JOURNAL OF GEOPHYSICAL RESEARCH
February 2003; 108(3) : 108 (C3) NIL_27-NIL_41
http://dx.doi.org/10.1029/2001JC001202

The FETCH experiment: An overview

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Abstract: 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.

Keywords: air/sea-interactions; surface-ocean-waves; remote-sensing; marine-atmospheric-boundary-layer; coastal-oceanography; Gulf-of-Lion

1. Introduction

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,1999) followed by other Baltic sea experiments (Smedman et al 1994, Smedman et al, 1999). The case of non-homogeneous 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).

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.

In this context the international field campaign FETCH ("Flux, Etat de la mer, et Télédétection en Conditions de fetcH variable") 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, buoys), airborne observations (in situ and remote-sensing), surface fields available from several atmospheric and wave models, space-borne 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.

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.

More specifically, the experimental setup, procedure and scientific analysis were aimed at:

- further developing the methodology for estimating turbulent fluxes (in particular on a large ship), and assessing the turbulent flux estimates obtained from different methods
- analyzing the effect of wave development on the turbulent fluxes,
- 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,
- studying the boundary layer structure and its impact on fluxes in conditions of cold outbreaks,
- analyzing the relation between aerosol characteristics, foam coverage, wind and momentum flux,

- studying the surface wave properties (in particular growth law, directional spreading) in fetch-limited (and other) conditions,
- assessing wave prediction models and eventually proposing improvements to these models,
- 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, lidar) in coastal and fetch-limited conditions, since existing algorithms were generally developed and tested for open sea conditions
- estimating the relative impact of wind-forcing, river outflow, and large scale circulation on the mesoscale oceanic circulation in the coastal zone.

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 (2001) and its relation with white cap coverage is presented in 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.

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

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 March 13th and April 15th, 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 North-West 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.

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 ten 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

The experimental platforms deployed for the experiment were:

- The Research Vessel "L'Atalante" operated by Genavir and IFREMER (France), with a meteorological mast installed and equipped by Météo-France and CETP (France),
- A moored Air-Sea Interaction Spar (ASIS) buoy operated by the Rosenstiel School of Marine and Atmospheric Science (USA),
- A moored Datawell directional waverider operated by the Finnish Institute of Marine Research (Finland),
- A drifting Datawell non-directional wave buoy operated by Météo-France,
- Three aircraft used for both in situ and remote sensing measurements (France and Germany)

The main characteristics of these platforms are described below.

a) Research Vessel L'Atalante

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.

i) Atmospheric measurements from R/V L'Atalante:

A meteorological mast was mounted near the bow on the ship foredeck and equipped (see Fig 2) by Centre d'Etude des Environnements Terrestre et Planétaires (CETP) and Météo-France with sensors mounted at a level of 17.8m 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, 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.

The mast was also equipped, at the 17.8m level, with sensors for turbulent measurements: a three-axis ultra-sonic 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, this issue). 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.

Atmospheric radio-soundings 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.

ii) Surface measurements from R/V L'Atalante

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 minute 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 minutes (standard mode) or every 10 s (in certain occasions). This system was designed to provide both the foam coverage and the two-dimensional properties of the short waves (from about 30 cm to 30 m) by using the stereoscopic information (Weill et al, 2002).

iii) 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 to 150 m depth layer. Hydrological data were collected by deploying CTD (Conductivity-Temperature-Density) 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.

iv) 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 on-board the ship enabled zenith pointing or surface pointing (about 25 and 50° incidence angles).

b) Buoys

An ASIS buoy (see Graber et al, 2000, and Drennan et al this issue) was moored from March 18th to April 9th 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 100m (point B in Fig 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 to 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., 7m 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 this issue). 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 directional waverider (DWR) manufactured by Datawell was moored during FETCH by the Finnish Institute of Marine Research (FIMR). During the first part of the experiment (from March 16th to March 25th) 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, this issue). On March 25th, DWR was recovered and re-deployed closer to the shore at 43°09'34"N, 04°06'15"E, roughly half way between ASIS and the coast (point B' in Fig 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.

c) Aircraft

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 down-looking differential absorption lidar LEANDRE 2 (Bruneau et al, 2001a,b), 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 (Fig 3a), and 1-14 April (Fig 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.

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 Fig 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 to 12000 feet). Vertical soundings (between the surface and about 12000 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 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

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 km x 10 km and covering about 2000 km x 2000 km centered over France.

All these models provide three-dimensional fields of the atmospheric parameters (pressure, wind, temperature, humidity), every 6 hours (every 3 hours for ALADIN).

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° x 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 km x 25 km and driven by the ARPEGE wind fields.

In addition, off-line research versions of VAG and WAM have been implemented to provide wave fields at high-resolution (0.083° x 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, ALADIN).

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 km x 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 US Navy.

3. Dominant conditions

3.1 Mean atmospheric and wave conditions

Figure 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 Fig.1) by ASIS is also shown in the bottom panels. Three different periods can be distinguished.

The first period (13-25 March) was dominated by Mistral events, which occurred on 14-16 March, 20-21 March, 24-25 March. The synoptic situations leading to these Mistral events correspond to a N to NW 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 N to NW 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 N to NW winds. During these periods, wind measured on the R/V L'Atalante was from N to NW 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 (24-25 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 March 26th to April 2nd) 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 S to SW or mixed sea.

During the third period (from April 3rd to April 15th), 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 afterwards, 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 April 3rd to April 15th the largest significant wave heights of the campaign were observed (up to about 3 m) with frequent swell from S to SW or mixed sea.

3.2 Oceanic conditions

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 (Fig. 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.

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 (Fig. 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

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, 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

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 air flow 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 air flow distortions, and Yelland et al (1998) based on R/V measurements corrected for the mean air flow 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.

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.

The problem of the significance of surface fluxes estimated at a larger scale from models or satellite is discussed by Eymard et al 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 minutes. 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 to 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.

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, using a combination of numerical weather prediction model forecasts, airborne lidar measurements as well as in situ ship-borne, sea-borne and airborne measurements. It is shown that the non-stationary nature of the wind regime over the Gulf of Lion was controlled by the multi-stage 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 multi-platform surface turbulent flux measurements made over the Gulf of Lion on 24 March 1998.

In an other paper, Flamant et al 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, ship-borne 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 ship-borne 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 Directional Waverider) 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 one dimensional parameters of the wave spectrum consistently and the agreement on the directional parameters and the shape of the two dimensional 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 two dimensional spectra of RESSAC and ASIS during a strongly inhomogeneous situation.

4.3 Ocean circulation

The paper by Estournel et al 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 meso-scale 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

New developments in remote sensing of the ocean surface are presented in three papers. The two papers by Kudryavstev et al 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 which 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.

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 who present results obtained with the airborne LEANDRE2 lidar during a Mistral off-shore 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, atmospheric analyses). The spatial variability of wind speed in this non-homogenous Mistral case could be documented in detail. Secondly, 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

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

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 method. Based on motion corrected vertical velocity standard deviations, it associates the Panofsky (1972) parameterization with the TKE (Turbulent Kinetic Energy) 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 which 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.

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 data base (http://dataserv.cetp.ipsl.fr/FETCH) to other scientific groups. Furthermore, the turbulent data set of FETCH has been integrated in the new data base "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 ten years by scientific groups in France (Eymard et al, 2001, Weill et al 2001). With this approach, it is expected that new progress will be achieved in the future.

Acknowledgements

The FETCH experiment was supported by CNRS/Institut des Sciences de l'Univers (PATOM and PNTS programs), Météo-France, IFREMER, and the program MATER of the European Commission (grant CEE MAS3.CT96.0051). We thank all the technical personal, who contributed to the success of the experiment, in particular the officers and crew of R/V L'Atalante, the crew of the MERLIN-IV and ARAT aircraft. Special thanks also to the C. Abonnel and F. Marin from Météo-France who coordinated the scientific secretariat during the experiment.

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FIGURE CAPTIONS

Figure 1: Geographic location of the FETCH experiment. B is the location of the ASIS buoy (March 18th to April 9th) and of the Directional Waverider from March 16th to March 25th. B' is the location of the Directional Waverider after March 25th.

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 to 5 indicate the location of (1) mean meteorological sensors (wind speed, wind direction, temperature, humidity), (2) optical rain sensor (3) 3D- sonic anemometer (4) microwave refractometer (5) motion package.

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

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

Figure 5: Atmospheric and wave conditions from 13 to 29 March. From top to bottom: wind speed, wind direction, air temperature and SST, pressure , relative humidity, significant wave height. All parameters were measured on-board the R/V L'Atalante along its track during the first leg (see Fig.3a), except the significant wave height which was measured on board ASIS (position B in Fig.1)

Figure 6: Atmospheric and wave conditions from 1 to 15 April. From top to bottom: wind speed, wind direction, air temperature and SST, pressure , relative humidity, significant wave height. All parameters were measured on-board the R/V L'Atalante along its track during the second leg (see Fig.3b), except the significant wave height which was measured on board ASIS (position B in Fig.1)

Figure 7: Theta-S diagram for all hydrological casts performed in the Gulf of Lion during the FETCH cruise (14 march -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 depth, "Levantine Intermediate Water" (LIW) between 200 and 600 m depth and "Deep Western Mediterranean Water" (DWMW) below 1500 m depth.

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.

Figures

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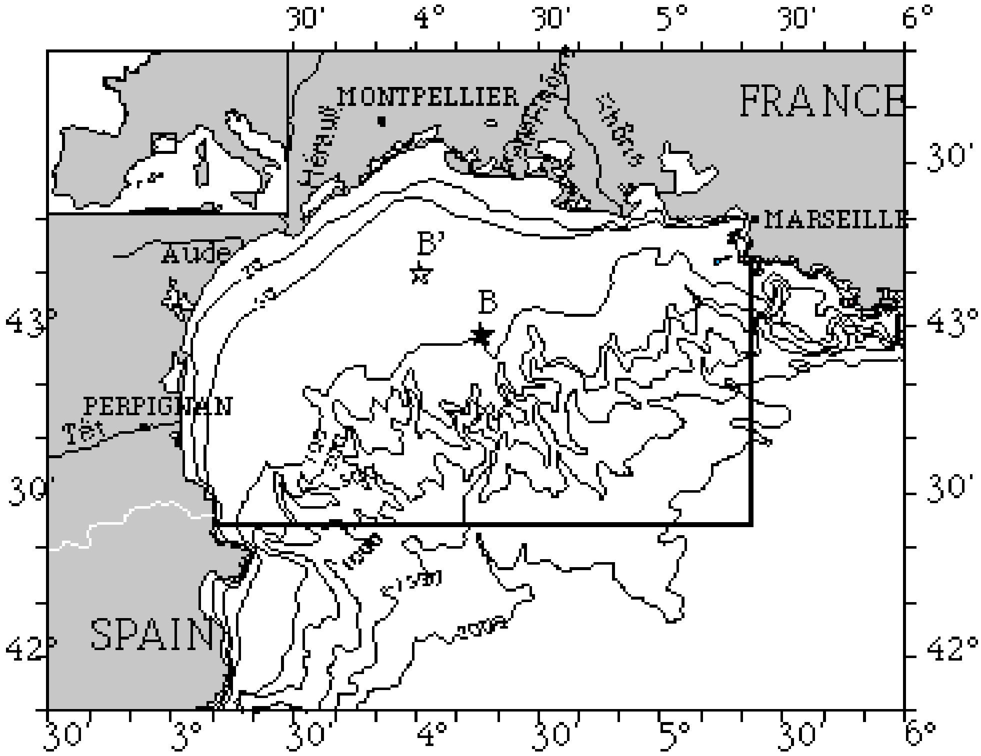

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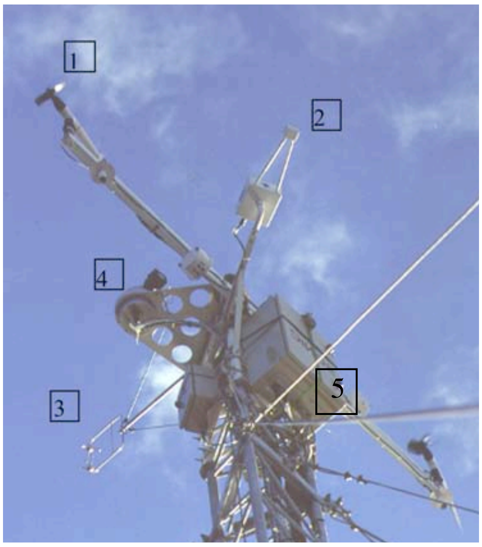

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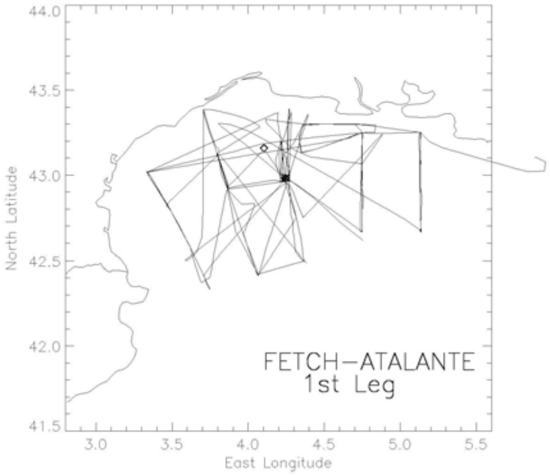


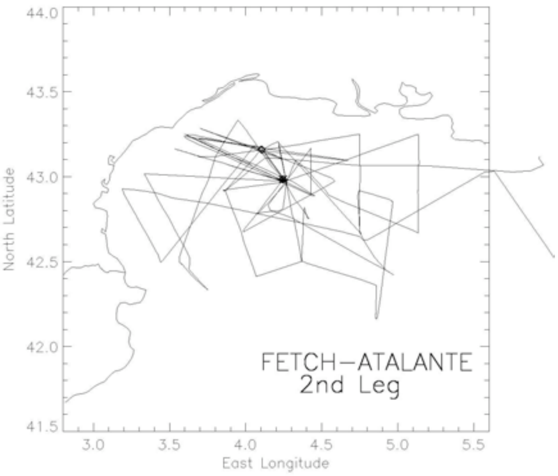


Figure 3a

Figure 3b

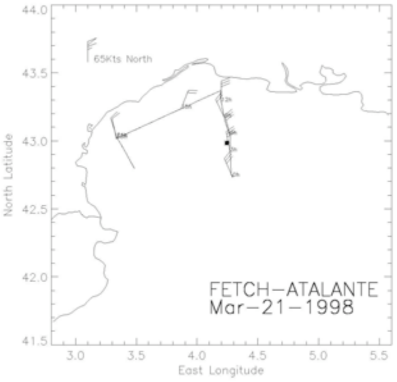
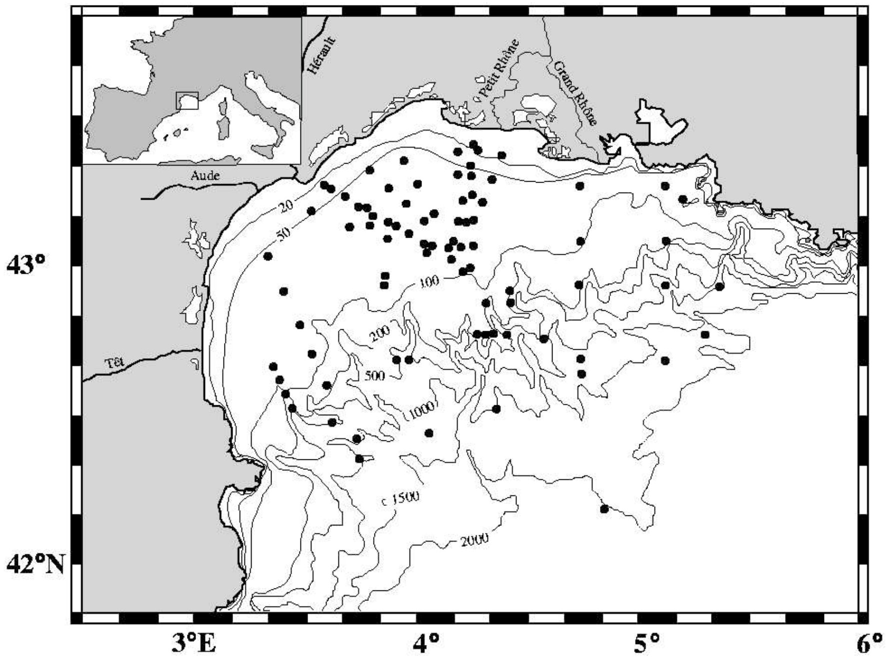


Figure 3c

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



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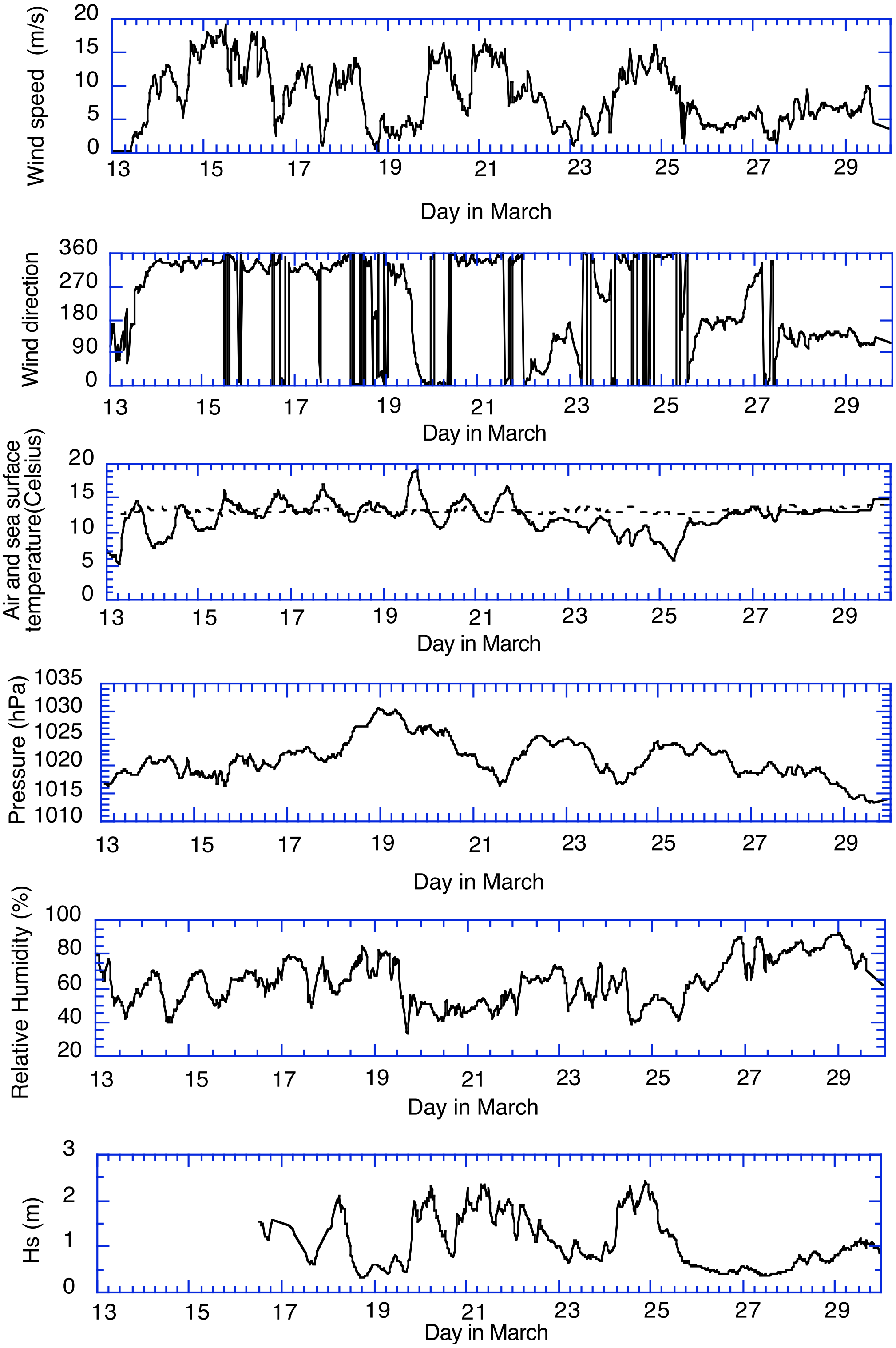

Figure 6: Atmospheric and wave conditions during from 1 to 15 April: from top to bottom: wind speed, wind direction, air temperature and SST, pressure , relative humidity, significant wave height). All parameters were measured on-board the R/V L'Atalante along it's track during the second leg (see Fig.3b), except the significant wave height which was measured on board ASIS (position B in Fig.1)

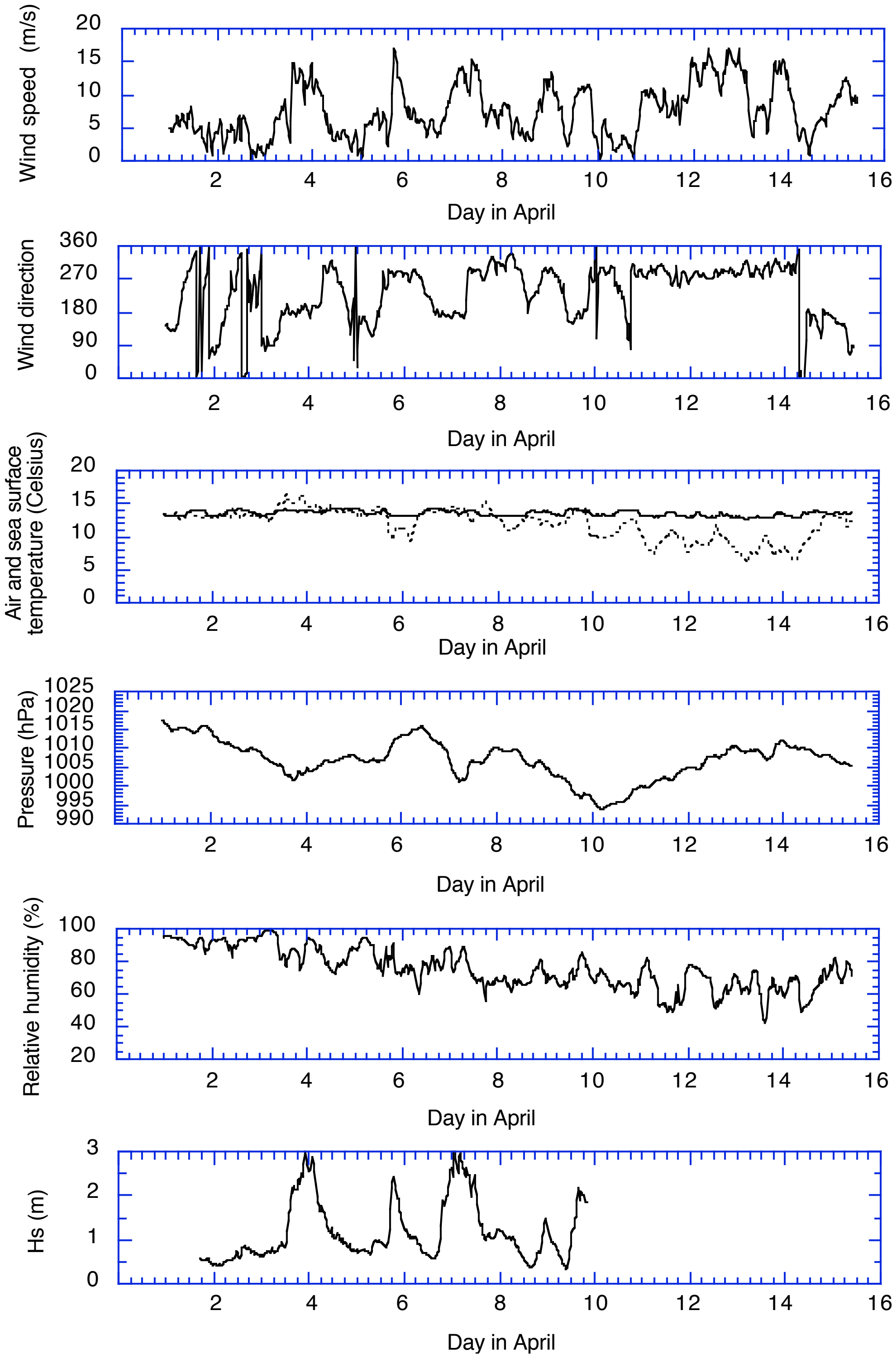

Figure 7: Theta-S diagram for all hydrological casts performed in the Gulf of Lion during the FETCH cruise (14 march -14 april 1997). "RPW" stands for "Rhône Plume Water". Classical water masses below 100 m depth are named "Winter Intermediate Water" (WIW) between 100 and 200 depth, "Levantine Intermediate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

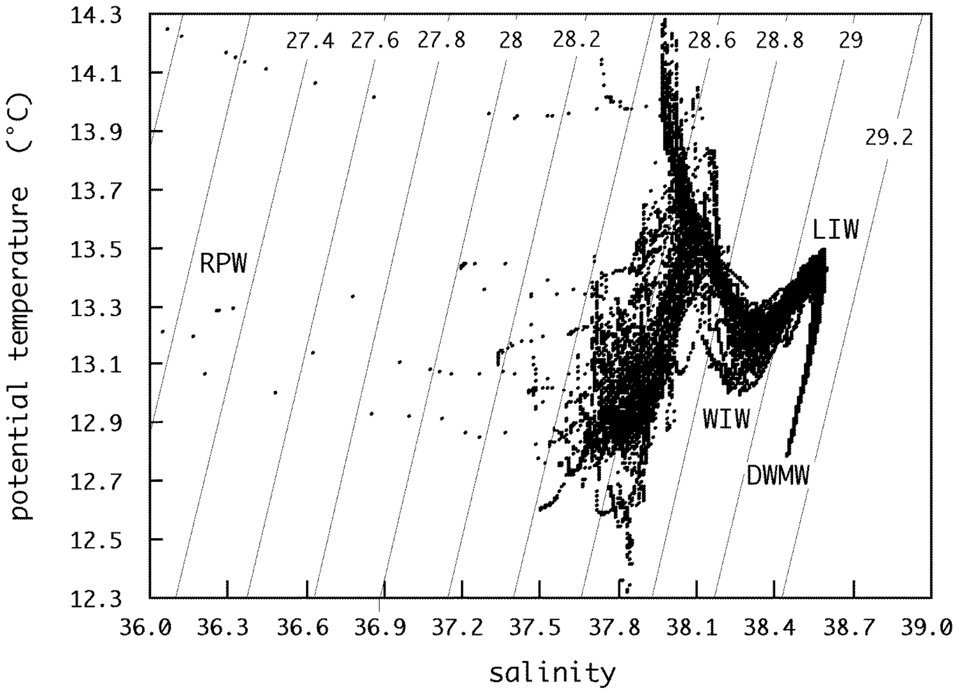

Figure 8: Along track current at 30 m depth during the 14-19 March, 1998 period characterized by northern (Mistral) and northwestern (Tramontane) winds, and the 22-26 March 1998 period characterized by northern (Mistral) wind only.