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Impact of Ocean Waves on Atmospheric Boundary Layer Dynamics: Mechanisms and Observations

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Abstract Ocean waves can significantly impact the Atmospheric Boundary Layer (ABL) by altering wind speed distribution, momentum transfer, and energy exchange processes near the ocean surface. The stress induced by waves modifies the structure of the ABL, affects the stability of wind profiles, and through the propagation of momentum and turbulence, further influences the overall dynamics of the atmospheric boundary layer. This study systematically analyzes how ocean waves impact ABL dynamics through various mechanisms, validates these theoretical models against actual observational data, and, by integrating the latest observational technologies such as sLiDAR and satellite remote sensing, further explores the regional and seasonal variations in wave-ABL interactions. The study also evaluates how these changes affect climate and weather forecasting. In the context of global climate change, accurately simulating and predicting wind-wave interactions is crucial for climate adaptation and mitigation strategies. This research aims to improve the accuracy of models that simulate extreme weather events and provide scientific evidence for enhancing climate models, optimizing offshore renewable energy utilization, and managing marine resources.

Keywords Atmospheric boundary layer (ABL); Wind-wave interaction; Energy exchange; Turbulence; Climate adaptation

1 Introduction

The interaction between the ocean and the atmosphere is a complex and dynamic process that significantly influences weather patterns, climate systems, and marine ecosystems. These interactions occur primarily through the exchange of momentum, heat, and moisture across the ocean surface, which is mediated by various physical processes such as wind stress, wave dynamics, and buoyancy fluxes. The presence of oceanic features like eddies, internal waves, and surface waves further complicates these interactions by introducing heterogeneity in surface roughness and temperature, which in turn affects atmospheric boundary layer (ABL) dynamics (Song et al., 2015; Ortiz-Suslow et al., 2019; Sullivan and McWilliams, 2022).

The ABL is the lowest part of the atmosphere and is directly influenced by its contact with the Earth's surface. It plays a crucial role in the transfer of energy, momentum, and mass between the surface and the free atmosphere. Understanding the dynamics of the ABL is essential for accurate weather forecasting, climate modeling, and the study of air-sea interactions. The ABL's structure and behavior are influenced by various factors, including surface roughness, thermal stratification, and turbulence, which are often modulated by oceanic processes such as surface waves and submesoscale eddies (Sun et al., 2015; Shrestha amd Anderson, 2019; Lemarié et al., 2020).

This study synthesizes the current knowledge on the effects of ocean waves on ABL dynamics, focusing on the mechanisms by which ocean waves affect the ABL and the observational evidence supporting these interactions. The theoretical framework and models of wave-ABL interactions, including modifications to the Ekman theory and the role of wave-induced stresses, are analyzed. Observational studies and numerical simulations that quantify the effects of ocean waves on ABL wind profiles, turbulence, and secondary circulation are discussed, and the impact of these interactions on weather forecasts, climate models, and marine environmental studies are emphasized. By providing a comprehensive overview of the mechanisms and observations associated with wave-atmosphere boundary layer interactions, this study aims to improve our understanding of the coupled ocean-atmosphere system and provide a scientific basis for future research and modeling work in this area.

2 Overview of Ocean Waves and Atmospheric Boundary Layer Dynamics

2.1 Characteristics of ocean waves

Ocean waves are surface waves generated primarily by wind forces acting on the sea surface. These waves can vary significantly in their characteristics, including wavelength, frequency, and amplitude. Infragravity waves, for instance, are a type of ocean wave with frequencies below those of wind-generated short waves, typically below 0.04 Hz. These waves are generated by mechanisms such as the modulation of wave breaking locations and the merging of bores within the surf zone (Bertin et al., 2018). Near-inertial waves (NIWs) are another type of ocean wave that appear nearly everywhere in the ocean, generated by wind, nonlinear interactions, and other mechanisms. NIWs can propagate over long distances and contribute to turbulent mixing due to their high shear (Alford et al., 2016).

2.2 Structure and dynamics of the atmospheric boundary layer

The Atmospheric Boundary Layer (ABL) is the lowest part of the atmosphere, directly influenced by its contact with the Earth's surface. The structure and dynamics of the ABL are complex and can be significantly affected by surface conditions, including the presence of ocean waves. The ABL is characterized by turbulent flows, which are influenced by factors such as surface roughness and thermal stratification. In stable conditions, the ABL can exhibit intermittent turbulence and wave-like motions, which are challenging to model accurately (Sun et al., 2015). The Marine Atmospheric Boundary Layer (MABL) is a specific type of ABL influenced by the ocean surface, where interactions between wind and waves can lead to deviations from the Monin-Obukhov similarity theory, especially under swell conditions (Liu et al., 2022).

2.3 Interaction between ocean waves and ABL

The interaction between ocean waves and the ABL is a critical area of study, as it influences weather patterns, climate models, and marine operations. Ocean waves can alter the surface roughness, affecting wind velocity and stress variance in the ABL. For example, the presence of nonlinear internal ocean waves can drive wind velocity and stress variance, setting up localized shear that enhances air-sea momentum flux (Ortiz-Suslow et al., 2019). Coupled ocean-wave-atmosphere models have shown that wave-induced processes, such as wave breaking and Stokes drift, significantly influence coastal areas by enhancing upper ocean mixing and reducing sea surface temperatures (Wu et al., 2019). These interactions are essential for understanding and predicting the dynamics of the ABL over the ocean, as they can lead to complex feedback mechanisms that affect both atmospheric and oceanic processes.

3 Mechanisms of Interaction

3.1 Wave-induced stress on the ABL

3.1.1 Momentum transfer mechanisms

The interaction between ocean waves and the atmospheric boundary layer (ABL) involves complex momentum transfer mechanisms. Surface waves introduce a wave-induced component to the total stress, which significantly alters the momentum flux between the ocean and the atmosphere. This wave-induced stress is influenced by factors such as wave growth, decay rates, and the directional wave spectrum (Song et al., 2015). The presence of internal ocean waves can also drive wind velocity and stress variance, enhancing the air-sea momentum flux over wave packets (Ortiz-Suslow et al., 2019). Langmuir circulations, which are wind-induced shear and surface wave interactions, contribute to the modulation of bathymetric stress and turbulence in coastal zones.

3.1.2 Impact on wind profiles

Surface waves have a considerable impact on the near-surface mean wind profile and the turbulence structure of the marine ABL. The wave-modified Ekman model demonstrates that surface waves can qualitatively change the structure of the ABL, affecting wind profiles significantly. Observations and simulations show that the mean wind profile and wave-induced stress components are enhanced at the height of wave crests, indicating the influence of intermittent airflow separation events (Husain et al., 2019). The presence of ocean spray, particularly at high wind speeds, can modify the wind profiles by increasing turbulent stress in the sea-spray generation layer.

3.1.3 Influence on surface layer stability

The stability of the surface layer is influenced by the interaction between surface waves and the ABL. The heterogeneity in surface roughness caused by internal ocean waves can set up localized shear, enhancing the air-sea momentum flux and affecting the stability of the surface layer. The presence of submesoscale processes, such as oceanic eddies, can induce surface stress anomalies that impact the stability and secondary circulations within the ABL (Sullivan and McWilliams, 2022). The wave boundary layer (WBL) height, determined by the decay rate of wave-induced flux, also plays a role in defining the stability of the surface layer (Cifuentes-Lorenzen et al., 2018).

3.2 Energy exchange processes

Energy exchange between the ocean and the atmosphere is a critical aspect of their interaction. The wave-induced momentum flux and the energy extracted from the WBL are closely related, with the decay rate of wave-induced flux being a key parameter. The turbulent kinetic energy (TKE) dissipation in the ocean surface boundary layer (OSBL) is dominated by surface processes, such as wind and waves, which contribute significantly to the energy exchange (Buckingham et al., 2019). The OSBL response to abruptly turning winds involves stages of TKE production and dissipation, highlighting the dynamic nature of energy exchange processes (Wang and Kukulka, 2021).

3.3 Wave breaking and turbulence generation

Wave breaking is a significant source of turbulence generation in the ABL. The interaction of wind and waves, particularly under high wind conditions, leads to enhanced turbulent stress and mean wind shear at wave crests. Langmuir turbulence, driven by wind-induced shear and surface waves, manifests as Langmuir cells, which have implications for coastal mixing and turbulence generation. The presence of surface waves and ocean spray also contributes to the generation of turbulence, with ocean spray playing a more dominant role at high wind speeds (Zhang and Song, 2018; Husain et al., 2019; Shrestha and Anderson, 2019). The phase-locked variations in wave and turbulent stresses observed in laboratory experiments further illustrate the complex nature of turbulence generation over wind-generated surface waves (Yousefi et al., 2020).

4 Observational Techniques and Measurements

4.1 In situ observations

4.1.1 Buoy and sensor deployments

Buoy and sensor deployments are critical for capturing real-time, continuous, and long-term marine data. Recent advancements have led to the development of low-cost, multi-parameter, miniature wave buoys capable of forming observation arrays. These buoys can measure sea surface parameters such as wind, waves, and currents with high spatial and temporal resolution, significantly enhancing the accuracy of ocean monitoring (Figure 1) (Zhong et al., 2022). Networks of free-drifting satellite-connected surface weather buoys have been deployed to provide extensive coverage and improve model forecast accuracy, demonstrating a 27% reduction in root-mean-square error in significant wave heights (Smit et al., 2021).

Laboratory tank tests revealed that these buoys can accurately measure water surface slopes and exhibit good frequency response capabilities compared to traditional wave instruments. In practical applications, these buoys can be deployed in offshore waters for long-term continuous monitoring, effectively improving the spatial coverage of ocean observations. Specifically, the study also analyzed the relationship between wind speed and the low-pass filtered mean square slope (LPMSS) and explored the impact of wave growth stages on LPMSS. The results indicate that by using these micro wave buoys, effective estimation of wind speed and direction can be achieved under varying conditions of wind speed and wave period.

4.1.2 Ship-based measurements

Ship-based measurements play a vital role in atmospheric, oceanic, and biogeochemical observations. Ships, including research vessels, merchant ships, and automated surface vessels, are equipped with various sensors to measure essential climate and ocean variables. These measurements are crucial for understanding and forecasting exchanges across the ocean-atmosphere interface. The integration of private and autonomous vessels into the observing system, along with advancements in sensor technology and data management, is recommended to enhance the quality and scope of ship-based observations (Smith et al., 2019). The use of ship-launched unmanned aerial vehicles (UAVs) has extended the capabilities of research fleets, allowing for detailed characterization of the marine atmospheric boundary layer and ocean surface processes (Reineman et al., 2016).

4.1.3 Field campaigns and long-term monitoring

Field campaigns and long-term monitoring efforts are essential for capturing comprehensive data on ocean-atmosphere interactions. For instance, the Atlantic Tradewind Ocean-Atmosphere Mesoscale Interaction Campaign (ATOMIC) utilized the NOAA P-3 aircraft to obtain extensive observations over the Atlantic Ocean. These observations included high-altitude circles with dropsonde deployment, slow descents and ascents for water vapor distribution, and remote sensing instruments for cloud and ocean surface measurements (Pincus et al., 2021). Long-term projects like the Biogeochemical-Argo (BGC-Argo) project are building global networks of autonomous floats equipped with biogeochemical sensors to monitor marine processes and ecosystem dynamics (Chai et al., 2020).

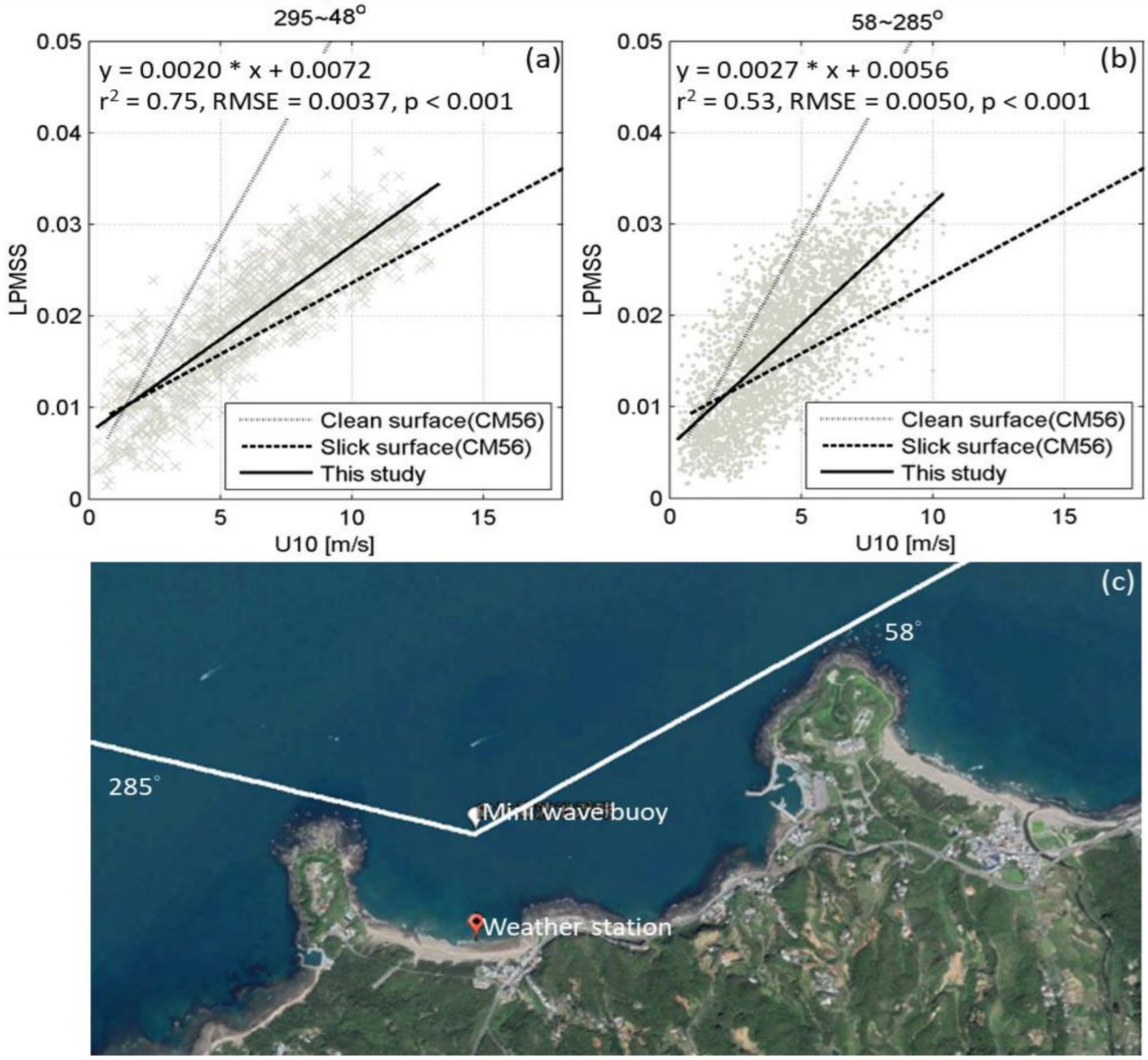

Figure 1 Relationship between U10 and LPMSS measured by the miniature buoy (Adopted from Zhong et al., 2022)

Image caption: (a) Onshore and (b) offshore wind conditions. (c) Criteria for distinguishing whether wind conditions are influenced by coastal topography (Adopted from Zhong et al., 2022)

4.2 Remote sensing methods

Remote sensing methods are indispensable for observing ocean waves and atmospheric boundary layer dynamics. Techniques such as satellite observation, coastal radars, and scanning LiDAR systems provide valuable data on sea surface conditions and wind-wave interactions. For example, scanning LiDAR deployed onshore can capture wave-induced disturbances in the lower marine atmospheric boundary layer, offering new perspectives for studying micro-scale wind-wave interactions (Paskin et al., 2022). Satellite observations complement in situ measurements by providing large-scale data on ocean surface parameters, which are crucial for model validation and improving forecast accuracy (Rossi et al., 2021).

4.3 Data integration and analysis

The integration and analysis of data from various observational techniques are crucial for enhancing our understanding of ocean-atmosphere interactions. Combining in situ observations with remote sensing data allows for comprehensive monitoring and improved model simulations. For instance, the assimilation of wave buoy observations into models has shown significant improvements in forecast accuracy (Smit et al., 2021). The development of integrated data management systems and high-throughput communications is essential for efficient data handling and dissemination, ensuring that observational data benefits a wide range of users (Centurioni et al., 2019). Enhanced observational networks and data integration efforts are necessary to address the challenges posed by sparse spatial and temporal coverage, particularly in remote regions like the Southern Ocean (Swart et al., 2019).

5 Case Studies and Regional Variations

5.1 Impact of ocean waves on coastal abl dynamics

The interaction between ocean waves and the atmospheric boundary layer (ABL) is particularly pronounced in coastal regions. Studies have shown that the heterogeneity in surface roughness caused by transient, nonlinear internal ocean waves significantly impacts the marine atmospheric surface layer. For instance, the presence of internal waves can drive wind velocity and stress variance, and adjust the wind gradient across individual wave fronts, enhancing the air-sea momentum flux over the internal wave packet (Figure 2) (Ortiz-Suslow et al., 2019). The use of scanning LiDAR (sLiDAR) systems has demonstrated the ability to capture wave-induced disturbances propagating into the lower part of the marine ABL, providing new insights into micro-scale wind-wave interactions in coastal environments (Paskin et al., 2022).

This study quantitatively assessed the impact of nonlinear internal waves on the marine atmospheric boundary layer through field experiments, revealing how internal waves alter sea surface roughness, thereby affecting the dynamic structure of the ocean surface atmosphere. These findings are significant for further understanding fine-scale ocean-atmosphere interactions and the influence of internal waves on the marine environment.

5.2 Influence in open ocean environments

In the open ocean, the dynamics of surface waves also play a crucial role in shaping the ABL. The impact of surface waves on steady near-surface wind profiles has been studied using modified Ekman theory, which incorporates a wave-induced component on the total stress. This approach has shown that surface waves significantly alter the near-surface mean wind profile and the turbulence structure of the marine ABL (Song et al., 2015). Submesoscale processes, although less represented in ocean models, contribute to turbulent kinetic energy (TKE) dissipation in the open-ocean surface boundary layer. Observations and simulations indicate that surface processes dominate TKE dissipation, suggesting that submesoscale processes do not dramatically modify vertical TKE budgets (Buckingham et al., 2019; Lin, 2024).

5.3 Seasonal and climatic variability

The impact of ocean waves on the ABL also exhibits seasonal and climatic variability. Climate projections indicate that changes in atmospheric circulation and wave conditions, driven by natural climate cycles or anthropogenic factors, can significantly affect coastal sea-level changes and wave-induced coastal hydrodynamics. For example, regional wave climate projections for Europe show a general decrease in wave heights and periods in the Atlantic Europe for the late twenty-first century, which is attributed to changes in atmospheric pressure systems (Pérez et al., 2015). The interaction between atmosphere, waves, and ocean can influence the formation and evolution of severe weather phenomena, such as Mediterranean tropical-like cyclones (medicanes). Coupled simulations have revealed that waves can attenuate cyclones by enhancing sea surface temperature (SST) cooling through mechanisms like Ekman pumping and vertical mixing (Varlas et al., 2020).

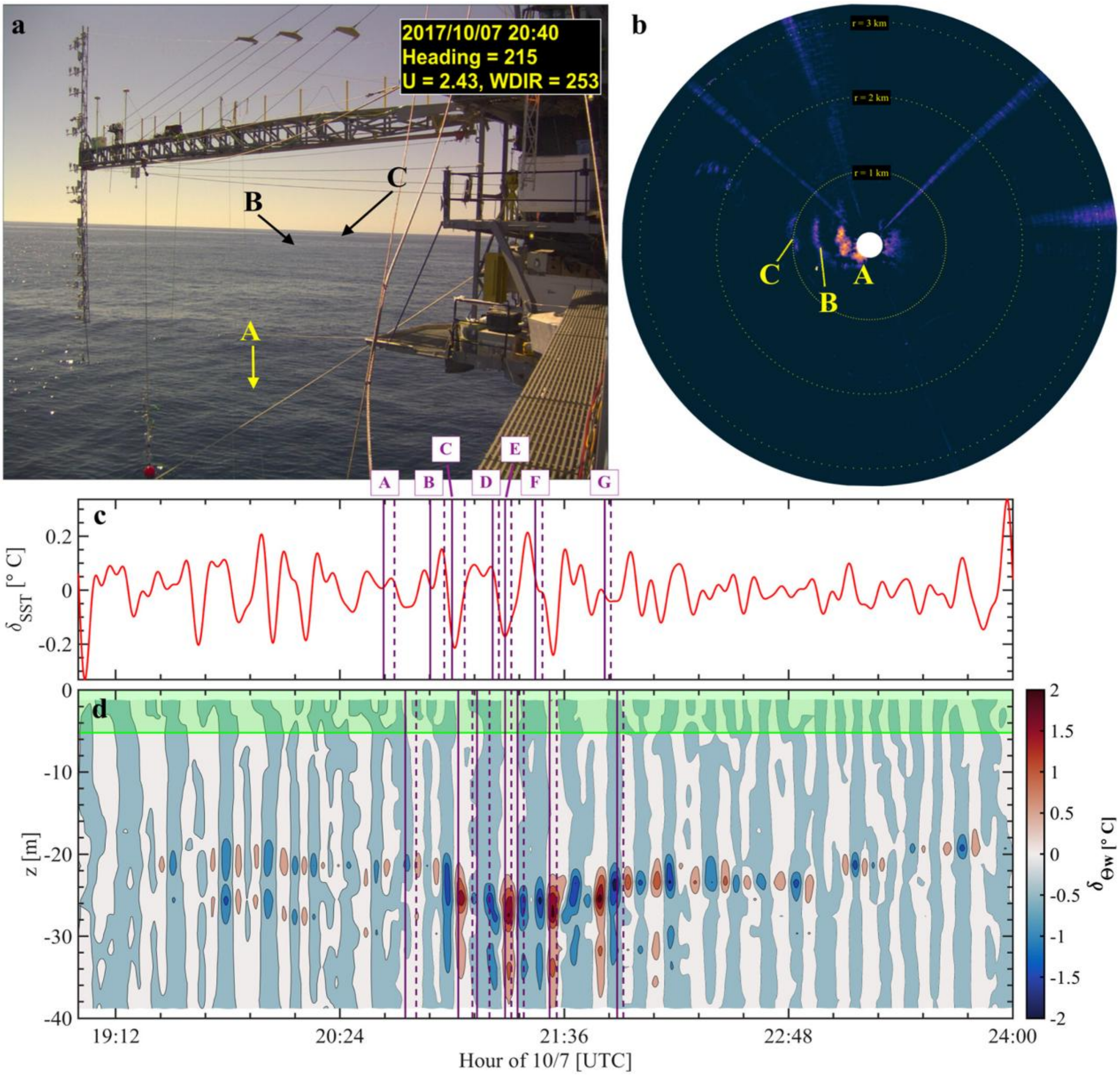

Figure 2 Interaction between nonlinear internal waves and the marine atmospheric boundary layer (Adopted from Ortiz-Suslow et al., 2019)

Image caption: (a) Image from the FC during case study period, heading refers to the look direction of the FC, while U and WDIR refer to mean wind speed and direction (clock-wise from north), respectively, as observed from 3 m above the surface; (b) normalized backscatter intensity map from the WAMOS; (c) and (d) show the ocean skin and water temperature anomalies, respectively, from the surface to a depth of 40 m. The identified nonlinear internal wave-associated bands (A–G) are noted in (c) and (d), with select fronts marked in (a) and (b) (Adopted from Ortiz-Suslow et al., 2019)

The impact of ocean waves on the ABL varies significantly across different regions and under different climatic conditions. Coastal areas experience pronounced effects due to internal waves and micro-scale interactions, while open ocean environments are influenced by surface and submesoscale processes. Seasonal and climatic changes further modulate these interactions, highlighting the complex and dynamic nature of air-sea interactions.

6 Theoretical Models and Simulations

6.1 Numerical modeling of wave-ABL interactions

Numerical modeling of wave-atmospheric boundary layer (ABL) interactions is crucial for understanding the complex dynamics at the air-sea interface. A simplified atmospheric boundary layer model, ABL1d, has been developed and integrated into the Nucleus for European Modelling of the Ocean (NEMO) to improve the representation of air-sea interactions in oceanic models. This model aims to capture key processes associated with air-sea interactions at mesoscale oceanic scales, showing good agreement with observations and fully coupled ocean-atmosphere models (Lemarié et al., 2020). The Weather Research and Forecasting (WRF) model has been enhanced with a moving bottom boundary condition to simulate realistic meteorological and wave conditions, validating the model with idealized test cases and demonstrating satisfactory agreement with literature results (Zhu et al., 2023).

6.2 Simulation of turbulence and energy fluxes

Turbulence and energy fluxes in the ocean surface boundary layer (OSBL) are significantly influenced by surface and submesoscale processes. Observations and simulations indicate that surface processes, such as winds and waves, dominate turbulent kinetic energy (TKE) dissipation, while submesoscale processes play a lesser role (Buckingham et al., 2019). Large-eddy simulations (LES) coupled with Lagrangian stochastic models have been used to explore wave-driven OSBL turbulence, capturing Langmuir turbulence and breaking wave effects, which enhance near-surface dispersion and turbulent diffusivities (Kukulka and Veron, 2019). Wave-turbulence interactions have been shown to enhance vertical mixing in the ocean, which is critical for general ocean circulation models and climate studies (Qiao et al., 2016).

6.3 Validation of models with observational data

Validation of theoretical models with observational data is essential to ensure their accuracy and reliability. The ABL1d model integrated into NEMO has been tested against several boundary-layer regimes and evaluated using standard metrics, showing very good agreement with observations (Lemarié et al., 2020). Similarly, the WRF model with moving bottom boundary conditions has been validated with idealized test cases, demonstrating accurate simulation of turbulent flows over moving waves (Zhu et al., 2023). Observations from moorings in the North Atlantic have been used to quantify the contributions of surface and submesoscale processes to TKE dissipation, supporting the dominance of surface processes in turbulent exchanges. Comparisons between theoretical predictions and observations from a tower on Östergarnsholm Island in the Baltic Sea have demonstrated the significant impact of surface waves on near-surface wind profiles and turbulence structure (Song et al., 2015).

7 Challenges and Future Research Directions

7.1 Limitations in current observational techniques

Current observational techniques face significant limitations in accurately capturing the complex interactions within the atmospheric boundary layer (ABL) over the ocean. For instance, the challenging conditions in the Southern Ocean have led to sparse spatial and temporal coverage of observations, increasing uncertainty in atmosphere and ocean dynamics (Swart et al., 2019). Similarly, the lack of high-resolution observations in the rotor-swept area of offshore wind turbines constrains the validation of numerical models, which is crucial for understanding the physics of atmospheric flow within and around wind plants (Shaw et al., 2022). While scanning LiDAR systems have shown promise in measuring micro-scale wind-wave interactions, their application is still limited to specific conditions, such as old-sea states where waves travel significantly faster than the mean wind 3.

7.2 Improving model accuracy

Improving the accuracy of models that simulate the ABL dynamics over the ocean requires addressing several key challenges. One major issue is the need for better subgrid-scale parameterizations within highly non-linear models, as current computing capabilities cannot resolve all relevant spatial and temporal scales simultaneously. The implementation of moving wave boundary conditions in models like the Weather Research and Forecasting (WRF) model has shown potential in simulating realistic meteorological and wave conditions, but further validation and refinement are necessary (Zhu et al., 2023). The coupling of ocean, wave, and atmospheric models has been shown to reduce biases in sea surface temperature predictions, highlighting the importance of dynamic feedbacks between these systems (Lewis et al., 2019). Enhanced parameterizations of momentum fluxes within the wave boundary layer, as proposed in recent studies, could also improve the accuracy of cyclone and typhoon wave predictions.

7.3 Emerging areas of research

Several emerging areas of research hold promise for advancing our understanding of ocean wave impacts on ABL dynamics. The study of submesoscale processes, which occur at small scales and are not yet represented in most ocean models, is one such area. These processes have been shown to contribute significantly to turbulent kinetic energy dissipation in the open-ocean surface boundary layer, although their overall impact on vertical TKE budgets remains to be fully understood. Another promising area is the use of advanced measurement techniques developed for studying rogue waves in optics, which could provide new insights into the formation and prediction of oceanic rogue waves (Dudley et al., 2019). The development of robust and miniaturized sensors for autonomous platforms could significantly enhance the spatial and temporal coverage of observations, particularly in remote and challenging environments like the Southern Ocean (Swart et al., 2019). By addressing these challenges and exploring these emerging research areas, we can improve our understanding of the complex interactions within the ABL over the ocean, leading to more accurate weather and climate forecasts and better engineering solutions for exploiting offshore renewable energies.

8 Concluding Remarks

The impact of ocean waves on atmospheric boundary layer (ABL) dynamics has been extensively studied, revealing several key mechanisms and observations. Research using scanning LiDAR (sLiDAR) has shown that ocean waves can significantly affect the lower marine atmospheric boundary layer by inducing disturbances that propagate into the atmosphere, particularly in old wave conditions where the wave propagation speed is faster than the wind speed. Coupled atmosphere-wave-ocean models indicate that ocean waves can enhance sea surface temperature (SST) cooling through mechanisms such as Ekman pumping and vertical mixing, thereby weakening cyclones and reducing atmospheric energy. The implementation of moving wave boundary conditions in models like WRF has improved the simulation capability of real wind-wave coupling, validating the impact of waves on atmospheric stress and wind parameters. Lagrangian analysis and field experiments have emphasized the role of wave-driven turbulence in the ocean surface boundary layer (OSBL), demonstrating that breaking waves and Langmuir turbulence significantly enhance near-surface turbulence and mixing. The sensitivity of weather forecasting to atmosphere-ocean-wave coupling has been confirmed, with coupled models showing higher accuracy in predicting wind speeds and sea surface temperatures, especially in nearshore regions.

These findings have profound implications for climate and weather forecasting. Incorporating wave dynamics into atmospheric models can improve the accuracy of weather forecasts, particularly for extreme weather events such as cyclones and mid-latitude storms. This is crucial for early warning systems and disaster preparedness. Understanding wave-induced turbulence and mixing helps improve climate models, leading to better predictions of sea surface temperatures and ocean-atmosphere heat exchanges, which are critical for long-term climate forecasting. Accurate simulation of wind-wave interactions is vital for optimizing offshore renewable energy facilities and managing marine resources, as it influences wind energy potential and wave energy extraction.

To further deepen the understanding of the impact of ocean waves on ABL dynamics, future research should focus on several key areas. Deploying more high-resolution observation tools, such as sLiDAR and moored buoys, to capture detailed wind-wave interactions and turbulence under various oceanic conditions. Continuing to develop and refine coupled atmosphere-ocean-wave models to improve their accuracy and applicability across different climatic and geographic environments, including the integration of sub-mesoscale processes and validation with field data. Establishing long-term monitoring programs to study the seasonal and interannual variations of wave impacts on the atmospheric boundary layer, which will help in understanding broader climate impacts. Promoting interdisciplinary research that combines meteorology, oceanography, and climate science to develop comprehensive models capable of simulating the complex interactions between the ocean and atmosphere. By addressing these challenges, future research can significantly enhance our ability to predict and mitigate the impacts of ocean waves on weather and climate systems.

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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.

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