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Simulations of oil spill dispersion report

D5.2

WP5: Strategic Net Environmental Benefit Analysis (sNEBA)

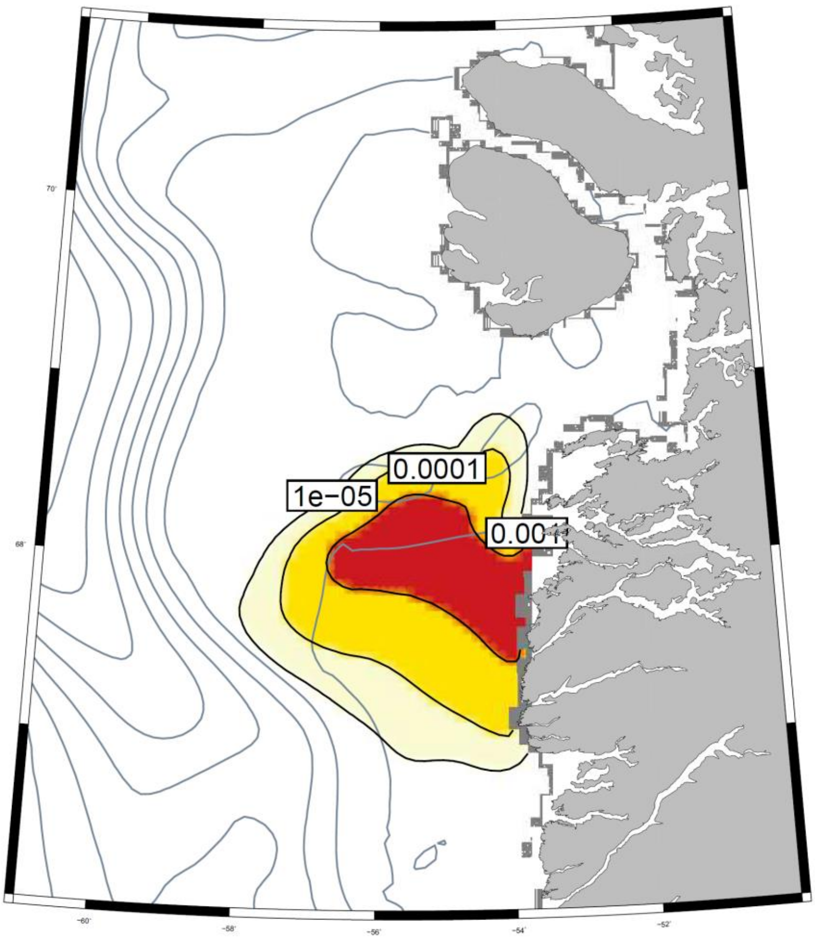

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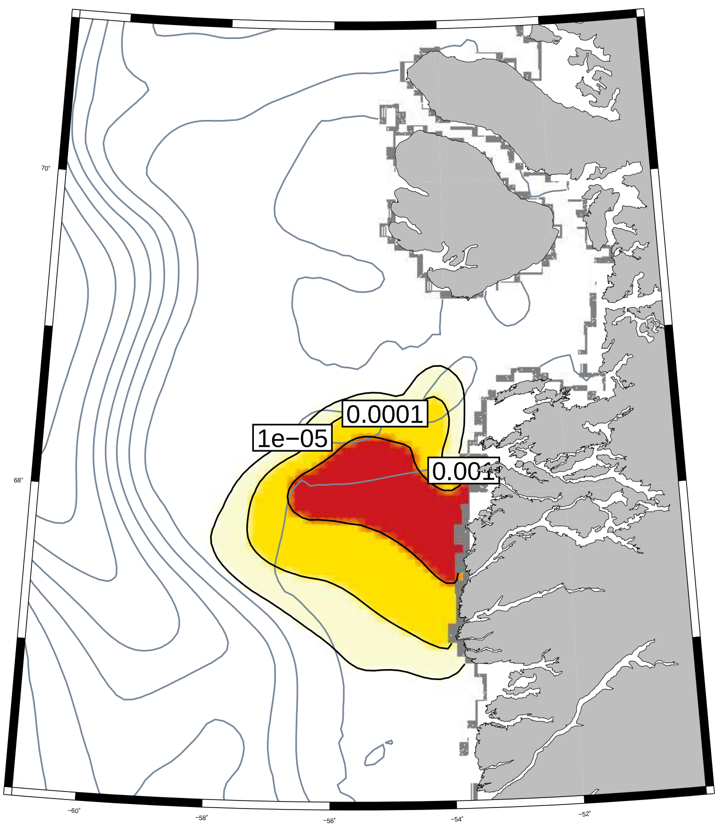
Table of Content

Executive Summary

Oil spill scenarios in the Baffin Bay and the Baltic Sea are simulated by high resolution ocean circulation models. These scenarios consider a case where 1000 tonnes of oil is released from a specific location with a constant rate during 24 hours. The oil substance is represented by a passive tracer and two transient tracers with a specified decay rate. The passive tracer represents the case where dissolution due to mixing with ambient water is the only mechanism for reducing the oil concentration. The transient tracers represent oil compounds where different rates of biological, chemical or mechanical degradation also contribute to the gradual reduction of the oil concentration. Six locations are investigated along the west coast of Greenland in the area around Disco Island and St. Hellefiske Bank. Four locations are investigated in the Baltic Sea located in the Bothnian Bay, Bothnian Sea, at the entrance to the Gulf of Finland and in the Gulf of Finland off Helsinki. All scenarios are simulated in three different seasons during the year, including periods with sea ice cover. The spatial distributions of the oil compounds are simulated during a two month period and the dispersal rate is documented as a sequence of maps of the three tracers. The volumes affected by oil concentrations above specified threshold values are calculated and presented as time series for all scenarios. The report contains a description of the oil spill locations, the model system, and an example of an oil spill scenario in the Baltic Sea. The complete documentation of all the scenarios are presented in three Enclosures: Enclosure 1 and 2 show scenarios in the Baffin Bay and in the Baltic Sea, respectively. The analysis of oil volumes affected above specified threshold values for all the scenarios is finally presented in Enclosure 3.

GRACE dispersion scenarios
in the Baffin Bay and the Baltic Sea



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Frontpage: Dispersion of oil spill in the Baffin Bay

Contents

List of Figures

List of Tables

1 Summary

Oil spill scenarios in the Baffin Bay and the Baltic Sea are simulated by high resolution ocean circulation models. These scenarios consider a case where 1000 tonnes of oil is released from a specific location with a constant rate during 24 hours. The oil substance is represented by a passive tracer and two transient tracers with a specified decay rate. The passive tracer represents the case where dissolution due to mixing with ambient water is the only mechanism for reducing the oil concentration. The transient tracers represent oil compounds where different rates of biological, chemical or mechanical degradation also contribute to the gradual reduction of the oil concentration.

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The report contains a description of the oil spill locations, the model system, and an example of an oil spill scenario in the Baltic Sea. The complete documentation of all the scenarios are presented in three Enclosures: Enclosure 1 and 2 show scenarios in the Baffin Bay and in the Baltic Sea, respectively. The analysis of oil volumes affected above specified threshold values for all the scenarios is finally presented in Enclosure 3.

2 Introduction

Oil spill at sea results in a mixture of non-dissolved and dissolved oil compounds. The dispersal of the non-dissolved fraction is influenced by the buoyancy of the oil, surface winds and ocean currents and mixing, whereas the dissolved oil fraction solely is transported by ocean currents and mixing as other tracers in the ocean, e.g. salinity. This report considers dispersal of the dissolved oil substances. Thus, dispersal of this oil fraction is only influenced by ocean currents and horizontal and vertical turbulent mixing in the water column.

The report describes oil spill scenarios in the Baffin Bay and in the Baltic Sea. The oil spill scenarios are analysed by applying three different tracers, representing various types of oil substances: A passive tracer and two transient tracers show the dispersal from a specific location. The passive tracer shows the dispersal of an inert substance where the temporal decrease in concentration only is due to mixing with ambient water. The transient tracers, with specified half life's of 5 and 25 days, respectively, represent oil substances where the concentration also is influenced by biological or chemical degradation of the substance. These tracers, therefore, show a more rapid temporal decrease of their concentration.

The report is organised as follows: First the oil spill scenarios are defined. Thereafter, the model system is presented and the formulation of transient tracers, representing oil-compounds with different decay time scales, and the analysis of threshold volumes are described. Finally, an example of an oil spill scenario and calculation of threshold volumes from the Baltic Sea is shown.

All oil spill scenarios from the Baffin Bay and the Baltic Sea are documented in Enclosure 1 and 2, respectively, and calculations of volumes with oil concentrations above specified threshold concentrations are included in Enclosure 3.

3 Oil spill scenarios

The oil spill scenarios simulate oil spills from different locations and during different periods during the year, as described below.

3.1 Oil spill locations

Oil spill locations are defined for the Baffin Bay and the Baltic Sea. Six oil spill locations are defined in the Baffin Bay: two locations at Store Hellefiske Bank, three locations in Disco Bay and one location west off Disco Island. The locations are summarized in Table 1 and shown in Figure 1.

Four oil spill locations are defined in the Baltic Sea: One is located in the Bothnian Bay, one is located in the Bothnian Sea, one is located at the entrance to the Gulf of Finland and one is located in the Gulf of Finland off Helsinki. The locations are summarized in Table 2 and shown in Figure 2.

The oil spill locations represent different physical conditions in terms of distance from the coast and water depth. Locations in the Baffin Bay is located at relatively shallow areas on the shelf (S1, S2 and S6) or, in the case of locations in Disco Bay (S3, S4 and S5), at deep and relatively narrow entrances from the deeper slope area. The Baltic Sea locations represent different parts of the Baltic where ice conditions and traffic density varies during the year.

3.2 Oil spill size and duration

All simulations consider an oil spill of 1000 Tonnes released during 24 hours. The release is taking place the 5th in the first month of each scenario. The scenarios are then analysed in a two months period. For example, the early spring simulation in the Baffin Bay starts the first of May and last to the 30th of June. The Oil is released the 5th of May and the model simulation then describes the dispersal of the oil until the end of June.

Simulations in the Baffin Bay starts in May, July and October and they represent partly ice covered conditions in May, summer conditions in July and late fall conditions in October. These scenarios are summarized in Table 3.

The Baltic Sea simulations starts in February, July and October and they represent ice covered conditions in the northern Baltic Sea in February, summer conditions in July and late fall conditions in October. These scenarios are summarized in Table 4.

ID	longitude	latitude	Depth	Comment
S1	55.15 °W	67.54°N	67 m	S1 location
S2	53.68 °W	68.08°N	153 m	S2 location
S3	53.68 °W	68.80°N	457 m	S3 location
S4	51.93 °W	68.88°N	219 m	S4 location
S5	55.96 °W	70.01°N	120 m	S5 location
S6	51.66 °W	69.20°N	329 m	S6 location

Table 1: Baffin Bay locations: Locations of oil spills in the Baffin Bay.

ID	longitude	latitude	Depth	Comment
S1	22.45 °E	64.60°N	90 m	S1 location
S2	19.85 °E	63.10°N	99 m	S2 location
S3	21.85 °E	59.20°N	109 m	S3 location
S4	24.94 °E	59.82°N	55 m	S4 location

Table 2: Baltic Sea locations: Locations of oil spills in the Baltic Sea.

Exp.	Location	Total load [Tonnes]	Duration [hours]	Start	Simulation in 2013	Comment
1	S1	1000	24	5th May	May-Jun	sea ice
2	S2	1000	24	5th May	May-Jun	sea ice
3	S3	1000	24	5th May	May-Jun	sea ice
4	S4	1000	24	5th May	May-Jun	sea ice
5	S5	1000	24	5th May	May-Jun	sea ice
6	S6	1000	24	5th May	May-Jun	sea ice
7	S1	1000	24	5th July	Jul-Aug	ice free
8	S2	1000	24	5th July	Jul-Aug	ice free
9	S3	1000	24	5th July	Jul-Aug	ice free
10	S4	1000	24	5th July	Jul-Aug	ice free
11	S5	1000	24	5th July	Jul-Aug	ice free
12	S6	1000	24	5th July	Jul-Aug	ice free
13	S1	1000	24	5th Oct	Oct-Nov	ice free
14	S2	1000	24	5th Oct	Oct-Nov	ice free
15	S3	1000	24	5th Oct	Oct-Nov	ice free
16	S4	1000	24	5th Oct	Oct-Nov	ice free
17	S5	1000	24	5th Oct	Oct-Nov	ice free
18	S6	1000	24	5th Oct	Oct-Nov	ice free

Table 3: Baffin Bay scenarios: Locations and periods of oil spills in the Baffin Bay.

Exp.	Location	Total load [Tonnes]	Duration [hours]	Start	Simulation in 2013	Comment
1	S1	1000	24	5th Feb	Feb-Mar	sea ice
2	S2	1000	24	5th Feb	Feb-Mar	sea ice
3	S3	1000	24	5th Feb	Feb-Mar	sea ice
4	S4	1000	24	5th Feb	Feb-Mar	sea ice
5	S1	1000	24	5th July	Jul-Aug	ice free
6	S2	1000	24	5th July	Jul-Aug	ice free
7	S3	1000	24	5th July	Jul-Aug	ice free
8	S4	1000	24	5th July	Jul-Aug	ice free
9	S1	1000	24	5th Oct	Oct-Nov	ice free
10	S2	1000	24	5th Oct	Oct-Nov	ice free
11	S3	1000	24	5th Oct	Oct-Nov	ice free
12	S4	1000	24	5th Oct	Oct-Nov	ice free

Table 4: Baltic Sea scenarios: Locations and periods of oil spills in the Baltic Sea.

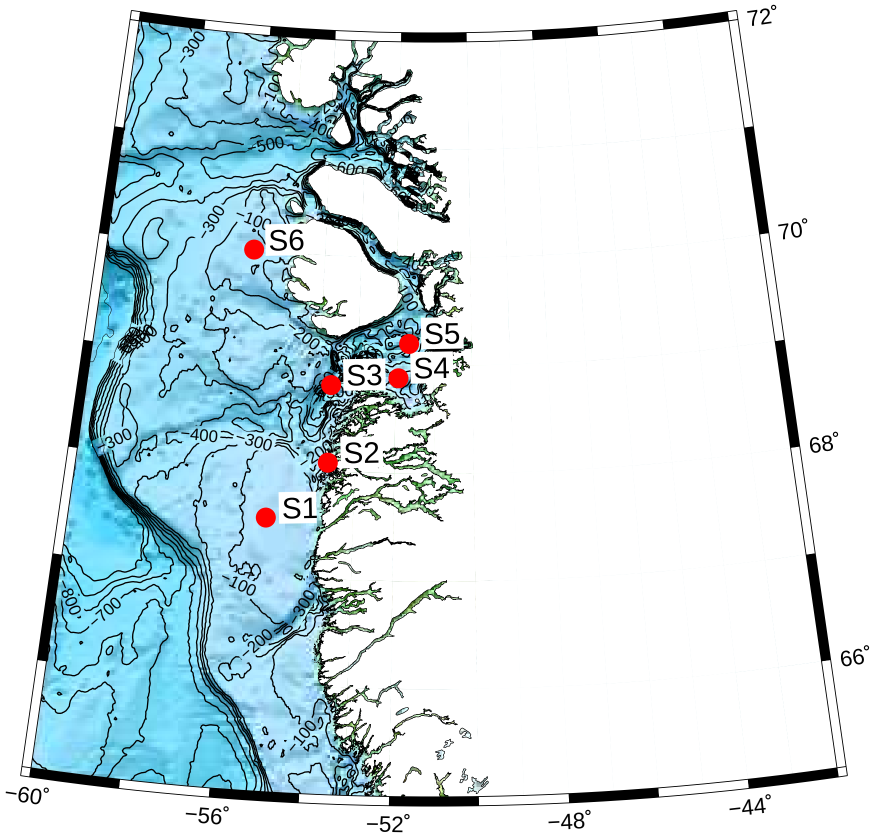

Figure 1: Map of St. Hellefiske bank (S1, S2), Disko Bay (S3-S5) and the area off Disko Island (S6). Oil spill locations S1 - S6 are indicated with red bullets. Contour lines show the bottom depth in the model.

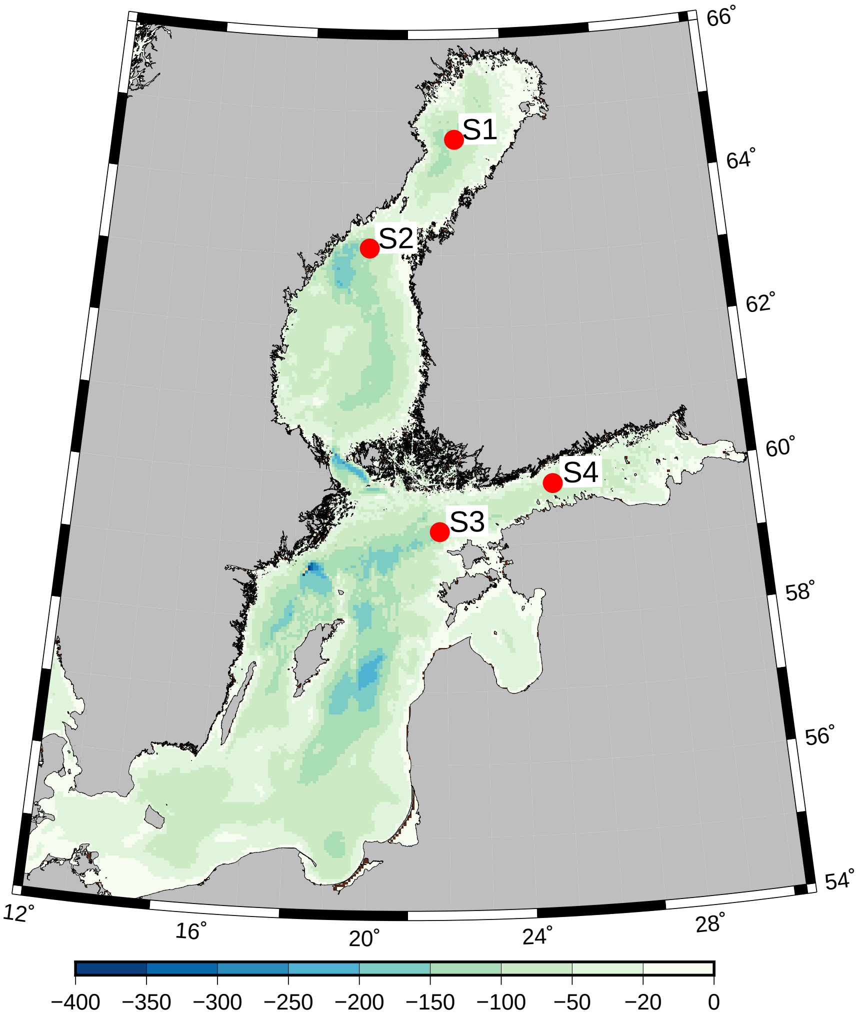

Figure 2: Map of the Baltic Sea. Oil spill locations S1 - S4 are indicated with red bullets. The color scale shows the bottom depth in the model.

4 Model description and analysis

The oil spill scenarios are implemented in a three dimensional ocean circulation model. The model setup is based on the ocean circulation model system COHERENS. The COHERENS model is an open-source model, originally developed in several EU-projects and currently there are more than thousand users of the model system around the world (see, http://odnature.naturalsciences.be/coherens/). The general model description is documented in Luyten (2014).

The model is a primitive equation model and solves the three-dimensional hydrodynamical equations in a finite difference numerical grid. The three dimensional fields of current velocities, temperature, salinity and other dissolved substances are determined with a specified temporal and spatial resolution defined in the model setup. The vertical resolution in the model is determined by a general s-coordinate system and this imply that there are a constant number of vertical layers in the whole model domain. In order to increase the resolution near the surface, the vertical layers are stretched accordingly, such that the surface layer is relatively thinner than the bottom layers in deep areas. The vertical turbulent mixing is described by a k-epsilon turbulence model with a background mixing of $0.5 \cdot 10^{-5}$ m^2 s^{-1}. This parameterization has been found to provide a good description of vertical mixing in the water column in previous studies. The advection is solved by an up-stream scheme and a horizontal viscosity and diffusion coefficient of 100 m^2 s^{-1} has been added to resolve subgrid scale mixing.

The models for the two areas were integrated for the whole year of 2013 and restart files were saved at the start of each month. The scenarios were then initiated from the saved initial conditions.

4.1 Baffin Bay: Model domain and boundary conditions

The model domain covers the area from 62.00 °N - 78.25 °N and 80.50 °W - 50.00 °W. The bathymetry is based on the high resolution ETOPO1 data set (Amante and Eakins, 2009) and from this the bathymetry is interpolated onto the model grid and subsequently the model bathymetry is low-pass filtered to avoid numerical instabilities.

The spatial resolution is determined by a horizontal spherical grid of 2.5 arc minutes (4.6 km) in the north-south and 8.1 arc minutes in the the east-west direction. The longitudinal distance corresponds to about 5 km in the area of interest. The vertical resolution is described by a stretched s-coordinate with 25 layers.

The initial conditions are obtained from the Arctic Regional Climatology (Boyer et al., 2012; Seidov et al., 2014) where a high resolution climatology of the Arctic area has been made based on a comprehensive observational data set. Temperature and salinity are interpolated onto the model grid and define the initial conditions in January 2013 and the data set also provides the monthly open boundary conditions at the three northern straits and at the southern open boundary at 62 °N.

Transports through the open boundaries are specified according to the estimated annual transports by Tang et al. (2004). The transport through Lancaster, Jones and Smith sound is prescribed as 1.1, 0.2 and 0.9 Sv (1 Sv = 10^6 m^3 s^{-1}) into the Baffin Bay and the transport at 62 °N is specified to about 20 Sv northward towards Davis Strait. A major fraction is recirculated south of Davis Strait and only a small fraction continues into the Baffin Bay as a slope and shelf current. Tidal forcing is specified by the seven most dominating tidal constituents, as described below. The open boundary conditions is determined by the method of characteristics as described in Luyten (2014).

Runoff is included from 17 rivers along the west coast of Greenland (shown in Figure 1). A total annual river runoff of 9 mSv is prescribed and the seasonal variations follow the seasonal change in runoff observed in Godthaabsfjord.

4.2 Baltic Sea: Model domain and boundary conditions

The model domain covers the Baltic Sea until the northern Kattegat (57.75 °N). The model is formulated on a spherical grid with a resolution of 2 arc minutes in latitude and 4 arc minutes in longitude, corresponding to about 3700x3700 km. The vertical resolution is defined by stretched s-coordinate with 20 layers. The model setup has been applied and documented in previous studies (Rantajärvi, 2012). Open boundary conditions of temperature and salinity in the northern Kattegat are based on monthly averaged ctd-profiles from 2013 (data obtained from ICES, http://www.ices.dk/). Open boundary conditions of sea level are defined from observed water level in Ringhals in 2013 (data obtained from SMHI, http://www.smhi.se). Runoff to the model is defined from a monthly averaged climatology for the Baltic Sea and specified from 40 river outlets in the model domain.

4.3 Model resolution and application of nested models

The applied model resolutions of the Baffin Bay and the Baltic Sea made long seasonal integrations feasible. The model resolution in Baffin Bay of about 5 km is a relatively fine resolution for this area and limitations are mainly due to limited information about the initial and weather conditions in the more remote parts of the Baffin bay. The model resolution of about 3.7 km in the Baltic Sea resolves mesoscale features and is suitable for carrying out the long model integrations which provided the initial conditions for the oil spill scenarios.

A nested model solution was tested for the Disco Bay area in a much finer spatial resolution of about 500 m. In principle, such a model setup would resolve finer scale features which are not simulated in the coarser model setup for the whole Baffin Bay area. However, the Disco Bay area is relatively deep (about 800 m at the deepest locations) and the tidal forcing of the area is also relatively large and this made the nested model setup sensitive to the formulation of the open boundary conditions. Thus, it was decided to base all the scenario simulations on the large scale Baffin Bay model setup, because the circulation in the Disco Bay area were then dynamically consistent although the spatial resolution was about 5 km. However, this resolution was considered to be sufficient to resolve the dispersal in the oil spill scenarios.

4.4 Meteorological forcing and sea ice

Meteorological forcing was obtained from the NCEP re-analysis data set for the period 2013 (Kalney et al., 1996). The meteorological forcing is applied at 6 hourly intervals and interpolated onto the model grids in the Baffin Bay and in the Baltic Sea area. The applied fields include air temperature, surface wind at 10 m height, cloudiness, relative humidity and precipitation. In addition the daily sea ice cover is applied as a boundary condition such that energy fluxes and the wind stress is reduced when sea ice is present.

4.5 Tracer equations

Additional tracers was included in the model simulations and these were implemented in the COHERENS model system. The tracers represent dissolved oil substances as described below.

In general, a dissolved substance is described in the model by solving the transport equation:

$$\frac{\partial \phi}{\partial t} + A(\phi) = D(\phi) + S(\phi), \tag{1}$$

where the partial derivative with respect to time (t) describes the temporal evolution of a tracer ϕ. The advective and diffusive operators are described by A(ϕ) and D(ϕ), respectively, and they describe changes in the concentration of ϕ due to the transports of currents and subgrid-scale transport processes associated with turbulent mixing. The source term S(ϕ) describes changes in the concentration ϕ due to internal sinks and sources.

Three dissolved oil substances are considered and the first substance are a passive tracer, i.e. the tracer is conservative such that there are no internal sinks or sources affecting the distribution of the tracer. This tracer is referred to as “passive” because no other “active” processes are influencing it besides physical transport processes.

Two transient tracers are included in the model simulations and they are characterised by having an internal sink due to an exponential decay:

$$S(\phi) = -\lambda\,\phi, \qquad (2)$$

where the exponential decay time constant (λ) is related to the half-life ($T_{1/2}$) of the substance as:

$$T_{1/2} = \frac{ln(2)}{\lambda} \qquad (3)$$

4.6 Calculation of threshold-volumes

The oil spill scenarios were analysed for the distribution of oil compounds above four threshold-concentrations defined by: 10^{-4}, 10^{-3}, 10^{-2} and 10^{-1} g m^{-3}. The three-dimensional model output was stored for the two model domains with an time-interval of 48 hours and the volume with concentrations above the four threshold values were then calculated. Time series of threshold-volumes were calculated for both the passive tracer and the two transient tracers.

Figures of threshold-volume time series were made for all scenarios and the different scenarios were identified from their experiment number for both the Baffin Bay (Table 5) and the Baltic Sea (Table 6). For example, the reference in the figures to “baltic_exp05” and oil compound no. 2 corresponds to the the Baltic Sea S1 scenario in July. This is further explained in section 6.

ID	Oil no.	Model Domain	Location	Period
baffin_exp01	1	Baffin Bay	S1	May
baffin_exp01	2	Baffin Bay	S2	May
baffin_exp02	1	Baffin Bay	S3	May
baffin_exp02	2	Baffin Bay	S4	May
baffin_exp03	1	Baffin Bay	S5	May
baffin_exp03	2	Baffin Bay	S6	May
baffin_exp04	1	Baffin Bay	S1	July
baffin_exp04	2	Baffin Bay	S2	July
baffin_exp05	1	Baffin Bay	S3	July
baffin_exp05	2	Baffin Bay	S4	July
baffin_exp06	1	Baffin Bay	S5	July
baffin_exp06	2	Baffin Bay	S6	July
baffin_exp07	1	Baffin Bay	S1	October
baffin_exp07	2	Baffin Bay	S2	October
baffin_exp08	1	Baffin Bay	S3	October
baffin_exp08	2	Baffin Bay	S4	October
baffin_exp09	1	Baffin Bay	S5	October
baffin_exp09	2	Baffin Bay	S6	October

Table 5: Baffin Bay locations for threshold-volumes

ID	Oil no.	Model Domain	Location	Period
baltic_exp01	1	Baltic Sea	S1	February
baltic_exp01	2	Baltic Sea	S2	February
baltic_exp02	1	Baltic Sea	S3	February
baltic_exp02	2	Baltic Sea	S4	February
baltic_exp04	1	Baltic Sea	S1	July
baltic_exp04	2	Baltic Sea	S2	July
baltic_exp05	1	Baltic Sea	S3	July
baltic_exp05	2	Baltic Sea	S4	July
baltic_exp07	1	Baltic Sea	S1	October
baltic_exp07	2	Baltic Sea	S2	October
baltic_exp08	1	Baltic Sea	S3	October
baltic_exp08	2	Baltic Sea	S4	October

Table 6: Baltic Sea locations for threshold-volumes

5 Simulations of oil spill scenarios

Oil spill scenarios from the Baffin Bay and the Baltic Sea are documented in Enclosure 1 and 2, respectively. One example from the simulations and the associated figures are discussed below.

Figure 3 shows the simulations from the Baltic Sea at location S4. The figures show the surface concentration of oil and the colors follow a logarithmic color scale where the darkest red color has a value of 0.01 g m^{-3} and a change in color then reflect a decrease in concentration by a factor of 10.

The Oil spill occurs the 5th July and during 24 hours a total of 1000 tonnes of oil is released from that location. The upper left panel in Figure 3 shows the distribution of the passive tracer after two days, i.e. the 7th of July, and the oil distribution is seen to be relatively concentrated near the spill location. The following panels show the surface concentration in intervals of six days, e.g. the upper right panel shows the distribution the 13th of July, and the two lower panels show the distribution at the 19th and 25th of July, respectively. In Figure 4 the distribution is shown in the following month, i.e. starting from the 1st of August and then in six days interval, as in Figure 3, until the 19th of August. Thus, figure 4 is a continuation of the distributions shown in Figure 3.

Figure 5 shows the temporal evolution of the transient tracer with a half life of $T_{1/2}$=5 days. The figure can be compared with figure 3 and it can be seen that the concentration of the transient tracer decreases faster due to its continuous decay and in the end of the month (Figure 5, lower right panel) the concentration and spatial extent is much smaller than the corresponding distribution of the passive tracer (Figure 3, lower right). Figure 6 shows the similar distribution for the transient tracer with a half life of $T_{1/2}$=25 days and it can be seen that the distribution follows a pattern between the passive tracer and the faster decaying transient tracer with a half life of only five days.

The documentation of all the simulations follows the same structure in Enclosure 1 and 2, i.e first two figures show the distribution of the passive tracer during the two month period following the oil spill, and then two figures show the distribution of the transient tracer in the same month as the oil spill has taken place.

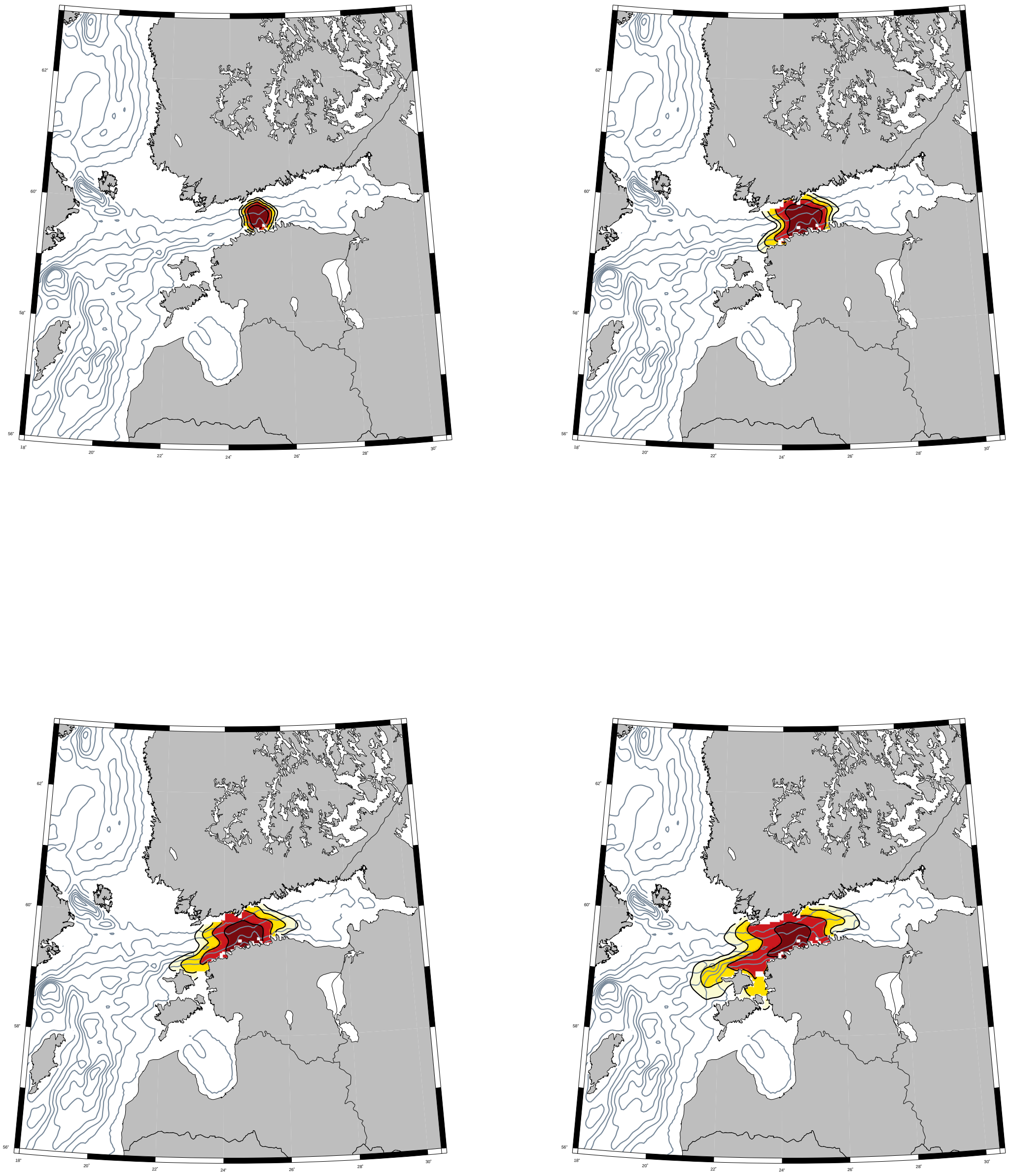

Figure 3: Surface distribution of a passive dissolved substance released at the surface at location S4 (units is g m^{-3}). In total 1000 Tonnes pr. day was released in the surface layer during 1 day, starting at 00:00 the 5th of July, 2013. The surface distribution is shown every 6 days after the second day of the spill (i.e. the 07th at 00:00, upper left, the 13th, upper right, the 19th, lower left and the 25th of July, lower right).

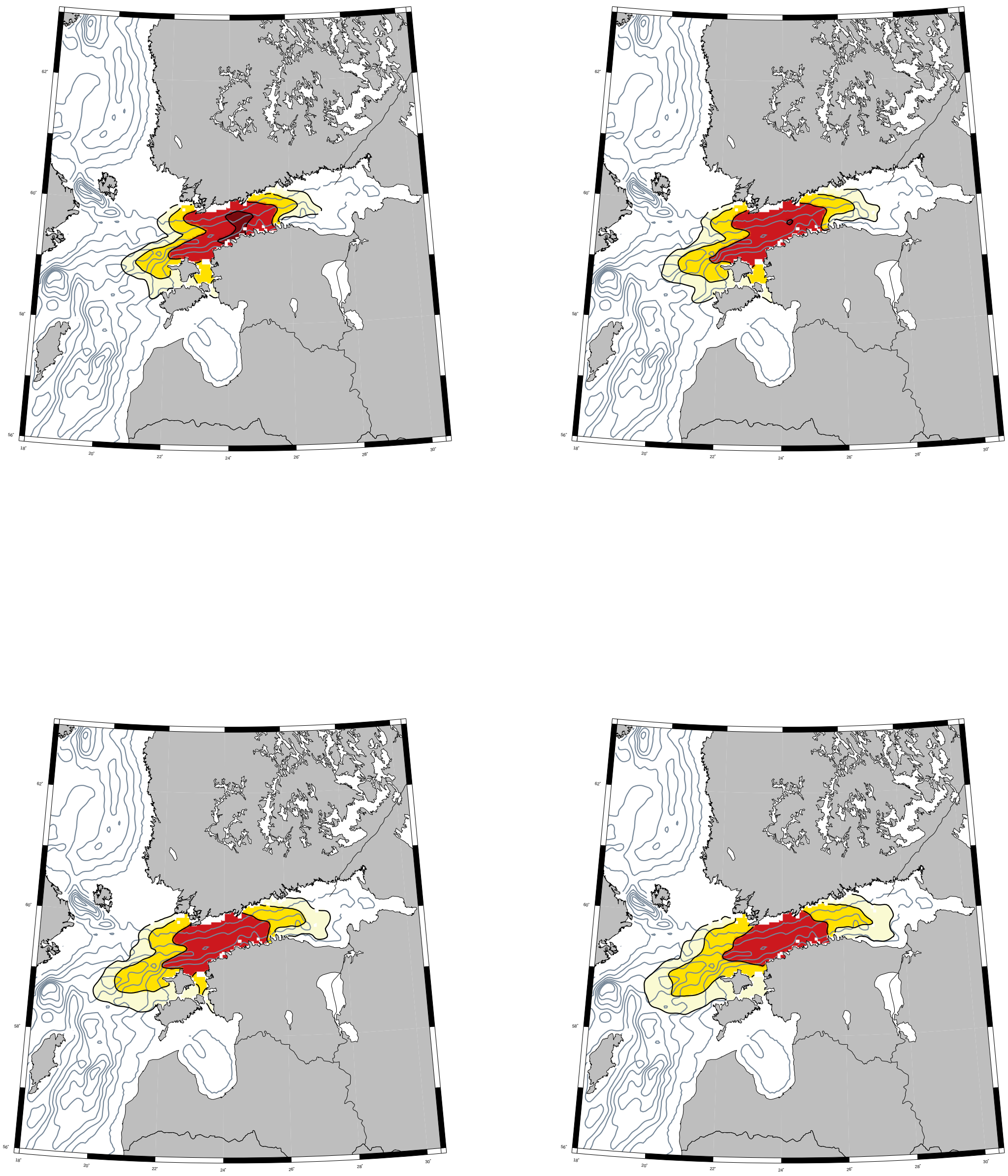

Figure 4: Surface distribution of a passive dissolved substance released at the surface at location S4 (units is g m^{-3}). In total 1000 Tonnes pr. day was released in the surface layer during 1 day, starting at 00:00 the 5th of July, 2013. The surface distribution is shown every 6 days in August (i.e. the 01st at 00:00, upper left, the 07th, upper right, the 13th, lower left and the 19th of August, lower right).

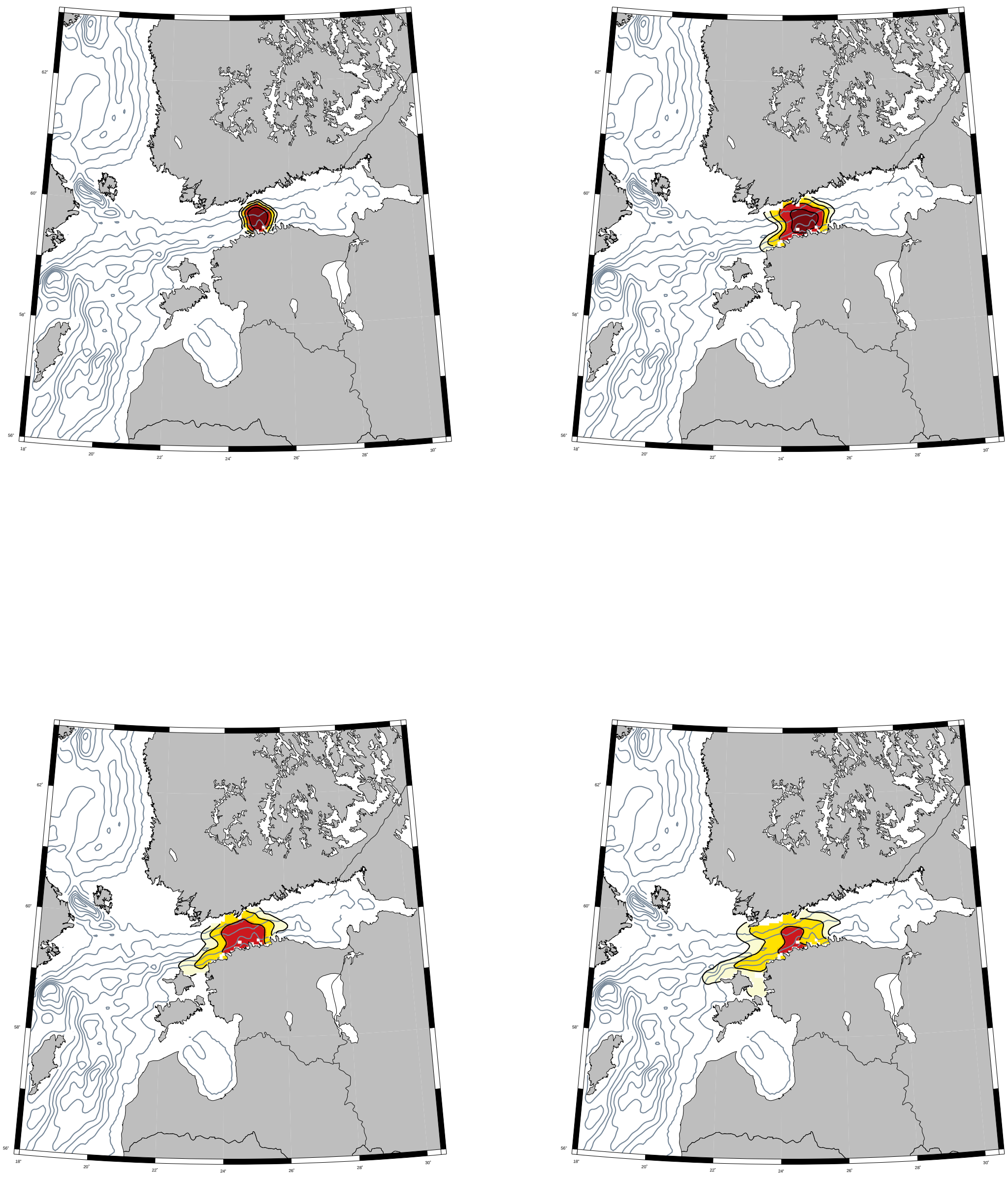

Figure 5: Surface distribution of a dissolved substance with a half life of 5 days (tracer($T_{1/2}$=5 days)) released at the surface at location S4 (units is g m^{-3}). In total 1000 Tonnes pr. day was released in the surface layer during 1 day, starting at 00:00 the 5th of July, 2013. The surface distribution is shown every 6 days after the second day of the spill (i.e. the 07th at 00:00, upper left, the 13th, upper right, the 19th, lower left and the 25th of July, lower right).

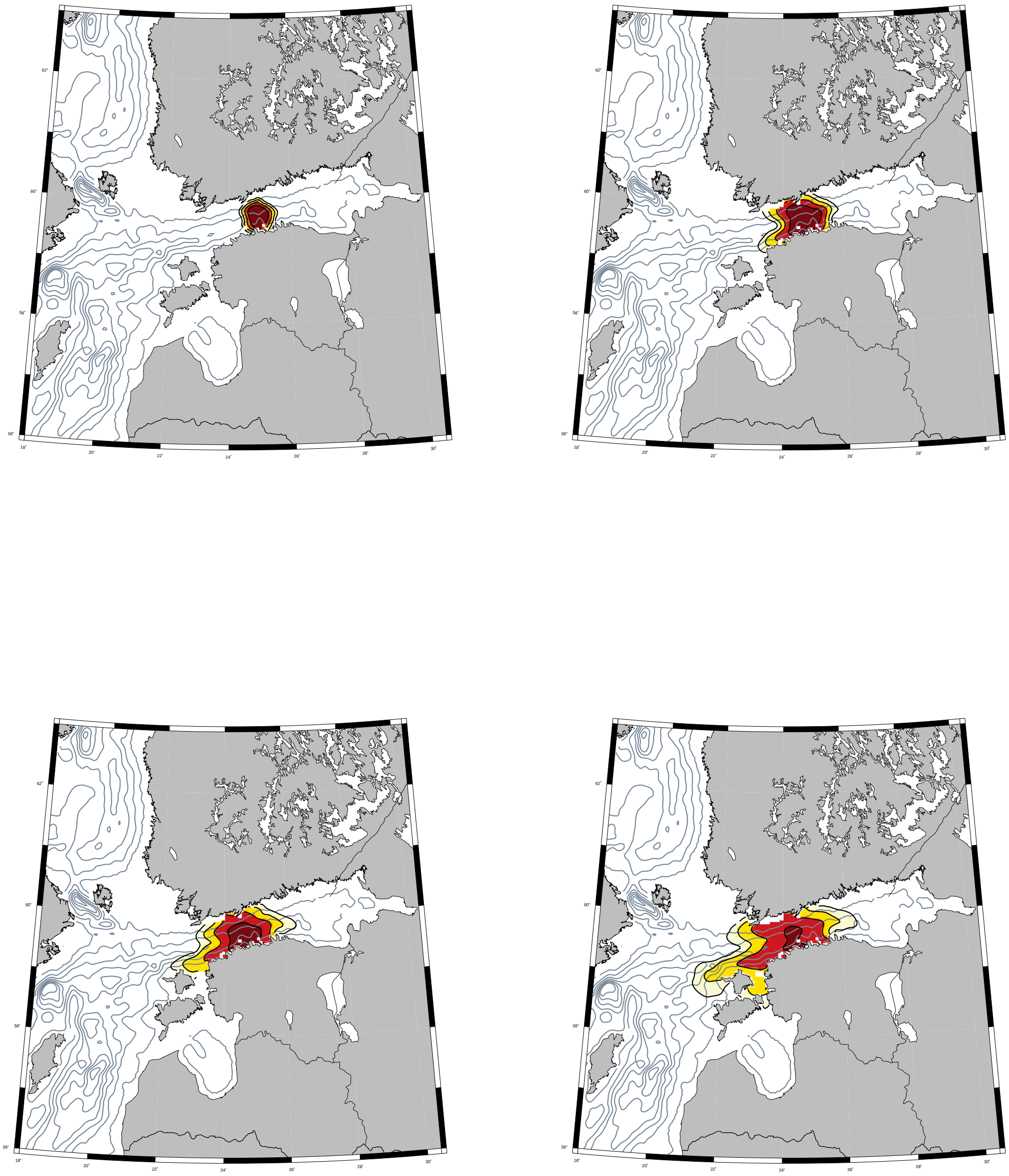

Figure 6: Surface distribution of a dissolved substance with a half life of 25 days (tracer($T_{1/2}$=25 days)) released at the surface at location S4 (units is g m^{-3}). In total 1000 Tonnes pr. day was released in the surface layer during 1 day, starting at 00:00 the 5th of July, 2013. The surface distribution is shown every 6 days after the second day of the spill (i.e. the 07th at 00:00, upper left, the 13th, upper right, the 19th, lower left and the 25th of July, lower right).

6 Time series of threshold-volumes

An example of threshold volume calculations is shown in Figure 7 for experiment baltic_exp05, representing the oil spill scenario in the Baltic Sea in July 2013 (cf. Table 6). Oil compound number 1 (solid line) and 2 (dashed line) represent location S3 and S4, respectively (according to Table 6). The black dashed line in the upper panel thereby represents the passive tracer in the S4 scenario,and it shows the total volume with concentrations larger than 0.0001 g m^{-3}. It can be seen that the volume gradually increases during the first 60 days after the oil spill. The green and orange dashed lines show the corresponding volumes for the transient tracers with half life's of 5 and 25 days, respectively.

The three panels below shows similarly the total volume of the tracers with concentrations above 0.001, 0.01 and 0.1 g m^{-3}, respectively. The ordinate axis shows the volume in units of km^3, and the maximum value of the ordinate axis in each panel corresponds to the maximum volume possible, i.e. if all material was distributed equally and having the threshold concentration. For example, in the lower panel a volume of 10 km^3 (i.e. the maximum value of the ordinate axis) with a concentration of 0.1 g m^{-3} equals 1000 tonnes, i.e. the total amount of oil released in the scenarios.

In general it can be seen from the calculations in Enclosure 3 that up to about 3 km^3 of water have concentrations above 0.1 g m^{-3} shortly after the release of the 1000 tonnes of oil. Also the different dynamical regimes characterising the Baffin Bay near the Disco Island and the Baltic Sea is apparent from the volume calculations where high concentrations in the Baffin Bay is more rapidly dispersed than in the Baltic Sea. In general the Baffin Bay is characterised by a strong tidal amplitude and this results in relatively large currents and also significant vertical mixing, and this explains the faster reduction in oil concentration.

7 References

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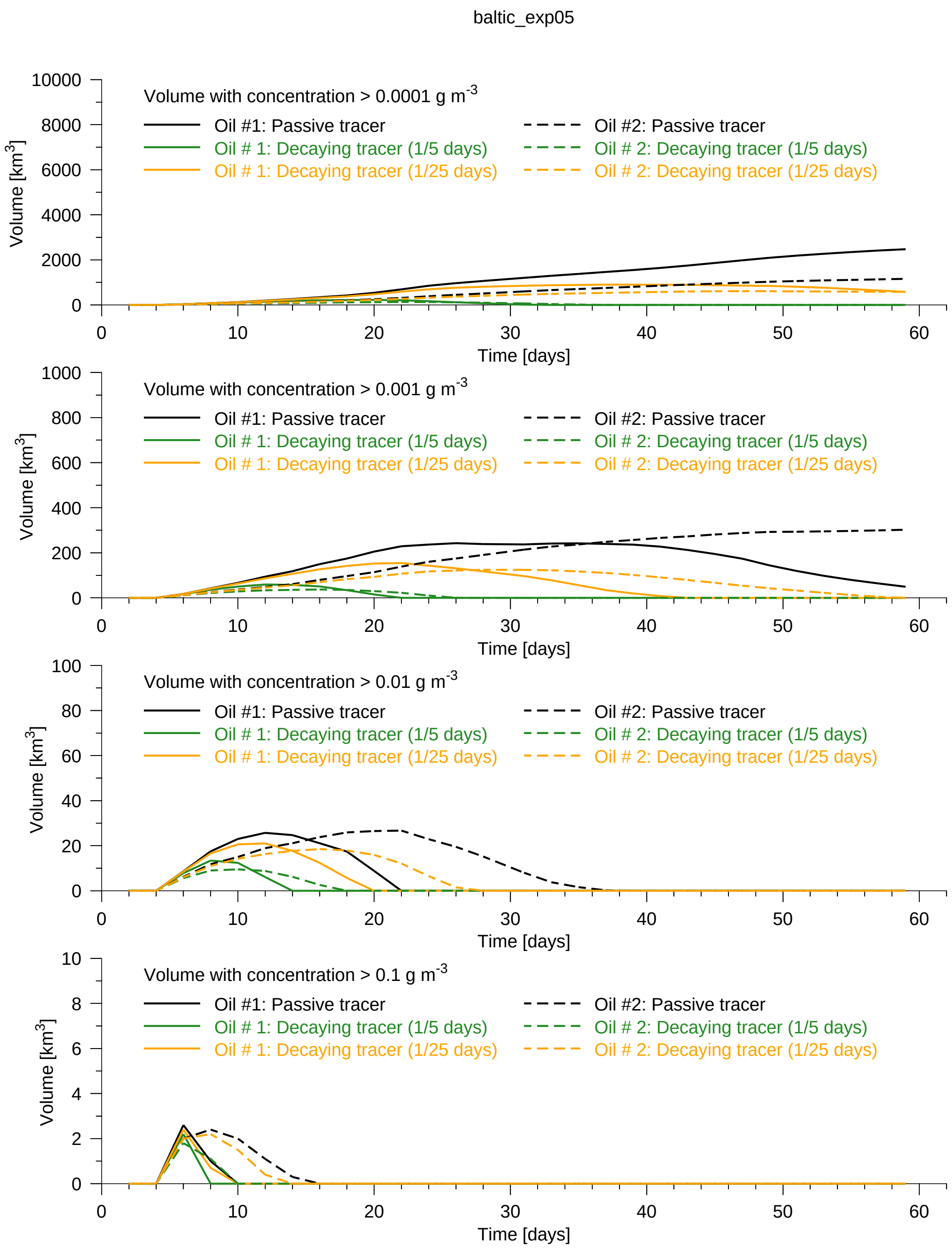

Figure 7: Threshold volume calculations for experiment baltic_exp05. The solid and dashed lines represent oil compounds from location 1 and 2, respectively (cf. Table 6).