Investigating the Dynamics of Stokes Drift Along the Coastal Waters of Ratnagiri and Karwar

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DECLARATION BY STUDENT

I hereby declare that the data presented in this Dissertation report entitled **"Investigating the Dynamics of Stokes Drift Along the Coastal Waters of Ratnagiri and Karwar"** is based on the results of investigations carried out by me in the **Marine Sciences** at the School of Earth, Ocean and Atmospheric Sciences, Goa University under the Supervision of **Dr. Sanil Kumar V. V.** and the same has not been submitted elsewhere for the award of a degree or diploma by me. Further, I understand that Goa University or its authorities will be not be responsible for the correctness of observations / experimental or other findings given the dissertation.

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<u>**COMPLETION CERTIFICATE**</u>

This is to certify that the dissertation report "**Investigating the Dynamics of Stokes Drift Along the Coastal Waters of Ratnagiri and Karwar**" is a bonafide work carried out by **Ms. Ashis Karthika** under my supervision in partial fulfilment of the requirements for the award of the degree of **Master of Science** in the Discipline of Marine Sciences at the School of Earth, Ocean and Atmospheric Sciences, Goa University.

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PREFACE

The genesis of this dissertation emerged from a fervent curiosity about the intricate coastal dynamics along the eastern coast of the Arabian Sea. This study undertakes a thorough exploration, focusing on the nuanced aspects of Stokes drift. Drawing from the earlier research endeavors, we meticulously computed Stokes drift from wave parameters, unraveling its variations at distinct locations—Karwar and Ratnagiri stations. Our prior work also delved into the intricate analysis of particle net drift within these regions.

Building upon this foundation, our inquiry expanded to incorporate the calculation of Taylor dispersion. This dissertation encapsulates a comprehensive investigation into the interplay between wave characteristics, Stokes drift, and particle dispersion. Notably, we scrutinized how these dynamics manifest under varying conditions of swell and sea waves.

The significance of this research lies in its potential to unravel the subtle connections that underlie coastal processes in the Arabian Sea. By adopting a holistic approach, we aim to enhance our comprehension of the intricate interrelationships between wave phenomena and their consequential impacts on particle dynamics along the coastal stretch under consideration.

I extend my sincere appreciation to my esteemed advisors for their invaluable guidance, unwavering support, and scholarly insights throughout this research journey. Their expertise has been instrumental in shaping the depth and direction of this dissertation.

As this dissertation comes to fruition, I hope it serves as a stepping stone for future investigations, providing a richer understanding of the complex dynamics that govern the coastal regions along the eastern Arabian Sea.

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FIGURES

ABBREVIATIONS USED

Entity	Abbreviatons
East	E
North-East	NE
South-West	SW

ABSTRACT

Stokes drift, a phenomenon elucidated by George Gabriel Stokes in 1847, plays a critical role in ocean dynamics, influencing fluid motion, transport mechanisms, and environmental processes. This study presents an analysis of Stokes drift dynamics along the eastern coast of the Arabian Sea, focusing on its implications for particle dispersion and wave-driven mixing. Utilizing wave data collected from moored buoys at Ratnagiri and Karwar stations, the study investigates seasonal variations in Stokes drift, particle net-drift, and Taylor dispersion. Results reveal significant fluctuations in Stokes drift values throughout the year, with peak occurrences during the monsoon season. Analysis of particle net-drift illustrates heightened displacement during monsoon months, emphasizing the direct influence of wave dynamics on particle transport patterns. The wave directions in the range of 250° - 270° are only responsible for stronger Stokes drift. Also, the distinction between different wave types highlights the robust influence of intermediate and swell waves on Stokes drift compared to wind-sea waves. Moreover, a positive correlation between Stokes drift and Taylor dispersion indicates the crucial role of Stokes drift in enhancing particle dispersion dynamics. The study underscores the importance of understanding Stokes drift dynamics for predicting coastal processes and informs effective management strategies for coastal ecosystems.

KEYWORDS

● Stokes drift ● Eastern Arabian Sea ● Coastal Waters ● Taylor dispersion

CHAPTER 1

1. INTRODUCTION

1.1. Background

In the course of its regular motion, a particle positioned at the free surface of a water wave undergoes a noticeable continuous displacement in the direction of the wave's propagation. This phenomenon is commonly referred to as Stokes Drift (Stokes, 1847), a concept initially elucidated by the eminent physicist George Gabriel Stokes in 1847 during his pioneering investigations into water wave dynamics. In a broader context, Stokes Drift velocity encompasses the disparity between the average Lagrangian flow velocity of a fluid parcel and the average Eulerian flow velocity of the fluid at a fixed location. This non-linear occurrence continues to hold great significance within the field of fluid dynamics (van den Bremer & Breivik, 2018).

Stokes drift emerges as a critical phenomenon in ocean dynamics, playing a multifaceted role with far-reaching implications. It serves as a fundamental component in the intricate tapestry of oceanic processes, offering insights into the dynamics of fluid motion and shaping our understanding of environmental phenomena on both local and global scales. Understanding Stokes drift is crucial for comprehending transport mechanisms, surface mixing processes, and even the generation of magnetic fields in planetary and stellar bodies. In coastal environments, Stokes drift significantly influences material transport, ecosystem connectivity, and sediment dynamics. Its intricate dynamics, as explored in studies by Monismith & Fong (2004) and Smith (2006), highlight the interplay between Eulerian and Lagrangian mean velocities, shedding light on the movement of scalars, organisms, and pollutants. By accurately representing Stokes drift in ocean models, researchers can improve predictions of coastal erosion, sediment transport, and the dispersion of contaminants, aiding in the management and preservation of coastal ecosystems.

Stokes drift, arising from wave averaging on the mean flow, is pivotal in understanding ocean dynamics (Craik & Leibovich, 1976). It signifies net particle motion despite the absence of time-averaged Eulerian velocity, crucial for various marine phenomena. From shaping surface gravity waves to impacting transport mechanisms, air-sea interactions, and even generating magnetic fields in celestial bodies, Stokes drift underpins the complexity of oceanic processes. Surface gravity waves induce orbital motions contributing to Stokes drift, the difference between phase-averaged Eulerian velocity and mean Lagrangian motion (Bremer & Breivik, 2018). It influences wind-induced drift, trajectories of drifting entities, and mass flux, leading to offshore-directed undertow and influencing upper ocean features (Liu et al., 2014). Interactions with mean Eulerian current shear generate instabilities like Langmuir turbulence and Craik-Leibovich vortex force, further shaping ocean dynamics (McWilliams & Restrepo, 1999).

Understanding Stokes drift is vital for estimating surface wave-driven mixing in global climate models and predicting paths of floating objects and marine debris accurately (Webb & Fox-Kember, 2015). Neglecting it can overestimate marine debris residence time, emphasizing its role in effective pollution management (Bosi et al., 2021). Stokes drift profoundly influences coastal environments, affecting scalar and organism transport processes (Monismith & Fong, 2004). It dictates marine population movement and habitat connectivity along the inner shelf. Examining Eulerian and Lagrangian mean velocities provides insights into transport mechanisms influenced by surface waves, enriching our understanding of oceanic dynamics.

Moreover, Stokes drift affects air-sea interactions, particularly in Langmuir circulation generation (Smith, 2006). Intermittent wave-breaking transmits stress to underlying flow, influencing motion to greater depths. Spatial and temporal variations challenge existing theories, offering insights into its role in oceanic processes. Beyond Earth's oceans, Stokes drift finds applications in planetary and stellar bodies (Herremen & Lessefre, 2011). Mean-field dynamo theory uses it to understand magnetic field generation in rapidly rotating systems, offering new perspectives on dynamo action.

Stokes drift is fundamental in ocean dynamics, shaping surface waves, transport, air-sea interactions, and magnetic field generation (Breivik et al., 2014). Understanding its significance is crucial for modeling marine environments accurately and guiding environmental conservation efforts. It has also an important role in wave-driven upper ocean mixing and interactions between waves and mean flows. Studies by Webb & Fox-Kember (2015) emphasize the significance of parameterizing wave-driven mixing in global climate models, highlighting the need for accurate representation of Stokes drift to enhance our understanding of climate dynamics and ocean circulation patterns. Bosi et al. (2021) demonstrate the importance of accurately incorporating Stokes drift in particle tracking models to predict the trajectories of marine debris and inform effective policies for prevention and removal.

In fluid mechanics, Taylor dispersion is observed as an effect whereby shear flow increases the effective transport of passive tracers (Nakad et al., 2020). The rate at which particles are transported vertically in the water column due to turbulent mixing processes is referred to as vertical diffusivity. The variation of the Stokes drift velocity contributes to the Taylor dispersive effect in the longitudinal direction (Sheng et al., 2022). That is, when the Stokes drift velocity varies spatially along the direction of fluid motion (longitudinal direction), it introduces gradients or differences in velocity within the fluid. These velocity gradients can cause fluid parcels or passive tracers to experience differential advection, where particles moving at different velocities spread out over time. For better understanding, consider the Stokes drift velocity increases or decreases along the longitudinal direction, then the fluid parcels experiencing different velocities will spread apart from each other as they move along the flow. This spreading effect is akin to the dispersion of ink droplets in water, where variations in flow velocity cause the ink to spread out over a larger area.

The Arabian Sea is a semi-enclosed tropical basin, landlocked by the Asian continent to the north. The Indian coastline along the AS experiences the influence of seasonally reversing monsoon winds. During the South-West (summer) monsoon period from June to September, prevailing winds originate from the south-west direction, while during the North-East (winter) monsoon period from October to January, winds shift to the north-east. The intermediate period between the NE and SW monsoons is known as the pre-monsoon period or the fair weather period. The SW monsoon winds are robust, contributing significantly to an annual rainfall of approximately 3 meters in the region. Tidal patterns in this area are predominantly semi-diurnal (Kumar et al., 2014). Remarkably, nearly 80% of India's annual precipitation occurs during the southwest monsoon period (Adith et al., 2023).

1.2. Aim and Objectives

This study investigates a comprehensive examination of the dynamics of Stokes drift along the eastern coast of the Arabian Sea. In our prior work, we precisely calculated Stokes drift from wave parameters, analyzed its variations across different locations—Karwar and Ratnagiri — and analyzed the net drift of particles in these regions. Furthermore, we extended our investigation to include the calculation of Taylor dispersion resulting from Stokes drift multiplied by vertical diffusivity. Notably, we studied how these dynamics differ under swell and wind-sea wave conditions. This comprehensive approach facilitates the identification of connections between wave characteristics, Stokes drift, and particle dispersion, thereby enhancing our understanding of the intricate coastal processes in the Arabian Sea.

1.3. Hypotheses

It is hypothesized that the variation in Stokes drift velocity along the eastern coast of the Arabian Sea is intricately linked to the seasonal changes in monsoon winds. Specifically, it is proposed that higher velocities of Stokes drift will be observed during the Southwest (SW) monsoon period compared to the Northeast (NE) monsoon period. This hypothesis underscores the significance of Stokes drift in predicting and analyzing ocean currents during different climatic periods, particularly in regions strongly affected by seasonal monsoon dynamics.

Under the study's comprehensive examination of wave characteristics, Stokes drift, and particle dispersion, it is hypothesized that distinct spatial distribution patterns of Stokes drift will be observed under swell wave conditions compared to wind-sea wave conditions. This hypothesis suggests that different mechanisms of particle displacement and dispersion may operate along the coast, depending on the prevailing wave conditions, thus highlighting the complexity of coastal dynamics influenced by Stokes drift.

Also, the calculation of Taylor dispersion resulting from Stokes drift multiplied by vertical diffusivity is expected to reveal significant differences in the longitudinal spreading of passive tracers between different locations along the coast, such as Karwar and Ratnagiri. This hypothesis emphasizes the role of Stokes drift in enhancing vertical mixing processes within the water column, thereby influencing the dispersion of particles along the Arabian Sea coastline.

Furthermore, it is hypothesized that Stokes drift plays a pivotal role in shaping the spatial distribution of particles along the eastern coast of the Arabian Sea, particularly during periods of intense monsoon activity. This hypothesis underscores the importance of considering Stokes drift dynamics in predicting material transport and dispersion patterns, which are crucial for understanding and managing coastal ecosystems in this region.

Lastly, the comprehensive analysis of wave characteristics, Stokes drift dynamics, and particle dispersion is expected to provide valuable insights into the interconnected processes driving coastal dynamics in the Arabian Sea. By addressing these hypotheses, the study aims to contribute to a better understanding of oceanographic systems in this region, ultimately facilitating informed decision-making and conservation efforts related to coastal management and environmental preservation.

1.4. Scope

The study of Stokes Drift in oceanography holds significant importance in solving the intricate dynamics of water waves and fluid behavior. Originating from George Gabriel Stokes' pioneering investigations in 1847, Stokes Drift elucidates the continuous displacement of particles at the free surface of waves. Stokes Drift's role in turbulent mixing processes and Taylor dispersion enhances our comprehension of vertical diffusivity in the water column. The seasonal reversal of monsoon winds along the Indian coastline, coupled with the robust southwest monsoon winds, underscores the importance of Stokes Drift in predicting and analyzing ocean currents during different periods. Studying Stokes Drift comprehensively involves exploring coastal dynamics, understanding fluid parcel movement, and analyzing its effects on precipitation patterns. This approach provides a thorough perspective for examining the intricate complexities within oceanographic systems.

CHAPTER 2

2. LITERATURE REVIEW

A study by Breivik et al. (2014), addresses the modeling challenges in Eulerian ocean models incorporating Langmuir turbulence and Coriolis–Stokes forcing. Emphasizing the importance of accurate Stokes drift velocity profiles, the study discusses the conventional use of monochromatic profiles, despite their limitations. Implemented in the ECMWF's NEMO ocean model, the proposed profile is compared to the monochromatic profile, and the study outlines a comprehensive analysis and recommendations for computing approximate Stokes drift profiles. They approximate Stokes drift profiles for water of arbitrary depth, linking the Stokes drift profile to the wave variance spectrum.

$$Vs(z) = g \iint_{-\infty}^{\infty} F(k) \frac{k}{\omega} \left[\frac{2kcoshk(z+h)}{sinh2kh} \right] dk \quad (2.1)$$

where $k = |k|$ is the magnitude of the wave-number vector, h is the bottom depth (positive), g is the gravitational acceleration, $\omega = 2\pi f$ is the circular frequency, and z is the vertical coordinate (positive up).

The deep-water limit of the dispersion relation is considered, simplifying the expression. The east and north components of the Stokes drift profile are presented in frequency-direction coordinates. To address the computational cost, the study discusses approximating the Stokes drift profile from the transport equation and surface Stokes drift velocity, often using a monochromatic profile. Analytical expressions for the monochromatic and an alternative exponential integral profile are derived and compared, with the latter showing better agreement with the Phillips spectrum. The proposed profile is parameterized and computationally efficient.

In a comprehensive review by Bremer & Breivik (2018) on surface gravity waves, particular focus is given to the consequential Stokes drift. The authors meticulously explore the periodic motion and net drift induced by surface gravity waves, dissecting the fundamental physics and applications of Stokes drift. The study adeptly navigates theoretical derivations, laboratory studies, and field measurements, providing a well-rounded perspective on this vital aspect of fluid mechanics. Here, Stokes drift is taken as an attribute inherent to waves, and in the context of small wave steepness, it can be computed as the resultant velocity arising from minor displacements of a Lagrangian particle throughout its phase cycle:

$$u_{SD} = \overline{\xi^{(1)}.\,\Delta u^{(1)}} \tag{2.2}$$

Here, $u^{(1)}$ represents the velocity field of the linear wave, and $\xi^{(1)}$ is the corresponding linear displacement vector with components given by $\xi^{(1)} = (\xi_x^1, \xi_y^1, \xi_z^1)$. The overline indicates averaging over the linear waves, and the superscript (1) denotes the first order in wave steepness.

Also this study considered periodic deep water surface gravity waves, where the water depth significantly exceeds the wavelength, allowing the Laplace equation $\Delta^2\emptyset^{(1)} = 0$ for an in-compressible and irrotational fluid. The linearized free surface boundary conditions yield $\emptyset^{(1)}$ and $\xi^{(1)}$, representing the linear velocity potential and free surface displacement, respectively. With wave parameter a, ω, and k denoting amplitude, frequency, and wave-number, and x and z as horizontal and vertical coordinates, solving $\partial\,\xi^{(1)}/\partial$ t= $u^{(1)}$ yields the linear displacement vector $\xi^{(1)}$. Substituting $u^{(1)}$ and $\xi^{(1)}$ into the Stokes drift expression (1.1.2) results in:

$$u_{SD} = c(ak)^2 e^{2kz} + O((ak)^6) \qquad (2.3)$$

In this expression, the vertical displacement contribution is unaffected by finite depth, while the horizontal displacement contribution becomes more significant in shallower water.

A study by Monismith & Fong (2004) delves into the intricate dynamics of transport processes influenced by surface waves in coastal environments. Emphasizing the interplay between Eulerian and Lagrangian mean velocities, the authors highlight the concept of Stokes drift and explore its potential implications on the movement of scalars and organisms. The study offers a theoretical framework, drawing attention to the critical factor of Stokes drift velocity. By providing a detailed overview of wave-induced velocities, wave amplitudes, wave-numbers, and water depths, the authors contribute valuable insights into the quantifiable aspects of Stokes drift. Furthermore, the study underscores the practical applications of this research, suggesting its relevance for understanding transport mechanisms affecting marine populations and the connectivity of diverse habitats in the inner shelf. This study offers a nuanced perspective on the potential impact of surface waves on scalar and organism transport.

The exploration of water waves, situated in a historical context (Craik, 2004), experienced a notable advancement through Sir Gabriel Stokes' groundbreaking work in 1847. A consequential outcome of his analysis, Stokes drift, manifests as a net particle motion, even when the time-averaged Eulerian velocity is zero. This phenomenon, resulting from wave averaging on the mean flow, bears significant implications for oceanic dynamics. Craik & Leibovich (1976) established its role in generating a body force on the mean velocity field, fostering instabilities such as Langmuir cells. Monismith & Fong (2004) underscored the importance of the Lagrangian mean velocity, a composite of Stokes drift and Eulerian mean velocity, in material transport within oceanic environments. Monismith's recent study (2019) delves deeper into our understanding of Stokes drift, emphasizing its theoretical intricacies and experimental applications.

In a study conducted by Monismith et al. (2007), the focus lies in elucidating the transport mechanisms of scalars and organisms by surface waves, building upon the foundational work of Stokes (1847). Stokes' discovery of non-closed orbits in the potential solution for water waves at the lowest order in wave slope leads to the manifestation of Stokes drift, a net forward motion of fluid particles, particularly notable in deep-water waves. Monismith and colleagues present an approximation for Stokes drift, emphasizing its depth-dependent nature. The authors integrate concepts of Eulerian and Lagrangian mean velocities, with Longuet-Higgins (1953) providing corrections for mass transport velocity due to viscous boundary layers. Laboratory experiments, including those by Russell & Osorio (1957) and Swan (1990), challenge theoretical expectations, revealing negatively sheared mean Eulerian flows below water waves. The study discusses further observations, including velocity measurements in wave flumes, emphasizing consistent findings that waves do not fundamentally alter pre-existing Lagrangian mean flows.

In the study by Liu et al. (2014), the authors delve into the crucial role of Stokes drift in marine environments induced by the periodic orbital motions of progressive surface gravity waves. Stokes drift, represented as the difference between phase-averaged Eulerian velocity and mean Lagrangian motion, is explored for its profound implications. The study emphasizes the diverse impacts of Stokes drift, including its contribution to wind-induced drift, vertical shear, and its pivotal role in determining trajectories of drifting objects, pollutants, and substances over the ocean surface. Mass flux induced by Stokes drift leads to offshore-directed undertow and influences sub-mesoscale fronts and filaments in the upper ocean. The authors discuss the interaction between Stokes drift and mean Eulerian current shear, resulting in the Craik-Leibovich vortex force, driving instabilities and generating Langmuir turbulence. The study also delves into the Stokes-Coriolis force, altering mean current profiles and momentum distribution. Techniques for estimating Stokes drift profiles are explored, highlighting the challenges of using simplified monochromatic wave formulations and advocating for more accurate representations using frequency-directional wave spectra. The study evaluates the improvements in coupled modeling by incorporating discrete integration over wave spectra, providing insights into the significance of two-way coupling in evolving wave spectra and Stokes drift.

The investigation of Stokes drift velocity in ocean waves, as explored in Kenyon's study (1969), emphasizes a generalized expression derived from a two-dimensional energy spectrum. Bye (1967) calculated the Stokes drift within the equilibrium range of the wind wave spectrum, while Chin & Pierson (1969) provided examples of surface drift computations for the entire North Atlantic. Theoretical conditions for the validity of the analysis are delineated, necessitating small wave amplitudes in comparison to wavelength and water depth. When applied to the deep ocean, empirical energy spectra, particularly those by Pierson and Moskowitz, are utilized. The resulting Stokes drift formula is versatile, incorporating considerations for surface tension. Key observations include the rapid reduction of Stokes drift in proximity to the ocean surface and its dependence on water depth.Utilizing empirical spectra, surface drift estimates range from 1.6% to 3.6% of wind speed at a depth of 19.5 meters. This investigation underscores the importance of a statistically stationary and horizontally homogeneous wave field in comprehending the overall wave drift phenomenon.

Restrepo's (2001) study was more focused on the findings of the study on the interaction of waves and currents, specifically focusing on the Stokes drift in shallow water wave conditions. The derived model reveals that the Stokes drift contributes to the long-term motion of the fluid through a vortex-force term and a mass flux term. The theory is an extension of a wind-driven circulation model, adapted for shallow-water wave motions. The presented model can be modified for various applications, including the dynamics of tracers and pollutants in coastal regions and shallow lakes. The study explores the implications of the Stokes drift on sediment dynamics, particularly in the formation of shore-oblique sand ridges. It suggests that the presence of waves can significantly affect the dynamics of these structures, and the analysis involves linear instability considerations. The results indicate that the drift velocity, under certain conditions, can modify the advection speed and structure of the bars, influencing their orientation. The assumption of hydrodynamic steady state is found to be crucial to the formation of shore-oblique bars, but the model in its present form does not fully support this assumption. The study suggests that determining the strength and structure of the drift velocity in coastal zones could be valuable for understanding the transport of pollutants and tracers subjected to both waves and currents.

In Jansons & Lythe (1998) study, the focus is on understanding the impact of diffusion on the magnitude and direction of Stokes drift—a small drift velocity experienced by suspended particles in a fluid due to the presence of traveling waves. The study considers scenarios where multiple waves contribute to the drift velocity and explores the influence of diffusion in cases where the classical Stokes drift could sum to zero. The research delves into the dynamics of small particles in solution, particularly their directed motion without a macroscopic force, drawing parallels to the mechanisms observed in biological motors. The study introduces the concept of "ratchet" effects, mechanisms for particle motion without a net force, with potential applications in areas such as the separation of particles in solution based on their diffusion coefficients. Jansons highlights the experimental generation of drift velocity in the presence of an asymmetric periodic potential and underscores the importance of understanding dynamics dominated by noise. The author emphasizes the derivation of a general expression for the drift velocity of diffusing particles through a stochastic asymptotic expansion scheme. Importantly, it is noted that the drift velocity can persist even when the classical Stokes drift is absent. For instance, counter-propagating sinusoidal forcings are shown to produce a drift velocity dependent on diffusion coefficients, intensities, frequencies, and wave numbers of the forcings.

The study by McWilliams & Restrepo (1999) challenges the traditional understanding of ocean circulation by incorporating the influence of surface gravity waves, particularly focusing on the Stokes drift. While the standard theory neglects the sea-state, this study recognizes the significant impact of Stokes drift on large-scale sea state and ocean currents. The authors develop a generalized Boussinesq model that considers the average dynamical effects of the gravity wave field. By decomposing dynamics into rapidly and slowly varying components, they derive the Stokes drift and wave-averaged modifications to boundary conditions. The study introduces two steps: first assuming an irrotational wave field and then making further approximations for a specific oceanic dynamical regime. The resulting generalized planetary geostrophic equations reveal the importance of wave-added terms, such as Stokes-drift vortex and Coriolis forces, in influencing surface pressure and velocity. Notably, the study highlights that the traditional relations for Ekman and Sverdrup transports apply to the total Lagrangian-mean transport, emphasizing the role of Stokes transport.

In Smith's (2006) study on surface waves and their impact on air-sea interactions, a key focus is on Stokes drift, which arises from the difference between the Lagrangian and Eulerian velocities in the ocean. The study underscores the crucial role of intermittent wave-breaking events in transmitting stress to the underlying flow, with simulations revealing vortical structures influencing motion to a depth greater than previously thought. The study delves into the significance of Stokes drift in Langmuir circulation generation, emphasizing the bending of vortex lines by vertically nonuniform Stokes drift. While previous analyses of Langmuir Circulation considered an overall mean Stokes drift, this study suggests the importance of examining the spatial and temporal variations of Stokes drift due to the intermittent nature of wave-breaking events. This study presents novel observations of Eulerian surface current responses to short-wave groups in open-ocean, deep-water conditions, focusing on an area off the west-northwest shore of Oahu. Methods for estimating Stokes drift reveal unexpected Eulerian counter-flows that surpass predicted responses based on irrotational theories.

Two significant scientific results emerge from the study: firstly, as wave groups pass, Eulerian counter-flows at the surface exceed predictions, challenging current understanding. Secondly, the observed Stokes drift resulting from open-ocean surface waves is highly intermittent, with coherent wave packets not observed previously in deep-water conditions. The study addresses technical issues, including the impact of acoustic sheltering on measurements and the development of methods to estimate Stokes drift from the data. Smith highlights the complex dynamics of Stokes drift, challenging existing theories and providing valuable insights into its intermittent nature and role in oceanic processes, particularly in the context of wave-breaking events and Langmuir circulation.

In the study by Herremen & Lessefre (2011), the authors explore the application of mean-field dynamo theory to understand the generation of magnetic fields in planetary and stellar bodies. They introduce the concept of the Stokes drift, a Lagrangian mean flow associated with fluctuation flows with short correlation times. The study reveals that dynamo action by rapid fluctuation flows is controlled by the Stokes drift, which acts on the mean magnetic field as a mean flow. They apply their model to inertial wave flows in rapidly rotating systems, showing that the Stokes drift plays a crucial role in understanding the generation of magnetic fields in these contexts. The significance of the Stokes drift in dynamos driven by rapid fluctuation flows and provides a new perspective on mean-field dynamo theory without spatial averaging.

In the study by Webb & Fox-Kember (2015), the significance of Stokes drift in understanding the effects of ocean surface gravity waves is highlighted. Stokes drift plays a crucial role in wave-driven upper ocean mixing, open ocean interactions between waves and mean flows, and sea surface transport. The paper emphasizes the importance of parameterizing wave-driven mixing in global climate models and explores the challenges in measuring depth-dependent and depth-integrated Stokes drifts. The authors discuss the common practice of assuming unidirectional seas, which simplifies the measurement of Stokes drift but may not accurately represent real-world conditions. They address the difficulty in accurately measuring higher moments of the wave spectrum needed to estimate surface or subsurface unidirectional Stokes drift. The study underscores the sensitivity of near-surface Stokes drift magnitudes to higher-frequency wind seas and the potential impact of directional spreading on magnitude losses.

In a comprehensive investigation conducted by Bosi et al. (2021), the study delves into the timescales of dispersal from the ocean surface to coastal accumulation areas through the phenomenon of "beaching."Their previous study highlighted the significant impact of Stokes drift, showing its magnitude comparable to Eulerian current speed and its enduring influence on the trajectories of floating objects. Employing two particle tracking models (PTMs) named PTM-SD (with Stokes drift) and PTM-REF (without Stokes drift), the study utilized global reanalysis datasets for Eulerian velocity and Stokes drift data in particle advection. Notably, PTM-SD exhibited a beaching rate twice that of PTM-REF on a yearly basis, resulting in a 20% larger quantity of beached particles after a 12-year simulation. Long-term predictions indicated that all particles in PTM-SD beached within 100 years, while 8% remained afloat in PTM-REF. These findings underscore the imperative need to accurately incorporate Stokes drift in particle models to avoid overestimation of marine debris residence time, informing effective policies for prevention and removal.

CHAPTER 3

3. DATA AND METHODOLOGY

The investigation utilized wave data collected during the period from January 1, 2017, to December 31, 2017, from two specific locations positioned along the eastern Arabian Sea. The data were gathered through the utilization of a moored Datawell Directional Waverider-MkIII buoy, with a diameter of 0.9 m, as detailed by Kumar and Mandal in 2022.

The chosen stations for examining Stokes drift along the eastern coast of the Arabian Sea are Ratnagiri and Karwar. The distances between these locations were approximately 270 km. Kumar and Mandal (2022) strategically selected these measurement points to comprehensively capture wave characteristics and variability across distinct regions of the eastern Arabian Sea.

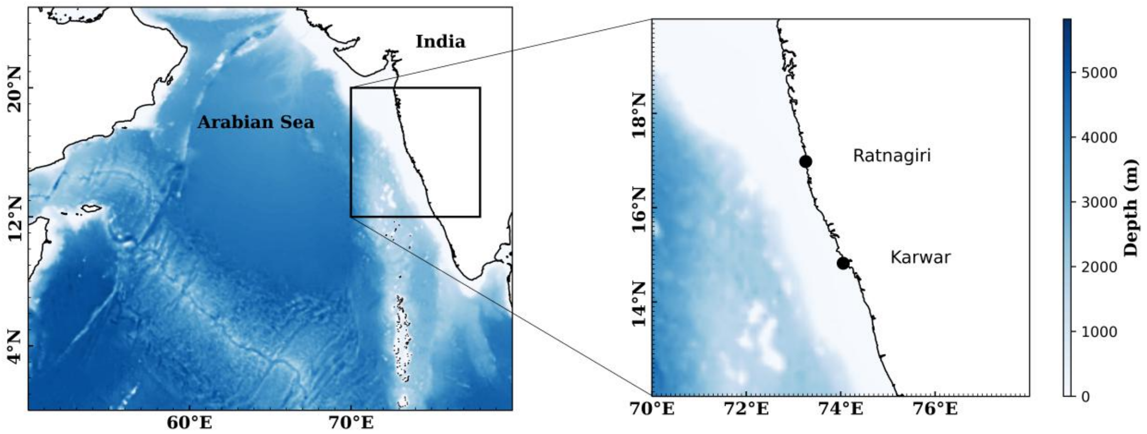

Figure 3.1. Map showing the location of wave-rider buoy in the eastern Arabian Sea. The colour shade is the water depth in metre.

The methodology employed in this study centers around the computation of Stokes drift (V_S), representing the mean Lagrangian velocity of fluid particles within deep-water ocean waves.

The calculation relies on an equation expressing V_s a function of wave characteristics and water depth, specifically utilizing the formula:

$$V_s = \frac{1}{2}c(ak)^2\frac{cosh2k(H_m + d)}{sinh^2(kd)} \qquad (3.1)$$

The parameter involved, including wave celerity(c), wave number (k), mean wave height (H_m), water depth (d), and wave amplitude (a), are carefully considered and integrated into the equation (Breivik et al., 2014, Bremer & Breivik, 2018). Mean wave height can be found using equation 3.2. We are analyzing the Stokes drift for half hour and hence we have to multiply the V_s using number of waves. ie, 60 x 30 / mean wave period.

$$H_m = \frac{H_s}{1.68} \qquad (3.2)$$

The estimation of the wavelength (L) associated with different wave periods involves iteratively solving the wave dispersion relation using the relevant wave period and water depth. Despite assuming a constant water depth at the buoy location during wavelength estimation, this assumption does not hold true. The study area experiences an average tidal range of approximately 2 m, leading to fluctuations in water depth attributable to tidal changes (Anju and Kumar, 2023). The methodology entails a systematic computational process, involving precise evaluations of hyperbolic trigonometric functions, power terms, and numerical implementation where necessary. Sensitivity analysis is conducted, systematically varying individual parameters to understand their influence on the resultant Stokes drift.

The net drift of the particle was determined by analyzing its displacement in the x and y directions. The particle's horizontal position is represented by *x*, while its vertical position is represented by *y*.

$$x = -Vs sin\theta \tag{3.3}$$

$$y = -Vs cos\theta \tag{3.4}$$

Vs is the Stokes drift and θ is the wave direction. These mathematical formulations were employed to characterize the particle's movement in response to external factors. Subsequently, the obtained values for *x* and *y* were utilized to plot the net drift of the particle. This analytical approach allowed for a comprehensive understanding of the particle's trajectory, incorporating both horizontal and vertical components influenced by the Stokes Drift and the wave direction.

The calculation of the Taylor dispersion coefficient multiplied by vertical diffusivity involves utilizing the formula derived by Broeck in 1990.

$$KD_z = \frac{H^4}{T^2}\frac{\pi^2}{16tanh^2kh}\left(\frac{sinh4kh - 4kh}{4kh(cosh4kh - 1)} + \frac{1}{2(kh)^2} - \frac{cosh2kh}{khsinh2kh} + \frac{1}{3}\right) \tag{3.5}$$

This methodology allows for an inclusive understanding of the Stokes drift phenomenon within the context of wave dynamics, providing crucial insights into fluid particle behavior in coastal waters wave environments.

CHAPTER 4

4. RESULTS AND DISCUSSIONS

4.1 Stokes drift and other wave parameters

The analysis of wave parameters at Ratnagiri and Karwar stations highlights influential trends tied to seasonal variations and specific meteorological events (see Figure 4.1). In the winter months, that is January and February, both stations experience subdued wave heights, averaging around 1.2 m. Wave heights gradually increase as summer approaches, reaching around 2 m. The monsoon months, especially June and July, exhibit peak wave heights about 4 m. August witnesses a decrease, maintaining consistency through November, with a noticeable increase in wave heights observed in December at both locations. While observing both the locations, we can see Ratnagiri station has a slightly higher value in wave height when compared to Karwar station.

The shorter periods in both stations during winter correlate with lower wave heights. May sees periods extend to around 7 s, while June and July exhibit consistently long periods around 9 s aligning with peak wave heights. In Karwar, January and February show a consistent period of 4.2 s, increasing to 7 s in June and July. August stabilizes at 6.5 s, and September decreases to 5.9 s. October and November maintain lower periods, with an increase in December.

Wavelength patterns at both stations mirror wave heights and periods, with shorter wavelengths in winter corresponding to tranquil conditions. In Karwar, as summer progresses, wavelengths elongate, reaching over 80 m in June and July. While Ratnagiri has a wavelength of about 60 m in June and July. November sees a spike before reverting to averages by December.

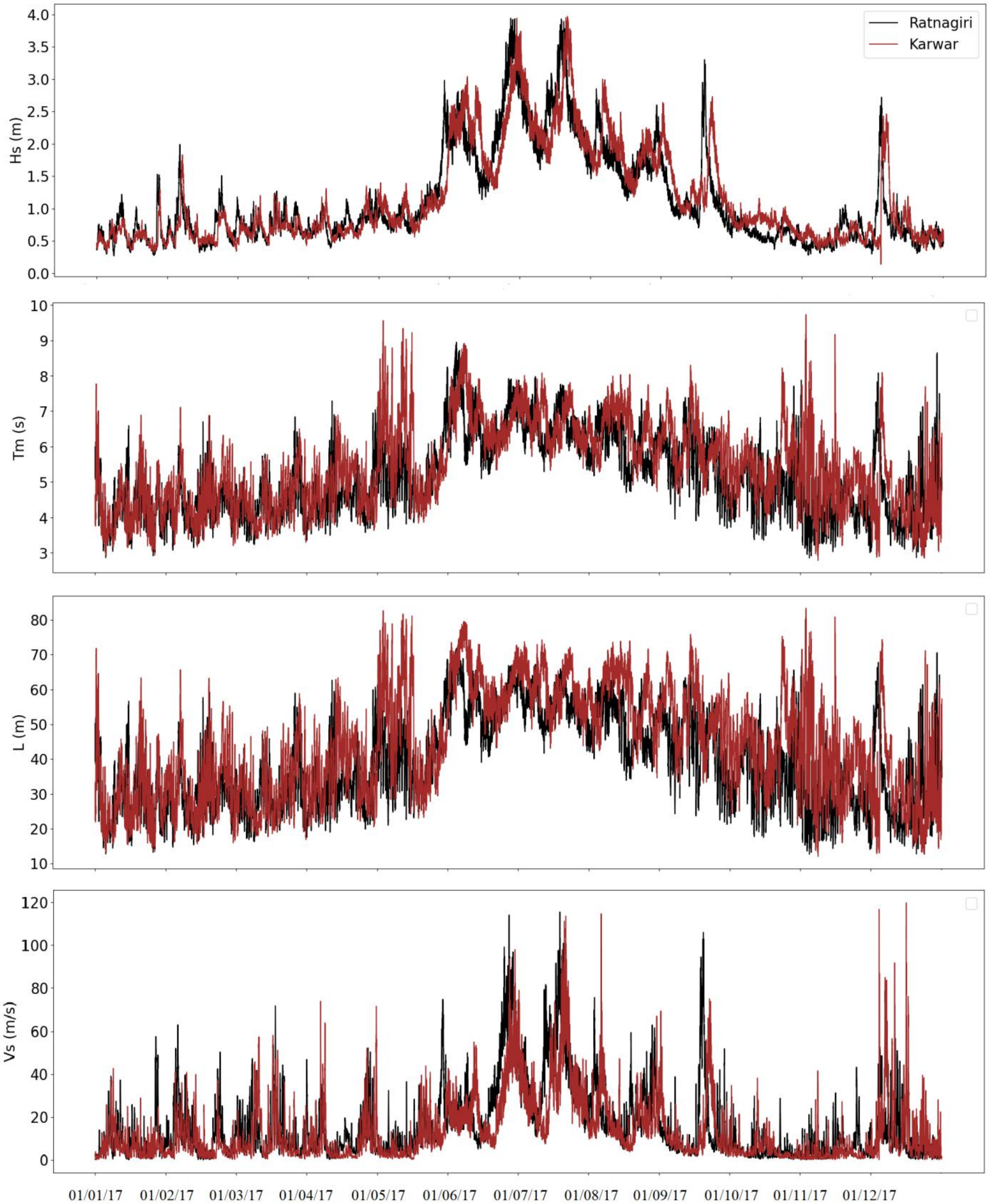

Figure 4.1. Half-hour variations in Significant Wave height (H), Wave period (T), Wave length (L), Wave steepness (S) and Stokes drift (Vs) observed at the Karwar and Ratnagiri station of the year 2017

The variation in Stokes drift values reveals substantial fluctuations throughout the year. During winter months, both stations register the lowest Stokes drift values, signifying a state of utmost tranquility. In contrast, the transition to summer months marks an increase in Stokes drift, attributed to heightened wind intensity and wave energy. The most significant surge in Stokes drift values occurs during the monsoon months (June through September), closely aligning with the season's characteristics. As the monsoon season subsides, a gradual descent in Stokes drift values occurs, continuing into the post-monsoon period and early winter. December deviates slightly with a minor upswing, possibly influenced by external factors such as the impact of Cyclone Ockhi. When comparing both the stations, Ratnagiri exhibits a higher Stokes drift.

4.2 Percentage of Occurrence

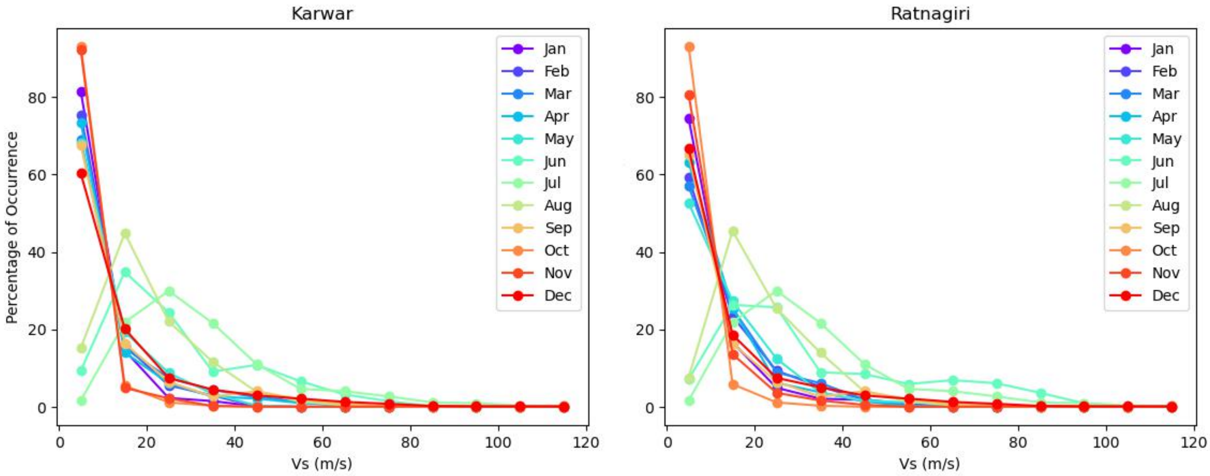

Figure 4.2. Percentage of occurrence calculated for Stokes drift (Vs) that observed at the Karwar and Ratnagiri station of the year 2017

The analyzes of the percentage of occurrence of Stokes drift in two coastal stations, Karwar and Ratnagiri, depict the strength of Stokes drift, allowing for the understanding of its variability throughout the year which is shown in the Figure 4.2.

In Karwar, (represented in Figure 4.2a.) the percentage occurrence of Stokes drift across different ranges of values for each month reveals that the majority of occurrences fall within the lower ranges of Stokes drift, particularly between 0 and 30, indicating that relatively low-magnitude events are more common. There is a notable seasonal variation in Stokes drift occurrences. For instance, in January, February, and March, higher percentages occur in the lower ranges, suggesting calmer sea conditions during these months. From April to September, there is a significant increase in occurrences across all ranges, with a considerable events falling within the 10 to 40 range, indicating stronger drift events during these months, possibly due to increased wave activity. In October and November, there is a decrease in occurrences compared to the previous months, particularly in the higher ranges, suggesting a reduction in the intensity of drift events as the year progresses towards the end. December sees a slight increase again, although not as pronounced as in the preceding months.

Overall, the data suggests a seasonal variability in Stokes drift occurrences in Karwar, with stronger events typically observed during the warmer months and relatively calmer conditions during the cooler months. Similarly, Ratnagiri showcases notable occurrences of stronger Stokes drift, particularly in June, July and August. Throughout the year, occurrences in the higher strength ranges are prevalent, even during months with lower overall occurrences. August and September show moderate occurrences of stronger Stokes drift, indicating its persistence even during less active periods.

Comparing Karwar and Ratnagiri, both stations exhibit consistent occurrences of stronger Stokes drift, especially during certain months. While lower strength events predominate, the importance of higher strength occurrences is evident, emphasizing their influence on coastal dynamics. Differences in occurrences between the stations may stem from local oceanographic conditions and geographical factors. The analysis underscores the significance of stronger Stokes drift events in coastal regions, as they play a crucial role in sediment transport and coastal processes.

4.3 Net-drift of the Particles

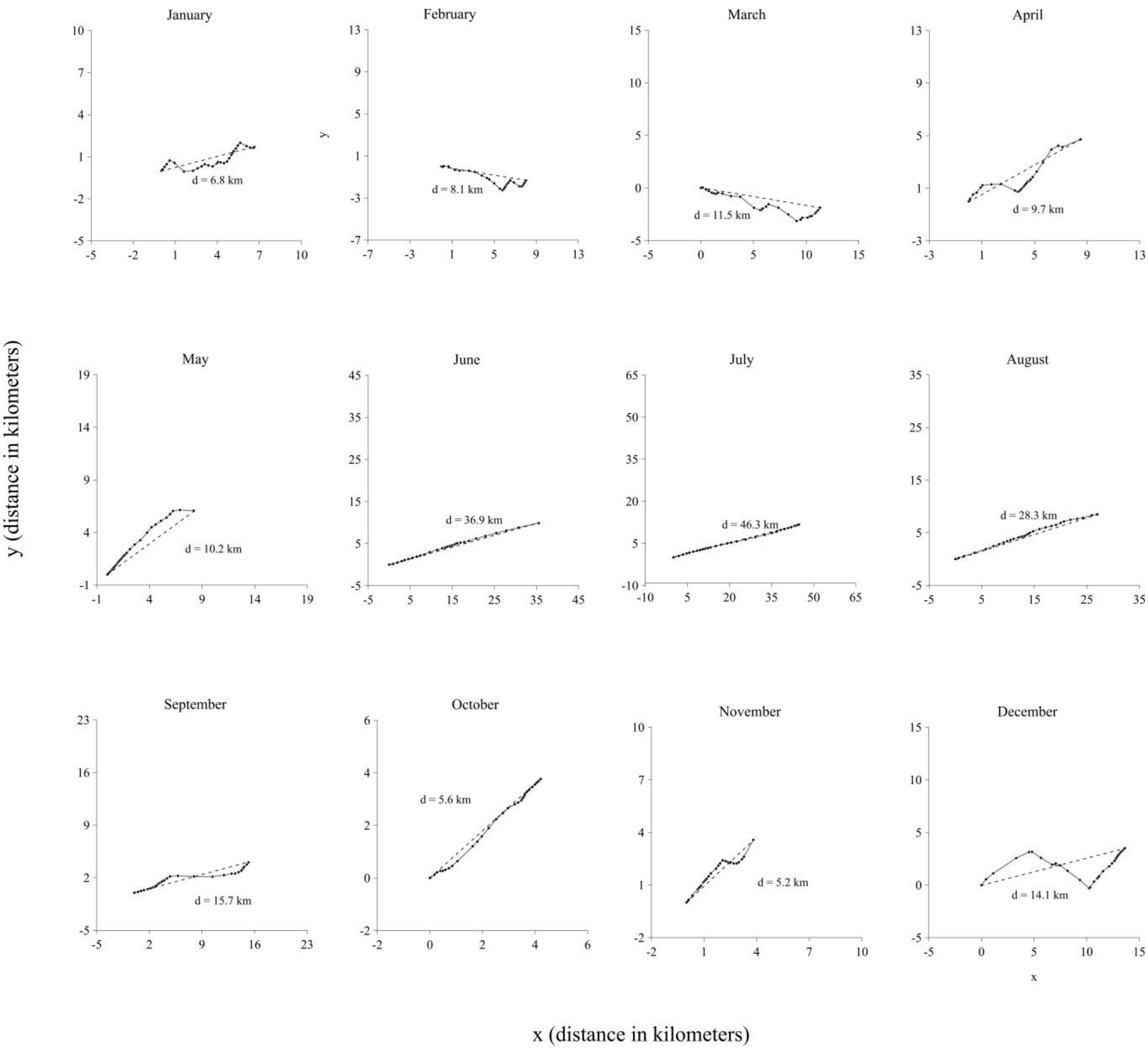

Figure 4.3. Net-drift of the particles at the Karwar station

Figure 4.3. and 4.4. shows the Net-drift of the particle in Karwar and Ratnagiri stations respectively, which represents a component of the Stokes drift that is perpendicular to the wave direction and influenced by the sine and cosine of the wave direction in the horizontal and vertical direction respectively. It describes the complex motion of fluid particles in a wave field.

When examining particle movement, the months of June, July, and August showcase greater particle displacement in both stations. However, the Ratnagiri station demonstrates a comparatively higher Stokes Drift, resulting in increased particle displacement. The predominant movement of particles towards the northeast direction during these months provides compelling evidence that the wave direction originates from the southwest. The stronger Stokes drift in the SW monsoon period influences the greater particle displacement (see Figure 4.1). From October, according to the trend, the particle displacement has to decrease in December. But December exhibits a greater displacement, which is much higher than what we observed in November.

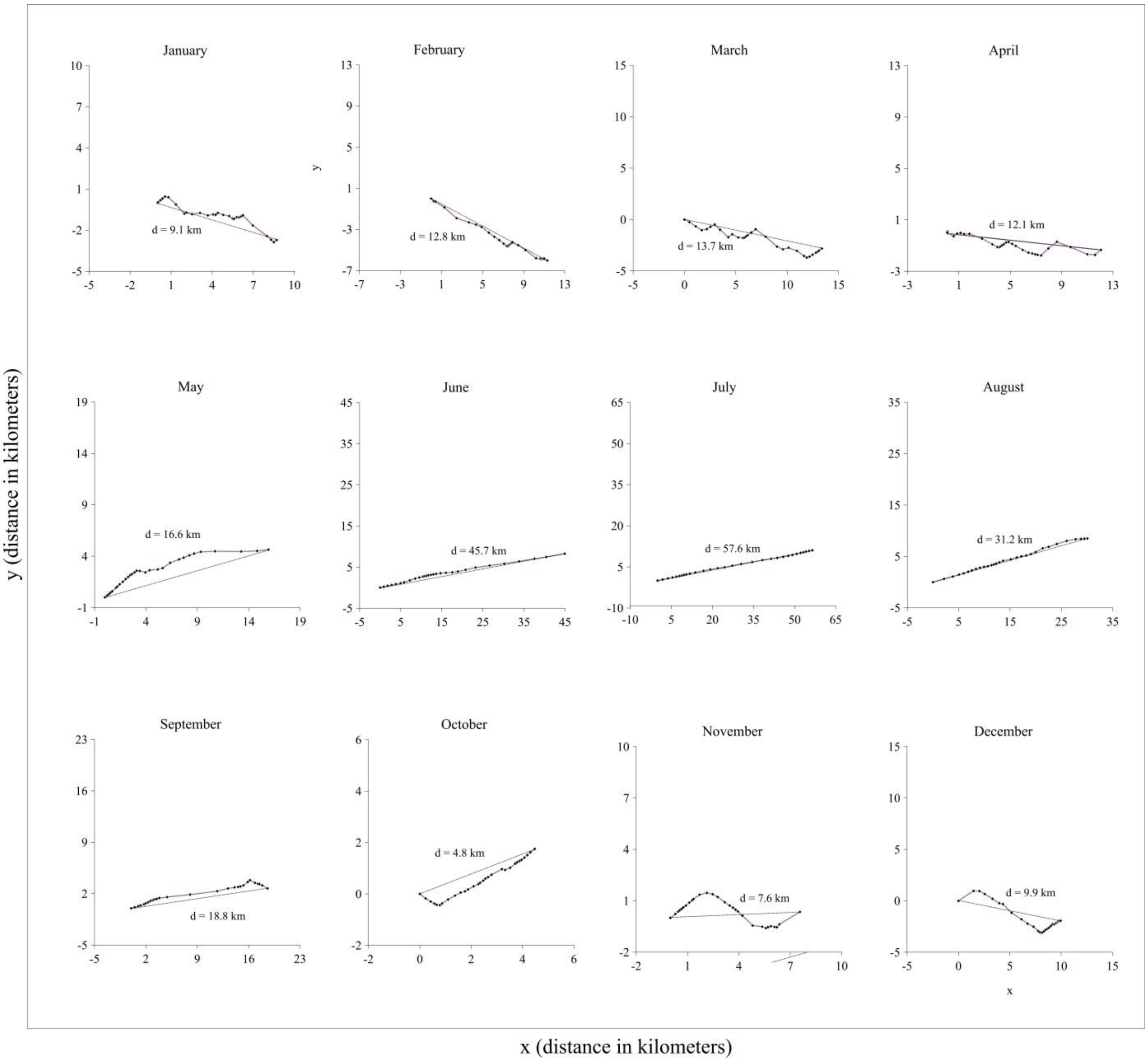

Figure 4.4. Net-drift of the particles at the Ratnagiri station

Except during the SW monsoon period, there are particle displacements in the NE as well as in the SW direction, which results in a zig-zag pattern in the displacement. Whereas during SW monsoon, the particle displacement takes place more in a linear pattern.

Both the stations show a similar pattern, but the range is different. Elevated Stokes drift is particularly prominent during the monsoon months, on certain days in September and the initial days of December due to the occurrence of Cyclone Ockhi as previously noted.

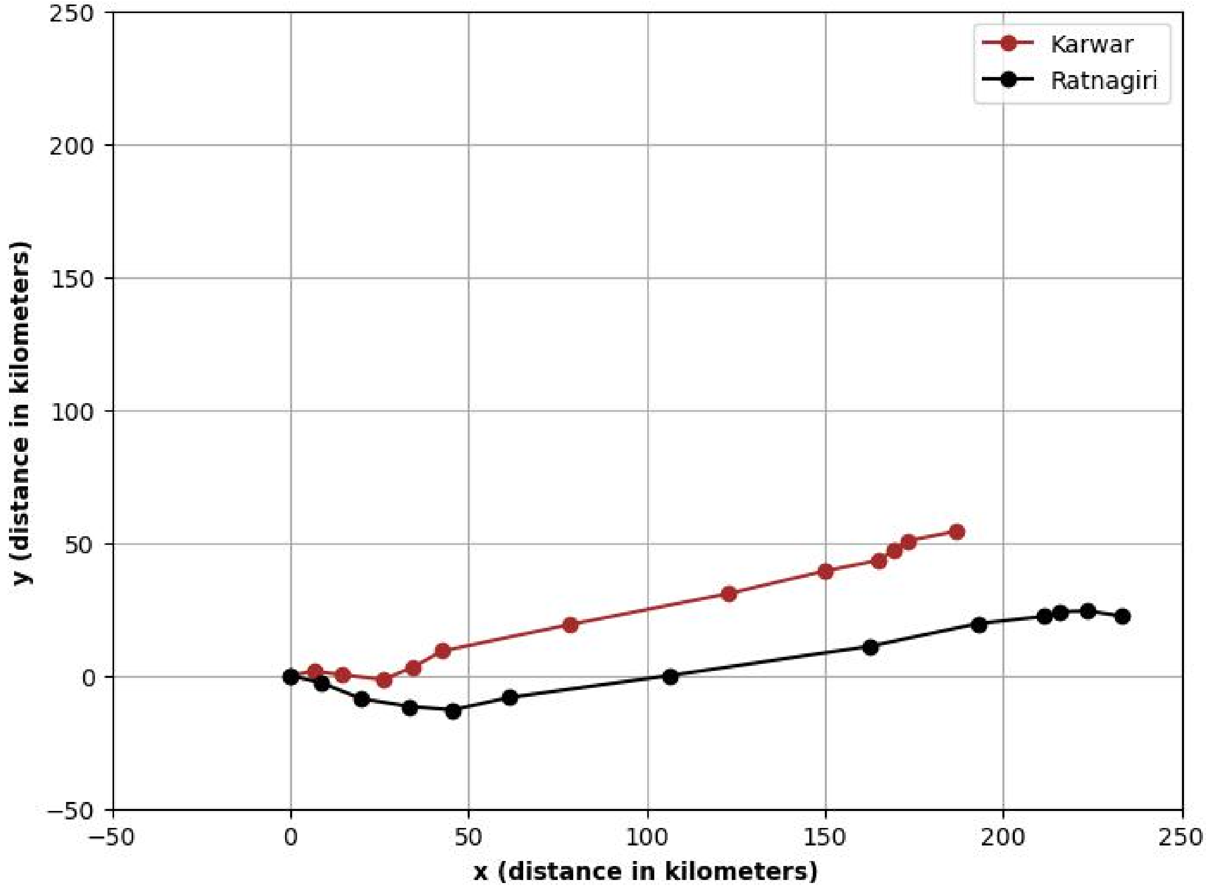

Figure 4.5. Net drift of the particle throughout the year 2017 at the Karwar and Ratnagiri station

The net drift of particles over the course of the year 2017 is illustrated in Figure 4.5. Interestingly, both stations demonstrate a consistent pattern of particle movement, indicating a shared influence of environmental factors on particle transport. However, notable differences exist in the range of particle displacement between the two stations. Specifically, the displacement of particles at the Karwar station is slower than that observed at the Ratnagiri station.

The particle movement in the months May, June, July, August and September is toward the E-NE direction. From the wave direction plot (figure 4.7 and 4.8), it is evident that the waves in this months are from the 250 to 270 range. Among them, June and July show larger displacement in particles in both the stations.

During the months of May, June, July, August, and September, particle movement consistently occurs in the northeast direction. This directional trend coincides with the wave direction plot depicted in Figures 4.6 and 4.7, which indicates that waves during these months originate from the range of 250 to 270 degrees. Notably, June and July stand out with larger particle displacements observed in both stations. This alignment between particle movement and wave direction underscores the direct influence of wave dynamics on particle transport patterns. The increased displacement during June and July suggests intensified wave activity during these months, potentially due to seasonal variations, leads to understand the temporal patterns in the net drift of the particle.

4.4 Stokes drift and wave direction

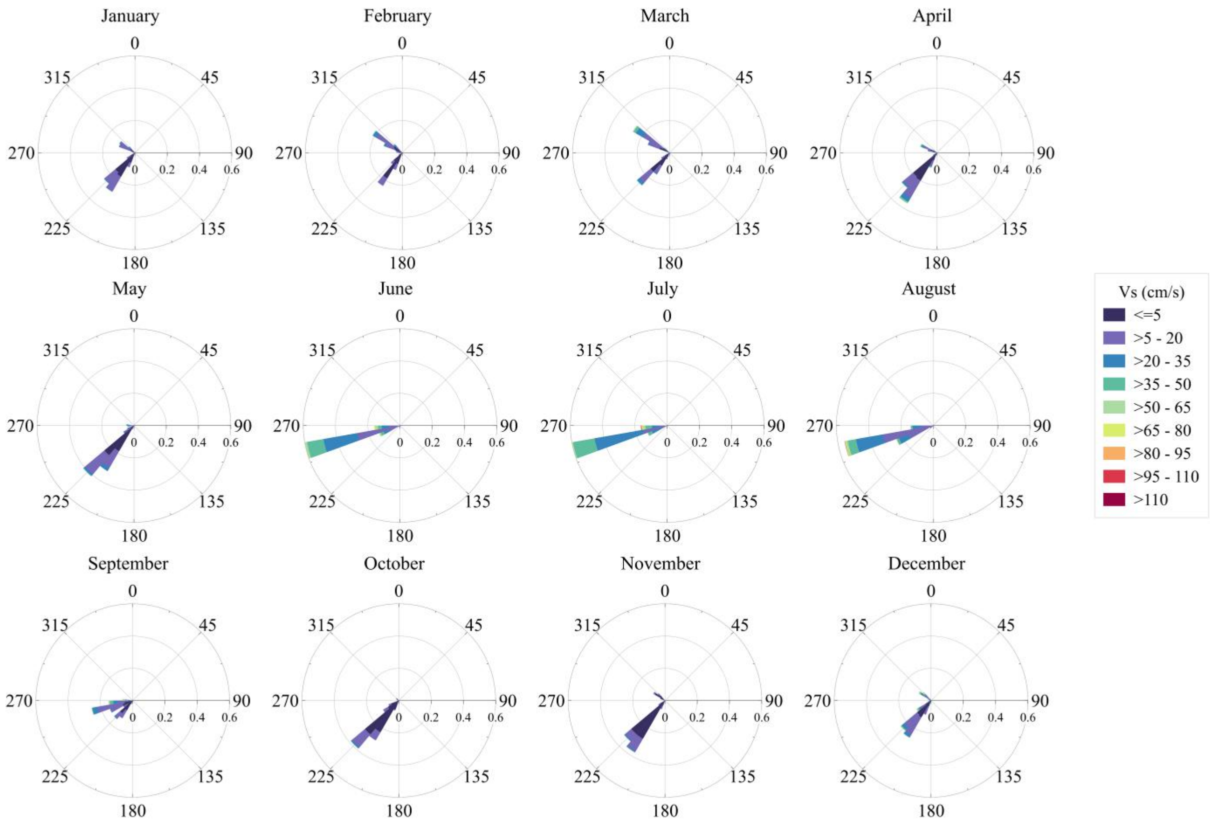

Figure 4.6. Wave direction at the Karwar station

Figure 4.6 displays a Rose plot illustrating wave direction at the Karwar station. Notably, during the monsoon months, the direction consistently falls within the range of 250 to 270 degrees. Interestingly, these directions correspond to higher Stokes drift values. Conversely, directions outside of this range result in lower Stokes drift. Wave direction predominantly falls within the west or southwest during most months, except for February and March, which notably exhibit a significant presence of wave direction in the northwest.

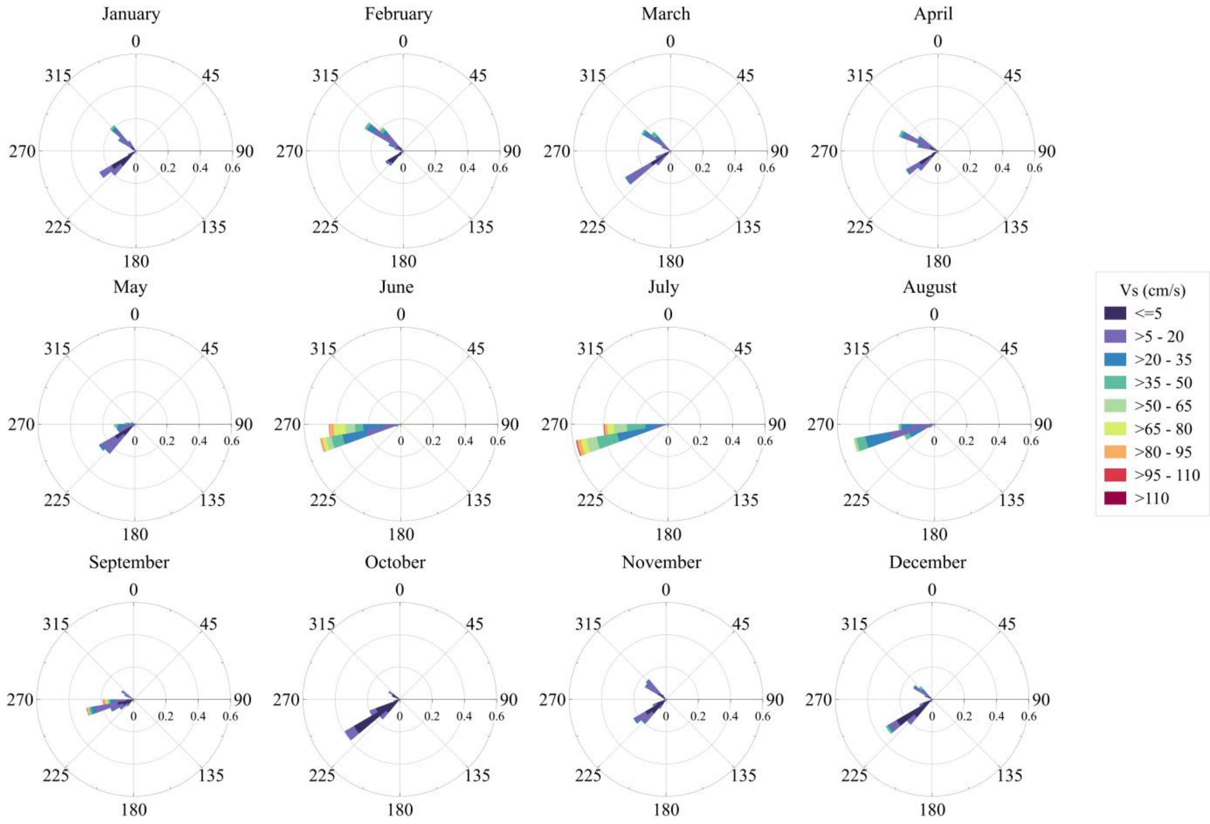

Figure 4.7. Wave direction at the Ratnagiri station

Rose plot illustrating wave direction at the Ratnagiri station is shown in Figure 4.7. The patterns are similar to the Karwar station. During the monsoon months, wave direction consistently aligns within the range of 250 to 270 degrees, corresponding to higher Stokes Drift values compared to the Karwar station. However, May, June, July, August, and September deviate from this pattern, with wave direction predominantly in the west-southwest direction. In all other months, wave direction is primarily in the northwest and southwest direction. Notably, Stokes Drift values are lower for directions other than west-southwest.

Throughout the year, both stations experience varying wave patterns. January, February and March shows a similar wave direction. As we move into April and May, predominantly northward waves emerge, along with increased Stokes drift, indicating stronger currents.

From June to August, there's a noticeable shift in wave direction towards the west and southwest, with varying Stokes drifts. September and October exhibit diverse wave directions, generally coming from the west and northwest. November sees a return to northerly waves, albeit with decreased Stokes drifts. Finally, December's dominant wave direction aligns closely with that of February and March, but it has one of the highest recorded Stokes drifts among them.

4.5 Taylor dispersion due to Stokes drift

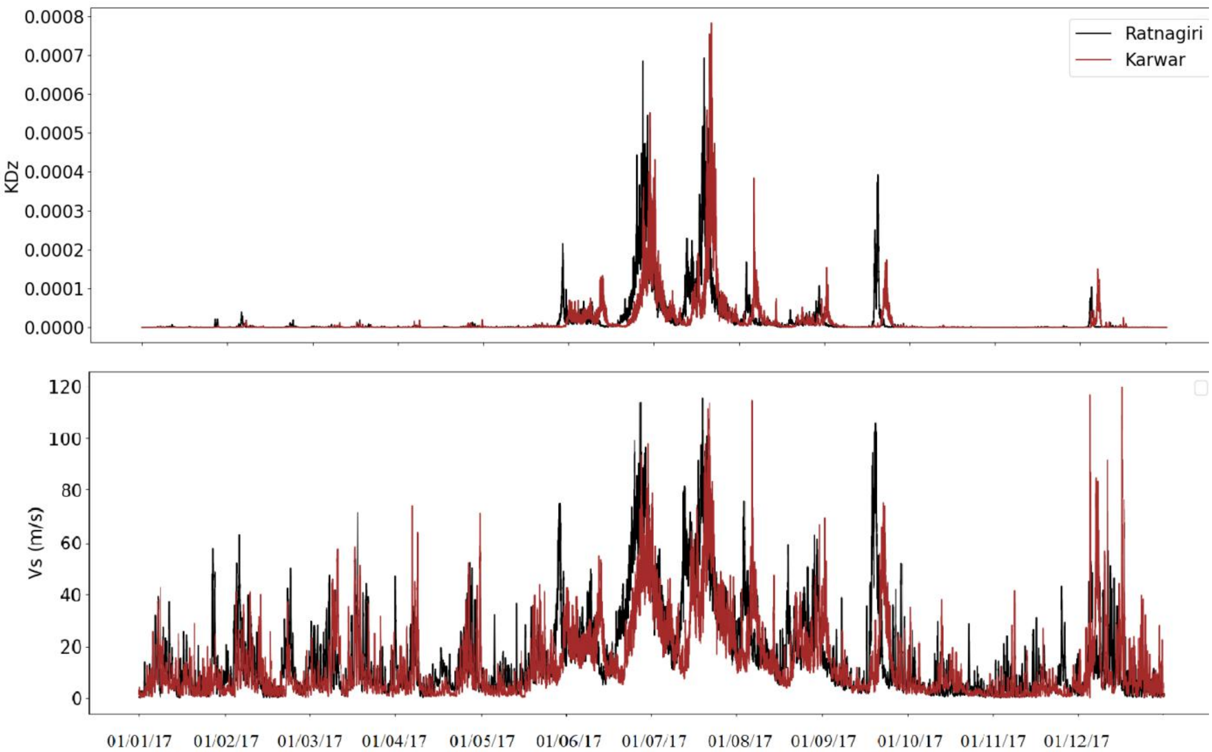

Figure 4.8. Variations in Stokes Drift and KDz in the Karwar and Ratnagiri station

In Figure 4.8, the variations in Stokes Drift and KDz at both stations are depicted, illustrating a positive correlation between them. The data indicates that they exhibit similar changes, differing primarily in magnitude. Specifically, minor fluctuations in Stokes Drift correspond to limited dispersion in particles, whereas more significant alterations lead to stronger dispersion effects. This relationship suggests that higher Stokes Drift enhances the effective diffusivity of particles due to shear flow - known as Taylor Dispersion. That is, the observed correlation underscores the pivotal role of Stokes Drift in influencing particle dispersion dynamics.

Moreover, a comparison between Ratnagiri and Karwar stations reveals that Stokes Drift is higher in Ratnagiri. This trend is mirrored in the KDz values at both stations, indicating greater dispersion in Ratnagiri. This disparity underscores the influence of geographical location as well as the wave parameters on the Stokes drift.

4.6 Long-period waves and Wind-sea waves

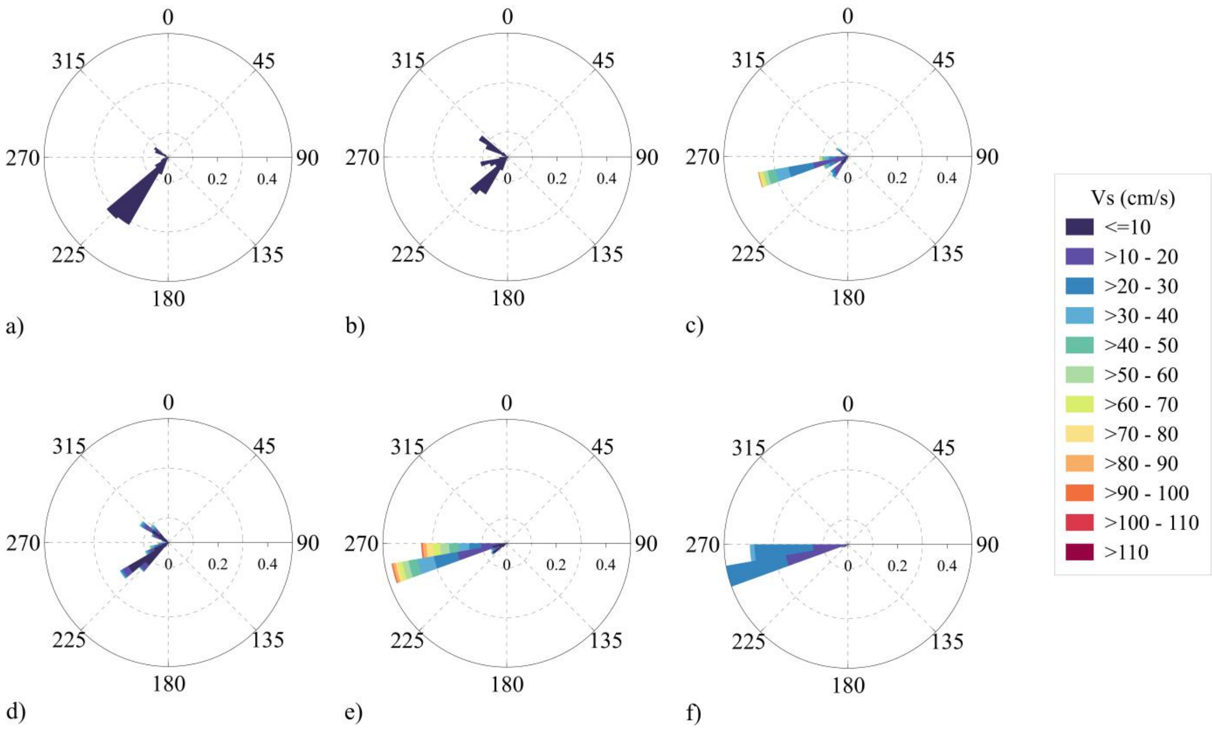

Figure 4.9. Stokes drift variations for different wave types at the Karwar (long period waves - a, intermediate waves - b, wind-sea waves - c) and Ratnagiri(long period waves - d, intermediate waves - e, wind-sea waves - f) station

Stronger Stokes drift is prominently evident in long period waves (Figure 4.9. c,f), compared to the intermediate and wind-sea waves (Figure 4.9. a,b,d,e). The waves coming from the west direction particularly exhibit higher Stokes drift, emphasizing its robust influence. In contrast, the north-west and south-west directions display comparatively lower Stokes drift. In Ratnagiri station, intermediate waves have higher stokes drift when compared to long period waves. But they occurred only in a lower percentage. This higher stokes drift in the intermediate wave is exhibited in wave directions between 250-270 degrees. The months influenced by monsoons contribute substantially to the development of significant and strong

Stokes drift. During these monsoon months, the impact of Stokes drift becomes particularly pronounced, highlighting its crucial role in the dynamic behavior of ocean waves.

Also, the wind sea waves are having a higher stokes drift in the Karwar station when compared to intermediate waves. This is because of the influence of wind direction in these region.

CHAPTER 5

5. CONCLUSIONS

The investigation into Stokes drift along the eastern coast of the Arabian Sea reveals its important role in shaping coastal dynamics and particle transport phenomena. Through meticulous analysis of wave parameters and particle movements at Ratnagiri and Karwar stations, significant insights into seasonal variations and spatial distributions of Stokes drift emerge. The observed patterns underscore the intricate interplay between wave characteristics, environmental factors, and Stokes drift dynamics.

Seasonal variations exhibit a pronounced influence on Stokes drift, with peak values coinciding with the monsoon months, showcasing heightened wave activity. The consequential impact on particle displacement highlights the direct correlation between wave dynamics and particle transport patterns. Notably, the prevalence of higher Stokes drift values during monsoon months underscores its importance in driving oceanic processes and influencing coastal dynamics. Also the stronger Stokes drift are exhibited by the wave direction in the range 250° - 270°.

Furthermore, the analysis elucidates the relationship between Stokes drift and Taylor dispersion, revealing a positive correlation indicative of Stokes drift's significant role in particle dispersion dynamics. The observed disparities between Ratnagiri and Karwar stations emphasize the influence of geographical factors and wave parameters on Stokes drift variations.

Moreover, the distinction between different wave types highlights the robust influence of intermediate and swell waves on Stokes drift compared to wind-sea waves. This underscores the importance of considering wave characteristics in understanding Stokes drift dynamics and its implications for coastal processes.

In conclusion, the analysis of Stokes drift along the eastern coast of the Arabian Sea underscores its multifaceted significance in shaping ocean dynamics and particle transport phenomena. By elucidating the complex interactions between wave characteristics, environmental factors, and Stokes drift dynamics, this study contributes to advancing our understanding of coastal processes and underscores the importance of considering temporal and spatial factors in oceanographic research and management efforts.

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