

Udine Workshop CISM

Interaction of Surface Waves and Turbulence in the Upper Ocean

Tuesday, 6. October - Friday, 9. October 2026

Location: CISM (International Center for Mechanical Sciences), Udine, Italy

Organizers: Filippo Coletti (ETH Zurich) and Luc Deike (Princeton University)

<https://exp.ethz.ch/events/CISM-workshop-on-wave-turbulence-interaction.html>

Summary

The transfer of momentum and energy between the atmosphere and the ocean is a crucial subject in atmospheric and oceanic modeling. It involves the coupling of three turbulent systems: the turbulent atmospheric boundary layer (the wind), the multiscale surface waves, and the underwater oceanic boundary layer (the current). The properties of the upper ocean turbulence, especially the vertical profiles of current velocity, Reynolds stresses and dissipation rate of turbulent kinetic energy, are essential to predict air-sea transfer of heat, carbon dioxide and oxygen, and the transport of pollutants such as oil spills and microplastics, and ice debris.

The workshop aims to bring together experts on small scale processes at the ocean-atmosphere, including waves dynamics and turbulence processes, using a wide range of tools, from laboratory experiments, high fidelity numerical simulations, large scale modeling and ocean remote sensing. We aim to foster discussion on the coupled dynamics of surface waves and boundary layer turbulence and discuss how to further improve upper ocean turbulence modeling and interpretation of data from remote sensing and autonomous floats.

Keynote Speakers

Alexander Babanin, University of Melbourne

Michelle DiBenedetto, Princeton University

Baylor Fox-Kemper, Brown University

Lian Shen, University of Minnesota

Chris Zappa, Columbia University

Contacts

fcoletti@ethz.ch

ldeike@princeton.edu

agnes.guentner@ethz.ch

Program

	Tuesday, Oct. 6	Wednesday, Oct. 7	Thursday, Oct. 8	Friday, Oct. 9
08:30		Keynote #2 Baylor Fox-Kemper Brown University	Keynote #4 Lian Shen University of Minnesota	Keynote #5 Alex Babanin University of Melbourne
09:30		Brandon Reichl NOAA	Silvia Matt Naval Research Laboratory	Sophia Brumer French National Center for Scientific Research
10:00		Seth Zippel Oregon State Univ.	Nick Pizzo University of Rhode Island	Wouter Mostert University of Oxford
10:30		Coffee break	Coffee break	Coffee break
11:00		Christine Baker Stanford University	Bruno Deremble Université Grenoble Alpes	Jason Hearst NTNU
11:30		Stephane Perrard ESPCI Paris	Martin Erinin University of Michigan	Alfredo Soldati TU Wien
12:00		Lunch Break	Lunch break	Lunch break
13:30			Simone Di Giorgio Institute of Marine Engineering	Kevin Zhong, University of Twente
14:00	Welcome & Registration	Stephane Popinet Sorbonne Université	Clara Martin Blanco Princeton University	Dan Ruth ETH Zurich
14:30		Yasushi Fujiwara Kobe University	Simen Ellingsen NTNU	Alessandro Iafrati Institute of Marine Engineering
15:00	Keynote #1 Chris Zappa Columbia University	David Richter Univ. of Notre Dame	Detlef Lohse University of Twente	Bertrand Chapron French Institute for Ocean Science
15:30		Coffee break	Coffee break	Closing Remarks
16:00	Leonel Romero Univ. of Connecticut	Zixuan Yang Chinese Academy of Science	Kianoosh Yousefi University of Texas at Dallas	
16:30	Galen Egan Princeton University	Marc Buckley Helmholtz-Zentrum Hereon	Ton van den Bremer TU Delft	
17:00	Yan Li University of Bergen	Keynote #3 Michelle DiBenedetto Princeton University	Luc Deike Princeton University	
17:30	Filippo Coletti ETH Zurich			
19:30	Dinner Casa Della Contadinanza <i>Piazzale del Castello, 33100 Udine</i>	Dinner Trattoria Antica Maddalena <i>Via Pelliccerie 4, 33100 Udine</i>		

Tuesday

14:00 Welcome & Registration

15:00 Keynote **Chris Zappa**, Columbia University
Novel Measurements of the Wind Stress Partition and its Modulation by Breaking Waves

16:00 Regular talk **Leonel Romero**, University of Connecticut
Directional Infrared Observations of Bubble-Entraining Breaking Waves

16:30 Regular talk **Galen Egan**, Princeton University
Surface wave effects on the TKE budget above and below the air-sea interface

17:00 Regular talk **Yan Li**, University of Bergen
Surface waves interacting with subsurface currents

17:30 Regular talk **Filippo Coletti**, ETH Zurich
Turbulence scaling laws under wind-driven waves

19:30 [Dinner at Casa Della Contadinanza, Piazzale del Castello, 33100 Udine](#)

Wednesday

8:30 Keynote **Baylor Fox Kemper**, Brown University
How Well Do We Know the Wave Effect? Langmuir Turbulence Parameterization, Wave-Current Consistency, and Coupled Boundary Layer Energetics

9:30 Regular talk **Brandon Reichl**, NOAA
Multiscale representation of Langmuir turbulence in an ocean model

10:00 Regular talk **Seth Zippel**, Oregon State University
Fourier Modes of Wind Velocity and Pressure over Surface Waves Derived from Field Observations

10:30 [Coffee break](#)

11:00 Regular talk **Christine Baker**, Stanford University
Vorticity generation by finite-depth wave breaking

11:30 Regular talk **Stephane Perrard**, ESPCI Paris
Wave attenuation in the marginal ice zone

12:00-14:00 [Lunch](#)

14:00 Regular talk **Stephane Popinet**, CNRS, Sorbonne Université
Models for the interaction of surface waves and turbulence in the upper ocean

14:30 Regular talk **Yasushi Fujiwara**, Kobe University
Turbulent Airflow over Irregular Surface Waves: DNS and Linear Analysis

15:00 Regular talk **David Richter**, University of Notre Dame
SASCWATCH: A multifaceted campaign for understanding waves, fluxes, and turbulence at the high-wind air-sea interface

15:30 Coffee break

16:00 Regular talk **Zixuan Yang**, Chinese Academy of Sciences
Numerical Investigations of Wind Turbulence over Breaking Waves

16:30 Regular talk **Marc Buckley**, Helmholtz-Zentrum Hereon
Observations of momentum and energy exchange processes between wind and waves

17:00 Keynote **Michelle DiBenedetto**, Princeton University
Diffusion in waves and turbulence: a Lagrangian perspective

19:30 Dinner at Trattoria Antica Maddalena, Via Pellicceria 4, 33100 Udine

Thursday

8:30 Keynote#4 **Lian Shen**, University of Minnesota
Computational and Theoretical Studies of Wind & Upper-Ocean Turbulence Interacting with Surface Waves

9:30 Regular talk **Silvia Matt**, Naval Research Laboratory
Near-surface coherent structures under developing wind waves: laboratory experiment and numerical model

10:00 Regular talk **Nick Pizzo**, University of Rhode Island
How do surface gravity waves organize turbulent currents

10:30 Coffee break

11:00 Regular talk **Bruno Deremble**, Université Grenoble Alpes
Erosion of the Oceanic Mixed Layer under an Active Wave Field

11:30 Regular talk **Martin Erinin**, University of Michigan
The transport of droplets generated by mechanically forced plunging breakers

12:00-13:50 Lunch break

13:50 Early career talk **Simone Di Giorgio Clara**, CNR-INM
Gas transfer in breaking waves: a DNS study

14:10 Early career talk **Clara Martin Blanco**, Princeton University
Kinematics & growth rates of nonlinear gravity-capillary waves under wind forcing & underwater currents

14:30 Regular talk **Bertrand Chapron**, Institut Français de Recherche pour l'Exploitation de la Mer
TBA

15:00 Regular talk **Detlef Lohse**, University of Twente
Heat transport through a turbulent interface in a Rayleigh-Bénard configuration

15:30 Coffee break

16:00 Regular talk **Kianoosh Yousefi**, University of Texas at Dallas
Simultaneous measurements of air- and water-side flow across surface wind waves

16:30 Regular talk **Ton van den Bremer**, TU Delft
Wave-induced drift on a rotating Earth

17:00 Regular talk **Luc Deike**, Princeton University
Gas transfer at the air-sea interface: integrating small scale bubble dynamics into large scale ocean models

Friday

8:30 Keynote#5 **Alex Babanin**, University of Melbourne
Wave-Induced Turbulence, Linking Small and Large Scales in the Upper Ocean

9:30 Regular talk **Sophia Brumer**, University of Toulouse
Sea Spray – bulk and microphysics coupled wave-atmosphere frameworks

10:00 Regular talk **Wouter Mostert**, University of Oxford
Direct numerical simulations of spume production on ocean waves

10:30 Coffee break

11:00 Regular talk **Jason Hearst**, Norwegian University of Science and Technology
Turbulence matters at the air-water interface

11:30 Regular talk **Alfredo Soldati**, TU Wien
Scaling Laws for Ice Ripple Celerity under Turbulent Shear

12:00 Lunch break

13:50 Early career talk **Kevin Zhong**, University of Twente
CO₂ gas transport across strongly turbulent free surfaces: insights from direct numerical simulations

14:10 Early career talk **Dan Ruth**, ETH Zurich
How does a free surface deform in response to subsurface turbulence?

14:30 Regular talk **Alessandro Iafrati**, Institute of Marine Engineering
Energy dissipation and coherent vortical structures in breaking waves

15:00 Regular talk **Simen Ellingsen**, Norwegian University of Science and Technology
Direct experimental measurement of wave-enhanced mixing in Langmuir(like) turbulence

15:30 Closing remarks

Abstracts

Novel Measurements of the Wind Stress Partition and its Modulation by Breaking Waves

Christopher J Zappa, Lindsay Hogan, and Junzhe Liu, Columbia University, Lamont-Doherty Earth Observatory, Palisades, NY, USA

Prof. Nathan Laxague, Shantanu Soumya, University of New Hampshire Main Campus, Durham, USA

Ivan B. Savelyev, U. S. Naval Research Laboratory, Washington, United States,

Marc Buckley, Janina Tenhaus, Helmholtz-Zentrum Hereon, Geesthacht, GERMANY,

Brian K Haus, University of Miami, Rosenstiel School of Marine, Atmospheric, and Earth Science, Miami, FL, USA

Accurate description of air-sea momentum flux relies on partitioning the wind stress into viscous tangential stress and form drag (wave-related stress). The wind stress partition and viscous sublayer properties vary with wave phase due to poorly resolved processes such as airflow separation and breaking waves. In particular, resolving the viscous tangential stress and properties of the viscous sublayer in the field remains a major challenge. To address this fundamental knowledge gap, a multi-spectral thermal infrared imaging instrumentation system, the MultIR, was developed. This novel device enables the observation of viscous stress and heat transfer in the uppermost layer of the sea (top 100 microns) without disrupting the flow.

This study presents a first-test of the MultIR system in the wind-wave tank of the Surge Structure Atmosphere Interaction Facility (SUSTAIN) at University of Miami in August-September 2022 and March 2024. We tested the system over a range of wind speed (3-14 m/s) over calm surfaces at 10 m fetch. The MultIR measurements compare well with PIV measurements of the air-side and aqueous viscous tangential stress in 2022. For the 2024 campaign, the comparison of the tangential viscous stress from the MultIR with the profiled hot-wire anemometry of the air-side Reynolds or total stress provides insight into the wave-related stress (or form drag) as a function of wind speed. Results from SUSTAIN are also shown to be comparable with previous tangential viscous stress estimates of Banner & Peirson (1998), Grare (2009), Peirson et al. (2014), Bopp (2018), and Yousefi et al. (2020).

The laboratory measurements of wind-wave coupling under strongly-forced conditions are evaluated in the context of non-linear stress partitioning models. The variability of the stress partition with wind speed and wave development agree well both with previous laboratory measurements of viscous stress and with stress partitioning models. Additionally, these results present direct observations of the modulation of the viscous stress by microscale breaking waves: enhanced viscous stress on the crest of the breaking wave and diminished viscous stress on the leeward side where air-flow separation is expected. These results are pertinent wind-wave coupling in wave models, including decomposition of the total wind stress, modulations of the viscous stress by microscale breaking waves, and momentum flux into near-surface currents by microscale breaking waves.

Directional Infrared Observations of Bubble-Entraining Breaking Waves

Leonel Romero, University of Connecticut, Department of Marine Sciences

Surface wave breaking plays a central role in air-sea exchanges of energy, momentum, heat, and gases. While much of our understanding of breaking waves in the open ocean comes from field observations, few studies have examined the directionality of active, bubble-entraining breakers. We present a directional analysis of wave-breaking kinematics based on three-dimensional stereo reconstruction of the ocean surface using combined visible and infrared (IR) imagery collected over a wide range of wind and wave conditions, spanning wind speeds from approximately 6 to 20 m s⁻¹.

A key advantage of the IR observations is their ability to track actively breaking fronts while filtering out rapidly cooling residual foam. This enables robust characterization of active breaking across a broad range of scales, including short gravity waves, where the wave spectrum exhibits strong azimuthal bimodality with angular separations of up to $\pm 80^\circ$. Our results show that the directionality of active breaking is much narrower than the energy spectrum and that the predominant breaking direction can vary substantially across scales under strongly misaligned wind and wave conditions. The observed breaking direction is broadly consistent with a scale-dependent mean wave direction weighted by the cumulative mean-squared slope. The results are discussed in the context of long-short wave interactions, the spectral energy balance, and improved wave-breaking parameterizations in spectral wave models.

Surface wave effects on the TKE budget above and below the air-sea interface

Galen Egan, Malcolm Scully, Seth Zippel

On either side of a flat, rigid boundary, turbulence energetics are well-described by Monin-Obukhov similarity theory, with TKE dissipation balanced by shear and buoyancy production. The situation can change considerably in the presence of surface waves, with implications for the TKE budget in both the near-surface ocean and atmosphere. In this talk I present results from a field campaign in Buzzards Bay, MA, where vertically-resolved measurements of velocity and pressure were collected on both sides of the air-sea interface, enabling estimates of each term in the horizontally homogeneous TKE evolution equation. Using the atmospheric observations during the most energetic storm conditions, we find that closing the TKE budget requires accounting for both energy lost to the growing wave field and an unexpected mismatch between the turbulent pressure and TKE transport terms. Though these terms are frequently assumed to cancel one another, a similar imbalance has been seen in DNS studies of the atmospheric boundary layer over waves, and our observations suggest additional modulation by the directional spread of the wave field. In the ocean, deviations from Monin-Obukhov are less subtle: as waves begin to break, Langmuir circulation develops and begins to interact with low frequency bound waves. This interaction drives an energy flux deep into the water column via pressure work. The resulting pressure work convergence increasingly balances dissipation with increasing wind speed. These observations motivate a novel scaling for the vertical structure of dissipation, which is enhanced relative to log-law predictions. The same Langmuir turbulence that enhances dissipation also suppresses mean shear below its log-law estimate. In sum, these observations point to a nuanced but central role for transport processes in near-surface ocean and atmospheric turbulence energetics.

Surface waves interacting with subsurface currents

Yan Li, University of Bergen

Department of Mathematics, University of Bergen, Bergen 5007, Norway

Small-scale surface waves widely coexist with subsurface currents in the upper ocean. The interaction between the two drives forces to important physical processes at the air-sea interface, and thereby playing a crucial role to the mass, momentum, and energy transfers at the air-sea interface and to marine life and regional climate (McWilliams, 2016). The subsurface current-induced velocity largely varies in the physical space and time and can greatly modifies the properties of small-scale surface waves. In this work, how the modifications differ are examined owing to different current profiles. Three representative currents are examined, including vertically and horizontally sheared current (Li & Chabchoub, 2024; Li *et al.*, 2024; Zheng et al. 2023; Li, 2026; Halsne & Li, 2025), and wave-induced currents (Wang & Li, 2026) in coastal

regions. These currents are typical of those induced by wind actions, large-scale circulations, tidal currents, and swell. Theoretical derivations and approximations are derived for describing the ray path of waves, orbital motions, Stokes drift, and wave actions. The findings show that the current-induced vorticity in the horizontal plane and vertical direction can modify the vertical profile of the Stokes drift and ray direction of waves (Li *et al.*, 2024; Halsne & Li, 2025). When the current is a result of long waves, the vertical shear of the velocity induced by short waves, especially near the surface, are considerably altered by the phase of the long waves (Wang & Li, 2026). When the system of waves atop a vertically sheared current is superposed by small perturbations, modulation instability and Langmuir circulation type 2 instability may occur (Li & Chabchoub, 2024). The two different instability mechanisms suggest a plausible hypothesis of energy transfers within the system to either the growth of small-scale waves, large-scale circulations, or both, which remains to be validated.

References:

- Halsne, T., & Li, Y. (2025). Coastal wave refraction in variable currents over a varying bathymetry. *Journal of fluid mechanics*, 1019, A6.
- Li, Y. & Li, X. (2021). Weakly nonlinear broadband and multi-directional surface waves on an arbitrary depth: A framework, Stokes drift, and particle trajectories. *Physics of Fluids*. vol. 33 (7).
- Li, Y., Zheng, Z., & Kalisch, H. (2024). Stokes drift and particle trajectories induced by surface waves atop a shear flow. *Frontiers in Marine Science*, 11, 1445116.
- Li, Y. & Chabchoub, A. (2024) How currents trigger extreme sea waves. The roles of Stokes drift, Eulerian return flow, and a background flow in the open ocean. *Geophys. Res. Lett.*, 51(6), e2023GL107381.
- McWilliams J. C. (2016). Submesoscale currents in the ocean. *P. R. Soc London. A*. 472, 20160117.
- Li, Y. (2026). Spatiotemporal evolution of surface waves in open ocean current. (pre-submission).
- Wang, J. & Li, Y. (2026). A revisit to ocean surface waves riding on long waves (pre-submission).
- Zheng, Z., Li, Y., & Ellingsen, S. Å. (2024). Dispersive Wave Focusing on a Shear Current: Part 2—Nonlinear Effects. *Water Waves*, 6(2), 413-449.

Turbulence scaling laws under wind-driven waves

Filippo Coletti, ETH Zurich, Switzerland

Below wind waves, a boundary layer develops with similarities and differences with respect to the classic wall-bounded turbulence. This so-called drift layer features significant shear driven by the tangential stress from the wind, but also orbital motions that periodically stretch, compress and tilt vortical structures. Under such conditions, scaling laws for the turbulent sub-surface flow are not trivial to formulate, because the assumptions behind established theories are questionable. Such relations are also difficult to test experimentally: measurements are challenging, and the mean current, orbital motions and turbulent fluctuations are not easy to disentangle. Here we use data from extensive campaigns in a wind-water tunnel where particle image velocimetry, laser induced fluorescence, and infrared thermography are used to characterize the fluid dynamics below young wind-driven waves. This allows us to test the Prandtl-von Kármán theory of the mean velocity profile and the Kolmogorov theory of the velocity structure function in the drift layer. The logarithmic profile predicted by the Prandtl-von Kármán theory is retrieved only under wave crests, as shown by phase-locked averaging of the surface-parallel velocity. In the other wave phases, the momentum is redistributed in approximate agreement with linear wave theory. The Kolmogorov theory does apply in the inertial range of the turbulent fluctuations, but only if the latter are appropriately separated from the orbital motions. The Reynolds stresses, on the other hand, are profoundly different compared to those in a solid-wall boundary layer with similar friction velocity, and can be compared with the predictions by the Craik & Leibovich theory of Langmuir circulations.

How Well Do We Know the Wave Effect? Langmuir Turbulence Parameterization, Wave–Current Consistency, and Coupled Boundary Layer Energetics

Baylor Fox-Kemper, Department of Earth, Environmental and Planetary Sciences, Brown University, Providence, RI, USA

Surface gravity waves reorganize upper-ocean turbulence through the Stokes forces (Suzuki & Fox-Kemper, 2016), and the resulting Langmuir turbulence is now represented in many global ocean and climate models. This talk contextualizes that representation using three vantage points: a controlled intercomparison and a structural analysis of the turbulence itself, a new variational formulation of the wave–current problem, and a coupled boundary layer perspective.

Li et al. (2019, *JAMES*), **Johnson et al. (2023, *JPO*)**, and **Li & Fox-Kemper (2020, *Phys. Rev. Fluids*)** are in the first category. **Li et al. (2019)** compares six Langmuir turbulence schemes and five non-Langmuir counterparts as implemented in a single-column-ocean framework and compared under identical initialization from observations, forcing, discretization, and time stepping as each parameterization is called with the same GOTM/CVMix interface. Thus, the software, algorithms, and numerics of a scheme are evaluated *alongside* its physics rather than confounded with the biases of whichever host model called it. The result: Langmuir schemes do deepen the mixed layer relative to their non-Langmuir counterparts — 6% in the global monthly mean (–1% to 14%, 90% confidence; 5.2 m, –0.2 to 17.4 m), rising to 9% (2% to 17%) in the Langmuir-dominated regime and 5–25% in extratropical zonal means, largest in the Southern Ocean in austral summer. But the *spread among* the Langmuir schemes (15% standard deviation in MLD) is larger than the Langmuir signal they are meant to capture, and larger than the spread among the non-Langmuir schemes (6%). Climatologically, disagreement is worst exactly where Langmuir turbulence matters most (Figure 1).

Johnson et al. (2023) asks *when* and *why* the schemes disagree using a *finite-time* ensemble vector (EV) method, in which ten OSBL schemes are repeatedly branched from an LES truth run and the short-interval divergence is measured in a reduced state space of mean and turbulent fields. Applied to the 2018 monsoon onset in the Bay of Bengal (MISO-BOB), with paired shear-turbulence and Langmuir-turbulence LES as reference, the method localizes disagreement to specific events rather than reporting a time-mean bias: wind-driven mixed layer deepening with near-inertial shear at the pycnocline, strong precipitation, and strong diel warm layers during the break period.

Li & Fox-Kemper (2020) attacks uncertainty in entrainment from the structure of the turbulence. Using LES pairs we characterize anisotropy with the Reynolds-stress eigenvector *directions*. Langmuir turbulence a near-surface signature — two-component anisotropy with the minor axis oriented along the Lagrangian shear, tilted counter-rotating vortices. Shear turbulence is cigarlike with a downwind major axis and dominated by vortex sheets.

The wave–current formulations of **Vanneste & Young (2022, *Phil. Trans. R. Soc. A*; 2026, *J. Fluid Mech.*)** shows that the Stokes velocity is not unique: one version is exactly divergence-free and coordinate-independent, and with it the Craik–Leibovich equations hold. Vanneste & Young build on this theory to propose a variational, two-way coupled model (CWCW) in which the wave-action equation in $(\mathbf{x}, \mathbf{k})$ space and the CL system in $(\mathbf{x}, z)$ communicate through the pseudomomentum $\mathbf{p}$ and a wavenumber-dependent, depth-weighted Doppler velocity, and identifying the *Lagrangian* kinetic energy $|\mathbf{u}^L|^2/2$ as the one budgets should be written in.

I close with the coupled boundary layer perspective of **Hell, Fox-Kemper & Ayouche (submitted)**, which carries the energy argument across the interface and across scales. Applying the increment operator to the mass-weighted, vertically integrated Ekman-layer momentum equation of each fluid yields a *scale-selective* kinetic energy budget built from structure functions: exact wherever the momentum equation is exact, computable from instantaneous fields without a coarse-graining kernel, and with bootstrapped sampling (PyTurbo_SF) estimable from gappy observations. Examining a NASA km-scale coupled model and the S-MODE observations, we find two competing pathways: synoptic events drive mesoscale ocean-work and wind-work with fast downscale cascades in *both* boundary layers, while ocean submesoscale instability

drives an inverse cascade to the mesoscale and generates its own negative wind work at scales where the density-weighted ocean out-energizes the atmosphere. The coupled boundary layer *including* waves (in both 3D models and 1D CBL mixing) will be a next step!

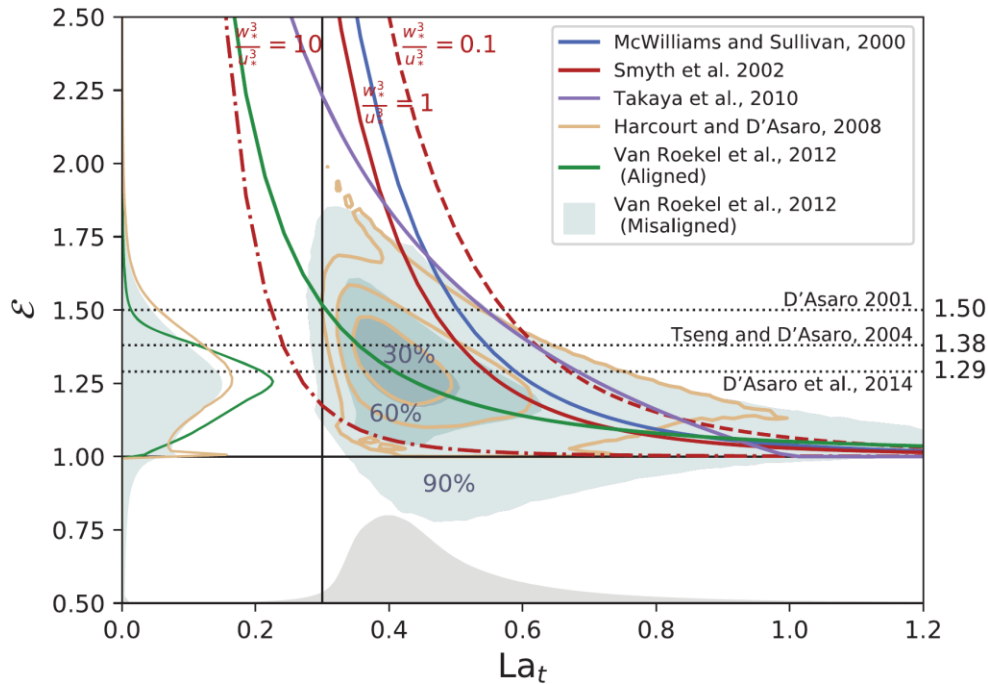


Figure 1. After Li et al. (2019), Figure A1. Langmuir enhancement factor $\mathcal{E}$ applied to the turbulent velocity scale, as formulated by McWilliams & Sullivan (2000), Smyth et al. (2002), Takaya et al. (2010), Harcourt & D’Asaro (2008), and Van Roekel et al. (2012, aligned and misaligned), plotted against the turbulent Langmuir number La_t . Shading and contours give the joint PDF of $\mathcal{E}$ and La_t (30%, 60%, 90% enclosed) from single-column simulations forced by JRA55-do and WAVEWATCH III over twelve months; the gray distribution at the bottom is the PDF of La_t itself. Dotted lines mark enhancement factors inferred from direct observations (D’Asaro 2001: 1.50; Tseng & D’Asaro 2004: 1.38; D’Asaro et al. 2014: 1.29). The formulas converge where waves do not matter ($La_t \gtrsim 1$) and diverge without bound where the ocean actually sits.

Key references

- Li, Q., B. G. Reichl, B. Fox-Kemper, A. J. Adcroft, S. E. Belcher, G. Danabasoglu, A. L. M. Grant, S. M. Griffies, R. Hallberg, T. Hara, R. R. Harcourt, T. Kukulka, W. G. Large, J. C. McWilliams, B. Pearson, P. P. Sullivan, L. Van Roekel, P. Wang, and Z. Zheng (2019), Comparing ocean surface boundary vertical mixing schemes including Langmuir turbulence, *J. Adv. Model. Earth Syst.*, **11**, doi:10.1029/2019MS001810.
- Johnson, L., B. Fox-Kemper, Q. Li, H. T. Pham, and S. Sarkar (2023), A finite-time ensemble method for mixed layer model comparison, *J. Phys. Oceanogr.*, **53**, 2211–2231, doi:10.1175/JPO-D-22-0107.1.
- Li, Q., and B. Fox-Kemper (2020), Anisotropy of Langmuir turbulence and the Langmuir-enhanced mixed layer entrainment, *Phys. Rev. Fluids*, **5**, 013803, doi:10.1103/PhysRevFluids.5.013803.
- Li, Q., and B. Fox-Kemper (2017), Assessing the effects of Langmuir turbulence on the entrainment buoyancy flux in the ocean surface boundary layer, *J. Phys. Oceanogr.*, **47**, 2863–2886.
- Suzuki, N., and B. Fox-Kemper (2016), Understanding Stokes forces in the wave-averaged equations, *J. Geophys. Res. Oceans*, **121**, 3579–3596, doi:10.1002/2015JC011566.
- Vanneste, J., and W. R. Young (2022), Stokes drift and its discontents, *Phil. Trans. R. Soc. A*, **380**, 20210032, doi:10.1098/rsta.2021.0032.
- Vanneste, J., and W. R. Young (2026), A consistent phase-averaged model of the interactions between surface gravity waves and currents, *J. Fluid Mech.* (arXiv:2602.21976).
- Hell, M., B. Fox-Kemper, and A. Ayouche (submitted), Scale-dependent, episodic pathways of turbulent air–sea kinetic energy transfer.

Multiscale representation of Langmuir turbulence in an ocean model

Brandon Reichl, National Oceanic and Atmospheric Administration

Ocean surface waves drive many aspects of air-sea interaction and have implications for coupled ocean models across timescales from weather events to centennial projections. One key process is how waves modify vertical mixing and currents within the ocean surface boundary layer. This work examines the effects of wave-current coupling on the upper ocean through applications of the wave-averaged

equations. At small-scales ($<O(100)m$), the resulting coupling between background currents and Stokes drift drives the emergence of Langmuir turbulence. Due to its small length scale, Langmuir turbulence requires parameterizations for representation in ocean models. The implications of Langmuir turbulence parameterizations are now well known, primarily achieving a deepening of the mixed layer in wind-driven regimes and contributing to reducing stubborn shallow mixed layer biases in models. We discuss the primary considerations and approaches for representing Langmuir mixing in the ePBL parameterization used by the MOM6 ocean model, including recent progress to better represent the coupling between shear turbulence and Langmuir turbulence. We then expand our focus to larger-scales ($>O(1)km$), where the same equations result in coupling of the wave field to the model's resolved currents. While Langmuir turbulence is better understood, the impact of resolved-scale wave-ocean coupling remains under-explored. We conduct a set of idealized tropical cyclone experiments to examine the impact of resolved-scale wave-ocean coupling on the storm's cold wake response. Our model simulations indicate a range of potential impacts, depending on model resolution and the background conditions. We find that even with sufficient horizontal resolution, small-scale ($<10\text{ km}$) circulations are often suppressed in our idealized tropical cyclone model results, resulting in little impact of wave-current coupling on the cold wake. However, in cases with reduced vertical mixing, these scales can become energetic so that the wave-current coupling exerts a significant influence on the cold wake SST cooling and patterns ($>20\%$). Finally, we present the applications of both results in different models being developed at NOAA's Geophysical Fluid Dynamics Laboratory, including regional and global applications. Our results demonstrate that while full-complexity wave coupling is important for extreme weather event applications, simpler approaches may be advantageous in long-term simulations due to computational constraints.

Fourier Modes of Wind Velocity and Pressure over Surface Waves Derived from Field Observations

Seth Zippel, Oregon State University, USA

The wave-coupled wind and pressure patterns over the ocean surface are critical for the exchange of momentum and kinetic energy between the atmosphere and ocean. One theoretical approach has been to linearize the equations of motion and to seek solutions to the Rayleigh equation either through approximate analytic or numerical methods. This approach has been used to develop parameterizations for wind/wave growth and wave/atmosphere coupling used in prominent spectral wave models and weather models.

Here, we present linear modes for wind and pressure over waves as normalized transfer functions, and compare them with linearized equations underpinning the Rayleigh equation. Field observations are taken from three deployments across two field campaigns where vertical arrays of sonic anemometers and pressure sensors were logged synchronously with a wave lidar allowing for spectral processing of wave-coherent modes. Wave-coherent spectra of along-wave velocity, vertical velocity, and atmospheric pressure are normalized by wave orbital motions, and mapped to a non-dimensional height and frequency grid. Heights are scaled by the surface wavenumber, kz , and frequencies are normalized by the critical frequency, such that f is mapped to U/c . Transfer functions representing the average atmospheric response to waves are significant over the parameter space spanning roughly $0.3 < kz < 3$ and $0.3 < U/c < 3$. These functions represent average linear behavior from a composite of approximately ten thousand instrument-hours of field observations.

The magnitude and phase of these transfer functions demonstrate qualitative agreement with damped-driven oscillator systems, with velocity components showing a distinct notch in magnitude and exhibiting a phase shift across $1 < U/c < 2$. Averaged velocity modes are consistent with the linearized continuity equation, however pressure modes are not fully consistent with the linearized momentum equations, particularly in the vicinity of $U/c=1$. We present empirical fits to the complex transfer functions, which we hope will guide future observational and theoretical descriptions of airflow over waves. Last, we highlight and contrast several examples where intermittent but likely wave-induced pressures suggest that linear Fourier modes

do not fully describe atmospheric response, and multiple wind-over-wave theories may be needed in tandem to capture the total momentum and energy exchange.

Vorticity generation by finite-depth wave breaking

Christine Baker, A. Pihl, S. Treillou, Stanford University, Department of Civil & Environmental Engineering

Breaking waves transfer momentum into the water column within finite, surface-intensified regions. In deep water, breaking occurs as discrete events that drive a coherent, localized near-surface current. In shallow water, by contrast, breaking is continuous across the shoreface, rather than isolated to individual events, and drives vertically sheared undertow that balances the near-surface onshore forcing with a return flow. Unlike transient vortical structures generated by individual deep-water breaking, continuous breaking in shallow water may generate vorticity persisting over longer timescales, but how this occurs remains poorly constrained.

Here, we focus on two mechanisms that can result in vorticity at infragravity timescales: (1) finite-crested wave breaking and (2) shear instabilities in undertow. For each mechanism, we quantify their spatial extent, temporal persistence, and relationship with wave forcing through idealized experiments in a new wave basin (e.g., Fig. 1). Through wave-resolving simulations, we find that finite-crested wave forcing largely contributes to surf-zone ‘stirring’, while shear instabilities in undertow contribute to ‘mixing’, together enhancing cross-shore diffusivities. We discuss how these finite-depth processes relate to vorticity-generation mechanisms in deep-water breaking, and the implications for particle transport.

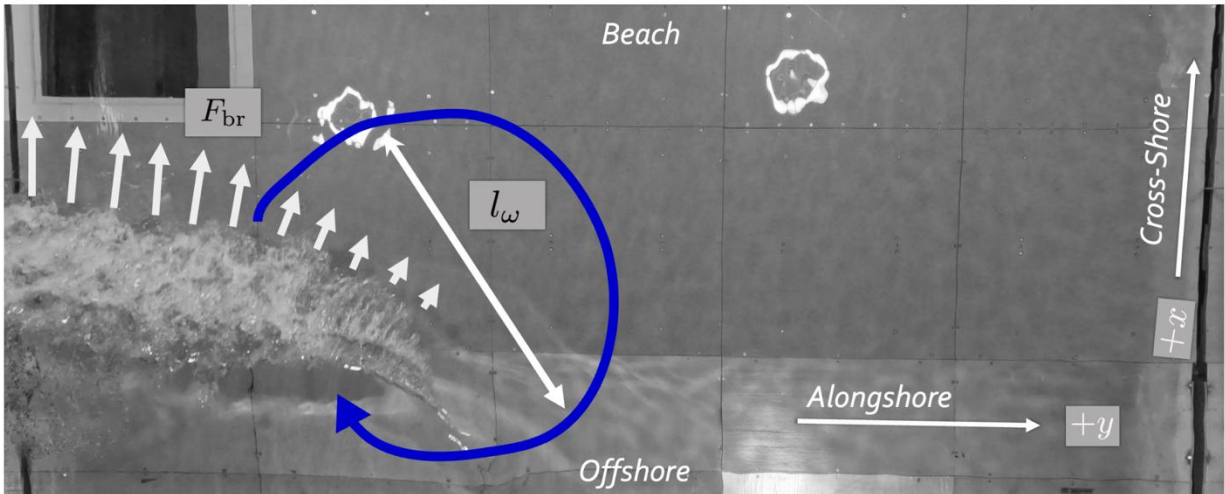


Figure 1: Half of a finite-crested breaking wave on a beach in wave basin experiments. The relationship between the breaking force (F_{br}) and spatial scale (l_ω) of vertical vorticity are investigated.

Wave attenuation in the marginal ice zone

S. Perrard¹, S. Kuchly¹, M. Bureau¹, F. Pillet¹, P. Nicot², V. Dansereau^{3,4}, A. Eddi¹, D. Dumont²

¹ Laboratoire PMMH, UMR 7636, ESPCI, PSL-University, Sorbonne Université, UPC, Paris, France

² Institut des Sciences de la Mer (ISMER), UQAR, Rimouski, Québec, Canada

³ Institut des Sciences de la Terre (ISTerre), Université Grenoble-Alpes (UGA), Grenoble, France

⁴ Institut des Geosciences de l'environnement (IGE), Université Grenoble-Alpes (UGA), Grenoble, France

Sea ice is a key component of the Arctic climate system. In the context of global warming, the Arctic sea ice is shrinking and shifting towards a seasonal cover, which becomes more prone to external stresses such as ocean waves. The Marginal Ice Zones (MIZs) formed of ice fragments covering partially the ocean, are extending seasonally. Their relative importance on the arctic sea ice formation and melting budgets are also increasing. In the MIZs, ocean waves can partially propagate, which affect ice formation by enhancing thermal and momentum fluxes, and by suspending ice crystals in the water column. During the early sea ice growth, wave agitation can lead to the formation of a viscous icy layer named grease ice made of a partially suspended mixture of ice crystals which can quickly thicken. The formation of this mixture results from an interplay of ice growth, turbulent mixing and wave propagation. The critical height at which the mixture will eventually solidify, depending on wave and thermal conditions, remain an open question.

To better understand ice formation, we combine laboratory experiments and field observations of wave propagation in forming sea ice. In the laboratory, we conduct experiments on an analog system made of floating plastic grain of density close to ice density. In the field, we performed wave and ice characterizations in the Saint Lawrence Estuary for 3 consecutive winters, observing various wave propagation regime and ice stage. We also recently perform rheology experiments on plastic and ice grains, to quantify how this mixture lead to an enhance of wave attenuation.

In this talk, I will give an overview on our current understanding of wave propagation in grease ice combining field data and laboratory experiments. I will also discuss short-term perspectives on the thermal aspects, in particular in the context of the CASCADE expedition which will take place in the Baffin Bay in November 2026.

Models for the interaction of surface waves and turbulence in the upper ocean

Stéphane Popinet, Institut Jean le Rond d'Alembert, CNRS & Sorbonne Université, Paris, France

In this presentation I will give a summary of a selection of models useful to describe surface waves and the upper ocean. The relations and history of a range of models will be discussed including for example shallow-water models, dispersive wave models, potential flow theory, and Navier-Stokes approximations using a range of interfacial representations. Several examples of applications will be presented including wave breaking and the associated turbulence generation and atomisation or the statistical properties of large-scale breaking wave fields.

Turbulent Airflow over Irregular Surface Waves: DNS and Linear Analysis

Yasushi Fujiwara, Kobe University

Wind-generated surface waves mediate momentum transfer between the atmosphere and ocean, but the influence of air-side turbulence on this process remains incompletely understood. We investigate the airflow response and momentum transfer over irregular waves using an idealized direct numerical simulation (DNS). Turbulent airflow is driven by a uniform pressure gradient in a horizontally periodic domain, while a broadband, directionally distributed wave field is imposed at the lower boundary. Horizontal Fourier analysis is used to extract velocity and pressure variations that are phase-locked with individual wave components.

The DNS shows that relatively short waves receive momentum from the airflow, whereas sufficiently long waves transfer momentum to the air. These spectral characteristics are broadly reproduced by a linear analysis (i.e., Orr-Sommerfeld equation) based on the mean wind profile obtained from the DNS, supporting a mode-by-mode quasi-linear description of airflow over irregular waves. Wind-following and opposing swells also exchange momentum with the airflow largely independently of the shorter wind-sea components.

Nevertheless, the linear analysis substantially underestimates the wind-to-wave momentum flux for intermediate wave ages ($6 < c/u_* < 11$). We therefore examine the wave-coherent Fourier components of second-order velocity moments. The wave-coherent fluctuation of Reynolds stress components is markedly stronger over waves than in corresponding no-wave simulations, indicating a systematic modulation of turbulent momentum transport by the wave field. The results suggest that the mean-profile-based linear response captures the overall spectral behavior, a result consistent with the critical-layer mechanism proposed by Miles, while turbulence modifies the magnitude of momentum transfer in the intermediate wave-age range.

SASCWATCH: A multifaceted campaign for understanding waves, fluxes, and turbulence at the high-wind air-sea interface

David H. Richter, Bell M.M., Villas Bôas, B., Jayne, S.R., Potter, H., Sanabia, E., Rudzin, J.E., Schönauf, M., Zhang, J.A., Wadler, J., Sullivan, P.P., Davis, J., et al.

The exchange of momentum, heat, and moisture between the ocean and atmosphere plays a central role in the presence, timing, location, and severity of extreme weather events including tropical cyclones (TCs). Traditionally, the atmosphere-wave-ocean intersection has been frequently treated as three separate, nearly independent problems despite a growing recognition that these are highly coupled processes. What results from this, however, are incomplete descriptions of the principal modulators of momentum, heat, and moisture fluxes in high winds, including the role of waves, currents, and atmospheric turbulence.

The Study on Air-Sea Coupling with WAVes, Turbulence, and Clouds at High winds (SASCWATCH) project aims to close these gaps by using a coordinated combination of *in situ* observations, mesoscale coupled modeling, and high-resolution turbulence simulations. Wide-scope objectives include:

- (1) Characterizing surface waves and currents in TC conditions, particularly their storm-relative spatial distribution. Of special interest is the alignment of waves, currents, and winds, and the systematic biases these introduce as a function of position.
- (2) Understanding the effect of waves on air-sea fluxes of momentum, heat, and moisture. Do momentum and scalar fluxes differ in their dependence on waves? What role do wind-wave alignment or spray play?
- (3) Quantifying turbulence in the high-wind, extreme marine boundary layer, especially in its relation to coherent structures and fluxes. Can these be measured accurately and reliably, and how does this turbulence depart from the traditional planetary boundary layer?

Very few reliable measurements have been made in TC conditions which can meet these objectives, and zeroth-order questions persist. This talk will provide an overview of this multi-institutional effort, which is halfway through its 5-year lifetime. Observational efforts include ocean wave drifters, remote sensing of ocean and atmosphere properties, autonomous surface and aerial systems, and *in situ* aircraft data. These are joined with an array of modeling techniques ranging from turbulence and droplet-resolving to mesoscale ocean-wave-atmosphere coupled models.

Numerical Investigations of Wind Turbulence over Breaking Waves

Zixuan Yang, *Chinese Academy of Sciences*

Breaking waves play a crucial role in the ocean by dissipating wave energy into turbulence, facilitating vital air-sea exchanges, shaping shorelines, and driving nearshore sediment transport. This presentation focuses on our recent progress in numerical investigation of wind turbulence over breaking waves. The presentation contains two parts.

In the first part, our earlier work on wind turbulence over an isolated breaking wave is briefly reviewed. The simulation consists of two stages. In the precursor-simulation stage, a steep wave ($ka = 0.55$) is prescribed, and single-phase wind turbulence is developed by solving the governing equations. After the wind turbulence is fully developed, the coupled level-set and volume-of-fluid (CLSVOF) method is applied in the coupled-simulation stage to capture the interface evolution, and the coupled air-water system is solved. We analyze the effects of wave breaking on momentum and heat transfer in the airflow by comparing turbulent statistics at different stages of wave breaking.

However, this investigation of a single breaking event has two main limitations. First, because a steep wave is prescribed in the precursor-simulation stage, the wave steepening process is not dynamically coupled with the wind turbulence. Second, a critical aspect of wave-breaking interactions—namely, how wave breaking influences the time-averaged wind profile—cannot be addressed in a single-event simulation. To address these limitations, we conducted numerical simulations of wind turbulence over intermittent breaking waves. To generate these waves, we developed a body-force driving method. The breaking rate and wave steepness can be precisely controlled by adjusting the magnitude and period of the imposed body force. Intermittent breaking waves were then generated (see Figure 1), and time-averaged statistics over 80 breaking periods were calculated. The effects of wave breaking on momentum transfer in the airflow are analyzed by comparing the mean velocity and momentum fluxes between breaking and non-breaking waves (see Figure 2).

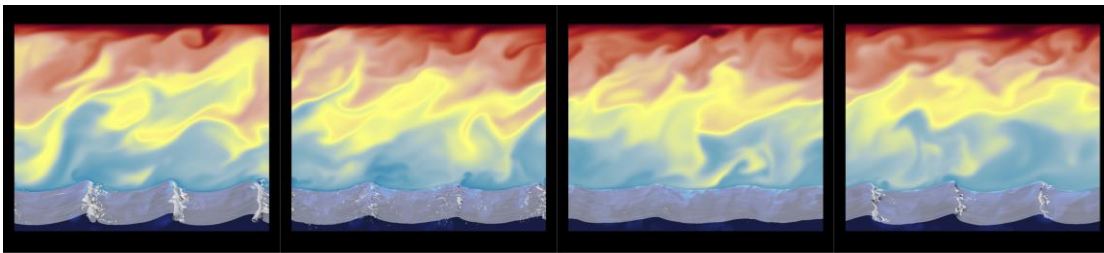


Figure 1 Wave geometry and contours of streamwise velocity between two breaking events

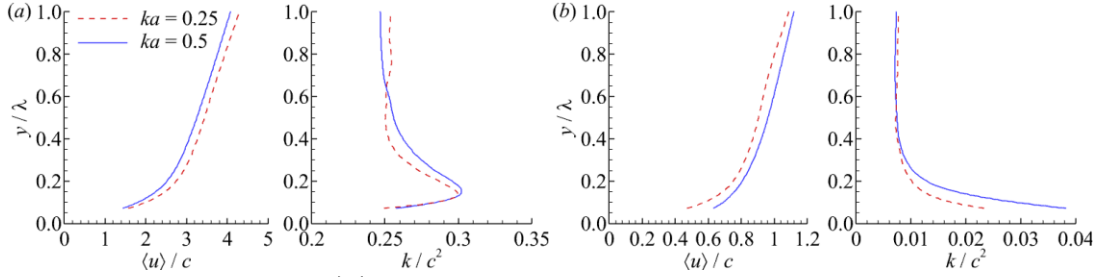


Figure 2 Profiles of mean velocity $\langle u \rangle$ and turbulent kinetic energy k over intermittently breaking and non-breaking waves for (a) young waves with $c/u_* = 3.7$ and (b) mature waves with $c/u_* = 20$.

Observations of momentum and energy exchange processes between wind and waves

Marc Buckley, Helmholtz Zentrum Hereon, Germany

Coupled airflow and water dynamics within the first few decimeters above and below ocean surface waves play a critical role in regulating atmosphere-ocean momentum and energy exchange. Direct observations of the underlying mechanisms remain difficult because of the technical challenges associated with measuring highly turbulent air and water flows in close proximity to a constantly moving water surface. We combine in situ and laboratory measurements of airflow (field) and coupled air-water (wind wave tank) kinematics above/below wind-generated waves using high-resolution two-dimensional Particle Image Velocimetry (PIV) and Laser-Induced Fluorescence (LIF) techniques.

Field observations obtained under low to moderate wind conditions captured 2D instantaneous velocity fields within the first 2m above the ocean surface. These reveal the simultaneous occurrence of multiple wind-wave interaction mechanisms. Short, slow wind waves (approximately 1 m wavelength) generate intermittent airflow sheltering events, whereas long, fast waves (approximately 70 m wavelength) induce pronounced orbital motions in the overlying airflow.

Complementary laboratory experiments were conducted in a wind-wave tank. These resolve the coupled airflow and water-side dynamics in the first microns to millimeters above/below the wavy surface, and provide detailed observations of airflow separation, boundary-layer structure, turbulence production, and vorticity generation over/below wind generated waves. The influence of microscale breaking is isolated through the introduction of an insoluble surfactant, which suppresses gravity-capillary waves and small-scale breaking processes. By comparing clean and surfactant-covered conditions, we assess how microscale surface roughness and breaking/airflow separating waves modify wave-coherent turbulence, alter the structure of the turbulent air-side boundary layer, and influence the stress partitioning near the surface. Particular emphasis is placed on understanding how momentum and energy transferred from the wind are partitioned between wave growth, surface drift currents, and turbulent motions in both the air and water. Together, the field and laboratory observations provide new insight into the multiscale mechanisms governing wind-wave momentum transfer and the relative importance of wave slope, phase-locked turbulence, microscale breaking, and surface roughness in controlling air-sea exchange.

Diffusion in waves and turbulence: a Lagrangian perspective

Michelle DiBenedetto, Princeton University

The transport of scalars in the upper ocean is affected by both surface gravity waves and turbulence. While waves clearly affect the advection of scalars through Stokes drift, their effects on mixing are less straightforward. In this talk, we directly consider the effects of wave orbital motion on diffusive transport. First, we present the results of a fully Lagrangian analysis of the advection-diffusion equation to show how

non-breaking waves can distort the diffusion of a passive scalar. We find that waves can enhance the horizontal diffusivity at a rate directly related to the Lagrangian mean water level. Second, we present results from laboratory experiments of particles in a wind-wave tank where we attempt to isolate the effects of waves and turbulence on vertical dispersion through a Lagrangian analysis. Together, these two studies offer a new perspective on the importance of waves to scalar diffusive transport and provide new models for interpreting observations.

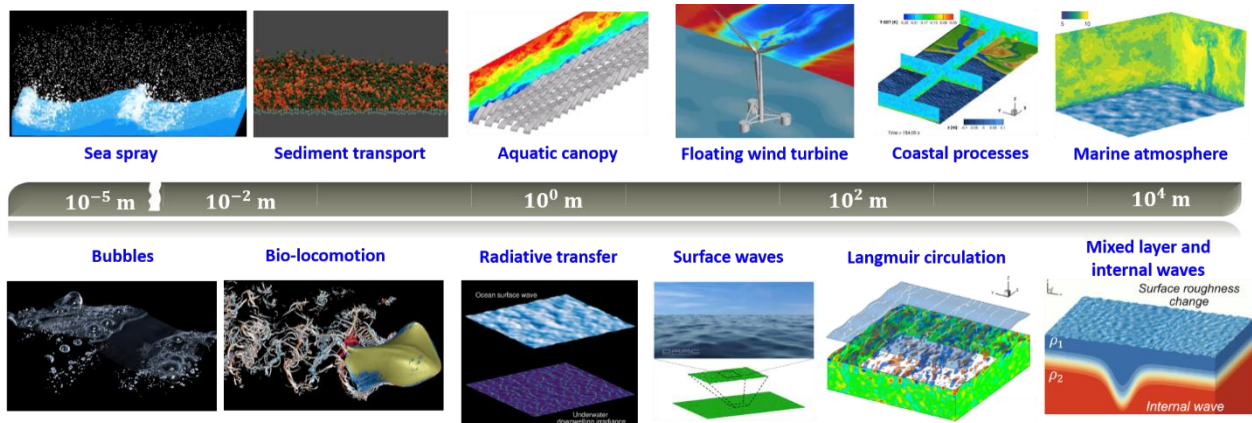
Computational and Theoretical Studies of Wind and Upper-Ocean Turbulence Interacting with Surface Waves

Lian Shen, *Department of Mechanical Engineering and St. Anthony Falls Laboratory, University of Minnesota*

The interaction of turbulence in the lower marine atmospheric boundary layer and the upper ocean with ocean surface waves is a profound problem in fluid mechanics. On the air side, the convex and concave wavy water surface imposes constraints on wind turbulence, and the wave velocity directly distorts the near-surface airflow. On the water side, the orbital velocity of the wave generates a periodically alternating strain-rate field that distorts turbulence. Meanwhile, the wave produces Stokes drift, which leads to a mean shear from the viewpoint of a Lagrangian average, with profound cumulative effects on turbulence. Given the importance of applications and the limited understanding of the fundamental mechanisms of turbulence–wave interaction, there is a critical need to advance theory and develop accurate, efficient modeling capabilities.

In this talk, some recent advancements in algorithms for high-fidelity simulations of free-surface flows will first be introduced, on topics selected from a GPU and mixed-precision augmented arbitrary-Lagrangian-Eulerian method for viscous flows on a wave-boundary-fitted grid and novel numerical schemes for interfacial flows, such as Lagrangian tracking of binary and non-binary fragmentation and coalescence of bubbles, sharp conservative integral formulation of surface tension, and inhibition and control of bubble coalescence in salt water.

The talk will then focus on our recent theoretical and modeling studies of wave effects on turbulence. The formulations of viscous and turbulence curvilinear models for wind over waves will first be introduced. Based on the curvilinear formulation, selected topics in turbulence amplitude modulation, input–output analysis of the effect of Reynolds stress on wave-coherent airflow, resolvent and Floquet–resolvent analyses of the effect of waves on turbulence, and machine learning-based wave-induced turbulence closure will be discussed.



High-fidelity simulations of turbulence and wave processes in the ocean environment

Near-surface coherent structures under developing wind waves: laboratory experiment and numerical model

Silvia Matt^{1*}, Shelby Metoyer², David Wang¹, Ivan Savelyev³, Brian Haus⁴

¹Naval Research Laboratory, Stennis Space Center, MS 39529, USA

²National Research Council Research Associate, Stennis Space Center, MS 39529, USA

³Naval Research Laboratory, Washington, DC 20375, US

⁴University of Miami, Coral Gables, FL 33124

*silvia.matt.civ@us.navy.mil

Wave phase-dependent processes at the air-sea boundary, including airflow separation and sheltering, are known to modify viscous stress and form drag at the air-sea interface, yet despite their significance, these effects remain underrepresented in coupled- and wave forecasting models. To understand phase-dependent effects on air-sea momentum flux and surface stress, a comprehensive experiment was conducted at the large University of Miami SUSTAIN (SURge-STructure-Atmosphere INteraction) wind-wave laboratory tank for a range of wind forcing conditions. To characterize changes to the water-side boundary layer under developing wind waves, in-water velocity fields near the air-sea interface were obtained with Particle Image Velocimetry, from low wind conditions with minimal wave generation to well-developed wind-wave fields. A companion multiphase Large-Eddy Simulation model, resolving velocity fields in both air and water, provides three-dimensional flow fields in the tank and thus context to the experimental findings. Both experimental and numerical data reveal a transition from shear-driven flow, where surface waves exert no notable impact, to a wind-wave regime where phase-dependent effects modulate the near-surface viscous and turbulent stresses. Ramp-like structures develop near the interface and eject fluid from the boundary layer into the interior thus altering near- and subsurface turbulent fields. As waves develop, the flow field organizes into features consistent with Langmuir dynamics. This changes the momentum profile in the boundary layer and impacts near-surface turbulent and viscous stresses, and thus the drag at the air-sea interface. Vertical profiles of turbulent kinetic energy, turbulent kinetic energy dissipation rate, and turbulent production in the near-surface layer provide insight into the change in regime under developing waves and connect phase-dependent variations at the interface to the subsurface dynamics.

How do surface gravity waves organize turbulent currents into jets?

Nicholas Pizzo, University of Rhode Island

In this talk we examine how surface gravity waves can organize turbulent currents into jets. We do this by studying the Craik-Leibovich equations, and draw on the analogy between the vortex force term and the Coriolis term that enters into descriptions approximating flow on the rotating sphere. In certain asymptotic regimes the analogy is exact. Physically, the curl of the Stokes drift, which we prefer to call the pseudomomentum, leads to a quantity akin to planetary vorticity. When this curl has a nonvanishing second derivative, the system supports the existence of vorticity waves. These waves can lead to jet formation, in line with Rhines's β -arrest, when there is an inverse cascade present (the usual inverse cascade of two-dimensional turbulence on the β -plane, and the inverse cascade due to Langmuir turbulence for the surface wave scenario). Numerical examples are given to support the theory.

Erosion of the Oceanic Mixed Layer under an Active Wave Field

Hugo Jacquet ⁽¹⁾, Bruno Deremble ⁽¹⁾, Julien Le Sommer ⁽¹⁾, Stéphane Popinet ⁽²⁾

⁽¹⁾ Université Grenoble Alpes, CNRS, INRAE, IRD, Grenoble-INP, Institut des Géosciences de l'Environnement, Grenoble, France

⁽²⁾ Sorbonne Université, CNRS, Institut Jean Le Rond d'Alembert, F-75005 Paris, France.

Surface gravity waves fundamentally modify the dynamics of the oceanic mixed layer by injecting momentum through wave breaking, generating Stokes drift, and triggering Langmuir turbulence. These processes control the vertical transport of turbulent kinetic energy (TKE) and the erosion of stratification, yet they remain only partially represented in contemporary ocean and climate models. In particular, most parameterizations assume that wave effects can be related directly to the local wind stress, neglecting the non-local and time-dependent nature of wave evolution.

We investigate the erosion of the oceanic mixed layer using large-eddy simulations with explicit surface waves and wave breaking. We analyze a series of idealized simulations spanning wind-driven, buoyancy-driven, and wave-dominated regimes to quantify the relative contributions of wave breaking, Stokes drift, and Langmuir turbulence to upper-ocean mixing. The simulations reveal that the presence of an active wave field substantially enhances the downward transport of TKE, accelerates mixed-layer deepening, and modifies the vertical structure of turbulent dissipation compared with simulations forced solely by atmospheric stress. The efficiency of mixed-layer erosion is shown to depend not only on wind intensity but also on wave age and wave-current alignment, highlighting the importance of explicitly accounting for wave dynamics.

The transport of droplets generated by mechanically forced plunging breakers

Krishanu Kumar¹, Baiyu Chen¹, Varun Verma Jaganth¹, and Martin A. Erinin¹

¹Department of Mechanical Engineering, University of Michigan, Ann Arbor

Abstract: Droplets generated by breaking waves play a central role in air-sea exchanges of mass, momentum, and energy, influencing cloud formation, radiation absorption, aerosol production, and tropical storm intensification. These exchange processes depend strongly on the droplet residence time, how long droplets remain airborne, which is governed by droplet size, initial ejection conditions, and, critically, ambient wind. In this talk, we present experiments of droplet transport dynamics based on two complementary datasets, mechanically generated plunging breakers in still air, and equivalent breakers under wind-forcing conditions in a wind-wave tank. Quasi-2D focused wave packets were generated using a wave-focusing technique, with central frequencies of $f = 1.15$ Hz (no-wind case, $\lambda = 1.18$ m) and $f = 1.08$ Hz (wind case, $\lambda = 1.34$ m). Surface elevation was measured via cinematic laser-induced fluorescence, and droplets ($d \geq 100$ μm) crossing a measurement plane 1 cm above the maximum wave crest height were captured using cinematic inline holography at 650 Hz. Droplet number, diameter, speed, ejection angle, and acceleration were quantified for droplets moving both up and down through the measurement plane under each condition. Using droplet statistics from the still-air experiments, a droplet transport model was developed and validated against measured droplet return statistics, see Figure 1 for comparison of droplet vertical velocity comparison between the model and measured data. This framework is extended using the wind-tunnel data that incorporates wind-driven advection, validated against downward-crossing droplet statistics and used to estimate time of flight, concentration profiles, and other transport parameters as functions of ejection conditions and wind speed.

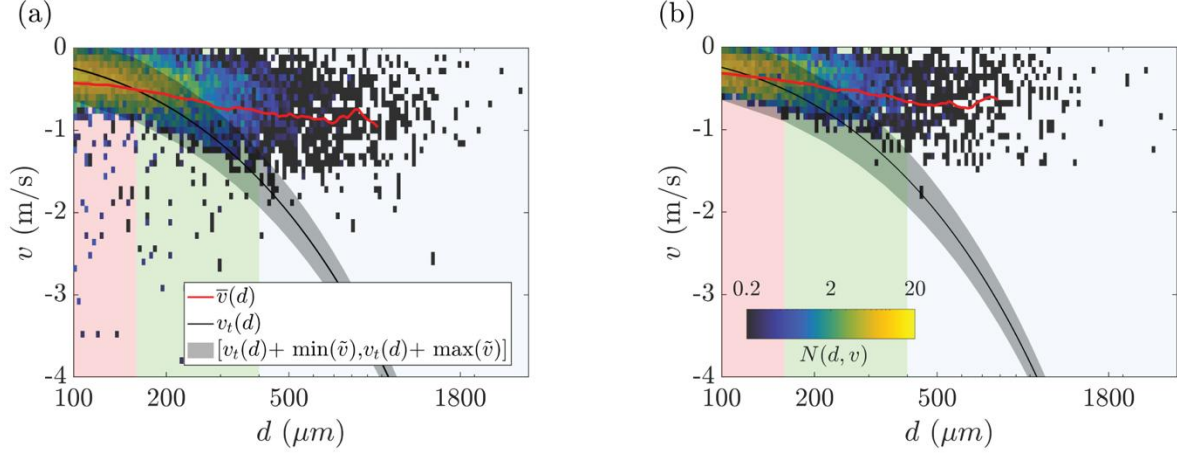


Figure 1. Diameter-dependent vertical velocity distribution $N(d, v)$ for droplets moving down the measurement plane from experiments (a) and the droplet transport model in (b). The red and black solid line denotes the mean velocity $\bar{v}(d)$ and still-air terminal velocity $v_t(d)$, respectively

Gas transfer in breaking waves: a DNS study

Simone Di Giorgio^{1,2}, **Sergio Pirozzoli**³ and **Alessandro Iafrati**¹

¹*Institute of Marine Engineering, CNR-INM, Rome, Ital*

²*Institute of Fluid Mechanics and Heat Transfer, TU Wien, Vienna, Austria*

³*Dept. of Mechanical and Aerospace Engineering, Sapienza University of Rome, Rome, Italy, simone.digiorgio@cnr.it*

Wave breaking is one of key driver of air-sea exchanges: the entrainment of air bubbles and the associated near-surface turbulence strongly enhance the transfer of gases such as CO_2 and O_2 across the ocean-atmosphere interface, yet the parametrization of the bubble-mediated contribution remains highly uncertain, as concentration fluctuations are confined to a sub-millimetric diffusive layer that is very hard to probe experimentally. We present high-fidelity two-phase Direct Numerical Simulations of gas transfer during the breaking of third-order Stokes waves, giving direct access to the time-resolved concentration field, the total air-water interface area and the gas transfer velocity with an accuracy unattainable in experiments [1].

The incompressible Navier-Stokes equations with variable properties across the interface are solved with an in-house geometric Volume-of-Fluid solver [2], augmented with a single-field model for interfacial gas diffusion satisfying Henry's law. Simulations are carried out at $We = 12,000$, $Re = 10,000$ and $40,000$, for initial steepness $\varepsilon = 0.25, 0.37$ and 0.50 , spanning non-breaking waves, mild spilling breakers and intense plunging breakers, on grids of up to $1152 \times 768 \times 576$ points.

The volume of gas transferred across the interface increases significantly with the entrained air, with peaks of transfer velocity concurrent with the peaks of energy dissipation rate and interface area: during plunging breaking the interface area doubles, and the gas flux grows even more than the sole area increase would imply, as bubble fragmentation magnifies the gradients around the interface (Fig. 1). The transfer velocity scales approximately as the one-fourth power of the energy dissipation rate, consistent with surface-renewal predictions [3], while the common waterplane-area estimate overestimates it by nearly a factor of two in plunging cases. Accounting for the active breaking area, the value extrapolated to $Sc = 660$ falls within the range of microbreaking experiments [4], helping constrain the parametrization of oceanic CO_2 uptake.

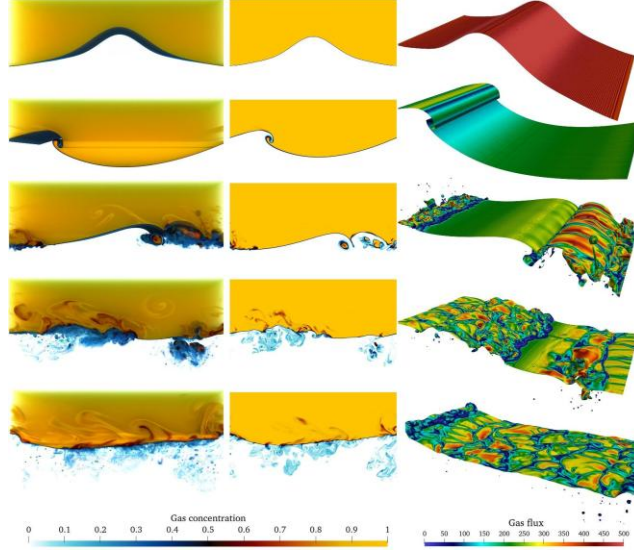


Fig. 1: Gas concentration (left, center) and interface gas flux (right) for $\varepsilon = 0.50$, $Re = 40,000$, at $t/T_p = 0, 0.5, 1, 1.5, 2$ (top to bottom) [1].

References

- [1] Di Giorgio, S., Pirozzoli, S. & Iafrati, A. (2025). Air entrainment and gas transfer in wave breaking events. *Geophys. Res. Lett.*, 52, e2025GL114907.
- [2] Di Giorgio, S., Pirozzoli, S. & Iafrati, A. (2022). On coherent vortical structures in wave breaking. *J. Fluid Mech.*, 947, A44.
- [3] Lamont, J. & Scott, D. (1970). An eddy cell model of mass transfer into the surface of a turbulent liquid. *AIChE J.*, 16, 513–519.
- [4] Zappa, C.J., Asher, W. & Jessup, A. (2001). Microscale wave breaking and air-water gas transfer. *J. Geophys. Res.*, 106(C5), 9385–9391.

Kinematics and growth rates of nonlinear gravity-capillary waves under wind forcing and underwater currents

Clara Martín Blanco, Luc Deike, Princeton University

We present direct numerical simulations of broadband gravity-capillary waves forced by a turbulent atmospheric boundary layer coupled with a developing underwater current, using the Basilisk solver. The wavenumber-frequency spectrum $\Phi(k, \omega)$ reveals wave energy propagating along multiple distinct branches: a primary branch following the linear dispersion relation, and higher-order branches associated with nonlinear bound harmonics. These harmonics travel at the phase speed of their carrier mode and are well described by a generalized Doppler-shifted nonlinear dispersion relation that remains valid as the underwater current transitions from a viscous to a turbulent regime. The number of observable branches increases with wave steepness, and the scale-dependent Doppler shift — consistent with the Stewart & Joy (1974) framework — allows reconstruction of the depth-varying current profile from the measured phase velocities.

Building on this kinematic framework established in Martín-Blanco et al. (*J. Fluid Mech.*, 2026), we investigate how the presence of nonlinear harmonic branches affects the dynamics of the waves. Growth rates $\beta(k)$ measured directly in wavenumber space conflate contributions from free and bound wave modes, so understanding them requires separating the harmonic branches in the (k, ω) plane. We show that the growth rate of the N -th harmonic $\beta_N(k)$ differs from that of the carrier mode $\beta_1(k)$ it is bound to — at a given wavenumber, bound harmonics can grow while the free wave decays — and we examine how wave steepness and wind forcing control both the branch growth rates and the spectral broadening of each branch.

Heat transport through a turbulent interface in a Rayleigh-Bénard configuration

Detlef Lohse, University of Twente

Rayleigh-Bénard (RB) flow has been used for more than a century to test various concepts in physics of fluid dynamics, from linear stability theory to pattern formation to turbulence. Here we employ turbulent two-phase flow RB systems to study interfaces between turbulent flows and in particular the heat transfer through such interfaces and the flow structures of such systems.

First, we will provide numerical and theoretical results on the breakup of the interface between two liquid turbulent layers of equal size, where we identify two different mechanisms, depending on the interfacial tension and the density ratio. Then we will extend this study and explain the dependence of the heat transfer and the flow structure on the volume fractions and on the interfacial tension.

This is joint work with Hao-Ran Liu, Kai Leong Chong, Rui Yang, and Roberto Verzicco and has been published in two articles in Journal of Fluid Mechanics.

Simultaneous measurements of air- and water-side flow across surface wind waves

Kianoosh Yousefi¹, Fabio Addona² and Fabrice Veron³

¹*Department of Mechanical Engineering, University of Texas at Dallas, Richardson, TX 75080, USA*

²*Department of Engineering and Architecture, University of Parma, Parma, 43124, Italy*

³*School of Marine Science and Policy, University of Delaware, Newark, DE 19716, USA*

Understanding air-sea fluxes requires simultaneous, phase-resolved measurements on both sides of the interface, particularly during the early stages of wave development when wave-coherent motion, shear-driven turbulence, and transient dynamics are tightly linked. In this study, we present a laboratory investigation of wind-driven waves using a combination of particle image velocimetry (PIV) and laser-induced fluorescence (LIF) to simultaneously measure velocity fields in both air- and water-side boundary layers. The dual-phase PIV-LIF measurements provide a direct, phase-resolved view of coupled dynamics across the air-water interface during both spin-up and quasi-steady regimes. The experiments span various wind-wave conditions with 10-m equivalent wind speeds of approximately 7-14 m/s, producing non-breaking, fetch-limited wind waves. The simultaneous velocity fields reveal asymmetric near-interface dynamics. In the air, localized regions of reduced or reversed streamwise velocity repeatedly develop on the leeward side of steep waves, co-located with enhanced vertical motion and intense near-surface shear layers, consistent with intermittent separation/reattachment events. Instantaneous spanwise-vorticity fields show thin, wave-modulated shear layers and Kelvin-Helmholtz-like roll-up, whereas the water-side vorticity is broader, more phase-locked, and set by orbital shear and subsurface mixing. Depth-resolved vorticity statistics quantify this asymmetry, showing that air-side vorticity extremes peak within a thin near-surface shear zone and decay rapidly with height, while water-side intermittency persists through a thicker boundary layer. Finally, an interfacial coupling metric based on the maximum normalized cross-correlation between air- and water-side velocity fluctuations shows near-unity coupling adjacent to the interface during the first 30 s of spin-up, followed by moderate quasi-steady coupling that decreases monotonically with depth; low-frequency motions exhibit intermittent, vertically coherent coupling events not captured by wave-coherent band correlations alone.

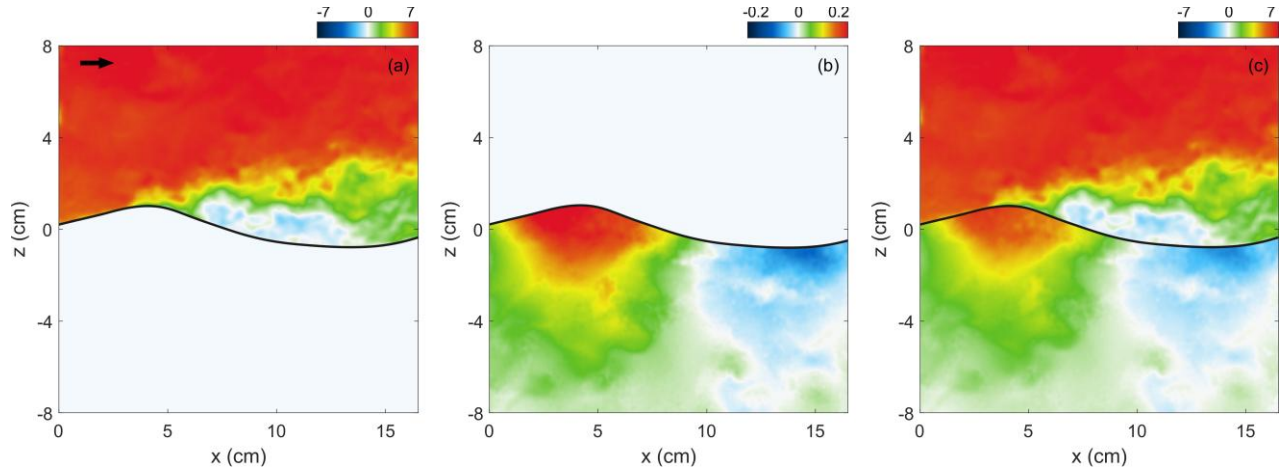


Figure 1: Instantaneous velocity fields for the experimental condition with $U_{10} = 7.6$ m/s in (a) the air phase, (b) the water phase, and (c) the combined air-water domain.

Wave-induced drift on a rotating Earth

Ton van den Bremer, TU Delft

Waves transport particles in the direction of wave propagation with the Stokes drift. When the Earth's rotation is accounted for, waves induce an additional (Eulerian-mean) current that reduces drift and is known as the anti-Stokes drift. This effect is often ignored in oceanic particle-tracking simulations, despite being important. Although different theoretical models exist, they have not been validated by experiments. We conduct laboratory experiments studying the drift induced by deep-water waves over the entire water column in a purpose-built rotating wave flume. With rotation, the Lagrangian-mean drift deflects to the right (counterclockwise rotation) and reduces in magnitude. Compared with two existing steady theoretical models, measured drift speed at the surface follows a similar trend with wave Ekman number but is larger. The difference is largely explained by unsteadiness on inertial time scales. The drift velocity shows (near-)inertial oscillations at every depth in the interior of the fluid with a mean that is greatly reduced compared to the non-rotating case, as predicted by theory. Without rotation, the Stokes drift is balanced by a depth-uniform return flow to ensure a zero net horizontal mass flux. This return flow also plays a crucial role in determining the magnitude of the inertial oscillations. We extend existing theoretical models by including the depth-uniform return flow in the initial condition and find good agreement for short times (one inertial period) but not for long times (many inertial periods) when damping of the inertial oscillations dominates. These findings highlight the role of (non-wave-driven) background currents in determining the amplitude of wave-driven inertial oscillations.

Gas transfer at the air-sea interface: integrating small scale bubble dynamics into large scale ocean models

Luc Deike, Princeton University

Bubble-mediated gas exchange associated with wave breaking is a critical pathway for ocean–atmosphere exchange of low solubility gases such as oxygen. Yet, ocean and climate models, as well as observation-based products, usually rely on wind-only air–sea flux formulations derived from carbon constraints that ignore the asymmetric nature of the bubble flux, contributing to discrepancies between estimates of oxygen inventories and their response to climate change. Without bubbles, gas exchange is controlled by a symmetric wind-driven exchange, with the ocean–atmosphere gas partial pressure difference controlling whether outgassing or uptake occurs. Bubbles entrained by wave breaking can enhance this symmetric turbulent exchange, and contribute an additional asymmetric flux, always leading to an uptake, as they get squeezed by hydrostatic pressure (large bubbles) or collapse and fully dissolve (small bubbles). We present an observation-constrained theoretical framework of the air–sea flux accounting for air entrainment due to wave breaking and symmetric and asymmetric bubble exchange. The combined evidence from theory, laboratory, and field measurements of carbon dioxide fluxes, oxygen concentration, and noble gas supersaturation yields a universal formulation of gas exchange which we implement into a global ocean biogeochemical model. We discuss the resulting carbon and oxygen fluxes. We demonstrate good agreement with carbon dioxide eddy covariance measurements and demonstrate that our wind–wave–bubble formulation better reproduces observed in situ oxygen concentrations in water mass formation regions, where air–sea exchange is high, than a commonly used wind-only formulation. We show that the asymmetric bubble flux is essential for evaluating air–sea oxygen fluxes and estimating the magnitude of the ocean oxygen loss associated with global warming.

Sea Spray – bulk and microphysics coupled wave-atmosphere frameworks

Sophia Brumer, University of Toulouse, CNRS

Sea spray generated by wave breaking exchange heat and momentum with the atmosphere. The enthalpy flux they induce is thought to play an important role in the intensification of tropical cyclones (TCs) while potentially inhibiting that of less powerful storms. The impact of sea spray depends on the number of droplets ejected and their size distribution described by a Sea Spray Generation Function (SSGF). SSGFs proposed in the literature are functions of wind speed and wave parameters but lack of direct measurements over the ocean result in high uncertainties. While existing SSGFs can readily be used to parameterize sea spray fluxes in bulk formulations of air-sea fluxes, they need to be adapted for efficient explicit microphysics schemes which allow to model the sea spray's life cycle in the atmosphere. In microphysics schemes a prognostic droplet population is transported and sea spray can evaporates/condensates beyond the surface layer potentially reaching several hundreds of meters in altitude in highly convective environments such as in TCs. For reduced computational cost, the droplet population is represented by the sum of distributions whose moments' evolution in time and space is modeled. Here I will present recent efforts to include sea spray in bulk algorithms and a log-normal microphysics scheme used a coupled model framework combining WAVEWATCH-III and the French community atmospheric model Meso-NH. Simulations at the km-scale will illustrate sea spray impacts in TCs and sensitivity to SSGFs and wave model physics will be discussed.

Wave-Induced Turbulence, Linking Small and Large Scales in the Upper Ocean

Alex Babanin, The University of Melbourne, Australia, a.babanin@unimelb.edu.au

Until recently, large-scale models did not explicitly take account of ocean surface waves which are a process of much smaller scales. However, it is rapidly becoming clear that many large-scale geophysical processes are essentially coupled with the surface waves, and those include ocean circulation, weather, climate, tropical cyclones, sea ice, and other phenomena in the atmosphere, at air/sea/ice/land/bottom interface and in the upper ocean below the surface. Furthermore, rapidly growing computing capabilities allows us to couple small-scale and large-scale environmental models, and therefore research on the coupled nature of such processes intensified significantly over the past two decades.

In the presentation, wave-induced influences at the ocean side, and specifically wave-induced turbulence and effects caused by its presence, will be discussed. In the system of surface waves, there are two different and largely unrelated length scales: wave height/amplitude and wavelength, and, respectively, there are two different associated mechanisms for wave turbulence: turbulence produced by wave breaking and that produced by wave orbital motion. The former is distributed at the scale of wave height away from the surface, and the latter at the scale of wavelength, i.e. an order of magnitude deeper.

We will briefly discuss the wave-breaking turbulence as it has been a subject of active research for decades, and will mostly concentrate on the wave-orbit-induced turbulence and related dynamics. Among such dynamics, the ocean mixing is among most important, particularly as turbulence produced by the orbital motion of surface waves is mostly not accounted for directly in oceanographic studies and practice, and this fact limits performance of the models for the upper-ocean circulation and ultimately for large-scale air-sea interactions, all the way to climate.

Theory and practical applications for the wave-induced turbulence will be reviewed in the presentation. These include viscous and instability theories of wave turbulence, direct numerical simulations and laboratory experiments, field and remote sensing observations and validations.

Impact of the wave mixing cannot be accounted for on average, or by tuning the mixing schemes in ocean models, because it is only relevant in presence of waves, i.e. coupling of wave- and ocean models is necessary. During storms, effects due to this impact are of the first order, they are not small and are comparable in magnitude with other wave-mixing processes. Outcomes of implementation of wave coupling with the upper-ocean circulation will be discussed and demonstrated in context of describing and prediction of upper-ocean dynamics and mixing, tropical-cyclone intensity, marginal ice zone, biogeochemistry, gas transfer, climate modelling.

Direct numerical simulations of spume production on ocean waves

Wouter Mostert, Oxford University, UK

The production of wind-driven sea spray, or spume, on the crests of ocean waves has long been considered to involve the direct action of wind on small-scale disturbances travelling on larger wave crests. Here we study the phenomenon by using direct numerical simulations of wind blowing over waves which have been perturbed by small, high-wavenumber monochromatic perturbations. We solve the variable-density Navier-Stokes equations with surface tension, in both two- (2D) and three-dimensional (3D) formulations. First, in 2D, a very steep periodic wave is initialised in the domain in the presence of an appropriate monochromatic perturbation wave. As the long wave approaches breaking, the perturbation wave undergoes explosive growth near or on the crest of the long wave (see e.g. Maileybaev & Nachbin, 2019). The phenomenon can be reproduced in 3D in the presence of a turbulent wind, and in this case the exploding perturbations can be inflated into bags (e.g. Troitskaya et al. 2017) and atomized by the wind above an appropriate threshold. In this talk we will discuss the role of perturbation wavenumber and slope, effective inverse wave age,

capillary and viscous effects, and any considerations for development for an appropriate parametrization describing bag formation and fragmentation on the wave crest.

Turbulence matters at the air-water interface

R. Jason Hearst, *Norwegian University of Science & Technology (NTNU)*

The air–sea interface is inherently complex and arises from a range of interacting processes, including wind forcing, water motion, waves, and chemistry. At NTNU, using our new air–water channel, we investigate the air–water interface by independently controlling wind, water flow, and waves to study how these processes interact and compete. The facility is novel in that it features active turbulence grids in both phases, allowing turbulence intensity, length scales, and intermittency to be adjusted independently in the air and the water.

Results for early stage wave development will be presented. Specifically, the wind velocity (U_{10}), surface topology characterised by the mean-square surface slope ($\langle(\partial\eta/\partial x)^2\rangle$), and the friction velocity (u^*) will be shown. It will be demonstrated that if the air-phase flow experiences a change in outer (away from the water) turbulence, it manifests in u^* at the surface. This then means that one can have different u^* values for the same U_{10} . The consequence of this is that scalings of the surface based on U_{10} fail. However, it will be demonstrated that rescaling based on u^* , or a U_{10} derived from u^* , is able to collapse the mean-square surface slope onto a single line for the various conditions. Interestingly, when compared with the field measurements of Lenain *et al.* (*J Phys Oceanog.*, 2019), the slope of the u^* vs. $\langle(\partial\eta/\partial x)^2\rangle$ curve is almost identical. It will further be demonstrated that changing the outer turbulence can have as significant an effect as changing U_{10} by 2 m/s. This suggests that turbulence effects are first-order, not second-order. Simultaneous measurements of the air flow, water flow, and surface topology will also be presented to demonstrate that spectral coherence exists between the turbulence above the surface and the surface itself. Finally, results for the gas transfer at various water turbulence intensities will be presented alongside a quantifiable imaging technique to map instantaneous fields of dissolved O_2 in water.

This work is unified under a constant theme: that turbulence around the air-water interface can play a significant (first-order) role in the way the interface manifests and on transport processes surrounding it.

Scaling Laws for Ice Ripple Celerity under Turbulent Shear

Diego Perissutti^{1,2}, Cristian Marchioli², and Alfredo Soldati^{1,2,}*

¹*Institute of Fluid mechanics and Heat Transfer, TU Wien, 1060 Wien, Austria*

²*Polytechnic Department, University of Udine, 33100 Udine, Italy*

Interfacial ripples generated by turbulent shear over melting ice strongly affect heat transfer and boundary-layer dynamics, yet their migration speed remains poorly understood. Using direct numerical simulations of turbulent flow over melting ice at shear Reynolds numbers $Re\tau = 848$ –1600 and Stefan numbers $St = 0.1$ –10, we investigate the celerity of self-organized ice ripples. Extending classical quasi-steady stability theory, we derive a finite-diffusion correction that introduces a dimensionless effective Stefan number $S = St + 1/3$. Two independent measurements - spectral phase tracking and Lagrangian crest tracking - show that ripple celerity obeys the universal scaling $c \sim S - 1/Re\tau - 1/1$. The proposed scaling collapses all simulated conditions and provides a predictive framework for shear-driven interfacial morphodynamics relevant to ice–ocean interactions.

CO₂ gas transport across strongly turbulent free surfaces: insights from direct numerical simulations

Kevin Zhong¹, **Simone di Giorgio²**, **Alessandro Iafrati²**, **Roberto Verzicco^{1,3}** and **Detlef Lohse^{1,4}**

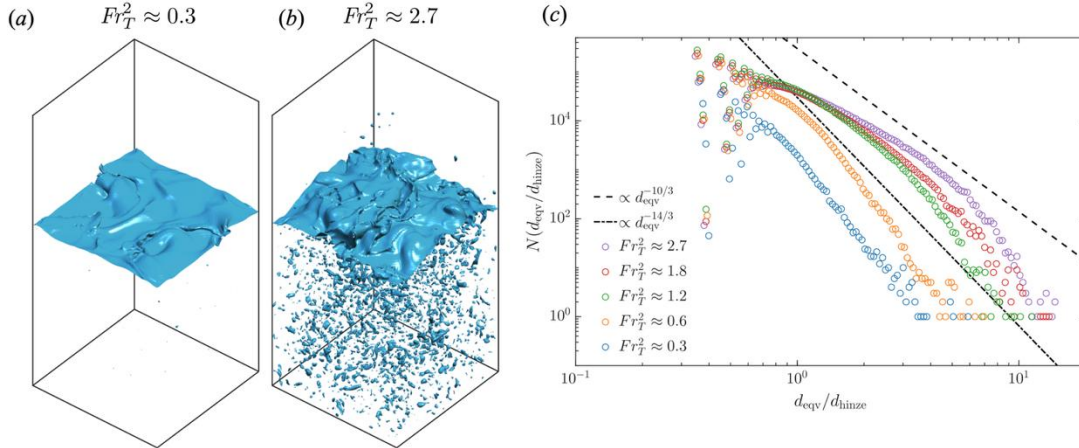
¹ Physics of Fluids Department, Max Planck Center for Complex Fluid Dynamics, and J.M. Burgers Centre for Fluid Dynamics, University of Twente, P.O. Box 217, Enschede 7500AE, The Netherlands

² Istituto di Ingegneria del Mare, Consiglio Nazionale delle Ricerche, Via di Vallerano 139, Rome 00128, Italy

³ Gran Sasso Science Institute, Viale F. Crispi, 7, 67100, L'Aquila, Italy

⁴ Max Planck Institute for Dynamics and Self-Organization, Am Fassberg 17, Göttingen 37077, Germany

Understanding CO₂ transport across the air–sea interface is critical for accurately modelling the oceanic carbon cycle. Here, we focus on two mechanisms known to significantly enhance this transport: turbulence and bubble entrainment. We investigate this using direct numerical simulations, where the setup coincides with that of ref. [1]. The flow is forced below the free surface and maintains a statistically steady state, providing an ideal setting for collecting turbulence statistics while avoiding the transient nature and additional complexities of classical breaking-wave simulations. CO₂ transport is modelled with the mixture mode of ref. [2]. Our central objective is to understand how the CO₂ flux depends on the relevant dynamical control parameters. In particular, we consider the Reynolds number, Re_T , which characterizes the strength of turbulent forcing, and the turbulent Froude number, Fr_T , which measures the relative importance of inertia against gravity. As seen in Fig. 1(a,b), Fr_T plays a decisive role in setting the bubble entrainment, and consequently, the bubble-mediated transfer of CO₂. A key quantity governing this contribution is the bubble size distribution, $N(d_{eqv})$, where d_{eqv} is the bubble equivalent diameter. The distributions shown in Fig. 1(c) reveal an interplay between fragmentation-driven dynamics ($N \propto d_{eqv}^{-10/3}$) [3] and entrainment-driven dynamics ($N \propto d_{eqv}^{-14/3}$). The competition between these regimes modifies the bubble population and therefore the resulting bubble-mediated gas transfer. These findings provide insight in the link between



turbulent free-surface dynamics and CO₂ exchange across the air–water interface.

Fig. 1: (a,b) Visualizations of the air–water interface showing strong dependence of bubble entrainment on Fr_T . (c) Bubble size distribution $N(d_{eqv})$ normalized on the Hinze scale d_{hinze} at varying Fr_T^2 . Reference lines for fragmentation-driven scaling $N \propto d_{eqv}^{-10/3}$ [1] and entrainment-driven scaling $N \propto d_{eqv}^{-14/3}$ [3] are provided.

References

- [1] D. B. Gaylo and D. K. P. Yue. Size distribution of large air bubbles entrained by strong free-surface turbulence. *J. Fluid Mech.*, 1020:A40, 2025.
- [2] D. Deising, H. Marschall, and D. Bothe. A unified single-field model framework for volume-of-fluid simulations of interfacial species transfer applied to bubbly flows. *Chem. Eng. Sci.*, 139:173–195, 2016.
- [3] G. B. Deane and M. D. Stokes. Scale dependence of bubble creation mechanisms in breaking waves. *Nature*, 418(6900):839–844, 2002.

How does a free surface deform in response to subsurface turbulence?

Daniel J. Ruth, Filippo Coletti, ETH Zurich

The flow just beneath the surface of a natural body of water is often turbulent, with the turbulence responsible for enabling interfacial transport processes. This near-surface turbulence is, to an extent, visible to the eye: in competition with gravity and surface tension, pressure fluctuations in the turbulence locally raise and lower the surface of the water, yielding a topological imprint of the near-surface flow on the interface.

We use the Euler equations evaluated at the free surface to model the surface-subsurface link, assessing the model with simultaneous time-resolved particle image velocimetry measurements of the sub-surface flow and background-oriented schlieren measurements of the surface deformation (as illustrated in Figure 1). A substantial instantaneous, local correlation (~ 0.5) between the measured and modeled surface curvature is obtained when pressure fluctuations are inferred from velocities taken less than a Taylor microscale beneath the surface.

We next investigate the depth dependence of this correlation—that is, how the relationship between the surface topology and the pressure fluctuations at a given depth weakens as that depth increases. The horizontal footprint of the smallest structure which influences the surface shape increases with the depth, providing information on which flow structures may be accessible from optical remote sensing techniques.

Finally, we investigate the behavior of gravity-capillary waves propagating on the surface. The measured surface curvature is decomposed into wavy and non-wavy motions with a spectral technique (accounting for the local Doppler shifts induced by the turbulent velocity field), and we then employ the action balance equation to understand the development of the waves.

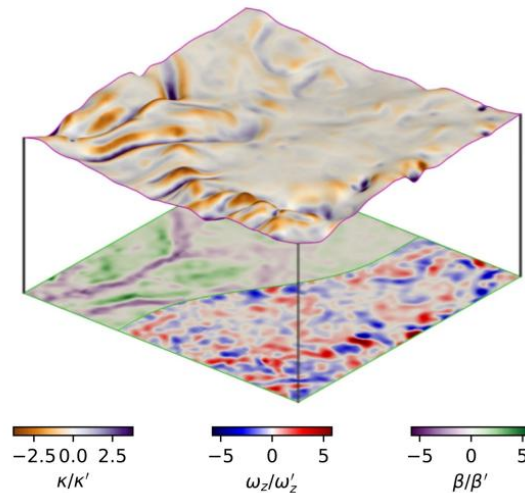


Figure 1. The simultaneous measurement of the water surface elevation (top, colored by the local curvature κ) and near-surface velocity field, represented by its vertical vorticity ω_z and horizontal divergence β .

Energy dissipation and coherent vortical structures in breaking waves

Alessandro Iafrati¹, Simone Di Giorgio¹ and Sergio Pirozzoli²

¹*Institute of Marine Engineering, CNR-INM, Rome, Italy;* ²*Dept. of Mechanical and Aerospace, Engineering, Sapienza University of Rome, Rome, Italy, alessandro.iafrati@cnr.it*

Wave breaking is the primary sink of energy of the wave field and a key driver of momentum, heat and gas exchange between atmosphere and ocean, yet the mechanisms by which the wave energy is dissipated remain only partially understood. Early two-dimensional two-phase Navier-Stokes simulations of third-order Stokes waves in a periodic domain highlight the different dissipation mechanisms characterizing spilling and plunging breaking waves: in spilling breakers the excess energy focuses into a bulge riding on the crest and is gradually dissipated by the shear layer at its toe, whereas in plunging breakers a substantial fraction of the dissipated energy, from about 10% up to 35% depending on the breaking intensity, is first spent in entraining the air cavity against buoyancy, and is mostly dissipated when the cavity collapses into a bubble cloud, with the total viscous dissipation decaying as t^{-2} after the onset [1].

Fully three-dimensional simulations at $Re = 10,000$ and $40,000$, performed with a more recent energy-preserving VOF solver, confirm this picture and allow the dissipation mechanisms to be related to the coherent vortical structures generated by the breaking [2]. Vortex tubes and vortex sheets are identified through dedicated vorticity-like indicators (Fig. 1): the correlation with the local dissipation rate shows that viscous dissipation is associated primarily with the vortex sheets, both in the mixing zone and in the pure water domain where the structures are transported downward, whereas vortex tubes, generated by sheet roll-up, mainly govern the flow intermittency. Although air entrainment and bubble fragmentation differ remarkably at the two Reynolds numbers, the dissipated energy fraction is essentially the same.

The reliability of these energy budgets rests on the numerical model. A dedicated validation study on a multiscale phase-inversion benchmark [3] shows that the surface tension contribution, usually neglected, may have a role in the energy balance: the estimate based on the time integral of the surface tension power fails to capture the positive work released when poorly resolved bubbles shrink or disappear, thereby overestimating the artificial dissipation of the scheme, while the estimate based on the interface area proves far more reliable.

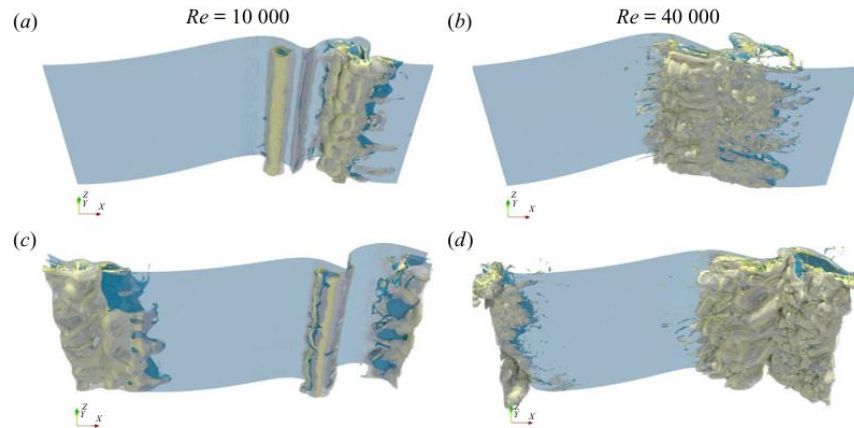


Fig. 1: Underwater view of vortex tubes (yellow, $\omega t = 20$ iso-surfaces) and vortex sheets (grey, $\omega s = 20$) in a plunging breaker at $Re = 10,000$ (left) and $Re = 40,000$ (right), at two instants during the breaking [2].

References

- [1] Iafrati, A. (2011). Energy dissipation mechanisms in wave breaking processes: spilling and highly aerated plunging breaking events. *J. Geophys. Res.*, 116, C07024.
- [2] Di Giorgio, S., Pirozzoli, S. & Iafrati, A. (2022). On coherent vortical structures in wave breaking. *J. Fluid Mech.*, 947, A44.
- [3] Di Giorgio, S., Pirozzoli, S. & Iafrati, A. (2024). Evaluation of advection schemes and surface tension model for algebraic and geometric VOF multiphase flow solvers. *J. Comput. Phys.*, 499, 112717.

Direct experimental measurement of wave-enhanced mixing in Langmuir(like) turbulence

Olav Rømcke, Priyanka Gautam, Øyvind Breivik, Mika P. Malila, R. Jason Hearst, S. Å. Ellingsen

Langmuir turbulence is a key mechanism to enhance mixing in the upper ocean. Although often associated with wind, the theoretical framework proposed by Craik and Leibovich requires only vorticity and wave-induced Stokes drift, regardless of their cause. In a laboratory flume we make waves interact with pre-existing turbulence to measure the vertical transport of a passive scalar directly. Once waves appear, the turbulent flow changes radically with long, intense Langmuir(like) vortices forming near the surface, aligned with the wave direction. Combining simultaneous stereo particle-image velocimetry and laser-induced fluorescence in the same field of view, we measure the instantaneous turbulent velocity field and the concentration field of a surface-injected dye, showing dramatic enhancement and deepening of the vertical turbulent scalar flux, increasing with wave steepness. The Langmuir enhancement factor for mixing is measured in the range 4 to 6. The results are consistent with three different variants of the most-used parameterization of oceanic wave-induced mixing, the KPP model.