Characteristics Of Southern Ocean Swells Propagating Into The Northern Indian Ocean

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Abstract
Experiments were carried out utilizing a numerical wave model to study the properties of swells propagating into the northern Indian Ocean from the Southern Ocean. It is a well-known fact that the northern Indian Ocean is distinguished from other oceans primarily by the annual reversal of wind twice during the southwest and northeast monsoon seasons. In this context a comparative study has been conducted regarding swell propagation for the months of July and December of 2015. The propagation of swell waves from Southern Ocean and South Indian Ocean to North Indian Ocean is studied in the present work. The complicated phenomena of Southern Ocean swells spreading into the northern Indian Ocean have important ramifications for coastal areas and marine industries. This research uses a combination of satellite measurements, computational models, and statistical studies to examine the properties of these swells. To capture the variability and patterns of Southern Ocean swell propagation into the northern Indian Ocean, it is analyzed data spanning several years. In the Arabian Sea and Bay of Bengal regions the swell waves follow the wind direction in July representing the southwest monsoons whereas they move opposite to the wind direction in December representing the northeast monsoons. The swells generated between 40^0S-60^0S take 6-8 days to reach the northern Indian Ocean and the speed calculated is nearly 1100km per day.

Keywords: *Numerical Wave Model; Southern Ocean; Northern Indian Ocean; Swell propagation; Monsoon seasons.*

1. Introduction

The wind-waves are young waves under growth which are in equilibrium with local wind. As it leaves their generating area, it disperses to become ocean swells which travel large distances. The dynamics of coastal habitats are frequently shaped in unanticipated ways by the interaction between distant oceanic areas. Melattur et al (2022) proposed how far-off surges that originate hundreds of kilometers away react at different points along coastal regions. The spread of swells from the Southern Ocean into the northern Indian Ocean is one example of these phenomena. The vastness and strength of the weather systems that define the Southern Ocean cause surges to travel thousands of kilometers to reach the far-off coastlines of the northern Indian Ocean. These waves carry with them a distinct set of properties that have a significant impact on coastal areas in eastern Africa, the Arabian Peninsula, and the Indian subcontinent. Although swells from the Southern Ocean can travel northward into the Indian Ocean all year long, their frequency and strength can change with the seasons. The strength and timing of these swell are influenced by air circulation and monsoon cycles, among other factors. As a rule of thumb, a period of 10 second may be taken as separating swell from wind wave Kinsman (1965). Previous studies by Ray et al. (2006) show how the Southern Ocean swells impacts the northern Indian Ocean. Alves (2006) showed that the northward propagation of Southern Ocean extra-tropical swells was an important feature of the wave climate in the northern oceanic basins. Chen et al. (2002) studied the global ocean's dominating swells and wind waves, noting their seasonal and geographical patterns. Hanson and Phillips (1999) explored the use of wave characteristics in air-sea process modeling by examining the wind sea development and dissipation in an open ocean environment dominated by swells. Swells generated in extra tropical areas of the southern oceans spread energy throughout the entire global ocean, and are a potentially important component of the wave climate in most ocean basins in both hemispheres. Changes in major wave height are mostly caused by ocean swells Semedo (2011). Mukherjee et al (1982) discovered that strong swell comes at the Bombay high area of the Arabian Sea a few days before the monsoon begins over the Kerala beaches. Ray et al. (2006) and Kumar et al. (2009) found that swell is dominant in the Indian Ocean region. Chen et al. (2002) focused the geographical and seasonal patterns of dominating swells and wind waves in the global ocean. Three distinct swell pools, or tongue-shaped zones of dominance, were identified in the eastern tropical Pacific, Atlantic, and Indian Oceans. Pathirana et al. (2023) concentrated on the source terms—basically, tuning parameters—in the models that take into account negative wind input and swell decay. Chong-wei Zheng's (2022) attenuation rate of swell energy during propagation is determined. Sreelakshmi and Bhaskaran (2023) conducted the first extreme climatological analysis of swell waves in terms of energy flow and directional distribution. In recent decades, a variety of studies have sought to study swell behaviour using various methodologies. Despite this, there are still significant gaps in this knowledge domain Cavaleri et al (2007). The lack of understanding of swell propagation and decay can be attributed to limitations in measurement instrumentation and theoretical assumptions about the physical processes involved Phillips(1977), Komen et al., (1994), Tolman and Chalikov (1996), Rogers et al., (2003). This lack of knowledge has resulted in inaccurate projections of swell heights and arrival timings, compromising forecast accuracy and decision-making processes Rogers (2002) Rascle et al, (2008) Stopa et al.,(2016) Babanin et al.,(2019). The storms below 40°S, within extra tropical southern Atlantic, extra tropical southern Pacific and extra tropical southern India propagate to the east. The Indian Ocean is unique in that it is limited in the north by the Asian continent. One effect of this is that strong monsoon winds that reverse every year push into the Arabian Sea and the Bay of Bengal areas. Due to these reversing winds the sea conditions are also different. The Southern Ocean extends from 60^0s latitude to Antarctica and it encompasses 360^0 degrees of longitude. Because of the temperature difference between the open ocean and the ice, cyclonic storms usually have a high center of intensity as they move eastward over the continent. The ocean area below 40°S has the strongest average winds found anywhere on the Earth. Melattur et al (2021) determined multi-linear regression analysis was used to conduct a thorough investigation to determine how climatic indicators depend on PSW and DS. As they depart their generating zone and travel great distances throughout the world, wind-waves produced by powerful storms transform into ocean swells. It is supported by empirical evidence that the combined energy carried by wind seas and swells exceeds that of tides, tsunamis, coastal surges, and other waves on the ocean surface by over half. For this reason, research on the relationship between wind waves and distant ocean swell is crucial for a variety of oceanographic studies, coastal management initiatives, and ocean engineering applications. Forecasting swell waves is crucial for ship routing, naval operations, and offshore building planning. Limited area models cannot predict these occurrences once they have expanded beyond their roots. This study uses Global Wave Model (WAM) simulations for the year 2015 to look at how swell waves propagate in the Indian Ocean. In the present work WAM4C is integrated for the entire Indian Ocean for the year 2015 using six-hourly, and 0.5-degree QSCAT/NCEP blended winds. Initially model computed average swell wave heights, mean swell directions and mean swell periods are discussed for July and December of 2015 for the Indian Ocean region. Then daily plots are generated for the entire Indian Ocean region to analyze characteristics of individual swells coming to the northern Indian Ocean during the months of July and December.

2. Materials and methods

Numerical wave modeling has contributed a lot providing significant results related to marine and offshore activities. Going back to Sverdrup and Munk (1947) who developed the wave forecast technique, at present spectral wave models are used for forecasting waves and swells over the sea. The WAM model is a third-generation wave model used operationally for forecasting sea state on global and regional scales WAMDI group, (1988) and Komen et al, (1994). It is a widely tested model in which the two-dimensional ocean wave spectrum is computed by integration of the energy balance equation without any prior restriction on the spectral shape. The model is continuously updated, the most recent version being Cycle 4, as given by Gunther et al (1992). The WAM-4C is integrated for the entire Indian Ocean covering 30˚E to 120˚E and 70˚S to 30˚N for the year 2015. For this study, we used six-hourly, and 0.5-degree QSCAT/NCEP blended winds. These ocean surface wind data are derived from spatial blending of high-resolution satellite data (Sea winds instrument on the Quick SCAT satellite - QSCAT) and global weather center re-analyses (NCEP), resulting in high temporal and spatial resolution datasets. Bathymetry used is derived from ETOPO5. Monthly average wind fields are generated and discussed for July and December. Then monthly average model computed swell wave heights, mean swell directions and mean swell periods were processed and analyzed for July and December. Finally, propagation of swells from the Southern Ocean coming to the northern Indian Ocean is analyzed with the help of daily plots.

3. Results and Discussion

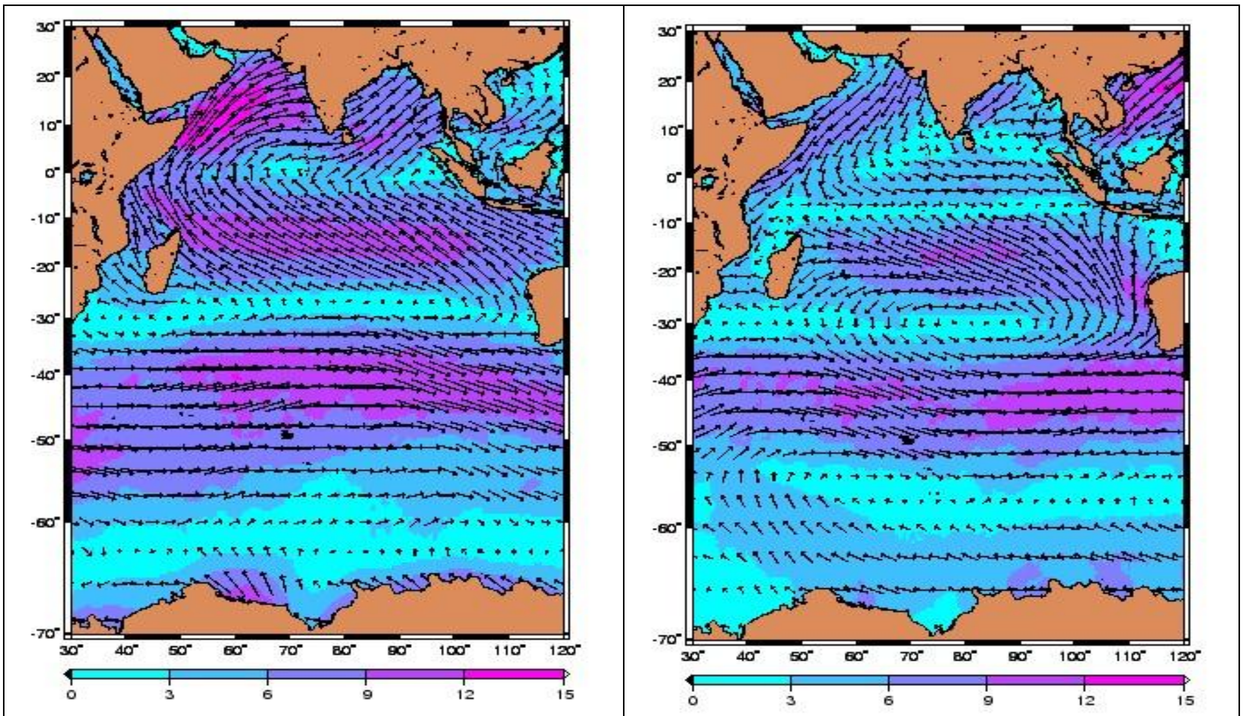
The study begins with a thorough examination of the complex wind field dynamics that prevail throughout our selected model area. Of particular importance is the characterization of the climate subtleties that are typical of the months of July and December. These two time-series markers are very important because they represent the change from the southwest to the northeast monsoon phases in the northern Indian Ocean. The average NCEP blended winds between the July and December of 2015 are shown graphically in Figure 1(a, b) which provides a broad picture of the atmospheric interactions across the vast area of the Indian Ocean region. Among this complex web of weather events, several patterns stand out that demonstrate significant differences in maximum average wind speeds. During July, in particular, there is an extreme peak in wind speed off the coast of Somalia, reaching up to 15 meters per second. On the other hand, December progresses with a rather mild intensity, with a peak that may be seen at 12 meters per second along the 20th parallel south. In addition, a continuous strip of maritime area, located between 40°s and 60°s latitude, appears as a stronghold of strong winds, indicating an area of increased precipitation. However, because measurements in these lower latitudes tend to show decreasing trustworthiness, care must be used when extrapolating wind data below the 60^0s parallel. This thorough analysis of wind patterns provides priceless insights into the seasonal and spatial nuances inherent in the Indian Ocean's climate, enhancing our comprehension of meteorological dynamics and their numerous implications in a variety of fields, such as weather forecasting, climate research, and maritime operations.

Expanding upon the previously described technique, a critical step towards deciphering the intricate dynamics of swell wave behavior in 2015 was the integration of the WAM-4C model with six-hourly, 0.5-degree QSCAT/NCEP blended winds data for the whole Indian Ocean. This thorough integration makes it possible to analyze swell wave properties in depth, with an emphasis on directionality and size in particular, which offers insightful information on oceanic dynamics. The resulting visualization, which is shown in Fig 2(a, b), provides a detailed representation of the swell wave heights calculated from the model, carefully averaged throughout the two different temporal contexts of July and December. Of particular note are the Arabian Sea and Bay of Bengal areas, which show clear trends in average swell wave heights. Average swell wave heights in these areas are between 0 and 3 meters in July, when the southwest monsoon is most noticeable. This is due to increased atmospheric activity and the resulting wave creation. December, on the other hand, presents a distinct picture with typical swell wave heights of between 0 and 2 meters. The drop in swell wave heights that has been recorded is consistent with the onset of the northeast monsoon, which is characterized by milder air conditions and lower wave energy. It is possible to get important insights into the seasonal dynamics of oceanic processes in these places by defining such temporal and geographical changes in swell wave characteristics. Moreover, it highlights the complicated relationship between oceanic reactions and meteorological events, illuminating the sophisticated mechanisms controlling wave formation and propagation. The results of this study have important ramifications for a number of fields, such as climate research, coastal engineering, and marine safety. They improve our comprehension of oceanic dynamics and enable more precise forecasting of tsunami behavior. This work advances our understanding of marine habitats and provides information for risk mitigation and sustainable ocean management techniques through the careful analysis and interpretation of the combined data. An intriguing contrast between July and December may be seen in the measured behavior of swell wave heights in the Arabian Sea and Bay of Bengal, which provides insight into the complex interplay between wind patterns and marine phenomena. The swell wave heights in both basins consistently shift northeastward throughout July, when the southwest monsoon is dominant, reflecting the direction of the dominant southwesterly winds. This alignment highlights the important role that wind direction plays in determining oceanic dynamics by emphasizing the direct impact of atmospheric forces on the propagation of swell waves. But December sees a significant divergence from this trend as the northeast monsoon starts to make its presence felt. Even though both basins had northeasterly winds at this time, the swell wave heights show a broad variety of directions, from 0^0 to 360^0. This departure from the anticipated wind direction alignment points to a decoupling of the behavior of swell waves from atmospheric stimuli. The lower wind intensity in December, which could not supply enough energy to control the direction of swell wave propagation, is one reasonable explanation for this disparity. Rather, at this moment, the direction of swell waves may be more strongly influenced by other elements such local terrain, ocean currents, and wave interactions. This discovery emphasizes how intricate oceanic processes are and how important it is to have a sophisticated grasp of the intricate relationships that exist between atmospheric and oceanic dynamics. Through the clarification of these nuances, this research advances our understanding of marine ecosystems and provides guidance for attempts to enhance prediction models for the behavior of swell waves, boosting maritime safety and coastal resilience in the face of changing climate conditions.

Continuing this work, it provides a more comprehensive knowledge of the temporal and spatial dynamics driving wave behavior over the Indian Ocean by going deeper into the calculated average swell wave periods for the months of July and December. The regional distribution of swell period averages, as shown in Fig. 3(a, b), provides important insights into the subtle differences in oceanographic conditions during these different monsoon seasons. In July, there is a noticeable peak in the number of 13-second swell waves in the northern Indian Ocean, especially in the Arabian Sea along the coast of Somalia. In addition, there are a lot of swell waves that are longer than 10 seconds in duration that can be seen in the Arabian Sea and Bay of Bengal this month, which is a sign of how prevalent the southwest monsoon is in terms of effecting wave formation and movement. On the other hand, a different picture emerges in December due to a change in the swell periods' geographical distribution. The eastern Arabian Sea and eastern Bay of Bengal are the main locations for swell waves that last longer than ten seconds in this month. This departure from July's observations highlights the intricate relationship between atmospheric factors and oceanic reactions, as well as the particular difficulties associated with the changeover to the northeast monsoon. A possible explanation for the observed decoupling between wave behavior and atmospheric forcing in December might be the decreased winds that are typical of the month. This is shown by the different directions of the prevailing winds and swell wave heights.

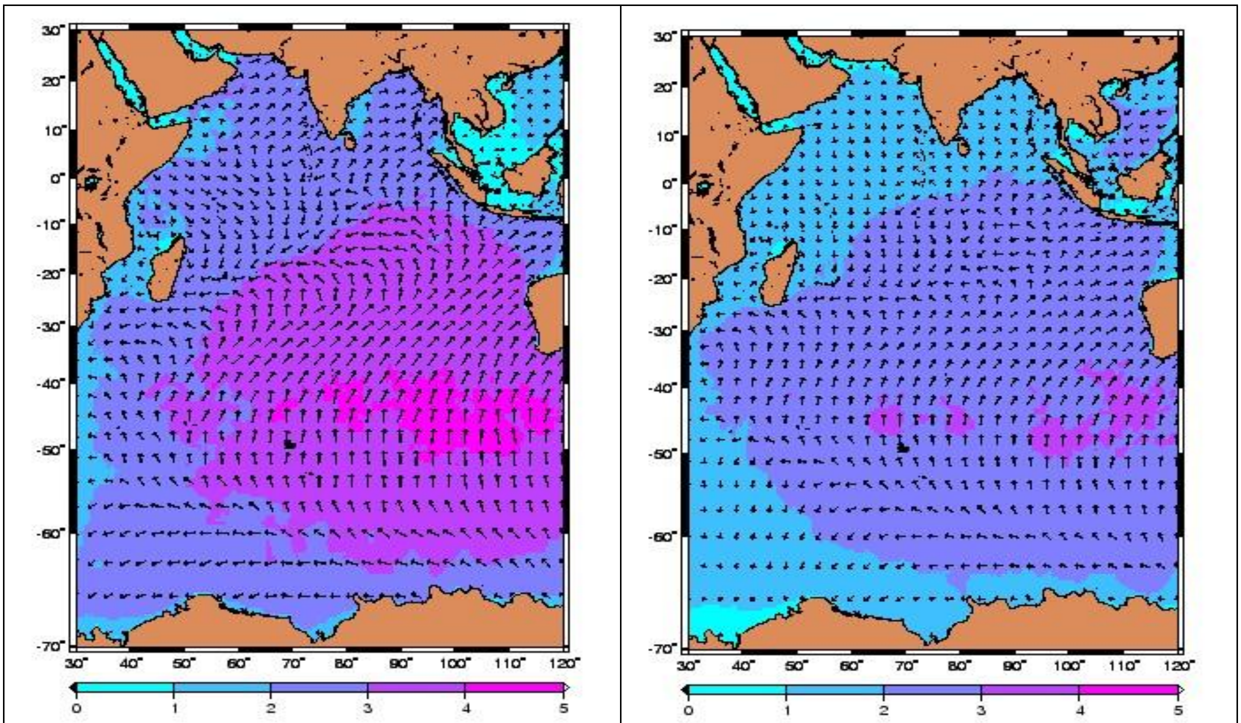
This study deviates from monthly mean plots to daily analysis, delving further into the complexities of swell propagation between July and December 2015. Two different swell episodes (Swell 1 and Swell 2) and their daily propagation paths from July 12 to July 23 are shown in Fig 4. Swell 1 is a continuously propagating northeastern wave that has its origins between 40^0s and 60^0s latitude. It takes around six days to reach the Bay of Bengal region. As an example, Swell 2 travels the same distance in around eight days, but it does so with a somewhat longer propagation period. Swell 2 is noteworthy for showing an increase in coverage area four days later, with part of the wave front pointing straight toward the Arabian Sea region. The dynamic character of oceanic processes and its significance for marine operations, coastal management, and climate research activities are highlighted by this detailed analysis, which offers essential insights into the temporal development of swell propagation patterns throughout the southwest monsoon season.

As it studies the propagation dynamics of Swell 3, which began on December 7 at about 55^0S latitude, as shown in Fig. 5, the analysis becomes even more detailed. This specific surge is an interesting case study since it sets out on an eight-day voyage over the huge Indian Ocean, finally landing in the Arabian Sea before heading to the Bay of Bengal. A noteworthy pattern in wave movement is revealed in December, with a more easterly direction that makes it more difficult for swells to reach the northern Indian Ocean. This change in propagation patterns highlights the impact of shifting air conditions linked to the arrival of the northeast monsoon, which may obstruct waves from spreading westward. Notwithstanding these difficulties, it is significant that waves produced between 40^0s and 60^0s latitudes often take 6 to 8 days to propagate to the northern Indian Ocean, regardless of the exact route they take. These swells travel at a predicted pace of about 1100 kilometers per day, highlighting how quickly they traverse large maritime stretches. This in-depth analysis of the dynamics of swell propagation not only advances our knowledge of oceanic processes but also demonstrates the ability of swell waves to travel great distances and the variety of factors that shape their paths. Because they aid in the creation of more precise prediction models and well-informed strategies for making decisions in the face of changing climate circumstances, these insights are extremely helpful for initiatives related to climate modeling, coastal management, and marine navigation.



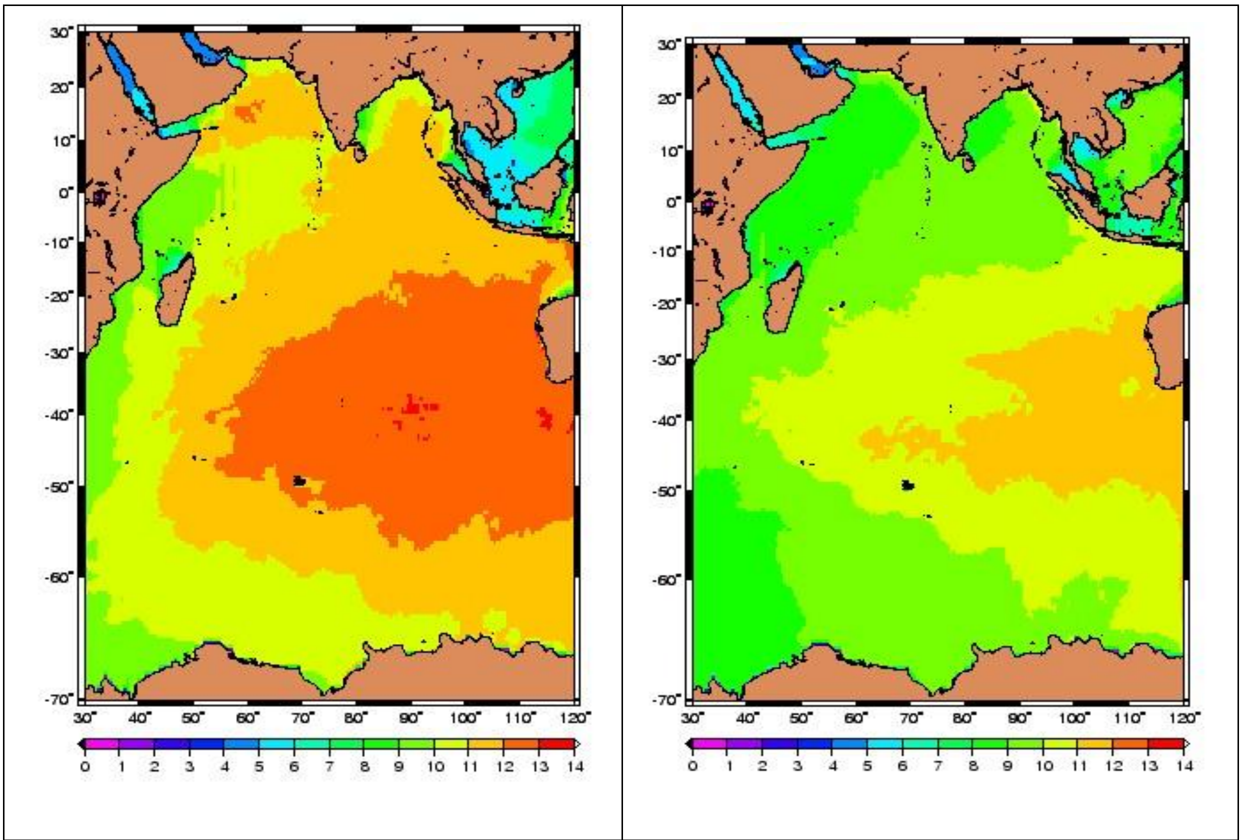
meter/second (a)	meter/second (b)

Fig 1: Average winds (2015) for the Indian Ocean (a) July (b) December



meter/second (a)	meter/second (b)

Fig 2: Average swell wave heights (2015) in the Indian Ocean (a) July (b) December



Second (a)	Second (b)

Fig 3: Mean swell periods (2015) in the Indian Ocean (a) July (b) December

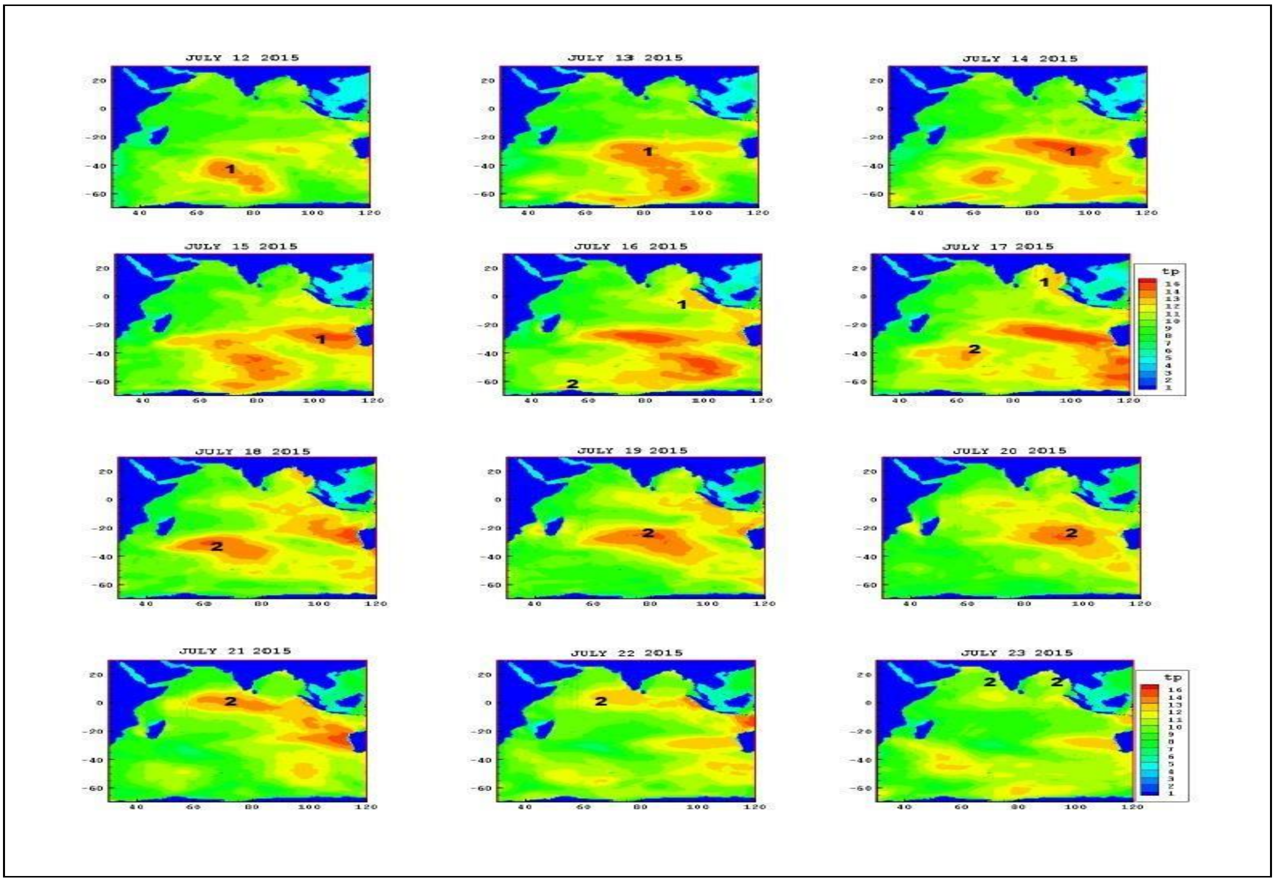


Fig 4: Propagation of swell (1) and swell (2) in July 2015

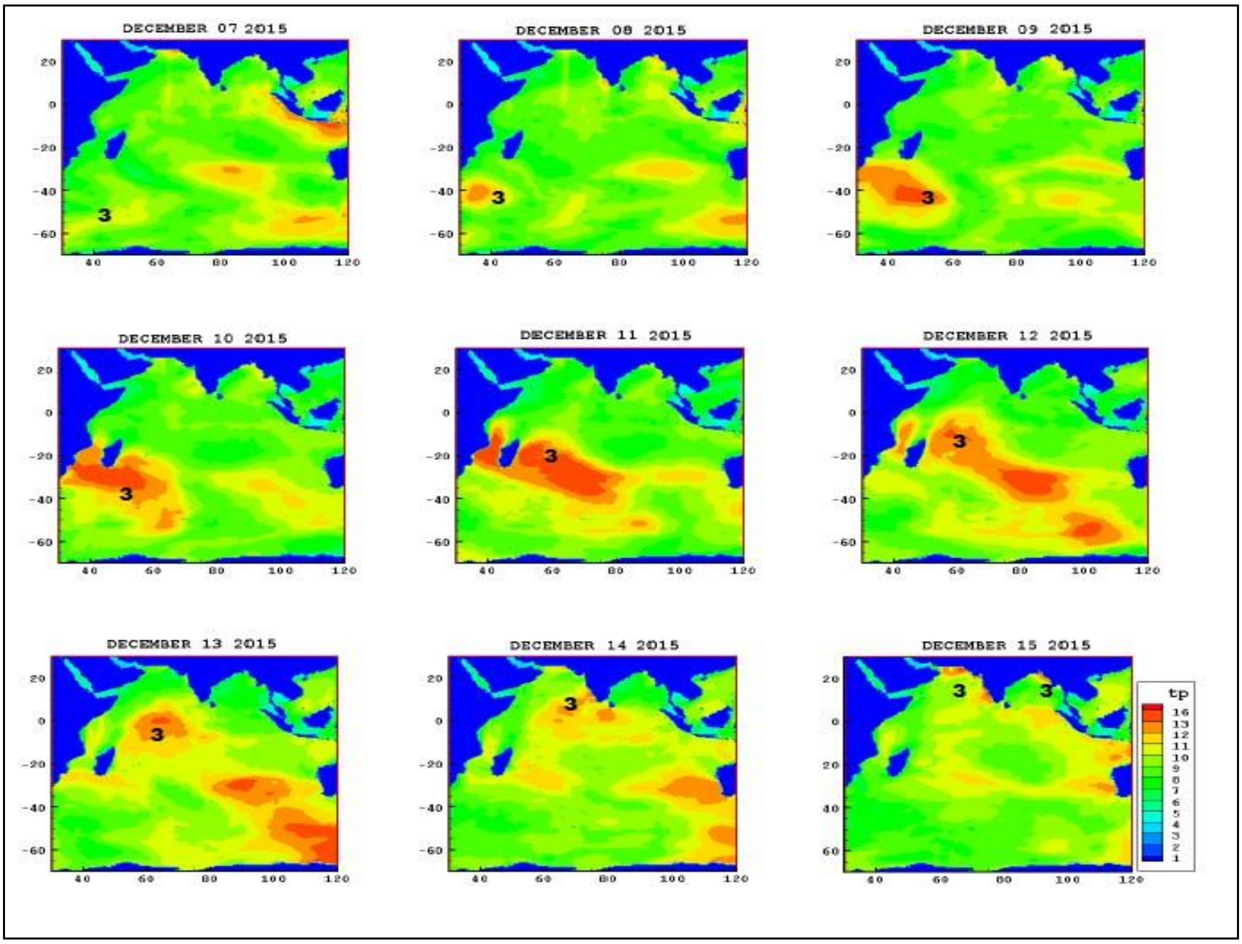


Fig 5: Propagation of swell (3) in December 2015

4. Conclusions

After the integrating of the WAM-4C model for the whole Indian Ocean region in 2015, a detailed analysis of the monthly average swell wave characteristics for July and December was carried out, offering a more sophisticated comprehension of the seasonal dynamics influencing oceanic behavior. Notably, the analysis showed a noticeable variation in the average height of swell waves in the Arabian Sea and Bay of Bengal regions between July and December. Higher heights were recorded in July, a phenomenon that was ascribed to the stronger winds linked to the southwest monsoon season at that time. A continuous northeastward propagation of swell waves was seen in both basins, despite the change in wind direction from southwesterly to northeasterly between July and December, highlighting the complex interaction between wind forcing and wave dynamics. Daily charts added even more value to the analysis by providing specific details on the features of swell propagation from the Southern Ocean moving northward into the northern Indian Ocean. Among other things, the research showed that large waves were generated in the storm-prone region between latitudes 40^0s and 60^0s. These swells were driven by the atmospheric conditions at the time and followed a determined northeasterly path until they reached the northern Indian Ocean. Critically, there was a noticeable difference in the direction of wave movement from July to December. July showed a more easterly passage of swells from the Southern Ocean, which led to more arrivals in the Bay of Bengal than in the Arabian Sea. Alternatively, December saw a change in the direction of the swell movement toward the east, together with stronger winds in the northern basins that were in opposition to each other. This created difficulties for the swell movement as it propagated northeastward toward the northern Indian Ocean. The velocity of propagation, which is close to 1100 kilometers per day, is highlighted by the fact that the time it takes for swell waves to travel from the Southern Ocean to the northern Indian Ocean was pretty constant at around 6 to 8 days, even with these seasonal changes. In-depth knowledge of the intricate and dynamic nature of swell wave propagation across the Indian Ocean is provided by this thorough analysis, which is essential for a variety of fields including climate research, coastal management, and maritime navigation. This helps to make informed decisions and improves knowledge of oceanic processes and their implications in general.

5. References

1. Alves, G.M. (2006) "Numerical modeling of ocean swell contributions to the global wind-wave climate", *Ocean Modelling*, 11, 98–122. https://doi.org/10.1016/j.ocemod.2004.11.007

2. Babanin A. V. (2012). “Swell attenuation due to wave-induced turbulence,” in Proceedings of the ASME 31st International Conference on Ocean, Offshore and Arctic Engineering, Vol.2. 439-443. July 1–6, 2012.
3. Babanin A. V., Rogers W. E., de Camargo R., Doble M., Durrant T., Filchuk K., et al. (2019). “Waves and swells in high wind and extreme fetches, measurements in the Southern Ocean”, *Sec. Ocean Observation*, 6. doi:
4. 10.3389/fmars.2019.00361.
5. Cavaleri L., Alves J. H. G. M., Ardhuin F., Babanin A., Banner M., Belibassakis K., et al. (2007). “Wave modelling – The state of the art”, *Prog. Oceanography,* 75 (4), 603–674. doi: 10.1016/j.pocean.2007.05.005
6. Chen, Ge Chapron, B, Ezraty, R, and Vandermark, D J (2002): “A global view of swell and wind sea climate in the Ocean by Satellite Altimeter and Scatterometer”, *Atmos. & Oceanic Tech*, 19, 1849-1859.
7. DOI: https://doi.org/10.1175/JTECH-D-15-0219.1
8. Guenther, H., Hasselmann, S., & Janssen, P.A.E.M. (1992). The WAM model cycle 4 (DKRZ-TR--4(reved)). 26(1), Germany.
9. Hasselmann, S. Hasselmann, K. Bauer, E. Janssen, P.A.E.M. Komen, G.J. Bertotti, Lionello, L. Guillaume, A. Cardone, V.C. Greenwood, J.A. Reistad, M. Zambresky L. and Ewing, J.A. (1988), The WAM Model- a third generation ocean prediction model. *J. Physical Oceanography* 18, 1775-1810. doi/pdfdirect/10.1029/97JC02568.
10. Hanson, J. L. and Phillips, O. M.: (1999) “Wind Sea Growth and Dissipation in the Open Ocean”, *J. Phys. Oceanogr*., 29, 1633–1648.
11. DOI: https://doi.org/10.1175/1520-0485(1999)029<1633:WSGADI>2.0.CO;2
12. Komen, G.J. Cavaleri, L. M. Donelan, K. Hasselmann, S. Hasselmann and P.A.E.M. Janssen, (1994), Dynamics and modeling of ocean waves, *Cambridge University Press*. DOI: 10.1017/S0032247400067619
13. Kumar R, Bhowmick, S A, Ray, S, Bhatt, V, Surendran, S, Basu, S., Sarkar, A, and Agarwal, V K (2009):
14. “Improvent of predictability of waves over Indian Ocean”, *Nat Hazards,* 49, 275–291. https://doi.org/10.1260/1759-3131.4.1.63
15. Melattur, S. Bhaskaran, P. (2021) “Extreme swell wave energy and its directional characteristics in the Indian Ocean”, *Climate Dynamics,* 58(2), 1-20. DOI: 10.1007/s00382-021-06000-7
16. Melattur, S. Bhaskaran, P. (2022) “Swell wave propagation and its characteristics while approaching the Indian Coast”, *Climate Dynamics,* 60(2), 1-25. DOI: 10.1007/s00382-022-06378-y.
17. Pathirana, S. Young, I. Meucci A. (2023), “Modelling swell propagation across the pacific”, *Physical Oceanography*, 10, DOI 10.3389/fmars.2023.1187473.
18. Phillip, O. M. (1977). “The dynamics of the upper ocean”, *Journal of Fluid Mechanics* (New York: Cambridge University Press). 793 - 794
19. Ray, S. Kumar,R. Sarkar, A. (2006), “Study of the impact of Southern Ocean swell using wave model, Remote Sensing and Modeling of the Atmosphere”, *Oceans, and Interactions, Proceedings of the SPIE*, 6404, pp. 64040C. DOI: 10.1117/12.693962
20. Rascle N., Ardhuin F., Queffeulou P., Croizé-Fillon D. (2008) “A global wave parameter database for geophysical applications”, Part 1: Wave-current–turbulence interaction parameters for the open ocean based on traditional parameterizations. *Ocean Model*. 25 (3-4), 154–171. doi: 10.1016/j.ocemod.2008.07.006.
21. Rogers W. E. (2002). “The US Navy's global wind-wave models: An investigation into sources of errors in lowfrequency energy predictions”. Tech. Report Oceanography Division *Naval Res. Laboratory* Stennis Space Center, 7320–02-10035.
22. Rogers W. E., Hwang P. A., Wang D. W. (2003). “Investigation of wave growth and decay in the SWAN model: Three regional-scale applications”. *J. Phys. Oceanography* 33 (2), 366–389. doi: 10.1175/15200485 (2003)033<0366: IOWGAD>2.0.CO;2
23. Sverdrup, H.U. Munk, W.H. (1947), “Wind, Sea and Swell: Theory relations for Forecasting”, *Navy Hydrographic Office*, U.S, 601.
24. Semedo, A. Sušeljet, K. Rutgersson, A. Sterl, A. (2011) “A global view on the wind sea and swell climate and variability from ERA-40”, *Journal of Climate*, 24, 1461–1479. https://api.semanticscholar.org/CorpusID:14855678
25. Sreelakshmi, S., Bhaskaran, P.K.(2023) ”Swell wave propagation and its characteristics while approaching the Indian Coast”, *Clim Dyn* 60, 1271–1295. https://doi.org/10.1007/s00382-022-06378-y
26. Stopa J. E., Ardhuin F., Husson R., Jiang H., Chapron B., Collard F. (2016). “Swell dissipation from 10 years of Envisat Advanced Synthetic Aperture Radar in wave mode”. *Geophysical Res. Lett*. 43 (7), 3423–3430. doi: 10.1002/2015GL067566
27. Tolman H. L., Chalikov D. (1996). “Source terms in a third-generation wind wave model”. *J. Phys. Oceanography* 26 (11), 2497–2518. doi: 10.1175/1520-0485(1996)026<2497:STIATG>2.0.CO;2
28. Zheng, C. Hai-lang Wu, Guo,J. Shen, C. Tian, Tian, X. Xiao, Z. Zhou, W. Li, L (2022), “Propagation and attenuation of swell energy in the Pacific Ocean”, *Renewable Energy*, 188, 750-764. https://doi.org/10.1016/j.renene.2022.02.071