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Nonlinear Mechanisms of Oceanic Wave and Mixing Processes

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Abstract Nonlinear processes in ocean dynamics play a critical role in wave propagation, energy transfer, and internal wave and mixing processes. Traditional linear models have limitations in explaining many phenomena in oceanic wave and mixing processes, such as wave breaking, nonlinear energy transfer, and the complex propagation behavior of internal waves. By analyzing wave-current interactions, the generation and propagation of internal waves, and turbulence-induced nonlinear mixing, this study aims to deepen the understanding of these complex phenomena and explore their impacts on climate prediction and marine ecosystems. The study seeks to provide a theoretical basis for further revealing key processes in oceanic environmental changes.

Keywords Nonlinear processes; Ocean dynamics; Wave propagation; Internal waves; Turbulent mixing

1 Introduction

Oceanic waves and mixing processes are fundamental components of ocean dynamics, influencing the distribution of heat, nutrients, and other properties within the marine environment. Internal waves, which propagate along density interfaces within the ocean, play a crucial role in vertical mixing and energy transfer. These waves are generated by various sources, including tides, winds, and geostrophic currents, and can travel long distances before breaking and dissipating their energy (Whalen et al., 2022). The breaking of internal waves leads to turbulent mixing, which is essential for the vertical transport of water, heat, and other climatically important tracers. Additionally, nonlinear internal waves (NLIWs) have been observed to significantly impact sediment transport and boundary-layer dynamics, further highlighting the complexity of oceanic mixing processes (Zulberti et al., 2020).

Nonlinear mechanisms are critical in understanding the full spectrum of oceanic wave and mixing processes. Traditional linear theories often fall short in explaining the observed energy transfer and mixing rates, especially in regions with complex topography and strong currents (Zemskova and Grisouard, 2021). Nonlinear interactions, such as those between internal waves and topography, can lead to enhanced energy transfer and mixing, which are not adequately captured by linear models. For instance, nonlinear dynamics have been shown to play a significant role in the dissipation of internal waves above rough topography, where linear theory fails to account for the observed energy distribution and mixing rates(Zemskova and Grisouard, 2021). Furthermore, nonlinear processes are essential in the vertical mixing of heat and momentum, particularly in the surface mixed layer and during deep convection events (Woodson, 2018). These processes are crucial for accurately parameterizing mixing in ocean general circulation models, which are used to predict climate and ocean behavior.

This study synthesizes current knowledge about the nonlinear mechanisms that drive ocean waves and mixing processes, which includes examining the generation, propagation, and dissipation of internal waves, as well as their interaction with topography and electric currents. By integrating recent research findings, it aims to highlight the importance of nonlinear dynamics in shaping ocean mixing and energy transfer. In addition, identify gaps in current understanding and propose directions for future research.

2 Fundamental Concepts in Nonlinear Ocean Dynamics

2.1 Nonlinear wave interactions

Nonlinear wave interactions are a critical aspect of ocean dynamics, playing a significant role in the energy cascade from large to small scales, which ultimately leads to ocean turbulence and mixing. These interactions can be categorized into weakly and strongly nonlinear processes. Weakly nonlinear interactions, such as those described by resonant and near-resonant internal wave triads, are essential for understanding energy transfer in non-uniform stratifications and varying bathymetry (Gururaj and Guha, 2021). These interactions are governed by wave amplitude equations that account for the spatial and temporal variations in wave properties.

In the context of internal gravity waves, nonlinear interactions are a principal part of the dynamics, contributing to the overall energy cascade. Various approaches, including the evaluation of transfer integrals, turbulence theories, and numerical simulations, have been employed to study these interactions. However, each method has its limitations, particularly in handling high-wave number, high-frequency waves and interactions with vortical modes (Whalen et al., 2020).

Nonlinear wave interactions also play a significant role in equatorial wave-current dynamics, where the Hamiltonian formulation of the governing equations reveals differences between short- and long-wave regimes. In particular, weakly nonlinear long-wave regimes can capture wave-breaking phenomena, which are crucial for understanding the energy distribution in the ocean (Constantin and Ivanov, 2019).

2.2 Basics of oceanic mixing mechanisms

Oceanic mixing mechanisms are fundamental to the transport of heat, momentum, and other climatically important tracers within the ocean. Turbulent mixing driven by breaking internal waves is a key process that influences vertical transport and shapes the circulation and distribution of heat and carbon in the climate system (Whalen et al., 2020). The life cycle of internal waves, including their generation, propagation, and breaking into turbulence, is complex and varies spatially and temporally.

Nonlinear vertical mixing processes are particularly important in the surface mixed layer and during deep convection. Large-eddy simulation (LES) models have been used to study these processes, revealing the roles of Langmuir circulation, organized circulations, and shear instability in the mixed layer. These studies help develop more effective parameterizations for ocean general circulation models.

Additionally, the effects of vertical mixing on nonlinear Kelvin waves highlight the importance of submesoscale processes along coastal boundaries. These processes, characterized by strong turbulent mixing and nonlinearity, significantly modify the flow and contribute to the dissipation of mesoscale kinetic energy (Crowe and Johnson, 2020). Observations of sediment transport by nonlinear internal waves further emphasize the role of bed-stress intensification, turbulent transport, and vertical pumping mechanisms in boundary-layer dynamics (Polzin and Lvov, 2017).

3 Nonlinear wave-current interactions

3.1 Impact of currents on wave propagation

Currents significantly influence the propagation of oceanic waves, including internal waves and surface waves. The interaction between currents and waves can modify wave characteristics such as amplitude, wavelength, and direction. For instance, internal waves generated by tides, winds, and geostrophic currents can be altered by background currents, which affect their propagation and energy distribution (Whalen et al., 2020). Additionally, submesoscale currents, which are intermediate-scale flow structures, play a crucial role in the energy transfer towards microscale dissipation and diapycnal mixing, thereby impacting wave propagation (McWilliams, 2016).

3.2 Energy transfer mechanisms

3.2.1 Wave breaking and dissipation

Wave breaking is a critical mechanism for energy dissipation in oceanic waves. It occurs when waves become unstable and break, leading to turbulent mixing and energy loss. This process is particularly important for internal solitary waves (ISWs) breaking over slope-shelf topography, where shear and convective instabilities trigger wave breaking, resulting in significant energy dissipation (He et al., 2023). Moreover, wave breaking is essential for the dissipation of energy input into ocean waves by wind and transferred across the spectrum by nonlinearity (Eeltink et al., 2022). The dissipation of internal waves, especially above rough topography, also contributes to energy loss and mixing in the ocean (Zemskova and Grisouard, 2021).

3.2.2 Resonant interactions and energy cascades

Resonant interactions among oceanic internal waves are a key mechanism for energy transfer within the wave field. These interactions involve the transfer of energy between different wave components, leading to energy cascades across various scales. Analytical evaluations of nonlinear resonant interactions, such as elastic scattering, induced diffusion, and parametric subharmonic-instability mechanisms, reveal their significant role in the energy transfer processes within the internal wave field (Gula et al., 2016). Additionally, nonlinear energy transfers involving infragravity frequencies contribute to the redistribution of energy within the wave spectrum, with energy cascading to higher frequencies where it is eventually dissipated (Bakker et al., 2015).

3.2.3 Wave-current instabilities

Wave-current instabilities arise from the interaction between waves and currents, leading to enhanced mixing and energy dissipation. For example, submesoscale processes along coastal boundaries, characterized by strong turbulent mixing and nonlinearity, can cause wave breaking and modify the flow of baroclinic Kelvin waves (Crowe and Johnson, 2020). Furthermore, the generation of submesoscale flows through topographic interactions with geostrophic currents provides a significant route for energy dissipation, as seen in the context of the Gulf Stream (Gula et al., 2016). These instabilities play a crucial role in the overall energy budget and mixing processes in the ocean.

In summary, the nonlinear interactions between waves and currents, including wave breaking, resonant interactions, and wave-current instabilities, are fundamental mechanisms driving energy transfer and mixing in the ocean. These processes significantly impact the propagation and dissipation of oceanic waves, contributing to the dynamic and complex nature of oceanic wave and mixing processes (Wang, 2024).

4 Nonlinear Internal Waves and Mixing Processes

4.1 Generation and propagation of internal waves

4.1.1 Internal solitary waves

Internal solitary waves (ISWs) are large-amplitude, horizontally propagating waves that play a significant role in ocean dynamics. These waves are often generated by the interaction of barotropic tidal currents with topographic features such as continental shelves, sills, and bottom ridges (Grimshaw, 2016). The generation of ISWs can be modeled using nonlinear evolution equations of the Korteweg-de Vries (KdV) type, which account for the variable coefficients due to changing bottom topography (Grimshaw et al., 2007; Whalen et al., 2020). For instance, in a coastal plain estuary, ISWs evolve from internal lee waves generated at the channel-shoal interface, transforming through nonlinear steepening and dispersion effects (Li and Li, 2023).

4.1.2 Interaction with topography

The interaction of internal waves with topography is a critical factor in their evolution and transformation. When ISWs encounter variable bottom topography, such as underwater obstacles or slopes, they can undergo significant changes. For example, in stratified lakes, the interaction with lake boundaries and bottom features can lead to the formation of secondary waves and wave trains, as well as wave breaking and turbulent mixing (Yi et al., 2021). Numerical simulations have shown that the response of ISWs to topographic features depends on the Froude number and the height of the topographic forcing term, which can result in the generation of undular bores and solitary waves (Grimshaw and Helfrich, 2017).

4.1.3 Nonlinear dispersion effects

Nonlinear dispersion effects are crucial in the propagation and transformation of ISWs. These effects can lead to the splitting of a solitary wave into a sequence of secondary waves, as observed in various scenarios of wave evolution over variable bottom topography (Yuan et al., 2017). The balance between nonlinear steepening and frequency dispersion determines the formation and stability of solitary waves. For instance, the propagation of ISWs over a three-dimensional semicircular shoal can result in wave splitting and the formation of multiple waves of decreasing amplitudes (Zhong and Wang, 2019). Additionally, the vertical structure of ISWs is influenced by nonlinearity, which affects their energy distribution and interaction with background flows (Yi et al., 2021).

4.2 Role in vertical mixing

Internal waves, particularly ISWs, play a significant role in vertical mixing within the ocean. The breaking of internal waves leads to turbulent mixing, which drives the vertical transport of water, heat, and other climatically important tracers. This process is essential for shaping the circulation and distribution of heat and carbon within the climate system (Whalen et al., 2020). The energy pathways from tides, winds, and geostrophic currents to internal wave mixing are complex and involve interactions with topography and other internal waves. These interactions transfer energy to smaller scales, leading to turbulent dissipation and mixing across density classes. The cumulative effects of nonlinearity and dispersion in ISWs contribute to enhanced mixing in the turbulent benthic boundary layer, as observed in stratified lakes and coastal regions (Li and Li, 2023).

5 Turbulence and Nonlinear Mixing in the Ocean

5.1 Nonlinear instabilities leading to turbulence

Nonlinear instabilities play a crucial role in the transition from wave motions to turbulence in the ocean. One significant mechanism is the parametric subharmonic instability, which can amplify disturbances in internal gravity waves, leading to secondary instabilities and eventually to turbulence. This process is characterized by the transfer of wave energy into turbulence energy, which is then dissipated (Onuki et al., 2020). Additionally, the Kelvin-Helmholtz instability, driven by stratified shear flows, is another key process. This instability grows to finite amplitude and transitions to turbulence, with the nature of secondary instabilities being influenced by the Prandtl number (Salehipour et al., 2015). The presence of pre-existing turbulence can also modify the evolution of stratified shear layers, suppressing classical billow structures and affecting the mixing efficiency (Kaminski and Smyth, 2019).

5.2 Turbulent mixing in stratified waters

Turbulent mixing in stratified waters is a complex process influenced by various factors, including the nature of the stratification and the presence of internal waves. In stratified shear flows, the mixing efficiency is affected by the Prandtl number, with higher values leading to enhanced convective instabilities and reduced scale selectivity. The role of overturns is also critical, as the optimal mixing occurs when the Ozmidov length scale is comparable to the Thorpe overturning scale, indicating efficient stirring by large overturns (Mashayek et al., 2017). Experimental observations have shown that internal wave turbulence can transition through different regimes, with the buoyancy Reynolds number marking the transitions between weak wave turbulence and strongly stratified turbulence (Rodda et al., 2022). Furthermore, the interaction of nonlinear internal waves with the bottom boundary layer can lead to asymmetries in turbulence and sediment transport, with onshore pulses being more energetically turbulent and carrying more sediments than offshore pulses (Figure 1) (Becherer et al., 2020). The mixing across stable density interfaces is another important aspect, where significant mixing can occur in anisotropic statically stable regions, often associated with high vertical shear (Couchman et al., 2022).

6 Numerical and Experimental Studies

6.1 Modeling nonlinear oceanic processes

Numerical modeling plays a crucial role in understanding and predicting nonlinear oceanic processes. Recent studies have utilized advanced simulation techniques to explore various aspects of these complex phenomena. For instance, large-eddy simulation (LES) models have been employed to investigate the role of wind and heat-flux forcing in the tropical western Pacific Ocean's surface mixed layer. These studies revealed that mixing is dominated by Langmuir circulation, organized circulations, and shear instability at the mixed-layer base (Dudley et al., 2019). Additionally, numerical experiments using nonhydrostatic and non-Boussinesq regional oceanic circulation models have been conducted to study the nonlinear processes generated by supercritical tidal flow in shallow straits . These simulations highlighted the importance of topography in the formation of internal solitary waves and local breaking events, both of which are significant turbulence-producing phenomena (Bordois et al., 2017).

Furthermore, algorithms for reconstructing and predicting nonlinear ocean wave fields from remote measurements have been developed. These algorithms, which include linear, weakly nonlinear, and highly nonlinear prediction methods, have shown that accurate modeling of wave shape nonlinearities is essential for improving prediction accuracy, particularly under severe wave conditions (Desmars et al., 2023). The implementation of the vortex force formalism in coupled ocean-atmosphere-wave-sediment transport modeling systems has also been shown to enhance the simulation of wave-induced flows and surf zone dynamics, providing better agreement with observed data (Kumar et al., 2012).

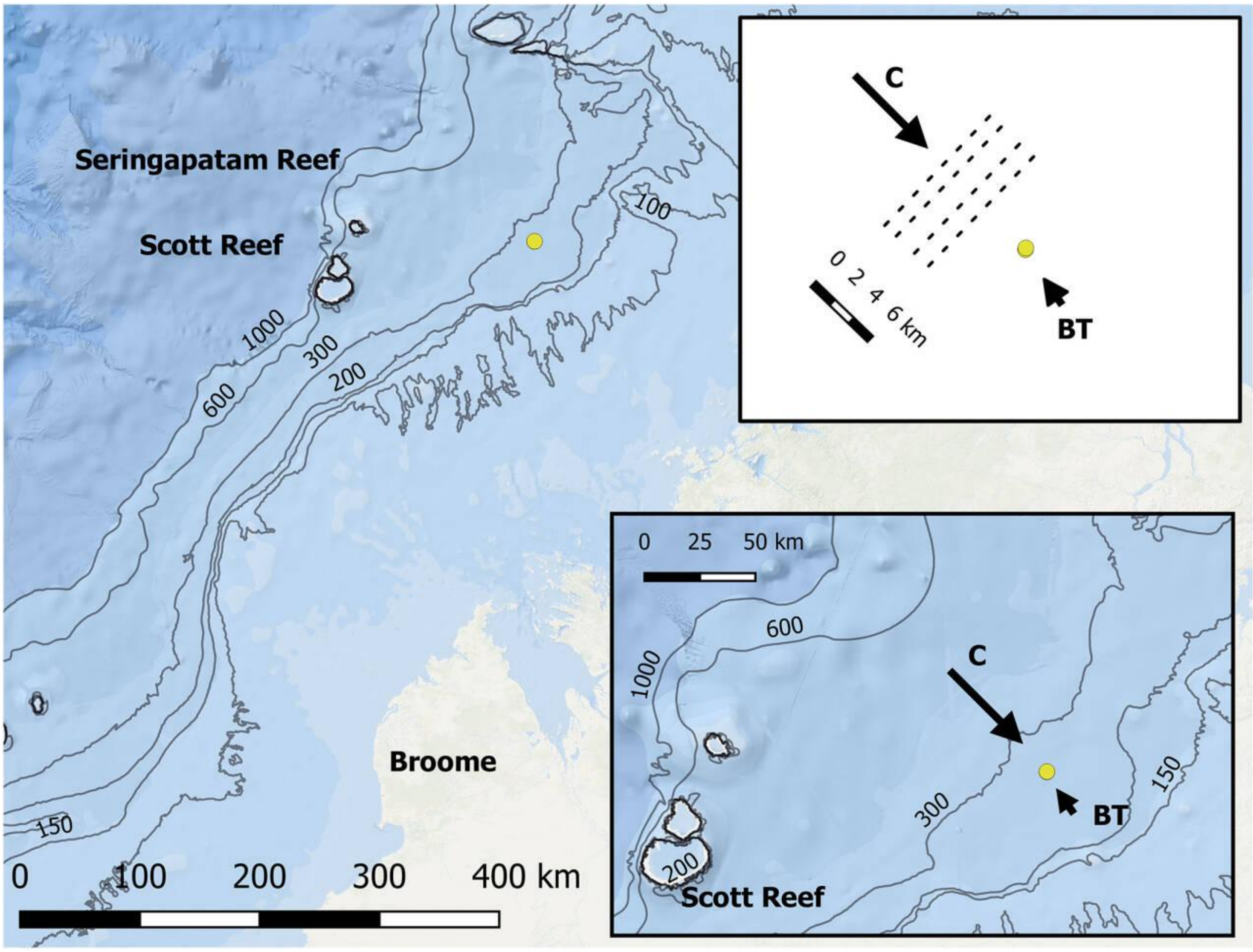

Figure 1 A map of the study site, the illustration depicts the observed wave packets: c represents the direction of wave propagation, while BT represents the local direction of the barometric flow upon arrival. The dotted lines indicate the spacing of the four largest slots in the package, but the exact shape along the crest is unknown (Adopted from Zulberti et al., 2020)

6.2 Laboratory experiments and field observations

Laboratory experiments and field observations are indispensable for validating numerical models and gaining insights into nonlinear oceanic processes. For example, wave tank experiments have been used to study the dynamics of rogue waves, revealing that both linear and nonlinear mechanisms contribute to their formation. These experiments have also demonstrated the applicability of real-time measurement techniques developed for optical systems to oceanographic studies (Dudley et al., 2019). Similarly, laboratory experiments comparing mechanically generated waves in a three-dimensional basin with numerical simulations have shown that numerical models can accurately describe the evolution of weakly nonlinear waves and predict the occurrence of extreme waves (Toffoli et al., 2010).

Field observations have provided valuable data on sediment transport by nonlinear internal waves (NLIWs). Novel measurements of the turbulent benthic boundary layer beneath NLIWs have shown that these waves drive sediment transport through bed-stress intensification, turbulent transport, and vertical pumping mechanisms (Figure 2) (Zulberti et al., 2020). Additionally, observational and numerical modeling methods have been combined to quantify coastal ocean turbulence and mixing, highlighting the importance of integrating both approaches for a comprehensive understanding of these processes.

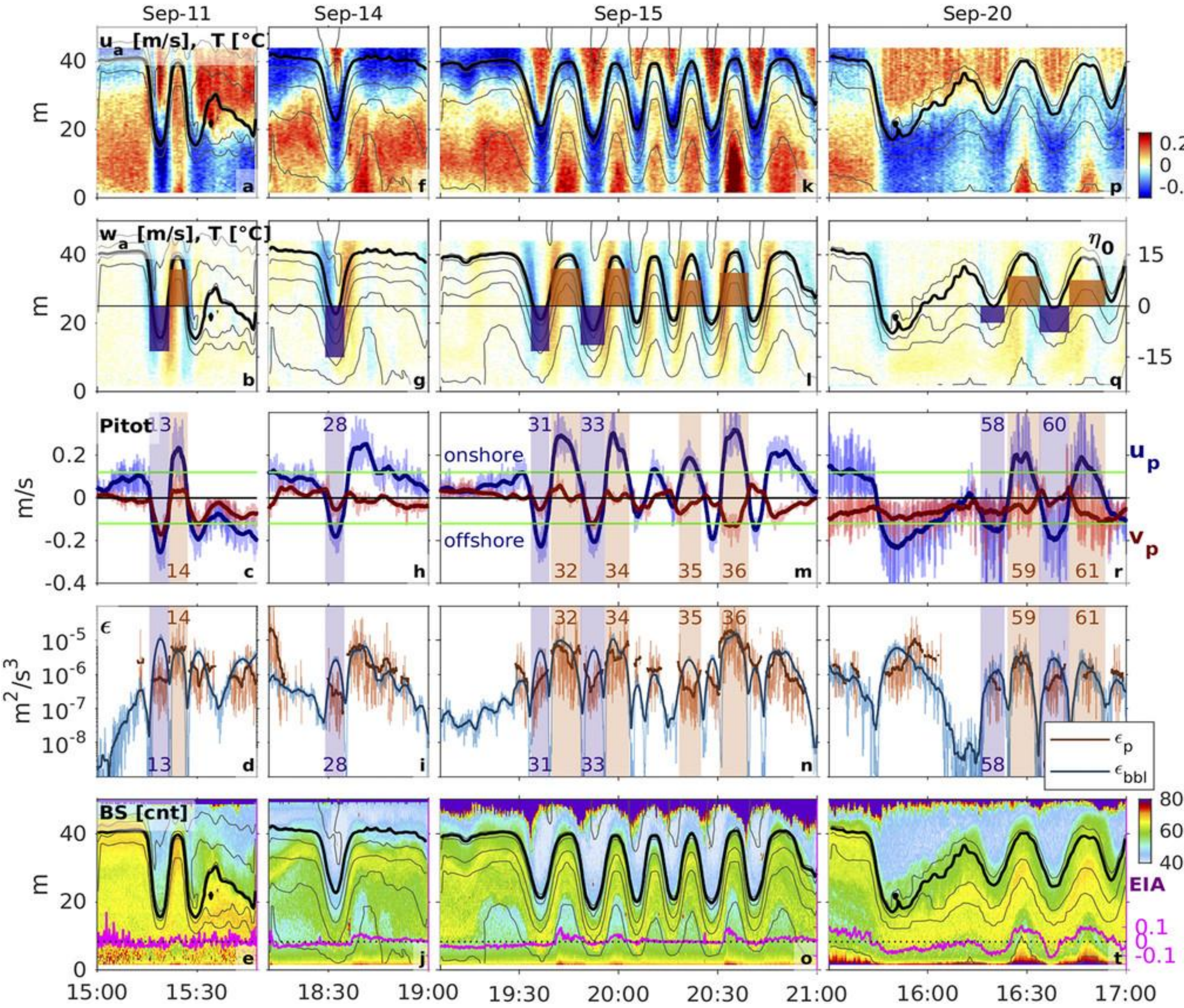

Figure 2 Groups of high-frequency NLIWs (times correspond to green lines inFigure 2) (Adopted from Becherer et al., 2020)

Image caption: (a) Image plot of onshore velocity component u_a and isotherms (gray contours; 12 °C~19 °C). (b) Image plot of vertical velocity component wa and maximum isopycnal displacement of NLIWs $\eta 0$ associated with bottom pulse events (purple: offshore, orange: onshore). (c) Onshore u_p (blue) and alongshore υ_p (red) components derived from pitot-static tube speed measurements (light color 100-Hz sampling rate, dark thick lines 30-s averages). (d) Dissipation rate of TKE from BBL scaling εbbl (blue) and pitot-static tube ε_p (red). (e) Backscatter intensity as measured by the ADCP (color) and EIA (magenta) (Adopted from Becherer et al., 2020)

7 Applications and Implications

7.1 Impacts on climate and weather prediction

The nonlinear mechanisms of oceanic wave and mixing processes have significant implications for climate and weather prediction. Turbulent mixing driven by internal waves plays a crucial role in the vertical transport of water, heat, and other climatically important tracers in the ocean. This process influences the global climate system by affecting the distribution of heat and carbon, which in turn shapes ocean circulation and air-sea interactions. The spatial and temporal variability of internal wave-driven mixing, particularly its generation, propagation, and dissipation, is essential for understanding and predicting climate patterns (Whalen et al., 2010).

Moreover, the North Atlantic Oscillation (NAO) exemplifies how atmospheric and oceanic variability can orchestrate coherent climate variations over large regions, impacting weather patterns and marine ecosystems (Holbrook et al., 2020). The NAO affects ocean heat content, gyre circulations, and mixed layer depth, which are critical for climate variability and prediction. Additionally, incorporating wave-induced processes such as Stokes drift and nonbreaking surface waves into ocean models has been shown to improve simulations of sea surface temperature and mixed layer depth, further enhancing climate prediction capabilities (Fan et al., 2023).

7.2 Implications for marine ecosystems

The implications of nonlinear oceanic wave and mixing processes extend to marine ecosystems, which are highly sensitive to changes in ocean physics and biogeochemistry. Marine heatwaves (MHWs), driven by prolonged periods of anomalously warm water, have devastating impacts on marine ecosystems, including mass coral bleaching and declines in kelp forests and seagrass meadows (Smith et al., 2022). Improved prediction of MHWs, which relies on understanding the physical drivers and monitoring approaches, is crucial for marine conservation and management (Holbrook et al., 2020).

Furthermore, the predictability of key marine ecosystem drivers such as temperature, pH, oxygen, and net primary production is essential for managing marine resources and ecosystems (Frölicher et al., 2020). These drivers are influenced by climate variability and ocean mixing processes, and their predictability varies regionally and with depth. Enhanced observational networks and modeling efforts are needed to support ecosystem forecasting and to develop adaptive management strategies (Capotondi et al., 2019).

8 Concluding Remarks

The study of nonlinear mechanisms in oceanic wave and mixing processes has revealed several critical insights. One of the primary nonlinear mechanisms identified is the formation of rogue waves, which can be attributed to both linear and nonlinear processes. The analogy between wave propagation in hydrodynamics and optics has provided significant insights into the physical mechanisms and dynamical features that underpin the occurrence of rogue waves. Real-time measurement techniques in optics have highlighted the emergence of localized breather structures associated with nonlinear focusing, a scenario confirmed in wave-tank experiments.

Nonlinear wave focusing, driven by modulation instability, is another key mechanism that contributes to the formation of extreme water waves. This process involves the random localization of energy, which can grow significantly due to the interplay between modulation instability properties and the statistical properties of wave groups. Additionally, nonlinear dynamics play a crucial role in the formation and evolution of large wave groups in random seas, where nonlinearity can increase the duration of extreme wave events and modify the structure of wave groups.

Nonlinear vertical mixing processes are also critical in the transport of heat and momentum throughout the ocean. These processes are especially important in the surface mixed layer and in deep convection, where they are dominated by Langmuir circulation, organized circulations, and shear instability. Furthermore, nonlinear internal waves significantly impact sediment transport through mechanisms such as bed-stress intensification, turbulent transport, and vertical pumping.

Future research in ocean dynamics should focus on several key areas to further our understanding of nonlinear mechanisms and their implications. One promising direction is the application of machine learning techniques to forecast and predict ocean rogue waves. These techniques could help identify new areas of physical analogy and overlap between optics and hydrodynamics, potentially leading to improved predictive models.

Another important area of research is the development of inexpensive, short-term predictors of large water waves. By tracking the energy of the wave field over critical length scales, researchers can robustly predict the location of intense waves, circumventing the need for solving complex governing equations. Additionally, further investigation into the nonlinear dynamics of wave groups in random seas could provide deeper insights into the formation and evolution of extreme wave events.

Advancements in numerical modeling and parameterization of nonlinear vertical mixing processes are also crucial. Improved parameterizations of these processes in ocean general circulation models could enhance our understanding of the role of wind and heat-flux forcing in turbulence and the onset and strength of deep oceanic convection. Moreover, research on the nonlinear dynamics of internal waves, particularly in the context of varying stratification and bathymetry, could shed light on the mechanisms driving energy cascades and ocean turbulence.

Researchers need to continue their efforts to understand the effects of nonlinear internal waves on sediment transport and boundary layer processes, and detailed field measurements and advanced modeling techniques are necessary to unravel the complex interactions between internal waves and sediment dynamics, which have implications for large-scale transcontinental shelf transport and coastal management.

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Conflict of Interest Disclosure

The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

References

Bakker A., Herbers T., Smit P., Tissier M., and Ruessink B., 2015, Nonlinear infragravity–wave interactions on a gently sloping laboratory beach, Journal of Physical Oceanography, 45: 589-605.
https://doi.org/10.1175/JPO-D-14-0186.1

Becherer J., Moum J., Colosi J., Lerczak J., and McSweeney J., 2020, Turbulence asymmetries in bottom boundary layer velocity pulses associated with onshore-propagating nonlinear internal waves, Journal of Physical Oceanography, 50(8): 2373-2391.
https://doi.org/10.1175/jpo-d-19-0178.1

Bordois L., Auclair F., Paci A., Dossmann Y., and Nguyen C., 2017, Nonlinear processes generated by supercritical tidal flow in shallow straits, Physics of Fluids, 29: 066603.
https://doi.org/10.1063/1.4986260

Capotondi A., Jacox M., Bowler C., Kavanaugh M., Lehodey P., Barrie D., Brodie S., Chaffron S., Cheng W., Dias D., Eveillard D., Guidi L., Iudicone D., Lovenduski N., Nye J., Ortiz I., Pirhalla D., Buil M., Saba V., Sheridan S., Siedlecki S., Subramanian A., Vargas C., Lorenzo E., Doney S., Hermann A., Joyce T., Merrifield M., Miller A., Not F., and Pesant S., 2019, Observational needs supporting marine ecosystems modeling and forecasting: from the global ocean to regional and coastal systems, Frontiers in Marine Science, 6: 623.
https://doi.org/10.3389/fmars.2019.00623

Constantin A., and Ivanov R., 2019, Equatorial wave–current interactions, Communications in Mathematical Physics 370: 1-48.
https://doi.org/10.1007/s00220-019-03483-8

Couchman M., Kops S., and Caulfield C., 2022, Mixing across stable density interfaces in forced stratified turbulence, Journal of Fluid Mechanics, 961: A20.
https://doi.org/10.1017/jfm.2023.253

Crowe M., and Johnson E., 2020, The effects of vertical mixing on nonlinear Kelvin waves, Journal of Fluid Mechanics, 903: A22.
https://doi.org/10.1017/jfm.2020.654

Desmars N., Hartmann M., Behrendt J., Hoffmann N., and Klein M., 2023, Nonlinear deterministic reconstruction and prediction of remotely measured ocean surface waves, Journal of Fluid Mechanics, 975: A8.
https://doi.org/10.1017/jfm.2023.841

Dudley J., Genty G., Mussot A., Chabchoub A., and Dias F., 2019, Rogue waves and analogies in optics and oceanography, Nature Reviews Physics, 1(11): 675-689.
https://doi.org/10.1038/s42254-019-0100-0

Eeltink D., Branger H., Luneau C., He Y., Chabchoub A., Kasparian J., Bremer T., and Sapsis T., 2022, Nonlinear wave evolution with data-driven breaking, Nature Communications, 13(1): 2343.
https://doi.org/10.1038/s41467-022-30025-z

Fan P., Jin J., Guo R., Li G., and Zhou G., 2023, The effects of wave-induced stokes drift and mixing induced by nonbreaking surface waves on the ocean in a climate system ocean model, Journal of Marine Science and Engineering, 11(10): 1868.
https://doi.org/10.3390/jmse11101868

Frölicher T., Ramseyer L., Raible C., Rodgers K., and Dunne J., 2020, Potential predictability of marine ecosystem drivers, Biogeosciences, 17(7): 2061-2083.
https://doi.org/10.5194/bg-2019-506

Grimshaw R., 2016, Nonlinear wave equations for oceanic internal solitary waves, Studies in Applied Mathematics, 136(2): 214-237.
https://doi.org/10.1111/sapm.12100

Grimshaw R., and Helfrich K., 2017, Internal solitary wave generation by tidal flow over topography, Journal of Fluid Mechanics, 839: 387-407.
https://doi.org/10.1017/jfm.2018.21

Grimshaw R., Pelinovsky E., and Talipova T., 2007, Modelling internal solitary waves in the coastal ocean, Surveys in Geophysics, 28: 273-298.
https://doi.org/10.1007/S10712-007-9020-0

Gula J., Molemaker M., and McWilliams J., 2016, Topographic generation of submesoscale centrifugal instability and energy dissipation, Nature Communications, 7(1): 12811..
https://doi.org/10.1038/ncomms12811

Gururaj S., and Guha A., 2021, Resonant and near-resonant internal wave triads for non-uniform stratifications, Part 2, Vertically bounded domain with mild-slope bathymetry, Journal of Fluid Mechanics, 943: A33.
https://doi.org/10.1017/jfm.2022.431

He X., Chen X., Li Q., Xu T., and Meng J., 2023, Numerical simulations and an updated parameterization of the breaking internal solitary wave over the continental shelf, Journal of Geophysical Research: Oceans, 128(11): e2023JC019975.
https://doi.org/10.1029/2023jc019975

Holbrook N., Gupta A., Oliver E., Hobday A., Benthuysen J., Scannell H., Smale D., and Wernberg T., 2020, Keeping pace with marine heatwaves, Nature Reviews Earth and Environment, 1: 482-49.
https://doi.org/10.1038/s43017-020-0068-4

Kaminski A., and Smyth W., 2019, Stratified shear instability in a field of pre-existing turbulence, Journal of Fluid Mechanics, 862: 639-658.
https://doi.org/10.1017/jfm.2018.973

Kumar N., Voulgaris G., Warner J., and Olabarrieta M., 2012, Implementation of the vortex force formalism in the coupled ocean-atmosphere-wave-sediment transport (COAWST) modeling system for inner shelf and surf zone applications, Ocean Modelling, 47: 65-95.
https://doi.org/10.1016/J.OCEMOD.2012.01.003

Li R., and Li M., 2023, Generation and evolution of internal solitary waves in a coastal plain estuary, Journal of Physical Oceanography, 54(2): 641-652.
https://doi.org/10.1175/jpo-d-23-0151.1

Mashayek A., Caulfield C., and Peltier W., 2017, Role of overturns in optimal mixing in stratified mixing layers, Journal of Fluid Mechanics, 826: 522-552.
https://doi.org/10.1017/jfm.2017.374

McWilliams J., 2016, Submesoscale currents in the ocean, Proceedings, Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences, 472(2189): 1-32.
https://doi.org/10.1098/rspa.2016.0117

Onuki Y., Joubaud S., and Dauxois T., 2020, Simulating turbulent mixing caused by local instability of internal gravity waves, Journal of Fluid Mechanics, 915: A77.
https://doi.org/10.1017/jfm.2021.119

Polzin K., and Lvov Y., 2017, An oceanic ultra-violet catastrophe wave-particle duality and a strongly nonlinear concept for geophysical turbulence, Fluids, 2: 36.
https://doi.org/10.3390/FLUIDS2030036

Rodda C., Savaro C., Davis G., Reneuve J., Augier P., Sommeria J., Valran T., Viboud S., and Mordant N., 2022, Experimental observations of internal wave turbulence transition in a stratified fluid, Physical Review Fluids, 7(9): 094802.
https://doi.org/10.1103/physrevfluids.7.094802

Salehipour H., Peltier W., and Mashayek A., 2015, Turbulent diapycnal mixing in stratified shear flows: the influence of Prandtl number on mixing efficiency and transition at high Reynolds number, Journal of Fluid Mechanics, 773: 178-223.
https://doi.org/10.1017/jfm.2015.225

Smith K., Burrows M., Hobday A., King N., Moore P., Gupta A., Thomsen M., Wernberg T., and Smale D., 2022, Biological impacts of marine heatwaves, Annual Review of Marine Science, 15(1): 119-145.
https://doi.org/10.1146/annurev-marine-032122-121437

Toffoli A., Gramstad O., Trulsen K., Monbaliu J., Bitner-Gregersen E., and Onorato M., 2010, Evolution of weakly nonlinear random directional waves: laboratory experiments and numerical simulations, Journal of Fluid Mechanics, 664: 313-336.
https://doi.org/10.1017/S002211201000385X

Wang L.T., 2024, Advances in monitoring and managing aquatic ecosystem health: integrating technology and policy, International Journal of Aquaculture, 14(2): 101-111.
https://doi.org/10.5376/ija.2024.14.0012

Whalen C., Lavergne C., Garabato A., Klymak J., MacKinnon J., and Sheen K., 2020, Internal wave-driven mixing: governing processes and consequences for climate, Nature Reviews Earth and Environment, 1: 606-621.
https://doi.org/10.1038/s43017-020-0097-z

Woodson C., 2018, The fate and impact of internal waves in nearshore ecosystems, Annual Review of Marine Science, 10: 421-444.
https://doi.org/10.1146/annurev-marine-121916-063619

Yi G., Song H., Zhao Z., Guan Y., and Kuang Y., 2021, On the vertical structure of internal solitary waves in the northeastern South China Sea, Deep Sea Research Part I: Oceanographic Research Papers, 173: 103550.
https://doi.org/10.1016/J.DSR.2021.103550

Yuan C., Grimshaw R., Johnson E., and Chen X., 2017, The propagation of internal solitary waves over variable topography in a horizontally two-dimensional framework, Journal of Physical Oceanography, 48: 283-300.
https://doi.org/10.1175/JPO-D-17-0154.1

Zemskova V., and Grisouard N., 2021, Energetics and mixing of stratified rotating flow over abyssal hills, Journal of Physical Oceanography, 52(6): 1155-1177.
https://doi.org/10.31223/x5xc8m

Zhong Z., and Wang K., 2019, A fully nonlinear and weakly dispersive water wave model for simulating the propagation interaction and transformation of solitary waves, Journal of Hydrodynamics, 31: 1099-1114.
https://doi.org/10.1007/s42241-019-0083-4

Zulberti A., Jones N., and Ivey G., 2020, Observations of enhanced sediment transport by nonlinear internal waves, Geophysical Research Letters, 47(19): e2020GL088499.
https://doi.org/10.1029/2020GL088499

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