

Wind variability across in the Tomini Bay

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Abstract. This study aimed to investigate the wind variability and spectral analysis from wind data, specially focusing on Tomini Bay. We accessed data from Copernicus at <https://marine.copernicus.eu/>. We collected wind data in 2023 with longitude and latitude in the study area from 119° W to 130° E and 3° N to 2° S. The wind product includes hourly Level-4 sea surface wind and stress fields, with a horizontal spatial resolution of 0.125 degrees. In the Tomini Bay, the factors that are responsible for these one-of-a-kind spatial characteristics are the upwelling and downwelling conditions. Coastal areas exhibit consistent positive or negative anomalies, probably associated with upwelling and downwelling processes. Open-ocean areas have significant patterns of anomalies, indicating large-scale meteorological phenomena such as trade winds or monsoonal influences. The PSD graph focuses on the variations in wind pressure anomalies in Tomini Bay throughout 2023. Persistent oscillations around values close to zero suggest that the anomalies originate from either the long-term average or climate factors. The graph's peaks and troughs signify periods of volatility in wind pressure anomalies, either from seasonal variability, atmospheric dynamics, or particular climatic variables affecting regional wind patterns.

1. Introduction

In the investigation of atmosphere-ocean interactions [1-4], wind variability is particularly critical. Wind is a component of the weather that affects existence, including the utilization of renewable energy sources [7, 8], as well as the ecosystem as a whole [9]. Solar radiation, Earth's rotation [10], and uneven heating pressure gradients [11] interact to shape wind variability on a global scale. Surface roughness [12] and terrain [11] are examples of regional and local scale factors that can affect wind properties, leading to intricate and variable patterns of variability. This dynamic system has the potential to substantially influence the formation of monsoon and trade winds [13, 14], as well as the circulation of the atmosphere and ocean currents [4, 6]. Recent study has enhanced understanding of the elements

affecting wind variability in both temporal and spatial dimensions, highlighting the influence of climate events [15] and anthropogenic [14, 16].

Current instruments and methods have developed rapidly, such as the use of supercomputers [4, 17] in computing so that they will be able to predict wind variability that has an impact on climate. With these instruments and technologies, researchers can find out the causes of wind variability in region that has high accuracy on a spatial and temporal scale [4-6].

The European Union initiated the Copernicus programme, which has become a critical initiative for Earth observation, providing a comprehensive collection of environmental data. Copernicus Atmosphere Monitoring Service (CAMS) and Copernicus Climate Change Service (C3S) are exceptional sources of wind and climate data, enabling researches to conduct highly precise studies of atmospheric and oceanic dynamics. These data are instrumental in the advancement of meteorology, oceanography, and energy applications, as well as the support of global initiatives to comprehend and mitigate the effects of climate change [18-21].

Tomini Bay is one of Indonesia's major bays; the closing line between the two mouths is more than 24 nautical miles long. The island of Sulawesi officially divides Tomini Bay into three provinces: Gorontalo, North Sulawesi, and Central Sulawesi. The Molucca Sea borders the exposed eastern edge of Tomini Bay [22, 23]. This study aimed to investigate the wind variability and spectral analysis from wind data, specially focusing on Tomini Bay.

2. **Materials and Methods**

We accessed data from Copernicus at <https://marine.copernicus.eu/>. We collected wind data in 2023 with longitude and latitude in the study area from 119° W to 130° E and 3° N to 2° S. The wind product includes hourly Level-4 sea surface wind and stress fields, with a horizontal spatial resolution of 0.125 degrees. We compute temporally-averaged difference fields [24] using scatterometer data from Metop-B and Metop-C ASCAT and corresponding variables from the European Centre for Medium-Range Weather Forecast (ECMWF) operational model. Copernicus's development and uses have made many important steps forward in coastal oceanography by using sentinel improvements and land effluents for shores and oceans. These changes have also made it easier for both old and new stakeholders to use CMEMS-based products [4, 21]. In this study we used variables latitude, longitude, air density, northward and eastward wind for u and v component, respectively. Analysis of wind using scatterometer are active sensors in that they transmit a microwave radar signal to the water surface and monitor the received energy [25].

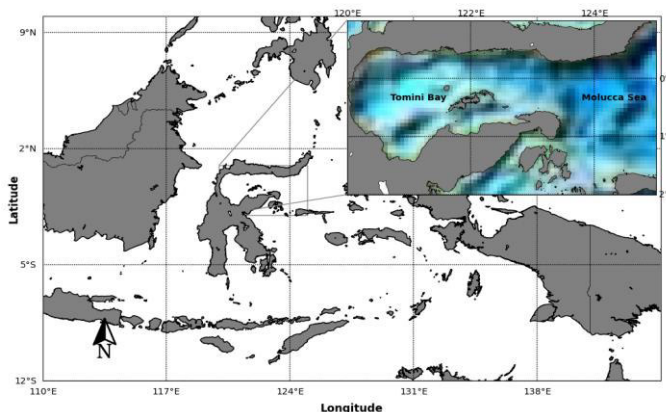


Fig 1. Research Location

3. Results and Discussion

3.1. Wind Variability

The extent of the wind variance that can be seen in Tomini Bay is shown in **Figure 2**, which can be found over here. The months of May through August were usually slow, and September to December were usually significant. However, the months of January through April were very different from these patterns. According to the findings of a spatial study, the primary portion of Tomini Bay was subjected to more intense wind conditions during the whole year. Both the topographic and oceanographic qualities have an impact on the development of spatial patterns that are either strengthened or weakened.

In the Tomini Bay, the factors that are responsible for these one-of-a-kind spatial characteristics are the upwelling and downwelling conditions. In Tomini Bay, the nutrient mixing and sea surface temperature (SST) variability may be determined by the effect of ocean circulation, such as the Indonesia Throughflow (ITF), which is both affected and produced by the wind.

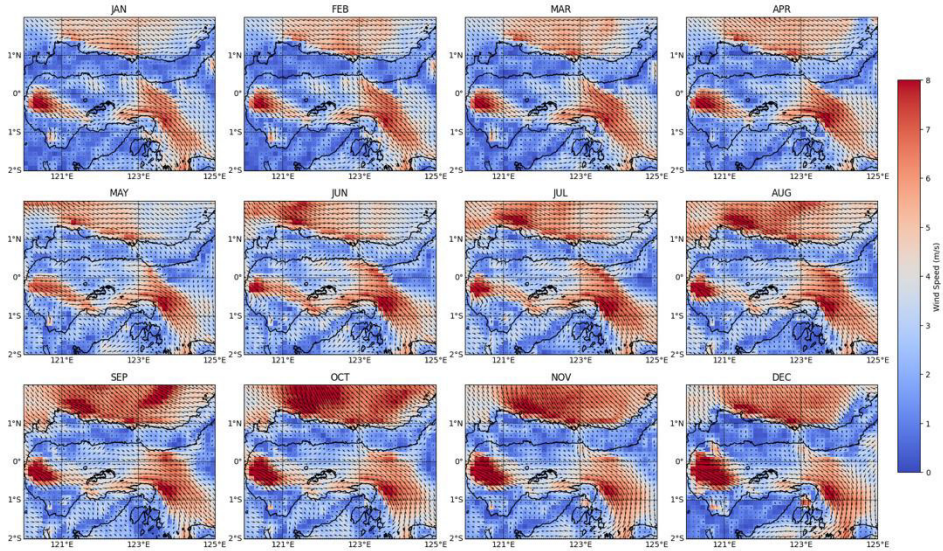


Fig 2. Wind variability in the Tomini Bay Periods 2023

3.2. Wind Stress Curl and Ekman Pumping Velocity

The monthly plots January to December (**Fig. 3**) exhibit distinct geographical and temporal fluctuations in wind stress curl anomalies throughout the research area. Positive anomalies (red hues) and negative anomalies (blue hues) alternate throughout the year, indicating strong seasonal fluctuation. Significant positive anomalies are noted in certain months, indicating heightened cyclonic activity or circumstances conducive to upwelling at these times. In contrast, pronounced negative anomalies, indicative of anticyclonic activity, prevail in other months. This indicates that the atmospheric circulation in this area is influenced by both seasonal dynamics and local wind patterns.

The geographical patterns indicate specific areas with significant abnormalities, perhaps associated with topography and oceanographic characteristics such as coasts, bathymetry, and ocean currents. Coastal areas exhibit consistent positive or negative anomalies, probably associated with upwelling and downwelling processes. Open-ocean areas have significant patterns of anomalies, indicating large-scale meteorological phenomena such as trade winds or monsoonal influences.

Seasonal variations are evident, particularly in March, April, and October, when anomaly patterns see significant alterations. Changes in large-scale atmospheric circulation, such as the beginning or decrease of monsoons or variations in the location of atmospheric pressure systems, may be a sign that the transition months are now occurring. It is possible that prevailing summer wind regimes, which may either exacerbate or attenuate wind stress curl anomalies, are responsible for the persistence of some patterns during the summer months (for example, from June to August).

The abnormalities in wind stress curl presumably significantly influence ocean-atmosphere interactions in this area. Positive curl anomalies may augment upward Ekman pumping, affecting thermocline dynamics and nutrient accessibility in the

upper ocean. This affects biological productivity and regional climatic variability. Negative curl anomalies indicate downward Ekman pumping, which inhibits vertical nutrient transfer and influences surface ocean conditions. The identified anomalies correspond with established atmospheric and oceanic processes, such as monsoon systems, ENSO effects, or regional circulation patterns. Further inquiry is required to elucidate the factors behind these anomalies, especially their association with large-scale climatic patterns.

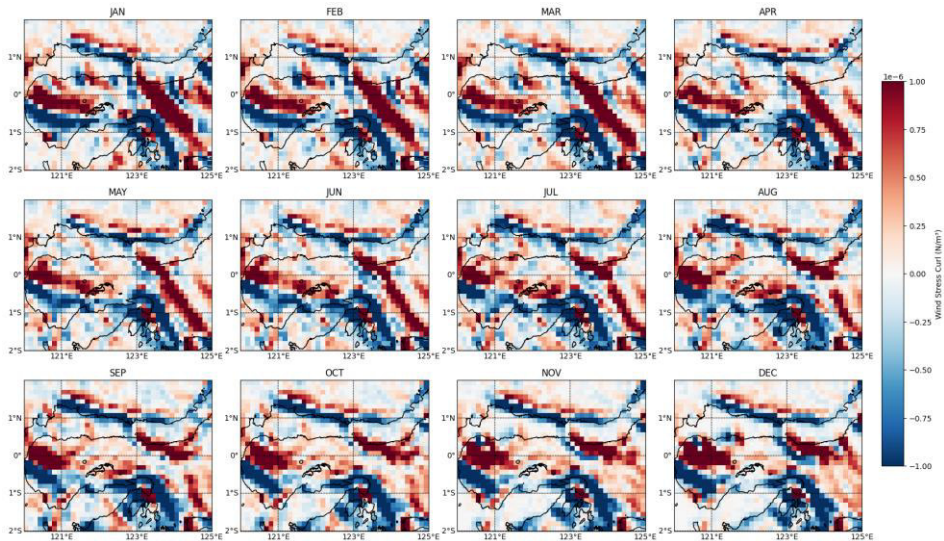


Fig 3. Wind Stress Curl

The distribution of EPV during January to May (**Fig. 4**), Tomini Bay has negative EPV values reaching -15 to -5 m/s which indicates the direction of vertical velocity is moving upwards. The results of EPV values show the same intensity and wind speed during the 5 months. The peak of negative EPV occurred in May (transitional season 1), where the EPV speed reached -15 m/s upwards. Negative EPV can cause water masses to move towards the surface through Ekman pumping. According to Hori et al., [26] negative EPV can change sea surface conditions, because the results of the study show an indication of upwelling when EPV is negative. In June to August (east season), EPV begins to increase because in that season the wind speed also increases from the previous season. Wind speed has an influence on ocean dynamics, especially in the process of vertical movement of water masses [30]. EPV is part of the vertical circulation of seawater that occurs due to the interaction between the Coriolis force and wind stress at the sea surface [30].

Entering the second transitional season (September - November), the intensity of EPV is getting stronger and spreads throughout Tomini Bay, because the variation of wind stress along Tomini Bay causes divergence or convergence of water masses, thus triggering upwelling or downwelling [27]. Ekman pumping velocity is influenced by higher wind speeds that tend to produce greater friction at the sea surface. The friction can affect the pressure gradient, which in turn determines the intensity of Ekman transport [28]. Strong and stable winds can cause Ekman pumping velocities to tend to be higher, compared to low wind speeds because they

only produce smaller pressure gradients, thus weakening Ekman pumping [29]. Research Berdandes et al., [29] shows that EPV with negative values in the Arafura Sea indicates an upwelling phenomenon, but Ekman pumping is not only influenced by wind stress, but is influenced by depth factors that also affect the value of EPV in an area.

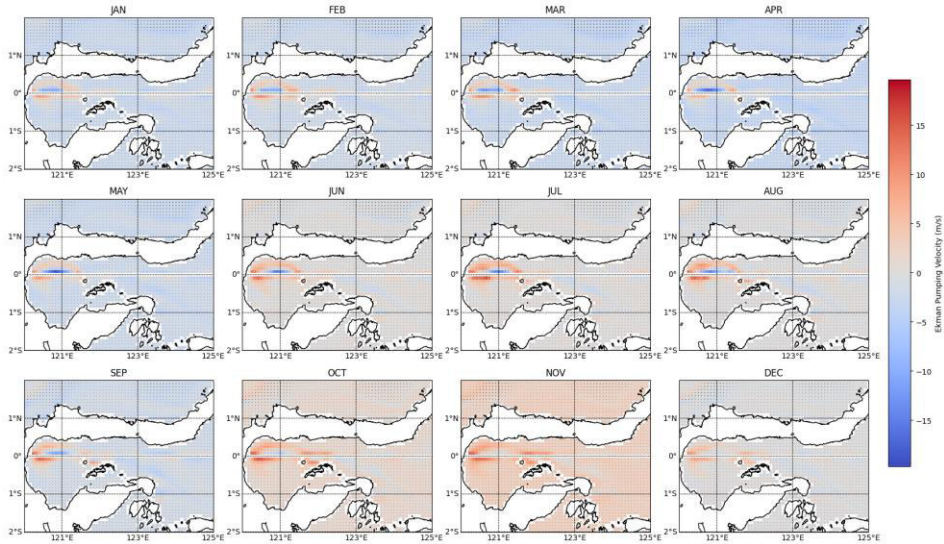


Fig 4. Ekman Pumping Velocity

3.3. Spectral Analysis

Figure 5 displays the results of the spectrum analysis. The initial graphic (above) illustrates the time series of the wind stress anomaly, recorded at coordinates (121° N, 0°E) throughout the year 2023. The second figure (below) depicts the power spectral density (PSD), which signifies the frequency domain attributes of a wind stress anomaly.

The PSD graph focuses on the variations in wind pressure anomalies in Tomini Bay throughout 2023. Persistent oscillations around values close to zero suggest that the anomalies originate from either the long-term average or climate factors. The graph's peaks and troughs signify periods of volatility in wind pressure anomalies, either from seasonal variability, atmospheric dynamics, or particular climatic variables affecting regional wind patterns.

The PSD approach enables the identification of atmospheric phenomena such as tropical cyclones or local winds through time series observations. The reason for this is the high-frequency fluctuations that result from ocean-atmosphere interactions, such as energy transfer in marine environments.

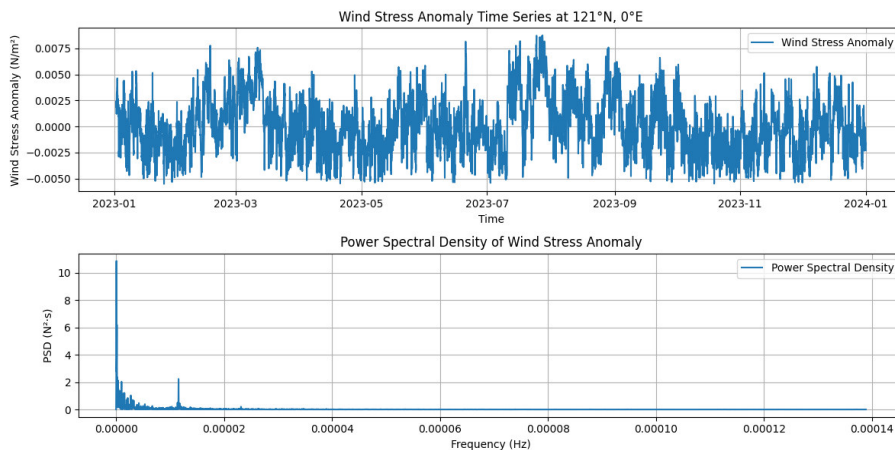


Fig 5. Spectral analysis and power spectral analysis

4. Conclusion

The monsoon that blow across in the area have an effect on the wind variability in the Tomini Bay. It is during the months of October and March that the transition and western season take place. The PSD analysis of CMEMS wind data, using coordinates 121° N, 0° E, indicated substantial variations in the data. Spectral analysis is a technique used to detect anomaly in the data.

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References

1. Capotondi, Antonietta, Shayne McGregor, Michael J. McPhaden, Sophie Cravatte, Neil J. Holbrook, Yukiko Imada, Sara C. Sanchez et al. "Mechanisms of tropical Pacific decadal variability." *Nature Reviews Earth & Environment* 4, no. 11 (2023): 754-769.
2. Trindade, Ana Filipa Mestre. "Development of high-resolution L4 ocean wind products." (2023).
3. Mayer, Michael, Magdalena Alonso Balsaseda, Stephanie Johnson, and Frederic Vitart. "Assessment of seasonal forecasting errors of the ECMWF system in the eastern Indian Ocean." *Climate Dynamics* 62, no. 2 (2024): 1391-1406.
4. Yari, Sadeqh, Volker Mohrholz, and Mohammad Hadi Bordbar. "Wind variability across the North Humboldt Upwelling System." *Frontiers in Marine Science* 10 (2023): 1087980.
5. Mockert, Fabian, Christian M. Grams, Tom Brown, and Fabian Neumann. "Meteorological conditions during periods of low wind speed and insolation in Germany: The role of weather regimes." *Meteorological Applications* 30, no. 4 (2023): e2141.
6. Wixtrom, Tyler. "High-Resolution Near-Surface Wind Analysis with the Weather Research and Forecasting Model." (2023).

7. Antonini, Enrico GA, Edgar Virgüez, Sara Ashfaq, Lei Duan, Tyler H. Ruggles, and Ken Caldeira. "Identification of reliable locations for wind power generation through a global analysis of wind droughts." *Communications Earth & Environment* 5, no. 1 (2024): 103.
8. Richardson, D., A. J. Pitman, and N. N. Ridder. "Climate influence on compound solar and wind droughts in Australia." *npj Climate and Atmospheric Science* 6, no. 1 (2023): 184.
9. Brunet, Dominique, Reza Valipour, and Yerubandi R. Rao. "Wind variability over a large lake with complex topography: Lake of the Woods." *Journal of Great Lakes Research* 49, no. 1 (2023): 112-121.
10. Li, Peiyao, Jijian Lian, Chao Ma, and Jinliang Zhang. "Complementarity and development potential assessment of offshore wind and solar resources in China seas." *Energy Conversion and Management* 296 (2023): 117705.
11. Allouche, Mohammad, Elie Bou-Zeid, and Juho Iipponen. "The influence of synoptic wind on land–sea breezes." *Quarterly Journal of the Royal Meteorological Society* 149, no. 757 (2023): 3198-3219.
12. Luu, Linh N., Erik van Meijgaard, Sjoukje Y. Philip, Sarah F. Kew, Jouke HS de Baar, and Andrew Stepek. "Impact of surface roughness changes on surface wind speed over western Europe: A study with the regional climate model RACMO." *Journal of Geophysical Research: Atmospheres* 128, no. 12 (2023): e2022JD038426.
13. Zhang, Gang-Feng, Cesar Azorin-Molina, Deliang Chen, Tim R. McVicar, Jose A. Guijarro, Kai-Qiang Deng, Lorenzo Minola et al. "Variability and trends of near-surface wind speed over the Tibetan Plateau: The role played by the westerly and Asian monsoon." *Advances in Climate Change Research* (2024).
14. Jia, Zixuan, Massimo A. Bollasina, Wenjun Zhang, and Ying Xiang. "Response of the link between ENSO and the East Asian winter monsoon to Asian anthropogenic aerosols." *EGU sphere* 2024 (2024): 1-28.
15. Zhou, Yongchao, Xin Gao, and Jiaqiang Lei. "Characteristics of dust weather in the Tarim Basin from 1989 to 2021 and its impact on the atmospheric environment." *Remote Sensing* 15, no. 7 (2023): 1804.
16. Ullah, Irfan, Sourav Mukherjee, Sidra Syed, Ashok Kumar Mishra, Brian Odhiambo Ayugi, and Saran Aadhar. "Anthropogenic and atmospheric variability intensifies flash drought episodes in South Asia." *Communications Earth & Environment* 5, no. 1 (2024): 267.
17. Jiang, Jianhong, Yongjin Yu, Yang Zhou, Shimeng Qian, Hao Deng, Jianning Tao, and Wei Hua. "Influence of Model Resolution on Wind Energy Simulations over Tibetan Plateau Using CMIP6 HighResMIP." *Atmosphere* 15, no. 11 (2024): 1323.
18. Ricker, Marcel, Arno Behrens, and Joanna Staneva. "The operational CMEMS wind wave forecasting system of the Black Sea." *Journal of Operational Oceanography* (2024): 1-22.
19. Buontempo, Carlo, Samantha N. Burgess, Dick Dee, Bernard Pinty, Jean-Noël Thépaut, Michel Rixen, Samuel Almond et al. "The Copernicus climate change service: climate science in action." *Bulletin of the American Meteorological Society* 103, no. 12 (2022): E2669-E2687.
20. Garrigues, Sebastien, Julien Chimot, Melanie Ades, Antje Inness, Johannes Flemming, Zak Kipling, Istvan Laszlo et al. "Monitoring multiple satellite aerosol optical depth (AOD) products within the Copernicus Atmosphere Monitoring Service (CAMS) data assimilation system." *Atmospheric Chemistry and Physics* 22, no. 22 (2022): 14657-14692.

21. Sanchez-Arcilla, Agustin, Joanna Staneva, Luigi Cavaleri, Merete Badger, Jean Bidlot, Jacob T. Sorensen, Lars B. Hansen et al. "CMEMS-based coastal analyses: conditioning, coupling and limits for applications." *Frontiers in marine science* 8 (2021): 604741.
22. Rachma, Tia Rizka N., and Rizka Windiastuti. "Spatial Study of Indonesia's Historic Bay: A Case Study in Tomini Bay." In *IOP Conference Series: Earth and Environmental Science*, vol. 618, no. 1, p. 012038. IOP Publishing, 2020.
23. Tita, Aprilia Da Cruz, Anindya Wirasatriya, Denny N. Sugianto, Lilik Maslukah, Gentur Handoyo, Muhammad Helmi, and Praditya Avianto. "Persistence of high sea surface temperature ($> 30^{\circ}$ C) in Tomini Bay." In *IOP Conference Series: Earth and Environmental Science*, vol. 530, no. 1, p. 012038. IOP Publishing, 2020.
24. Access on <https://marine.copernicus.eu/> with <https://doi.org/10.48670/moi-00305>.
25. Young, Ian R., Ebru Kirezci, and Agustinus Ribal. "The global wind resource observed by scatterometer." *Remote Sensing* 12, no. 18 (2020): 2920.
26. T. Horii, I. Ueki, and K. Ando, Coastal upwelling events along the southern coast of Java during the 2008 positive Indian Ocean Dipole. *J. Oceanogr.* **74**, 499–508 (2018).
27. F. Veron and W. K. Melville, Experiments on the stability and transition of wind-driven water surfaces, *J. Fluid Mech.*, 446, 25–65 (2001).
28. D. Li, P. Chang, S. Ramachandran, Z. Jing, and Q. Zhang, Contribution of the Two Types of Ekman Pumping Induced Eddy Heat Flux to the Total Vertical Eddy Heat Flux. *Geophys. Res. Lett.* **48**, (2021).
29. H. Bernades, A. A. D. Bernades, A. Wirasatriya, G. Handoyo, A. Rifai, L. Maslukah, and D. N. Sugianto, The effect of Ekman mass transport and Ekman pumping velocity on the variability of sea surface temperature in the Arafura Sea. *IOP Conf. Ser. Earth Environ. Sci.* **919**, 012026 (2021).
30. M. B. Rivas, A. Stoffelen, and A. Bentamy, Sea surface winds and Ekman pumping. *Journal Of Operational Oceanography*, **12**, (2019).