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Comparison of sea surface flux measured by instrumented aircraft and ship during SOFIA and SEMAPHORE experiments

Pierre Durand,^{1,2} H el ene Dupuis,³ Dominique Lambert,¹ Bruno B enech,¹ Aim e Druilhet,¹ Kristina Katsaros,^{4,5} Peter K. Taylor,⁶ and Alain Weill⁷

Abstract. Two major campaigns (Surface of the Oceans, Fluxes and Interactions with the Atmosphere (SOFIA) and Structure des Echanges Mer-Atmosph ere, Propri et es des H et erog enit es Oc eaniques : Recherche Exp erimentale (SEMAPHORE)) devoted to the study of ocean-atmosphere interaction were conducted in 1992 and 1993, respectively, in the Azores region. Among the various platforms deployed, instrumented aircraft and ship allowed the measurement of the turbulent flux of sensible heat, latent heat, and momentum. From coordinated missions we can evaluate the sea surface fluxes from (1) bulk relations and mean measurements performed aboard the ship in the atmospheric surface layer and (2) turbulence measurements aboard aircraft, which allowed the flux profiles to be estimated through the whole atmospheric boundary layer and therefore to be extrapolated toward the sea surface level. Continuous ship fluxes were calculated with bulk coefficients deduced from inertial-dissipation measurements in the same experiments, whereas aircraft fluxes were calculated with eddy-correlation technique. We present a comparison between these two estimations. Although momentum flux agrees quite well, aircraft estimations of sensible and latent heat flux are lower than those of the ship. This result is surprising, since aircraft momentum flux estimates are often considered as much less accurate than scalar flux estimates. The various sources of errors on the aircraft and ship flux estimates are discussed. For sensible and latent heat flux, random errors on aircraft estimates, as well as variability of ship flux estimates, are lower than the discrepancy between the two platforms, whereas the momentum flux estimates cannot be considered as significantly different. Furthermore, the consequence of the high-pass filtering of the aircraft signals on the flux values is analyzed; it is weak at the lowest altitudes flown and cannot therefore explain the discrepancies between the two platforms but becomes considerable at upper levels in the boundary layer. From arguments linked to the imbalance of the surface energy budget, established during previous campaigns performed over land surfaces with aircraft, we conclude that aircraft heat fluxes are probably also under-estimated over the sea.

1. Introduction

In the past few years it appeared that measurement of the surface flux of sensible heat, latent heat, and momentum was not a solved problem. This was exhibited from cooperative field programs during which several platforms were deployed in order to measure, on land reference areas, the various terms of the surface energy budget (therefore including the sensible and latent

heat flux). These platforms were twofold: first, ground-based micrometeorological stations, on which the flux was measured by eddy-correlation, profile or even Bowen ratio methods, and, secondly, instrumented aircraft generally measuring flux by the eddy-correlation technique on straight and level runs of several tens of kilometers long. Surface flux was deduced from aircraft flux either directly from the lowest altitude runs, if it can be assumed that these runs lie within the constant flux surface layer, or extrapolated toward the surface from the flux calculated at various altitudes from vertically stacked runs.

Over land, several comparisons were performed between these platforms. As an example, the results from First International Satellite Land Surface Climatology Project (ISLSCP) Field Experiment (FIFE) presented by *Kelly et al.* [1992] showed a considerable underestimation of aircraft sensible heat flux with respect to the ground-based flux. Although less important, a difference of the same sign was observed on the latent heat flux. *Crawford et al.* [1993] also quoted differences in heat fluxes, although their aircraft runs were performed at very low altitude (between 12 and 25 m above ground). More recently, the results from the Hydrologic Atmospheric Pilot Experiment in the Sahel (HAPEX-Sahel) also showed considerable underestimations of aircraft sensible heat and latent heat flux [*Lucotte and Said, 1996*]. Over land the underestimation of flux-computed values can be demonstrated by the importance of the residual term in the balance of the energy budget; this balance expresses that the net radiation at the surface is converted into sensible heat flux toward

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the atmosphere, latent heat flux (evaporation in most of the cases), and heat storage into the ground. Aircraft cannot measure the latter term and therefore deduce it from the balance of the energy budget. A too-high value of this residual term therefore demonstrates an underestimation of the sensible heat and/or latent heat flux or an overestimation of net radiation. *Lucotte and Said* [1996] performed an exhaustive comparison between aircraft and ground measurements of these various terms and unambiguously concluded that aircraft sensible and latent heat flux were underestimated by 30% or even more.

Over the sea the balance of the surface energy budget cannot be used in the same way as over land, because the major part of the net radiation is converted in heat storage into the oceanic mixed layer. The accuracy on the balance of the surface energy budget is therefore generally poor. In particular, advection terms play a significant role in the heat budget of the oceanic mixed layer. Nevertheless, direct comparisons can be made between airborne and shipborne flux over the ocean. Recently, *Bradley and Weller* [1995] have reported from the Tropical Ocean-Global Atmosphere Coupled Ocean-Atmosphere Response Experiment (TOGA COARE) data that airborne sensible heat and latent heat flux were lower than shipborne flux. However, *Fairall et al.* [1996] present a better comparison from the same data set. Comparisons between shipborne and airborne flux over the sea could help to solve the problem of flux measurement, because the turbulence over the sea presents different characteristics (in particular, the Bowen ratio is generally much lower over the sea than over land). Furthermore, at a horizontal scale of several tens of kilometers the sea surface is generally much more homogeneous (in roughness, temperature, and albedo) than a similarly sized continental surface. In the end, horizontal homogeneity of sea surface allows the momentum flux to be compared between shipborne and airborne estimates, whereas over land, airborne and ground-based estimates cannot be easily compared, because the footprint of these two estimations is of very different size, and the "equivalent roughness" cannot therefore be compared between local (as seen by the ground-based platform) and regional (as seen by the aircraft run) scale. That is why we have performed a comparison between sea surface flux of momentum, sensible heat, and latent heat deduced from an instrumented ship and two instrumented aircraft. These platforms were deployed in the Azores region during two cooperative experiments: Surface of the Ocean, Fluxes and Interactions with the Atmosphere (SOFIA) in 1992 and Structure des Echanges Mer-Atmosphère, Propriétés des Hétérogénéités Océaniques: Recherche Expérimentale (SEMAPHORE) in 1993.

The two campaigns, and the main instruments used for this work, will be described in a first section. We will then present the data processing, and the technique used to determine surface flux from aircraft and ship measurements. Afterwards, the comparison between aircraft and ship flux will be analysed and in a final section an analysis of the errors involved in flux computation will be done and some hypotheses will be checked to try to explain the discrepancies between the two types of platforms.

2. The Campaigns

The two campaigns, whose data are presented here, were performed in the Azores region. SOFIA [*Weill et al.*, 1995] was a part of the Atlantic Stratocumulus Transition Experiment (ASTEX) [*Albrecht et al.*, 1995] and extended from June 1 to 28, 1992. During SEMAPHORE [*Eymard et al.*, 1996] the airborne

and shipborne measurements covered the period ranging from October 4 to November 17, 1993.

The same platforms were deployed for both campaigns. The shipborne measurements were performed on the R/V *Le Suroît* (from Institut Français de Recherche pour l'Exploitation de la Mer (IFREMER)) on the foredeck of which a meteorological mast was deployed. On this mast the fast response sensors were set up; a three-dimensional sonic anemometer (Gill Solent type, from Institute of Oceanographic Sciences (IOS) during SOFIA and from Météo-France during SEMAPHORE), installed at 16.6 m above the sea surface, measured the three wind components and the "sonic" temperature (deduced from the velocity of sound) at a rate of 21 s⁻¹. A Lyman- α hygrometer, from University of Washington, measured the absolute humidity (it was calibrated against slower humidity sensors, as described by *Dupuis et al.* [1997]) and a fast thermocouple (from University of Washington) measured the temperature fluctuations; both instruments, installed at 15.0 m above the sea surface, were acquired at a rate of 20 s⁻¹. Turbulence measurements were performed with the ship moving into the mean wind in the atmospheric surface layer. Furthermore, mean meteorological measurements (temperature, moisture, wind speed, and wind direction relative to the ship) were performed at two altitudes (10.7 m and 15.2 m above the sea surface).

The two instrumented aircraft were a Fokker 27 (called Avion de Recherche Atmosphérique et de Télédétection (ARAT)), instrumented by the French Institut National des Sciences de l'Univers (INSU) and a Merlin IV of Météo-France. The two aircraft have the same capabilities in measuring thermodynamics and turbulence, although the sensors are different; the fast response probes are installed at the tip of the nose boom, 5-m long, on the Fokker 27, whereas the nose of the Merlin IV presents a hemispheric radome on which various pressure ports are installed. The temperature measurements, collected on the nose boom of the Fokker 27 and on the radome of the Merlin IV, by a non-deiced Rosemount 102E2AL probe, were corrected for the adiabatic heating due to the airspeed of the aircraft. The moisture fluctuations were measured by a Lyman- α device, calibrated against a chilled-mirror, dew-point hygrometer. The three components of the wind vector were deduced from the sum of the airspeed vector and the ground-speed vector. The former is computed from the dynamic pressure and the attack and sideslip angles measured at the tip of the nose boom or on the radome, whereas the latter is measured by the inertial navigation system installed close to the center of gravity of the aircraft. Given the airspeed of the aircraft and the sampling rate of the various instruments, fluctuations in wind (three components), temperature, and moisture can be obtained with a good signal quality down to a spatial resolution of 5 m, which is sufficient (see section 3.2) to capture the energetic eddies even at the lowest flight altitudes. Because the two aircraft were frequently flown in coordinated missions, aircraft-to-aircraft intercomparison was done for both mean thermodynamical parameters and turbulence moments [*Lambert and Durand*, this issue]. No significant bias was detected between the two aircraft, which were therefore used interchangeably.

3. Data Processing

3.1. Ship Data

From the ship data at the foredeck mast the turbulent flux of momentum, sensible heat and latent heat were computed, when

the turbulence instruments were operating, with the inertial dissipation technique in order to compute the bulk coefficients [Dupuis *et al.*, 1995, 1997]. It was assumed that the turbulence measurements were performed in the surface, constant flux layer within which the Monin-Obukhov similarity theory can be applied, and that the computed flux can be considered as surface flux. Lambert [1997] presents characteristic values of the mixed layer thickness encountered during SEMAPHORE. These values are, on average, of the order of 900 m, which ensure the turbulence measurements on the ship to be performed well within the lowest 10% of the mixed layer. Starting from the Kolmogorov formulation of the energy spectra in the inertial subrange, the dissipation rate of the turbulent kinetic energy (TKE), and the destruction rates of the variances of temperature and specific humidity, were computed in a frequency range that is not affected by the ship motion (we adopted for that the commonly used values of 0.55 and 0.80 for the Kolmogorov and Obukhov-Corrsin constants, respectively). The turbulent fluxes of sensible and latent heat and of momentum were thus deduced by solving the rate equations of TKE and variances of temperature and moisture. Different algorithms can be used for solving these equations, according to the value of the stability parameter, which itself depends on the three fluxes. Dupuis *et al.* [1997] described in detail the iterative algorithms developed for computing the fluxes, according to the number of sensors working at the same time during the experiment. Among the various sensors the sonic anemometers are the more reliable for measurements close to the sea surface, whereas fast hygrometers are more difficult to use routinely, and temperature sensors are often salt contaminated. This led us to use the sound velocity measured by the sonic anemometer to calculate the "pseudo virtual" temperature (the so-called sonic temperature) and thus derive the "pseudo buoyancy" flux instead of the sensible heat flux. If the three dissipation rates (for wind speed, pseudo-virtual temperature, and humidity) are not available at the same time, bulk estimates of the corresponding fluxes are required for computing the fluxes by the inertial dissipation method. This method was described in detail by Dupuis *et al.* [1997], who presented a discussion on the parameterization of the different terms in the TKE budget equation. From the turbulent fluxes the bulk coefficients were thus deduced for the whole campaigns (SOFIA and SEMAPHORE).

The data set corresponds to 950 momentum fluxes derived from 12-min runs every 15 min when the relative wind direction was within 20° of the bow. A few additional samples within this range of relative wind direction presented the expected -5/3 power law in the inertial subrange and therefore allowed the computation of the dissipation rates. However, these samples were removed because the stratification was very unstable and the algorithm of the inertial-dissipation method did not converge. Similarly, 544 pseudo-buoyancy fluxes and 220 latent heat fluxes were computed. The corresponding bulk coefficients present a high statistical confidence and can therefore be considered as valid for the various conditions encountered during the campaigns. The following formulations were retained for the whole data set of SOFIA and SEMAPHORE

$$10^3 C_{D_n} = \frac{11.7}{U_{10_n}^2} + 0.668 \quad U_{10} < 5.5 \text{ m/s} \quad (1)$$

$$10^3 C_{D_n} = 0.019 U_{10_n} + 0.978 \quad 5.5 \text{ m/s} \leq U_{10} < 7.5 \text{ m/s} \quad (2)$$

$$10^3 C_{D_n} = 0.07 U_{10_n} + 0.6 \quad U_{10} \geq 7.5 \text{ m/s} \quad (3)$$

$$10^3 C_{H_n} = 10^3 C_{E_n} = \frac{2.79}{U_{10_n}} + 0.66 \quad U_{10} < 5.2 \text{ m/s} \quad (4)$$

$$10^3 C_{H_n} = 10^3 C_{E_n} = 1.20 \quad \text{for } U_{10} \geq 5.2 \text{ m/s} \quad (5)$$

where C_{D_n} , C_{H_n} and C_{E_n} are the neutral values of the drag coefficient, the Stanton number, and the Dalton number, respectively, and U_{10_n} is the neutral wind at 10 m. For more details, see Dupuis *et al.* [1997]. Reviews of the experimental determination of the exchange coefficients can be found in work by Geernaert [1990] and Saïd and Druilhet [1991]. The parameterizations mentioned in the above formulae lie well within the scatter of the results reported in these two papers, as far as the wind speed is $> 5 \text{ m s}^{-1}$. The main difference appears on the drag coefficient at low wind speed, for which only few data can be found in the literature; Dupuis *et al.* [1997] showed the importance of the "imbalance" term associated with the pressure-correlation and turbulent transport in the budget equation for the TKE and proposed a parameterization of this term. This resulted in considerable modifications on the computed momentum flux via the inertial-dissipation technique and therefore on the drag coefficient, which reaches very high values at low wind speeds. These values, much higher than in numerous previous studies, are in good agreement with the recent works of Greenhut and Khalsa [1995] and Yelland and Taylor [1996]. Moderate winds were frequently observed during SOFIA and SEMAPHORE, as can be seen on the wind histogram presented in section 5.3. We therefore compared the bulk coefficients, as deduced from the above formulae for the 10-m wind speed of 5 and 10 m s^{-1} , with some of the most widely used values for unstable conditions. The results are given in Table 1. It can be seen that the bulk coefficients deduced from SOFIA and SEMAPHORE lie well within the scatter of the various estimations; for example, for the Stanton and Dalton numbers our coefficients are slightly greater than those obtained from HEXOS and TOGA COARE but slightly lower than those of Liu *et al.* [1979]. For the drag coefficient most of the authors agree that it increases with the wind, and our values are very close to the other estimates.

The sensible heat flux, latent heat flux, and momentum flux were thus computed using the above bulk formulae for the whole data set of SOFIA and SEMAPHORE. These bulk fluxes were compared with the corresponding surface fluxes deduced from aircraft measurements when the two platforms operated in the same area. This technique allowed us to increase the number of points in the comparison diagrams, in spite of several periods during which one or another turbulence instrument was inoperable on the ship or navigation conditions did not allow turbulence measurements (mainly because of the relative wind direction).

3.2. Aircraft Data

Aircraft flux was computed using the eddy-correlation technique on straight and level runs 25 to 30 km long. Flux computation requires the knowledge of the fluctuations of the air vertical velocity and another parameter (horizontal velocity, temperature, or specific humidity) in the whole frequency range contributing to the flux; that is the range where the corresponding cospectrum is significant. On the high-frequency range the resolution used (about 5 m in wavelength) allows us to reach the limit of the cospectrum significant energy: let us consider a typical low-altitude level flight (say 100 m). The

Table 1. Neutral Bulk Coefficients at 10 m for Wind Velocities at 10 m (U_{10}) of 5 and 10 $m s^{-1}$, and for Unstable Conditions

	$U_{10} = 5 m s^{-1}$			$U_{10} = 10 m s^{-1}$		
	$10^3 C_{D_n}$	$10^3 C_{H_n}$	$10^3 C_{E_n}$	$10^3 C_{D_n}$	$10^3 C_{H_n}$	$10^3 C_{E_n}$
Liu <i>et al.</i> [1979]	1.20	1.36	1.39	1.44	1.26	1.30
Anderson and Smith [1981]	–	–	0.96	–	–	1.38
Large and Pond [1981, 1982]	1.14	1.13	1.15	1.14	1.13	1.15
Geernaert <i>et al.</i> [1987]	1.01	–	–	1.43	–	–
Smith [1988, 1989]	1.03	1.00	1.20	1.30	1.00	1.20
HEXOS [Smith <i>et al.</i> , 1992 ; DeCosmo <i>et al.</i> , 1996]	0.85	1.14	1.12	1.43	1.14	1.12
TOGA COARE [Fairall <i>et al.</i> , 1996]	1.02	1.10	1.13	1.29	1.09	1.12
SOFIA SEMAPHORE [Dupuis <i>et al.</i> , 1997]	1.14	1.22	1.22	1.30	1.20	1.20

C_{D_n} , C_{H_n} , and C_{E_n} represent the neutral bulk coefficients for momentum, sensible heat, and latent heat, respectively.

characteristic length scale (defined as the wavelength of the vertical velocity spectrum peak or of the cospectrum peak) is of the order of several hundreds of meters (see, for instance, Kaimal *et al.* [1972] and Saïd [1988]). Given the resolution of aircraft measurements (5 m, i.e., 2 orders of magnitude lower than the characteristic wavelength) and the decrease in the cospectral energy in the inertial subrange (according to a $-7/3$ power law), we can conclude that the high-frequency limit of the cospectra is properly attained. These arguments can be quantitatively reinforced; let us consider a universal shape for the inertial subrange cospectra in the surface layer for moderately unstable conditions, like that proposed by Kaimal *et al.* [1972] for the sensible heat flux

$$nC_{w\theta}(n) = \langle w'\theta' \rangle_0 0.14(nz/U)^{-4/3} \quad (6)$$

where n is the frequency, $C_{w\theta}$ is sensible heat flux cospectrum, z the altitude of the sample, and U is the airspeed of the sensor. Knowing that the frequency integral of the cospectrum is the covariance, integrating (6) from the Nyquist frequency n_q up to the infinite frequency gives

$$\frac{(w\theta)_{HF}}{\langle w'\theta' \rangle_0} = 0.10(n_q z/U)^{-4/3} \quad (7)$$

where $(w\theta)_{HF}$ represents the contribution to the flux of the frequencies greater than the Nyquist frequency. Considering the lowest altitude aircraft measurements ($z = 60$ m), $U = 80$ $m s^{-1}$ and $n_q = 8$ s^{-1} (typical values for the Fokker 27), the right-hand-side term of (7) only reaches about 0.009. The values are even lower for the momentum flux.

On the low-frequency side the problem is much more ambiguous, because cospectra are not well bounded (see, for instance, Kaimal *et al.* [1976]). These low-frequency transfers increase what Lenschow and Stankov [1986] call the "random" error in flux computation. In order to reduce this error a high-pass filter is generally applied on aircraft turbulence data. This filtering is done on the Fourier transform of the time series and does not therefore modify the phase of the signal (as opposed to the real-time filtering). The drawback of this filtering is what Lenschow *et al.* [1994] call the "systematic" error, which results in an underestimation of the flux. The choice of the cutoff of the

filter is thus a compromise between these two sources of error: when the cutoff frequency increases, the random error diminishes, whereas the systematic error increases. Our choice was a cutoff wavelength of 5 km, which allowed to capture, at least in the lower part of the boundary layer, most of the eddies contributing to the transfer (see Lambert and Durand [this issue] for more details). We will examine the consequences of this filtering on the flux values later on.

3.3. Estimation of Surface Flux From Aircraft and Ship Data

The aircraft runs selected for the airborne-shipborne comparisons were those performed close to the ship (generally within a distance of 30 to 50 km). Figure 1 presents an example of the horizontal tracks of the two aircraft and of the ship during a typical coordinated experiment. The two aircraft described the "L"-shaped pattern shown on Figure 1 at eight altitudes ranging between 80 m and 1870 m above the sea surface. The rectangle displayed in Figure 1 indicates the horizontal area (about 57 (longitude) \times 44 km (latitude)) within which the airborne measurements were retained for comparison with shipborne measurements. At this spatial scale the surface flux can be considered as homogeneous enough to allow a comparison between "surface-based" and spatially averaged measurements. The shipborne fluxes were averaged during the time interval corresponding to the vertically stacked runs performed by the aircraft in the area (generally 2 hours). The aircraft surface flux is defined by a linear extrapolation toward the surface of the flux measured at various altitudes within the marine atmospheric mixed layer: the individual runs performed at similar altitude were first averaged. A linear regression was then fitted through these averaged values in order to determine the surface value. In the case of the momentum flux, only the transfer of the wind component parallel to the mean wind along each run was retained. An example of surface flux determination is given in Figure 2, which presents the profile of the covariance $\langle w'\theta' \rangle$ (proportional to the sensible heat flux) measured during the pattern shown in Figure 1. Only the measurements below 900 m (which is the altitude of the top of the mixed layer for this situation) were used for the regression. As can be seen on Figure 2, there is a good coherence between the measurements of the two aircraft. These data also illustrate the variability of the flux

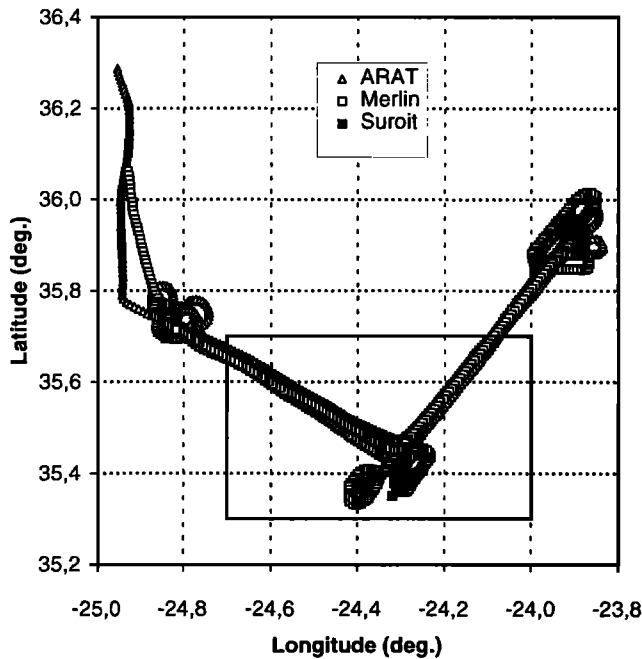


Figure 1. Horizontal tracks of the two aircraft (Merlin IV and Fokker 27 "ARAT") and of the ship R/V Le Suroit (solid squares) during a typical coordinated experiment. The two aircraft described the "L"-shaped pattern at eight altitudes spaced between 80 and 1870 m above the sea surface. The rectangle indicates the horizontal area within which the airborne measurements were retained for comparison with shipborne measurements.

estimation between various runs performed at the same altitude over areas close to each other.

The extrapolation toward the surface assumes that the flux divergence is almost constant through the lower part of the mixed layer. This assumption could fail, in particular in the surface layer within which the fluxes are assumed to be constant by the Monin-Obukhov similarity theory. However, taking into consideration that the surface layer thickness does not exceed 10% of the mixed layer thickness (and is probably lower because of the low values of the sea surface roughness), we will consider that the surface values are little affected by this problem; given the flux profiles in the mixed layer, as presented by Lambert [1997], we can conclude that a constant flux layer provokes a slight underestimation of the sensible heat flux and momentum flux (in absolute value), whereas the latent heat flux is little affected. Nicholls [1985] analyzed various methods to determine surface values from aircraft measurements, based either on the extrapolation of the flux profile or on the computation of the flux divergence between the lowest flight level and the surface, from the basic equations of the mean parameters (wind, temperature, and moisture). He stated that the various methods generally agree well, provided that the mixed layer thickness was greater than a few hundred meters, which is well verified for our data set.

4. Comparison Between Airborne and Shipborne Flux

Figures 3, 4, and 5 present the comparison between aircraft and ship values of sensible heat flux, latent heat flux, and the sum of these two fluxes, respectively. The comparison of the

momentum flux is presented in Figure 6. The error bars in Figures 3, 4, and 6 will be discussed in section 5. The flux was weaker (in average) for SOFIA than for SEMAPHORE, which can be explained by a greater variability of meteorological conditions during the latter campaign than during the former; SOFIA was performed in June with anticyclonic, light wind conditions, whereas during SEMAPHORE, anticyclonic and perturbed conditions alternated regularly. However, the following conclusions are valid for the two campaigns. In order to quantify the differences between the two platforms a linear regression has been set through the data, with the following relation

$$F_s = a F_a + b \quad (8)$$

with

$$a = \sigma_s / \sigma_a \quad b = \langle F_s \rangle - \langle F_a \rangle (\sigma_s / \sigma_a) \quad (9)$$

In the above formulae, F represents the considered flux; the subscripts "s" and "a" refer to ship and aircraft, respectively; the brackets denote the average; and σ is the standard deviation of the flux data set. We chose this kind of regression in order to not "a priori" define what are the dependent and independent variables. Table 2 indicates the values of a , b , and the corresponding correlation coefficient r , as well as the root-mean-square (rms) of the difference between the two platforms σ_{sa} and the same parameter normalized by the average ship flux $\sigma_{sa} / \langle F_s \rangle$.

The sensible heat flux presents weak values (lower than 30 W m^{-2}), resulting from moderate winds and low differences in temperature between the sea surface and the air above. Given these weak values, the correlation between the two platforms is reasonably good. However, the aircraft values are considerably smaller than the ship values. Although the difference was weak in terms of energy budget (some W m^{-2}), it appears to be significant in terms of turbulent flux measurement; the ship values are 37% greater than the aircraft values, which is greater than the scatter of the data.

The latent heat flux values are an order of magnitude greater than the sensible heat flux ones (between 50 and 200 W m^{-2}). As

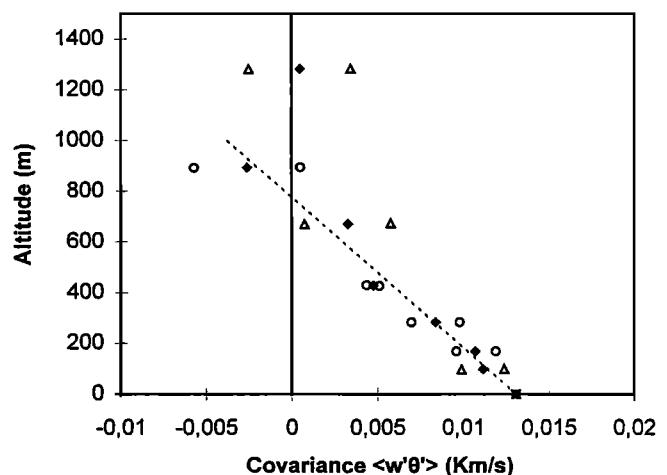


Figure 2. Example of sensible heat flux airborne measurements. Open triangles and circles represent the individual runs of the Fokker and Merlin, respectively. Averaged values at quasi-constant altitudes are represented by the solid diamonds through which the linear regression (dashed line) allows us to determine the surface flux (solid square).

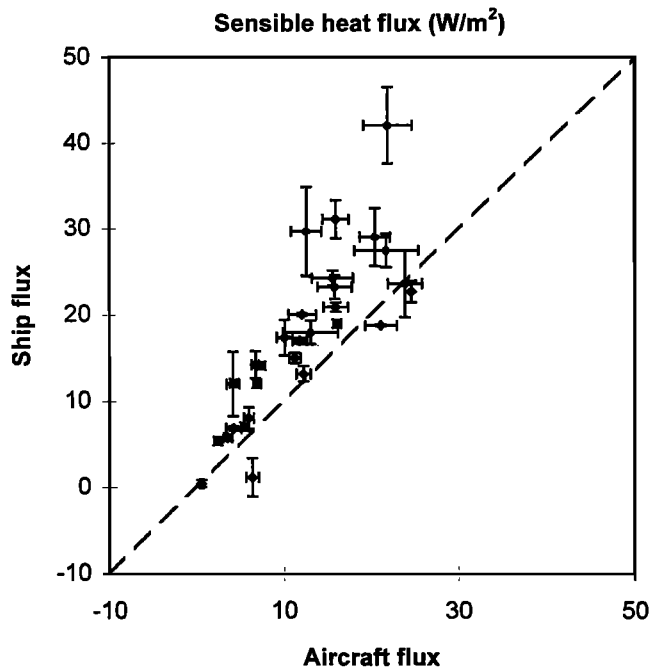


Figure 3. Surface sensible heat flux measured by aircraft versus that measured by ship for the SOFIA (squares) and SEMAPHORE (diamonds) experiments. The error bars are indicated on the SEMAPHORE data.

for the sensible heat flux, the aircraft values are lower than the ship values. The correlation between the two platforms is good, indicating the coherence of the measurements. The difference between the two estimations is composed on the one hand by a systematic bias of 12 W m^{-2} and also by a scale factor of 13%. The scatter is lower than for the sensible heat flux. However, if we regard the surface energy budget and therefore the absolute value of the flux, the discrepancy between the two platforms is greater for the latent heat flux than for the sensible heat flux.

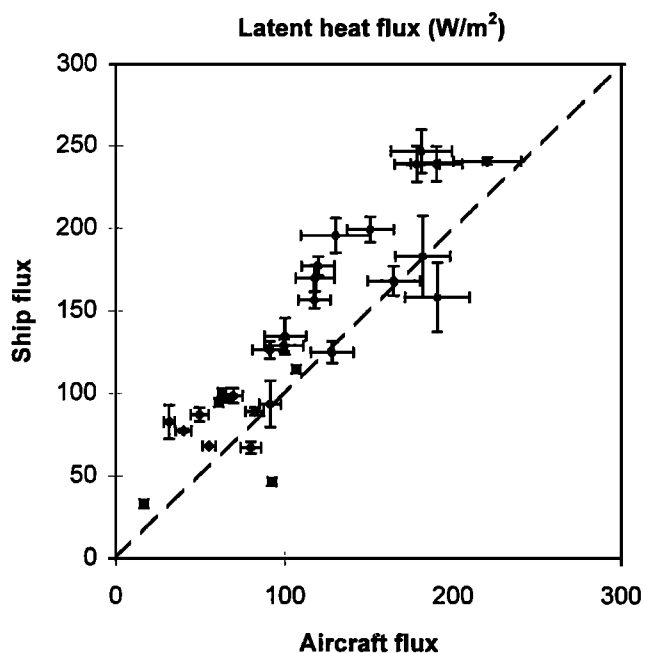


Figure 4. Same as Figure 3, but for latent heat flux.

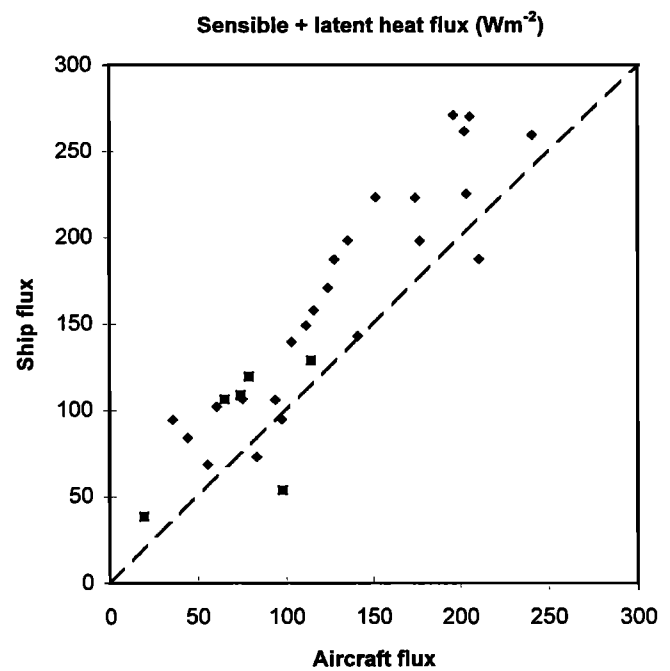


Figure 5. Surface latent heat flux plus sensible heat flux measured by aircraft versus that measured by ship. Same symbols as in Figure 3.

In the frame of the knowledge of the surface energy budget, we attempted to correlate between the two platforms the sum of the sensible and latent heat flux. Most values lie between 50 and 270 W m^{-2} , i.e., close to the latent heat flux values. The comparison between the two platforms also gives results similar to those concerning the latent heat flux.

The behavior is noticeably different for the momentum flux. Better correlation between the two platforms is obtained for this parameter. However, it appears that the aircraft low fluxes are smaller than the corresponding ship ones, whereas it is the opposite for greater fluxes.

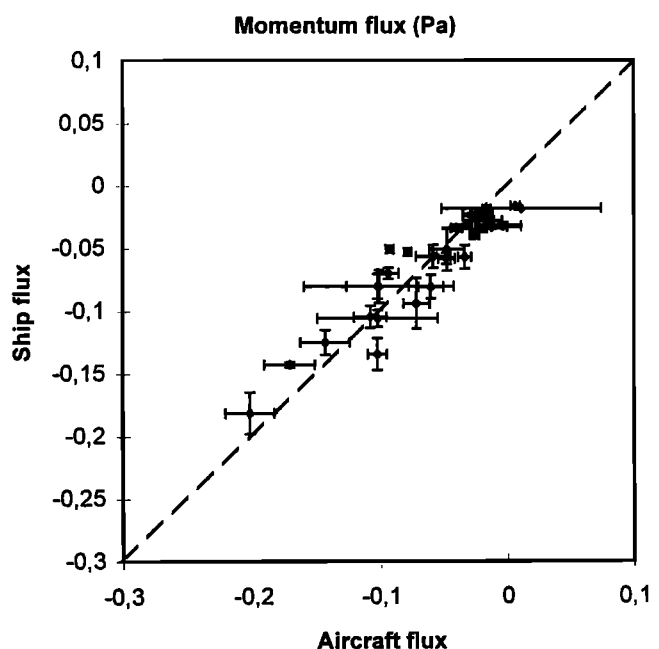


Figure 6. Same as Figure 3, but for momentum flux.

Table 2. Regression Characteristics Between the Two Platforms

	<i>a</i>	<i>b</i>	<i>r</i>	σ_{sa}	$\sigma_{sa}/\langle F_s \rangle$
Sensible heat flux (<i>H</i>)	1.37	1.*	0.82	5.5*	0.32
Latent heat flux (LE)	1.13	12.*	0.89	27.8*	0.20
<i>H</i> + LE	1.15	12.*	0.91	28.1*	0.19
Bowen ratio <i>H</i> / LE	0.97	0.02	0.58	0.047	0.37
$\overline{w'\theta_v'}$	1.27	0.001†	0.91	0.005†	0.21
Momentum flux	0.81	-0.014‡	0.93	0.019‡	0.31
- <i>T</i> *	1.41	0.0006§	0.82	0.018§	0.29
- <i>Q</i> *	1.09	0.018	0.76	0.045	0.22
$\log_{10}(-L_{mo})$	0.92	0.04	0.90	0.20	0.12

Regression characteristics are as defined in (8) and (9). Here, *F* represents the considered flux, the subscripts "s" and "a" refer to ship and aircraft, respectively, the brackets denote the average, and σ is the standard deviation of the flux data set.

- * W m⁻²
- † K m s⁻¹
- ‡ Pa
- § K
- || g kg⁻¹.

Table 2 also includes several parameters that have been computed from the three fluxes. First of all, the Bowen ratio *B* represents the ratio of the sensible heat flux to the latent heat one ; *B* = *H* / LE. This parameter does not present any systematic difference between the two platforms. However, the scatter is high and the correlation poor, which results from the low values of *B* and from the fact that the computation of *B* cumulates the errors on *H* and LE.

Another term which can be deduced from the fluxes is the buoyancy flux defined as

$$\overline{w'\theta_v'} = \overline{w'\theta'} + 0.61\overline{\theta'w'q'} \tag{10}$$

where θ_v is the virtual potential temperature and *q* is the specific humidity. Here $\overline{w'\theta_v'}$ is proportional to the buoyancy term in the budget equation of the TKE. Given the values of *H* and LE (and, accordingly, of $\overline{w'\theta'}$ and $\overline{w'q'}$), the two terms of the right-hand side of the above equation are of the same order of magnitude ; that is, the contribution of moisture fluctuations to surface buoyancy is as high as that of temperature fluctuations. The ship values of the buoyancy flux are 27% higher than the aircraft ones, with a scatter comparable to that of the latent heat flux.

Several scales can be deduced from the surface fluxes. According to Monin-Obukhov similarity theory we can define the temperature scale (*T**), the moisture scale (*Q**), and the Monin-Obukhov length (*L*_{mo}) as

$$-T_* = \frac{\overline{w'\theta'}}{u_*} \tag{11}$$

$$-Q_* = \frac{\overline{w'q'}}{u_*} \tag{12}$$

$$-L_{mo} = \frac{u_*^3}{k(g/T)\overline{w'\theta_v'}} \tag{13}$$

where *u** is the friction velocity, *k* is von Karman's constant (*k* ≈ 0.4), and *g* is the gravity. The estimations of these three characteristic scales from the two platforms were compared. Dealing with *T** and *Q** allows the removal from the flux comparison of a possible discrepancy coming from the *u** values. As can be seen in Table 2, the differences in *T** and *Q** between the two platforms are comparable to those observed on the sensible heat flux and latent heat flux, respectively. Finally, *L*_{mo}, which characterizes the stability conditions in the surface layer, presents a good correlation between the two platforms. The aircraft values are, however, slightly greater than the ship ones.

An attempt was made to correlate the discrepancy between the two platforms with the characteristic scales of the surface layer, *u** and *L*_{mo}. The results, presented by Lambert [1997], do not show any relationship for any of the three fluxes. In the following section we will concentrate on the various errors involved in the aircraft and ship flux estimates.

5. Discussion

5.1. Random Error on Aircraft Flux Estimates

For people familiar with aircraft measurements the behavior of the momentum flux, which seems to be at least as good as the scalar fluxes, constitutes a pleasant surprise. It is a common advice to consider that, for a given run, momentum flux measurement is of poorer quality than scalar flux measurements. This opinion has been motivated by the work of Lenschow and Stankov [1986], which performed an analysis of the integral scales of the various turbulent processes in the convective boundary layer. Given a run length in the boundary layer, the accuracy on a flux estimation (the so-called random error) results from the integral scale of this instantaneous flux. In other words, and to simplify, the greater the length of the run, the better the sampling of the characteristic eddies and the better the accuracy on the flux estimation. The knowledge of these length scales therefore allows determination of how long the run has to be to attain the required accuracy. As an example, Lenschow and Stankov [1986] proposed simple parameterizations to compute the required lengths *L*_{wu} and *L*_{wx} for a 10% accuracy on the momentum and scalar fluxes, respectively (scalar flux could relate to either sensible or latent heat flux). Combining their formulae (17) and (27) gives

$$L_{wu} / L_{wx} = (z / h)^{-1/3} (-0.60h / L_{mo})^{4/3} \tag{14}$$

where *z* is the altitude of the run and *h* is the mixed layer thickness. We can see from (14) that, in the mixed layer, *L*_{wu}/*L*_{wx} is always greater than unity, provided that -0.60*h* / *L*_{mo} > 1., which was verified in most of the situations encountered during SOFIA and SEMAPHORE. As a consequence, the required length would be greater for the momentum flux than for the scalar flux, for the same accuracy ; for a given length the expected accuracy would be better for scalar flux than for momentum flux.

According to Lumley and Panofsky [1964] and Wyngaard [1983] the theoretical formulation for the random error can be expressed as

$$\sigma_{ab} / \langle a'b' \rangle = \left[2 \frac{\lambda_{ab}}{L_{ab}} (1 + r_{ab}^{-2}) \right]^{1/2} \tag{15}$$

where σ_{ab} is the error on the covariance $\langle a'b' \rangle$, λ_{ab} is the integral scale of the instantaneous covariance $a'b'$, L_{ab} is the length of the run on which $\langle a'b' \rangle$ is computed, and r_{ab} is the correlation coefficient between a and b . Here, λ_{ab} was computed from the autocorrelation of the signal $a'b'$. We computed σ_{wb} , σ_{wq} , and σ_{wu} in the following way: we only considered the lowest altitude runs (generally 90 m) because they have the greatest influence on the surface flux determination. As mentioned before, several runs performed at close altitude were averaged before extrapolation toward the surface. We computed the average value of λ_{ab} , L_{ab} , and r_{ab} on these runs and computed σ_{ab} with (15). Considering that σ_{ab} represents a random error, which can therefore be reduced by increasing the number of the runs, the final error was expressed as $\sigma_{ab}/n^{1/2}$, where n represents the number of runs performed at the lowest altitude. These computations were only performed for the SEMAPHORE data. The corresponding error bars are plotted on Figures 3, 4, and 6 for the sensible heat flux, latent heat flux, and momentum flux, respectively. It can be seen on these figures that the relative errors on the sensible and latent heat flux are of the same order of magnitude and smaller than those on the momentum flux, in qualitative agreement with the work of *Lenschow and Stankov* [1986]. It can also be seen on Figures 3, 4, and 6 that for sensible and latent heat flux the discrepancy between aircraft and ship estimates is generally greater than the error, whereas for the momentum flux it lies within the scatter of the results.

5.2. Systematic Error on Aircraft Flux Estimates

Among the various hypotheses invoked in the literature to explain the differences between airborne and surface-based flux estimates, one concerns the consequences of the high-pass filtering of the aircraft signals. This reason was invoked to

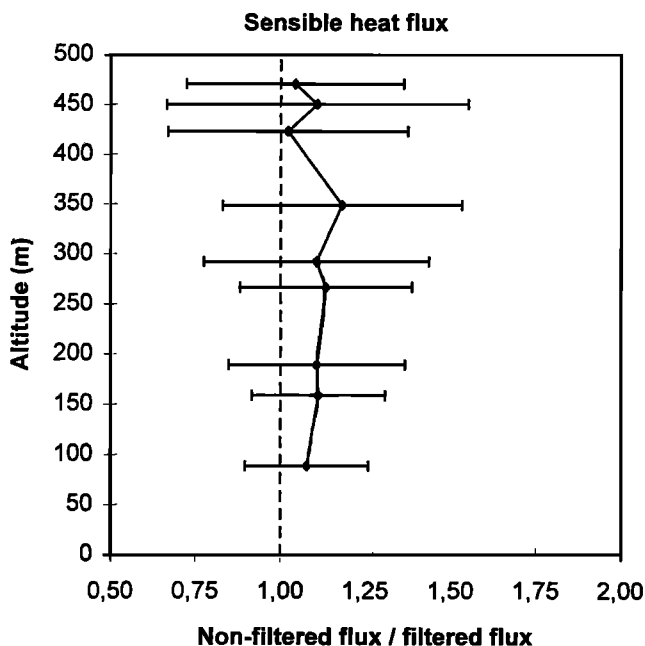


Figure 7. Ratio of the nonfiltered to the high-pass-filtered aircraft sensible heat flux versus altitude. The diamonds represent the average of individual runs in altitude bins of about 60 m. The horizontal lines represent the standard deviation within each altitude bin.

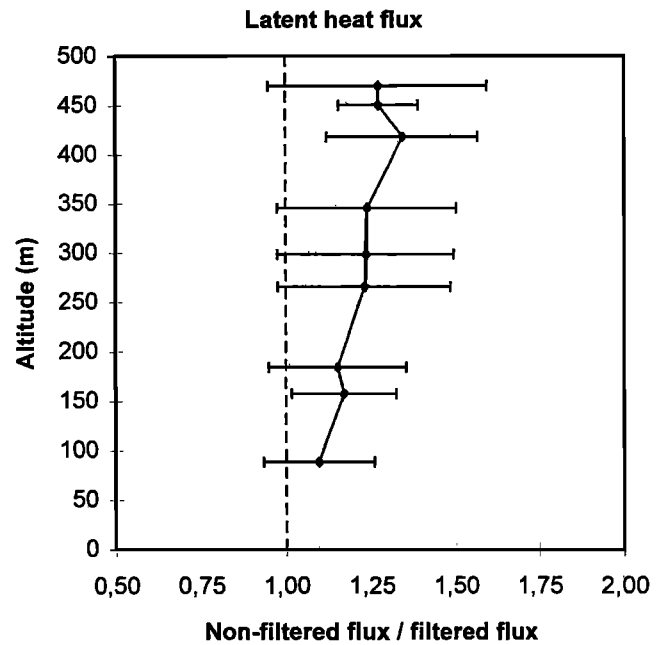


Figure 8. Same as Figure 6, but for latent heat flux.

explain the aircraft underestimation of flux during FIFE. High-pass filtering is generally considered as a "necessary damage" which cuts a part of the signals (and thus provokes a systematic error, as explained by *Lenschow et al.* [1994]) but is required to reduce the scatter of the estimated turbulence moments. As mentioned above, the cutoff frequency used is about 5 km in wavelength. This filtering could reduce the computed flux if wavelengths > 5 km (for example, coherent structures like roll vortices) contribute to the transfer. In order to carefully check this reduction we have computed the ratio of the flux computed from nonfiltered signals to that computed from high-pass filtered signals. "Nonfiltered", in fact, relates to raw signals from which the linear trend was removed. Owing to the increase in the turbulence characteristic scales according to altitude we have represented this ratio as a function of the altitude for the whole SEMAPHORE experiment. The results are presented in Figures 7, 8, and 9 for the sensible heat flux, latent heat flux, and momentum flux, respectively. Since the nonfiltered flux is much more scattered than the filtered one (because of the increasing random error, as explained above), this ratio presents some scatter as well. That is the reason why we present the values averaged within nonoverlapping altitude bins of about 60 m. More than 500 runs have been used to obtain these diagrams. The result is unambiguous: close to the surface, only a small fraction of the flux (a few percent) is transported by eddies whose size is comprised between 5 km and the sample length (generally, 25 to 30 km), which cannot explain the difference in sensible and latent heat flux observed between the two platforms. However, this proportion increases with altitude; for latent heat and momentum flux it reaches 20 to 30% at altitudes greater than about 300 m. The behavior of the sensible heat flux is quite different; the contribution of the low frequencies remains almost the same or even decreases at the highest altitudes. This difference can be explained as follows. As altitude increases, the turbulent length scales increase as well, and the cospectra are moved toward lower frequencies. Since the filter cutoff frequency is fixed to a constant value (i.e., it does not vary

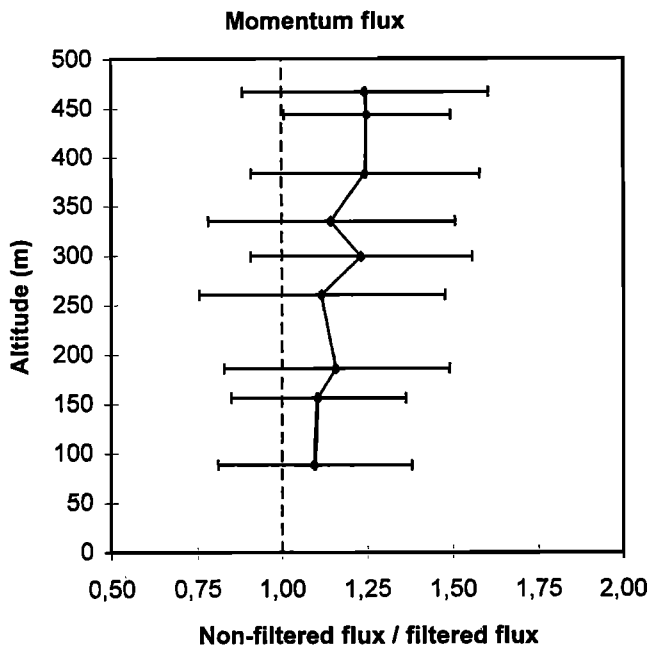


Figure 9. Same as Figure 6, but for momentum flux.

according to altitude), the relative contribution of the low-frequency range of the cospectrum to the filtered flux increases according to the altitude. If the low-frequency and "turbulent" contributions to the flux are of same sign, then the ratio nonfiltered flux / filtered flux increases as well. This is the case for the latent heat flux and (in most of the cases) for the momentum flux : the flux at lower altitude (transported by small-scale eddies) is of the same sign as the flux at the top of the mixed layer (transported by "mesoscale" eddies). If we now consider the case of the sensible heat flux, we know that the lower altitude flux (transported by small-scale eddies) is upward, whereas the flux in the upper part of the mixed layer is downward (transported by mesoscale eddies). In the medium part of the mixed layer these two scales are generally present. So the filtering in fact cuts off a "counter-flux" area of the cospectrum, which explains why this ratio does not continue to increase with altitude.

The mesoscale contribution to the flux is therefore of considerable importance except at the lowest altitudes in the atmospheric mixed layer. Given the cutoff wavelength of the filter, this contribution cannot be considered as turbulent. It, rather, relates to mesoscale eddies, like coherent structures which develop in the boundary layer, or mesoscale circulations. These results demonstrate that the role of the coherent structures has to be taken into account in the transfers in the atmospheric marine boundary layer (in spite of the horizontal homogeneity of the sea surface at mesoscale), as already shown by *Réchou and Durand* [1997]. *Mahrt* [1991] also pointed out the role of mesoscale circulations in the transfers, even at low altitude (100 m). However, his measurements were taken above a heterogeneous land surface. Our results show that close to the surface, the low frequencies do not significantly contribute to the flux, and the filtered and nonfiltered values are therefore close each other. As a consequence, the slope of the flux profile is different for filtered and nonfiltered flux, but the value extrapolated toward the surface is almost the same in both cases. Our current analyses therefore suggest that mesoscale transfer is not sufficient to

explain the discrepancy between the aircraft and ship surface flux.

5.3. Errors on Ship Flux Estimates

Owing that the ship flux estimates were computed with bulk coefficients, which themselves were deduced from the inertial-dissipation fluxes, we can identify three main sources of error : (1) instrumental errors, (2) errors in the estimations of the destruction rates of variances, and (3) errors related to the inertial-dissipation method itself.

We can consider that the first error is weaker than the others, provided that the various instruments worked properly, were correctly calibrated, and presented a high enough signal-to-noise ratio in the frequency range used. The Solent sonic anemometer has been extensively tested against other sensors [*Yelland et al.*, 1991], and it has been shown that its performance is good for the horizontal wind component (it is supposed to be less effective for the vertical component because of the contamination by the sensor structure). In particular, the behavior of the spectra in the frequency range chosen for the computation was verified to follow the "-5/3" power law [*Yelland et al.*, 1994]. The ship superstructure has, however, an effect on the measurement and can either accelerate or decelerate the flow. The flow distortion associated with experimental conditions on *Le Suroît* was however minimized by the sensor location [*Yelland et al.*, 1998].

Errors in the estimation of the destruction rates of variance could be provoked by a nonexact transformation of frequencies into wavenumber by the Taylor's hypothesis, because of the fluctuations of the horizontal airspeed of the sensor. This problem becomes important as the ratio of the velocity variance to the square of the mean wind increases, i.e., in free-convection conditions. *Wyngaard and Clifford* [1977] have shown that for moderately unstable conditions the consequences of the fluctuations of the sensor airspeed are limited to a few percent of the energy spectra in the inertial subrange. For the SEMAPHORE experiment the ratio of velocity standard deviation to the mean wind speed (relative to the ship) was carefully analyzed and it was shown that even at near-zero wind speed associated with very unstable stratifications, the Taylor hypothesis is still valid because of the ship's speed [*Dupuis et al.*, 1997]. Another source of error results from the fluctuation of the energy spectra in the inertial subrange around Kolmogorov's -5/3 power law. The consequences on the flux estimated by the inertial-dissipation technique were analyzed by *de Sà* [1992] from low-altitude airborne measurements. He showed that (1) the resulting error varies according to $L^{-1/2}$, where L is the length of the sample, and (2) this error is lower than the corresponding random error associated with the eddy-correlation technique on the same run.

We would infer from the above arguments that the major error on the inertial-dissipation flux lies in the method itself, i.e., in the validity of the approximations used and in the knowledge of the parameterizations of the remaining terms of the rate equations for variances. The first part of the problem has been discussed by *Fairall and Larsen* [1986]. Uncertainties associated with the parameterizations of the different terms in the TKE (or variance of temperature or humidity) budget equation are mainly related to low wind speeds or unstable stratifications. In contrast, at moderate wind speeds and for near-neutral stratifications, *Large and Pond* [1981] showed from comparisons between eddy-correlation and inertial-dissipation methods that the turbulent transport terms are negligible. As described in detail by *Dupuis et*

al. [1997] and *Yelland et al.* [1994], recent measurements show the necessity to account for the turbulent transport terms. Parameterizations have thus been proposed, whose influence on the flux values is great in conditions close to free convection. This remains a limitation of the inertial-dissipation method as long as an agreement for the parameterizations of the turbulent transport term is not found. It should, however, be noted that in the present study this problem mainly concerns low wind speed conditions, below 4 m s^{-1} [*Dupuis et al.*, 1997], for which the fluxes are weak. For higher wind speeds, turbulent flux estimations are not very sensitive to the chosen parameterization. Figure 10 presents the histogram of the average wind speeds observed during the experiments used for comparison between the two platforms. The wind was computed from the lowest-altitude aircraft measurements and can be considered as representative of the wind at the top of the surface layer. It is therefore probably slightly greater than the 10 m altitude wind which is used in the bulk formulae but is less affected by the stability conditions. Only 5 cases among the 30 intercomparison experiments present a wind speed $< 5 \text{ m s}^{-1}$, for which the exchange coefficients present a high variability. Thus, even if the relative uncertainty on the weak fluxes deduced from the inertial-dissipation method is highly increased due to the method itself, its consequence on the comparison between ship and aircraft measurements is weak. Indeed, regression equations described in section 4 are more sensitive to high values of the fluxes.

The random error on ship flux estimates can be quantified by the standard deviation of the computed bulk fluxes in the period of time during which the comparison between the two platforms

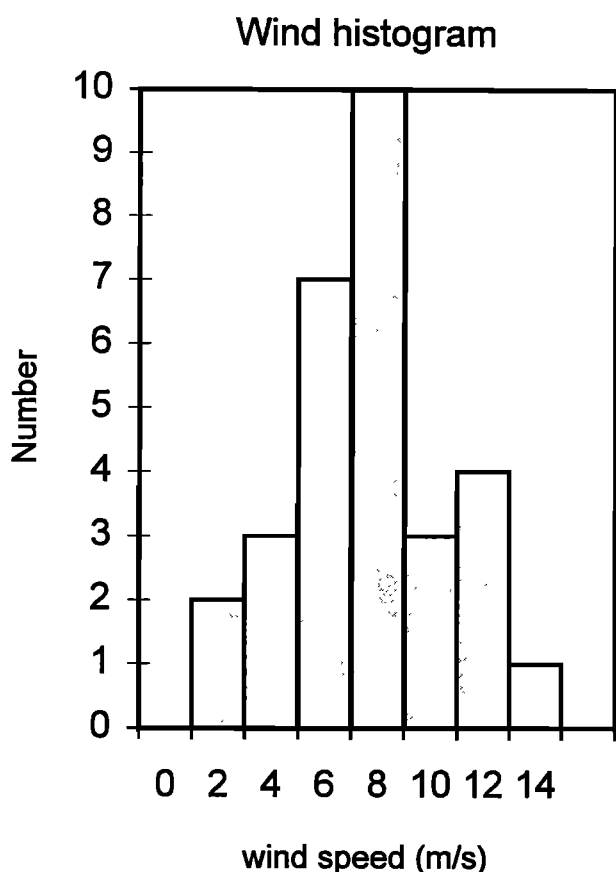


Figure 10. Histogram of the mean value of wind speed for the whole data set (SOFIA and SEMAPHORE).

was done. This time is on average of 2.0 hours and corresponds to the realization of the vertically stacked aircraft runs used to compute the flux profiles. This standard deviation is plotted on Figures 3, 4, and 6 for the sensible heat flux, latent heat flux, and momentum flux, respectively. As for the aircraft fluxes, only the SEMAPHORE data are concerned. We can see that the errors on the two platforms are comparable for the sensible and latent heat flux and are lower than the discrepancy between the two platforms. For the momentum flux the aircraft error is generally greater than the ship one.

5.4. Horizontal Nonisotropy of Turbulence

Durand et al. [1996] showed from the SEMAPHORE data that the estimation of the characteristic length scale of the turbulent vertical velocity (computed as the wavelength of the energy spectrum peak) was different whether the sampling direction of the aircraft was almost parallel or perpendicular to the mean wind. This behavior is most likely due to structures elongated along the mean wind. Such characteristics have already been evidenced over the sea by *Nicholls and Readings* [1981] and *Lenschow and Stankov* [1986]. As a consequence, the cospectra, when sampled along the mean wind, are shifted toward lower frequencies with respect to the cospectra sampled across the mean wind. *Durand et al.* [1996] showed that for a similar cutoff frequency the consequences of the high-pass filtering of the signals are thus different on the two perpendicular runs; along-wind runs are more affected than across-wind runs. However, this has few consequences on the aircraft surface flux determination because the filtering effects vanish close to the surface.

The consequences of this turbulence anisotropy on the ship flux measurements have to be examined, because ship measurements were always performed with the ship oriented into the wind. Since the orientation of the aircraft runs with respect to the mean wind was almost randomly distributed during the campaigns, we checked a possible relationship between the spectrum energy (for velocity, temperature, and moisture) in the inertial subrange and the orientation of the run. No relationship was found. So we conclude that the inertial-dissipation flux estimates aboard the ship were not affected by the constant orientation of the ship track along the wind. This was confirmed by *Durand et al.* [1996], who showed from aircraft measurements that the estimates of the dissipation rates do not depend on the orientation of the aircraft with respect to the wind.

5.5. Other Methods to Calculate Surface Fluxes

It would probably have been more appropriate to use the same method on the two platforms to compute the turbulent fluxes. However, the use of the eddy-correlation technique on ship measurements was not possible because the correction of the ship movement in the velocity computation is too important. Another possibility would have been to use the inertial-dissipation technique on the aircraft measurements. This method was already used by *Durand et al.* [1991] on very low altitude measurements. However, these authors have shown that this method did not work properly for low values of the sensible heat flux, as is the case during SOFIA and SEMAPHORE (this is probably due to the poor quality of the temperature measurements in the inertial subrange, because of the low values of the signal-to-noise ratio). Furthermore, this method is only valid in the surface layer and the lowest-altitude measurements were generally performed at 90 m, which probably is often above the top of the surface layer.

6. Conclusion

We compared from SOFIA and SEMAPHORE experiments the airborne eddy-correlation surface flux to the shipborne bulk flux estimates computed with the bulk coefficients deduced from inertial-dissipation fluxes measured on the ship. As for previous measurements performed over land during several campaigns, it appears that airborne sensible heat and latent heat fluxes are lower than corresponding measurements made in the atmospheric surface layer. The difference between the two platforms appears quite similar to that observed during the FIFE experiment, with an aircraft underestimation greater for the sensible heat flux (37%) than for the latent heat one (13% but with a bias of 12 W m⁻²). However, we must take into account that the sensible heat flux values are very low and that the discrepancy between the two platforms does therefore not exceed a few W m⁻². The momentum flux does not present a systematic difference, and the rms difference between the two types of platforms is of the order of 30% of the average value. This result is pleasantly surprising, since previous results showed that, on a given aircraft run, momentum flux estimates are considerably less accurate than heat flux ones. The difference between the two platforms obviously depends on the formulations used for the bulk coefficients, but the values computed from the SOFIA and SEMAPHORE data are close to other previous estimates, and the differences between the two platforms (for the sensible and latent heat flux) are greater than the difference between various bulk estimates.

The errors on the ship and aircraft flux were computed for the data of SEMAPHORE and validated the discrepancy for the sensible and latent heat flux. At present, no convincing explanation has been found to explain this discrepancy. Airborne-to-airborne comparisons have given good results, and the coherence of the airborne flux profiles through the marine atmospheric boundary layer is also good. This problem therefore does not seem to be limited to the low-altitude measurements but is probably relevant to the eddy-correlation airborne measurements (this conclusion can be established from measurements over land, because of the imbalance of the surface energy budget from airborne flux measurements ; it is probably also valid over the sea). The contribution to the flux of the lower frequencies was examined ; if it cannot explain the difference between the two platforms at low altitude, it is of considerable importance at higher altitudes in the atmospheric mixed layer and must therefore be taken into account in the estimation of the transfers throughout the boundary layer.

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