Strengthening the Early Detection and Tracking of Tropical Cyclones near Indonesian Waters

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Abstract. In early April 2021, the territory of Indonesia, around the province of East Nusa Tenggara in particular, was severely damaged due to being hit by tropical cyclone Seroja. The impact of tropical cyclone Seroja does not only occur in Nusa Tenggara but also in Australia. In fact, the impact that hit Australia exceeded the damage that occurred in East Nusa Tenggara. The impacts caused by tropical cyclone Seroja in East Nusa Tenggara included 181 deaths and 74,222 houses damaged. Tropical cyclones are extreme weather anomalies that hit many countries, especially in the middle latitudes associated with vast oceans, such as the area around the South China Sea, the Pacific Ocean and the Atlantic Ocean, such as the Philippines, Japan, America, Australia, Europe, etc. Early detection systems for the genesis of tropical cyclones are still being developed by international collaborations such as The Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction (RAMA) in the Indian Ocean, Tropical Atmosphere Ocean (TAO) in the Pacific Ocean, and Prediction and Research Moored Array in the Tropical Atlantic (PIRATA).

To find out the early sign of a tropical cyclone, it is characterized by sea surface temperatures > 26.5°C, the growth of very broad and thick convective clouds, and rotating wind speeds of > 63 km/hour. For this reason, continuous observations are needed in the area where the tropical cyclone first developed. Observation equipment required includes satellite observations, buoys, and weather radar. Unfortunately, in the territory of Indonesia, especially in the Indian and Pacific oceans around Indonesia, this equipment is not equipped with such equipment due to very expensive funding factors and vandalism constraints. For this reason, in the future, national and international cooperation will be needed to start building an early warning system for the emergence of tropical cyclones among research centers globally.

Keywords: tropical cyclone-disaster risk reduction-buoy array-early warning system

1. Introduction

In general, tropical cyclones occur in middle latitudes, but it is possible that these disturbances also occur in low latitudes such as in Indonesia, although the possibility of occurrence is very rare. Tropical cyclones generally have direct and indirect impacts. The direct impact of tropical cyclones is the
accompanying meteorological conditions at the time the cyclone takes place. These direct impacts include increased rainfall [1-3], increased wind speed[4] and high waves[5]. Indirect impacts are further impacts due to the increase in meteorological activity, including floods [6], landslides[7,8], erosion and changes in coastal ecosystems [9], coastal flooding and damage to various infrastructures[5].

There are at least 7 tropical cyclones that occur and are close to the territory of Indonesia, including Tropical Cyclone Vamei (26 – 31 December 2001), Tropical Cyclone Inigo (30 March – 9 April 2003), Tropical Cyclone Durga (22 – 24 April 2008), Cyclone Tropical Cyclone Kirrily (26 – 27 April 2009), Tropical Cyclone Cempaka (26 – 29 November 2017) and Tropical Cyclone Dahlia (29 November – 4 December 2017). The most recent is Tropical Cyclone Seroja in South Nusa Tenggara on 2-9 April 2021.

Economic losses due to the emergence of tropical cyclones are often caused by flooding, as explained by Villarini in 2016[10] that flood events in the West and East America which tend to occur in October-March are strongly influenced by tropical cyclone activity. Assuming that tropical cyclones trigger high rainfall intensity, rainfall characteristics in Java and Madura are related to the occurrence of tropical cyclone Cempaka. Tropical cyclone Cempaka that hit Indonesia in November 2017 showed a significant increase in the area close to the cyclone's center and when the cyclone reached its peak[11]. The tropical cyclone Cempaka at that time coincided with the MJO phase in the maritime continent region. The above-normal sea surface temperature at the location of the emergence of tropical cyclone Cempaka is the starting point for the birth of a tropical cyclone. Even in several locations of rain gauges, daily rain data was recorded which reached a record high that had never been experienced before[12].
Figure 2. Data on the impact of tropical cyclone Seroja (BNPB, 2021)
Economic losses and even large numbers of deaths as a result of the tropical cyclone Seroja in April 2021 were felt directly by the Indonesian population, specifically the people of East Nusa Tenggara. Tropical cyclone Seroja has a direct impact on increasing the amount of rainfall and strong winds in the East Nusa Tenggara region. Nakano et al[13] defined the critical radius of impact (precipitation) as 300 km from the centre of each cyclone (tropical cyclone) which is known as direct impact.

BMKG is given the authority and operational responsibility to carry out tropical cyclone monitoring by the WMO-World Meteorology Organization through the Tropical Cyclone Warning Centre (TCWC) Jakarta which was established in 2008. Under its authority, TCWC Jakarta has operational areas including AoR-Area of Responsibility and AoM-Area of Monitoring. BMKG is internationally responsible for issuing and disseminating information and High Seas Warnings, and assigns an internationally recognized name (WMO) to tropical cyclone events in the Jakarta TCWC AoR. Besides that, TCWC Jakarta also has the responsibility to make analysis and forecasts of tropical cyclones, as well as to issue and disseminate information and early warnings of tropical cyclones and the impact of bad weather they cause to communities throughout mainland and coast of Indonesia.

Figure 3. Areas of Responsibilities and Monitoring of TCWC Jakarta

2. Data and Method

The data used in this study are:

1. Historical data on tropical cyclone events obtained from the International Best Track Archive for Climate Stewardship (IBTrACS) for the period 1970-2021.
2. Data on the intensity and movement of tropical cyclone Seroja from TCWC Jakarta.
3. Distribution data for regional offices and observation networks from BMKG.
4. Data on losses due to natural disasters from BNPB

Strengthening early detection and prediction of Tropical Cyclone movement is carried out by considering the factors that play a very important role. These factors are divided into 3 types, namely observation, numerical modelling and human resources.
3. Results and Discussion

3.1. Trends in the Emergence of Cyclones near Indonesia linked to climate change and global warming issues

By utilizing the data from 1970-2021 for tropical cyclone events in the Indian Ocean region and performing special filtering for events within the Jakarta TCWC monitoring area, an overview of tropical cyclone events in southern Indonesia is obtained, namely 0°-20° South Latitude, 90-141° East Longitude. It is known that in the south of Indonesia in the AoM TCWC Jakarta area, the most tropical cyclones occur in January and February, namely 20% of events in a month. Followed by March (19%), December (16%) and April (13%). In the last 51 years, the months in which there were almost no tropical cyclones at all were June, July, August and September.
The highest frequency of tropical cyclones in the AoM TCWC Jakarta area was in February, namely 132 events and the average incidence per year was 2.5. January is the next most active month (127 events) with an average of 2.4 events per year.

![Figure 6. Average Tropical Cyclone Occurrence in the AoM TCWC Area, South Jakarta, Indonesia.](image)

Period 1970-2021 (51 years)

The following graph illustrates the occurrence of tropical cyclones each year specifically in the 0-10° South latitude region of southern Indonesia. The incidence of tropical cyclones in southern Indonesia are the most numerous and closest to the equator in 1975, 1980, 1996, and 2017.

![Figure 7. The occurrence of tropical cyclones per year in the 0-10° latitude region](image)

3.2. *Strengthening Early Detection of Tropical Cyclones*

3.2.1. *Strengthening Weather Data Observation.* In this case, the observed weather data on the surface is measured in real-time weather elements consisting of rainfall, temperature, wind direction and speed, humidity, air pressure and solar radiation.

Observations of weather parameters play a role in detecting the onset of tropical cyclones, especially from indicators of air pressure, humidity, wind speed and rainfall. The arrival of the cyclone is
characterized by a very significant decrease in air pressure when compared to normal conditions. If there is a rapid decrease in pressure and is characterized by an increase in wind speed and an increase in humidity, this can be used as an early indication of a tropical cyclone.

Figure 8. Location of Automatic Weather Station (AWS, 444 sites) (a) and location of Automatic Rain Gauge (ARG, 687 sites) (b)

In general, these observation locations are still concentrated in the mainland area and have not been spread evenly due to many technical controls in the field. To strengthen early detection, additional observation sites are needed on certain islands, especially in the middle of the sea which is quite wide in the waters east of Indonesia. For this reason, a strong communication tool is needed and regular maintenance is needed to ensure data can be obtained continuously.
3.2.2. Strengthening Upper Air Observation (Radiosonde). Radiosondes are atmospheric sensors that provide an accurate, high-resolution description of the Earth’s atmosphere from the ground to 100,000 ft. Radiosondes are carried into the air by latex weather balloons filled with helium or hydrogen. Radiosondes measure atmospheric pressure, air temperature, water vapor (humidity) and winds (speed and direction). Modern radiosondes contain a GPS receiver to calculate wind speed and direction, and a radio transmitter to send the data back to the ground. Since they were first developed in the 1930s, radiosondes have become smaller, lighter, more accurate and less expensive. The most common use of radiosondes is for synoptic soundings, which are released once or twice a day (at 00Z and 12Z) from fixed locations around the globe. These soundings are carried out simultaneously by national weather services around the world to create a three-dimensional picture of the Earth’s atmosphere at one point in time. Data from approximately 600 sites is transmitted to data centres for use in numerical weather prediction (NWP) models maintained by major governments and research institutions. These models produce the two to seven-day weather forecasts that everyone relies on for daily activities (www.intermetsystem.com).

BMKG routinely launches radiosondes in 20 locations twice a day under normal conditions. Sometimes the number of launches may decrease due to budget constraints and transmitter/balloon availability. To increase the number of launches, it is very necessary, especially in research activities in eastern Indonesia to study the characteristics of cyclone genesis. For this reason, national and international research collaborations are needed, especially with Australia and Japan, which also have high attention on the existence of tropical cyclones in the territory of Indonesia.

![Figure 9. Location of radiosonde launch by BMKG (updated 2019)](image)

3.2.3. Strengthening Remote Sensing Observations with weather radar and satellite. Based on the existing weather radar data, the performance of the weather radar and its utilization can be known. Of the 41 radars currently operating, the national average operability rate is 78.6%. A total of 29 sites have an operability level above 75% and 3 weather radar sites have an operability level of less than 25%. The low level of weather radar operability is caused by several things, namely: malfunctioning...
hardware/software, decreased performance due to equipment age, and damage due to natural disasters (e.g., earthquakes). However, some weather radar locations with equipment age above 8 years, with proper maintenance, have good performance with a relatively high level of operability.

Based on an internal study, to cover the entire territory of Indonesia, weather radar is needed in 75 locations with variations in the type of weather radar, 5 S-band locations, 50 C-band locations and 20 X-band locations. In the BMKG Strategic Plan document for 2020-2024, it is planned to build weather radars in at least 22 locations for the next 5 (five) years. It is hoped that the target of 75 weather radar locations can be met by 2029. In addition to considering the fulfilment of needs in supporting the tasks and functions of BMKG, the number of planned locations for weather radars in Indonesia can be more than 75 locations. This can be caused by several things, including the consideration of filling in the gaps in radar data, private requests, political and strategic considerations, construction of a new airport, the new State Capital, and other needs. In determining the number, placement location and ideal weather radar technology, there are several factors to consider, namely the Law of the Republic of Indonesia Number 31 of 2009 concerning Meteorology, Climatology and Geophysics, Presidential Regulation no. 37 of 2018 concerning the Master Plan for the Implementation of Meteorology, Climatology and Geophysics for 2017-2041, Regulation of the Meteorology, Climatology and Geophysics Agency Number 4 of 2020 concerning the BMKG Strategic Plan for 2020-2024, and WMO No. 8 (2018 edition), Guide to Instruments and Methods of Observation (CIMO Guide), Volume III – Observing Systems, Chapter 7, Radar Measurement and input from the Deputy for Meteorology, MKG centre and the Technical Implementation Unit as well as a team of experts from LIPI, ITB, PSTA-LAPAN, BPPT, PT 247, and PT LEN.

Based on considerations that include the BMKG Strategic Plan (RENSTRA) 2020-2024, proposals from the MKG centre Region 1-5 in the assessment form that has been carried out, proposals from the private sector related to weather modelling, and related to special research, so that a list of the distribution of proposed locations is compiled. Additional weather radars are shown in the following Figure and table.

Figure 10. Distribution of Existing Radar Site Points, Radar Proposals Submitted Based on the 2020-2024 BMKG RENSTRA, and Additional Radar Proposals
The weather radar observation network consists of 83 locations consisting of 41 existing weather radars and 42 proposed weather radars. The type of C-Band weather radar dominates the distribution of the existing weather radar with a total of 37 locations compared to the X-Band Radar which only has 4 locations. However, based on the planning, the X-Band weather radar has the most proposals with 20 locations, then 17 locations for the C-Band weather radar, and 5 S-Band locations. The proposal for the X-Band type of weather radar is mostly due to the effectiveness of coverage for areas surrounded by mountains or to overcome blank areas. Meanwhile, the presence of the S-Band type weather radar is expected to cover a wider area with a relatively flat topography.

3.2.4. Strengthening Remote Sensing Observations with weather radar and satellite. Tropical Cyclone Emergence Prediction and Tracking with Weather Modelling (InaNWP) and Ocean Modeling. The InaNWP model is a regional model developed by BMKG which employs the Weather Research Forecasting (WRF) assimilated with BMKG observation data. The specifications of the InaNWP model are as follows:

1. **InaNWP software:**
   - Operating system Fedora 31 Server Edition
   - Weather Research Forecasting (WRF) version 4.2
   - WRF-Data Assimilation (WRFDA) version 4.2
   - WRF-Pre-Processing (WPS) version 4.2
   - ARWPost version 3.1
   - Fortran compiler, Gfortran version 9.3.1

2. **InaNWP Libraries:**
   - Message Passing Interface mpich version 3.3.2
   - Zlib version 1.2.11
   - Szip version 2.1.1
   - Jasper version 1900.1
   - Libpng version 1.6.37
   - Hdf5 version 1.12.0
   - Netcdf-c version 4.74
   - Netcdf-fortran version 4.5.3

3. **Data Assimilation (3DVAR):**

   The system assimilates weather radar, upper air sounding, synoptic data, and automatic weather station data throughout Indonesia.
   - Including: ± 360 manual and automatic weather stations, and upper air data in ± 22 sites.
   - Radar data in 40 sites (five radar sites not operating, three radar sites are in progress for assimilation, data from 32 radar sites are already assimilated)
   - Using default background error (BE)
   - Radar assimilation technique: directly assimilate reflectivity with a new observation operator
   - Wind speed/direction assimilation: assimilate wind/speed value directly from data input
   - The InaNWP model is run regularly (2 times a day) at 23.30 JST (valid for 12 UTC) and 11.30 JST (valid for 00 UTC) using an automatic script based on the Linux language (bash shell).

The current weather prediction configuration is arranged according to the hardware capability: 3 days forecasts with 9 km spatial resolution for domain 1 and 3 km for domain 2 (details of specifications are attached in Table 1). To run 1 (one) cycle of prediction takes 6-8 hours on average. As an integrated system (work and performance system is interdependent), it requires good application system management to ensure that all processes run successfully and are appropriately recorded (in the log file), so the information of error can be easily obtained.
Figure 11. Indonesia Numerical Weather Prediction (InaNWP)

http://puslitbang.bmkg.go.id/wrf/

Figure 12. The early detection of TC Seroja from InaNWP product
3.2.5. Capacity Building. Forecasters are the main factor in conducting assessments to issue early warnings of tropical cyclones such as detecting the low pressure trend in particular locations. For decision making, materials are needed as a decision support system (DSS). Following a procedure, the forecaster will analyse the synoptic weather maps, satellite photos, weather radar images, marine data, especially sea surface temperatures and analyse the output of weather modelling and ocean modelling. From the results of the compilation of various data, a conclusion will be drawn for decision making. The more cases that occur, the more experience the forecaster will have to make the best decisions. To accelerate the increase in forecaster capacity, training from experts in their fields is needed to share experiences, especially subjective knowledge transfer (expert decisions).

3.3. Strengthening Climate and Weather Service Capacity – Marine Meteorology System (MMS-BMKG)

Analysis of ocean observations near Tropical Cyclones (TC) will improve understanding of their development and improves in different geographic regions and different seasons. Obviously, ocean observations are crucial in TC research and prediction because they can examine the details of the air-sea interaction processes that led to the formation and intensification of these systems. Additionally, ocean observations are increasingly viewed by the forecasting community as a key part of improving extreme weather forecasts.

In order to meet the need for oceanographic data in Indonesian seas, BMKG continues to strive to complete the availability of such data through the Strengthening of Marine Meteorology System program for the next five years. In this program, BMKG will complete the availability of a meteorological-oceanographic monitoring system consisting of Marine Automatic Weather Station (AWS), AWS Vessel, High-Frequency Radar, Drifter Buoy, Profiling Float, etc (figure.14).
Figure 14. Map Of Ocean Observing system (Existing and Planned)

The data from these observations will be integrated into one system that will be very helpful in supporting the analysis of tropical cyclogenesis in Indonesian seas, and also, the data will be assimilated into the couple atmospheric-wave and ocean model which was also developed in this project.

The availability of data from drifter buoys in Indonesian seas is still very rare, for example the Basin areas of Tropical Cyclones such as the Banda Sea (figure.15), so that in this program BMKG will also increase availability by deploying drifter buoys around the Banda Sea. The drifter buoy will be very useful in conducting SLP analysis in cyclone genesis areas where the availability of this data is still very rare, besides that this data will also serve as a verifier and assimilator to reduce forecast errors in the model. The profile buoy also provides valuable insights into the upper ocean processes that contribute to the formation and strengthening of TCs. In general, adaptive fine-scale, high-frequency profile buoy samples are needed to fully capture the mesoscale ocean features usually associated with storm enhancement, and describe the upper ocean response caused by storms in detail.
4. Conclusions

Although tropical cyclones do not occur frequently in Indonesia, the impact of the disaster is extraordinary. To reduce this impact, it is necessary to strengthen the capacity for early warning such as detection and prediction of cyclones in Indonesia. For this reason, it is necessary to increase the network of observation instruments on land and at sea, adding the location of weather radars and upper air observation, numerical weather prediction, ocean modelling and increase the capacity building of weather forecasters. To realize these activities, collaboration among stakeholders and budget allocations are needed as well.

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