Progress Report

Meeting 1 | **Date:** 11 December, 2025

PhD Topic: The Implication of Surface Waves on Air-sea Interactions and Associated Coastal Upwelling System
PhD candidate: Muxin Hu
Panel Members: Prof. Dr. Jin-Song von Storch (Panel Chair), Dr. Nils Brüggemann (Primary supervisor), Dr. Noel Gutierrez-Brizuela (Co-supervisor), Dr. Christopher Higgins

1. Thesis synopsis

Surface waves play a fundamental role in mediating air-sea exchanges of momentum, heat, and turbulent energy, and their influence is expected to be particularly important in wind-driven coastal upwelling systems (Wu et al., 2019b, 2022). Coastal upwelling results from wind-driven horizontal divergence that causes cold, nutrient-rich subsurface water to rise to the surface. Its intensity and structure are therefore primarily controlled by the along-shore wind stress and the associated offshore Ekman transport that induces this divergence (Belmadani et al., 2014; Tarazona and Arntz, 2001). Any process modifying the magnitude or direction of stress at the air-sea interface thus has the potential to substantially affect coastal upwelling dynamics. Surface waves may contribute to this modulation through multiple wave-induced effects, including wave-modified momentum fluxes, Stokes-drift-related processes, wave-induced turbulence kinetic energy (TKE) fluxes, and changes in surface roughness.

Previous studies have demonstrated that surface waves can significantly influence air-sea interactions in coastal regions and associated upwelling systems. For example, based on a wave hindcast generated with WAVEWATCH III forced by Climate Forecast System Reanalysis data, Wu et al. (2022) found that the redistributive effects of waves on momentum and TKE fluxes are significant in several major coastal upwelling regions worldwide. Similarly, using a regional configuration of Nucleus for European Modelling of the Ocean (NEMO) model forced by the WAve Model (WAM), Wu et al. (2019a) showed that the wave-induced momentum and TKE fluxes exert a stronger influence on Baltic coastal upwelling than that from Stokes-Coriolis forcing and Stokes drift on the mass and tracer advection. These results thus indicate that various wave-induced processes can play distinct roles in shaping air-sea fluxes and upwelling dynamics, leading to a complex combined effect.

However, the interpretation of these results is constrained by methodological limitations. In particular, most existing studies employ uncoupled or one-way coupled modelling frameworks, which prevent feedbacks between the atmosphere, wave field, and ocean interior (Wu et al., 2019a,b). As a result, the simulated wave-field is not evolving interactively with the atmospheric and ocean states, thereby limiting the dynamical consistency of the simulated coastal air-sea exchange. In addition, not all relevant wave-induced processes are represented consistently across studies. For example, the Langmuir turbulence, an important contributor to the upper-ocean TKE production (Kantha et al., 2009, 2010), is not always included or is treated in a simplified manner. Consequently, while previous work provides valuable insights into individual wave-induced processes within specific model configurations, it does not yet offer a dynamically consistent assessment of these processes and their combined effects of surface waves on coastal upwelling systems.

To address the limitations identified above, this PhD research aims to investigate wave-induced processes on air-sea interactions in the upwelling system using a fully coupled ocean-wave-atmosphere modelling framework. Specifically, we aim to employ the ICON model, in which

ICON-a (atmosphere), ICON-Wave (Wave), and ICON-o (Ocean) are coupled using a new energetically consistent exchange of momentum and energy. This framework allows surface waves, atmospheric forcing, and oceanic responses to evolve interactively, while enabling a more realistic representation of key wave-induced processes, including the Langmuir turbulence. The Southeast Pacific (Peru-Chile) upwelling system is selected as the focus of this study. Persistent alongshore winds sustain upwelling throughout the year in this region Tarazona and Arntz (2001), making it a representative of the wind-driven eastern boundary upwelling system. In addition, the Southeast Pacific features a complex and highly variable wave climate, largely driven by the coexistence of locally generated higher-frequency wind waves and remotely generated low-frequency swells, both of which can influence air-sea exchanges (Echevarria et al., 2019). Besides, this variability is strongly modulated by large-scale climate modes, including El Niño Southern Oscillation (ENSO) and Pacific-South American (PSA) pattern, which can substantially affect regional wind patterns, thereby influencing wave characteristics (Tarazona and Arntz, 2001; Echevarria et al., 2020). Observational and hindcast studies indicate pronounced wave variability in this region, including increasing trends in high-frequency significant wave height extremes, while future projections suggest further changes in the regional wave climate (Casas-Prat et al., 2024). These characteristics make the Southeast Pacific a sensitive and well-suited test bed for a fundamental, process-based investigation of how surface waves modulate air–sea fluxes and influence coastal upwelling dynamics.
Specifically, this PhD research seeks to address the following research questions:

1. Which wave-induced processes, namely wave-modified momentum fluxes, Stokes-drift related effects (i.e., Langmuir turbulence, the Coriolis-Stokes force, and Stokes drift on mass and tracer advection), and wave-induced changes in surface roughness, play the dominant role in the modulation of air-sea exchanges in the coastal upwelling region in the Southeast Pacific?

2. How do these wave-induced modifications influence the intensity, vertical structure, and temporal variability of Southeast Pacific coastal upwelling?

3. What are the relative contributions of locally generated wind waves and remotely generated swells to air-sea exchanges in the Southeast Pacific upwelling system?

By systematically incorporating and evaluating multiple wave-induced processes within a fully coupled and energetically consistent modelling framework, this research seeks to provide a process-based and quantitative assessment of surface-wave impacts on air-sea interactions in one of the key upwelling systems. The results are expected to improve understanding of the mechanisms linking surface waves, air-sea interactions, and upwelling dynamics, and to help clarify the relative importance of different wave-induced processes in such systems.

2. Brief status report

2.1 Previous Work

The initial phase of the PhD has focused on establishing a solid theoretical and technical foundation to support the planned modelling experiments. The work completed to date can be broadly classified into the following components.

Theoretical and Conceptual Preparation

The theoretical component has primarily involved a review of the literature relevant to the fundamental physics and real-world application (i.e., wave model) of surface waves. This includes:

- Prognostic wave modelling; including model design, governing equations, and key physical parameterisations in other wave model (e.g., WAM, described in (Janssen, 2004))
- Fundamental surface-wave theory and wave-related physical processes:
  - Fundamentals of gravity waves and surface waves;
  - Stokes drift and its representation in numerical models;
  - Wave contributions to the upper-ocean TKE balance;
- Physical mechanisms and dynamical characteristics of coastal upwelling systems;

Technical and Model-related Work

The technical component has focused on gaining familiarity with the ICON model and establishing a reference framework for subsequent analyses. This includes:

- Becoming familiar with the ICON model structure and workflow.
- Learning ICON analysis and post-processing tools, (e.g., `pyICON`, `quickplots`);
- Conducting reference simulations using the ICON-XPP configuration (b5b7, default control setup), which will serve as a baseline for later sensitivity experiments;

2.2 Plans until next AP meeting

Before the next AP meeting, the PhD will aim to address:

- **Short-term milestone 1: Consolidation of Literature review**
  - Complete a focused review of wave-induced processes relevant to air–sea interactions and coastal upwelling systems.
  - Refine the conceptual framework linking surface-wave effects to upwelling dynamics.
- **Short-term milestone 2: Develop analysis workflow on ICON model output**
  - Develop and test analysis scripts based on the control simulation, with a particular focus on diagnostics relevant to coastal upwelling systems.
  - Design strategy and numerical details of ICON fully coupled simulation, with a focus on the sensitivity experiments on isolating individual wave-induced processes.
- **Short-term milestone 3: Conduct and preliminary analysis of fully-coupled ICON simulations**

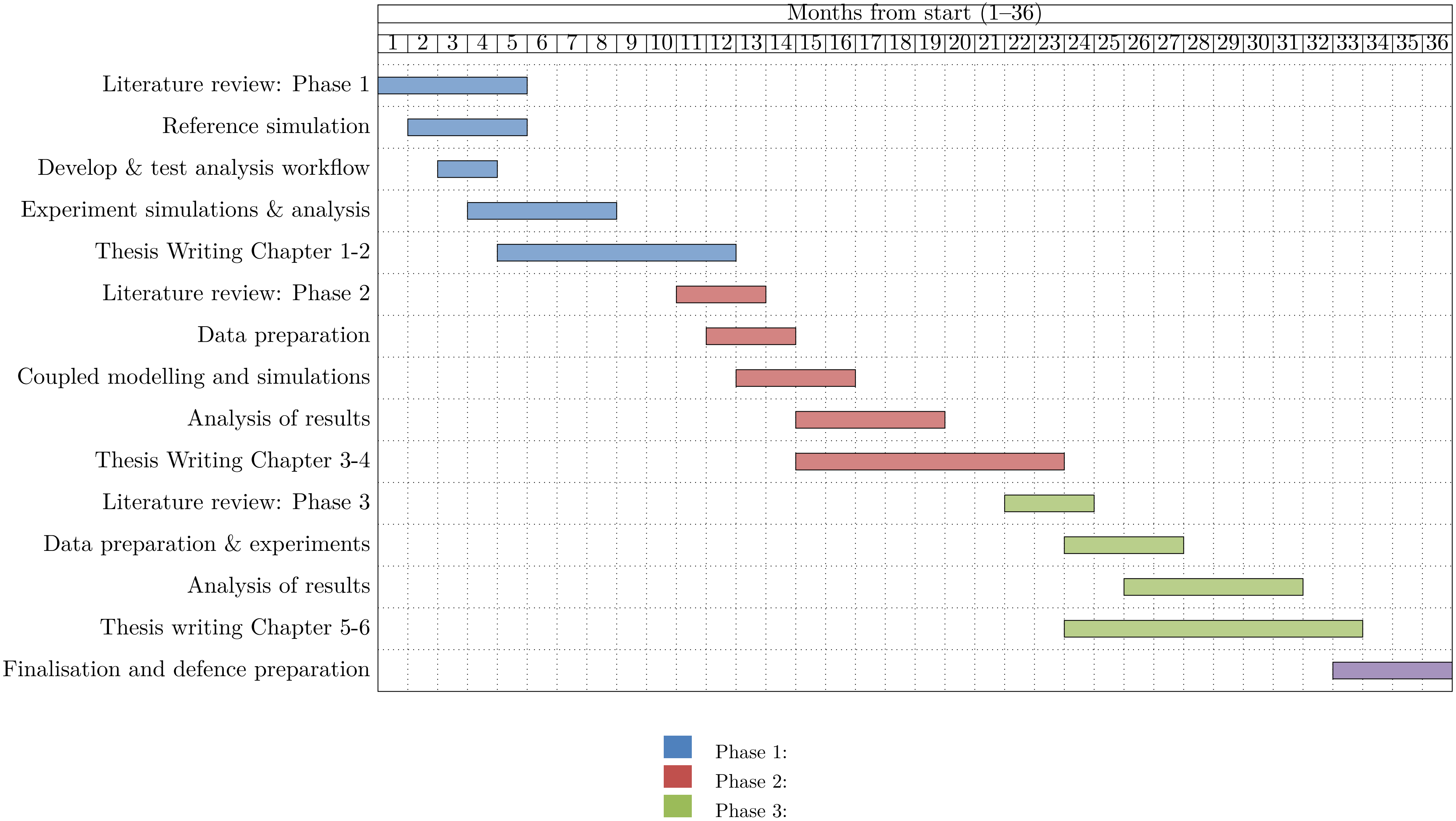
  - Conduct the simulation once the fully-coupled ICON-waves setup is available.
  - Test and refine the analysis workflow

Expected deliverables for the next AP meeting

- A refined experimental design document, including planned coupled and sensitivity simulations. This will eventually be summarized in the draft of the methods section.
- Preliminary diagnostic plots illustrating key upwelling-related processes, and wave-induced modulations on the target coastal upwelling region.

3. Time Schedule

Note:
This timeline only represents a basic and schematic planning for the PhD project! A refined and updated time schedule will be presented at the next AP meeting.



References

Belmadani, A., Echevin, V., Codron, F., Takahashi, K., and Junquas, C. (2014). What dynamics drive future wind scenarios for coastal upwelling off Peru and Chile? *Climate Dynamics*, 43(7):1893–1914.

Casas-Prat, M., Hemer, M. A., Dodet, G., Morim, J., Wang, X. L., Mori, N., Young, I., Erikson, L., Kamranzad, B., Kumar, P., Menéndez, M., and Feng, Y. (2024). Wind-wave climate changes and their impacts. *Nature Reviews Earth & Environment*, 5(1):23–42. Publisher: Nature Publishing Group.

Echevarria, E. R., Hemer, M. A., and Holbrook, N. J. (2019). Seasonal Variability of the Global Spectral Wind Wave Climate. *Journal of Geophysical Research: Oceans*, 124(4):2924–2939.

Echevarria, E. R., Hemer, M. A., Holbrook, N. J., and Marshall, A. G. (2020). Influence of the Pacific-South American Modes on the Global Spectral Wind-Wave Climate. *Journal of Geophysical Research: Oceans*, 125(8):e2020JC016354.

Janssen, P. (2004). *The Interaction of Ocean Waves and Wind*. Cambridge University Press.

Kantha, L., Lass, H. U., and Prandke, H. (2010). A note on Stokes production of turbulence kinetic energy in the oceanic mixed layer: observations in the Baltic Sea. *Ocean Dynamics*, 60(1):171–180.

Kantha, L., Wittmann, P., Sclavo, M., and Carniel, S. (2009). A preliminary estimate of the Stokes dissipation of wave energy in the global ocean. *Geophysical Research Letters*, 36:L02605.

Tarazona, J. and Arntz, W. (2001). The Peruvian Coastal Upwelling System. In Caldwell, M. M., Heldmaier, G., Lange, O. L., Mooney, H. A., Schulze, E.-D., Sommer, U., Seeliger, U., and Kjerfve, B., editors, *Coastal Marine Ecosystems of Latin America*, volume 144, pages 229–244. Springer Berlin Heidelberg, Berlin, Heidelberg. Series Title: Ecological Studies.

Wu, L., Breivik, , and Qiao, F. (2022). The Redistribution of Air–Sea Momentum and Turbulent Kinetic Energy Fluxes by Ocean Surface Gravity Waves. *Journal of Physical Oceanography*, 52(7):1483–1496. Publisher: American Meteorological Society Section: Journal of Physical Oceanography.

Wu, L., Breivik, , and Rutgersson, A. (2019a). Ocean-Wave-Atmosphere Interaction Processes in a Fully Coupled Modeling System. *Journal of Advances in Modeling Earth Systems*, 11(11):3852–3874.

Wu, L., Staneva, J., Breivik, , Rutgersson, A., Nurser, A. J. G., Clementi, E., and Madec, G. (2019b). Wave effects on coastal upwelling and water level. *Ocean Modelling*, 140:101405.