-collision systems of ships (e.g., ARPA radar solutions), have contributed to the improvement of navigation safety. However, navigational focused Decision Support Systems with the capacity of providing reliable solutions to highly complicated encounter situations, thus feeding the navigator with simple but user friendly information, are still at the development stage (Ożoga and Montewka, 2018).

It must be noted that maritime transportation can be dangerous due to different kinds of threats. Phenomena such as piracy, foul weather, natural disasters (and the catastrophic events following them such as tsunamis, earthquakes, etc.), geomorphological attributes such as narrow water ways, dangerous un-charted areas and unintentional vessel collisions are only some of the identified threats to the safety and security of vessels, their transported loads, and of course the seafarers involved. The introduction of international maritime regulations, as adopted by the industry, has to a great extent, multiplied safety and security standards. After all, decision making can be better achieved only if risk exposures can be accurately determined ahead of time, leading the way for adequate measures in order to mitigate the effects (Lim *et al.*, 2018).

In broader terms, the risk assessment and risk control are also considered as a ship and company specific phenomenon. Hedji and Knapp identify that although current risk profiling methods adopted by the maritime sector heavily rely on detention risk, a much-needed extension is proposed. This extension constitutes as the consideration of various risk dimensions and the evaluation of a wide range of risk factors such as pollution and damage costs. Identified risk factors should also include ship particulars (e.g., vessel type), but also the nature of companies and owners. Additional data are also “historical information on past accidents, inspections, and changes of particulars” (Heij and Knapp, 2012). As an alternative approach, the same authors with their 2017 paper, propose “the empirical evaluation of maritime risk exposure based on the monetary value at risk (MVR)”. MVR is considered to incorporate “individual safety quality data of about 130,000 vessels, insurable values related to various potential damages, and proxies for fractions of values lost at incidents”. Therefore, it provides “a tool to enhance strategic planning of maritime administrations and insurance providers, which is illustrated by a high level comparison of annual risk exposure with insurance premiums" (Knapp and Heij, 2017). In any case, it should be noted that some fundamental aspects of the risk assessment and risk control approaches are still debated among researchers, within the plethora of proposed solutions and the choice of the right approach (Goerlandt and Montewka, 2015). These examples can be considered as a generic DSS for risk management focused basely on the strategic level of the decision-making process.

Another issue indirectly related to maritime accident prevention, but constantly cost infusing for the maritime industry, is the environmental aspect of ship operations. DSS have been examined as a way forward to minimize the environmental impact of ships operations. In the past few years, due to the environmental pressures sustained to the maritime industry through legislation procurement (e.g., IMO GHG guidelines), the need arises for a reduction of the carbon footprint of maritime shipping, preferably via adopting sustainable operations management practices. These include not only operational decisions such as speed reduction and / or market base measures (Psaraftis and Kontovas, 2013), but also berth scheduling and route re-engineering to rationalize fuel consumptions, thus minimizing CO2 emissions. Mansouri et al., in their 2015 paper state that "The earlier work in this area has regarded minimizing GHG emissions as an implicit objective, surrogated by minimizing fuel consumption and cost, which could be combined with other items (such as penalty charges)" (Mansouri, Lee and Aluko, 2015). The adoption of Energy Efficiency Design Index (EEDI), based on sea trials, has provided a basic design roadmap for GHC reduction for newbuilds. The methodological approach is considered as inadequate for the daily operations of any given ship, as this approach is based on laboratory condition checks, rarely encountered at the real world (Lindstad *et al.*, 2019). On the other hand, semi empirical methodologies are suggested for voyage optimization in order to reduce the GHC of the shipping operations (Lu *et al.*, 2015) which can be considered as an indirect contribution to safety at sea. Based on these examples, the enforcement of environmental sustainability issues into the day-to-day ship operations, can be considered as a pressure adding factor to the decision maker, in my opinion potentially leading up to increased risk-taking attitudes.

As a general remark at this point, a note should be made that maritime accidents rarely occur as the result of a single point of failure. A plethora of adverse parameters must come together, cohabit at the exact spacetime frame, thus leading to an accident. Relevant research indicates that human factors often coexist with parameters related to the condition of the ship and other external factors (i.e. bad weather) (Lema, Papaioannou and Vlachos, 2014). The development of DSS not solely focused on the ship's (tactical) level, but also on the shore-based company (operational) level, should at least alleviate the probability of adverse wave field parameters coming together, leading up to rough weather - related mishaps. The need for reliable, timely provided, relevant, coherent and above all user friendly environmental meteorological and oceanographic data, is paramount to improve and mitigate the marine risk assessment factors (e.g. Adland et al., 2021). After all, risk management is considered as an integral part of fleet operations, across all segments of maritime operations.

A DSS on the operational level, should be based on two main pillars. The first is the environmental forecast data provided across the full spectrum of ship operations. Operational oceanography achievements after almost 70 years of research have provided the maritime industry with an informational revolution. Data provision for operational use has gone a long way from experimental and strictly scientific research laboratory results, to user friendly, easily assessed informational data provision services (Von Storch and Hasselmann, 2010). The second equally important pillar is the ship's handling and hydrodynamic properties. Each vessel behaves differently to the encountered sea state. And the size factor comes to an intriguing and sometime chaotic interplay with the wave field. Chroni and Papanikolaou recently examined the maneuvering behavior of a ship under the actions of environmental forces (Chroni and Papanikolaou, 2020). Another prime example in the interplay between speed optimization, fuel consumption and service level agreement obligations is presented in Lee *et al.*, (2018). Archived big data of wave field analysis play a pivotal role to the service speed selection managerial problem. The ship stability functions and upgrades presented by Umeda et al., in their 2008 paper indicate that mishaps attributed to parametric rolling phenomena of modern mega container ships, is an emerging serious problem (Umeda *et al.*, 2008). Imai et al., have identified the container loading problem, as the interplay of two opposing forces between ship stability and container terminal needs as early as 2002 (Imai *et al.*, 2002). Even a mixed-integer optimization program – with operating cost and transport risk objectives, which could be used to prepare routes and schedules for a heterogeneous fleet of crude oil tankers is presented by Siddiqui and Verma, (2015). All these papers examine aspects of the decision-making process based correctly to the specific ship's nautical properties, as defined by its constructional particulars.

The literature review presented above is obviously not exhaustive neither complete. The area of DSS is a constantly evolving sector both on a scientifical but also on an operational level. The proposed DSS of this thesis can be considered as a systematic approach to the ship specific problem of route optimization, with safety at sea as the sole focus of the system. The main contribution (and aspiration) of the proposed DSS, is aimed at presenting in a user-friendly way (even for the layperson to maritime environment and nautical art), the areas where the wave field can present a clear and present danger to the ship handling and stability properties. It should be combined to an identify and avoid approach, obviously whenever possible based on the service level commitments of the ship. Based to the recent work done by Gil *et al.* (2020), the proposed DSS can be allocated under more than one thematic DSS categories, but primarily under the routing and weather conditions categories.

To create the proposed DSS, the need for a well-defined methodology is vital. Relative approaches such as the one found in Padhy, Sen and Bhaskaran, (2008), were considered as an initial approach to the wave field analysis on an area specific case. Another example of route optimization algorithms can be found at Zhou, Wang and Guan, (2019), recent research. Algorithms and corrective measures of the results are proposed as an alternative approach to the weather routing optimization problem. Maki et. al., in their 2011 paper, present an indicative result on the weather routing algorithm problem under certain constrains. The need for parametric rolling avoidance is identified, alongside with the inadequacy of the existing weather routing algorithms, to identify and incorporate to the proposed route such areas avoidance (Maki *et al.*, 2011).

Other examples of routing DSS are presented to a plethora of relevant papers. For instance Knapp presents an econometric analysis of the wave field effects on ships (Knapp *et al.*, 2011). As a parallel approach, Chroni and Papanikolaou at their recent 2020 paper present a modelling tool for simulating the ship's maneuvering ability under the wave field effects (Chroni and Papanikolaou, 2020). Earlier research, has presented the calculations and a proposed method for assessing the added resistance to ship movement due to wave field effects (Liu, Papanikolaou and Zaraphonitis, 2011). Passing on to the strategic decision support level, Fagerholt et. al. in their 2010 paper presented a DSS for strategic planning in maritime transportation, based on a Monte Carlo simulation framework (Fagerholt *et al.*, 2010). Even a tramp shipping DSS for maximizing revenue on the relevant operations ecosystem is proposed by Norstad, Fagerholt and Laporte, (2011). Keeping up to the strategic level, dealing with route optimization for multi modal transportation is also presented by Sinesi *et al.* (2017). The foundation of this method rests on the accessibility of the hinterland per port and suggest routing solutions (as destination port choice), for any container ship (even at sea). The DSS is optimized for the port selection problem of container shipping but skips the examination of dynamic phenomena such as weather and / or accident-prone areas evasion. Afterall, the relevant constrains to weather routing services provided to the maritime community are identified more than a decade ago in the work of Chen, (2011). In this commercial presentation, besides the need for product marketing of a specific software, the serious drawbacks of the weather routing approach, as a safety enhancement tool are very well documented.

All the above examples, although adequately presented and scientifically sound, cannot be considered as user friendly approaches on the operational level of ship management, nor do they present the danger areas due to wave field characteristics in a user-friendly manner. The ship management operational level needs a DSS which is easy to use, relatively simple to construct and above all, from a nautical point of view, accepted by the maritime community of sailors and maritime executives alike. The mechanisms underlining parametric rolling phenomena, leading to potentially dangerous ship performance is also well documented even from in situ data collected during the post analysis of a parametric rolling incident aboard RV Polarstern in 2011 (Bruns *et al.*, 2011). Therefore, the methodological basis selected in the current thesis is found in IMO MSC.1/Circ. 1228 from 11 Jan 2007 titled: “Revised Guidance to the Master for Avoiding Dangerous Situations In Adverse Weather and Sea Conditions” (Herein referred to as IMO Guide) (IMO, 2007).

Besides the maritime community, the acceptance of IMO Guide is also well documented within the scientific research community. For example Krata and Wawrzynski, (2017) emphasize on the relevant limits of IMO proposed methodology and extent the calculations past the acceptance of the overall approach. Moreover, Begovic et. al. in their recent 2018 paper note the need for a redefinition of IMO’s guidelines, named as Second Generation Intact Stability Criteria (SGISC) as early as the drawing board of a newbuild (Begovic *et al.*, 2018). From a classification society perspective, the American Bureau of Shipping, has issued a guide for the assessment of parametric roll resonance for the design of containerships based primarily on IMO guide, as late as 2019 (ABS, 2019). The acceptance of the above guidelines both from the maritime and scientific community, combined with the institutional role of the IMO, is the basis upon which the selection of the proposed methodology is made.

Chapter 3 – Methodology

As the data input for wave field analysis, a state-of-the-art contemporary wave field model is selected. The input file is wave field data as downloaded from Copernicus Marine Environmental Monitoring Service (CMEMS), subsetting them to the area of interest per case. A detailed analysis of the implemented wave modelling forecast and hindcast procedures is beyond the scope of the current thesis. The reader is encouraged to visit the relevant page https://doi.org/10.48670/moi-00017 where a full detailed presentation of the model for global ocean is available. A short description of the model is also provided in Appendix C of the current thesis.

The selection of wave field data from CMEMS as input, is based on the unique attributes of the service. The last decades of Operational Oceanography evolution have procured the need of multi-platform data collection systems. For many years, one of the fundamental problems of Operational Oceanography was the scarcity of available wave field data across the vast areas of the world ocean. The development of satellites equipped with wave field suitable sensors, created the much-needed breakthrough in terms of wide area data collection. The combination of wide area satellite data coupled with *in situ* observations from surface platforms into one single service, allowed the development of holistic services for wave field data collection and analysis. This holistic approach, based primarily on the multi-platform data availability and the newly developed 3DVAR data assimilation schemes, is one of the cornerstones for the development of wide area services and worldwide wave data availability. In the case of the global wave model, the assimilation scheme is based on optimal interpolation of the assimilated observations of Significant Wave Height (SWH) using satellite altimeters as provided by satellites such as Jason3, Saral, Cryost-2, Sentinel 3 A/B and CFOSAT plus radar based Sentinel-1-SAR spectrum.

From the multitude of the available wave parameters, two are selected as the calculation input for the DSS. The first is the sea surface wave significant height (SWH). As procured by World Meteorological Organization (WMO) (Laing *et al.*, 1998), the significant wave height is a well-established operational oceanographic parameter, which is considered as adequate for the quantitative description of the encountered sea state with regard to the maritime domain. A broad definition, in a time-domain analysis, is that SWH presents the mean average of the top 1/3rd waves found within the total wave spectrum (Bai and Jin, 2016). The significant wave height is a term used to introduce a well-defined and standardized statistic, to denote the characteristic height of the random waves in a sea state. It is defined in such a way that it corresponds to what a mariner observes when visually estimating the average wave height. It is critical to understand that, when experiencing a significant wave height of e.g., 4 m, this is an average, and waves close to double this height can be expected to occur, albeit infrequently. The most probable wave height is 60% of the SWH and the mean average is 64%. The SWH therefore presents an averaged statistically derived measurement of the chaotic wave field of the sea surface thus representing a range of wave heights from 60% to 200% of the SWH (Ainsworth, 2006).

The second parameter defining the attributed to SWH wave period is the sea surface wave mean period from variance spectral density inverse frequency moment (VTM10) (CMEMS Service desk personal communication). The definition of the VTM10 parameter is also in accordance with the definitions of ocean wave model output parameters as proposed by the leading agency ECMWF (Bidlot, 2016). The need for correlating the SWH and the Wave Period with the natural rolling period of a ship, is of paramount importance for the risk assessment indexes to be created based on IMO's guide methodology. The output data of the model used as the calculation basis for the DSS are provided in a Netcdf format. Further information and analysis of the Netcdf format, lays beyond the scope of this thesis. The reader is encouraged to visit https://www.unidata.ucar.edu/software/netcdf/ page for a fully detailed analysis. Brief notations of the Netcdf structuring and the included herein point data are presented in Appendix B of the current thesis.

As a general remark at this point, Netcdf format is a well establish file format for environmental data structuring. It is based specifically on inherit advantages in terms of minimizing size, network peak capacity requests and transmission speed. It is also incorporating machine to machine automated interaction capabilities, while at the same time remains a human operator friendly format.

Carrying on, after careful consideration of IMO's Guide methodology the following methodological assumptions are made:

- The angle between wave field propagation direction and ship course is unknown. The operational level for which the DSS is created, does not examine the relative angle between the ship and the wave field, as it is constantly changed and controlled by bridge personnel.

- The metacentric height of the ship (GM) is reported when the ship is loaded at the loading facility / port of origin. The GM is used as a fixed parameter, considered as stable at least for the timeframe of the wave field analytics data reaching up to 10 days of forecast.
- The basic ship parameters LPP (Length Between Particulars), Ship Beam (B) on waterline, Ship Loaded Draft (d), Ship Service Speed (V_{sh}) and of course GM are known and requested as hard inputs by the software. The ship particulars are defined to implement the calculations described by IMO Guide.
- The main scope of the DSS is to create a new informational base, by classification of the Wave Field data, deduced to risk levels in adverse wave conditions, but on a ship specific basis. The final Netcdf output, presenting the risk matrix, is used as the foundational basis, plotted with the right color code as a geo referenced risk index thematic map, for *human decision making upon ship's voyage planning.*
- From all the possible wave encounter angles (0 to 180 degrees), the worst-case scenarios for head seas (0 degrees), beam seas (90 degrees) and following seas (180 degrees) are primarily examined by the DSS. These angles are considered as the worst-case scenario for a maritime accident to happen, due to the wave field characteristics and their interaction with the ship's hull reducing its stability.
- The final assumption made, is the minimal difference between the forecasted and hindcasted wave data. This assumption is made to correlate the available wave field data to the accident case which will be presented in chapter 4.

Considering the above assumptions, the proposed herein DSS can be allocated as a classification algorithm, generating a new Netcdf format file, containing the risk factor final score on a geo referenced grid. The newly created file has the exact same time and geospatial dimensions as the original wave field data and is a new Netcdf formatted dataset containing one out four (4) risk classes per point. The calculations performed are programmed in a Java environment and all data are loaded to RAM for the processing and results output.

Following the IMO Guide calculation steps (IMO, 2007), the following rules form the calculation basis of the DSS. Five intermediate risk criteria classes are created, in order to allocate a final risk index per data point. The classes as constructed are:

Class I: The SWH is compared to LPP to designate a risk factor level based on the guidelines of Japan P&I club based upon the statistical analysis of post maritime accidents (Japan P&I Club, 2019).

If $SWH < 0.03 * LPP$ than the risk factor is defined as zero (0)

If $0.03 * LPP \leq SWH < 0.04 * LPP$ than the risk factor is defined as one (1)

If $0.04 * LPP \leq SWH$ than the risk factor is defined as two (2)

Class II: An internal calculation is performed before the execution of Class II. As defined by WMO, the wavelength (WL) of any wave spectra *at the open sea* (areas of the world ocean where depth is at least twice the wavelength), is correlated to its period (VTM10 in our case) by the following type:

$$WL = 1.56 * (VTM10)^2$$

Therefore, based on the available VTM10 wave period, an internal integration is performed by calculating the wavelength across the total area of selected data. After the definition of the wavelength as an internal result (which can be plotted as a separate output parameter of the DSS), the following risk factor levels are defined.

If $WL < 0.6 * LPP$ than the risk factor is defined as zero (0)

If $0.6 * LPP \leq WL < 0.8 * LPP$ than the risk factor is defined as one (1)

If $0.8 * LPP \leq WL \leq 1.2 * LPP$ than the risk factor is defined as two (2)

If $1.2 * LPP < WL \leq 1.4 * LPP$ than the risk factor is defined as one (1)

If $1.4 * LPP < WL$ than the risk factor is defined as zero (0)

Class III: This class is created to examine the risk factor of the wave field data leading to parametric rolling phenomena in a beam seas scenario. The parametric roll resonance of any ship is considered as the wave period being close to the natural rolling period of the ship (Tr).

Based on the IMO guide, the natural rolling period (Tr) of any ship can be defined as:

$$Tr = \frac{(2 * C * B)}{\sqrt{(GM)}}$$

Whereas ship empirical coefficient is defined as:

$$C = 0.373 + 0.023 * \left(\frac{B}{d}\right) - 0.043 * (\frac{Lpp}{100})$$

Parameter's definitions are:

C: Ship empirical coefficient based on principal ship dimensions

B: Ship beam on the waterline

d: Ship draught as loaded

LPP: Ship length between particulars

GM: Ship metacentric height (GM) as per loading plan

Therefore, the following classification is created based on the absolute difference between the rolling period of the ship and the wave field period (all units are in seconds).

If $abs(Tr - VTM10) \leq 0.5$ than the risk factor is defined as two (2)

If $0.5 \leq abs\ (Tr - VTM10) \leq 1$ than the risk factor is defined as one (1)

If $abs\ (Tr - VTM10) > 1$ than the risk factor is defined as zero (0)

Class IV: This class can be considered as a special case of class III. It is calculated only at the sectors where the wavelength is close to the LPP. In cases where head or following seas are encountered, parametric rolling phenomena can be developed whenever the wave period is close to half the natural rolling period of the ship. It is obvious that the Class IV results are mutually exclusive compared to Class III results. Therefore, using the same approach as Class III the following classification is created.

If $abs\ (0.5 * Tr - VTM10) \leq 0.5$ than the risk factor is defined as two (2)

If $0.5 < abs\ (0.5 * Tr - VTM10) \leq 1$ than the risk factor is defined as one (1)

If $abs\ (0.5\, Tr - VTM10) > 1$ than the risk factor is defined as zero (0)

Class V: Based on the ratio between ship service speed (Vsh) and VTM10, the danger zone of multiple dangerous phenomena to occur, for multitude following seas angles is presented in the IMO guide. Recompositing the relevant schematic of IMO's guide, the following classification is created.

If $\frac{Vsh}{VTM10} \leq 1.35$ than the risk factor is defined as zero (0)

If $1.35 < \frac{Vsh}{VTM10} < 1.45$ than the risk factor is defined as one (1)

If $1.45 \leq \frac{Vsh}{VTM10} \leq 1.55$ than the risk factor is defined as two (2)

If $1.55 < \frac{Vsh}{VTM10} \leq 1.65$ than the risk factor is defined as one (1)

If $1.65 < \frac{Vsh}{VTM10}$ than the risk factor is defined as zero (0)

As a final step to compute the time / geospatial results of the output Netcdf of the DSS, the sum of all classes risk indexes is calculated per point and per time frame. Therefore four (4) risk classification indexes are created as the total risk index, numbered from zero to three.

The results logical table per point per timeframe is defined as (with the relevant selected color table):

	I	**II**	**III**	**IV**	**V**	**Total Risk Index**
Case 1	0	0	0	0	0	0
Case 2	1	0	0	0	0	0
Case 3	1	1	0	0	0	1
Case 4	1	1	1	0	0	1
Case 5	1	1	1	0	1	2
Case 6	2	1	1	0	1	2
Case 7	2	2	0	1	1	3
Case 8	2	2	2	0	1	3

Table 3.1: Total Risk Index indicative classification based on the 5 Risk Classes.

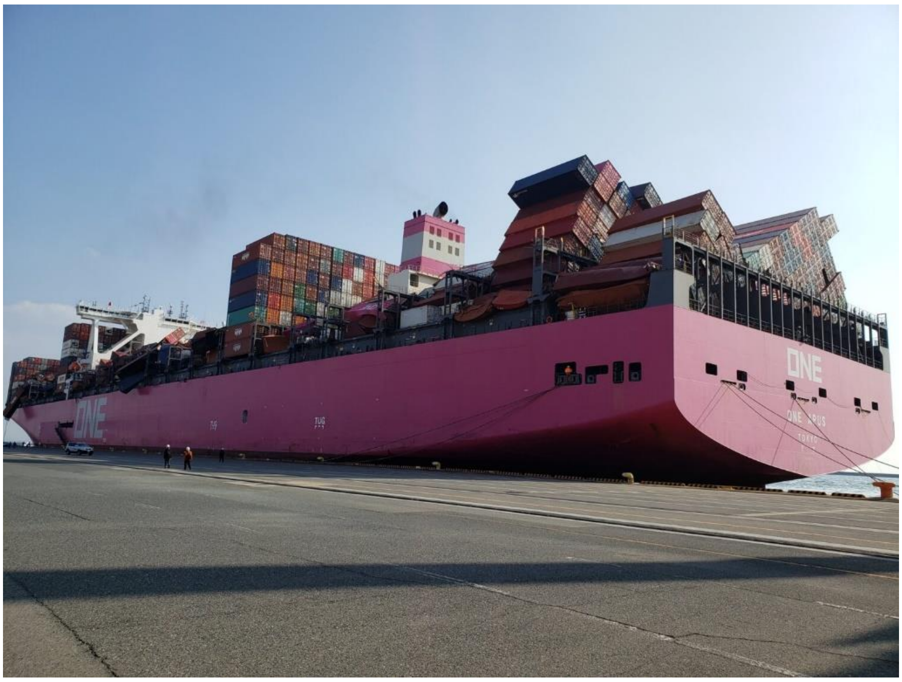
As a final step, a simple summing operation of the totals received by the five risk classes is conducted, defining the final numerical integer of the output file. The logic behind the classification of the total risk index is the conjunction and coexistence of more (if / and all) than one adverse parameter (each with its own risk index), at the same time-space frame. The combination of more than one adversary within the natural characteristics of the wave field, compared to the ship particulars as entered at the beginning of the program, is the main cause for mishaps and maritime accidents due to adverse sea state conditions. Afterall, one of the fundamental goals of the proposed DSS is to present in graphical and user-friendly way, dangerous sectors of the world ocean, outside the obvious ones (e.g., single parametric approaches based solely on sea state forecasts). The output file can then be plotted with the use of any suitable Netcdf viewer software (NASA Panoply netcdf viewer in our case). The choice of the suitable color code is also implemented as to highlight potential danger areas of the wave field. In this thesis, a Red / Orange / Yellow / Green (inverted) color code is selected. Each color represents a final risk evaluation level, numbered from zero (0) up to three (3). The green areas represent the minimal risk whereas the red the maximum. Above the color bar, a line with the selected ship particulars is noted. The relevant header above the map is inserted, before saving the final map on a JPEG format. Worth noting is that the presented solutions in chapter 4, are only the analytical results on a specific ship mishap case study, constrained as they are, in terms of length and quantity in an M. Sc. Thesis. The user interface of the DSS is presented in Appendix B of this dissertation.

Chapter 4 – Results

The use of the proposed DSS tool is applied to observe the analytic schematic results on a highly publicized event which took place at NE Pacific Ocean in November 2020.

On November 2020, the Container Vessel APUS ONE was crossing the Pacific Ocean loaded with containers close to its maximum capacity. She had departed from Yantian (CHI) bound to Long Beach – California (US). While steaming approximately 1600nm NW of the Hawaii Island complex, she encountered rough seas. On the night of November 30, around 23:15 local time, great roll angles and heavy rolling phenomena occurred. As a result of tie down failures, 1816 containers were lost overboard. Out of these, 64 were loaded with dangerous cargo (54 with fireworks, 8 with batteries, 2 with liquid Ethanol). She managed to limp back to Cobbe Japan, where a significant effort was made to offload the collapsed stacks of containers and the ship to be thoroughly checked, before returning to service some 2 months later.

Figure 4.1: Apus One Docked at Kobe Japan post-accident



Source: https://e-nautilia.gr/1816-conteiner-exase-sth-thalassa-to-one-apus/ (accessed 12/01/2022)

MV APUS ONE was constructed by JAPAN MARINE UNITED CORPORATION, KURE SHIPYARD, Hull No 5124. The Keel was laid on Dec 07, 2015, launched on Nov 30, 2018, and delivered on April 12, 2019. She is registered under the flag of Japan with

IMO No: 9806079 and Classification No: 191054, under NK Class registry, with a registered Gross Tonnage 146694 ton and Dwt of 138611 ton. (Class, NK) The ship has a 14052 TEU carrying capacity, and she is powered by a 42180 Kw engine driving a single constant pitch propeller at 74.6rpm.

As far as the critical input data for the DSS the following ship particulars have been found and inserted to the DSS as inputs:

Ship beam (B): 50.60 m
Lpp: 349.20 m
Ship draught: 11.0 m
Selected Ship Service speed: 18 knots
Selected GM: 2 scenarios are calculated for different loadout distribution. One with a GM of 2m simulating a ballasted load and one with a GM of 8m (fully loaded ship).

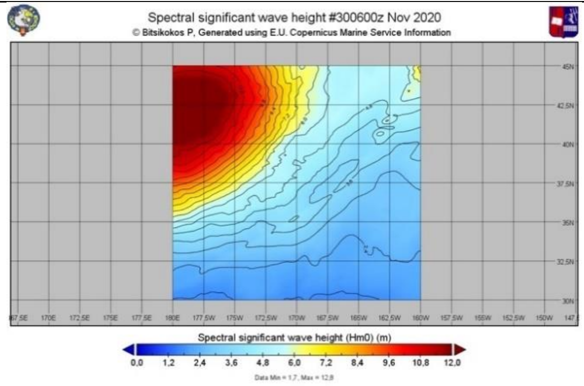
Before proceeding to the explicit solutions created by the proposed DSS the approximate area of the mishap had to be specified. Based on open source published information, taking also into account that the exact position of the container loss is not made publicly available, an area around a mark 1600nm NW of Hawaii is defined.

The area selected is therefore defined as the area between Lat 35 to 45 deg N and Lon of 180W to 160W. This area is inserted to the subsetting script for wave data extraction from the Global Wave model hindcast of the CMEMS. The time frame selected is from 0600Z time of Nov,30 2020 up to 1200Z time of December, 01 2020, with a 6-hours data timestep.

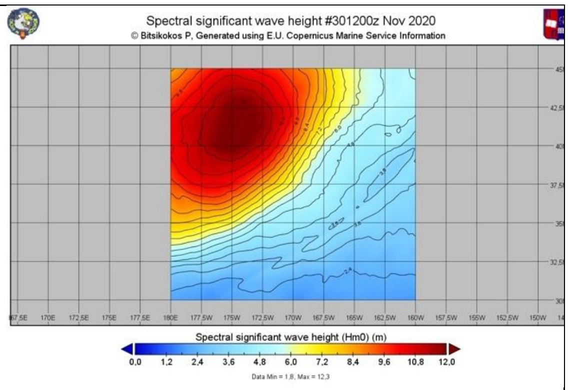
Applying the above sub setting, a NetCdf file containing the SWH, and Inverse Frequency Moment (VTM10) is downloaded. The original wave file is a 2.83 MB sized file, small enough for a typical home laptop to handle all the plotting and calculation load. The file contents of the wave data are presented in Annex B.

In figure 4.2 the plotting of the SWH for the area of interest is presented via thematic maps created out of NetCdf data with the use of Panoply Netcdf viewer software (Schmunk).

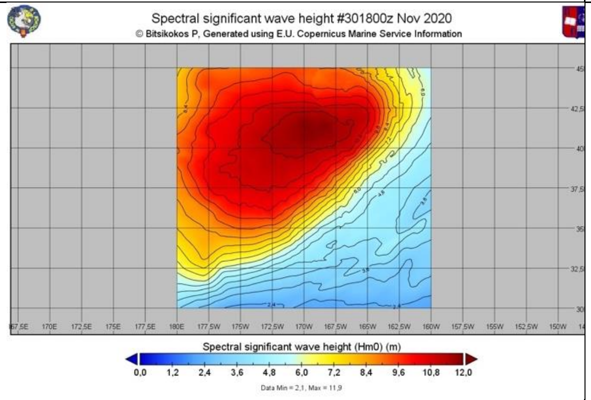
Figure 4.2: Spectral Significant Wave Height (SWH) in area of interest from 300600Z Nov 2020 up to 011200Z Dec 2020 (six hour hindcast step)



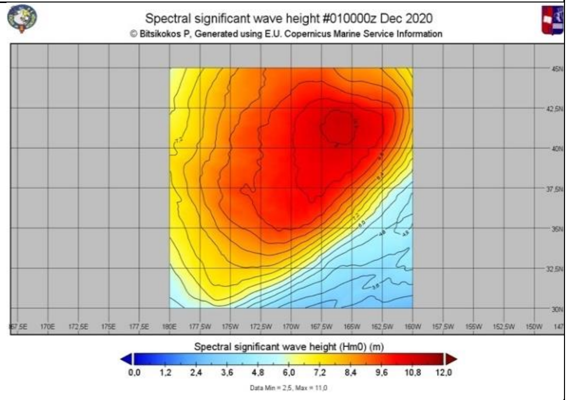
a. 300600Z Nov 2020



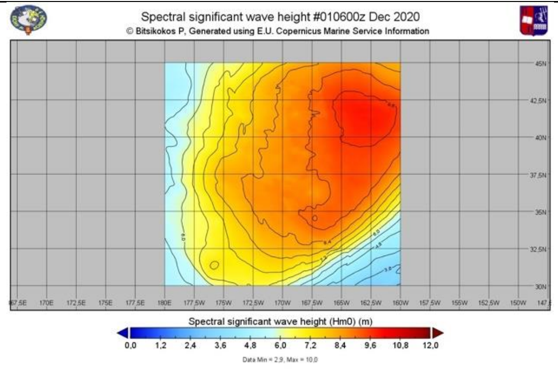
b. 301200Z Nov 2020



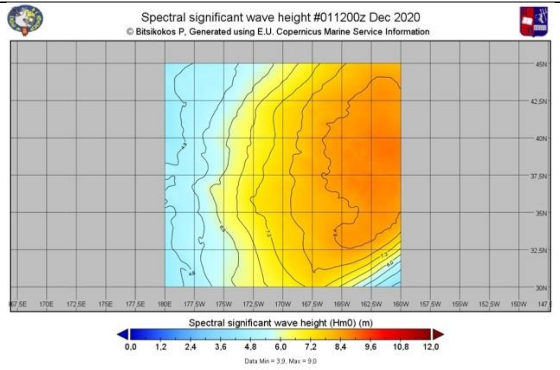
c. 301800Z Nov 2020



d. 010000Z Dec 2020



e. 010600Z Dec 2020



f. 011200Z Dec 2020

Source: © Bitsikokos P, generated using E.U. Copernicus Marine Service Information

The six thematic maps presented in figure 4.2 represent the significant wave height on November 30th 2020 up to December 01st 2020 within the area of interest. The maps are interpolated results of the hindcasted data available for this area. A 6-hour analysis step is selected to cover the time window of the mishap. It should be noted that all maps correlate to UTM time and present the significant wave height with the color table being set from 0m (blue) up to 12m (dark red) and are geo referenced (a latitude – longitude grid is overlayed).

Past assessment of the wave data, it must be taken into consideration the fact that the great circle route across the pacific from Asia to US West Coast, is known to mariners for the notorious typhoon phenomena occurring regularly. DNV / GL class society has already noted that 70-80% of ships using this route, are subjected to high following seas most of the time (Haas, 2016). It seems that on the day of the mishap, a severe meteorological system is moving across the area of interest on an easterly direction, at a rapid pace from NE to W of the area generating elevated SWH. This meteorological info was available to the ship as 12m high seas across such an area of the ocean are easily identified and forecasted by the Pacific Weather Services. The crew therefore new that a system was following the ship and might have changed their original route planning to avoid the worst of the weather.

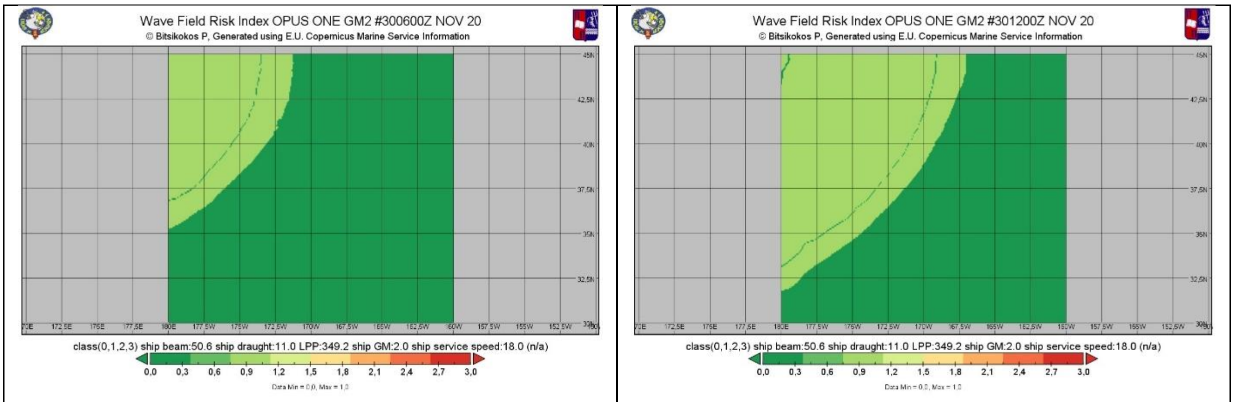
A typical and prudent maritime decision would be to detour towards the southern latitudes, in order to avoid the worst sea state areas. As the service level commitments are not made public, a change of course, probably combined with an increase of service speed, to make up for the nautical miles added to the 5742nm great circle transit, is the most possible action on behalf of the ship's crew.

Up to this point, the sheer numbers of the SWH across the area are defining a dangerous area for the ship. It should be noted that SWH up to 3m, can be considered as easily handled by a ship of APUS ONE size. Another parameter of interest is the wave period, which in turn should be "kept" as far away as possible from the natural rolling period of the ship. The right actions for the bridge personnel and the Master would be a change of course, or a change of speed or a combination of these changes. There is no evidence that wave period data were provided to the crew by the weather service, or if they did, were used in any capacity by the crew to alter the original voyage planning. The areas where wave period is close to the natural rolling period of the ship, are primarily considered as high-risk areas (reduced stability phenomena such as hull hogging, slamming or parametric rolling are expected).

Another important safety factor is the wavelength analysis. Based on the methodology presented in chapter three, the definition of the wavelength at the high seas is purely a matter of simple calculation. Points in space at which wavelength is close to or equal to the ship length, can be silent adversaries leading to sagging and hogging phenomena of the ship's hull, further reducing the stability criteria.

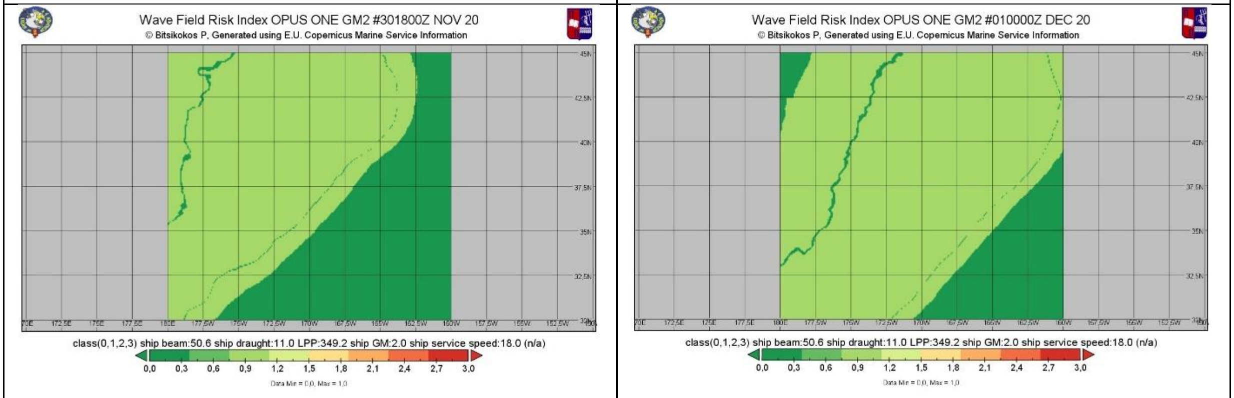
A synoptic effect of the herein presented interplay between wave field characteristics and ship particulars, is provided as the explicit solutions for two different arbitrary chosen GM values (as no real-world data for achieved GM of APUS ONE are made available).

Figure 4.3: Wave Risk Index for OPUS ONE with a GM=2M



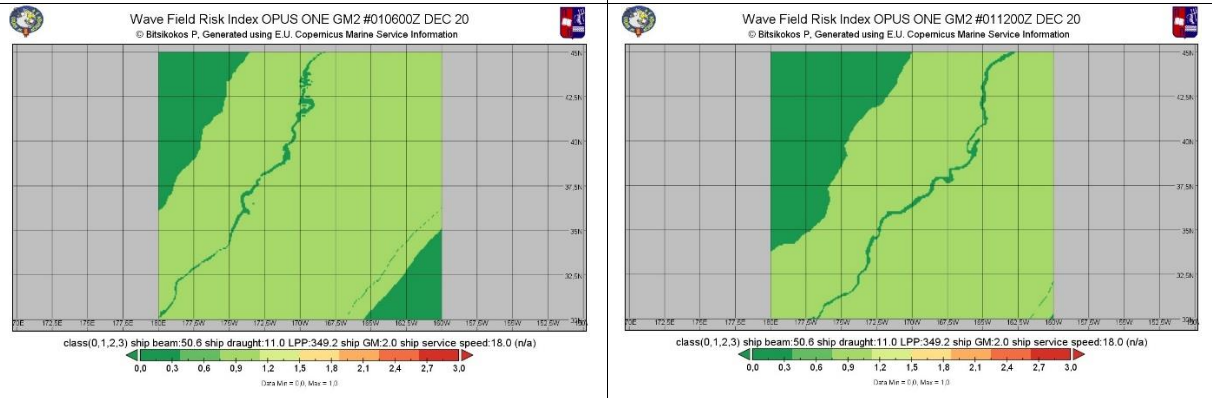
a. 300600Z Nov 2020

b. 301200Z Nov 2020



c. 301800Z Nov 2020

d. 010000Z Dec 2020



e. 010600Z Dec 2020

f. 011200Z Dec 2020

Source: © Bitsikokos P, generated using E.U. Copernicus Marine Service Information

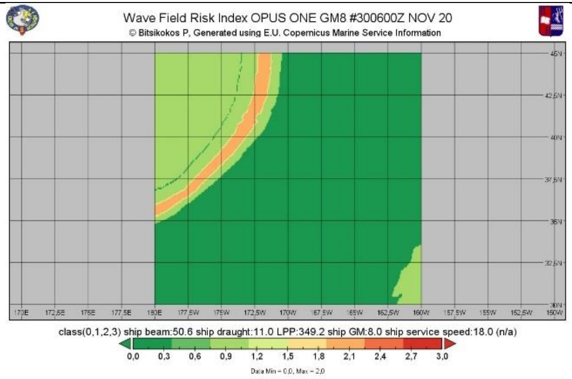
Figure 4.3 presents the risk index of the wave field for APUS ONE if loaded in such a manner that the final GM value equals to 2m. The Risk Index plotted is created by the DSS, and all thematic maps present the risk index at the exact same timestamps as the original wave data for the area. The color table presenting the final risk index as calculated based on table 3.1, is set from 0 (Green) up to 3 (Red). Zero (0) represents minimal risk areas while, three (3) represents maximum risk areas. All data plotted are interpolated in space, therefore the final thematic map is also presenting decimal results. As a general remark at this point, for a GM value of 2m, no risk value above 1 is indicated. Additionally, the area with risk index more than zero (0) is coherent with the area of high SWH when comparing the maps of figure 4.2 and 4.3.

Worth noting at this point is the fact that within the area of risk index 1 a small perturbating band of risk index 0 is identified. The small 0 risk band is moving along the SWH increase front, but also on the opposite side (the tail) of the front as it sweeps across the area. This phenomenon can be allocated to the fact that SWH is not independent from the rest of wave field parameters (wavelength and period). The small stringlike structure, plotted in a user-friendly way, manifests the analytic value of the proposed DSS. As the wave front develops across the area, the interplay between the wave field parameters and APUS ONE particulars are interacting in a nonlinear manner. Small wave field perturbations to the wave properties can impose significant changes to the Risk Index for severe rolling phenomena to occur.

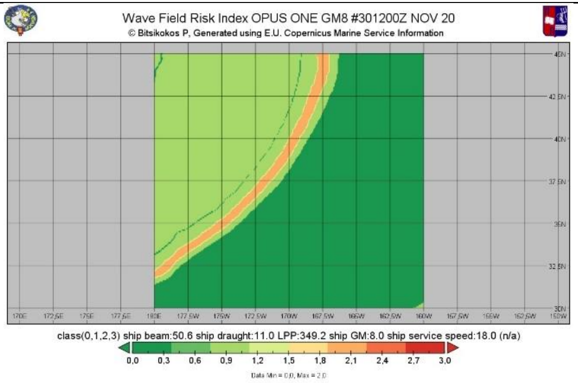
To access the effect of loading distributions across the ship, another GM value for APUS ONE is inserted. Due to the lack of relevant data from open sources and considering based on the available data, that APUS ONE was loaded close to full capacity for the transit under consideration, another extreme value GM is selected.

In my opinion the upper limit for GM on a ship of APUS ONE class is not strictly defined. Obviously, the rule of thumb during loading operations is to procure a GM which is not considered as minimal (e.g., a GM=0.25m), as it is correctly deemed unsafe. On the other hand, extreme upper limit values are not documented (or at least not publicly available). Therefore, to examine the loadout effect on wave field interaction with the ship, as a fully loaded case, the results for wave field risk index, for an extreme GM value of 8m are presented in figure 4.4.

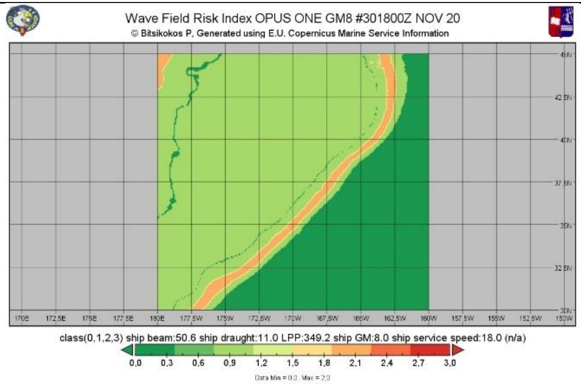
Figure 4.4: Wave Risk Index for OPUS ONE with a GM=8M



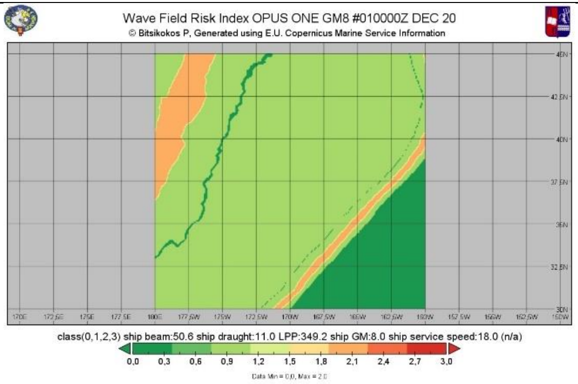
a. 300600Z Nov 2020



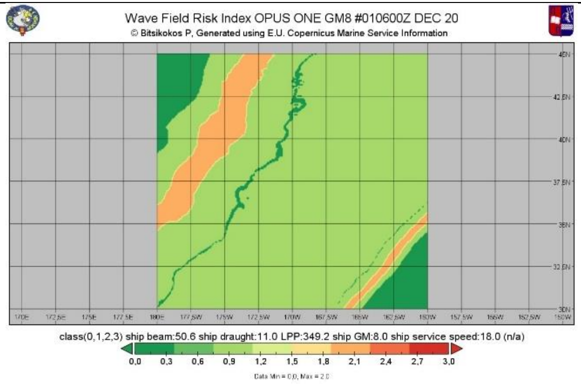
b. 301200Z Nov 2020



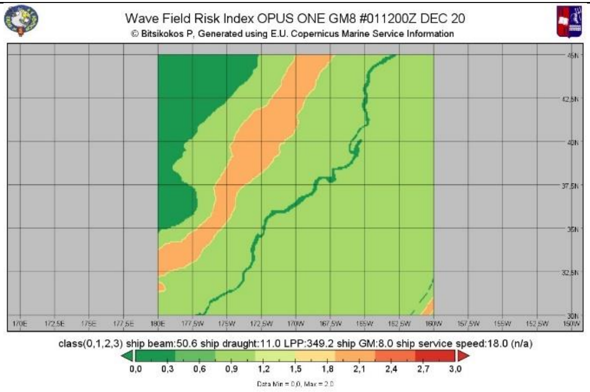
c. 301800Z Nov 2020



d. 010000Z Dec 2020



e. 010600Z Dec 2020



f. 011200Z Dec 2020

Source: © Bitsikokos P, generated using E.U. Copernicus Marine Service Information

As plotted at the above results, in the case of a fully loaded ship, with a grave increase of GM value between 2 and 8m, the same wave field conditions present bands (small perturbating areas) of risk indexes close to 3 (the maximum value). The extreme value of GM=8m is probably an overestimate of the real GM value at the time of the accident. Nevertheless, the sudden onset of the phenomenon, compared with the minimal duration of maximal roll angles observed, manifests that such a small band of high-risk index, swept over the ship and the mishap came to existence. A note should be made that the accident took place in moderate sea conditions with waves 5 to 6 meters high and winds at force 4 on the Beaufort range (moderate breeze) (Maritime Executive, 2020). Conditions like that are far from deemed as troublesome for a ship the size of APUS ONE. An additional note that should be made is the high-risk index found at the tail of the weather system. A point is made that the danger area is not only at the active front of the high sea state as it sweeps across the area, but also another more acute and expanded high risk area is identified behind the epicenter of the system. That is contrary to the well-established knowledge taught to all maritime academies about the dangerous and navigable semicircles around a weather depression. Wave field can procure parametric rolling phenomena even within the so-called navigable semicircle.

The comparative study of the above results is the foundation basis for the conclusions presented in chapter 5. The goal of this study is to create a simple, imagery-based tool on which routing corrections are made, thus time restrictions of service level agreements can be reformulated. Change of routing options and *ad hoc* changes to route scheduling is always a *human decision.* This human aspect needs a clear and precise tool to avoid not only the obvious danger areas, but also the areas where wave field characteristics can present a danger to the ship in a non-obvious matter.

Chapter 5 – Conclusions / Discussion

While examining the results obtained and graphically presented in chapter 4 (figures 4.2 to 4.4), the basic purpose of this research is meticulously presented. The ultimate objective is to create a user friendly DSS which can be used by the company as a risk assessment tool for any given ship within time and space finite wavefield data. Based on widely accepted IMO methodology presented in chapter 3, thematic maps are created by plotting the NetCdf formatted results of the DSS, as a user friendly and easily conceived and comprehended product so humans can reach decisions regarding the choice of the safest route (passage) planning of the ship. The marking of potential high risk (danger) areas of the ocean, via a simple 4 color table representing the different risk levels within the area of interest, makes the DSS a suitable tool for risk mitigation based on wave field analysis. The human readout of the output of the system is as simple as a Green (Go) – or Red (No Go) area identification. Obviously, the last statement is an oversimplification of the calculations involved in the background but simultaneously, it is also the goal of the DSS.

The proposed DSS is aspiring to cover an identified research gap. This gap can be correlated to the multitude of existing DSS methodologies, as presented in chapter 2 of the current thesis, combined with the complexity of the needed calculations being neither user friendly nor computational light. The maritime industry needs simple, reliable, user friendly, easily controlled by the average mariner (at the ship or at the desk) and not calculation intensive tools. Any DSS that needs a supercomputer to work, is more than probable that it will not be made available for the average maritime company (at least in the foreseeable future). Therefore, this DSS fills the gap between labor and computationally intensive methods on one hand, while at the same time, provides a simple easily identifiable color-coded thematic map of risk indexes as the final output.

Based on the results presented in chapter 4 and considering the assumptions made in chapter 3, for the reader to correlate the results of the proposed DSS with the actual value of the thematic maps created, a cross examination of the wave data and the results should be made (figures 4.2 to 4.4).

The first remark reached is that for any given wave field, no same results regarding risk assessment will be obtained, even for the same ship. The effect of loading to the stability peculiarities of the ship (through the resulting GM value obtained), the distribution of the load within it and more importantly the interaction between the given load status and the ship's handling properties, results in totally different values of the final risk index. Therefore, as plotted at figures 4.3 and 4.4 the very same ship behaves totally different, in terms of stability criteria and risk indexing within the same wave field. A future subject to be addressed is the load distribution optimization during loading procedures at the port of origin. Ideally the forecasted wave data for the upcoming voyage should be incorporated to the loadout plan. A predefined value for the ideally proposed GM value, based on the wave field data, has the potential of multiplying the safety factor. A challenging task it is, especially under the time pressure for quick loading and thus port time minimization. Further study in this area is needed. The port needs to know the forecasted conditions expected upon the voyage. Moreover, the ship needs to define and execute a loading plan securely based on much more than just a minimal accepted GM value.

A second remark is the observed dissimilarities between the identified area of high risk based on a single parametric approach and the areas plotted by the exploitation of DSS. High risk areas within the given wave field can be found well outside the obvious danger area of high SWH values. Small spacetime perturbations of the wavefield physical characteristics can present a silent adversary to the inherit stability properties of any ship. These areas (as depicted with a stringlike feature in figure 4.4), are not located only at the frontal area of high sea state sectors but can also be localized as a trailing peculiarity of the hurricane center. This graphical approach puts a strain to the well-established marine knowledge base of navigable and danger semicircles around a typhoon center. Traditional approaches of mariner's basic knowledge training in oceanography and meteorology (as currently defined by STCW), should be reassessed. The DSS is not a tool to prove that a calculating system is better than the invaluable knowledge of the high seas a Master possesses. It is created to help the Master and the personnel ashore, to identify in a graphical and user-friendly way, potential danger areas for ship stability. These areas are sometimes elusive and lost within the wavefield peculiarities. A sound oceanographic knowledge base of wave field interactions is not included at the knowledge arsenal of any company. Nor will it be (although it should). A tool therefore to highlight these chaotic interchanges between the ship and the sea surface, is an adding value process leading to security enhancements, thus resulting to probable lower insurance premiums.

A third remark is the exponential enrichments of the wave field available prognostic data. Not so long-ago, available data providing wave field period, for the vast expanses of the world oceans were far and few between. The achievements in the modelling capabilities of the wave field, combined with the computational capacity of modern-day computing arrays, have provided the grounds for analysis and data availability at an unprecedented level, considered as sci-fi not so many years ago. The information provided and the ease of access, even with a simple personal computer accessing the web, has multiplied the capability analysis of the intricate interplay between the ship and the sea surface.

Operational Oceanography has been expanded to levels of detail unheard of in the past. The data needed for analysis are available on an open-source basis, therefore it is up to the maritime company to make good use of them. The idea of an outsourced meteorological service, consumed by the client as provided (as it is), should be considered as a thing of the past. The capability development of wave field analysis DSS, combined with the prompt and efficient use of the results at all levels of command, can lead to mitigating risk measures. The use of the proposed DSS has the potential for less insurance premiums to the company that implements a tool like this in the ship operations route scheduling. The risk mitigation for accident avoidance like the APUS ONE incident, can only be accomplished by operating tools like the presented DSS. Adequate voyage planning systems are already in place, but they are primarily focused on the ship and not the company. The DSS of this dissertation is suitable for use by the company and does not stand against the Master’s overriding authority. Moreover, the assumptions made about the angle between the wave field propagation direction and the ship’s course and speed, makes this tool more suitable for company than ship use. These limitations, due to the lack of real time dynamic data, are the price to be paid for an operational and not a tactical approach to the proposed DSS. In any case, the digitalization already happening at a rapid pace, will allow the real time data transmission of ship’s handling properties and can provide an additional input to the system (e.g. dynamic documentation and analysis of GM values underway).

A future study item for the proposed DSS, is the integration of angle measurements between the ship’s base course and wave field propagation direction. Another add on feature, would be the dynamic and real time update of the selected field analysis area in symphony with the ship’s real time position. A 10-day forecast is already available through the weather services, albeit with a reduced reliability of the results past the 72hours mark.

Operational Oceanography is a constantly expanding universe of updates, enhancements, and things yet to be discovered. The “eminent oceanographer and geophysicist Walter Munk, who is one of the "grand old men" of oceanography” (Von Storch and Hasselmann, 2010) and his aspiring work still acknowledged as a constant source of inspiration for all of us, modern day Oceanographers, probably never imagined the evolution of the science field he gave birth to. The fast pace in this field presents a unique capability enhancement ecosystem with safety at sea focused tools yet to be defined.

Mishaps like the one presented cannot be totally avoided, as any DSS is not a panacea for parametric rolling phenomena extinction. In any case, all systems providing the capability of security enhancements are in need for constant evolution. Maritime operations are inherently considered as a high-risk human endeavor. But as history has taught us, the gains are exponentially larger than the risk. Throughout human progress, the ocean was the mean and not an obstacle. From prehistoric times, mankind chooses to be a mariner transporting goods and ideas. The need (or lust) made humans to create the very first floating vessel to conquer the high seas. The price to be paid was and probably is still very high. The difference of today, is that epic journeys can be made in a safe as possible manner. Goods transportation across the globe is a fundamental aspect of current societal development. Trade might have been changing forms across human history, but its goals and reasoning are the same nowadays as they were thousand years ago. Therefore, the safety and mishaps avoidance serve a greater goal than just being a niche service to the maritime community. It eventually expands the foundations of our current globalized economies. -

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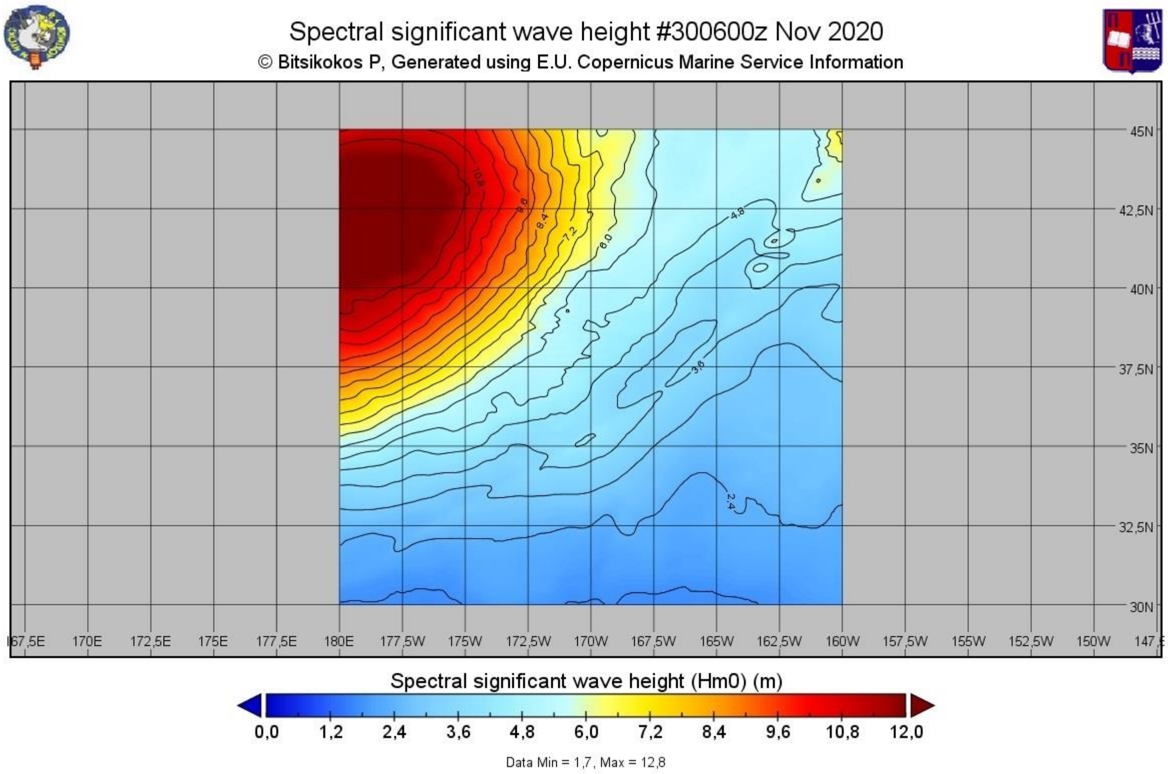
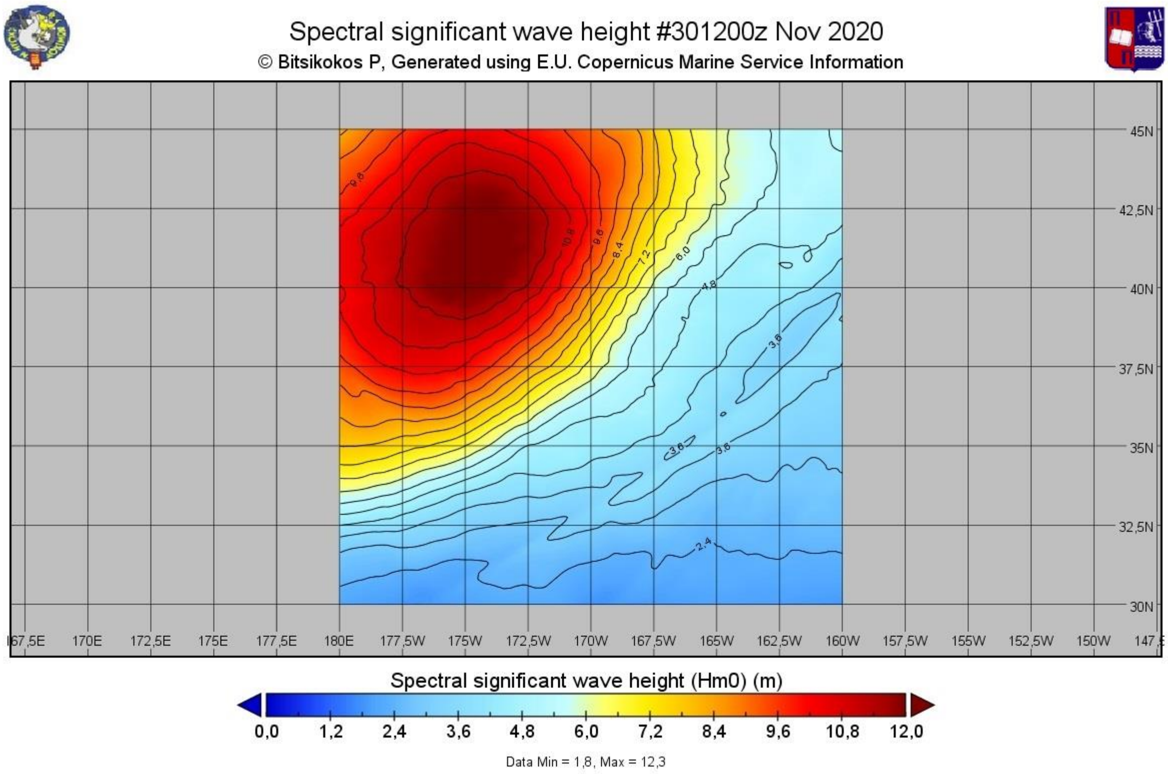
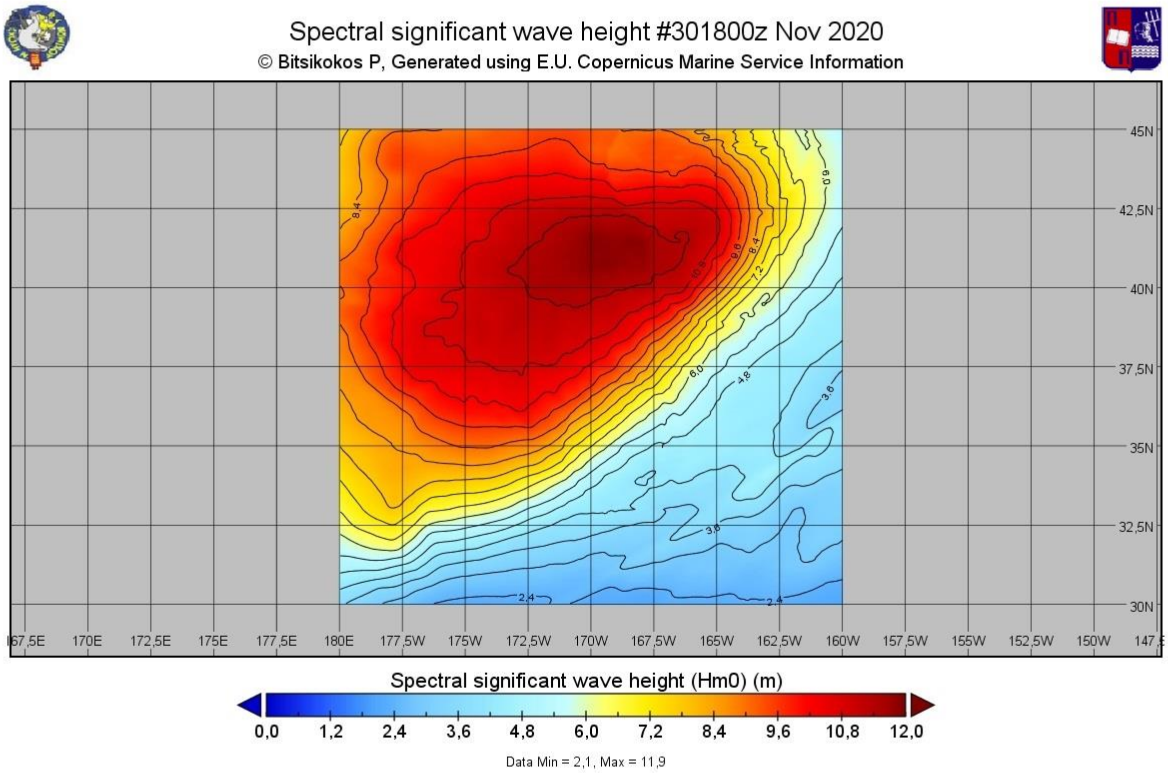
Appendix A: "Thematic maps inventory"







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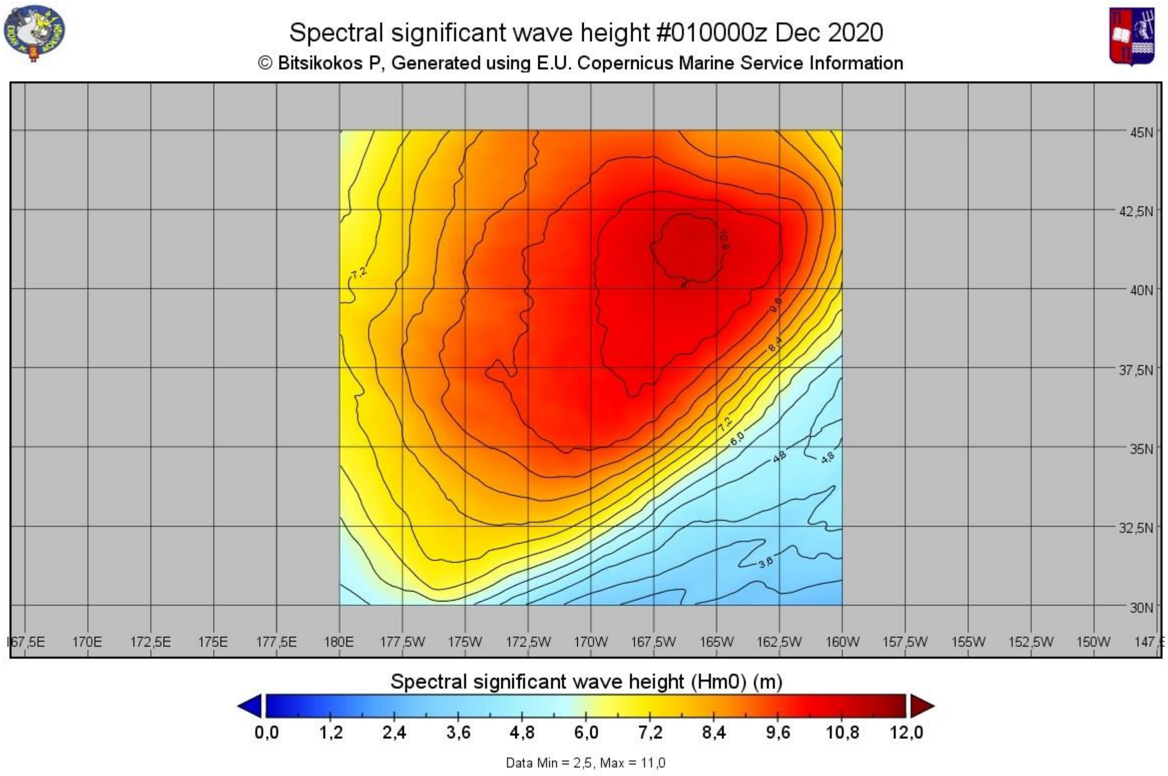
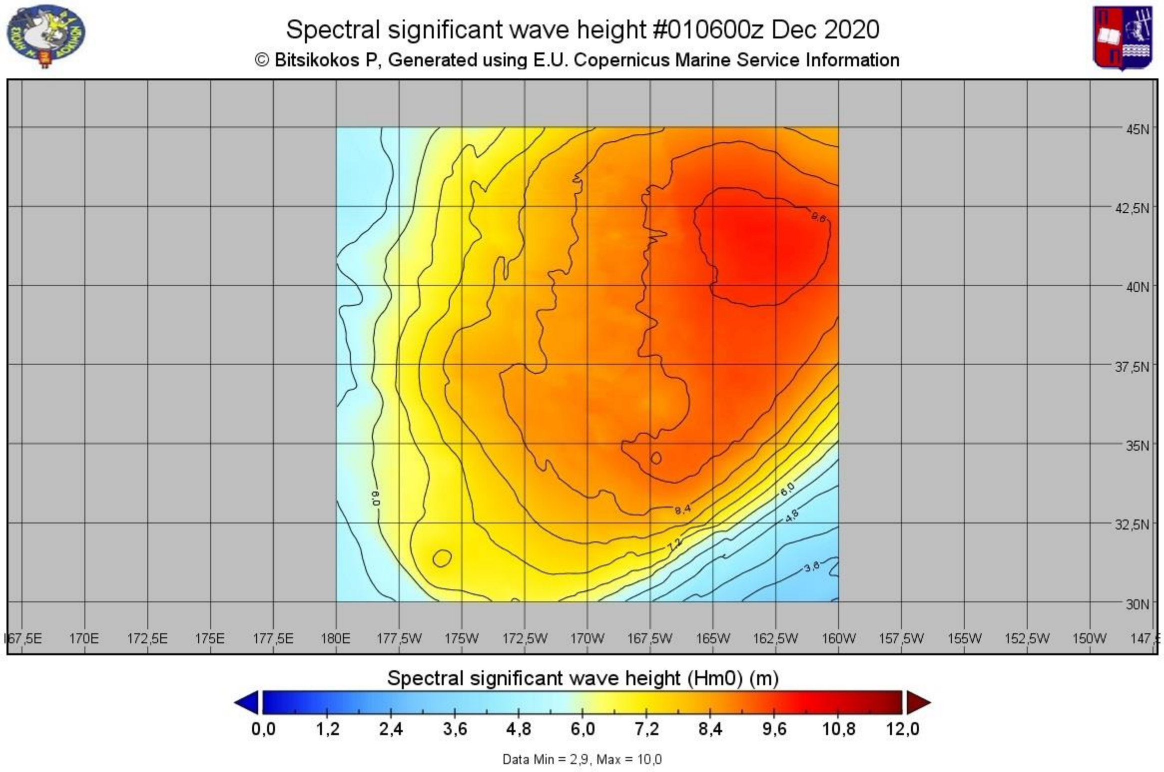
© Bitsikokos P, Generated using E.U. Copernicus Marine Service Information



Spectral significant wave height #010000z Dec 2020

© Bitsikokos P, Generated using E.U. Copernicus Marine Service Information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© Bitsikokos P, Generated using E.U. Copernicus Marine Service Information
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42,5N
40N
37,5N
35N
32,5N
30N
167,5E
170E
172,5E
175E
177,5E
180E
177,5W
175W
172,5W
170W
167,5W
165W
162,5W
160W
157,5W
155W
152,5W
150W
147,5
9,6
8,4
7,2
6,0
4,8
3,6
6,0
Spectral significant wave height (Hm0) (m)
0,0
1,2
2,4
3,6
4,8
6,0
7,2
8,4
9,6
10,8
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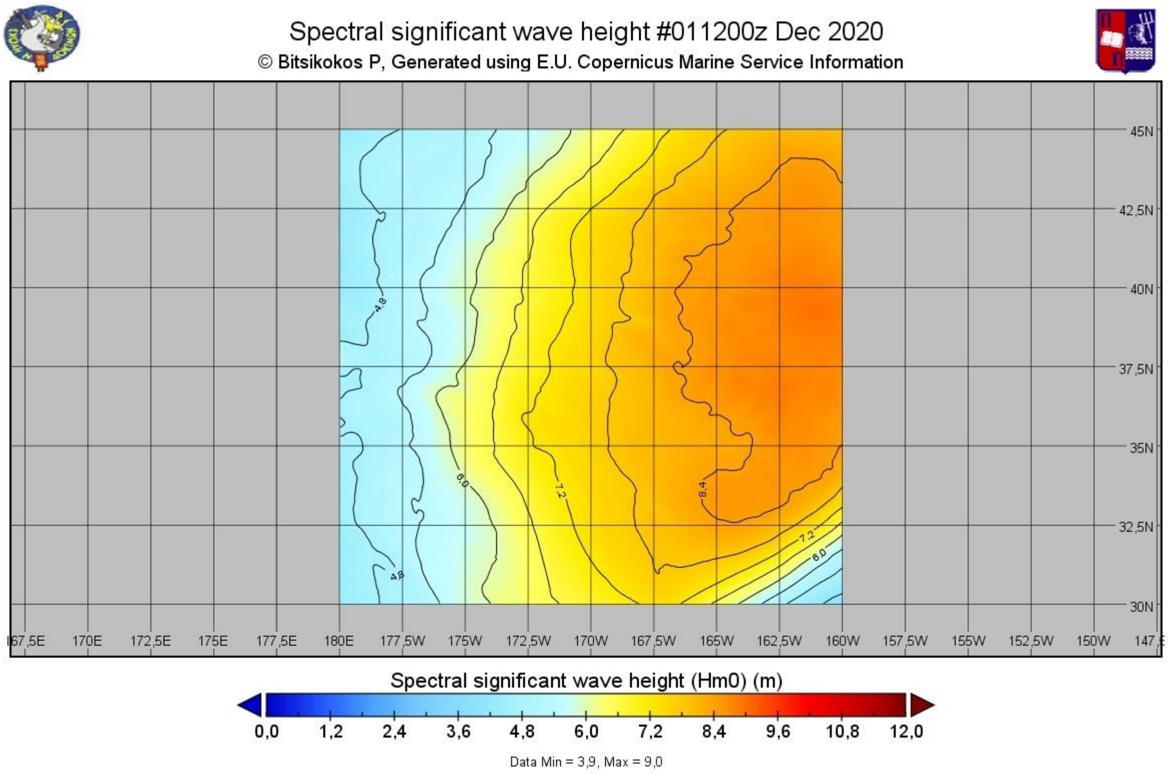
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40N
37,5N
35N
32,5N
30N
167,5E
170E
172,5E
175E
177,5E
180E
177,5W
175W
172,5W
170W
167,5W
165W
162,5W
160W
157,5W
155W
152,5W
150W
147,5
4,8
6,0
7,2
8,4
7,2
6,0
4,8
Spectral significant wave height (Hm0) (m)
0,0
1,2
2,4
3,6
4,8
6,0
7,2
8,4
9,6
10,8
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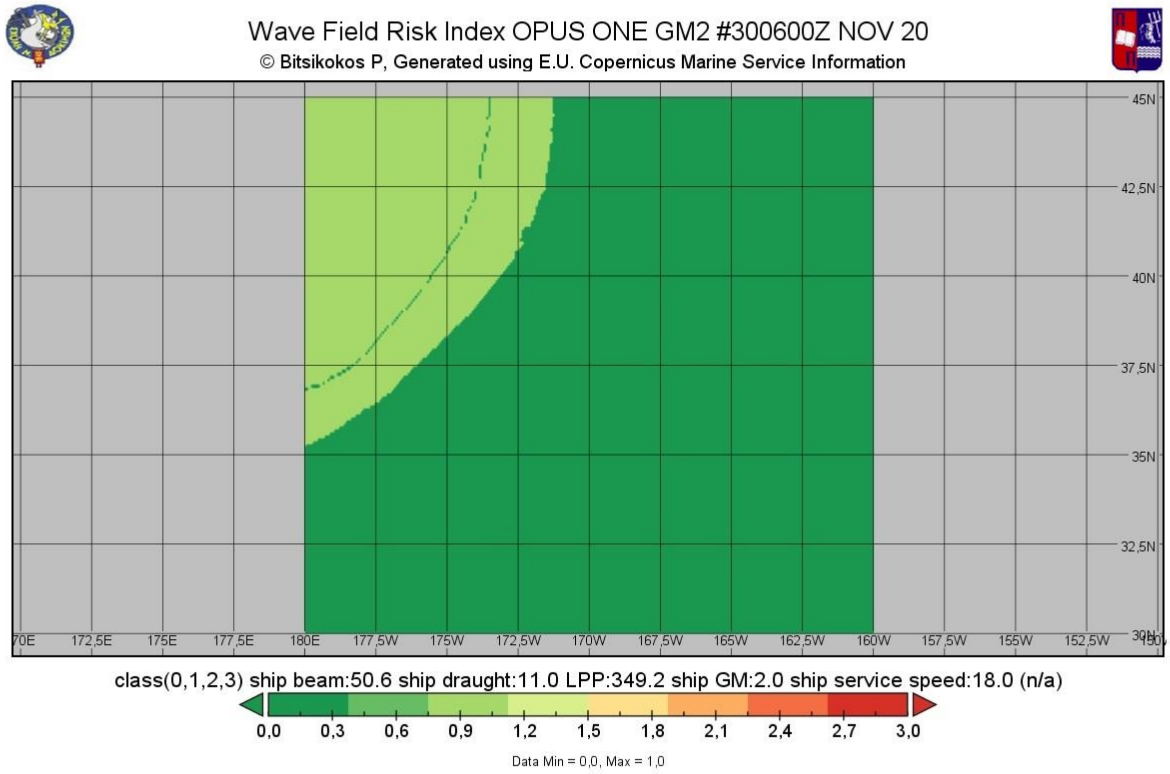
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© Bitsikokos P, Generated using E.U. Copernicus Marine Service Information
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172,5E
175E
177,5E
180E
177,5W
175W
172,5W
170W
167,5W
165W
162,5W
160W
157,5W
155W
152,5W
45N
42,5N
40N
37,5N
35N
32,5N
30N
class(0,1,2,3) ship beam:50.6 ship draught:11.0 LPP:349.2 ship GM:2.0 ship service speed:18.0 (n/a)
0,0
0,3
0,6
0,9
1,2
1,5
1,8
2,1
2,4
2,7
3,0
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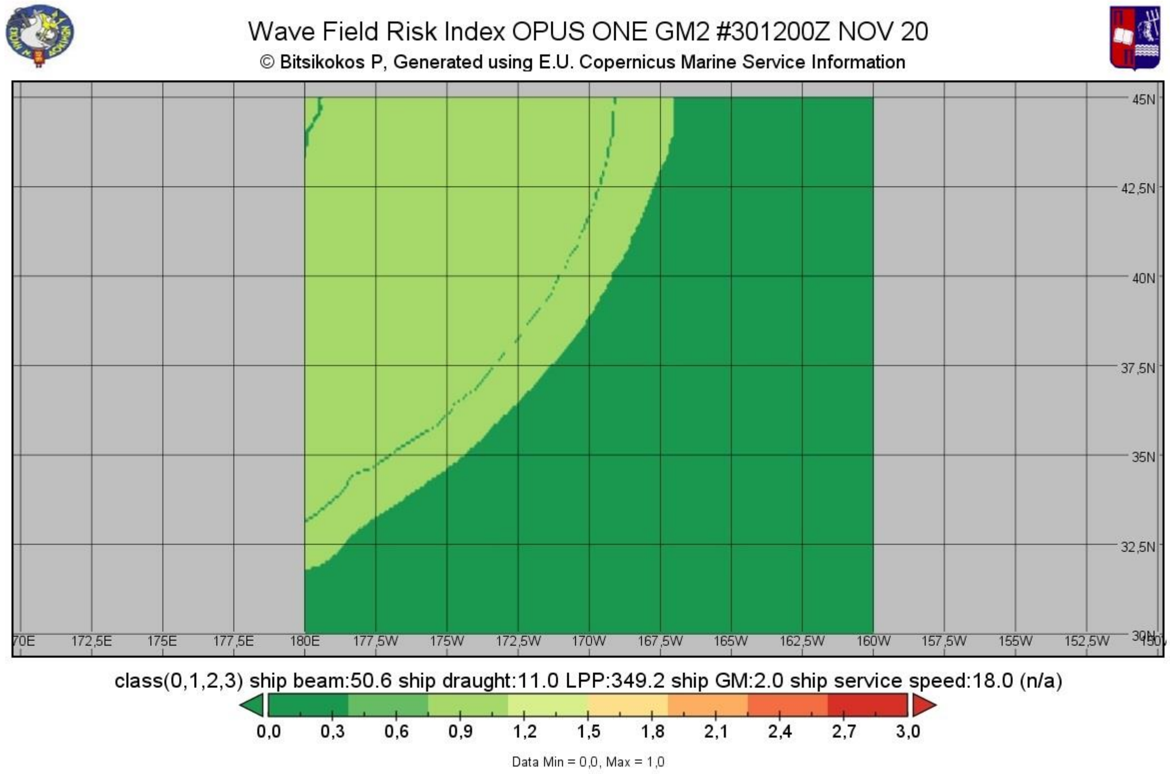
Wave Field Risk Index OPUS ONE GM2 #301200Z NOV 20
© Bitsikokos P, Generated using E.U. Copernicus Marine Service Information
70E
172,5E
175E
177,5E
180E
177,5W
175W
172,5W
170W
167,5W
165W
162,5W
160W
157,5W
155W
152,5W
45N
42,5N
40N
37,5N
35N
32,5N
30N
class(0,1,2,3) ship beam:50.6 ship draught:11.0 LPP:349.2 ship GM:2.0 ship service speed:18.0 (n/a)
0,0
0,3
0,6
0,9
1,2
1,5
1,8
2,1
2,4
2,7
3,0
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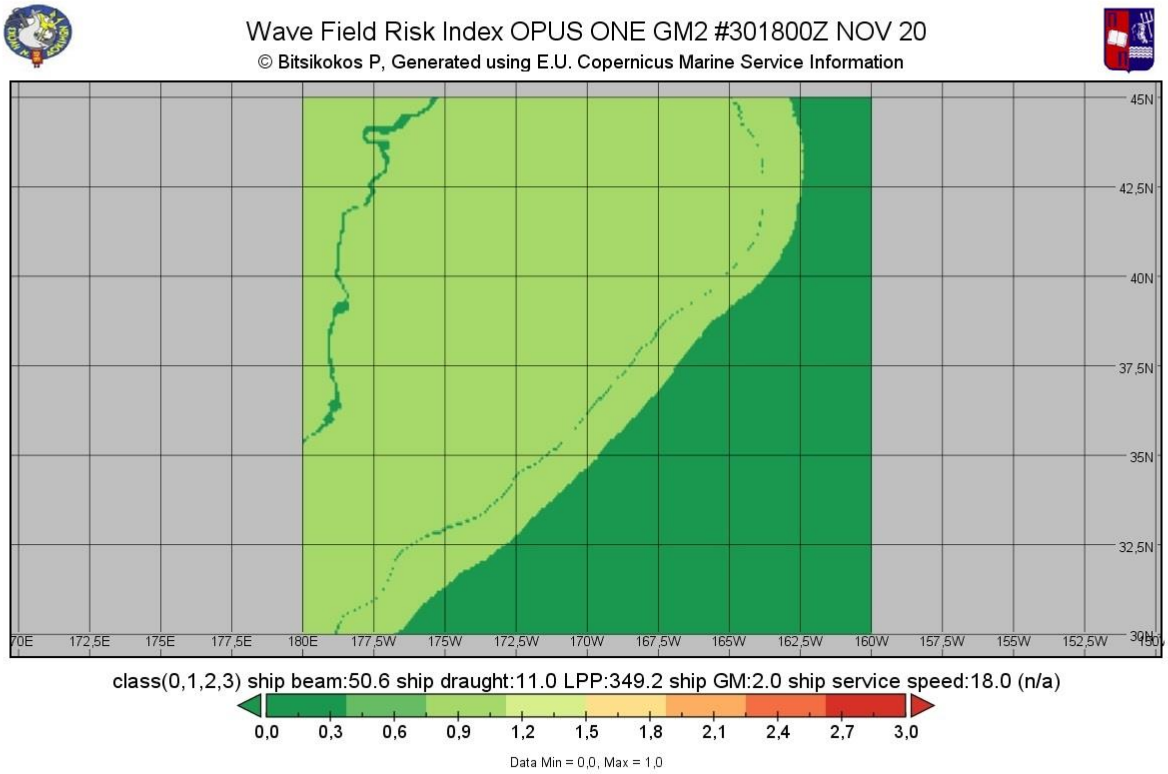
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© Bitsikokos P, Generated using E.U. Copernicus Marine Service Information
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42,5N
40N
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35N
32,5N
30N
70E
172,5E
175E
177,5E
180E
177,5W
175W
172,5W
170W
167,5W
165W
162,5W
160W
157,5W
155W
152,5W
class(0,1,2,3) ship beam:50.6 ship draught:11.0 LPP:349.2 ship GM:2.0 ship service speed:18.0 (n/a)
0,0
0,3
0,6
0,9
1,2
1,5
1,8
2,1
2,4
2,7
3,0
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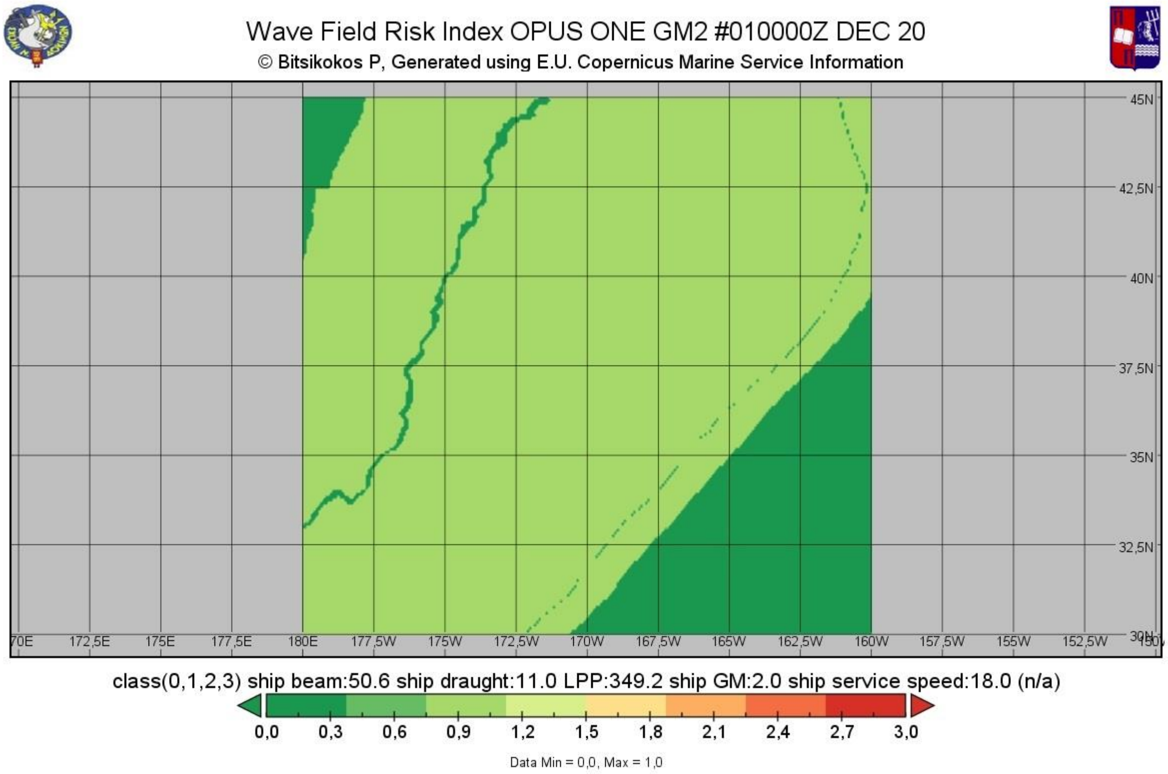
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35N
32,5N
30N
70E
172,5E
175E
177,5E
180E
177,5W
175W
172,5W
170W
167,5W
165W
162,5W
160W
157,5W
155W
152,5W
class(0,1,2,3) ship beam:50.6 ship draught:11.0 LPP:349.2 ship GM:2.0 ship service speed:18.0 (n/a)
0,0
0,3
0,6
0,9
1,2
1,5
1,8
2,1
2,4
2,7
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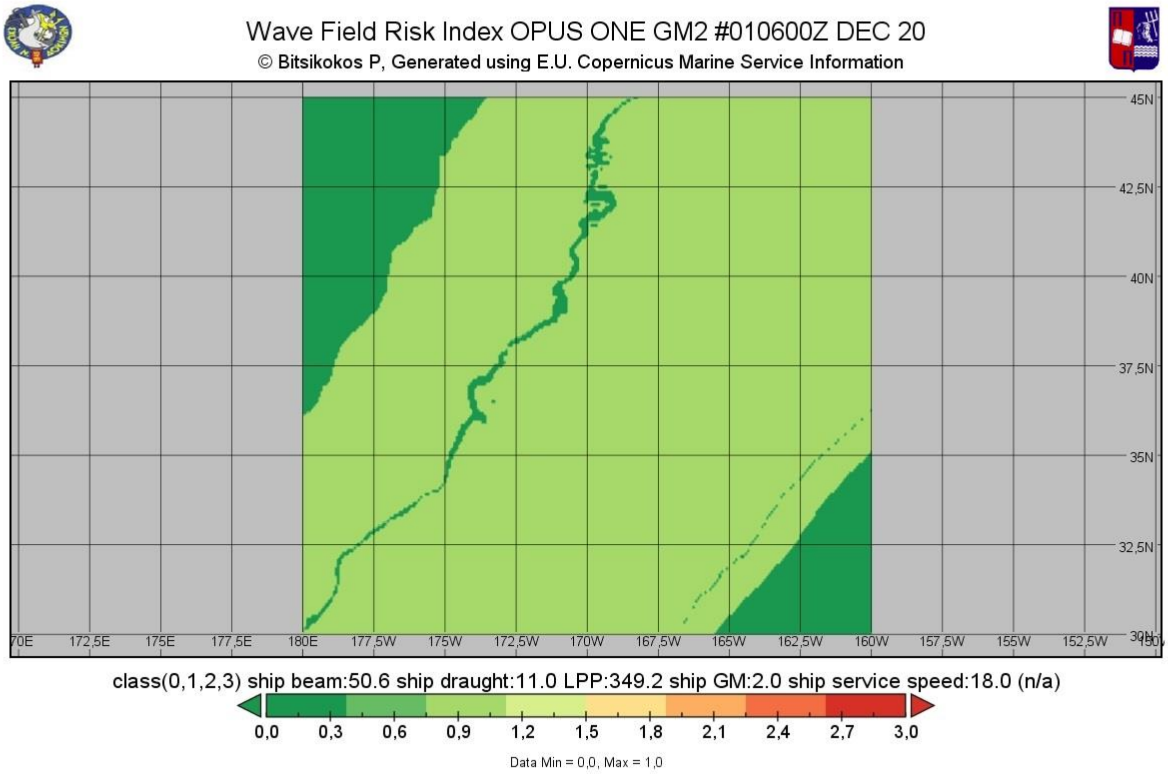
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32,5N
30N
70E
172,5E
175E
177,5E
180E
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175W
172,5W
170W
167,5W
165W
162,5W
160W
157,5W
155W
152,5W
150
class(0,1,2,3) ship beam:50.6 ship draught:11.0 LPP:349.2 ship GM:2.0 ship service speed:18.0 (n/a)
0,0
0,3
0,6
0,9
1,2
1,5
1,8
2,1
2,4
2,7
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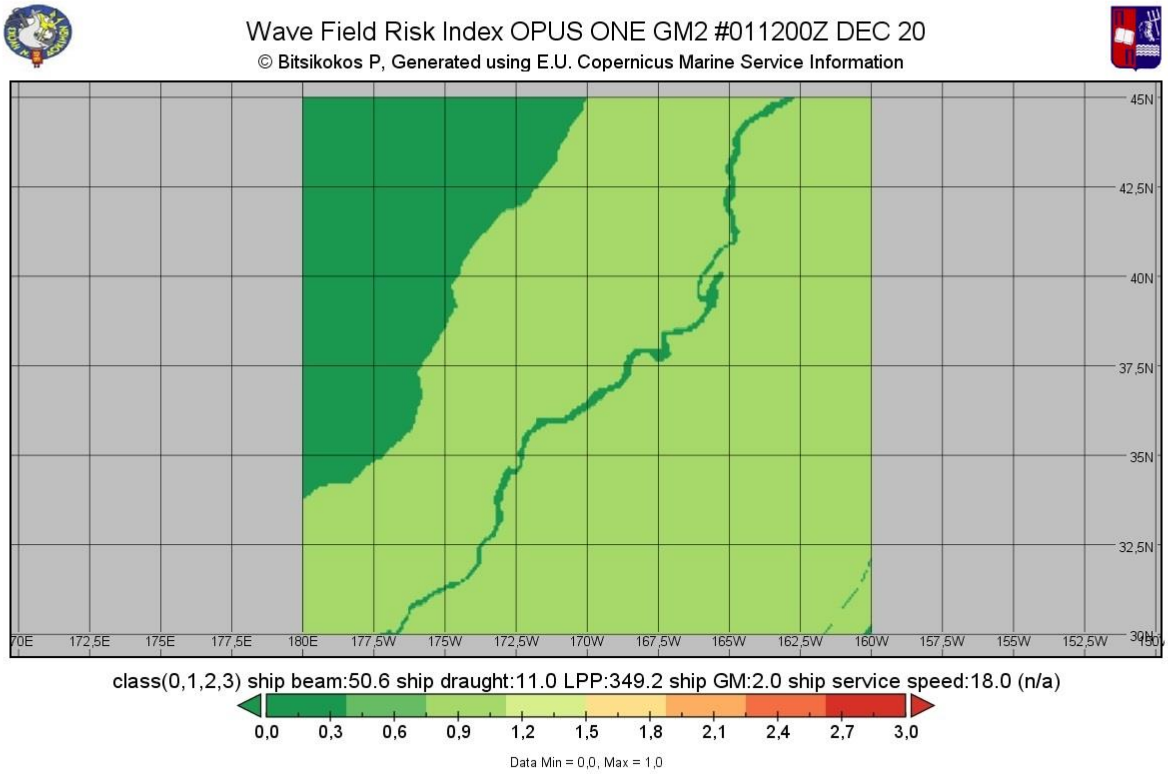
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32,5N
30N
170E
172,5E
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175W
172,5W
170W
167,5W
165W
162,5W
160W
157,5W
155W
152,5W
150W
class(0,1,2,3) ship beam:50.6 ship draught:11.0 LPP:349.2 ship GM:2.0 ship service speed:18.0 (n/a)
0,0
0,3
0,6
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1,2
1,5
1,8
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2,4
2,7
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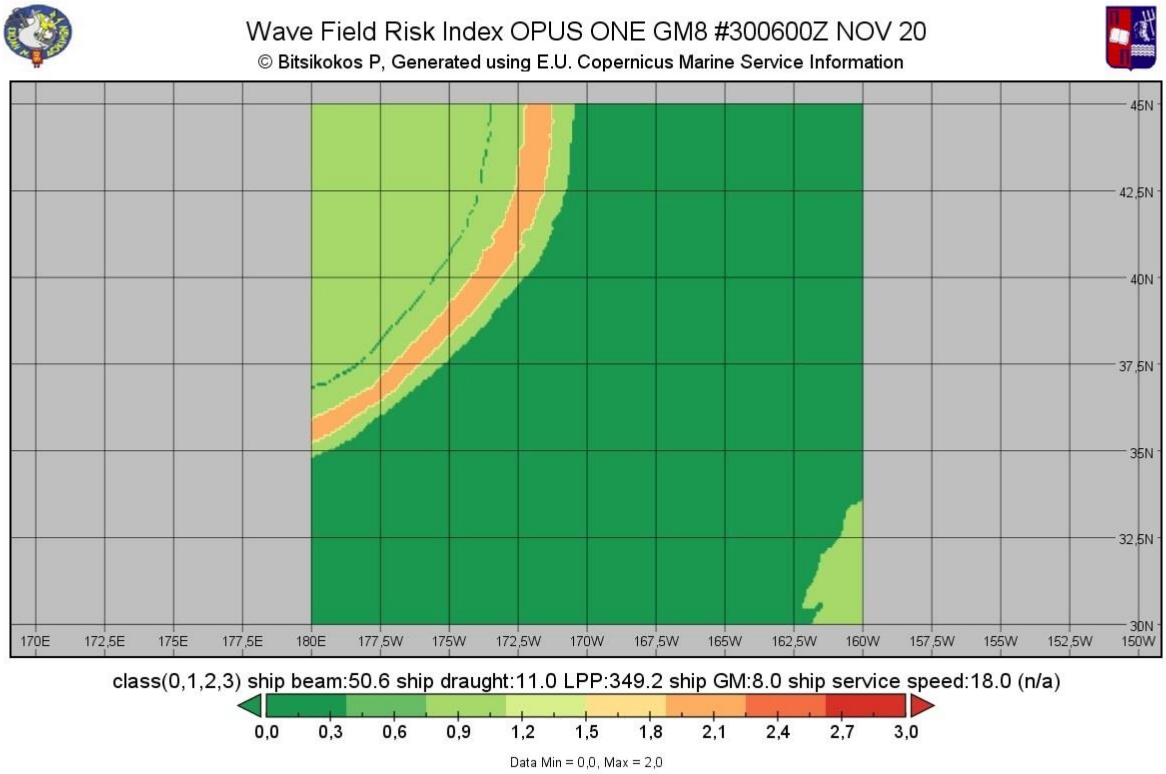
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35N
32,5N
30N
170E
172,5E
175E
177,5E
180E
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172,5W
170W
167,5W
165W
162,5W
160W
157,5W
155W
152,5W
150W
class(0,1,2,3) ship beam:50.6 ship draught:11.0 LPP:349.2 ship GM:8.0 ship service speed:18.0 (n/a)
0,0
0,3
0,6
0,9
1,2
1,5
1,8
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2,4
2,7
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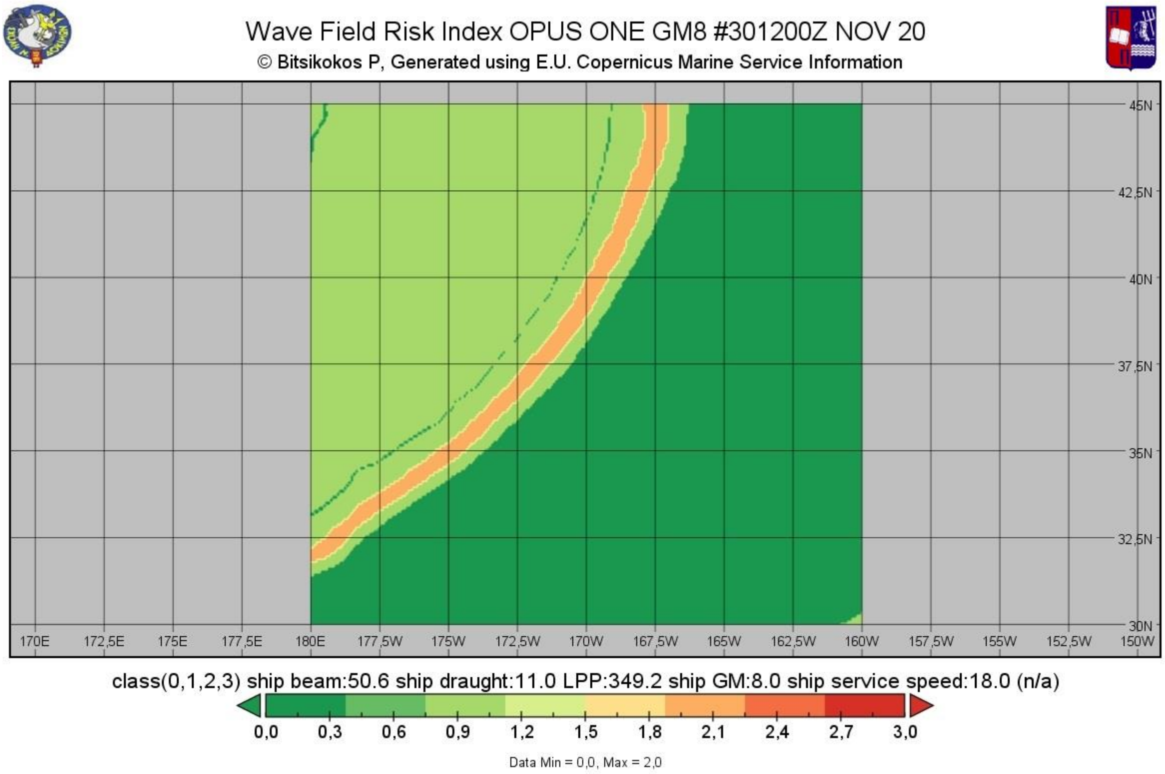
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155W
152,5W
150W
class(0,1,2,3) ship beam:50.6 ship draught:11.0 LPP:349.2 ship GM:8.0 ship service speed:18.0 (n/a)
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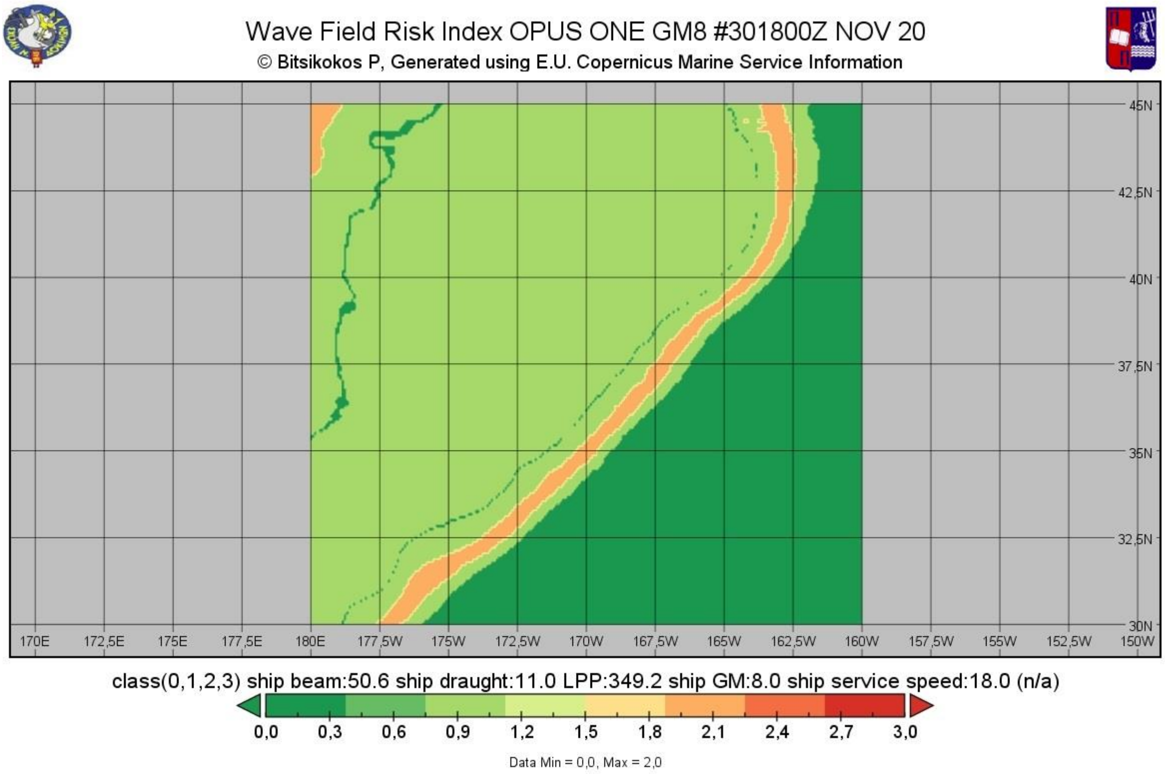
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155W
152,5W
150W
class(0,1,2,3) ship beam:50.6 ship draught:11.0 LPP:349.2 ship GM:8.0 ship service speed:18.0 (n/a)
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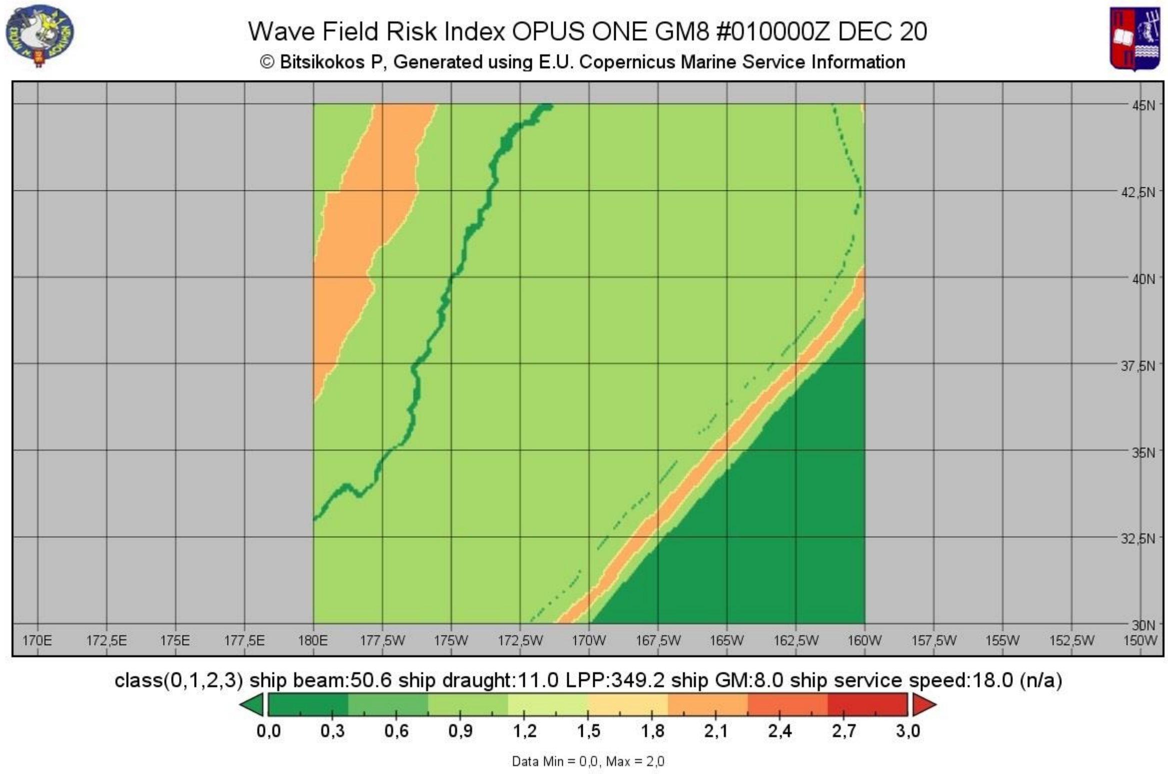
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180E
177,5W
175W
172,5W
170W
167,5W
165W
162,5W
160W
157,5W
155W
152,5W
150W
class(0,1,2,3) ship beam:50.6 ship draught:11.0 LPP:349.2 ship GM:8.0 ship service speed:18.0 (n/a)
0,0
0,3
0,6
0,9
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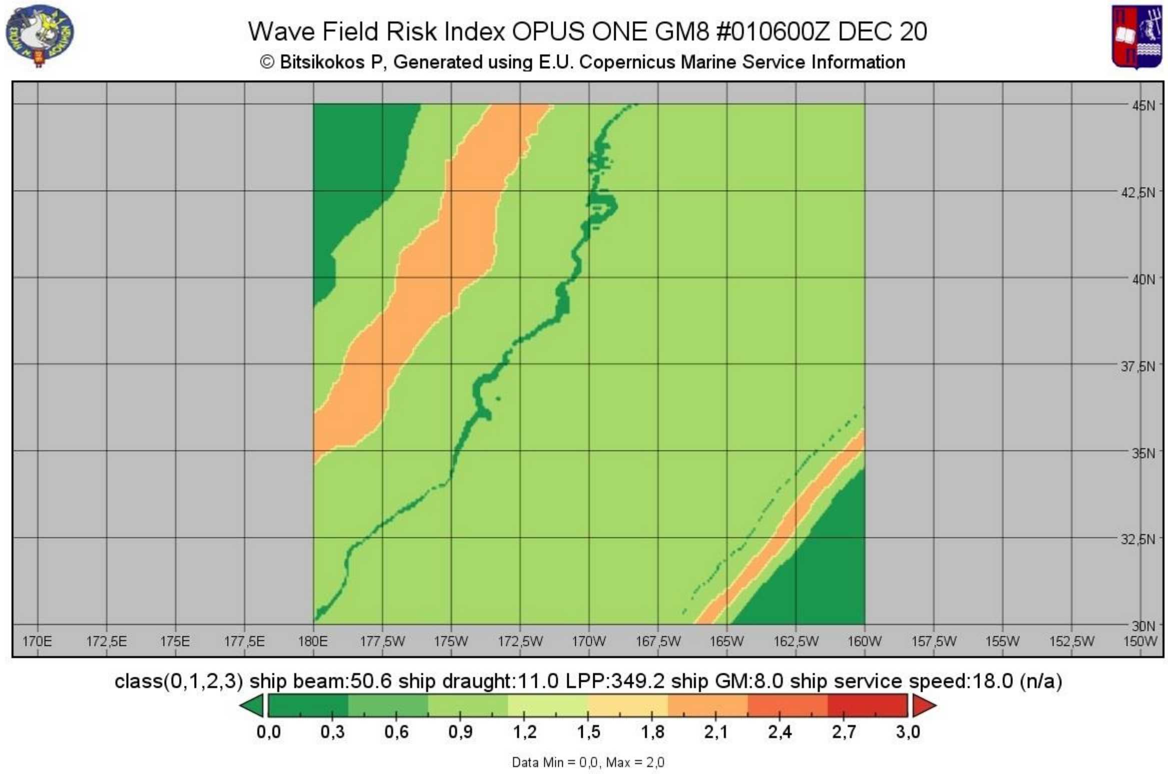
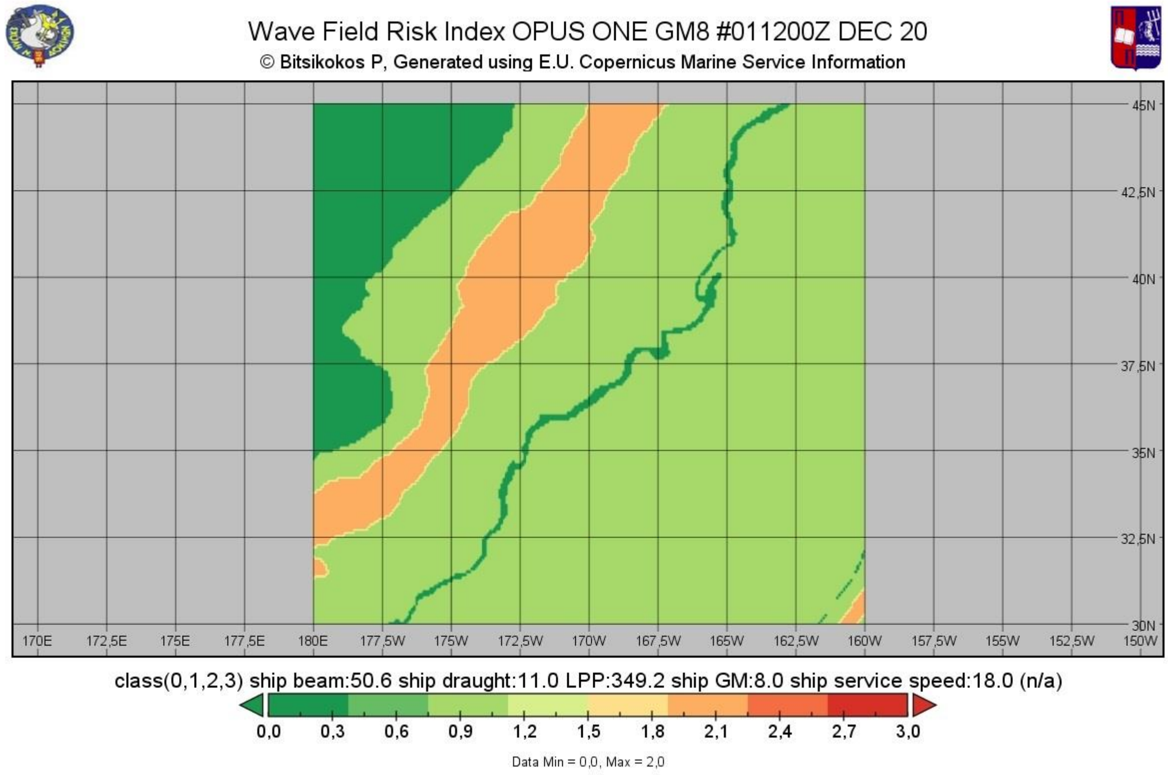
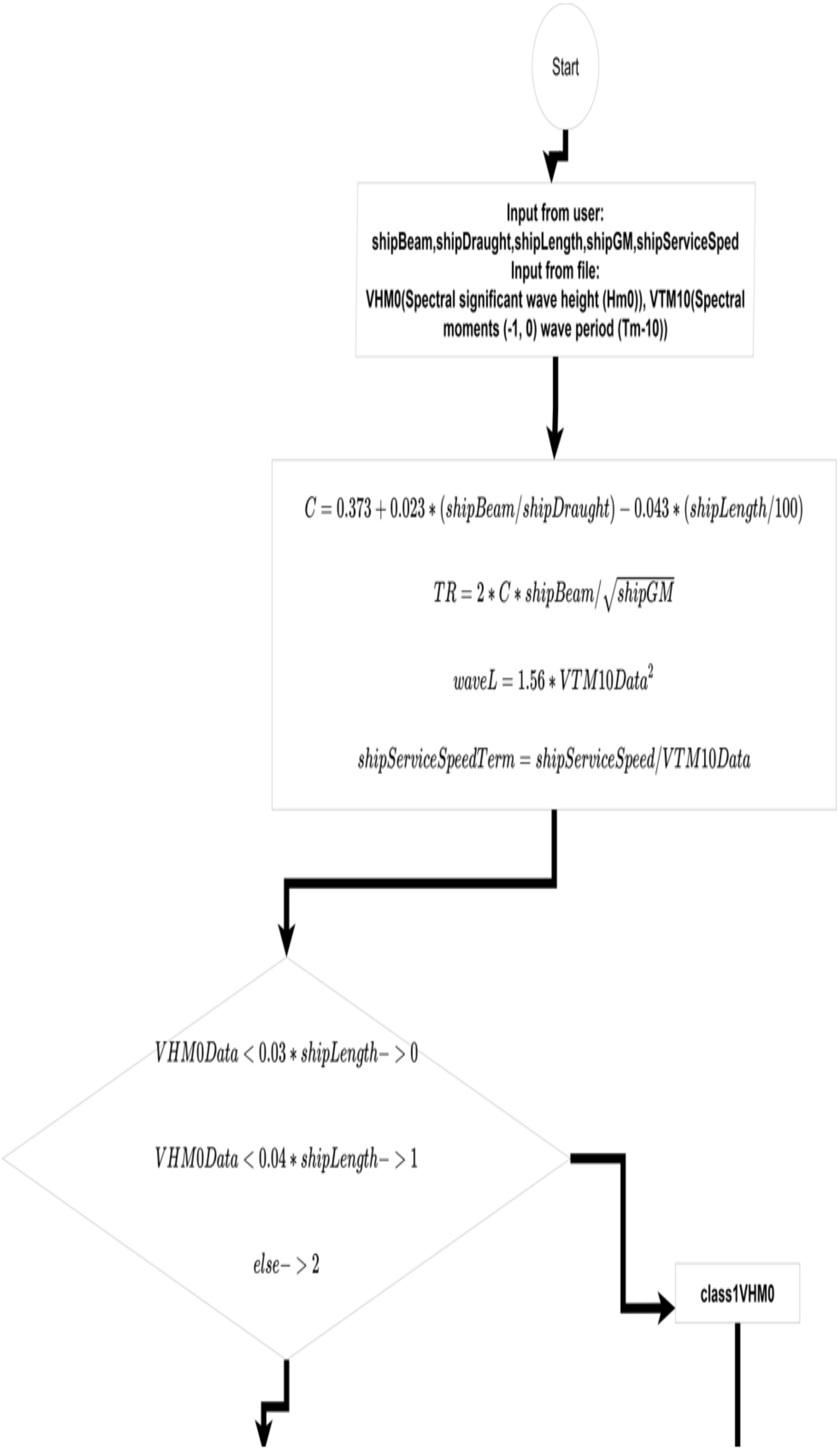
1,5
1,8
2,1
2,4
2,7
3,0
Data Min = 0,0, Max = 2,0


Wave Field Risk Index OPUS ONE GM8 #010600Z DEC 20
© Bitsikokos P, Generated using E.U. Copernicus Marine Service Information
45N
42,5N
40N
37,5N
35N
32,5N
30N
170E
172,5E
175E
177,5E
180E
177,5W
175W
172,5W
170W
167,5W
165W
162,5W
160W
157,5W
155W
152,5W
150W
class(0,1,2,3) ship beam:50.6 ship draught:11.0 LPP:349.2 ship GM:8.0 ship service speed:18.0 (n/a)
0,0
0,3
0,6
0,9
1,2
1,5
1,8
2,1
2,4
2,7
3,0
Data Min = 0,0, Max = 2,0

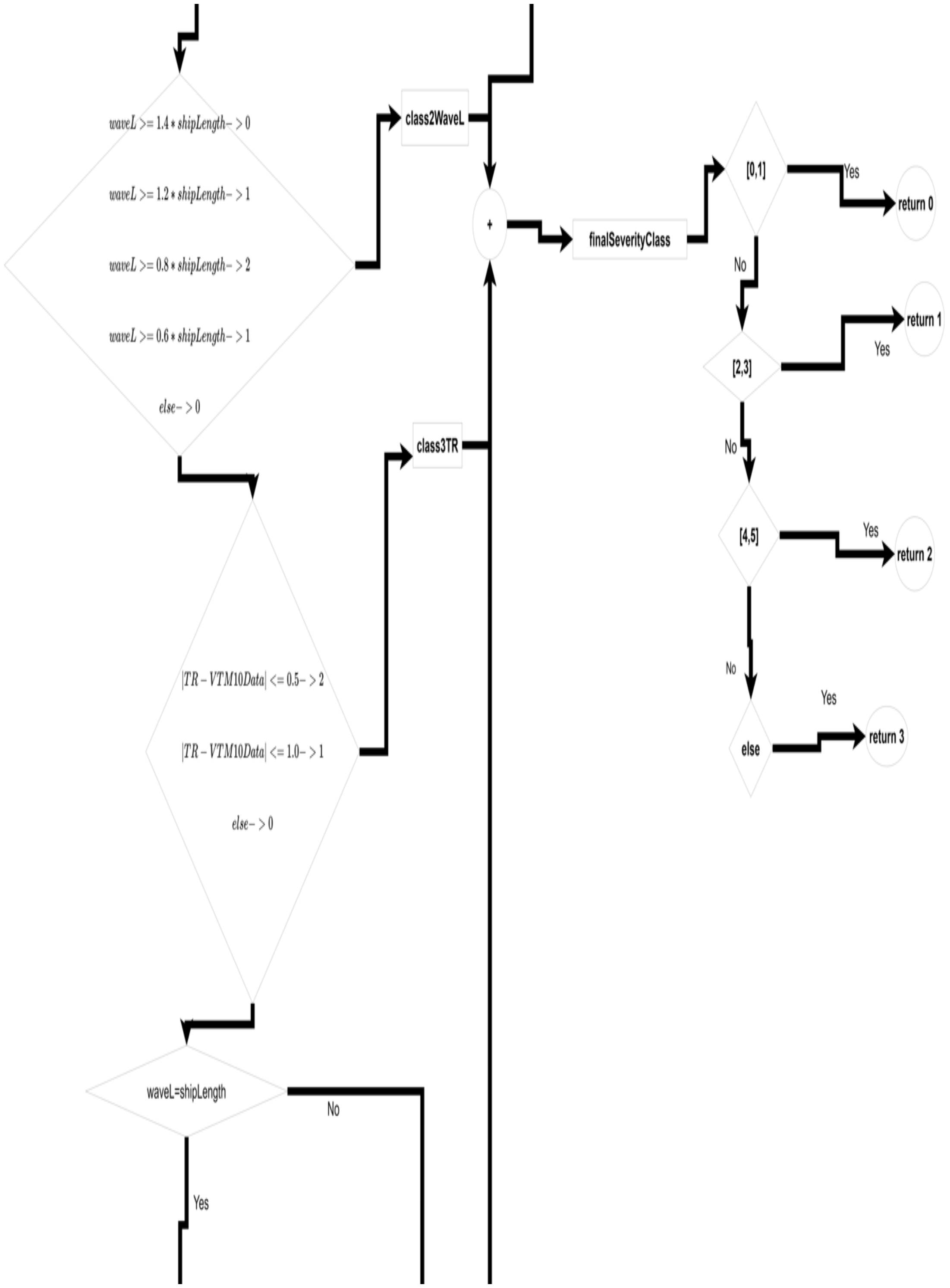

Wave Field Risk Index OPUS ONE GM8 #011200Z DEC 20
© Bitsikokos P, Generated using E.U. Copernicus Marine Service Information
45N
42,5N
40N
37,5N
35N
32,5N
30N
170E
172,5E
175E
177,5E
180E
177,5W
175W
172,5W
170W
167,5W
165W
162,5W
160W
157,5W
155W
152,5W
150W
class(0,1,2,3) ship beam:50.6 ship draught:11.0 LPP:349.2 ship GM:8.0 ship service speed:18.0 (n/a)
0,0
0,3
0,6
0,9
1,2
1,5
1,8
2,1
2,4
2,7
3,0
Data Min = 0,0, Max = 2,0

Appendix B: "DSS functional diagram, basic user interface and data structuring schematics"

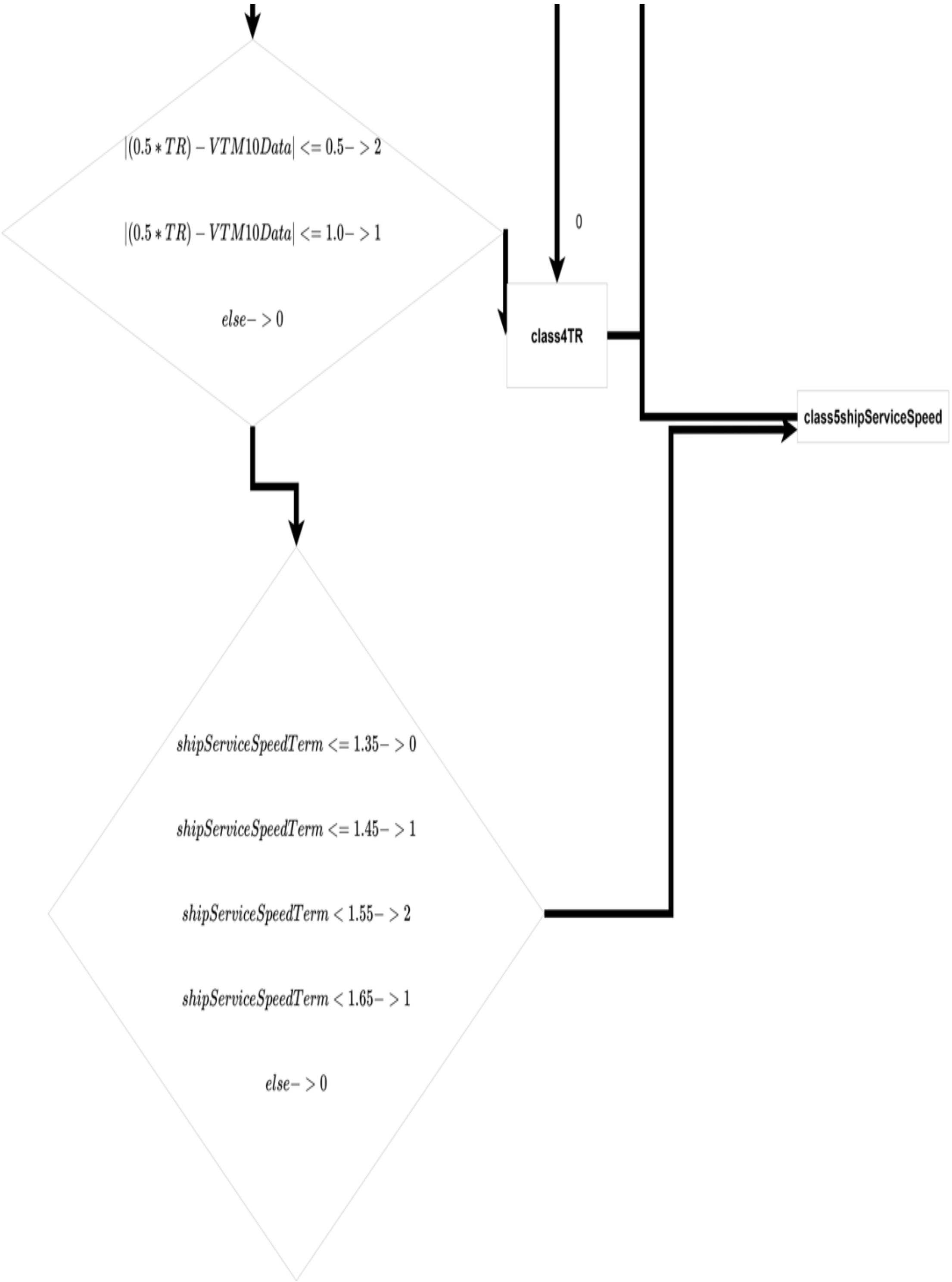
DSS functional diagram (part 1)



DSS functional diagram (Part 2)



Dss functional diagram (part 3)


|(0.5 * TR) – VTM10Data| <= 0.5– > 2
|(0.5 * TR) – VTM10Data| <= 1.0– > 1
else– > 0
0
class4TR
class5shipServiceSpeed
shipServiceSpeedTerm <= 1.35– > 0
shipServiceSpeedTerm <= 1.45– > 1
shipServiceSpeedTerm < 1.55– > 2
shipServiceSpeedTerm < 1.65– > 1
else– > 0

DSS short user description

The NetcdfDangerClassificationV4.jar is a Java Application which uses the netcdfAll-4.5 (Source: https://jar-download.com/artifacts/edu.ucar/netcdf4/4.5.5/source-code)
and javax.swing java libraries to read, construct and manipulate .nc files, through a user friendly desktop graphic interface.

Java Standard Development Kit (JDK) used: 1.8.0_282
(Source: https://www.oracle.com/in/java/technologies/javase/javase8-archive-downloads.html)

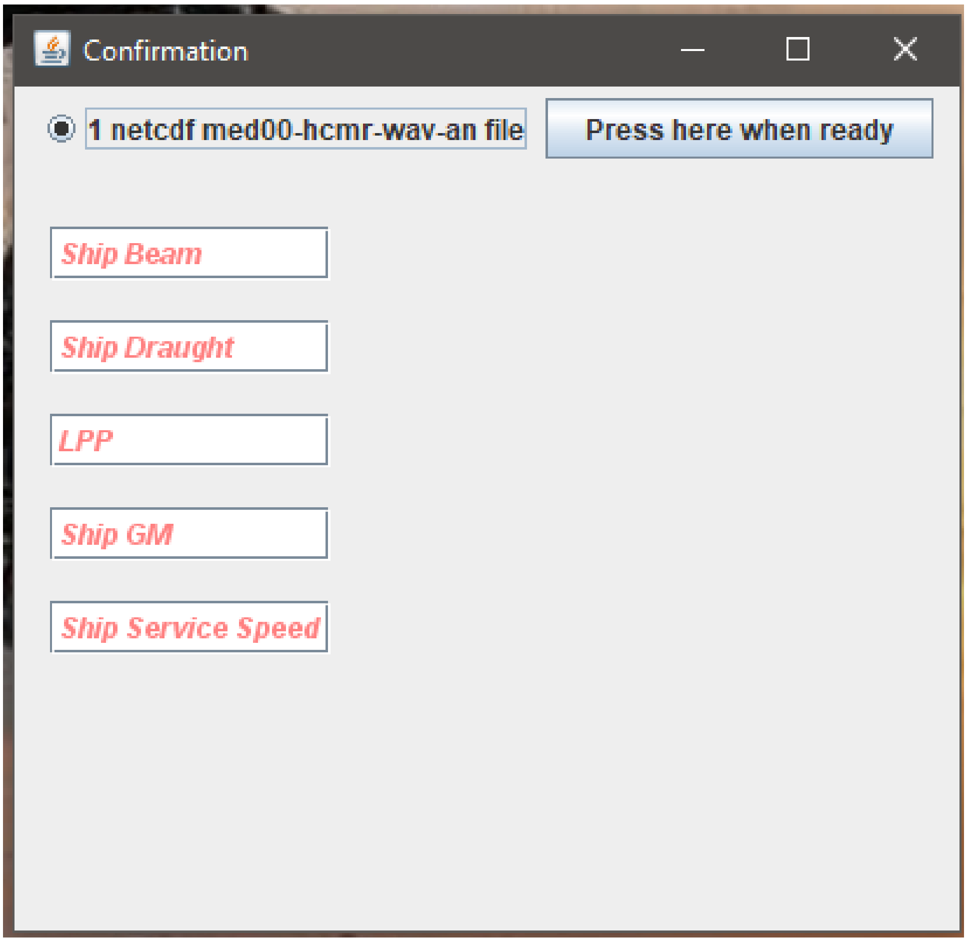
This client-side application is customizable to utilize a .nc file, with Spectral significant wave height (Hm0): variable "VHM0" and Spectral moments (-1,0) wave period (Tm-10): variable "VTM10" data for a common chronological period, with the purpose of creating a new .nc file, at the same timestamps, containing the following output data:

a) the Wavelength variable based on formula: WL = 1.56*VTM10*VTM10
b) the Danger Classification value: Produced results are 0,1,2 or 3.

The input file for the program to process is a netCDF (network common data form) file, containing array-oriented scientific data, which pertain to Unidata’ s Common Data Model (CDM). Acceptable file type is NetCDF3/CDM.

Finally, the user's requested input parameters for this program are:
a) ship's beam
b) ship's draught
c) ship's length
d) ship's GM
e) ship's service speed

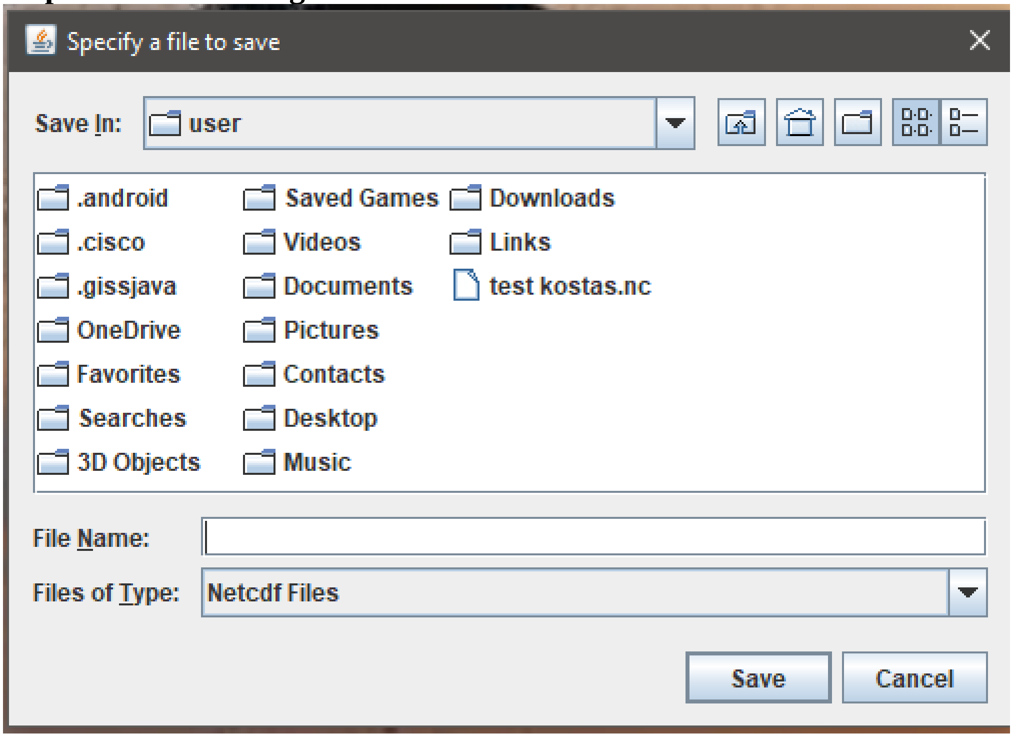
DSS user interface for data input



Confirmation

● 1 netcdf med00-hcmr-wav-an file

DSS Output data file saving interface



Specify a file to save

Save In: user

File Name:

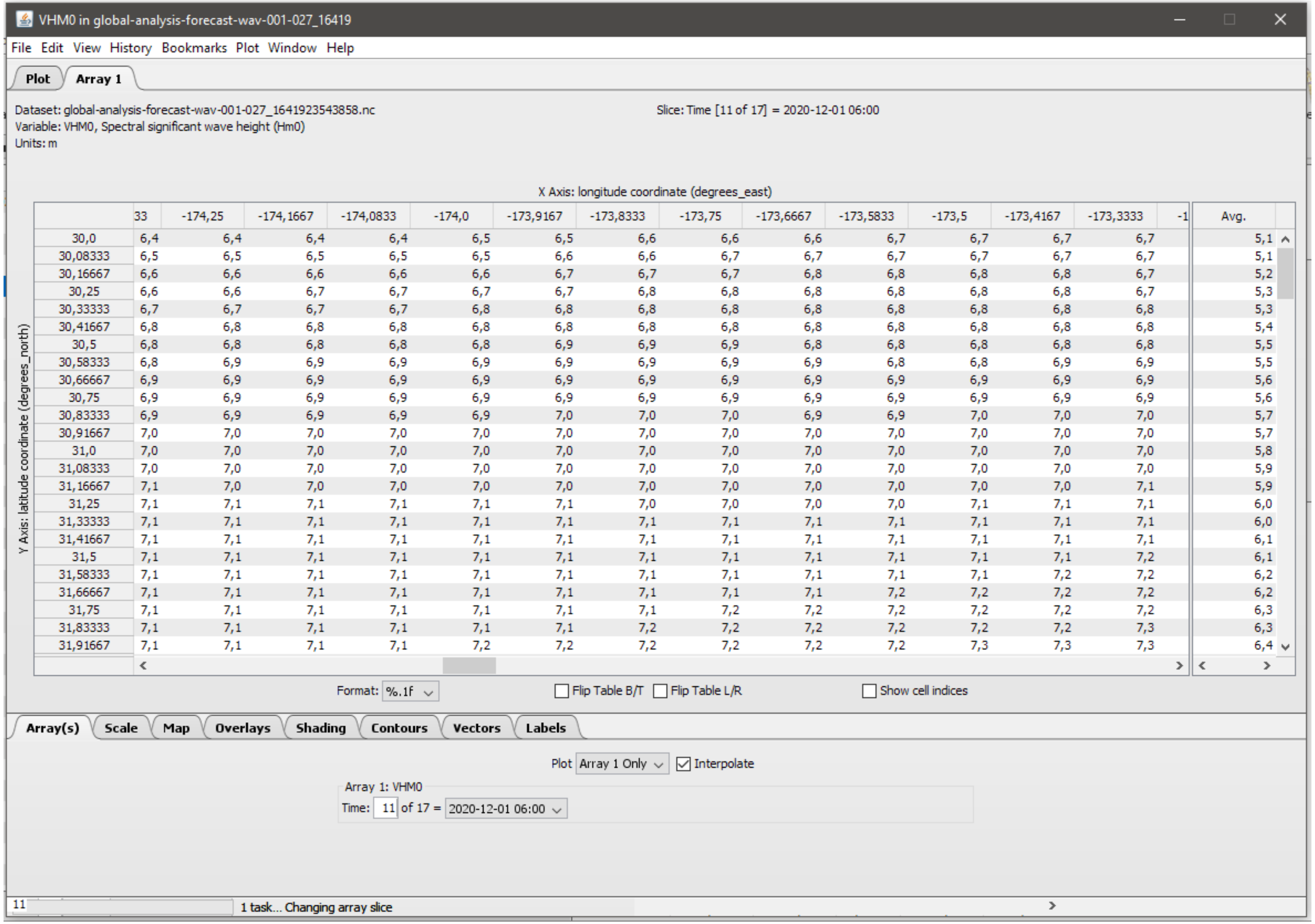
Files of Type: Netcdf Files

Netcdf input wave data headers

```
netcdf
file:/C:/Users/user/Documents/MASTER%20ΣΝΔ/ΠΤΥΧΙΑΚΗ%20ΕΡΓΑΣΙΑ/data/OPUS%20ONE/global-
analysis-forecast-wav-001-027_1641923543858.nc {
  dimensions:
    time = 17;
    latitude = 181;
    longitude = 241;
  variables:
    double latitude(latitude=181);
      :standard_name = "latitude";
      :long_name = "latitude coordinate";
      :units = "degrees_north";
      :axis = "Y";
      :step = 0.08333588f; // float
      :_ChunkSizes = 2041; // int
      :_CoordinateAxisType = "Lat";
      :valid_min = 30.0; // double
      :valid_max = 45.0; // double

    double time(time=17);
      :standard_name = "time";
      :long_name = "time";
      :units = "hours since 1950-01-01 00:00:00";
      :calendar = "standard";
      :axis = "T";
      :step = 3; // int
      :_ChunkSizes = 1; // int
      :_CoordinateAxisType = "Time";
      :valid_min = 621624.0; // double
      :valid_max = 621672.0; // double

    short VHM0(time=17, latitude=181, longitude=241);
      :long_name = "Spectral significant wave height (Hm0)";
      :units = "m";
      :add_offset = 0.0f; // float
      :scale_factor = 0.01f; // float
      :_FillValue = -32767S; // short
      :standard_name = "sea_surface_wave_significant_height";
      :cell_methods = "time:point area:mean";
      :type_of_analysis = "spectral analysis";
      :WMO_code = 100; // int
      :_ChunkSizes = 1, 681, 1440; // int

    short VTM10(time=17, latitude=181, longitude=241);
      :long_name = "Spectral moments (-1,0) wave period (Tm-10)";
      :units = "s";
      :add_offset = 0.0f; // float
      :scale_factor = 0.01f; // float
      :_FillValue = -32767S; // short
      :standard_name =
"sea_surface_wave_mean_period_from_variance_spectral_density_inverse_frequency_moment";
      :cell_methods = "time:point area:mean";
      :type_of_analysis = "spectral analysis";
      :WMO_code = 201; // int
      :_ChunkSizes = 1, 681, 1440; // int
```

```
    double longitude(longitude=241);
      :standard_name = "longitude";
      :long_name = "longitude coordinate";
      :units = "degrees_east";
      :axis = "X";
      :step = 0.08332825f; // float
      :_ChunkSizes = 4320; // int
      :_CoordinateAxisType = "Lon";
      :valid_min = -180.0; // double
      :valid_max = -160.0; // double

  // global attributes:
  :Conventions = "CF-1.6";
  :time_coverage_start = "20220120-03:00:00";
  :time_coverage_end = "20220121-00:00:00";
  :date_created = "20220111-07:35:00";
  :product_type = "forecast";
  :product = "GLOBAL_ANALYSIS_FORECAST_WAV_001_027";
  :product_ref_date = "20220111-00:00:00";
  :product_range = "D+9";
  :product_user_manual = "http://marine.copernicus.eu/documents/PUM/CMEMS-GLO-PUM-001-027.pdf";
  :quality_information_document = " http://marine.copernicus.eu/documents/QUID/CMEMS-GLO-QUID-
001-027.";
  :dataset = "global-analysis-forecast-wav-001-027";
  :title = "Mean fields from global wave model MFWAM of Meteo-France with ECMWF forcing";
  :institution = "METEO-FRANCE";
  :references = "http://marine.copernicus.eu";
  :credit = "E.U. Copernicus Marine Service Information (CMEMS)";
  :licence = "http://marine.copernicus.eu/services-portfolio/service-commitments-and";
  :contact = "servicedesk.cmems@mercator-ocean.eu";
  :producer = "CMEMS - Global Monitoring and Forecasting Centre";
  :area = "GLO";
  :FROM_ORIGINAL_FILE__geospatial_lon_min = -180.0f; // float
  :FROM_ORIGINAL_FILE__geospatial_lon_max = 179.9167f; // float
  :FROM_ORIGINAL_FILE__geospatial_lon_step = 0.08332825f; // float
  :FROM_ORIGINAL_FILE__geospatial_lon_units = "degree";
  :FROM_ORIGINAL_FILE__geospatial_lat_min = -80.0f; // float
  :FROM_ORIGINAL_FILE__geospatial_lat_max = 90.0f; // float
  :FROM_ORIGINAL_FILE__geospatial_lat_step = 0.08333588f; // float
  :FROM_ORIGINAL_FILE__geospatial_lat_units = "degree";
  :_CoordSysBuilder = "ucar.nc2.dataset.conv.CF1Convention";
  :comment = "";
  :source = " ";
  :history = "Data extracted from dataset http://localhost:8080/thredds/dodsC/global-analysis-forecast-wav-
001-027";
}
```

Netcdf input wave data structuring



Dataset: global-analysis-forecast-wav-001-027_1641923543858.nc
Variable: VHM0, Spectral significant wave height (Hm0)
Units: m

Slice: Time [11 of 17] = 2020-12-01 06:00

X Axis: longitude coordinate (degrees_east)

Y Axis: latitude coordinate (degrees_north)

	33	-174,25	-174,1667	-174,0833	-174,0	-173,9167	-173,8333	-173,75	-173,6667	-173,5833	-173,5	-173,4167	-173,3333	-1	Avg.
30,0	6,4	6,4	6,4	6,4	6,5	6,5	6,6	6,6	6,6	6,7	6,7	6,7	6,7		5,1
30,08333	6,5	6,5	6,5	6,5	6,5	6,6	6,6	6,7	6,7	6,7	6,7	6,7	6,7		5,1
30,16667	6,6	6,6	6,6	6,6	6,6	6,7	6,7	6,7	6,8	6,8	6,8	6,8	6,7		5,2
30,25	6,6	6,6	6,7	6,7	6,7	6,7	6,8	6,8	6,8	6,8	6,8	6,8	6,7		5,3
30,33333	6,7	6,7	6,7	6,7	6,8	6,8	6,8	6,8	6,8	6,8	6,8	6,8	6,8		5,3
30,41667	6,8	6,8	6,8	6,8	6,8	6,8	6,8	6,8	6,8	6,8	6,8	6,8	6,8		5,4
30,5	6,8	6,8	6,8	6,8	6,8	6,9	6,9	6,9	6,8	6,8	6,8	6,8	6,8		5,5
30,58333	6,8	6,9	6,9	6,9	6,9	6,9	6,9	6,9	6,9	6,8	6,8	6,9	6,9		5,5
30,66667	6,9	6,9	6,9	6,9	6,9	6,9	6,9	6,9	6,9	6,9	6,9	6,9	6,9		5,6
30,75	6,9	6,9	6,9	6,9	6,9	6,9	6,9	6,9	6,9	6,9	6,9	6,9	6,9		5,6
30,83333	6,9	6,9	6,9	6,9	6,9	7,0	7,0	7,0	6,9	6,9	7,0	7,0	7,0		5,7
30,91667	7,0	7,0	7,0	7,0	7,0	7,0	7,0	7,0	7,0	7,0	7,0	7,0	7,0		5,7
31,0	7,0	7,0	7,0	7,0	7,0	7,0	7,0	7,0	7,0	7,0	7,0	7,0	7,0		5,8
31,08333	7,0	7,0	7,0	7,0	7,0	7,0	7,0	7,0	7,0	7,0	7,0	7,0	7,0		5,9
31,16667	7,1	7,0	7,0	7,0	7,0	7,0	7,0	7,0	7,0	7,0	7,0	7,0	7,1		5,9
31,25	7,1	7,1	7,1	7,1	7,1	7,1	7,0	7,0	7,0	7,0	7,1	7,1	7,1		6,0
31,33333	7,1	7,1	7,1	7,1	7,1	7,1	7,1	7,1	7,1	7,1	7,1	7,1	7,1		6,0
31,41667	7,1	7,1	7,1	7,1	7,1	7,1	7,1	7,1	7,1	7,1	7,1	7,1	7,1		6,1
31,5	7,1	7,1	7,1	7,1	7,1	7,1	7,1	7,1	7,1	7,1	7,1	7,1	7,2		6,1
31,58333	7,1	7,1	7,1	7,1	7,1	7,1	7,1	7,1	7,1	7,1	7,1	7,2	7,2		6,2
31,66667	7,1	7,1	7,1	7,1	7,1	7,1	7,1	7,1	7,1	7,2	7,2	7,2	7,2		6,2
31,75	7,1	7,1	7,1	7,1	7,1	7,1	7,1	7,2	7,2	7,2	7,2	7,2	7,2		6,3
31,83333	7,1	7,1	7,1	7,1	7,1	7,1	7,2	7,2	7,2	7,2	7,2	7,2	7,3		6,3
31,91667	7,1	7,1	7,1	7,1	7,2	7,2	7,2	7,2	7,2	7,2	7,3	7,3	7,3		6,4

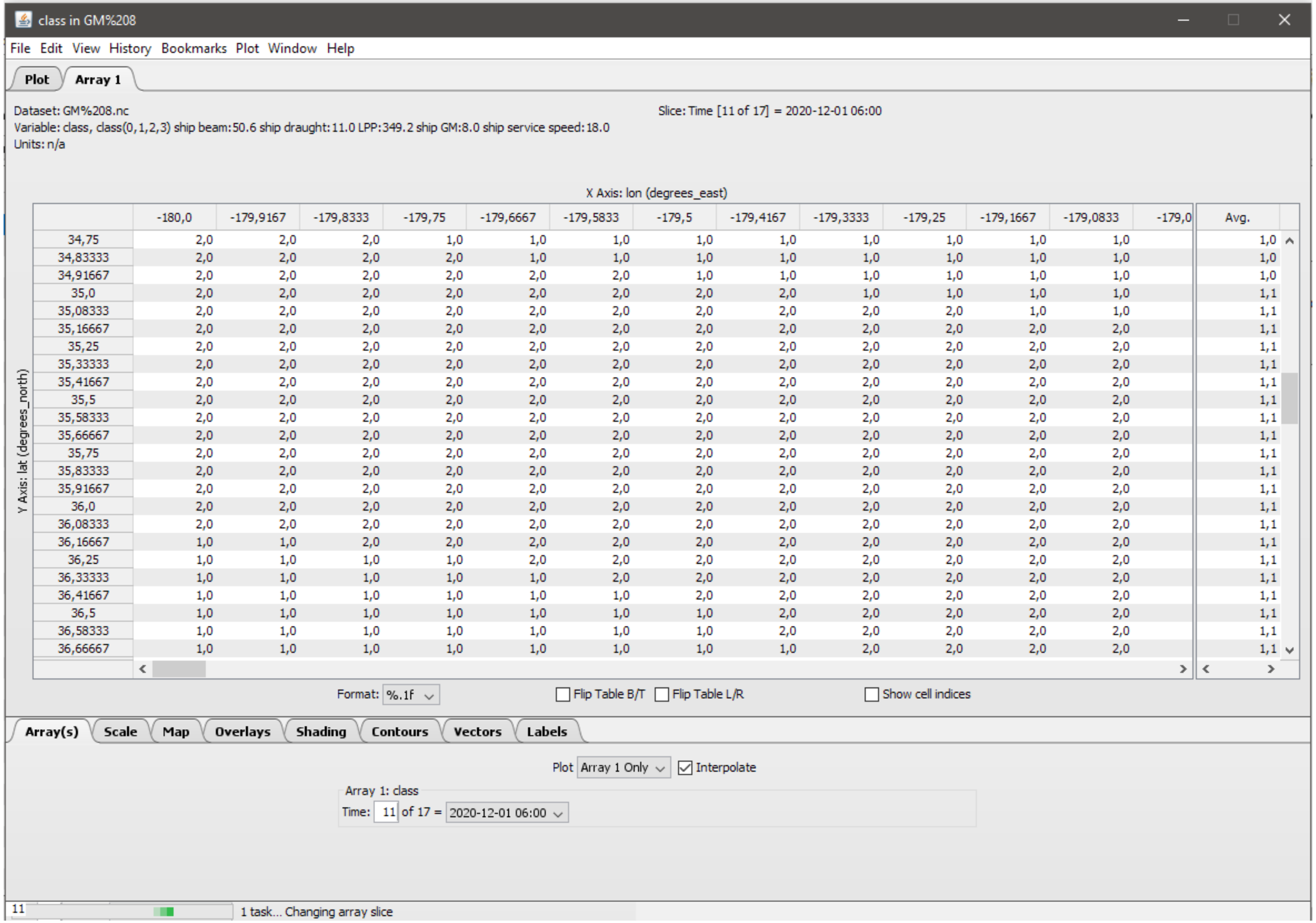
Format: %.1f
☐ Flip Table B/T ☐ Flip Table L/R ☐ Show cell indices

Plot: Array 1 Only ☑ Interpolate

Array 1: VHM0
Time: 11 of 17 = 2020-12-01 06:00

11 1 task... Changing array slice

DSS Netcdf output risk index data structuring



Dataset: GM%208.nc
Variable: class, class(0,1,2,3) ship beam:50.6 ship draught:11.0 LPP:349.2 ship GM:8.0 ship service speed:18.0
Units: n/a

Slice: Time [11 of 17] = 2020-12-01 06:00

X Axis: lon (degrees_east)

Y Axis: lat (degrees_north)

	-180,0	-179,9167	-179,8333	-179,75	-179,6667	-179,5833	-179,5	-179,4167	-179,3333	-179,25	-179,1667	-179,0833	-179,0	Avg.
34,75	2,0	2,0	2,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0		1,0
34,83333	2,0	2,0	2,0	2,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0		1,0
34,91667	2,0	2,0	2,0	2,0	2,0	2,0	1,0	1,0	1,0	1,0	1,0	1,0		1,0
35,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	1,0	1,0	1,0	1,0		1,1
35,08333	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	1,0	1,0		1,1
35,16667	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0		1,1
35,25	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0		1,1
35,33333	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0		1,1
35,41667	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0		1,1
35,5	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0		1,1
35,58333	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0		1,1
35,66667	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0		1,1
35,75	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0		1,1
35,83333	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0		1,1
35,91667	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0		1,1
36,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0		1,1
36,08333	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0		1,1
36,16667	1,0	1,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0		1,1
36,25	1,0	1,0	1,0	1,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0		1,1
36,33333	1,0	1,0	1,0	1,0	1,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0		1,1
36,41667	1,0	1,0	1,0	1,0	1,0	1,0	2,0	2,0	2,0	2,0	2,0	2,0		1,1
36,5	1,0	1,0	1,0	1,0	1,0	1,0	1,0	2,0	2,0	2,0	2,0	2,0		1,1
36,58333	1,0	1,0	1,0	1,0	1,0	1,0	1,0	2,0	2,0	2,0	2,0	2,0		1,1
36,66667	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	2,0	2,0	2,0	2,0		1,1

Format: %.1f

☐ Flip Table B/T ☐ Flip Table L/R ☐ Show cell indices

Plot Array 1 Only ☑ Interpolate

Array 1: class
Time: 11 of 17 = 2020-12-01 06:00

11 1 task... Changing array slice

Appendix C: “Wave data model short description”

Short description:

The operational global ocean analysis and forecast system of Météo-France with a resolution of 1/12 degree is providing daily analyses and 10 days forecasts for the global ocean sea surface waves. This product includes 3-hourly instantaneous fields of integrated wave parameters from the total spectrum (significant height, period, direction, Stokes drift, etc.), as well as the following partitions: the wind wave, the primary and secondary swell waves.

The global wave system of Météo-France is based on the wave model MFWAM which is a third-generation wave model. MFWAM uses the computing code ECWAM-IFS-38R2 with a dissipation term developed by Ardhuin et al. (2010). The model MFWAM was upgraded on November 2014 thanks to improvements obtained from the European research project « my wave » (Janssen et al. 2014). The model mean bathymetry is generated by using 2-minute gridded global topography data ETOPO2/NOAA. Native model grid is irregular with decreasing distance in the latitudinal direction close to the poles. At the equator the distance in the latitudinal direction is fixed with grid size 1/10°. The operational model MFWAM is driven by 6-hourly analysis and 3-hourly forecasted winds from the IFS-ECMWF atmospheric system. The wave spectrum is discretized in 24 directions and 30 frequencies starting from 0.035 Hz to 0.58 Hz. The model MFWAM uses the assimilation of altimeters with a time step of 6 hours. The global wave system provides analysis 4 times a day, and a forecast of 10 days at 0:00 UTC. The wave model MFWAM uses the partitioning to split the swell spectrum in primary and secondary swells.

Source: DOI (product) https://doi.org/10.48670/moi-00017