Surface fluxes in the North Atlantic current during CATCH/FASTEX

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(Received 28 September 1998; revised 14 July 1999)

SUMMARY

CATCH (Coupelage avec l’Atmosphère en Conditions Hivernales) was the oceanic component of FASTEX (Fronts and Atlantic Storm-Track EXperiment). It took place in January and February 1997, in the Newfoundland Basin near 47°N, 40°W, a region characterized by the presence of the warm North Atlantic Current and cold surrounding waters. CATCH was devoted to the study of the parametrization of surface turbulent fluxes in strong winds and changing directions, the surface-flux variability related to the passage of atmospheric fronts and the influence on fluxes of the strong sea surface temperature gradients associated with the North Atlantic Current. This paper presents first results of ship data analysis. A large range of wind and stratification conditions were experienced: 5% of measured winds were higher than 20 m s⁻¹; 30% of unstable stratification (air–sea temperature differences lower than −5 degC) and 30% of very dry conditions (air–sea moisture differences lower than −2.5 g kg⁻¹) were sampled. Surface turbulent heat and momentum fluxes were obtained using the inertial-dissipative method from which a bulk algorithm was derived. A significant increase of latent-heat and momentum-transfer coefficients with increasing wind is obtained. This parametrization is compared to others published using the CATCH dataset. For high winds and unstable stratifications, differences between schemes reach 200 W m⁻² for latent-heat flux values of 600 W m⁻². Radiative and turbulent ship-measured fluxes are compared with modelled fluxes from the European Centre for Medium-Range Forecasts (ECMWF) along the ship’s trajectory: each component of the net heat budget is higher in the ECMWF model, consequently the heat loss of the ocean is 35% higher in the model. Finally, the effect of sea surface temperature fronts on surface turbulent fluxes is analysed by evaluating the contribution of the various terms in the flux variations, showing a significant impact of the surface temperature change in all unperturbed cases.

KEYWORDS: Air–sea flux measurement Air–sea flux parametrization FASTEX Inertial dissipation method Sea surface temperature

1. INTRODUCTION

Sea surface exchanges may contribute to the initiation and amplification of cyclogenesis (Grotchahn and Wang 1989; Newton and Holopainen 1990) and to the intensification of precipitation in frontal bands (Hobbs 1987; Huang and Raman 1992). Surface fluxes (momentum and heat) can considerably influence cyclogenesis, and induce cloud organization (via the latent-heat flux). However, knowledge about these effects remains poor, and relies more on simulations than on data analyses. The Fronts and Atlantic Storm-Track EXperiment (FASTEX, Joly et al. 1997), therefore, provided a contribution to the analysis of the influence of the ocean–atmosphere exchanges on cyclogenesis. This oceanic component of FASTEX was called CATCH (Coupelage avec l’Atmosphère en Conditions Hivernales) and was carried out in the north-western Atlantic Ocean near 47°N, 40°W. Since Iselin (1936, see Rossby 1996) this area is known to have anomalously high sea surface temperatures (SSTs) due to the Gulf Stream and its continuation the North Atlantic Current (NAC). This area is often crossed by cold air masses, and is therefore of high interest for the study of momentum, heat and water exchanges between the ocean and the atmosphere. During the winter season, the experimental area (30–45°W, 40–50°N) is characterized by significant transfers of heat between the ocean and the atmosphere (Budyko 1974). Winter losses of heat (>150 W m⁻², Bunker 1976) and

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Figure 1. Track of RV Le Suroît during CATCH (see text), superimposed on the isobaths at depths of 500 m, 2000 m and 4000 m. The coast lines of Newfoundland and the Azores are also marked with bold lines. The North Atlantic Current (NAC) system with its different branches are also shown as bold arrows according to Sy (1988).

water (>50 cm year\(^{-1}\), Schmitt et al. 1989) are high and place this zone, in spite of its latitude, south of the null-heat-flux line of the North Atlantic.

CATCH had four main objectives: (i) to document the various jets associated with the branching of the NAC and its interaction with the Labrador current (Fig. 1); (ii) to collect an air–sea parameter dataset during varying and strong winds to improve the surface flux parametrization in these conditions; (iii) to document the variability of sea surface fluxes associated with the passage of atmospheric fronts and across the ocean SST gradients; (iv) a fourth component, especially associated with FASTEX, consisted of carrying out radiosoundings at a high frequency (every 1.5 or 3 h) to study atmospheric cyclogenesis.

This paper presents the major features and first results of the experiment, focusing on the ocean–atmosphere fluxes. Other studies in progress are centred more specifically on ocean circulation. Section 2 describes the ship operations, section 3 the mesoscale characteristics of the sea surface and section 4 the meteorological data. In section 5 radiative fluxes are compared with satellite calculations; in section 6, the surface-flux determination is discussed, and in section 7 several bulk-flux formulae are compared using the CATCH dataset. A comparison with the European Centre for Medium-Range Weather Forecasts (ECMWF) computed fluxes is presented in section 8, and the effect of SST fronts is detailed in section 9.

2. Experimental strategy

Prior to the experiment, cyclogenesis events were shown to occur in clusters (one per day), when zonal flow was established across the Atlantic. January and February are the most favourable months for zonal flow. The area around 35°W, between 40°N and 55°N,
was found to be a critical zone for atmospheric frontal-wave evolution. Here frontal systems are young and high-altitude precursors move rapidly. This zone is also a 'hole' region in the atmospheric observation network between the American continent and the region of explosive cyclogenesis development, off the European coasts (Joly et al. 1997). Four ships were engaged in FASTEX to make systematic observations in this region: the Icelandic Aegir and the Ukrainian Bugaev only carried out radiosoundings; two other ships focused on ocean–atmosphere interactions, the US RV Knorr and the French RV Le Suroît. These latter two ships made surface-flux and boundary layer measurements, as well as radiosoundings.

Operations on Le Suroît were defined so as to optimally combine the regular launch of radiosounding as required for FASTEX, surface meteorological and turbulence measurement, and the realization of Conductivity Temperature Depth (CTD) cross-sections. These sections were arranged to form a trapezoid to document water properties and oceanic jets. The sections were stopped several times during 12 to 48 h periods, when the wind exceeded 15 m s⁻¹ or when the sea state was too rough. However the oceanic survey was completed satisfactorily. The operational decisions were generally taken 24 to 48 h in advance using specific weather forecasts sent daily by the FASTEX operational centre based in Shannon (Ireland). The experiment included two legs: the first from 8 January to 3 February and the second one from 4 February to 3 March, separated by a short stop on the Azores Island of Fayal (Fig. 2).

On board Le Suroît, continuous measurements were made using the following instruments.
• Meteorological sensors, some mounted on a 11 m mast (16 m above the sea surface) located on the foredeck, and others on the upper deck: temperature, moisture (HMP35D from Vaisala) and wind (WIND MONITOR AQ from Young); incoming short-wave (CM3 RDV ISO 9060 from Kipp and Zonen) and long-wave radiation (CGI from Kipp and Zonen) sensors were located at the top of the foredeck mast as well as a sonic anemometer (Gill Solent symmetric instrument) and a refractometer (developed at CETP) for turbulence measurements. A laser telemeter (from IMPULS PHYSIK) measured the cloud base, an optical precipitation gauge (ORG100 from SCIENTIFIC TECHNOLOGY INC.) and a two-channel upward-looking microwave radiometer (developed at CETP (Eymard 1999), to monitor the integrated water vapour and cloud liquid water content) were located on the upper deck.

• A SBE 21 SEACAT thermostalinograph, at a depth of 2.5 m, provided measurements of SST and sea surface salinity (SSS).

• An RDI 150 kHz narrow-band, vessel mounted, Acoustic Doppler Current Profiler (ADCP) provided the 8 metre binned currents between 12 m and 240 m. The ship velocity, obtained from Global Position System (GPS), was added to ADCP velocities to calculate the absolute water velocity of each bin after standard correction; a similar procedure was applied for computing absolute wind vectors.

• A UHF radar provided by the National Center for Atmospheric Research (NCAR).

Radiosoundings were launched four times a day at the synoptic hours and, during FASTEX Intensive Observation Periods (IOPs), at a higher frequency (up to every one-and-a-half hours), according to decisions of the FASTEX operational centre.

The location of CTD profiles along the sections are displayed in Fig. 2. A total of 87 observations were made every 20 or 40 km. The westernmost section enters the Labrador Sea waters and the eastern north–south section (along 35°W) crosses several branches of the NAC. Within each CTD profile, 12 bottles were filled at various depths for the measurement of alkalinity, pH, dissolved oxygen, nutrients and pigments. The profiles were systematically carried out down to 2000 m in order to sample the complete layer concerned with the main currents.

3. LARGE-SCALE OCEANIC FEATURES

The experimental area (40–50°N, 30–45°W) is located in the Newfoundland Basin, which has been extensively studied since the pioneering works of Iselin (1936), Mann (1967) and Worthington (1976). This zone is at the confluence between the Labrador current, the western branch of the sub-polar gyre and the NAC issuing from the Gulf Stream (Krauss 1986; Schmitz and McCartney 1993; Rossby 1996; Kearns and Rossby 1998) as shown in Fig. 1. In a recent review of the NAC, Rossby (1996) found the positions of the currents and fronts to be relatively stationary, and stressed the role of the topography on the NAC.

A strong SST gradient (from 5 to 17 °C) exists from north and south, maintained by a succession of fronts and associated jets (Sy 1988; Reynaud et al. 1995). This mean gradient is maintained throughout the year, even in winter. This area is also a zone of possible water formation which will then occupy the permanent thermocline further to the South—the so-called 11.5–13 °C mode water (McCartney and Talley 1984) at a potential-density anomaly \( \sigma_g = 27.3 \) to 27.5 (Speer and Tziperman 1992).

(a) The SST data

In order to place the ship observations on a larger scale, we need large-scale SST maps. Operational analyses performed with the French weather forecast model
Figure 3. (a) The ARPEGE (see text) sea surface temperature (SST) field (°C) used as a first guess for the first analysis. (b) As (a) but SST analyses for the time centred on 8 January; (c) 24 January; (d) 8 February; and (e) 23 February. Currents from the ship Acoustic Doppler Current Profiles (ADCP) are superimposed on (c) and (e) which have shaded isotherms corresponding to the keys given.
TABLE 1. COMPARISON OF THE SST REANALYSES WITH THE VARIOUS DATA OBSERVED FROM 1 JANUARY TO 1 MARCH 1997

<table>
<thead>
<tr>
<th></th>
<th>Observed</th>
<th>Reanalysis</th>
<th>r.m.s.</th>
<th>r</th>
</tr>
</thead>
<tbody>
<tr>
<td>Merchant Ships</td>
<td>13.2</td>
<td>13.2</td>
<td>1.25</td>
<td>0.97</td>
</tr>
<tr>
<td>Le Suroît</td>
<td>12.5</td>
<td>12.5</td>
<td>0.56</td>
<td>0.98</td>
</tr>
<tr>
<td>Bugaev</td>
<td>15.3</td>
<td>15.3</td>
<td>0.45</td>
<td>0.99</td>
</tr>
<tr>
<td>Buoys smt</td>
<td>12.9</td>
<td>12.9</td>
<td>0.45</td>
<td>0.99</td>
</tr>
<tr>
<td>Buoys cmm</td>
<td>12.7</td>
<td>12.7</td>
<td>0.5</td>
<td>0.99</td>
</tr>
<tr>
<td>Total</td>
<td>12.7</td>
<td>12.7</td>
<td>0.86</td>
<td>0.98</td>
</tr>
</tbody>
</table>

Values are °C. r is the correlation coefficient.

ARPEGE (Action de Recherche, Petite Echelle, Grande Echelle) are not adequate because the major SST front associated with the NAC is very roughly depicted (Fig. 3(a)). ECMWF SST analyses present the same drawback; consequently it has been necessary to perform SST analyses using in situ measurements in order to more realistically describe the SST features in this region.

SST analyses were performed in the domain 35–55°N, 25–60°W using all available data collected during the months of January and February 1997. The domain is larger than the experimental domain, and has 150 × 150 points with a grid mesh size of about 18 km.

Two datasets were used during the two months of FASTEX: the operational data collected by operational buoys ‘smt’ and merchant ships, which are sent on the Global Telecommunication System (GTS), and the experimental data collected by ‘cmm’ buoys and the Le Suroît, Bugaev and Knorr. Satellite data were not used because of the large amounts of cloud throughout the experiment. The spatial density of SST data is particularly high (9968 points) and well distributed all over the domain. Experimental data are generally of good quality, while operational data collected on the GTS are not so accurate. Consequently, a filtering was applied to merchant ship data before they were assimilated.

This filtering was carried out using two criteria: (i) in the NAC, within the area delimited by a minimal SST gradient of 0.02 degC km⁻¹, data are assimilated whatever the difference from the first guess; and (ii) outside of this area (SST gradient less than 0.02 degC km⁻¹) data are assimilated only if the difference from the first guess does not exceed 3 degC. Thus strong anomalous gaps are eliminated.

(b) The SST analyses and validation

Four SST analyses were produced through a classic objective-analysis algorithm (De Mey and Ménard 1989). They are centred on 8 and 24 January and on 8 and 23 February. Data were assimilated within a temporal radius of 7 days and a large isotropic correlation scale of 150 km in order to cover the whole domain. The first analysis (8 January) was obtained using the SST analysis of the ARPEGE model as the first guess. The following analyses each used the previous analysis as the first guess.

The consistency of the analyses has been checked by comparison with the processed data in order to assess whether the objective analysis system is reliable. Table 1 summarizes this comparison. The analysis is not biased, and matches well statistically with the observations (correlation 0.98 and root mean square (r.m.s.) difference 0.86 degC for the whole dataset). The r.m.s. difference for the merchant ship data reaches 1.25 degC, and ranges between 0.4 and 0.6 degC for the other data. The statistics are best when the Le Suroît, Bugaev, buoys ‘smt’ and ‘cmm’ series are used. The analysis system is thus
able to check the spatial coherence within the data itself, and between the data and the guess, and then to filter out the doubtful data.

The major SST front (hereafter noted as SSTF) between 12 °C and 8 °C marks the position of the NAC (Figs. 3(b) to 3(e)): its trajectory is found to correlate precisely with the topography along the continental shelf of the Newfoundland Basin. Downstream near the north-west corner (located near 51°N), the surface temperature gradients are weaker but an SSTF is still clearly present east of 38°W, developing large meanders between 50 and 52°N. Another SSTF is present in the zonal band between 42°N and 43°N, and separates southern and northern water masses whose SSTs are respectively 16 °C and 14 °C. These two fronts issued from the Gulf Stream, where they split apart near 43°N, 45°W. All these features have been largely described in the literature (e.g. see the review of Rossby 1996 or Kearns and Rossby 1998) and are well captured in the analyses due to the large amount of data used. The superimposed 3 h sampled ADCP velocities in the 30–160 m layer (Figs. 3(c) and 3(e)) confirm that the main SSTFs are associated with jets. Note also the good correspondence between thermal structures and currents even for small-scale features (see for example the small anticyclonic eddy at 51°N, 35°W near the Charlie Gibbs fracture zone* in Fig. 3(c)).

* The fracture zone of the Mid-Atlantic Ridge located near 51°N, 35°W.
Figure 5. From top to bottom: histograms of wind (m s\(^{-1}\)), air-sea temperature difference (degC) and moisture difference (g kg\(^{-1}\)) frequencies, collected during the two legs of the experiment. The averaging period of these parameters is 10 min.
4. Meteorological data

On board *Le Suroît*, all the sensors listed in section 2 had been calibrated before the experiment and were not subject to post-calibration. During bad weather, the ship stayed facing the wind and continued to gather atmospheric and oceanic data. Only two instruments were soon broken, due to very rough seas: the boom with the net radiation sensor at the bow, and the rain-gauge due to oxidation. At the end of the experiment, after five weeks, the moisture sensors broke down during a strong storm (15 February), followed by the air temperature and wind acquisition system due to power supply failure (21 February).

The atmospheric parameters were sampled at a 10 s$^{-1}$ rate. SST and SSS were measured every minute and calibrated by direct comparison with CTD stations. The whole dataset was re-sampled as one-minute means and archived in the FASTEX Data Base. A description of the instrumentation and data processing can be found in reports (Lachaud 1997; Amar et al. 1998).

Time series of pressure, wind, temperature, relative humidity and SST collected during the two legs of the experiment are displayed in Fig. 4. The pressure ranges between 978 and 1038 hPa. Strong fluctuations were recorded during the second leg with one storm nearly every other day. Deep atmospheric lows were followed by anticyclonic ridges with quick pressure rises.

Large ranges of winds and stratification parameters were observed (Fig. 5). For the wind (not height-corrected, measured 16 m above the sea surface with a 10 min averaging interval), 25% of the values are higher than 15 m s$^{-1}$ and 5% higher than 20 m s$^{-1}$. The sea–air temperature and moisture differences range from −12.5 to 3.5 degC and from −5.4 to 2 g kg$^{-1}$, respectively. Of the measurements, 30% were carried out in very unstable stratifications (temperature difference lower than −5 degC) and 30% in very dry conditions (moisture difference lower than −2.5 g kg$^{-1}$). In contrast, 18% of the measurements were collected in stable stratifications (positive air–sea temperature differences) and 26% in wet conditions (positive air–sea moisture differences).

5. Radiative fluxes

*In-situ* ship measurements of radiative fluxes (downward short wave and long wave) are of great interest for validating satellite estimates. Here METEOSAT satellite-derived surface irradiances are compared with ship pyranometric and pyrgeometric measurements. For this comparison, the same method was used as for two previous experiments: Surface Océanique, Flux et Interactions avec l’Atmosphère (SOFIA, Weill et al. 1995) in June 1992, and Structure des Echanges Mer-Atmosphère, Propriétés des Hétérogénéités Océaniques Recherche Expérimentale (SEMAPHORE, Eymard et al. 1996) in October and November 1993 in the Azores Basin. Results are displayed in Table 2. Despite the extreme satellite zenith angle (below 70 degrees, at the limit of the METEOSAT usable disc), results obtained during CATCH are better than during SOFIA and SEMAPHORE in terms of bias error, due to an improved cloud classification. The weaker correlation (0.84) for the short-wave radiation is probably due to reduced solar zenith angle, but still remains in the usual range of the algorithm error. We thus conclude that these results are good enough to extend the confidence we can give to satellite estimates, even in a region at high latitude and low solar zenith angle.
TABLE 2. LONG-WAVE AND SHORT-WAVE VALIDATION RESULTS DURING SOFIA, SEMAPHORE AND CATCH EXPERIMENTS

<table>
<thead>
<tr>
<th>Experiment</th>
<th>No. of cases</th>
<th>Mean calculated</th>
<th>Mean measured</th>
<th>Bias</th>
<th>r.m.s.</th>
<th>r</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOFIA* June 1992</td>
<td>289</td>
<td>368.9</td>
<td>371.0</td>
<td>-2.1</td>
<td>11.3</td>
<td>0.87</td>
</tr>
<tr>
<td>SEMAPHORE* October/November 1993</td>
<td>640</td>
<td>374.3</td>
<td>370.0</td>
<td>4.3</td>
<td>15.7</td>
<td>0.71</td>
</tr>
<tr>
<td>CATCH January/February 1997</td>
<td>719</td>
<td>322.9</td>
<td>322.6</td>
<td>0.3</td>
<td>17.0</td>
<td>0.84</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Experiment</th>
<th>No. of cases</th>
<th>Mean calculated</th>
<th>Mean measured</th>
<th>Bias</th>
<th>r.m.s.</th>
<th>r</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOFIA* June 1992</td>
<td>149</td>
<td>456.5</td>
<td>433.1</td>
<td>23.6</td>
<td>75.5</td>
<td>0.97</td>
</tr>
<tr>
<td>SEMAPHORE* October/November 1993</td>
<td>197</td>
<td>315.1</td>
<td>304.5</td>
<td>10.6</td>
<td>58.1</td>
<td>0.95</td>
</tr>
<tr>
<td>CATCH January/February 1997</td>
<td>232</td>
<td>131.8</td>
<td>133.1</td>
<td>-1.3</td>
<td>49.9</td>
<td>0.84</td>
</tr>
</tbody>
</table>

*After Brisson et al. (1996).

6. DETERMINATION OF SURFACE TURBULENT FLUXES

(a) Instrumentation for turbulence

Two sensors were devoted to turbulence measurements in the atmospheric surface layer. They were located at the top of the foredeck mast. The first is a sonic anemometer (see Table 3) which is now widely used for momentum flux. Its use as a sonic thermometer is still under development (Dupuis et al. 1997) and will, therefore, not be discussed in the following, because the sonic temperature spectra showed very small signal to noise ratio during CATCH. The second turbulence instrument is a refractometer, which was used as a first attempt to derive latent-heat flux from onboard ship.

The refractometer sensor consists of proven cavity geometry made of material with the lowest coefficient of expansion (Zerodur-M glass ceramics). The signal delivered by the refractometer is the air refraction index (ARI). For a cavity of constant shape, at a frequency of 9.4 GHz and in the absence of liquid water, ARI depends on air specific humidity (Q), temperature (T) and pressure (P), through:

\[ ARI = P\{77.604/T + 3.776.10^5 Q/(622T^2)\} \]

Equation (1) applies to mean measurements (denoted by capital letters), as well as to fluctuations, hereafter denoted by small letters.

Specific improvements were carried out on the shipborne model.

- In order to avoid condensation, dry air is insufflated into the electronic unit with a pressure regulated pump,
- In order to preserve the cleanness of the cavity, a suction fan is used for the ejection of all sorts of particles (water droplets, sea spray) at low wind speeds. The larger ones are, however, stopped by a thin stainless steel mesh attached at the front. Tests in a wind-tunnel showed that the effect of the suction fan on the air sample in the cavity is negligible.
Rainfall events are easily detected since they produce significantly different spectra (no $-5/3$ slope) or ARI with higher spectral densities. The specific improvements were shown to allow the cavity to be dry just after the rain has stopped.

(b) Derivation of turbulent fluxes

Measurements of turbulent fluxes of momentum, latent heat and sensible heat ($\tau$, $\Delta Q$, $H$) over the ocean are used to derive bulk formulae using mean meteorological measurements and drag and exchange coefficients (respectively, $C_d$, $C_e$ and $C_h$):

$$\tau = C_d n U_{10n}^2$$

(2)

$$\Delta Q = C_e n U_{10n} \Delta Q_{10n}$$

(3)

$$H = C_h n U_{10n} \Delta T_{10n},$$

(4)

where 10 metre heights with neutral equivalent parameters are used (suffix 10n); $U$ is wind speed.

Several research cruises were devoted to turbulent-flux measurements and parameterizations over the sea. The estimates are either based on the direct eddy correlation method or on the inertial-dissipation method (IDM). Accurate measurement of turbulent fluxes is still a challenge since several factors are involved, such as the air flow distortion around the structure. Heat fluxes are less documented due to salt contamination of the sensors, therefore tests and developments of new sensors such as the refractometer are helpful. Results of turbulent flux measurements during CATCH with extreme meteorological conditions are now described using the IDM. Previous results with this method based on the SOFIA and SEMAPHORE datasets give a more comprehensive description of the algorithm (Dupuis et al. 1997).

The method used here with a refractometer can be summarized as follows.

- Dissipation rates of different parameters ($\varepsilon_u$, $\varepsilon_v$, $\varepsilon_w$ and $Nari$) are calculated from the energy spectra of the signals (fluctuations of along-wind, $u$, cross-wind, $v$, vertical wind speed, $w$, and air refraction index, ari). Here, the spectra have been calculated every half hour and the best fitting inertial sub-range is chosen among 6 frequency bands, whose beginnings and widths are given in Table 3. As mentioned above, spectra of temperature are of poor quality, with contamination above a few Hz, and will not be used here. Only samples with relative wind direction within $\pm 30^\circ$ of the bow are selected. Other applied criteria concern the steadiness of the ship trajectory, the quality of the $-5/3$ slope (see Dupuis et al. 1997) and the $4/3$ ratio of the product of $v$ (or $w$), spectral energy, $E$, and frequency, $f$, at power $5/3$ over the same quantity for $u$, underlying local isotropy (in the form $E u(f) f^{5/3} / E u(f) f^{5/3} \geq 4/3$).

- Kinematic fluxes ($u_w$, $v_w$) (or the friction velocity $u_*$) and ($w_*$) are first estimated using a first guess of the Monin–Obukhov Length, $L$, and universal stratification
functions \( \Phi_m \) and \( \Phi_{ari} \) (concerning \( \Phi_{ari} \), a formula for another passive scalar such as temperature is used):

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

(5)

\[
\langle w.ari \rangle = \left[ kZu_\ast N_{ari} / \Phi_{ari}(Z/L) \right]^{1/2}
\]

(6)

\[
L = -T_v u_\ast^3 / (g k \langle w.t \rangle)
\]

(7)

where \( T_v \) is the virtual temperature of the air, \( Z \) is the height of measurement above the sea surface and \( \Phi_{imb}(Z/L) \) is an imbalance function introduced in Yelland and Taylor (1996) and Dupuis \textit{et al.} (1997) to account for vertical-transport contributions. This imbalance function had been found necessary in order to minimize the dependence of the calculated drag coefficient on stability. This term was established to be about \(-0.5Z/L \) for SOFIA and SEMAPHORE.

- the latent-heat flux, \( \langle w.q \rangle \), is then derived from:

\[
\langle w.q \rangle = (\langle w.ari \rangle - \partial ARI/\partial T \langle w.t \rangle) / (\partial ARI/\partial Q)
\]

(8)

The flux of air refraction index, \( \langle w.ari \rangle \), is seen to depend mostly on \( \langle w.q \rangle \) for the usual Bowen Ratio over the sea, since \( \partial ARI/\partial Q \) is one order of magnitude higher than \( \partial ARI/\partial T \) (with opposite sign).

In the absence of reliable sonic temperatures, \( \langle w.t \rangle \) is estimated using a bulk formula. Iterations can be applied to Eqs. (4), (5), (6) and (7). As described in Dupuis \textit{et al.} (1997), one disadvantage of the IDM is that it is based on an under-determined set of equations, and the way these equations are solved (whether or not using iterations, an imbalance factor, or bulk estimates for some missing fluxes) can lead to very different results, if stratification is far from near neutral.

The next section will be devoted to a description of the parametrization of turbulent fluxes obtained by the IDM during CATCH (i.e. drag and exchange coefficients for evaporation). The effect of iterations will be emphasized, whereas the imbalance function of Eq. (5) will not be discussed, since it has a much lower impact on average in this dataset.

\( (c) \) \textit{CATCH bulk parametrizations}

Figure 6 shows the results of the parametrizations of \( Cdn \), and \( Cen \) in panels (a) and (b), respectively, with the impact of iterations on the IDM. Dotted and solid lines with error bars correspond to results with or without iterations, respectively (i.e. without iteration a bulk estimate of \( Z/L \) is used based on parametrizations of Smith (1980) for the momentum flux and DeCosmo \textit{et al.} (1996) for heat fluxes).

Figure 6 shows that the iterations have an impact of about 100% on the \( Cdn \) values at lower wind speeds, with a significant increase when iterations are used. The reason why iterations are generally used is that the results obtained without iteration depend upon the choice of the bulk parametrization. However, during CATCH, since dissipation rates of the sonic temperature are missing, bulk parametrizations of sensible-heat fluxes must also be used with iterations. Hence, \( Z/L \) still depends upon bulk parametrizations, even while using iterations for \( u_* \). Hence the relevance of \textit{CATCH Cdn} values at low wind speeds, with only one third of samples associated with refractometer measurements below 6 m s\(^{-1}\) (and one in five below 4 m s\(^{-1}\)), is limited due to the impact of bulk parametrizations of heat fluxes. It is, therefore, difficult to conclude whether iterations give better results but it is easy to understand that if, without iterations there is an overestimate compared to the initial bulk value, it will be increased with iterations. The discussion in next section will help to understand this overestimate.
Figure 6. Panels (a) and (b) display drag and exchange coefficients, respectively, for evaporation versus neutral wind speed (m s\(^{-1}\)) at 10 m, \(U_{10n}\). In both panels, dotted and solid lines with error bars correspond to computation with and without iterations, respectively. The number of samples in bins is indicated at the top of the error bars. Parametrizations of Smith (1980) for the momentum flux and DeCosmo et al. (1996) for heat fluxes, are used to estimate \(Z/L\). No imbalance factor is used. This last parametrization is also shown for comparison; it is displayed as a dotted line and squares. Stars show the CATCH parametrization used in section 7 (see Table 4). See text for further details.

For wind speeds ranging between 9 and 11 m s\(^{-1}\), a good agreement is, however, found with Smith (1980), with no impact from iteration. Above 10 m s\(^{-1}\), \(C_{dn}\) values are found to increase much more rapidly with the wind speed than in Smith (1980). For instance, CATCH \(C_{dn}\) values are 20% higher than Smith (1980) ones at 20 m s\(^{-1}\). The overestimation reaches 40% at 27 m s\(^{-1}\) but the \(C_{dn}\) values were obtained with only 2 samples. Between 15 and 20 m s\(^{-1}\) the \(C_{dn}\) values are, however, very similar to those obtained with another dataset collected during the Flux Et Télédétection en Conditions de fetcH variable (FETCH) experiment, which took place in the Mediterranean sea in March and April 1998 (Dupuis et al. 1999). The results in Fig. 6 were obtained with a
zero imbalance function. Using an imbalance function as in Dupuis et al. (1997) leads to an impact reduced by 10% even at low wind speeds.

For the exchange coefficient $C_{dn}$, values beyond 10 m s$^{-1}$ are found to be in the usual range of 1.1 to $1.2 \times 10^{-3}$. Over 10 m s$^{-1}$ a significant increase is found, leading to a $C_{en}$ value of about $1.4 \times 10^{-3}$ at $U_{10n} = 20$ m s$^{-1}$, which was not observed by DeCosmo et al. (1996).

The following equations are the best fits to the data shown in Fig. 6 with iterations:

$$C_{dn} = 0.01084/U_{10n}^2 + 0.000559/U_{10n} + 0.0010187 \quad U_{10n} \leq 9.8 \text{ m s}^{-1}$$  \hspace{1cm} (9)

$$C_{dn} = 0.0001121U_{10n} + 9.316 \times 10^{-5} \quad U_{10n} \geq 9.8 \text{ m s}^{-1}$$  \hspace{1cm} (10)

$$C_{en} = 0.00113 \quad U_{10n} \leq 6.5 \text{ m s}^{-1}$$  \hspace{1cm} (11)

$$C_{en} = 2.336 \times 10^{-5}U_{10n} + 0.00097 \quad U_{10n} \geq 6.5 \text{ m s}^{-1}$$  \hspace{1cm} (12)

Due to uncertainties related to the iterative process at low wind speed, to the high values of $C_{dn}$ at low and high wind speeds, as well as to a first use of a refractometer, these results are further discussed in the next section. $C_{dn}$ and $C_{en}$ values at moderate and high wind speed have been used in combination with SEMAPHORE results for lower wind speeds, to provide the so-called CATCH parametrization used in sections 7 and 8.

(d) Discussion and further work on turbulent fluxes by IDM

The results in the previous section suggest significantly different results, compared to other experiments and are analysed hereafter. As for $C_{dn}$ values, a test has been devised to analyse the significance of the results obtained during CATCH, by using three other independent datasets collected during the SOFIA, SEMAPHORE, and FETCH experiments. In order to examine whether higher $C_{dn}$ were due to methodological problems and to focus on the measurement quality, scatter plots of measured dissipation rates, $\varepsilon$, multiplied by $Z$, the height of measurements, and simulated dissipation rates are presented in Fig. 7. Using the simplest form of the turbulent kinetic energy (TKE) budget, and taking the Smith (1980) parametrization for $u_*$ and $Z/L$ we have:

$$Z.\varepsilon = u_*^3/k.\{Fm(Z/L) - Z/L\}. \hspace{1cm} (13)$$

Figure 7 helps one to understand the general features of the measurements collected during all these experiments. The following observations can be made.

• For wind speeds of about 8 m s$^{-1}$, corresponding to $Z.\varepsilon$ of about 0.1 m$^3$s$^{-3}$, all three experiments agree with one another and also with Smith (1980).

• At higher wind speeds ($\geq 12$ m s$^{-1}$), SOFIA and SEMAPHORE did not provide any measurements. But CATCH and FETCH dissipation rates both agree in being respectively 30 to 40% higher (see fit equations on Fig. 7) than those simulated from Smith (1980). Note that this is in agreement with an overestimated $C_{dn}$ by about 20% at 20 m s$^{-1}$ in Fig. 6. The CATCH $C_{dn}$ values at high winds are found to be in the upper range of experimental values in open ocean. The very recent study of Hare et al. (1999), based on measurements obtained on Knorr in December 1996 and January 1997 in the framework of FASTEX, shows a very high Charnock constant at high winds compared to the more classical value of 0.011. Indeed they obtained a Charnock constant of 0.02 at wind speeds of 21 m s$^{-1}$, which is equivalent to a $C_{dn}$ value of about 0.002; thus it is closer to the CATCH value than to the Smith (1980) value.
Figure 7. Scatter plots of the products of altitude (Z) with measured and simulated dissipation rates (ε). The simulated Z,ε are determined using Smith (1980) flux parametrizations (see the right-hand side of Eq. (13)). Panels (a), (b) and (c) correspond respectively to CATCH, FETCH and SOFIA/SEMAPHORE experiments. The solid lines indicate the identity lines, while dotted lines display the regression fits whose equation is given in each panel. See text for further details.

There are two main possible explanations for this overestimate: either the effect of sea state (with 'young-wind' seas) or the effect of flow distortion. Since several studies strongly indicate that the latter effect could be responsible for the whole discrepancy (Nacass 1999 and Yelland et al. 1998), a complete analysis is in progress, based on three-dimensional (3D) simulations around the ship. The analysis will include a large range of wind speeds and angles at the bow, as well as dynamical effects associated with the wave motion. The latter effect, not yet taken into account in most studies, might be significant (numerical simulations by Nacass (1999), although still computed on a stationary mode, show an unsymmetrical distribution of wind speed bias with pitch angles). Although the same mast was used as for the previous experiments SOFIA and SEMAPHORE on the same vessel, pitch and roll are one order of magnitude higher during CATCH. Compared with other experiments, high sea-states were encountered
during CATCH: average, standard deviation and maximum significant wave height are respectively 4.6, 1.6 and 9 m (according to the Météo-France wave model (Guillaume 1987)), with a dominance of swell at moderate wind speeds (maximum significant wave height was about 3 m during previous experiments). A complete analysis is therefore undertaken, the objectives of which are to establish the role of artifacts (flow distortion) and of physical effects (sea state) in these high \( C_{dn} \) values at high wind speeds. Note that the results of Hare et al. (1999), which are smaller by about 10% than the CATCH results, were obtained after reducing the wind measurements by 4–5% to account for flow distortion by the ship, leading to a 15% decrease on the flux. Thus further analysis will be necessary to give a final conclusion for flux parametrization at high wind speeds.

- At low wind speeds, it should be first noted that the CATCH dataset only contains 29 samples at wind speeds below 5 m \( \text{s}^{-1} \), see Fig. 6. This is few compared to other experiments, and CATCH data will not allow us to provide a very accurate parametrization at low wind speeds. It is, however, possible to analyse the observed high \( C_{dn} \) values. These 29 samples at wind speeds below 5 m \( \text{s}^{-1} \) (associated with turbulent measurements) were collected during four days: on 21, 29 and 30 January and on 12 February. On 21 January and 12 February, the ratio of measured and simulated \( Z_e \) are all less than 1, while the ratios are all greater than 1 for the two other days. In Fig. 4, one can confirm that unstable stratifications prevailed during the first two days (ratio \( \leq 1 \)) while the two other days were associated with near-neutral to slightly stable stratifications. Consequently CATCH measurements at low wind speeds indicate the need for an imbalance function with a stratification dependence. From a more global point of view, if we compare the three experiments CATCH, FETCH and SOFIA/SEMAPHORE, average \( Z_e \) values are found to decrease (compare \( Z_e \) below 0.1 in panels (a), (b) and (c) of Fig. 7). The average (standard deviation) values of \( Z/L \) are \(-1.8 \) \((2.57)\), \(-1.98 \) \((2.39)\) and \(-3.48 \) \((3.57)\) for CATCH, FETCH and SOFIA/SEMAPHORE, respectively. This confirms that there is a relationship between \( Z_e \) values at low wind speeds and stability (CATCH has a mean ratio of measured and simulated \( Z_e \) greater than 1, with mean \( Z/L \) of \(-1.8 \); while SOFIA/SEMAPHORE has a mean ratio well below 1 with a mean \( Z/L \) equal to \(-3.48 \); FETCH ranges between them). In addition, we have tried to establish a relationship between the ratio of measured and simulated \( Z_e \) (Eq. (13)) during CATCH and sea-state based on energy of pitch/roll/heave, according to some authors who examined the validity of Monin–Obukhov similarity theory or a local imbalance in the vertical transport terms in presence of swell (Edson and Fairall 1997) or evidence of sea-surface and momentum-flux coupling (Rieder et al. 1994; Rieder and Smith 1998). However, although this energy has been found to be much higher than during previous experiments, no relationship could be found, in contrast with the stability dependence of the ratio of measured and simulated \( Z_e \). However, if the imbalance term obtained for SOFIA/SEMAPHORE, with \( F_{\text{imb}}(Z/L) = -0.5Z/L \), decreases the scatter in ratio of measured and simulated \( Z_e \) during CATCH, it also gives more \( C_{dn} \) in the higher range at low wind speeds, and thus slightly increases the overestimate of CATCH compared with other experiments. Further analysis of this stability-dependent imbalance function will be necessary, including a wide range of stability, to determine an optimal form.

- Concerning results from the refractometer, the increase of \( C_{en} \) with wind speed should be confirmed when the results on \( C_{dn} \) values at high wind speeds are corrected for flow distortion if necessary. After the first use of this instrument, it should be noted that realistic heat-flux values were obtained, and the sensor sensitivity to spray contamination will be analysed in laboratory measurements.
In summary, the CATCH turbulence measurements on board *Le Scuroit* are interesting since they correspond to extreme conditions. Obvious differences in the parametrizations were obtained compared with other studies: high $Cdn$ values at high wind speeds and a dependence of exchange coefficients on the wind speed. Two reasons were invoked to explain the $Cdn$ results: they can be related either to artifacts (flow distortion) or to physical processes. We suspect that airflow distortion needs seriously to be taken into account; this problem is still a matter of concern in the scientific community but at this stage is beyond the scope of this study. At low wind speeds, the need for a stability-dependent imbalance function is again evidenced.

7. **Bulk flux scheme-to-scheme variations**

In this section the previous parametrization is compared with other published parametrizations. The extensive CATCH dataset (temperature, humidity, pressure, wind and SST parameters) is used, in order to investigate the validity of these schemes and to test their robustness.

(a) *The bulk formulae used*

Extensive reviews of turbulence and stress parametrizations can be found in Geernaert (1990) and Saïd and Druilhet (1991) for example. We selected parametrizations from amongst recent ones, valid for the open ocean and presenting consistent parametrizations for latent-heat, sensible-heat and momentum fluxes (except Smith 1980).

The selected schemes are as follows.

- Smith (1980): this formulation is derived from an offshore stable platform in the Nova Scotia area (44°N, 60°W). Wind stresses were obtained by the eddy correlation method at wind speeds ranging from 6 to 22 m s\(^{-1}\). Sensible-heat flux was also observed but not latent-heat flux. So we adopt the DeCosmo *et al.* (1996) coefficient for latent heat, obtained during the Humidity EXchange Over the Sea (HEXOS) experiment. During this experiment, wind speeds ranged from 5 to 18 m s\(^{-1}\).

- Large and Pond (1981, 1982): this formulation was selected because of its frequent use in the literature, as well as the broad range of wind values (4 to 26 m s\(^{-1}\)) used for its calibration and the good agreement between IDM and correlation methods obtained by their authors.

- Anderson (1993): this parametrization was deduced from the IDM during 7 series of measurements from George Bank to the Labrador Sea on board the CSS *Dawson*. Measured winds ranged from 6 to 21 m s\(^{-1}\) and air–sea temperature differences reached 6 degC.

- Dupuis *et al.* (1997): this parametrization was derived from the SOFIA and SEMAPHORE experiments in the Azores basin, by applying the IDM. Weak to moderate winds (0.5 to 12 m s\(^{-1}\)) were sampled. At higher winds, the drag coefficient proposed by Yelland *et al.* (1998) was used. This last parametrization was adjusted, with winds varying from calm to 26 m s\(^{-1}\) after air-flow distortion correction (see the previous parametrization proposed by Yelland and Taylor (1996)) and air–sea temperature differences ranging from −15 to +7 degC. This dataset was collected during several cruises in the Southern Ocean under rather similar weather conditions to those during CATCH.

- Fairall *et al.* (1996): this parametrization results from the Tropical Ocean/Global Atmosphere Coupled Ocean–Atmosphere Response Experiment (TOGA-COARE). It is an extension of the method developed by Liu *et al.* (1979), including: a new specification of the roughness stress relationship, a gustiness velocity to account for the increase of
TABLE 4. FORMULATIONS OF THE TRANSFER COEFFICIENTS USED IN THE DIFFERENT BULK FORMULAE

<table>
<thead>
<tr>
<th></th>
<th>(Cdn \times 10^3)</th>
<th>(Chn \times 10^3)</th>
<th>(Cen \times 10^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large and Pond (1982)</td>
<td>1.14 ((U_{10n} \leq 10))</td>
<td>0.66 ((Z/L \geq 0))</td>
<td>1.15 ((U_{10n} \geq 10))</td>
</tr>
<tr>
<td></td>
<td>0.49 + 0.065U_{10n} ((U_{10n} \geq 10))</td>
<td>1.13 ((Z/L \leq 0))</td>
<td></td>
</tr>
<tr>
<td>Anderson (1993)</td>
<td>0.40 + 0.079U_{10n} ((U_{10n} \leq 10))</td>
<td>0.79 ((Z/L \geq 0))</td>
<td>1.2 (Chn)</td>
</tr>
<tr>
<td></td>
<td>((Z/L \leq 0))</td>
<td>1.11 ((Z/L \leq 0))</td>
<td></td>
</tr>
<tr>
<td>Fairall et al. (1996)</td>
<td>0.79 + 0.049U_{10n} ((U_{10n} \geq 10))</td>
<td>1.19 - 0.012U_{10n} ((U_{10n} \geq 10))</td>
<td>1.22 - 0.011U_{10n} ((U_{10n} \geq 10))</td>
</tr>
<tr>
<td></td>
<td>0.61 + 0.063U_{10n} ((U_{10n} \leq 5))</td>
<td>0.83 ((Z/L \geq 0))</td>
<td>1.12 ((Z/L \leq 0))</td>
</tr>
<tr>
<td>Smith (1980)</td>
<td>((U_{10n} \geq 5))</td>
<td>1.10 ((U_{10n} \leq 5))</td>
<td></td>
</tr>
<tr>
<td>De Cosmo et al. (1996)</td>
<td>((U_{10n} \leq 5))</td>
<td>0.66 + 2.79/U_{10n} ((U_{10n} \leq 5))</td>
<td>(Chn)</td>
</tr>
<tr>
<td></td>
<td>((U_{10n} \geq 5))</td>
<td>1.2 ((U_{10n} \leq 5))</td>
<td></td>
</tr>
<tr>
<td>Dupuis et al. (1996)</td>
<td>0.67 + 11.7U_{10n}^2 ((U_{10n} \leq 5.5))</td>
<td>0.66 + 2.79/U_{10n} ((U_{10n} \leq 5.5))</td>
<td></td>
</tr>
<tr>
<td>Yelland and Taylor (1998)</td>
<td>0.50 + 0.071U_{10n} ((U_{10n} \geq 5.5))</td>
<td>1.2 ((U_{10n} \leq 5.5))</td>
<td></td>
</tr>
<tr>
<td>CATCH</td>
<td>0.67 + 11.7U_{10n}^2 ((U_{10n} \leq 7.2))</td>
<td>0.66 + 2.79/U_{10n} ((U_{10n} \leq 7.2))</td>
<td>0.97 + 0.023U_{10n} ((U_{10n} \geq 6.1))</td>
</tr>
<tr>
<td></td>
<td>((U_{10n} \geq 7.2))</td>
<td>1.2 ((U_{10n} \geq 7.2))</td>
<td></td>
</tr>
</tbody>
</table>

\(Cdn\), \(Chn\) and \(Cen\) stand for the wind stress, sensible-heat and latent-heat transfer neutral coefficients respectively, as functions of the neutral 10 m wind \((U_{10n})\) or stability parameter \((Z/L)\).

flux induced by boundary-layer-scale variability, and new calibrated profile functions obeying the convective limit. The algorithm was adjusted using the measurements made on board the Moana Wave. During TOGA/COARE, the data collected were representative of tropical weather conditions with warm waters, low to moderate winds up to 10 m s\(^{-1}\) and calm seas, but with a strong boundary layer diurnal cycle in light winds. No specification was given by the authors for wind speeds larger than 10 m s\(^{-1}\), so no modification of their algorithm was applied for stronger winds.

- CATCH parametrization: this formulation was presented in the previous section. However, due to the small number of light-wind cases, the Dupuis et al. (1997) algorithm is used in these conditions. The transition between the two formulations has been adjusted in order to avoid any discontinuity in the formulae; the transition occurs at 7 m s\(^{-1}\) for \(Cdn\), and at 6 m s\(^{-1}\) for \(Cen\). For \(Chn\), the Dupuis et al. (1997) algorithm is also used.

The different transfer coefficients are listed in Table 4. In the Fairall et al. (1996) scheme, the transposition of roughness/drag coefficient by strong winds is easy to establish, but no simple dependence exists at low wind speed. Only the Dupuis et al. and Fairall et al. formulations were calibrated by light winds. Sensible-heat transfer coefficients depend on stability in Large and Pond’s and Anderson’s formulations. At high winds, sensible- and latent-heat transfer coefficients are generally constant, except in Fairall’s algorithm where they decrease with increasing wind.

(b) Methodology

A simple statistical method, as suggested by Blanc (1985), is used for this inter-comparison. One calls \(\eta_{n,m}(i)\) the percentage of variation of the flux scheme \(n\{F_{ln}(i)\}\)
relative to the flux scheme $m \{F_l_m(i)\}$, i.e.:

$$\eta_{n,m}(i) = \begin{cases} 
\frac{|F_l_n(i) - F_l_m(i)|}{|F_l_m(i)|} & F_l_n(i) \neq F_l_m(i) \\
0 & F_l_n(i) = F_l_m(i)
\end{cases}$$

(14)

where $n$ and $m$ range from 1 to 6. In the case where $n = m$, the inter-comparison of a formula is null. We can define a mean scheme-to-scheme variation by the following operation:

$$\bar{\eta}(i) = \sum_{n=1}^{6} \sum_{m=1}^{6} \eta_{n,m}(i)/30,$$

(15)

and the maximum scheme-to-scheme variation by:

$$\eta(i)_{\text{max}} = [\eta_{n,m}(i)]_{\text{max}}.$$

(16)

Finally the variability of the results according to the intensity of fluxes obtained through an average flux is as follows:

$$\bar{F_l}(i) = \sum_{n=1}^{6} F_l_n(i)/6.$$

(17)

(c) Results

Bulk flux calculations were made for 10 min averages over the whole dataset. A linear interpolation between adjacent points was applied to blocks where missing or incomplete 10 min data were found. This procedure ensures a full record of nearly 4200 values (approximately 700 h) in which all the data (pressure, air temperature and moisture, SST, wind) are available.

Results are presented in the following way: the flux of each scheme ($F_l_n(i)$) is presented on a scatter-plot as function of the mean flux ($\bar{F_l}(i)$) in Fig. 8; the average and maximum percentages of scheme-to-scheme variation (respectively $\bar{\eta}(i)$ and $\eta(i)_{\text{max}}$) are plotted as a function of the mean flux ($\bar{F_l}(i)$) in Fig. 9. Figure 10 shows 2D plots of mean scheme-to-scheme variation as a function of the wind at 10 m and of the differences $\Delta Q$ and $\Delta T$, respectively, for latent and sensible heat (here $\Delta Q$ and $\Delta T$ stand, respectively, for differences between the humidity-mixing ratio at sea level and at 10 m, and between the SST and the potential temperature at 10 m).

(i) Wind stress. Mean wind stress reaches 2.6 hPa. The CATCH formula gives stronger wind stress than the average and than all other parametrizations (see section 6). Dupuis and Anderson’s schemes remain close to the diagonal, and lowest values are obtained by the schemes of Large and Pond, and of Fairall. For large stress, the average difference between formulae reaches 15% and the maximum departure 40%. For small stress, the scheme-to-scheme variations reach values higher than 100%, because $\eta_{n,m}(i)$ is calculated with very small quantities as denominator. For weak to moderate stress (0.1 to 1 hPa) the average and maximum variations are 10% and 25%, respectively.

(ii) Sensible-heat flux. Sensible-heat fluxes range from -100 to 400 W m$^{-2}$. Negative values were observed as warm air passed over cold water, especially north of the NAC. Parametrizations give quite homogeneous values for positive fluxes, except Fairall’s
which is systematically lower. This is the consequence of decreasing the transfer coefficient with increasing winds. The average scheme-to-scheme variation remains, however, lower than 10% for mean fluxes between 100 and 350 W m$^{-2}$, and maximum differences reach 30% for the largest fluxes.

Between 20 and 75 W m$^{-2}$ there is an increase of the scheme-to-scheme variation, reaching 20% for the average and 50% for the maximum variations. This occurs in light winds and with significant air–sea temperature differences. This dispersion is mainly due to the fact that only 3 formulae were calibrated for light winds (Fairall et al.
Figure 9. Mean and maximum scheme-to-scheme variation amongst 6 bulk-flux formulae according to the mean sensible-heat flux (top; W m$^{-2}$), mean latent-heat flux (middle; W m$^{-2}$) and wind stress (bottom; hPa). Symbols as Fig. 8; see text for further discussion.

1996, Dupuis et al. 1997, and CATCH) and only one (CATCH) for strong negative stratification.

Another surprising result is for negative sensible-heat fluxes: the average and maximum scheme-to-scheme variations are approximately constant (at 28% and 76% respectively). In that range of values all the schemes diverge. This divergence may be the consequence of the lack of documented cases of strong stability.

(iii) Latent-heat flux. Latent-heat fluxes extend from $-50$ to 600 W m$^{-2}$ and generate the greatest scheme-to-scheme variations. The CATCH and Fairall et al. schemes differ greatly for high fluxes. In particular, above a mean flux of 300 W m$^{-2}$ the mean
Figure 10. Mean scheme-to-scheme (a) sensible-heat and (b) latent-heat flux variation as functions of the wind \((U, \text{ m s}^{-1})\) and air-sea temperature difference (degC) or moisture difference (g kg\(^{-1}\)), respectively. Wind, potential temperature and air moisture were calculated at a 10 m reference height. Crosses indicate data for which most of the algorithms used do not converge. See text for further details.
difference is 100 W m\(^{-2}\); this difference increases to 200 W m\(^{-2}\) for a 450 W m\(^{-2}\) mean flux. In contrast, the other formulations, using quite similar transfer coefficients, give similar results. Consequently, due to the large Fairall et al. and CATCH differences, maximum scheme-to-scheme variations reach 75% at high fluxes. Near 100 W m\(^{-2}\), the average and maximum variations increase under light winds and strong air–sea moisture differences.

In Figs. 10(a) and 10(b) average scheme-to-scheme variations are plotted; these figures also give an idea of the dispersion of winds and stratifications sampled during CATCH. Light winds were associated with air–sea temperature (moisture) differences from \(-4\) to \(12\) degC (\(-1\) to \(7\) g kg\(^{-1}\)). The strongest winds reached \(30\) m s\(^{-1}\) with air–sea temperature and moisture differences of, respectively, \(8\) degC and \(4\) g kg\(^{-1}\). When the air was warmer than the sea surface, winds varied from \(2\) to \(22\) m s\(^{-1}\).

The various sensible-heat flux schemes differ from each other by less than 10% in a broad range of wind speeds and air–sea temperature differences. However, the dispersion is larger than 25% for stable stratification, for any wind velocity. This indicates that under these conditions, calculation of sensible-heat flux is for the most part uncertain.

For latent-heat flux, the scheme-to-scheme variations remain lower than 15% over a wide range of winds and moisture differences. For light winds (less than \(2\) m s\(^{-1}\)) and for high wind velocity (greater than \(25\) m s\(^{-1}\)) the schemes differ from each other by more than 20%.

Cases of non-convergence of the iterative algorithm occur. They are represented by crosses in Fig. 10. Most of them occur at low wind speeds, but also either under strong unstable stratifications, or under weakly negative air–sea temperature difference and weakly positive air–sea moisture difference. Very close to neutrality, the iterative algorithms swing alternately between stability and instability and finally diverge.

In conclusion, in the range of atmospheric parameters currently investigated in the literature, stress and turbulent fluxes are found to differ by less than 10%. However, large differences exist if one compares bulk formulae in broad ranges of atmospheric parameters as sampled during CATCH. In light or strong wind regimes the determination of fluxes is very sensitive to the parametrization used. It is likely that there is not yet any bulk formula that can be used universally for in situ estimates of flux and over a sufficiently wide range of atmospheric parameters.

8. Comparisons of Fluxes with the ECMWF Model

To study mesoscale and large-scale atmospheric systems in the North Atlantic during FASTEX, the help of meteorological models is required in many cases. However, the surface-flux parametrizations used in these models are generally based on rather old studies. In view of the results obtained in the previous sections, the quality of the surface fluxes predicted by the ECMWF model has been checked by comparison with flux measurements from ships.

In the ECMWF model, the turbulent surface fluxes are expressed using the Monin–Obukhov similarity theory, in terms of gradients of wind, dry static energy (or dry enthalpy) and specific humidity, which are assumed to be proportional to universal functions of the stability parameter \(\zeta = -Z/L\). The transfer coefficients providing the surface fluxes require the estimation of the stability parameter \(\zeta\), itself a function of the surface fluxes. Therefore, an implicit equation relating \(\zeta\) to the bulk Richardson number \(Ri_b\) is solved iteratively. Over the sea, the roughness lengths for momentum, heat and
moisture are expressed following Beljaars (1994). These expressions include a free-convection velocity scale \( w_* \), which represents the near-surface wind induced by large eddies in the free-convection regime. When the surface is heated, this term guarantees a finite surface wind forcing in the transfer law even for vanishing horizontal wind intensity \( (U) \), and prevents \( U \) and \( L \) from vanishing. Beljaars (1994) showed that this empirical term, when added into the standard Monin–Obukhov scaling, is in agreement with scaling laws for free convection, and provides a good fit to observational data both over land and over sea.

To evaluate the performance of the ECMWF surface bulk-flux algorithm, the ECMWF fluxes were computed along the ship trajectory. Ship measured bulk fluxes were computed every 10 minutes with the CATCH and the Smith (1980) algorithms, and then averaged over 6 h in order to be compared with the 6 h accumulated ECMWF fluxes. The ECMWF forecast values have then been systematically interpolated at the location of the ship.

Figure 11 portrays time series of ship-measured fluxes together with CATCH and Smith (1980) fluxes along the ship trajectory. It shows that the CATCH and Smith bulk fluxes are close, but the Smith parametrization leads to systematically lower values than the CATCH parametrization, in agreement with the results of sections 6 and 7. The differences reach 9.6%, 10.6%, 5.3%, 9.8%, respectively, for the sensible-heat, latent-heat, the friction velocity and the net heat fluxes (Tables 5a, 5b). The ECMWF fluxes show the same general features as those measured from the ship (Fig. 11) thanks to the good correspondence between forecast atmospheric parameters and ship mean measurements and radiosounding profiles (not shown). These good results are quantified by high correlation coefficients, \( r \), \( r > 0.7 \); Tables 5a, 5b) and confirm the ability of the model to reproduce a significant part of the variability of bulk fluxes measured by the ship. Nevertheless, the sensible- and latent-heat fluxes, and friction velocity of the ECMWF model are often greater than the ship-measured values, particularly when using the Smith fluxes since they are smaller than the CATCH values (Tables 5a, 5b). Biases are positive and reach 47.6 and 60.7 \( \text{W m}^{-2} \) for the latent-heat flux when compared with the CATCH and Smith fluxes, respectively. Moreover, the dispersion of the ECMWF turbulent fluxes around those from ship observation, evaluated by means of r.m.s. values, is high, and ECMWF fluxes strongly differ locally from the ship-measured fluxes. Nevertheless, Tables 5a and 5b show that the dispersion of the ECMWF turbulent fluxes around the CATCH fluxes is significantly smaller than around the Smith fluxes, confirming that the ECMWF turbulent fluxes better compare to the CATCH fluxes than the Smith fluxes.

The ECMWF solar fluxes, net infrared fluxes and net radiative fluxes reproduce quite well the ship values, as confirmed by high correlation displayed in Table 5. Nevertheless, bias and r.m.s. differences are nearly the same order of magnitude as the ship’s mean. This indicates again a strong dispersion of the model compared to ship values.

The dispersion of these results may have several origins: the difference of parametrization, the difference due to input parameters or the difference of computational iterative schemes. Moreover, ECMWF and CATCH bulk algorithms use different thermodynamic constants and different stability functions, and the ECMWF fluxes are accumulated over 6 h at the frequency of the model time step (30 min) whereas the CATCH fluxes are accumulated over 6 h at the sampling rate of 10 min. Consequently the CATCH fluxes include more temporal variability than those of ECMWF, which can also be a source of dispersion.

The best strategy to evaluate the origin of these differences, would have been to extract the algorithm from the ECMWF model and to perform many tests: this problem
Figure 11. Time series of ship fluxes using the CATCH (full line) and Smith (1980) (long-short dashed line) and ECMWF fluxes (long-dashed line) along the ship trajectory: (a) sensible-heat flux ($H$, W m$^{-2}$); (b) latent-heat flux ($LE$, W m$^{-2}$); (c) friction velocity ($U_*, $ m s$^{-1}$); (d) net heat flux ($G$, W m$^{-2}$). See text for discussion.

### Table 5. Comparisons of the ECMWF surface fluxes (W m$^{-2}$) with those estimated on board Le Suroît

(a) Using the CATCH parametrization

<table>
<thead>
<tr>
<th>Flux</th>
<th>Ship mean</th>
<th>Bias</th>
<th>r.m.s.</th>
<th>$r$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensible-heat</td>
<td>+60.0</td>
<td>+8.0</td>
<td>40.8</td>
<td>0.86</td>
</tr>
<tr>
<td>Latent-heat</td>
<td>+136.6</td>
<td>+47.6</td>
<td>89.0</td>
<td>0.73</td>
</tr>
<tr>
<td>Short-wave</td>
<td>-99.2</td>
<td>+44.0</td>
<td>61.7</td>
<td>0.79</td>
</tr>
<tr>
<td>Long-wave</td>
<td>+49.1</td>
<td>+16.5</td>
<td>26.8</td>
<td>0.75</td>
</tr>
<tr>
<td>Net heat</td>
<td>+203.0</td>
<td>+74.0</td>
<td>140.0</td>
<td>0.82</td>
</tr>
<tr>
<td>$U_*$ (m s$^{-1}$)</td>
<td>+0.4</td>
<td>-0.12</td>
<td>0.19</td>
<td>0.81</td>
</tr>
</tbody>
</table>

(b) Using the Smith (1980) bulk parametrization

<table>
<thead>
<tr>
<th>Flux</th>
<th>Ship mean</th>
<th>Bias</th>
<th>r.m.s.</th>
<th>$r$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensible-heat</td>
<td>+54.7</td>
<td>+13.5</td>
<td>43.4</td>
<td>0.86</td>
</tr>
<tr>
<td>Latent-heat</td>
<td>+123.4</td>
<td>+60.8</td>
<td>96.0</td>
<td>0.72</td>
</tr>
<tr>
<td>Net heat</td>
<td>+184.9</td>
<td>+92.0</td>
<td>151.0</td>
<td>0.82</td>
</tr>
<tr>
<td>$U_*$ (m s$^{-1}$)</td>
<td>+0.38</td>
<td>+0.14</td>
<td>0.2</td>
<td>0.81</td>
</tr>
</tbody>
</table>
is largely beyond the scope of this paper. Nevertheless, in order to remove the influence of the input parameters, and to test (at the first order) the difference between the two bulk algorithms, it was decided to compare the ECMWF fluxes with those obtained with the CATCH algorithm by using the ECMWF atmosphere and SST parameters as input, at one point of the domain. However, ECMWF fluxes are accumulated over 6 h and fluxes obtained from atmospheric parameters are ‘instantaneous’ fluxes every 6 h. In order to minimize the errors induced by this inconsistency, the comparison is performed during two long periods of one month (January and February).

The comparison shows that the ECMWF sensible-heat flux is not biased and is well correlated \((r = 0.91)\) to the CATCH sensible-heat flux. On the other hand, the ECMWF latent-heat flux is on average 20 W m\(^{-2}\) stronger than the CATCH value, but the correlation between the two series is high \((r = 0.91)\). The ECMWF mean friction velocity underestimates the CATCH value by 0.1 m s\(^{-1}\) on average over two months, and they are less well correlated \((r = 0.73)\) than the heat fluxes.

In summary, the dispersion obtained reaches 2.5%, 11%, and 21%, respectively, for the sensible-heat flux, the latent-heat flux and the friction velocity, which are less than the dispersion along the ship trajectory. These results indicate that not only do the ECMWF and CATCH flux algorithms differ, but that an important part of the bias observed along the ship trajectory comes from differences of input data and/or differences of computational schemes.

9. TURBULENT FLUX VARIATIONS OVER SST FRONTS (SSTF)

The effect of SSTFs on the atmospheric boundary layer and surface fluxes was studied during the Frontal Air–Sea Interaction Experiment (FASINEX, Frihe et al. 1991) and SEMAPHORE. Depending on the orientation of the flow with respect to the front, and on the stability, the SST gradient can have either a weak effect, or an important one (increase of the boundary-layer height, of heat fluxes, modification of the atmospheric boundary layer, ageostrophic circulation), as shown by Frihe et al. (1991), Kwon et al. (1998), Giordani (1997). Contrary to the previous experiments, the lack of near simultaneous accurate measurements on both sides of the SSTF prevented us from analyzing in detail the effect of the SST gradient on turbulent fluxes and boundary-layer properties. As shown in section 3, the atmospheric models use a very smooth SST map, which prevents them simulating the effect of SSTF on surface fluxes and the boundary layer. We propose in this section to estimate the impact of the SST gradient on turbulent fluxes, in cases where the atmospheric characteristics do not change strongly during the ship section of the SSTF.

The Le Suroît crossed the major surface thermal discontinuities in the area several times. The SSTF associated with the NAC was crossed near 45°W, 47°N. As noted in section 2, it is characterized by a stronger gradient (10 degC over 50 km) than the other SSTF (2–3 degC). Because of the slow ship motion, the atmosphere is generally not stationary whilst measuring the cross-section of the SSTF (several hours). Moreover, some of these cases correspond to the arrival or the passage of an atmospheric low. In six cases, however, near stationary conditions were observed (no or weak pressure variations), giving some confidence that the cross-section was made in the same air mass. The main ship observations are summarized in Table 6. For each case, we determined the orientation of the main atmospheric flow with respect to the SSTF, the boundary-layer height change, the SST, atmospheric temperature, wind and horizontal humidity gradients, taking a two-hour period (apart from the SST gradient). The SSTF
### TABLE 6. MEAN CHARACTERISTICS OF THE SIX SSTF CROSS-SECTIONS IN WHICH NEAR-STATIONARY CONDITIONS WERE OBSERVED

<table>
<thead>
<tr>
<th>Section</th>
<th>SST (degC)</th>
<th>T (degC)</th>
<th>Q (g kg⁻¹)</th>
<th>h (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>43.2°W 46.4°N</td>
<td>01/16 0030 to 0400</td>
<td>+7</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>16 m s⁻¹ 6°C</td>
<td>16 m s⁻¹ 13°C</td>
<td>+2</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>Ps = 1002 hPa</td>
<td>H_e, H_w, L_e, L_w, τ_e, τ_v, Δ_s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>43°W 46.5°N</td>
<td>01/16 2200 to 01/18 0400</td>
<td>+7.4</td>
<td>+0.3</td>
</tr>
<tr>
<td></td>
<td>13 m s⁻¹ 6°C</td>
<td>12.7 m s⁻¹ 13°C</td>
<td>+1.6</td>
<td>+0.3</td>
</tr>
<tr>
<td></td>
<td>Ps = 1019 hPa</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>35°W 49.3°N</td>
<td>01/23 1600 to 2100</td>
<td>+2.1</td>
<td>-0.34</td>
</tr>
<tr>
<td></td>
<td>10 m s⁻¹ 12°C</td>
<td>12 m s⁻¹ 10°C</td>
<td>-1.1</td>
<td>-0.34</td>
</tr>
<tr>
<td></td>
<td>Ps = 1013 hPa</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>39.2°W 42.3°N</td>
<td>01/30 1600 to 2000</td>
<td>+3.0</td>
<td>-0.7</td>
</tr>
<tr>
<td></td>
<td>6.5 m s⁻¹ 17°C</td>
<td>5.5 m s⁻¹ 14°C</td>
<td>-0.9</td>
<td>-0.7</td>
</tr>
<tr>
<td></td>
<td>Ps = 1019 hPa</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>36.2°W 51.3°N</td>
<td>02/11 1700 to 2200</td>
<td>+3</td>
<td>-0.3</td>
</tr>
<tr>
<td></td>
<td>17.6 m s⁻¹ 10°C</td>
<td>14 m s⁻¹ 7°C</td>
<td>+0.9</td>
<td>-0.3</td>
</tr>
<tr>
<td></td>
<td>Ps = 998 hPa</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>38.5°W 50°N</td>
<td>02/13 1800 to 2300</td>
<td>+4.5</td>
<td>+1.0</td>
</tr>
<tr>
<td></td>
<td>1.3 m s⁻¹ 12°C</td>
<td>5.6 m s⁻¹ 7.5°C</td>
<td>-1.0</td>
<td>+1.0</td>
</tr>
<tr>
<td></td>
<td>Ps = 1018 hPa</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Each case is schematized in the first column, in which are given the SST and wind magnitude on both sides of the front (+: warm side; -: cold side), the surface pressure (Ps), date (mm/dd) and the beginning and end times (UTC) of the cross-section. Other columns give ΔSST, ΔT and ΔQ which are the horizontal variations of SST, air temperature and specific humidity at 16 m, respectively; and Δh, the atmospheric boundary-layer height variation, which is estimated using the radiosounding profiles and the cloud-base height measurements. The surface turbulent fluxes and stability are calculated over two-hour periods, and are given on the cold and warm sides (indices c and w).
crossing itself was of a duration ranging between half an hour (case 6) and 2 hours (case 1).

(a) Analysis of surface flux variations

The surface turbulent fluxes were calculated using the Smith (1980) algorithm over 10 min intervals; averages were then taken over each period of two hours on both sides. Calculations were made using the mean wind magnitude, instead of the magnitude of the mean wind vector, because the wind direction measurement is sometimes noisy due to difficulties in correcting for ship direction fluctuations. This problem occurred in a few cases, after rapid changes of the ship’s direction (case 3 mainly). We only retained data for which the wind direction does not change strongly during the sampling interval ($\pm 30^\circ$ maximum).

To quantify the effect of the atmospheric and surface changes on surface flux variations across the SSTF, we estimated their individual contributions, varying one parameter while keeping all the others constant. Such a method has been used previously by Eymard et al. (1996) and Kwon et al. (1998). The constant values were taken as the average over the two sides away from the SSTF. As an example, Eqs. (18) to (20) show how calculations of the contributions of the SST, the atmospheric potential temperature and the wind on the sensible-heat flux, $H$, are made (noted as $\Delta_{SST}H$, $\Delta_T H$, $\Delta_U H$, respectively):

$$\Delta_{SST}H = C_h \overline{\nabla} (SST_w - \overline{T}) - C_h \overline{\nabla} (SST_c - \overline{T})$$

$$\Delta_T H = C_h \overline{\nabla} (ST - T_w) - C_h \overline{\nabla} (ST - T_c)$$

$$\Delta_U H = C_h U_w (ST - \overline{T}) - C h U_c (ST - \overline{T})$$

where $SST_w$ and $SST_c$ are the SST on the warm and cold sides, respectively, and similarly $T_w$ and $T_c$ for atmospheric temperature, $Q_w$ and $Q_c$ for humidity, and $U_w$ and $U_c$ for the near-surface wind. The surface humidity is derived from the SST assuming near saturation: $Q_s = 0.98 Q_{sat}(SST)$. Averages over the two sides are noted by an overbar. The contributions for the latent-heat flux and the momentum flux are calculated in a similar way.

As we use an iterative algorithm, the drag and exchange coefficients are calculated at every 10-minute step. By decomposing the flux variation into these three contributions, we neglect the second-order term related to the coefficient variations. We therefore estimate the error by comparing the sum of the three contributions and the actual flux variation:

$$err = \Delta H - \Delta_{SST}H - \Delta_T H - \Delta_U H$$

with $\Delta H = H_w - H_c$.

(b) Results

For the 6 selected cases, Tables 7, 8 and 9 summarize the mean-flux variations and contributions of the SST, and atmospheric temperature and humidity and the wind to the sensible-heat, latent-heat and momentum fluxes, all taken as the difference between the averages on the warm side and the cold side.

The momentum-flux variations range between $-0.06$ and $+0.22$ hPa. It is mainly driven by the wind, since the contribution of the wind is generally much higher than contributions from temperature and humidity variations. The contribution of the thermal
TABLE 7. CONTRIBUTIONS TO THE SENSIBLE-HEAT FLUX (∆H)

<table>
<thead>
<tr>
<th>Case</th>
<th>Date (mm/dd)</th>
<th>∆H (W m⁻²)</th>
<th>∆U H</th>
<th>∆T H</th>
<th>∆SST H</th>
<th>∆SST–Τ H</th>
<th>Residual error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>01/16</td>
<td>+134.3</td>
<td>-2.8</td>
<td>-43.7</td>
<td>+182.2</td>
<td>+137.6</td>
<td>+1</td>
</tr>
<tr>
<td>2</td>
<td>01/17</td>
<td>+123.0</td>
<td>-1.4</td>
<td>-35.4</td>
<td>+159.2</td>
<td>+124.1</td>
<td>+0</td>
</tr>
<tr>
<td>6</td>
<td>02/13</td>
<td>+9.9</td>
<td>-41.1</td>
<td>+9.3</td>
<td>+42.4</td>
<td>+51.7</td>
<td>-8</td>
</tr>
<tr>
<td>5</td>
<td>02/11</td>
<td>+68.8</td>
<td>+18.9</td>
<td>-24.0</td>
<td>+73.6</td>
<td>+49.8</td>
<td>+1</td>
</tr>
<tr>
<td>3</td>
<td>01/23</td>
<td>+47.3</td>
<td>-13.1</td>
<td>-20.6</td>
<td>+38.4</td>
<td>+58.8</td>
<td>-3</td>
</tr>
<tr>
<td>4</td>
<td>01/30</td>
<td>+31.4</td>
<td>+1.8</td>
<td>-0.0</td>
<td>+32.2</td>
<td>+32.0</td>
<td>-8</td>
</tr>
</tbody>
</table>

∆H is the actual heat-flux shift; the next columns give the heat-flux variation (in W m⁻²) obtained by varying only the wind (∆U H), the atmospheric temperature (∆T H), the sea surface temperature (∆SST H) and the vertical temperature gradient (∆SST–Τ H). The final column gives the residual error (actual flux variation minus the sum of the contributions, in percent). Cases are sorted as functions of the mean wind/SSTF conditions: the first three, cases 1, 2 and 6, are ‘Cold to Warm’; then case 5 is the ‘Warm to Cold’ case; finally cases 3 and 4 are ‘Parallel’ cases.

TABLE 8. AS TABLE 7, BUT FOR THE LATENT-HEAT FLUX (∆LE)

<table>
<thead>
<tr>
<th>Case</th>
<th>Date (mm/dd)</th>
<th>∆LE (W m⁻²)</th>
<th>∆U LE</th>
<th>∆Q LE</th>
<th>∆QS LE</th>
<th>∆QS–Q LE</th>
<th>Residual error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>01/16</td>
<td>+166.0</td>
<td>-3.5</td>
<td>-26.2</td>
<td>+222.0</td>
<td>+196.5</td>
<td>+16</td>
</tr>
<tr>
<td>2</td>
<td>01/17</td>
<td>+172.9</td>
<td>-2.1</td>
<td>-6.3</td>
<td>+194.7</td>
<td>+198.9</td>
<td>-15</td>
</tr>
<tr>
<td>6</td>
<td>02/13</td>
<td>-28.0</td>
<td>-63.0</td>
<td>-23.9</td>
<td>+53.8</td>
<td>+25.5</td>
<td>-19</td>
</tr>
<tr>
<td>5</td>
<td>02/11</td>
<td>+136.5</td>
<td>+34.0</td>
<td>+36.4</td>
<td>+85.1</td>
<td>+120.4</td>
<td>-14</td>
</tr>
<tr>
<td>3</td>
<td>01/23</td>
<td>+45.1</td>
<td>-25.1</td>
<td>+1.3</td>
<td>+52.1</td>
<td>+54.3</td>
<td>+37</td>
</tr>
<tr>
<td>4</td>
<td>01/30</td>
<td>+81.0</td>
<td>+6.9</td>
<td>+16.7</td>
<td>+60.1</td>
<td>+75.6</td>
<td>-3</td>
</tr>
</tbody>
</table>

The SST is replaced here by the corresponding humidity taken as 98% of saturation.

TABLE 9. AS TABLE 7, BUT FOR THE MOMENTUM FLUX (τ)

<table>
<thead>
<tr>
<th>Case</th>
<th>Date (mm/dd)</th>
<th>∆τ (N m⁻²)</th>
<th>∆Uτ</th>
<th>∆SSTτ</th>
<th>Residual error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>01/16</td>
<td>+0.005</td>
<td>-0.015</td>
<td>0.026</td>
<td>+2</td>
</tr>
<tr>
<td>2</td>
<td>01/17</td>
<td>+0.011</td>
<td>-0.009</td>
<td>0.026</td>
<td>-3</td>
</tr>
<tr>
<td>6</td>
<td>02/13</td>
<td>-0.032</td>
<td>-0.036</td>
<td>0.003</td>
<td>-4</td>
</tr>
<tr>
<td>5</td>
<td>02/11</td>
<td>+0.222</td>
<td>+0.212</td>
<td>0.014</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>01/23</td>
<td>-0.060</td>
<td>-0.070</td>
<td>0.006</td>
<td>+1</td>
</tr>
<tr>
<td>4</td>
<td>01/30</td>
<td>+0.022</td>
<td>+0.015</td>
<td>0.009</td>
<td>-7</td>
</tr>
</tbody>
</table>

In this case the vertical thermal gradient is not included.

The term affects the momentum flux through the stability changes; the SST contribution is always positive, and is greater than 0.01 hPa only in three cases: 1, 2 and 5.

Variations of the sensible-heat flux are positive from the cold to warm sides in all cases. They range from 10 to 134 W m⁻². The latent-heat flux variations range from -28 to 172 W m⁻².

We analyse the effect of the surface temperature gradients as a function of the relative wind–SSTF direction, as in Frieh et al. (1991) and Kwon et al. (1998). Among the 6 selected cases, three are situations with the wind blowing from the cold to the warm side of the SST gradient (cases 1, 2 and 6); one is a case of warm to cold wind direction (5); and two are parallel situations (3 and 4).

- **Cold to warm**. Cases 1 and 2 are situations where of a cold-air outbreak follows the passage of a low pressure system over a strong SST gradient (about 7 degC).
Figure 12. Sea surface temperature (SST) and surface flux time series for case 2, 16–17 January. From top to bottom: SST (degC); stability (−Z/L dashed line); friction velocity (U*, full line); latent-heat and sensible-heat fluxes (W m⁻²). The stars superimposed on the SST plot show the limits of the averaging periods before and after passing the front. Time is in decimal Julian days. See text for further details.
The wind is strong, and the atmosphere cold and dry. The heat-flux variation is high
more than 120 and 165 W m$^{-2}$ for the sensible-heat and latent-heat-flux variations,
respectively), whereas the momentum flux does not change much from the cold to
the warm side. The major contribution to the heat-flux variation is the SST variation,
whereas the temperature and humidity variations tend to reduce it, because the boundary
layer is heated by the warm water. Figure 12 shows the heat fluxes, friction velocity and
stability variations for case 2; it shows strong variations of heat fluxes and a stability
decrease, but no change in the momentum flux. Case 6 corresponds to a light wind
blowing over a weaker SSTF (4.5 degC). The SST variation again explains most of
the heat-flux variation, which is much smaller than in the two first cases because of
the light wind. The positive latent-heat flux variation due to the SST gradient is
counterbalanced by contributions from the wind decrease and humidity increase; the
wind is less than 5 m s$^{-1}$ during the SSTF cross-section, so free convection can possibly
develop on the warm side, explaining the humidity increase and the negative latent-heat
flux variation.

- Warm to cold. In case 5 the wind is higher on the warm than the cold side,
explaining the significant contribution of the wind on all flux variation. The atmos-
pheric temperature and humidity changes across the SSTF, follow the SST gra-
dient. The stability does not differ significantly from one side to the other, and
heat-flux variations are thus explained mostly by the SST and for a small part
by the wind variations. Such a wind variation was also observed by Frieha et al.
(1991) in a similar case of FASINEX. In this case, the sensible-heat flux vari-
ation is well correlated with the SST gradient, while the latent-heat flux variation is
smoother.

- Parallel. In case 3, the wind blows parallel to the SST isotherms over a long
distance, whereas in case 4 the cross-section was made through a meander of the SSTF.
In case 3, the temperature and humidity increase with time (due to a slow synoptic
evolution) as well as the wind, while the ship crossed the SSTF from warm to cold
sides. Small-scale variations of the atmospheric temperature and wind could be due
to the SSTF, but there is probably a superposition of the SST gradient and large-

scale atmosphere contributions on the heat fluxes, which explains the stability and
flux variations. In case 4 also, the pressure increased slightly during the cross-section,
associated with a decrease in humidity. The temperature increases with the SST, whereas
the wind is nearly constant except for a maximum over the SSTF itself. The heat-flux
variations are, however, well correlated with SST variations, associated with a strong
change in stability, and the momentum flux presents a strong maximum on the SSTF
itself (as also does the latent-heat flux). Again, to analyse small-scale variations would
need a more detailed analysis.

In conclusion, the SST gradient is the major cause of heat-flux variation in all cases
but one, for which very light wind and unstable situation make the flux calculation less
accurate (see the discussion in section 6). The atmospheric temperature generally varies
in the same sense as the SST, but it is not as systematic for humidity at the scale of
the SST gradient-scale, and impact of the SSTF on heat fluxes is of the same order of
magnitude or greater than the flux variation itself (about 100% of the variation for $H$
in all cases, 30 to 100% for $LE$). Its effect on the momentum flux is always positive,
due to the stability variation, but is generally smaller than the flux variation due to the
wind changing. These results concerning the heat fluxes are in agreement with previous
studies (Frieha et al. 1991; Kwon et al. 1998), despite the longer duration of the cross-
sections (they used aircraft sections or data from two ships away from the front). They
show the importance of a good knowledge of the SST in correctly understanding the surface fluxes and boundary-layer variations. These ship data also suggest that small-scale processes occurred over the front, as observed in previous studies. They cannot, however, be correctly analysed using only this dataset, and further study, including a modelling tool, is needed.

10. CONCLUSION

The CATCH experiment was devoted to the study of air–sea interactions in the presence of strong atmospheric forcing, in the framework of the FASTEX experiment. The major mesoscale oceanic features are surface thermal fronts associated with the various branches of the NAC and the North Atlantic cold water.

Shipborne turbulent measurements on the RV Le Suroît were analysed to evaluate the surface fluxes and bulk parametrizations in strong-wind cases. Estimates of drag and exchange coefficients for heat and evaporation have been performed by the IDM. While the sensible-heat flux measurements are of poor quality in general and useless at low fluxes, $Cdn$ and $Cen$ values, obtained by a Gill sonic anemometer and a refractometer, lead to the following conclusions:

- $Cdn$ values at low wind speeds are found to be slightly higher than during previous experiments and show a non-negligible impact of iterations, which enhance the $Cdn$ values. No effect of sea-state has been established, but a partition in terms of stability: high values for neutral or slightly stable stratifications and lower values for unstable stratifications. These results are in qualitative agreement with previous studies (Dupuis et al. 1997) which proposed a stability-dependent imbalance function in the TKE budget; however, the CATCH measurements with near-neutral conditions at low wind speed are higher than corrected unstable results. At moderate wind speeds ($7 \,\text{m s}^{-1} \leq U \leq 11 \,\text{m s}^{-1}$), the $Cdn$ values are in agreement with Smith (1980). They are, however, found to be much higher at high wind speeds. The difference is up to 30\%, but $Cdn$ values are, nevertheless, of the same order of magnitude as those obtained in the FETCH experiment (Dupuis et al. 1999) and slightly larger (10\%) than the Hare et al. (1999) results during FASTEX. These discrepancies are not yet fully explained and much effort will now be put into simulations of flow distortion to take into account the effect of the ship structure.

- $Cen$ values are found to be in the usual range of $1.1$ to $1.2 \times 10^{-3}$ for moderate wind speeds. At higher wind speeds, a significant increase of $Cen$ is observed, which might be a contribution from marine aerosol. These $Cen$ values should, however, be also affected by flow distortion if it is shown to be significant.

A comparison of friction velocities from 4 different experiments (SOFIA, SEMAPHORE, CATCH and FETCH) with the same algorithm gave rise to the following observations:

- at high wind speeds, where only CATCH and FETCH are concerned, $Cdn$ values converge to the same relationship versus $U_{10m}$;

- at moderate wind speeds, the different experiments lead to significantly varying $u_*$, which might be explained in terms of swell, i.e. experiments with significant swell, such as CATCH and SEMAPHORE, show higher $u_*$ than others.

All these observations need further work to be confirmed. Both the effects of the sea-state, and of the method used to derive turbulent fluxes, should be analysed using wave-spectra measurements and by developing eddy-correlation measurements.
This new bulk formulation was then compared to various published bulk-flux parametrizations. A vast range of winds were sampled from weak to strong wind speeds (5\% larger than 20 m s\(^{-1}\)). These data also cover a vast range of stability: strong stabilities (18\%) were associated with warm air passing over cold water, which generated downward sensible-heat or latent-heat fluxes. Strong instabilities were met (26\% of the dataset) over a broad range of wind speeds, and contribute to a strong increase in turbulent flux up to extreme values (400 W m\(^{-2}\) for sensible heat and 600 W m\(^{-2}\) for latent heat). Generally, bulk formulae used for the calculation of the wind stress and turbulent fluxes were not calibrated over such a wide range, and the disparity of the results is clearly due to the scarcity of flux measurements in weak or high wind associated with large air–sea temperature and moisture differences. Consequently, significant disparities were highlighted by comparing 6 bulk parametrizations. For a mean sensible-heat flux of 350 W m\(^{-2}\), variations up to 100 W m\(^{-2}\) were encountered, and for a mean latent-heat flux of 450 W m\(^{-2}\), scheme-to-scheme variations reach 200 W m\(^{-2}\).

Concerning radiative fluxes, comparisons carried out between in-situ data and calculations deduced from METEOSAT, confirm results obtained during previous experiments in the North Atlantic during different seasons and for different values of zenith angle. Even for large values of viewing zenith angle, biases are not so large as those deduced from other recent studies (Chertock et al. 1992) and were not in excess of a few W m\(^{-2}\) for both long-wave and short-wave fluxes during CATCH. This result confirms the great potential for improvements in estimates of radiative fluxes through the use of satellite observations (Darnell et al. 1992), either to force oceanic models or for climatic purpose.

As well as for satellite flux estimates, the ship data were used to evaluate the ECMWF forecast surface fluxes. Although the ECMWF turbulent and radiative surface fluxes are well correlated with those from the ship, ECMWF bias and r.m.s. difference are strong and could induce strong drifts in an oceanic mixed-layer thermal budget. Unfortunately, bias and r.m.s. difference are generally not universal features but depend on the season and the geographical position. A similar conclusion was obtained from the SEMAPHORE experiment (Giordani et al. 1998).

Six cross-sections of the SSTF were analysed to evaluate the effect of these horizontal gradients on the surface fluxes. While various mean meteorological conditions were encountered during making measurements for these cross-sections, the SST gradient has been found to strongly contribute to the variations of turbulent sensible- and latent-heat fluxes, being of the same order of magnitude as, or greater than, the measured flux variation (about 100\% of the flux variation for H; 30 to 100\% for LE). Its effect on the momentum flux is always positive, but is generally smaller than the flux variation due to the wind changing. These results are in agreement with previous studies (Frieha et al. 1991; Kwon et al. 1998), despite the duration of the observing programme being too long to ensure that the atmosphere is stationary. They show the importance of a good knowledge of the SST to correctly understand the surface fluxes and boundary-layer variations.

The SST analyses allowed us to obtain realistic SST structures in comparison with those observed during CATCH and operational data. In particular, the strong SST gradients linked to the NAC have been reproduced realistically by the analyses. Therefore, it is now possible to use these analyses as the lower boundary condition of an atmospheric mesoscale model, in order to study the effects of the differential surface heating (linked to the SSTF) on the atmospheric boundary-layer properties and
cyclogensis. This work is consequently being continued, by studying the sensitivity of a deepening cyclone (FASTEX/IOP15, 14–15 February 1997) to the SST, using non-hydrostatic simulations in which the SST field is taken to be either uniform (cold or warm), or realistic.

ACKNOWLEDGEMENTS

We acknowledge the officers and crew of the RV Le Suroît and the scientific staff of CETP, CNRM, LPCM, ETH and NCAR, who all struggled under very difficult conditions to acquire the data presented in this paper. We are grateful to the scientific staff at the Shannon FASTEX operation centre, who provided us with real-time information during the cruise, and to Météo-France/SCEM who provided wave model outputs. We thank the three reviewers for their comments on the manuscript. This work has been supported by INSU/CNRS, Météo-France and SHOM.

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