# SMALL-SCALE LABORATORY EXPERIMENTS ON BURNING CRUDE OIL IN ICE MELT POOLS

Scientific Report from DCE – Danish Centre for Environment and Energy No. 514 2022

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Abstract: Responding to an oil spill in high-Arctic marine ice-infested waters is extremely challenging. In situ burning (ISB) of oil spills is recognised as an effective oil removal method for oil spills in both open and ice-infested waters. The aim of this project was to increase the knowledge base for combatting oil spills in ice-infested waters by ISB. The project included small-scale laboratory burns of oil released from ice designed to imitate a spring melt pool situation. The results suggested that the diameter of the brine channels as well as the hydrostatic pressure of the oil are the driving mechanisms for oil migrating from the reservoir to the oil pool. In addition, the results indicated that the heat from the burn was used to melt ice rather than burn oil. It is recommended to undertake larger-scale experiments with more replicates to be able to conclude on the different results from the experiment

Keywords: High-Arctic, Oil, In-situ burning, Oil Spill Response, Ice, Greenland

Front page photo: Cross section of an ice block with the melt pool at the top, the oil in ice reservoir at the bottom and the connecting channel. J. Fritt-Rasmussen

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# Contents

# Preface

This report describes the results of small-scale laboratory experiments on burning crude oil in ice. The study is part of the *Strategic Environmental Study Program for Northeast Greenland* and specifically included in the research theme: “In situ burning (ISB) of oil spills in high-Arctic ice-infested water”.

The *Strategic Environmental Study Program for Northeast Greenland* was funded by Environment Agency for the Mineral Resources Activities (EAMRA), Greenland Government. The DCE study program on environment and raw material extraction in Greenland was supported by the Ministry of Environment of Denmark.

The study was carried out as a collaboration between Aarhus University (AU), DCE – Danish Centre for Environment and Energy and SINTEF Narvik.

# Sammenfatning

Det er meget vanskeligt at bekæmpe marine oliespild i højarktiske, isdækkede farvande. Afbrænding af olie på vandoverfladen (in situ burning, ISB) vurderes som en effektiv metode, og tilstedeværelsen af is kan bidrage til at begrænse nedbrydning af olien og også til at holde olien indespærret i et tykt lag på havoverfladen, der kan antændes. ISB betragtes derfor som en lovende bekæmpelsesmetode under arktiske forhold. Sker der et oliespild under havis samtidig med dannelse af havis, kan der også ske en indefrysning af olie i havisen. Når isen smelter, vil olie bevæge sig gennem små kanaler i isen (brine channels) til overfladen af isen og lægge sig oven på vand i smeltevandspytter, hvor den vil kunne antændes.

Formålet med nærværende studie var at undersøge – i lille skala – hvilke faktorer der er væsentlige for, at olie indesluttet i is kan transporteres til isens overflade, hvor den afbrændes. Derved øges vidensgrundlaget for bekæmpelse af olieudslip i isfyldte farvande.

Projektet omfattede laboratorieforsøg med afbrænding af olie frigivet fra is. Under frysning vokser isen nedad og kan indkapsle olie, der ligger under isen (NORCOR 1975; Faksness 2008; Nelson 1982). Olie akkumuleret under isen har tendens til at bevæge sig opad i isen om vinteren på grund af tæthedsmedieret migration og fremstår uforvitret ved overfladen. Migrationen sker gennem saltvandskanalerne i isen.

Forsøgsopsætningen var designet til at efterligne en forårsafsmeltningssituation, hvor olie, der er fanget i isen, frigives til smeltebassiner, hvor den efterfølgende kan brændes. Opstillingen bestod af en isblok med en fordybning / hulrum i toppen (smeltebassinet), en forbindelseskanal (brine channel) og et oliereservoir i isen.

Formålet var at studere mekanismerne for afbrænding af olie i et smeltebassin på isen, som stadig er forbundet med tilbageværende olie i isen. Vi havde som hypotese, at varmen fra afbrændingen ville resultere i en øget frigivelseshastighed / migrering af olie fra reservoiret, og derved øge mængden af olie, der fjernes fra isen.

Resultaterne tyder på, at det især er diameteren på de små kanaler i isen (brine channels) og oliens hydrostatiske tryk, der er afgørende for transporten af olie fra reservoirer i isen til isens overflade og dermed for effektiviteten af afbrændingen. Derudover indikerede resultaterne, at varmen fra afbrændingen blev brugt til at smelte is frem for at brænde olie, hvilket forventes at føre til øgede olieudslip fra oliegennemtrængt havis i markmiljøer. Vi forventer dog, at denne effekt aftager med stigende bassindiameter. Men det kræver forsøg i en større skala og med flere forsøgsgange at kunne drage endelige konklusioner.

# Summary

Responding to an oil spill in high-Arctic marine ice-infested waters is extremely challenging. In situ burning (ISB) of oil spills is recognised as an effective oil removal method for oil spills in both open and ice-infested waters. The presence of ice can contribute to reducing oil weathering and under the right circumstances contain the oil slick as a thick ignitable layer on the surface. Therefore, ISB is often mentioned as a promising method for oil spill response in the Arctic.

The aim of this project was to increase the knowledge base for combatting oil spills in ice-infested waters by ISB. The project included small-scale laboratory burns of oil released from ice. During freezing, ice grows downwards and can encapsulate oil lying beneath it (NORCOR 1975; Faksness 2008; Nelson 1982). Such oil accumulated under the ice tends to move upwards within the ice during winter due to density-mediated migration and appear un-weathered at the surface when the ice starts to melt. The migration is occurring through the brine channels in the ice.

The study was designed to imitate a spring melt pool situation, where oil captured in the ice is released during the spring melt and contained in melt pools and subsequently burned. The set-up consisted of an ice block with an indentation / cavity in the top (the melt pool), a connecting channel (the brine channel) and an oil reservoir in the ice.

The purpose was to study the driving mechanisms for burning oil in an ice melt pool still connected to oil remaining in the ice. It was hypothesised that the heat from the burn would result in an increased release rate / migration of oil from the reservoir, thereby increasing the oil amount removed from the ice.

The results from the burns suggested that the diameter of the brine channels as well as the hydrostatic pressure of the oil are the driving mechanisms for oil migrating from the reservoir to the oil pool. In addition, the results indicated that the heat from the burn was used to melt ice rather than burn oil, which is expected to lead to increased oil release rates from oil-permeated sea ice in a field setting. However, we expect this effect to decline with increasing pool diameter.

It is recommended to undertake larger-scale experiments with more replicates to be able to conclude on the different results from the experiment.

# 1 Introduction

In situ burning (ISB) of oil spills on water is recognised as an effective oil removal method for oil spills in both open and ice-infested waters. During open water burning, the oil is contained by fire resistant booms. In ice-infested waters, ice floes can be used to secure an ignitable thickness and a continuous slick. The presence of ice can also contribute to reduce the weathering of the oil, thus increasing the window of opportunity for an ISB operation. Even so, oil spill response in High Arctic waters relates to great challenges. This is primarily due to the sea ice as it complicates the accessibility to the spill site and makes it impossible / less efficient to use conventional response methods. Remoteness, darkness for many months of the year and lack of infrastructure also add to the challenges.

ISB is an oxygen-starved combustion process where the oil is converted to $CO_2$, water, soot and other combustion products. The burn efficiency, i.e., the amount of oil removed from the water surface, typically ranges between 85 and 90 %. During the *Deepwater Horizon* incident in the Gulf of Mexico, 411 burns were conducted (Allen et al. 2011), and the estimated burn efficiency was 85% (Stout and Payne 2016). After flaming out, a burn residue is left at the place of the burning. This residue might sink or drift to the coast and adversely impact sensitive ecosystem components. Furthermore, though the overall amount of oil is reduced by the burn, there seems to be a relative increase in the proportion of large poly-aromatic hydrocarbons (PAH) in the residue (Fritt-Rasmussen et al. 2015).

The overall purpose of this project was to increase the knowledge base for combatting oil spills in ice-infested waters by ISB. The project included small-scale laboratory burns of oil released from ice. The study was designed to imitate a spring melt pool situation, where oil captured in the ice is released during the spring melt, contained in melt pools and subsequently burned. The set-up consisted of an ice block with an indentation in the top (the melt pool), a connecting channel (the brine channel) and an oil reservoir in the ice.

The aim of the study was to improve our preliminary understanding of the driving mechanisms and limiting factors when burning oil in ice surface melt pools that are still connected to oil remaining in the ice. This would help to improve the method for burning of oil in ice-infested waters. It would thus act as a steppingstone for more experimental work to investigate and understand these driving mechanisms for further improvement of ISB as a method for removal of oil spills in ice-covered waters. Within a broader perspective, the output of the study will expectedly improve our knowledge about when and where to implement ISB as a response method.

The following hypothesis was investigated: Heat from the burn results in an increased release rate / migration of oil from the reservoir, thereby enhancing the oil amount potentially removed from the ice.

The results of our study were directly linked to another project: EU Horizon 2020 GRACE (Jørgensen et al. 2019) that investigated and reported the heat feedback mechanisms from burning oil in ice to the ice and the potential related melting of the ice (Petrich et al. 2018 and deliverable reports (http://www.grace-oil-project.eu/en-US/About/Deliverables)).

# 2 Background – burning oil in ice

This chapter gives an overview of the research completed in relation to burning oil in ice. More details can be found in Fritt-Rasmussen and Petrich (2017).

## 2.1 Burning oil on solid ice

In the beginning of the 1970s, research including burning oil in ice-filled waters was initiated by the Norcor experiments (Norcor 1975). These experiments included discharges of a total of 56 $m^3$ crude oil in a small bay in Canada. When the oil was released during the spring melt, burning of the released oil was studied. The burn efficiency reported from these studies was 90% (Norcor 1975). The heat from the burning resulted in a slight enlargement of the melt pool as well as of the oil pool entrained in snow on top of the ice flowing into the burning pools (Norcor 1975).

Several other experiments involving burning of oil in melt pools were conducted and reported in the late 1970s/80s; however, these reports are not available but are referred to in the summery report by Buist et al. (2013). It was, for example, found that wind (up to 7 m/s) and herding agents could herd the oil against the ice edge into an ignitable thickness (Energetex 1977 in Buist et al. 2013). Another test simulated a subsea blowout under land-fast first-year sea ice. When the oil appeared during the spring break-up, approximately 50% was ignited and burned with a burn efficiency of 90% and an average burn rate of 1 mm/min (which is somewhat lower than reported elsewhere) (Buist et al. 1981 in Buist et al. 2013; Dickins and Buist 1981 in Buist et al. 2013). A few other studies found similar burning efficiencies even at low air temperatures (-32°C) and for emulsions appearing during the spring melt (63%). Further details can be found in Buist et al. (2013).

More recently, in 2006, 3400 L crude oil were released under 45 cm first-year sea ice on Svalbard. The oil was ignited after its natural appearance on the ice surface after 23 days. The burn efficiency was 96% and the average burn rate 3.1 mm/min (Dickins et al. 2008).

In 2013-2015, laboratory studies were completed at Worcester Polytechnic Institute, US, to elucidate the fundamental problem of "burning oil in an ice cavity" (cavities have different sizes and shapes) from a fire science point of view (Shi et al. 2016; Rangwala et al. 2013; Bellino et al. 2013; Farahani et al. 2015). Overall, the findings revealed that burning of oil in ice cavities is determined by the ice walls that act as a significant heat sink and, particularly for small cavities (5-10 cm), this resulted in considerable lateral heat loss. Lateral heat loss to the ice caused increased melting whereby the ullage height (free space) decreased, and the oil diameter increases, resulting in reduced oil film thickness. With increasing diameter, the impact on the walls declined, however. During burning, the ice melted, allowing the fuel to penetrate the ice, thereby creating a small ice lip above the oil. Also, the burning efficiencies were relatively low compared to those of the burning without ice, which was suggested to be a result of trapping of the oil in pockets – lateral cavities appearing during burning, but the initial oil film thickness and the size of the cavity also influenced the burning efficiency.

## 2.2 Burning oil in broken ice/pack ice

The first test showing that it was possible to burn oil in broken ice was conducted in 1983 (Tier II large-scale tests, Buist and Dickins 2003). Following this test, several laboratory-scale and larger-scale tests were made at The National Oil Spill Response Research & Renewable Energy Test Facility (OHMSETT) to determine different ranges of ice cover (30-90%) and different crude oils and emulsions (Smith and Diaz 1985a, b, 1987). These tests showed that burning of emulsions was difficult due to high flashpoints and that the burn rate (regression rate) and burn efficiency decreased when lowering the water temperature. The laboratory experiments showed much lower burning efficiencies compared to the large-scale tests (30-50% vs 85-95%). This is explained by the differences in heat transfer regimes that depend on the pool size – a pool diameter above 1 m is considered to cause turbulent burning (Smith and Diaz 1985b).

Brown and Goodman (1986) found that the regression rate (oil thickness reduction with time) was impacted by wind, stronger wind (to a certain extent) resulting in a higher regression rate, most likely due to wind herding of the oil and a more efficient heat transfer from flames to the oil. In contrast, brash ice reduced the burn rate because of diminished heat transfer (Brown and Goodman 1986).

Small field tests conducted in basins on the fjord ice at Svalbard using fresh and weathered crude oils demonstrated that it is possible to ignite and burn emulsified oils (water-in-oil emulsion) with the right igniter (Bech et al. 1992; Bech et al. 1993; Guenette and Wighus 1996). It was also found that secondary burns took place in basins placed 1.5 and 3.5 m away due to relatively high wind speeds that deflected the flames (Guenette and Wighus 1996). Extensive information on these ISB tests on Svalbard is compiled in Guenette (1997).

Buist et al. (2003) conducted a range of experiments to study the minimum ignitable thickness, combustion rate, residue amount and effects of waves on thin oil slicks burned in frazil or brackish ice. In Buist et al. (2013), rules of thumbs based on these experiments can be found:

- *The minimum ignitable thickness for fresh crude in frazil ice or small brash ice pieces is up to double that on open water, or about 1 to 2 mm.*
- *The minimum ignitable thickness for evaporated crude oil in frazil ice or small brash ice pieces can be higher than on open water but is still within the range quoted for weathered crude on water, about 3 mm with gelled gasoline igniters.*
- *For a given spill diameter, the burn rate in calm conditions is about halved on relatively smooth frazil/slush ice and halved again on rougher, brash ice. Wave action slightly reduces the burn rate on open water, but the halving rule seems to apply in waves as well.*
- *The residue remaining on broken ice in calm conditions is about 50 % greater than that on open water or 1.5 mm. The residue remaining in brash or frazil ice in waves is slightly greater than in calm conditions, at about 2 mm.*

A series of experiments undertaken at Svalbard (from laboratory to field-scale) increased knowledge about the window of opportunity of igniting oil as a function of oil weathering in pack ice (Fritt-Rasmussen and Brandvik 2011; Sørstrøm et al. 2010).

# 3 Burning oil in simulated small-scale melt pools

During freezing, ice grows downwards and can encapsulate oil lying beneath it (NORCOR 1975; Faksness 2008; Nelson and Allen 1982). Such oil accumulated under the ice during winter tends to move upwards within the ice due to density-mediated migration and appears un-weathered at the surface when the ice starts to melt. The migration occurs through the brine channels in the ice. The porosity and connectivity of pores increase as the ice warms, and oil moves upwards through the connected pore space if the pores are sufficiently large. The laboratory set-up designed for this project imitated in a simple manner the trapping of an oil spill under or in sea ice, followed by spring thaw and release in ice surface melt pools due to oil migration in the brine channels in the ice.

## 3.1 Materials and methods

The experimental small-scale set-up consisted of an ice block with an indentation / cavity at the top (the melt pool) and a connecting channel (the brine channel) from the melt pool at the top to a reservoir in the ice (see Figure 3.1). Some of the reservoirs had no bottom – i.e. the reservoir was considered "open", thereby providing a higher hydrostatic pressure from the surrounding water. The burn was sheltered from two sides with 0.45 x 0.8 m high walls to prevent wind blowing directly across the surface (Figure 3.1).

The ice block had a diameter of 280 mm and a height of 160-170 mm. The channel was 80 mm high and had a diameter of either 6 mm or 10 mm. The diameter size was selected based on Lake and Lewis (1970), who reported diameters of 2 mm – 4 cm. The melt pool diameter was 120 mm and its depth 45 mm. The intended dimensions of the reservoir were a height of 45 mm and a width of 120 mm but differed markedly due to variations in ice growth during ice formation. The ice was made from tap water in a freezer set at around -20 °C for two days.

The ice block was placed in the middle of a steel basin (1.0 x 1.0 x 0.25 m) filled with tap water (approx. 10 °C). The oil (naphthenic crude oil) was injected from the top into the reservoir until the melt pool contained oil with a thickness of approximately 10 mm. The amount of oil was recorded.

The temperature of the oil (10 and 55 mm into the channel, measured from the ice surface), in the water in the steel basin and of the flames at three heights (140 mm, 395 mm and 580 mm, measured from the ice surface) were measured for each burn with K-type thermocouples. A Campbell Scientific CR1000 logger recorded temperatures and ambient weather conditions from a weather station during the burns.

Following each burn, the remaining oil and burn residue were collected on oil-absorbent pads and weighed to allow calculation of the burn efficiency (BE%, for details see below). Also, for each experiment, a small sample was taken of the burn residue on the water to calculate the density of the residue by gravimetrical measures.

Ice profile measurements were completed along two perpendicular lines before and after each burn to determine pool development and surface ablation (removal of ice by melting).

Eight burns were completed in total. The key parameters of the eight experimental burns are shown in Table 3.1.

The wind was very calm on 28 Oct 2019, below 2 m/s, whereas 25 Oct 2019 was windier, but still below 5 m/s and well below the limit for oil burning.

**Figure 3.1.** Overview of the burn experiment with the ice block in the water basin, the melt pool in the centre of the ice block and vertical temperature probes. Inserted picture: sectional view of the ice block and the oil-containing reservoir in the ice and the connecting brine channel to the top melt pool.

**Table 3.1.** Key parameters of the eight experimental burns.

| Burn ID | "Brine" channel diameter (mm) | Reservoir bottom | Air temperature (°C) | Total oil mass [g] | Oil pool film thickness (mm) |
|---|---|---|---|---|---|
| **1a** | 6 | Closed | 11 | 213 | 10 |
| **1b** | 6 | *Open* | 8 | 129 | n.m. |
| **2a** | 6 | Closed | 11 | 281 | 14 |
| **3a** | 10 | Closed | 15 | 68 | 10 |
| **3b** | 10 | Closed | 12 | 323 | 10 |
| **3c** | 10 | *Open* | 11 | 172 | 10 |
| **4b** | 10 | *Open* | 12 | 146 | 10 |
| **4c** | 10 | Closed | 13 | 264 | 10 |

### 3.1.1 Oil types

For modelling oil spill trajectories in the Greenland Sea, the Danish Meteorological Institute (Nielsen et al. 2008) used Statfjord crude based on advice from GEUS (Boertmann et al. 2020). It would have been most convenient to use that oil type in our experiments, but as it was not possible to obtain the necessary amounts, a naphthenic North Sea crude was used instead. The physical and chemical properties of this crude are given in Table 3.2.

**Table 3.2.** Indications of the physical/chemical properties of the fresh oils used in the experiments. From https://www.equinor.com/en/what-we-do/crude-oil-and-condensate-assays.html and Faksness (2008) (viscosity, North Sea crude) and Fritt-Rasmussen (2010) (Statfjord). Note that the values are guiding values so variations are likely.

| Oil type | Density [g/cm³] | Pour point [°C] | Wax [wt. %] | Viscosity [cP] |
|---|---|---|---|---|
| North Sea naphthenic crude oil | 0.847 | -30 | 4.2 | 299 at 2 °C |
| Statfjord | 0.835 | -6 | 4.3 | 824 at 3 °C |

### 3.1.2 Calculations of derived parameters from the experiments

Burn efficiency (BE%) is a gravimetric estimation of the amount of oil consumed during the burn and is calculated from the initial oil amount and the amount of burn residue:

$$BE\ [\%] = 100\ (1 - m_f/m_0) \qquad \textit{Equation 1}$$

where $m_0$ is the mass of the initial amount of oil, and $m_f$ is the mass of the oil residue.

Another and often used measure to express the burning is the regression rate, which is the oil thickness reduction in time (SL Ross 1998):

$$\dot{r}''\ [mm/mn] = \frac{\dot{m}}{A\rho_0} \qquad \textit{Equation 2 (SL Ross 1998)}$$

where $\rho_0$ is the initial oil density of 0.850 g / cm³, $A$ is the oil slick area, and $\dot{m}$ is the mass burning rate defined as the mass lost per unit time of burning. Here, we only calculated the overall mass burning rate as it was not possible to measure the weight loss during the experiments. The global overall mass burning rate can be calculated by the following equation:

$$\dot{m}_{global}[g/s] = \frac{(m_0 - m_f)}{t_f} \qquad \textit{Equation 3}$$

where $t_f$ is the time of the burning experiment, $m0$ is the mass of the initial amount of oil, and $m_f$ is the mass of the oil residues.

To calculate the volume of surface ablation (volume of ice melted during the burn), the two perpendicular lines measured before and after the burn of the ice profile were used. By subtracting the pre-burn from the post-burn, the “ablation profile” was found. By working in cylindrical coordinates relative to the centre of the original oil pool and assuming each measuring point in the ablation profile as a representation of the height in a fourth of a hollow cylinder, the volume was estimated (Petrich et al. 2018).

According to Petrich et al. (2018), the corresponding enthalpy was estimated by multiplying the surface ablation volume with the ice density, ρice=920 kg / m3, and latent heat of fusion of ice, L=334 kJ / kg.

## 3.2 Results

Key parameters of the eight experimental burns are shown in Table 3.1, and the derived results from the experiments are given in Table 3.3. Important visual observations from the experiment are gathered in Table 3.4. Explanations of the meaning of these observations are presented in Table 3.5.

Ice surface profiles before and after the burn for each experiment are shown in Figure 3.2 and Figure 3.3 and were used to calculate the ablation, i.e. the volume of ice melted during the burn.

Correlations between a selected range of key parameters and derived results from the experiment are demonstrated in Figure 3.4.

All other experimental data from each burn are gathered in Appendix 1.

**Table 3.3.** Key derived results of the burn experiments.

| Burn ID | Burn efficiency [%] | Total ablation [$cm^3$] | Enthalpy in ablation [kJ] | Regression rate [mm/min] | Burn time [s] | Total residue mass [g] |
|---|---|---|---|---|---|---|
| **1a** | 6 | 144 | 44 | 0.59 | 130 | 200 |
| **1b** | 13 | 961 | 295 | 0.35 | 312 | 112 |
| **2a** | 15 | 199 | 61 | 1.29 | 208 | 238 |
| **3a** | 22 | 516 | 159 | 1.02 | 90 | 53 |
| **3b** | 22 | 158 | 49 | 2.10 | 211 | 252 |
| **3c** | 4 | 2001 | 615 | 0.08 | 606 | 164 |
| **4b** | 2 | 726 | 223 | 0.11 | 150 | 144 |
| **4c** | 13 | 627 | 193 | 0.92 | 240 | 228 |

**Table 3.4.** Visual observations from each burn after flameout. Yellow = open reservoir; red = 6 mm channel, blue = 10 mm channel. Explanations of the visual observations are given in Table 5.

| Burn ID | Lip formation | Overflow/melt through | Ice plug in the channel | Oil at bottom of melt pool under layer of re-frozen ice | Oil in reservoir Yes/no | Oil movement from reservoir into melt pool |
|---|---|---|---|---|---|---|
| 1a | Yes | Yes | Yes | Yes | Yes | * |
| 1b | Yes | No | No | No | No | * |
| 2a | No | Yes – oil continued to burn on water surface | No | No | No – likely due to hole in reservoir | Yes – also after burn out |
| 3a | No | Yes | Yes | No | Yes | * |
| 3b | Yes | No | Yes | Yes | Yes | * |
| 3c | No | Yes – but after 10 min burn | No – melted channel | No | No | Yes – all oil migrated |
| 4b | Yes | Yes | No | No | No | Yes – oil was reignited |
| 4c | Yes | Yes | Yes | Yes | Yes | * |

**Table 3.5.** Explanations of the visual observations in Table 3.4.

| Visual observation | Explanation |
|---|---|
| ***Lip formation*** | Melting of ice edge in the oil surface and ice edge interface resulting in a small horizontal cavity into the ice edge. |
| ***Overflow/melt through*** | Heat from the burn melts the ice edge and thereby reduces the freeboard so that the oil can escape from the melt pool. |
| ***Ice plug in the channel*** | During the burn, the temperature in the channel increases. After burn out, the melt water in the channel may refreeze, resulting in an ice plug in the channel. |
| ***Oil at bottom of melt pool under layer of refrozen ice*** | During the burn, the temperature in the melt pool increases, causing ice melt. After flameout, the melt water in the channel refreezes, but oil may still flow from the channel. This results in an oil layer under a layer of refrozen ice |
| ***Oil in reservoir yes/no*** | Presence/absence of oil in the reservoir after the burn is recorded. |
| ***Oil movement from reservoir into melt pool*** | In some of the experiments, oil flow from the reservoir into the melt pool was observed. |


**Figure 3.2.** Ice surface profiles before (black lines) and after (orange lines) burns for the north-south transect (marked NS, left) and the west-east transect (marked EW, right). X-axis is distance in cm, and y-axis is depth in mm. For burn ID 1a, 1b, 2a, 3a and 3b.

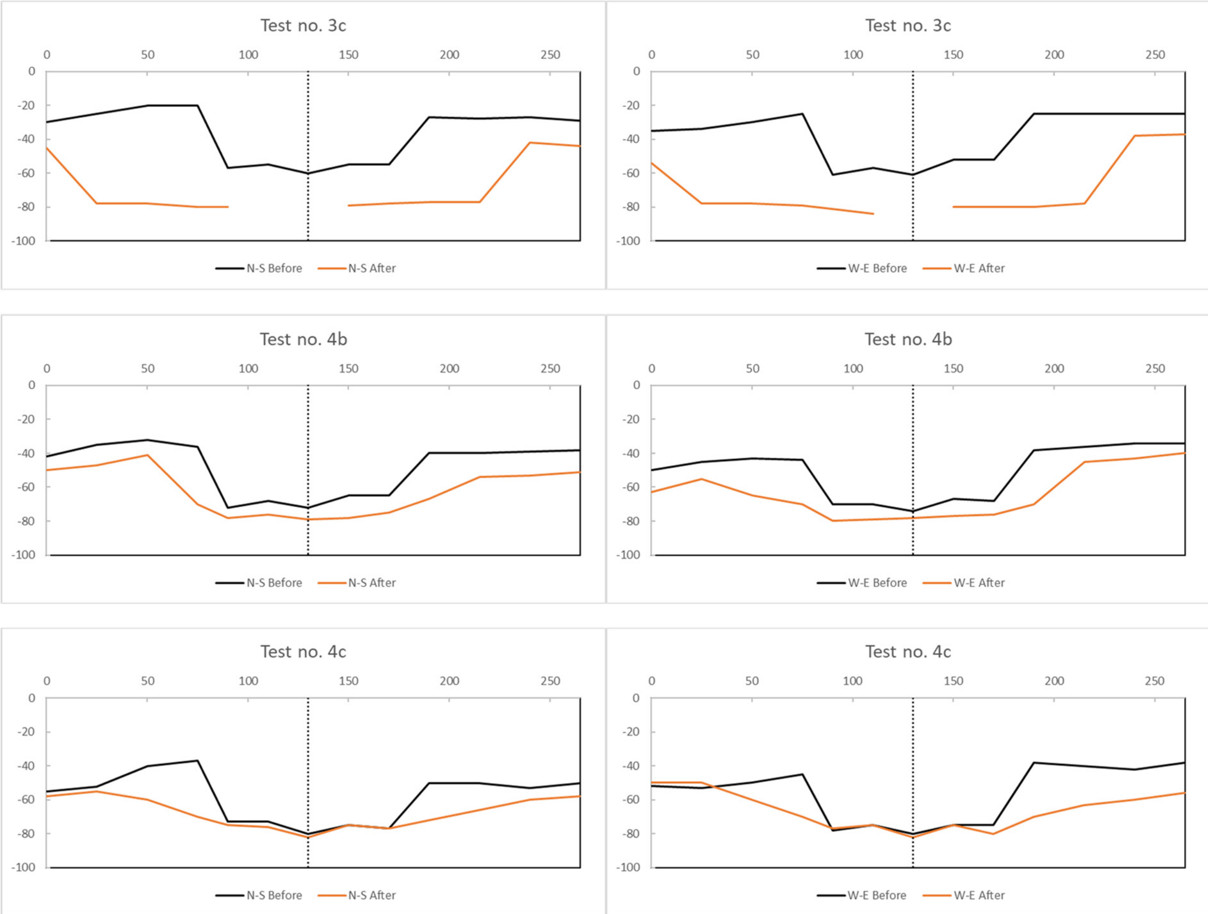
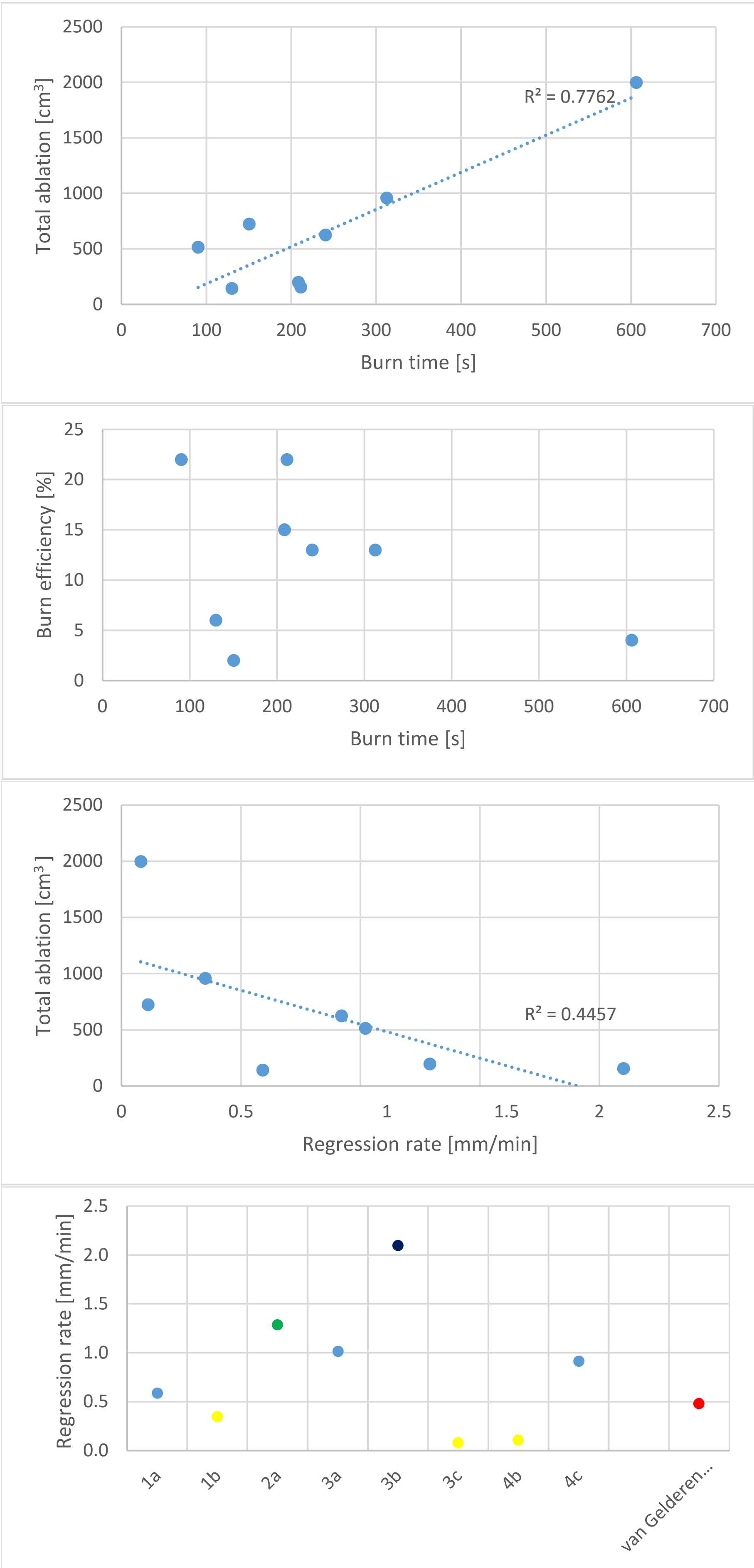



**Figure 3.3.** Ice surface profiles before (black lines) and after (orange lines) burns for the north-south transect (marked NS, left) and the west-east transect (marked EW, right). X-axis is distance in cm, and y-axis is depth in mm. For burn ID 3c, 4b and 4c.

**Figure 3.4.** Correlations between selected key parameters and derived results from the experiments. Trend lines computed by Excel. The colours of the bottom figure represent as follows: yellow = open bottom, blue = closed bottom; green = closed bottom and 14 mm initial oil slick thickness, dark blue = closed bottom and no overflow of oil; red = data from van Gelderen (2017).



## 3.3 Discussion

The work involved laboratory studies to investigate the driving mechanisms for burning oil in an ice melt pool connected by brine channels to an oil reservoir / pocket in the ice.

### 3.3.1 Burn efficiency

The burn efficiencies were very low, ≤ 22%, compared with other small-scale laboratory experiments (e.g. Fritt-Rasmussen and Brandvik 2011; Petrich et al. 2018; Buist et al. 2013). It is not feasible, however, to compare laboratory-scale burning efficiencies with large-scale field burning efficiencies as it is quite difficult to mimic field conditions at small scale due to e.g. variations in burning regimes and water exchange. Nevertheless, the low burning efficiencies can partly be explained by the lateral spread of the oil pool due to ice surface melt combined with a relatively thin initial oil layer thickness (10 mm). This agrees with Petrich et al. (2018). Further, as also reported by Rangwala et al. (2013), the icy walls might function as a heat sink, resulting in lateral heat losses, particularly for smaller melt pools (5-10 cm). However, in most of the experiments, the burn ended as a result of lateral melt through the ice block and thus flow-out of oil into the surrounding water basin, leading to a fast slick thickness reduction and consequent flameout. When oil slick thickness decreases, the insulating capacity of the oil declines, and the oil cools until a burn can no longer be sustained (Buist et al., 2013). This happens at a slick thickness of 1-2 mm (Buist et al. 2013). Thus, the observed burn time is a result of this melt-through of the ice edge and is likely to be more pronounced in a small-scale laboratory set-up compared to a large melt pool in the field.

### 3.3.2 Regression rate

The regression rates (oil thickness reduction with time) calculated were, in spite of the random termination of the burn, within the same range as that reported by e.g. van Gelderen (2017) for burning experiments in pools with the same diameter as in our set-up (the regression rate increases with increasing pool diameter). The highest regression rate of > 2 mm / min was recorded in the only experiment (3b) that did not end due to melt-through or oil overflow. This experiment also had a closed reservoir, i.e. a bottom in the reservoir.

For the reservoir experiments with an open bottom (1b, 3c, 4b), the regression rates were very low. The oil loss due to burn was low and / or the burn time was long, both factors leading to a low regression rate. The key factors behind these findings cannot be determined, and more research is needed to understand this fully, but it suggested that lateral leakage of oil is an explanation. Nevertheless, there are indications of a correlation between total ablation and burn time as for regression rate and total ablation. This indicates that for short burns, the heat was "used" for oil evaporation and burning, whereas for longer burns the heat was used for ice melt ice rather than oil evaporation. This "phenomenon" was quite clear for burn 3C, with an approximately 10 min burn but a burn efficiency of only 4% and a regression rate of 0.08 mm / min; however, burn 3C also had the highest measured total surface ablation: 2001 $cm^3$ (Table 3.1, Table 3.3 and Figure 3.4).

### 3.3.3 Oil migration

For the open bottom experiments only (1b, 3c, 4b), flow of oil from the reservoir through the "brine" channel to the melt pool occurred. The lack of a bottom in the reservoir likely resulted in a higher hydrostatic pressure, and a similar pressure would occur during ongoing oil release from ice and possibly also during manual oil recovery from individual ice-encapsulated lenses (e.g., Nelson and Allen 1982).

Sea ice is porous, and the porosity and connectivity of pores increase as the ice warms, and oil moves upwards through the connected pore space if the pores are sufficiently large. Hence, different diameters of brine channels, 6 mm and 10 mm, were studied, and the temperatures in the brine channels at 10 and 55 mm depth were recorded. The variations of the initial temperature in the ice (which was problematic to control) made it difficult to identify a clear trend in the variations between the 6 mm and 10 mm channel experiments (Appendix 1). However, oil migration was observed for both the 6 mm and 10 mm brine channels but only in the open bottom experiments. In two of these experiments (2a and 3c), the temperatures, measured 55 mm down the brine channel, increased and reached the same levels as those measured 10 mm down the channel (above 0 °C). At these temperatures, the ice surrounding the channel may melt and thereby enlarge the channel diameter, which again may increase the rate of oil release to the surface and thus potentially the amount of oil burned.

More investigations are required to fully elucidate oil migration rates in small brine channels; however, our results clearly demonstrate that a certain pressure is needed for the oil to migrate through the channel at a sufficient rate to supply the melt pool with oil.

### 3.3.4 Ambient weather conditions

The experiments were conducted over two days. The air temperatures ranged between 8 and 15 °C, presumably not influencing the results since the latent heat of ice fusion is very high.

The wind was very calm on 28 Oct 2019, below 2 m/s, whereas 25 Oct 2019 (burns 3a, 3b, 4c) was windier but still below 5 m/s and well below the limit for oil burning. The burn was sheltered from two sides with 0.45 x 0.8 m high walls to prevent wind from blowing directly across the surface (Figure 3.1).

## 3.4 Conclusions and research suggestions

Our experimental findings suggest that channel diameter and the hydrostatic pressure of the oil are the driving mechanisms behind oil migration from the reservoir to the oil pool and thus have a significant influence on the burn efficiency. However, more investigations are required to fully elucidate this subject.

In the longest experiments, the heat from the burn seemed to melt the ice rather than enhance burning of the oil. Such ice melt could lead to increased oil release rates in oil-permeated sea ice in a field setting due to the enhanced channel diameter. However, we expect this effect to decline with increasing pool diameter.

It is recommended to undertake larger-scale experiments with more replicates to enable conclusions on these parameters – e.g. channel diameter, hydrostatic pressure, pool diameter and oil migration rates.

The selected oil type had a low pour point and low viscosity. Oils with a high pour point and viscosity, such as heavy fuel oils, will expectedly show very different results under similar conditions.

# 4 Acknowledgement

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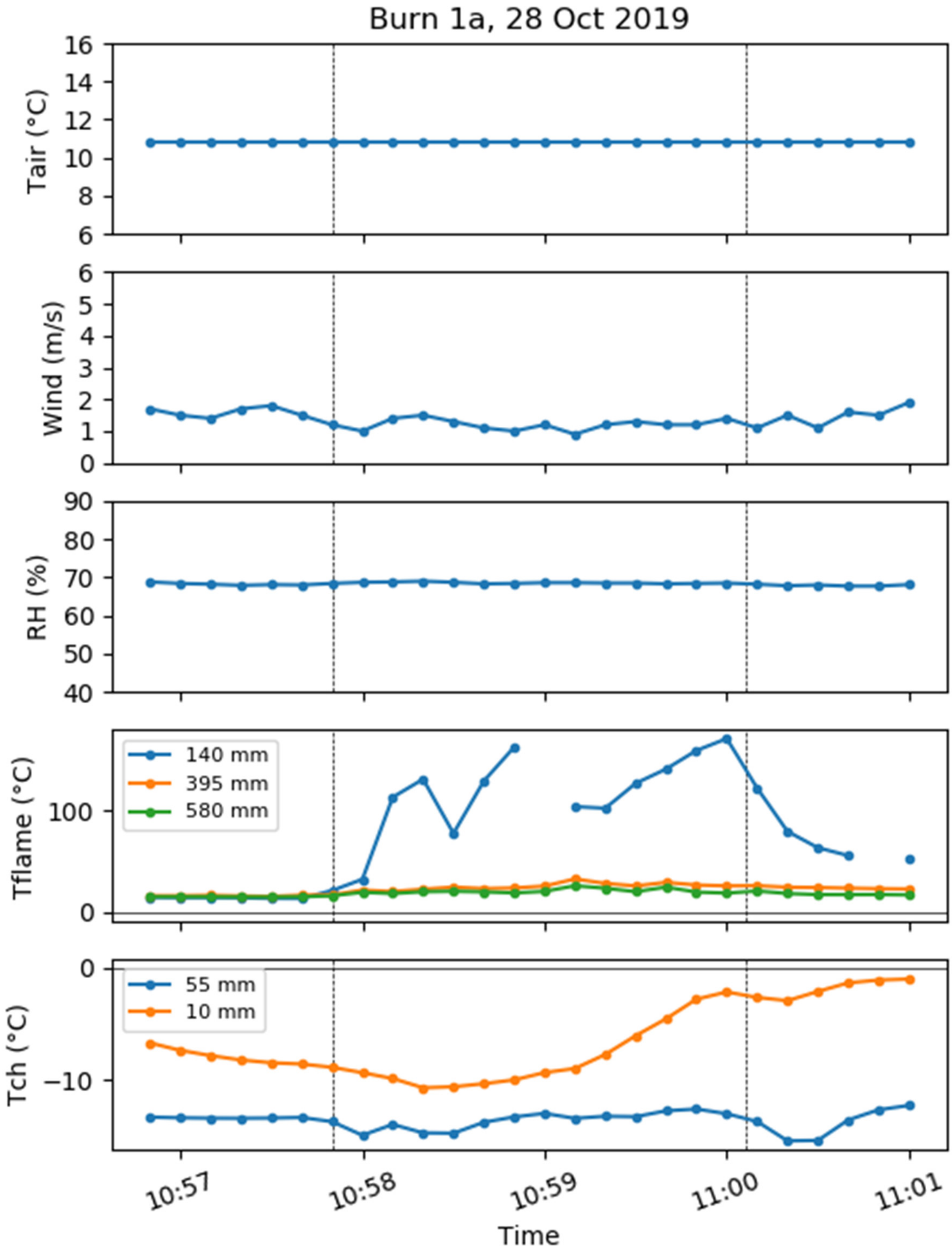
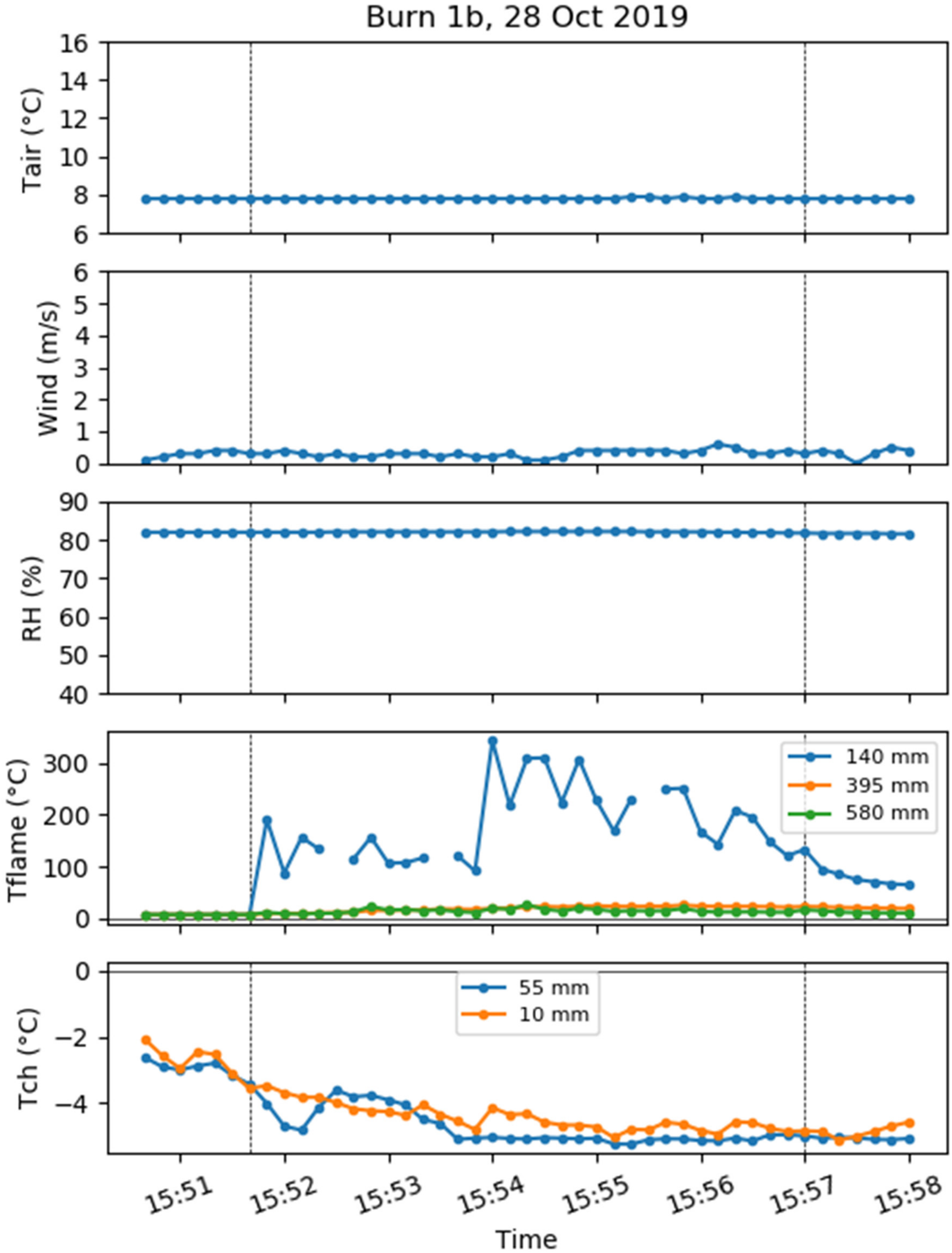
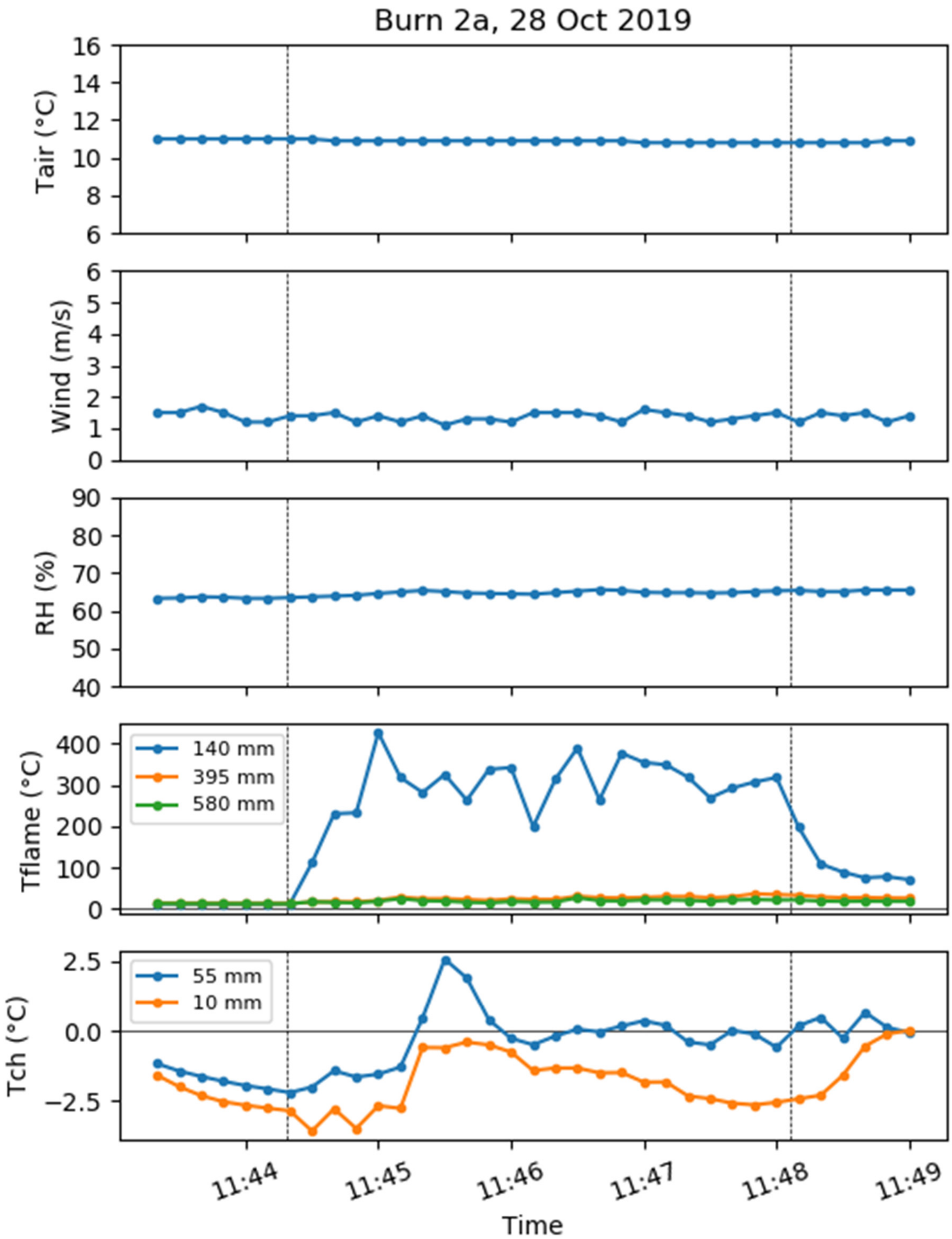
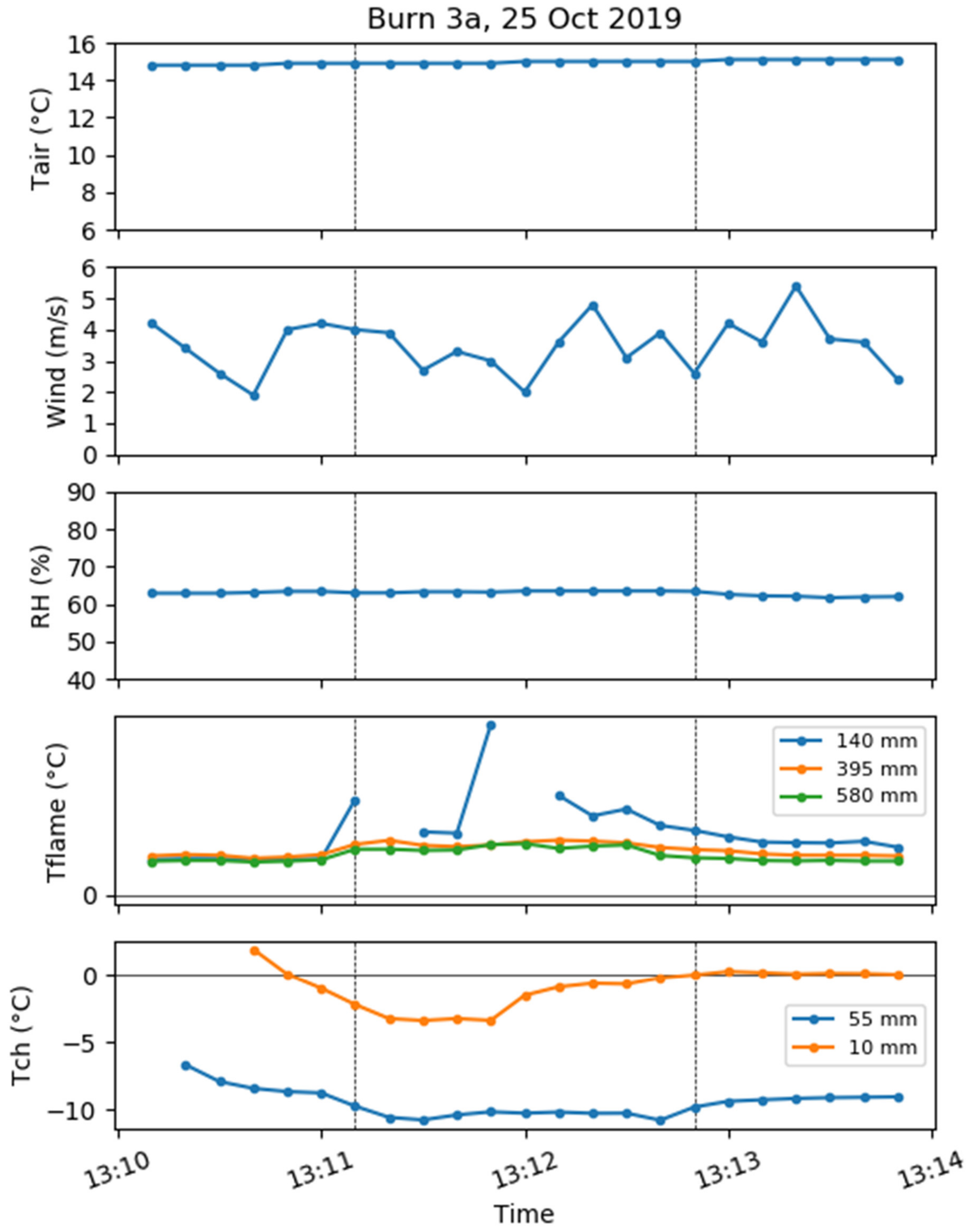
# Appendix 1

Temperature measurements and weather data from burning oil in ice. Dotted lines indicate the “burn window”.

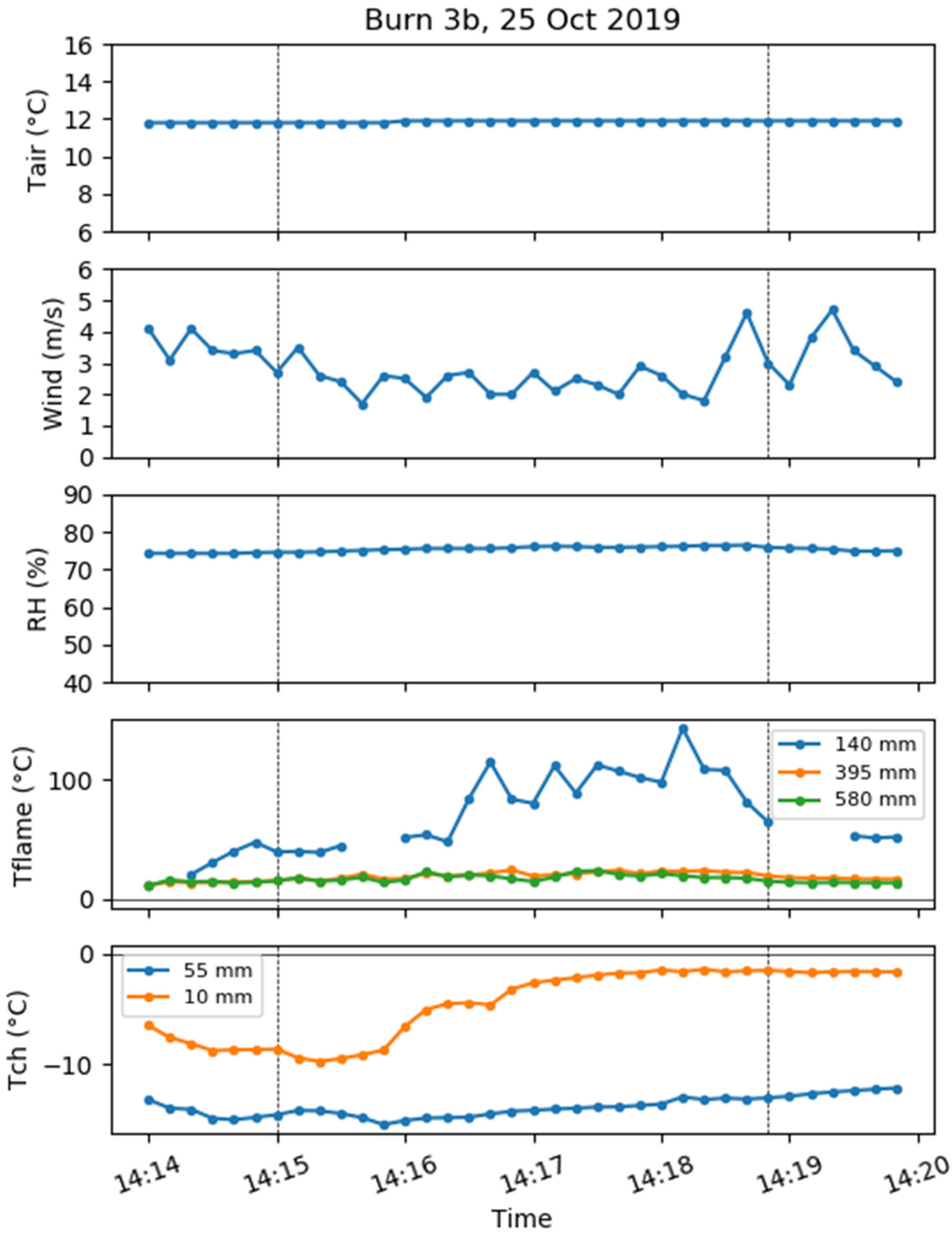


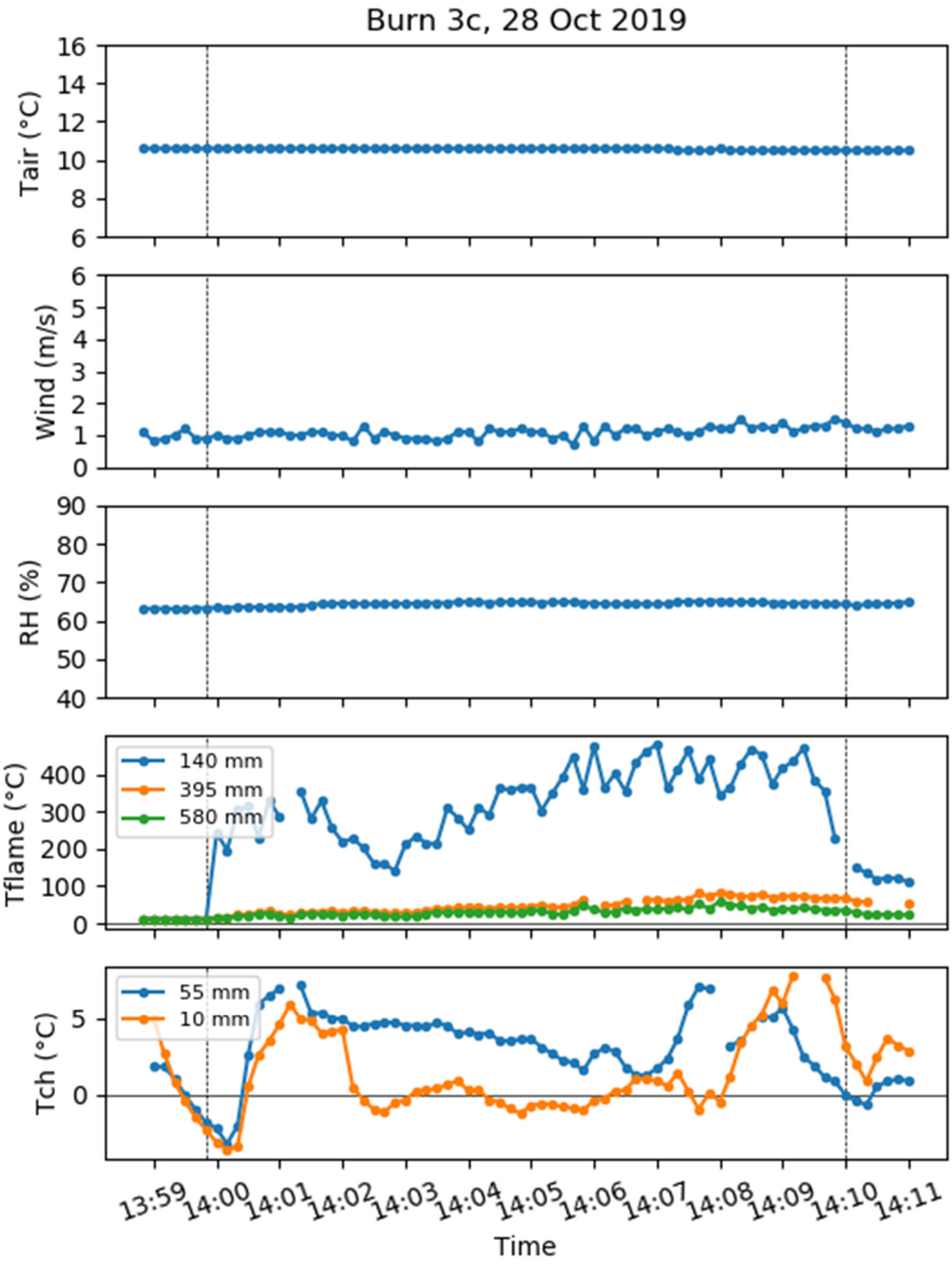

Burn 1b, 28 Oct 2019
Tair (°C)
Wind (m/s)
RH (%)
Tflame (°C)
140 mm
395 mm
580 mm
Tch (°C)
55 mm
10 mm
15:51
15:52
15:53
15:54
15:55
15:56
15:57
15:58
Time

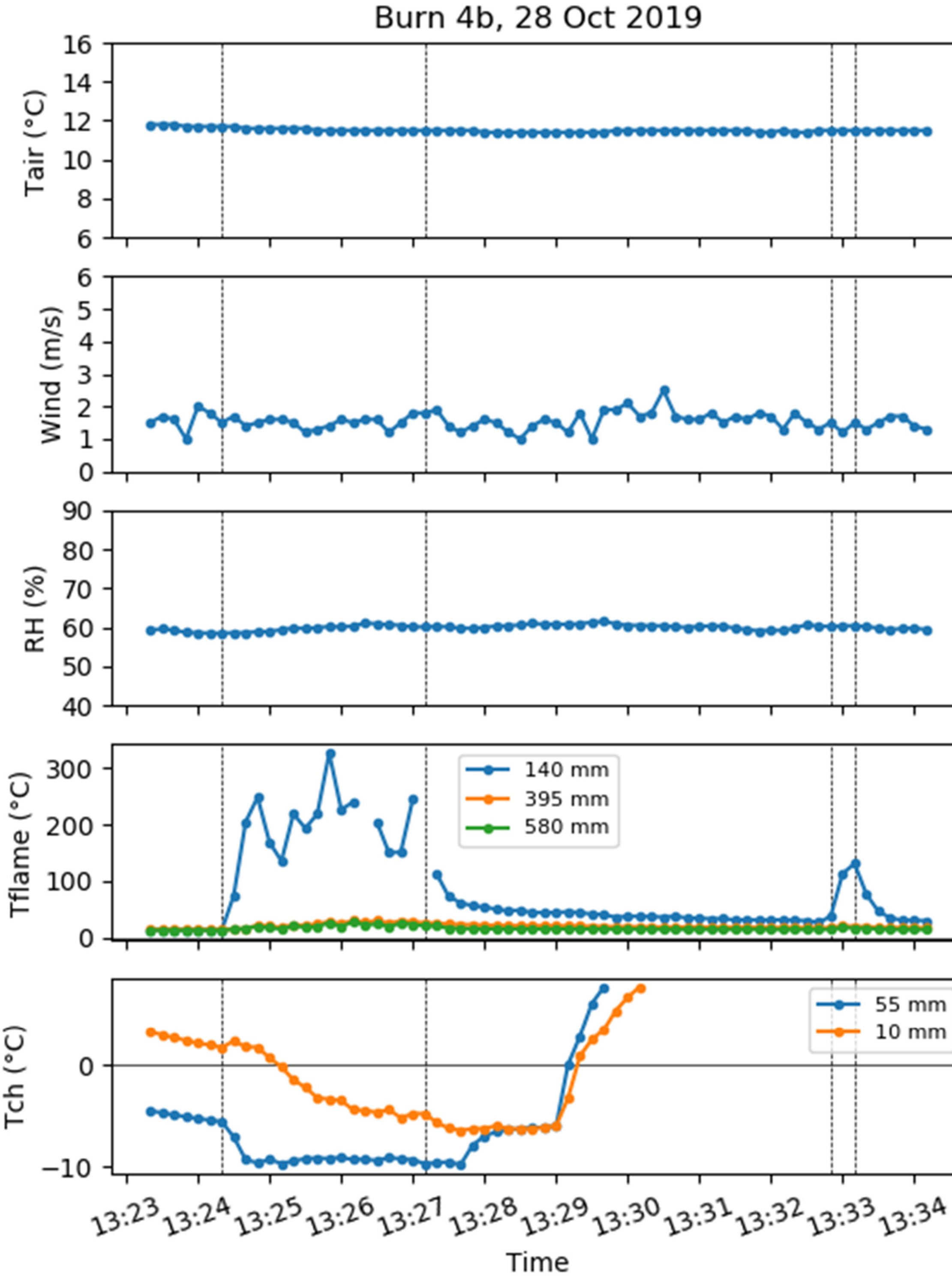

Burn 2a, 28 Oct 2019
Tair (°C)
Wind (m/s)
RH (%)
Tflame (°C)
140 mm
395 mm
580 mm
Tch (°C)
55 mm
10 mm
11:44
11:45
11:46
11:47
11:48
11:49
Time



Burn 3a, 25 Oct 2019
Tair (°C)
16
14
12
10
8
6
Wind (m/s)
6
5
4
3
2
1
0
RH (%)
90
80
70
60
50
40
Tflame (°C)
0
140 mm
395 mm
580 mm
Tch (°C)
0
−5
−10
55 mm
10 mm
13:10
13:11
13:12
13:13
13:14
Time


Burn 3b, 25 Oct 2019
Tair (°C)
Wind (m/s)
RH (%)
Tflame (°C)
140 mm
395 mm
580 mm
Tch (°C)
55 mm
10 mm
14:14
14:15
14:16
14:17
14:18
14:19
14:20
Time


Burn 3c, 28 Oct 2019
Tair (°C)
Wind (m/s)
RH (%)
Tflame (°C)
140 mm
395 mm
580 mm
Tch (°C)
55 mm
10 mm
13:59
14:00
14:01
14:02
14:03
14:04
14:05
14:06
14:07
14:08
14:09
14:10
14:11
Time


Burn 4b, 28 Oct 2019
Tair (°C)
Wind (m/s)
RH (%)
Tflame (°C)
140 mm
395 mm
580 mm
Tch (°C)
55 mm
10 mm
13:23
13:24
13:25
13:26
13:27
13:28
13:29
13:30
13:31
13:32
13:33
13:34
Time

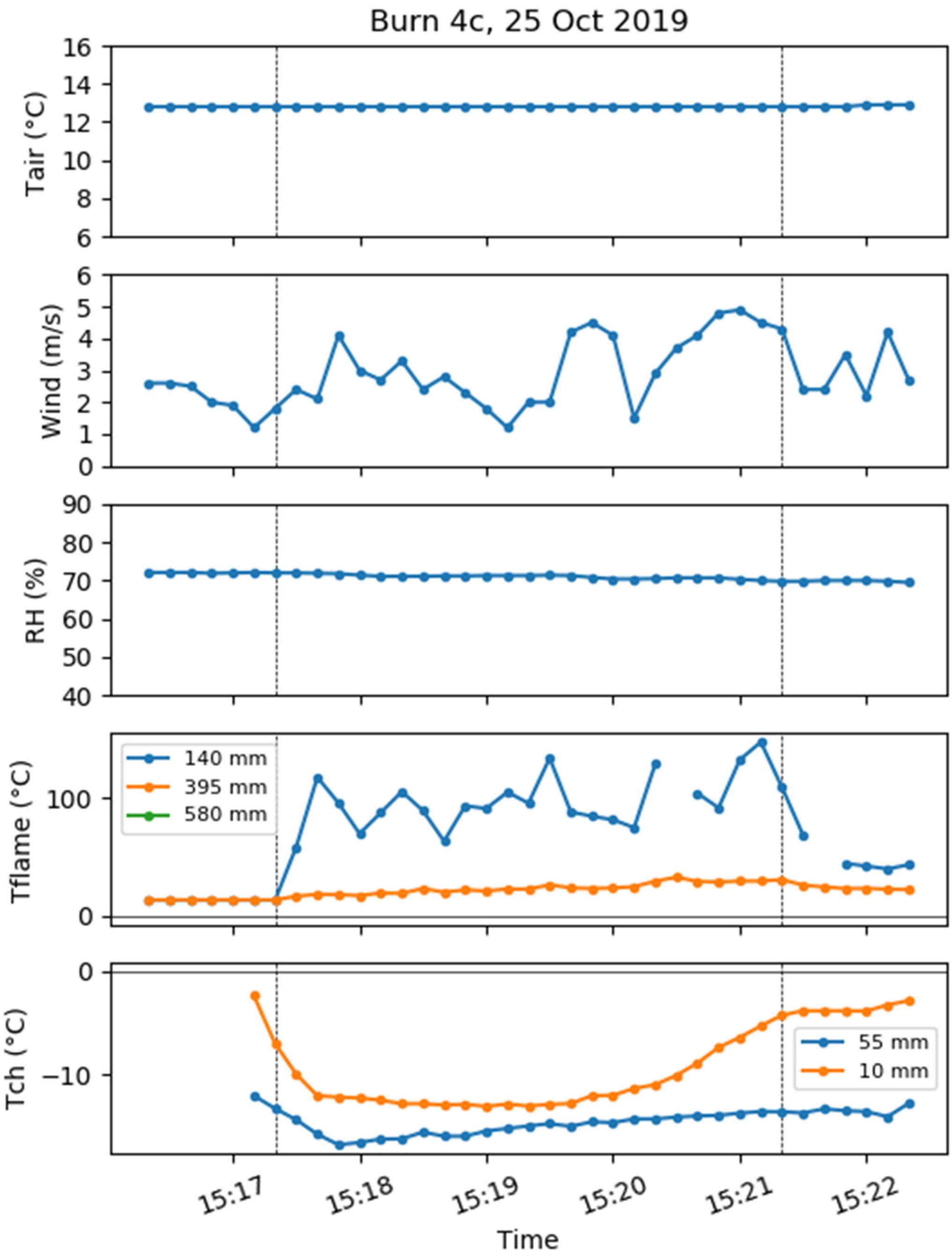



**Figure Ap.1.** Temperature measurements and weather data from burning oil in ice. Dotted lines indicate the “burn window”.

# SMALL-SCALE LABORATORY EXPERIMENTS ON BURNING CRUDE OIL IN ICE MELT POOLS

Responding to an oil spill in high-Arctic marine ice-infested waters is extremely challenging. In situ burning (ISB) of oil spills is recognised as an effective oil removal method for oil spills in both open and ice-infested waters. The aim of this project was to increase the knowledge base for combatting oil spills in ice-infested waters by ISB. The project included small-scale laboratory burns of oil released from ice designed to imitate a spring melt pool situation. The results suggested that the diameter of the brine channels as well as the hydrostatic pressure of the oil are the driving mechanisms for oil migrating from the reservoir to the oil pool. In addition, the results indicated that the heat from the burn was used to melt ice rather than burn oil. It is recommended to undertake larger-scale experiments with more replicates to be able to conclude on the different results from the experiment

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