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SHORT COMMUNICATION

Thin chlorophyll layer concomitant of the thermohaline intrusion in the confluence of the Gulf Stream and Labrador Current (a case study)

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Summary Based on the depth-cycling data of a fluorometer probe in the northwestern Atlantic ocean, this paper considers features of the chlorophyll fluorescence layer against a background of concurrent variability of seawater temperature and fluorescence of CDOM (Colored Dissolved Organic Matter). The vertical distributions of chlorophyll fluorescence complied with the criteria of a thin chlorophyll layer at the site where changes of temperature and CDOM fluorescence were indicative of the intrusion of Labrador waters into adjacent warmer waters below the upper mixed layer. As may be supposed, the thin chlorophyll layer was due to the gyrotactic trapping of phytoplankton cells induced by water shear between the upper mixed layer and the intrusion.

This presentation is based on observations accomplished in September 1991 in the northwestern Atlantic ocean (the 23rd cruise of the r/v *Vityaz*, Shirshov Institute of Oceanology (SIO), USSR Academy of Sciences). In brief, the use of a fluorometer probe resulted in evidence of a thin chlorophyll layer away from coastal zone and shallows. Nothing of this kind was observable during two previous decades of fluorimetric measurements carried out by the author in the oceans. For a number of circumstances, the thin layer results of the *Vityaz* cruise remained unpublished. Recent researches on thin chlorophyll layers in the marine environment (Durham and Stocker, 2012) suggest examining the abandoned data in the context of present-day achievements and difficulties.

The airborne laser lidars show a capacity for detecting subsurface thin layers of particles in aquatic areas spanning hundreds of miles (Churnside and Donaghay, 2009; Vasilkov

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et al., 2001). However, such sensors are unable to discriminate mineral and living (chlorophyll-bearing) particles in the backscattered light or to take advantage of red chlorophyll fluorescence from subsurface clouds of phytoplankton because pure water severely attenuates the red light (Jerlov, 1976). The advent of submersible fluorimeters and other optical instruments in the seventies—eighties of the 20th century facilitated obtaining high-resolution vertical profiles of chlorophyll concentration and resulted in the discovery of thin layers of phytoplankton mainly in coastal and shelf waters (Dekshenieks et al., 2001; Durham et al., 2009; Sullivan et al., 2010).

Impressive results regarding thin layers of chlorophyll in a coastal environment were obtained with the help of moored autonomous profilers (Sullivan et al., 2010) but this approach is difficult to implement in offshore regions. The Bio-Argo-buoys may be useful for obtaining a general idea of thin layer occurrence. However, being uncontrollable after start up, these buoys are unsuitable for monitoring the evolution of a thin layer of moderate extent. The underwater gliders (Rudnick et al., 2004) are much more flexible owing to their suitability to be operated as a fleet of gliders (Bhatta et al., 2005). A glider travel speed makes up 40—45 cm/s (Rudnick et al., 2004) and is comparable to or lower than a flow speed typical of chlorophyll-bearing subsurface waters. Therefore, a single glider does not allow us to distinguish spatial changes of a mesoscale structure from its variations in time. Among others, such structures involve the thermohaline intrusions of roughly 10—15 km in extent and about 10 h in residence time (Schmitt, 1994). The present communication aims to demonstrate the suitability of a ship-borne submersible fluorometer probe for studying thin chlorophyll layers associated with the intrusions common in large-scale thermohaline fronts.

The submersible fluorometer MZF (transliterated Russian capital letters for Marine Fluorometer Probe) is a ship-borne probe for recording the vertical profiles of four quantities from zero to the 250 m depth and transmitting respective signals via armored cable into the laboratory data processing unit (Karabashev and Khanaev, 1988). These quantities are the hydrostatic pressure as a measure of submersion depth z, seawater temperature T°C, the intensity of fluorescence of CDOM (Colored Dissolved Organic Matter) F_{CDOM}, and the intensity of chlorophyll fluorescence F_{chl}. Both fluorescences are excited with light pulses of a xenon flash lamp in separate seawater volumes outside the housing of a submersible module. Light traps protect these volumes from ambient light. Their design allows filling them with standard samples for on-deck calibration of F_{chl} channel in units of chlorophyll concentration. The CDOM fluorescence is excited in the near UV spectral range and recorded in the blue-green window. The chlorophyll fluorescence is excited in the blue and recorded in the red where the peak of F_{chl} belongs.

The rate of data acquisition is 8 Hz. The signals of T°C, F_{CDOM}, F_{chl}, and z are digitized and transmitted to the laboratory module. Successful operation of the MZF probe in the SIO RAS field missions in 1984—1987 demonstrated its reliability. Depending on the signal level, the accuracy of optical signal estimates is 5—10%. The resolution of the temperature channel is 0.03°C in the range from zero to 33°C. The resolution of the depth channel is 0.25 m from zero to 250 m depth.

Fig. 1 displays the localization of cruise stations 3579, 3581, 3587, and 3588 in reference to main currents and

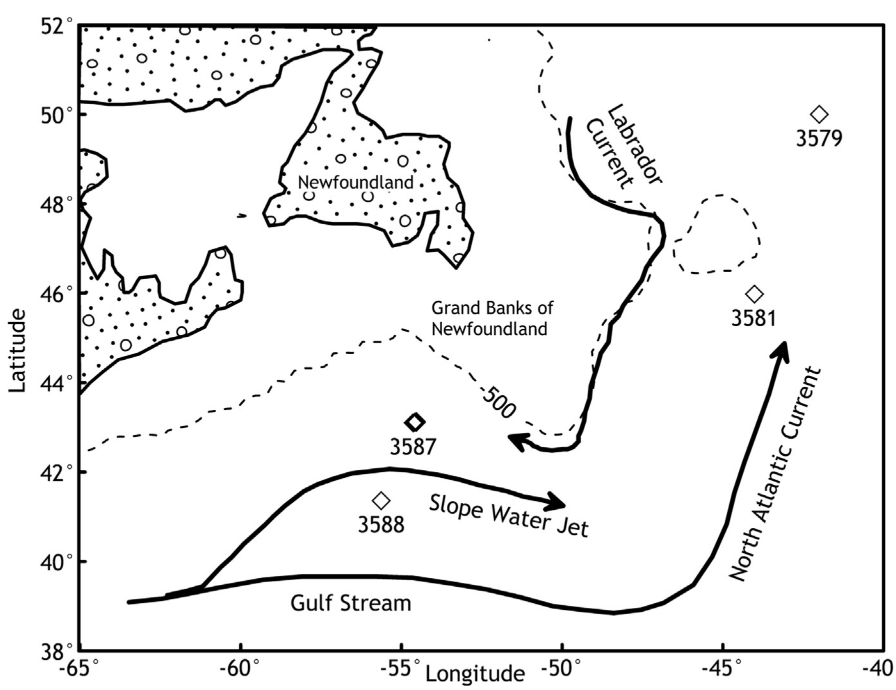

Figure 1 Coordinates, date, and initial local time of stations 3579 (42.00°W, 49.98°N, 09/08/1991, 15:22), 3581 (43.98°W, 45.96°N, 09/09/1991, 11:14), 3587 (54.53°W, 43.05°N, 09/18/1991, 00:25), and 3588 (55.61°W, 41.34°N), 09/18/1991, 15:22) occupied with the MZF fluorometer during the 23rd cruise of r/v *Vityaz* in the NW Atlantic Ocean. The pathways of the Gulf Stream, North Atlantic Current, Slope Water Jet, and Labrador Current are adapted from Pickart et al. (1999). Depth contours 0 m (solid) and 500 m (dashed) are plotted from the bathymetry gridded with the help of GEBCO Grid Demonstrator (https://www.bodc.ac.uk/).

continental slope (500 m isobath as dashed contour). When *Vityaz* arrived at scheduled station 3587 on the evening of September 17, 1991, the wind enhanced up to 18 m/s, and the MZF probe proved to be the only instrument suitable for on-deck activity without breaking the safety rules. This opened the way to a depth cycling in the upper 250 m thick layer by means of the MZF probe during nighttime. The following considerations justified this activity.

(i) Station 3587 located in the Gulf Stream and Labrador Current confluence between the shelf-break and the Slope Water Jet (Fig. 1). This is an appropriate place for monitoring the impact of water dynamics on the distribution of natural seawater admixtures.
(ii) The MZF channel of chlorophyll fluorescence has been calibrated in units of chlorophyll concentration C_{chl} [mg/m^3] based on water samples taken concurrently with the MZF casts at the earlier station of the same cruise. The linear dependence of F_{chl} upon C_{chl} has been found at $R^2 > 0.9$.
(iii) Night time is optimal for determinations of chlorophyll with a submersible fluorometer because specific fluorescence of chlorophyll in living phytoplankton cells is unaffected by sunlight at night (Karabashev, 1987). Elimination of probable sunlight impact on the chlorophyll fluorescence is desirable when using depth-dependence of chlorophyll fluorescence F_{chl} as a proxy for the vertical distribution of chlorophyll in the water.
(iv) Fast vessel's drift of wind as strong as 18 m/s promised high spatial resolution of observations by means of the MZF depth-cycling for several hours.

Operations at station 3587 took place on September 18 and involved four series of seven MZF casts each. Their timing and results are given in Fig. 2. The following findings merit attention.

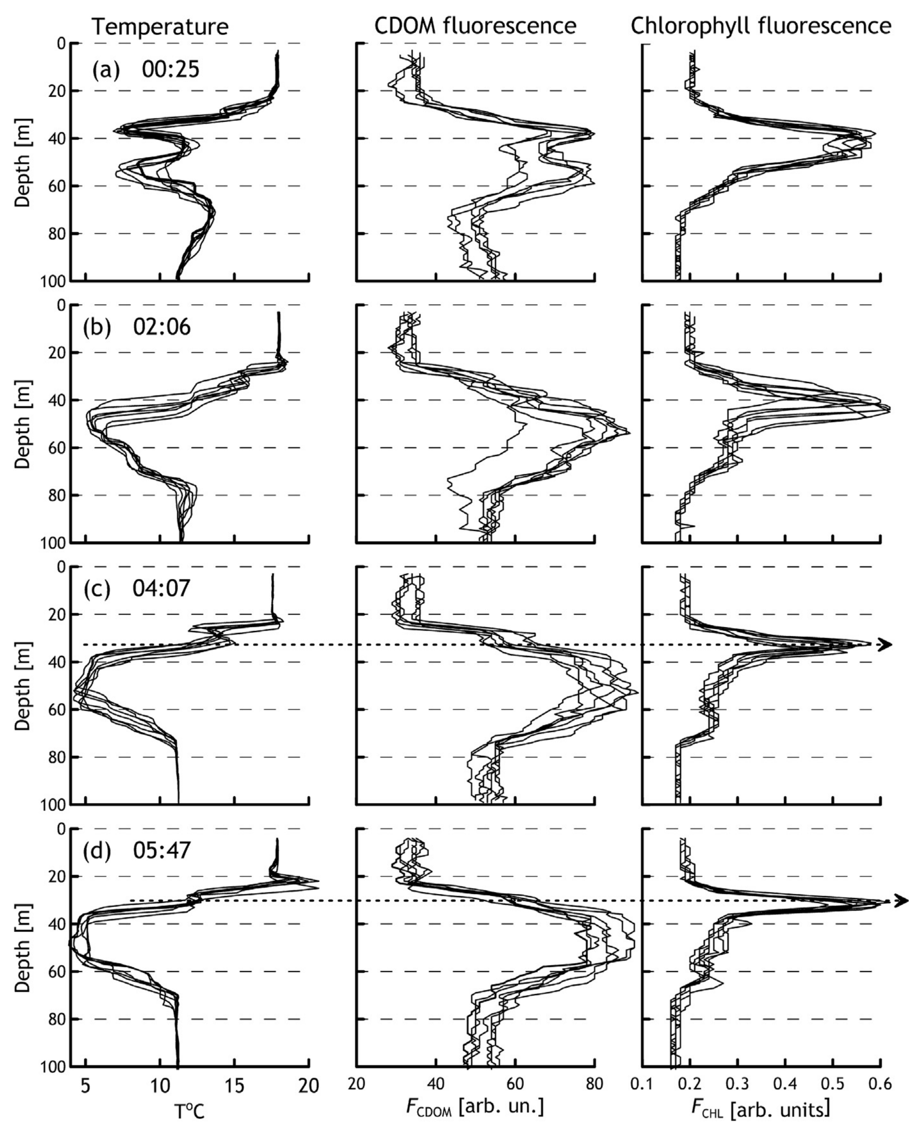

Figure 2 The results of using the MZF fluorometer at station 3587 on September 18, 1991, in the depth-cycling mode for concurrently recording seawater temperature T°C, the CDOM fluorescence intensity F_{CDOM}, and chlorophyll fluorescence intensity F_{chl}. The cycling series (a)—(d) took roughly 20—25 min each and started at 00:25, 02:06, 04:07, and 05:47 local time.

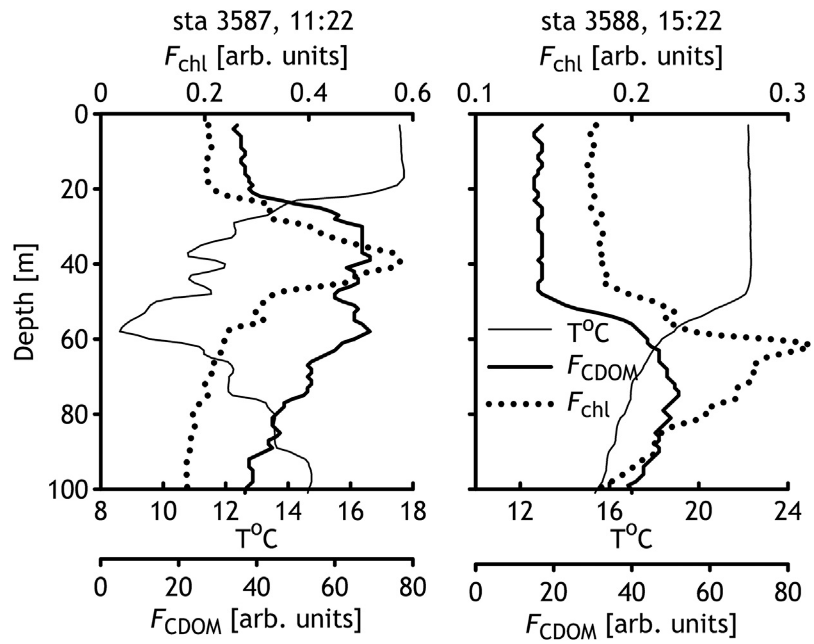

Figure 3 Profiles of T°C, F_{CDOM}, and F_{chl} recorded with the MZF fluorometer on September 18, 1991, at stations 3587 (11:22) and 3588 (15:22).

(a) The profiles of every quantity exhibited specific shapes. They changed from one series to another and remained hardly distinguishable within individual series.
(b) A strong inverse correlation was inherent to the vertical distributions of T°C and F_{CDOM}.
(c) The temperature minima and CDOM fluorescence maxima enhanced from series to series. The F_{chl} maxima decreased in the half-width and increased in amplitude. They occurred at the same depth that remained shallower in reference to the extrema of T°C and F_{CDOM}.

These changes took place against a background of unsteady wind. It was permanent in the direction from west to east, but changed in strength. The wind speed dropped from 18 m/s during the first series to 5—6 m/s during the fourth one. As a result, the lengths of depth-cycling tracks made up 3.1, 1.5, 1.1, and 0.8 km from the first series to the last one and the whole drift of the vessel was 12—15 km long.

Wind easing in the morning of September 18 allowed resuming the works in the scheduled section at 55°W, and *Vityaz* returned to the site of the first profiling series at station 3587 (stations 3587 and 3588 in Fig. 1 indicate the northern part of this section). Fig. 3 displays the profiles of F_{chl}, F_{CDOM}, and T°C recorded at station 3587 where the first MZF series has been started 11 h earlier. It is evident that the general view of vertical distributions of F_{chl}, F_{CDOM}, and T°C remained the same, but later profiles exhibited larger half-widths as compared to the earlier ones. Fifty miles south of station 3587, the distributions of the same quantities have radically changed in thickness of the upper mixed layer and shape of vertical distributions of F_{chl}, F_{CDOM}, and T°C (Fig. 3, station 3588).

It is remarkable that the shapes of F_{chl}, F_{CDOM}, and T°C profiles at earlier stations (Fig. 4 and Fig. 5 at 11:32) were similar to those at station 3587 in Fig. 3.

By now, there is solid evidence that (1) high-latitude waters are more abundant in refractory CDOM as compared to waters of moderate latitudes and (2) the CDOM is a tracer of ocean interior mixing (Nelson et al., 2010). The map of the climatology of surface water CDOM shows a fast decrease of this tracer from north to south exactly where above stations of the *Vityaz* cruise belong (Fig. 1 in Nelson et al. (2010)). These and earlier findings (Kalle, 1963; Karabashev and

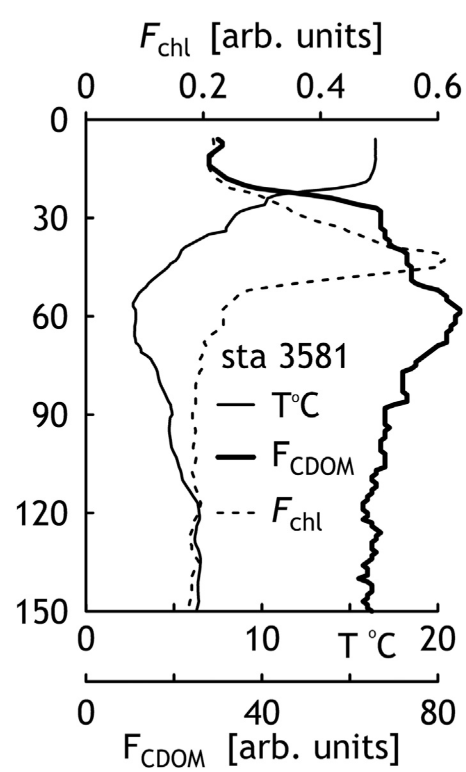

Figure 4 Profiles of T°C, F_{CDOM}, and F_{chl} recorded on September 9, 1991, at station 3581 (11:22).

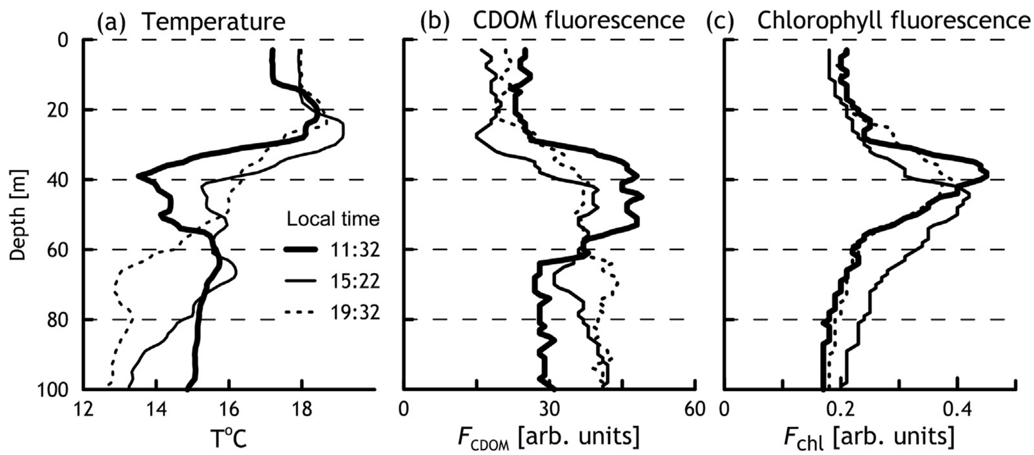

Figure 5 Profiles of T°C (a), F_{CDOM} (b), and F_{chl} (c) recorded on September 8, 1991, at station 3579 (11:32, 15:22, and 19:32 local time).

Solov'yov, 1973) justify the use of CDOM fluorescence as a universal conservative tracer of water exchange in the ocean thickness.

The seasonal variations of subsurface chlorophyll maximums in the northwestern Atlantic Ocean were investigated in Cox et al. (1982). They relied on determinations of this pigment performed from 1961 to 1977 to the west of 60°W in slope waters (484 samples at 67 stations) and in the northern Sargasso Sea (379 samples at 43 stations). The above profiles of chlorophyll fluorescence are consistent with the generalized vertical distributions of chlorophyll in depth and amplitude of early-autumn chlorophyll maximums (Fig. 1 and Fig. 2 in Cox et al. (1982)).

The area in Fig. 1 refers to a region known for the particular complexity of its water dynamics (Fratantoni, 2001). The flow arrows in this figure represent a pattern of local currents based on a generalization of observational data (Pickart et al., 1999) relevant to the period of the 23rd cruise of the r/v *Vityaz*. The hydro-physics team led by S.N. Shustenko observed a thermohaline front between stations 3587 and 3588 and revealed the intrusion-favorable thermohaline structure of waters in the vicinity of station 3581 and found that the North Atlantic Current bifurcated and turned eastwards in the vicinity of station 3579.

At station 3587, the vessel drifted in the direction 78°—90° toward the cold waters of the Labrador Current rich in CDOM. The latter agrees well with the shape of the profiles in Fig. 2: the temperature decreased and CDOM fluorescence increased from earlier depth-cycling series to the later ones in the layer between 20 m and 70 m depth levels. The vertical distributions of T°C and F_{CDOM} exhibited more intricate shapes and lower amplitudes during the first series as compared to the later one. This is expectable of a liquid medium inhomogeneity at the final stage of its disintegration. The shape and features of T°C and F_{CDOM} profiles behaved as if they were shaped by an intrusion of the Labrador Current waters into the local warmer waters. The depth of the chlorophyll maximum remained unchanged throughout the drift, but the half-width of chlorophyll profile decreased noticeably with the approach to the source of the intrusion (depth-cycling series (c) and (d) in Fig. 2).

At a minimum distance from the presumed source of the intrusion, the F_{chl} maximum occurred at the depth of the thermocline ledge noticeable in the profiles of T°C and F_{CDOM} (dashed arrows in panels (c) and (d) in Fig. 2 designate the depth of ledge). Apparently, the ledge marks the junction of local profiles of temperature and CDOM fluorescence with profiles of the same characteristics in the intrusion of Labrador waters.

It is conventional to distinguish the deep chlorophyll maxima up to tens of meters thick and the thin layers (Durham and Stocker, 2012). Specific features of the thin layers: (i) they are reproducible when depth-cycling, (ii) their vertical extent is smaller than 5 m, (iii) maximal content of chlorophyll is at least thrice as large as its background concentration in water. Profiles of F_{chl} in panel (d) of Fig. 2 adequately satisfy criteria (i)—(iii). The average peak of these profiles measures 6.2 ± 0.5 m in half-width and is the largest in amplitude relative to those in panels (a)—(c). At that, the amplitudes of T°C minimum and F_{CDOM} maximum in panel (d) exceed their estimates in panels (a)—(c). These relations suggest that the distributions in panel (d) were obtained at the point, which was nearest to the source of the intrusion. Respectively, the profiles in panel (a) were obtained at the maximum distance from the same point where chlorophyll peak exhibited much larger half-width.

Durham and Stocker (2012) consider six mechanisms responsible for the origination of thin chlorophyll layers in areas where coastal and riverine waters interact with the ocean waters. The authors give emphasis to the fact that chlorophyll bearers are living particles able to aggregate contrary to the instability of water flows. One of the mechanisms is the intrusion proper when intruding waters are richer in phytoplankton in reference to local waters. Such is not the case for patterns in Fig. 2 because chlorophyll fluorescence maximum is shallower than the core of intrusion. The constancy of the depth and amplitude of chlorophyll maximum in Fig. 2 is contradictory to straining of a phytoplankton patch by differential advection over depth (mechanism (a) in Durham and Stocker (2012)).

In panels (c) and (d) in Fig. 2, the arrows mark the depth of the thin chlorophyll layer interfacing the subsurface mixed water thickness and the intrusion. There is a good probability of the largest water shear at a depth of contact of oppositely sensed flows. According to Durham and Stocker (2012), high fluid shear suppresses the vertical migration of motile phytoplankton to the extent that living particles turn out to be trapped in a thin layer (gyrotactic trapping). This scenario appears the most appropriate for explaining the patterns in Fig. 2.

Intrusion slowing is destructive for shear-driven layering of non-conservative chlorophyll-bearing cells. In contrast, the conservative water properties, the temperature and CDOM fluorescence alike, are much less sensitive to short-lived forcings of local significance. That is why intrusive shapes of T°C and F_{CDOM} profiles at station 3587 survive while an intrusion-induced thin layer of F_{chl} transforms into a broad unimodal distribution (Fig. 3). By analogy with the daytime patterns at station 3587, it may be assumed that co-existence of extrema of T°C and F_{CDOM} with a broad vertical profile of F_{chl} below the upper mixed layer (Fig. 4 and Fig. 5) is indicative of the final stages of thermohaline intrusions of Labrador waters in the study area. According to modeling results (Durham and Stocker, 2012), the residence time of a thin chlorophyll layer due to gyrotactic trapping may be more than 12 h long. This is consistent with time scales of the above changes of distributions of T°C, F_{CDOM}, and F_{chl}. In total, the foregoing estimates and patterns are consistent with the inference that fine-scale horizontal intrusions occur in water mass fronts at all latitudes and measure 5—100 m in vertical extent at a horizontal scale of order 10 km (Schmitt, 1994).

The thermohaline intrusions in the offshore ocean waters may be accompanied by chlorophyll layers only a few meters thick much like the thin phytoplankton layers associated with the coastal zone phenomena. Further studies are needed to obtain an adequate notion of thin chlorophyll layers induced by intrusions in the offshore thermohaline fronts. This information is difficult to be obtained from determinations of light scattering because inorganic particles are usually the main contributors into the seawater turbidity and exhibit much longer residence time in the subsurface waters of the offshore areas as compared to the chlorophyll in living phytoplankton cells.

It is obvious that the scarcity of information on chlorophyll behavior in the offshore thermohaline intrusions is due to their covertness and unpredictable occurrence. Therefore, the accumulation of such information is likely to occur due to improvised research during ship expeditions in the frontal zones of the ocean. Modest dimensions of the intrusions in offshore fronts and high precision of present-day marine guidance are favorable for mapping an intrusion by means of a ship-based CTD probe, completed with a fluorometer module and operated at the low-speed depth-cycling mode. It is highly desirable to accompany this activity with observations of the sub-mesoscale water dynamics combined with the determination of species composition and the state of local phytoplankton. This again counts in favor of the ship-based approach.

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