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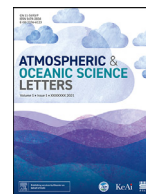
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# Comparison of ERA5 turbulent fluxes at the air–sea interface with measurements from a wave-following platform

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## ABSTRACT

Turbulent fluxes at the air–sea interface were estimated with data collected in 2011–2020 with a low-profile platform named OCARINA during eight experiments in five regions: 2011, 2015, and 2016 in the Iroise Sea; 2012 in the tropical Atlantic; 2014 in the Chile–Peru upwelling; 2017 and 2018 in the Mediterranean Sea, and 2018 and 2020 in Barbados. The observations were carried out with moderate winds ( $2\text{--}10\text{ m s}^{-1}$ ) and average wave heights of 1.5 m. In this study, the authors used the fluxes calculated by the bulk method using OCARINA-sampled data as the input. These data can validate the fluxes estimated from ERA5 reanalysis data. The OCARINA and ERA5 data were taken concomitantly. To do this, the authors established an algorithm to extract the OCARINA data as closely as possible to the reanalysis data in time and position. The measurements of the OCARINA platform can conclude on the relevance of the widely used reanalysis data.

## 1. Introduction

The challenge of scientific observation of the oceans is immense owing to the complexity of spatial and temporal scales. Nevertheless, our knowledge of the ocean has progressed in recent years thanks to increasingly sophisticated measurement methods and satellite observation techniques (Tavakoli et al., 2023). The reliability of our real ocean simulation models has improved considerably, further favored by the exponential increase in the performance of computational resources. Assimilation methods have made it possible to correct defects in models using observations.

The aerodynamics and size of measurement platforms influence the precision of the flow estimates collected. Thus, the latter can differ depending on whether measurements are carried out by buoy or on board an 80-m-long oceanographic vessel.

There are different types of platforms used for taking measurements: fixed platforms, platforms towed behind a boat (Edson et al., 1998), and floating platforms (Anctil et al., 1994; Weller et al., 2012; Graber et al., 2000). Some measurements are even carried out directly on large research vessels using an instrumented mast (Katsaros et al., 1993; Christensen et al., 2013). These different platforms each have their strengths. Research vessels equipped with an instrumented flux mast can collect good quality data for the estimation of air–sea tur-

bulent fluxes. This is the method most currently used to study ocean–atmosphere exchanges.

Satellite, model, and ship data used in the work of Weill et al. (2003) showed that mesoscale ocean–atmosphere turbulent exchanges are not fully interpretable based on data from the ECMWF’s model.

In order to increase the quantity and quality of in situ ocean data, buoys are essential. They allow, depending on the model used, for precise parameters (e.g., temperature, salinity) to be recorded. Recent work by Mounet et al. (2023) showed that the data collected by buoys can be used to calibrate and validate data from satellites or those from observation ships. One of the best-known buoys dedicated to measuring turbulent fluxes at the ocean–atmosphere interface is the ASIS (Air–Sea Interaction Spar) buoy developed at the Rosenstiel School of Marine and Atmospheric Science (Graber et al., 2000).

Flow parameterization is a physical model based on theories (Kolmogorov, 1941; Monin and Obukhov, 1954). Note, however, that these theories involve empirical relationships, the determination of which involves taking measurements at sea. The experimental estimation of these relationships remains a challenge owing to the difficulty in obtaining reliable measurements at sea in all types of conditions.

Fluxes can be estimated by different independent methods, the results of which are not always consistent, depending on environmental

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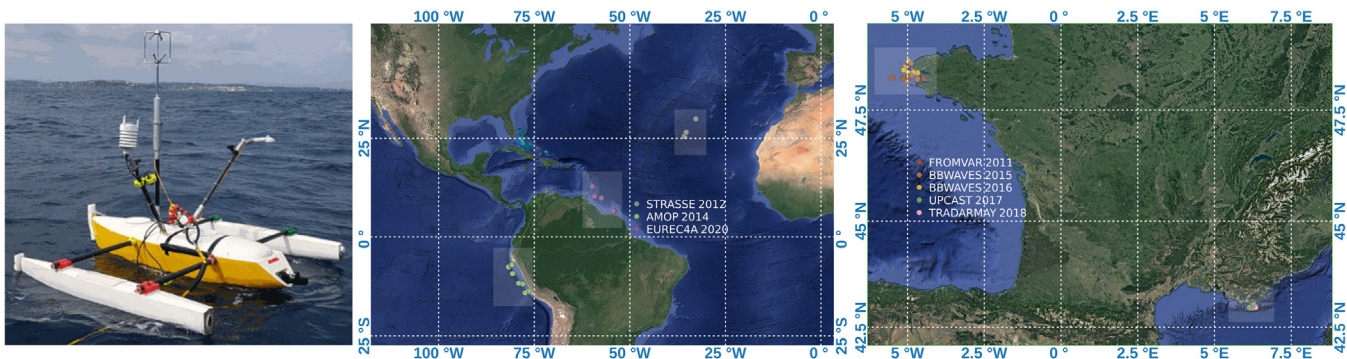


Fig. 1. Photo of OCARINA, along with its locations and years of deployment during eight campaigns at sea.

conditions. Thus, the parameterizations that we adjust to the data collected are not as universal as we would like. For example, the relationship between surface flux and sea state is an open question, particularly for momentum flux. Existing parameterizations do not completely converge.

It was in an attempt to answer these different questions that a new measurement platform called OCARINA (Ocean Coupled with the Atmosphere: Instrumental Research on Annex Ship; Fig. 1), designed by LATMOS (Atmospheres, Space Observations Laboratory, France) was developed (Bourras et al., 2014, 2019). This facility allows us to remedy a large number of defects in existing platforms and it brings several improvements—for example, by reducing the impact of aerodynamic distortion to the point that the use of correction functions is now unnecessary. The platform was designed to follow the movement of the surface as closely as possible and provides us with measurements of atmospheric turbulence at a height of 1.5 m, which allows us to precisely study not only the turbulent fluxes at the interface, but also the relationships on a small scale between wind and vertical movements of the surface.

To increase the number of measurements at sea and participate in a greater number of campaigns, OCARINA was designed to be easily transportable and sufficiently versatile to be adaptable to most research vessels, with the same instrument configuration, the same position, and the same spacing between them, to ensure a common basis in the measurements and thus facilitate data comparisons between different campaigns.

The platform, consisting of a small trimaran (Fig. 1), instrumented for measurements of turbulence near the surface, was designed to be repeatedly deployed in the open sea from a ship (research vessel in particular) and left in autonomous operation for around 10 h at a distance from the host ship. Bourras et al. (2014) validated the very first flow estimates from a time-limited dataset, obtained during the FROMVAR campaign in the Iroise Sea in 2011. Following the good performances observed, OCARINA was proposed and selected to participate in various oceanographic projects and campaigns and provide precise data for the estimation of energy balances at the air–sea interface.

The trimaran shape was specifically chosen to significantly reduce rolling movements compared to a monohull type design. In addition, this configuration allows all the load to be gathered in the central float. However, like any trimaran, OCARINA tends to have small precession movements, but these do not influence the measurements, at the frequencies we use.

OCARINA typically drifts 10 km during 10 h of operation, in winds of  $\sim 5 \text{ m s}^{-1}$ . Despite the lightness of the platform and its small dimensions, OCARINA carries a complete set of instruments allowing the estimation of turbulent fluxes at the ocean–atmosphere interface. The acquisition system samples data from the mast instruments at a frequency of 50 Hz.

The aerodynamic distortion of the platform has been evaluated by numerical simulations. In the most unfavorable situation, when the wind

cuts across the platform, the vertical distortion at the highest point of the platform, at 1.5 m, is around  $3^\circ$ . This is half as much as on a research vessel 50–80 m long, where the vertical distortion of the wind is  $7^\circ$ – $10^\circ$  when the wind comes from the front (Bourras et al., 2009). For OCARINA, when the wind comes from another direction, the distortion is less than  $3^\circ$ , which is again better than on a research vessel, where the minimum value found is  $6^\circ$  (Atalante, for example). On research vessels, distortion increases with the relative angle between the boat’s axis and the wind direction, to the point that when the angle is greater than about  $40^\circ$ , the data are no longer used. In practice, it was found on FROMVAR 2011 that the distortion angles are even lower than in the simulations, with an average angle of  $1.27^\circ$ . It is therefore not necessary to apply distortion correction to the data from the OCARINA platform; the distortion does not need to be corrected.

The work presented in this paper concerns the study of turbulent fluxes at the ocean–atmosphere interface based on data collected by the OCARINA platform during eight cruises at sea, in five regions: 2011, 2015, and 2016 in the Iroise Sea; 2012 in the tropical Atlantic; 2014 in the Chile–Peru upwelling; 2017 and 2018 in the Mediterranean Sea; and 2018 and 2020 in Barbados (Fig. 1). These data were used to validate the parameters of the fifth major global reanalysis produced by ECMWF (ERA5; Hersbach et al., 2020). We chose this product, in particular, for its reliability mentioned in several works (Slocum et al., 2022; Kondylia et al., 2022; Truong et al., 2022; Giovanni, 2021).

In the following section, we present the data and methods used to perform our OCARINA–ERA5 comparisons. Then, in section 3, we discuss the results obtained, before ending the paper with our conclusions.

## 2. Data and methods

To calculate turbulent fluxes at the ocean–atmosphere interface from data recorded by the OCARINA platform, we used four different methods (Bourras et al., 2019), each involving a specific part of the wind power spectrum and sonic temperature: the eddy-correlation method, the inertio-dissipative method, the bulk method, and the profiles method. However, in order to streamline the presentation of our findings in this paper, we chose to focus on comparing OCARINA and ERA5 by using parameters from the bulk method (Fairall et al., 2003), which is a direct application of Monin–Obukhov similarity theory (Monin and Obukhov, 1954). This method is widely used in oceanographic and atmospheric models because it involves only average quantities, as compared to the turbulent quantities on which the inertio-dissipative and eddy-correlation methods are based.

The ERA5 data used were the air temperature at 2 m above the sea surface and at the surface of the sea, the temperature of the sea near the surface, the “neutral wind”, and the friction velocity. We gathered hourly ERA5 data that covered the OCARINA data in date-time and latitude/longitude. The study areas are visible on the maps in Fig. 1, and the date-times for the different campaigns are given in Table 1.

**Table 1** Date times (local time) of different campaigns. For the dates, we indicate the month-day of the start and that of the end.

Campaign	2011	2012	2014	2015	2016	2017	2018	2020
Dates	12 Sep. 15 Sep.	27 Aug. 10 Sep.	27 Jan. 19 Feb.	22 Oct. 27 Oct.	21 Oct. 27 Oct.	13 Sep. 14 Sep.	6 May 9 May	25 Jan. 17 Feb.
Start time	7 a.m.	12 a.m.	12 a.m.	8 a.m.	6 a.m.	8 a.m.	10 a.m.	10 a.m.
End time	5 p.m.	11 p.m.	11 p.m.	4 p.m.	2 p.m.	12 p.m.	3 p.m.	9 p.m.

In practice, we retrieved the ERA5 fields at a 1-h resolution for each year, and we wrote an algorithm that allowed us to extract the OCARINA data at close to the reanalysis data in time and position ( $0.25^\circ \times 0.25^\circ$  latitude/longitude grid). We proceeded in two steps: first, we searched for the ERA5 data closest in time to within  $\pm 30$  min of each available piece of OCARINA data, which required preparing sequences of ranges using the algorithm, i.e., date-times corresponding to each measurement campaign. Then, we searched for the data of the ERA5 pixel closest to OCARINA in latitude/longitude. More precisely, we calculated the distance in kilometers from each piece of OCARINA data to each ERA5 pixel using the radius of the Earth to make the conversion (Eq. (1)), and then required from the code a minimum distance among those found for each iteration of calculation—a distance that allowed us to have the best quality of comparison.

For latitude  $\varphi$  and longitude  $\lambda$ , we calculated the distance as follows:

$$x = \frac{\lambda}{360} 2\pi R \cos(\varphi), \quad y = \frac{\varphi}{360} 2\pi R, \quad d = \sqrt{(\Delta x)^2 + (\Delta y)^2}, \quad (1)$$

Then, we integrated Louis' parameterization into the comparison code to calculate the drag coefficient at each time step. The direct method of Louis (1979) aims to calculate the exchange coefficients from atmospheric mean fields via the calculation of a Richardson coefficient  $Ri$  and a roughness length (Eq. (6)). It is a method that limits the calculation cost. Louis' parameterization is a direct analytical method (Louis, 1979), approximating fluxes and requiring no iterative means. It therefore appears faster in many cases and particularly in stable situations. In this approach,

$$C_D = C_{D10n} F_D^2, \quad (2)$$

where  $F_D$  is the stability functions of Louis. The neutral coefficient at 10 m,  $C_{D10n}$ , is expressed as a function of the roughness.

$$\sqrt{C_{D10n}} = \frac{k}{\ln\left(1 + \frac{z}{z_0}\right)}, \quad (3)$$

where  $k$  is the Von Kármán constant, considered to be universal ( $k \approx 0.40$ ).  $z$  is the measurement altitude, generally corresponding to the first level of the model or 10 m. The  $z_0$ , the dynamic roughness length, is calculated from the Charnock relation (Charnock, 1955):

$$z_0 = 0.015 \frac{u_*^2}{g}. \quad (4)$$

The drag coefficient is generally represented by its neutral value at 10 m,  $C_{D10n}$ , defined thus to refer to similar conditions for all the flow measurements carried out by bringing them back to neutral stability conditions and to a standard altitude of 10 m.  $u_*$  is friction velocity and  $g$  is the gravitational acceleration.

$$F_D(Ri, z, z_0) = \begin{cases} \left( A - \frac{b_D Ri}{1 + c_D \sqrt{-Ri}} \right)^{\frac{1}{2}} & \text{for } Ri \leq 0 \\ \left( \frac{A}{1 + b'_D \frac{Ri}{\sqrt{1 + c'_D Ri}}} \right)^{\frac{1}{2}} & \text{for } Ri \geq 0 \end{cases}. \quad (5)$$

$Ri$  is a dimensionless parameter indicating the stability of the atmosphere. When  $Ri > 0$ , the atmosphere is thermodynamically stable; when  $Ri < 0$ , it is unstable; and when  $Ri = 0$ , the surface boundary layer is neutral.  $Ri$  is given by

$$Ri = \frac{\beta g(TA - SST)z}{U^2}, \quad (6)$$

where  $\beta$  is the thermal expansion coefficient ( $= 3.67 \times 10^{-3} / ^\circ\text{C}$ ),  $SST$  is the sea surface temperature,  $TA$  is the air temperature,  $U$  is the modulus of the horizontal mean wind vector (relative to the surface).

The values of the coefficients  $A$ ,  $b_D$ ,  $b'_D$ ,  $c_D$ , and  $c'_D$  (Giordani et al., 1996) are given by

$$\begin{cases} A = 1, \quad b_D = b'_D = 10, \quad c'_D = 5, \quad c_D = b_D C_{D10n} CM^* \left( \frac{z}{z_0} \right)^{PM} \\ CM^* = 6.8741 + 2.6933 \ln\left(\frac{z_0}{z_{0t}}\right) - 0.3601 \ln\left(\frac{z_0}{z_{0t}}\right)^2 + 0.0154 \ln\left(\frac{z_0}{z_{0t}}\right)^3 \\ PM = 0.5233 - 0.0815 \ln\left(\frac{z_0}{z_{0t}}\right) + 0.0135 \ln\left(\frac{z_0}{z_{0t}}\right)^2 - 0.0010 \ln\left(\frac{z_0}{z_{0t}}\right)^3 \end{cases}, \quad (7)$$

where  $z_{0t}$  denotes the thermal roughness lengths, substantially equal to  $z_0$ .

### 3. Results and discussion

Fig. 2 compares ERA5 and OCARINA for the five most significant campaigns in terms of data density. The correlations between the two datasets are good for the wind and the drag coefficient calculated by the Louis method, as well as for the SST minus TA (SST-TA), except for the 2014 campaign. However, overall we found that the two datasets are consistent.

The average wind reduced to neutral stratification conditions at 10 m,  $u_{10n}$ , was used to calculate the Richardson number and the roughness lengths used in the Louis parameterization, which were calculated using the friction velocities  $u_*$ . The SST-TA values were used at each time step to calculate the drag coefficient, which characterizes the transfer of momentum between the ocean surface and the atmosphere. Fig. 2(d) shows a good correlation between the ERA5 and OCARINA data. The average of the median  $CD$  values calculated for each campaigns is  $1.218 \times 10^{-3}$  for OCARINA and  $1.167 \times 10^{-3}$  for ERA5, which are very close in value and not far from the value usually used:  $1.2 \times 10^{-3}$  (Bourras et al., 2019).

If we take into account the surface current, the results from OCARINA and ERA5 will be close and the comparisons will therefore be good. Currents play a significant role in air-sea exchanges. The Research Activities Dedicated to the Eastern Pacific Oxygen Minimum (AMOP) 2014 campaign took place in the Pacific Ocean, off the coast of Peru (Fig. 1). The weather conditions were quite mild during this campaign. Note also the existence in this area of the Humboldt current or Peru current, which is a surface marine current running through the Pacific Ocean. Originating near Antarctica, it is cold—about  $7^\circ\text{C}$  to  $8^\circ\text{C}$  lower than the average sea temperature at the same latitude—and runs along the coasts of Chile and Peru. The AMOP 2014 campaign was an at-sea research campaign whose aim was to study one of the main oxygen-minimum zones in the ocean, which is located off the coast of Peru. One of the consequences of global warming is a reduction in the oxygen content of the oceans. There are areas in the ocean where deoxygenation

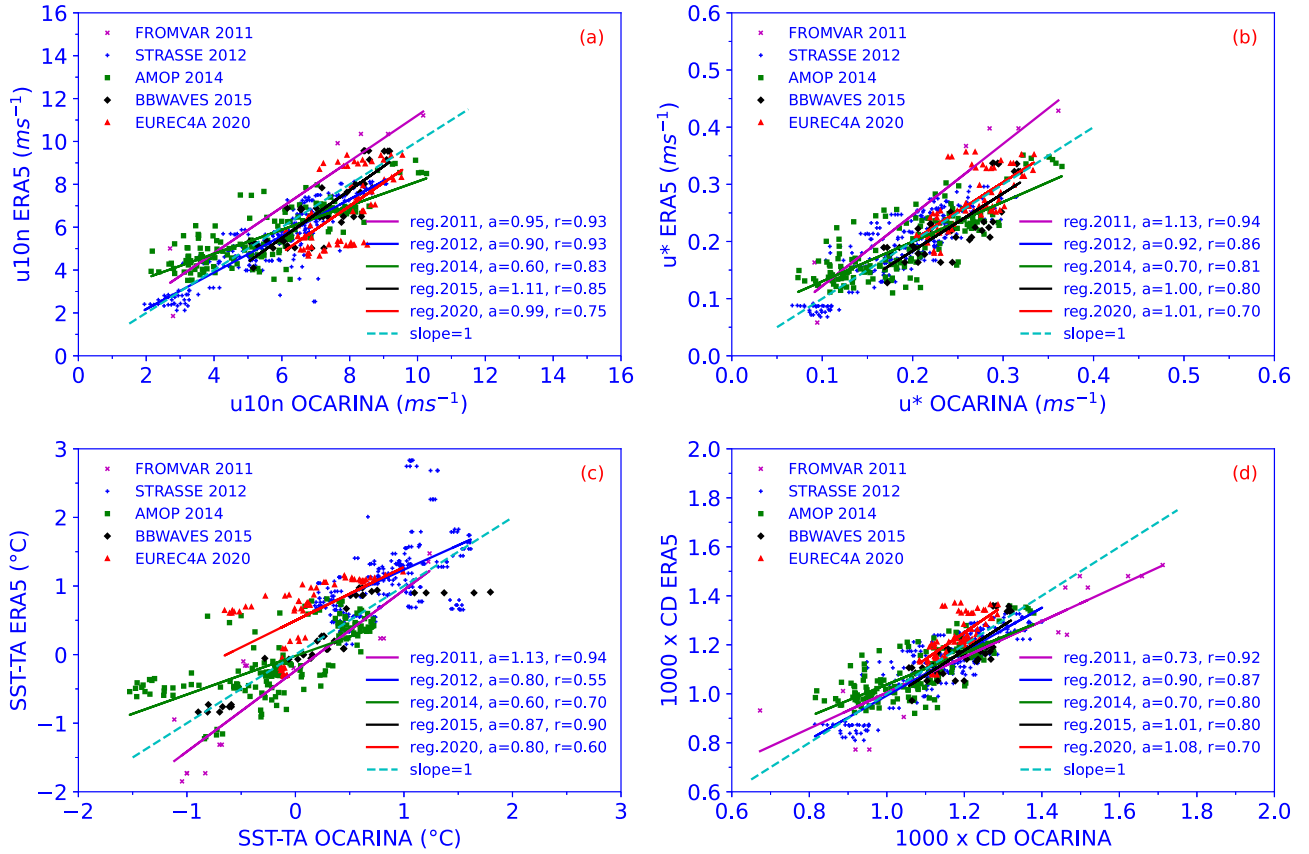


Fig. 2. OCARINA-ERA5 comparisons: (a) neutral wind speed at 10 m (units:  $m s^{-1}$ ); (b) friction speed (units:  $m s^{-1}$ ); (c) SST minus air temperature (units:  $^{\circ}C$ ); (d) drag coefficient. The solid lines are the regression lines with slope  $a$  and  $r$  corresponding correlations. The dashed line represents the perfect correspondence line; slope = 1.

is even more significant, and where the oxygen level is close to zero, and these are called “oxygen-minimum zones”. Climate change induces a warming of waters, which reduces the solubility of oxygen in water and modifies the stratification and ocean circulation, in turn reducing the supply of oxygen within the ocean.

The drift speed and the route followed by OCARINA depend on ocean surface currents and wind speed. The measurement of ocean surface currents is not accessible to us because the platform is not equipped with sensors to obtain these data, so we assume it to be zero. Despite the extensive integration of the instruments on board OCARINA, we cannot consider the set of instruments used either as definitive or exhaustive. We are currently developing an instrument for measuring surface currents. Note also that the ERA5 data do not take the surface current into account in the estimation of the different speeds.

The values do not move away from slope 1, but poorer correlations (0.70 and 0.55) are observed for SST-TA, which represents the thermal stability of the surface boundary layer. Note that along certain coastlines, the sea temperature exceeds the air temperature at 1 m, and therefore the atmosphere is thermally unstable. We tried to find an explanation for the differences in SST-TA between ERA5 and OCARINA, from a physical point of view and also in terms of the ERA5 data. This discrepancy of SST-TA, which is not entirely obvious for certain campaigns, in particular that of 2014, may come from the fact that OCARINA measures the air temperature at 1 m above the surface while ERA5 gives this same parameter at 2 m.

In ERA5, SST is a basic parameter, which means that there are no variations due to the daily cycle of the sun (diurnal variations). The SST in ERA5 is provided by two external providers. From September

2007, the OSTIA (Operational Sea Surface Temperature and Ice Analysis) dataset has been used, which is an optimal multi-scale interpolation designed for applications in numerical weather prediction and ocean forecast systems (Donlon et al., 2012).

SST remains a vital component of the climate system because it exerts a major influence on the exchange of energy, momentum and gases between the ocean and the atmosphere. Its spatial distribution reflects the underlying ocean dynamics, being structured not only by ocean fronts, eddies, and the rise to the surface of deep cold waters along certain oceanic coastlines, but also by the exchanges between the coastal shelf and the ocean. Many studies have analyzed the relationship between SST and certain climate events by using ERA5 SST products, which, according to Yao et al. (2021), are not entirely satisfactory.

For OCARINA, the SST taken into account is the “skin” SST, estimated from the SST measured at 15 cm below the surface and reduced to the surface temperature of the first micrometers below the ocean surface, taking into account exchanges with the atmosphere. To go from the SST measured by OCARINA to the “skin” SST, we used the model provided in the COARE3.0 algorithm (Fairall et al., 2003). Indeed, the COARE3.0 algorithm includes a “skin” temperature calculation model, based on a “bulk” temperature. The “skin” SST is generally a few tenths of a degree lower than the SST at 15 cm below the surface, in particular because of heat losses due to sensible (positive, unstable case) and latent heat fluxes. The “skin” SST is  $0.3^{\circ}C$  lower than the SST at 15 cm depth.

Terrain differences could be part of the problem, as the coast is actually the boundary of the ERA5 SST data. This is resolved to a point with remapping. The coarser resolution of the ERA5 data may lead to discrepancies with our dense measurements because ERA5 might “lose”

the temperature information between grid points (which we can measure with the OCARINA platform), which represents a great advantage of our wave-tracking platform. Additionally, how this parameter is considered for the ERA5 dataset may result in some differences (Truong et al., 2022). In order to have grid points as close as possible, a bilinear remapping allowed us to avoid possible missing values over the sea and to make the two datasets “comparable”, in particular for the coastal campaign in 2014.

The coarse grid of ERA5 ( $0.25^\circ \times 0.25^\circ$ ) did not allow us a very good comparison for the campaigns near the coasts. In fact, the SSTs are given with a mask, which refers to the continental part of our study area. Therefore, for certain cases that can extend offshore, certain values above the sea are therefore omitted, which led us to refine this grid and make interpolations of the missing values in order to continue our comparison. The data from the OCARINA platform do not have the same spatial and temporal resolution as the ERA5 data, and the longitudinal movements of OCARINA are as dense as the latitudinal movements (Fig. 1). This is why we wrote a code that allows us to choose the most concomitant points of comparison possible by imposing a time difference of 30 min.

In summary, the analyses presented in this section show that the OCARINA data obtained during the various measurement campaigns are of sufficient quality to estimate and study turbulent fluxes at the ocean-atmosphere interface.

#### 4. Conclusion

This study sought to validate ERA5 data using measurements carried out by a wave-following platform, OCARINA, which has a fairly complete set of instruments for measuring and estimating the turbulent fluxes at the air-sea interface. By design, it is not sensitive to the aerodynamic distortion of airflow, and its measurements do not require distortion corrections.

The principle of this comparison, of the coefficients of turbulent exchanges, temperatures and winds, is based on the search for concomitant points between the two datasets, i.e., OCARINA and ERA5, by imposing a minimal spatial rapprochement. To do this, we wrote a code that carries out this comparison between the various variables and for the different measurement campaigns. The problem of the coarse sampling of ERA5 could be overcome by carrying out a remapping, essentially for the estimation of the surface temperature of the sea. The drag coefficient was compared via the Louis formulation and the comparison results of this parameter showed a good overall agreement between ERA5 and OCARINA.

Overall, the two datasets showed fairly good correlation for the different estimated fluxes. The comparisons carried out in this work have highlighted, once again, the reliability of reanalysis data, and our results generally agree with the various conclusions of previous works that have used these data to parameterize turbulent fluxes at the air-sea interface, which also proves the performance of our OCARINA platform.

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