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Extreme Significant Wave Height Map of Indonesia Based on SEAFINE and ERA5 Database

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Highlights:

- The ERA5 database is comparable to the SEAFINE database in terms of data length, temporal resolution and spatial resolution for extreme significant wave height analysis.
- The extreme value analysis from the SEAFINE database is approximately 33% to 200% higher than ERA5 for a 1-yearly return period and 25% to 100% higher for a 100-yearly return period in most western and central Indonesian seas.
- The developed extreme significant wave height maps based on SEAFINE and factored ERA5 analysis results showed a good fit between both databases.
- Field measurements are required to further verify the analysis results.

Abstract. Significant wave height, H_s, is one of the most utilized ocean parameters. Extreme H_s with 1-yearly and 100-yearly return periods are required for the design of most offshore structures. A previous study by Wurjanto, *et al.* (2020) attempted to utilize the SEAFINE database to develop extreme H_s maps of Indonesian seas. However, SEAFINE does not cover the eastern Indonesian seas. This study analyzed the extreme values from ERA5 data for Indonesian seas and utilized the data to complete the extreme H_s map previously developed by Wurjanto, *et al.* (2020). The ERA5 H_s data on the eastern Indonesian seas as well as the central and western seas were extracted for validation purposes. The ERA5 extreme value was less than half the H_s value compared to the SEAFINE-based results in most intersecting areas. For the development of the map, we took the SEAFINE-based map from Wurjanto *et al.*, which covers the western and middle Indonesian seas, and filled the eastern part with extreme ERA5 H_s data. It was found that a wave height multiplying factor of 2.0 was the most suitable for ERA5 in the developed map to make a seamless wave height transition from SEAFINE to ERA5 data.

Keywords: *ERA5; Indonesia; SEAFINE; significant wave height; wave hindcast.*

1 Introduction

Significant wave height, H_s, is the average height of the top one-third waves in a wave group [1]. H_s has usage for many purposes, ranging from coastal studies, maritime transportation, ocean energy utilization, to offshore engineering and

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operations [2]. Its high importance means that H_S is collected daily by the national meteorological agencies of most countries, such as the National Oceanic & Atmospheric Administration (NOAA) of the US [3] and Japan Meteorological Agency [4].

These wave data need to be accurately obtained. An overestimation of wave height may lead to an overdesign of offshore structures. Underestimation, on the other hand, can make the built structure prone to failure since its components will not be designed to withstand the actual environmental load. Inaccurate wave data can also put ocean-going ships at risk, especially if the prediction underestimates the current wave climate's harshness.

The offshore engineering field requires extreme H_S data with particular return periods that represent operational and storm conditions. Offshore steel platform design, according to Det Norske Veritas [5] and the American Petroleum Institute [6], requires 1-yearly and 100-yearly return period H_S's. These extreme H_S's should be defined in at least eight directions. The number of required directions for the structural analysis increases as the number of platform legs increases [6].

During the feasibility study and the early part of the FEED phase, the knowledge of single, omnidirectional extreme H_S in an area can be very valuable. The offshore structure designer can make basic offshore structure design alternatives based on the knowledge of extreme wave values in the designated area. These basic designs are essential in the feasibility study to have a rough estimate of the construction cost.

An attempt to provide this extreme H_S has been done through the ISO 19901-1 standard by the International Standards Organization, which contains annexes that describe the ocean meteorological and oceanographic parameters for several ocean regions. The latest volume, from 2015, includes Southeast Asia [7].

The coverage of ISO 19901-1, however, is insufficient for offshore development in Indonesia. The country has more than 500 operating offshore platforms spread across the archipelago [2], while the information provided by ISO 19901-1 only covers the Natuna Island in the west. To provide general significant wave height information on the Indonesian seas, long-term H_S data that cover the entire Indonesian waters are required.

The H_S data can be acquired with several methods, such as direct measurement, hydrodynamic modeling, or satellite altimetry. Direct measurement is arguably the most accurate and reliable way to measure wave height. However, the initial and operational costs can be very high and buoys must be periodically maintained [8]. Hydrodynamic modeling is a more accessible way to acquire H_S data since open-source software for ocean hydrodynamic modeling are available, such as SWAN [9]. The software is capable of generating H_s data based on wind, tide, and bathymetry data. Some satellite altimeter data, for example from NOAA, are also publicly available. However, while the H_s data from satellite altimeter measurement from open oceans are useful, their quality tends to be low in coastal areas [10].

One of the commercially available meteorology-oceanography (metocean) databases that include long-term H_s is SEAFINE from Oceanweather, Inc. [11]. SEAFINE is a wind and wave hindcast model that covers the southern part of the South China Sea. The SEAFINE spatial resolution (the spatial interval of available data) is 6 km in the South China Sea, Offshore Madura, and Makassar Strait, and 25 km elsewhere. The SEAFINE data are recorded at an hourly interval and cover a continuous period from 1956 to 2015.

The unavailability of field recorded wave data from buoys in the Indonesian ocean region makes it difficult to thoroughly assess the accuracy of the SEAFINE data [12]. However, the SEAFINE data have been used by several past studies in Indonesia [2,13]. Past studies regarding wave height comparison between SEAFINE and field measurement showed varying results. The study by Ragupathi, *et al.* [14] attempted to compare the peaks of SEAFINE H_s and measured data, which revealed that the hindcast data were lower than the measured data collected near a platform in Offshore Serawak, Malaysia. In general, hindcast overestimates field measurements. However, it is also possible that the wave measurements were inaccurate due to the blocking effect caused by a nearby offshore platform.

In another case, the study by Mayeetae, *et al.* [15] showed that the SEAFINE data had a good correlation with measured wave data. The wave hindcast was able to capture past hurricanes with fair accuracy. This gives confidence for extreme wave height analysis, which requires a statistical approach with accurate data.

Based on these past studies it can be concluded that SEAFINE is one of the best available hindcast datasets for metocean studies within its spatial coverage. The dataset, however, still requires more validation based on long-term measured data.

Previous research by Wurjanto, *et al.* [2] attempted to create extreme H_s maps of Indonesian seas based on the SEAFINE database. However, the maps only covered the Indonesian seas up to the extent of the database, which is limited to the western and middle Indonesian seas. This study aimed to complete the previously developed extreme H_s maps by utilizing a database that covers the eastern Indonesian waters. The data used in this study were ERA5 reanalysis data from the European Center for Medium-range Weather Forecasts (ECMWF), which are described in Section 2 along with the methodology. In Section 3, the analysis result is shown in the form of an extreme H_s map. Chapter 4 discusses the map and how it compares to the previous studies. Finally, the conclusion of this study is given in Section 5.

2 Methodology

2.1 About ERA5

The H_s database used in this study was ERA5 from the European Centre for Medium-range Weather Forecasts (ECMWF), which provides hourly global weather and climate data. ERA5 replaced the ERA-Interim reanalysis when it ended on 31 August 2019. The reanalysis of the data from 1979 from 2-3 months to real-time was done in 2016 and 2017. The data from 1950 to 1978 are 2 to 5 days behind real-time [17].

ERA5 utilizes both satellite altimetry and hydrodynamic modeling to acquire the wave height data. The H_s produced in the database is based on the latter, with wind data acquired from satellite measurement. The data are available at an hourly temporal resolution and a 0.5° x 0.5° spatial resolution [17].

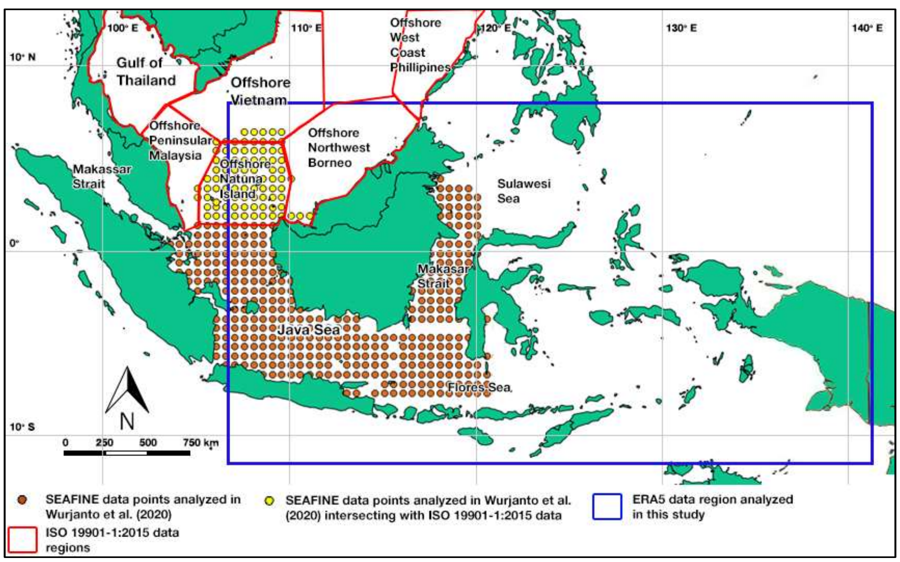

Figure 1 SEAFINE data points from Wurjanto *et al.* (2020), the ISO 19901-1:2015 data regions, and the ERA5 data region analyzed in this study.

Sources:
ISO 19901:2015 Data regions : International Standards Organization [7]
SEAFINE data points : Wurjanto *et al.* [2]

2.2 General Methodology

The methodology of this study is outlined in Figure 2. The first phase of this study was to extract ERA5 H_s data [17]. ERA5 data can be extracted from the ECMWF website (https://cds.climate.copernicus.eu/). These data can be freely accessed with an ECMWF account. We extracted the data from ERA5 with coverage as shown in Figure 1.

The extracted data cover the entire eastern Indonesian seas and as well as a portion of the middle and western parts. These portions were extracted to see how the ERA5 data compare to the SEAFINE data in the same locations. The data length was limited to the last ten years, which is considered sufficient for extreme-value analysis.

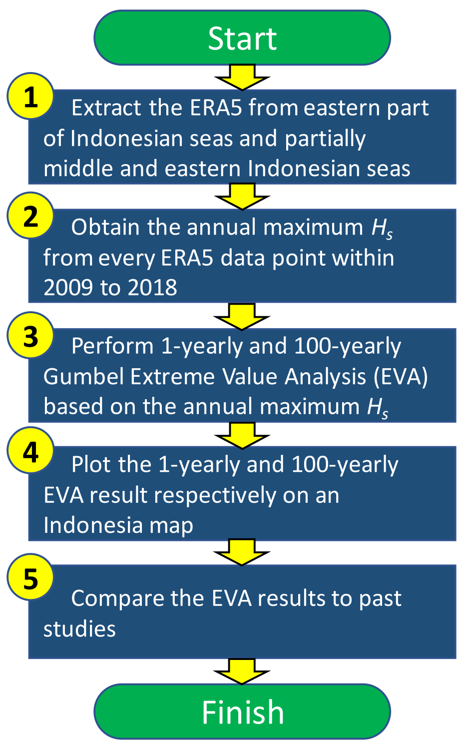

Figure 2 General methodology of this study.

After the hourly data had been extracted, the annual maximum H_s was obtained. These annual maxima were the basis for extreme-value analysis using the Gumbel method, which is commonly used in extreme-value analysis [18]. By having the annual maxima, the 1-yearly and 100-yearly return period values of H_s can be predicted. The formula of the Gumbel method is as follows:

$$X_p = \bar{X} + (S_x \times K_p) \tag{1}$$

where:

X_p = expected value of the return period (m)
$\bar{X}$ = average of data (m)
S_x = standard deviation of data X
$= \left(\frac{\sum_{i=1}^{N}(X_i-\bar{X})^2}{N-1}\right)^{0,5}$
N = number of data in X
K_p = Gumbel distribution frequency factor for return period p

A Gumbel-method analysis was performed to obtain 1-yearly and 100-yearly return period H_s. After the extreme H_s had been obtained from all data points, the values were plotted into extreme wave height maps.

3 Significant wave from ERA5

The 1-yearly extreme H_s values from ERA5 are shown in Figure 3. The Indonesian inner seas have lower H_s values, ranging from 0.5 to 1.0 m. More sheltered seas such as Makassar Strait and Sulawesi Sea have even lower H_s, at 0.0 to 0.5 m. However, the outer seas have higher H_s, at 1.0 to 1.5 m. These higher H_s values are expected since these seas are exposed to the Pacific and the Indian Ocean.

The difference in H_s between areas is more apparent in the 100-yearly map shown in Figure 4. The Eastern Indonesian Sea has the highest H_s among the inner Indonesian seas. The H_s ranges from 2.0 to 3.5 m in the Banda Sea and reaches 3.5 to 4.0 m in the Arafura Sea. However, sheltered areas such as Cendrawasih Bay and behind Wokam Island have significantly lower H_s, where it reaches 1.0 to 1.5 m. The outer seas, however, have significantly higher H_s, at 4.0 to 5.5 m in the south, 2.5 to 4.5 m in the northeast, and 2.0 to 8.5 m in the northwest near the South China Sea.

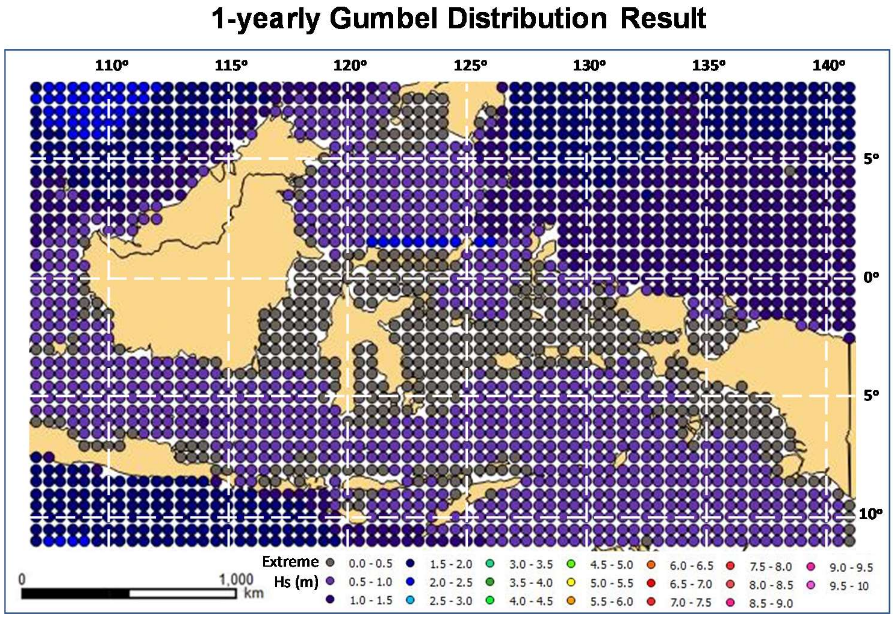

Figure 3 1-yearly H_s values of Indonesian seas based on the ERA5 database.

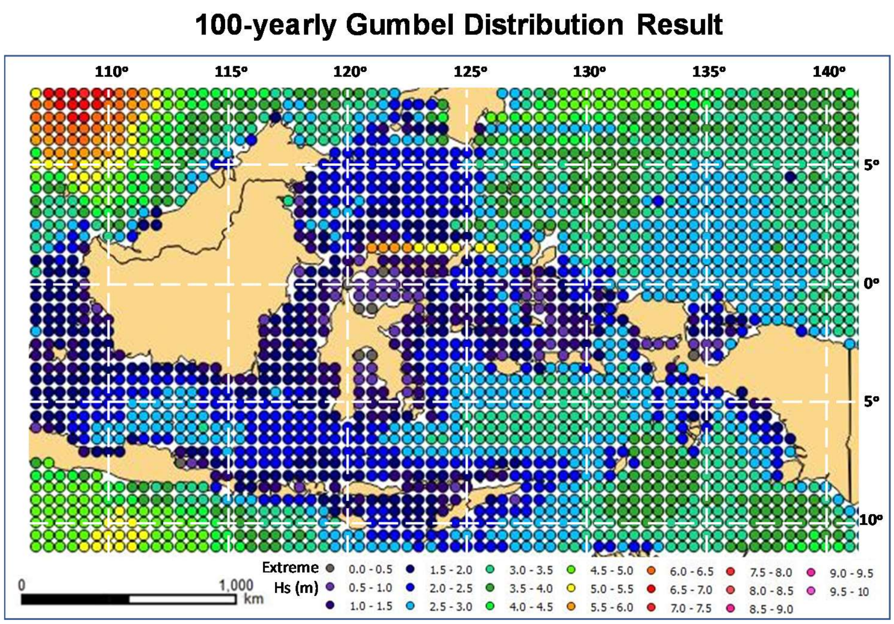

Figure 4 100-yearly H_s values of Indonesian seas based on the ERA5 database.

4 Discussion

Compared to the SEAFINE-based map in Wurjanto, *et al.* [2], the produced ERA5-based extreme H_S map significantly underestimated the wave height. As an example, the H_S values across the inner seas are within the range of 0.5 to 1.0 m. The H_S values reach 1.5 to 2.0 m in the outer side of the Indonesian seas. This is relatively low compared to maps based on the SEAFINE data, which give 0.5 to 2.5 m for the Java Sea.

The SEAFINE-based map shows even higher H_S, at 3.0 m in Madura Offshore and the Banda Sea. This underestimation is in agreement with the study by Muliati, *et al.* [15]. They compared ERA-Interim, the predecessor of ERA5, the Simulating Waves Nearshore (SWAN) hydrodynamic model, and SEAFINE in the Natuna Sea. It was found that the SEAFINE model produced approximately 25% higher values than ERA-Interim. A similar result was also found in the present study, where the 100-yearly H_S values in Natuna Offshore were within 3.5 to 4.5 m while the study by Wurjanto, *et al.* [2] yielded 4.0 to 5.0 m.

The 100-yearly H_S map has notably higher values at every data point than the 1-yearly map. However, it still shows overall lower H_S values than the SEAFINE-based map. The ERA5-based map shows 1.5 to 2.5 m to the north of West Java and 2.0 to 3.0 m to the north of Central Java and East Java. These H_S values are still significantly lower compared to the SEAFINE-based map, which shows 2.5 to 3.5 m and 4.5 to 5.5 m respectively.

Only a few past studies have been conducted on 1-yearly H_S. Bappenas (National Development Planning Agency) has published satellite altimeter data from 2006 to 2008 [19]. The study showed that the average H_S within the measurement period ranged from 1.0 to 1.2 m in the Banda Sea and the Arafura Sea. The same wave height was also found in the Java Sea, with waves becoming higher from 1.2 to 1.8 m in Sunda Strait. Compared to this study, these mean values are still higher than the ERA5's H_s. Moreover, the Bappenas data had an average H_S, which means that the actual wave height could be much higher. For example, Goda [1] proposed the mean of the top-10 wave height $H_{1/10}$ to be 2.03 of average wave height $\overline{H}$.

The next step was to create H_s maps of the entire inner Indonesian seas. We used the SEAFINE map from a previous study [2] as the basis. This map covers the inner Indonesian seas but is limited in the western and middle part. To cover the eastern part, we used ERA5 data. However, since the ERA5 values are lower than those from SEAFINE, one of the database extreme value analysis results must be adjusted to avoid a large gap in extreme H_s values between the SEAFINE and ERA5 data in adjacent locations.

The lack of actual long-term measurement data for Indonesian waters makes it difficult to validate the results from SEAFINE and ERA5. As already mentioned in the introduction, Indonesia currently lacks publicly available measured wave height data. However, both tend to underestimate the actual wave height. For example, the report from [20] describes that the wave height in the Sunda Strait can reach 5 m during extreme weather. The SEAFINE data indicate only 1.5 m to 2.0 m for the 100-yearly H_s near the Sunda Strait, while ERA5 has even lower values, i.e. 0.5 to 1.0 m near the Java Island coastline.

More conservative wave height values are preferred for the design of offshore structures to avoid structural failures, both during the construction and operation phases. Therefore, we used the existing SEAFINE-based map as the basis and filled in the eastern seas with the H_s from the ERA5 result. To compensate for the lower overall H_S result from ERA5, we multiplied the H_S at each point by 2.0. The maps based on coupled 1-yearly and 100-yearly extreme value analysis results from both databases are shown in Figure 5.

The factored ERA5 results shows a good fit with the existing SEAFINE-based map. The combination yielded a smooth gradation between SEAFINE-based to ERA5-based data in the transition area in the Flores Sea. The average maximum H_S distribution found in the study by Sofian & Wijanarto [21] had the same distribution as found in this study, where H_S is generally higher in the Arafura Sea, the Banda Sea, and east of Sulawesi Island. In their research it was found that the average maximum H_S in these regions was around 3 to 5 m regardless of the season.

A more recent report from BMKG [22] shows that during extreme weather on June 5th, 2020, the wave height around the Makassar Strait, the Flores Sea, and the East Banda Sea was around 1.25 to 2.50 m. The wave height reached 2.50 to 4.00 m in the Arafuru Sea and the Western Banda Sea. While maximum wave height is not directly comparable to H_s data, the wave height trend agrees with the composed map, where H_s is generally higher in eastern Indonesia.

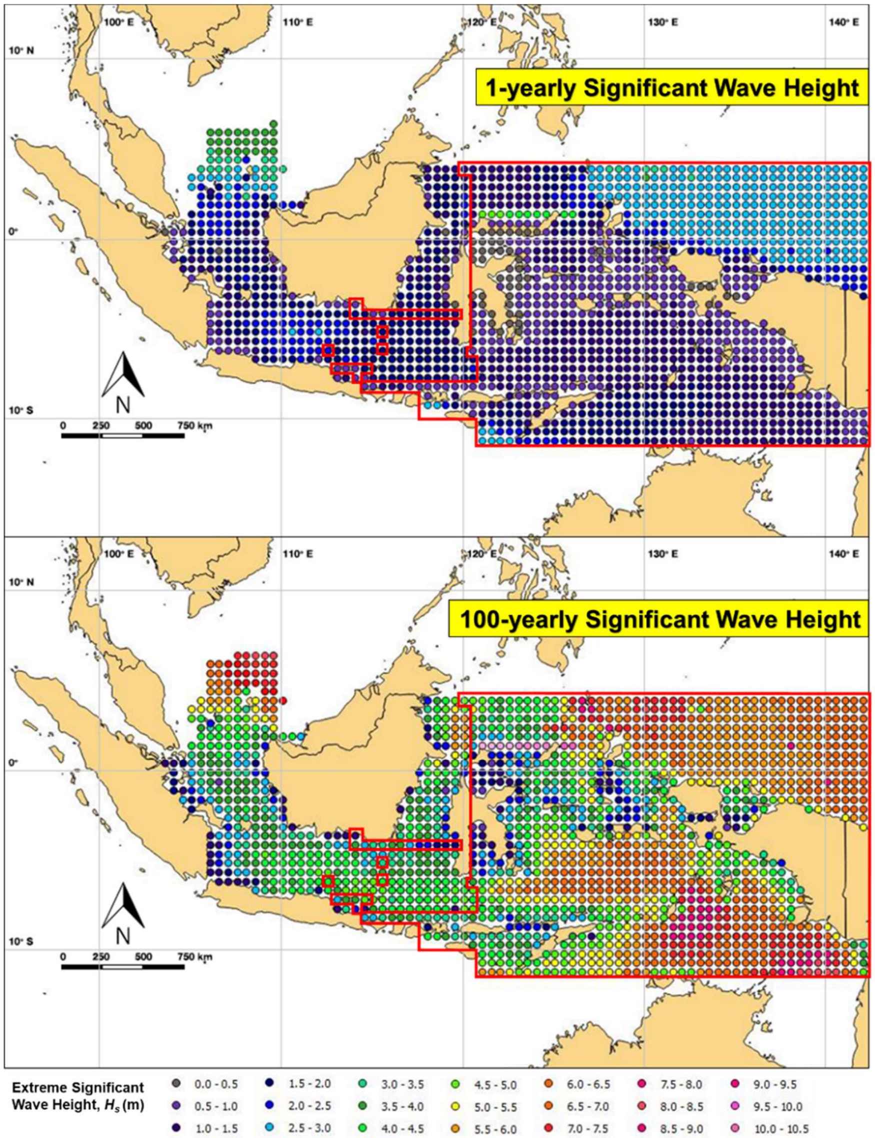

Figure 5 1-yearly and 100-yearly H_S map based on combined SEAFINE and 2.0x factored ERA5 database extreme analysis result. Regions based on 2.0x factored ERA5 results are shown as dots within red boxes.

5 Conclusion

ERA5 is adequate for the use of extreme value analysis in terms of data period length, spatial, and temporal resolution. Extreme value analysis of H_s data from the ERA5 database was performed. In general, the analysis of the ERA5 data resulted in lower extreme H_s values than those from SEAFINE. For a 1-yearly return period, the SEAFINE data are approximately 200% higher in the Makassar Strait, 33% higher in the Natuna Islands, and 150% higher in Madura Offshore and the Banda Sea compared to ERA5.

The 100-yearly ERA5 H_s, however, had a slightly better agreement with SEAFINE. The difference in the Natuna Islands was only approximately 25% higher in SEAFINE, while it was 75% in Madura Offshore. The gap was 100% in the Banda Sea and the Makassar Strait.Extreme H_s maps for Indonesia based on SEAFINE and the newly developed ERA5 reanalysis database were developed in this study. The added multiplying factor of 2.0 to the ERA5 part of the map produces excellent agreement with the transition between the database results, which further validated the H_s distribution from previous studies.

Improvement of the result of this study can be done in the future by conducting field measurements across the Indonesian inner seas. Since both SEAFINE and ERA5 performed best on open, offshore regions, the measurements should ideally be performed near operating offshore platforms.

References

[1] Goda, Y., *Random Seas and Design of Maritime Structures*, **15**, World Scientific, 2000.

[2] Wurjanto, A., Mukhti, J.A., Wirasti, H.D. & Widyaningtyas, Y.E., *Extreme Significant Wave Height of Western and Central Indonesian Seas and Its Correlation with ISO 19901-1:2015*, Journal of Engineering and Technological Sciences, **52**(3), pp. 331-342, 2020.

[3] National Weather Forecast Service, *Hourly Weather Forecast Graph*. Available at https://forecast.weather.gov/gridpoint.php?site=key& TypeDefault=graphical (21 December 2019).

[4] Japan Meteorological Agency, *Wave Analysis Chart – Seas Around Japan @ 00UTC, 21 Dec. 2019*. Available at https://www.data.jma.go.jp/ gmd/waveinf/chart/awjp_e.html (21 December 2019).

[5] Det Norske Veritas, *Offshore Standard DNV-OS-C101: Design of Offshore Steel Structures, General (LRFD Method)*, 2011.

[6] American Petroleum Institute, *API Recommended Practice 2A-WSD 22nd Edition: Planning, Designing, and Constructing Fixed Offshore Platforms – Working Stress Design*. API Publishing Services, 2014.

[7] ISO/TC 67 Committee of International Organization for Standardization, *ISO 19901-1:2015 (E) Petroleum and Gas Industries – Specific Requirements for Offshore Structures – Part 1: Metocean design and operating considerations*, ISO, Geneva, 2015.

[8] Loehr, H., Boulay, S.O.C., Warner, W.J., Johnson, D., Beamlsey, B. & McComb, P., *Development of a Low Cost Wave Buoy by Utilising Smartphone Technology*, Coast and Ports, pp.116-120, 2013.

[9] Liang, B., Gao, H., & Shao, Z., *Characteristics of Global Waves based on the Third-generation Wave Model SWAN*, Marine Structures, **64**, pp. 35-53, 2019.

[10] Wiese, A., Staneva J., Schulz-Stellenfleth, J., Behrens, A., Fenoglio-Marc, L. & Bidlot, J.R., *Synergy of Wind Wave Model Simulations and Satellite Observations during Extreme Events*. Ocean Science, **14**, pp. 1503-1521, 2018.

[11] Oceanweather, Inc., *SEAFINE Southern South China Sea, Makassar Strait, Java Sea*, Available at https://www.oceanweather.com/metocean/ seafine/index.html. (6 June 2019)

[12] CNN Indonesia, *BNPB: All Tsunami Deterction Buoys in Indonesia were Broken*, available at https://www.cnnindonesia.com/nasional/ 20180930160115-20-334439/bnpb-seluruh-buoy-deteksi-tsunami-di-indonesia-rusak. (15 July 2020)

[13] Muliati, Y., Tawekal, R.L., Wurjanto, A., Kelvin, J. & Pranowo, W.S., *Wind Wave Modeling in Natuna Sea: A Comparison Among SWAN, SEAFINE, and ERA-INTERIM*, International Journal of Geomate, **16**(54), pp. 176-184, 2019.

[14] Raghupathi, L., Randell D., Jonathan, P. & Ewans, K.C., *Consistent Design Criteria for South China Sea with a Large-scale Extreme Value Model*, Offshore Technology Conference Asia, Malaysia, 2016.

[15] Hersbach, H., Bell, B., Berrisford, P., Horányi, A., Sabater J.M., Nicolas, J., Radu, R., Schepers, D., Simmons, A., Soci, C. & Dee, D. *Global Reanalysis: Goodbye ERA-Interim, Hello ERA5*. ECMWF Newsletter, **159**, pp. 17-24, Spring 2019.

[16] Mayeetae, Z., Liew, M.S. & John, K.V., *Parametric Study on Environmetal Loads of Hindcast and Measured Full Scale Data*, National Postgraduate Conference, IEEE, Malaysia, 2011.

[17] Copernicus Climate Data Store, *ERA5 Hourly Data on Single Levels from 1979 To Present*. Available at https://cds.climate.copernicus.eu/cdsapp#! /dataset/reanalysis-era5-single-levels?tab=overview (23 December 2019).

[18] Det Norske Veritas, *Offshore Standard DNV-RP-C205: Environmental Conditions and Environmental Loads*, 2010.

[19] The National Development Planning Agency (Bappenas), *Indonesia Climate Change Sectoral Roadmap (ICCSR) Scientific Basis: Analysis and Projection of Sea Level Rise and Extreme Weather Events*, 2010.

[20] OkeNews, High Waves up to 5 Meters Halts the Ferry Operation in Sunda Strait. Available at https://news.okezone.com/view/2017/11/29/1/45049/gelombang-tinggi-hingga-5-meter-hambat-arus-penyeberangan-kapal-ferry-di-selat-sunda. (15 July 2020)

[21] Sofian, L. & Wijanarto, A.B., *Simulation of Significant Wave Height Climatology using WaveWatch III*, International Journal of Geoinformatics, **6**(4), pp. 13-19, Dec. 2010.

[22] Kompas.com, BMKG: Beware of High Waves until Tonight, Here is the List. Available at https://news.okezone.com/view/2017/11/29/1/45049/gelombang-tinggi-hingga-5-meter-hambat-arus-penyeberangan-kapal-ferry-di-selat-sunda. (15 July 2020)