Article

Comparisons between Mean and Turbulent Parameters of Aircraft-Based and Ship-Based Measurements in the Marine Atmospheric Boundary Layer

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Abstract: The Structure des Echanges Mer-Atmosphère, Propriétés Océaniques/Recherche Expérimentale (SEMAPHORE) experiment was conducted over the oceanic Azores current located in the Azores Basin. The evolution of the marine atmospheric boundary layer (MABL) was studied based on the evaluation of mean and turbulent data using in situ measurements by a ship and two aircrafts. The sea surface temperature (SST) field was characterized by a gradient of approximately 1 °C/100 km. The SST measured by aircraft decreased at a ratio of 0.25 °C/100 m of altitude due to the divergence of the infrared radiation flux from the surface. With the exception of temperature, the mean parameters measured by the two aircrafts were in good agreement with each other. The sensible heat flux was more dispersed than the latent heat flux according to the comparisons between aircraft and aircraft, and aircraft and ship. This study demonstrates the feasibility of using two aircraft to describe the MABL and surface flux with confidence.

Keywords: marine atmospheric boundary layer; sea surface temperature; infrared flux divergence; heat flux; SEMAPHORE

1. Introduction

The determination of boundary layer conditions at the air–ocean interface is an important issue in atmospheric and oceanic predictive numerical models. The air–sea exchanges of momentum, heat, and water are substantial in atmospheric and oceanic movements at different scales. Accurate predictions of complex and poorly understood marine environments require an improved understanding of spatial variability and highly precise parameterization of turbulent surface flows [1]. The atmospheric turbulent fluxes of heat, water vapor, and momentum across the air–ocean interface play a substantial role in the development of climate and the weather system. Therefore, they should be an integral part of numerical weather prediction and climate prediction models. Because this exchange is primarily at the sub-grid scale, it is parameterized by a surface bulk exchange parameterization scheme that is semi-empirical. Abundant intensive observations of turbulent exchange are required to improve the algorithm, typically by estimating the exchange coefficients [2,3].

Interactions between the ocean and atmosphere have been experimentally studied from turbulence to synoptic scales for several years. Many of the associated studies focused on the examination of physical processes in the marine atmospheric boundary layer (MABL) and on surface turbulent fluxes, for example, the Joint Air–Sea Interaction (JASIN) [4] and the Genesis of Atlantic Lows Experiment (GALE) [5,6]. The horizontal variability was experimentally revealed for the first time during JASIN and the Frontal
Air–Sea Interaction Experiment (FASINEX) pertaining to the physical processes in atmospheric and oceanic boundary layers [7,8]. They were conducted in conditions caused by the presence of a thermal front in the upper ocean. Powell et al. [9] described the transfer of momentum between the atmosphere and the ocean in terms of the vertical variation of wind speed and a drag coefficient that increases with wind speed and sea surface roughness. Persson et al. [10] presented ship-based eddy covariance and inertial dissipation fluxes from the central North Atlantic. Aircraft-based covariance flux observations have been reported for hurricanes [11], during barrier winds and tip jets [12]. Haynes et al. [13] examined the Southern Ocean (SO) clouds using multi-satellite products and reported that most SO clouds reside in the MABL and, hence, are difficult to accurately detect from space. Owing to a lack of in situ observations, understanding the thermodynamic structure of the MABL in the SO remains a challenge. Truong et al. [14] utilized 2186 high-resolution soundings from four recent field campaigns to construct a climatology profile of the MABL and to examine relationships between the synoptic meteorology and thermodynamic structure by means of composite analysis of fronts and cyclones in the SO. Williams et al. [15] highlighted that the height of the SO MABL in the Transpose-Atmospheric Model Intercomparison Project simulation was consistently underestimated in comparison to an operational analysis product. However, when compared with historical atmospheric soundings over Macquarie Island, the height of the MABL in a reanalysis (European Centre for Medium-Range Weather Forecasts reanalysis (ERA)-Interim) product was underestimated [16,17]. Andreas et al. [3] investigated the dependence of the 10 m drag coefficient in a neutral condition over the sea in the context of the Monin–Obukhov similarity theory by analyzing four different aircraft datasets from 11 different experiments.

As aircraft observation is highly convenient in MABL, it is necessary to control the quality and validate the measurement data. The Structure des Echanges Mer-Atmosphère, Propriétés Océaniques/ Recherche Expérimentale (SEMAPHORE) experiment was performed from June to November 1993, south of the Azores islands, primarily characterized by a thermal front [18]. An instrumented ship undertook in situ observations and an aircraft undertook remote observations over the sea surface temperature (SST) front [19]. The experimental area was situated between 31°–38°N and 21°–28°W (500 × 500 km). The SEMAPHORE experiment was performed to improve our knowledge of ocean–atmosphere interactions from the local scale to the mesoscale [19]. Giordani et al. [20] showed the atmospheric response to SST changes based on a numerical model. Kwon et al. [18] and Lambert and Durant [21] dealt with the vertical variation of the turbulence fluxes in PBL affected by the SST gradient. Although Lambert and Durant [22] made an aircraft-to-aircraft comparison, turbulence parameters were the main factor and ship observation-based data were not addressed. In the SEMAPHORE experiment performed in this study, the accuracy of surface layer mean and turbulent parameters were evaluated by comparing aircraft data to ship data once the aircraft-to-aircraft comparison was completed.

Absolute calibration of most instruments installed on the aircraft is difficult because the measurements are affected by the airspeed of the sensor. Because there is no absolute reference for in-flight measurements, aircraft-to-aircraft inter-comparisons are the best means to ensure coherence between various platforms [22]. Calibration against ground-based measurements cannot be considered satisfactory owing to the different sampled areas and sampling time for the two platforms. Furthermore, ground-based measurements generally cannot be used over the open ocean. Air-to-air cross-comparison experiments have been conducted during several campaigns; however, the results of applying a calibration process compared to in situ ship observations are elusive. To study characteristics of the atmospheric surface layer with remotely sensed data from an aircraft, we validated the observation data obtained by two aircraft, which were compared with the ship-based observation. This paper presents the validation of the data by analyzing the references for SST and atmospheric surface measurements. We discuss the experimental site, exper-
imental method, and airborne equipment utilized in the context of the characteristics of the MABL.

2. Materials and Methods

2.1. Instrumented Aircraft

Two aircraft, the Fokker 27 (ARAT) and the Fairchild Merlin IV (Merlin IV), were instrumented by the Institut National des Sciences de l’Univers (INSU) and the French Meteorological Office (FMO), respectively, to investigate the MABL characteristics and the surface fluxes. The datasets were enhanced with geophysical parameters derived from meteorological satellites (NOAA, Meteosat, and Defense Meteorological Satellite Program). This study was completed with the cooperation of the Centre de Recherches Atmosphériques, one of the SEMAPHORE experiment organizers, eliminating the limitation of data availability (the data of the SEMAPHORE are not currently publicly available).

Both the aircrafts measured atmospheric turbulence and radiation with different sensors. ARAT was installed with a 5 m long nose boom with fast response sensors. A Rosemount 858 probe (Rosemount Engineering Co., Eden Prairie, MIN 55344, USA) observed slide slip and attack angles, along with dynamic and static pressures. An inertial navigation system (INS) detected the ground velocity, the horizontal geographical position, and the attitude angles: roll, pitch, and true heading [23]. On Merlin IV, a radome measured the slide slip and attack angles, and total pressures [24]. The INS was equipped behind the nose of ARAT and close to the gravity center of Merlin IV. The temperature was observed by a Rosemount 102E2-AL probe (Rosemount Engineering Co., Eden Prairie, MIN 55344, USA) located on both aircrafts, and the moisture was observed by a Lyman-α sensor (Buck Research, Novato, CA 94945-1400, USA) and a dew-point hygrometer [18]. Upward and downward longwave radiation (4–40 µm band) and shortwave (0.2–2.8 µm band) radiation were measured using Eppley sensors (The Eppley Laboratory Inc., Newport, RI 02840, USA). The sea surface brightness temperature was measured by a downward-looking Barnes PRT5 (Barnes Engineering Company, Colorado Springs, CO 80916, USA) thermo-radiometer. A radio altimeter measured the altitude above the sea level. The SST was corrected to incorporate the vertical divergence of the longwave radiation from the sea surface to the flight level of Merlin IV. The incoming radiation, which can be as significant as the surface emissivity, was excluded for the SST correction.

2.2. Flight Plans

The aircraft observations were performed simultaneously in the same area of the ship. The wind orientation and the SST front in the MABL was taken into consideration. The radio-sounding on the ship provided the wind in the experimental zone. During the IOP, three types of flight plans were used: (i) two long perpendicular tracks of 100 km crossing the oceanic front in two different regions between 80 m and the top of the mixed layer or at the bottom of clouds. Three soundings completed the flight plan (Figure 1a). (ii) A main axis of 200 to 300 km was associated with three perpendicular segments of 30 km at the middle point and at both ends of the long axis. This flight plan was completed by the two planes at five different levels with their vertical soundings of up to 2.5 km (Figure 1b). This flight plan was able to analyze transversal and longitudinal flows in the intermediate zone. (iii) One flight axis of 300 km was constituted by two or three soundings at the end of the axis (Figure 1c). This flight plan was adapted for the thermal transitions and enabled characterization of the atmospheric turbulence along the longest axis. The mean parameters were averaged, and the turbulent parameters were calculated on segments of approximately 25 km long. They were named AC1, AC2, and AC3 from point A to C, and CB1, CB2, CB3, CB4, CB5, CB6, CB7, CB8, and CB9 from point C to B.
Figure 1. Flight plans: (a) perpendicular axes (approximately 100 km), (b) a long axis (200–300 km) with three perpendicular segments, and (c) one long axis of 300 km. Tracks of ARAT and Merlin IV are depicted in blue and red, respectively.

2.3. Data from Aircraft

The airborne data treatments are of interest in the turbulent thermodynamics of the atmosphere and radiation parameters, in addition to the dynamic and averaged variables. The mean parameters were defined for approximately 1 km, which is equivalent to a temporal resolution of 10 s. The turbulent variables were produced statistically for the length of various atmospheric scales contributing to the eddies. Because the turbulent parameters were calculated in an orderly manner via statistically accurate evaluation of the quantities, the flight axes were straight and integrated at altitude. The length of the axis was approximately 25 km of flight, which is defined as 5 min. The treatment of fluctuation parameters was composed of: three components of the wind—longitudinal \(u'\), transversal \(v'\) and vertical \(w'\) fluctuation; the mixing ratio \(q'\); and the potential temperature \(\theta'\). The mean wind consisted of three components \((u, v, w)\) calculated using the ground velocity, and the small-angle approximation for the side slip and the attack angles [25]. Assuming the mean vertical velocity to be zero, only fluctuations were calculated. The static temperature was corrected considering the adiabatic warming due to the flight speed. The specific humidity from the Lyman-\(\alpha\) signal was calibrated against the dew-point hygrometer.

High-pass filtering of the fluctuation with a frequency of 0.016 Hz was applied to the calculated turbulent sets, thereby the maximal wavelength was limited to approximately 5 km. Low-frequency signals that were not involved in turbulence generation were eliminated. The length of the cut wave was determined according to the scale characteristics of the vertical velocity spectrum and the co-spectrum in the form of the momentum flux, the sensible heat flux, and the latent heat flux.

Therefore, the fluxes were deduced on samples with a length of approximately 25 km and filtered with a wavelength of 5 km. This analysis exhibited a satisfactory result, which resulted in a minimal error in the flux estimation. Limiting the analysis from a large scale to 5 km was effective in reducing the scattering distribution [21]. However, this removal suppressed a small amount of information, resulting in errors in the estimation of the turbulence parameters. The contribution scales of the variance and covariance were studied on the integral of spectra (or co-spectra) according to the wavelength (or frequency), while integrating from the limited low wavelength (or high frequency) [26]. The vertical velocity forms a large-scale asymptotic distribution that transforms the spectrum of turbulence. Variances in the longitudinal velocity, mixing ratio, and potential temperature contribute significantly at the large scale due to the mesoscale’s gradient. For these meteorological variables, it is difficult to determine the maximum of the energy spectrum. These properties imply no spectral gap between the mesoscale and turbulent fluctuations, at least for the hor-
horizontal velocities and the scalar variables. Variations in vertical fluxes are more analogous to the variance of the vertical velocity, which is calculated using the correlation method. This means that the flux is controlled by a dynamic mechanism. The turbulent kinetic energy, the vertical momentum flux, and the latent heat were slightly underestimated near the surface and underestimated by 20% at high altitudes [18,19,24].

2.4. Infrared (IR) Flux Divergence

A Barnes-PRT5 was used to measure the IR radiation from the sea surface and to produce the brightness temperature along the flight trajectory. Due to the temporal difference of the ARAT sensor, data from Merlin IV was only used for SST correction. The SST was corrected for the divergence of the atmospheric radiation flux between the surface and the flight altitude. In particular, the cloud cover has a significant influence on divergence. The decrease in SST with altitude was restored to take into account the emissivity. If the SST varies with time and space:

\[ \text{SST} = f(x, y, t) \]  

The apparent temperature \( T_a \) is a function of SST, emissivity, descending IR, and altitude:

\[ T_a = f(\text{SST}, \epsilon\lambda, \text{IR}_{\text{de}}^\lambda, z) \]  

At the surface, the radiation is given by:

\[ \sigma T_a^4 = \epsilon\lambda \sigma (\text{SST})^4 + (1 - \epsilon\lambda) \text{IR}_{\text{de}}^\lambda \]  

At the altitude \( z \), the radiation is decreased by the atmospheric absorption:

\[ \sigma T_a^4 = \epsilon\lambda \sigma (\text{SST})^4 - \Delta \left[ \epsilon\lambda \sigma (\text{SST})^4 \right]_0^z + (1 - \epsilon\lambda) \text{IR}_{\text{de}}^\lambda - \Delta \left[ (1 - \epsilon\lambda) \text{IR}_{\text{de}}^\lambda \right]_0^z \]  

If \( \text{IR}_{\text{de}}^\lambda \) is measured only at altitude \( z \):

\[ \text{IR}_{\text{de}}^{\lambda(z)} = \text{IR}_{\text{de}}^{\lambda(0)} - \Delta \left[ \text{IR}_{\text{de}}^{\lambda(0)} \right]_0^z \]  

Ignoring the third-order terms:

\[ \sigma T_a^4 = \epsilon\lambda \sigma (\text{SST})^4 - \Delta \left[ \epsilon\lambda \sigma (\text{SST})^4 \right]_0^z + (1 - \epsilon\lambda) \text{IR}_{\text{de}}^\lambda + (1 - \epsilon\lambda) \Delta \left[ \text{IR}_{\text{de}}^\lambda \right]_0^z \]  

where the left-hand side is the measured radiation at the flight altitude, term II is unknown (\( \epsilon\lambda \) and \( T_a \)), and term III is calculated by a statistical method at different altitudes. In term IV, \( \text{IR}_{\text{de}}^\lambda \) is measured. When \( \epsilon\lambda \neq 0 \), \( T_a \) depends on the vertical variation of \( \text{IR}_{\text{de}}^\lambda \). Figure 2 shows the descending IR radiation flux as a function of the SST difference between the ship and the aircraft (\( \text{SST}_{\text{ship}} - \text{SST}_{\text{aircraft}} \)), which decreases when the IR flux increases. Assuming that the SST and \( \epsilon\lambda \) vary little between the two measurements over the same flight trajectory, \( \epsilon\lambda \) is calculated and the corrected SST is estimated.
Figure 2. Descending infrared flux depending on the SST difference (SST<sub>ship</sub> − SST<sub>aircraft</sub>).

The SST was corrected on each flight track of approximately 30 km. Figure 3 shows the correction rate of the SST, with altitude plotted against the IR flux divergence. According to the measurement of Merlin IV, the major correction rate was 0.25 °C per 100 m, as shown in the histogram for the different applied days.

3. Results

3.1. SST Field

The SST measured by Merlin IV was, on average, 1 °C lower than that measured by the ship. This is not anomalous, because the measurement system of the ship is different from that of the aircraft; the former measured the water temperature at a depth of 2.5 m, whereas the latter detected the surface brightness temperature incorporating the effects of air–sea interaction. The ship measurements were considered to be a reference for the correction of the aircraft measurements. The SST from buoys and the ship were assimilated in the Action de Recherche Petite Echelle Grande Echelle (ARPEGE) model analysis [27]. The temperature front could be easily determined on SST fields for the entire experiment. Thus, the exact direction of the aircraft pattern relative to the iso-SST level was known. In contrast, when the MABL characteristics were analyzed across the SST front, the SST measured along the flight axis was taken into account. In six experiments, the SST values measured from the aircraft were compared with those from the ARPEGE numerical analysis model along the aircraft track.
In general, the aircraft position was in very good agreement with the route across the SST front, for the October 31 and November 1 cases. This slight departure was caused by the time lag of the numerical model to assimilate the fast change of SST due to the storm on October 29 in the northern part of the experimental area. Nevertheless, for the ARPEGE model analysis, the flight track could be planned with respect to the SST front.

In the intensive observation period (IOP), advanced very-high-resolution radiometer (AVHRR) images were obtained from the NOAA satellite. The spatial resolution was $1 \times 1$ km in the five channels: visible (0.58–0.68 $\mu$m), near-IR (0.72–1 $\mu$m), and IR (3.55–3.93, 10.3–11.3, and 11.5–12.5 $\mu$m). The cloudy structures were evaluated and their relationship with the SST fields was determined based on the AVHRR images.

The oceanic circulation at the mesoscale was characterized by the Azores front and influenced by its eddies [28,29]. For November 11, Figure 4 shows the SST field from the ARPEGE analysis and the flight axis with the ship position near point B. The SST field dominated by a large meander was oriented NW–SE in the northwestern part and W–E in the southern part of the experimental domain. All aircraft observations were conducted in the northwestern region of the meander. The SST gradient was increased from point A to point B. The SST minimum was 19.2 $^\circ$C at 24.8° W–36° N and the maximum temperature recorded was 23.4 $^\circ$C at 27.5° W–34.8° N. During the IOP, the SST front was quasi-stationary, even though local variations were found in the cold area. The orientation of the SST front changed from 20° to 30° on October 31 and on November 13 with respect to north. A mean gradient of 1–2 $^\circ$C/100 km continued throughout the IOP, which was significantly lower than those recorded in the FASINEX [7,8].

Figure 4. Sea surface temperature (SST) (isolines) at 12:00 UTC from ARPEGE with the aircraft track (thin black lines) on November 11. The reference points are denoted by A, B, and C.

In the SEMAPHORE experiment, a cloudy area was assumed when the albedo was >10%, which was deduced from the visible radiation of the NOAA satellites [18]. During the first period (October 31 to November 2), the ocean cloud coverage was dominated by synoptic conditions rather than the surface temperature field. In the JASIN experiment, lower cloud cover was related to SST changes [7,30]. Zelinka and Hartmann [31] reported that clouds were critical factors used to define the budget of regional radiation in the SO region and to transport the energy and moisture from the tropical zone to the Antarctic. However, large differences in cloud amount and properties over the SO were retained in the reanalysis products and in the climate simulations [32,33]. It was difficult for the
climate models to produce low-level clouds behind cold fronts and in the cold-air sector of extratropical cyclones [15]. Brilouet et al. [34] considered that cloud cover/structure height, or thermodynamic characteristics, are systematically similar. They also found that during the strong wind periods, the latent and sensible heat flux reached 500 and 300 Wm$^{-2}$, respectively. Despite intense cold-air outbreaks, the SST variations were weak. In the SEMAPHORE, based on two AVHRR images per day on different channels, it was found that no cloud organization was related to the SST field, although pronounced local effects were observed during the anticyclonic periods.

3.2. Comparison of the Data from the Two Aircrafts

Comparison of data from the two aircraft is an important process, because it determines the precision of the thermodynamic and dynamic fields acquired under different experimental conditions. Aircraft are valuable platforms for exploring the ABL; however, it is difficult to completely standardize measurement devices because measured data are influenced by the airflow entering the sensor. The standardization of the airborne sensor is carried out in the laboratory by considering the effects of pressure exerted on the sensors during the flight [25]. Standardization based on measurements carried out at the surface cannot be precise. Due to the absence of an absolute reference during the in-flight measurement, comparisons between the two aircraft are the most appropriate means to ensure the consistency of measurements.

3.2.1. Air Temperature

Air temperature was measured using three probes in each of the two aircraft. The mean temperature measured by Merlin IV was 0.5 $^\circ$C higher than that of ARAT between 950 and 900 hPa. There was no defrosted Rosemount probe, resulting in the intermediate value between the three probes of ARAT. In addition, the difference between the two temperature sensors used as references was approximately 0.7 $^\circ$C at this altitude [33]. Figure 5 shows vertical profiles of the average temperature measured by the Rosemount probe at a 30 km segment. Adiabatic profiles were found through five levels: the two profiles were lower as measured by the ARAT and the other three profiles were higher as measured by Merlin IV. A difference of 0.7 $^\circ$C was revealed between the air temperatures measured by the two aircraft. Because the measured static pressures of the two aircraft were coherent, temperature correction was applied to the potential temperature [21].

![Figure 5](image_url) Temperatures measured by Merlin IV (three higher levels) and ARAT (two lower levels). Six segments were divided from point B to point A via point C along the long flight axes.
3.2.2. Wind Speed and Mixing Ratio

The comparison of wind averaged on 10 s and based on the turbulence at a length of 30 km showed satisfactory results; specifically, there was no bias, and deviations of 3.5° for wind direction and 0.5 m s\(^{-1}\) for wind speed between the two aircraft.

A difference of 0.1 g kg\(^{-1}\) in the mixing ratio was observed between the two aircraft. This difference is in the allowable range for sensor precision and, hence, no correction was applied to the mixing ratio for the data from ARAT and Merlin IV.

3.2.3. Turbulence Parameters

The comparison of turbulent data on the SEMAPHORE experiment was carried out using the fast measurements of the two aircraft [22]. The dispersion of variance was approximately 10%, which indicates a good agreement between the two measurements.

In Figure 6, the bias of the latent heat flux is smaller (approximately 25% of the mean value) than that of the sensible heat flux (approximately 40% of the mean value). This scattering is explained by the weak sensible heat flux. The longitudinal and transversal momentum fluxes are distributed around the mean flux because the range of momentum flux is greater than that of heat transport [35]. This is very difficult to measure in the case of weak covariance. The dissipation rate calculated from the filtered variance [22,36,37] showed a good concordance between the two aircraft. The wavelength scale from the spectrum of the vertical velocity was relatively correlated, except in the case of the two maximal spectral picks, presumably due to the presence of organized structures in the MABL [22].

![Figure 6](image_url)

(a) heat flux  
(b) momentum flux

**Figure 6.** Comparison of (a) heat flux and (b) momentum flux between the two aircrafts.

3.3. Comparison between the Aircraft and the Ship

Mean and turbulent parameters for the surface are produced from airborne measurements and from direct measurements at the lowest flight level, assuming that fluxes are constant in the surface boundary layer [38]. Comparisons of the mean data between the ship and the aircraft were performed for SST, wind speed, mixing ratio, and air temperature. These parameters were compared with the measurements obtained from the ship by extrapolating the measurement at 10 m and at the sea level.

3.3.1. Temperature and Mixing Ratio

The temperature at the reference level of 10 m was extrapolated from the mean temperature at the flight levels (Figure 5) maintaining adiabatic profiles in the MABL.
Figure 7a shows that the extrapolated temperatures from flight levels were higher by 0.5 °C than those measured on the ship.

Because the mixing ratio was constant in the marine atmospheric mixed layer, the mixing ratio measured at the lowest flight level was compared with that calculated using parameters (relative humidity, temperature, and pressure) measured on the ship. The comparison (Figure 7b) shows negligible variation, indicating no bias.

3.3.2. Wind Speed

Figure 7c demonstrates the comparison of the wind speed measured between the lowest flight level and on the ship. The former is marginally higher than the latter (approximately 0.5 m s\(^{-1}\)). This difference was obtained using the power law to the wind profile [39] between 10 and 90 m of altitude with an exponent of 0.1, in the weakly unstable condition, and 0.06, in the unstable condition above the sea. This agreement implies that wind variations were weak near the surface during SEMAPHORE.

3.3.3. SST

The SST measured by the aircraft is evaluated in Section 3.1. On the ship, the SST was observed directly at a depth of 2.5 m. The difference between the SST measured at the ship and at Merlin IV was about 1 °C (Figure 8). The divergence of IR flux caused this correction, which can vary by a few tenths of a degree, based on cloud cover. The SST assimilated in the ARPEGE model exhibited a good correlation.

3.3.4. Turbulence Parameters

For the measurement of turbulence, the correlation method was implemented by the aircraft and the inertial dissipation method was implemented by the ship [40]. The fluxes were extrapolated to the surface near the ship using a linear regression of airborne flux measurements at four different flight heights (Figure 9). The sensible heat and latent heat fluxes of the aircraft were weaker than those measured on the ship (Figure 10a,b). The sensible heat flux and the latent heat flux was underestimated by 37% and 13%, respectively, by the aircraft. These values are comparable with those evaluated during the first ISLSCP (International Satellite Land Surface Climatology Project) Field Experiment (FIFE) [41]. The low estimate of the sensible heat was influenced by the weak sensible heat fluxes over the ocean. No significant difference was observed in the momentum flux (Figure 10c) with a deviation of dispersion of approximately 30%. During the Hydrological cycle in the Mediterranean Experiment (HyMeX) Special Observing Period 2 field campaign,
the turbulence structure of the MABL was analyzed to be localized in the northwestern Mediterranean basin [34]. A comparison between the extrapolated bulk fluxes and surface fluxes computed at a moored buoy revealed considerable differences, mostly with respect to the latent heat flux under strong wind conditions. Because the wind speed was relatively weak in the SEMAPHORE and Studies On Fission with Aladin (SOFIA) experiments [42], the latent heat flux according to the aircraft was less dispersed than the sensible heat flux. In the SEMAPHORE experiment, the temporal segment of the ARPEGE model-based sensible heat flux recorded a bias of $-8 \text{ W m}^{-2}$ in comparison with the ship-based sensible heat flux. However, this was not the case for latent heat flux [27].

![Figure 8](image1.png)

**Figure 8.** Comparison of SST between the aircraft and the ship.

![Figure 9](image2.png)

(a) Warm zone (reference point B)  
(b) Cold zone (reference point A)

**Figure 9.** Vertical variations of the sensible heat flux at (a) warm zone and (b) cold zone for six segments on November 1.
Figure 10. Comparison of (a) sensible heat fluxes, (b) latent heat fluxes and (c) momentum fluxes between the ship and the aircraft.

Cook and Renfrew [43] found a difference in turbulence fluxes between legs flown along-wind and those flown across-wind. The along-wind legs do not capture all the fluxes; the ends of the spectra are shifted to remarkably long scales. A multi-resolution spectral technique was demonstrated to show that the turbulent eddies were elongated in the downwind direction for both stable and unstable conditions and moderate to strong wind speeds. Gioli et al. [44] demonstrated that the aircraft-based latent heat flux is slightly overestimated compared to ground fluxes, whereas the sensible heat flux is consistently underestimated. This discrepancy is attributed to substantial vertical flux divergence. The rate of change of the flux with height depends on the differences in temperature between
the boundary layer of the free troposphere, surface flux, and boundary layer depth, which are difficult to predict and require direct measurements.

4. Conclusions

The SEMAPHORE experiment was performed to investigate the development of the marine atmospheric boundary layer over the oceanic Azores current. A ship and two aircrafts observed the turbulent parameters and the mean parameters. Measurements of the ship and the aircraft were undertaken using geophysical parameters derived from meteorological satellites. The atmospheric parameters were compared using measurements obtained through a combination of several remote sensors. The results were validated through analysis of data obtained using a ship and two aircraft. The SST and surface layer parameters measured at the ship were used as references. The SST, remotely measured by aircraft, vertically decreased because the IR radiation flux diverged on the passage from the surface to the airborne sensors. The correction of IR radiation flux divergence in remote sensing is an important process for studying the characteristics of MABL. The decrease in the SST with height was corrected by the emissivity factor, which was 0.25 °C per 100 m in this experiment.

Obtaining in situ observations is difficult at sea; hence, heat flux calculation is typically performed using the bulk method. The bulk heat flux is determined as the product of the difference between SST and air temperature, and wind speed. An underestimation of SST implies that the buoyancy flux can be erroneously underestimated, especially in summer when the temperature difference is small between the ocean and the atmosphere.

The comparison of the mean thermodynamic and dynamic parameters of the two aircraft were consistent, with the exception of the temperature, which exhibited a mechanical bias of 0.7 °C. This correction value was adjusted in all the analyses, including temperature. In terms of the turbulent measurements, the momentum flux was comparable despite a large dispersion. The sensible heat flux was weaker than the latent heat flux and, hence, it was more scattered. The mean parameters measured by the aircraft were highly correlated with those of the ship. However, the sensible heat and the latent heat fluxes of the aircraft were weaker than those measured by the ship. In this study, the feasibility of implementing two aircraft was validated to account for the evolution of MABL and the surface flux. The consistency of the extrapolated fluxes with the ship data implies that we can take advantage of the linearity of fluxes in the MABL to indirectly yield fluxes in the MABL as well as in the surface layer.

In this study, the inertial dissipation and the eddy covariance methods, which, even today, are the most commonly used methods for measuring turbulence were implemented to calculate fluxes on the ship and the aircraft, respectively. Comparing the latest aircraft-mounted observation equipment with the previously used equipment, the specifications were almost the same. Although radiometer and radar were added, they were not useful for SST or sea wind measurements. Aircraft Integrated Meteorological Measurement System (AIMMS-20) is a state-of-the-art observation device mounted on a meteorological aircraft. It provides the aircraft’s position and attitude information, and measures temperature, humidity, pressure, and wind. Korea’s National Institute of Meteorological Sciences is currently conducting a comparative experiment between the AIMMS-20 data and Rose-mount Total Temperature Sensor (RTTS) data used in this study. We look forward to the opportunity to complete an analysis of the comparative experimental results obtained using these measurement systems.
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