# THE AIR-SEA INTERFACE
## Radio and Acoustic Sensing, Turbulence and Wave Dynamics

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# INVESTIGATION OF THE OCEAN-ATMOSPHERE INTERACTION IN THE NORTH ATLANTIC MID-LATITUDE FRONTAL ZONE

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Abstract. The paper summarizes results from the boundary layer field experiments carried out in the Newfoundland basin in the period 1988-1990. On-board meteorological measurements, radiosondes, and tethered balloons were used to study sea-air fluxes in the vicinity of the Gulf Stream SST front. For some synoptic situations (north winds in the back parts of cyclones) local maxima of sensible and latent fluxes south of the SST front are obtained. In the lower part of the boundary layer submesoscale thermal inhomogeneities were measured. Finally, we discuss possible ways to parameterize the observed effects.

## 1 Introduction

There is significant evidence that extremely high sea-air fluxes can be associated with mid-latitudinal SST fronts. Results of the FASINEX (Friehe *et at,* 1991) and ERICA (Bane and Osgood, 1989) experiments include eddy-correlation measurements showing maxima of sensible and latent heat fluxes in the vicinity of SST fronts in the subtropics and Gulf Stream regions. There are a number of articles, concerning so-called cold-air outbreaks over coast lines and margin zones (Overland *et at.*, 1983; Sethuraman *et al.*, 1986; Konrad *et at.*, 1989; Chao, 1992), or the modification of the atmospheric boundary layer by the advection of warm air over relatively cold water (Hsu, 1983). There is even evidence of the possibility of indicating such events using satellite data (Katsaros and Brown, 1991). As a result many efforts are undertaken in modelling of processes in the atmospheric boundary layer with the use of 1D and 2D models (Overland et.al., 1983; Wai, 1988; Wai and Stage, 1989). At the same time most data are collected for off-shore regions or marginal zones. There are only a few measurements of sea-air interaction processes over open ocean mid latitudinal frontal zones. This study attempts to consider synoptic-scale and mesoscale sea-air interaction processes in the Newfoundland basin, characterized by the existence of a sharp SST frontal zone, connected with Gulf Stream splitting, and by strong synoptic and mesoscale variability of the atmospheric boundary layer as well.

## 2 Data

Data for this study were collected during synoptic sea-air interaction field experiments in the Newfoundland basin, carried out within the last 5 years by the Ocean Climate and Marine Meteorology Laboratory of the State Oceanography institute. Interested readers can find details of these expeditions in Lappo *et al.* (1989). Gulev and Kolinko (1990), Gulev *et al.* (1991). These experiments were designed to study air-sea interaction processes primarily in the region 40-50 N, 40-50 W. Ships, tethered balloons, buoys and moorings were used to measure the atmospheric and oceanic structures and properties. We will use in this study only those data that were obtained during fine-resolution cross-sections of SST fronts. These cross-sections were taken a couple of times during each experiment. The principal idea of all these efforts was to cross the SST front under relatively stable wind conditions, determined by the advection of cold air from the North across the SST front (cold air outbreak), or warm and moist air from the south. These situations are primarily connected with the appearance of back parts (north wind) or forward parts (south wind) of cyclones, developed within the experimental site. The genesis and life cycle of these cyclones, often driven by SST fronts, have been explored in a number of studies, taken partially during CASP and CASP-II experiments (Yau and Jean, 1989). Figure 1 demonstrates the location of the experiments and Table I contains information about the measurements, which were taken along every cross-line. Usually we were focused to combine fine resolution meteorological measurements, radiosondes, and tethered balloon data to collect comprehensive data sets for every section. We used radiosonde systems METEORIT and CORA, that depend on the type of oceanographic research vessel (ORV), standard meteorological packages with additional hand sampling of some variables and 6 $m^3$ tethered balloons with air temperature, humidity and wind speed sensors (Vystavkin *et al.*, 1992). Balloon profiles usually were taken with higher separation between every two radiosondes in order to cover at least the lower part of the atmospheric boundary layer with fine resolution data.

## 3 Results

We will consider below results from four cross-sections, which were taken during the winter-spring periods of 1990 and 1992 (Table 1). These case studies will be denoted below CS1, CS2, CS3, and CS4. We will use here the notation Rl.l,.... and Bl.l,.... for radiosondes profiles and tethered balloon profiles respectively, where the first number indicates the case study and the second corresponds to the current number of the profile in every series of measurements. Cross-section CS1 was carried out in the period from May 3 until May 5, 1990 in the back part of mid-latitudinal cyclone, characterized by the advection of cold air from the North-west over warm water (cold-air outbreak). Cross-sections CS3 and CS4 have been taken under comparable conditions during periods from April 9 until April 11, 1992 and from December 27 until December 29, 1992 respectively. Cross-section CS2 was carried out in the forward part of a cyclone, where atmospheric conditions are determined by the advection of relatively warm and moist air over extremely cold water, north of the Gulf Stream SST front.

Figure 2 shows the behavior of meteorological variables and heat fluxes along cross-sections CSl and CS2. Sensible and latent heat fluxes were calculated by the bulk aerodynamic method with transfer coefficients taken from Ariel *et al.* (1981). Interested readers can find details of this parameterization and its comparison with others (for example with Liu *et* al.(1979)) in Gulev (1993). In all cases the SST front is characterized by sharp gradients of surface temperature.

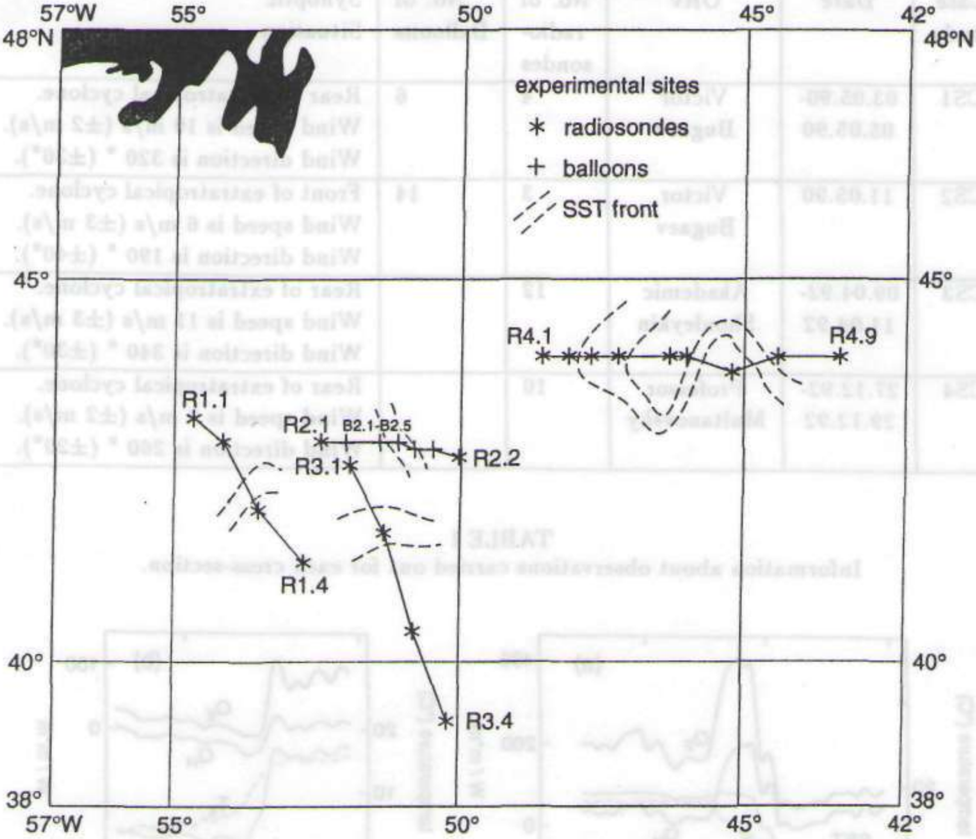

Fig. 1. Spatial location of meteorological data sets in Newfoundland basin. Notation of profiles is indicated in the text.

Usually the SST changes range from 0.2°C/km to 2.0°C/km and actually the SST can be considered as a step-function. The most sharp changes were observed for CS2, when SST gradients were even higher than 2 °C/km.

For the wind, directed from the cold water to the warm, both air temperature and humidity increase not as sharply as SST. The increase of humidity occurs even more slowly than that of air temperature. Thus, the most considerable disagreement between thermal characteristics of the ocean and the atmosphere is observed exactly over the zone of the highest SST gradient, or 20-30 kilometers southward. Already 100 kilometers southward from the SST front line air temperature and humidity are much more adjusted to each other. Thus section CS1 indicates a sea-air temperature difference over the frontal zone, equal to 10°C, and a humidity difference, equal to 8 mb. Over the warm water both differences become several times smaller and range from 1 to 5°C and from 2 to 6 mb respectively. Local processes over SST fronts can also force the increase of surface wind due to additional generation of kinetic energy. This phenomenon, observed in some of studies, mentioned in the introduction, has been also found

| Case Study | Date | ORV | No. of radiosondes | No. of Balloons | Synoptic Situation |
|---|---|---|---|---|---|
| CS1 | 03.05.90-05.05.90 | Victor Bugaev | 4 | 6 | Rear of extratropical cyclone.<br>Wind speed is 10 m/s (±2 m/s).<br>Wind direction is 320 ° (±30°). |
| CS2 | 11.05.90 | Victor Bugaev | 3 | 14 | Front of extratropical cyclone.<br>Wind speed is 6 m/s (±3 m/s).<br>Wind direction is 190 ' (±40°). |
| CS3 | 09.04.92-11.04.92 | Akademic Shouleykin | 12 |  | Rear of extratropical cyclone.<br>Wind speed is 11 m/s (±3 m/s).<br>Wind direction is 340 ° (±30°). |
| CS4 | 27.12.92-29.12.92 | Professor Multanovsky | 10 |  | Rear of extratropical cyclone.<br>Wind speed is 9 m/s (±2 m/s).<br>Wind direction is 260 ° (±20°). |

TABLE I
Information about observations carried out for each cross-section.

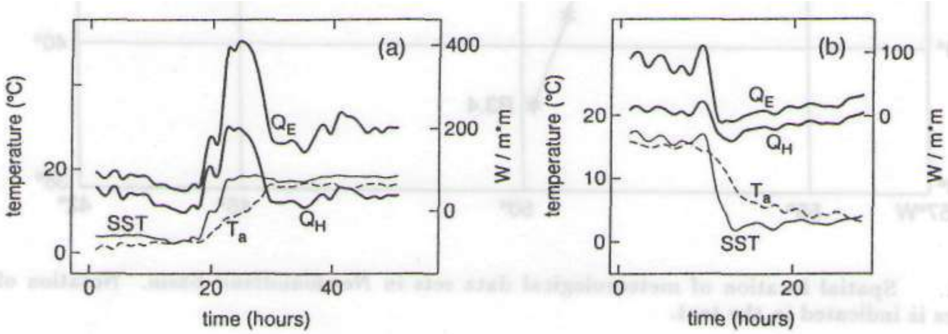

Fig. 2. Changes of SST, air temperature and calculated sensible and latent heat fluxes along crosslines CSl (a) and CS2 (b).

for cross-sections CSl and CS3. Nevertheless it is difficult to discuss this fact with confidence because the biggest changes range from 0.5 to 2.0 m/s, often within the accuracy of measurement.

As a result of the described disagreement, both sensible and latent heat fluxes indicate pronounced maxima just over the SST front. Cross-section SC1 gives 200 $W/m^2$ for sensible heat flux and more than 400 $W/m^2$ for latent heat flux. For CS3 and CS4 (not displayed here) fluxes are a bit lower, but nevertheless significantly higher than over the warm water 100 km southward from the SST front. In May, 1990 several series of direct flux measurements were taken, using the eddy-correlation technique by the flux team of the Institute of Atmospheric Physics. Comparison with bulk estimates gives considerable, but systematic differences. Undoubtedly, connected with the use of the selected scheme for transfer coefficients.

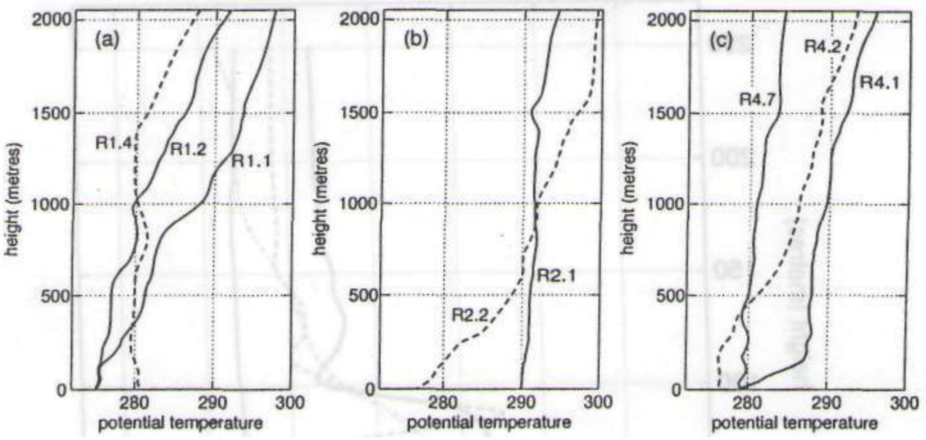

Fig. 3. Radiosonde profiles of potential temperature from cross-sections CS1 (a), CS2 (b) and CS4 (c). Notation of profiles is indicated in the text.

Under the advection of warm air over cold water (CS2) air temperature and humidity decrease, which, again, appears to be more slow than those for SST (Figure 2). Thus the most stable stratification is observed again in the vicinity of the SST front. As a result, local maxima, characterized by considerably negative sensible fluxes, are indicated in Figure 2. At a distance of about 50-60 kilometers to the north air temperature becomes adjusted with SST, and both sensible and latent heat fluxes become higher than in the vicinity of the SST front.

Let us turn our attention now to the structure of the atmospheric boundary layer, studied with the use of radiosondes and tethered balloons. Some technical details of the equipment used, data processing and control, and interpolation procedures for so-called "way-up" profiles and "way-down" profiles are presented in Vystavkin *et al.* (1992). Figure 3a shows the profiles of potential temperature for the cross-section CS1. The thickness of the mixed layer increased from 200 meters over cold water (R1.1) to about 1500 meters over relatively warm water (R1.4). Profiles R1.2 and R1.4 also demonstrate a remarkable unstable layer between 700 and 100 meters, that indicates intensive convection in the atmospheric boundary layer. Profiles from CS4 (Figure 3c) are comparable with those from CS1. Again, as before, profiles R4.1 and R4.2 show that a strong inversion over cold water practically blocks energy exchange with the upper layers of the atmosphere, though R4.2 taken exactly over the SST front, indicates a mixed layer with thickness of about 200 meters. Observed cloudiness changed from Sc to Cu between R4.1 and R4.2. South of the front line a well developed convective boundary layer, with thickness ranging from 1000 to 1500 meters, has been formed.

Figure 4 shows the potential temperature for CS3, when the ship crossed the SST front and additionally crossed a cold meander after that. For this case the development of the mixing layer in the lower 500 meters starts already over

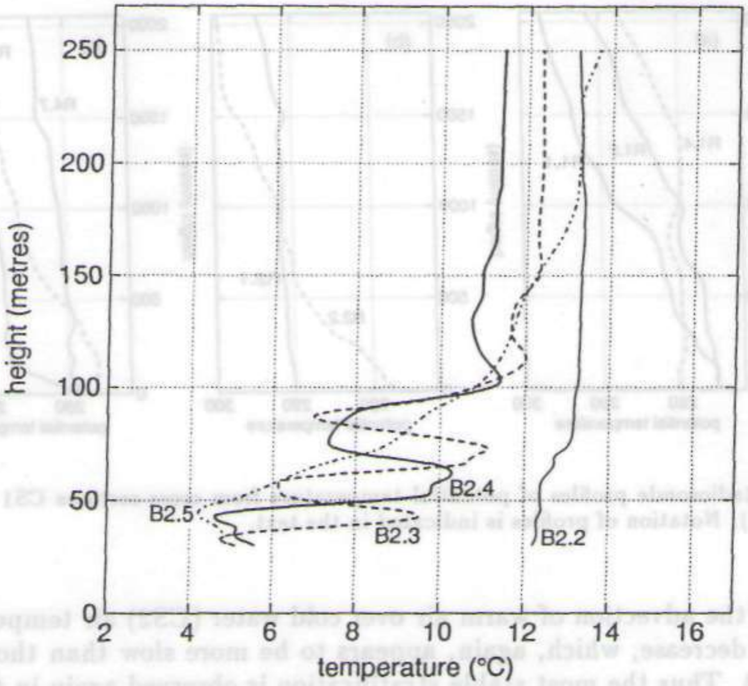

Fig. 4. Tethered balloon profiles of air temperature in the lower part of the atmospheric boundary layer. Notation of profiles is indicated in the text.

relatively cold water with temperatures about 5-6°C. The reason for that is very cold air with significantly negative temperatures, coming from the North-west. All profiles, carried out under north-west advection indicate the influence of the SST front thorough the whole boundary layer up to the height of about 2000-3000 meters.

Figure 3b shows two radiosonde profiles of potential temperature for the cross-section CS2. Figure 4 displays tethered balloon profiles, taken between two of those radiosondes. Advection of warm air to the cold water is associated with strong advective fog, which appeared just behind the frontal zone. Balloon profiles show strong instability in the lower atmosphere. Typical scales of thermal inhomogeneities are from 3°C to 6°C degrees and from 15 to 30 meters. The distance between B2.2 and B2.5 is about 50 kilometers. It is interesting to note, that considerable cooling of the atmospheric boundary layer takes place only in the lower several hundred meters. Already at a height of 1 km, profile R2.2 indicates significant heating of the air due to condensation.

## 4 Summary and conclusions

To summarize the described experimental results we can say that mid-latitudinal SST fronts play a really important role in the ocean-atmosphere interaction on

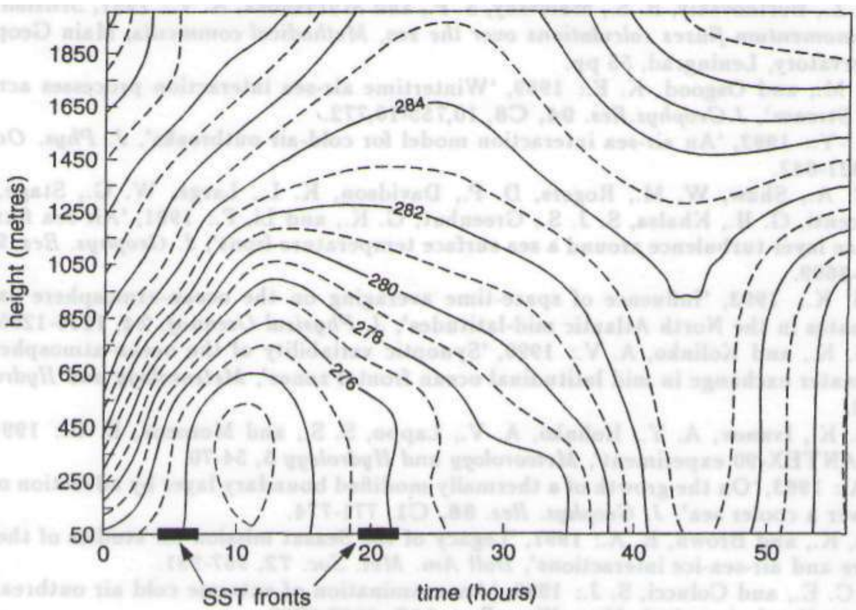

Fig. 5. Distribution of potential temperature for the cross-section CS3.

synoptic and sub-synoptic scales. Because the Gulf Stream SST front in the North Atlantic mid-latitudes is associated with the North Atlantic storm track, cyclones permanently exist and develop in the vicinity of the frontal zone. Thus one can expect even large-scale manifestations of the obtained effects in climatological heat flux fields. Some efforts, taken in this direction (Gulev and Kolinko, 1990) give evidence of the relationships between the location of SST fronts and surface flux maxima. On the synoptic scale it is possible to parameterize this effect in terms of variables (for example SST and sea level pressure) that are easily available from global weather services. SST can indicate the location of frontal zones and transfrontal gradients. Sea level pressure gives information about wind speed and wind direction. The vector product of two vectors, which can be computed from atmospheric pressure (geostrophic wind) and from SST fields (oceanic analog of thermal wind) gives appropriate characteristics of heat fluxes in the vicinity of frontal zones. Details of this parameterization can be found in Gulev and Kolinko (1990).

Another possible line of future investigations is connected with 1D and 2D modelling of the atmospheric boundary layer over mid-latitudinal frontal zones in order to study the significance of different physical processes for the transformation of the atmospheric boundary layer. Some studies, referred to in the introduction, give evidence of success of such kinds of research.

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