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SURFACE HEATING OF OIL SPILLS IN ICE CONDITIONS

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ABSTRACT
Measurements of oil spill temperature were performed on the drifting ice in the Barents Sea in the May of 2008 and 2009 during the research cruises of RV Lance. Oil spills were produced at the water surface inside the basins artificially produced in sea ice. In the experiment of 2008 the basin had ice bottom with through holes, while in 2009 the pool didn't have ice bottom. The effect of oil heating up to +6^{o}C was observed in 2008 experiment, while the oil temperature was about -1.6 C and similar to the sea water temperature in 2009 experiment. We consider observed effects in relation to oil heating by sun radiation in conditions when oil spill can be insulated from the oceanic heat due to the influence of ice bottom in the basin.

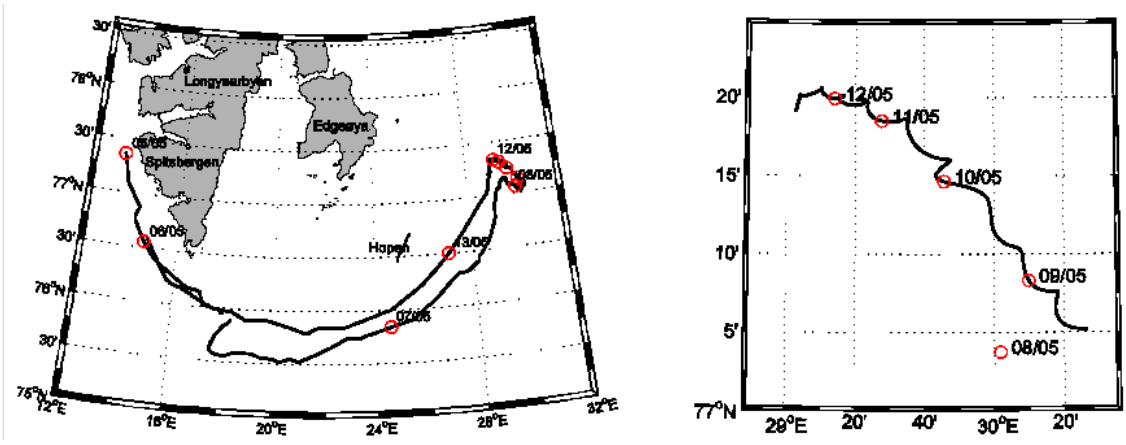
INTRODUCTION
A number of natural processes influence the change of chemical properties of crude oil when the oil is spilled at sea. Set of these natural processes called as a weathering includes evaporation, water-in-oil emulsification, oil-in-water dispersion, the release of oil components into the water column, spreading, sedimentation, oxidation and biodegradation. The effect of low temperatures on the rate and extend of oil weathering in ice covered waters was studied in Canada and Norway with focus on evaporation loss, water uptake, emulsion stability and viscosity variations. It was indicated that the time-dependent weathering can substantially slow down depending on ice type, ice coverage and energy conditions (Sørstrøm et al, 2010)

In solid ice conditions the oil spill behaviour depends on whether the oil has been spilled on or under the ice. When oil was spilled below the ice oil fractions with densities smaller sea water density can migrate through the ice and concentrate around the water level above liquid brine. The speed of migration depends on the ice permeability and liquid brine content which is depending on the ice salinity and temperature. The oil can be burned when it appears near the ice surface (Dickins, 2011). Penetration of oil in brine channels inside the ice can influence the increase of melting rate due to the absorption of sun radiation. The influence of coal particles on the melting rate of sea ice was investigated in the Van Mijen Fjord in Spitsbergen (Bogorodskiy et al, 2014). It was discovered that the coal concentration of ice cores correlates with their salinity. Oil droplets also become additional absorbents and attenuators in seawater causing changes in apparent optical properties (Rudz et al, 2013).

In the present paper the in-situ experiments on the measurement of surface temperature of crude oil spilled in the water basins cut off in the drifting ice are discussed. The results of measurements are used to estimate the coefficient of absorption of the oil layer at the water surface.

EXPERIMENTAL SETUP

In-situ experiments for the study of oils spills in ice environment were performed during the cruises of the research vessel Lance in 2008 and 2009 in the North-West Barents Sea. The filed works were supported by UNIS budget for the courses AT-321 Fate and Modelling of Arctic Pollutants and AT-208 Thermo-mechanical properties of materials. During the cruises the Lance was moored to the drifting ice in approximately 100 km to the North-East from the Hopen Island for 4-5 days. The Lance drift was extended from May 8 to May 12 in 2008 and from May 1 to 3 in 2009. The Lance track and drift in 2008 are shown in Fig. 1. Field works on the drifting ice included experiment with oil spill spread in a water basin made in drifting ice, ice strength tests, morphological investigation of ice ridges, and oceanographic measurements in ice adjacent boundary layer.
In order to imitate an oil release in the ice conditions 10 m² basins were cut out in the ice floes. In 2008 the floe thickness reached 1.5 m, and the basin depth was 0.6 m. Several holes were drilled through the basin bottom to fill it by sea water. After that 100 litters of Statfjord blend were released on the water surface in the basin. The oil spill was systematically tested for the chemical content and viscosity during the field works, then it was collected in plastic bags and the rest of the oil was burned in the basin. Similar experiment was repeated in 2009 on the floe of 0.4m thickness. The difference was that the basin was cut through the ice and didn't have an ice bottom.



a) b)

Figure 1. The track of RV Lance in the Barents Sea on May 5-15, 2008 (a), and the trajectory of the Lance drift on May 8-12, 2008 (b).

In parallel with chemical experiments temperature and pressure recorder SBE-39 was used to measure vertical profiles of the temperature in the water and oil in the basin and for the monitoring of the temperature in the surface layer of the basin with high concentration of the oil. According to the User Manual provided by Sea Bird Electronics, Inc., the SBE-39 measures temperature with accuracy of 0.002^{o} C and resolution 0.0001^{o} C, and pressure with accuracy of 0.1% and resolution of 0.002% from full scale range 20 m.

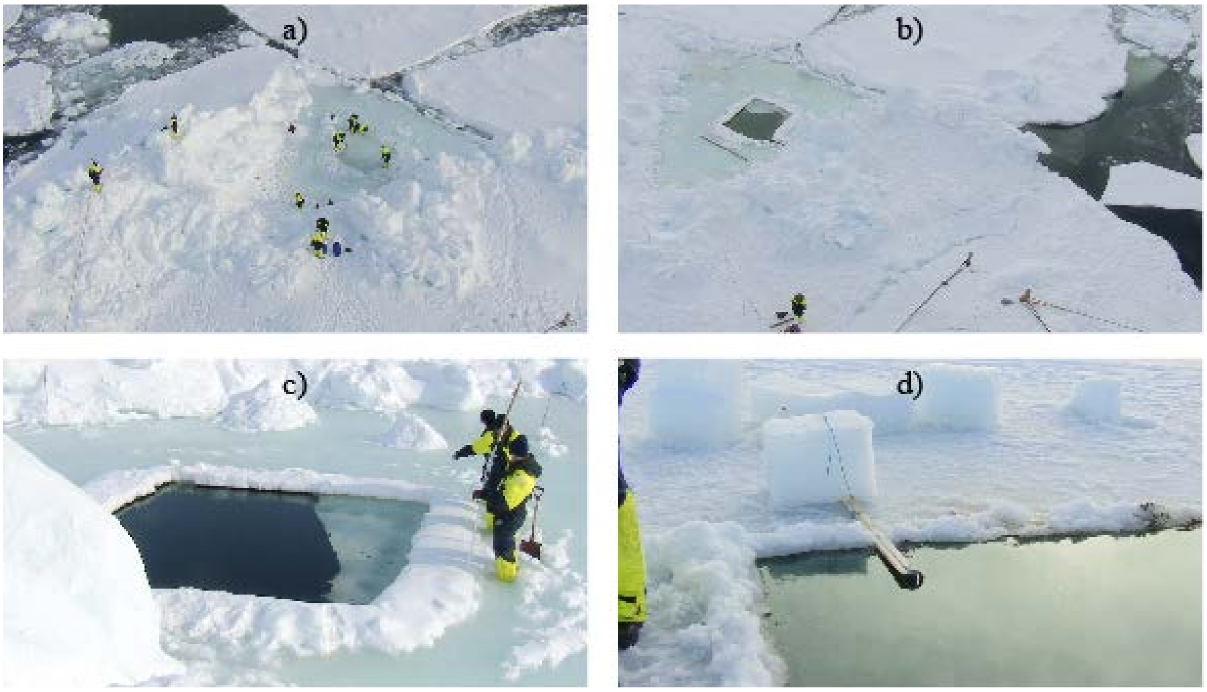


Figure 2. Location of water basin on the floe (a), water basin field with oil (b,c), mounting of the recorder SBE-39 at the edge of the water basin (d).

The recorder was mounted on the wooden boards fixed in the horizontal position at the edge of the basin as it is shown in Fig. 3a in 2008 and Fig. 9a in 2009. The locations of the temperature probe and the pressure sensor on the hull of SBE-39 are shown in Fig. 3b. The length of SBE-39 is 291.6 mm and the diameter is 48.2 mm. The sampling frequency 1 Hz was used in the experiments.

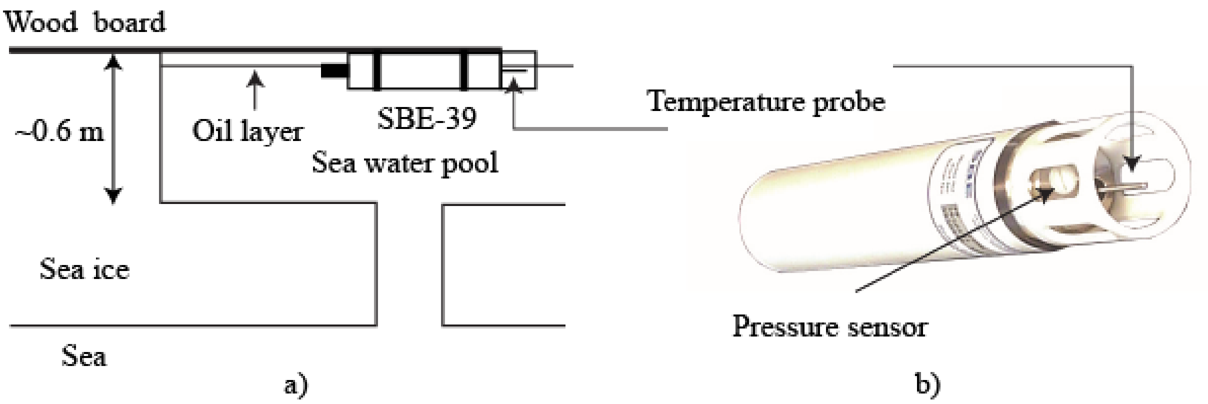


Figure 3. Scheme of the mounting of SBE-39 at the edge of the water basin on May 11-12, 2008 (a). Locations of the temperature probe and pressure sensor on the top cap of SBE-39 (b).

RESULTS OF MEASUREMENTS

Vertical profiles of the temperature measured with SBE-39 recorder on 14:00, 17:00 and 19:00 of UTC time on May 11, 2008, are shown in Fig. 4a. The recorder was moved gradually in vertical directions through the water and oil layer. Records of the pressure sensor show locations of the temperature measurements. The temperature within 30 cm near the bottom of the pool is similar to the sea water freezing point. The temperature within surface layer with thickness of 5 cm is much higher. Maximal temperature in the middle of the surface layer exceeded 5°C. Temperature at the surface of the layer is dropped to -1°C. Scheme of the vertical temperature profile is shown in Fig. 4b. One can see the layer with high temperature gradient between depths 5 cm and 30 cm. Temperature gradients are estimated as 250°C/m at the oil surface and 50°C/m at the depth 10 cm.

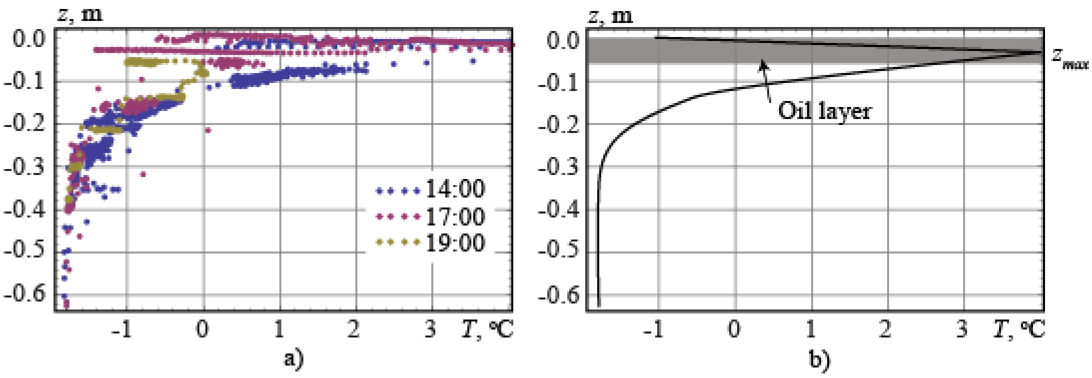


Figure 4. Vertical temperature profiles measured in the water basin on May 11, 2008 (a). Scheme of the vertical temperature profile in the water basin with ice bottom and oil layer at the surface (b).

Blue line in Fig. 5a shows the temperature of surface layer with high oil concentration versus the time measured from 00:00 to 10:40 of UTC time on May 12, 2008. Purple line in the same figure shows the air temperature registered by the meteorological station on the Lance board. One can see that the air temperature varied between -4°C and -6 °C, while the oil temperature was around the water freezing point during night time, begin to rise up around 04:00 and reached +6°C around 10:40. Photographs from the Web camera installed on the Lance bridge demonstrate that the oil temperature increase could be associated with the influence of sun radiation (Fig. 6). Brightness of image in Fig. 6b made on 04:00 is much higher than brightness of image in Fig. 6a because of the sun light.

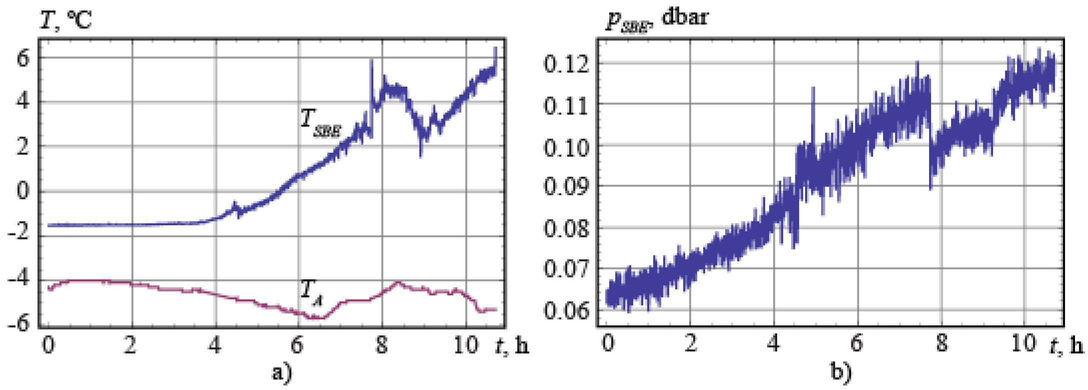


Figure 5. Air temperature and the temperature recorded by SBE-39 (a), the pressure recorded by the SBE-39 (b) on May 12, 2008.

Records of the pressure sensor show the gradual pressure increase associated with the increase of the atmosphere pressure on 6 hPa over 10 hours. Sudden pressure drop between 07:30 and 08:00 can be explained by small displacement of the wood board. Figure 7 shows fluctuations of the pressure and the temperature recorded by SBE-39 recorder in the surface layer. The fluctuations are explained by the influence of swell on the water level in the basin. Figure 8 demonstrating the fluctuations with high resolution around 04:00 and 06:00 shows that the swell period was around 11 s. Figure 7 shows that the amplitude of the pressure fluctuations was around 5 mm during the period of the measurements. Figure 7b shows that the amplitudes of the temperature fluctuations increses after 04:00, and reaches 0.3^{o}C around 10:00. Since SBE-39 recorder was fixed relatively the ice the pressure fluctuations could be explained by the variations of water and oil levels in the pool due to incoming swell. This observation gives possibility to calculate vertical gradient of the oil temperature from the measurements. It is estimated as a ratio of the amplitides of the temperature and pressure fluctuations, i.e. it is about 60^o C/m.

Measurements of the temperature in the basin made from 14:40 of May 2 to 11:20 of UTC time on May 3 in 2009 show that the surface temperature was similar to the water temperature in the sea (Fig. 8b). The air temperature and sun radiation had insignificant effect on the oil temperature in the basin.

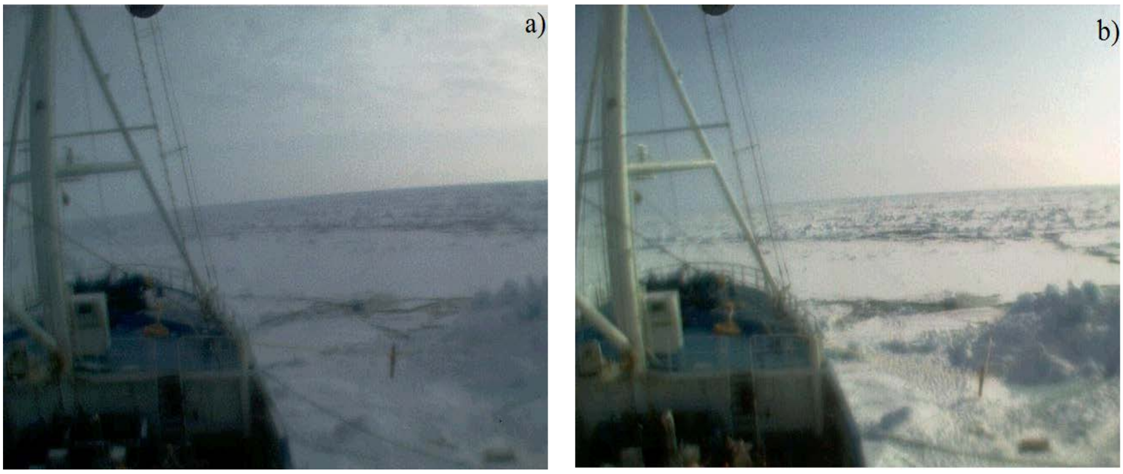


Figure 6. Photographs made by the Lance web camera on 04:00 (a) and 06:00 (b) of UTC time on May 12, 2008.

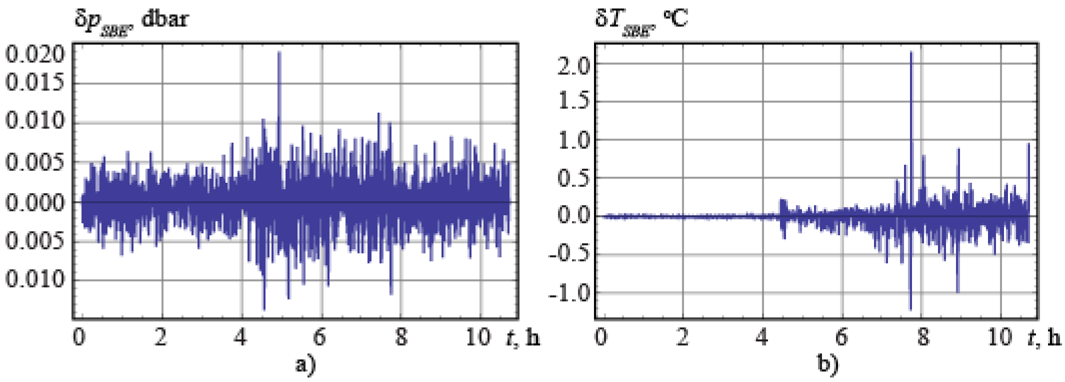


Figure 7. Fluctuations of the pressure (a) and the temperature (b) measured by SBE-39.

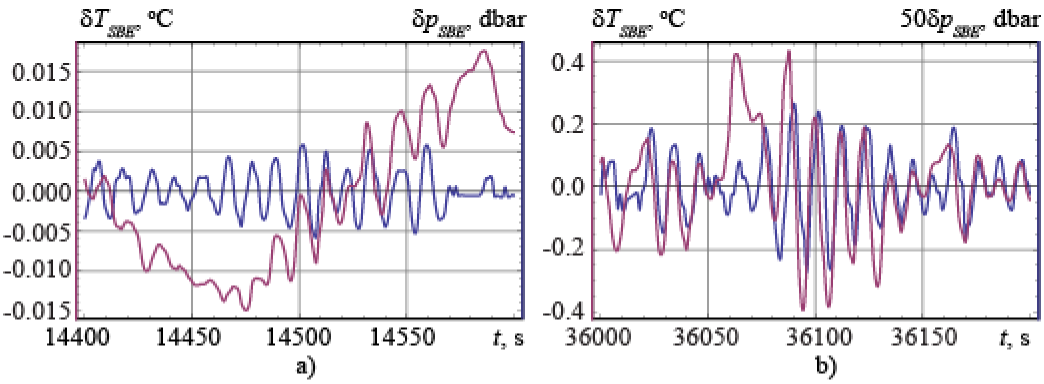


Figure 8. Temperature (purple lines) and pressure (blue lines) fluctuations calculated from the records of SBE-39 around 04:00 (a) and 06:00 (b) of UTC time on May 12, 2008.

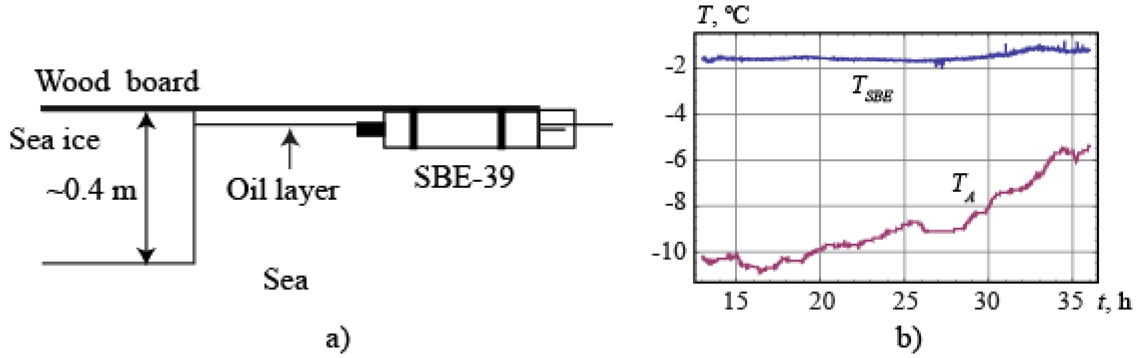


Figure 9. Scheme of the mounting of SBE-39 at the edge of the water basin (a). Air temperature and the temperature recorded by SBE-39 (b). May 2-3, 2009.

ESTIMATES OF THE ABSORPTION COEFFICIENT

The schemes of energy fluxes to the oil layer at the water surface in the basin in the experiments performed in 2008 and 2009 are shown respectively in Fig. 10a and Fig. 10b. The energy balance in the oil layer is expressed by the formula

$$\rho_{oil} c_{oil} h \frac{dT}{dt} = R + HF_A + HF_w, \qquad (1)$$

where t is the time, ρ_{oil}, c_{oil}, h, and T are the density, the specific heat capacity, the thickness and the temperature of the oil layer at the water surface, R is the flux of solar radiation, HF_A and HF_w are the fluxes of sensible heat to the atmosphere and into the water.

The radiation and heat fluxes are determined by the formulas

$$R = (1-\alpha) Q_{sol} \left(1 - e^{-\kappa h}\right), \quad HF_A = k_{oil} \left.\frac{\partial T}{\partial z}\right|_{z=0}, \quad HF_w = -k_w \left.\frac{\partial T}{\partial z}\right|_{z=-10\text{cm}}, \qquad (2)$$

where α is the surface albedo, Q_{sol} is the flux of solar radiation, κ is the absorption coefficient of the oil layer, k_{oil} and k_w are the thermal conductivities of the oil and the water.

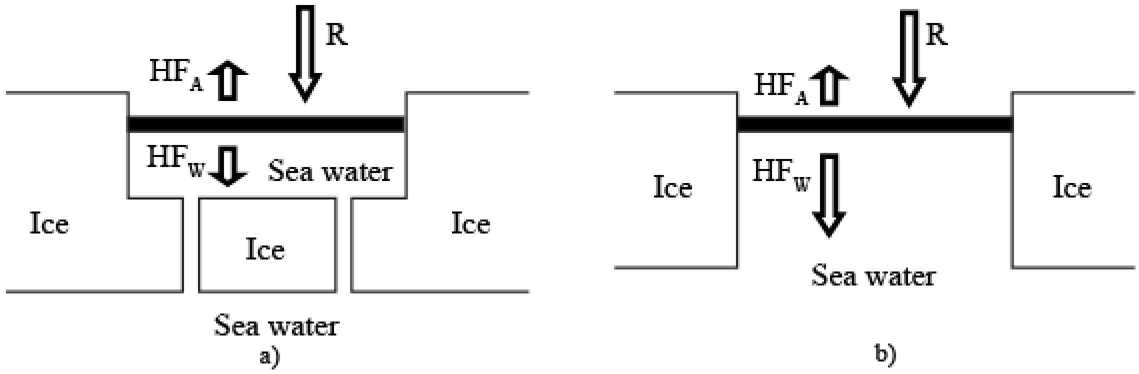


Figure 10. Scheme of the energy fluxes in the experiments in 2008 (a) and (2009).

The flux of solar radiation is calculated by the formula (see, e.g., Zillman, 1972)

$$Q_{sol} = \frac{S\cos^2 Z(1-0.52C)}{(\cos Z + 27) re(T_A)/p_A + 1.085\cos Z + 0.1}, \quad (3)$$

where S=1370 W/m^2 is the solar constant, $C \in (0,1)$ is a part of sky covered by clouds, **S** is solar zenith angle, $e(T)$ is the vapor pressure, r is the relative humidity and p_A is the atmosphere pressure. Daytime value of solar radiation flux with C=0 in the beginning of May at the latitude 77^{o}N is estimated around 115 W/m^2.

From formulas (1) and (2) follows

$$\kappa h = -\ln\left[1 - \frac{\rho_{oil} c_{oil} h dT/dt - HF_A - HF_w}{(1-\alpha)Q_{sol}}\right]. \quad (4)$$

Numerical estimates of the absorption coefficient κ are performed with the following numerical values corresponding to 10:00 of UTC time or 12:00 of the local time in Svalbard

$$\rho_{oil} = 800\ \text{kg/m}^3,\ c_{oil} = 1.7\ \text{kJ/kg}\cdot\text{C},\ h = 1\ \text{cm},\ k_{oil} = 0.1\ \text{W/m}\cdot\text{C},\ k_w = 0.6\ \text{W/m}\cdot\text{C}, \quad (5)$$
$$\left.\frac{\partial T}{\partial z}\right|_{z=0} = -250\ ^\circ\text{C/m},\ \left.\frac{\partial T}{\partial z}\right|_{z=-10cm} = 50\ ^\circ\text{C/m},\ HF_A + HF_w = -55\ \text{W/m}^2,\ \frac{dT}{dt} = 2\ ^\circ\text{C/h}.$$

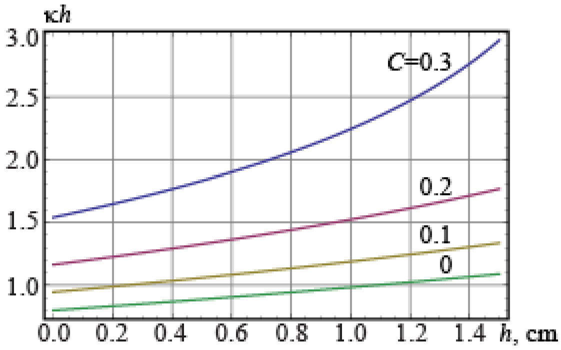


Figure 11. Normalized coefficient of absorption versus the oil layer thickness calculated with different values of the cloudiness.

Measurements performed with BWTek spectrometer shown that surface albedo of the crude oil is practically 0. Figure 11 shows the dependence of the normalized coefficient of absorption κh from the oil layer thickness h calculated from formula (4) with different values of the cloudiness C and with the surface albedo α=0. Mean value of κh is estimated around 1.5 and $\kappa \approx 1.5$ cm^{-1} when h=1 cm. This value is much higher the absorption coefficients of oil polluted waters varying within 0.1-5 m^{-1} (Rudz et al, 2013).

The specific coefficient of absorption is estimated with the formula

$$Kch = \lg\left(e^{\kappa h}\right), \tag{6}$$

where c is the concentration of the oil in the water measured in g/l. Assuming that $c=\rho_{oil}$, h=1 cm and κh=1.5 we find $K\cdot 1000$=0.8 g/l·cm. This value is much lower than the absorption coefficients of oils measured in the laboratory condition on wave length 500 nm ($K\cdot 1000$>6 g/l·cm) (Antipenko and Lukyanov, 2009).

CONCLUSIONS

Oil spills spread on the ice surface can be heated by incoming solar radiation up to high temperature above +5^{o}C even if the air temperature is around -5 ^{o}C. The ice takes a role of insulation of oil spills from the oceanic heat flux in this process. The ice should melt below the oil spills much faster than when it is covered by snow or melt water.

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