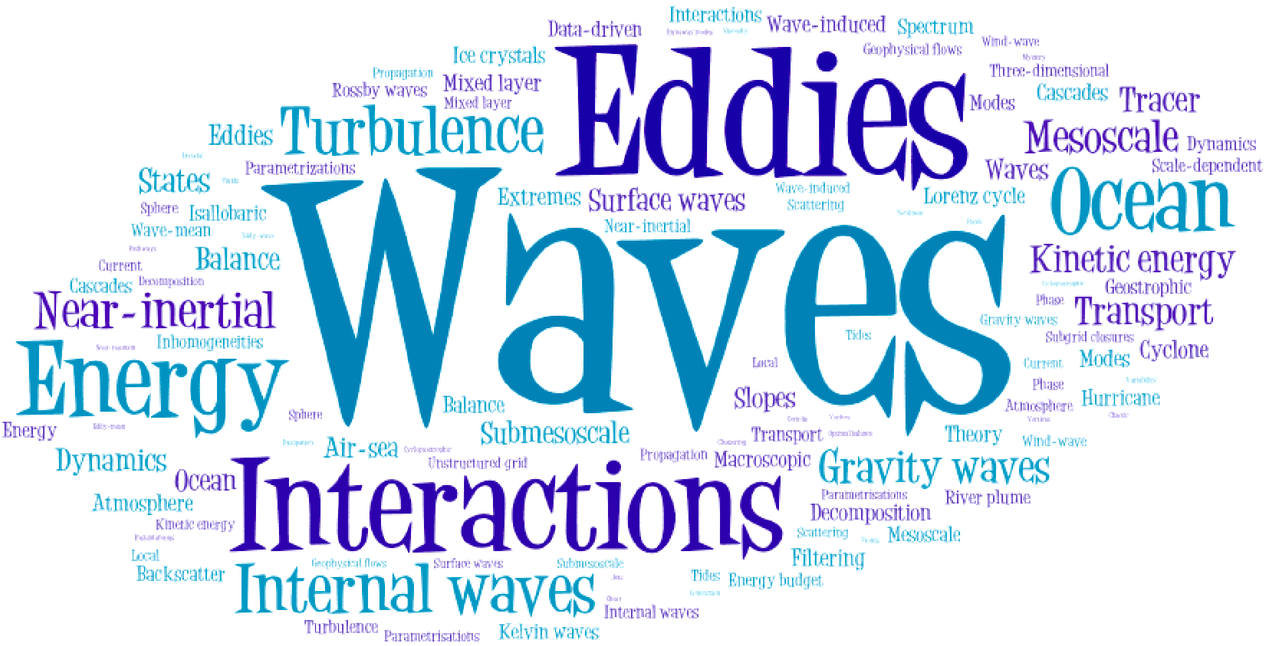
Eddies and Waves:
Theory, Models, and Observations

28-30 April 2026, Hamburg



TRR181

Welcome Address

This workshop is a continuation of a series of international workshops we have organised over the last decade within the framework of the collaborative project TRR 181 “Energy Transfers in Atmosphere and Ocean”, on the topics of eddies and waves both in ocean and atmosphere, from theory, modelling, and observations.

The workshop is aimed at enhancing our understanding of the interactions and energy transfers between balanced eddies and internal and/or surface waves, their generation and dissipation mechanisms, as well as their relevance to the global energy cycle, and how to parameterise them in numerical or conceptual models.

With this meeting, we intend to bring together the recent advancements in oceanography, meteorology, and geophysical fluid dynamics by combining theory, modelling, observations, and novel developments in data science.

Best wishes!

Organizing Committee:

Manita Chouksey
Carsten Eden

Contents

Abstracts: Talks

Waves and eddies in geophysical fluids

Leo Maas

University of Utrecht

Geophysical fluids - fluids subject to Earth's gravity and rotation - display an inverse energy cascade and anisotropy. This is illustrated by lab experiments in which internal or inertial waves of fixed inclination are generated by periodical forcing. Sloping boundaries focuses these waves. Their associated intensified shear gives rise to instabilities, TRI and mixing, which generates a sheared, unstable mean flow developing a vortex cluster.

Interactions of near-inertial waves and vortices under cyclogeostrophic balance

Yilin Xiao[1], Hossein Kafiabad[1] and Laura Currie[1]

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We expand the phase-averaged model of YBJ to cyclogeostrophic balance, which better describes submesoscale vortices. Using anticyclonic shielded vortices, we formulate an eigenproblem to characterise wave trapping and validate the results with high-resolution 3D Boussinesq simulations.

On wave-induced viscosity: Revealing a long-standing mystery

Dirk Olbers

Alfred-Wegener-Institut

We revisit Mueller's (1976) analysis on wave-induced viscosities. The interaction of small-scale internal gravity waves with a large-scale shear flow was analyzed and a very large vertical viscosity, of order $1\text{m}^2\text{s}^{-1}$, was found. It could never be substantiated in observed relations between wave-induced stress and mean vertical shear. The origin of the failure of the theory, however, was never revealed. On the contrary, Mueller's approach is still used for the interaction of waves with a mean horizontal shear and leading to reasonably sized wave-induced horizontal viscosities. Mueller's theory is based on seemingly harmless assumptions – an ocean wave climate was taken as basis, an isotropic Garrett-Munk state. We solve the energy balance (radiation balance) of the problem exactly, with forcing and boundary conditions at top and bottom, and show where the failure occurs. The interactions lead to an intrinsically anisotropic state which is non-viscous. Only in case that vertical propagation times are less than characteristic interaction times of the wave-mean flow process viscous behavior becomes possible and much smaller viscosities apply which are orders of magnitude smaller than Mueller's values.

Optimal balance in geophysical models with non uniform Coriolis parameter

Ojesh Koul[1], Silvano Rosenau[2], Manita Chouksey[2,3] Carsten Eden[2], and Marcel Oliver[1]

[1]Catholic University of Eichstaett-Ingolstadt; [2]Universität Hamburg; [3]Leibniz Institute for Baltic Sea Research Warnemünde

We investigate the method of optimal balance for the decomposition of flows into slowly varying balanced and fast varying unbalanced parts. This decomposition finds application in areas such as improving weather predictions, gravity wave parametrizations. The method works due to the balanced component evolving on an almost adiabatic invariant manifold under slowly varying perturbations. A ramp function is used to slowly deform the fully non linear system into a linear system where the balanced part and unbalanced part of the system are clearly delineated. While in the linear state, the unbalanced part of the flow is projected out. This requires explicit knowledge of the projection operator, which is available when the Coriolis parameter is uniform. This is not the case when a non-uniform Coriolis parameter is involved. In this study we extend the method by using the ramping process to eliminate the Coriolis force as well, deforming to a linear, non-rotating system where the balanced component is stationary and can be obtained by either a projection operator or by averaging out the fast varying unbalanced component. We show, through numerical experiments, that the balanced component is an adiabatic invariant of the ramping process and that the leakage into unbalanced components decreases rapidly with decreasing Rossby number and increasing ramping period. We supplement these results with analytical estimates of leakage from the balanced component into the unbalanced component showing the invariance of eigenstates of the linear system when the Coriolis terms are slowly ramped to zero and show that leakages into unbalanced states get exponentially small as ramp duration is increased.

The case of the invisible waves: Emission by jets and fronts

Manita Chouksey[1,2] and Carsten Eden[2]

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Rotating stratified flows, such as the ocean and atmosphere, appear as a two-timescale system featuring slow balanced and fast gravity wave dynamics. The balanced flow can nonlinearly generate unbalanced internal gravity waves via spontaneous loss of balance. How much of these 'apparent' wave signals are really gravity waves? Here, we investigate the case of the 'invisible' (or apparently visible) waves generated from jets and fronts, with nonlinear flow decomposition applied to an idealised atmospheric model of the baroclinic lifecycle of the jet stream. We discuss whether the wave-like structures in the upper troposphere are in fact part of the balanced flow, the so-called 'slaved modes', or true gravity wave signals.

Tropical convective organization maintained by inverse cascade driven by gravity waves

Jun-ichi Yano
CNRM, Météo France, and CNRS

Analysis of the idealized convection-resolving simulation shows that the kinetic energy is transferred upscales in association with tropical convective organizations. The energy-cycle analysis in wavelet furhter shows that the transient gravity waves are main responsible for this nonlinear cascade process.

The curious occurrence of runaway modes

Jens Rademacher
Universität Hamburg

Runaway modes are unboundedly growing solutions in fluid models and can be exact linear modes in which energy accumulates. I report on their occurence in some geophysically motivated models: (1) Navier-Stokes and Boussinesq with simple kinetic energy backscatter, (2) Fourier-Galerkin mode truncations of rotating convection, (3) a class of troposphere wave models.

Nonlinear normal modes flow decomposition on the sphere based on instantaneous wave phase speeds

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[1]University of Hamburg

Normal modes of hydrostatic primitive equations decompose the flow into the slow propagating Rossby, fast propagating inertio-gravity (IG), and equatorial Kelvin and MRG waves, filling the speed/frequency gap in the linear approximation. However, wave-wave, wave-mean flow interactions, and diabatic forcing can significantly alter the wave speeds in the nonlinear system. Nonlinear normal mode decomposion (NNMD), or nonlinear normal mode initialization (NNMI) when discussed in the context of numerical weather prediction, aims at determining the slowly evolving component of the nonlinear flow , the so called slow manifold. In the classical NNMD, the slow manifold consists of Rossby waves, which are postulated to propagate slowly, plus part of the IG flow that is "slaved" to them, i.e. is pinned stationary in the nonlinear system due to the wave-wave and wave-mean flow interactions. The main drawback of the classical NNMD is that it suppresses slowly propagating tropical circulation. For instance, the Hadley cell is not present in the slow manifold computed with classical NNMD. These issues lead to the NNMD methods being eventually abandoned by the numerical weather prediction community. We propose a new method of fast-slow flow decomposition based on explicitly computing instantaneous phase speeds of the waves in the nonlinear system, without any assumptions on the composition of the slow manifold. Instead, the decomposition is obtained from a constraint optimization problem that minimizes the norm of the fast component, while requiring that the slow manifold does not contain modes propagating faster than the selected cutoff speed. We apply the method to reanalysis data, demonstrate its efficiency, and study the sensitivity to the cutoff speed. When the cutoff is approximately equal to the fastest linear Rossby wave speed, most of the tropical circulation, including the Hadley cell is retained in the slow manifold. Our analysis reveals a number of conceptual questions related to the wave propagation on the sphere, which are poorly understood and will be discussed in the talk.

Pathways to dissipation of near-inertial waves in the presence of mesoscale eddies

M.-Pascale Lelong
NorthWest Research Associates

We examine the life cycle of wind-generated, near-inertial internal waves with a suite of nested high resolution simulations spanning a range of scales from hundreds of kilometers to a few meters. The outer domain encompasses a region that includes the Sidra Gyre, a semi-permanent anticyclone located off the coast of Libya, while the innermost domain moves with the eddy core and is limited to the region at the base of Sidra. The coordinated nested simulations produce a dynamically-coupled flow field consisting of mesoscale eddies, submesoscale filaments, near-inertial and higher frequency internal waves, shear-driven instabilities, and nearly isotropic turbulent motions below the Ozmidov scale, allowing for a comprehensive detailed study of dynamical processes from the meso- to turbulent scales in a realistic ocean setting. Our one-way nesting approach reproduces energy cascades tracked from wind-forced near-inertial waves in the surface mixed layer, through refraction and trapping in a baroclinic anticyclone, downward propagation into the pycnocline, critical-layer amplification and ultimately to shear instability, yielding insight unattainable with stand-alone simulations. We examine the possible pathways to dissipation as the waves and address the fundamental question of how near-inertial internal waves lead to diapycnal mixing: Do near-inertial waves break and directly produce small scale, isotropic turbulence or is there an intermediate transition to large-scale anisotropic turbulence on the path to isotropy and dissipation?

Modelling of Southern Ocean decadal variability arising from eddy-mean interactions

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The Southern Ocean is an important component of the Earth climate system through its role in regulating and impacting the global ocean circulation. The Southern Ocean is known to be strongly turbulent, and that eddies play a role in regulating the mean and vice-versa. It is of interest to understand and model the resulting internal variability arising from such eddy-mean interactions, from a theoretical point of view because it provides further understanding to strongly interacting fluid systems, but also in practical terms because such internal variability is present in eddy-present/rich models but not so in coarse resolution parameterised models, which has consequences for example for anthropogenic carbon uptake. Here a low-order dynamical systems model of the eddy-mean interaction is constructed/derived, bearing resemblance to nonlinear oscillator and/or predator-prey type models of storm-tracks in the atmosphere and those in plasma physics for zonal-flow/drift-wave turbulence. Oscillatory time-scales for the model are derived, and testing is done on whether the derived time-scales are present in a hierarchy of numerical ocean models ranging from layered models to a primitive equation sector model. Evidence is presented that the GEOMETRIC parameterisation for geostrophic mesoscale eddies may improve the representation of decadal variability in the Southern Ocean, potentially leading to impacts in the modelled ventilation of oxygen and anthropogenic carbon in the Southern Ocean.

Diagnosing kinetic energy cascades

Alexa Griesel[1], Julia Dräger-Dietel[1] and Emelie Breunig[1]
[1]Universität Hamburg

The third-order velocity structure function provides a physical-space diagnostic of interscale kinetic energy transfer, as exact turbulence relations link its scaling and sign to the magnitude and direction of the energy cascade. However, its applicability to geophysical flows - characterized by anisotropy, inhomogeneity, and limited inertial ranges— remains uncertain.

Here we diagnose the oceanic energy cascade from satellite-derived surface geostrophic velocities using two approaches: third-order velocity structure functions and the coarse-graining method, which directly quantifies scale-to-scale kinetic energy fluxes in physical space. We assess the consistency between these diagnostics in terms of flux magnitude and direction at mesoscale ranges resolved by altimetry.

Both methods yield generally consistent flux signs at mesoscale ranges, confirming predominant upscale transfer. Nevertheless, some months exhibit apparent downscale fluxes, reflecting temporal variability and the intermittent influence of coherent structures.

Near-resonant eddy-wave interactions on the sphere

Marcel Oliver[1] and Marc Tiofack Kenfack[1]
[1]KU Eichstätt- Ingolstadt

We show that nonlinear transfer of energy between Rossby and gravity wave modes on the sphere takes place predominantely via low-wavenumber Kelvin modes. A first diagnostics is done via an implementation of "optimal balance" in the TIGAR spectral shallow water model. A second approach is the use of a higher-order singular value decomposition (HOSVD) on the structure tensor in a weakly nonlinear approximation. The results qualitatively agree, where the HOSVD gives a fine-grained description of the interacting modes and their sensitivity on system parameters.

Characteristics of mesoscale eddies in the South Indian Ocean and their impacts on basin-scale heat and salt transport

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This study explores the mesoscale eddy dynamics of the South Indian Ocean (30-120°E, 45-5°S) using AVISO altimetry data (1/8° resolution) spanning the period 1993-2023. The results indicate a strong eddy concentration in the southeastern Indian Ocean near the west coast of Australia, decreasing toward the west. The region exhibits a distinct seasonal cycle, characterized by enhanced eddy generation from April to August (southern hemisphere winter), followed by a reduction toward summer. During the peak eddy-generation period (July–October), the mean eddy radius is comparatively small, increasing to a maximum in December-March. Eddy amplitude remains low between May and September and strengthens toward December. Moreover, cyclonic eddies show greater average lifetimes, radii, and amplitudes than their anticyclonic counterparts. Eddies with radii greater than 100 km are predominantly observed north of 25°S. High-amplitude eddies are mainly concentrated in the Agulhas and Agulhas Return Current regions, as well as off the west coast of Australia. The cyclonic eddies generated in the eastern basin tend to propagate southwards, while anticyclonic

eddies tend to propagate northwards. Additionally, a greater number of cyclonic eddies persists for longer duration compared to anticyclonic eddies, with all of them originating off the west coast of Australia, and six of these even lasted for more than 4 years. We aim to quantify the zonal and meridional heat and salt transport associated with these eddies. In addition, we plan to perform eddy-resolving simulations using the MOM6 ocean model to better understand the role of mesoscale eddies in modulating regional ocean circulation and tracer transport.

Internal tide near-inertial wave interactions at deep seamounts around the critical latitude

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Seamounts are prominent bathymetric features widely distributed over the world ocean. They affect the deep ocean circulation by generating internal waves at different frequencies. Internal wave interactions mainly occure through wave-wave triad interactions, which transfer wave energy to smaller scales until they eventually break and dissipate. In this work, we analyse two 3-week lasting moorings that were deployed on the flank of two seamounts in the southwest Pacific, equator- and poleward of the critical latitude for M2 PSI. We show the occurence of triad interactions implying M2 internal tides and near-inertial waves generated at seamounts, which generate M2-f and M2+f waves. Rotary spectra show that poleward of the critical latitude (where M2-f is sub-inertial), the M2-f waves are trapped on the seamount flank and propagate counterclockwise as expected from the theory of coastal-trapped waves. This is to our knowledge the first evidence of wave-wave triad interactions at seamounts.

Clustering and chaotic transport in deforming oceanic eddies

Anu V. S. Nath[1] and Anubhab Roy[2]

[1]École Normale Supérieure de Lyon; [2]Indian Institute of Technology Madras

Understanding how coherent oceanic eddies transport and disperse material is central to problems such as search-and-rescue operations, pollutant spreading, and plankton dynamics. Motivated by this, we study the motion of heavy inertial particles in the flow generated by an isolated, non-axisymmetric vortex. We use the Kirchhoff vortex as a minimal model of a balanced eddy, and its strained counterpart, the Kida vortex, to represent the effect of interacting vortices or large-scale deformation. While heavy particles are typically expelled from vortical regions, we show that non-axisymmetry can instead promote clustering near co-rotating attractors. As particle inertia increases, these attractors migrate, merge, and eventually disappear through bifurcations. When external strain is present, chaotic transport emerges, reflecting the competition between coherent eddy trapping and deformation-induced dispersion. A Melnikov analysis reveals that sufficiently large particle inertia can suppress chaotic transport. These results provide a simple theoretical framework to understand how balanced eddies interacting with background strain influence material transport, mixing, and irreversible pathways, with implications for parameterising subgrid-scale transport in oceanic flows.

Arctic ocean tidal dynamics from high-resolution FESOM model.

Ekaterina Bagaeva[1], Friederike Pollmann[1], Qiang Wang[1], Patrick Scholz[1], Sergey Danilov[1]
[1]Alfred-Wegener-Institut

In this study, we examine tidal forcing as a key driver of internal wave generation in the Arctic Ocean and quantify its contribution to vertical mixing using the internal wave energy model IDEMIX. We analyze the spatial distribution of internal wave energy, associated dissipation rates, and resulting mixing patterns throughout the Arctic basin.

Surface wave-induced mass transport and ocean current responses

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Stokes drift associated with surface waves induces a net mass transport, known as "Stokes transport", which can be comparable in magnitude to wind-driven Ekman transport. It modifies the oceanic dynamics relative to wave-free conditions, and its effects can be parameterized through "Stokes forcing" terms derived from wave-current interaction theory. Here, we provide an overview of large-scale ocean current responses to an imposed Stokes transport field, using idealized wave-resolving and wave-averaged numerical simulations. On superinertial timescales, horizontal convergence and divergence of Stokes transport trigger a gravity-wave adjustment. In contrast, when the transport is sustained over timescales longer than the inertial period, the inertial adjustment results in a Eulerian flow that locally cancels the Stokes transport. The inertial adjustment process to horizontally inhomogeneous Stokes transport is accompanied by surface-layer convergence and divergence, which drive geostrophic flow through an effective Ekman pumping mechanism. In the presence of realistic topography, this effective Ekman pumping further excites topographic Rossby waves.

In situ observations of wind-wave interactions

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Airflow dynamics in the first few centimeters to meters above ocean waves plays a crucial role in setting wind stress and governing air–sea exchange processes. However, direct measurements in this region remain limited due to the challenges of capturing highly turbulent motions near a moving water surface. In this work, we present in situ observations of airflow kinematics above ocean waves under low to moderate wind conditions, obtained using a custom high resolution 2D Particle Image Velocimetry (PIV) system. The setup resolves instantaneous two dimensional velocity fields within the lowest 2 m of the atmosphere above surface waves. Our measurements reveal multiple wind–wave interaction mechanisms occurring simultaneously. Short, slow wind waves (≈1 m wavelength) generate intermittent airflow sheltering, while long, fast waves (≈ 100 m wavelength) induce pronounced orbital motions in the air. On average, the shorter waves consistently produce sheltering effects, consistent with previous laboratory findings. We further examine how variations in wave age and slope shape the observed airflow structures and discuss their combined influence on overall wind stress.

Direct numerical simulations of surface wave-induced forces

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A gradient force, together with the Coriolis-Stokes and vortex force are residual surface-wave driven forces showing up in the equations of motion averaged over the wave cycle under certain assumptions. They are part of the so-called Craik-Leibovich equations, which are often used to understand surface wave-driven (Langmuir) turbulence, and to simulate the wave effects on the ocean's mixed layer in numerical models. The surface wave effects can be implemented in those models by the wave-driven forces without directly resolving the waves, which is otherwise numerically challenging. Since observational or modelling evidence for the surface-wave driven forces is only partly available, we diagnose here the Reynolds stresses of a two-phase model of air and water directly simulating surface waves, to compare with all corresponding forces in the Craik-Leibovich equations in a systematic manner, the first time to our knowledge. We also explore the limits of the assumptions of the Craik-Leibovich equations by using mean flow of different magnitude and shear. It turns out that the Coriolis-Stokes and vortex force are very good approximations within the limits of the assumptions, and that they remain useful even beyond those limits. The gradient force, however, differs from a version put forward in the literature. The latter finding has consequences for the treatment of wave-driven turbulence in mixed layer closures.

The failure of normal modes in quantifying gravity wave propagation in shear flows

Jeff Carpenter
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When studying gravity wave behaviour, it is common practice to conduct a normal mode analysis. This leads to a discrete spectrum of modes to describe the solution. However, this neglects the continuous spectrum, and can lead to incorrect interpretations of gravity wave behaviour.

Revisiting the Lorenz energy cycle with exact local APE theory

Remi Tailleux
University of Reading

The Lorenz energy cycle (LEC) is one of the most widely used diagnostics for characterising ocean circulation energetics. The LEC framework partitions energy into mean and eddy components of kinetic energy (KE) and available potential energy (APE). However, due to historical difficulties in partitioning exact APE into mean and eddy components, APE reservoirs have traditionally been computed using the Lorenz approximation, which treats APE as quadratic in density anomalies relative to the horizontal mean density field. While this approximation considerably simplifies the mathematics of the problem, it introduces significant errors whose nature and magnitude remain poorly understood. This work clarifies these errors by revisiting the LEC using exact local APE theory. We demonstrate that the exact LEC differs from the approximate LEC primarily in two aspects: (1) predictions of APE production rates in equatorial regions, and (2) the mean-to-eddy APE conversion term, which can differ dramatically in certain conditions. These findings have important implications for accurately diagnosing energy pathways in ocean circulation models and observations.

A novel EOF method for internal tide modal decomposition and its application to the Walvis Ridge region

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Max Planck Institute for Meteorology

We investigate the interaction between internal tides (IT) and mesoscale eddies in a 5km ICON simulation using a novel modal decomposition method based on EOF. We argue that the commonly used Sturm–Liouville (SL) approach has difficulty in providing an unambiguous interpretation of the identified three-dimensional nodal structures, due to an inconsistency between the SL eigenvalue, which determines the wavelength locally through the respective dispersion relation, and the plane-wave assumption, which underlies the dispersion relation but implies globally. The novel EOF method alleviates this difficulty by assuming a fixed vertical structure. A comparison between the two methods suggests that the fixed-vertical-structure assumption is appropriate for mode 1, but becomes less accurate for higher modes. As a result, mode 1 can be interpreted as a horizontally propagating wave with the same vertical structure but horizontally varying wavelength, a wave form which has not been explicitly demonstrated for mode-1 IT so far. For M2 internal tide, we show that an Agulhas ring crossing a mode-1 tidal beam leads only to a refraction of the beam, characterized by a southward shift and an essentially unchanged vertical structure, indicating that the Agulhas ring does not scatter mode-1 IT into higher modes. This interpretation is further supported by the fact that higher IT modes are found to be trapped within Agulhas rings before interacting with mode-1 beams.

Scattering of internal gravity waves by inhomogeneities

Michael R. Cox

University of Hamburg

Internal gravity waves are scattered by inhomogeneities, such as background currents and bottom topography. Scattering modifies the wave's length and direction of propagation and in doing so, redistributes energy across wavenumbers and frequencies. When inhomogeneities are large relative to the waves, scattering reduces to a spectral diffusion process. Prior work on spectral diffusion considers only current-induced scattering via Doppler shift of the wave frequency. We generalise the diffusion framework to account for all large-scale inhomogeneities. This includes current-induced effects other than Doppler shift, and entirely different mechanisms such as scattering on bottom topography. We support our results with ray tracing simulations and analytical solutions.

Do near-inertial waves enhance tracer transport across the mixed layer base?

Michal Shaham

Tel Aviv University

Vertical transport of heat, salinity, and biogeochemical tracers from the ocean surface into the interior is governed by mixed-layer dynamics, such as mesoscale eddies and submesoscale flows. Although interactions between internal waves, mesoscale eddies and submesoscale currents are known to modify the upper-ocean energy budget, their role in vertical tracer exchange remains poorly quantified. We address this gap using two nested, realistic simulations of the Eastern Mediterranean Sea: one that forces near-inertial waves (NIWs) and one in which NIWs are suppressed. At low resolution (3km), NIWs enhance tracer export when diagnosed across a fixed, horizontal upper-ocean surface. However, when evaluated relative to an evolving, non-horizontal mixed layer, NIWs primarily deepen the mixed layer rather than increase net tracer export. Process decomposition shows that modifications to advection, vertical mixing, and entrainment associated with mixed-layer deepening explain the apparent export pattern. These results establish the low-resolution baseline and highlight the role of NIWs–eddy interactions in regulating upper-ocean material exchange, motivating the next phase of this ongoing work: higher-resolution simulations to resolve submesoscale effects.

Scale-dependent wave-mean decomposition of kinetic energy from surface drifters

Han Wang

Universität Hamburg

Decomposing wave motions from balanced flows is a fundamental challenge in oceanic fluid dynamics. Lagrangian filtering—frequency filtering of time series measured by passive tracers—provides a robust separation of waves and balanced motions because the relevant time scales are often cleanly split in the Lagrangian frame. Here we apply a Lagrangian-filtering framework to surface drifters designed to follow the upper 1 m of the ocean, with the goal of quantifying the respective contributions of waves and balanced flow to surface kinetic-energy statistics. Using surface-drifter campaign data in the Gulf of Mexico, we compute second-order velocity structure functions for the wave and balanced components across spatial scales, and then perform a Helmholtz decomposition formulated to accommodate anisotropic statistics. A key methodological choice is to implement the filtering within the generalized Lagrangian mean (GLM) framework, in which filtered velocities are attributed to mean trajectories rather than particle trajectories. Beyond its conceptual advantages, the GLM attribution yields diagnostics that are more directly interpretable in the drifter observations. We interpret the results from two complementary perspectives. First, we clarify how GLM-based Lagrangian filtering differs from decompositions (e.g., purely spatial Helmholtz-based partitions) that are often employed as pragmatic alternatives when data or computational resources are limited. Second, the decomposed results provide insight into the seasonally varying dynamics in the Gulf of Mexico. The balanced component exhibits strong submesoscale divergence in both summer and winter. The wave component is broadly consistent with linear wave models, with near-inertial signatures dominating at larger scales; in winter, wave energy increases at smaller spatial scales and the inertial peak broadens in frequency space, compatible with enhanced transfer from the mean/balanced flow into the wave field. These results demonstrate how GLM-based Lagrangian filtering can provide a scale-aware and energetically interpretable partition of drifter kinetic energy, supporting observational constraints on wave–eddy interactions and surface energy transfers.

Abstracts: Posters

Spatial filtering framework for scale-aware turbulence modeling on the ICON unstructured grid

Aditya Baksi
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Dynamic sub grid-scale turbulence closures require explicit spatial filtering to separate resolved and sub filter-scale contributions. In unstructured-grid atmospheric models, such as ICON, constructing consistent filtering operators is nontrivial due to the triangular mesh and the staggered placement of prognostic variables on cells and edges. This work presents the implementation of a spatial filtering framework for the ICON nonhydrostatic dynamical core, designed as methodological infrastructure for scale-aware turbulence modeling. A coarse-graining filter based on neighbor averaging has been developed on the ICON triangular grid. Cell-centered variables are filtered using edge-connected neighboring cells, while edge-centered variables are treated consistently using the adjacent cell-edge connectivity. The filter may be applied iteratively to achieve a prescribed effective filter width and is compatible with ICON's block-based data layout on an unstructured mesh. The filtering operators are integrated into the diffusion module as a diagnostic operation applied after explicit diffusion and halo synchronization, ensuring consistency across MPI subdomain boundaries. Ongoing work focuses on extending this framework toward a dynamic Smagorinsky-type closure using a test-filter formulation.

Stimulated wave emission by balanced flow

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Internal gravity waves propagate within the ocean's stratified interior and enable downscale energy transfer from large-scale balanced motions, such as mesoscale eddies, to dissipative scales. Balanced flows can transfer energy to internal waves through nonlinear generation via two mechanisms: spontaneous emission, in which waves are generated without external forcing, and stimulated emission, in which energy transfer occurs in the presence of a pre-existing wave field. Here, we investigate stimulated emission using nonlinear flow decomposition within the full Boussinesq system. The model is initialized with a balanced jet-like flow and an imposed wave field, and the system is freely evolved over a range of Rossby numbers. We apply higher-order balance, based on an asymptotic expansion in Rossby number, to decompose the flow into balanced and wave components and to diagnose energy transfers between them. Initial results show a clear increase in internal wave energy over time, with wave energy growth under stimulated emission significantly exceeding that from spontaneous emission.

Revisiting Rossby wave phase speeds: The impact of global vs. local reference states

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Understanding and accurately predicting decadal climate variability remains an important challenge in climate science. Ocean temperature variations are driven by diverse dynamical and thermodynamic processes, ranging from passive density-compensated advection to anomalies induced by large-scale waves. Among these, baroclinic Rossby waves and thermal Rossby waves (which propagate along the ocean's meridional temperature gradient) play a central role. Theoretically, these waves are understood through normal mode theory, which typically describes linear perturbations to a globally defined, horizontally uniform state of rest. However, in practice, normal modes are often computed using locally defined, horizontally varying reference states. Previous studies utilizing this local approach have concluded that observed Rossby waves propagate faster than linear theory predicts. This work revisits this discrepancy by employing a globally defined reference state to determine whether the choice of reference framework accounts for the observed differences in Rossby wave phase speeds.

Data-driven gravity wave source parameterization using machine learning

Erfan Mahmoudi

Goethe University Frankfurt

Accurate representation of gravity wave (GW) sources continues to be a challenge for climate models. Parameterizations for orographic and convective gravity waves have been established, though studies indicate that sources including fronts, jet streams, and jet exit regions also generate gravity wave activity. These dynamically driven sources are not always clearly defined in current parameterization methods, which can result in biases in momentum deposition and large-scale circulation. This study presents a machine learning-based framework to model gravity wave sources in a unified and data-driven way. We use high-resolution ICON simulations to resolve gravity wave generation from a wide range of atmospheric processes. We train supervised machine learning models to learn the nonlinear relationship between the atmospheric state and the resulting gravity wave emission. The resulting parameterization accounts for gravity wave generation related not only to orography and convection but also to dynamically driven sources such as frontogenesis and jet-related processes.

Does turbulence affect light scattering by ice crystals?

Himanshu Mishra

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Cirrus cloud optical properties strongly depend on the orientation of nonspherical ice crystals, which are influenced by the interplay between turbulence and gravitational settling. In this study, we introduce a stochastic modelling framework that predicts ensemble-averaged light scattering from ice crystals with turbulence-driven orientation distributions. The orientation statistics are derived from a stochastic representation of turbulent velocity gradients, and single-particle scattering properties are computed using a Lattice Boltzmann Method–based electromagnetic solver. Integrating over the derived orientation probability density function yields bulk optical quantities such as phase functions and scattering intensities. Results show that turbulence modulates scattering anisotropy and phase function features, revealing measurable optical impacts even in weakly turbulent regimes. The framework offers a physically consistent and computationally efficient approach for incorporating orientation effects into radiative transfer and remote sensing models of ice clouds.

Energy cascades and anomalous transport in ocean macroscopic turbulence from surface drifter observations of three cruises in the South Atlantic

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We analyse two point velocity data from surface drifter experiments of three cruises in the Walvis-Ridge, the Agulhas-region and in the Benguela upwelling region off the coast of Namibia and derive the energy transfer rates ε of the corresponding (inverse) energy cascades in the different regions. Intimately connected to the energy transfer between the scales is the dispersion and mixing of passive tracers, e.g. pollutants and nutrients, within the ocean turbulent flow. Here a seminal role is played by Richardson's famous law, $\langle s^2(t)\rangle = g\varepsilon t^3$, which describes the mean squared relative displacement $\langle s^2(t)\rangle$ of particle pairs at time t in a turbulent flow. The combination of ε with Richardson dispersion reveals Richardso-Obhukov constant of g which (besides some theoretical interests, e.g. whether g is universal) is also of fundamental quantitative relevance as it relates the amount of pair dispersion to the level of fluctuating energy. While the fractal nature of drifter trajectories in the ocean is know for a long time (Osborne et al. 1989) we aim to explain anomalous transport by means of transport in 'topological' space, i.e along the trajectory metric, where sticking events lead to power-law residence-time distributions.

On the interpretation of the pressure vertical velocity

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Pressure vertical velocity ($\omega = Dp/Dt$) is commonly approximated from the geometric vertical velocity ($w = Dz/Dt$) as $\omega \approx -\rho g w$, which invokes the hydrostatic relation $\partial p/\partial z \approx -\rho g$ together with the additional assumption that local pressure tendency and horizontal pressure advection term are negligible at planetary and synoptic scales. Using global nonhydrostatic simulations with the ICON model, we show that the horizontal pressure advection term can be relatively large compared with the vertical pressure advection term at planetary-to-synoptic scales in regions of strong jets such as in the winter stratosphere, contradicting the conventional assumption $\omega \approx -\rho g w$. We further show that the horizontal and vertical pressure advection terms exhibit a predominantly out-of-phase structure and that their comparable amplitudes lead to substantial cancellation. As a consequence, ω can be suppressed or amplified at large scales relative to the $-\rho g w$ diagnostic, despite the validity of the hydrostatic balance. Scale diagnostics indicate that the large-scale enhancement of the horizontal pressure advection arises from interactions between the mean flow and eddies. From an energetic perspective, these advection terms correspond to compensating contributions of pressure-gradient work in different directions. Consequently, ω behaves more like the net pressure gradient work, rather than a direct measure of vertical motion.

Internal gravity wave dynamics in three-dimensional geostrophically turbulent flows

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Internal gravity waves (IGWs) are a ubiquitous and dynamically active component of the ocean. As a distributed wave field, they interact continuously with the three-dimensional, geostrophically turbulent flow. These interactions redistribute energy across scales, modify spectral structure, and can ultimately promote wave breaking and diapycnal mixing, thereby contributing to the maintenance of the large-scale circulation. The propagation of IGWs is strongly shaped by refraction in varying horizontal and vertical shears. To investigate the evolution of a broadband IGW spectrum embedded in a realistic three-dimensional, geostrophically turbulent flow, we employ the Internal Wave Energy Model (IWEM), a numerical framework that solves the six-dimensional radiative transfer equation governing the spectral energy balance of the full IGW field. Ray-tracing diagnostics and spectral energy budgets reveal two complementary mechanisms: coherent energy exchange with the mean shear, exhibiting critical-layer-like behaviour, and broadband spectral redistribution caused by turbulent eddy scattering along constant-frequency cones. Together, these processes lead to significant reorganisation of the internal wave field and systematic energy transfer between waves and balanced turbulence.

Effects of the air-side turbulence on the wind-wave interaction

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Although the mechanism of wind-wave interactions is important and one of the most fundamental questions in physical oceanography, its understanding is still limited due to its complexity. One reason is that air-side wave-induced motions interact with the turbulent airflow. In this study, we performed low-Reynolds-number direct numerical simulations (DNS) of turbulent flow over idealised water waves. We then compared the results with quasi-laminar linear solutions for wave-induced motions derived under a background shear flow obtained from DNS, which are equivalent to those derived in the so-called Miles' theory. We found substantial turbulence effects on the solution in low wave-age regimes, leading to wave growth rates being amplified. On the other hand, from the intermediate to high wave-age regimes, the linear solution had good agreement with the DNS results, indicating that the turbulence effect is minor. Moreover, we found that a simple eddy-viscosity model cannot express the wave-induced turbulent Reynolds stress tensor, suggesting a need for a more complex model. We also revealed that only specific Reynolds stress components contribute to the solution, which could help elucidate the advanced turbulence model.

Observed near-inertial wave propagation below the mixed layer following a hurricane in an internal tide-dominated region

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In this study, we focus on the propagation of near inertial waves (NIWs) using a time-series derived from a mooring in close proximity to a seamount chain south of the Azores, which are considered to be one of the main generation sites for internal tides (ITs) in the North Atlantic. The dataset consists of measurements from an Acoustic Doppler Current Profiler (ADCP) and Aquadopp profilers distributed on the water column from 100m to 4500m. Spanning two consecutive deployment periods, August 8, 2017, and May 18, 2018, it covers 20 months of observations. A spectral analysis of the measured velocities shows evidence of NIW packets propagating downwards after numerous wind events during the deployment period. A notable case occurred in September 2018, when Hurricane Leslie, a category one hurricane, passed north of the mooring inducing the strongest observed near-inertial kinetic energy peak of the entire time series. Moreover, an observed shift of the semi-diurnal tide M2 frequency by the inertial frequency in the energy spectra hints at potential interactions between the wind generated NIWs and the ITs. These observations provide new insight into the vertical propagation of NIWs, in a region with strong ITs, highlighting the importance of wind-driven processes in deep ocean mixing and the broader energy balance of the ocean interior.

Kelvin wave emission from interaction of balanced flow with boundaries

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Balanced vortical flow in the ocean is typically separated from internal waves by a frequency gap, limiting energy transfer between these components. At lateral boundaries, however, Kelvin waves can exist at arbitrarily low frequencies, potentially bridging this gap. We investigate the generation of Kelvin waves by the interaction between balanced flow and lateral boundaries. Classical flow decomposition methods fail in this setting due to the lack of Fourier modes caused by boundary conditions. To overcome this issue, we employ a novel method that separates linear normal modes, including vortical modes, internal wave modes, and Kelvin wave modes, by forming inner products with the respective eigenfunctions directly in the physical space. We combine this with the Optimal Balance method to account for the nonlinear terms. Our results show that the balanced flow interacting with boundaries does generate Kelvin waves, but the absolute energy transfer is very small. This mode decomposition method goes beyond this application and offers a general tool for studying wave–vortex interactions in bounded domains.

Does ENSO set the footprint of extreme rainfall? Insights from dynamical eddy length scales

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The spatial footprint of extreme rainfall events (EREs) governs the extent of affected regions and strongly influences flood severity and socio-economic impacts. While changes in the intensity of precipitation extremes are relatively well understood, a robust physical framework for characterising their spatial scales remains lacking. In particular, it is unclear to what extent large-scale dynamical constraints regulate the size of extreme precipitation systems if they. In this study, we investigate whether the theoretical eddy length scale, specifically the Rhines scale and the Rossby radius of deformation, can provide a physical basis for understanding the spatial extent of EREs during ENSO. We examine whether variations in these length scales are reflected in observed changes in ERE size during El Niño–Southern Oscillation (ENSO), which is known to modulate the large-scale background flows. By stratifying EREs according to ENSO phase, we assess how changes in the background circulation during ENSO influence the relationship between eddy length scales and the spatial footprint of extreme rainfall. This work would provide a dynamical framework linking large-scale atmospheric eddy scales to precipitation extreme size. Results to be presented at the conference will discuss on the extent to which theoretical length scales constrain ERE spatial organisation and how these constraints vary across ENSO phases, with implications for understanding and projecting flood risk under climate variability.

Suppression of mesoscale eddy and river plume mediated submesoscale currents on the passage of a tropical cyclone

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Using high-resolution submesoscale-permitting Regional Ocean Modelling System (ROMS) simulations with and without river runoff, this study investigates how a category 5 tropical cyclone modulates submesoscale currents (SMC) in the Bay of Bengal (BoB). The analysis reveals a three-stage sequence: pre-storm genesis of SMC, their suppression during the cyclone's passage, and partial post-storm recovery. Before the storm, offshore advection of a river plume by a cyclonic eddy generated sharp lateral buoyancy gradients and velocity shear along the plume edges that sustained fronts, filaments, and ageostrophic secondary circulations through frontogenesis and mixed-layer instabilities. During the in-storm stage, strong winds and vertical mixing disrupted these buoyancy gradients, reversed energy conversion from kinetic to potential energy, and diminished frontal jets as wind-stress-driven frictional forcing overwhelmed buoyancy control. After landfall, weaker but reappeared buoyancy gradients once again supported frontogenesis and the gradual re-emergence of SMC. These findings demonstrate a novel cyclone-plume-SMC coupling in the BoB with implications for vertical exchanges, cyclone intensity, and biogeochemical responses in freshwater-dominated basins.

Energy transfers and heat budget analysis in the Peru-Chile upwelling system: Insights from eddy-rich ICON

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We investigate the interaction between balanced eddies and the mean circulation in the Eastern Tropical Pacific using high-resolution ICON-ESM-ER output from the EERIE project. This study quantifies the energy transfers between the mean state and the mesoscale field through the calculation of baroclinic conversion from available potential energy and barotropic conversion from mean shear.We find that the 5 km ocean resolution allows for a four-fold increase in Eddy Kinetic Energy (EKE) compared to standard 100 km configurations, primarily driven by resolved baroclinic instabilities at the shelf break. This shift in the Lorenz Energy Cycle directly impacts the regional heat tendency. We present a closed heat budget for the Peru-Chile upwelling region, demonstrating that the resolved zonal eddy heat flux $\overline{u'T'}$ provides the necessary cooling to eliminate the coastal warm bias. Furthermore, we examine the interplay between these oceanic dynamical changes and atmospheric cloud-radiation feedbacks, concluding that oceanic energy transfers serve as the primary trigger for the improved model climatology.

Computation of the eddy kinetic energy budget from observations

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This study presents a method to estimate the eddy kinetic energy (EKE) budget using sea surface observations and vertical structure functions. Two approaches are compared in 5 km global ICON-Ocean setup: (1) solving the Sturm-Liouville eigenvalue problem to derive analytical vertical modes, and (2) constructing empirical structure functions from eddy composites derived from synthetic Argo data and eddy tracks. These structure functions enable the projection of sea surface signals into the ocean interior, allowing for the reconstruction of subsurface EKE dynamics. The results assess the feasibility of inferring subsurface eddy variability from surface observations alone, offering a promising pathway for improving ocean monitoring and modeling.

Adjoint-optimized parametrization of mesoscale eddies across the Cape Darnley continental slope

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The continental slope off Cape Darnley, East Antarctica, is a region where mesoscale eddies mediate the onshore transport of warm circumpolar deep water, influencing dense shelf-water formation and the basal melt of ice shelves. In coarse-resolution ocean models akin to state-of-the-art climate models, these eddies are not fully resolved and their effects must therefore be parameterized. Here, we investigate an adjoint-based framework to optimize two traditional parameterization schemes — namely the Gent–McWilliams (GM) and Redi schemes — against a high-resolution MITgcm benchmark simulation in the region off Cape Darnley. The optimization is formulated as a nonlinear least squares problem, comparing spatially and temporally averaged benchmark hydrographic fields with those of coarser-resolution simulations. Control parameters are here restricted to spatially varying GM and Redi coefficients. The MITgcm adjoint capability is leveraged to compute exact gradients of the cost function, thereby enabling the tractable application of quasi-Newton methods to this high-dimensional problem. This approach provides practical guidance for tuning these widely used mesoscale eddy schemes, while also highlighting their limitations.

Submesoscale dynamics in the Agulhas ring path

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Submesoscales are particularly abundant in the weakly stratified surface and bottom boundary layers. These ageostrophic features, characterized by O(1) Rossby number, bridge the gap between the mesoscales and small-scale turbulence, providing a pathway for the transfer of energy toward the dissipation scales. In this study, we investigate surface and interior submesoscale dynamics using a novel configuration of the ICON ocean model. By employing the so-called SubMesoscale-Telescope (SMT), we achieve local grid refinement down to 500 m across the eastern South Atlantic. We focus specifically on the Walvis Ridge region, which lies in the path of Agulhas eddies. Consistent with available observational data, our results indicate rich submesoscale activity in the surface mixed layer. Strong submesoscale filaments are developing

particularly in between mesoscale eddies, as well as within the eddies themselves. In the oceanic interior, submesoscales appear to be generated through flow-topography interactions near sloping bottoms. Anticyclonic vortices with high Rossby numbers emerge when the Agulhas rings cross the Walvis Ridge. The dynamics of these surface and interior phenomena are explored through a series of sensitivity experiments.

Scale interactions of kinetic energy and their representation via subgrid closures

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Mesoscale and submesoscale turbulence drive important energy transfers in the ocean, yet most models can only partially resolve these scales, requiring subgrid closures to represent their effects. Classical approaches use dissipative viscosity schemes, while kinetic energy backscatter, a more recent method, re-injects energy at large scales but maintains viscous dissipation near the grid scale. We study the impact of different subgrid closures on the oceanic energy budget using an idealised double gyre testcase of the unstructured-mesh ocean model FESOM2. We use various horizontal resolutions and introduce simplified bathymetry. Simulations are run both with and without kinetic energy backscatter to assess how these choices affect the distribution of kinetic energy and the interactions between different spatial scales. To analyse the resulting energy pathways, we use a coarse-graining method based on implicit filtering with discrete Laplacians. In contrast to classic Fourier analysis that requires regular grids, this approach enables direct application of diagnostics on the native unstructured mesh, avoiding interpolation-induced spurious signals. First results show that backscatter increases the variability in energy transfers across scales through its large-scale injection. The injected energy spreads throughout the spectrum, energizing all scales relative to purely dissipative closures.

Drivers of the continuous oceanic energy spectrum at high frequencies: A realistic modeling approach

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The dynamic processes that generate a continuous oceanic energy spectrum remain poorly understood. We investigate the relative roles of tides, mesoscale eddies, high-frequency winds, and nonlinear interactions using a submesoscale-resolving ICON simulation of the South Atlantic, which captures substantially more ocean variability than conventional eddy-resolving models. Model realism is demonstrated by comparing simulated energy spectra with observations from a dedicated field campaign and satellite data. Sensitivity experiments isolate individual processes, including simulations without tidal forcing to suppress tidal waves, without high-frequency winds to suppress near-inertial waves and without mesoscale eddies to reduce wave–mean-flow interactions. Frequency–wavenumber spectra are used to distinguish random variability from wave-driven variability by identifying elevated energy along the first modes of the dispersion relation. We find that tides and high resolution are essential to reproduce realistic energy levels in the internal wave band. Suppressing near-inertial waves reduces energy between tidal peaks while enhancing energy at the peaks, highlighting the importance of wave–wave interactions in sustaining a continuous spectrum. In contrast, suppressing mesoscale eddies has a weaker effect, suggesting that wave–mean-flow interactions play a less significant role.

Submesoscale isallobaric effects

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Although the gradient wind considers additional to the geostrophic balance the steady centrifugal acceleration (and can be derived for the first time at fine scales from the two-dimensional sea-surface height data observed by SWOT which provides the information on the sea-surface height curvature), the geostrophic prediction is found to slighty perform better than the gradient wind. In a flow-following framework, we attribute this surprising finding to that the flow is out of balance with relevant differences between streamline and trajectory curvature that compensate parts of the steady centrifugal term and lead to a reduced net centrifugal effect. The dominant contribution to the unsteady centrifugal acceleration is found to result from the temporal change in the pressure field, which means from isallobaric effects. Contributing processes are eddy propagation and centrifugal leakage. Our results highlight limitations for the estimation of oceanic submesoscale flows from SWOT due to the too low frequent orbits.

Air-sea submesoscale interactions

Ruirui Wang

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Air-sea submesoscale interactions, including CO_2, heating and momentum flux by observation saildrones.(1) What look like does CO_2 flux around front observed by saildrone? (2) Is "front killing," a process analogous to "eddy killing," related to momentum flux? (3)As the ocean is a major source of water vapor for precipitation, what is the significance of submesoscale fronts in regulating this water supply?

Role of mixed layer turbulence on the generation of internal waves

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Turbulence in the ocean mixed layer is a major source of internal gravity waves, yet the efficiency and pathways of this energy transfer remain less understood. We investigate how mixed-layer turbulence excites internal waves and drives the rapid decay of mixed-layer kinetic energy following strong forcing events. Using numerical simulations of a turbulent mixed layer overlying a stratified interior, we explicitly resolve the generation and propagation of internal waves. The non-hydrostatic model shows that surface wave-generated turbulence in the mixed layer radiates high-frequency internal waves near the buoyancy frequency, exporting 13% of the mixed-layer energy in 20 hours. A hydrostatic model shows that near-inertial baroclinic modes, especially mode 2, redistribute this energy vertically over 2–10 days. These mechanisms provide a fast, localized pathway for upper-ocean mixing. Normal-mode and spectral analyses link this turbulent radiation to low-baroclinic modes, near-inertial adjustment, and anisotropic wave emission in the presence of a background flow. Together, these results provide compact scaling relations that connect observable mixed-layer properties and turbulence intensity to internal-wave energy fluxes, enabling realistic parameterizations of mixed–layer–to–interior energy transfer in ocean and climate models.

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