The FETCH experiment (Part 1/5)

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The FETCH experiment: An overview

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[1] The “flux, état de la mer, et télédétection en conditions de fetch variable” (FETCH) was aimed at studying the physical processes associated with air–sea exchanges and mesoscale oceanic circulation in a coastal region dominated by frequent strong offshore winds. The experiment took place in March–April 1998 in the northwestern Mediterranean Sea (Gulf of Lion). Observations were collected with the R/V L’Atalante, with an air–sea interaction spar (ASIS) buoy, with waveider buoys, and with research aircraft equipped for in situ and remote sensing measurements. The present paper is an introduction to the following special section, which groups 11 papers (including this one) presenting results on turbulent flux measurements at the ocean surface, on the behavior of the marine atmospheric boundary layer, on the ocean waves characteristics, on the ocean circulation, and on remote sensing of surface parameters. This overview presents the background and objectives of FETCH, the experimental setup and operations, and the dominant atmospheric and oceanic conditions and introduces the different papers of the special section.


1. Introduction

[2] The exchange of momentum and energy occurring near the air–sea interface and their relation with the atmospheric boundary layer or the ocean mixed layer have been the subject of many field experiments in the last 25 years. To quote a few, we can mention JASIN in 1978 [Pollard et al., 1983], HEXOS in 1984 [Katsaros et al., 1987], SOFIA/ASTEX in 1992 [Weill et al., 1995], RASEX in the Baltic Sea 1994–1995 [Vickers and Mahrt, 1997] followed by other Baltic Sea experiments [Smedman et al., 1994, 1999]. The case of nonhomogeneous surface conditions in the open ocean was specifically addressed with GALE [Dirks et al., 1988], JASIN [Pollard et al., 1983], FASINEX [Weller, 1991], SEMAPHORE [Eymard et al., 1996], and CATCH/FASTEX [Eymard et al., 1999]. The evolution of wave fields and the effect of sea state on turbulent exchanges were among the objectives of HEXOS [Smith et al., 1992], SWADE [Weller et al., 1991], MBL [Edson and Fairall, 1998], and SOWEX [Banner et al., 1999; Chen et al., 2000].

[3] These experiments have yielded important new knowledge on the physics underlying air–sea transfers, and in particular on the importance of surface waves on the problem. However, there remains a need to improve the understanding and modeling of the coupled air–sea system in a large range of conditions, most notably at high winds, where measurements are sparse and where sea spray may have a significant effect on the physics, and also at low winds where free convection becomes important, and where the presence of swell waves have been shown to have an effect. In addition, coastal conditions present specific characteristics, which need to be investigated, in particular to improve regional-scale atmospheric, wave, and oceanic prediction models.

[4] In this context, the international field campaign “flux, état de la mer, et télédétection en conditions de fetch variable” (FETCH) was organized in 1998 in the northwestern Mediterranean Sea (Gulf of Lion). It was
aimed at studying the physical processes associated with air–sea exchanges, and mesoscale oceanic circulation in a coastal region dominated by frequent strong offshore winds. It took place in March–April 1998. French, American, and Finnish groups participated in the experiment (see affiliations of the co-authors of the present paper). The specific characteristic of FETCH was to combine a large number of complementary data: in situ observations (ship and buoys), airborne observations (in situ and remote sensing), surface fields available from several atmospheric and wave models, spaceborne observations collected in a region characterized by deep water, frequent offshore winds (i.e., FETCH-limited situations), and ocean characteristics governed by three processes, namely wind forcing, river outflow, and large-scale circulation.

[5] When defining the experiment, four main general objectives were defined:
1. to develop and assess the methods of estimating turbulent fluxes of heat and momentum at the air–sea interface, and to analyze the turbulent and radiative fluxes in coastal conditions and their relation with the atmospheric boundary layer;
2. to document and analyze the evolution of the wave field in coastal (but deep water) conditions, including FETCH-limited situations, and to analyze the impact of sea state on the turbulent fluxes;
3. to improve the inversion algorithms and use of remote sensing measurements to describe the air–sea interface in general and in particular in coastal conditions;
4. to better describe the dominant factors of the ocean circulation in the Gulf of Lion and to develop the corresponding numerical modeling.

[6] More specifically, the experimental setup, procedure, and scientific analysis were aimed at:
1. further developing the methodology for estimating turbulent fluxes (in particular on a large ship), and assessing the turbulent flux estimates obtained from different methods;
2. analyzing the effect of wave development on the turbulent fluxes;
3. assessing the estimate of turbulent and radiative fluxes from models and satellites and further estimating the potential of remote sensing for documenting the fluxes at the mesoscale;
4. studying the boundary layer structure and its impact on fluxes in conditions of cold outbreaks;
5. analyzing the relation between aerosol characteristics, foam coverage, wind and momentum flux;
6. studying the surface wave properties (in particular growth law, directional spreading) in FETCH-limited (and other) conditions;
7. assessing wave prediction models and eventually proposing improvements to these models;
8. improving our knowledge on the relation between microwave and optical signatures of the ocean surface and surface properties, and assessing the methods for estimating wind and wave parameters from these observations (altimeter, SAR, and lidar) in coastal and FETCH-limited conditions, since existing algorithms were generally developed and tested for open sea conditions;
9. estimating the relative impact of wind forcing, river outflow, and large-scale circulation on the mesoscale oceanic circulation in the coastal zone.

[7] The following special section aims at presenting some of the results obtained on these subjects. Note that other papers have already been published elsewhere, in particular an analysis of aerosol properties is presented by Sellegri et al. [1991] and its relation with white cap coverage is presented by Massouh et al. [1999]. A study on the estimate of the wind vector from Synthetic Aperture Radar in these coastal conditions is also presented by Horstmann et al. [2001]. Studies are still ongoing on several topics so that other publications will probably appear in the future to complete this analysis.

[8] Before presenting the different papers (section 4), we first give an overview of the experiment and the data set (section 2), and of the dominant atmospheric and oceanic conditions (section 3).

2. The FETCH Experiment
2.1. General Presentation

[9] The location of the experiment is the Gulf of Lion, in the northwestern Mediterranean Sea (see Figure 1). The intensive period of observation of the campaign took place between 13 March and 15 April 1998. During this early spring period meteorological conditions at the experimental site are characterized by frequent events of strong northerly (Mistral) or northwesterly (Tramontane) winds generated by the synoptic atmospheric situation and the topography of the south of France, north of Italy, and northwest of Spain. According to a 34-year climatology archived by Météo-France, the March–April period is associated with 26% of the annual occurrences of Northwesterly to Northerly winds exceeding 8.5 m s$^{-1}$. Due to the land–sea temperature difference at this period of the year, cold air outbreaks were expected.

[10] Regarding the sea conditions, the gulf has a fairly large continental shelf that is largely open toward the deep basin, and a steep continental slope incised by numerous submarine canyons. The adjacent land area is drained by more than 10 rivers. The Rhône River supplies about 80% of the total fresh water and solid discharge to the gulf. The oceanic currents on the shelf are intimately linked to the winds and the dispersal of the Rhône river plume. The permanent Liguro-Provençal Current that represents the northern branch of the cyclonic circulation of the western Mediterranean Basin dominates the circulation along the slope.

2.2. Experimental Setup

[11] The experimental platforms deployed for the experiment were:
1. The R/V L’Atalante operated by Genavir and IFREMER (France), with a meteorological mast installed and equipped by Météo-France and Centre d’Étude des Environnements Terrestres et Planétaires (CETP) (France),
2. A moored air–sea interaction spar (ASIS) buoy operated by the Rosenstiel School of Marine and Atmospheric Science (USA),
3. A moored Datawell directional waverider (DWR) operated by the Finnish Institute of Marine Research (Finland),
4. A drifting Datawell nondirectional wave buoy operated by Météo-France,
5. Three aircraft used for both in situ and remote sensing measurements (France and Germany). The main characteristics of these platforms are described below.

2.2.1. R/V L’Atalante

[12] The mission of R/V L’Atalante was to provide measurements in the atmosphere (mean and turbulent parameters), at the surface (waves, white capping, sea surface temperature, and salinity), and in the ocean (current and hydrological profiling). In addition, microwave remote sensing of both the atmosphere and the surface was performed from the ship.

2.2.1.1. Atmospheric Measurements From R/V L’Atalante

[13] A meteorological mast was mounted near the bow on the ship foredeck and equipped (see Figure 2) by CETP and Météo-France with sensors mounted at a level of 17.8 m above mean sea level. Conventional sensors were used to measure mean parameters: wind speed, and direction (from two Young propellers), air pressure, dry air temperature, relative humidity, and incident solar total and IR radiation (from pyranometers and pyrgeometers). In addition, a radiation sensor (REPS,Q7) mounted on a horizontal boom fixed above the sea surface 8 m ahead of the bow of the ship measured the net IR radiative flux. All these meteorological data as well as additional data from the ship navigation system (position, heading, speed, yaw, etc.) and thermosalinograph (see below) were recorded on a dedicated data acquisition system at 0.1 Hz.

[14] The mast was also equipped, at the 17.8 m level, with sensors for turbulent measurements: a three-axis ultrasonic anemometer provided the three components of wind velocity and the sonic temperature, and a so-called refractometer based on a resonant microwave cavity measured the refractive index of the air [Delahaye et al., 2001]. Both instruments were synchronized, and continuously sampled at 50 Hz. Combination of these instruments provided the turbulent fluxes of momentum, latent and sensible heat using the inertial dissipation method [see Dupuis et al., 2002]. An inertial motion package was also mounted on the mast to acquire the ship attitude (pitch, roll) and vertical (heave) acceleration with the same sampling rate. This motion information, together with the ship yaw and ship speed provided by the navigation system was used to estimate the turbulent fluxes using the “eddy-correlation” method. Analysis of these results will be published separately.

[15] Atmospheric radiosoundings were launched from the deck of the ship at least twice a day or more frequently depending on the meteorological situation. Measurements of the size distribution and chemical properties of aerosols were also performed on R/V L’Atalante.

2.2.1.2. Surface Measurements From R/V L’Atalante

[16] Two optical systems were used on the ship to monitor the structure of the ocean surface (foam coverage, wave properties at short scale). The first one was an analog video camera, used over limited periods of observation (usually 10 min sequences during high wind conditions). Digitalization of the images was performed off-line and the images have
been used to estimate the foam coverage. A pair of synchronized digital still cameras was mounted on the ship’s rail of the upper deck and acquired pairs of images every 2 min (standard mode) or every 10 s (in certain occasions). This system was designed to provide both the foam coverage and the two-dimensional (2-D) properties of the short waves (from about 30 cm to 30 m) by using the stereoscopic information [Weill et al., 2002a, 2002b].

2.2.1.3. Ocean Measurements From R/V L’Atalante

Current and hydrological data were continuously collected along the ship’s track. Current profiles were obtained with an Acoustic Doppler Current Profiler (300 kHz RDI ADCP) mounted on the hull of the R/V L’Atalante. Currents were measured every 2 min in 50 bins of 4 m length each in the 10–150 m depth layer. Hydrological data were collected by deploying conductivity-temperature-density (CTD) probes. Finally, a thermsalinograph was used to measure the near-surface (3 m deep) temperature and conductivity along the ship’s track, with a sampling period of 10 s.

2.2.1.4. Remote Sensing of the Atmosphere and of the Surface From R/V L’Atalante

A microwave dual-frequency radiometer (23.8 and 36.5 GHz) called DRAKKAR [Gérard and Eymard, 1998; Eymard, 2000] was mounted on the guardrail of the upper deck of the ship (close to the stereo camera system) to measure the atmospheric water content and the brightness temperature of the sea surface. The installation onboard the ship enabled zenith pointing or surface pointing (about 25° and 50° incidence angles).

2.2.2. Buoys

An ASIS buoy [see Graber et al., 2000; Drennan et al., 2002] was moored from 18 March to 9 April 1998, by the University of Miami at 42°58’56”N, 04°15’11”E, roughly 50 km SSW of the Rhône delta at a depth of 100 m (point B in Figure 1). The mission of ASIS during FETCH was to provide the temporal evolution of turbulent momentum fluxes and directional wave spectra along with supporting mean parameters describing the atmospheric boundary layer and the ocean mixed layer. The location of ASIS was chosen to measure these parameters in FETCH-limited conditions, with a distance of ASIS from the coast of 60–80 km, respectively, in the northern to northwestern directions (Mistral and Tramontane directions). For turbulent fluxes in the atmosphere, ASIS was equipped with a Gill 3-Axis Solent sonic anemometer. The anemometer was mounted on top of a 4 m meteorological mast, i.e., 7 m above the mean surface level. A motion package was also installed on the ASIS underwater base to provide the six components of motion of the buoy. Mean air temperature and humidity at 5m above mean sea level were provided by a standard sensor. Sea surface temperature was measured at 2 m depth by a temperature transducer. Directional wave measurements were made using six capacitance wave gauges mounted in a centered pentagonal array. The wave gauge data were combined with the buoy motion data to
obtain the true elevation surface [see Drennan et al., 2002]. All the above ASIS data were continuously sampled and recorded at 12 Hz. During FETCH, a 300 kHz RDI ADCP system was also installed on the mooring of the tether buoy of ASIS (linked to ASIS by a surface floating line) to provide the current and turbidity profiles close to the sea bottom (between 78 and 98 m deep in 1 m vertical bins).

A DWR manufactured by Datawell was moored during FETCH by the Finnish Institute of Marine Research (FIMR). During the first part of the experiment (from 16 to 25 March) the DWR buoy was deployed close to the ASIS buoy location (2 km apart) in order to provide wave data for an intercomparison study [Pettersson et al., 2002]. On 25 March, DWR was recovered and redeployed closer to the shore at 43°09′34″N, 04°06′15″E, roughly halfway between ASIS and the coast (point B in Figure 1). This change of location was chosen to allow for shorter FETCH conditions compared to ASIS. The water depth at this location is 90 m.

To complement these surface wave measurements, an omnidirectional wave buoy of Datawell was also used. It was deployed from the R/V ‘L’Atalante’, left drifting, and recovered after successive periods of a few days.

2.2.3. Aircraft

Two aircraft from the French scientific community participated in the FETCH campaign: the Fokker 27 “ARAT” (Avion de Recherche Atmosphérique et de Télé-détection), operated by INSU (Institut National de Sciences de l’Univers) and a Fairchild MERLIN-IV operated by Météo-France. Both are research aircraft [see Chalon et al., 1998] equipped for atmospheric measurements (mean and turbulent parameters), and for remote sensing. During FETCH, the ARAT embarked the downlooking differential absorption lidar LEANDRE 2 [Bruneau et al., 2001a, 2001b], designed for water vapor mixing ratio profiling in the lower troposphere, with an emphasis on atmospheric boundary layer processes and surface–atmosphere moisture exchanges. The MERLIN-IV carried the RESSAC C-Band radar [Hauser et al., 1992] designed to study the ocean surface (wind, waves), using a conical scanning antenna. A third aircraft participated for a limited period of the experiment: the Falcon 20 of DLR equipped with the ADOLAR Doppler lidar system. Unfortunately, problems were encountered with this system and the data are not usable for analysis.

2.3. Operations

The operational plan was designed to take advantage of the complementary nature of the different platforms, in fulfilling the different experimental objectives. The cruise of the R/V ‘L’Atalante’ was composed of two legs: 13–29 March (Figure 3a), and 1–14 April (Figure 3b). During Figure 3. Ship track (a) for the first leg, (b) for the second leg, and (c) during a Mistral event (21 March). The star indicates the location of ASIS and the diamond indicates the position of the DWR after 25 March. In (c), the wind measured by R/V ‘L’Atalante’ along its track is indicated every 3 hours.
the first leg, the ship was shared with another scientific
group for the MOOGLI campaign [Díaz et al., 2000; Denis
et al., 2001] devoted to the study of biogeochemical aspects
of the Gulf of Lion. FETCH and MOOGLI cooperated for
some common measurements and operations, such as CTD
profiling.

During periods of offshore moderate to strong winds
(Mistral or Tramontane events), the priority was put on
along-wind transects performed by the R/V L’Atalante. Here
the ship headed at constant speed into the wind, providing
optimal exposure to the bow mast and sensors. When
possible these transects were chosen so that the ship would
pass near one or both moored buoys (see one example in
Figure 3c). Continuous acquisition of atmospheric and
hydrographic data from the ship was performed. During
several of these events, aircraft operations were carried out.
Aircraft sampled the atmosphere both along and across-
wind, usually with one or more passes over the ship and
the ASIS buoy. Low-level transects (300–1000 feet) were
performed to characterize the low-level atmospheric boun-
dary layer (mean and turbulent parameters). Higher-level
transects were flown for remote sensing measurements
(8000–12,000 feet). Vertical soundings (between the surface
and about 12,000 feet) were also performed by the aircraft
at least at two different locations during each flight.

Outside these periods of Mistral or Tramontane
events, the priority for the ship was to document the
oceanic characteristics (CTD profiling). A total of 169
CTD probes were deployed during the experiment (Figure
4). Alternatively, on several occasions the ship position was
chosen to provide data coincident with satellite measure-
ments (ERS or TOPEX/Poseidon), and specific transects
were performed in certain high onshore wind conditions.
For aircraft, the flights performed outside the period of
Mistral or Tramontane events were aimed at collecting in
situ and remotely sensed observations coincident with the
observations of the ERS and TOPEX/Poseidon satellites or
to provide observations in some high onshore wind con-
ditions.

2.4. Satellite and Model Data

In addition to the equipment specially deployed for
FETCH, relevant satellite data and model results were
acquired and archived for FETCH. Furthermore, some
specific hindcasts of wave prediction models have been
performed after the experiment.

The analysis and forecasts of three operational
atmospheric circulation models were archived for FETCH:
1. the IFS (Integrated Forecast System) of ECMWF with
a horizontal resolution at that time of approximately 50 km,
2. the global atmospheric model ARPEGE of Météo-
France with a resolution of approximately 25 km,
3. the limited area ALADIN model of Météo-France
(coupled with ARPEGE), with a horizontal resolution of
about 10 × 10 km and covering about 2000 × 2000 km
centered over France.
All these models provide 3-D fields of the atmospheric parameters (pressure, wind, temperature, and humidity), every 6 hours (every 3 hours for ALADIN).

[28] Also archived for FETCH are the forecast wave fields (directional wave height spectra) from two operational wave prediction models. The first one is the Mediterranean version of the WAM model [WAMDI Group, 1988] run at ECMWF with a 0.25° × 0.25° latitude–longitude resolution and driven by the IFS wind fields. It uses the cycle 4 version of WAM without wind wave coupling. The second wave model is the Mediterranean version of the VAG model of Meéteé-France [Guillaume, 1990] run with a resolution of about 25 × 25 km and driven by the ARPEGE wind fields.

[29] In addition, off-line research versions of VAG and WAM have been implemented to provide wave fields at high resolution (0.083° × 0.083° in latitude and longitude) over the Gulf of Lion. Three different hindcasts for each of the VAG and WAM models have been run with the three available wind fields respectively (IFS, ARPEGE, and ALADIN).

[30] Satellite data specially considered in the analysis of the FETCH campaign are those related to microwave measurements: ERS altimeter, and Synthetic Aperture Radar data, TOPEX/Poseidon altimeter data, and SSM/I data. During the FETCH period, the experimental zone was crossed over by 6 TOPEX/Poseidon and 6 ERS-2 altimeter tracks. 5 SAR images (100 × 300 km) of ERS-2 were acquired with coincident FETCH measurements. Some scatterometer data of ERS-2 are also available but wind fields derived from this instrument near the coast are subject to significant errors due to the coarse resolution and the geometry of acquisition. Concerning the microwave radiometer SSM/I, 3 to 5 coincident satellite swaths per day are available, thanks to the presence of three DMSP satellites (F11, F13, and F14) of the U.S. Navy.

3. Dominant Conditions

3.1. Mean Atmospheric and Wave Conditions

[31] Figures 5 and 6 show the atmospheric conditions measured on R/V L’Atalante for respectively the first and second leg. The significant wave height measured at point B (see Figure 1) by ASIS is also shown in the bottom panels. Three different periods can be distinguished.

[32] The first period (13–25 March) was dominated by Mistral events, which occurred on 14–16, 20 and 21, and 24 and 25 March. The synoptic situations leading to these Mistral events correspond to a NNW flow at 500 hPa, on the East side of a high-level pressure center located over the East Atlantic. At low levels, due to orographic constraints, the NNW wind is channeled and accelerated in the South of France by the Rhône river valley. A low-pressure center over the Gulf of Genova, at the boundary between France and Italy reinforces these NNW winds. During these periods, wind measured on the R/V L’Atalante was from NNW
with wind speeds reaching 19 m s\(^{-1}\). During the first two Mistral events, the air–sea temperature difference was variable due to diurnal variation of the air temperature, but it usually remained small (±2°C). In contrast, the 3rd Mistral event (24 and 25 March) was characterized by a larger negative air–sea temperature difference (up to −7°C). Waves measured at the position of the ASIS buoy during the last two of these Mistral events were characterized by a maximum of significant wave height between 2 and 2.5 m associated with wind sea.

The second period (from 26 March to 2 April) was dominated by weak Easterly to Southerly winds. The air–sea surface temperature difference was almost zero. Sea state was characterized by low wave height (less than 1.5 m) with swell from SSW or mixed sea.

During the third period (from 3 to 15 April), the synoptic situation over Western Europe was characterized by the presence of a near-stationary low-pressure center located between Ireland, England and Northwest of France (Brittany). This led to frequent passages of frontal discontinuities over France. Several of them reached the Gulf of Lion, and were associated with rapidly changing winds (SSE winds before the frontal passage rotating to WNW afterward, with wind speeds up to 17 m s\(^{-1}\)). During the last of these events sampled by R/V *L’Atalante* over a period of 3 days (11–14 April), an almost constant wind direction from NNW with high wind speeds was observed. This is a Tramontane event. From 3 to 15 April, the largest significant wave heights of the campaign were observed (up to about 3 m) with frequent swell from SSW or mixed sea.

### 3.2. Oceanic Conditions

[35] The hydrological structures on the eastern and western ends of the shelf evidence mixed temperature and salinity profiles throughout the water column, which is characteristic of winter conditions. An interleaving of water masses is observed in the central part (Figure 7). Brackish water, characteristic of the Rhône river plume, is observed in the upper water column. Close to the bottom, warm and
salty upwelled slope water is confronted with colder and fresher downwelled coastal water.

[36] Current measurements show the path of the cyclonic circulation of the Liguro-Provençal current along the slope. The core of the current, centered above the 1000 m isobath, is about 25 km wide and shows maximum velocities between 40 and 50 cm s\(^{-1}\) near the surface (Figure 8). The circulation of the shelf is more complex and dominated by large and temporary eddies. The current profiles are rather homogeneous over most of the shelf and indicate maximum speed of 30 cm s\(^{-1}\).

### 4. Overview of the Special Session

[37] Ten papers follow the present introduction. Five of them deal with turbulent fluxes or the atmospheric boundary layer, one with ocean waves, one with ocean circulation, and three with remote sensing of surface parameters (wind and waves). A short summary of the collection of contributions included in this volume is given below.

#### 4.1. Turbulent Fluxes and the Atmospheric Boundary Layer

[38] The paper of Dupuis et al. deal with the estimate of turbulent fluxes from the R/V *L’Atalante*. Results obtained with the inertial dissipation method are discussed and the effects of flow distortion, are analyzed in detail. In this study, results obtained through a “computational fluid dynamic” model [Nacass, 2001] applied on a numerical model of the ship and with its mast are used to obtain the drag coefficient. The consistency of the results for the drag coefficients are checked by analyzing their dependence with the relative wind direction (with respect to the ship heading). Only when the correction for flow distortion is applied, do the results converge to a unique parameterization of the drag coefficient. This correction leads to a decrease of about 18% in average for the drag coefficients. Bulk relationships are then proposed for the momentum and heat fluxes and compared to those obtained from the fixed ASIS platform and to results published earlier. Results for the momentum flux from ATALANTE and ASIS are very comparable at wind speeds of about 13 m s\(^{-1}\). Thus, at first order, the airflow correction of R/V *L’Atalante* leads to momentum flux in agreement with those of the ASIS buoy. At second order, however, a slight difference between the two data sets is evidenced by the slightly different slopes of the drag coefficient values with the wind speed (the slope is higher on ASIS data). The results are also similar within 2% to the parameterization of Smith [1980] using a buoy supposed to minimize airflow distortions and of Yeiland et al. [1998] based on R/V measurements corrected for the mean airflow distortion based on numerical simulation and restricted to bow-on flows. This study provides parameterizations for the latent heat flux obtained from a refractometer. In contrast, the tentative to calculate sensible heat flux based on the solar temperature measurements is less satisfactory due to the bad response of the sensor at high frequencies.

[39] In another paper, Drennan et al. present a combined analysis of FETCH turbulent momentum flux from ASIS with results from four other experiments, to estimate the effect of wave development on the momentum flux and its parameterization. The main result is that for developing wind waves the drag coefficient is a function only of wind speed, but also on wave age. This result was obtained by combining data obtained in a large range of wave age and wind speed which allowed to avoid as much as possible the effects of self-correlation in the analysis.

[40] The problem of the significance of surface fluxes estimated at a larger scale from models or satellite is discussed by Eymard et al. [2002] with a comparison of turbulent and radiative fluxes estimated from atmospheric models, ship, and satellites. This includes a detailed study about the temporal scales relevant to perform such comparisons, from which it was concluded that the optimal scale for computing fluxes from ship measurements was 20 min. These fluxes were then taken as a reference for the comparison with models and satellites. None of the radiative fluxes predicted by atmospheric models is consistent with ship measurements. On the contrary, Meteosat-derived downward radiative fluxes are comparable with the ship data. Turbulent fluxes from atmospheric models were calculated two ways: from bulk formulae applied on the meteorological analysis and from the predicted meteorological fields (every 3–6 hours). Large discrepancies are found between predicted fluxes and ship fluxes in strong wind conditions, due to the different parameterization for heat fluxes. Model bulk fluxes thus compare better to ship than predicted fluxes. Latent heat fluxes derived from a combination of microwave brightness temperature of SSM/I and Sea Surface Temperature from AVHRR or Meteosat are of a quality similar to model bulk fluxes, and provide a better description of mesoscale heterogeneities.

[41] The influence of Alpine lee cyclogenesis on air–sea heat exchanges and marine atmospheric boundary layer thermodynamics during the 24 March 1998 Mistral event is analyzed at the mesoscale by Flamant [2002], using a combination of numerical weather prediction model forecasts, airborne lidar measurements as well as in situ ship, seaborne, and airborne measurements. It is shown that the nonstationary nature of the wind regime over the Gulf of Lion was controlled by the multistage evolution of an Alpine lee cyclone over the Tyrrhenian Sea. In the early stage, the Tramontane flow prevailed over the Gulf of Lion. As the low deepened, the prevailing wind regime shifted to a well-established Mistral, which peaked around 1200 UTC. In the afternoon, the Mistral was progressively disrupted by a strengthening outflow coming from the Ligurian Sea. In the evening, the Mistral was again well established over the Gulf of Lion as the low-pressure system continued to deepen but moved to the southeast, reducing the influence of outflow from the Ligurian Sea on the flow over the Gulf of Lion.

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**Figure 6.** (opposite) Atmospheric and wave conditions from 1 to 15 April. From top to bottom: wind speed, wind direction, air temperature and SST, pressure, relative humidity, and significant wave height. All parameters were measured onboard the R/V *L’Atalante* along its track during the second leg (see Figure 3b), except the significant wave height that was measured onboard ASIS (position B in Figure 1).
air–sea heat exchanges and the structure of the marine atmospheric boundary layer over the Gulf of Lion were observed to differ significantly between the established Mistral period and the disrupted Mistral period. In the latter period, surface latent and sensible heat fluxes were reduced by a factor of 2, on average. During that latter period, air–sea moisture exchanges were mainly driven by dynamics, whereas during the former period, both winds and vertical moisture gradients controlled moisture exchanges. The boundary layer was shallower during the latter period (0.7 km instead of 1.2 km) due to reduced surface turbulent heat fluxes and increased wind shear at the top of the boundary layer in connection with the outflow from the Ligurian Sea.

Over the Gulf of Lion, the ubiquitous presence of sheltered regions (i.e., regions of reduced wind speed in the boundary layer) was shown to have an impact on surface turbulent heat fluxes. The position of these sheltered regions, which evolved with the synoptic conditions, was the key to a correct interpretation of multiplatform surface turbulent flux measurements made over the Gulf of Lion on 24 March 1998.

In another paper, Flamant et al. [2002a, 2002b] discuss the consistency and errors associated with the Special Sensor Microwave Imager (SSM/I) integrated water vapor content (IWVC) estimates over the Gulf of Lion during the same Mistral event. Results are based on a combined analysis of IWVC obtained from SSM/I, shipborne microwave radiometry, airborne lidar measurement, and numerical weather prediction model outputs (ALADIN model). Large IWVCs (between 8 and 10 kg m$^{-2}$) were observed over the Gulf of Lion in connection with the prevailing Tramontane regime. The period of well established Mistral (i.e., from 1200 to 2100 UTC) was characterized by lower IWVCs (between 3 and 6.5 kg m$^{-2}$).

Comparisons of IWVCs from SSM/I and from the ALADIN model, with collocated shipborne microwave radiometry, were carried out on a full diurnal cycle. SSM/I products yielded a root-mean-square (RMS) deviation of 2.1 kg m$^{-2}$ while ALADIN outputs yielded a RMS deviation of 1 kg m$^{-2}$. Comparisons were also carried out with collocated airborne lidar measurements to analyze the spatial evolution of the IWVC in the period of perturbed Mistral. The RMS deviation between SSM/I and LEANDRE 2 was 3.4 kg m$^{-2}$ in the drier Mistral region and 3 kg m$^{-2}$ in the moister region. The ALADIN-related RMS deviation was 0.85 kg m$^{-2}$ in the drier Mistral region and 0.75 kg m$^{-2}$ in the region perturbed by the return flow of the Tyrrhenian cyclone. Nevertheless, the trends of the temporal and spatial evolutions of IWVC were well captured by SSM/I, more so than those exhibited by ALADIN.

4.2. Ocean Waves

The ocean surface waves are studied in the paper by Pettersson et al., which analyzes the directional wave measurements from three wave sensors operated during the experiment. Two of them were moored buoys (ASIS and DWR) and the third the airborne radar RESSAC. This intercomparison study was motivated by the fact that the compatibility in terms of directional information from wave sensors based on...
different operational principles, is not well known. The three sensors reported the 1-D parameters of the wave spectrum consistently and the agreement on the directional parameters and the shape of the 2-D spectrum was also satisfactory. The two buoys showed disagreement on the directional width of the spectrum during a swell dominated event and small differences were found in the 2-D spectra of RESSAC and ASIS during a strongly inhomogeneous situation.

4.3. Ocean Circulation

[45] The paper by Estournel et al. [2002] deals with the observation and modeling of the oceanic circulation in the Gulf of Lion. The oceanic circulation is simulated with a free surface 3-D model using realistic forcing. The conditions and forcing are typical of the winter period. The model outputs are in agreement with the main hydrological and circulation patterns observed during the cruise. The results further emphasize the important influence of the mesoscale structure of the wind field linked to the local orography on the generation of oceanic eddies on the shelf and on the exchanges of water between the shelf and the slope.

4.4. Remote Sensing

[45] New developments in remote sensing of the ocean surface are presented in three papers. The two papers by V. Kudryavtsev et al. (A semi-empirical model of the normalized radar cross-section of the sea surface, 1, The background model, submitted to *Journal of Geophysical Research*, 2002a) and V. Kudryavtsev et al. (Radar backscatter from the sea surface: A semi-empirical model including non-Bragg scattering, part 2, Modulations due to long waves, submitted to *Journal of Geophysical Research*, 2002b) concern the modeling of the radar backscatter of the ocean surface and its relation with the surface characteristics (wave spectrum) or hydrodynamic processes. The originality of this study is to propose a model that accounts for non-Bragg effects due to wave breaking. The model is built in a way that ensures consistency between the description of the wave spectrum and of the breaking statistics. It is shown that wave breaking has an impact, not only on the behavior of the mean radar cross section, but also on the radar modulation transfer function, which relates the modulation of the radar backscatter to the long ocean surface waves. Airborne radar data obtained during FETCH with the RESSAC radar are used (among others) to assess these model developments.

[46] Optical remote sensing of the ocean surface by airborne lidar can also be used to derive surface parameters (surface wind speed, roughness length). This is discussed by Flamant et al. [2002a, 2002b] who present results obtained with the airborne LEANDRE2 lidar during a Mistral offshore wind event. With respect to earlier studies, the originality is first to account for the specificity of the coastal Mediterranean environment when analyzing the surface reflectance (atmospheric corrections due to aerosol, contribution of the submarine reflectance, white cap contribution). This allowed the authors to obtain wind speed estimates in good agreement with the other sources of data (Topex altimeter, ship and buoy measurements, aircraft observations, and atmospheric analyses). The spatial variability of wind speed in this nonhomogenous Mistral case could be documented in detail. Second, the combination of lidar and radar measurements and of the results obtained by Drennan et al. (see above) on the relation between roughness length and wave age, made it possible to analyze the spatial variation of the roughness length and drag coefficient with distance from the shore line (i.e., with FETCH). Results show, in agreement with the results of Drennan et al., that in the region of wave development, roughness length and drag coefficient depend not only on wind speed but also on wave age.

5. Conclusions

[47] The main characteristics of the FETCH experiment have been presented here. The scientific studies presented in the papers that follow cover almost all the subjects defined in the initial objectives of FETCH and have reached the main objectives of FETCH.

[48] Work based on the FETCH data is still in progress on several topics. In particular, the analysis of turbulent fluxes estimated from the research ship using the Eddy-Correlation Method, shows that this method is very promising for heat flux estimates. In an other study, an alternative method to derive the friction velocity is proposed corresponding to a modification of the classical inertio-dissipative method. Based on motion corrected vertical velocity standard deviations, it associates the Panofsky [1972] parameterization with the Turbulent Kinetic Energy (TKE) equation from which a friction velocity is estimated. This method involves a deterministic system of two equations with two unknowns. This allows to alleviate the indetermination that intrinsically exists when using the inertio-dissipative method alone. Work is also in progress concerning the analysis of wave growth laws derived from in situ observations and wave models, and on remote sensing of wind and wave height in coastal conditions from radar altimeter observations, and future papers are anticipated to complete this special section.

[49] In spite of this important amount of work, it is clear that a single field experiment is not enough to answer all the open questions. A combination of several data sets from field experiments may be a very valuable way to further progress. Some of the papers presented here take advantage of this fact. To facilitate such a possibility in the future, it was decided to make the FETCH data set accessible to the larger scientific community by opening (on request) the database (http://dataserv.cetp.ipsl.fr/FETCH) to other scientific groups. Furthermore, the turbulent data set of FETCH has been integrated in the new database “ALBATROS” (Autoflux Linked Base for Transfer at Ocean Surface (http://dataserv.cetp.ipsl.fr/FLUX)) providing a consistent tool to analyze turbulent fluxes over several field campaigns in different conditions. Today, ALBATROS groups data from five field campaigns carried out during the last 10 years by scientific groups in France [Eymard et al., 2001; Weill et al., 2002a, 2002b]. With this approach, it is expected that new progress will be achieved in the future.

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SHIP BORNE WIND MEASUREMENTS CORRECTED FOR AIRFLOW DISTORTION BY COMPUTATIONAL FLUID DYNAMICS

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ABSTRACT

During the FETCH (Flux, Etat de la mer et Télédetection en Condition de fetcH variable or Flux) experiment, conducted in March-April 1998 in the Mediterranean Sea (Gulf of Lion), several platforms were deployed to provide mean atmospheric parameters and turbulent fluxes of momentum and heat at the air/sea interface. In particular, the Research Vessel L'Atalante and a moored spar buoy (ASIS, Air-Sea Interaction Spar) have been instrumented for mean and turbulent measurements above the sea-surface (Hauser et al., 2002).

The effect of flow distortion around instrumented platforms has been pointed out as a possible cause for differences between flux estimates from one platform to the other in similar experimental conditions. This effect may be particularly important when large structures as research vessels are used and it is necessary to estimate the distortion due to the ship structure in order to take this effect into account in the analysis (Dupuis et al., 2002).

Here, we present results obtained from a numerical simulation of the airflow around the R/V L'Atalante. The analysis is based upon the use of the Fluent 5 numerical model, commercially available from Fluent Inc. To use this code, the chosen body has been paneled. The pre-processor available in the same package, was used to compute the geometry modeling and the mesh generation. The distortion of the air flow caused by the ship and its hull, the decks and the instrumented mast has been simulated in three dimensions.

The results show that distortion of the flow over and around the ship, results in increased winds at the sensor location at the top of the mast. This effect increases with wind speed but depends significantly on the wind direction relative to the ship. When both the ship and the mast are taken into account in the simulation, and for relative wind directions in the (-90° +90°) range, slope angles of the airflow are found to be of about 7° and the vertical wind component increases by about 13%. This is in agreement with data recorded from the sonic anemometer.

In addition, the simulation have shown that this effect is mainly due to the presence of the mast in particular by the flat platform and instrument boxes mounted at its top. That why a very detailed design of the pylon alone but with the instrument booms and boxes is now meshed and the turbulent airflow simulated.
1. INTRODUCTION

Atmospheric measurements recorded by sensors mounted on ships are biased with the airflow distortion caused by the hull, decks, masts, the supports of sensors and the instrumental body itself. Effect of flow distortion over the platforms was pointed out (Blanc 1986) as a possible source of differences between flux estimates from one platform to the other in similar experimental conditions in terms of sea state.

The ship borne measurements must be corrected, so this distortion may be determined by a physical simulation in a water channel or wind tunnel but may be too simulated in three dimensions by a Computational Fluid Dynamics (CFD) software (Yelland et al., 1998).

Since 1987, the Centre d'Aviation Météorologique (CAM) of Météo-France has used Computational Fluid Dynamics codes to estimate the errors and to correct data recorded by aircraft-borne sensors measuring dynamics and thermodynamics parameters. In 1998, it was easy for the CAM to transfer its experience in flow simulation from aircraft to ship even if the velocity decreases from about 100-120 m.s\(^{-1}\) to about 10-15 m.s\(^{-1}\) and if body length increases from 10-20 m to 80-100 m.

![Photograph of the Research Vessel L'Atalante](image)
Well forward in the bow of the R/V L’Atalante, a 12 meter high instrumented pylon was erected and instrumented by Meteo-France. Several sensors were mounted on its summit, 18 meters above the mean sea surface, in particular, this bow pylon was equipped for fast dynamical measurements with a sonic anemometer, a refractometer and a motion sensor for heave compensation (figure 2).

The R/V L’Atalante (figure 1), built in 1989 and operated by the IFREMER (French Research Institute for Exploitation of the Sea) was the first ship to be modeled. The main ship dimensions are 85 m in length from stem to stern, 16 m in width and about 27 m in height for a load displacement of 3550 tons.

To use a CFD code, the chosen body must be paneled. So, the full ship model of L’Atalante, from stem to stern, is so meshed and is enclosed in a large volume of measurements to simulate a wind tunnel. The simulation allows the relative wind direction and speed to be specified in a large range of values. The model takes count of the thermodynamical characteristics of the sea surface and of the materials of the ship. Some motions of roll and pitch are even tested to know the limits of the model.

Figure 2 : Photograph of the instrumented pylon
2 - NUMERICAL SIMULATIONS OF AIRFLOW DISTORTION

2.1 - FIRST CFD PACKAGE

In 1998, a first code (Rampant developed by Fluent Inc) runs on a workstation to begin simulations of airflow distortion around the R/V L’Atalante. The numerical model is a finite volume suited for incompressible and compressible flows in complex geometry with two turbulence models (k-ε and RNG k-ε).

The pre-processor (Geomesh developed by Control Data) available in the same package, is used to compute the geometric model and the mesh generation. The volume of measurement is reduced with a longitudinal symmetry and the model fits only a half hull truncated after the main deck ; the instrumented pylon is omitted. This three dimensional interior volume is fully structured by 15500 hexahedral 3D cells composed by 43600 rectangular faces. Boundary sides of the domain, the ship hull and the sea surface are respectively composed of 4200, 558 and 406 rectangular faces.

2.2 - FIRST SIMULATIONS

Several hours of calculation are done with this first mesh. Pressure coefficient, velocity magnitude and velocity components are calculated in every point of the domain around the head of the pylon. For example, a slope of 2° is found at the location near the summit of pylon for a velocity inlet slope of 0°. So, this slope is due only to the airflow distortion by the ship hull. More, the model shows that if the pylon would be 4 meters higher (so 16.00 m instead of 12.00 m, that is mechanically impossible) the distortion angle would be still of 1.3°.

Figure 3 : Up to the top of a wave
Some motions of roll and pitch are tested to know the limits of the model. These calculations simulate a heavy swell effect with the ship in the trough and on the top of a wave. But as a mesh modification would not be easy to build for those tests, the above mesh is used with a couple of inlet angles of slope of the wind (± 20 degrees) that is to say with a pitch angle for the ship. In these simulations, airflow distortion due to the stem reaches the sensors at the summit of the pylon (figure 3).

With this first mesh, the results were good but not enough in agreement with the ship borne data recorded during the experience FETCH (Nacass, 1999). A more detailed model has to be built.

2.3 - NEW CFD PACKAGE AND MORE DETAILED MODEL

In 2000, a more powerful code (Fluent 5 developed too by Fluent Inc) running on a PC computer deals with a finite volume suited for incompressible and compressible fluid flow in complex geometry with six turbulence models, among them the RSM (Reynolds stress model) and the LES (large eddy simulation model). This code provides three different solver formulations (segregated, coupled implicit and coupled explicit).

![Figure 4 : Comparison between the real ship and the virtual model](image)

The new pre-processor (Gambit developed by Fluent Inc) included in the package allows structured, unstructured and mixed meshes to be created. The complete vessel model is built (figure 4) with a more detailed design near the stem and the instrumented pylon (figure 5). The vessel model is enclosed in a large rectangular volume of measurements that is 200 m long, 60 m wide and 60 m high above the sea level to simulate a wind tunnel. This 3D interior volume is no structured by 88700 tetrahedral 3D cells composed by 171000 triangular faces.

For the ship skin and the sea surface (figure 6), the panels are respectively generated as an unstructured mesh of 7900 and 5700 triangular cells, allowing the model to have a fine resolution near the hull and the sea. The thermodynamical characteristics of the sea surface and of the materials of the ship are parameterized. The boundary sides of the volume of measurement are paneled with a structured mesh of 1700 rectangular cells. So, the vertical profile of the inlet wind speed near the sea surface is easily adjusted with the vertical distribution of the mesh. Three dimensions cells in the shape of pyramid and prism are needed to link the tetrahedral cells (adjacent to triangular cells) and the hexahedral cells (adjacent to the rectangular cells).
But due to the scale amplitude of the body modeled, the code has to simulate airflow in a 500 meter long wind tunnel, around the ship's hull (about 100 m), near the instrumented pylon (10 m) and the pods and booms of sensors (1 m). The volume of measurement of the sonic anemometer is about a few centimeters. Therefore, in this model, the instrumented pylon is designed and meshed as a full pylon, that is to say without the three uprights and the rungs across them.
2.4 - NEW SIMULATIONS

With both laminar and k-ε turbulent models, flow conditions show very similar results at the sensor locations, so the most of the simulations run in laminar flow conditions.

The wind velocity inlets called infinite upstream velocities \( V_O \) of which components are \( u_O \), \( v_O \) and \( w_O \) are chosen to initiate the software runs with four different values \( V_O = 5, 10, 15 \) and \( 20 \text{ m.s}^{-1} \).

The wind direction at infinite upstream called azimuth angle \( \chi_O \) is equals to:

\[
\chi_O = \arctan(v_O / u_O)
\]

For the simulations, six different values \( \chi_O = 0, 20, 50, 90, 150 \) and 180 degrees, measured with respect to the ship axis on each board are defined for the incident stream.

In any cell of the mesh, the velocity magnitude \( V \) and its components \( u, v \) and \( w \) are computed by the model. The local horizontal wind \( u_H \), the local azimuth angle \( \chi \) and the local slope angle \( \gamma \) are defined by:

\[
\begin{align*}
\chi &= \arctan(v / u) \\
\gamma &= \arctan(w / u_H)
\end{align*}
\]

The post processing allows to display graphical analysis and to visualize flow fields displaying, for example, the contours of the pressure coefficient (figure 7) or the velocity vector components.

![Figure 7: Contours of pressure coefficient](image)
The contours of pressure and the velocity vectors are calculated on the center of each cell of the three dimensional volume but are only displayed, for a better visualization, on three reference planes: two vertical slice planes intersecting the vertical axis of the pylon and one horizontal plane, parallel to the sea surface, located at the altitude of its summit. The three interceptions between these three planes create three reference lines. The transversal and the lateral lines are located at the altitude of the summit of the pylon and the vertical line is the axis of the pylon.

3 - COMPARISON WITH SHIPBORNE DATA

In order to evaluate the reality of airflow characteristics calculated by the model at the sonic anemometer location, computed results are compared with FETCH data recorded on the R/V L’Atalante, for example the three components $u$, $v$ and $w$ of the mean relative wind $V$ measured at regular intervals of 30 minutes along a leg for about 16 days.

So, the vertical component $w$ of the wind may be plotted against its horizontal component $u_H$ for data recorded by the sonic anemometer at the summit of the pylon (figure 8a) and for the results computed by the model in a cell near the sensor location (figure 8b).

Simulations are plotted for $V_O = 5, 10, 15$ and $20$ m.s$^{-1}$ and for $\chi_O = 0$ (Δ), 20 (O), 50 (□), 90 (◊), 150 (+) and 180 (×) degrees. That is to say a wind blowing on the starboard side from bow wind to back wind. The three points fitted right on the straight line (Δ), are for a wind blowing with an angle of azimuth of 0 degree and for velocities of 5, 10 and 15 m.s$^{-1}$. The two series of three points just near the straight line (O and □) are for azimuth angles of 20 and 50 degrees and the same three velocities. The other three points (◊, + and ×) are for a velocity of 10 m.s$^{-1}$ but with three larger angles of azimuth (90, 150 and 180 degrees).

Another comparison may be done plotting the slope angle $\gamma$ against the azimuth angle $\chi_O$ from data recorded on board (figure 9a) and computed by the model (figure 9b). On these figures, azimuth angles between 0 and +180 degrees (starboard side) are only considered. An almost symmetrical shape is found for angles varying from 0 to -180 degrees on the port side.

Assuming that, for the model, the wind is horizontal at infinite upstream, that is to say that the vertical velocity and the slope are $w_O = 0$ and $\gamma_O = 0$, simulations give a variation of the slope at the summit of the pylon that is, for this range of velocity, no dependent of the speed of the wind but varies with the angle of azimuth. But this last variation is small for angles smaller than 90 degrees.

So, after all these comparisons, it may be assumed that the predicted values for the mean wind components are in accord with the measured components of wind speed from the sonic anemometer, even if the entire probe itself and its mounting pod lead to deformation of the airflow and are not meshed. Distortion caused by objects near the sensors such as pods, support structures, booms or instrument boxes will be too modeled.
Figure 8: Variation of the vertical and horizontal components of the wind, (a) recorded by the sonic anemometer, (b) computed by the model
Figure 9: Variation of the slope of the wind with its azimuth, (a) recorded by the sonic anemometer, (b) computed by the model
4 - PRESSURE COEFFICIENT VARIATION

One of the coefficient determined by the model and used to characterize biases and contamination terms in the measured wind is the pressure coefficient (Nacass, 1992).

With the static pressure at infinite upstream $P_O$ and the pressure $P$ at any point in the flow, the pressure coefficient $K_p$ at this point is a dimensionless parameter defined, with the fluid velocity $V_O$ and density $\rho_O$ at infinite upstream, by:

$$K_p = \frac{P - P_O}{\frac{\rho_O V_O^2}{2}} \Rightarrow P - P_O = \frac{\rho_O V_O^2}{2} K_p$$

The pressure coefficient $K_p = 0$ at the infinite upstream, at infinite downstream and when the flow is not disturbed. The $K_p = 1$ when the flow impacts a body, for example at a stagnation point. Around a body, the pressure coefficient is smaller than zero in most cases.

This equation of the pressure coefficient is true for incompressible and compressible fluids. But for the velocity range of the ships, the fluid is assumed to be incompressible and $\rho_O$ is constant. The pressure coefficient $K_p$ may be written with the ratio $S = V/V_O$ called the over speed:

$$K_p = 1 - \frac{V^2}{V_O^2} = 1 - S^2 \Rightarrow V = V_O \sqrt{1 - K_p}$$

The $K_p$ is easy to use for comparison of the airflow distortion around a body in a stream. For example, in this model, it is plotted along the transversal reference line at the altitude of the summit of the pylon at different speeds and angles of wind blowing.

At a constant angle of azimuth, the coefficient $K_p$ is independent of $V_O$ that is to say, the disturbance of the airflow is only a function of the angle of the relative wind direction.

So, when the $K_p$ is plotted, whatever the infinite upstream velocity, along the same transversal reference line, for different angles of azimuth, the effects of flow distortion are very sensitive to the relative wind direction. This is true for a relative wind blowing from ahead of the ship at 0, 20 and 50 degrees (figure 10). As the pylon is full and its section is an equilateral triangle, the distortion is mainly due to the shape of the hull.

In front, near the stem, the incident airflow is cut in two clean streams following the hull side. On the contrary, when the incident airflow is broadside on, the hull is like a vertical step wall by comparison with the smooth shape of the stem and the distortion of the airflow is stronger.

The values of the pressure coefficient at the exit of the domain show that the disturbance of the ship is still important far from the stern. The infinite downstream of the flow with $K_p = 0$ is about 200 meters behind the stern.
5 - VELOCITY VARIATION

A very complete study of the velocity and its components was made along the three reference lines.

For example, the ratio $\frac{w}{V_O}$ of the vertical component of the velocity on the undisturbed inlet velocity magnitude may be plotted along the transversal reference line. At different angles of azimuth, the ratio variations are less different than those of the Kp and the greater values are at the summit of the pylon.

For the first three angles of azimuth $\chi_O = 0, 20$ and $50$ degrees, the ratio equals respectively $12.5, 12.0$ and $13.0$ % (figure 11). As the values for angles of $90, 150$ and $180$ are also calculated ($13.8, 5.9$ and $-8.0$ %) the variation of the ratio with the angle of azimuth may be found (figure 12). One of the best curves that passes through these six given points may be written:

$$\frac{w}{V_O} = 12.463 - 0.0738\chi_O + 0.0031\chi_O^2 - 4.10^{-5}\chi_O^3 + 2.10^{-7}\chi_O^4 - 4.10^{-10}\chi_O^5$$
Figure 11: Longitudinal variation of the relative vertical velocity for three azimuth angles

In the same way, the curve of variation for the slope angle $\gamma$ is plotted (figure 9b). For azimuth angles of $\chi_O = 0, 20, 50, 90, 150$ and 180 degrees, the slope angles values computed by the model are respectively $\gamma = 7.5, 7.0, 6.7, 6.6, 3.2$ and -5.8 degrees. Even if more points would be computed by the model, one of the best curves passing through these six points is:

$$\gamma = 7.5393 - 0.036\chi_O + 0.0007\chi_O^2 - 9.10^{-6}\chi_O^3 + 7.10^{-8}\chi_O^4 - 3.10^{-10}\chi_O^5$$

The sensor does not measure the right azimuth of the infinite upstream airflow. It measures the local azimuth contaminated by the disturbance. The error done by the sensor at the sonic anemometer location is computed for the five values of $\chi_O$ and the best curve passing through these points is:

$$\chi = 0.3777 + 1.3342\chi_O - 0.0022\chi_O^2 - 3.10^{-5}\chi_O^3 + 3.10^{-7}\chi_O^4 - 4.10^{-10}\chi_O^5$$

And the variation of the ratio $u_H/V_O$ with the local azimuth angle $\chi$ at the sensor location, shows how the airflow distortion modifies the wind measurement:

$$\frac{u_H}{V_O} = -5.7624 - 0.1918\chi + 0.0151\chi^2 - 0.0001\chi^3 + 4.10^{-7}\chi^4 - 1.10^{-10}\chi^5$$
$y = -4E-10x^5 + 2E-07x^4 - 4E-05x^3 + 0.0031x^2 - 0.0738x + 12.463$

$R^2 = 1$

**Figure 12**: Relative variation of the vertical velocity with azimuth angles at infinite upstream

6 - REVERSED PATHLINE

Another question is to know the relation between the point of the undisturbed flow at a given altitude and the point measured at the altitude of the sensors at the summit of the pylon.

Pathlines are used to visualize the flow of massless particles in the problem domain. The particles are released from one or more surfaces created. To determine the source of a particle that leaves the domain through an exit boundary for which the final destination (for example the sonic anemometer) is know, the pathlines may be reversed and follow these particles from their destination back to their source.

So, it can be determined that the change in height of the airflow pathline, computed by the model from the cell located at the sonic anemometer volume of measurement to the infinite upstream is $\Delta z = -1.21$ m for a velocity inlet of 10 m.s$^{-1}$ and an azimuth angle equals to zero. The airflow is raised by the presence of the ship's hull and the pylon.
7 – SIMULATION OF A WELL DETAILED HEAD OF PYLON

The mast alone (without the ship) is designed and meshed, that is to say a complete lattice pylon with the three uprights, the rungs across them and the electronic boxes (figure 13). For a 10 ms⁻¹ inlet wind, airflow distortion is computed. Hence the perturbation is mainly due to the presence of electronic boxes fixed on top of the mast and located near the anemometer. These containers induce an aerodynamic break point and force a strong perturbation at this level.

Figure 13 : The new design of the well detailed head of the pylon

Figure 14 : Simulation of the turbulences around the pylon head, instrument pods and electronic boxes
CONCLUSION

The results of this simulation show that the flow over the R/V L’Atalante provide a good estimate of the error in the speed of the mean flow around the anemometer site. Distortion of the flow over and around the ship results in increased winds at the sensor location on the summit of the pylon.

These wind speed errors do not have significant dependence on the incident wind speed. Even if this effect is more pronounced at higher wind speeds, it is very dependant of the wind direction with respect to the ship. For relative wind directions (or azimuth angles) included in a ±90° interval from the bow axis, slope angles are found to be about 2° with the first mesh (without pylon) and is about 7° with the new mesh (with a full pylon) in agreement with data recorded from the sonic anemometer. The vertical component of the wind increases up about 13%.

The ship borne measurements by the sensors overestimate the free stream. This model may be used to examine and correct by the influence of the flow distortion on the mean wind and the turbulence measurements recorded during FETCH.
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Impact of flow distortion corrections on turbulent fluxes
estimated by the inertial dissipation method during the FETCH
experiment on R/V L’Atalante

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Abstract

The FETCH campaign was for a large part devoted to the measurement and analysis of turbulent fluxes in fetch-limited conditions. Turbulent measurements were performed on board the R/V L’Atalante, on an ASIS spar buoy and on aircraft. On the R/V L’Atalante, turbulent data were obtained from a sonic anemometer and from a microwave refractometer. The main focus of this paper is to present results of momentum and heat fluxes obtained from the R/V L’Atalante, using the inertial-dissipation method and taking into account flow distortion effects. Numerical simulations of airflow distortion caused by the ship structure have been performed to correct the wind measurements on the R/V L’Atalante during the FETCH experiment. These simulations include different configurations of inlet velocities and six relative wind directions. The impact of airflow distortion on turbulent flux parameterizations is presented in detail. The results show a very large dependence on azimuth angle. When the ship is heading into the wind (relative wind direction within ±38° of the bow), the airflow distortion leads to an overestimation of the drag coefficient, associated with a wind speed reduction at the sensor location. For relative wind directions of more than ±38° from the bow, flow distortion causes the wind to accelerate at the sensor location, which leads to an underestimate of the drag coefficient. The vertical displacement of the flow streamlines could not be fully established by numerical simulation, but the results are in qualitative agreement with those inferred from the data by prescribing the consistency of momentum flux as a function of azimuth angle. Both show that the vertical elevation of the flow can be considered as constant (1.21m from numerical simulations) only within about ±20° from bow axis. Values of vertical displacements up to 5m are found from the data for high wind speeds and beam-on flows. Our study also shows that the relative contributions of the streamline vertical displacement and the mean wind speed under- or over- estimate vary significantly with relative wind direction. The relative contribution due to vertical streamline displacement is higher for heat flux than for momentum flux.

The consistency of our correction for airflow distortion is assessed by the fact that the correction reduces the standard deviation of the drag coefficient: only if this correction is taken into account, do the curves of the drag coefficient versus wind speed become similar for data corresponding to wind in the bow direction and from the side.

When the complete numerical airflow correction is applied to the data set limited to relative wind directions at ±30° from the bow axis, the drag coefficient formula is:

$$C_{D10N} \times 1000 = 0.56 + 0.063 U_{10N}, \text{ for } U_{10N} > 6 \text{ m.s}^{-1}$$

This formula provides $C_{D10N}$ values comparable to the ones found from the ASIS buoy data for wind speeds of about 13m.s$^{-1}$. They are however smaller by 9% at higher winds (>15m.s$^{-1}$). This formula is also similar, within a few percent, to the parameterizations of Smith [1980], Anderson [1993] and Yellan et al. [1998]. The exchange coefficient for evaporation is found to be 1.00x10$^{-3}$ on average with a small standard deviation of 0.31x10$^{-3}$. A slight increase of $C_{E10N}$ value with wind speed is however observed with a variation of about 20% (0.2x10$^{-3}$) for wind speeds between 6 and 17 m.s$^{-1}$, following:

$$C_{E10N} \times 1000 = 0.82 + 0.02 U_{10n}, \text{ for } U_{10n} > 6 \text{ m.s}^{-1}$$
1 Introduction

Many experimental campaigns have been undertaken during the last decades to parameterize turbulent fluxes over the ocean. A good accuracy of these parameterizations is required to reduce uncertainties of the global modeling of the ocean/atmosphere system. Over the ocean, the turbulent fluxes of heat and momentum are estimated using several platforms such as R/Vs of different sizes and shapes, moored buoys or coastal platforms. Concerning the methods, the inertial dissipation method has been used for years [Large and Pond, 1981; Fairall and Larsen, 1986; Edson et al., 1991]. The main advantage of this method is that it can avoid motion corrections, since measurements are done in the inertial subrange at higher frequencies than those of the platform motion. More recently, technical improvements have allowed the use of the direct method of eddy correlation from ship or buoys (e.g. Fujitani, 1981; Pedreros et al., submitted; Drennan et al., this issue) with motion corrections obtained from measurements of a motion package.

It unfortunately appears that the set of bulk coefficients available in the literature present a significant scatter. Several factors can be invoked to explain this fact. The first is experimental. The effect of flow distortion around measurement platforms has been pointed out as a possible cause for differences between flux estimates from one platform to the other in similar experimental conditions [Ching, 1976; Blanc 1986; 1987; Yelland et al., 1998]. Whereas little is known about the distortion of turbulent eddies, the effect of flow distortion on the mean flow is better quantified [Edson et al., 1998; Oost et al., 1994]. For eddy correlation measurements on bulky platforms, it has been suggested that corrections to both the mean flow and turbulence should be carried out. In contrast, the turbulence scales in the inertial sub-range seem to be unaffected by flow distortion, so that flow distortion effects on inertial dissipation fluxes are limited to mean flow distortion. Although the full modeling of turbulent flow around a distorting body is a difficult task, the effects of flow distortion on the mean flow can be accurately estimated, either by numerical simulation (e.g. Yelland et al. [1998]; Nacass, [1999]) or using small-scale models in wind tunnels [Butet, 2001; 2002]. The effect of mean flow distortion can be significant: for example, Yelland et al. [1998] attributed air flow distortion as responsible for initial overestimations of their drag coefficients by up to 60%. They therefore strongly recommended corrections of air-sea fluxes for flow distortion, particularly when measured from large structure R/Vs.

A second factor which leads to scatter in the bulk parameterizations is the role of sea state. Surface waves are not passive roughness elements, but interact with the atmosphere. In particular, it is now known that the presence of either strong swell [Volkov 1970; Donelan et al., 1997], or developing wind-waves [see Kitaigorodskii 1970; Drennan et al., this issue] can modify the momentum flux over typical open ocean values. A third factor, related to sea state, is that of nonstationarity of either the wind or wave fields [Geernaert et al., 1986].

To understand the physical coupling between wind and waves, and to progress in the parameterization of the turbulent fluxes, an analysis over a wide range of conditions is needed. These measurements of turbulent fluxes have to be very carefully performed to ensure the validity of the datasets, and to avoid possible discrepancies between methods or platforms.

The FETCH experiment [see also Hauser et al., this issue] took place in March and April 1998 in the North Mediterranean Sea (Gulf of Lion). One of its main
objectives was the estimation and parameterization of turbulent fluxes in this coastal area, often dominated by short fetch conditions, due to the frequent occurrence of on-shore winds (Mistral events). Other objectives deal with the wave field evolution, and with remote sensing of the marine atmospheric boundary layer and of the ocean surface (see Hauser et al., this issue).

Concerning the flux measurement and parameterization, the FETCH experiment provides an interesting data set since it includes in situ observations from different platforms. In particular, turbulent flux measurements were performed both on the oceanic R/V L’Atalante, which cruised over an area of about 100 km × 100 km and on the ASIS Spar buoy (Grabert et al., 2000) moored in deep water at about 60 km from the shore. In addition to long legs performed by the R/V L’Atalante to sample a variety of wind/wave conditions, several periods of observations with the R/V in the vicinity of the buoy were organized with the aim of comparing turbulent fluxes estimated from different platforms and methods.

The general meteorological and oceanic conditions during FETCH are described in Hauser et al. [this issue] and summarized hereafter. Wind speeds range from about 1 m.s\(^{-1}\) to 19 m.s\(^{-1}\). Stratification conditions are mainly unstable, except in light wind conditions (less than about 5 m.s\(^{-1}\)). Wave conditions include wind-sea cases with inverse wave age, defined as \(u^*/C_p\), (where \(u^*\) is the friction velocity and \(C_p\) the phase speed of the dominant waves), from 0.03 to 0.1, as well as mixed sea cases and swell cases.

In this study, we focus on the impact of distortion of the mean flow on turbulent fluxes calculated by the inertial dissipation method. This effect on measurements from large R/V must be fully discussed before the influence of sea state can be analyzed. A thorough study on the impact of airflow distortion indeed appeared necessary because preliminary results from the R/V L’Atalante data during FETCH, without accounting for flow distortion, showed \(C_{D10N}\) values significantly in excess compared to measurements of the ASIS buoy (Dupuis et al., 1999; Hauser et al., 2000). In this paper, the sensitivity of the drag and heat exchange coefficients to the corrections for airflow distortion is evaluated. These corrections are based on 3D numerical simulations of flow distortion around the R/V L’Atalante, including the instrumented mast deployed on the foredeck during the FETCH experiment. Drag and exchange coefficients for heat and evaporation are compared using a full correction, a simplified correction or no correction. Results from the R/V L’Atalante by the inertial dissipation method and accounting for a correction of airflow distortion are then compared to those of the ASIS buoy; calculated by the eddy correlation method, to evaluate the consistency of the dataset. A further comparative analysis including eddy correlation results on R/V L’Atalante is presented in Pedreros et al. [submitted].

We first describe in section 2 the experimental set-up used on the R/V L’Atalante during FETCH for turbulent fluxes. Then, in section 3, the main results obtained from the airflow numerical simulations are presented. Sections 4 and 5 summarize the method used to estimate the fluxes, and to account for the flow distortion in the estimates. Section 6 presents the analysis of the vertical displacement due to airflow distortion and results for the drag and exchange coefficients with different conditions for flow distortion correction: no correction, complete correction (horizontal relative wind speed and direction), partial correction (horizontal wind speed and direction correction function of the relative wind direction, and no vertical displacement), and simplified correction (constant horizontal wind speed and vertical displacement correction). The consistency of the complete
correction is evaluated by comparing $C_{D10N}$ values for different ranges of relative wind direction. As a second validation, wind speeds and friction velocities are compared to those of the ASIS buoy for different ranges of separation distances. Then, the effect of the different corrections is analyzed. Finally, parameterizations are proposed for the FETCH turbulent fluxes estimated by the inertial dissipation method on R/V L’Atalante and compared to those of the ASIS buoy during FETCH and to other studies.

2. Experimental set-up

2.1 Shipborne measurements

During FETCH, the R/V L’Atalante was equipped with sensors to investigate air-sea interactions and particularly sensors devoted to the measurements of turbulent fluxes of heat and momentum. The present study is based on the data from several turbulent meteorological sensors. A Gill ultra sonic anemometer (R3 research HS, from Gill Instruments Ltd) is used to provide the three components of wind velocity, along with sonic temperature. In addition, a microwave refractometer, based on a resonant microwave cavity, is used to provide the fluctuations of the air refraction index. This device combines a circular cylindrical “open” cavity made of Zerodur-M glass ceramics from SCHOTT operating near 9.4 GHz with a frequency measurement system. The determination of the resonant frequency is related with the air (filling the cavity) refraction index. Sonic anemometer and refractometer are synchronized and work with a sampling rate of 50Hz. A full description of the refractometer, designed at CETP, is given in Delahaye et al. [1988, 2001]. This sensor provides very reliable measurements [Dupuis et al., 1999; Eymard et al., 1999] for humidity fluctuations as demonstrated by Figure 11 of Delahaye et al. [2001] showing normalized spectra of air refraction index as a function of frequency and wavelength for a large range of wind speed and stratification. In contrast, reliable measurements of temperature fluctuations are very difficult to obtain over the ocean, mostly due to salt contamination on sensors. Both sonic temperature and air refraction index depend on air temperature and humidity. Hence, both the latent and sensible heat fluxes can be derived (see section 4 below). Although the sonic thermometer is a promising technique to estimate the sensible heat flux (because it is not affected by salt contamination), especially when the data are analyzed with the eddy correlation method [Pedreros et al., submitted], we confirm here that it still needs improvements to accurately estimate sensible heat flux when the inertial dissipation method is applied (see also Larsen et al. [1993]; Dupuis et al. [1999] and Eymard et al. [1999]). This is due to the poor accuracy of the sonic temperature measurements at the high frequencies needed for the inertial dissipation method. Hence, only an order of magnitude of the sensible heat flux is provided here while momentum and latent heat flux estimates are of better quality.

The turbulence sensors were located at about 17.8m, at the top of a foredeck mast (see Fig. 1a). Figure 1 of Pedreros et al. [submitted] also provides a detailed sketch of the experimental set-up on the mast. In addition to observations from the turbulent sensors, data from the following instruments are used in the present study. Meteorological sensors (humidity and temperature transmitter HMP233 manufactured by Vaisala Oy., PTB220 barometer) are used to provide mean parameters such as air temperature, humidity and pressure. GPS and navigation data from the vessel are used to transform the wind measurements to the earth reference frame. Additional shipborne measurements include: currents by Acoustic Doppler Profilers (ADCP); wave conditions by video and photo-stereogrammetry; and oceanic and atmospheric profiles by CTD and radio soundings respectively. It is worthwhile noting that the surface currents
as measured by shipboard ADCP are negligible in the wind direction and are thus not accounted for. Indeed, at meso-scale, currents are parallel to the coast. The order of magnitude of currents at the level nearest to the surface (in 10 m depth) is of 20 or 30 cm/s after the highest wind events (in these cases the wind blew perpendicular to the coast).

Figure 1: Photographs of the R/V L’Atalante and the ASIS buoy during the FETCH experiment (respectively on panels a and b).

2.2 ASIS buoy measurements

For comparison with the R/V L’Atalante data, data from an ASIS (Air-Sea Interaction Spar) buoy are used. ASIS buoys were designed specifically for research at the air-sea [Graber et al, 2000]. The buoys are constructed using an open structure (see Fig. 1b), and hence cause very little flow distortion to the wind field. The largest structural elements above the surface are 20cm diameter cylinders, and these terminate 4m below the anemometer. The mast itself is an open triangular pylon constructed with 3.5cm (max) diameter members. Although flow distortion studies have not yet been carried out for ASIS, such effects are expected to be very small.

The ASIS buoy was moored at 42°58’56" N, 04°15’11" E, roughly 50 km SSW of the Rhone delta. The fluxes are calculated using the eddy correlation method, with data from a Gill R2A sonic anemometer located 7m above mean sea level. The full motion of the buoy is measured, and these motion signals are used to correct the measured velocities prior to calculating the fluxes- see Drennan et al. [this issue] for details. When comparing the L’Atalante and ASIS fluxes, we restrict our attention to periods when the ship is located close to ASIS, thus ensuring that the two platforms are in similar sea states. In general, this is not the case, and quite often the ship and buoy are experiencing quite different sea state conditions. See Drennan et al. [this issue] for a discussion of the effect of wave development (wave age) on momentum flux.

3. Airflow simulation

The distortion of the air flow caused by the ship and its hull, the decks and the instrumented mast was simulated in three dimensions by computational fluid dynamics software. The numerical model, which is based on a finite volume method, is suited for incompressible and compressible fluid flow in complex geometries and can be run with several turbulence models such as the standard k-ε or large eddy simulation.

The simulations were run with the Fluent 5 numerical model, commercially
available from Fluent Inc.. To use this code, the chosen body must be paneled. The preprocessor available in the same package, is used to compute the geometry modeling and the mesh generation. It allows structured, unstructured and mixed meshes.

The R/V L’Atalante is 85 m long from stem to stern and 16 m wide. Its height is 18 m above the sea level at the summit of the mast. The mast is located on the centerline of the ship, about 2 meters behind the stem. The turbulent sensors are located at the top of the mast (refractometer) and at the end of a 1 meter boom in front of the upper part of the mast (sonic anemometer). The latter point is the reference taken in this study for airflow distortion correction. In the numerical model, the ship body is enclosed in a large rectangular volume of 195 m long, 60 m wide and 60 m high above the sea level to simulate a wind tunnel. Considering R/V’s projected surface areas of 223m$^2$ and 759m$^2$ respectively in the front and port (or starboard) directions, a blocking ratio of 0.06 is obtained in both cases [Castro and Robins, 1977]. Therefore, due to the finite dimension of the wind tunnel in the simulations, the maximum error can be as high as 6% for the horizontal wind speed magnitude, particularly at the navigation bridge. However, the projected surface area of the foredeck is much smaller and a maximum error due to the blockage of 1% is more realistic at the sonic location. This is supported by the good agreement between numerical simulation and the physical simulations of Butet [2002] who used a maximum blocking ratio of 0.024. These are described below. Hence, although the conditions of simulation are not completely optimal (the flow might be slightly accelerated in the wind tunnel simulations), it is likely that the error is less than 1% and of the same order for bow and port-starboard directions, due to the same blocking ratio in both directions.

For the ship body and sea surface, the panels are generated as an unstructured mesh of triangular cells, allowing the model to have a fine resolution near the sea surface and the ship body. The boundary sides of the measurement volume are paneled with a structured mesh of rectangular cells. The vertical profile of the inlet wind speed may be adjusted with the vertical distribution of the mesh. The volume is meshed by 90000 hybrid cells composed with 186000 faces. Three dimensional cells in the shape of pyramids and prisms are needed to link the tetrahedral cells (adjacent to the ship body and sea surface) and the hexahedral cells (adjacent to the boundary sides). The model uses a finer resolution of 450mm for the side of the tetrahedral cells near the instrumented mast. The distance between the sensor and the center of gravity of its corresponding cell is less than 5mm. However, due to the large difference between the dimensions of the ship hull and of the rungs of the mast lattice, the mast was represented as a full volume of equal size. The validity of this simplification was examined by Butet [2002], who carried out physical simulations with the detailed mast. It was shown that considering a solid mast remains appropriate for sensors located within 2m of the top of the mast (as is the case for the turbulent sensors here) because of the presence of electronic boxes at the top of the mast (Fig. 1).

The numerical model also takes into account the thermodynamic characteristics of the sea surface and the material of the ship. Because the processing time to reach convergence is too long with the turbulent flow model, most of the simulations were run in laminar flow conditions. Results obtained in both laminar and k-ε turbulent flow conditions show that considering a laminar flow instead of a turbulent one does not change significantly the results at the sensor location.

The evaluation of the mean airflow vertical displacement was difficult due to the grid configuration. It has however been estimated for wind speeds of 10m/s and relative wind directions of 0, 20, 50 and 90° by visual observation of the path line of mass-less particles on outputs of the
numerical simulations. The freestream flow is obtained at the inlet of the tunnel. A mean upward streamline displacement of 1.21 m was found at bow angles, while values of about 2.5 m were obtained for other wind directions as shown in Table 1.

<table>
<thead>
<tr>
<th>Wind speed, $\phi$</th>
<th>Distance (m)</th>
<th>$\Delta z$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 m/s, 0°</td>
<td>62</td>
<td>1.21</td>
</tr>
<tr>
<td>10 m/s, 20°</td>
<td>66</td>
<td>2.43</td>
</tr>
<tr>
<td>10 m/s, 50°</td>
<td>39</td>
<td>2.12</td>
</tr>
<tr>
<td>10 m/s, 90°</td>
<td>30</td>
<td>2.79</td>
</tr>
</tbody>
</table>

Table 1: Vertical displacement in meters as obtained by reversed pathline in the numerical simulations for upstream wind velocity of 10 m/s and 4 azimuth angles. The distance to which the reversed pathline is followed between the sensor and the “upstream” source location is indicated in second column.

Note that due to the simulation configuration, the horizontal distance of the streamline between its origin at an inlet wall and the sensors varied from 30 to 66 m depending on the azimuth angle of the wind (see Table 1). Butet [2002] obtains a similar value of +1.10 m for bow-on flows. Furthermore, the +1.21 m vertical displacement obtained at bow angles seems reasonable compared to other studies with foredeck masts [Yelland et al., 1998; Butet, 2001]. Indeed, these authors find a value of 1±0.3 m for anemometers on masts near the bow of 5 other ships, while greater values of up to 1.5 or 2 m are found for anemometers on a ship’s main mast above the accommodation block. Therefore, a good confidence is obtained for the value for the vertical elevation for bow-on flows. In contrast, for beam-on flows, there is an underestimation of the vertical elevation of the order of 1 to 2 m. Similar results were found by Yelland et al. [2002] in their simulations of the R/V James Clark Ross, a vessel similar to L’Atalante (see their Fig. 13). A complete discussion of the vertical elevation of the flow, including the functions deduced from the data set, can be found in Section 6.1. Indeed, we shall thereafter consider two functions for the vertical elevation. First a constant value of 1.21 m, and second a function of both azimuth angle and wind speed as derived from the FETCH data. As shown in section 6.1, the latter function, defined to minimize the flux dependence on azimuth angle, is in qualitative agreement with the initial numerical simulations, which are however found to be underestimated at beam-on flows due to the too small distance of the inlet of the tunnel as suggested by Yelland et al. simulations [2002].

For the simulations, wind direction and velocity were specified in a large range of values, with four different (upstream) velocities (5, 10, 15 and 20 m.s$^{-1}$) and six different inlet azimuth angles (0, 20, 50, 90, 150 and 180 degrees) with respect to the ship axis. It is assumed that the results are the same for port-side flows as for starboard flows since the mast is on the centerline of the ship (Butet [2002] however identified a small asymmetry due to the ship superstructure). Other calculations have been performed to simulate the effect of swell with the ship in the trough and on the top of a wave. Preliminary simulations have been carried out with the domain tilted in order consider “stationary” effects of roll and pitch (see Nacass, 1999). The results suggest that the mean wind speed error for two opposite tilts is not the same as the error without a tilt.

Validation of the simulations is discussed by comparing the simulated and measured slope angles at the anemometer location over 30 minutes (Fig. 2). The slope angle $\beta$ is defined as $\beta = \tan(W/U)^{-1}$, where $W$ and $U$ are the simulated or measured mean vertical and horizontal wind speeds at the sonic anemometer location.
Figure 2: Slope angle $\beta$ (in degrees) as a function of the relative wind direction (or azimuth angle). Dots: observed slope angles. Plus symbols: slope angles obtained from the numerical simulation of airflow distortion. Solid line: $4^{\text{th}}$ order polynomial fit to the model results.

As Figure 2 shows, a good agreement is obtained between simulated (cross symbols and line) and observed (dots) values of $\beta$, for the six azimuth angles. Indeed, much of the scatter in the data can be attributed to effects not taken into account in the simulations (variation of relative wind magnitude and direction within the time interval, turbulent flow distortion due to the waves...). For relative wind directions (or azimuth angles) within $\pm 100^\circ$ from the bow axis, the slope angles are found to be about $7^\circ$ both for data and simulations (simulations show a slight decrease of $1^\circ$ when the absolute relative wind direction is varied from 0 to 100$^\circ$). Also, the variations at larger azimuth angles are consistent between simulations and observations. The results obtained in a wind tunnel by Butet [2002] are also consistent since they provide a slope angle of $6^\circ$ at similar bow angles at the sensor location. In contrast, previous simulations in which the instrumented mast was not included did not show this agreement: the simulated slope angle for low relative wind directions was found to be about $3^\circ$ [Nacass, 1999]. This indicates that the mast itself plays a major role in the airflow disturbances, even for a large R/V such as L’Atalante. More precisely, physical simulations performed in the wind tunnel with a realistic mast [fig. 10 in Butet, 2002], confirmed that the major disturbance to the flow is caused by the electronic boxes at the top of mast. Indeed, vertical profiles of the slope angle at the sonic anemometer location show that the perturbation has (i) a general feature: a decrease of the slope angle from $3.2$ to $2.3^\circ$ for heights varying from $-5$ to $+5$ m relative to the top of the mast and (ii) a superimposed local feature limited $-2$ to $+2$ m relative to the top of the mast, associated with a maximum of the slope angle of $6^\circ$ at the top of the mast. This fact seems to be of considerable importance and should be better taken into account in the placement of sensors on meteorological masts for future experimental work. It also implies that simulations have to be re-done if another sensor/mast configuration is used on the same R/V.

Simulation results showing the perturbation of the horizontal wind speed relative to the ship due to airflow distortion are presented in Figure 3. Fig. 3a shows the relative perturbation of the horizontal wind, in percentage of wind speed, only as a function of azimuth angles and for different wind speeds. The relative wind speed error appears to be independent of the wind speed since data from all wind speeds have been collapsed on a single curve. In contrast, Yelland et al. [1998] showed that the wind speed error (and the vertical displacement) both vary slightly with wind speed. A large dependence of the wind speed error is observed with azimuth angle: this error is about $-6\%$ (underestimate of the wind speed at the sonic location) when the bow points into the wind, tends to 0 at angles close to $\pm 38^\circ$ from the bow axis and becomes positive (overestimate of the wind speed) above that angle, up to $20\%$ at $100^\circ$. Similar values within $1\%$ were obtained by Butet [2002] for azimuth angles limited to $30^\circ$ ($-7\%$ at bow angles for example). Fig. 3b shows that the wind direction is also affected by airflow distortion, with errors up to $10^\circ$ at $50^\circ$ azimuth angle. $5^{\text{th}}$ and $4^{\text{th}}$ order polynomial fits obtained from these simulations are
indicated respectively in Fig. 3a and b as solid lines. They can be expressed as:

\[
\frac{U_s - U_u}{U_u} \times 100 = -5.76 \cdot 0.192 \phi + 0.015 \phi^2 - 1.39e^{-4} \phi^3 + 3.51e^{-7} \phi^4 - 1.43e^{-10} \phi^5 \quad [1]
\]

\[
\phi_u = -0.2056 + 0.7283 \phi + 8.626e^{-4} \phi^2 + 3.130e^{-5} \phi^3 - 1.534e^{-7} \phi^4, \quad [2]
\]

where subscript \(u\) stands for the upstream value (value which would be observed in absence of flow distortion) and subscript \(s\) for the value at the sensor location with flow distortion.

Figure 3: Results from the numerical simulation of flow distortion. (a): horizontal relative wind speed error (in %) due to air flow distortion as a function of the measured azimuth. (b): deviation of the relative wind direction (or azimuth angle) due to flow distortion.

Figure 4 shows the comparison of the uncorrected versus corrected relative wind speeds for the whole data set on R/V L’Atalante during FETCH (averaging time of 30 minutes). The corrected values are calculated by using Eq. 1. The scatter diagram is split in two parts, with positive (respectively negative) corrections of the horizontal relative wind speeds for absolute values of the apparent wind direction smaller (respectively larger) than 38°. Maximum corrections reach about 2.5 m.s\(^{-1}\) at high wind speed (above 25 m.s\(^{-1}\), in the ship reference frame) and for relative wind directions higher in magnitude than 38°. Due to the larger number of data points at small relative wind directions in the dataset (i.e. 80% of the data correspond to absolute values of relative wind directions less than 20° from the bow axis), the corrected wind speeds are higher on average than the measured ones.

Figure 4: Scatter plot of corrected versus uncorrected horizontal relative wind speed. The corrected wind speed was obtained through Eq. 1. + symbols: samples for absolute azimuth angles less than 38° (771 samples), diamond symbols: samples for absolute angles between 38 and 90° (221 samples).

Before we show how these corrections are introduced in the flux calculations and how they affect flux parameterizations, the
4. Flux derivations

The dissipation method has been used for 30 years over the ocean. The method was reviewed by Fairall and Larsen [1986] and Edson et al. [1991], among others. These latter authors, as well as Large and Pond [1981] and Smith et al. [1992], have also contributed to the validation of the method by comparison of the results with those by eddy correlation. In this study, the method to derive the turbulent fluxes of momentum, sensible and latent heat is quite similar to what is presented in Dupuis et al. [1999]. For FETCH, dissipation rates are calculated every 30 minutes from the density spectra of the along-wind wind component, sonic temperature, and refractive index. A minimum frequency range of 2 Hz is selected to estimate the dissipation rates within the inertial sub-range by using:

\[ \varepsilon_u = \left( \frac{L_u}{\alpha_u} \right)^{3/2} \left( \frac{2\pi}{U_r} \right) \]

\[ \varepsilon_{ts} = \left( \frac{L_{ts}}{\alpha_{ts}} \right)^{1/3} \left( \frac{2\pi}{U_r} \right)^{2/3} \]

\[ \varepsilon_n = \left( \frac{L_n}{\alpha_n} \right)^{1/3} \left( \frac{2\pi}{U_r} \right)^{2/3} \]

where subscripts u, ts, and n refer to the along-wind wind component, the sonic temperature, and the refractive index, respectively. \( L_i \) for each of these variables (subscript i stands for u, ts, or n), is the mean spectral energy multiplied by \( f^{5/3} \) where f is the frequency, and \( \alpha_i \) are universal constants. The experimental values of the Kolmogorov constant, \( \alpha_u=0.55 \), and of the Obukhov-Corrsin constant, \( \alpha_{ts,n} = 0.8 \) are used respectively in Eqs 3-5. \( U_r \) is the relative wind speed.

Derivation of the fluxes using the Turbulent Kinetic Energy (TKE) and scalar variance budgets is based on the following Eqs 6-9, and has been described in detail by Dupuis et al. [1997; 1999]. Kinematic vertical fluxes \(<uw>\), \(<wts>\) and \(<wn>\) (defined with brackets indicating time averaging of lower case variables as turbulent quantities) are estimated through:

\[ u^* = \left[ \kappa Z \varepsilon_u / (\Phi_m(Z/L) - Z/L - \Phi_{imb}(Z/L)) \right]^{1/3} \]

\[ <wts> = \left[ \kappa Z u^* \varepsilon_{ts} / \Phi_{ts}(Z/L) \right]^{1/2} \]

\[ <wn> = \left[ \kappa Z u^* \varepsilon_n / \Phi_{n}(Z/L) \right]^{1/2} \]

\[ L = -T_v u^*^3 / (g \kappa <wt_s>) \]

where Z is the height of measurement above the sea surface, \( u^* = <uw>^{1/2} \) is the friction velocity, \( T_v \) is the virtual temperature, \( \kappa \) is the Von Karman constant (0.4), L is the Monin Obukhov (MO) Length, estimated using the bulk parameterization as defined in section 5, and the stratification functions \( (\Phi_m, \Phi_{ts}, \Phi_n) \) are estimated according to Large and Pond [1982].

In Equation (6), \( \Phi_{imb}(Z/L) \) is an empirical imbalance function of the TKE budget [e.g. Wyngaard and Coté, 71; Yelland and Taylor, 1996; Jansen, 1999; Taylor and Yelland, 2000…]. Dupuis et al. [1997] found that it was necessary to introduce this stability dependent imbalance term in order to minimize the dependence on stability of the drag coefficient over the ocean calculated by the inertial dissipation method. Further analysis applied to 4 experiments including very different stratifications [Eymard et al., 1999] corroborate this stability dependent imbalance term. This term was estimated as \( 0.5Z/L \). It is used with the same parameterization in the present study. We note that, as shown by Dupuis et al. [1999], the FETCH experiment did not encounter extreme stratifications, so that except for a few samples, the impact of this imbalance term on the \( C_{Dion} \) values from FETCH is much less than 1%.
The sensible and latent heat fluxes are calculated by using a decomposition of the terms $<wt>$ and $<wn>$ of Eqs 7-8 as linear functions of the more classical vertical kinematic fluxes of humidity $<wq>$ and dry air temperature $<wt>$:

$$<wt> = \partial T_s/\partial T <wt> + \partial T_s/\partial Q <wq>[10]$$

$$<wn> = \partial N/\partial Q <wq> + \partial N/\partial T <wt>.[11]$$

where $\partial T_s/\partial T$ and $\partial T_s/\partial Q$ are the partial derivative of mean parameters $T_s$ with respect to air temperature $T$ and specific humidity $Q$, respectively. They can be expressed as (1+0.518Q) and 0.518T, respectively where $Q$ and $T$ are the mean values for $q$ and $t$. Indeed:

$$N = P(77.6/T + 3.73 10^5Q /0.622T^2) [12]$$

$$T_s = T(1+0.518Q), [13]$$

From these expressions, it can be verified that the flux of the air refraction index, $<wn>$, depends mainly on $<wq>$, for typical Bowen Ratios over the sea. This is because $\partial N/\partial Q$ is one order of magnitude larger than $\partial N/\partial T$ (with opposite sign). The partial derivative of the mean air pressure $P$ is neglected because it is a third order term. This is discussed in detail, with Bowen ratios typical for the FETCH experiment, in Delahaye et al. [2001]. A bulk estimate of $<wt>$ is used to estimate $<wq>$ from Eq. 11. Although the system of Eqs 10-11 could have been solved for both $<wt>$ and $<wq>$, it was not done, because the poor quality of $<wt>$ estimated from the sonic temperature would have added significant noise in the latent heat flux estimates. In contrast, the fluctuations of the air refraction index are of good quality (again, see Figure 11 of Delahaye et al. [2001]).

The main changes concerning the processing compared to these previous publications are:

- the frequency range of the inertial sub-range is adapted at each sample, using a criteria based on the goodness fit of a -5/3 power law. Typically, this inertial sub-range is at least 2Hz wide;

- the dissipation rates are computed every 30 minutes of observations, using at least 120 independent averaged spectra of 512 samples each (10.24 seconds long), thus covering a minimum of 20.48 minutes of data. This allows more samples to be considered than using a single spectra over 30 minutes;

- the wind speed used in the bulk formulae is taken from the sonic measurements instead of from the measurements of the YOUNG propeller has it was previously. This ensures a consistency in the corrections for flow distortion, which has been estimated at the sonic sensor location.

- data were rejected if: the range of relative wind direction exceeds ±100 (instead of ±50) degrees from the bow axis. This wider azimuth range allows us to analyze the impact of wind azimuth on the flow distortion corrections.

5. Method of flux corrections

The corrections are based on the assumption that only the mean characteristics of the wind speed are disturbed by the R/V, while the turbulence in the inertial sub-range is not affected. Thus the turbulent fluxes are corrected as follows:

- dissipation rates are calculated with Eqs 3-5 using the measured uncorrected values for the mean relative wind speed, $U_r$ and the spectral densities (indeed, the relative wind speed is used here to transform frequency in wave number following the Taylor hypothesis and it should not be corrected);
- the relative wind speed averaged over 30 minutes is corrected for air flow distortion using Eqs 1-2. The wind speed in the earth reference frame is then calculated from this corrected relative wind speed;

- the measurement height $Z$ is corrected for vertical displacement which is fixed at a value of 1.21m, hereafter denoted with subscript CVE, at a first step (Section 6.1) and then computed using Eq. 18 (Section 6.2 and in the following), hereafter denoted the “complete flow distortion correction”;

- bulk formulae are used to derive the MO length $L$ (Eq. 9): the parameterization of Smith [1980] is used for the neutral drag coefficient in the momentum flux; for the heat fluxes we use transfer coefficients of $1.2 \times 10^{-3}$ at unstable stratification and $0.7 \times 10^{-3}$ at stable stratification (only for the sensible heat flux). These values are consistent with most experimental studies [Large and Pond, 1982; De Cosmo et al., 1996; Smith, 1988], see Fairall et al. [1996] for a detailed description of bulk parameterizations;

- Eqs 6-11 are solved using sensor elevations corrected for the vertical displacement;

- Drag and exchange coefficients for latent and sensible heat fluxes ($C_{D10N}, C_{E10N}$ and $C_{H10N}$) are derived using the 10m equivalent neutral parameters noted “10N” and using the corrected wind speed in the earth reference frame:

$$C_{D10N} = \frac{u'^2}{U_{10N}}$$  \hspace{1cm} [14]

$$C_{E10N} = \frac{<w'q'>}{U_{10N}(Q_{sat}-Q_{10N})}$$  \hspace{1cm} [15]

$$C_{H10N} = \frac{<w't'>}{U_{10N}(SST-10N)}$$  \hspace{1cm} [16]

where $U$, SST and $Q_{sat}$ stand respectively for mean values of wind speed, sea surface temperature and humidity at saturation (a coefficient of 0.98 is used in the calculation of $Q_{sat}$ for the salt water correction).

6. Results

6.1 Estimation of the vertical elevation by prescribing a consistency of momentum flux as a function of azimuth angles

Consistency of the airflow correction provided by the “Fluent” simulations (so called “CVE”) is assessed by the analysis of the drag coefficients. We focus on the drag coefficient here, because the impact of the correction is more significant than for the heat coefficients (the wind speed is squared in Eq. 14 in contrast with heat flux equations, Eqs 15-16). Parameterizations for heat fluxes will however be discussed in the next sections.

Due to the opposite effect of the flow distortion on the mean wind speed for absolute azimuth angles less than and larger than about 38°, the data set has been separated in two subsets, one with absolute azimuth angles less than 30°, and the other ranging between 40° and 90° . Figure 5 shows the $C_{D10N}$ values in these two classes of azimuth angles. The top panel displays the drag coefficients with no flow distortion correction, showing a factor of nearly 2 for $C_{D10N}$ between the two classes at moderate wind speeds (data within ±30° from the bow axis are larger than data corresponding to wind angles from port or starboard). Differences in $C_{D10N}$ values increase with wind speed. When the correction with constant vertical elevation is applied as explained in Section 5, the two subsets agree remarkably well for wind speeds below 10 m.s$^{-1}$ (Fig. 5b). Above 10 m.s$^{-1}$, $C_{D10N}$ values for those data with wind direction from port or starboard are somewhat larger than those for data with wind directions within ±30° of the bow. Thus the FETCH data indicate that if a constant vertical elevation is suitable at a low to moderate wind speed regime (<10m/s), a more sophisticated vertical
elevation has to be considered at higher winds.

Figure 5: $C_{D10N}$ values versus $U_{10N}$ obtained from the R/V L’Atalante measurements with the inertial dissipation method (a) without correction for airflow distortion; (b) with “CVE” correction for airflow distortion. In each panel, two ranges of absolute values of the azimuth angles are distinguished: within ±30° of the bow (plus symbols, solid lines in black), from the port or starboard directions (between ±40 and ±90° of the bow) - (plus symbols, solid lines in grey). Solid lines join the mean values of $C_{D10N}$ calculated in classes of 2 m s⁻¹ bins. Error bars indicate the standard deviation with respect to the mean in each wind speed bin. The dotted line is the parameterization of Smith (1980). The number of samples in each bin of wind direction changes when the flow distortion correction is applied, following Eq. 2.

In the following it is supposed that the only source of inconsistency in relative wind direction that remains in the FETCH data is due to the constant vertical elevation used in the airflow distortion correction.

To determine the variation of the vertical streamline elevation with both relative wind direction and wind speed, data corrected for air flow distortion are used with the correction of the mean wind (error in magnitude and direction) and with the constant vertical elevation of 1.21m (CVE).

Eq. 6 implies that if we have knowledge of the true value of the friction velocity, $u^{*}_{true}$, and the estimated value $u^{*}_{CVE}$ obtained by IDM using air flow distortion correction with constant vertical elevation with altitude Z CVE, then:

$$u^{*}_{CVE}/u^{*}_{true} = (Z_{CVE}/Z_{true})^{1/3} \quad [17]$$

provided stratification is near neutral.

Bow-on flow ($|\phi| <10^\circ$) samples are used to determine $u^{*}_{true}$ by interpolation based on mean friction velocities in 2 m/s wind speed bins. Figure 6 shows the ratio $u^{*}_{CVE}/u^{*}_{true}$ as a function of absolute value of relative wind direction (in 10° direction bins) as error plots with the mean values and standard errors of the ratio. The range of Z over L used in figure 6 is -0.5 to 0.2 which corresponds to 770 samples.

Figure 6: Mean and standard errors (standard deviation divided by the root mean square of number of samples) of the ratio of friction
velocities as a function of azimuth angle at the sensor location in 10° bins. The ordinates are the mean friction velocity obtained for bow-on flows divided by the friction velocity at any relative wind direction by IDM with constant vertical elevation correction (CVE).

Figure 6 shows that the ratio depends not only on relative wind direction, but also on wind speed as suggested by Figure 5. Indeed, the two error plots correspond to relative wind speeds smaller or greater than 10m/s, respectively for diamond and plus symbols. Fig. 6 shows ratio of about 1.09 for relative wind directions above 30° and relative wind speeds larger than 10m/s. This trend is independent of the threshold on relative wind speed and stability. In contrast, for low wind speeds, values of the ratio are found to vary significantly with the relative wind direction. Moreover, for $U_r<10$m/s, the mean values in 10° bins are found to vary with the threshold on wind speed and stability. The averaged ratio for all wind direction and for wind speeds below 10m/s is however always found to be about 1. Thus, we have considered that the vertical elevations do not depend on wind direction for low wind speed and that the variations of mean values in 10° bins was due to low statistical degrees of freedom.

As for the highest wind speeds, the ratio is found to increase for relative wind directions greater than about 30°, the flow is thus elevated by more than the constant value used in the “CVE” algorithm. The fit proposed for $(Z_{CVE}/Z_{true})^{1/3}$ is:

$$(Z_{CVE}/Z_{true})^{1/3} = f(U_r) \ast 0.0425 \ast [\tanh(\phi_s - 30)/5] + 1 \quad [18]$$

where $f(U_r)= 0.5 \ast [\tanh(U_r - 10) +1]$ is introduced to allow for a smooth transition between the two wind speed regimes (the dashed line in Figure 6 corresponds to Eq. 18).

Figure 7 shows the resulting vertical displacement as a function of relative wind direction for 4 different relative wind speeds.

Figure 7: Comparison of vertical elevations as obtained from the FETCH data (Eq. 18) and from the numerical simulations.

The maximum value of about 5m is reached for 90° at high wind speeds. It implies that the shape of the blocking body in the stream is an important parameter. Indeed, a ship is designed to receive the sea and the wind by the stem not by the side. From the side, the shape is more vertical and the flow is significantly elevated. These results are in qualitative agreement with Yelland et al. [2002] results. Indeed, they obtain with three dimensional Computational Fluid Dynamics model, vertical elevations of 1 and 5m respectively for simulations of flows at 0 and 90° from the bow of the ship. The FETCH data on R/V L’Atalante suggest that the vertical elevation can be considered as constant (1.21m from numerical simulations) up to relative wind directions of 20 or 25°. Above these angles it is also more or less constant (both data and numerical simulation) for a given wind speed. The agreement with values obtained from the numerical simulations is good – see Fig. 7, where the simulation results of Table 1 are displayed with large triangles. However, the shift between bow and side values is observed at under 20° for the numerical simulations while it is at 30° for the data analysis. Also, slightly smaller values than from the data are obtained ($\Delta z$ of about 2.5 and 3m are respectively obtained for 10m/s relative wind
speed with numerical simulations and data analysis). But it should be noted that the threshold of 10 m/s to separate low and high wind speeds in the data, as well as the shape of Eq. 18 is somewhat arbitrary. A complete validation of the formula for the vertical elevation should take into account numerical simulations for a wider range of relative wind directions (mostly between 0 and 50°) and relative wind speeds (such as 5 and 15 m/s).

Figure 8 is the similar to Fig. 5b but Eq. 18 has been used to compute the vertical elevation using the “complete flow distortion correction”. The data are now consistent for all wind speeds and directions, providing a verification that Eq. 18 provides a realistic estimation of the vertical displacement.

6.2 Comparison with the ASIS buoy results

The FETCH experiment provides the opportunity to compare two different platforms and methods in terms of momentum flux. However, attention should be paid to effects of spatial inhomogeneities since the R/V L’Atalante moved in a 100 km x 100 km area while the ASIS buoy was fixed [Hauser et al., 2000]. To take this into account two different thresholds, 5 and 20 km in the maximum distance between the two platforms have been selected in scatter plots of $U_{10N}$ and $u^*$ in Figure 9 (2 ranges of relative wind direction are considered, below 30° and above 40°, but it does not allow a complete study for angles above 40° since there are very few samples and they correspond to low wind speed conditions). The larger distance threshold yields larger number of samples in the comparison (66 compared to 30 for $U_{10N}$). The number of samples for the friction velocity comparison is slightly smaller due to a few negative <$u_w>$ values by eddy correlation at low wind speeds: the dissipation method can yield only positive values. Figures 9a and c show that the flow distortion correction based on Fluent numerical simulations as described above allows a very good agreement for $U_{10N}$ measurements between ASIS and L’Atalante since the regression lines are very close to the identity, although the slopes are slightly less than 1 (regression lines calculated for open symbols with relative wind directions within ±30° from the bow axis are indicated in the Figures). In contrast, regression lines obtained without flow distortion corrections were instead, respectively for 5 and 20 km distance, $y=0.80+0.86x, r=0.99$ and $y=0.69+0.85x, r=0.98$, both associated with wind speed underestimation. The increase in the range of distance only introduces a higher scatter (correlation coefficients are 0.99 and 0.98 for the 5 and 20 km distance thresholds, respectively in Fig. 9a and c).
Figure 9: Comparison of the R/V L’Atalante and ASIS buoy wind speeds (left panels) and friction velocities (right panels) after flow distortion corrections, using two different thresholds on the maximum distance between the two platforms (5 and 20 km). The comparison is shown as a scatter plot between the ship and buoy data. Two different symbols display two ranges of relative wind direction. In panels b and d, the momentum flux is defined as $u^*$ for the inertial dissipation method and the root mean square of $<-uw>$ for the eddy correlation method.

In the comparison of $u^*$ by L’Atalante (inertial dissipation) and the root mean square of $<-uw>$ by ASIS (Eddy Correlation), ASIS values are statistically lower (respectively higher) than those of L’Atalante at low (respectively high) winds (see Fig. 9b and d). The ASIS results are those using only the along-wind component $<-uw>$ [Drennan et al., this issue]. The regression line cuts the identity line at wind speeds of about 12 m/s (or friction velocities of about 0.45 m/s). Taking the cross-wind component, $<-vw>$, into account increases the ASIS momentum fluxes for wind speeds below 6 m/s, leading in this case to greater $u^*$ (or $C_{D10N}$) values than those from L’Atalante in the range of smooth aerodynamic flows but it has no significant effect at higher winds. Again increasing the separation distance between the two platforms increases both the scatter in the data and the numbers of samples for which...
the momentum flux is higher at ASIS at high winds. The regression slope remains less than 1 without the correction for distortion on the R/V L’Atalante. Indeed, the correction effect is mostly restricted to the vertical displacement. This correction amplifies by 3% the discrepancy for u* (for example the slope in the regression line was found to be 0.87 compared to 0.84 after corrections in Figure 9b). This value of 3% is fully explained by Eq. 6 showing that in the simpler case of neutral stratification, u* derived by the inertial dissipation method is proportional to $Z^{1/3}$ (an increase of 2.3% of $u^*$ is hence expected when the vertical displacement correction is applied).

In summary, this comparison indicates that mean wind speeds of the R/V L’Atalante are well corrected for airflow distortion around the ship although the regression indicates a very slight underestimation of L’Atalante wind speeds compared to the buoy at high wind speeds. This suggests that the wind speed error function provided by numerical simulation is realistic. However, the correction (principally due to vertical displacement) for the L’Atalante fluxes does not improve their agreement with the ASIS fluxes. On the contrary, the slope of the regression between the friction velocities decreased from 0.87 to 0.84 after correction.

Since horizontal distances between platforms of less than 20km or even 5km were considered, differences in sea state cannot be responsible for the observed flux differences. The small discrepancy is likely due to the method (dissipation versus correlation), or to sonic anemometer calibrations.

Since the correction for wind speed is of higher magnitude than that for $u^*$ for bow-on flows using the inertial dissipation method (respectively about 9 and –2%), the behaviour of $C_{D10N}$ values is significantly improved by this correction, as also shown by the better self-consistency of $C_{D10N}$ in the previous section. Since the regression lines tend to cut the identity line at wind speeds of about 12m/s, over and under-estimates of L’Atalante $C_{D10N}$ values are awaited compared to ASIS values respectively at wind speeds below and above this threshold, as will be further discussed in section 6.4 extrapolating the drag coefficient comparison to all data independently of the distance between the two platforms.

In the next section, an analysis of the sensitivity of drag or exchange coefficients to simplifications in the airflow correction is described.

### 6.3 Effects of flow distortion on the transfer coefficients

This section deals with modifications in $C_{D10N}$, $C_{E10N}$ for different configurations of airflow corrections. Relative wind directions (azimuth angles) up to ±90 degrees are analyzed to discuss the modifications for different ranges of relative wind directions: ±30, ±50, ±70 and ±90°. The effect of the complete correction (subscript c) on turbulent flux parameterization is compared to the “uncorrected” parameterization (subscript u). Then, to estimate the impact of the two parts of the correction (wind vector and vertical air flow displacement) we also show results for a “wind only” flow distortion correction (subscript w), which means that correction for vertical airflow displacement is not taken into account in this case. Finally, results for a “simplified” air flow distortion correction (subscript s) are shown. In this latter case, we correct for a constant wind error affecting only the wind speed, independent of azimuth angle and we fix the vertical displacement. The values chosen in this “simplified correction” are an error of -5% on wind speed (underestimation) and a value of 1m for the upward mean air flow displacement [Hare et al., 1999].

Averaged exchange coefficients $C_{D10N}$, $C_{E10N}$ and $C_{H10N}$ are presented in Table 2 for
the four cases of airflow corrections and for azimuth angles within ±30° from the bow axis. The values in Table 2 are calculated as median values for 2 m s⁻¹ wind speed bins. Standard deviations are displayed in parentheses below the median value.

<table>
<thead>
<tr>
<th>U m s⁻¹</th>
<th>0-2</th>
<th>2-4</th>
<th>4-6</th>
<th>6-8</th>
<th>8-10</th>
<th>10-12</th>
<th>12-14</th>
<th>14-16</th>
<th>16-18</th>
</tr>
</thead>
<tbody>
<tr>
<td>C_D10Na</td>
<td>1.10 (0.53)</td>
<td>1.113 (0.29)</td>
<td>1.072 (0.26)</td>
<td>1.180 (0.26)</td>
<td>1.311 (0.27)</td>
<td>1.459 (0.28)</td>
<td>1.747 (0.20)</td>
<td>1.939 (0.26)</td>
<td>2.016 (0.22)</td>
</tr>
<tr>
<td>C_D10Ne</td>
<td>0.987 (0.42)</td>
<td>1.020 (0.28)</td>
<td>0.921 (0.22)</td>
<td>0.983 (0.22)</td>
<td>1.077 (0.25)</td>
<td>1.141 (0.17)</td>
<td>1.374 (0.18)</td>
<td>1.502 (0.18)</td>
<td>1.594 (0.18)</td>
</tr>
<tr>
<td>C_D10Nw</td>
<td>0.971 (0.44)</td>
<td>1.070 (0.30)</td>
<td>0.960 (0.21)</td>
<td>1.039 (0.24)</td>
<td>1.140 (0.27)</td>
<td>1.205 (0.18)</td>
<td>1.462 (0.19)</td>
<td>1.600 (0.19)</td>
<td>1.767 (0.21)</td>
</tr>
<tr>
<td>C_D10Nc</td>
<td>1.008 (0.44)</td>
<td>1.010 (0.27)</td>
<td>0.933 (0.20)</td>
<td>1.018 (0.24)</td>
<td>1.114 (0.27)</td>
<td>1.179 (0.19)</td>
<td>1.421 (0.17)</td>
<td>1.559 (0.17)</td>
<td>1.750 (0.20)</td>
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<tr>
<td>C_D10Ne</td>
<td>1.376 (0.63)</td>
<td>0.912 (0.28)</td>
<td>0.946 (0.26)</td>
<td>1.045 (0.17)</td>
<td>1.122 (0.19)</td>
<td>1.155 (0.16)</td>
<td>1.215 (0.10)</td>
<td>1.235 (0.10)</td>
<td>1.218 (0.08)</td>
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<tr>
<td>C_D10Nw</td>
<td>1.113 (0.47)</td>
<td>0.817 (0.26)</td>
<td>0.852 (0.16)</td>
<td>0.911 (0.16)</td>
<td>0.943 (0.17)</td>
<td>1.015 (0.13)</td>
<td>1.058 (0.10)</td>
<td>1.069 (0.11)</td>
<td>1.090 (0.05)</td>
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<tr>
<td>C_E10Nw</td>
<td>1.168 (0.50)</td>
<td>0.873 (0.27)</td>
<td>0.902 (0.24)</td>
<td>0.968 (0.17)</td>
<td>1.006 (0.19)</td>
<td>1.069 (0.13)</td>
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<tr>
<td>C_E10Nc</td>
<td>1.157 (0.48)</td>
<td>0.822 (0.25)</td>
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<td>C_E10Na</td>
<td>1.186 (0.67)</td>
<td>0.927 (0.27)</td>
<td>1.054 (0.39)</td>
<td>1.359 (0.49)</td>
<td>1.631 (0.62)</td>
<td>1.504 (0.49)</td>
<td>2.156 (0.70)</td>
<td>2.045 (0.61)</td>
<td>2.628 (0.48)</td>
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<tr>
<td>C_H10Nc</td>
<td>0.941 (0.42)</td>
<td>0.830 (0.28)</td>
<td>0.917 (0.35)</td>
<td>1.134 (0.43)</td>
<td>1.414 (0.67)</td>
<td>1.316 (0.36)</td>
<td>1.844 (0.79)</td>
<td>1.679 (0.49)</td>
<td>1.960 (0.52)</td>
</tr>
<tr>
<td>C_H10Nw</td>
<td>1.009 (0.44)</td>
<td>0.911 (0.33)</td>
<td>0.987 (0.37)</td>
<td>1.228 (0.46)</td>
<td>1.469 (0.66)</td>
<td>1.416 (0.38)</td>
<td>2.016 (0.84)</td>
<td>1.779 (0.53)</td>
<td>2.215 (0.52)</td>
</tr>
<tr>
<td>C_H10Na</td>
<td>0.968 (0.48)</td>
<td>0.812 (0.26)</td>
<td>0.907 (0.33)</td>
<td>1.187 (0.45)</td>
<td>1.417 (0.62)</td>
<td>1.321 (0.35)</td>
<td>1.920 (0.79)</td>
<td>1.698 (0.51)</td>
<td>2.134 (0.46)</td>
</tr>
</tbody>
</table>

Table 2: C_D10N, C_E10N and C_H10N values obtained in 2 m s⁻¹ wind speed bins for the different flow distortion correction algorithms and for azimuth angles within ±30°. The mean values are indicated as well as standard deviations in brackets. The air flow correction algorithms are listed as “uncorrected”: subscript u, “wind only”: subscript w, “simplified”, subscript s and “complete flow distortion correction”: subscript c.

Table 2 shows that in all cases, the exchange coefficients are decreased when a correction for flow distortion is applied. It can also be noted that, for all wind speeds, applying a correction leads to a smaller standard deviation with respect to the results obtained without correction for flow distortion. The largest modifications to drag or exchange coefficients are found at high winds but the relative error is largely independent of wind speed. Tables 3 and 4 present the relative errors for C_D10N and C_E10N respectively, where the case of complete correction of flow distortion (subscript c) is taken as a reference. Results for different limits of azimuth angles (from ±30° to ±90°, every 20°) are distinguished in Tables 3 and 4. It should however be noted that the distribution of the FETCH data on the R/V L’Atalante is not equally distributed with respect to relative wind direction since the cruise plan called for the ship to steam into the wind when ever possible. Therefore, the trends with the wind direction observed here
could be stronger when applied to other datasets. Indeed, the order of magnitude of vertical displacement and wind speed error correction on \( C_{D10N} \) values are of \(-4.6\%/-12\%, -19\%/0\% \) and \(-19\%/+40\% \) for relative wind directions of respectively \( 0, 38\° \) and \( 90\° \) if high wind speeds are considered (Eqs 1,2,18). The two corrections are in competition for angles above \( 38\° \), with the wind speed error dominating for bow-off flows; the vertical displacement effect dominates in the middle range of relative wind angles. Also, at some wind direction, the two corrections cancel. The results of Tables 3 and 4 are a combination of these corrections applied to a particular distribution of wind speeds and directions.

Concerning the \( C_{D10N} \) values, the second column of Table 3 shows that the complete airflow correction applied to the narrowest range of azimuth angles (\( \pm 30\° \)) leads to a decrease of about \( 17\% \) in the \( C_{D10N} \) values. The decrease is smaller when the azimuth angle range is wider, with a minimum value of \( 9\% \) for the wider range (\( \pm 90\° \)). One should keep in mind that if errors in average values of \( C_{D10N} \) without airflow distortion corrections are decreased by using a wider range of relative wind direction, this is due to the averaging of samples whose errors cancels. Thus the scatter is in this case very large and individual samples may be significantly biased.

<table>
<thead>
<tr>
<th>Azimuth angle limit (deg)</th>
<th>( \frac{C_{D10N_c}-C_{D10N_u}}{C_{D10N_c}} ) on samples (%)</th>
<th>( \frac{C_{D10N_c}-C_{D10N_w}}{C_{D10N_c}} ) on samples (%)</th>
<th>( \frac{C_{D10N_c}-C_{D10N_s}}{C_{D10N_c}} ) on samples (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>±90 (925)</td>
<td>-8.9</td>
<td>-6.6</td>
<td>4.4</td>
</tr>
<tr>
<td>±70 (854)</td>
<td>-11.1</td>
<td>-6.3</td>
<td>2.7</td>
</tr>
<tr>
<td>±50 (755)</td>
<td>-14.1</td>
<td>-5.6</td>
<td>0.4</td>
</tr>
<tr>
<td>±30 (651)</td>
<td>-17.1</td>
<td>-5.0</td>
<td>-1.9</td>
</tr>
</tbody>
</table>

Table 3: Comparison of % errors in \( C_{D10N} \) values using different flow distortion correction algorithms: “uncorrected”: subscript u, “wind only”: subscript w and “simplified”, subscript s, using the “complete flow distortion correction”: subscript c as a reference. The errors are shown as a function of azimuth angle (or relative wind direction) in degrees. The number of samples in indicated in parenthesis in the first column.

<table>
<thead>
<tr>
<th>Azimuth angle limit (deg)</th>
<th>( \frac{C_{E10N_c}-C_{E10N_u}}{C_{E10N_c}} ) on samples (%)</th>
<th>( \frac{C_{E10N_c}-C_{E10N_w}}{C_{E10N_c}} ) on samples (%)</th>
<th>( \frac{C_{E10N_c}-C_{E10N_s}}{C_{E10N_c}} ) on samples (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>±90 (559)</td>
<td>-10.0</td>
<td>-7.2</td>
<td>0.3</td>
</tr>
<tr>
<td>±70 (544)</td>
<td>-10.4</td>
<td>-7.1</td>
<td>0.0</td>
</tr>
<tr>
<td>±50 (494)</td>
<td>-11.6</td>
<td>-6.3</td>
<td>-0.9</td>
</tr>
<tr>
<td>±30 (442)</td>
<td>-12.7</td>
<td>-5.7</td>
<td>-1.8</td>
</tr>
</tbody>
</table>

Table 4: Comparison of % errors in \( C_{E10N} \) values using different flow distortion correction algorithms: “uncorrected”: subscript u, “wind only”: subscript w and “simplified”, subscript s, using the “complete flow distortion correction”: subscript c as a reference. The error is shown as a function of azimuth angle (or relative wind direction) in degrees. The number of samples in indicated in parenthesis in the first column.
As seen in last line of column 3 in Table 3, showing the error between the full air flow distortion and the wind only correction, the vertical displacement of 1.21m (with respect to the 17.80m height for measurements) leads to a decrease in $C_{D10N}$ values of 5% which is fully explained by the proportionality of $u^2$ to $Z^{2/3}$ in Eq. 6 mentioned above. At low azimuth angles ($\pm 30^\circ$), the vertical displacement represents about 25% of the $C_{D10N}$ correction while 75% is due to horizontal wind speed correction which is the same order of magnitude as the values indicated above for bow angles. For larger ranges of azimuth angle, vertical displacement has a greater impact and the wind only configuration gives higher errors (-6.6% for $90^\circ$ as a threshold).

The error in the case of a simplified correction for air flow distortion (last columns of Table 3) is about -2% if the azimuth angles are limited to $\pm 30^\circ$ (partly due to the difference in the vertical elevation of 0.21m at bow-on flow). Due to a cancelling of the two correction terms, the error first decreases as the flow angle range increases, finally the error reaches +4% if the azimuth angles are limited to $\pm 90^\circ$. At these large angles, the wind speed error is overestimated (or even of the wrong sign) in the simplified correction. Again, as mentioned above for the complete correction, one should keep in mind that if, at first glance, the simplified correction may give small errors in average up to angles of $70^\circ$ within the bow axis, this is only due to error cancellations. In fact this correction works properly for individual samples only for bow-on flows.

Very similar trends are observed for $C_{E10N}$ values (Table 4), although the correction for airflow distortion has less impact than on $C_{D10N}$ values: the relative error of $C_{E10N}$ varies from less than -13% for the smallest range of azimuth angles ($\pm 30^\circ$) to -10% in for the $\pm 90^\circ$ range. Using Eqs 6-8, we can establish that at unstable stratification, the dependence of $<w_t>$ or $<w_n>$ on the height of measurement follows a 5/6 power law. Therefore a relative correction of -5.7% is obtained for a vertical displacement of 1.21m (respectively -23% for 5m) from 17.80m, which is similar to the value of -5.7% in Table 4. At low azimuth angles, the vertical displacement represents 45% of the total correction for the exchange coefficient for evaporation compared to 27% for the drag coefficient. Table 4, shows that the use of the simplified correction leads to smaller impact on $C_{E10N}$ values than on $C_{D10N}$ values (1.8% maximum error compared to 4.4%).

Due to the similarity of Eqs 7 and 8, the corrections on $C_{E10N}$ values are very similar to those of $C_{E10N}$ values.

6.4 Discussion of the FETCH parameterizations

Figure 10 compares drag coefficients of this study using data limited to bow-on flow ($\pm 30^\circ$) with results from the ASIS buoy (including all sea states, using only $<-uw>$) and with those of Smith [1980]. Again, it clearly shows that if no correction for flow distortion is applied (grey line with error bars) an overestimation by about 15% on $C_{D10N}$ values is obtained compared to other studies. In contrast, when the correction is applied (black heavy line with error bars) the wind speed error is overestimated (or even of the wrong sign) in the simplified correction. Again, as mentioned above for the complete correction, one should keep in mind that if, at first glance, the simplified correction may give small errors in average up to angles of $70^\circ$ within the bow axis, this is only due to error cancellations. In fact this correction works properly for individual samples only for bow-on flows.
It should be noted that the results of Anderson [1993] and Large and Pond [1981], although obtained on ship-mounted instruments and not corrected for airflow distortion also compare well to Smith [1980]. Yelland et al. [1998] suggest that it could be due to cancelling effects of the dissipation function (or imbalance term) and relatively small airflow distortion (about 3% wind speed error). The relatively large range of relative wind directions used in these studies (see Table 5) should also be pointed out (see Section 6.3).

![Diagram](image)

**Figure 10**: $C_{D10N}$ versus $U_{10N}$ relationships obtained during FETCH from the R/V L’Atalante observations with the inertial dissipation method and from the ASIS buoy using the eddy correlation method. For the FETCH results, lines with error bars show the average and standard deviation of $C_{D10N}$ values in 2m.s$^{-1}$ wind speed bins, whereas the lines with symbols are the regression curves given in Table 5 for wind speeds above 6 and 8 m.s$^{-1}$, respectively for the L’Atalante and ASIS. The Smith [1980] relationship is shown as the dotted line.

However, some differences are noticeable between the 3 curves of ASIS, R/V L’Atalante and Smith [1980], although they all collapse for $U_{10N}$ around 13m.s$^{-1}$. Indeed, if the aerodynamic rough flow conditions are considered (associated with a linear trend between $C_{D10N}$ and $U_{10N}$), Figure 10 indicates that the three datasets have different slopes with $U_{10N}$. The difference observed between L’Atalante and ASIS buoy $C_{D10N}$ values is similar to what was awaited from $U_{10N}$ and $u^*$ comparisons in section 6.2 (while the two platforms were in the vicinity of each other). Also, the threshold above which a linear trend is observed is higher for the ASIS results. Therefore, the coefficients for the regressions are expressed in Table 5 using the two thresholds for $U_{10N}$ of 6 and 8 m.s$^{-1}$. The correlation coefficients show that only for ASIS results is the threshold of 8m.s$^{-1}$ necessary (using the 6 m.s$^{-1}$ threshold leads to a smaller correlation coefficient and a poor fit of the regression line at high wind speeds). The slopes of other studies conducted in the open ocean mentioned in Table 5 are found to vary between 0.063 to 0.071 (first column in Table 5), whose differences are not statistically significant according to the standard errors of the slopes (the differences in the slopes are less or equal than twice the mean standard error, where the mean is the root mean square of the average of the squared standard errors). The linear regressions presented in Table 5 for the ASIS buoy (for wind speed larger than 8 m.s$^{-1}$) and the R/V L’Atalante are also displayed in Figure 10 as the thin and thick lines with symbols. The slopes of the present study with R/V L’Atalante data are within the range of previous estimates, while the ASIS results provide a higher slope of 0.100. In this case, the difference in the slope is statistically significant. If, however, the slope is calculated over the wider wind speed range used by Smith (U>6m.s$^{-1}$), the slope of the ASIS data drops to 0.77. Corresponding differences between the $C_{D10N}$ values of the R/V L’Atalante and Smith [1980] are all within 6% (the maximum of 6% is obtained for 8m.s$^{-1}$). Maximum differences between the $C_{D10N}$ values of ASIS and Smith [1980] are -18% at 8m.s$^{-1}$ and +8% at 17.80m.s$^{-1}$.

Drennan et al. [this issue] associate these differences with a wave age effect. Considering the subset of FETCH data representing pure wind seas, the high wind speed ASIS data were found to be representative of young, underdeveloped waves. The Smith [1980] curve, on the other
hand, was found to represent near fully developed seas. With this in mind, a preliminary study has been done to compare wave age as $U_{10N}/Cp$ both on the R/V L’Atalante and ASIS buoy during FETCH in the 8-18m.s$^{-1}$ wind speed range (corresponding to rough flows and sea states dominated by wind seas). Here $Cp$ represents the phase speed of waves at the peak of spectrum. The preliminary results, based on wave ages estimated using the VAG model [Guillaume, 1990], did not indicate a sea state effect with the L’Atalante data sufficient to account for the differences in $C_{D10N}$ values which is supported by the similar trends obtained in section 6.2 while the two platforms encountered similar sea states; further analysis will be undertaken also to consider the controversy about use of IDM in high wind conditions [Janssen, 1999; Taylor and Yelland, 2000], indicating that this question is still unresolved. As pointed out above, accounting for the cross wind component $\langle-vw\rangle$ in the wind stress of the ASIS buoy data does not change significantly the drag coefficient for rough flow conditions. In contrast data for low and moderate wind speeds, the ASIS drag coefficients are increased after including this term.

<table>
<thead>
<tr>
<th>Study</th>
<th>a (Slope)</th>
<th>b (constant)</th>
<th>r</th>
<th>Range in $U_{10N}$ (m.s$^{-1}$)</th>
<th>Data (length)</th>
<th>Relative wind direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smith 1980</td>
<td>0.063</td>
<td>0.61</td>
<td>0.70</td>
<td>6-22</td>
<td>63</td>
<td>N/A</td>
</tr>
<tr>
<td>Large and Pond 1981</td>
<td>0.065</td>
<td>0.49</td>
<td>0.74</td>
<td>10-26</td>
<td>973</td>
<td>-90 to +45°</td>
</tr>
<tr>
<td>Anderson 1993 IDM</td>
<td>0.071</td>
<td>0.49</td>
<td>0.91</td>
<td>4.5-18</td>
<td>84</td>
<td>-45 to 45°</td>
</tr>
<tr>
<td>Yelland et al. 1998</td>
<td>0.070</td>
<td>0.50</td>
<td>0.80</td>
<td>6-25</td>
<td>1111</td>
<td>-10 to +10°</td>
</tr>
<tr>
<td>ASIS / FETCH ECM</td>
<td>0.077</td>
<td>0.38</td>
<td>0.67</td>
<td>6-20</td>
<td>524</td>
<td>-30 to +30°</td>
</tr>
<tr>
<td>ASIS / FETCH ECM</td>
<td>0.100</td>
<td>0.08</td>
<td>0.77</td>
<td>8-20</td>
<td>346</td>
<td>-30 to +30°</td>
</tr>
<tr>
<td>(this study) IDM</td>
<td>0.063</td>
<td>0.56</td>
<td>0.56</td>
<td>6-19</td>
<td>395</td>
<td>-30 to +30°</td>
</tr>
<tr>
<td>(this study) IDM</td>
<td>0.069</td>
<td>0.47</td>
<td>0.54</td>
<td>8-19</td>
<td>291</td>
<td>-30 to +30°</td>
</tr>
</tbody>
</table>

Table 5: Drag coefficient relationships obtained in previous open ocean studies. In each case, the formulae quoted were of the form $1000* C_{D10N} = a U_{10N} + b$ by linear regression (the standard errors of a and b are indicated in brackets when available). The regression coefficients, the wind speed and direction ranges, and the number of samples used in each study are indicated.

Results for the heat fluxes are shown in Figure 11. The confidence in $C_{H10N}$ is very low (very large standard deviations compared to any other kind of measurements as also shown in Table 2). These large standard deviations are partly due to rather small air-sea temperature differences during FETCH, although air-sea temperature differences less than $0.5^\circ C$ in magnitude have been excluded of the present analysis. In addition, although we have tried to use the lowest frequency part of the inertial sub-range for the sonic temperature, systematic errors due to the poor quality of the spectra also affect the order of magnitude of the sensible heat flux. It is therefore difficult to draw conclusions either on the order of magnitude of $C_{H10N}$ values, or on the dependence of $C_{H10N}$ values on $U_{10N}$.

In contrast, the $C_{E10N}$ values do not show this large scatter thanks to the refractometer measurements which provide
refraction index fluctuation spectra with a high accuracy. The average value and standard deviations of $C_{\text{E10N}}$ values are respectively $1.00 \times 10^{-3}$ and $0.31 \times 10^{-3}$ (480 samples). This compares reasonably well with previous studies by DeCosmo et al. [1996], Anderson [1993], Smith [1980], Large and Pond [1982], reporting values between 1 and $1.2 \times 10^{-3}$ although it is slightly lower on average, especially at moderate wind speeds. The standard deviations are very small compared to previously mentioned studies. This is very encouraging for latent heat fluxes provided by these new refractometer devices. A slight dependence of $C_{\text{E10N}}$ values with $U_{\text{10N}}$ is observed both with or without flow distortion correction as reported in Dupuis et al. [1999]. This slight dependence on $U_{\text{10N}}$ (20% within a 10m.s$^{-1}$ wind speed range) is expressed by the following regression line (showing uncertainties of 2 standard errors):

$$C_{\text{E10N}} \times 1000 = 0.02 \pm 0.05 \ U_{\text{10N}} + 0.83 \pm 0.054, \ r=0.22 \ (290 \ samples)$$

The remaining uncertainties due to the limit of the simulation of air flow distortion does not allow us to conclude whether this slight linear trend is real.

![Figure 11: $C_{\text{E10N}}$ (a) and $C_{\text{H10N}}$ (b) versus $U_{\text{10N}}$ obtained during FETCH from the R/V L’Atalante observations with the inertial dissipation method. The azimuth angles are limited to $\pm 30^\circ$ and the cases for “complete” (diamond Symbols and black line with error bars) and “uncorrected” (grey line with error bars) airflow distortion corrections are displayed. Error bars are shown within 2m/s bins in wind speed. The average value is displayed with dashed line and the $1.2 \times 10^{-3}$ value with the dotted line.](image)

7. Conclusions

This study concerns the estimation and parameterization of the turbulent fluxes of momentum, sensible heat and latent heat. Results were obtained by using the inertial dissipation method on the R/V L’Atalante during the FETCH experiment. Momentum and latent heat flux derived from a sonic anemometer and a refractometer are of good
quality whereas the sensible heat flux derived from the sound speed provided by the sonic anemometer is doubtful (due to spikes in the spectra, noise limiting the inertial subrange, and also very small air-sea temperature differences leading to large standard deviations in the $C_{D10N}$).

The main objective of the present study was to analyze the impact of airflow distortion due to the ship structure on the flux parameterizations. Therefore, numerical simulations of the flow around the ship structure have been performed [Nacass, 1999]. They provide numerical estimates of the wind speed error, of the relative wind direction error and of the streamline slope angle as a function of the azimuth angle.

These numerical simulations show a constant slope angle of about 7° for relative wind direction within ±100°. The horizontal wind speed error is found to vary from -6% to 0 to +20% for relative wind directions of respectively 0, 38 and 100°. Comparisons of simulated streamline slope angles with those measured at the sonic anemometer location show good agreement. A good agreement is found also with physical simulations realized by Butet [2002].

Estimate of the vertical elevation of the streamline is cruder, due to the discretization and to the limited size of the domain used in the simulation. This vertical streamline displacement was however estimated by following the reverse pathline and found to be 1.21m for bow-on flows at 10 m/s. A complete expression for the vertical displacement as a function of the relative wind speed and direction (Eq. 18) has been established by requiring consistency of the data for different relative wind directions, in qualitative agreement with the results of the numerical simulations obtained only at wind speeds of 10m/s.

As a result of combined effects of horizontal mean wind error and vertical displacement correction, the drag coefficients $C_{D10N}$ are found to be almost independent of wind direction conditions, whereas a discrepancy of a factor of 2 was found without applying the correction. For wind directions aligned within ±30° of the bow axis, the correction of $C_{D10N}$ values is in average -17%, divided into -12% for the wind speed correction and -5% for the vertical elevation correction. For heat flux, the relative effect of the vertical elevation correction on exchange coefficients is slightly larger, reaching -5.7%, while the wind speed correction reaches -7.4%. A simplified correction independent of azimuth angles as used in Hare et al. [1999] has been tested. Consistent with the high sensitivity on azimuth angles in the wind speed error found by the simulations, this simplified correction is found to apply only for data with wind directions aligned within ±30° of the bow; otherwise if, for example a range of ±90° is used for azimuth angles, the error in $C_{D10N}$ values reaches 4.4%.

These results therefore show how this flow correction is needed. The comparison of wind speeds and momentum fluxes between estimates from the R/V L’Atalante and from the ASIS buoy when they were closer than 20km, shows that the wind speeds are in good agreement when the flow distortion correction is applied. Furthermore, the agreement for the parameterization of the drag coefficients with other studies in the open ocean and with the ASIS buoy for rough flow is satisfactory. This was not the case when no correction for airflow distortion was applied. However, although similar values are observed around 13m.s^{-1} for the R/V L’Atalante, ASIS and Smith et al. [1980], the slopes of the linear regressions are rather different.

The slightly higher momentum fluxes observed at ASIS compared to those from the R/V L’Atalante when they were in the vicinity during the FETCH cruise, as well as the different $C_{D10N}$ values for the overall datasets at high wind speeds is one point which is not yet fully explained. Because measurements on ASIS and the R/V L’Atalante were obtained with two different
methods, it is still difficult to draw any conclusions but this study has shown that the air flow distortion correction removes much of the discrepancies between bow-on and beam-on $C_{D10N}$ data, yielding reasonable $C_{D10N}$ to $U_{10N}$ relationship and reducing the scatter (Table 2).

The exchange coefficient for evaporation exhibits a very slight dependence on wind speed. Further measurements, particularly at very high wind speeds, and an enhanced confidence in the flow correction algorithm (particularly on the vertical displacement), will be needed to establish if this dependence is significant or if the average value of $1.00 \times 10^{-3}$ is to be used.

Results on the exchange coefficient for sensible heat flux show that a better quality of sonic temperature measurement is needed for an accurate estimation of the sensible heat flux or exchange coefficient using the inertial dissipation method. It is hoped that the improved sonic thermometer developed by Gill Instr. in the framework of the “Autoflux” European Community Program [Larsen et al., 2000] will fulfill this requirement.

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