The FETCH experiment : an overview

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The FETCH experiment: An overview

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[1] The "flux, etat 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 waverider 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 12 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. *INDEX TERMS:* 3307 Meteorology and Atmospheric Dynamics: Boundary layer processes; 3339 Meteorology and Atmospheric Dynamics: Ocean/atmosphere interactions (0312, 4504); 3360 Meteorology and Atmospheric Dynamics: Remote sensing; 4219 Oceanography: General: Continental shelf processes; 4255 Oceanography: General: Numerical modeling; *KEYWORDS:* air/sea interactions, surface ocean waves, remote sensing, marine atmospheric boundary layer, coastal oceanography, Gulf of Lion

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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

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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, etat 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'Etude des Environnements Terrestre et Planétaires (CETP) (France),
2. A moored air–sea interaction spar (ASIS) buoy operated by the Rosenstiel School of Marine and Atmospheric Science (USA),

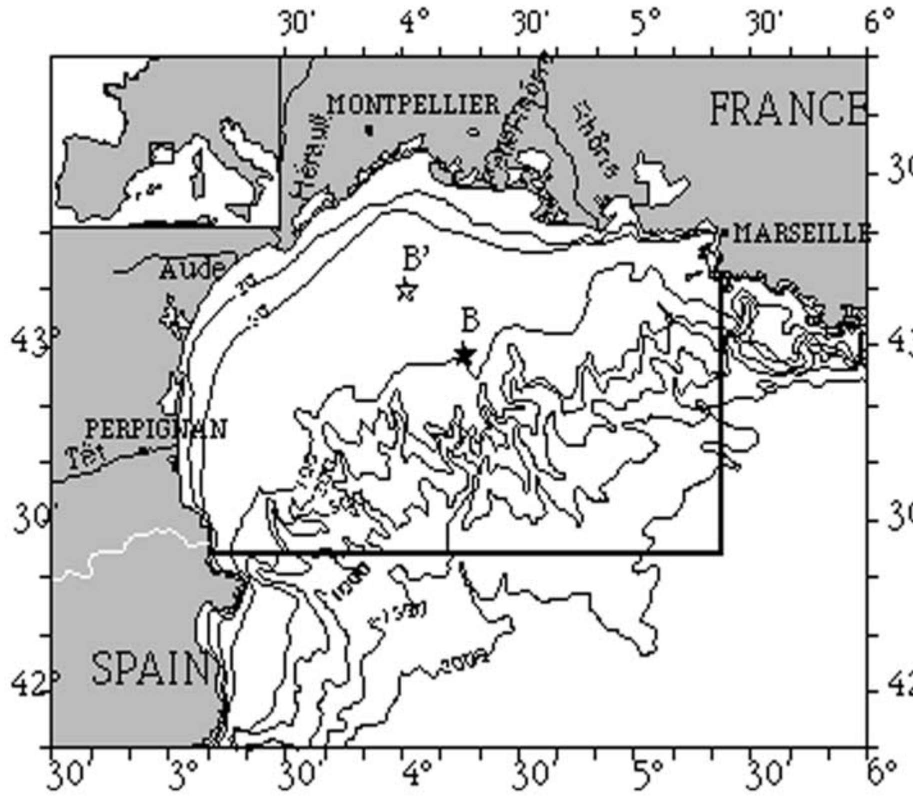


Figure 1. Geographic location of the FETCH experiment. B is the location of the ASIS buoy (18 March to 9 April) and of the DWR from 16 to 25 March. B′ is the location of the DWR after 25 March.

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.*, 2003]. 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

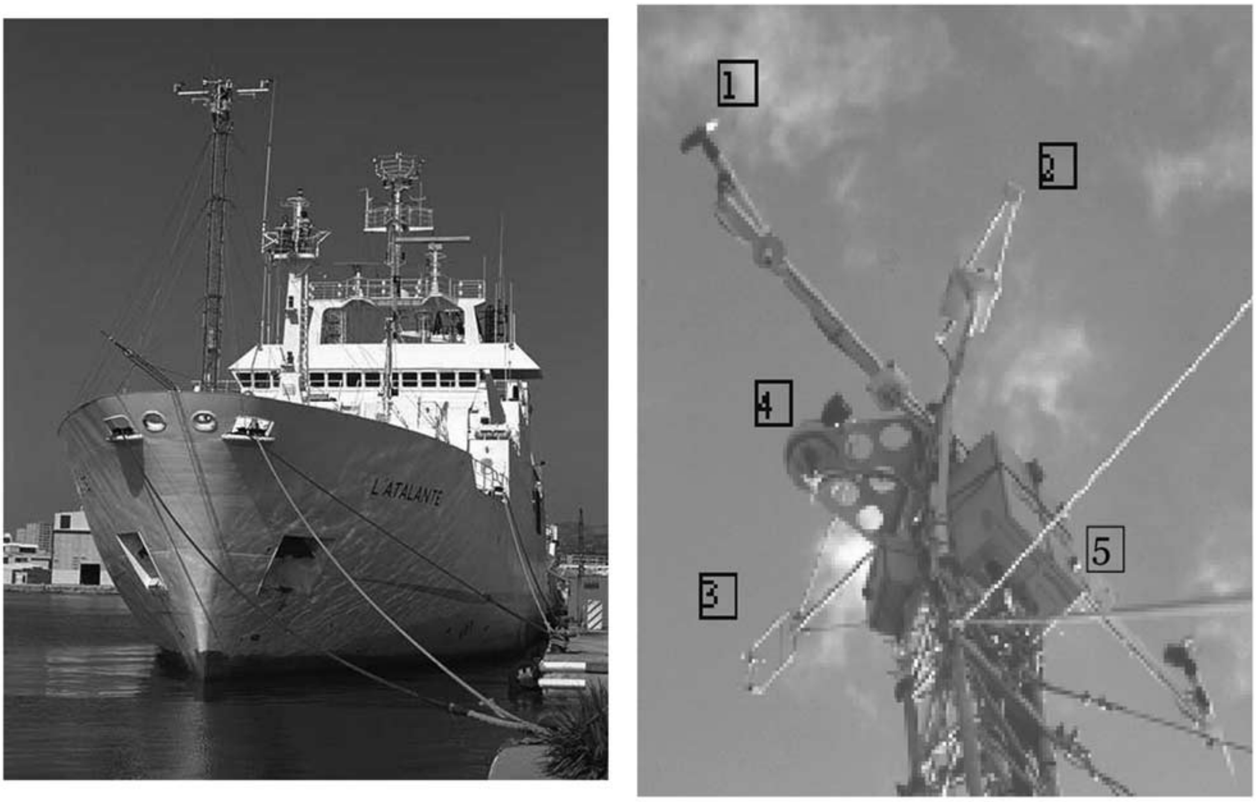


Figure 2. Meteorological mast on the R/V *L'Atalante*. (a) Overview of the R/V and its meteorological mast. (b) Zoom on the top of the mast. Labels 1–5 indicate the location of (1) mean meteorological sensors (wind speed, wind direction, temperature, and humidity), (2) optical rain sensor, (3) 3-D sonic anemometer, (4) microwave refractometer, and (5) motion package.

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].

2.2.1.3. Ocean Measurements From R/V *L'Atalante*

[17] 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 thermosalinograph 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*

[18] A microwave dual-frequency radiometer (23.8 and 36.5 GHz) called DRAKKAR [*Gérard and Eymard*, 1998; *Eymard*, 1999] 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

[19] An ASIS buoy [see *Graber et al.*, 2000; *Drennan et al.*, 2003] 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 50–80 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 meas-

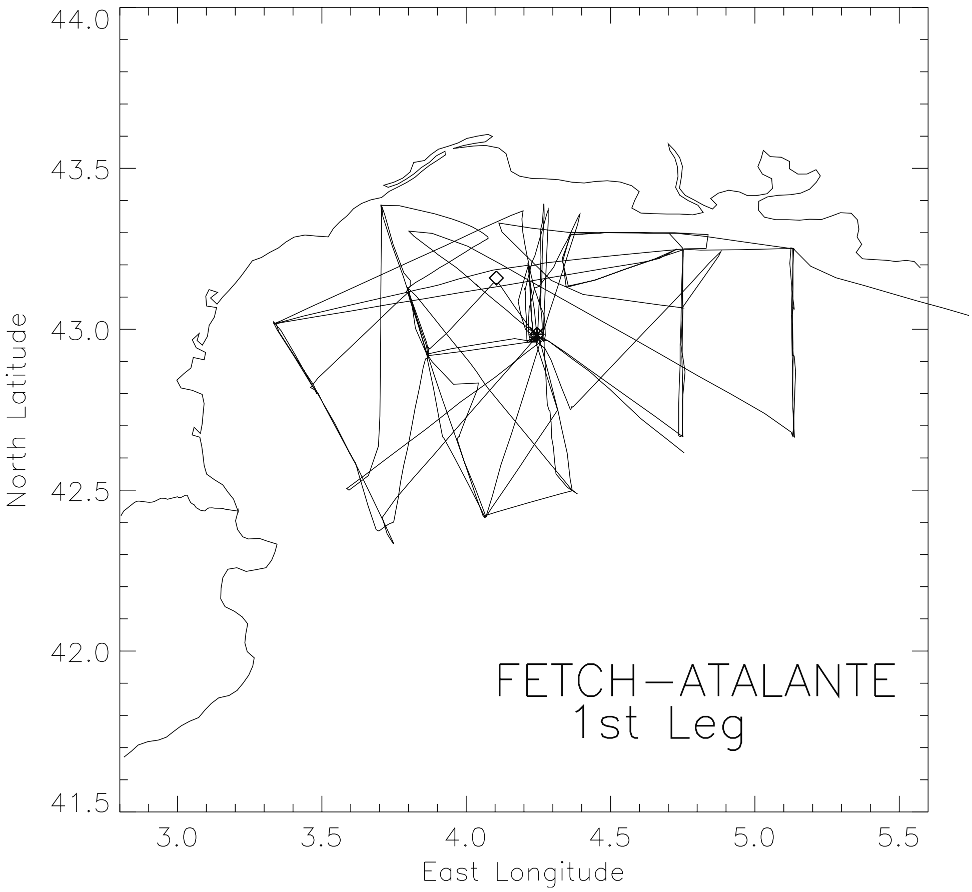


Figure 3. Ship track (a) for the first leg, (b) for the second leg, and (c) during a Mistral event (21 March). The star indicates the location of ASIS and the diamond indicates the position of the DWR after 25 March. In (c), the wind measured by R/V *L'Atalante* along its track is indicated every 3 hours.

ured 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.*, 2003]. 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).

[20] A directional wave rider (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.*, 2003]. 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.

[21] 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

[22] Two aircraft from the French scientific community participated in the FETCH campaign: the Fokker 27 "ARAT" (Avion de Recherche Atmosphérique et de Télédétection), 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

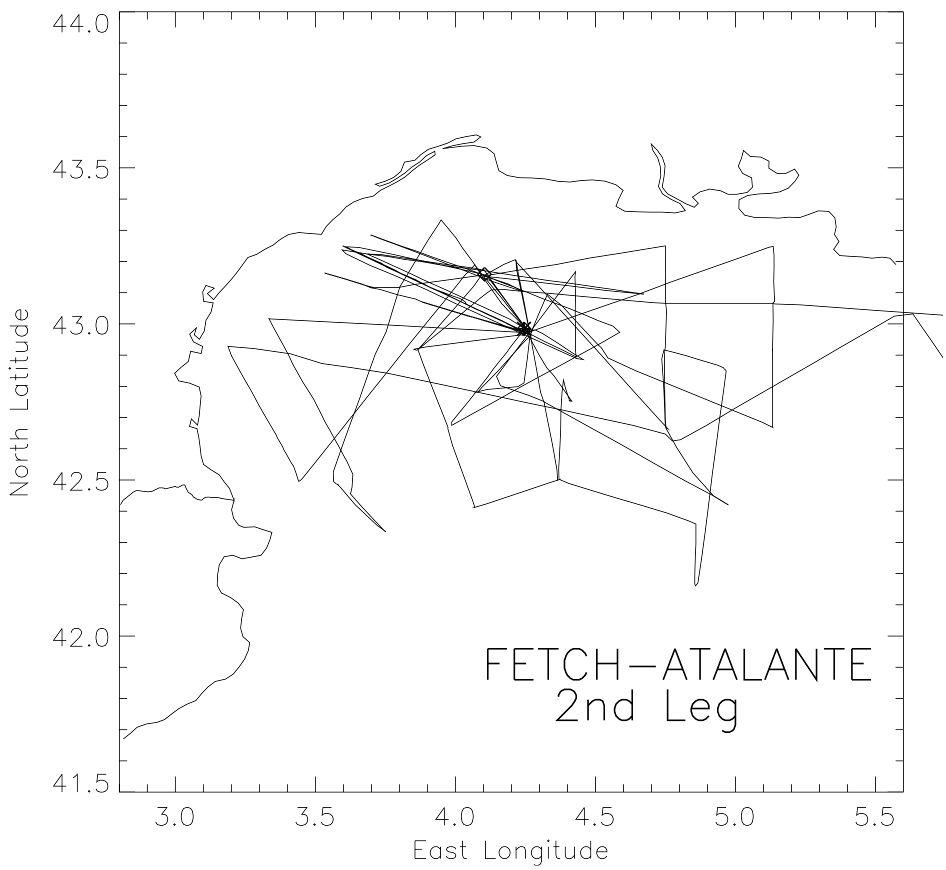


Figure 3. (continued)

were encountered with this system and the data are not usable for analysis.

2.3. Operations

[23] 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 the first leg, the ship was shared with another scientific group for the MOOGLI campaign [*Diaz 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.

[24] 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 boundary 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.

[25] 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 measurements (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 conditions.

2.4. Satellite and Model Data

[26] 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.

[27] The analysis and forecasts of three operational atmospheric circulation models were archived for FETCH:

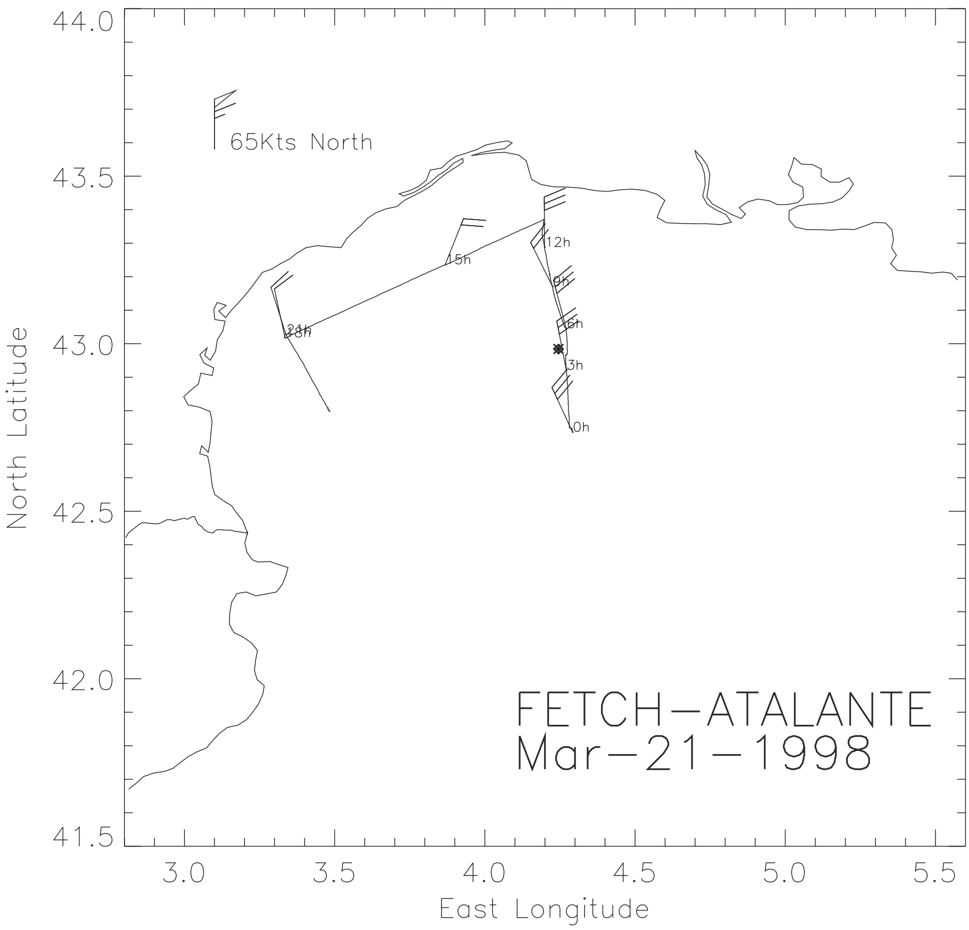


Figure 3. (continued)

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 Météo-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

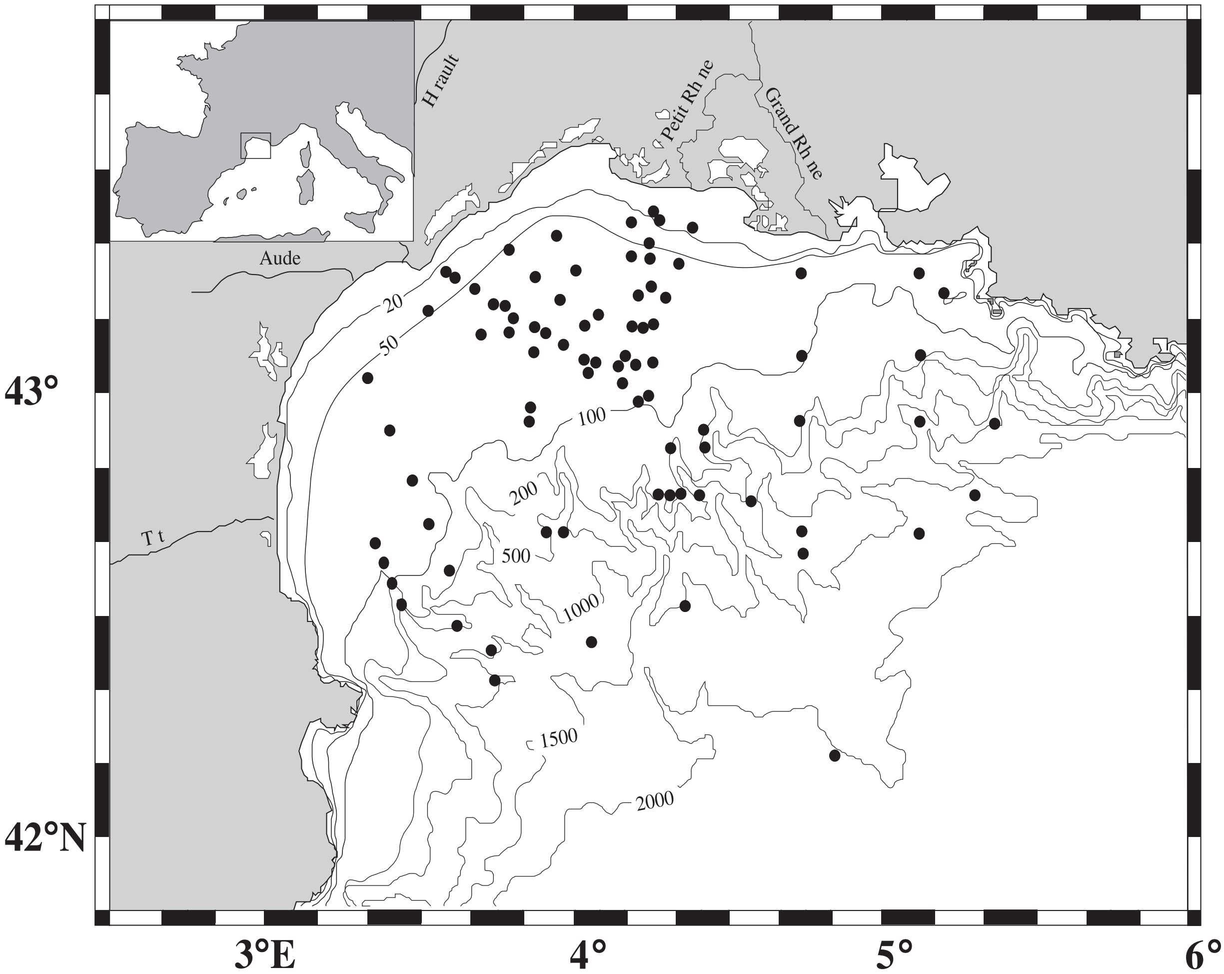


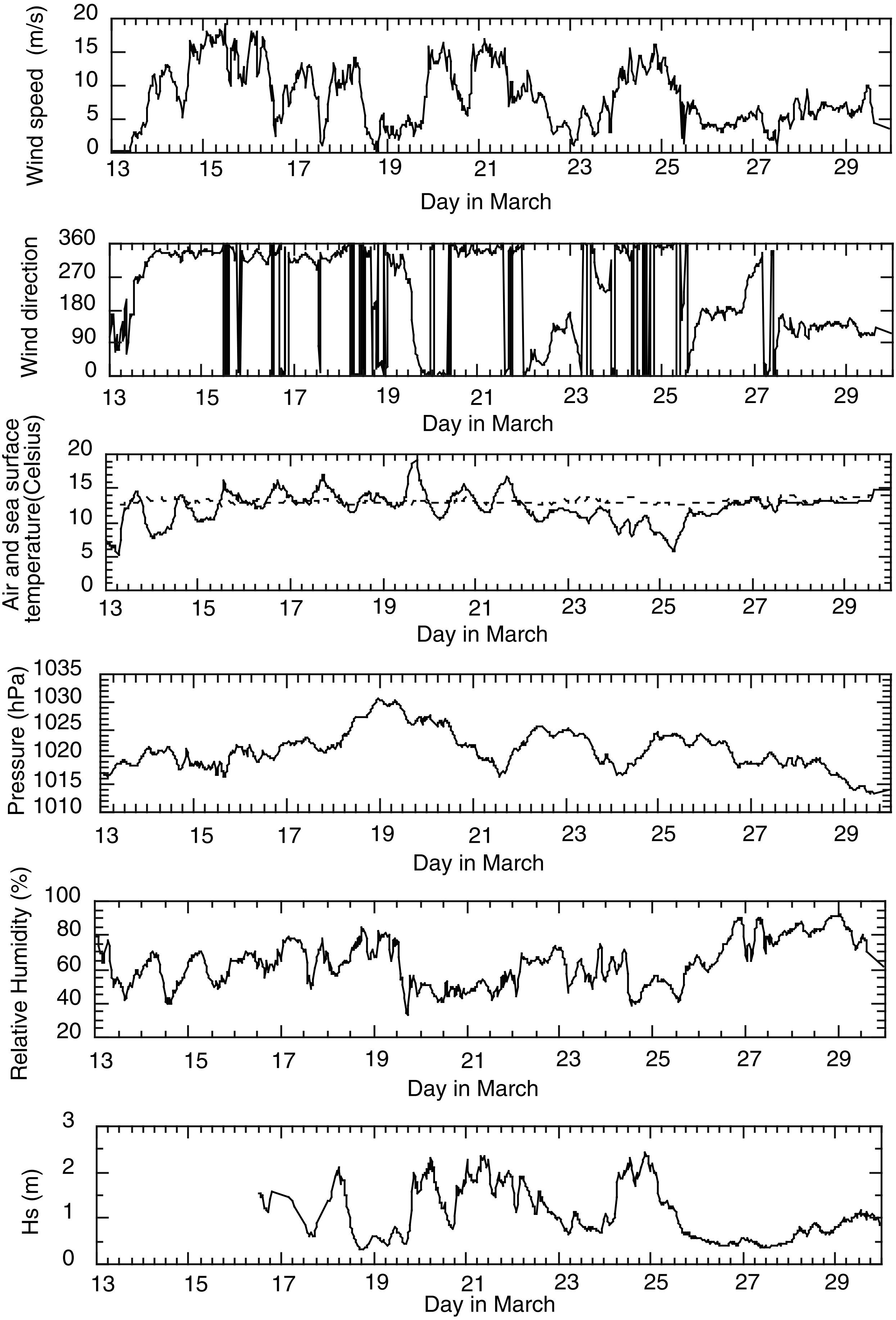
Figure 4. Locations of CTD measurements during the FETCH campaign (dots).

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.

[33] 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.

[34] 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

Figure 5. (opposite) Atmospheric and wave conditions from 13 to 29 March. 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 first leg (see Figure 3a), except the significant wave height that was measured onboard ASIS (position B in Figure 1).


Wind speed (m/s)
Wind direction
Air and sea surface temperature(Celsius)
Pressure (hPa)
Relative Humidity (%)
Hs (m)
Day in March

(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] Eleven papers follow the present introduction. Six 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.

[38] In an other study by *Dardier et al.* [2003], 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.

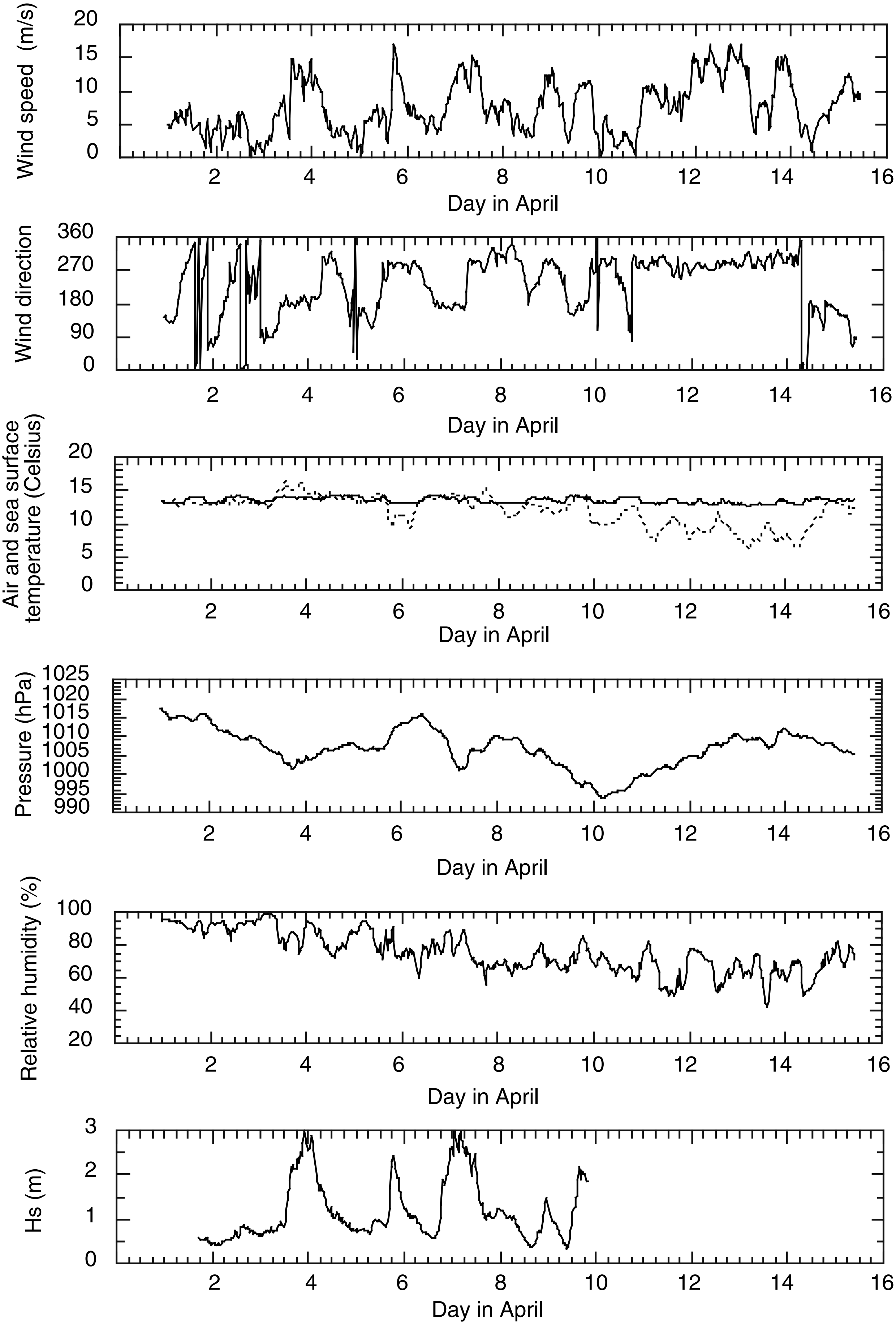
4.1. Turbulent Fluxes and the Atmospheric Boundary Layer

[39] 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 with its mast are used to correct the flux estimates from flow distortion. 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 corrections, 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 *Yelland 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 sonic temperature measurements is less satisfactory due to the bad response of the sensor at high frequencies.

[40] In an other 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 not 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.

[41] The problem of the significance of surface fluxes estimated at a larger scale from models or satellite is discussed by *Eymard et al.* [2003] 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 Sur-

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).


Wind speed (m/s)
0
5
10
15
20
2
4
6
8
10
12
14
16
Day in April
Wind direction
0
90
180
270
360
Day in April
Air and sea surface temperature (Celsius)
Day in April
Pressure (hPa)
990
995
1000
1005
1010
1015
1020
1025
Day in April
Relative humidity (%)
20
40
60
80
100
Day in April
Hs (m)
0
1
2
3
Day in April

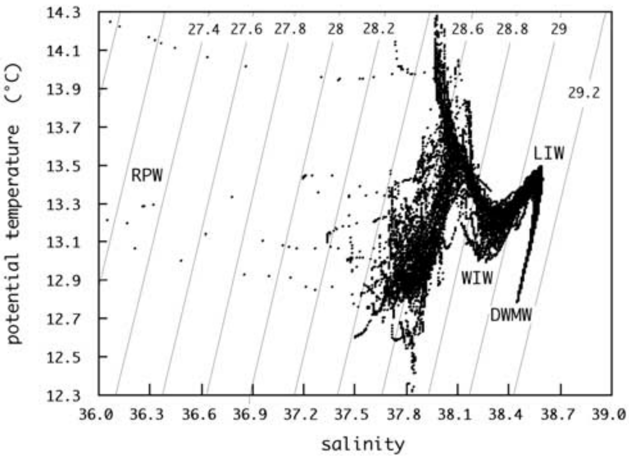


Figure 7. Theta-S diagram for all hydrological casts performed in the Gulf of Lion during the FETCH cruise (14 March to 14 April 1997). "RPW" stands for "Rhône Plume Water." Classical water masses below 100 m depth are named "Winter Intermediate Water" (WIW) between 100 and 200 m depth, "Levantine Intermediate Water" (LIW) between 200 and 600 m depth, and "Deep Western Mediterranean Water" (DWMW) below 1500 m depth.

face Temperature from AVHRR or Meteosat are of a quality similar to model bulk fluxes, and provide a better description of mesoscale heterogeneities.

[42] 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* [2003], using a combination of numerical weather prediction model forecasts, airborne lidar measurements as well as in situ shipborne, 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. The 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) in the lee of the three major mountain ranges surrounding the Gulf of Lion (namely, the Pyrénées, the Massif Central and the Alps) 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.

[43] In an other paper, *Flamant et al.* [2003a, 2003b] 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}).

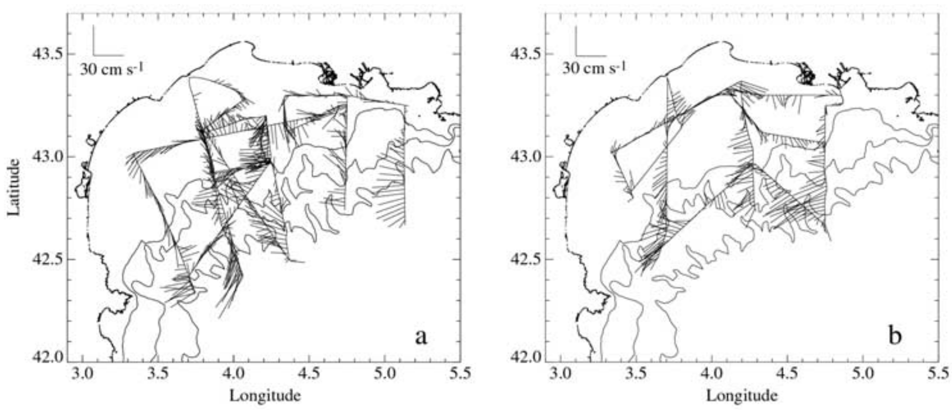


Figure 8. Along-track current at 30 m depth during the 14–19 March 1998 period characterized by northern (Mistral) and northwestern (Tramontane) winds and the 22–26 March 1998 period characterized by northern (Mistral) wind only.

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

[44] 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.* [2003] 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

[46] New developments in remote sensing of the ocean surface are presented in three papers. The two papers by [*Kudryavtsev et al.*, 2003a, 2003b] 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.

[47] 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.* [2003b] 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

[48] 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.

[49] 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. 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.

[50] 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.*, 2002b]. With this approach, it is expected that new progress will be achieved in the future.

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