The Air-Sea Interaction (ASI) submesoscale: physics and impact

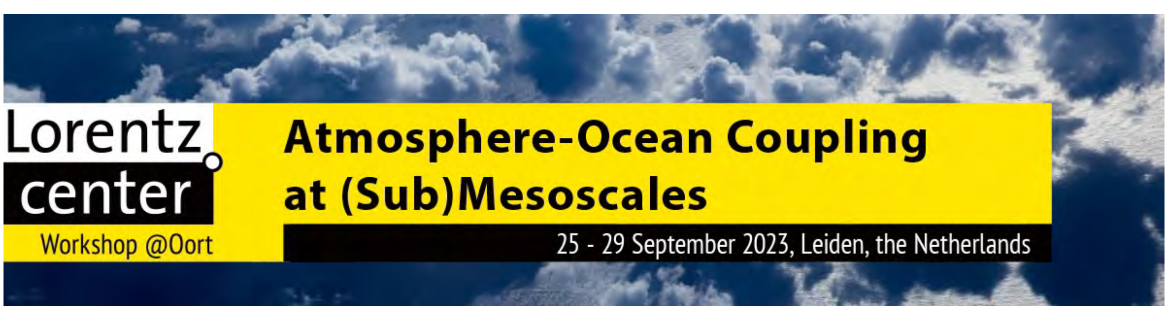
White-paper from the Lorentz-Center Workshop in Leiden, the Netherlands, Sept 2023

Authors

Louise Nuijens, Jacob Wenegrat, Paco Lopez Dekker, Claudia Pasquero, Larry W. O'Neill, Fabrice Ardhuin, Alex Ayet, Peter Bechtold, William Bruch, Lucas C. Laurindo, Xuanyu Chen, Fabien Desbiolles, Ralph Foster, Ivy Frenger, Geet George, Rianne Giesen, Emily E. Hayden, Momme Hell, Suneil Iyer, Josh Kousal, Nathan Laxague, Luc Lenain, Mariana Maia Pacheco, Agostino N. Meroni, Shoshiro Minobe, Caroline Muller, Owen O'Driscoll, Vera Oerder, Nick Pizzo, Dian Putrasahan, Jean-Luc Redelsperger, Lionel Renault, Björn Rommen, Cesar Sauvage, Niklas Schneider, Mingming Shao, Pier Siebesma, Justin Small, Bjorn Stevens, Ad Stoffelen, Ehud Strobach, Peter Sullivan, Elizabeth J. Thompson, LuAnne Thompson, Igor Uchoa, Doug Vandemark, Bia Villas Boas, Bowen Yang, Dongxiao Zhang, Seth Zippel

Abstract

During a 2023 Lorentz Workshop in Leiden, the Netherlands, a diverse community working in atmospheric and oceanic sciences and in observations and modeling met to discuss emerging ideas and questions on physical air-sea interaction (ASI) processes at the ASI *submesoscale*, where submesoscale is meant to include both ocean submesoscale and atmosphere mesoscale interactions. This white paper presents a strategy to unravel this emerging research theme, introducing a proposed definition of the ASI submesoscale and a hierarchy of possible interactions, as well as leading challenge questions for different ocean and atmosphere phenomena. It also outlines opportunities to target these questions, inviting the scientific community to take up the challenge to combine efforts across the different disciplines.



1 Submesoscale air-sea interaction: unknown source of variability?

Coherent structures in the ocean and atmosphere and at their interface are rich at scales spanning hundreds of meters to hundreds of kilometers. In the ocean, these are typically characterized as submesoscale or mesoscale phenomena, for example, sharp fronts and filaments near the edges of larger-scale features, and smaller eddies generated through instabilities of the surface mixed-layer [1] (Figure 1). In the atmosphere, these same spatial scales encompass mesoscale phenomena such as the organization of atmospheric convection into rolls, streets or clusters, cold pools from precipitation and shallow overturning circulations.

To date, much of our understanding of physical air-sea interaction (ASI) comes from studying the larger end of the ocean mesoscale, which has traditionally been more accessible for satellite-based observations and numerical modeling. This has established the influence of mesoscale ocean features on convection and mixing in the marine atmospheric boundary layer (MABL) and its subsequent depth, with impacts on cloudiness and precipitation, and feedbacks on winds and air-sea fluxes [2]. But advances in computational power and instrument-development now allow the rich fine-scale variability, which exists through the ocean mesoscale into the submesoscale, to be resolved and observed.

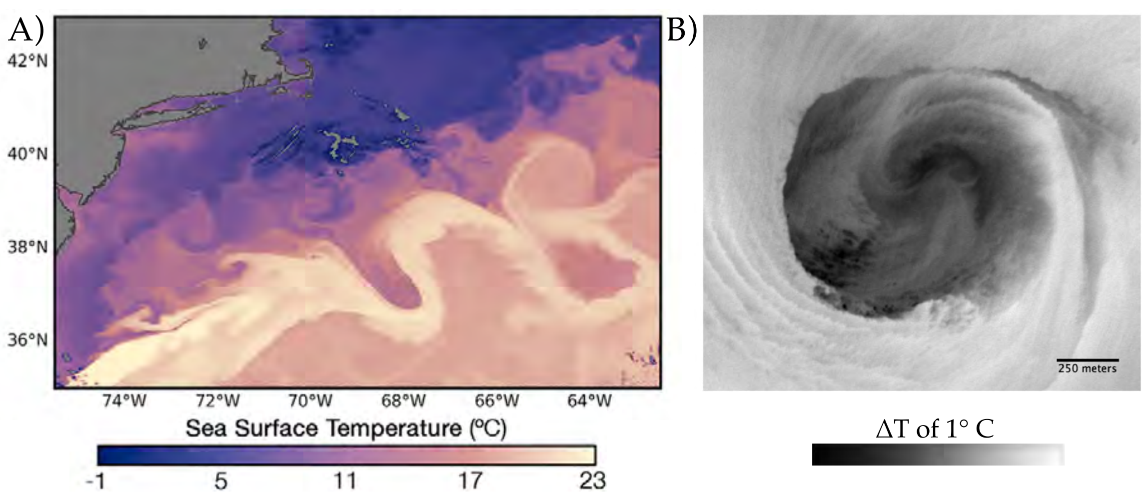


Figure 1. Example of the various scales of SST variability. A) Observations of the Gulf Stream from the NASA Moderate Resolution Imaging Spectroradiometer (MODIS) instrument, showing how sharp fronts are embedded in larger scale features such as western boundary currents and ocean mesoscale eddies. Panel adapted from [3]. B) Sharp sub-mesoscale features extend below the current resolution of satellite remote sensing, as evident in airborne infrared imagery, showing a coherent submesoscale vortex in the Santa Barbara channel. Panel adapted from [4].

At these scales a myriad of patterns can be found in (tropical) cloudiness and MABL circulations, whose link to an equally rich ocean structure is still subject to many open questions. The small horizontal length scales of ocean features (comparable to the depth of the MABL) suggest that new, as of yet unidentified, physical processes may be at play in air-sea interaction on both sides of the fluid interface [5]. It may even be possible that air-sea interaction identified in space-based observations as mesoscale interaction —such as wind responses to sharp SST gradients—are, in fact, a footprint of interactions that take place at submesoscales instead, changing both the conceptual and quantitative understanding of these processes.

Because the inflection point in the inverse and forward energy cascades of both the ocean and the atmosphere fall into the 200 m - 200 km range, air-sea interaction may also have very different effects depending on whether it sends energy upscale or downscale. The degree and impact of coupling across the air-sea interface at these scales is largely unknown, but refute the working assumption of a mesoscale gap in the energy spectrum. For this reason it is expected that climate and weather models distort the coupling of the ocean to the atmosphere, and may miss important sources of variability in the Earth system.

The key challenge is to understand *how atmospheric and oceanic structure at scales of 200 m - 200 km influence air-sea interaction and the statistics of larger-scale circulations.*

The goal of this white paper is to present emerging ideas and questions on physical air-sea interaction processes at the above scales. For brevity, we refer to these scales as the ASI *submesoscale*, where submesoscale is meant to include both submesoscale and mesoscale interactions of ocean and atmosphere, which we describe next in section 2. We invite the scientific community to work on these questions and take up the challenge to link the disciplines that now cluster on either side of the air-sea interface. We define a hierarchy of hypothetical degrees of coupling (section 3) and discuss key processes and weather in areas that require particular focus in section 4, including the low-wind speed (doldrums) and high-wind speed (cyclones or storms) counterparts in the tropics, shallow cloud organization in the subtropics, western boundary currents and storm tracks in the extra-tropics, and marine heat waves in the extra-tropics and arctic. The challenges and opportunities in observations, computation, and coupled modeling to answer those questions are outlined in section 5.

2 Scales of interaction: a proposed new definition

The atmosphere and ocean interact through fluxes of heat, momentum, and matter (including gases) across the air-sea interface, with variability at horizontal length scales reflecting processes occurring on both sides of the air-sea interface. However, despite both fluids 'seeing' the same boundary at the sea surface, the surface fluxes will necessarily project differently onto ocean and atmosphere processes, due to the different dynamical regimes occupied by the ocean and atmosphere in the same wavenumber space (Figure 2). Corollary to this, current definitions of the submesoscale (defined independently for the atmosphere or ocean) do not fully capture the range of scales relevant to submesoscale air-sea interaction.

As such, we propose a definition of the **Air-Sea Interaction (ASI) submesoscale**, and the range of length scales it encompasses, guided by the following unique fundamental characteristics:

1. The ASI-submesoscale contains most spatial scales of ocean submesoscale forcing. Within the oceanographic community, this is usually defined dynamically using criteria of $\mathcal{O}(1)$ Rossby and Richardson numbers, which are found for motions in the surface boundary layer with characteristic horizontal length scales of approximately 200 m to 20 km at midlatitudes [1]. The lower bound on this scale is set by the transition to turbulence, which can be roughly estimated by the scale of the ocean mixed-layer depth (H) such that $H/L \sim 1$ at scales of

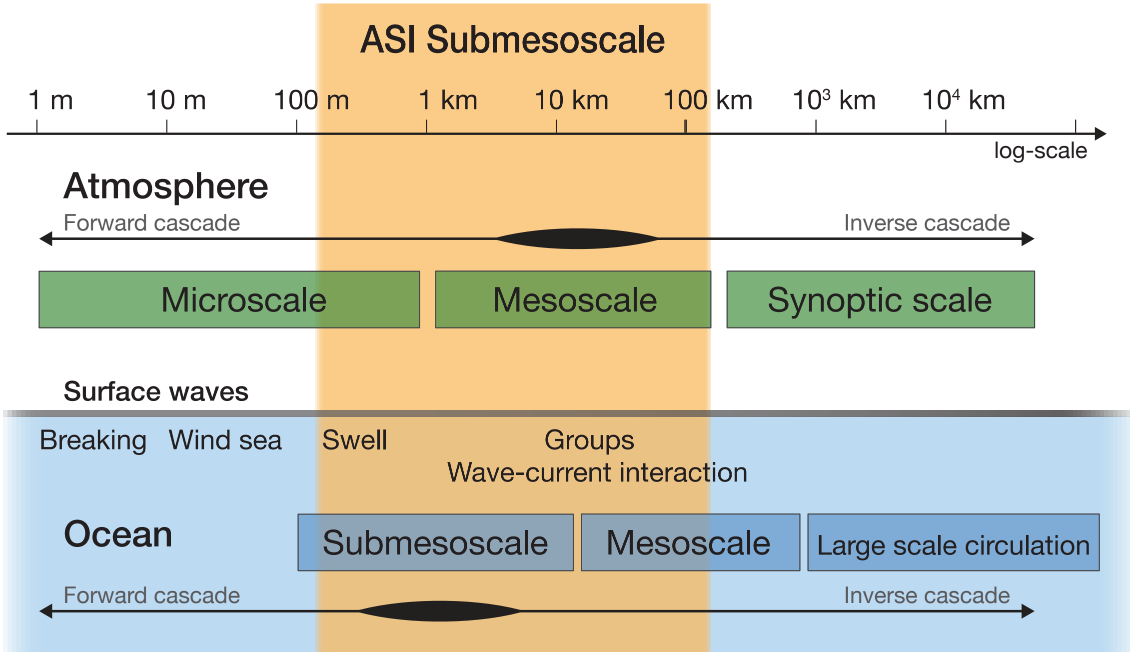


Figure 2. Relationship between the atmospheric (green), oceanic (blue) and ASI (orange) submesoscale regimes. The range of length scales associated with the transition between the turbulent forward and inverse kinetic energy cascades in each fluid are shown in red, with the approximate transition denoted in black. Schematic based on [1]

order 10 m -100 m. The upper bound on the submesoscale is set by the Rossby radius $L \sim U/f$ which for typical velocity scales of $\mathcal{O}(0.1$ m/s) will be $\mathcal{O}(10$ km) in midlatitudes but may grow to $\mathcal{O}(100$ km) at lower latitudes. Because processes at these spatial scales also evolve on inertial timescales, there exists the possibility of disequilibrium responses in both space and time.

2. The ASI-submesoscale contains the range of length scales for which the ABL remains in disequilibrium with a submesoscale ocean forcing feature. The length scale of atmospheric adjustment to a surface forcing perturbation spans the ocean submesoscale to mesoscale transition, with, for example, the atmospheric pressure (and temperature or wind stress) adjustment to a step function SST or surface current front occurring over a characteristic length scale of $Uh^2/\kappa \sim 10 - 100$ km where U is a wind velocity scale, h is a vertical scale of the ABL, and κ scales the vertical diffusion coefficient [6, 7, 8, 9]. The initial atmospheric adjustment to a stepwise forcing perturbation will be in the form of an internal boundary layer [IBL; 10] which exists within the ABL and measures the degree of disequilibrium between the atmosphere and surface forcing condition. Depending on the nature of the surface forcing, the equilibrium ABL structure will develop out of the IBL, with the distance between the surface forcing perturbation and return to equilibrium proposed as an indicator of the air-sea interaction submesoscale regime. This suggests that the ABL response (in for instance temperature) will remain in disequilibrium, with potential impact on the magnitude of surface fluxes within a certain distance defined by the ASI-submesoscale, a key distinction from larger-scale air-sea interaction.

The proposed ASI-submesoscale will therefore span scales of approximately 200 m - 200 km —a range that includes scales both larger than the ocean submesoscale, and smaller than the atmospheric mesoscale. This corresponds to Orlanski's micro-α through meso-γ and meso-β scales (200 m - 200 km) [11]. The ASI-submesoscale is illustrated in Figure 2, along with the relationship of the ASI-submesoscale to the atmospheric and ocean dynamical regimes.

Several consequences of this classification of length scales that are relevant for understanding air-sea interaction processes immediately follow. The ASI-submesoscale:

1. Encompasses the scales of transition between forward and inverse energy cascades in both the ocean and atmosphere. The inflection point in the inverse and forward kinetic energy cascades of the atmosphere and ocean fall into the ASI-submesoscale regime, highlighting that air-sea interactions may have very different non-local effects depending on whether they send energy up or downscale. The inflection point differs between atmosphere and ocean. This suggests that the coupled responses to submesoscale surface variability may be sensitive to the processes that determine cross-scale energy fluxes in each fluid.
2. Contains a range of scales in which surface flux parameterizations are especially uncertain. Assumptions in Monin-Obukhov similarity theory (MOST) which govern parameterization of surface fluxes may fail to hold within the ASI-submesoscale regime. Even if the magnitudes of flux uncertainties are not large in an absolute sense, systematic errors which correlate with features within the oceanic or atmospheric submesoscale regimes can affect the dynamics of air-sea interaction. The importance of this is currently unknown for air-sea interaction as flux uncertainties may not be large even if MOST does not technically hold, while upscale impacts may be sensitive to the partitioning of uncertainty between random and systematic errors.
3. May formally violate many of the assumptions on which the current understanding of the dynamics of air-sea interaction mechanisms are based. This includes assumptions of a steady-state response (as above, the ABL may remain in disequilibrium), homogeneity (an ABL in disequilibrium will show inhomogeneous turbulence regimes), small aspect ratio (at the lower end of the ASI-submesoscale the ratio of the atmospheric boundary layer depth to the scales of surface variability is not small), and an advective timescale that is long relative to the vertical adjustment (such that the response can not necessarily be treated as local).

Finally, we note that the identified ASI-submesoscale range also encompasses the resolution limits of current and near-term future remote sensing capabilities and the resolution of our current generation of storm-resolving (1 km - 10 km) models, and even ASI-submesoscale resolving (100 m) simulations that can be run for timescales of days to weeks. Especially for these models, the presence of non-equilibrium interactions between the ocean and atmosphere that are not included in common bulk flux formulae may be a source of errors that limit our understanding of the processes.

3 A hierarchy of hypothetical interactions

To investigate the role of submesoscale ASI in ocean and atmosphere dynamics we define a hierarchy of hypothetical interactions:

0. In zero- or agnostic interaction, the ocean and the atmosphere only feel the homogenized mean state of the other, and as such are essentially uncoupled. Atmospheric and oceanic

variability at 200 m - 200 km scales evolves solely through intrinsic dynamics and instabilities, through forward and inverse energy cascades in each fluid separately. This variability is felt as noise to the other fluid, with zero impact. Atmosphere- or ocean-only modeling studies with a non-interactive and homogeneous boundary condition, by definition, have agnostic interaction and yet demonstrate the emergence of (sub)mesoscale coherent structure in the atmosphere or ocean. Examples include evolving oceanic sub-mesoscale motions and fronts generated through larger-scale ocean circulation and forced by surface fluxes that are effectively uniform on these scales, or the self-organization of mesoscale cloud systems over a homogeneous ocean. Existing evidence indicates this description is incomplete, as fine-scale variability at the air-sea interface modifies the subsequent ocean and atmosphere evolution, as reviewed more completely below.

1. In one-way forced interaction, submesoscale variability in one fluid influences the evolution of the other fluid through air-sea fluxes, but there is no subsequent feedback. Such a one-way coupling exists in atmosphere- or ocean-only models when they prescribe heterogeneous boundary conditions (for instance, a constant SST gradient in atmosphere-only models, or a wind-stress responsive to ocean surface currents in ocean-only models). Much of the current work on fine-scale interaction to-date has focused on the evolution of only one side of the air-sea interface, consistent with this level of interaction. However in reality, any atmospheric or oceanic response to existing structure at the interface will immediately feedback to properties at and near the interface, and thus feedback to air-sea energy and momentum fluxes.

2. In two-way weak interactions, a forced response of one boundary layer to the fluxes induced by the other introduces feedbacks, but at a different scale or location, so that the coupling is weak. An example of this interaction is that an ocean eddy with locally enhanced SST changes the surface heat input to the atmosphere locally and leads to a deepening of the atmospheric boundary and enhanced near-surface wind speeds. But when the air mass is advected over the ocean eddy at high wind speed, the distance over which the atmospheric boundary layer adjusts is much larger, and the downstream response may quickly weaken in the absence of the initial forcing. Thus, under this level of feedback coupled interactions at these scales may be negligible.

3. In two-way strong interactions, a (near) match of scale or resonant frequency in the forced response of the boundary layers implies stronger feedbacks with the possibility of coupled instabilities, coupled circulations, or propagation of variance. This may lead to rectified or integrated responses that affect the larger scale statistics of weather and climate. For example, regional coupled high-resolution ocean-atmosphere models hint at rectified responses of the intensity and path of the extra-tropical storm tracks to the ASI-submesoscale in western boundary currents [12, 2]. The strength of the coupling is likely conditioned by larger-scale conditions. For example, under weak background winds, advective time scales are long, so that ocean submesoscale and atmospheric convective scale perturbations have time to come into equilibrium. High background wind speeds instead lead to stronger air-sea momentum and heat fluxes and a tighter coupling of the boundary layers, but a longer adjustment length scale.

4 Key processes in different weather and climate regimes

Based on emerging evidence of two-way coupling, we define a number of key challenges in different regimes in the next subsections. We emphasize that this is not intended as a comprehensive review, rather a curation of several areas of specific interest.

4.1 Air-sea fluxes (transport across the interface)

How does the ASI-submesoscale affect larger scale air-sea fluxes?

Energy, momentum and matter fluxes are sensitive to the structure of the air-sea interface, and hence processes at the ASI-submesoscale that help set this structure [13, 14, 15, 16, 17, 18]. The state-of-the-art approach for estimating air-sea fluxes involves the covariance of fluctuating turbulent quantities [19, 20]– hence the name "eddy (or direct) covariance". For this procedure to yield reasonable fluxes, the turbulent velocities must be carefully corrected for platform motion [21] and the corresponding co-spectra should be subjected to reasonable quality control [22]. Furthermore, it is assumed that all measurements are made in a constant flux layer [23] with minimal flow distortion [24]. Due to the myriad of challenges associated with this approach, so-called "bulk" parameterizations have been developed to infer air-sea fluxes given measurement of key environmental state variables. Bulk flux algorithms, such as COARE 3.6 [25, 22], are founded upon Monin-Obukhov Similarity Theory (MOST) and informed by thousands of direct covariance fluxes.

Bulk fluxes are typically computed using averaging periods from 10 minutes to 1 hour for which the flux footprint has a wind speed dependent size that can sit within the ASI-submesoscale [26, 27]. In the presence of large spatial heterogeneity in surface temperature [28] and waves and currents [29], fluxes can of course exhibit large variations within that footprint, but spatial heterogeneity is not typically considered as input to bulk flux parameterizations. In regions characterized by strong submesoscale fronts or mixed seas, bulk fluxes may then fail to represent the full range of flux variation [30, 13, 31].

Naturally, bulk parameterization can only be correct to the extent that the reference dataset (eddy covariance fluxes) and bulk flux input parameters are correct and comprehensive. Missing, or misrepresentation of, fine scale spatial variability in measured eddy covariance or bulk flux input parameters—for instance when the wind direction is not aligned with dominant spatial heterogeneity, or when ergodicity is violated—is likely the dominant source of error in air-sea flux estimates [13, 32]. The input variables for the flux parameterizations also depend on the (mis)representation of boundary layers, which affect input grid-scale parameters such as wind stress and its directionality [33]. In particular, missed variance in wind speed and co-variance in wind stress, sea surface temperature, air moisture, and air temperature can lead to non zero mean effects in fluxes [17, 34].

The derived bulk exchange coefficients should also only be considered valid at the averaging scales of 10 min - 1 hr. However bulk parameterizations are currently applied in the same fashion across models with different resolutions, from climate models with 100 km grid spacing to meter-scale Large Eddy Simulations, assuming that flux uncertainties due to the exchange coefficients are usually relatively small (10-15% for wind speeds greater than 5 m s^{-1}, [35]). Recomputing transfer coefficients, and particularly the gustiness parameter, at different (model) scales would help quantify the uncertainty associated with this approach. Key here is that even small absolute changes to air-sea fluxes can have significant integrated effects when they are systematically correlated with ocean or atmosphere processes [36, 37].

As models approach a grid spacing that falls within the ASI-submesoscale, there is a need to identify which non-equilibrium corrections need to be applied to accurately represent mean fluxes at the ASI submesoscale, especially in the presence of strong sensitivity to local or short-lived variations in fluxes that average out in the mean. For instance, submesoscale-permitting ocean-only models suggest $\mathcal{O}(10$ - 100 W m$^{-2})$ of upward surface heat flux arising from high-frequency ocean submesoscale motions [38, 39]. What remains to be studied is how the atmosphere responds to such strong variations in heat flux in a way that cannot be captured with a spatial-mean flux.

While this white paper does not address bio-geochemical processes, we note that biological activity can have important and often ignored impacts on physical air-sea exchange, e.g. vertical plankton distributions can influence the extinction of sunlight and the heating profile of the upper ocean, or natural slicks from organic material can change the surface tension and molecular conduction through the surface.

Leading questions Which ASI submesoscale processes have a rectifying effect on larger-scale air-sea fluxes? Which corrections are needed in current bulk flux parameterizations to express coupling at the ASI submesocale?

4.2 Western Boundary Currents

How does submesoscale ASI in Western Boundary Currents impact storm tracks and the global atmospheric circulation?

Western Boundary Currents (WBCs) are key components of Earth's climate system due to their significant air-sea exchanges of heat, moisture, momentum, and gases. Large amounts of heat and moisture are passed from the ocean to the atmosphere over WBCs and interact with mid-latitude jet streams and in so doing condition the extra-tropical storm tracks. Exemplary of this influence is the partial reproduction of NH storm track structure only by a Gulf-stream like surface temperature anomaly [40]. How SST variations associated with WBCs mediate the coupled ocean-atmosphere system is known to be strongly influenced by air-sea coupling at ocean mesoscales [2, 41].

While past work has established the importance of ocean mesoscales, it is also known that boundary current regions are sites of very active submesoscale turbulence [42, 43], including both extensive regions of approximately isotropic submesoscale variability, and strong anisotropic fronts embedded in the larger scale currents (for instance the Gulf Stream North wall, Figure 1). The question is then, to what extent is submesoscale variability along WBCs also important?

A first set of questions centers around the role of submesoscale variability in signals already identified at the mesoscale and larger. This includes both the direct, local, response of ABL to the individual feature (SST or current), and how submesoscale variability might influence the larger-scale ocean (e.g. WBCs, through an inverse energy cascade) and consequently exert indirect effects on the atmosphere. Extensive work has documented the role of WBCs in shaping storm tracks [as reviewed in 2], however much of this work has been based on observational or model results that present a highly smoothed version of the sharp WBC fronts. For instance, while a mesoscale resolving model might present a transition between the subpolar and subtropical waters occurring over 10s of km (as set by the model effective resolution), in reality the transition can occur over scales of less than a km. This suggests that submesoscale ASI may be aliased into our current understanding of WBC air-sea interaction developed considering a 'smoothed' version of actual WBC fronts.

The effects of small ocean features are expected to be particularly important in situations of strong winds and cold, dry air blowing over warm waters, that induce large enthalpy fluxes. For example, observations have identified persistent low-level clouds that are 'anchored' to the position of the Gulf Stream north wall [44, 45]. Models suggest that changes in the ABL dynamical balance across SST fronts can lead to the development of secondary circulations that reach the free troposphere [46, 47]. At larger scales the change in ABL height across fronts can also act as virtual topography, generating a stationary lee-wave response [48], however at smaller scales the response is likely in the evanescent regime, with unknown consequences for the atmospheric response. On the ocean side, instabilities along the sharp north wall front generate highly elevated dissipation of turbulent kinetic energy, and contribute to the inter-gyre mixing of tracers such as nutrients and freshwater [49, 50]. The presence of these instabilities, and the strength of the subsequent turbulence they generate, are directly linked to the strength and alignment of the surface winds relative to the ocean front, opening a possible mechanism for coupled interaction [5].

The sensitivity of coupled WBC interactions to the scale of the SST front is not currently well understood, but model results suggest it will also be tied to larger-scale environmental conditions. Examination of the response of the atmosphere to fields of imposed ocean eddies was done in [16] (mesoscale and submesoscale, near-zero winds only) and [51] (stated for mesoscale only, for a wide range of background wind conditions and stability). In the first study, a strong response was found for zero background winds, but for a background wind of just 1 m s^{-1} the response rapidly weakened. In the second study, the relative role of vertical mixing and pressure adjustment mechanisms was examined as a function of background wind and stability, with a larger role of vertical mixing under strong winds and a larger role for pressure adjustment mechanisms under weak winds. Recently, these questions have been revisited using newer metrics [9], and the geographical regions and seasons in which the atmospheric response is strongest has been further characterized [52, 53]. Future work might further parse these types of results as a function of spatial scales of SST variability, with theory predicting a strong scale dependent response to the relative influences of horizontal advection and vertical mixing in the ABL [6].

A second category of questions related to air-sea interaction in WBC regions are the processes active in the extensive regions of submesoscale turbulence found equatorward of the boundary currents themselves. These active regions of submesoscale variability are energized seasonally with the increase of wintertime available potential energy, and are understood to play an important role in seasonal modulation of larger-scale ocean circulation through the inverse energy cascade [54, 55]. These are also the formation regions for the subtropical mode waters, which are sensitive to both air-sea interaction and submesoscale variability [56, 57], and which play an important role in decadal scale ocean variability through the export of heat and freshwater into the interior [58]. In contrast to the WBCs themselves, here submesoscale variability is much more isotropic, highlighting uncertainty around the time and length scales of atmospheric adjustment when forced by more randomly distributed heterogeneous surface temperature variability. Lessons learned from recent efforts to understand the effect of subgrid heterogeneity over land (e.g. the CLASP[1] Climate Process Team) may be valuable to informing approaches for the marine ABL [59].

Leading questions How do the mechanisms of air-sea interaction differ between regions of isotropic vs anisotropic fronts, both of which are found in the vicinity of WBCs? To what extent does subme-

[1]Coupling of Land and Atmospheric Subgrid Parameterizations

soscale variability in, for instance, the Gulf Stream front modify the mechanistic understanding of air-sea interaction in WBCs? Does submesoscale variability affect the extra-tropical storm tracks? To what extent will new observational and modeling capabilities (reviewed in section 5) prompt a revisiting of our current understanding of WBC air-sea interactions?

4.3 Tropical and subtropical clouds

How does tropical cloud organization depend on and feedback to ocean structure?

The subtropical atmosphere is characterized by a predominantly anticyclonic regime with typical large-scale surface winds of 5-7 m s^{-1} and convective boundary-layer cloud regimes [60] depending on the SST and free tropospheric forcing. The sub-tropical atmosphere exhibits a rich variety of boundary layer and cloud structures on the atmospheric mesoscale (2 km - 200 km). Due to the more stationary flow compared to the mid-latitudes and deep tropics, and locally comparable magnitudes in wind speed and ocean currents, the possible mutual imprints of atmospheric and oceanic boundary layers are expected to be enlarged. Convective clouds are sensitive to changes in the boundary layer structure and can modulate the boundary layer response to ocean forcing and, in return, the atmospheric forcing to the ocean.

In the deep tropics, where comparably weak wind conditions and high SSTs prevail, *e.g.* in the Pacific warm pool [61] or doldrums, the moisture content and instability in the atmosphere is so high that just a few tenths of local SST anomaly can strongly influence the development of deep convective clouds. Features such as tropical instability waves (TIWs) are associated with extremely sharp SST fronts that, while large in zonal extent, are dynamically submesoscale and which can release gravity currents associated with step-like surface temperature changes [62, 63]. In the doldrums, or regimes of weak wind speed, < 5 ms^{-1}, flux uncertainties due to exchange coefficients are comparably large and at least in storm-resolving models (1 km - 10 km grid spacing) the structure of precipitation in the tropics (double ITCZ) is very sensitive to arbitrary minimum wind-speed parameters used in bulk formulae, which can vary between 1 - 4 ms^{-1}. Coupled model results also suggest that variations in winds, currents, or wave-current interactions can generate small submesoscale variability in SST and air-sea fluxes in the absence of strong SST fronts or eddies.

None of these impacts of ocean structure on atmospheric convection are well examined, and it is an open question to what extent convective clouds and their mesoscale structure depend on the upper ocean. And although it is now well appreciated that the rich structure in convective cloudiness plays an important role in setting the distribution of precipitation, little is known about the influence of strong rain showers on ocean freshwater fluxes and air-sea interaction.

Both shallow and deep convection and associated cloudiness exhibit horizontal structure at the ASI submesoscale - from rolls, streets and cells in shallow convection [64], to 'gravel'-like structures where precipitating shallow convection organizes in lines or arcs surrounding cold pools, to aggregated shallow cloud clusters with frequent precipitation ('flowers') [65] and shallow meridional overturning circulations with length scales $\mathcal{O}$(100 km - 500 km) [66]. Such convective structures are tied to structure in wind. Model simulations and EUREC^{4}A observations suggest that enhanced convective organization changes the directionality of boundary layer and surface winds averaged over scales of $\mathcal{O}$(200 km)[67, 68], and leave a clear imprint on ocean surface roughness across the ASI submesoscale. The upper-left panel in Figure 3 shows a $\sim$ 250 x 250 km^2 Sentinel-1 *roughness* image around the location of the WHOTS mooring buoy, close to Hawaii, acquired on April 11th 2023 at 4:40

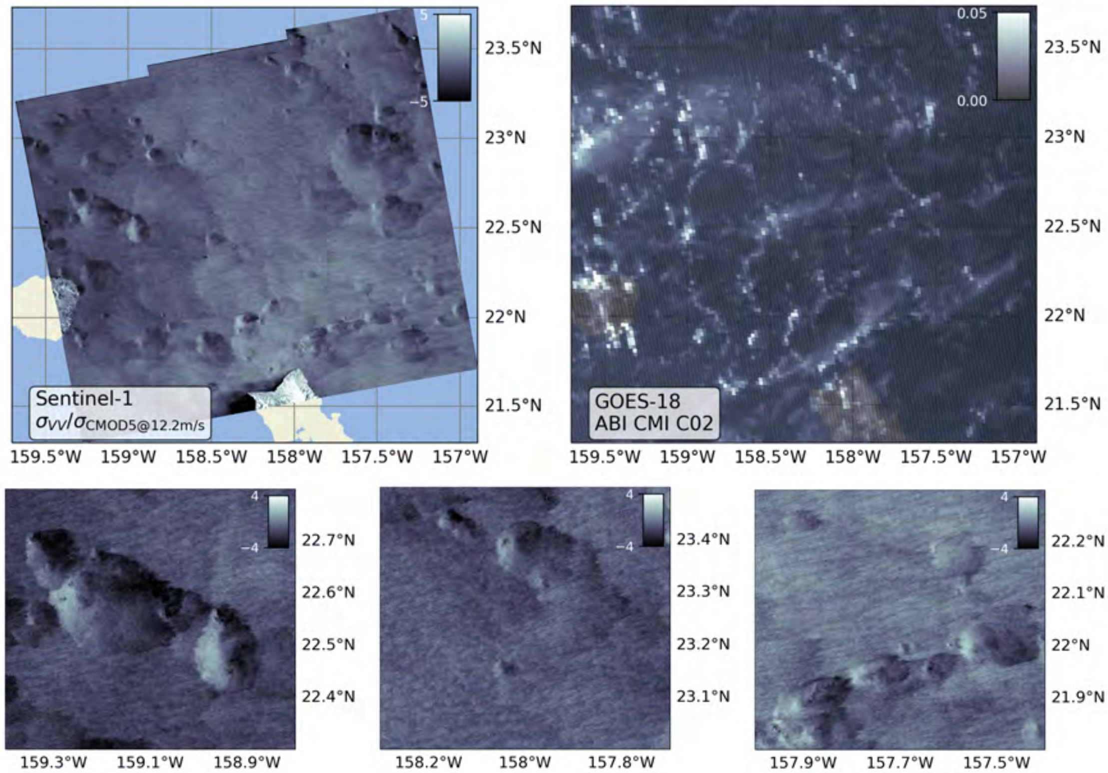


Figure 3. Upper left: Image taken northeast of Hawaii, showing Sentinel-1 *roughness*, calculated as the ratio (in decibel) of measured VV-polarized NRCS to a reference NRCS value obtained feeding the median ERA-5 surface wind to the CMOD-5 Geophysical Model Function (GMF). Upper right: GOES-18 red visible channel image acquired within a few minutes of the radar acquisition, revealing shallow cumulus clouds organized in arcs along cold pools. The lower panels zoom in on the cold pools and show how MABL structures such as wind streaks (tied to rolls or streets) or cellular convection are suppressed.

UTC (18:40 local time). A series of cold-pools and gust fronts can be identified that are associated with 'gravel' as seen from the GOES-18 red visible channel image in the upper right. The lower panels illustrate how the cold-pool gusts result in increased or decreased roughness depending on the direction of the gust with respect to the background wind. It can also be seen that large organized eddies within the sub-cloud mixed-layer, such as wind-streaks (in the presence of convective roll or street formation) or cellular convection, are suppressed.

Tropical deep convective clouds can organize into even larger-scale squall lines or clusters of $\mathcal{O}$(100-2000 km)[69], such as those observed during the Madden-Julian oscillation (MJO) or in tropical cyclones. When clustered, deep convection strongly influences diabatic heating profiles and momentum transport that impact atmospheric circulations and tropospheric winds [70, 71], while changes in the horizontal distribution of water vapor and clouds impact the radiation budget [72, 73, 74] and extreme precipitation [75, 76].

Convective clustering does not depend on heterogeneous oceanic forcing, but can be largely autonomously driven. Upscale growth of mesoscale structure is intrinsic to convective heating structures and, like radiative cooling, can drive mesoscale circulations that converge moisture into already moist convective areas [77, 78, 79, 75, 80]. Convective organization can also arise in response to large-scale atmospheric forcing (convectively-coupled waves) [81].

However, there are some reasonably well understood examples where oceanic SST anomalies are linked to precipitation and convection [82, 83]. A notable example are equatorial TIWs where wind speeds are enhanced or reduced in phase with the alternating warm and cold SST anomalies $\mathcal{O}(1°C)$ [84]. By adjusting its wind response to the evolving TIWs, the atmosphere helps reduce the growth of TIWs [85]. In the subtropics, EUREC^{4}A [86] observations also show that anomalously warm SST patches (and cold SST patches) of $\mathcal{O}(<1°C)$ can enhance surface wind speed and reduce cloud fraction [87, 88], qualitatively similar to composite results over eddies and fronts at ocean mesoscales [89, 90, 91, 52]. The correlations likely depend on the scale of the SST anomalies: the smaller the spatial scale, the sharper the gradients, and the more important moisture convergence can become for enhancing cloudiness [92].

Convective clouds likely alter the classical "thermal feedback" that has been invoked on ocean mesoscales [93], which involves a response of pressure gradients, stability and mixing in the boundary layer to SST anomalies that in turn adjust atmospheric winds. Clustered convection can inject low equivalent potential temperature air into the boundary layer through (precipitating) downdrafts that alter near-surface stability and hence air-sea fluxes [94], or produce propagating gust fronts at the edge of spreading cold pools [95] that increase air-sea heat fluxes locally and impact ocean roughness as shown in the tropical Pacific and Indian Ocean field campaigns TOGA-COARE and CINDY/DYNAMO [96, 97], and in satellite wind products [98, 99] and Figure 3. Other impacts include convective cloud shading that can lead to horizontally extended cooling at the ocean surface that can penetrate 1-2 m into the ocean mixed-layer, or freshwater lenses from rain that can create a thin stable ocean surface layer [100].

The horizontal scale, structure and variability of such process-driven interactions, or how they contribute to (sub)mesoscale ocean dynamics, is not well understood. However, the fast-evolving impacts of SST on the wind field and on evaporation play a major role in interannual variability, whose feedbacks are still poorly represented in most climate models, and convective gustiness is a crucial component in the variability of surface fluxes that regulate intraseasonal variability (e.g., MJO) [101]. Considering gustiness in air-sea flux computations has significantly improved tropical teleconnections in CAM3 and GAMIL CM simulations [102, 103] and other, fast-evolving, (sub)mesoscale interactions may prove to be similarly important.

Leading questions Does air-sea interaction at ASI submesoscales dampen or amplify the upscale growth mechanism that leads to cloud mesoscale organization? Do the location and patterns of deep convective rainfall depend on SST patterns (what sets the edge of the Pacific warm pool)? Does precipitating convection impact the ocean mixed layer primarily through heat (radiation), wind, or (fresh)water? What sets air-sea coupling at low wind speeds? How is the thermal feedback modulated by convective clouds?

4.4 Other regimes of interest

In this section we briefly touch on several other regimes of interest for submesoscale air-sea interaction. This includes both regional topics (e.g. coasts and high-latitude processes), as well as the possible influence on extreme events (e.g. tropical cyclones and marine heatwaves).

4.4.1 Tropical cyclones

How does air-sea coupling at the ASI submesoscale influence tropical cyclone intensification?

Tropical cyclones comprise air-sea interaction at high-wind speed conditions: the counterpoint to the low-wind speed doldrum conditions. Cyclone intensification strongly depends on the conversion of latent heat of condensation into kinetic energy of the winds and is ultimately driven by the evaporation at the sea surface. Despite the fact that the air-sea fluxes grow within an intensifying cyclone because of the increasing surface winds (a.k.a. Wind Induced Surface Heat Exchange, WISHE, process, [104]), it remains to be understood whether they are also modulated in a significant way by heterogeneous properties at the interface, originating from either atmospheric dynamics, ocean dynamics, or some coupled process.

For instance, cold pools from precipitating clouds in a developing tropical storm or in the spiraling bands of mature tropical cyclones, are associated with colder, typically drier and gusty conditions [105, 106] that can impact the distribution and amplitude of surface fluxes and interact with the ocean surface and ocean mixed layer [107]. Particularly interesting is the potential role of submesoscale oceanic motions ($<$ 50 km) in transferring heat from the colder ocean interior to warmer near-surface waters, which recent studies show can be much larger than the heat transport on mesoscales (50 km - 200 km). This can lead to anomalous vertical heat fluxes from the ocean to the atmosphere [38, 39]. Tropical cyclones are sensitive to ocean heat content at mesoscales in coupled model configurations [108], and dependent on upper ocean stratification, where a strong coupled feedback is found for low upper ocean heat content (or shallow warm mixed-layers) while a very weak coupled feedback is found when the ocean has a thick warm mixed layer. These sensitivities highlight potentially important roles of air-sea coupling at submesoscales in driving the heat flux that can intensify tropical cyclones.

Leading questions Is submesoscale air-sea interaction important for storms/cyclones? How do small-scale cold pool properties impact ocean-atmosphere interactions and, thus, potentially feedback on cyclone formation and intensification?

4.4.2 Marine heat waves

How does submesoscale ASI influence the life cycle of marine heat waves?

Marine heat waves (MHW) are periods of extreme temperatures in the upper ocean that persist for weeks. They pose a major threat to marine ecosystems [109, 110],and can have significant socioeconomic effects [111]. The increased incidence of MHWs affects a range of ecosystem levels, as temperature is a dominant factor in influencing physiological processes [112, 110]. Ecosystem response results in changes in biological production, toxic algal blooms, massive coral bleaching events, and mortality of fish species. Over the last few decades the frequency, duration, extension, and depth of MHW have all increased, and are projected to further increase under global warming scenarios [109, 113].

The drivers of MHWs are not fully understood. In some cases ocean temperature extremes have been associated with synoptic scale and climate variability (and related anomalous turbulent fluxes) [114, 115], with a possible role of SST-cloud feedbacks [116]. Mesoscale eddies in the marine heat wave life cycle may also favor heat convergence over large portions of the oceans [117]. The role of submesoscale activity in MHW evolution has also not yet been fully explored. There is potential for vertical motions associated with the submesoscale to accelerate the termination of MHW events [118] and for frontogenesis to act in combination with upwelling-favorable winds to initiate MHW on the continental shelf [119].

Leading questions Does the presence of marine heatwaves enhance or inhibit submesoscale activity? What is the role of submesoscale oceanic/atmospheric variability in the initiation/dissipation of MHWs? Do the vertical motions associated with submesoscale activity act to damp near surface temperature extremes? Are there enhancements of submesoscale vertical velocity when a MHW encounters a coastline?

4.4.3 Coastal upwelling regions and shallow seas

Coastal seas form another regime in which the impacts of submesoscale interaction can be pronounced. Shallow coastal seas have shorter response time scales and regionally unique ocean eddies, currents, and coastal winds shaped by the coastal shelf and nearby land. Transitioning from the smooth sea to rough surface roughness over land may lead to unique wind-wave interaction. These are the regions in which significant wave energy dissipation occurs and where ocean mixing and sediment transport are crucial for coastal stability. With high marine biodiversity, but also trace gas and pollution emissions on land nearby, it is a regime where the coupling to biogeochemical processes may be rich (because biogeochemistry was not the core focus of this workshop, this subject is not further elaborated upon here).

In Eastern Boundary Upwelling Systems (EBUS), the coastal wind is the main oceanic forcing and its nearshore spatial variability has a major influence on the coastal dynamics. This is evident in the wind speed decreasing within $\sim$ 150 km from the coast (wind "drop-off"), which impacts the vertical velocities, the coastal undercurrent [121, 122, 123, 124, 125], and the offshore export of particles [126]. At ASI-submesoscales, wind variations may arise from orographic, current and SST anomalies [127, 128] and can have broader impacts, for instance, local wind intensification can lead to the strengthening of submesoscale eddies [129]. Recent airborne and in situ observations from the NASA Sub-Mesoscale Ocean Dynamics Experiment (S-MODE) reveal a strong response of low-level winds to submesoscale fronts (Figure 4). The wind accelerates as it crosses from cold to warm SST, with a downstream adjustment scale that falls into the ASI submesoscale (section 2). These modulations in wind-speed are coincident with strong submesoscale ocean variability generated along the upwelling front, as evidenced in the $\mathcal{O}(1)$ Rossby numbers of the ocean surface currents (Figure 4b). The emerging opportunities for studying submesoscale ASI via new technologies such as those used in S-MODE is discussed further in section 5.3.

EBUS are less energetic than WBCs, but activity within the ASI-submesoscale plays a crucial role in regional heat transport and the structure of highly intense regional biological activity. Specifically, oceanic cross-shore eddy heat advection contributes significantly to offshore ocean cooling necessary to maintain the stratus clouds [130]. Furthermore, activity at these scales is associated with intense vertical velocities that subducts plankton and nutrients, exerting a negative impact on the primary production [131, 132, 133, 123, 134]. Submesoscale ASI in EBUS regions decreases the eddy kinetic energy [135, 36, 93], eddy potential energy [37],and the coherent eddy heat content [136, 137]. While simulations suggest that short-wave and long-wave heat fluxes experience only

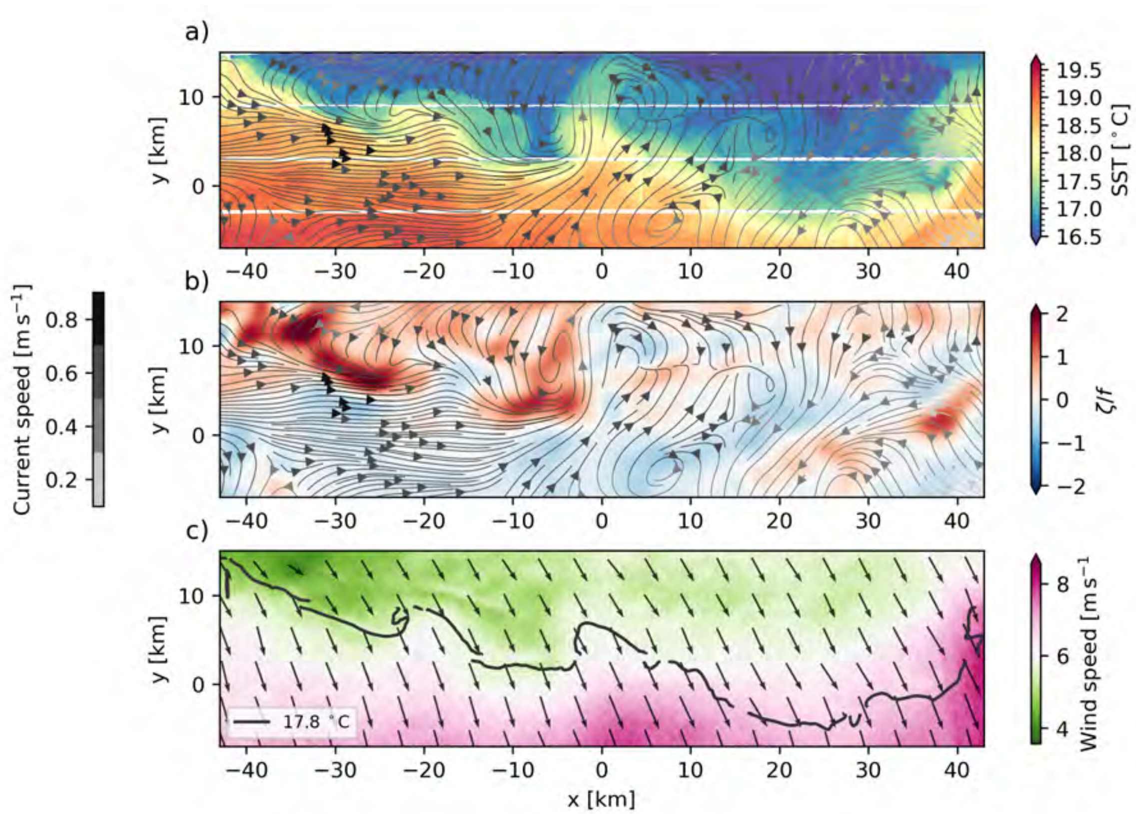


Figure 4. Airborne observational evidence of submesoscale ASI during S-MODE, from [120]. a) SST from airborne infrared observations (MOSES), with simulataneous ocean current streamlines from Ka-band scatterometery (DopplerScatt). b) Vertical vorticity of ocean surface currents at 2 km resolution showing strong submesoscale variability (section 2). c) Surface wind vectors and wind speed (colors) with the 17.8 °C SST isotherm indicated (black). The winds accelerate crossing the front from cold to warm, with a downstream adjustment scale that falls into the ASI submesoscale.

marginal modifications (less than 1%) above coherent eddies [137], little is known about the impact on the heat balance, stratus clouds and primary productivity. Thus, the full extent to which similar ASI mechanisms influence coastal submesoscale processes and variability, and how these may vary across different seasons and EBUS regions, remains an open research challenge [127, 138, 137].

Leading questions What is the significance of ASI-submesoscale processes on coastal wind patterns, ocean heat contents and vertical mixing, cloudiness and primary productivity? To what extent does the lack of representation of submesoscale ASI play a role in persistent model biases of SST in EBUS regions?

4.4.4 Ocean-ice-atmosphere interaction

Submesoscale ASI may play a key role in ice formation and accumulation in winter, and sea-ice break-up and melt-rate in the summer. Because sea-ice acts as an insulator between the ocean and atmosphere, the influence of submesoscale air-sea interaction on the marginal sea ice zone may have an underestimated impact on the global heat balance at high latitudes, with potentially far-reaching effects on weather and climate. At the ice edge, the sharp contrast in air-sea heat and momentum fluxes can produce large surface stress curls and gradients in water masses that lead to strong and highly unstable currents [139]. Air-sea fluxes in ice leads can be a potential energy source that energizes the ocean submesoscale [140]. Small-scale oceanic currents and surface winds, in turn, can accelerate the sea-ice melt rate by allowing warm waters to move into colder regions under individual ice sheets (floes) [141]. Waves can break up/fracture the sea ice [142, 143], thereby exposing the ocean to the atmosphere and allowing for enhanced heat fluxes from the ocean to the atmosphere. In addition, wave attenuation in sea ice also provides a momentum/stress source. This effectively compresses the marginal ice zone and controls where its edge sits [144, 145].

Air-sea heat fluxes are poorly parameterized at high-latitudes, particularly in locations where both sea ice and open ocean are present over a small area [146]. The sea ice surface can be highly heterogeneous at ASI submesoscales, but is often treated as a continuum fluid in the bulk formulation of the air-sea fluxes over ice. Yet large amounts of heat exchange between the ocean and atmosphere can occur due to small-scale, short-lived features in the sea ice surface such as polynyas and leads, which often result from wind forcing. These features develop rapidly, and the large temperature difference between the newly exposed ocean surface and the overlying atmosphere drives large magnitude surface heat fluxes.

Leading questions What is the influence of short-lived sea ice features and rapidly varying fluxes on the mean surface energy budget of sea-ice regions? How do we represent strongly heterogeneous sub-grid-scale sea-ice and subsequent air-sea fluxes in models?

5 Methodological challenges

The challenge questions we have put forward are broad, reflecting the depth of uncertainty about when and how (sub)mesoscale interactions lead to an integrated response. Instead, they reflect where and under what conditions we believe submesoscale interactions can matter, based on current evidence. The reason we know so little yet is that our tools have not been designed to study interactions at high $\mathcal{O}$(10 m -100 m) resolution, observing platforms generally focus measurements *either* on the ocean or the atmosphere, and high-resolution *coupled* simulations are only now emerging at sufficiently large scale to be applicable to considering cross-scale interactions. Furthermore, sustained field measurements and space-based observation are often limited to the surface or near-surface, limiting our understanding of oceanic and atmospheric boundary layer processes. The status reflects that oceanography and meteorology are practiced by different communities, with different expertise and tools. The first step is thus to develop a better integration of the tools we develop and use to study cross-scale ocean and atmosphere interaction. Once we have those tools, we can start addressing discrepancies between observations and simulations.

5.1 In modeling

Models are a key tool for disentangling the influence of different physical processes, deciphering the relative contributions of scales to local air-sea interactions, and assessing large-scale and remote impacts. To explore the various hypotheses a new generation of higher-resolution large-domain models are now feasible, limited mainly in the time scales they can simulate and the required level of coupling between atmosphere, ocean and waves that allows for a hierarchy of experiments.

5.1.1 Hierarchy of coupled models

A number of technical developments are needed (some are in progress) to develop the required hierarchy of modeling approaches:

1. **Coupled 1D models**: In many models, boundary layer turbulence and surface flux schemes are based on the zeroth-order and first-order paradigms of a forced or agnostic boundary layer. By definition, these ignore submesoscale interaction. Building a toy-model framework that combines existing BL and flux schemes that mimic coupling in current ESMs can be informative about the intrinsic timescales and behavior of those coupled parameterizations, and the model errors they may produce. Such models can also be augmented with simple representations of horizontal variability (eg. imposed mean gradients) or representations of sub-mesoscale interaction and provide tools for testing null hypotheses related to the zeroth and first-order hypothesis outlined in section 3, or how these can be extended to "higher-order "interactions.

2. **Coupled Large-Eddy Simulation (LES)**: LES models have been instrumental in our understanding of 3D turbulence in *either* the atmosphere or ocean. The majority of LES used so far are forced by conditions that are held fixed at the interface between the two fluids, hence, very little is known as to how atmospheric and oceanic boundary layers couple and mutually adjust at the ASI submesoscale. Independent efforts have started to develop wave-phased averaged and wave-phase resolved LES models [147, 148] and atmospheric LES coupled to a 1D ocean model [149, 100], and their use is strongly encouraged in order to contribute answers to the numerous questions raised above. These are most easily explored with idealized settings to systematically explore impacts, followed by more realistic setups, initialized and validated by field experiments that sample the coupled Ocean Boundary Layer - Marine Boundary Layer (OBL - MABL) system at local scales. Simulations with an increasing level of mutual coupling between the atmosphere and the ocean's mixed layer should be carried out, which include a. Prescribed SST patterns (one-way coupling), b. Fixed ocean mixed-layer depth (various experiments using depths from 10 to 100m), c. Interactive 1D mixed layer (either slab-averaged or per atmospheric column), and d. Fully coupled eddy-resolving boundary layers (two-way coupling). Effort needs to be devoted to developing a physical representation of the air-water interface. Especially the representation of surface waves and their impact is a major challenge to the coupled modeling framework since typical LES scales start to overlap with long wavelengths, and hence, they have to account for partially phase-resolved waves while – at the same time – typical spectral wave representations may not be valid anymore either. The simulations domains will depend on the level of complexity. Constrained by the ocean, fully coupled LES will likely be limited to order 10 km x 10 km domains given current computational resources, while atmosphere-only LES with prescribed SST patterns are already run at domains of 1500km with a resolution of 100m for periods of a month. This mismatch arises from the differing resolutions necessary for well-resolved LES of air versus water and poses a technical challenge that will require creative experimental design.

3. **Coupled ocean-atmosphere-wave(-sea-ice) regional models**: These models are a powerful tool to investigate regional-scale phenomena such as extreme weather or coastal events with

the necessary submesoscale-resolving grid. Current efforts need to focus on developing a better coupling of the ocean-atmosphere system with wave and sea-ice models, as many coupled models do not yet properly represent the wind-wave misalignment or wave-current interaction in bulk surface flux algorithms and Langmuir turbulence. Likewise, new experimental designs may be needed to disentangle how air-sea interaction modifies submesoscale dynamics, as cross-scale interactions and shared parameter dependencies between processes can complicate the interpretation of simulation results [5]. The dependence of these simulations on the validity of bulk flux formula at finescales is again highlighted.

4. **Coupled global models**: These models now simulate global climate at submesoscale-permitting scales (1.5-10km) and can be used to address the impact of submesoscale ASI on storm tracks, jet stream variability, ocean heat/carbon uptake, but also the ocean circulation and water mass formation (mode water and deep convection), and consequent remote effects. Ongoing projects include DYAMOND, EERIE, NextGEMS and DestinE, with much recent development in e.g., the NICOCO, NASA/ECCO, ICON, IFS, CESM Hi-resglobal models. In these, attention must be paid to the different adjustment timescales of various parts of the ocean-atmosphere system and how that might affect conclusions about the effect of high-res air-sea coupling on larger scales from relatively short high-resolution model integrations. It also remains unclear how changes in model resolution affect the skill of boundary-layer parameterizations in the coupled interface, as well as the representation of the ocean mesoscale in general.

5.1.2 Model experiments

Submesoscale—or turbulence resolving—simulations with a fully coupled ocean-atmosphere are key to understanding processes and interactions at high frequencies in space and time, but these are limited in the time period or domain they can simulate. Lower-resolution regional and global models, and the coupled 1D conceptual models listed above, thus play an important role as toy models to play with mechanisms, disentangle feedbacks, and assess how they influence remote or larger-scale weather patterns. Different sensitivity experiments that can be performed include:

1. Performing semi-coupled runs, in which, for instance, the atmosphere is forced with prescribed SSTs to evaluate the impact of submesoscale structure on the atmosphere only, or running ocean models coupled to a simplified atmospheric boundary layer model to evaluate the impact on the ocean only.

2. (Un)plugging of coupled feedbacks by, for instance, removing the coupling of waves to the atmosphere or ocean or removing the coupling of ocean waves with sea ice. An analysis challenge for simulations of this type is the role of cross-scale interactions which can confound interpretation of local dynamics [150].

3. Global smoothing of surface fields (e.g SST or surface currents), and selected smoothing over specific regions, can be used to assess the impact of scale-dependent air-sea coupling [37].

4. Multi-nested simulations with grid refinement for specific regions or phenomena of interest, which is of importance to study upscaling effects. Other approaches can be to nudge to climatological (meridional) wind velocities, which may prevent the development of tropical instability waves or submesoscale structure in atmospheric winds, or to turn off non-linear advection (see [132]), but this may directly modify the mean state.

The outcomes of such global and regional modeling experiments help hypothesize mechanisms that can establish rectified effects, and subsequently, turbulence-resolving simulations can be used to investigate these mechanisms in detail. Importantly, these experiments should also help identify regions where submesoscale interactions are important and guide where observational efforts should concentrate.

5.2 In space-based observations

5.2.1 General

There is a wealth of Earth Observation (EO) satellites providing observations of the air-sea interface at varying spatial and temporal scales. In the following we provide a brief overview of the observations that are most relevant to physical air-sea couplings.

One of the most powerful tools for studying air-sea couplings are radar scatterometers (e.g. [151, 152]). Although often understood as providing surface wind measurements, it is important to emphasize that the small-scale roughness to which radars are mostly sensitive is driven by surface stress. Scatterometric measurements of backscatter intensity are therefore inverted to stress-equivalent 10-meter wind vectors ($\mathbf{U}_{10s}$, [153]) which are provided operationally at $\mathcal{O}$(20 km) resolutions. This $\mathbf{U}_{10s}$ can, in principle, be converted to surface stress vectors following the Charnock—or equivalent—relations [154, 155].

Smaller scale ($\mathcal{O}$(1 km) or even smaller) modulations of the surface stress can be observed using Synthetic Aperture Radar (SAR) systems. ASI-submesoscale phenomena that modulate the ocean surface roughness are identifiable by their characteristic roughness patterns. On the atmospheric side of the air-sea interface, wind fields forced by sub-mesoscale phenomena locally alter ocean roughness, leaving behind a projection of the mesoscale wind field onto the ocean surface. These patterns are, in turn, visible in the roughness-sensitive SAR observations. Through this mechanism, SAR imagery capture the intricate variations of atmospheric boundary layer wind fields. Information contained in these wind-field projections is sufficient to identify specific atmospheric conditions[156, 157]. In an unstable MABL, this information can be used to provide estimates of, for example, the Obukhov length or latent heat fluxes [158, 159].

Since the mid-1970s, observations of Sea Surface Temperature (SST) using spaceborne thermal infrared (TIR) instruments at steadily increasing resolutions have been available [160]. Due to the penetration depth of IR radiation in water, TIR-derived SST corresponds to the temperature of the upper $10\,\mu\mathrm{m}$, approximately. Though small, this results in an observed temperature typically $0.1\,\mathrm{K}$ to $0.2\,\mathrm{K}$ higher than the skin temperature, but also typically lower than in-situ measurements of subskin temperature. While geostationary sensors provide SST products with spatial resolution of a few km, polar-orbit SST product resolutions are now $\mathcal{O}(250\,\mathrm{m})$. TIR measurements are impaired by cloud cover, making users often rely on composite products, which involve implicit spatiotemporal filtering [161]. Microwave radiometers provide all-weather observations of SST but at much coarser, $\mathcal{O}$(10 km) resolutions, and representative of a 1 mm depth, approximately.

Ocean surface waves can be characterized using different remote sensing techniques. Radar nadir altimeters provide well-validated estimates of the significant wave height down to scales of about 10 km [162, 163] including in the most severe sea states for which no equivalent in situ record exist, but with poor relative accuracy for wave heights under 1 meter. Complementary information on the contributions from wind-driven waves and from swell can be provided by SAR imagery, including for waves under sea ice. In this respect, the sparse coverage of the Wave Mode used by European Space Agency and Chinese SAR systems has an ideal sampling for ocean scale swell fields, with recent key improvements on the accuracy of retrieved wave parameters brought by machine learning in the past decade [164]. Better spectral information, including the shorter wave components that are relevant for the Stokes drift and mean period, can be obtained by wave spectrometers such as the SWIM (Surface Waves Investigation and Monitoring) instrument onboard CFOSAT (China France Oceanography Satellite) [165, 166]. These radar data, including recent developments of "fully focused" SAR processing, just like the analysis of wave-resolving optical imagery, rely on semi-empirical transfer functions (MTFs) from image modulation to surface elevation. Further analysis and understanding of these MTFs should lead to improved sea state retrieval algorithms and provide detailed information on surface slope statistics that are probably relevant for analysis of air-sea exchange coefficients.

Wave breaking fraction, W, which plays an important role in regulating air-sea fluxes, can be quantified using a range of satellite-based techniques. Foam strongly affects the emissivity of the water surface, allowing the estimation of W from multi-frequency microwave radiometer data [167, 168], with the advantages in terms of coverage, temporal sampling, and weather-independence associated to microwave radiometers, and also the limited spatial resolution. Breaking waves also have a clear signature in multi-polarized radar systems (e.g., [169, 170]). Although the retrieval of W from radar observations is less developed, it clearly opens the door to higher-resolution observations. Under favorable conditions, whitecaps are easily observed with optical sensors.

To date, direct space-based observations of surface current vectors are largely missing. Mesoscale currents are only resolved under the assumption of geostrophic balance from a combination of sea level anomaly provided by altimetry and mean dynamic topography that relies on a combination of gravimetry and in situ drifter data [171]. At present, only scales larger than 200 km and 28 days are resolved, with even coarser resolution in the tropics [172]. The currently in orbit Surface Water and Ocean Topography (SWOT) satellite will clearly provide much higher spatial resolution for geostrophic currents but with a revisit timescale on the order of 10 days. Exploiting the Doppler shift in the radar echoes, current SAR systems are sensitive to surface currents, albeit only to the cross-track components [173, 174].

5.2.2 Observational gaps and future missions

To estimate heat fluxes through the use of bulk equations, aside from SST and the surface stress vector (or, more or less equivalently, U_{10s}), the near-surface air temperature, T_{air}, and humidity, q_{air} are urgently needed and currently missing at the resolutions of interest. In principle, all four variables, and in particular the latter two, can be estimated using a hyperspectral microwave atmospheric sounding radiometer [175], which is at the core of the Butterfly satellite concept, which was proposed but not selected, as a NASA Earth Venture mission. If implemented, Butterfly would provide the state variables needed to estimate air-sea sensible, latent, and therefore buoyancy fluxes at $\mathcal{O}$(25 km) resolution, with 91% global coverage in 2 days. The QLEO mission concept, based on a differential absorption lidar (DIAL), that was proposed within ESA's Call for Ideas for its twelfth Earth Explorer (EE) mission is of interest as it would directly target q_{air} through provision of humidity profiles, including the near-surface, at high vertical resolution and low bias. The QLEO mission concept was not selected as an EE12 candidate mission, but highly recommended to be further studied.

As mentioned earlier, satellite-based observations of surface current vectors are missing. In the context of ASI, these are of particular interest in combination with surface stress vectors (or $\mathbf{U}_{10s}$) and preferably in combination with other state variables. Several mission concepts have been proposed for this purpose. SKIM (Sea surface KInematics Multiscale monitoring) narrowly missed the selection as the European Space Agency 9th Earth Explorer mission. It was conceived as a conically-scanning Ka-band Doppler scatterometer that would have provided total surface current vectors (TSCV), in addition to sea surface height, significant wave height and high-quality directional wave spectra. The SKIM orbit was chosen to allow a loose formation with METOP-SG(B1), thus providing collocated measurements (within 150s) with MWI and SCA for wet tropospheric correction, to flag precipitation as well as to provide accurate wind vector information. Similarly, ODYSEA [176] has been proposed to NASA by JPL and CNES. ODYSEA is also a conically scanning pencil-beam Ka-band scatterometer with Doppler measuring capabilities. The 55° angle of incidence leads to a 1500 km swath, providing daily simultaneous observations of surface stress and surface currents over 80% of the globe at scatterometric resolutions ($\mathcal{O}$(25 km)).

Concepts such as Butterfly, SKIM, and ODYSEA, target frequent global coverage at moderate resolutions, while imaging-radar concepts exploiting along-track-interferometry, such as SEASTAR[177] and Harmony[178, 179], are conceived to provide $\mathcal{O}$(1 km) resolution observations, targeting process understanding, over some large but limited region of interest. Harmony is particularly relevant because it was selected and is being implemented as the tenth ESA Earth Explorer mission. Set to be launched by the end of the decade, one of its main objectives is the observation of small-scale processes related to air-sea interaction. Harmony consists of two identical satellites orbiting in convoy with a Copernicus Sentinel-1 radar satellite. Both Harmony satellites carry two instruments: a receive-only Synthetic Aperture Radar (SAR), working together with Sentinel-1's radar instrument as the illumination source, and a multi-view Thermal Infra-Red (TIR) instrument. The SAR instrument will exploit the multi-angle viewing geometry uniquely offered by the combination of a Sentinel-1 radar satellite with two additional bistatic receive-only companions.

The radar component of Harmony can be understood as a very high-resolution Doppler-scatterometer. It will provide estimates of $\mathbf{U}_{10s}$ at sub-kilometer resolution, and estimates of relative TSCV with a typical uncertainty (1-sigma) of around 15 cm/s at 2 km resolution, or better. In absence of clouds, the TIR component will provide simultaneous observations of SST, with an emphasis on capturing the spatial structure of the field. When clouds are present, the TIR component will exploit the parallax effect to estimate the height of the cloud-edges, their motion vectors, and provide some information about their evolution.

5.2.3 Challenges

As discussed, despite quite rapidly increasing Earth Observation capabilities, there are clear remaining observational gaps, in particular the lack of measurements of near-surface air temperature and humidity. At the same time, high-resolution imagery, possibly in combination with Machine Learning approaches, offers largely unexploited possibilities to quantitatively characterize the MABL.

The largest challenge for space-based observations with respect to surface fluxes of heat, gas and momentum exchange across the air-sea interface is the lack of temporal revisit. Some satellite systems offer a capability to sample at quasi synoptic timescales providing global coverage measurements every day. Many other systems provide a revisit on the order of 2-6 days or longer. While spatial resolution of many measurements is at or below 1 km, (with the notable exception of scatterometer winds and low frequency,10GHz and below, microwave radiometer measurements), this is not commensurate with the time evolution of the processes governing the air-sea fluxes. For example, ocean waves must be measured at periods of <2 hours and in the strong tidal regime of northern Europe, ocean surface currents must be ideally resolved at hourly intervals. This poses a significant challenge to the Earth Observation community for the foreseeable future. Options to address this issue include the use of more satellites or the deployment of lower-cost small satellite constellations to improve temporal sampling.

A more general challenge is that, in most cases, space-based observations provide indirect measurements of the variables of interest. The retrieval of the target geophysical variables relies on, in most cases, empirical or semi-empirical algorithms, which need careful training and validation. In the same way that numerical models need to be re-validated and re-tuned as they resolve smaller scales, it should be assumed also that the inversion of geophysical products from satellite data will have scale dependencies. For example, ocean-driven features observed in high-resolution radar images, and which are of interest for our subject matter, may average out at scatterometric resolutions but need to be considered if the inversion delivers $\mathcal{O}(1\text{ km})$ resolution products. An immediate challenge is therefore to develop and validate algorithms to directly retrieve surface stress vectors, rather than stress equivalent winds, from scatterometers and SAR systems.

Thus, a consistent triad of space-based observations, ground-based and in-situ observations, and numerical model runs are needed to be able to calibrate and interpret space-based observations. This is challenging given the completely different spatio-temporal observation capabilities of satellites and in-situ sensors, implying the need for long-term Fiducial Reference Measurements (FRM) to provide independent measurements of the variables of interest, including momentum and heat fluxes. Importantly, they should be capable of validating the spatial variability captured by the satellite data under a sufficiently large set of representative conditions.

Finally, we highlight as a future challenge that even for those future proposed missions with spatial resolution at the larger end of the ASI-submesoscale, understanding the variability and processes active at smaller scales will be necessary to interpret the observed signal—both in terms of physics and possible aliasing.

5.3 In field observations

The development of a theoretical basis adapted to (sub)mesoscale inhomogeneity is highly reliant on field measurements that remain very scarce to this day. No existing measurement site or platform currently measures both the atmosphere and ocean over a deeper layer than just near the surface for extended periods of time, and with attention to spatial sampling. Long-term simultaneous observations of current and wind profiles also do not exist. Several intensive in situ studies have begun to move towards this goal, including NASA S-MODE [180, 120] (Figure 4) and the EUREC4A/ATOMIC field campaigns [86, 181]. We identify two core considerations for intensive and persistent observations of coupled boundary layer structure and air-sea exchange:

1. Sampling strategies for simultaneous measurements across the interface must account for both temporal and spatial characteristics of submesoscale processes. The large dimensional inertial range of submesoscale processes coupled between the ocean and the atmosphere mean that temporal averages may not be representative of spatial means, thus violating ergodicity. Spatial inhomogeneity and non-equilibrium may also locally decorrelate the air-sea interface

from boundary layer characteristics.

2. Long-term observational programs and super sites are key for capturing a range of phenomena (e.g. along- and cross-front winds, various sea and current states, low and high winds, low and high ocean mixed-layer depth and seasonality, as well as extremes), and for validating and calibrating large-scale models and satellite products.

In the following, we briefly review current platforms and promising state of the art field observations for profiling the ABL and OBL, sampling spatial submesoscale structure and measuring air-sea fluxes. We conclude with section 5.4, which describes the need to group (field and satellite) observational technology, data collection and numerical modeling at so-called super sites.

5.3.1 Simultaneous profiling of the ABL and OBL

Though difficult to achieve, ABL and OBL profiling are essential to verify a range of key assumptions that may not hold in real-world conditions and to study how both boundary layers exchange energy, momentum and gases. For example, in the ABL, unique wind speed profiles collected within the first 30 meters above the sea surface by [182] shed light on possible departure from the classical logarithmic profile and question the validity of a constant flux layer in cases of decaying swell waves. To help develop a new theoretical basis for boundary layer processes in such complex real-world conditions, to improve our capacity to measure and predict key parameters such as U_{10s}, and to maximize the potential of tools such as satellite observation and numerical modeling, it is necessary that single-point direct near-surface measurements that dominate existing air-sea parameterizations [e.g. 22] should be accompanied by multi-point measurements [183].

Research vessels (R/Vs), charters, and vessels of opportunity can probe both the full ABL and OBL simultaneously, using remote sensing such as lidar for the ABL and CTD measurements for the OBL. However, these operations are often limited to along-track measurements for up to several weeks only and can not capture the critical region near the ocean surface. They also need a high enough mast far enough forward for measuring high-quality fluxes [184]. Besides R/Vs, there is little infrastructure in place that profiles both the ABL and OBL. Routine measurements focus either on the surface, on the OBL, or on the ABL.

An example of the first and second are surface buoys and deep ocean moorings (such as those used by the Oceans Observations Initiative, National Data Buoy Center, or Salinity Processes in the Upper Ocean Regional Study (SPURS, WHOI)), Lagrangian surface drifters, specialized research buoys (e.g., SWIFT, X-SPAR, ASIS), wave buoys (e.g. Spotter), buoy-based profilers (Wirewalker, Prawler) or uncrewed autonomous platforms such as Saildrones, wave gliders, sea/deep gliders and ARGO, where the latter three have been very effective at profiling the upper ocean. Larger arrays of surface buoys exist in the tropics, such as the Tropical Atlantic PIRATA array, the Pacific Tropical Atmosphere Ocean (TAO) array, and the Indian Ocean RAMA array. Away from the equator, where stronger wind and wave activity lead to more challenging conditions, fewer long-term, open ocean surface moorings include, in the trades, the three Ocean Reference Stations (ORS), and in the midlatitudes, the Ocean Climate Stations (OCS, including KEO off Japan and station PAPA in the Gulf of Alaska) and the Australian Southern Ocean Time Series mooring south of Tasmania. These long-term moorings are coordinated Internationally by OceanSITES (http://www.oceansites.org) as part of the Global Ocean Observing System. They primarily collect time series of surface meteorology and upper ocean hydrography that can be used to compute bulk air-sea fluxes and near surface stratification and heat content, but they do not probe temperature or stability across the ABL, and critically for the purposes outlined here at best only resolve very large-scale horizontal structure.

Compared to the OBL, the marine ABL is profiled less routinely and with poor global sampling, except for the atmospheric surface layer up to some tens of meters (at most 100 m), which is measured permanently from a number of fixed platforms or towers off the coast. This includes for instance the WHOI Air-Sea interaction tower at the Martha's Vineyard Coastal Observatory, the Acqua Alta Oceanographic Tower in the Adriatic Sea, the FINO 1, 2 and 3 towers in the North Sea and Baltic sea. The unique R/P FLIP, a floating US oceanographic instrument platform, has inspired Polar POD, a planned novel infrastructure, which can be towed horizontally to the research zone and tilted vertically [2]. Buoy-based (short-range) profiling of wind and currents extending up to several hundred meters above the surface is increasingly common, such as in the case of offshore wind energy sites. Wind lidars positioned at coastal observatories or offshore platforms also allow a recent and non-invasive solution to wind measurements, and are promising for the continuous vertical profiling of wind in the MABL. Infrequent sampling of the ABL across a deeper layer is done with sounding balloons, research aircraft and dropsondes, and in recent years, uncrewed aerial vehicles or drones are emerging as a potentially valuable tool that could perform more automated profiling throughout the lowest kilometers of the atmosphere.

Thus, while much of the technology needed for sustained in situ coincident sampling of the ABL and OBL exists, it has not yet been deployed in a manner designed specifically to resolve spatial variations in the ASI submesoscale.

5.3.2 Spatial submesoscale structure

Observations have been used extensively to document the 1-D response of the ocean to various atmospheric forcing, but a wide range of uncertainty exists about how mesoscale atmospheric processes imprint on the equivalent ocean submesoscale and vice versa. Some key questions emerge: What are the possible spatial scales of responses, and what are key lateral processes and effects? Does the imprint of finescale atmospheric variability have dynamical significance for the ocean, or does it rapidly 'diffuse' away? Does the imprint of finescale ocean variability likewise significantly affect atmospheric boundary layer process? For example, we know from satellite data that near-surface stable diurnal warm layers can span entire ocean basins, and near-surface stabilization by rain and river output can cover large areas commensurate with the freshwater source (i.e., size of rain and output volume of river). Freshwater lenses spread at the speed of a gravity current if they can outlast the initial turbulent mixing and surface cooling involved with the rain event itself. Recent field campaigns such as SPURS aimed to understand the fine-scale (in space and time) near-surface salinity variability. Submesoscale fronts imprint on surface fluxes of heat and ABL structure locally, but it is unclear whether this significantly modifies ABL dynamics at these scales or larger [46, 47, 17]. Uncertainty extends down to fundamental processes that are not well understood even outside of possible submesoscale modifications. For example, wave breaking has been observed to be enhanced on wave-current gradients associated with submesoscale fronts, however wave breaking itself remains poorly understood. Without more fundamental knowledge of this process, it is difficult to quantify the impact.

[2] https://www.polarpod.fr/en/polar-pod

Although no single instrument or platform is a panacea for the study of the ocean submesoscale, recent developments in the processing and analysis of marine radar have greatly improved its usefulness for interrogating the lateral [185] and vertical [186] structure of the ocean surface layer. An example of the former is provided in Figure 5. Airborne instruments have demonstrated in recent years their usefulness by capturing velocity gradient statistics [187] inferred from optical observations of the spatiotemporal evolution of surface waves, whose dispersion is altered by the presence of an underlying current [188, 189] and radar instruments such as DopplerScatt [190, 176, 191], capable of providing coincident and collocated observations of winds and currents (Figure 4).

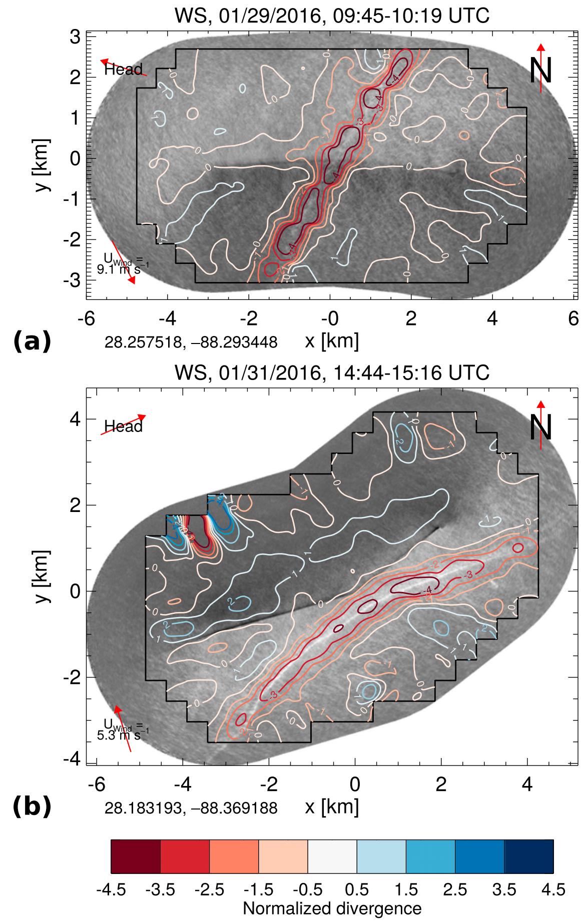


Figure 5. Marine radar-derived surface divergence (contours), normalized by the local inertial frequency. Marine X-band radar backscatter intensity is shown in gray. Taken from Lund *et al.,* (2018) [185].

5.3.3 The interface: fluxes and influence of waves

Both direct (eddy covariance) and bulk (e.g., COARE) approaches are used for estimating air-sea fluxes 4.1. Eddy covariance techniques are required or recommended in situations when bulk formula cannot adequately constrain all sources of variability on the exchanges of momentum, heat, or moisture across the interface, notably at times when currents and/or waves are misaligned with the wind, including wind-current interactions and mixed/confused seas. However, hardly any long-term site measures the turbulent fluctuating quantities and high-accuracy platform motion required for the direct computation of fluxes via eddy covariance.

The state variables that are needed for estimating fluxes through bulk parameterizations are routinely measured at surface moorings and buoys and might include many, but not all, of the following parameters: near-surface air temperature, relative humidity, pressure, rain rate, wind speed and direction, SST, SSS, surface currents, shortwave and longwave radiation, wave age through period and significant wave height. Due to a lack of coincident collocated measurements of all wave and current states alongside all bulk state variables noted above, COARE for instance has only been able to constrain the impact of wave age on the roughness and, therefore, momentum flux (the contribution to heat and moisture fluxes is negligible). Wave directional information is also important: in bulk parameterizations all stress is assumed to be in the direction of the mean wind (i.e. cross stream stress is not computed), which is violated in regions where the wave state is modulated by strong horizontal current gradients [29]. As more data are collected from various complementary platforms, a more accurate parameterization of how waves regulate the momentum flux can be implemented, with a recent example being an improved wave-based COARE3.5 formulation based on EUREC^{4}A/ATOMIC observations [31].

Wave buoys are at present the most used platform for wave-informed flux measurements, but are limited in that they only yield the frequency-directional (not wavenumber-directional) spectra–and those spectra are band-limited, only resolving waves with periods longer than one second. The latter constraint prevents buoys from characterizing waves of length $\lessapprox$1.5 m, eliminating the short-scale roughness elements that support more than 75% of the waveform drag [192]. Due to the strong dependence of wave-supported air-sea momentum flux on surface wave scale, it is important to partition wave measurement capabilities. For example, pressure sensors are well suited to measure swell (>=10 s) and long wind waves (5-10 s), while small wave buoys are capable of sensing medium wind-waves (1-5 s). Short wind-waves (0.1-1 s, including waves at least partially restored to equilibrium by capillarity) are generally resolvable only through imaging or radar-based techniques. Even relatively small absolute errors in flux parameterizations due to wave effects could have a significant impact if they are systematically related to submesoscale ocean features (section 2).

Following in the steps of the Argo program and its transformative impact on oceanographic and climate research on both global and regional scales, there are emerging technologies to measure air-sea fluxes from other low-cost, small, uncrewed platforms. Arrays of instrumented drifters, along the lines of the SOFAR Spotter buoys program used for global predictions of surface wave conditions, should be explored to support and inform future (e.g. Harmony) and proposed (e.g. Butterfly, ODYSEA, QLEO) satellite missions to help validate, constrain, and advance the usage of existing operational products being made from combined satellite and reanalysis products (OAFlux, ERA5, etc) and potentially increase product spatial resolution. Uncrewed autonomous platforms, such as WaveGliders or Saildrones, can provide additional spatial information that is important for contextualizing the role of horizontal variability and validating upcoming higher-resolution satellite products. The design of arrays of in-situ platforms could take inspiration from recent long-term mooring observations targeted at the ocean submesoscale, such as the OSMOSIS program, which involved nesting of two square mooring arrays (an outer array and an inner array) augmented by autonomous seaglider lines that together allow gradients to be calculated at multiple scales [193].

5.4 "Supersites"

The study of air-sea coupling requires an integrated effort that combines numerical modeling with in-situ and remote sensing observations, which to a large extent, can be articulated through the implementation of *supersites*. A transformational observing strategy would be one that captures the vertical and temporal evolution of the MABL across submesoscale ocean features as they evolve, while simultaneously collecting vertical profiles of that same ocean feature, along with the evolution of the sea surface and air-sea fluxes. This requires grouping observational technology and data collection at "supersites", whereby novel approaches for sampling across a larger spatial area surrounding a permanent measurement site or R/V include autonomous vehicles, fast scanning remote sensing, collocated high-resolution satellite measurements, and numerical modeling:

1. Continuous remote sensing of the marine ABL in a vertical and horizontal scanning pattern is a recommended approach to resolve boundary layer thermodynamics and dynamical circulations, as well as cloudiness and precipitation. This has been accomplished, so far, only on

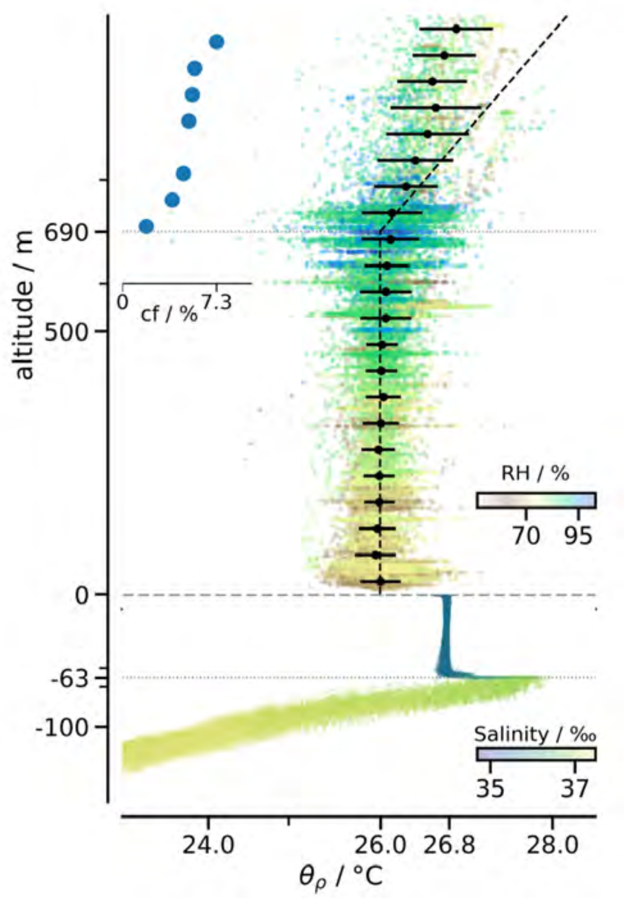


Figure 6. The ocean and atmospheric boundary layer observed during EUREC^{4}A upwind of the Barbados Cloud Observatory, taken from [86]. Dots above the sea surface show UAV measurements of the density potential temperature vs. altitude (by the CU RAAVEN), as well as underwater glider measurements of the temperature below the surface. Values are normalized to compensate for differences associated with either synoptic variations or from variations in the depth of the sampled planetary boundary layers. Blue dots show profile of cloud fraction from all MPCK (a large tethered CloudKite) profiles. The dashed (black) line marks the potential temperature of near-surface air isentropically lifted from the surface; the slope discontinuity at the lifting condensation level (690 m) marks the shift from an unsaturated to a saturated isentrope. The temperature difference between the sea surface and the lower atmosphere is taken from Saildrone data.

ships with active motion stabilization of lidars, cloud radars, and ceilometers. Stabilization is typically not needed for ceilometers. If infrared or passive microwave sounders are used at a high enough temporal frequency, active motion stabilization is recommended.

2. Ocean temperature and salinity data (in both the horizontal and vertical directions) are critical for estimating mixed and barrier layer depths and estimating the distribution and strength of surface fronts. This data can be obtained from a combination of moored instruments and autonomous platforms. Moorings provide the capability of high temporal and vertical resolution and can be augmented with other instrument types (eg. those discussed below). Autonomous platforms provide horizontal spatial resolution, which is difficult to achieve with moorings only. Seagliders are regularly deployed for long (multi-month) missions, and because of their 'zig-zag' sampling pattern, they can provide high-resolution in both the vertical and horizontal directions. Other autonomous platforms, such as Wavegliders, can likewise be deployed for long-duration missions and are capable of observing the near-surface transition zone. Recent developments that allow the deployment of winched CTDs onboard surface platforms extend their capabilities to vertical profiling. 'Anchoring' repeat autonomous platform lines with moored observations is a particularly useful approach that leverages the advantages of each measurement platform [193].

3. Observations of turbulence (e.g., turbulent kinetic energy dissipation rate) and turbulent fluxes (direct eddy covariance) in the atmospheric and oceanic boundary layers are needed using multiple persistent sensors to capture spatial gradients, or using platforms that can make fast response turbulence measurements, while they transect small scale feature. Similar measurements are now relatively routinely taken in the ocean from seaglider platforms.

4. Observation of the surface wave field, capturing the presence of non-locally generated surface waves (swell) and characterizing the spatiotemporal variation of local wind-generated waves down to scales sufficient for computing the wave-supported momentum flux. Capturing the directional propagation of surface waves over these scales is essential for investigating the complex wave-current interaction processes, which are (1) understood to be an important component of the air-sea energy balance, (2) play a key role in air-sea heat and gas flux, and (3) expected to be significant in the presence of submesoscale ocean surface features. A combination of point (e.g., arrays of buoys) and field-of-view (e.g., radar, lidar, and optical imaging from orbital and suborbital platforms) techniques would provide substantial coverage in both spectral and physical space, enabling quantification of the role of submesoscale features in modulating air-sea interaction processes which are mediated by ocean surface waves.

5. Observations of parameters contributing to bulk air-sea fluxes (air and ocean temperature, RH, wind, currents, cloud cover, rain-rate and longwave- and short-wave radiation) can be accomplished with in-situ sensors on buoys, space-based or upward looking remote sensing, or (for rain-rate) subsurface acoustic sensors with a 5 km footprint [194], or traditional air-side surface gauges. These observations require collocated direct covariance/inertial dissipation air-sea flux measurements to evaluate submesoscale spatial variability on fine scales. This might allow us to infer the rectified effects of small-scale variations when compared to coarser resolution observations, i.e., from satellite/reanalysis products such as OAFlux (including newer 0.25 degree resolution OAFlux), as well as the same grid scales as those used in global models. This could be done through a targeted observational analysis with buoys, uncrewed

surface vehicles (e.g., Wave Gliders or Saildrones), or drifters in a location with known strong, recurring submesoscale structures. An alternative approach might be to use platforms with wider spatial coverage, such as airborne platforms or repeated ship transects.

6. Fine-resolution (temporal/spatial) model output and remote sensing products are critical for providing context for localized in-situ observations. Modeling and remote sensing teams also seek in-situ observations to better understand and validate retrievals and results, as well as test physical hypotheses. This would foster ongoing collaborations among usually disparate fields (in-situ, remote sensing, modeling) in several key regions that are sensitive to submesoscale air-sea interaction.

Exemplary of such a super-site effort is EUREC^{4}A/ATOMIC [86, 181], a two-month campaign that sampled a large area surrounding the Barbados Cloud Observatory with numerous aircraft, RVs and autonomous vehicles that sampled both atmosphere and ocean, drawing out, for instance, profiles of density potential temperature across the air-sea interface by combining UAV, glider and Saildrone measurements (Figure 6). The campaign has been instrumental in guiding numerous individual modeling efforts and a model intercomparison project (MIP) for atmospheric turbulence-resolving LES and atmospheric mesoscale models [3].

Supersites are also a key element for the validation and calibration of space-based observations, providing fiducial reference measurements that are required to accelerate the take-up of new remote sensing products. It should be emphasized that while space-based are essential to capture the spatial structure of submesoscale ASI processes, the interpretation of the observations, which relies heavily on empirical relation, cannot be done without the availability of collocated in-situ small-scale, hyper-temporal measurements.

6 Summary

The following shortly summarizes the main points of this paper:

1. Because fluxes of energy and momentum across the air-sea interface will project differently onto ocean and atmosphere processes due to the different dynamical regimes occupied by the ocean and atmosphere, in the same wavenumber space, it is recommended as conceptually useful to consider a new scale: the **ASI-submesoscale**. The ASI-submesoscale contains the range of length scales for which the marine atmospheric boundary layer remains in disequilibrium with a submesoscale ocean forcing feature, encompassing also the scales of transition between forward and inverse energy cascades in both the ocean and atmosphere. It will typically span 200 m - 200 km in the mid-latitudes —a range that includes scales both larger than the ocean submesoscale (200 m - 20 km) and smaller than the atmospheric meso-β scale (2 km - 200 km).

2. Studies focusing on the ASI-submesoscale regime can benefit from a distinction in different hypothetical interactions. In **zero- or agnostic** interaction, the ocean and the atmosphere only feel the homogenized mean state of the other, and as such are essentially uncoupled. In **one-way** forced interaction, submesoscale variability in one fluid influences the evolution of the other fluid through air-sea fluxes, but there is no subsequent feedback, such as in

[3] www.eurec4a.eu

atmosphere- or ocean-only models when they prescribe heterogeneous boundary conditions. In **two-way weak** interactions, a forced response of one boundary layer to the fluxes induced by the other introduces feedbacks, but at a different scale or location, so that the coupling is weak. In **two-way strong** interactions, a (near) match of scale or resonant frequency in the forced response of the boundary layers implies stronger feedbacks with the possibility of coupled instabilities, coupled circulations, or propagation of variance. This may lead to rectified or integrated responses that affect the larger scale statistics of weather and climate.

3. The key challenge for studies focused on ASI at submesoscales is to unravel if and how observed atmospheric and oceanic structures (e.g. cloud organization, ocean eddies and filaments) within the ASI-submesoscale involve 2^{nd}-order ASI with strong responses, or whether they develop without meaningful interaction (one-way coupling as in most models). In other words: *how does atmospheric and oceanic structure at scales of 200 m - 200 km influence air-sea interaction and the statistics of larger-scale circulations?*

4. The ASI-submesoscale contains a range of scales in which widely used assumptions to estimate surface fluxes, in particular the Monin-Obukhov Similarity Theory, may fail to hold. A leading question is to what extent errors introduced by assumptions are systematic and affect estimates of air-sea energy and momentum exchange on larger scales. Simultaneous surface, OBL, and ABL measurements are key to the testing of current classical theory and for the development of a new theoretical framework.

5. Key climate zones and weather phenomena in which the ASI submesoscale can play important roles are, in the tropics, the low-wind speed doldrums and high-wind speed cyclones or storms; in the subtropics, shallow cloud organization; in the extra-tropics, western boundary currents and storm tracks and marine heat waves (also in the Arctic). In certain regimes (western boundary currents), we already have emerging evidence of 2^{nd}- ASI that lead to impacts on regional scales (e.g. the storm track), while in other regimes there is an abundance of structure at the ASI-submesoscale that has not yet been attributed to interactions across the air-sea interface, but where potentially large impacts may arise. We also suspect a potential role in a number of other regimes that include coastal upwelling regions and shallow seas and regions with sea-ice.

6. A new generation of higher-resolution km-scale global models are now feasible, limited mainly in the time scales they can simulate and in the required level of coupling between atmosphere, ocean and waves. These models may fail to represent important variability in the Earth system by distorting interactions at the ASI-submesoscale and needed model development should focus on coupled simulations at large eddy resolving scales (submesoscale domains), at submesoscale-resolving (regional domains), and submesoscale-permitting scales (global domains). This new era of models can make use of semi-coupled runs, (un)plugging of coupled feedbacks, smoothing of structure (in specific) regions and multi-nested simulations with grid-refinement to study upscaling effects of ASI at submesoscales.

7. While many new and existing in-situ and remote sensing observations can measure relevant parameters for ASI-submesoscale processes, they are often made only in the MABL or in the OBL. A transformative strategy would be to create "supersites" that bundle longer-term measurements in the ocean, atmosphere, and at their interface (and keeping such an effort low-cost and easy to maintain), essentially building long-term versions of *e.g.* EUREC^{4}A/ATOMIC. A key challenge is to measure the exchange of heat and energy in the vertical in an undisturbed way

and with information on the sea state, while also providing adequate spatial sampling within the whole ASI-submesoscale range. For the latter, high-resolution space-based observations offer exciting opportunities. Super-sites are not only a great testbed for models and space-based sensors, they also provide an opportunity for targeted modeling studies that can provide spatial context for the observations and an experimental tool to (de-)couple feedbacks. Consistent with this recommendation is the description of needed supersites in the US CLIVAR Air-Sea Transition Zone Study Group Report [195].

8. Despite rapidly expanding Earth Observation capabilities and exciting upcoming missions (e.g. ESA's tenth Earth Explorer mission Harmony), there are critical gaps in space-borne observations. These include near-surface air temperature and humidity measured from space, which are needed to derive $\mathcal{O}$(10-20 km) surface heat and latent fluxes globally. Also missing are space-borne observations of surface current vectors (as currently proposed with ODYSEA), needed for understanding air-sea interaction and coupling. Related EO mission concepts such as Butterfly, QLEO, and SKIM were proposed but not selected. Such missions are highly recommended to be further studied and reviewed.

Acknowledgments

Financial and organizational support provided through the Lorentz Center (https://www.lorentzcenter.nl/) was key to the success of this workshop, and is gratefully acknowledged. Travel support for US participants was provided in part through NASA award 80NSSC23K0778 (Program Manager Nadya Vinogradova Shiffer). Travel support for EU participants was provided in part through the NWO Talent Scheme Vidi project CMTRACE (grant no. 192.050) awarded to Louise Nuijens by the Dutch Research Council (NWO).

References

[1] J. R. Taylor and A. F. Thompson. "Submesoscale dynamics in the upper ocean". In: *Annual Review of Fluid Mechanics* 55 (2023), pp. 103–127. DOI: 10.1146/annurev-fluid-031422-095147.

[2] H. Seo et al. "Ocean mesoscale and frontal-scale ocean–atmosphere interactions and influence on large-scale climate: A review". In: *Journal of Climate* 36.7 (2023), pp. 1981 –2013. DOI: 10.1175/JCLI-D-21-0982.1.

[3] Y. Liu et al. "Gulf Stream transport and mixing processes via coherent structure dynamics". In: *Journal of Geophysical Research: Oceans* 123.4 (2018), pp. 3014–3037. DOI: 10.1002/2017JC013390.

[4] G. O. Marmorino et al. "Application of airborne infrared remote sensing to the study of ocean submesoscale eddies". In: *Frontiers in Mechanical Engineering* 4 (2018), p. 10. DOI: 10.3389/fmech.2018.00010.

[5] J. O. Wenegrat. "The current feedback on stress modifies the Ekman buoyancy flux at fronts". In: *Journal of Physical Oceanography* 53.12 (2023), pp. 2737–2749. DOI: 10.1175/JPO-D-23-0005.1.

[6] N. Schneider and B. Qiu. “The atmospheric response to weak sea surface temperature fronts”. In: *Journal of the Atmospheric Sciences* 72.9 (2015), pp. 3356–3377. DOI: 10.1175/JAS-D-14-0212.1.

[7] Michael A. Spall. “Midlatitude Wind Stress–Sea Surface Temperature Coupling in the Vicinity of Oceanic Fronts”. In: *Journal of Climate* 20.15 (2007), pp. 3785 –3801. DOI: 10.1175/JCLI4234.1.

[8] R. J. Small et al. “Air-sea interaction over ocean fronts and eddies”. In: *Dynamics of Atmospheres and Oceans* 45.3-4 (2008), pp. 274–319. DOI: 10.1016/j.dynatmoce.2008.01.001.

[9] A. N. Meroni, F. Desbiolles, and C. Pasquero. “Introducing new metrics for the atmospheric pressure adjustment to thermal structures at the ocean surface”. In: *Journal of Geophysical Research: Atmospheres* 127.16 (2022), e2021JD035968. DOI: 10.1029/2021JD035968.

[10] J. R. Garratt. “The internal boundary layer - A review”. In: *Boundary-Layer Meteorology* 50.1-4 (1990), pp. 171–203. DOI: 10.1007/BF00120524.

[11] I. Orlanski. “A rational subdivision of scales for atmospheric processes”. In: *Bulletin of the American Meteorological Society* 56.5 (1975), pp. 527–530.

[12] R. Schubert, J. Gula, and A. Biastoch. “Submesoscale flows impact Agulhas leakage in ocean simulations”. In: *Communications Earth & Environment* 2.1 (2021), p. 197. DOI: 10.1038/s43247-021-00271-y.

[13] M. Shao et al. “The variability of winds and fluxes observed near submesoscale fronts”. In: *Journal of Geophysical Research: Oceans* 124.11 (2019), pp. 7756–7780. DOI: 10.1029/2019JC015236.

[14] P. Gaube et al. “Satellite observations of SST-induced wind speed perturbation at the oceanic submesoscale”. In: *Geophysical Research Letters* 46.5 (2019), pp. 2690–2695. DOI: 10.1029/2018GL080807.

[15] X. Song et al. “Air-sea latent heat flux anomalies induced by oceanic submesoscale processes: An observational case study”. In: *Frontiers in Marine Science* 9 (2022). DOI: 10.3389/fmars.2022.850207.

[16] J. Lambaerts et al. “Atmospheric response to sea surface temperature mesoscale structures”. In: *Journal of Geophysical Research: Atmospheres* 118.17 (2013), pp. 9611–9621. DOI: 10.1002/jgrd.50769.

[17] S. Iyer et al. “Small-scale spatial variations of air-sea heat, moisture, and buoyancy fluxes in the tropical trade winds”. In: *Journal of Geophysical Research: Oceans* 127.10 (2022), e2022JC018972. DOI: 10.1029/2022JC018972.

[18] S. Iyer et al. “Variations in wave slope and momentum flux from wave-current interactions in the tropical trade winds”. In: *Journal of Geophysical Research: Oceans* 127.3, e2021JC018003 (2022). DOI: 10.1029/2021JC018003.

[19] W. G. Large and S. Pond. “Open ocean momentum flux measurements in moderate to strong winds”. In: *Journal of Physical Oceanography* 11.3 (1981), pp. 324 –336. DOI: 10.1175/1520-0485(1981)011<0324:OOMFMI>2.0.CO;2.

[20] W. G. Large and S. Pond. “Sensible and latent heat flux measurements over the ocean”. In: *Journal of Physical Oceanography* 12.5 (1982), pp. 464 –482. DOI: 10.1175/1520-0485(1982)012<0464:SALHFM>2.0.CO;2.

[21] J. B. Edson et al. "Direct covariance flux estimates from mobile platforms at sea". In: *Journal of Atmospheric and Oceanic Technology* 15.2 (1998), pp. 547 –562. DOI: 10.1175/1520-0426(1998)015<0547:DCFEFM>2.0.CO;2.

[22] J. B. Edson et al. "On the exchange of momentum over the open ocean". In: *Journal of Physical Oceanography* 43.8 (2013), pp. 1589 –1610. DOI: 10.1175/JPO-D-12-0173.1.

[23] H. Tennekes and J. L. Lumley. *A first course in turbulence*. Cambridge MA, USA: MIT press, 1972.

[24] A. Weill et al. "Toward a better determination of turbulent air–sea fluxes from several experiments". In: *Journal of Climate* 16.4 (2003), pp. 600 –618. DOI: 10.1175/1520-0442(2003)016<0600:TABDOT>2.0.CO;2.

[25] C. W. Fairall et al. "Bulk parameterization of air-sea fluxes for Tropical Ocean-Global Atmosphere Coupled-Ocean Atmosphere Response Experiment". In: *Journal of Geophysical Research: Oceans* 101.C2 (1996), pp. 3747–3764. DOI: 10.1029/95JC03205.

[26] U. Högström et al. "Momentum fluxes and wind gradients in the marine boundary layer - a multi-platform study". In: *Boreal Environment Research* 13.6 (2008), pp. 475–502.

[27] N. Kljun et al. "A simple two-dimensional parameterisation for Flux Footprint Prediction (FFP)". In: *Geoscientific Model Development* 8.11 (2015), pp. 3695–3713. DOI: 10.5194/gmd-8-3695-2015.

[28] J. B. Edson et al. "The coupled boundary layers and air–sea transfer experiment in low winds". In: *Bulletin of the American Meteorological Society* 88.3 (2007), pp. 341–356. DOI: 10.1175/BAMS-88-3-341.

[29] F. W. Zhang et al. "On wind-wave-current interactions during the Shoaling Waves Experiment". In: *Journal of Geophysical Research: Oceans* 114.C1 (2009). DOI: 10.1029/2008JC004998.

[30] M. A. Donelan, W. M. Drennan, and K. B. Katsaros. "The air–sea momentum flux in conditions of wind sea and swell". In: *Journal of Physical Oceanography* 27.10 (1997), pp. 2087 –2099. DOI: 10.1175/1520-0485(1997)027<2087:TASMFI>2.0.CO;2.

[31] C. Sauvage et al. "Improving wave-based air-sea momentum flux parameterization in mixed seas". In: *Journal of Geophysical Research: Oceans* 128.3, e2022JC019277 (2023). DOI: 10.1029/2022JC019277.

[32] S. Blein et al. "Meso-scale contribution to air–sea turbulent fluxes at GCM scale". In: *Quarterly Journal of the Royal Meteorological Society* 146.730 (2020), pp. 2466–2495. DOI: 10.1002/qj.3804.

[33] M. Belmonte Rivas and A. Stoffelen. "Characterizing ERA-Interim and ERA5 surface wind biases using ASCAT". In: *Ocean Science* 15.3 (2019), pp. 831–852. DOI: 10.5194/os-15-831-2019.

[34] P. Fernández et al. "On the importance of the atmospheric coupling to the small-scale ocean in the modulation of latent heat flux". In: *Frontiers in Marine Science* 10 (2023). DOI: 10.3389/fmars.2023.1136558.

[35] S. P. Bigorre et al. "A surface mooring for air–sea interaction research in the Gulf Stream. Part II: Analysis of the observations and their accuracies". In: *Journal of Atmospheric and Oceanic Technology* 30.3 (2013), pp. 450–469. DOI: 10.1175/JTECH-D-12-00078.1.

[36] L. Renault et al. "Modulation of wind work by oceanic current interaction with the atmosphere". In: *Journal of Physical Oceanography* 46(6) (2016), pp. 1685–1704. DOI: 10.1175/JPO-D-15-0232.1.

[37] I. Uchoa, J. Wenegrat, and L. Renault. "Sink of eddy energy by submesoscale sea surface temperature variability in a coupled regional model". In: *Journal of Physical Oceanography* (submitted). DOI: 10.31223/X59H6N.

[38] Z. Su et al. "Ocean submesoscales as a key component of the global heat budget". In: *Nature Communications* 9.1 (2018). DOI: 10.1038/s41467-018-02983-w.

[39] Z. Su et al. "High-frequency submesoscale motions enhance the upward vertical heat transport in the global ocean". In: *Journal of Geophysical Research: Oceans* 125.9, e2020JC016544 (2020). DOI: 10.1029/2020JC016544.

[40] Y. Kaspi and T. Schneider. "Winter cold of eastern continental boundaries induced by warm ocean waters". In: *Nature* 471.7340 (2011), pp. 621–624. DOI: 10.1038/nature09924.

[41] K. A. Kelly et al. "Western boundary currents and frontal air–sea interaction: Gulf Stream and Kuroshio Extension". In: *Journal of Climate* 23.21 (2010), pp. 5644–5667. DOI: 10.1175/2010JCLI3346.1.

[42] J. Callies and R. Ferrari. "Interpreting energy and tracer spectra of upper-ocean turbulence in the submesoscale range (1-200 km)". In: *Journal of Physical Oceanography* 43.11 (2013), pp. 2456–2474. DOI: 10.1175/JPO-D-13-063.1.

[43] C. B. Rocha et al. "Seasonality of submesoscale dynamics in the Kuroshio Extension". In: *Geophysical Research Letters* 43.21 (2016). DOI: 10.1002/2016GL071349.

[44] Wayne Sweet et al. "Air-Sea Interaction Effects in the Lower Troposphere Across the North Wall of the Gulf Stream". In: *Monthly Weather Review* 109.5 (May 1981), pp. 1042–1052. DOI: 10.1175/1520-0493(1981)109<1042:ASIEIT>2.0.CO;2.

[45] George S. Young and Todd D. Sikora. "Mesoscale Stratocumulus Bands Caused by Gulf Stream Meanders". In: *Monthly Weather Review* 131.9 (Sept. 2003), pp. 2177–2191. DOI: 10.1175/1520-0493(2003)131<2177:MSBCBG>2.0.CO;2.

[46] J. O. Wenegrat and R. S. Arthur. "Response of the atmospheric boundary layer to submesoscale sea surface temperature fronts". In: *Geophysical Research Letters* 45.24 (2018), pp. 13505–13512. DOI: 10.1029/2018GL081034.

[47] Peter P. Sullivan et al. "Marine Boundary Layers above Heterogeneous SST: Across-Front Winds". In: *Journal of the Atmospheric Sciences* 77.12 (Dec. 2020), pp. 4251–4275. DOI: 10.1175/JAS-D-20-0062.1.

[48] Thomas Kilpatrick, Niklas Schneider, and Bo Qiu. "Boundary Layer Convergence Induced by Strong Winds across a Midlatitude SST Front*". In: *Journal of Climate* 27.4 (Feb. 2014), pp. 1698–1718. DOI: 10.1175/JCLI-D-13-00101.1.

[49] Leif N. Thomas et al. "Symmetric Instability, Inertial Oscillations, and Turbulence at the Gulf Stream Front". In: *Journal of Physical Oceanography* 46.1 (Jan. 2016), pp. 197–217. DOI: 10.1175/JPO-D-15-0008.1.

[50] Jacob O. Wenegrat et al. "Enhanced mixing across the gyre boundary at the Gulf Stream front". In: *Proceedings of the National Academy of Sciences* 117.30 (July 2020), pp. 17607–17614. DOI: 10.1073/pnas.2005558117.

[51] A. Foussard, G. Lapeyre, and R. Plougonven. "Storm track response to oceanic eddies in idealized atmospheric simulations". In: *Journal of Climate* 32.2 (2019), pp. 445–463. DOI: 10.1175/JCLI-D-18-0415.1.

[52] F. Desbiolles et al. “Environmental control of wind response to sea surface temperature patterns in reanalysis dataset”. In: *Journal of Climate* 36.12 (2023), pp. 3882–3893. DOI: 10.1175/JCLI-D-22-0373.1.

[53] A. N. Meroni, F. Desbiolles, and C. Pasquero. “Satellite signature of the instantaneous wind response to mesoscale oceanic thermal structures”. In: *Quarterly Journal of the Royal Meteorological Society* 149 (2023), 3373–3382. DOI: 10.1002/qj.4561.

[54] Jörn Callies et al. “Seasonality in submesoscale turbulence”. In: *Nature Communications* 6 (Apr. 2015), p. 6862. DOI: 10.1038/ncomms7862.

[55] Marcela Contreras, Lionel Renault, and Patrick Marchesiello. “Understanding Energy Pathways in the Gulf Stream”. In: *Journal of Physical Oceanography* 53.3 (Mar. 2023), pp. 719–736. DOI: 10.1175/JPO-D-22-0146.1.

[56] S. Billheimer and L. D. Talley. “Annual cycle and destruction of Eighteen Degree Water”. In: *J. Geophys. Res.* 121 (2016), pp. 6604–6617.

[57] Jacob O. Wenegrat et al. “Effects of the Submesoscale on the Potential Vorticity Budget of Ocean Mode Waters”. In: *Journal of Physical Oceanography* 48.9 (Sept. 2018), pp. 2141–2165. DOI: 10.1175/JPO-D-17-0219.1.

[58] Terrence M. Joyce, Clara Deser, and Michael A. Spall. “The Relation between Decadal Variability of Subtropical Mode Water and the North Atlantic Oscillation*”. In: *Journal of Climate* 13.14 (July 2000), pp. 2550–2569. DOI: 10.1175/1520-0442(2000)013<2550:TRBDVO>2.0.CO;2.

[59] Kirsten L. Findell et al. “Accurate assessment of landâatmosphere coupling in climate models requires high-frequency data output”. In: *Geoscientific Model Development* 17.4 (Feb. 2024), pp. 1869–1883. DOI: 10.5194/gmd-17-1869-2024.

[60] M. Ahlgrimm et al. “Understanding global model systematic shortwave radiation errors in subtropical marine boundary layer cloud regimes”. In: *Journal Advanced Modeling Earth System* 10 (2018), pp. 2042–2060. DOI: 10.1029/2018MS001346.

[61] Y. Li and R. E. Carbone. “Excitation of rainfall over the tropical western Pacific”. In: *Journal of the Atmospheric Sciences* 69.10 (2012), pp. 2983–2994. DOI: 10.1175/JAS-D-11-0245.1.

[62] R. M. Holmes and L. N. Thomas. “The modulation of equatorial turbulence by tropical instability waves in a regional ocean model”. In: *Journal of Physical Oceanography* 45.4 (2015), pp. 1155–1173. DOI: 10.1175/JPO-D-14-0209.1.

[63] S. J. Warner et al. “Buoyant gravity currents released from tropical instability waves”. In: *Journal of Physical Oceanography* 48.2 (2018), pp. 361–382. DOI: 10.1175/JPO-D-17-0144.1.

[64] G. S. Young et al. “Rolls, streets, waves, and more: A review of quasi-two-dimensional structures in the atmospheric boundary layer”. In: *Bulletin of the American Meteorological Society* 83.7 (2002), pp. 997–1002. DOI: 10.1175/1520-0477(2002)083<0997:RSWAMA>2.3.CO;2.

[65] B. Stevens et al. “Sugar, gravel, fish and flowers: Mesoscale cloud patterns in the trade winds”. In: *Quarterly Journal of the Royal Meteorological Society* 146.726 (2020), pp. 141–152. DOI: 10.1002/qj.3662.

[66] G. George et al. “Widespread shallow mesoscale circulations observed in the trades”. In: *Nature Geoscience* 16 (2023), 584–589. DOI: 10.1038/s41561-023-01215-1.

[67] L. Nuijens et al. “The frictional layer in the observed momentum budget of the trades”. In: *Quarterly Journal of the Royal Meteorological Society* 148.748 (2022), pp. 3343–3365. DOI: 10.1002/qj.4364.

[68] Alessandro C M Savazzi et al. "Momentum Transport in Organized Shallow Cumulus Convection". In: *Journal of the Atmospheric Sciences* 81 (2 2024), pp. 279 –296. DOI: 10.1175/JAS-D-23-0098.1.

[69] R. A. Houze. "100 years of research on mesoscale convective systems". In: *Meteorological Monographs* 59 (2018), pp. 17.1–17.54. DOI: 10.1175/AMSMONOGRAPHS-D-18-0001.1.

[70] D. L. Hartmann, H. H. Hendon, and R. A. Houze. "Some implications of the mesoscale circulations in tropical cloud clusters for large-scale dynamics and climate". In: *Journal of Atmospheric Sciences* 41.1 (1984), pp. 113–121. DOI: 10.1175/1520-0469(1984)041<0113:SIOTMC>2.0.CO;2.

[71] T. P. Lane and M. W. Moncrieff. "Characterization of momentum transport associated with organized moist convection and gravity waves". In: *Journal of the Atmospheric Sciences* 67.10 (2010), pp. 3208–3225. DOI: 10.1175/2010JAS3418.1.

[72] C. E. Holloway et al. "Observing convective aggregation". In: *Surveys in Geophysics* 38.6 (2017), pp. 1199–1236. DOI: 10.1007/s10712-017-9419-1.

[73] S. Bony et al. "Sugar, gravel, fish, and flowers: Dependence of mesoscale patterns of trade-wind clouds on environmental conditions". In: *Geophysical Research Letters* 47.7, e2019GL085988 (2020). DOI: 10.1029/2019GL085988.

[74] S. Bony et al. "Observed modulation of the tropical radiation budget by deep convective organization and lower-tropospheric stability". In: *AGU Advances* 1.3, e2019AV000155 (2020). DOI: 10.1029/2019AV000155.

[75] C. Muller et al. "Spontaneous aggregation of convective storms". In: *Annual Review of Fluid Mechanics* 54.1 (2022), pp. 133–157. DOI: 10.1146/annurev-fluid-022421-011319.

[76] S. Shamekh et al. "Implicit learning of convective organization explains precipitation stochasticity". In: *Proceedings of the National Academy of Sciences* 120.20, e2216158120 (2023). DOI: 10.1073/pnas.2216158120.

[77] C. J. Muller and I. M. Held. "Detailed investigation of the self-aggregation of convection in cloud-resolving simulations". In: *Journal of the Atmospheric Sciences* 69.8 (2012), pp. 2551–2565. DOI: 10.1175/JAS-D-11-0257.1.

[78] A. A. Wing and K. A. Emanuel. "Physical mechanisms controlling self-aggregation of convection in idealized numerical modeling simulations". In: *Journal of Advances in Modeling Earth Systems* 6.1 (2014), pp. 59–74. DOI: 10.1002/2013MS000269.

[79] C. S. Bretherton and P. N. Blossey. "Understanding mesoscale aggregation of shallow cumulus convection using large-eddy simulation". In: *Journal of Advances in Modeling Earth Systems* 9.8 (2017), pp. 2798–2821. DOI: 10.1002/2017MS000981.

[80] M. Janssens et al. "Nonprecipitating shallow cumulus convection is intrinsically unstable to length scale growth". In: *Journal of the Atmospheric Sciences* 80.3 (2023), pp. 849–870. DOI: 10.1175/JAS-D-22-0111.1.

[81] J. Dias et al. "Equatorial waves and the skill of NCEP and ECMWF forecast systems". In: *Monthly Weather Review* 146 (2018), pp. 1763–1784. DOI: 10.1175/MWR-D-17-0362.1.

[82] A. Kumar, L. Zhang, and W. Wang. "Sea surface temperature–precipitation relationship in different reanalyses". In: *Monthly Weather Review* 141 (2013), pp. 1118–1123. DOI: 10.1175/MWR-D-12-00214.1.

[83] J. Burdanowitz et al. “The sensitivity of oceanic precipitation to sea surface temperature”. In: *Atmospheric Chemistry Physics* 19 (2019), 9241–9252. DOI: 10.5194/acp-19-9241-2019.

[84] H. Hashizume et al. “Direct observations of atmospheric boundary layer response to SST variations associated with tropical instability waves over the eastern equatorial Pacific”. In: *Journal of Climate* 15.23 (2002), pp. 3379–3393. DOI: 10.1175/1520-0442(2002)015<3379:DOOABL>2.0.CO;2.

[85] H. Seo et al. “Feedback of tropical instability-wave-induced atmospheric variability onto the ocean”. In: *Journal of Climate* 20.23 (2007), pp. 5842–5855. DOI: 10.1175/JCLI4330.1.

[86] B Stevens et al. “EUREC4A”. In: *Earth Syst. Sci. Data* 13 (8 Aug. 2021), pp. 4067–4119. DOI: 10.5194/essd-13-4067-2021.

[87] C. Acquistapace et al. “Fast atmospheric response to a cold oceanic mesoscale patch in the north-western tropical Atlantic”. In: *Journal of Geophysical Research: Atmospheres* 127.21, e2022JD036799 (2022). DOI: 10.1029/2022JD036799.

[88] X. Chen et al. “Ubiquitous sea surface temperature anomalies increase spatial heterogeneity of trade-wind cloudiness on daily timescale”. In: *Journal of Atmospheric Sciences* (2023), 2969–2987. DOI: 10.1175/JAS-D-23-0075.1.

[89] I. Frenger et al. “Imprint of Southern Ocean eddies on winds, clouds and rainfall”. In: *Nature Geoscience* 6 (2013). DOI: 10.1038/ngeo1863.

[90] D. Byrne et al. “Atmospheric response to mesoscale sea surface temperature anomalies: Assessment of mechanisms and coupling strength in a high-resolution coupled model over the South Atlantic”. In: *Journal of the Atmospheric Sciences* 72.5 (2014), pp. 1872–1890. DOI: 10.1175/JAS-D-14-0195.1.

[91] F. Desbiolles et al. “Links between sea surface temperature structures, clouds and rainfall: Study case of the Mediterranean Sea”. In: *Geophysical Research Letters* 48.10, e2020GL091839 (2021). DOI: 10.1029/2020GL091839.

[92] S.-P. Xie. “Satellite observations of cool ocean–atmosphere interaction”. In: *Bulletin of the American Meteorological Society* 85.2 (2004), pp. 195–208. DOI: 10.1175/BAMS-85-2-195.

[93] L. Renault et al. “Disentangling the mesoscale ocean-atmosphere interactions”. In: *Journal of Geophysical Research: Oceans* 124.3 (2019), pp. 2164–2178. DOI: 10.1029/2018JC014628.

[94] D. J. Raymond. “Regulation of moist convection over the west Pacific warm pool”. In: *Journal of Atmospheric Sciences* 52.22 (1995), pp. 3945–3959. DOI: 10.1175/1520-0469(1995)052<3945:ROMCOT>2.0.CO;2.

[95] J. O. Haerter et al. “Circling in on convective organization”. In: *Geophysical Research Letters* 46.12 (2019), pp. 7024–7034. DOI: 10.1029/2019GL082092.

[96] J. S. Godfrey et al. “Coupled Ocean-Atmosphere Response Experiment (COARE): An interim report”. In: *Journal of Geophysical Research: Oceans* 103.C7 (1998), pp. 14395–14450. DOI: 10.1029/97JC03120.

[97] K. Yoneyama, C. Zhang, and C. N. Long. “Tracking pulses of the Madden-Julian Oscillation”. In: *Bulletin of the American Meteorological Society* 94 (2013). DOI: 10.1175/BAMS-D-12-00157.1.

[98] P. Garg et al. “Identifying and characterizing tropical oceanic mesoscale cold pools using spaceborne scatterometer winds”. In: *Journal of Geophysical Research: Atmospheres* 125.5 (2020). DOI: 10.1029/2019JD031812.

[99] P.-E. Brilouet et al. "Trade wind boundary layer turbulence and shallow precipitating convection: New insights combining SAR images, satellite brightness temperature, and airborne in situ measurements". In: *Geophysical Research Letters* 50.2, e2022GL102180 (2023). DOI: 10.1029/2022GL102180.

[100] P.-E. Brilouet et al. "A numerical study of ocean surface layer response to atmospheric shallow convection: Impact of cloud shading, rain and cold pool". In: *Quarterly Journal of the Royal Meteorological Society* 150.760 (2023), pp. 1401–1419. DOI: 10.1002/qj.4651.

[101] A. H. Sobel et al. "Surface fluxes and tropical intraseasonal variability: A reassessment". In: *Journal of Advances in Modeling Earth Systems* 2.1 (2010). DOI: 10.3894/JAMES.2010.2.2.

[102] Z. Li et al. "Improvement of sea surface turbulent fluxes parameterization scheme in CAM3 and its impact on climate simulation". In: *Acta Meteorologica Sinica* 6 (2009), pp. 1101–1112. DOI: 10.11676/qxxb2009.106.

[103] Z.-X. Li et al. "A method for improving simulation of PNA teleconnection interannual variation in a climate model". In: *Atmospheric and Oceanic Science Letters* 4.2 (2011), pp. 86–90. DOI: 10.1080/16742834.2011.11446909.

[104] K. A. Emanuel. "An air-sea interaction theory for tropical cyclones. Part I: Steady-state maintenance". In: *Journal of Atmospheric Sciences* 43.6 (1986), pp. 585 –605. DOI: 10.1175/1520-0469(1986)043<0585:AASITF>2.0.CO;2.

[105] P. Zuidema et al. "A survey of precipitation-induced atmospheric cold pools over oceans and their interactions with the larger-scale environment". In: *Surveys in Geophysics* 38.6 (2017), pp. 1283–1305. DOI: 10.1007/s10712-017-9447-x.

[106] Samantha M. Wills, Meghan F. Cronin, and Dongxiao Zhang. "Air-Sea Heat Fluxes Associated With Convective Cold Pools". In: *Journal of Geophysical Research: Atmospheres* 128.20 (Oct. 2023), e2023JD039708. DOI: 10.1029/2023JD039708.

[107] C. A. Davis. "The formation of moist vortices and tropical cyclones in idealized simulations". In: *Journal of the Atmospheric Sciences* 72.9 (2015), pp. 3499 –3516. DOI: 10.1175/JAS-D-15-0027.1.

[108] K. Mogensen, L. Magnusson, and J. Bidlot. "Tropical cyclone sensitivity to ocean coupling in the ECMWF coupled model". In: *Journal of Geophysical Research: Oceans* 122 (2017), 4392–4412. DOI: 10.1002/2017JC012753.

[109] T. L. Frölicher, E. M. Fischer, and N. Gruber. "Marine heatwaves under global warming". In: *Nature* 560.7718 (2018), pp. 360–364. DOI: 10.1038/s41586-018-0383-9.

[110] K. E. Smith et al. "Biological impacts of marine heatwaves". In: *Annual Review of Marine Science* 15.1 (2023), pp. 119–145. DOI: 10.1146/annurev-marine-032122-121437.

[111] K. E. Smith et al. "Socioeconomic impacts of marine heatwaves: Global issues and opportunities". In: *Science* 374.6566 (2021), eabj3593. DOI: 10.1126/science.abj3593.

[112] B. A. Seibel and J. C. Drazen. "The rate of metabolism in marine animals: Environmental constraints, ecological demands and energetic opportunities". In: *Philosophical Transactions of the Royal Society B: Biological Sciences* 362.1487 (2007), pp. 2061–2078. DOI: 10.1098/rstb.2007.2101.

[113] Y. Zhang et al. "Vertical structures of marine heatwaves". In: *Nature Communications* 14.1 (2023), p. 6483. DOI: 10.1038/s41467-023-42219-0.

[114] B. Phillips and L. O'Neill. "Observational analysis of extratropical cyclone interactions with northeast Pacific sea surface temperature anomalies". In: *Journal of Climate* 33.15 (2020), pp. 6745 –6763. DOI: 10.1175/JCLI-D-19-0853.1.

[115] D. J. Amaya et al. "The evolution and known atmospheric forcing mechanisms behind the 2013–2015 North Pacific warm anomalies". In: *US Clivar Variations* 14.2 (2016), pp. 1–6.

[116] D. J. Amaya et al. "Physical drivers of the summer 2019 North Pacific marine heatwave". In: *Nature Communications* 11.1 (2020), p. 1903. DOI: 10.1038/s41467-020-15820-w.

[117] C. Bian et al. "Oceanic mesoscale eddies as crucial drivers of global marine heatwaves". In: *Nature Communications* 14.1 (2023), p. 2970. DOI: 10.1038/s41467-023-38811-z.

[118] Z. Gao et al. "Study on seasonal characteristics and causes of marine heatwaves in the South China Sea over nearly 30 years". In: *Atmosphere* 14.12 (2023), p. 1822. DOI: 10.3390/atmos14121822.

[119] K. Chen, G. Gawarkiewicz, and J. Yang. "Mesoscale and submesoscale shelf-ocean exchanges initialize an advective marine heatwave". In: *Journal of Geophysical Research: Oceans* 127.1, e2021JC017927 (2022). DOI: 10.1029/2021JC017927.

[120] J. Thomas Farrar et al. "S-MODE: the Sub-Mesoscale Ocean Dynamics Experiment". In: *Bull. Amer. Meteor. Soc* in review (2024).

[121] X. J. Capet, P. Marchesiello, and J. C. McWilliams. "Upwelling response to coastal wind profiles". In: *Geophysical Research Letters* 31, L13311 (2004). DOI: 10.1029/2004GL020123.

[122] L. Renault et al. "Upwelling response to atmospheric coastal jets off Central Chile: A modeling study of the October 2000 event". In: *Journal of Geophysical Research: Oceans* 117.C2 (2012). DOI: 10.1029/2011JC007446.

[123] L. Renault et al. "Partial decoupling of primary productivity from upwelling in the California Current System". In: *Nature Geoscience* 9 (2016), 505–508. DOI: 10.1038/ngeo2722.

[124] R. J. Small et al. "The Benguela upwelling system: Quantifying the sensitivity to resolution and coastal wind representation in a global climate model". In: *Journal of Climate* 28.23 (2015), pp. 9409 –9432. DOI: 10.1175/JCLI-D-15-0192.1.

[125] J. Kurian et al. "Impact of the Benguela coastal low-level jet on the southeast tropical Atlantic SST bias in a regional ocean model". In: *Climate Dynamics* 56 (2021), 2773–2800. DOI: 10.1007/s00382-020-05616-5.

[126] F. Desbiolles et al. "Response of the Southern Benguela upwelling system to fine-scale modifications of the coastal wind". In: *Journal of Marine Systems* 156 (2016), pp. 46–55. DOI: 10.1016/j.jmarsys.2015.12.002.

[127] J. Boe et al. "What shapes mesoscale wind anomalies in coastal upwelling zones?" In: *Climate Dynamics* 36 (2011), pp. 2037–2049. DOI: 10.1007/s00382-011-1058-5.

[128] F. Desbiolles et al. "Origin of fine-scale wind stress curl structures in the Benguela and Canary upwelling systems". In: *Journal of Geophysical Research: Oceans* 119.11 (2014), pp. 7931–7948. DOI: 10.1002/2014JC010015.

[129] F. Kessouri et al. "Enhancement of oceanic eddy activity by fine-scale orographic winds drives high productivity, low oxygen, and low pH conditions in the Santa Barbara channel". In: *Journal of Geophysical Research: Oceans* 127.12, e2022JC018947 (2022). DOI: 10.1029/2022JC018947.

[130] F. Colas et al. "Heat balance and eddies in the Peru-Chile current system". In: *Climate Dynamics* 39.1-2 (2012), pp. 509–529. DOI: 10.1007/s00382-011-1170-6.

[131] C. Lathuilière et al. "On the role of the mesoscale circulation on an idealized coastal upwelling ecosystem". In: *Journal of Geophysical Research: Oceans* 115, C09018 (2010). DOI: 10.1029/2009JC005827.

[132] N. Gruber et al. "Eddy-induced reduction of biological production in Eastern Boundary Upwelling Systems". In: *Nature Geoscience* 4 (2011), 787–792. DOI: 10.1038/ngeo1273.

[133] T. Nagai et al. "Dominant role of eddies and filaments in the offshore transport of carbon and nutrients in the California Current System". In: *Journal of Geophysical Research: Oceans* 120.8 (2015), pp. 5318–5341. DOI: 10.1002/2015JC010889.

[134] J. Hauschildt et al. "The fate of upwelled nitrate off Peru shaped by submesoscale filaments and fronts". In: *Biogeosciences* 18.12 (2021), pp. 3605–3629. DOI: 10.5194/bg-18-3605-2021.

[135] H. Seo, A. J. Miller, and J. R. Norris. "Eddy-wind interaction in the California Current System: dynamics and impacts". In: *Journal of Physical Oceanography* 46 (2016), 439–459. DOI: 10.1175/JPO-D-15-0086.1.

[136] V. Oerder et al. "Impacts of the mesoscale ocean-atmosphere coupling on the Peru-Chile ocean dynamics: The current-induced wind stress modulation". In: *Journal of Geophysical Research: Oceans* 123.2 (2018), pp. 812–833. DOI: 10.1002/2017JC013294.

[137] V. Oerder et al. "Impacts of the mesoscale ocean-atmosphere coupling on the Peru-Chile ocean dynamics: impact of the thermal feedback". In: *Journal of Geophysical Research: Oceans* 129.6, e2023JC020351 (2024). DOI: 10.1029/2023JC020351.

[138] L. Renault, A. Hall, and J. C. McWilliams. "Orographic shaping of US West Coast wind profiles during the upwelling season". In: *Climate Dynamics* 46 (2016), pp. 273–289. DOI: 10.1007/s00382-015-2583-4.

[139] G. E. Manucharyan and A. F. Thompson. "Submesoscale sea ice-ocean interactions in marginal ice zones". In: *Journal of Geophysical Research: Oceans* 122.12 (2017), pp. 9455–9475. DOI: 10.1002/2017JC012895.

[140] Kaylie Cohanim, Ken X. Zhao, and Andrew L. Stewart. "Dynamics of Eddies Generated by Sea Ice Leads". In: *Journal of Physical Oceanography* 51.10 (Oct. 2021), pp. 3071–3092. DOI: 10.1175/JPO-D-20-0169.1.

[141] M. Gupta and A. F. Thompson. "Regimes of sea-ice floe melt: Ice-ocean coupling at the submesoscales". In: *Journal of Geophysical Research: Oceans* 127.9, e2022JC018894 (2022). DOI: 10.1029/2022JC018894.

[142] C. O. Collins III et al. "In situ measurements of an energetic wave event in the Arctic marginal ice zone". In: *Geophysical Research Letters* 42.6 (2015), pp. 1863–1870. DOI: 10.1002/2015GL063063.

[143] F. Ardhuin et al. "Ice breakup controls dissipation of wind waves across southern ocean sea ice". In: *Geophysical Research Letters* 47.13 (2020), e2020GL087699. DOI: 10.1029/2020GL087699.

[144] J. E. Stopa et al. "Wave attenuation through an Arctic marginal ice zone on 12 October 2015: 1. Measurement of wave spectra and ice features from Sentinel 1A". In: *Journal of Geophysical Research: Oceans* 123.5 (2018), pp. 3619–3634. DOI: 10.1029/2018JC013791.

[145] G. Boutin et al. "Wave–sea-ice interactions in a brittle rheological framework". In: *The Cryosphere* 15.1 (2021), pp. 431–457. DOI: 10.5194/tc-15-431-2021.

[146] M. A. Bourassa et al. “High-latitude ocean and sea ice surface fluxes: Challenges for climate research”. In: *Bulletin of the American Meteorological Society* 94.3 (2013), pp. 403–423. DOI: 10.1175/BAMS-D-11-00244.1.

[147] Peter P Sullivan, James C McWilliams, and Edward G Patton. “Large-Eddy Simulation of Marine Atmospheric Boundary Layers above a Spectrum of Moving Waves”. In: *Journal of the Atmospheric Sciences* 71 (11 2014), pp. 4001 –4027. DOI: 10.1175/JAS-D-14-0095.1.

[148] G. Deskos et al. “Review of wind–wave coupling models for large-eddy simulation of the marine atmospheric boundary layer”. In: *Journal of the Atmospheric Sciences* 78.10 (2021), pp. 3025–3045. DOI: 10.1175/JAS-D-21-0003.1.

[149] Pierre-Etienne Brilouet et al. “A case-study of the coupled ocean–atmosphere response to an oceanic diurnal warm layer”. In: *Quarterly Journal of the Royal Meteorological Society* 147 (736 2021), pp. 2008–2032. DOI: https://doi.org/10.1002/qj.4007.

[150] Lionel Renault, James C. McWilliams, and Jonathan Gula. “Dampening of Submesoscale Currents by Air-Sea Stress Coupling in the Californian Upwelling System”. In: *Scientific Reports* 8.1 (Dec. 2018). DOI: 10.1038/s41598-018-31602-3.

[151] R.K. Moore and A.K. Fung. “Radar determination of winds at sea”. In: *Proceedings of the IEEE* 67.11 (1979), 1504–1521. DOI: 10.1109/PROC.1979.11510.

[152] W. L. Jones et al. “The SEASAT-A satellite scatterometer: The geophysical evaluation of remotely sensed wind vectors over the ocean”. In: *Journal of Geophysical Research: Oceans* 87.C5 (1982), 3297–3317. DOI: 10.1029/JC087iC05p03297.

[153] J. de Kloe, A. Stoffelen, and A. Verhoef. “Improved use of scatterometer measurements by using stress-equivalent reference winds”. In: *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing* 10.5 (2017), 2340–2347. DOI: 10.1109/JSTARS.2017.2685242.

[154] H. Charnock. “Wind stress on a water surface”. In: *Quarterly Journal of the Royal Meteorological Society* 81.350 (1955), 639–640. DOI: 10.1002/qj.49708135027.

[155] S. D. Smith. “Coefficients for sea surface wind stress, heat flux, and wind profiles as a function of wind speed and temperature”. In: *Journal of Geophysical Research: Oceans* 93.C12 (1988), 15467–15472. DOI: 10.1029/JC093iC12p15467.

[156] D. Vandemark et al. “Measured changes in ocean surface roughness due to atmospheric boundary layer rolls”. In: *Journal of Geophysical Research: Oceans* 106.C3 (2001), 4639–4654. DOI: 10.1029/1999JC000051.

[157] T. D. Sikora et al. “Use of spaceborne Synthetic Aperture Radar imagery of the sea surface in detecting the presence and structure of the convective marine atmospheric boundary layer”. In: *Monthly Weather Review* 123.12 (1995), 3623–3632. DOI: 10.1175/1520-0493(1995)123<3623:UOSSAR>2.0.CO;2.

[158] G. S. Young, T. D. Sikora, and N. S. Winstead. “Inferring marine atmospheric boundary layer properties from spectral characteristics of satellite-borne SAR imagery”. In: *Monthly Weather Review* 128 (2000), 1506–1520. DOI: 10.1175/1520-0493(2000)128<1506:IMABLP>2.0.CO;2.

[159] O. O’Driscoll et al. “Obukhov length estimation from spaceborne radars”. In: *Geophysical Research Letters* 50.15, e2023GL104228 (2023). DOI: 10.1029/2023GL104228.

[160] P. J. Minnett et al. “Half a century of satellite remote sensing of sea-surface temperature”. In: *Remote Sensing of Environment* 233 (2019), p. 111366. DOI: 10.1016/j.rse.2019.111366.

[161] Toshio Michael Chin, Jorge Vazquez-Cuervo, and Edward M Armstrong. "A multi-scale high-resolution analysis of global sea surface temperature". In: *Remote Sensing of Environment* 200 (2017), pp. 154–169. DOI: https://doi.org/10.1016/j.rse.2017.07.029.

[162] Fabrice Ardhuin et al. "Observing Sea States". In: *Frontiers in Marine Science* 6 (2019). DOI: 10.3389/fmars.2019.00124.

[163] Guillaume Dodet et al. "Error Characterization of Significant Wave Heights in Multidecadal Satellite Altimeter Product, Model Hindcast, and In Situ Measurements Using the Triple Collocation Technique". In: *Journal of Atmospheric and Oceanic Technology* 39.7 (2022), pp. 887 –901. DOI: 10.1175/JTECH-D-21-0179.1.

[164] Xiao-Ming Li and Susanne Lehner. "Algorithm for Sea Surface Wind Retrieval From TerraSAR-X and TanDEM-X Data". In: *IEEE Transactions on Geoscience and Remote Sensing* 52.5 (2014), pp. 2928–2939. DOI: 10.1109/TGRS.2013.2267780.

[165] D. Hauser et al. "New observations from the SWIM radar on-board CFOSAT: Instrument validation and ocean wave measurement assessment". In: *IEEE Transactions on Geoscience and Remote Sensing* 59.1 (2021), 5–26. DOI: 10.1109/TGRS.2020.2994372.

[166] Marine De Carlo et al. "Wave Groups and Small Scale Variability of Wave Heights Observed by Altimeters". In: *Journal of Geophysical Research: Oceans* 128.8 (2023), e2023JC019740. DOI: https://doi.org/10.1029/2023JC019740.

[167] M. D. Anguelova and F. Webster. "Whitecap coverage from satellite measurements: A first step toward modeling the variability of oceanic whitecaps". In: *Journal of Geophysical Research: Oceans* 111.C3 (2006). DOI: 10.1029/2005JC003158.

[168] D. J. Salisbury, M. D. Anguelova, and I. M. Brooks. "On the variability of whitecap fraction using satellite-based observations". In: *Journal of Geophysical Research: Oceans* 118.11 (2013), 6201–6222. DOI: 10.1002/2013JC008797.

[169] V. Kudryavtsev et al. "Quad-polarization SAR features of ocean currents". In: *Journal of Geophysical Research: Oceans* 119.9 (2014), 6046–6065. DOI: 10.1002/2014JC010173.

[170] V. N. Kudryavtsev et al. "On quad-polarized SAR measurements of the ocean surface". In: *IEEE Transactions on Geoscience and Remote Sensing* 57.11 (2019), 8362–8370. DOI: 10.1109/TGRS.2019.2920750.

[171] M.-H. Rio, S. Mulet, and N. Picot. "Beyond GOCE for the ocean circulation estimate: Synergetic use of altimetry, gravimetry, and in situ data provides new insight into geostrophic and Ekman currents". In: *Geophysical Research Letters* 41.24 (2014), 8918–8925. DOI: 10.1002/2014GL061773.

[172] M. Ballarotta et al. "On the resolutions of ocean altimetry maps". In: *Ocean Science* 15.4 (2019), 1091–1109. DOI: 10.5194/os-15-1091-2019.

[173] B. Chapron, F. Collard, and F. Ardhuin. "Direct measurements of ocean surface velocity from space: Interpretation and validation". In: *Journal of Geophysical Research: Oceans* 110.C7, C07008 (2005). DOI: 10.1029/2004JC002809.

[174] H. Johnsen et al. "Ocean Doppler anomaly and ocean surface current from Sentinel 1 tops mode". In: *2016 IEEE International Geoscience and Remote Sensing Symposium (IGARSS)*. Beijing, China, 2016, 3993–3996. DOI: 10.1109/IGARSS.2016.7730038.

[175] W. J. Blackwell et al. "Hyperspectral microwave atmospheric sounding". In: *IEEE Transactions on Geoscience and Remote Sensing* 49.1 (2011), 128–142. DOI: 10.1109/TGRS.2010.2052260.

[176] A. Wineteer et al. "Measuring winds and currents with Ka-band Doppler scatterometry: An airborne implementation and progress towards a spaceborne mission". In: *Remote Sensing* 12.66 (2020), p. 1021. DOI: 10.3390/rs12061021.

[177] C. Gommenginger et al. "SEASTAR: A mission to study ocean submesoscale dynamics and small-scale atmosphere-ocean processes in coastal, shelf and polar seas". In: *Frontiers in Marine Science* 6.457 (2019), 1–7. DOI: 10.3389/fmars.2019.00457.

[178] P. López-Dekker et al. "Harmony: an Earth Explorer 10 mission candidate to observe land, ice, and ocean surface dynamics". In: *2019 IEEE International Geoscience and Remote Sensing Symposium (IGARSS)*. Yokohama, Japan, 2019, 8381–8384. DOI: 10.1109/IGARSS.2019.8897983.

[179] ESA. *Report for mission selection: Earth Explorer 10 candidate mission Harmony*. ESA-EOPSM-HARM-RP-4129. Noordwijk, The Netherlands, 2022, p. 369.

[180] J. T. Farrar et al. "S-MODE: The Sub-Mesoscale Ocean Dynamics Experiment". In: *2020 IEEE International Geoscience and Remote Sensing Symposium (IGARSS)*. Waikoloa, HI, USA, 2020, pp. 3533–3536. DOI: 10.1109/IGARSS39084.2020.9323112.

[181] P K Quinn et al. "Measurements from the RV Ronald H. Brown and related platforms as part of the Atlantic Tradewind Ocean-Atmosphere Mesoscale Interaction Campaign (ATOMIC)". In: *Earth Syst. Sci. Data* 13 (4 Apr. 2021), pp. 1759–1790. DOI: 10.5194/essd-13-1759-2021.

[182] A. Smedman et al. "A case study of air-sea interaction during swell conditions". In: *Journal of Geophysical Research: Oceans* 104.C11 (1999), pp. 25833–25851. DOI: 10.1029/1999JC900213.

[183] A. Ayet et al. "On the impact of long wind-waves on near-surface turbulence and momentum fluxes". In: *Boundary-Layer Meteorology* 174.3 (2020), pp. 465–491. DOI: 10.1007/s10546-019-00492-x.

[184] E. F. Bradley and C. W. Fairall. "A guide to making climate quality meteorological and flux measurements at sea". In: NOAA technical memorandum OAR PSD ; 311 (2007).

[185] B. Lund et al. "Near-surface current mapping by shipboard marine X-band radar: A validation". In: *Journal of Atmospheric and Oceanic Technology* 35.5 (2018), pp. 1077 –1090. DOI: 10.1175/JTECH-D-17-0154.1.

[186] B. Lund et al. "Marine X-band radar currents and bathymetry: An argument for a wave number-dependent retrieval method". In: *Journal of Geophysical Research: Oceans* 125.2 (2020), e2019JC015618. DOI: 10.1029/2019JC015618.

[187] M. Freilich, L. Lenain, and S. T. Gille. "Characterizing the role of non-linear interactions in the transition to submesoscale dynamics at a dense filament". In: *Geophysical Research Letters* 50.15, e2023GL103745 (2023). DOI: 10.1029/2023GL103745.

[188] S. P. Anderson et al. "Airborne optical remote sensing of ocean currents". In: *2013 OCEANS - San Diego*. San Diego, CA, USA, 2013, pp. 1–7. DOI: 10.23919/OCEANS.2013.6741308.

[189] L. Lenain et al. "Airborne remote sensing of upper-ocean and surface properties, currents and their gradients from meso to submesoscales". In: *Geophysical Research Letters* 50.8, e2022GL102468 (2023). DOI: 10.1029/2022GL102468.

[190] E. Rodríguez et al. "Estimating ocean vector winds and currents using a Ka-band pencil-beam Doppler scatterometer". In: *Remote Sensing* 10.4 (2018), p. 576. DOI: 10.3390/rs10040576.

[191] E. Rodríguez et al. "Ka-band Doppler scatterometry over a Loop Current eddy". In: *Remote Sensing* 12.15 (2020), p. 2388. DOI: 10.3390/rs12152388.

[192] V. K. Makin, V. N. Kudryavtsev, and C. Mastenbroek. "Drag of the sea surface". In: *Boundary-Layer Meteorology* 73.1-2 (1995), pp. 159–182. DOI: 10.1007/BF00708935.

[193] A. F. Thompson et al. "Open-ocean submesoscale motions: A full seasonal cycle of mixed layer instabilities from gliders". In: *Journal of Physical Oceanography* 46.4 (2016), pp. 1285–1307. DOI: 10.1175/JPO-D-15-0170.1.

[194] J. L. Bytheway et al. "Evaluating Satellite Precipitation Estimates Over Oceans Using Passive Aquatic Listeners". In: *Geophysical Research Letters* 50.6 (2023), e2022GL102087. DOI: https://doi.org/10.1029/2022GL102087.

[195] C. A. Clayson et al. "A new paradigm for observing and modeling of air-sea interactions to advance Earth system prediction". In: *OSTI.gov* (2023). Tech Rep. DOI: 10.2172/2222927.