PROJECT FINAL REPORT

FULL PROJECT TITLE Improving the representation of small-scale nonlinear ocean-atmosphere interactions in Climate Models by innovative joint observing and modelling approaches

Project acronym: **EUREC^{4}A-OA**

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Publishable summary

The transport of heat, water, and gases by the ocean and their exchanges at the air-sea interface were crucial for regulating the state and evolution of the climate system. Recent studies indicated that these processes were strongly influenced by small-scale ocean dynamics, which span characteristic lengths from 100 meters to 100 kilometers and vary over timescales ranging from a few hours to several weeks. To support effective societal responses to climate change, future climate projections will require either high-resolution coupled model simulations or improved parameterizations of small-scale processes in coarser-grid models. A key challenge for high-resolution modeling was the need to explicitly resolve phenomena that have traditionally been parameterized in lower-resolution simulations. Consequently, there was a growing recognition of a gap in process understanding needed to enhance and quantitatively evaluate seamless predictions (ranging from weather to seasonal and decadal forecasts) and projections, as well as to understand discrepancies among different models.

EUREC4A-OA was a large international project that built on and extensively complemented the Elucidating the Role of Clouds-Circulation Coupling in Climate (EUREC^{4}A, www.eurec4a.eu) initiative (Bony et al., 2017), which aimed to advance understanding of the interactions between clouds, convection, and circulation, and their role in climate change.

The core of EUREC^{4}A-OA was a one-month (Jan/Feb 2020) field campaign in the western tropical North Atlantic Ocean, during which high-resolution, synchronized observational data were collected using cutting-edge technology on airplanes, research vessels, and autonomous vehicles, complemented by time series from the Barbados Cloud Observatory (Stevens et al., 2021). EUREC^{4}A-OA, the ocean component of EUREC^{4}A, focused on understanding heat, momentum, water, and CO2 transport within the ocean and exchanges across the air-sea interface, utilizing innovative high-resolution ocean observations and a hierarchy of numerical models. The project emphasized small-scale ocean dynamics (0.1–100 km) and their interactions with atmospheric boundary layer processes. While EUREC^{4}A-OA was centered on the tropics, where the dominant external time scale was the diurnal cycle, the internal dynamics of the ocean and atmosphere intertwined diurnal, synoptic, seasonal, and longer time scales, contributing to climate variability.

Figure 1. Major observing platforms deployed during the EUREC^{4}A-OA international field experiment: 4 planes (from France, Germany, UK and Barbados), one atmosphere-observing station augmented with new instruments on Barbados, four research vessels (from France, Germany and the US), two cloud-kite deployed from the German ships, and many autonomous platforms such as air drones, Saildrones, Argo floats and ocean gliders.

EUREC4A-OA utilized significant observational infrastructure investments from participating countries, complemented by advanced third-party autonomous observing platforms (such as Saildrones, Autonaut, and Seagliders), to sample the upper ocean layers and the air-sea interface at temporal and spatial resolutions far beyond those achievable through traditional approaches. The project's success in observing these processes was closely linked to a strategic sampling plan for all platforms, which relied on day-to-day analyses of various satellite near-real-time products (specifically, multi-satellite altimetry, sea surface temperature (SST), and Chlorophyll-a produced by CLS, as well as sea surface salinity (SSS) from SMOS and SMAP). This approach enabled a series of in-depth analyses combining satellite and in-situ data to better understand the targeted phenomena and to validate and refine numerical simulations.

Additionally, the EUREC⁴A-OA consortium established an unparalleled hierarchy of numerical simulations, ranging from Large Eddy Simulations (LES)—including coupled ocean-atmosphere LES—to global high-resolution ocean-atmosphere models and Earth System Models (ESMs). The LES simulations resolved the ocean and ocean-atmosphere systems at scales as fine as 10 meters, allowing for direct simulation of small-scale ocean structures and their interactions with the atmosphere. These simulations were designed to inform the development and evaluation of global, coupled ESMs, enhancing the understanding and representation of fine-scale processes in climate models..

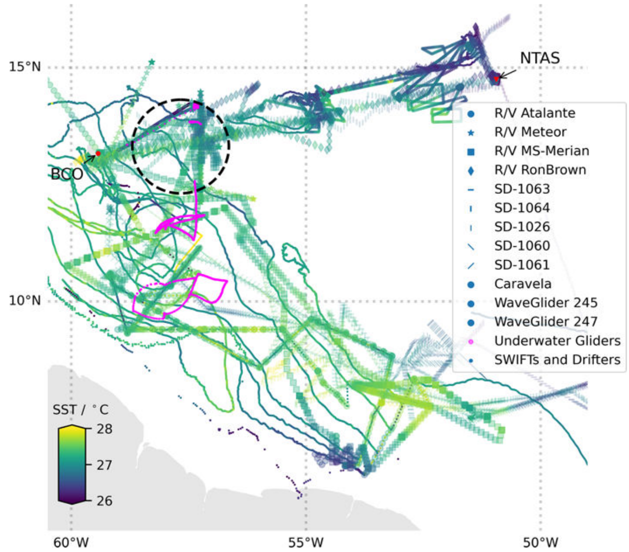

Figure 2. Map showing the coverage of air-ocean interface and ocean observations during the EUREC⁴A-OA field experiment in terms of surface- and subsurface-platform trajectories, colored by near-surface water temperature for platforms with near-surface measurements.

The EUREC⁴A-OA project connects European and USA experts of ocean and atmosphere observations and modelling to enhance the understanding of key processes and improve the skill of forecasts and future projections. In particular, these experts addresses four key objectives:

1) The assessment of how the diurnal cycle impacts ocean-atmosphere exchanges of energy, water and CO2 and to quantify how the diurnal cycle and related exchanges vary and are influenced at the small ocean scale;
2) The identification and quantification of the processes governing the internal dynamics of the ocean and the ocean-atmosphere exchanges of water, heat, momentum and CO2 at fine scale (0.1-100 km);
3) The characterization of the different surface ocean processes (diurnal cycle, small-scale ocean dynamics, aerosols) responsible for shallow atmospheric convection and cloud formation;
4) Provide data fields and new numerical parameterizations improving numerical models and prediction capabilities.

The results we obtained during the project have enabled us to advance considerably the scientific understanding towards the objectives. Among others, here below are listed some of the key achievements carried out within the JPI Ocean and Climate EUREC⁴A-OA project up to date.

Direct observations of the diurnal cycle in both, the atmosphere and the ocean, has allowed a precise assessment on how this cycle varies due to the particular ocean regimes. It has been then possible to isolate the processes in the ocean that modulate it and how it, in turn, affect the atmosphere marine boundary layer diurnal cycle.

The analyses carried out on the EUREC⁴A-OA observations revealed with unprecedented detail the particular characteristics of the ocean small-scale dynamics, enlightening that such scales are also very active in the tropical regions and not only over the mid and higher latitudes ocean. The ocean dynamics is very rich across all scales (from 0.1 to more than 100 km) and has large influence in the exchanges between the open ocean and the shelf. Moreover, it regulates the meridional transport of warm tropics waters to the mid-latitude. Most of this transport happens at the ocean subsurface and it is not in direct contact with the atmosphere, hence flow undisturbed up to higher latitudes.

Observations and models also unveil that the ocean's small scales are important in contributing to the exchanges of heat, freshwater and CO2 between the ocean and the atmosphere. Moreover, the evaluation of the intensity of the coupling between the ocean and the atmosphere assessed from high-resolution simulations show that they are very important and intimately linked with small-scale ocean dynamics. These findings support that the tropical ocean might not be a passive component in its interaction with the atmosphere as previously thought.

Direct aerosols observations and numerical simulations show that there is a large variability in the northwest tropical Atlantic Ocean. Such variability is due to both local origins as well as induced from Northern Africa dust inflow events. Whatever their origin, the aerosols relative fraction has significant influence on cloud formation and precipitation.

The project has also provided innovative results in terms of parametrization of different processes influencing the ocean and atmosphere exchanges that have been uncovered by the EUREC⁴A-OA field experiment. Notably a better representation of the small-scale freshwater patches due to precipitation has been introduced in the French Earth-System model that improves the overall simulations of air-sea interactions and clouds. A similar parametrization has now been introduced to take into account these physical processes in air-sea fluxes of CO2.

Other European Earth System model simulations have enlightened the importance of taking into account the ocean small scale in terms of SST but also in the three-dimensional complex structure of the ocean upper layers. Only with the inclusion of such elements in the simulations a more realistic ocean-atmosphere heat and freshwater fluxes and low-level cloud fraction are reproduced.

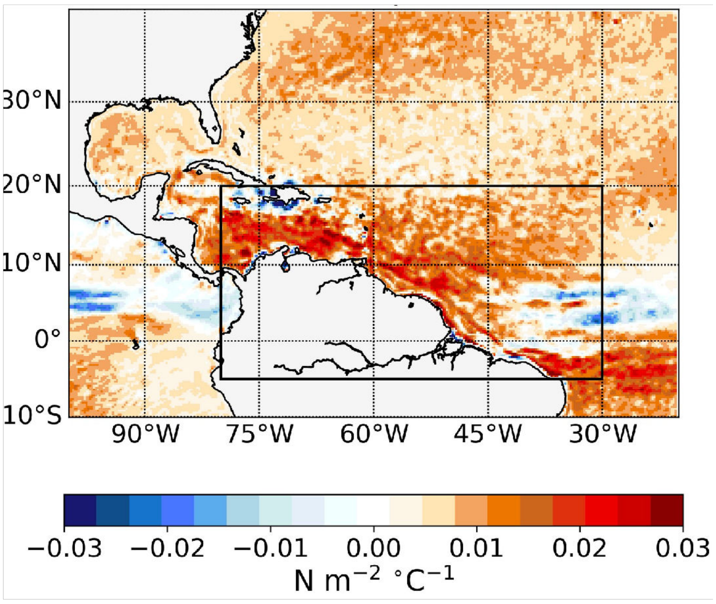

Figure 3. Map showing the amplitude of the coupling coefficient between the small-scale ocean sea surface temperature anomaly magnitude and the wind stress anomaly derived from the regional numerical coupled ocean-atmosphere simulations run at CNRS-LEGOS (Toulouse, France).

The JPI Ocean & Climate EUREC⁴A-OA has thus provided significant advancement in the understanding of key ocean-atmosphere processes and developed new parametrization that improves the realism of Earth-System models. EUREC⁴A-OA has been able to deliver novel knowledge to improve seamless ocean-atmosphere numerical predictions and climate projections and will have a significant impact on science and society.

Objective on sustainable development

The ocean and atmosphere are vast, dynamic fluids that continuously interact across a wide range of scales. Their complexity and variability make them challenging and costly to observe and model, yet understanding and predicting their behavior is more crucial now than ever. Accurate knowledge of these systems is essential for reconstructing, monitoring, understanding, attributing, predicting, and projecting climate change. This knowledge underpins efforts to mitigate and adapt to its impacts and is instrumental in informing assessments and policy initiatives, such as those led by the IPCC and the 2015 Paris Agreement. The demand for systematic climate observations and enhanced predictive capabilities is growing in response to the increasing urgency for high-resolution data needed to support adaptation and mitigation strategies.

Advancing sustainable and improved observation and modeling techniques for climate applications is therefore critical. These are the core elements of the EUREC4A-OA project, which directly contributes to Sustainable Development Goals (SDG) 13 (Climate Action) and 14 (Life Below Water). Specifically, EUREC4A-OA's approaches, objectives, and results provide valuable knowledge and resources to support SDG 13.1 (Strengthen resilience and adaptive capacity to climate-related hazards) and 13.3 (Improve education, awareness-raising, and human and institutional capacity on climate change mitigation, adaptation, impact reduction, and early warning). The project's overarching aim was to significantly advance our understanding of key ocean-atmosphere processes, thereby enhancing our ability to simulate and forecast the Earth system at multiple scales. This, in turn, provides more detailed information on climate change and supports the development of effective adaptation strategies.

Scientific report

EUREC^{4}A-OA was organized into 5 Working Packages (WPs) and 13 Tasks. All WPs had an integrated observing-modeling approach. WPs 1–3 addressed more specifically processes understanding, whereas WPs 4 and 5 focussed on developing and testing processes metrics and parameterizations.

Work package 1: Evaluating small-scale ocean-atmosphere energy and water exchange

In this WP we analyzed the EUREC^{4}A-OA direct observations and the large set of numerical simulations implemented within the project that resolve the diurnal cycle, small-scale ocean dynamical structures (filaments, fronts, eddies, jets) and correlated air-sea exchanges of energy and CO2 to explore extensively the phenomenology, amplitude and larger-scale implication of these processes. In this WP we also tried to assess the influence of the assimilation of observations at these scales in coupled model simulations (MeteoFrance, German Weather Service – the EUREC^{4}A-OA data have been made available on the GTS network).

1. A summary of progress towards objectives for each task

Significant work has been undertaken to reach the objectives, and this on both observations (in situ from the EUREC^{4}A-OA experiment, and satellite) and simulations that have been run specifically during the project. The results are particularly rich and do show the role of the ocean meso- and submesoscales on air-sea exchanges. All partners have been collaborating in this WP showing the potential and efficiency in science advancements of synergistic approaches.

Task 1.1 Quantifying the ocean-atmosphere energy and water exchanges at the ocean meso- and submesoscale (**LEGOS, CNRM**, GEOMAR/MPI, HZG/MPI, LMD, LOPS, NERSC, CIMA)

LMD and UniMiB analyzed observational data to infer the effects of small-scale ocean structures on the air-sea fluxes in the EUREC^{4}A-OA region. In particular, the co-variability of SST, relative moisture, and wind speed has been analyzed using remote sensing products and in situ observations. The relationships extracted from the data have been compared with those present in ERA5 reanalysis, showing relevant discrepancies which highlight the need of improved representations of small-scale processes in climate models. Using COARE algorithms for air-sea fluxes, the high-resolution fluxes have been computed and upscaled to O(100km) grid spacing. Results have then been compared with low resolution fluxes computed on the upscaled fields, to obtain biases related to the presence of nonlinearities.

At CNRM, a SST reanalysis was performed at hourly frequency from January 1 to March 31 2020. This reanalysis assimilated the hourly GOES data (OSISAF-L3C_GHRSST) over an extended domain of the Barbados (80W-41W & 0N-24N) at 4 km resolution. The first-guess used in this reanalysis was provided by the operational Mercator SST analysis at 1/12 that offered the opportunity to profit from a first round of altimetric and in-situ data assimilation. This reanalysis aims at better representing the SST diurnal cycle to finally have a better surface atmospheric forcing and better boundary layer properties (stability, wind, clouds).

Various regional numerical simulations have been developed in this context. At CIMA, UniMiB, and CNRM numerical simulations have been performed in the EUREC4A-OA region with the Weather Research and Forecast model (WRF) and Meso-NH forced by different SST products at high resolution (about 1 km) in order to investigate the boundary-layer sensitivity in terms of stability, water and energy budget, wind and clouds organizations to the previous SSTs, representing or not eddies in the North Brazilian Current (Boulevard des Tourbillons). The boundary layer response to fine scale SST structures has been documented in Borgnino et al., 2024.

The NBC SST-front imprints large-scale dipole-anomalies in the surface buoyancy flux, sea level pressure, sea surface wind intensity, vertical shear of zonal wind (main component of trade winds), liquid water content and precipitable water in the MABL ranging from 50 % to 100 %, compared to no NBC. The dynamics of the MABL adjustment is investigated through the precipitable water and temperature budgets. For the water budget, the NBC increases the water loss by advection ($\simeq$ 1 mm day-1) and entrainment ($\simeq$ 2 mm day-1) and increases the gain of water by surface evaporation ($\simeq$ 2 mm day-1). Regarding the energy budget, the NBC forces warming by surface sensible heat flux and water vapor and cloud-induced infrared radiation flux ($\simeq$ 1 K day-1), which are partially balanced by negative horizontal advection (Giordani et al., 2024). In addition the Meso-NH model was coupled with the MFWAM wave model operated at Météo-France in order to study the impacts of waves on the atmosphere. The results show that waves change the water and energy budgets over 2 months by around 1% compared to no waves, that is of the same order as the SST diurnal cycle. The assimilation of the CFOSAT wave spectrum significantly modifies the convergence /divergence of the surface wind, which ultimately changes the spatial distribution of boundary-layer clouds. Another aspect is that the waves modify the PW over the entire atmospheric column, which is an unexpected result.. This result argues for taking waves into account in seasonal and climate projections. An article is in preparation on this subject. Finally, an SST reanalysis at hourly frequency and kilometer resolution was carried out on the EURECA domain. This SST reanalysis assimilated satellite data between January and March 2020 and is available from herve.giordani@meteo.fr

LEGOS, has also developed two different coupled configurations. A mesoscale coupled simulation has been carried out for a period of 24-year. The simulation has been validated in terms of main oceanic and atmospheric variables (e.g., sea surface temperature, wind, heat and momentum fluxes, currents, …). In Larrañaga et al. (2022), twin ocean–atmosphere eddy-rich coupled simulations, with and without CFB, are performed for the period 1993–2016 over the Gulf of Mexico to assess to which extent the current feedback to the atmosphere (CFB) modulates the Gulf of Mexico dynamics. CFB, through the eddy killing mechanism and the associated transfer of momentum from mesoscale currents to the atmosphere, damps the mesoscale activity by roughly 20% and alters eddy statistics. We furthermore show that the Loop Current (LC) extensions can be classified into three categories: a retracted LC, a canonical LC, and an elongated LC. CFB, by damping the mesoscale activity, enhance the occurrence of the elongated category (by about 7%). Finally, by increasing the LC extension, CFB plays a key role in determining LC eddy separations and statistics. Taking into account CFB improves the representation of the Gulf of Mexico dynamics, and it should be taken into account in ocean models.

LEGOS and CNRM have developed a submesoscale ocean-atmosphere-wave coupled simulations. The spatial resolution of the smaller domain is 800 m. In Conejero et al (2024a), we developed a realistic submesoscale-permitting coupled oceanic and atmospheric model to quantify the spatiotemporal variability of TFB and CFB coupling in the northwest tropical Atlantic Ocean. While CFB still acts as a submesoscale eddy killer by inducing an energy sink from the SMCs to the atmosphere, it appears to be more efficient at the submesoscale by approximately 30% than at the mesoscale. Submesoscale CFB affects the surface stress, however, the finite time scale of SMCs for adjusting the atmospheric boundary layer results in a diminished low-level wind response, weakening partial ocean reenergization by about 70%. Unlike at the mesoscale, submesoscale CFB induces stress/wind convergence/divergence, influencing the atmospheric boundary layer through vertical motions. The linear relationship between the surface stress derivative or wind derivative fields and sea surface temperature gradients, widespread at the mesoscale, decreases by approximately 35% ± 7% or 77% ± 10%, respectively, at the submesoscale. In addition, submesoscale TFB induces turbulent heat fluxes comparable to those at the mesoscale. Seasonal variability in meso- and submesoscale CFB and TFB coupling is mostly related to background wind speed. Also, disentangling submesoscale CFB and TFB is challenging because they can reinforce or counteract each other. In Conejero et al. (2024b), we furthermore used ERA5 reanalysis and a set of coupled ocean-atmosphere model experiments to investigate the extent to which the spatial resolution of mesoscale structures influences the TFB mechanisms on a daily timescale in the northwestern tropical Atlantic. We show that the oceanic mesoscale TFB is independent of the spatial resolution of the ocean-atmosphere models, although its mechanisms vary considerably depending on whether mesoscale structures are fully represented or not. The Downward Momentum Mixing (DMM) and Pressure Adjustment (PA) mechanisms are overestimated by about 60\% and up to five times, respectively, when only large mesoscale structures (>100 km) in the ocean are resolved. Our findings suggest that climate models must accurately represent small-scale ocean thermal structures (<100 km), which directly influence TFB mechanisms and potentially affect cloud formation and precipitation.

The wind energy input to the ocean is found to depend on mesoscale eddies, which strengthen the "eddy-killing" process. Using the coupled ICON-ESM at a 5km resolution for both the atmosphere and the ocean, we are able to quantify the extent to which this process affect the wind-induced energy input to the ocean (von Storch and Lüschow, 2023).

At LOPS, the origin, structure and evolution of small-scale eddies have been determined from a very high resolution ocean model. It has been shown that such small eddies exist nearly always in the vicinity of large rings, due to the roll up of vorticity filaments torn from other currents. At depth, these small eddies come from the instability of shear layers along the continental slope. Surface and subsurface eddies interact vertically and can align. At the surface, the air-sea interaction processes, and the shearing by larger rings, compete in the evolution of small eddies. AIS has been found to provide high resolution data of surface currents for eddy-eddy interactions.

Task 1.2 Quantifying ocean-atmosphere energy and water exchanges at the diurnal scale (**GEOMAR/MPI,** LEGOS, LMD, LOCEAN, LOPS, MPI, NERSC)

The coupling between ocean and atmosphere on diurnal time scales was an important topic in EUREC^{4}A-OA. Analysis of field experiment data (this WP) but also the modeling aspects (see WP5) have been a focus. A first study made use of EUREC4A ship based and autonomous vehicle sensor data to investigate the diurnal warm layer. It was found that: (1) a clear diurnal warm layer exists in the region, (2) the diurnal cycle of the warm layer is accompanied by specific vertical mixing signals, (3) the interplay between diurnal warm layer induced stratification and diurnal momentum flux pattern generate a specific vertical shear pattern with highest shear not when strongest momentum flux but shallowest diurnal mixed layer (weaker surface momentum flux). This specific shear and subsequent mixing pattern derived from the observational data was subsequently compared with ICON simulations (by the MPI; WP5).

MPI analyzed the global coupled ICON atmosphere-ocean simulation at 5 km horizontal resolution to investigate the representation of the diurnal cycle by this high-resolution global coupled model. Indeed, such a simulation is representing the readiness of ICON for the EU project NextGCM, i.e., the state of the art coupled ocean-atmosphere global high-resolution simulations. An analysis of the simulated subsurface ocean in the EURECA-region is carried out. It has been found for this early version of the coupled ICON model, a) that the simulated temperature and salinity structures are by and large realistic, b) that the model is able to produce the upper-ocean temperature diurnal cycle characterized by a warm thin surface layer in the late afternoon local time. We also studied the effect of active air-sea coupling by comparing the diurnal cycle simulated by the coupled ICON with that simulated by an ocean-only run with the same ocean model. The active coupling has a clear impact on the temperature maximum which is located at about 55 m (see also WP5).

Estimating the diurnal cycle from time series observational data recorded from devices that operated in regions with changing background conditions and possibly frontal structures can be a challenging task. Not necessarily the diurnal cycle itself is of interest but the "cleaned" data that characterizes the background. In the study by Fernández et al. (2024) the aim was to extract the changing surface ocean background conditions (related to freshwater) and their impact on air/sea exchange. What was successfully done was applying a singular spectrum analysis (SSA) that operates without the restriction of fixed sine and cosine function as e.g., in classical Fourier Analysis.

Task 1.3 Quantifying the ocean heat and momentum uptake at the ocean small scale (**LOPS, LMD**, CNRM, LEGOS, LOCEAN, GEOMAR/MPI, UNIMIB)

LMD undertook a detailed analysis of the structuring of the ocean dynamics in the EUREC^{4}A-OA region during the oceanographic campaign but also extended the study in time via satellite data. We first gathered and co-analyzed the available satellite data (SST, SSS, Chlorophyll and altimetry) to detail all the mesoscale eddies in the region and if and when the different platforms deployed during the cruise measured them. The results we obtained are very different from previous published studies, both in terms of mean state and seasonal and interannual variability. What emerges is that Brazilian Current rings detected by altimetry are relatively shallow structures (they extend to 100-130 m of depth). They interact strongly with the slope and continental shelf flows, causing important cross-shore exchanges across the continental slope. These waters, relatively less salty because influenced by the Amazon River plume, wrap around the eddies and give rise to large surface filaments (warm, low-salinity waters) that, as they flow into the open ocean, become destabilized in turn. The turbulent interaction between the Brazilian Current rings and the coastal flow generates a layer of less salty water by lateral mixing, which diffuses towards the open ocean and almost completely covers the saltier tropical waters, advected towards the northwest in the Brazilian Current rings (Reverdin et al., 2020; Subirade et al., 2023). This has a consequence on the exchange of heat, momentum and gases (e.g. CO2) as well as on marine biodiversity (Olivier et al., 2022; Fernandez et al., 2023; 2024).

LMD together with LOPS has further analyzed the EUREC^{4}A-OA in-situ data with the aim of improving our understanding of the structure and coherence of ocean mesoscale eddies, which is essential for assessing the ocean role in the uptake and transport of heat and freshwater (as well as carbon, etc.). A first study introduced a new criterion for defining mesoscale eddy boundaries based on Ertel Potential Vorticity (EPV), identifying these boundaries as regions of steepened isopycnals and distinct water masses (Barabinot et al., 2024a). A second study assessed the material coherence of these eddies by analyzing thermohaline properties, finding that the outermost closed Brunt-Väisälä frequency contour provides a reliable boundary for estimating eddy volume (Barabinot et al., 2024b). A third study further refined our understanding of the mesoscale eddies structure, showing that the primary contributor to the density anomaly within anticyclonic eddies is the isopycnal slope, with the thermohaline properties of the trapped water mass having a secondary effect (Barabinot et al., 2024c). Collectively, these studies have advanced our ability to define, measure, and model mesoscale eddies, thereby enhancing our understanding of their role in ocean dynamics and climate processes.

Furthermore, at LOPS, the analysis of the meso and submesoscale dynamics has been performed in the region, using mainly a set of idealized numerical models and realistic high-resolution Atlantic CROCO simulations (dx = 1 km, 3 km, 6 km). During the first half of the project many different studies were carried out. They have been initiated. Among these we can cite a study establishing a formal mathematical framework for the interaction of vortices with the atmosphere, leading to various Ekman pumping effects and thus to source flows. This work has been initiated with the motion and interaction of point vortex sources (Carton et al., 2021, Vic et al., 2021) and then extended to finite-area vortices (Vic et al, 2022, Carton et al., 2024,, Vic et al., 2024). The aim here was is to determine how the oceanic vortex and jet stability are is modified by their interactions with the atmosphere. We have shown the appearance of baroclinically unstable long or short wavelengths, or the reduction in instability of medium wavelengths, when thermal or mechanical coupling is set on between the atmosphere and ocean, has been shown in a simple linear model. Its extension to the fully nonlinear ocean when other processes are at play, has to be done. Among other studies, using the high-resolution realistic simulations we can mention a study assessing the mesoscale eddy kinetic energy budgets and transfers between vertical modes in order to characterize the sources and sinks of energy for the mesoscale structures in the EUREC4A-OA region.

We have also used the GIGATL output (at 6 km, 3 km and 1 km resolution) to address different aspects of meso- and submesoscale dynamics and their interaction with Near Inertial Waves (NIW) and the Amazon River plume. A first study investigated the vertical coupling between NBC surface and subsurface rings and their role in transporting South Atlantic water (SAW) into the North Atlantic (Napolitano et al, 2024a). NBC rings, which typically extend to 400 m deep, often split into independent surface and subsurface structures. Through a theoretical model and numerical simulations, it was found that vertical coupling between these rings enhances their lifespan and travel distance. Coupled eddies can transport SAW over 1500 km to the Caribbean, while uncoupled eddies travel much shorter distances. This coupling may help NBC rings bypass topographic obstacles and increase the efficiency of SAW export. A second study examined sharp submesoscale density and salinity fronts created by the NBC and its eddies at the edge of the Amazon River plume. These fronts affect air-sea interactions and energy dynamics, with temperature-driven fronts leading weaker plumes, while strong plumes show reinforced salinity gradients. The Amazon runoff plays a key role in front formation near the shelf, with NBC dynamics dominating further poleward. Salinity largely governs surface gradients across the region. A paper on this study is currently under revision (Napolitano et al, 2024b).

Another study in collaboration with GEOMAR, addressed the propagation of near-inertial waves (NIW) in the EUREC4A-OA region characterized by mesoscale and submesoscale processed has been addressed by GEOMAR and LOPS, by comparing observations and model simulations. For example, D. Rudloff (GEOMAR) prepared his MSc thesis on the dynamical characterization of mesoscale eddies in the EUREC4A-OA region and focused on the vertical propagation of NIW in regions with negative relative vorticity. Combining observational data from different ships enabled tracking of NIW packages over short (few hours) and longer (days) time scales. The characteristics of NIW were found to match well what is expected from theory. Possible momentum flux variability that may have generated the observed NIWs was estimated from satellite wind fields, making use of a slab ocean model. This was compared to the high-resolution realistic simulation carried out at LOPS by another MSc student, Ophélie Lenoble, who found that the simulated processes matched the observations and revealing the complex 3D structure of the NIW propagation shaped by the presence of mesoscale eddies at the surface but even more so at depth. This is an important mechanism of momentum exchange between the ocean and atmosphere and its propagation in the ocean interior.

2. Significant results

The work in this WP has revealed the particular characteristics of the ocean mesoscale and meso-submesoscale in the EUREC^{4}A-OA region, which is located in the Tropics and thought to be less dynamic than higher latitude ocean areas. The ocean dynamics is very rich across all scales and has large influence in the meridional cross-shore transport of properties and on the exchanges with the atmosphere. In particular we have shown that the structure of the ocean mesoscale (eddies) is more complex than previously described, with the propagation and interaction of different eddies propagating northward at different depths, all transporting ocean properties across the area. The interaction of ocean eddies with the alongshore currents and freshwater plume (from the Amazon river), creates intense cross-shore exchanges. In particular, this leads to important freshwater export as large filaments that quickly destabilize and diffuse the freshwater laterally creating a very thin barrier layer that mask the presence of the warm and salty North Brazil Current rings from the atmosphere. This has shown to be capital in understanding the regional small-scales in the upper ocean as well as air-sea exchanges. Observations and models also unveil that the ocean's small scales are relatively important in contributing to the exchanges of heat, freshwater and CO2. This indicates that the tropical ocean might not be a passive component in its interaction with the atmosphere. We show that the exchange of heat and momentum induced by the air-sea interaction strongly modulate the dynamics of the larger EUREC^{4}A-OA region. We also show the presence of large coupling coefficients between the ocean and the atmosphere.

Furthermore, the particularly rich set of in-situ data collected during the experimental phase of the project has allowed us to improve the ability to define, measure, and model mesoscale eddies, thereby enhancing our understanding of their role in ocean dynamics and climate processes.

3. Challenges / difficulties encountered (where applicable)

The lock-down due to COVID has negatively impacted our working conditions everywhere inducing a delay in the analyses of the data and numerical simulations. This delay has been reabsorbed during the second phase of the project.

4. Work planned during the rest of the project, stemming from the work already performed.

The analysis of observations and modelling experiments is still continuing in the framework of different ongoing Master, and PhD studies. Many manuscripts in collaboration with EUREC^{4}A-OA partners are still in finalization and will be submitted for publication in the next months. Further investigations in the instability of coupled ocean-atmosphere flows, in particular in the nonlinear regimes, will be carried out.

Work package 2: Assessing ocean-atmosphere exchanges of CO2 at the ocean small-scale

Understanding and representing CO2 exchanges between the ocean and the atmosphere is essential to predict the evolution of global warming and ocean acidification that affects marine ecosystems. The CO2 uptake by the ocean is strongly affected by ocean variability at the meso- and submesoscales. Temperature and salinity influence these exchanges, for example, by modifying the solubility of this gas in seawater. The air-sea CO2 exchange and the mechanisms driving the exchange are to-date significantly under-sampled at present (e.g. Walker Brown et al. 2015). Some of the processes that have a potential impact on these exchanges and have been historically considered too small scale to be taken into account by actual climate models. As part of EUREC^{4}A-OA, we have implemented temperature, salinity and pCO2 observations at the interface of the ocean and atmosphere by carrying out a unique set of measurements undertaken by a large number of diverse platforms: four oceanographic vessels, Saildrones, Argo BGC floats, ocean gliders, drifters. This extremely rich and new data set is providing many key outcomes for the scientific community.

1. A summary of progress towards objectives for each task

Significant work has been achieved on the analyses of ocean-atmosphere CO2 exchanges from the very unique EUREC^{4}A-OA collection of observations. The adopted strategy in the field experiment not only allowed to gather an ad-hoc collection of data, but also permitted the use of collocated satellite information to extrapolate the observations in space and time providing the scientific community with a very original set of results.

Task 2.1 Quantifying ocean-atmosphere CO2 exchanges at ocean meso- & submesoscale (**LOCEAN**, HZG/MPI, LMD, NERSC)

In the context of Task 2.1, we have undertaken first a comparison of the surface data of different instrumentations used for measuring fCO2 on RV Atalante and Maria S Merian, suggesting that to within an uncertainty of 5 atm, the two datasets can be combined. On RV Atalante, this was further tested in comparison to discrete dissolved inorganic carbon/total alkalinity measurements. The fCO2 dataset collected by three vessels during EUREC^{4}A-OA/ATOMIC is unique and cover a wide range of conditions east of the Antilles and North of South America in Jan-Feb 2020, which was analyzed by comparing it to the large scale and meso-scale structures found in T, S and Chla (Olivier et al., 2022). In particular, this is used to identify very contrasting properties between salty waters flowing in the NBC from the equatorial area, slightly oversaturated in fCO2, very undersaturated fresh water entrained from the Amazon plume by an NBC ring in the first days of February 2020 (Reverdin et al., 2021), as well as oversaturated waters originating from the more salty shelf further west in interaction with another NBC ring, and finally, very undersaturated winter subtropical water further to the north-east. Based on the property distribution at the time of the experiment, a continuous mapping on a daily time scale was done from dedicated satellite products (including surface salinity from SMOS and SMAP missions). As shown in Fig. 4, this can be used to continuously estimate the air-sea CO2 fluxes in a statistical way, but note that this does not include the effect of near-surface daily stratification of skin effects, which is the topic of T2.2. The overall estimated flux is a large oceanic sink for the CO2 exchanges with the atmosphere (-1.7 TgC.month-1) (Olivier et al., 2022). This is much larger than what is estimated in different climatological products, for two main reasons: first, the fresh water transport of Amazon water in the area was not sampled/included in the climatological reconstructions; second, the north-east subtropical part of the domain was more of a sink with lower fCO2 than estimated in the climatology. This last result is still puzzling, but will be pursued further by examining February conditions in other years, using the same algorithm, or other approaches to take into account the temperature dependence.

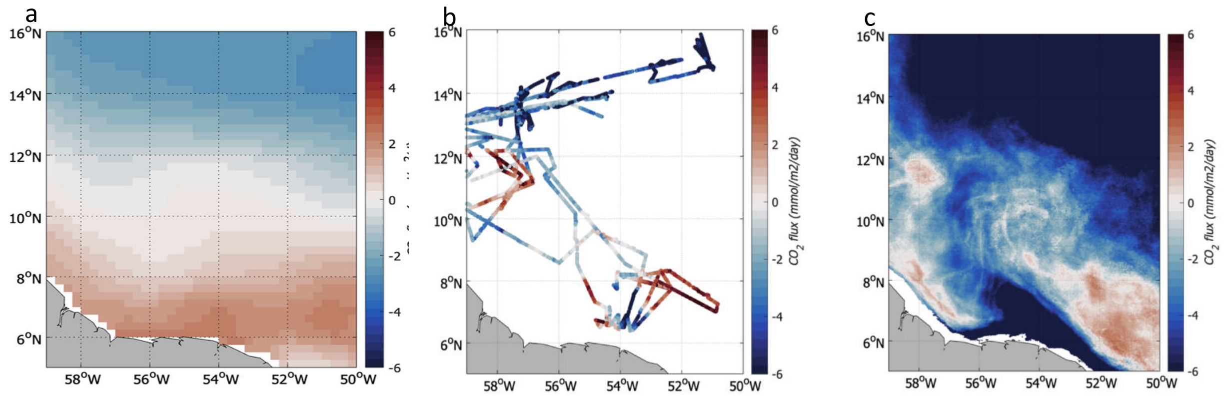

Figure 4. a) February climatology of the air-sea CO2 flux over 1998-2015 (Landschützer et al., 2020). b) Air-sea CO2 flux measured in Jan-Feb 2020 during the EUREC^{4}A-OA /ATOMIC cruise. c) Air-sea CO2 flux reconstructed over February 2020. Adapted from Olivier et al. 2022.

Using their self-developed coherent marine radar system (Horstmann et al., 2021), HEREON (formerly HZG) successfully conducted underway measurements of near-surface currents and air-side friction velocity, which have been made publicly available via PANGEA (Streßer et al., 2023; Carrasco et al., 2023). These measurements enabled the detailed assessment of the spatial and temporal variability of wind-induced shear on submesoscale ocean dynamics.

In addition, HEREON developed novel methods to estimate the probability of surface wave breaking and associated wave energy dissipation from radar backscatter data. By integrating these observations with water-side pCO2 measurements, HEREON was able to directly derive the wave-enhanced gas transfer coefficient and, consequently, estimate CO2 fluxes in real-time from underway data. The analysis revealed that the observed CO2 gas transfer coefficients — and therefore fluxes — deviated significantly from conventional wind-speed-only parameterizations (Wanninkhof, 1992), showing up to 110% deviation (99th percentile) and an average deviation of 19% (root-meansquare deviation, RMSD). When surface wave breaking effects were included (using the COAREG parameterization; Fairall et al., 2011, 2022), the deviations were reduced to 30% (99th percentile) and 11% (RMSD), highlighting the importance of accounting for wave dynamics in gas transfer models.

Task 2.2 Influence of the diurnal cycle and skin on the ocean-atmosphere exchanges of CO2 (**LMD**, LOCEAN, HZG/MPI)

The compilation of properties of upper-ocean stratification (skin, DWLs and CFLs) impacting the CO2 fluxes estimated from EUREC^{4}A-OA observations (MS4, D2.2) will take place in the coming months. This analysis will be done in the context of Laetitia Parc PhD (started in Nov. 2021 under the supervision of H. Bellenger, L. Bopp and D. Ho) during which she developed a tool to diagnose the impact of ocean stratification on the CO2 fluxes from ship-based observed meteorological parameters.

2. Significant results

The investigation based on the EUREC^{4}A-OA field experiment showed the importance of resolving the mesoscales for estimating, in this region, the net air-sea CO2 fluxes, and that this was rather dependent on salinity in the southern part of the domain close to South America, due to export of fresh water originating from the Amazon plume. To explore further this idea, and check the seasonality of the relationship and the feasibility of a similar approach, we participated to the legs of the Tara-Microbiomes expedition in this region in August-September 2022, with very encouraging results. This survey reinforced the EUREC^{4}A result that the export of freshwater from the Amazon plume to the open ocean happens in short-lived pulses, strongly evolving on a few-day time scales, due to the huge surface currents (which at times exceeded during that cruise 2 m/s). Thus, we also produced for that period daily fields of surface salinity from the SMOS and SMAP missions. This product is very rudimentary, and very encouraging efforts are underway to construct it more automatically for the whole period 2015-2022 (the final product being probably representative more of a few-day time scale, than daily).

Further investigation on the CO2 fluxes during the summer season, as well as during earlier summer cruises (Anacondas project) has started to outline the influence of the meso-scales on the fluxes. For that, we examined in particular the situation in the late summer 2021, when two cruises took place (Tara-Microbiomes legs 5 to 7 and Amazomix) with a focus on the Amazon plume. We observed extreme oversaturation (by 700%) in the AMazon estuary, followed a few hundred kilometers offshore by extreme undersaturation (down to 45 microatm). This is obviously coupled with strong biogeochemical processes, huge remineralisation in the particle-laden waters of the estuary or nearby, followed further offshore when sediment had deposited by huge productivity, but only in the fresh surface layer of a thickness often of 12 m or less. We also demonstrated huge spatial and temporal variability of the properties. In particular, we followed (with SSS, CHlA satellite daily products, as well as altimetry and drifters) the formation of a huge offshore fresh pool, separated from the coast by favorable winds and the presence of an NBC ring, a situation reminiscent of what happened in February 2020 during EUREC4A-OA. However, the signal is much larger in late summer, especially as 2021 was a year of very large Amazon outflow, and favourable winds in late summer for the freshwater drift to the Caribbean pathway, and less so for the transport to the east in the North Equatorial CounterCurrent. This fresh pool was tracked by over a month during a northwestward drift. Being able to assess the CO2 fluxes associated with these waters will require further research, as no pCO2 observations were later available in it. Anecdoctically, we also wondered why the fresh pools seemes undersampled by the Argo floats with a lot of missed pofiles seemingly coinciding with them. We indeed found that there were issues with early floats (until 2012-2013, mostly) that did not have the mechanical buoyancy capacity to lift to the surface. We also found software issues on some other floats, such as false detection of the bottom when reaching a sharp pycnocline, or time limitations on the profile length (slowed down when reaching very fresh surface waters). These issues imply that the Argo-based products can be highly biased to positive anomalies at the sea surface.

All radar-derived variables (HEREON) exhibited a distinct diurnal cycle, with reduced wind stress and wave breaking intensity accompanied by increased near-surface vertical current shear during the afternoon and evening periods.

3. Challenges / difficulties encountered (where applicable)

Lab closures during part of the project due to the pandemic emergency delayed some studies, but the situation rapidly recovered to normal in 2022 and most of the the analyses could be performed.

4. Work planned during the rest of the project, stemming from the work already performed.

We are and will continue the analyses of the available observations (including those acquired in 2021 during late summer on the TaraMicrobiome and Amazonmix field experiments) with a focus on the contribution of the fresh pools and other meso-structures to the overall ocean-atmosphere CO2 exchanges. We will also investigate, at least qualitatively, the high variability near the estuary.

Work package 3: Quantifying the variability of the marine boundary layer aerosols and their thermal effects

Aerosols influence cloud formation and characteristics both by acting as cloud condensation nuclei and by modifying atmospheric stability. EUREC⁴A-OA complements the massive study of stratocumulus clouds undertaken in EUREC⁴A by assessing the variability of marine boundary layer aerosols and their heating rate, and linking them to the diurnal cycle and to the upper ocean conditions.

1. A summary of work done for each task

Aerosol measurements have been performed using a combination of real-time and off-line instruments deployed on board the research ship ATALANTE from 20 January 2020 till 20 February 2020. Modeling work has been performed using the Weather Research and Forecast model (WRF) using an aerosol-aware microphysics scheme, to analyze the sensitivity of the meteoclimatic conditions to different aerosol concentrations. The experimental work has been done by UniMIB research unit. The modeling work has been done mainly by CIMA, with contributions by UniMIB.

Task 3.1 Variability of marine aerosol characteristics (**UNIMIB**, NERSC, LMD)

Real time aerosol data have been acquired using a combination of instruments (NanoScan 3910 TSI for measuring the aerosol number size distribution from 10 nm to 400 nm in 13 size classes, Optical Particle Counter (OPC) Grimm 1.107 for measuring the aerosol number size distribution from 250 nm to 32 μm in 31 size classes). Chemical analysis have been performed to divide the aerosols into 1) water-soluble inorganic ions and 2) Total Carbon (TC), Organic Carbon (OC) and Organic Matter (OM). Aerosol hygroscopicity has been determined using an Aerosol Exposure Chamber.

Task 3.2 Light absorbing aerosols and heating rate (**UNIMIB**, LMD, NERSC)

In order to determine the heating rate of aerosols, radiation measurements have been collected using a Multiplexer-Radiometer-Irradiometer ROX (diffuse, direct and reflected radiance: 350-1000 nm, 1 nm resolution) at 1 min time resolution and using a SPN1 broadband radiometer (global and diffuse radiation, 300-2800 nm). The aethalometer AE33 Magee Scientific has been used to measure the equivalent black carbon concentrations and the absorption coefficients in the UV-VIS-NIR region at high time resolution (1 min). Off-line aerosol data have been acquired by means of a total suspended particulate matter (TSP) sampler, collecting 23 samples.

In order to determine the effects of aerosols on the meteoclimatic conditions, the WRF model has been set up in the North Atlantic subtropical region using a double nested configuration for the different domains used. The highest resolution in the inner domain is about 3 km x 3 km. Different runs have been performed for three months (December 2019, January and February 2020) using ERA5 reanalysis as lateral boundary conditions and high resolution MUR-SST data as sea surface temperatures. Ensemble simulations have been performed by perturbing the initial conditions in each one of the 10 members. Sensitivity studies have been performed by varying the surface input of aerosols and by varying the effects of aerosols on the radiative transfer, isolating the direct, the semi-direct, and the indirect effects of aerosols on the energy budget.

2. Significant results

Large aerosol variability has been measured during the campaign, with total aerosol concentration ranging from 203 cm-3 till 3.15*10^5 cm-3 with an average of (5.23±0.25)*10^3 cm^-3. Similarly, equivalent black carbon concentrations ranged from 7 ng m^-3 to 2168 ng m^-3. During the whole cruise (from Pointe-à-Pitre to the French Guyana Atlantic waters and the way back) two distinct events of increasing eBC concentrations were observed: from 29/01/2020 till 05/02/2020 and between 09/02/2020 and 11/02/2020. In particular, the two distinct events have been related to aerosol transport from Northern Africa, primarily consisting of dust and, in the second event, biomass burning products. The amount of locally formed secondary aerosols has been computed, indicating that this process accounts for the vast majority (87±9%) of total aerosols in background conditions while it becomes less relevant in the two dust and dust + biomass burning events (about 58 ±14%). The diurnal cycle of the aerosol characteristics has been evaluated, indicating that the minimal size is reached after 10UTC (6am in local time) in agreement with atmospheric photochemical processes responsible for secondary aerosol formation. The interpretation of the diurnal behaviour of secondary formed aerosol concentration is complex and it is affected not only from its formation but also from dilution and dispersion within the marine boundary layer, which has a variable thickness throughout the day. Characterization of the inorganic ions indicates that the inorganic ions are mainly of sea salt origin, both from primary emissions (sea spray) and from secondary emissions, including a high level of marine biogenic emissions that also contribute to the organic fraction of aerosols. The marine contribution to aerosols during the transport events substantially decreases. The relevance of sea spray aerosols results in a high hygroscopicity (about twice as large as for typical continental aerosols).

The effects of increased aerosols on the marine atmospheric boundary layer have been evaluated by comparing different WRF simulations, either with a small (CTR) and with a large (EXS) surface flux of aerosols. In the EXS runs the concentration of aerosols is about 2 orders of magnitude larger than in the CTR one, a reasonable difference considering the variability observed during the campaign. Differences in surface fluxes, boundary layer height, cloudiness and precipitations between the different runs have been quantified. Low level cloud fraction increases by about 30% in EXS compared to CTR, resulting in a decrease of precipitation. Mid and high level clouds, when present, are less impacted. While the change in rainfall is mainly due to the larger number of smaller droplets, the change in cloudiness is attributed to the effects of absorbing aerosols, mainly dust particles, which are responsible for a rise of temperature that feeds back onto specific humidity. As in the boundary layer the increase of moisture dominates, the net effect is a higher relative humidity, which favors the formation of thin low non-precipitating clouds. The feedback accounts for a dynamical change in the lower troposphere: shortwave radiation absorption increases temperature at the top of the marine atmospheric boundary-layer and reduces entrainment of warm and dry air, increasing low level moisture content. Despite the overall increase in cloudiness, daytime cloud cover is reduced. The semi-direct effect of aerosols on clouds results in a warming of the surface, opposite to the indirect effect (Tartaglione et al. 2024).

3. Challenges / difficulties encountered (where applicable)

Laboratory and office closures during part of the project due to the pandemic emergency delayed some studies, but all the planned activities have been undertaken.

Work package 4: Developing climate model parametrizations for small-scale, non-linear ocean atmosphere exchanges

The main aim of WP4 is to identify and mitigate persistent biases in the tropical ocean that are related to their ability to capture the high-frequency, radiative and dynamic, coupled processes. This WP delivers analyses with high-resolution coupled simulations in a regional context (CROCO-WRF-WW3) and a new high resolution model version of the Norwegian Earth System model was set-up (NorESM-HR). A primary validation of air-sea interaction and climatological seasonal cycle performed. These simulations are used to develop new parametrization of the coupling between the ocean and the atmosphere, in particular for energy, gaz exchanges as well in cloud parametrization and vertical resolution in the marine boundary layer (MBL).

1. A summary of progress towards objectives for each task

The development of new numerical model parameterizations has progressed well during the first period of reporting based on observational results. Preliminary results have been already formulated in manuscripts submitted for publication in scientific journals.

Task 4.1 New coupling parametrization of ocean-atmosphere energy exchanges for processes at ocean meso- to submesoscale (**LEGOS**, CNRM, LOPS, NERSC, UIB)

The Current Feedback to the atmosphere (CFB) contributes to the oceanic circulation by diminishing the surface imprint of ocean mesoscale eddies. In an ocean-atmosphere coupled model, CFB can be correctly accounted for by using the wind relative to the oceanic current. However, its implementation in a forced oceanic model is less straightforward as CFB also enhances the 10 m wind. Wind products based on observations have "seen" real currents that will not necessarily correspond to model currents, whereas meteorological reanalyses often neglect surface currents or use surface currents that, again, will differ from the surface currents of the forced oceanic simulation. In this published study (Renault et al., 2020), we use a set of quasi-global oceanic simulations, coupled or not with the atmosphere, to (i) quantify the error associated with the different existing strategies of forcing an oceanic model, (ii) test different parameterizations of the CFB, and (iii) propose the best strategy to account for CFB in forced oceanic simulation. We show that scatterometer wind or stress are not suitable to properly represent the CFB in forced oceanic simulation. We furthermore demonstrate that a parameterization of CFB based on a wind-predicted coupling coefficient between the surface current and the stress allows us to reproduce the main characteristics of a coupled simulation. Such a parameterization can be used with any forcing set, including future coupled reanalyses, assuming that the associated oceanic surface currents are known. A further assessment of the thermal feedback of the surface wind in response to oceanic surface temperature gradients shows a weak forcing effect on oceanic currents. We also tested the parameterizations in Renault et al., 2021 but for the California Upwelling System.

Task 4.2 Improving CO2 ocean-atmosphere flux parameterizations (**LMD**, LOCEAN, HZG/MPI)

Concerning Task 4.2, the implementation of the Bellenger et al. (2017) parameterization in the IPSL coupled model (IPSL-CM6) has been completed (MS7). A report on how this implementation is achieved is in preparation (D4.1). Simulation with diagnostics CO2 fluxes computed taking into account the ocean skin has been performed and fully coupled simulations with IPSL-CM6 are currently being produced on the TGCC super calculator. These 15-years long simulations are designed to correspond to the 2000-2014 period. The evaluation of the impact of Bellenger et al. (2017) on CO2 flux on the global scale is now almost completed and an article should be submitted in the coming months (MS9, D4.3). More precisely, we study the effect on the CO2 flux of the temperature and salinity vertical gradients in the diffusive mass boundary microlayer (<1mm thick) and below within the ocean model first level (1m). We compare our results to a diagnostic made with a constant decrease in temperature of -0.17K and an increase in salinity of 0.1 psu within the mass boundary layer as proposed by Watson et al. (2020). Watson et al. (2020) shows an increase of 0.8 Pg/year of the global oceanic CO2 sink. Our diagnostic shows a weaker increase of 0.3 Pg/year that should be further reduced by the effect of coupling. Another interesting feature is that considering a constant difference in temperature and salinity lead to large overestimations of the carbon sink in the northern Pacific and Atlantic Oceans in winter and in the Southern Oceans in summer potentially impacting pathways of the carbon cycle. This overestimation comes from the fact that the gradients in the boundary layer should almost vanish there due to the wind induced intense mixing. This is what we indeed obtain when using an interactive skin (Bellenger et al. 2017). Furthermore, our parameterization leads to a noticeable increase in carbon sink in the EUREC A-OA region that will be further studied with the campaign observations.

Task 4.3 Evaluating cloud parameterization (**NERSC**, LMD)

We developed a high-resolution version of the Norwegian coupled global climate model, NorESM-HR, with ¼ degree resolution in both ocean and atmosphere. This model was used to investigate the impact of resolution on atmospheric boundary layer processes, including low-level cloud formation and deep convection. Data assimilation in the ocean and spectral nudging in the atmosphere allowed for accurate representation of slow oceanic processes and constraint of large-scale atmospheric circulation.

We identified 6 parameters which we considered to be likely to affect low level cloud cover, and conducted a literature review and an expert consultation with developers of the atmospheric models in CESM and NorESM, that include CLUBB, to identify most likely ranges for these parameters. We then conducted a 30 member ensemble of perturbed-parameter experiments for the period Dec 2019 to Nov 2020. We simultaneously perturbed parameters in this 30 member ensemble sampling them using a uniform distribution across evenly spaced blocks in the parameter space to ensure we covered the full range of possible values. The ERA5 reanalysis was used to evaluate the model skill in capturing low level cloud cover.

We developed a novel offline data assimilation methodology to estimate the values of these parameters that led to the least misfit with the ERA5 reanalysis. We identified two parameters that strongly controlled the model bias in low-level clouds, the most important one governs the skewness in updrafts within these clouds. Values of these two parameters that removed the model bias in low-level clouds were within the tested range, both when tuning to global and tropical bias. We conducted a second round of experiments where we fixed these two parameters to the values that led to zero bias globally, and allowed the others to vary. In this second round of experiments the bias in low level clouds was unaffected by the variations in these other parameters.

Task 4.4 Assessing bias-dependence on vertical resolution (NERSC, LMD, LEGOS, UIB)

In this task we intended to run twin simulations to test the effect of increased vertical resolution within the NorESM-HR using the optimized parameter set for the CLUBB scheme for the atmospheric boundary layer and shallow convection from Task 4.3.

The first step was to establish a new vertical resolution that would be stable, and so we conducted tests with perturbed vertical resolution within the one-dimensional version of the NorESM-HR model. We tested various approaches to increase the number of vertical levels in the model. During these tests, all significant increases in the vertical resolution encountered persistent spurious oscillations within the atmospheric boundary layer . Despite collaborative efforts with NOAA, a solution to this issue remained elusive, leading to the abandonment of this approach. Consequently, the focus shifted to other aspects of model improvement.

The team at the University of Bergen (UiB) concentrated on refining the 1/4 degree model, particularly exploring the sensitivity of the Intertropical Convergence Zone (ITCZ) to parameters within the Zhang-Macfarlane deep convection scheme. Concurrently, the Nansen Environmental and Remote Sensing Center (NERSC) developed an offline data assimilation methodology for parameter estimation. This method was pivotal in executing perturbed-parameter experiments with the low-resolution NorESM, aimed at identifying and mitigating model biases.

2. Significant results

The implementation of new parametrizations to simulate the fluxes of heat, freshwater and momentum between the ocean and atmosphere carried out within the EUREC^{4}A-OA project considerably improves the realism of simulations. In particular, an original parameterization that takes into account fresh-water patches at the ocean surface for heat fluxes has been successfully implemented in the IPSL Earth System Model. Major improvements in cloud covers and heat fluxes have been observed. The development of a similar parametrization applied to CO2 fluxes is being implemented. The preliminary evaluation shows a more realistic CO2 global flux budget than previous, more simple parametrizations applied to Earth System models. Furthermore, our parameterization leads to a noticeable increase in carbon sink in the EUREC^{4}A-OA region that will be further studied with the campaign observations.

A comparison of the regression analyses between the heat fluxes, SST and surface winds were carried out with the new HR version of NorESM (0.25° in atmosphere and 0.25° in the ocean) and with ERA5 reanalysis. The new HR model reproduces the positive correlation between SST and wind and mitigates the underestimation of latent heat flux. The new HR-NorESM greatly improves the climatological seasonal cycle over the tropical North Atlantic for SST and low-level cloud fraction compared to the NorESM at standard resolution (2° in atmosphere and 1° in the ocean).

UiB also conducted a high-resolution CAM5 simulation (atmospheric component of NorESM) whose resolution is approximately 0.25° x 0.25° forced by daily high-resolution OISST boundary conditions. The simulation shows patterns of meso-eddy-scale latent and sensible heat flux over the warm and cold SST eddies (a range of meso-scale SST eddy is from -0.9 to 0.9 K as spatial anomaly) in the northwestern tropical Atlantic similar to eddy-rich oceanic regions: more flux over warm eddies and less flux over cold eddies. Correspondingly, planetary boundary layer height (PBLH) tends to be higher/lower over the warm/cold SST eddies in a range from -80m to 80m, approximately. Although an eddy structure is unclear, low-level cloud fraction also seems to respond to the SST eddies. Interestingly over the warm/cold SST eddies, the low-level cloud fraction is larger/smaller in a range from -0.06 to 0.02. On the other hand, surface winds do not show a clear meso-scale structure over the warm and cold SST eddies. Whereas the response of surface heat fluxes and PBLH indicate that the vertical mixing mechanism (e.g., Hashizume et al., 2001) acts in the simulation, the relatively coarse resolution of the vertical layer in the atmospheric boundary layer might not be able to resolve the vertical mixing efficiently.

The EUREC4A-OA project has had a significant impact on climate modeling through the development of a high-resolution Norwegian Earth System Model (NorESM-HR) with reduced biases in the low level cloud cover. The enhanced resolution and accuracy of the NorESM model will support a wide range of applications, from forecasting extreme weather events to long-term climate change projections, thus providing valuable insights for climate adaptation and mitigation strategies.

The innovative method for offline parameter estimation using data assimilation that was developed here has already been applied to other model components in the Norwegian Earth System Model, e.g. within the biogeochemistry model to improve the simulation of key processes affecting ocean-atmosphere CO2 fluxes. This approach can greatly speed-up model tuning which will facilitate the delivery of more accurate simulations from NorESM to CMIP7, for example. This parameter estimation method is semi-automatic and relies much less on subjective choices about relative parameter importance and priority, facilitating a deeper understanding of model sensitivity to unknown parameters. This will enhance the overall robustness and reliability of future climate models, benefiting both the scientific community and society at large.

3. Challenges / difficulties encountered (where applicable)

This WP hads delays in T4.3 and T4.4 caused by the following1) the HR-NorESM showed initially showed substantial model bias and was unstable on the new high-performance computer. WP4 leader and NERSC-PI (R. Davy) has left the project in the early stages to go onon care benefit and is now on parental leave for one year. Further delays were caused by the sickness and passing of our colleague and friend Prof Yongqi Gao. Senior scientist Dr. Outten have tooktaken took over his duty while F. Counillon will replaced R. Davy as NERSC-PI in the meantime (return expected in September 2022). NERSC have moved most of their initial budget to 2022 and 2023 to complete D4.5 and D4.6. Similarly, work at UiB for T4.4 UiB also faced a further delay as a staff member who was recruited to work on this project (F. Tian) was not able to enter Norway on schedule due to COVID-19 related restrictions. Budget has been moved to 2022. No other tasks inon the project dependeddepends on T4.3 and T4.4 and so these delays did not affect other tasksso we do not expect further implications.

Work package 5: Observational and climate model data metrics to evaluate the representation of small scale, non-linear processes in climate models

Model/observational data metrics allowed us to further understand small-scale ocean physical and biogeochemical processes, their role in the large-scale circulation of the ocean and atmosphere and verify the representation of key mechanisms in ocean models. Here we consider metrics that are based on observations and have been applied to model data. We concentrated on metrics that cover the EUREC⁴A-OA time domain - diurnal up to (several) inertial periods (period: 4 days at 8°N/2 days at 16°N), and the relevant mesoscale /regional space domain.

1. A summary of progress towards objectives for each task

In this task we carried out assessments of the spatio-temporal metrics in the EUREC4A-OA region and we started the comparisons with similar assessments from numerical models.

Task 5.1 Space domain: Submesoscale heterogeneity and large scale pattern and fluxes (**LMD**, HZG/MPI, CIMA, CNRM, HZG, GEOMAR/MPI, LEGOS, LOCEAN, LOPS, NERSC, UNIMIB)

Mesoscale eddies, fronts, and filaments are coherent structures that may be important for linking surface mixed layers to the interior ocean dynamics. By virtue of a sharp contrast with their surroundings, these structures can efficiently transport heat, salt, and carbon through the ocean. Though satellite observations have enhanced knowledge of ocean mesoscale eddies, the assessment and understanding of their occurrence, their 3D structure and evolution as well as smaller-scale features remain limited because of the sparsity of direct observations. In this task we took advantage of the significant deployment of platforms within the EUREC⁴A-OA field experiment that provides a high-resolution spatiotemporal sampling. The analyses have provided robust assessments of the upper-ocean ocean (surface and subsurface) fine-scale characteristics as well as collect information on regional dynamical specificities (dynamical regimes, wind and buoyancy forcings).

The richness of structure observed in the upper ocean during the EUREC⁴A-OA can be quantified by the distribution of upper-ocean density and velocity fronts. To characterize the scale we use all the platforms deployed. This allowed us to survey a wide region and a large spectrum of ocean scales (ranging from 0.1 and 100 km). An example from one of such platforms, the Saildrones, are shown in Fig. 6. Here we explored the frontal density gradients distribution in terms of their spatial extent. The analyses show three different areas in terms of regimes with the North Brazil Current rings corridor showing the presence of different scales which depend on the active mesoscale eddies but also on their interaction with -shelf currents and water masses (Figs 6 and 7). For each length scale, the percentage frequency of each density gradient was calculated. This analysis demonstrates that smaller length scales yield larger density gradients (Coadou et al., 2024).

In this region, in particular, density gradients result not only from the mesoscale motions and atmospheric forcing, but also from the dynamics of the freshwater fluxes associated with the Amazon River system. Thus, the strongest gradients are found in the vicinity of the northwestward spreading freshwater plume (Fig. 7). The attenuation of surface density gradients away from the plume (Fig. 7) suggests that freshwater fluxes are a first-order parameter driving frontogenesis. Mesoscale motions, in particular two observed NBC rings, stirred this freshwater anomaly offshore. Our results suggest that this stirring of gradients enhances the horizontal strain and sets the conditions for submesoscale fronts to form through frontogenesis, and from which mixed layer eddies can grow.

While the large-scale fronts are strongly salinity dominated, these submesoscale fronts are found to be partially temperature compensated (Coadou et al., 2024). Analysis of the Saildrones ADCPs suggests that this compensation occurs at restratifying frontal regions. Because submesoscale fronts are dynamically unstable, they collapse, leading to increased stratification along the front. The atmospheric cooling over the region during winter is expected to form a temperature gradient as a result of a larger SST response over the shallow mixed layer. The weakening of the submesoscale fronts due to partial temperature compensation prevents the cascading of energy to smaller scales where dissipation occurs. Overall, the applied methodology could be extended to other datasets to assess the phenomenology of fine-scale structures in other dynamical regions.

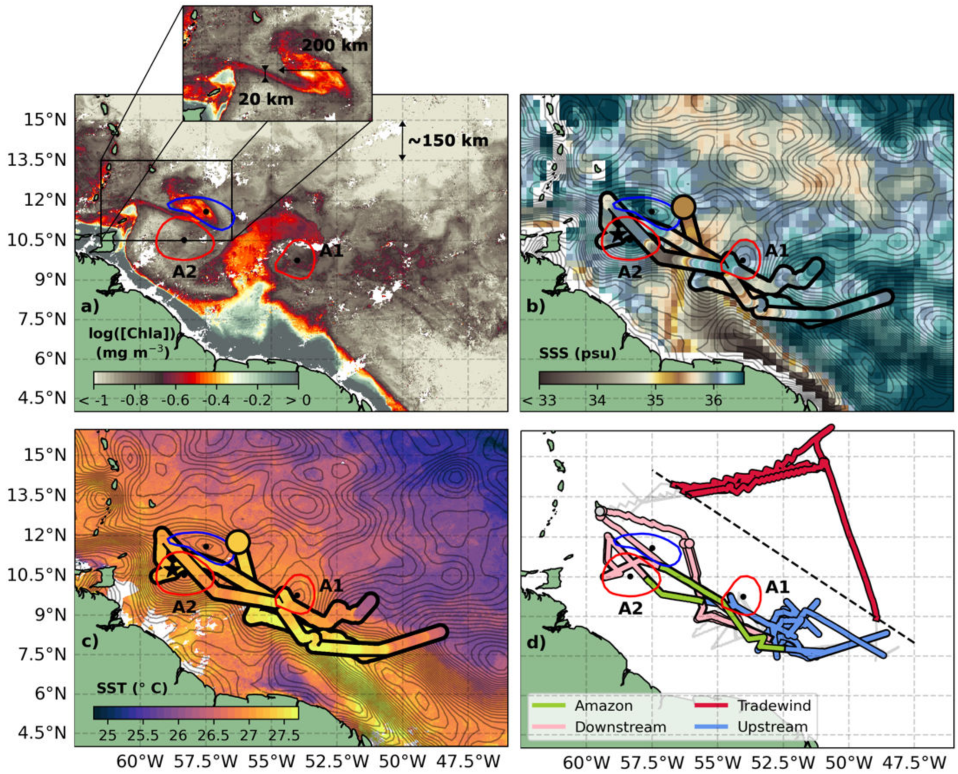

Figure 6. Satellite maps of Chl-a (a), SSS (b) and SST (c) on 12 February 2020. (d): Trajec- tories of the five Saildrones color-coded with the regions (Amazon (green), Downstream (pink), Tradewind (red) and Upstream (blue)). The light grey line indicates unused data from Saildrone 1064. Eddy contours are derived from the TOEddies eddy detection and tracking algorithm (Laxenaire et al., 2018) applied to Maps of Absolute Dynamic Topography (MADT): light grey contours in (b),(c) and (d), red contours for anticyclones, blue contours for cyclones. The trajec- tory of Saildrone 1026 is color-coded by in-situ measurements of salinity (b) and temperature (c). Its position at the time closest to the satellite map is indicated by a black star . In (b), (c) and (d), the start of the measurement period of each Saildrones is shown by a circle. A zoom in (a) highlights some of the mesoscale and submesoscale features tracked by the chl-a concentration. Some length scales are shown in (a). In (d), the dashed black line shows the separation between the Boulevard des Tourbillons and the Tradewind Alley. Adapted from Coadou et al., 2024.

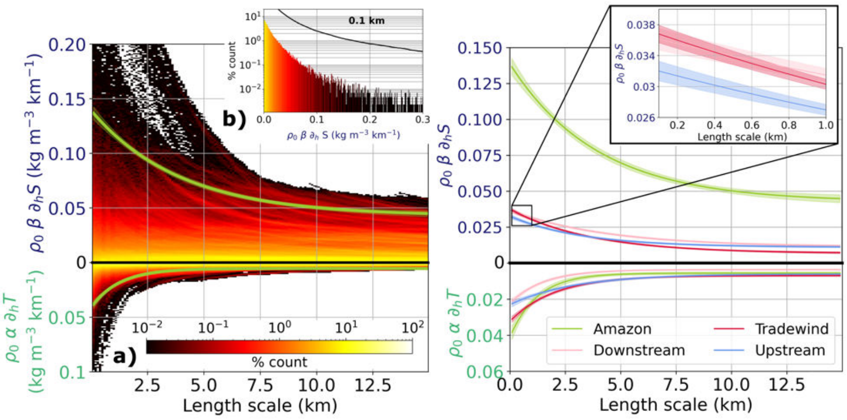

Figure 7. (a) Distribution of surface salinity (top) and temperature (bottom) gradients for horizontal length scales sampled from 0.1 to 15 km. The logarithmic color scale shows the per- centages at the different scales. Both ∂hS and ∂hT have been scaled to have density gradients unit (kg m−3 km−1). The green lines are the exponential 99-envelope fits to the two distributions. (b) Distribution of surface salinity gradients for the smallest scale (0.1 km), with the black line indicating the cumulative histogram. (c) Exponential fits to the distributions of the surface salinity (top) and temperature (bottom) gradients for the four regions. The shaded envelope gives the confidence bands (3σ) from the uncertainties in the best-fit parameters. (d) Zoom of (c) for the salinity distribution at scales below 1 km. Adapted from Coadou et al., 2024.

Task 5.2 Time domain: Metrics for diurnal to the inertial period (**GEOMAR/MPI**, CIMA, CNRM, HZG/MPI, LEGOS, LMD, LOCEAN, LOPS, NERSC)

In this task we work in computing the metrics that describe the temporal variability of properties characterizing the air-sea interface at the daily timescale. Here we consider metrics that are based on observations and can be applied to model data. Analyses of the EUREC[4]A-OA observations enabled us to assess the evolution of a daily formation of a near-surface ocean stratification (0 to 5m depth) caused by penetrating solar radiation. This so-called diurnal warm layer (DWL) modifies the heat fluxes through the air-sea interface, turbulence dissipation in the mixed layer, and the vertical profile of lateral transport. The transport is altered, because momentum from the wind is trapped in the thin near-surface layer. We have been also investigating the dynamics and variability of this layer, with particular attention to the vertical shear of horizontal velocity and identified the following metrics to evaluate (and investigate) these nonlinear processes in climate models:

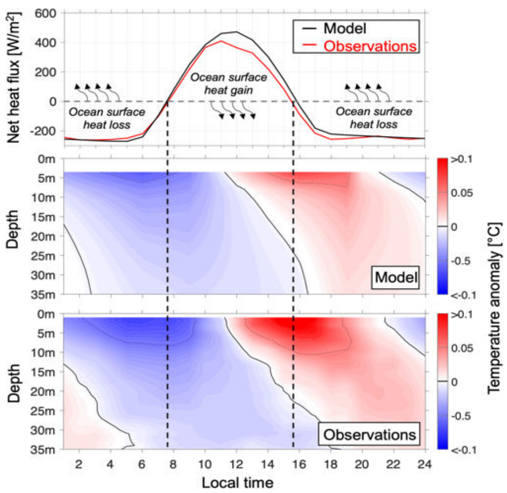

Figure 8. Diurnal cycle of Net Heat Flux gained Observations (red) and Model data (black) is shown upper panel. The lower colored panels are the upper diurnal cycle of temperature anomaly of the first 35m ocean: the first based on the coupled ICON simulatio km horizontal resolution and the second based on Glider data (both, Model as Observation averagec 30 days in Jan/Feb in the EURECA Region at the position).

a) The mean diurnal cycle of upper ocean mixed layer temperatures to characterize the DWL (the diurnal cycle in general is derived either from averaging over the same hours for the available data or from a harmonic analysis, the later produces the amplitude and phase of the diurnal cycle; see Fig. 8).

b) The mean diurnal cycle of the wind power input to the ocean and parameters, such current speed along and perpendicular to the winds, which are needed to diagnose the details of the momentum and energy exchange between the atmosphere and the ocean (see Fig.9)

c) Lagged correlations between the DWL and surface fluxes of momentum/shear, heat and fresh water, as functions of time lags. Note, that since these correlations are not symmetric (correlations at positive lags are not identical to those at negative lags), this metric can be used to identify to what extent the ocean generates the co-variability between the DWL and fluxes, for example.

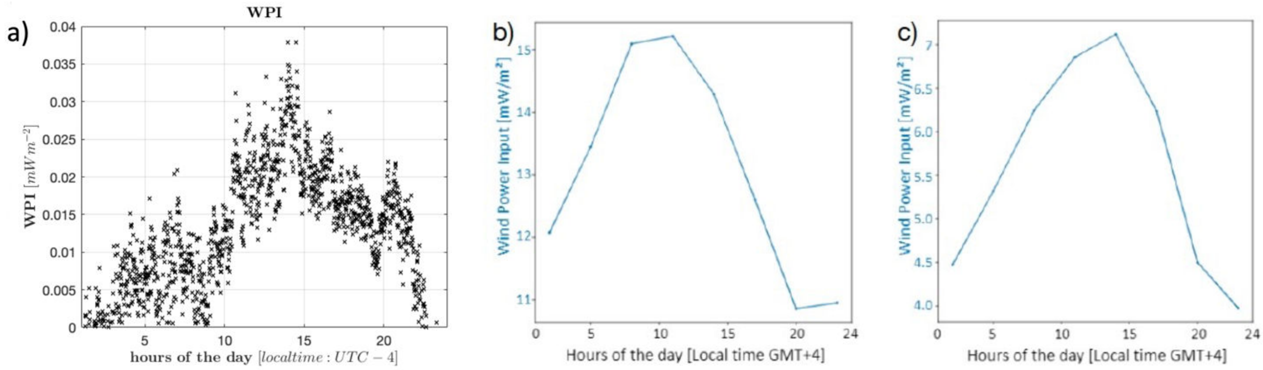

Figure 9. Diurnal cycle of the wind power input as a function of hours of a day obtained from a) the observations and two ICON-O model simulations with the thickness of the first model layer being 2 m in b) and 10 m in c).

2. Significant results

Our results do show the characteristics in terms of spatial scales. These range from the mesoscale (order 100 km) to the submesoscale that we measured down to 0.1 km. The latter characterize the largest fraction of the observed area. These scales show to be important on air-sea fluxes as well as on cross-shelf exchanges. Our results suggest that they also regulate both the diurnal cycle and processes at inertial period, such as inertial waves. There are very few observations over the ocean with sufficiently high temporal resolution (hourly) to capture the diurnal cycle. The EUREC4A-OA field experiments allowed such observation and this across different mesoscale and submesoscale features over a relatively large area.

The maximum wind power input to the ocean is found to occur around 3 pm in the observations (Fig.9a). In the ocean model ICON-O, this timing depends on the thickness of the first model layer. It is more realistic when a first model layer with a thickness of 10 m is used (Fig.9c) than when a first model layer with a thickness of 2 m is used. (Fig.9b)

3. Challenges / difficulties encountered (where applicable)

Laboratory and offices closures during part of the project due to the pandemic emergency delayed some studies, but the situation recovered and was back to normal in 2022.

4. Work planned during the rest of the project, stemming from the work already performed.

We are still formalizing two manuscripts to be submitted for publication in international scientific journals. Metrics such as the typical spatial scales involved in key processes (transport and air-sea exchanges) as well as the amplitude and phase of the diurnal cycle of SST, surface fluxes, and other near-surface variables including bio-geochemical tracers when available, are being computed and compared among models and with observations. Inertial current interaction with local vorticity anomalies (eddies and fronts) continued to be investigated with the aim of establishing their effect on transport.

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Deliverables and Milestones

Deliverables

Deliverable Nr.	Deliverable Title	Due (month)	Actual planning (month)	Deliverable achieved	References
D.1.1	Report/article discussing estimates of the spatial variability of the air-sea heat and water fluxes on the EUREC[4]A-OA domain.	18		24	3 articles delivered (Fernandez et al., 2023; 2024, Borgnino et al. 2024)
D1.2	Report/article describing the evaluation of air-sea processes responsible for the observed and simulated diurnal cycles obtained by identifying the dependence of the diurnal cycle on different weather and oceanic conditions and through sensitivity experiments and a report quantifying the impact of small scales on wind power input in model	30	30	30	2 articles delivered (Hohenegger et al., 2023; von Storch and Lüschow, 2023).
D1.3	Report/article on the basis of knowledge (or dynamical rules) to train expert systems, to prepare new experiments at sea, or to validate operational models	30	30	yes	1 article submitted (Laxenaire et al., 2024)
D2.1	Report/article on the estimate of the air-sea exchange of CO2 and its variability linked to submesoscale dynamics within the EUREC[4]A-OA domain.	18	18	yes	2 articles published (Olivier et al., 2022; 2024)
D2.2	Report/article on the sensitivity of CO2 fluxes on observed and diagnosed upper ocean stratification	30	30	yes	1 article published (Bellenger et al., 2023)
D3.1	Report/article on the diurnal cycle of the number concentration and size distribution of marine aerosols; spatio-temporal variability of sea spray and secondary particles from biogenic gaseous emissions	18	18	yes	Report delivered
D3.2	Report/article describing the quantification of the different radiative components in the heating rate by light absorbing aerosols at sea level	24	24	yes	Report delivered 1 article published (Tartaglione et al. 2024)
D4.1	Report/article on the parameterizations implemented in the models	24	12	yes	Renault et al. (2020, 2021)
D4.2	Report/article on the forced and coupled simulations and metrics	30	36	yes	Paper in preparation
D4.3	Report/article describing the implementation of Bellenger et al.	12	12	yes	Paper under review

Deliverable Nr.	Deliverable Title	Due (month)	Actual planning (month)	Deliverable achieved	References
	2017 in IPSLCM6 for the computation of CO_2 fluxes				
D4.4	Report/article presenting the impact of the parameterization in the 1D idealized oceanic simulations and on the global scale	34	34	Yes	Paper in preparation
D4.5	Report/article on sensitivity of representation of low clouds in NorESM to key closure parameters	24	30	yes	Report delivered, paper Davy et al., (in preparation)
D4.6	Report/article on sensitivity of representation of low clouds and surface coupling to vertical resolution in NorESM	30	33	yes	Report delivered
D4.7	Report/Journal article on the influence of the representation of low cloud cover on the ITCZ	36	36	yes	Paper in preparation
D5.1	Report on metrics derived from observational and model data for spatial domain	30	30	yes	6 articles published/submitted (Barabinot et al., 2024a; 2024b; 2024c; Coadou et al., 2024; Napolitano et al., 2024; Laxenaire et al., 2024, submitted)
D5.2	Report on metrics derived from observational and model data for temporal domain	30	36	yes	Paper in preparation
D6.1	Meeting reports: Kick-off video conference; project meeting 1; project meeting 2; project meeting 3; stakeholder meeting	3, 9, 18, 30, 36	3, 9, 20, 30, 36	yes	
D6.2	Quality controlled data from EUREC^{4}A-OA available	6	12	yes	1 article published (L'Hegaret et al., 2023)

Milestones

Milestone Nr.	Milestone Title	Due (month)	Actual planning (month)	Milestone achieved	Comments
M1	Set up of the coupled models in the EUREC^{4}A-OA domain	12	18	yes	
M2	Compilation of quantities involved in ocean-atmosphere energy and water exchanges in the diurnal cycle both from the EUREC^{4}A-OA field campaign and from numerical simulations	18	24	yes	1 article in minor revision to Dyn. Atmos. and Oceans (Giordani et al., 2024); Conejero et al. (2024a, JPO); Conejero et al. (2024b, submitted to GRL).
M3	Set up of idealized and realistic ocean very high-resolution numerical experiments to investigate mechanisms separately and then together in the context of the very high resolution regional model	18	24	yes	See Conejero et al. (2024a) and Larrañaga et al. (2022)
M4	Compilation of properties of upper ocean stratification (skin, DWLs and CFLs) impacting the CO2 fluxes estimated from EUREC^{4}A-OA observations	24	24	yes	
M5	Collection of filters under different environmental conditions in the EUREC^{4}A-OA study site	12	12	yes	
M6	Daily variability (subhourly time scale) of the heating rate by light absorbing aerosols at the sea level	24	24	yes	
M7	Implementation of Bellenger et al. 2017 in IPSLCM6 for the computation of CO2 fluxes	12	24	yes	
M8	Design of idealized 1D oceanic simulations to evaluate the parameterization on CO2 fluxes	24	24	yes	
M9	Realization of fully coupled simulation with IPSLCM6 and evaluation of the impact of the parameterization on CO2 fluxes	34	34	yes	
MS10	Completed coupled simulations and assessment of parameter space with NorESM	20	26	yes	
MS11	Completed NorESM twin experiments with perturbed vertical resolution	30	30	yes	
MS12	EUREC^{4}A-OA study website established	3		yes	http://eurec4a-oa.eu
MS13	Data Policy agreed	1		yes	
MS14	EUREC^{4}A-OA study data available	4		yes	

Financial Status

Name of partner	Grant budgets spent (in EUR and %)	Comments (if necessary) planning
CIMA	71 294,51 (100%)	
CNRM	20 630 (100%)	In fact there are 2832 euros left which will be used to pay for an article for DAO
GEOMAR	161 478,21 (99%)	In-kind: 162.00,00€
HEREON (ex HGZ)	180 197,00 (100%)	In-kind: 180.197,00€
LEGOS	136 625 (100%)	
LMD	141 579 (100%)	In-kind 320.000,00€
LOCEAN	106.905,00 (100%)	
LOPS	81 864 (100%)	
MPI	264.082,90€ (100%)	In-kind: 130.784€
NERSC	406 871 (100%)	
UNIMIB	99 900,50 (100%)	
UIB	193 000 (100%)	

Dissemination activities

Publications:

Type	Partners involved	Title and authors	DOI
Chapter in book	LOPS	Carton, X., F.C. Kouogang Tchuenkam, A. Vic, 2021: The interaction of two vortices near a boundary in rotating stratified incompressible flows. Ch.5, In Recent Trends in Chaotic, Nonlinear and Complex Dynamics. World Scientific Series on Nonlinear Science Series B:, 19, World Scientific Press, 99-131.	https://www.worldscientific.com/worldscibooks/10.1142/11872
Peer-reviewed journal	MPI, LMD, GEOMAR, LOPS, LOCEAN	Stevens B. et al. (2021): "EUREC^{4}A", Earth System Science Data, 13(8), 4067-4119.	https://doi.org/10.5194/essd-13-4067-2021
Peer-reviewed journal	LOPS	Vic, A. X. Carton, J. Gula, 2021: The interaction of two unsteady point vortex-sources in a deformation field in 2D incompressible flows. Reg. Chaotic Dyn., 26, 618-646, special issue: 200th anniversary of H von Helmholtz.	https://doi.org/10.1134/S1560354721060034
Peer-reviewed journal	LOPS	C. De Marez, X. Carton, 2021: Interaction of an upwelling front with External Vortices: Impact on Cross-shore Particle Exchange. Regul. Chaot. Dyn, 26, 543-561, special issue: 200th anniversary of H von Helmholtz.	https://doi.org/10.1134/S1560354721050063
Peer-reviewed journal	LEGOS	Renault, L., McWilliams, J. C., Kessouri, F., Jousse, A., Frenzel, H., Chen, R., & Deutsch, C. (2021). Evaluation of high-resolution atmospheric and oceanic simulations of the California Current System. Progress in Oceanography, 195, 102564.	https://doi.org/10.1016/j.pocean.2021.102564
Peer-reviewed journal	LEGOS	Renault, L., Masson, S., Arsouze, T., Madec, G., & Mcwilliams, J. C. (2020). Recipes for how to force oceanic model dynamics. Journal of Advances in Modeling Earth Systems, 12(2), e2019MS001715.	https://doi.org/10.1029/2019MS001715
Peer-reviewed journal	LOCEAN, LMD, MPI, GEOMAR	Olivier, L., Boutin, J., Reverdin, G., Lefèvre, N., Landschützer, P., Speich, S., Karstensen, J., Ritschel, M., and Wanninkhof, R.: Impact of North Brazil Current rings on air-sea CO2 flux variability in winter 2020, Biogeosciences Discuss. [preprint], https://doi.org/10.5194/bg-2021-269, in review, 2021	https://doi.org/10.5194/bg-2021-269
Peer-reviewed journal	LOCEAN, LMD, LOPS, HZG, GEOMAR + NOAA	Reverdin, G., Olivier, L., Foltz, G.R., Speich, S., Karstensen, J., Horstmann, J., Zhang, D., Laxenaire, R., Carton, X., Branger, H., et Carrasco, R., J. Boutin, 2020. Formation and evolution of a freshwater plume in the northwestern tropical Atlantic in February 2020. JGR Ocean.	https://doi.org/10.1029/2020JC016981
Peer-reviewed journal	LEGOS	Renault L., and Marchesiello P.: "Ocean tides can drag the atmosphere and cause tidal winds over broad continental shelves". Accepted in Nature Communications Earth & Environment	In press
Peer-reviewed journal	LEGOS, LOPS	Ramanantsoa, J. D., Penven, P., Raj, R. P., Renault, L., Ponsoni, L., Ostrowski, M., & Rouault, M. (2021).: "Where and how the East Madagascar Current retroflection originates?" Journal of Geophysical Research: Oceans, 126(11).	https://doi.org/10.1029/2020JC016203
Peer-reviewed journal	LEGOS	Gévaudan M., Jouanno J., Durand F., Morvan G., Renault L., Samson G (2021): "Influence of ocean salinity stratification on the tropical Atlantic Ocean climate". Climate Dynamics, 1-20.	https://doi.org/10.1007/s00382-021-05713-z

Type	Partners involved	Title and authors	DOI
Peer-reviewed journal	UIB, GEOMAR	Nnamchi, Hyacinth C.; Farneti, Riccardo; Keenlyside, Noel Sebastian; Kucharski, Fred; Latif, Mojib; Reintges, Annika; Martin, Thomas Pan-Atlantic decadal climate oscillation linked to ocean circulation (2023):	https://doi.org/10.1038/s43247-023-00781-x
Peer-reviewed journal	LMD	Cornec, M., R. Laxenaire, S. Speich, and H. Claustre, 2021. Impact Of Mesoscale Eddies On Deep Chlorophyll Maxima. Geophys. Res. Lett.	https://doi.org/10.1029/2021GL093470
Peer-reviewed journal	LMD	Bosser, P., Bock, O., Flamant, C., Bony, S., and Speich, S.: Integrated water vapour content retrievals from ship-borne GNSS receivers during EUREC⁴A, Earth Syst. Sci. Data, 13, 1499–1517, 2021.	https://doi.org/10.5194/essd-13-1499-2021
Peer-reviewed journal	MPI, LMD, GEOMAR, LOCEAN	Stephan, C. C., et al. 2021: Ship- and island-based atmospheric soundings from the 2020 EUREC⁴A field campaign, Earth Syst. Sci. Data, 13, 491–514, 2021.	https://doi.org/10.5194/essd-13-491-2021
Peer-reviewed journal	MPI, LOCEAN, LMD	Bailey, A., et al: Isotopic measurements in water vapor, precipitation, and seawater during EUREC⁴A, Earth Syst. Sci. Data Discuss., 2022	https://doi.org/10.5194/essd-2022-3
Peer-reviewed journal	UNIMIB, CIMA	Desbiolles, F., Alberti, M., Hamouda, M. E., Meroni, A. N., & Pasquero, C., 2021Links between sea surface temperature structures, clouds and rainfall, Geophys. Res. Letters.	https://doi.org/10.1029/2020GL091839
Peer-reviewed journal	LOPS	A. Vic, X. Carton, J. Gula, 2022: Eady baroclinic instability of a circular vortex. Symmetry, 14, 7, 1438, 1-18	https://doi.org/10.3390/sym14071438
Peer reviewed journal	LOPS, Univ. St Andrews	X. Carton, J. Reinaud, A. Vic and J. Gula, 2024: The nonlinear evolution of two surface quasi-geostrophic vortices. Geophys. Astrophys. Fluid Dyn., 1–27.	https://doi.org/10.1080/03091929.2024.2330646
peer-reviewed journal	LOPS	A. Vic, X. Carton, J. Gula, 2024: Baroclinic instability in a coupled oceanic atmospheric Eady model. To appear in Geophys. Astrophys. Fluid Dyn.	in press
Peer-reviewed journal	LMD, LOPS	C. Subirade, P. L'Hegaret, S. Speich, X. Carton, R. Laxenaire, J. Karstensen, 2023: Combining an eddy detection algorithm with in-situ measurements to study North Brazil Current rings. Remote Sensing, 15, 1897.	https://doi.org/10.3390/rs15071897
Peer-reviewed journal	UNIMIB	Meroni, A. N., F. Desbiolles, C. Pasquero, 2022. Introducing a new metrics for the atmospheric pressure adjustment to thermal structures at the ocean surface. J. Geophys. Res. Atmos.	https://doi.org/10.1029/2021JD035968
Peer-reviewed journal	UNIMIB, LMD	Acquistapace, C., A. N. Meroni, G. Labbri, D. Lange, F. Spath, S. Abbas and H. Bellenger, 2022, Fast atmospheric response to an SST mesoscale cold patch in the north-western subtropical Atlantic, submitted to J. Geophys, Res. Atmos.	https://doi.org/10.1029/2022JD036799
Peer-reviewed journal	LMD, LOPS	Barabinot, Y., Speich, S., & Carton, X. (2024). Defining mesoscale eddies boundaries from in-situ data and a theoretical framework. Journal of Geophysical Research: Oceans, 129, e2023JC020422. https://doi.org/10.1029/2023JC020422	https://doi.org/10.1029/2023JC020422
Peer-reviewed journal	LMD, LOPS	Barabinot, Y., S. Speich and X. Carton, 2024. Assessing the Material Coherence of Mesoscale Eddies using In Situ Data. ESS Open Archive. https://doi.org/10.22541/essoar.169833426.64842571/v1	In review
Peer-reviewed journal	LMD, LOPS	Barabinot, Y., S. Speich and X. Carton, 2024. On the 3D structure of Anticyclonic Eddies from in situ data (under review in J. Geophys. Res).	In review

Type	Partners involved	Title and authors	DOI
Peer-reviewed journal	LMD, MPI, +NOAA	Bailey, A., Aemisegger, F., Villiger, L., Los, S. A., Reverdin, G., Quiñones Meléndez, E., Acquistapace, C., Baranowski, D. B., Böck, T., Bony, S., Bordsdorff, T., Coffman, D., de Szoeke, S. P., Diekmann, C. J., Dütsch, M., Ertl, B., Galewsky, J., Henze, D., Makuch, P., Noone, D., Quinn, P. K., Rösch, M., Schneider, A., Schneider, M., Speich, S., Stevens, B., and Thompson, E., (2023). Isotopic measurements in water vapor, precipitation, and seawater during EUREC4A, Earth Syst. Sci. Data, 15, 465–495, 2023. https://doi.org/10.5194/essd-15-465-2023.	https://doi.org/10.5194/essd-15-465-2023
Peer-reviewed journal	LMD, LOPS, LOCEAN, GEOMAR +NOAA	L'Hégaret, P., Schütte, F., Speich, S., Reverdin, G., Baranowski, D. B., Czeschel, R., Fischer, T., Foltz, G. R., Heywood, K. J., Krahmann, G., Laxenaire, R., Le Bihan, C., Le Bot, P., Leizour, S., Rollo, C., Schlundt, M., Siddle, E., Subirade, C., Zhang, D., and Karstensen, J. (2023). Ocean cross-validated observations from R/Vs L'Atalante, Maria S. Merian, and Meteor and related platforms as part of the EUREC4A-OA/ATOMIC campaign, Earth Syst. Sci. Data, 15, 1801–1830, https://doi.org/10.5194/essd-15-1801-2023.	https://doi.org/10.5194/essd-15-1801-2023
Peer-reviewed journal	LMD, UNIMIB	Fernandez P, Speich S, Borgnino M, Meroni AN, Desbiolles F and Pasquero C. (2023) On the importance of the atmospheric coupling to the small-scale ocean in the modulation of latent heat flux. Front. Mar. Sci. 10:1136558. https://doi.org/10.3389/fmars.2023.1136558	https://doi.org/10.3389/fmars.2023.1136558
Peer-reviewed journal	LMD, GEOMAR, +NOAA	Fernandez, P., S. Speich, H. Bellenger, D. Lange Vega, J. Karstensen, D. Zhang, C. Rocha (2024). On the Mechanisms Driving Latent Heat Flux Variations in the Northwest Tropical Atlantic. J. Geophys. Res., 2024, 129 (5), https://doi.org/10.1029/2023JC020658	https://doi.org/10.1029/2023JC020658
Peer-reviewed journal	LMD	Bellenger, H., Bopp, L., Ethé, C., Ho, D., Duvel, J. P., Flavoni, S., et al. (2023). Sensitivity of the global ocean carbon sink to the ocean skin in a climate model. Journal of Geophysical Research: Oceans, 128, e2022JC019479. https://doi.org/10.1029/2022JC019479	https://doi.org/10.1029/2022JC019479
Peer-reviewed journal	MPI, GEOMAR	Hohenegger, C., Korn, et al.: ICON-Sapphire: simulating the components of the Earth system and their interactions at kilometer and subkilometer scales, Geosci. Model Dev., 16, 779–811, https://doi.org/10.5194/gmd-16-779-2023, 2023.	https://doi.org/10.5194/gmd-16-779-2023
Peer-reviewed journal	LMD+NOAA	Coadou-Chaventon, S., S. Speich, D. Zhang, C. Barbedo Rocha, S. Swart : Oceanic fronts driven by the Amazon freshwater plume and their thermohaline compensation at the submesoscale. Journal of Geophysical Research: Oceans, 129, e2024JC021326. https://doi.org/10.1029/2024JC021326, 2024.	https://doi.org/10.1029/2024JC021326
Peer-reviewed journal	LOCEAN, LMD, HEREON	Olivier, L., G. Reverdin, J. Boutin, R. Laxenaire, D. Iudicone, S. Pesant, Paulo H.R. Calil, J. Horstmann, D. Couet, J.M. Erta, P. Huber, H. Sarmento, A. Freire, A. Koch-Larrouy, J.-L. Vergely, P. Rousselot, S. Speich (2024). Late summer northwestward Amazon plume pathway under the action of the North Brazil Current rings, Remote Sensing of Environment, Volume 307, 114165, https://doi.org/10.1016/j.rse.2024.114165	https://doi.org/10.1016/j.rse.2024.114165
Peer-reviewed journal	LOPS, LMD	Boussidi, B.; Le Goff, C.; Galard, C.; Carton, X.; Speich, S. The Analysis of North Brazil Current Rings from Automatic Identification System Data and Altimetric Currents. Remote Sens. 2024, 16, 2828. https://doi.org/10.3390/rs16152828	https://doi.org/10.3390/rs16152828
Peer-reviewed journal	LEGOS	Larrañaga, Marco, Lionel Renault, and Julien Jouanno. "Partial control of the Gulf of Mexico dynamics by the current feedback to the atmosphere." Journal of Physical Oceanography 52.10 (2022): 2515-2530	https://doi.org/10.1175/JPO-D-21-0271.1

Type	Partners involved	Title and authors	DOI
Peer-reviewed journal	LEGOS, CNRM UNIMIB	Conejero, Carlos, et al. "Near-Surface Atmospheric Response to Meso-and Submesoscale Current and Thermal Feedbacks." Journal of Physical Oceanography 54.3 (2024): 823-848.	https://doi.org/10.1175/JPO-D-23-0211.1
Peer-reviewed journal	UNIMIB, LEGOS	Desbiolles, F., A. N. Meroni, L. Renault, C. Pasquero (2023) Environmental Control of wind response to sea surface temperature patterns in reanalysis dataset, J. Climate	https://doi.org/10.1175/JCLI-D-22-0373.1.
Peer-reviewed journal	UNIMIB	Meroni, A. N. , F. Desbiolles, C. Pasquero (2023) Satellite signature of the instantaneous wind response to mesoscale oceanic thermal structures, Quaternary Journal Royal Meteorological Society	https://doi.org/10.1002/qj.4561
Peer-reviewed journal	UNIMIB, CIMA	Tartaglione, N., F. Desbiolles, A. Del Moral-Méndez, A.N. Meroni, A. Napoli, M. Borgnino, A. Parodi, C. Pasquero (2024) Low cloud response to aerosol-radiation-cloud interactions: idealized WRF numerical experiments for EUREC4A project, Atmospheric Science Letters, Atmospheric Science Letters, e1208	https://doi.org/10.1002/asl.1208
Peer-reviewed journal	UNIMIB	M. Borgnino, F. Desbiolles, A.N. Meroni, C. Pasquero (2024) Lower tropospheric response to local sea surface temperature anomalies: a numerical study in the EUREC4A region, submitted	under review
Peer-reviewed journal	LOPS	Napolitano, D., X. Carton, & J. Gula, 2024 : Vertical interaction between NBC rings and its implications for South Atlantic Water export, J. Geophys. Res. Oceans, 129, e2023JC020741.	https: //doi.org/10.1029/2023JC020741
Peer-reviewed journal	LOPS, LMD	Napolitano, D., J. Gula, S. Coadou-Chaventon, S. Speich, J. C. McWilliams, C. B. Rocha, D. Zhang & X. Carton : Thermohaline gradients galore in the northwestern Tropical Atlantic, submitted	under review
Peer-reviewed journal	UiB, LMD	Tian, F., N. Keenlyside, I. Bethke, P. Fernández, S. Koseki, F. Li, 2024: Resolution-Dependent Sensitivity of Tropical Precipitation and Latent Heat Flux in the NorESM Model	In revision
Peer-reviewed journal	UiB	Koseki, S., R. Vázquez, W. Cabos, C. Gutiérrez, D. Sein, M.-L. Bachèrely, 2024: Dakar Niño under global warming investigated by a high-resolution regionally coupled model: Earth System Dynamics, accepted	in press
Peer-reviewed journal	MPI	von Storch, J.-S. and V. Lüschow, 2023: Wind power input to ocean near-inertial waves diagnosed from a 5-km global coupled atmosphere-ocean general circulation model. Journal of Geophysical Research: Oceans, 128, e2022JC019111.	https://doi.org/10.1029/2022JC019111
Peer-reviewed journal	HEREON (ex HZG)	Horstmann, J., J. Bödewadt, R. Carrasco, M. Cysewski, J. Seemann, and M. Streßer, A Coherent on Receive X-Band Marine Radar for Ocean Observations, Sensors, 21, 7828. https://doi.org/10.3390/s21237828, 2021.	https://doi.org/10.3390/s21237828
Dataset	HEREON (ex HZG)	Streßer, Michael; Carrasco, Ruben; Horstmann, Jochen; Karstensen, Johannes (2023): Radar-derived Friction Velocity along RV MARIA S. MERIAN cruise track MSM89 [dataset]. PANGAEA, https://doi.org/10.1594/PANGAEA.957096	https://doi.org/10.1594/PANGAEA.957096
Dataset	HEREON (ex HZG)	Carrasco, Ruben; Streßer, Michael; Horstmann, Jochen; Karstensen, Johannes (2023): Radar-derived Surface Current Fields along RV MARIA S. MERIAN cruise track MSM89 [dataset]. PANGAEA, https://doi.org/10.1594/PANGAEA.957162	, https://doi.org/10.1594/PANGAEA.957162
Dataset	LMD, LOPS	Speich S., X. Carton, G. Reverdin, P. Branellec, C. Le Bihan, R. Laxenaire, P. L'Hegaret, S. Leizour, P. Le Bot, C. Noisel, G. Manta, A. Meroni, A. Napoli, Y. Chen, S. Masson, A. Le Gal, L. Olivier (2021). CTD DATA - EUREC4A_OA Atalante Cruise. SEANOE. https://doi.org/10.17882/79096	https://doi.org/10.17882/79096

Type	Partners involved	Title and authors	DOI
Dataset	LMD, LOPS, GEOMAR	L'Hegaret P., S. Speich, J. Karstensen (2020). Concatenated Temperature, Salinity, and Velocity measurements from EUREC4A_OA/ATOMIC (CTD, uCTD, MVP and S-ADCP data from the R/Vs L'Atalante and Maria S. Merian). SEANOE. https://doi.org/10.17882/92071Branellec Pierre, Le Bihan Caroline, Speich Sabrina (2020). EUREC4A 2020. CTD-O2 Data report. ODE/LOPS/20-02. https://doi.org/10.13155/79038	https://doi.org/10.13155/79038
Dataset	LMD, LOPS, GEOMAR	L'Hégaret P., S. Speich, J. Karstensen (2020). uCTD Data 2nd QC- EUREC4A_OA/ATOMIC. SEANOE. https://doi.org/10.17882/91352	https://doi.org/10.17882/91352
Dataset	LMD, LOPS, GEOMAR	L'Hégaret P., S. Speich, J. Karstensen (2020). MVP Data 2nd QC-EUREC4A_OA/ATOMIC. SEANOE. https://doi.org/10.17882/91485	. https://doi.org/10.17882/91485
Dataset	LMD, LOPS	Branellec P., C. Le Bihan, S. Speich (2020). EUREC4A 2020. CTD-O2 Data report . ODE/LOPS/20-02 . https://doi.org/10.13155/79038	https://doi.org/10.13155/79038
Dataset	GEOMAR, LMD	Karstensen, Johannes et al. (2020): Physical oceanography (CTD) during Maria S. Merian cruise MSM60/1. PANGAEA, https://doi.org/10.1594/PANGAEA.915898	https://doi.org/10.1594/PANGAEA.915898

Valorization

- Participation to international conferences:
  More than 80 presentations by the JPI Ocean & Climate EUREC⁴A-OA project members.
- Sessions organized:
  EGU2024 (14.-19.04,2024) OS1.8: Observing and modelling the imprint of meso- and submesoscale dynamics, convenor: Fehmi Dilmahamod, Dongxiao Zhang, Pablo Fernández, Fangxing Tian
- Social media: twitter/X: @eurec4a
- Web-site: http://eurec4a-oa.eu

Impact

- **Contributions to regulations, policies and management practices**:
  - We are contributing in developing and improving ocean and air-sea observation practices thanks to the multi-ship and multi-platform EUREC4A-OA field experiment.
- **Innovation (Intellectual property rights, prototypes, testing activities resulting from the project):**
  - OCARINA-PICCOLO air-sea fluxes prototypes of buoys have been tested during the EUREC4A-OA field experiment and further developed for longer open-ocean studies (their deployment during the research cruise was the first carried out ever).
- **Interlinkages with other JPI Oceans and/or JPI Climate projects**
  - We have been invited to participate to General Meetings of the other JPI Ocean and Climate funded projects but due to the pandemic, the interactions have been relatively limited for now. However, we have provided important input on some other international projects (such as PIRATA, the H2020 EU TRIATLAS project).

- **Training**

Post-graduate courses organized:

We have been organizing a Summer School on Ocean Small Scale air-sea interactions in collaboration with CLIVAR and the First Institute of Oceanography in Quijndao, China, that will take place this Summer (August 2022).

EUREC^{4}A_OA Master's theses (funded by JPI Ocean & Climate or supported by in-kind contributions):

Student name	Partners involved	Title of the Master thesis	Source of funding	Year of defense
Corentin Subirade	LMD, LOPS	Surface and subsurface eddies in the Northwest tropical Atlantic and their role in the large scale ocean circulation	Project H2020 TRIATLAS	2022
Jérémie Lambert	LMD, LOPS	Study of the small-scale ocean dynamics in the Northwest Tropical Atlantic as simulated by very high-resolution numerical simulations	CNES	2022
Nicolas Michalezyk	LMD	Developing a detection method and assessments of subsurface ocean mesoscale eddies	CNES	2022
David Wai Quan Chin	LMD, UCT	Characterizing the Vertical Structure of the mesoscale eddies	CNES	2024
Armand Vic	LOPS	interaction of vortices under wind forcing	ENS Rennes	2020
Loic Eisenring	LOPS	dynamics of submesoscale eddies in Demerara Bay	CNES	2021
Marin Menard	LOPS	interaction of the Amazon plume with NBC rings	CNES	2021
Corentin Galard	LOPS. LMD, EoDyn	Use of AIS for the determination of surface currents north of Brazil	CNES	2022
Vincent Mokuenko	LOPS	Study of deep eddy interaction with topography	CNES	2024
Daniel Rudloff	GEOMAR, LMD	Observations of Vertical Propagation of Near Inertial Waves in a Complex Vorticity Field	GEOMAR	2021
Alessandro Storer	UNIMIB	Study of air-sea coupling in numerical simulations of the EUREC4A region	Italian MUR	2024

EUREC⁴A-OA postdoctoral studies (funded by JPI Ocean & Climate or supported by in-kind contributions):

Researcher name	Partners involved	Title of the study	Funding
Pierre L'Hégaret	LMD, LOPS, GEOMAR	Characterizing and quantifying the small-scale (0.1 - 100 km) variability and dynamics in the upper layers of the ocean using in-situ data	JPI Ocean & Climate
Dante Napolitano	LOPS	Meso- and submesoscale processes in the western tropical Atlantic	JPI Ocean & Climate and Région Bretagne
Carlos Conejero	LEGOS, CNRM	Near-Surface Atmospheric Response to Meso-and Submesoscale Current and Thermal Feedbacks.	JPI Ocean & Climate
Florian Schütte	GEOMAR, MPI	Analysis of diurnal cycles in Eurec4A observations and representation in ICOS model	JPI Ocean & Climate
Fehmi Dilmahamod	GEOMAR, HEREON, LMD	Observing design for submesoscale experiments (follow up on the Eurec4A experiments)	JPI Ocean & Climate GEOMAR
Rémi Laxenaire	LMD	Development of new metrics to assess the ocean small-scale (0.1 - 100 km) variability and dynamics in the upper layers of the ocean from in-situ, satellite and simulated data	CNES
Artemis Ioannou	LMD	Assessing the structure and role of ocean mesoscale dynamics	H2020 TRIATLAS
Matteo Borgnino	UNIMIB	Effects of small scale ocean structures on marine boundary layer clouds	JPI Ocean & Climate
Agostino Meroni	UNIMIB	Global and Local Atmospheric response to the Underlying Coupled Ocean	ESA and JPI Ocean & Climate
Michael Streβer	HEREON (ex HZG)	Marine Radar Measurements to Estimate Air-Sea CO2 Exchange	JPI Ocean & Climate
Fangxing Tian	UiB	Role of model resolution in representation of ocean-atmosphere interaction	JPI Ocean & Climate and EU H2020 NextGEMS

EUREC[4]A-OA PhD's theses (funded by JPI Ocean & Climate or supported by in-kind contributions):

Student name	Partners involved	Title of the PhD thesis	Source of funding	Year of defense
Pablo Fernandez	LMD, UNIMIB, LEGOS	Assessing the role of small-scale ocean dynamics on air-sea interactions taking advantage of the unprecedented observational and modelling EUREC[4]A-OA efforts in the northwest Tropical Atlantic ocean.	French Ministry of Research	2024
Yann Barabinot	LMD, LOPS	Characterizing the nature and general properties of ocean eddies	ENS-Paris Saclay	2025
Solange Coadou	LMD, LOPS	The role of small-scale ocean processes in the uptake of heat and carbon in a changing climate	ENS-Paris	2025
Léa Olivier	LOCEAN, LMD	Role of the ocean mesoscale dynamics in the tropical Atlantic Ocean on salinity and air-sea CO_2 fluxes	French Ministry of Research	2023
Armand Vic	LOPS	Vortex Océaniques Couplés avec l'Atmosphère a Meso Echelle (VOCA ME) / oceanic vortices coupled with the atmosphere at mesoscale.	ENS Rennes	2024
Ashwita Chouksey	LOPS	Long-lived deep coherent vortices in the Atlantic Ocean	ANR	2023
Fabius Cedric Kouogang Tchuenkam	Federal University of Pernambuco, LEGOS, LOPS	Internal tides interactions with eddies and currents off the Amazon shelf.	FUP	2027
Lorenzo Francesco Davoli	UNIMIB, U Delft	A Sub-mesoscale Study of Shallow Convective Circulation and Trade-cumuli in the North-West Atlantic Tropical Region	Italian Ministry of Research	2026
Niccolò Losi	UNIMIB	Three-dimensional study of the atmospheric heating rate from Equator to the Arctic	Italian Ministry of Research	2024

EUREC4A-OA Major Results (long version)

EUREC4A-OA explored the intricate interplay between ocean fine-scale structures and air-sea heat fluxes in the Northwest Tropical Atlantic, leveraging a comprehensive suite of satellite observations, in-situ measurements from a large international field campaign, reanalysis products, and high-resolution coupled simulations. The study revealed that the region's distinctive circulation—dominated by the North Brazil Current and associated mesoscale eddies—induces the formation of sharp temperature and salinity fronts. These submesoscale structures profoundly influence surface latent heat fluxes by modulating sea surface temperatures and altering near-surface atmospheric dynamics. By developing a linear SST-based latent heat flux (LHF) downscaling algorithm, **EUREC4A-OA** demonstrated that incorporating these fine-scale features can increase LHF estimates by up to 33% per °C, primarily due to dynamic contributions such as wind speed variations and specific humidity anomalies (Fernandez et al., 2024).

The project also emphasized the spatial heterogeneity in air-sea interactions, with stronger coupling observed near the South American coast compared to open-ocean regions. In areas impacted by the Amazon River plume, distinct water masses and surface salinity gradients further modulate latent heat exchanges, contributing to localized yet significant heat flux patterns (Fernandez et al., 2024). Moreover, the study provided robust evidence that ocean currents at these fine scales have a substantial influence on the low-level wind field and the exchange of heat and momentum between the ocean and atmosphere. Unlike mesoscale processes, submesoscale current feedback (CFB) induces wind stress convergence and divergence, leading to vertical motions that significantly impact the atmospheric boundary layer (Conejero et al., 2024).

EUREC4A-OA findings also underscored the sensitivity of low clouds to fine-scale sea surface temperature variations. Observations showed that over cold patches, increased atmospheric stability decouples the boundary layer from the free troposphere, limiting moisture transport into the cloud layer and resulting in thinner and sparser low clouds. These dynamics were analyzed using the **EUREC4A-OA** observational datasets (Acquistapace et al., 2022) and further explored through targeted modeling experiments (Borgnino et al., 2024).

EUREC4A-OA advanced our understanding of air-sea CO2 fluxes in the Northwest Tropical Atlantic, highlighting the critical role of resolving mesoscale and submesoscale features for accurate flux estimations. During the **EUREC4A-OA** /ATOMIC field experiment in early 2020, a unique dataset of fCO2 measurements collected by three research vessels captured the influence of various water masses, including slightly oversaturated salty waters from the North Brazil Current and highly undersaturated freshwater from the Amazon plume. These observations, combined with satellite-derived surface salinity and temperature data, indicated a substantial oceanic CO2 sink of -1.7 TgC/month—significantly higher than estimates from existing climatological products. This sink was primarily driven by the dynamic transport of Amazon freshwater and unexpectedly low fCO2 levels in the northeastern subtropical waters (Olivier et al., 2022).

Furthermore, the project introduced a novel offline data assimilation approach for parameter estimation, enabling the identification of key sources of model bias in low-level cloud and boundary layer processes within the widely used CLUBB scheme. Sensitivity experiments revealed that low-level cloud cover is particularly responsive to two parameters related to the skewness of updrafts, highlighting areas for targeted improvement. This methodology offers a powerful tool for accelerating model refinement, paving the way for the development of more accurate global climate models.

Overall, **EUREC4A-OA** findings provide a significant leap forward in our understanding of fine-scale air-sea interactions and their representation in climate models, setting a new benchmark for parameterizing heat and CO2 fluxes in the context of global climate modeling.

EUREC^{4}A-OA Major Results (short version)

EUREC^{4}A-OA has significantly advanced our understanding of fine-scale ocean dynamics and air-sea interactions in the Northwest Tropical Atlantic. The project highlighted how ocean currents and the distinct circulation patterns—driven by the North Brazil Current and Amazon River plume—create temperature and salinity fronts that modulate surface heat fluxes, wind dynamics, and low cloud formation. By integrating these features into a new latent heat flux downscaling algorithm, **EUREC^{4}A-OA** demonstrated that fine-scale structures can increase heat flux estimates by up to 33% per °C.

Leveraging a unique combination of high-resolution coupled models, satellite observations, and extensive in-situ measurements collected during the **EUREC^{4}A-OA** field campaign, the study provided the first detailed assessment of CO2 fluxes in the region, revealing a substantial oceanic CO2 sink (-1.7 TgC/month) linked to the dynamic transport of Amazon freshwater and low CO2 level in the northeastern subtropical Atlantic.

Moreover, **EUREC^{4}A-OA** introduced a novel framework to identify biases in cloud and boundary layer models using a hierarchy of numerical simulations, setting a new benchmark for representing fine-scale processes in climate models and significantly enhancing the accuracy of global heat and CO2 flux estimates.

Annex I: Identification of project participants/beneficiaries

ENS-LMD (Ecole Normale Supérieure, Laboratoire de Météorologie Dynamique, Paris, France)

1. Prof. Sabrina Speich, (project coordinator)
2. Dr. Guillaume Lapeyre
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5. Dr. Pierre L'Hégaret (postdoctoral fellow)
6. Mr Pablo Fernandez (PhD student)
7. Mr Corentin Subirade (Engineer)
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9. Mrs Solange Coadou (Master Internship)
10. Mr Yann Barabinot (Master Internship)

CNRS-LEGOS (CNRS, Laboratoire d'études Géophysiques et Océanographie Spatiale, IRD, Toulouse, France)

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CNRS-LOCEAN (CNRS, Laboratoire d'océanographie et du climat : expérimentations et approches numériques, Paris, France)

15. Dr. Gilles Reverdin
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CNRS-CNRM (CNRS, Centre national de recherches météorologiques, Toulouse, France)

19. Dr. Hervé Giordani
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UBO-LOPS (Université de Bretagne Occidentale, Laboratoire d'Océanographie Physique et Spatiale)

21. Prof. Jonathan Gula
22. Prof. Xavier Carton
23. Mr Dante Napolitano (postdoctoral fellow)
24. Mrs Ophélie Lenoble (Master internship)
25. Mrs Giulia Zerbini (Master internship)
26. Mr Marin Menard (Master internship)
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GEOMAR (GEOMAR Helmholtz Centre for Ocean Research, Kiel, Germany)

28. Dr. Johannes Karstensen
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30. Dr. Fehmi Dilmahamod (postdoctoral fellow)
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MPI (Max Plank Institute of Meteorology, Hambourg, Germany)

33. Prof. Jin-Song von Storch
34. Dr. Peter Landschuster
35. Dr. Florian Schütte (postdoctoral fellow)

HEREON (ex **HZG**: Helmholtz-Zentrum Geesthacht Zentrum für Material- und Küstenforschung GmbH, Fermany)

36. Dr Jochen Hortsmann
37. Dr Michael Streβer (postdoctoral fellow)

CIMA (Centro Internazionale In Monitoraggio Ambientale, Genova, Italy)

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47. Mr. Andrea Polesello (Master internship)
48. Mr. Matteo Di Leandro (Master internship)
49. Mr. Alessandro Storer (Master internship)
50. Mr. Lorenzo F. Davoli (PhD student)
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