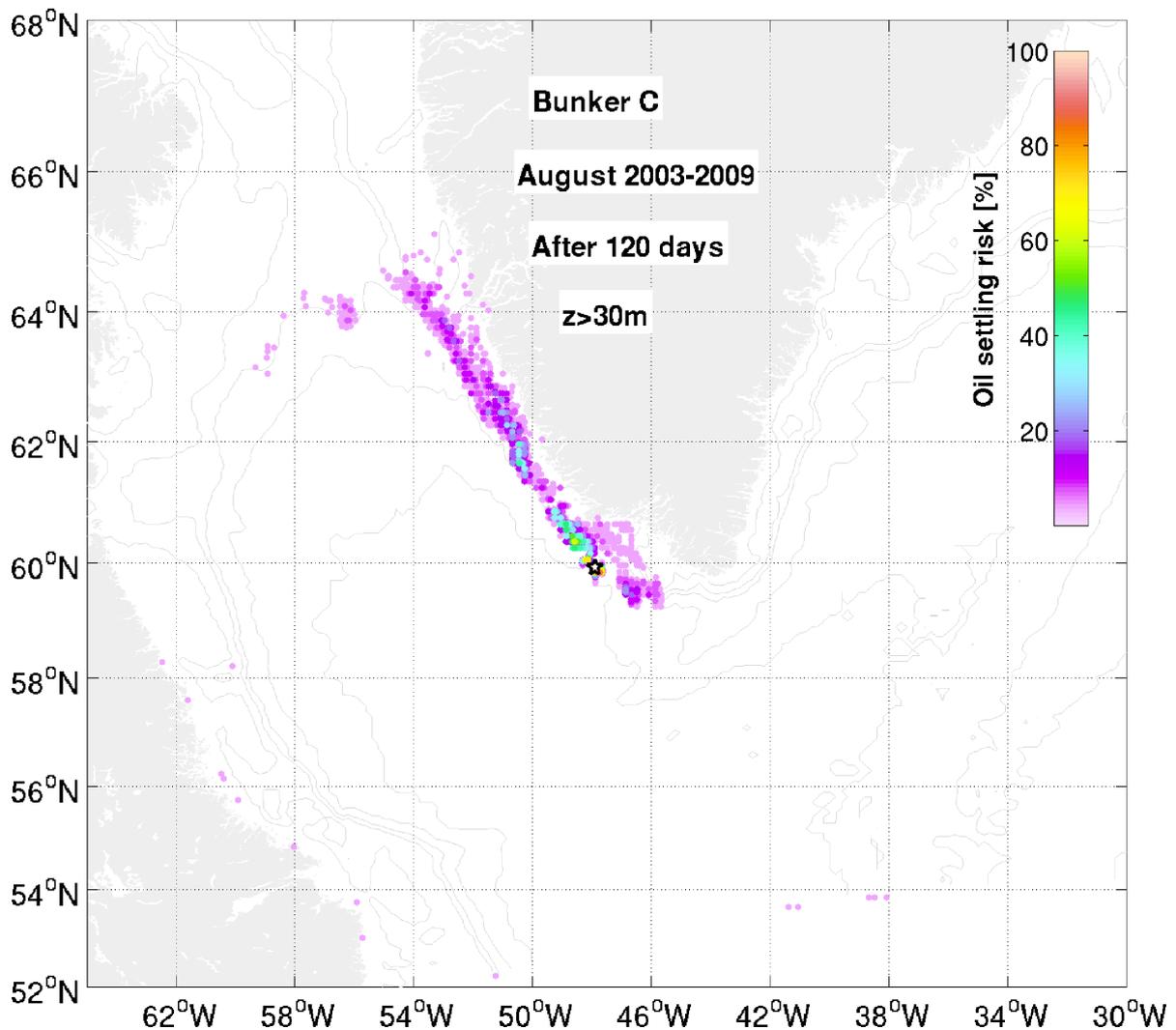




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Ensemble oil drift modelling for bottom spill off Southwest Greenland

Mads Hvid Ribergaard





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Abstract

An ensemble of four-month simulations of hypothetical oil spill from sea bed off Southwest Greenland results in estimates of the region affected, and an estimate of the probability of finding oil at a given location. Moreover the depth interval where dispersed oil is expected to be found is determined, the depth integrated oil thickness, how much has evaporated, and how much is grounded.

Resumé

Et ensemble af 4 måneders simuleringer af hypotetiske oliespild fra havbunden i de sydvest grønlandske farvande resulterer i en vurdering af hvilket område der påvirkes, samt et estimat af sandsynligheden for at finde olie i et givet område. Desuden bestemmes i hvilket dybdeinterval man kan forvente at finde olie, den dybde akkumulerede olietykkelse, hvor meget der er fordampet, samt hvor meget der er grundstødt.



1. Introduction

This report deals with oil drift simulations off Southwest Greenland focusing on the shelf region off Julianehaab Bight and further north. The calculations are done with an oil drift model which simulates the physical and chemical processes a hypothetical oil spill undergoes during the first days after the oil has been released from the sea bed into the sea water, and subsequently calculates the drift of the oil for an extended period. Prerequisites for the oil drift model are detailed knowledge of the surface wind and the 3-dimensional motion of the sea as obtained from the ECMWF ERA-Interim re-analysis and the semi-operational ocean model HYCOM-CICE, respectively.

A number of spill conditions have been prescribed by Aarhus University (AU), the department of biological sciences, Arctic environment¹ in order to represent envisaged oil spill conditions. 4 runs have been performed for each of the years 2003–2009 providing a total ensemble of 28 runs. Each run start in August (1., 11., 21., 31.) and all last for 4 months (122 days).

The work has been funded by AU, as part of the cooperation between AU and the Bureau of Minerals and Petroleum, Greenland Home Rule, on developing a Strategic Environmental Impact Assessment of oil activities in the Southwest Greenland waters.

The present report is a followup on the work done by Ribergaard et al., (2010). They did similar simulations from exactly the same location but for a hypothetical oil spill released at the surface whereas the present report deals with a hypothetical oil spill released at the sea-bed.

Much of the next chapters, describing the DMI oil spill model and the present setup, is similar to Ribergaard et al. (2010) but repeated for completeness. However, water density is now calculated and used together with water temperature as they are both important for a correct description of a sub-surface oil spill. In Ribergaard et al. (2010) these parameters was held constant throughout the simulations.

¹ Formerly: Danish National Environmental Research Institute (NERI)



2. DMI oil drift model

Since the 1990's, DMI has run an operational oil drift forecast service for the North Sea – Baltic Sea. Later this service has been extended by application of an oil drift and fate model (below referred to as DMOD), that in addition to passive advection, simulates a number of chemical processes collectively termed 'oil weathering'. The model applies surface winds and 3-dimensional ocean motion (horizontal and vertical current) in order to calculate drift and spreading of the oil. DMOD has been developed specifically for this region by the Bundesamt für Seeschifffahrt und Hydrographie (BSH) in Germany.

DMI has generalized and set up DMOD for Greenland waters and it is now in operational drift for the North Atlantic Waters. The forcing fields in the present simulations are obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) model ERA Interim re-analysis, and the coupled 3-D hydro-dynamical ocean and sea ice model HYCOM-CICE (HYbrid Coordinate Ocean Model/Community Ice Code), developed by the University of Miami and the Los Alamos National Laboratory.

DMOD runs decoupled from the weather and ocean models. With an extensive archive of HYCOM-CICE output data files, any period may be selected for spill studies once the drift model sub-region is properly defined.

The processes handled by DMOD are passive drift of oil, horizontal spreading, horizontal and vertical dispersion (by turbulent and buoyant motion), evaporation, emulsification (uptake of sea water), and settling on the bottom or at the shore. Dissolution and oxidation (by sunlight) are considered less important and are not included. Biodegradation is assumed to be important on long timescales only and is not modelled. The oil will either settle or stay in the water phase, and the only way oil can disappear from the simulations is by evaporation or emigration out of the model domain. A special procedure of taking the influence of sea ice on the oil drift into account has been implemented by reducing the effective wind speed according to the ice concentration (see below).

For a given spill, the oil is released into sea water at a fixed location (latitude, longitude, depth) either as an instantaneous release or at a fixed rate during a specified time interval. The ambient water temperature, provided by HYCOM, influences both weathering and the spreading processes. The water density is derived from HYCOM output of temperature and salinity and it has an influence on the buoyancy of the oil.

A brief summary of processes modelled by DMOD is given below. A detailed description of the processes and parameterizations are given in Dick and Soetje (1990), Christiansen (2003) and a general overview of the oil spill modelling is given by Reed et al. (1999). An overview of the present knowledge and gaps on marine oil fate from a deepwater blowout is given by Thibodeaux et al. (2011).

Oil particles

An oil spill is represented by a large number of particles, each of which has mass, volume and composition that change due to evaporation and emulsification processes. The total release may be envisaged as a particle 'cloud'. Each oil particle represents a fraction of the total release. A particle can not be subdivided but is treated as an entity, unable to interact with other particles. It is assumed to have a disc-like shape, with an area and thickness that increase and decrease respectively, as the oil spreads out horizontally. The particle thickness at the time of its release is 3 cm.

Oil composition

An oil particle is composed of 8 groups of hydrocarbon compounds including a residuum (tar). The initial composition constitutes an oil type. DMOD has 8 pre-defined oil types: 4 different crude oils and 4 fuel oils. The density of the oil is the weighted mean of the density of each compound which has densities within the range 710–1010 kg/m³. However, the composition, and the physical properties of the oil, changes with time due to weathering processes (see below).

Oil drift

The oil particles drift passively with the ocean current. In a thin surface layer the horizontal current is modified by adding a wind-induced logarithmic velocity profile which at the surface takes its maximum value of 3% of the wind speed. This compensates for the fact that due to finite vertical resolution the flow in the top layer (3 meter in HYCOM-CICE) may not be well enough resolved vertically to properly simulate drift of a surface oil slick with a thickness of a few centimeters. This wind-drift is reduced in the presence of sea ice depending of the ice concentration as discussed below. Both current and wind velocity are subject to turbulent motion modelled as random processes scaled by the velocity itself. Turbulence and sub-grid scale motion are further modelled by random walk, by giving the particles a small random motion on top of the passive drift, so that all particles do not experience exactly the same drift vector. This spreads out the particle cloud with time, even in total absence of wind or sea current.

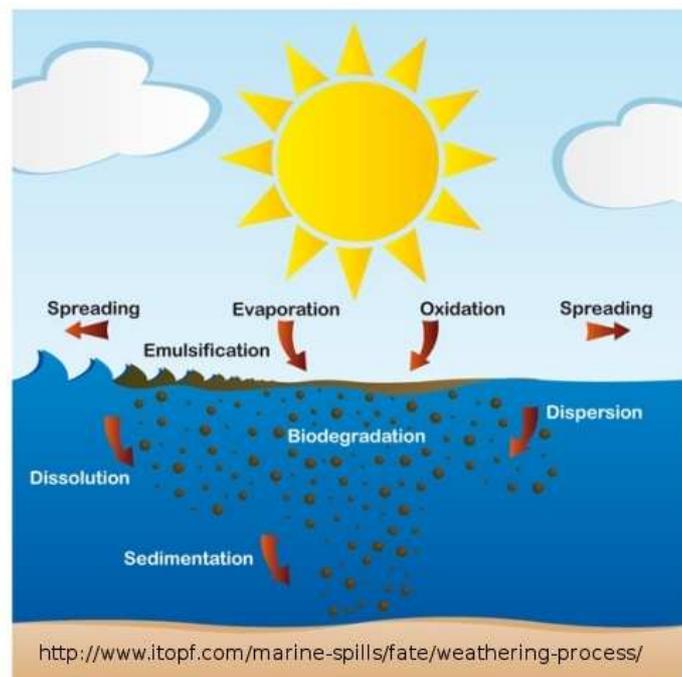


Figure 1. Weathering processes of an oil spill. From: <http://www.itopf.com/marine-spills/fate/weathering-process/>

The oil slick

Each oil particle gradually spreads out due to gravity, viscous forces and surface tension. The slick spreads out in three phases: initially the radius r increases by buoyancy-inertia forces, then, as the slick grows thinner, the spreading moves into a buoyancy-viscous regime, and the final stage is governed by viscosity and surface tension. The oil slick thickness decide which spreading phase is active. The slick area depends on the (strictly theoretically based) slick radius as $A = \pi r^2$. The limiting area (and thus thickness) of the slick depends on total spill volume as $A \text{ [m}^2\text{]} = 10^5 V^{3/4} \text{ [m}^3\text{]}$. Under constant wind and current, an instantaneous spill takes an asymmetric disk-like shape, elongated in the wind direction, while a continuous spill will resemble smoke from a chimney.

Weathering

An oil particle undergoes weathering processes that begin to act immediately or shortly after its release. Weathering processes is the collective term for oil spreading, evaporation, dispersion (vertical and horizontal), emulsification (uptake of sea water) and dissolution (Figure 1). These processes depend on the ambient water temperature and density, and the oil's chemical composition and physical properties (density, viscosity, maximum evaporation and pour point), and they change the composition, shape and total volume of an oil particle. Volatile components evaporate from oil at the sea surface, water is added through emulsification until saturated (when about two thirds of the particle is water), and the oil particle, being buoyant relative to sea water, displaces itself vertically and spreads out horizontally. The buoyant motion is modelled as a random process, dependent on a theoretical droplet size probability distribution. The density of the standard oil types within the oil spill model is all less dense than sea water. However as the oil uptake water (emulsification) and the lighter oil fractions evaporate the oil becomes denser. The downward mixing by surface waves is parameterized as a function of wind speed. The oil particles that are to be mixed downward are selected by a random process that sets in when the wind speed exceeds 5 m/s, and involves more and more particles as the wind speed increases. An oil slick resting at the surface will thus gradually be dispersed in windy weather. For further information on oil in sea water and weathering processes, see, e.g. Børresen (1993) and Christensen (2003).

Settling and emigration

Once released, an oil particle is tracked throughout the entire simulation period. When a particle sinks to the sea bed or reaches the shore (the model does not distinguish between the two), it settles and ceases to be active. The particle can not re-suspend or be washed off-shore again. The weathering processes are also assumed to come to a halt. The particle may also drift out of the model domain, and thereby cease to be active. All particles (active and inactive) are part of the statistical description of the total release or spill outlined below.

Oil in ice-covered waters

At low ice concentration the oil will simply drift and spread along with the ice floes. In case of nearly open water, the presence of ice does not strongly influence the drift and spreading of oil. As the ice concentration increases, the floes begin to interact and the movement of the ice then no longer directly reflects the prevailing wind and current.

In the present simulations, the influence of sea ice on the oil drift has been implemented by an algorithm taking sea ice concentration into consideration. The ocean surface currents is scaled linearly with the fraction of open waters, thus oil drift velocity is reduced in ice covered areas. A more correct implementation would additionally take the sea ice velocities into account, so that the ocean current equals ice velocity when ice concentration is 100%. This has not been implemented in the present setup. The ice concentrations are very low and often absent throughout most of the experiments for the selected area and time of year.

Drift model output

An oil drift simulation results in time series of mean position of the oil slick, total volume and area, and a percentage distribution of oil at the surface, dispersed vertically (in the water column), settled and evaporated, plus the total water uptake. The position and composition of each oil particle are also recorded.



Gridding

The oil particle cloud is gridded onto the DMOD model region and resolved in the vertical into a 0.5 m surface (skin) layer. The grid cell area is approximately 4 km² (0.2° latitude by 0.4° longitude). The depth of a particle determines its affiliation to one single layer (the vertical particle extent is of the order of mm or less, and therefore disregarded). Horizontally, a particle is treated as a square. It may cover more than one grid cell, and it may cover a grid cell only partly. The thicknesses of all particles covering a grid cell fully or partly, weighted by the fraction of the cell the particle covers, are added up, resulting in an oil thickness for that cell.

Slick thickness and oil concentration

The oil thickness can be directly converted into an oil volume per area: a thickness of 1 mm corresponds to a volume of 1000 m³/km². For the surface skin layer, the accumulated thickness is the gridded result. Conversion into oil concentration in subsurface layers is less straightforward (see schematic vertical distribution of oil particles in Figure 1). When a surface slick of 1 mm thickness is mixed downward, the resulting concentration will depend on the mixing depth. Mixing a 1 mm slick down to 10 m depth results in a concentration of 100,000 ppb total hydrocarbon in the top 10 m. From the DMOD output, however, there is no simple or obvious way of telling whether an oil particle located at a certain depth originates from below (subject to buoyant rise) or from above (subject to wave-induced downward mixing). Therefore, in this study a particle is assumed only to pollute the layer in which it resides. It is thus implicitly assumed that the oil is evenly distributed over the layer in question. To some extent the resulting concentration depends on the vertical subdivision of the water column.

In this report the concentration can be estimated by combining the depth integrated oil thickness and the standard deviation of the mean oil depth.

Validity

The advective-dispersive part of the drift model has been proven to give excellent results, provided the forcing data (wind and current maps) has high quality. In two cases in the Danish Domestic Waters, an oil spill caused by an accident at sea resulted in pollution of coastal stretches. Both timing and extent was well predicted by DMOD (Christiansen, 2003). Similar, using the same model, DMI recently made it plausible that oil pollution in September 2011 in the Kattegat at the Swedish west coast at Tjörn just north of Gothenburg stems from an oil spill due to a ship collision off Thyborøn on the northwest coast of Denmark.

(http://www.dmi.dk/dmi/dmi_sporer_kilde_til_olieforurening_i_sverige)

The oil weathering part is theoretically based, and the DMOD implementation has, to the authors' knowledge, not been tested against field data. The same is true for the oil concentrations resulting from gridding and post-processing.

3. Model setup

The oil drift module DMOD are forced by atmospheric re-analysis data (ERA Interrim) and ocean forcing (HYCOM-CICE) for the 7 year period 2003-2009 during two periods from August to November.

At present, ERA Interrim from ECMWF is believed to be the best available re-analysis for the atmospheric conditions for the past decades. It is using 4D-var assimilation techniques for observations, have a horizontal resolution of about 0.7 degrees and output time step of 3 hours.

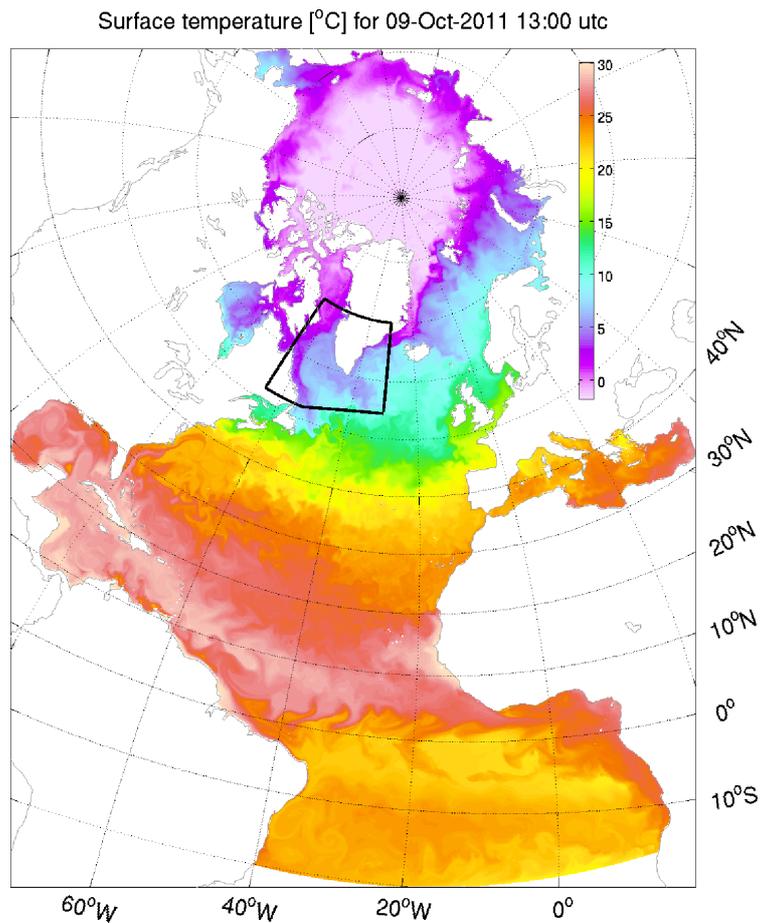


Figure 2. Model domain for the HYCOM-CICE ocean and sea ice model with modelled surface temperature valid at 09th October 2011 at 13:00 UTC. The model has a horizontal resolution of about 10 km. Black box showing the sub-domain extracted for the DMOD oil drift model for the present study.

The present ocean model setup is the same setup as used by Ribergaard et al. (2010) for a similar oil drift experiments for surface spills. It has significantly improved since the latter HYCOM setup (Ribergaard et al., 2006) also used for similar oil drift experiments (Nielsen, et al., 2006, 2008). The present model domain covers the entire Atlantic Ocean including the Arctic Ocean in an approximately 10 km horizontal resolution with 29 hybrid z and/or sigma vertical layers (Figure 2). For the Greenland Waters a correct representation of the sea-ice is crucial. Not only for the ocean properties beneath the sea-ice but also “upstream” the sea-ice, as continuous melting of the sea-ice e.g. within the East Greenland Current modifies the surface density and therefore give momentum in the surface currents. The sea ice module (CICE) has been coupled to the ocean model HYCOM. Beside thermodynamic, CICE also calculates sea-ice drift. The representation of the tides is represented as a body tide forcing using 8 constituents. Surface sea temperatures and ice

concentrations are assimilated into HYCOM-CICE on a daily basis. More than 100 rivers are included as monthly climatologic discharges obtained from the Global Runoff Data Centre (GRDC)² and scaled as in Dai and Trenberth (2002).

The model has been “spun up” from Levitus climatology by repeating year 1999 a number of times to adjust the vertical structure before starting the simulating of the period 2000-2010. ERA Interrim acts as the atmospheric forcing for the HYCOM-CICE model setup used for this study. Output frequency for the oil drift module is one hour for surface quantities and three hours for deeper layers. Values in deeper layers are linear interpolated to one hour time step for use in DMOD.

The oil drift module operates on a regular longitude-latitude mesh. Both the atmospheric and hydrodynamic models are interpolated in time and space onto the mesh of the oil drift model DMOD in time steps of one hour. The DMOD grid for the present setup covers the region approximate 65-30°W, 52-70°N with a latitude/longitude resolution of 0.2°/0.1°, respectively (approx. 10 km). The model has 30 layers, with layer interfaces located at 1, 5, 10, 20, 30, 50, 75, 100, 125, 150, 200, 300, 400, 500, 600, 700, 800, 900, 1000, 1100, 1200, 1300, 1400, 1500, 1750, 2000, 2500, 3000, 3500, 4000 m depth, which almost correspondence to Levitus depths with an addition of 5 meters. The gridded current velocities represent the average velocity of the layer in question. The particle advection velocity is found by bi-linear interpolation in the horizontal and linear in vertical in the DMOD data cube. The ocean velocities are then interpolated twice from the basic data: from HYCOM-CICE to DMOD grid and from DMOD to particle position. For the wind component an extra interpolation step is done as the wind component is initial interpolated to HYCOM-CICE grid.

The time step for all DMOD processes (as described above) is one hour. While fully adequate for chemical processes, this may be considered an upper limit for advective processes in flow with a strong tidal component and for vertical displacement by buoyancy forces.

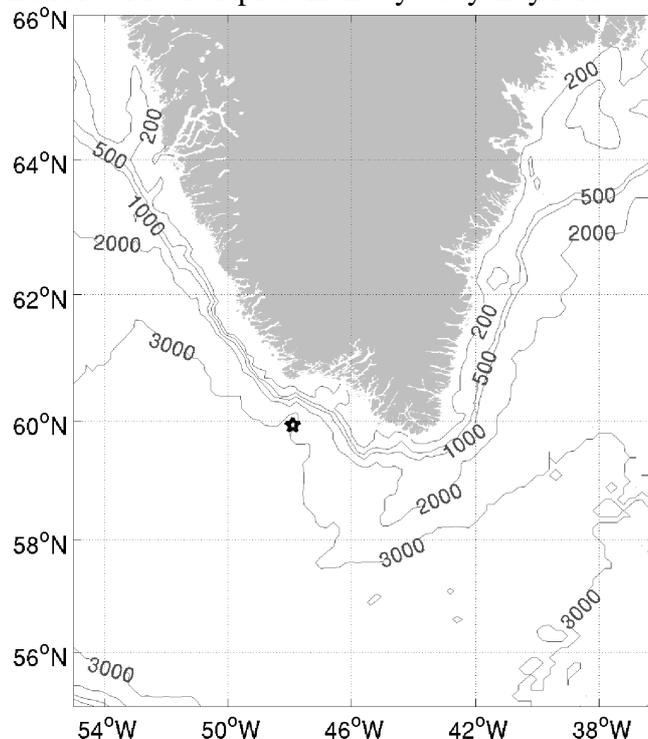


Figure 3 Map showing the bathymetry with yellow stars indicating the hypothetical spill positions. The position is 47°53'44''W ; 59°55'40''N and the interpolated model depth is 3073.7 meters. Release depth is 3.7 meters above bottom at 3070 meters. Depth contours shown: 200, 500, 1000, 2000, 3000 meters.

² <http://grdc.bafg.de>

4. Simulations

A hypothetical oil spill from bottom off Julianehaab Bight off Southwest Greenland was given (Figure 3). A continuous spill of ten days duration, taking place on 3070 meter depth 3.7 meter above seafloor within a subsurface canyon. The oil slick is then tracked for a further 112 days, in order to simulate the spreading of the oil within the subsurface until concentrations are low and/or until the oil has settled on shore or at bottom. The full simulation period is thus 122 days. The simulations are started day 1, 11, 21 and 31 in August from each of the seven years 2003-2009. Thus a total of 28 simulations are carried out over a 4 month period (August-December). Four crude oils are used given a total of 112 simulations, but only two of them are presented in this report graphically.

The oil is released at a constant rate of 3,000 t/day during the first ten days of each simulation. The total amount of oil released is 30,000 tons represented by 3000 individual particles. Four different oil types are chosen as the oil type representative for the region is unknown for us (Table 1). Two of them are presented graphically in the appendices, as they show quite different behavior:

- “Bunker C” represent the densest standard oil within the oil spill model and will evaporate about 10% within a day when it is present at the surface.
- “Statfjord” is a less dense North Sea crude oil which will evaporate about one third during the first 24 hours when present at the surface. This oil was used by Ribergaard et al. (2010) for a similar experiment but for surface spills.

All oil types have less density than the seawater off Southwest Greenland, which typically have densities within the range 1023–1028 kg/m³ with lowest densities over the continental shelf (see eg. Ribergaard, 2011). However, uptake of seawater (emulsification) and evaporation of the lighter fractions makes the oil denser.

Fraction	Description	Bunker C	Statfjord	Ekofisk	Iso450
1	C ₆ -C ₁₂ Paraffin	0	15	20	5
2	C ₁₃ -C ₂₅ Paraffin	1	13	15	5
3	C ₆ -C ₁₂ Cyclo-Paraffin	5	14	20	1
4	C ₁₃ -C ₂₃ Cyclo-paraffin	1	12	20	1
5	C ₆ -C ₁₁ Aromatic	5	7	7	1
6	C ₁₂ -C ₁₈ Aromatic	1	3.5	4	1
7	C ₉ -C ₂₅ Naphtheno-Aromatic	1	3.5	4	1
8	Residual Incl. Hetero-cycles	86	32	10	85
Total	[Percentage]	100	100	100	100
Oil density	[kg/m ³]	992.6	886.3	845.5	978.8

Table 1 Fraction of different compounds for the selected crude oils. The oil fractions 1, 3, and 5 will evaporate in less than two days if the oil is in contact with the atmosphere. Fractions 2, 4, 6 and 7 are volatile on longer timescales, while the tar residuum persists. The density of the oil fractions are in the range 710–1010 kg/m³.



5. Results

A total of 112 oil spill scenarios have been simulated using four different oil types, 7 years (2003–2009) started 4 times a year every 10th day (1st, 11th, 21st, 31st August). Southwest Greenland waters are usually ice free during autumn with only low concentration of sea ice, when present. Therefore the present oil drift modelling experiments have been run almost without sea ice. Even so, when sea ice is present it is handled as described in Chapter 2.

The basic output of a simulation is an hourly 3D particle location (xyz) and property/status table. The particle property specifies its chemical composition, including water content. Its status include particle age, size, active/settled and inside/outside model domain and some average properties of all the particles.

Spill statistics is generated by making accumulated sums and maximum statistics over all particles, and careful gridding, taking into account the size of each oil particle. Oil probability in each grid cell is calculated by dividing the accumulated sums by the total accumulated number of particles. Maximum thickness is found by a simple search throughout the simulations.

Appendix A contains maps of the probability of finding oil at a given location for two oil types. Shown is the probability accumulated after 5–120 days of simulation. Oil within the whole water column and the whole water column excluding the surface 30 meters is considered. The probabilities are calculated as the accumulated time with oil in each grid cell for each of the 28 simulation. An example: If oil is present at day 1 and then again at day 10, 11, 12 and 13, it have been in the grid cell in total 5 days. Accumulated after 15 days oil has been present in 1/3 or about 33% of the time. If oil is not present from day 15 to 30 the accumulated probability after 30 days are 5/30 or about 17%. This process is repeated for all 28 individual ensemble runs and the results are plotted in Appendix B. The probability for finding oil at the coast is easily seen, as the particle stops moving as it has stranded, but still counts within the statistics. Note the values sometimes exceed the color scaling. Obviously, during the first 10 days the probability of finding oil is 100% at the release site.

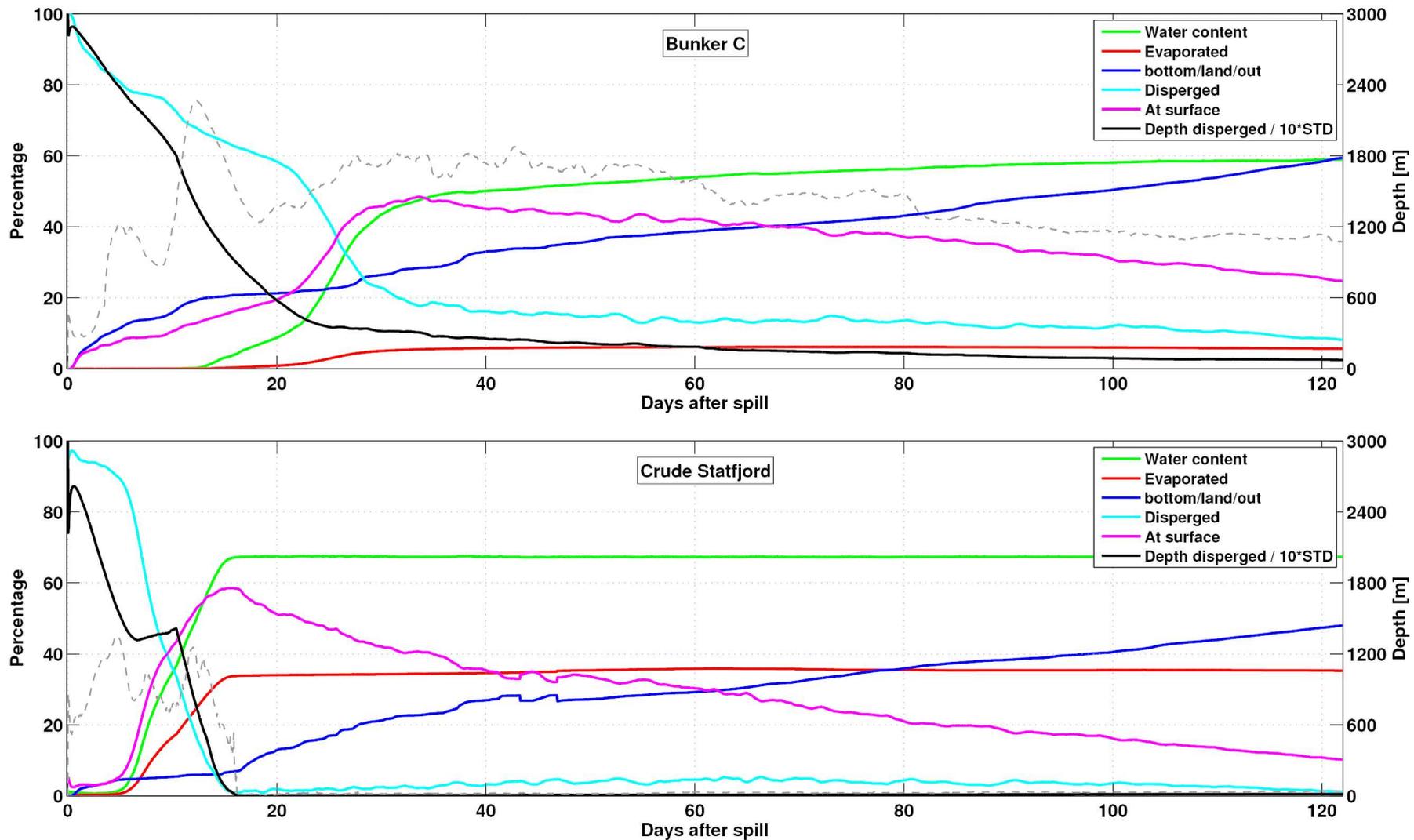


Figure 4. Oil history based on 28 ensemble runs as a function of time for a bottom release of two quite different oil types: "Bunker C" oil type (top) and the relative lighter oil type "Crude Statfjord" (bottom). Shown is the mean ensemble water content in percentage, the fraction of oil at surface, dispersed (within the water column), evaporated and oil settled either at bottom or land. Black line represents the mean depth of active oil excluding the oil at surface. Stippled thin line is the standard deviation of the mean depth multiplied by 10.

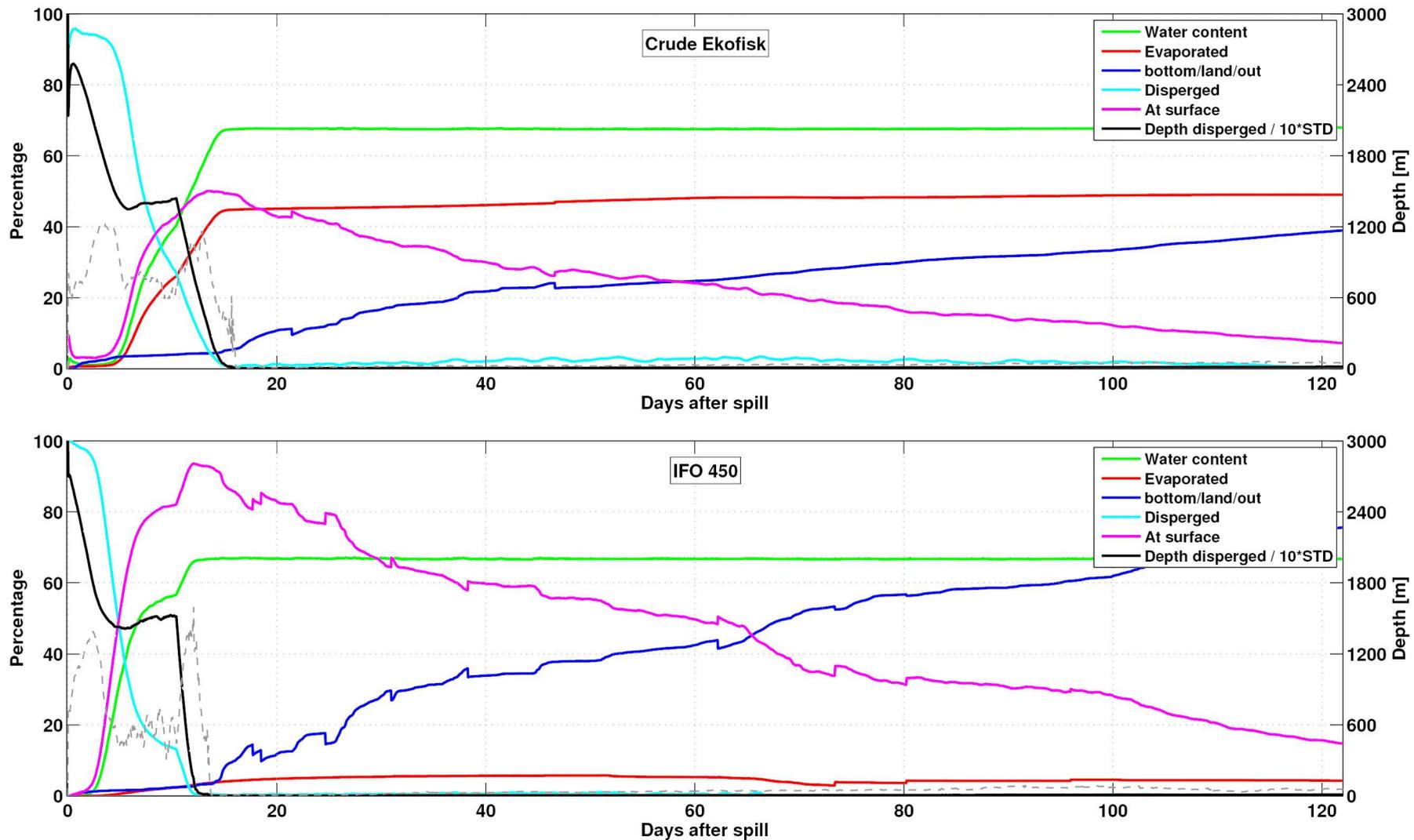


Figure 5. Oil history based on 28 ensemble runs as a function of time for a bottom release of two different oil types: "Crude Ekofisk" oil type (top) and the more dense oil type "ifo 450" (bottom). Shown is the mean ensemble water content in percentage, the fraction of oil at surface, dispersed (within the water column), evaporated and oil settled either at bottom or land. Black line represents the mean depth of active oil excluding the oil at surface. Stippled thin line is the standard deviation of the mean depth multiplied by 10.

Appendix B is similar to Appendix A except it shows the instantaneous probability derived from the 28 ensembles rather than the accumulated probability.

Appendix C contains maps of the risk of finding oil settled at the bottom excluding the upper 30 meters after 5–120 days. If oil settles at the bottom it will stay there throughout the rest of the simulation. Consequently the risk increases with time.

Appendix D contains maps of the depth integrated oil thickness, which can be used to estimate the oil concentration by combining the standard deviation of the oil mean depth.

Oil fate, settling and spreading

The fate of the oil for oil types “Bunker C”, “Crude Statfjord”, “Crude Ekofisk” and “ifo 450” is shown in Figure 4 and Figure 5.

Except for oil type “Bunker C”, within 15 days almost all the oil is found to be at the surface and the lighter part has evaporated which is only 5 days after the continuous release stopped. For “Crude Statfjord” a fraction (~5%) settle almost immediately after the release on the steep shelf slope close to the release site and only a small fraction do settle at the bottom along the West Greenland continental shelf slope (Figure 4, Figure 24–Figure 25). Hereafter, additional ~45% of the oil gradually settle – the main part on the West Greenland coast within the surface layers (Figure 10 – Figure 13). Most of it settle on the coast from 61–64°N, some reach 66°N and a minor part reach as far as 68°N and after 2 month even the Labrador Coast.

For the densest oil type “Bunker C”, a considerable fraction is found within the water column for several of months. After 20 days almost 60% of the oil is still dispersed at a mean depth of ~600 meter and after a month about 20% is dispersed at a mean depth of ~300 meter. The next three month the dispersed fraction decreases slowly to 10% and the mean depth is reduced to ~75 meter. About 20% of the oil do settle on the bottom close to the release point within the first 10 days. Additional, a fraction of the oil do settle mainly on the continental shelf slope along the West Greenland Coast as it moves north within the West Greenland Current (Figure 4, Figure 22–Figure 23). Stranded subsurface oil is in particular easily seen on the continental shelf slope and on the coast after 120 days in the instantaneous probabilities excluding the upper 30 meters (Figure 17), as stranded particles at any time keeps its position. A grand total of 60% has stranded or settled after 4 month. The main part of the stranded oil ends on the West Greenland Coast between 62–64°N at the beginning and between 61–66°N after 2-3 month. A small fraction does settle north to 67°N and on the Labrador coast.

The horizontal spreading of oil type “Crude Statfjord is higher than for “Bunker C” (Appendix A+B). The main reason is simply, that the less dense “Crude Statfjord” oil accent faster towards the surface where the horizontal spreading is much higher primarily due to wind forcing but also due to the stronger surface current velocities. This effect is easily seen by comparing the probability maps for the whole water column (Figure 6–Figure 7, Figure 10–Figure 11) to the probability maps excluding the upper 30 meters (Figure 8–Figure 9, Figure 12–Figure 13). Below 30 meters the oil is much more confined to the West Greenland continental shelf. The very low probabilities that covers almost all the Labrador Sea is likely due to strong wind events mixing the oil below 30 meter depth rather than spreading of oil within the sub-surface layers.

During the first month, “Bunker C” oil is mainly found along the West Greenland continental shelf break south of ~63°N (Figure 14), whereas “Crude Statfjord” oil is found north to about 64°N (Figure 18). This difference is mainly due to the fast accent of the “Crude Statfjord” oil, as it is

much more affected by the surface currents within the West Greenland Current but also the direct wind influence.

The oil affected areas for “Crude Statfjord” oil is quite similar to the findings from a surface spill experiment reported by Ribergaard et al. (2010) because the oil quickly accented to the surface and hereafter the oil is essential affected equal in the two studies. An interesting result is that East Greenland will not be affected by an oil spill off Southwest Greenland at the selected position off Julianehaab Bight even after 4 month of simulation. This result is independent on the oil type chosen and this result was also found by Ribergaard et al. (2010).

The oil concentration can be estimated from the depth integrated oil thickness maps in Appendix D in combination with the standard deviation of the mean depth of oil shown in Figure 4. For “Bunker C”, the resulting oil concentration is generally lower compared to “Crude Statfjord” due to the large presence of sub-surface oil spread vertically with a standard depth deviation of about 120–180 meters. Opposite, the “Crude Statfjord” oil type quickly accented to the surface concentration vertical in a much thinner depth interval resulting in higher oil concentrations despite of its higher evaporation.

Conclusion

The drift experiments with four very different oil types emphasis the importance of knowing the oil composition, as they give quite different results. For the crude oil “Crude Statfjord”, the vertical movement is fast and the resulting spreading is quite similar, but not equal, to a surface spill as reported in Ribergaard et al. (2010). However, similar simulating using the denser oil type “Bunker C” gives a quite different result. After one month about 20% is still disperged at a mean depth of ~300 meter and even after 4 month 10% is found at ~75 meters depth. However its depth integrated oil thickness which is linked to the oil concentration has decreased considerable.

For “Crude Statfjord” only a smaller fraction about 5% do settle at the bottom just after releasing. Contrary, for “Bunker C” about 20% do settle at the bottom just after release, and an additional fraction do settle along the continental shelf slope as it moves north within the West Greenland Current.

Consequently, given the much longer time in the subsurface “Bunker C” oil type is potentially a much more severe risk for pollution than the three other oil types. However, as it will stay subsurface longer time, the horizontal spreading is lower mainly due to lower influence directly by the wind but also the strong surface currents.



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Appendix A. Probability maps (accumulated)

The probabilities are calculated as the accumulated time with oil in each grid cell for each of the 28 simulation (7 years times 4 runs). An example: If oil is present at day 1 and then again at day 11, 12, 13 and 14, it have been in the grid cell in total 5 days. Accumulated after 15 days oil has been present in 1/3 or about 33% of the time. If oil is not present from day 15 to 30 the accumulated probability after 30 days are 5/30 or about 17%. This process is repeated for all 28 individual ensemble runs. The probability for finding oil at the coast or bottom is easily seen, as the particle stops moving as it has stranded, but still counts within the statistics. Note the values sometimes exceed the color scaling. Obviously, during the first 10 days the probability of finding oil is 100% at the release site.

These probability maps is shown for two oil types “Bunker C” and “Crude Statfjord” and for oil within the whole water column and for oil dispersed below 30 meters depth.

Note, the maps do not tell if the concentration of the settled oil is high or not. An estimate of the oil concentration can be estimated by combining the depth integrated oil thickness given in Appendix D and the standard deviation of depth given in Figure 4.

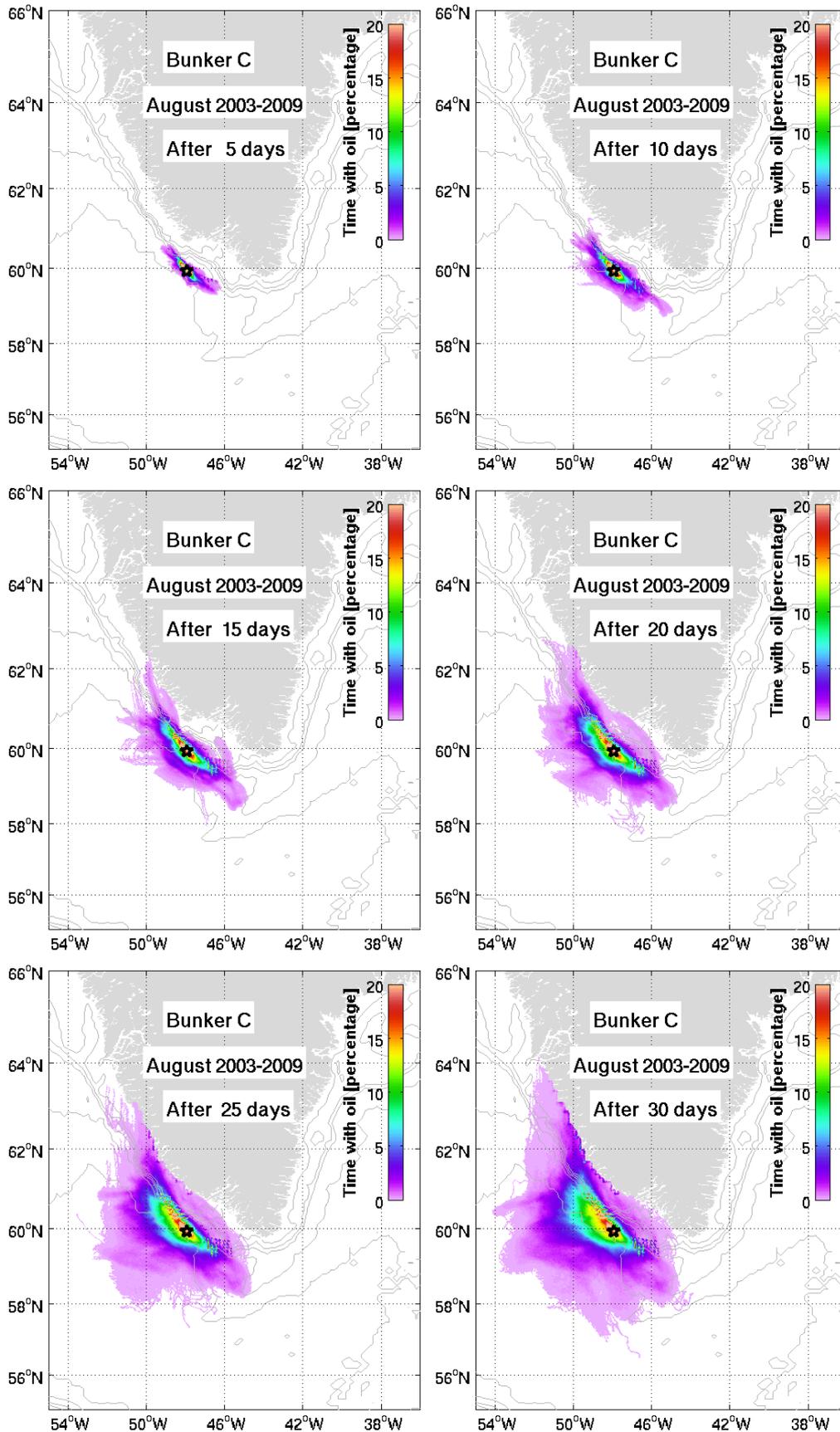


Figure 6. Probability maps for oil type “Bunker C” accumulated after 5–30 days of simulation using 28 ensembles. The oil is released during August/September over a 10 day period from bottom. The colors represent the percentage of time a grid box was filled by oil. Ex. 10% time with oil after 15 days simulation is 1½ day with oil.

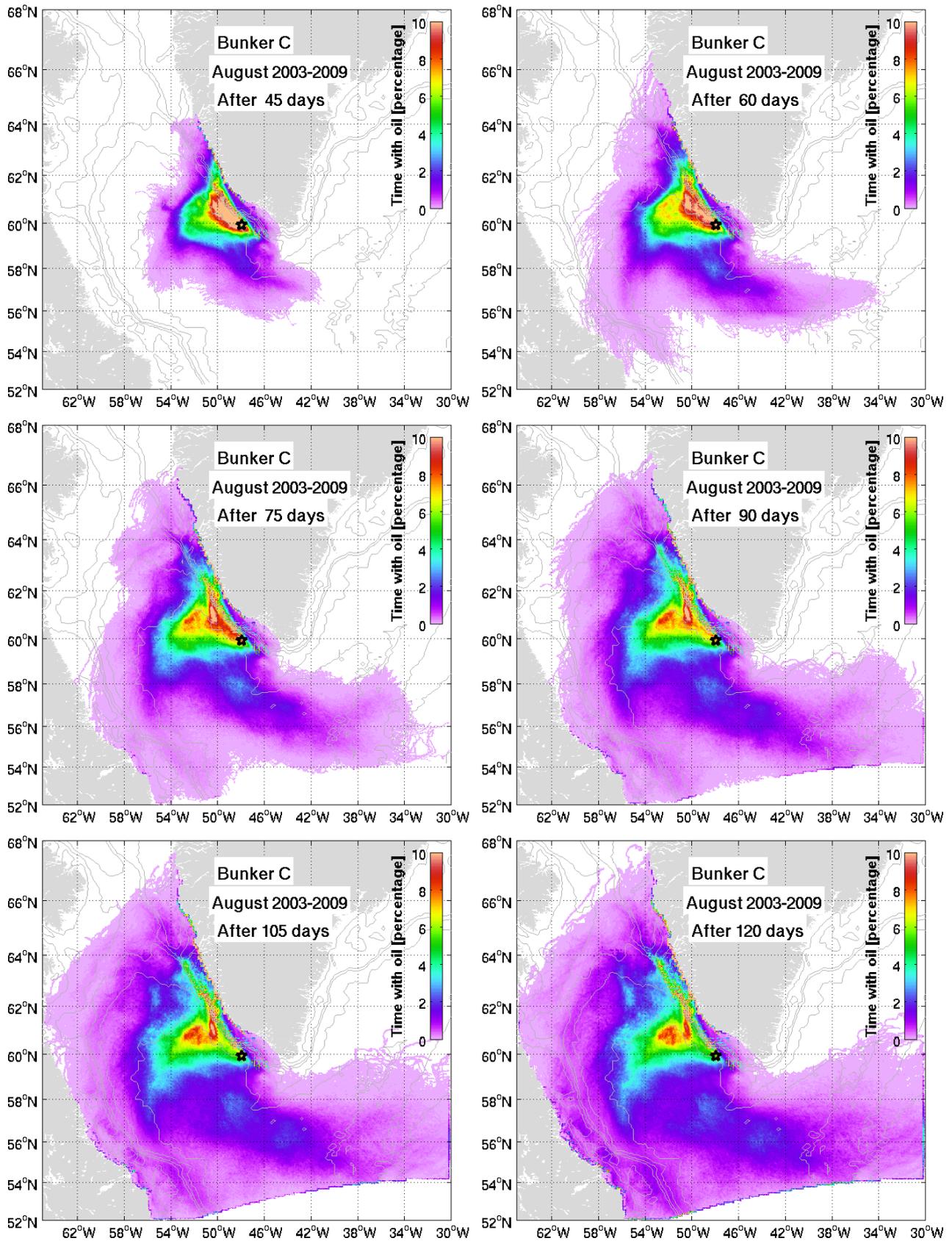


Figure 7. As previous figure but after 45–120 days of simulation. Note different color scale and different area.

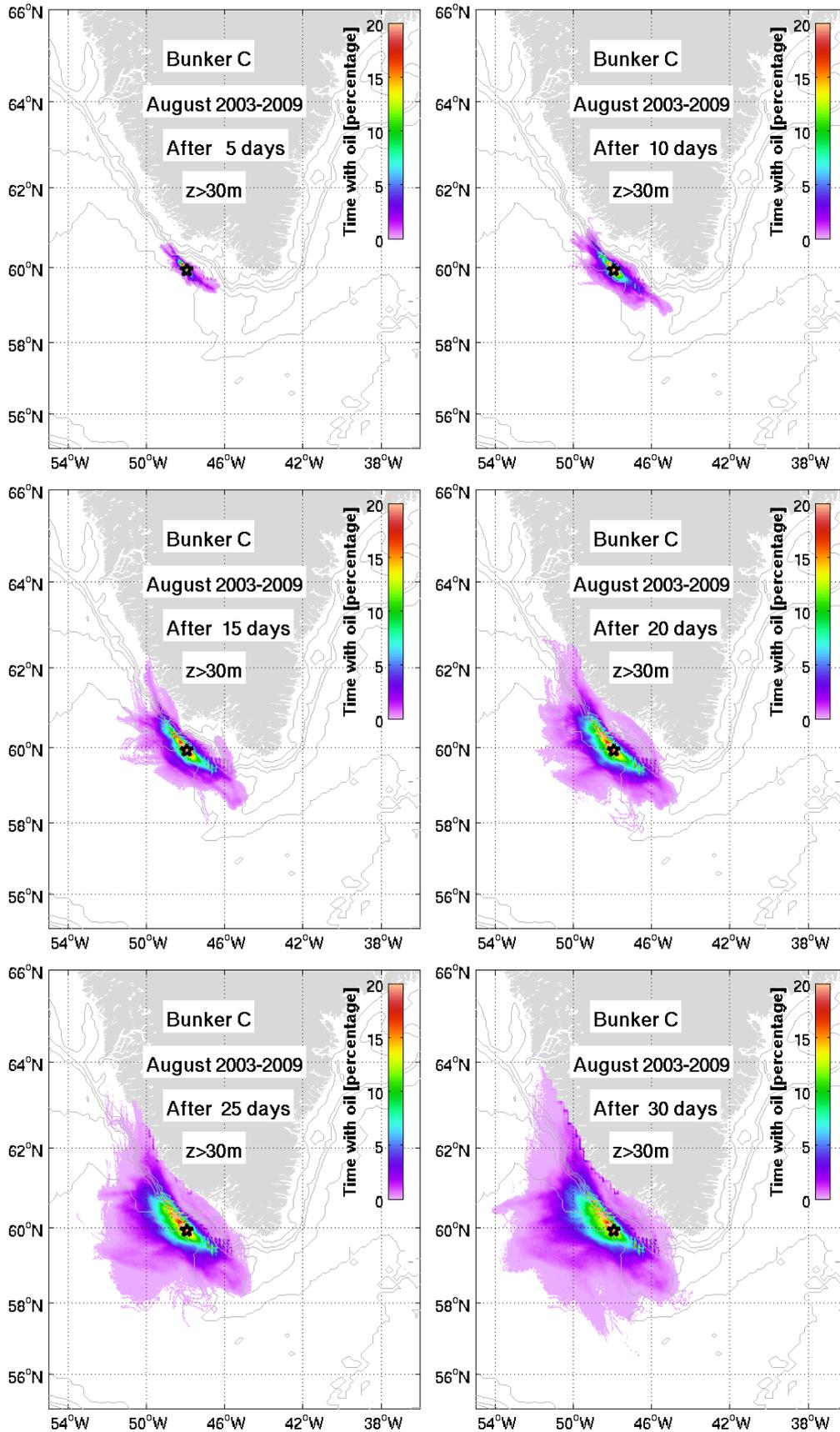


Figure 8. Probability maps excluding upper 30 meters for oil type “Bunker C” accumulated after 5–30 days of simulation using 28 ensembles. The oil is released during August/September over a 10 day period from bottom. The colors represent the percentage of time a grid box was filled by oil. Ex. 10% time with oil after 15 days simulation is 1½ day with oil.

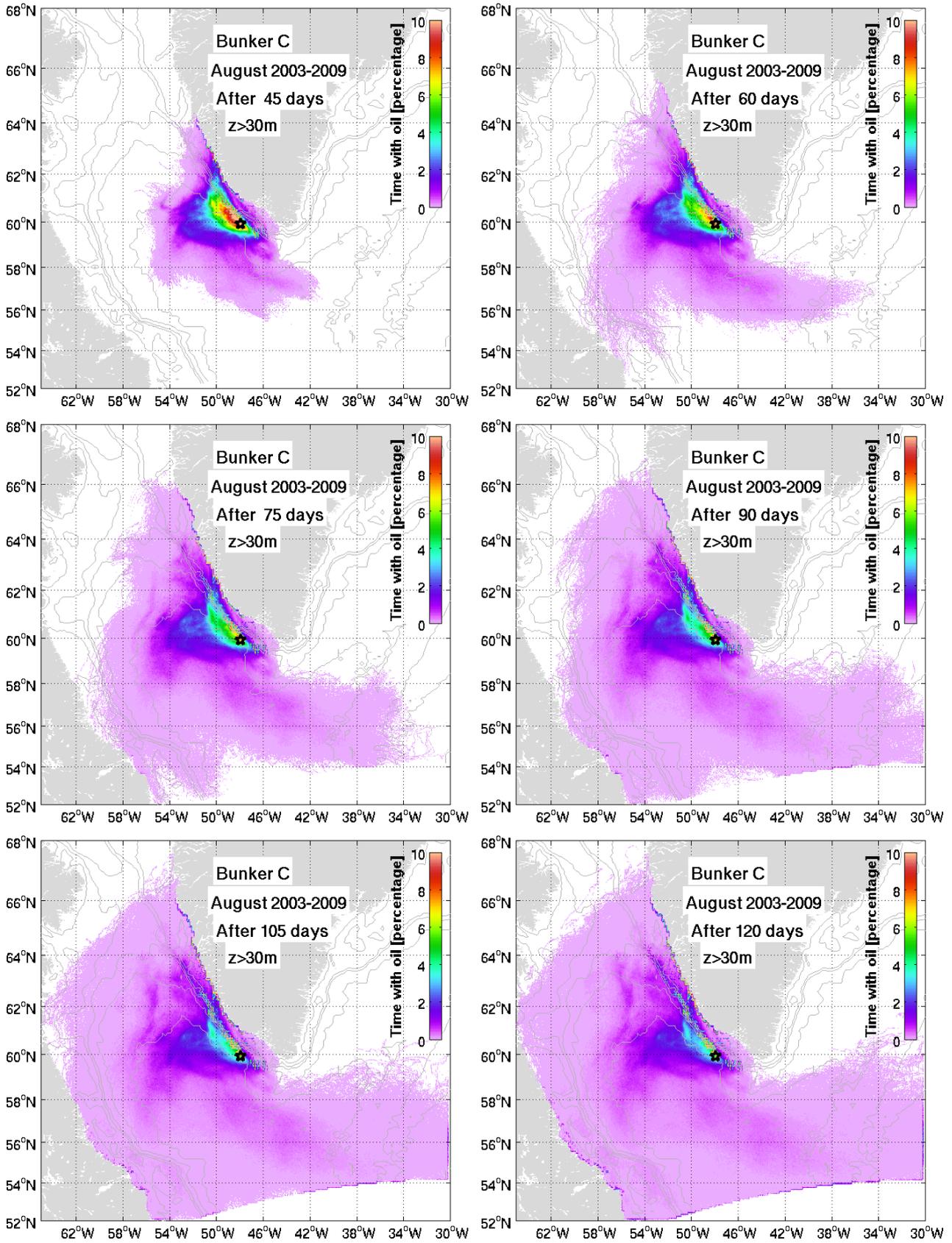


Figure 9. As previous figure but after 45–120 days of simulation. Note different color scale and different area.

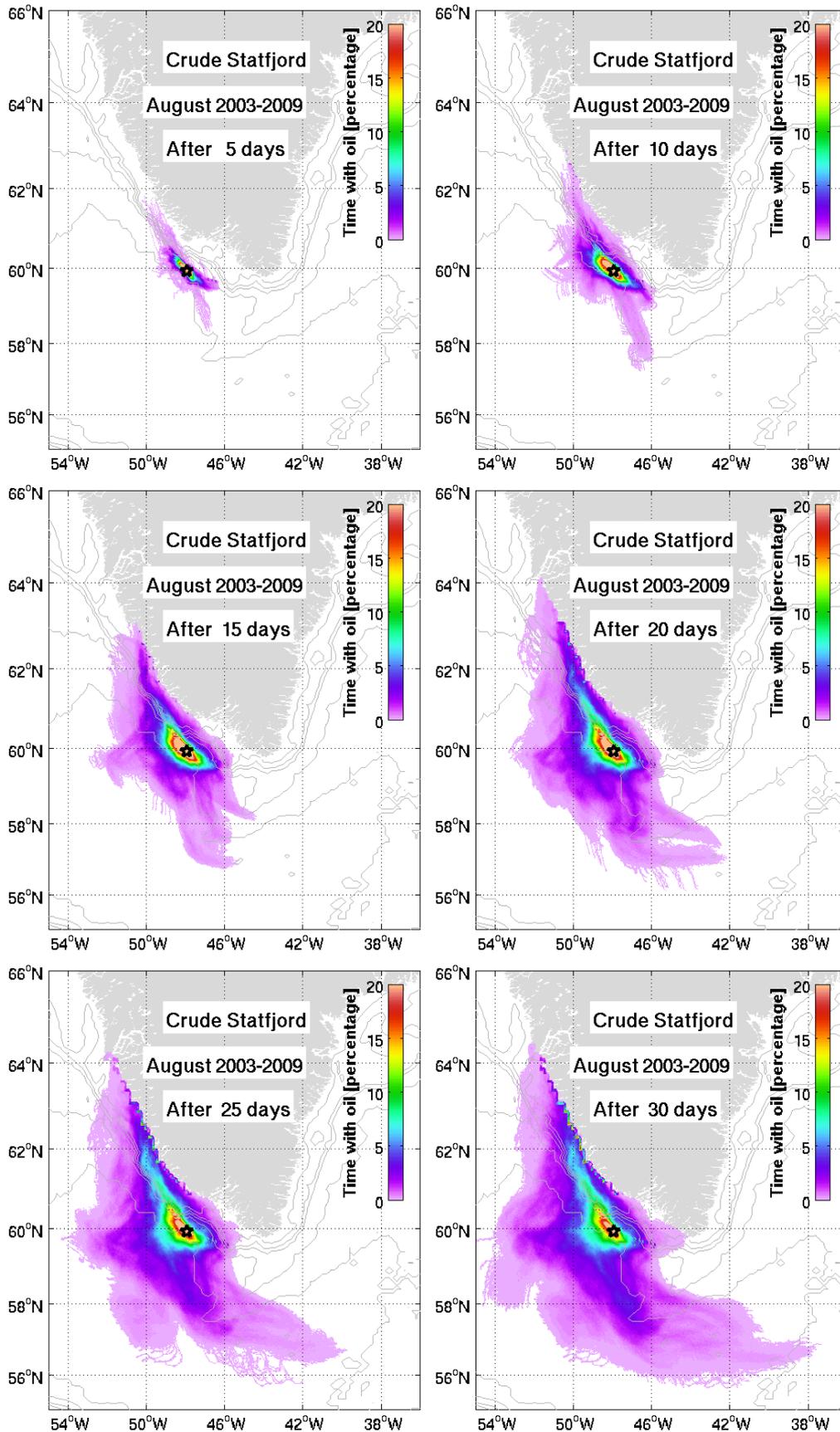


Figure 10. Probability maps for oil type “Crude Statfjord” accumulated after 5–30 days of simulation using 28 ensembles. The oil is released during August/September over a 10 day period from bottom. The colors represent the percentage of time a grid box was filled by oil. Ex. 10% time with oil after 15 days simulation is 1½ day with oil.

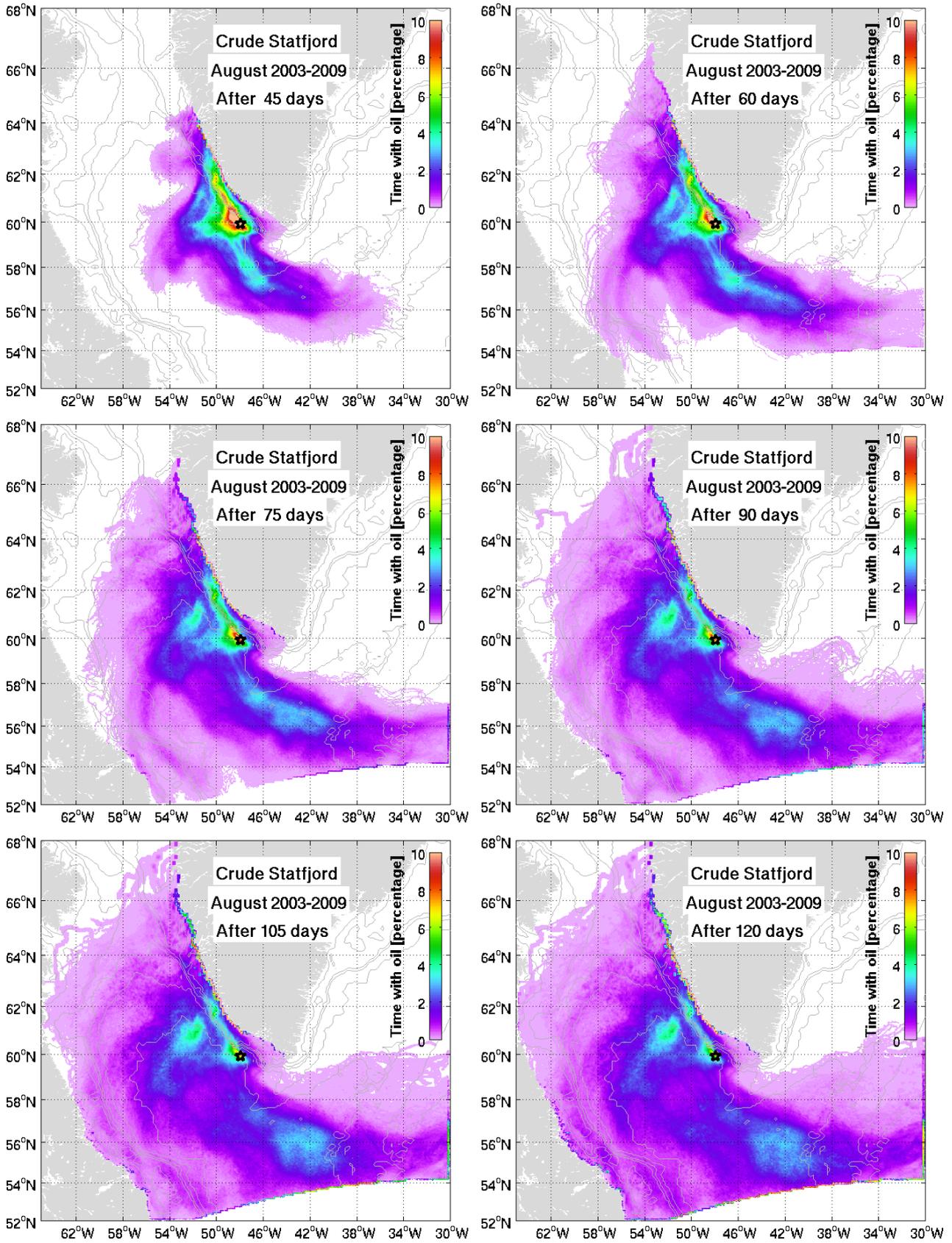


Figure 11. As previous figure but after 45–120 days of simulation. Note different color scale and different area.

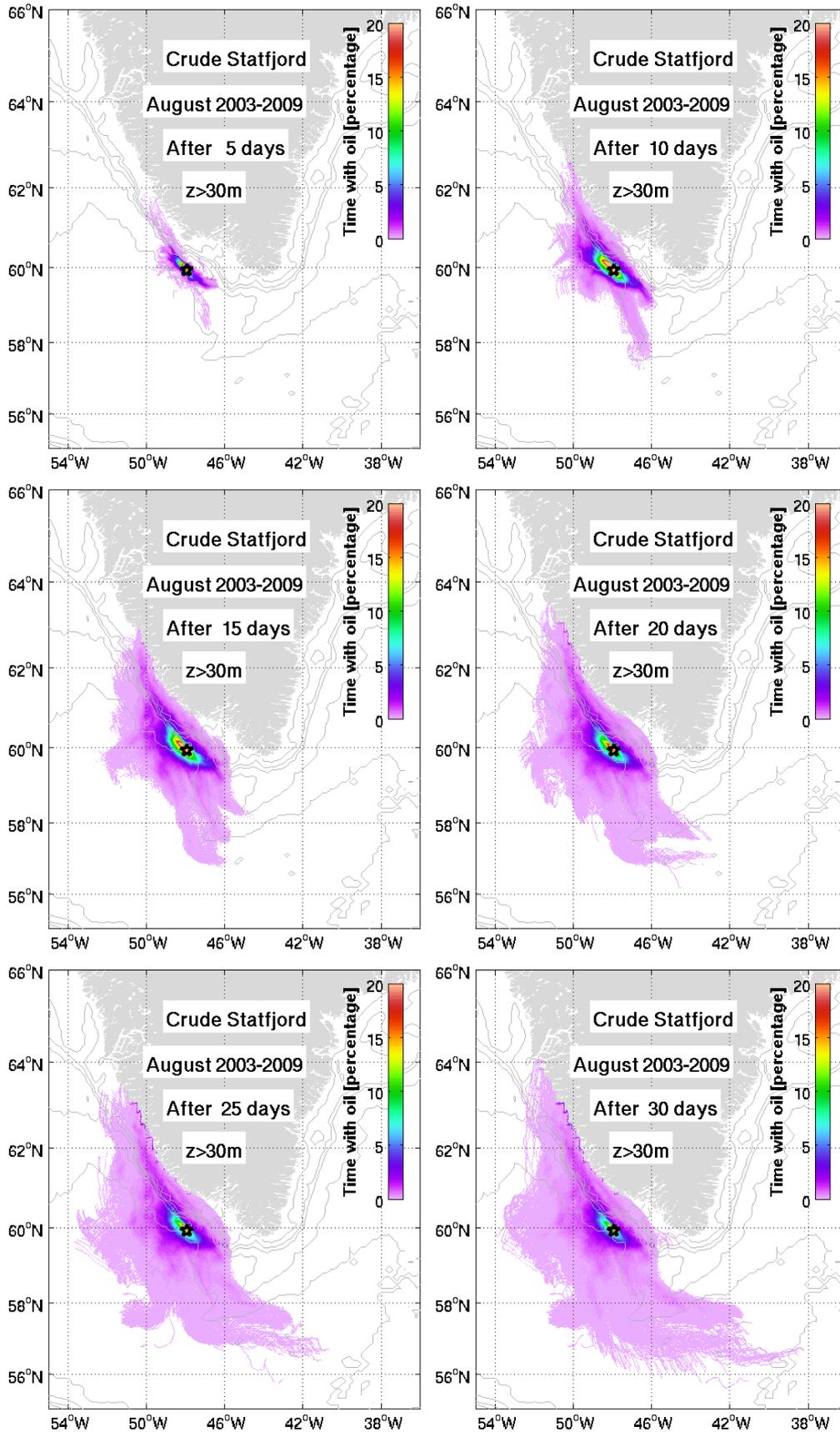


Figure 12. Probability maps excluding upper 30 meters for oil type “Crude Statfjord” accumulated after 5–30 days of simulation using 28 ensembles. The oil is released during August/September over a 10 day period from bottom. The colors represent the percentage of time a grid box was filled by oil. Ex. 10% time with oil after 15 days simulation is 1½ day with oil.

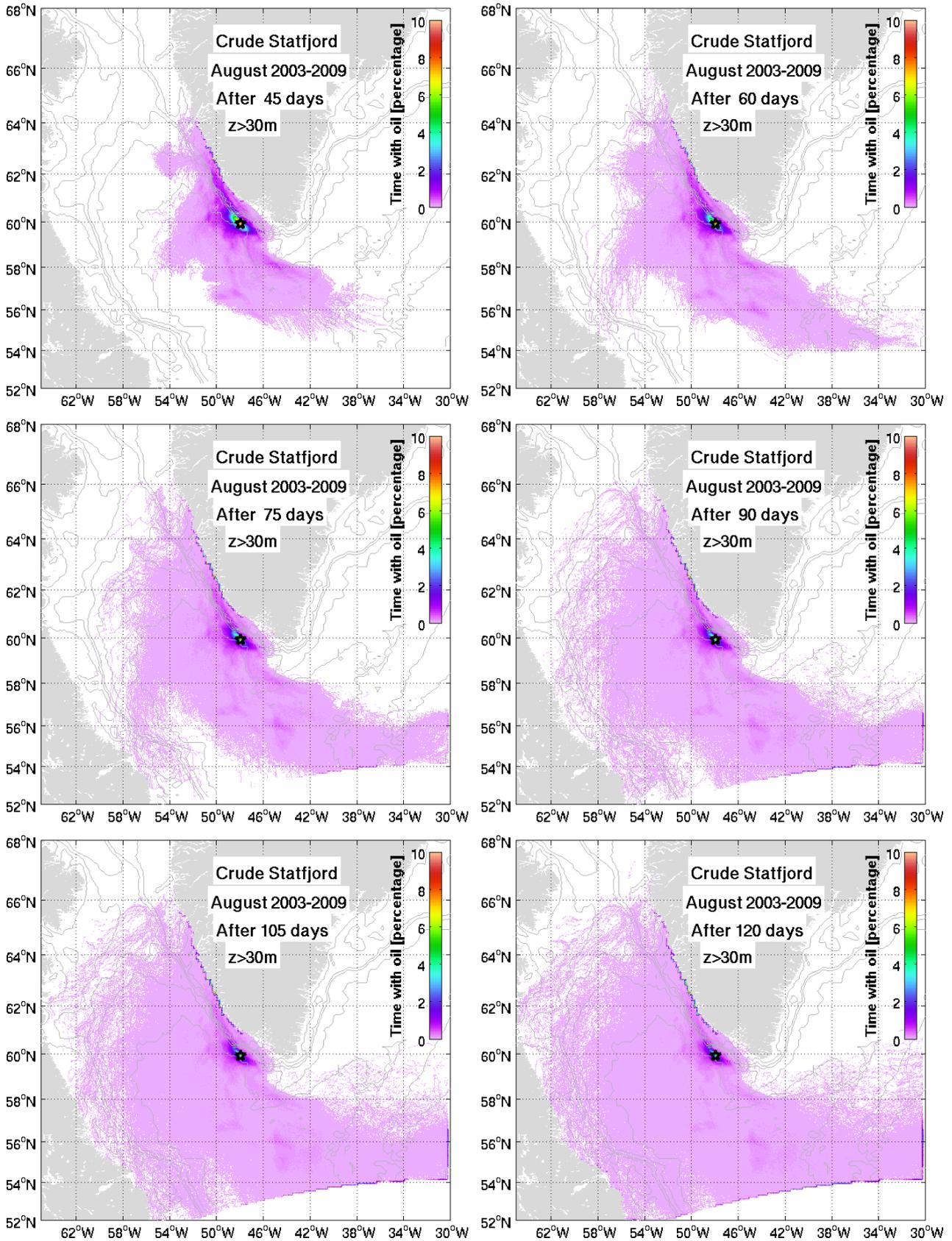


Figure 13. As previous figure but after 45–120 days of simulation. Note different color scale and different area.



Appendix B. Probability maps (instantaneous)

As Appendix A, except the probabilities are calculated as the instantaneous time with oil in each grid cell for each of the 28 simulation (7 years times 4 runs). Note as oil stand at the bottom or on the coast, it will be there for the rest of the simulation. Consequencely, stranded oil is easily recognized, when the oil has spread and drifted away from the coast at the end of the simulations. Oil stranded at the bottom is in particular easy recognized when excluding the upper 30 meters.

Note, the maps do not tell if the concentration of the settled oil is high or not. An estimate of the oil concentration can be estimated by combining the depth integrated oil thickness given in Appendix D and the standard deviation of depth given in Figure 4.

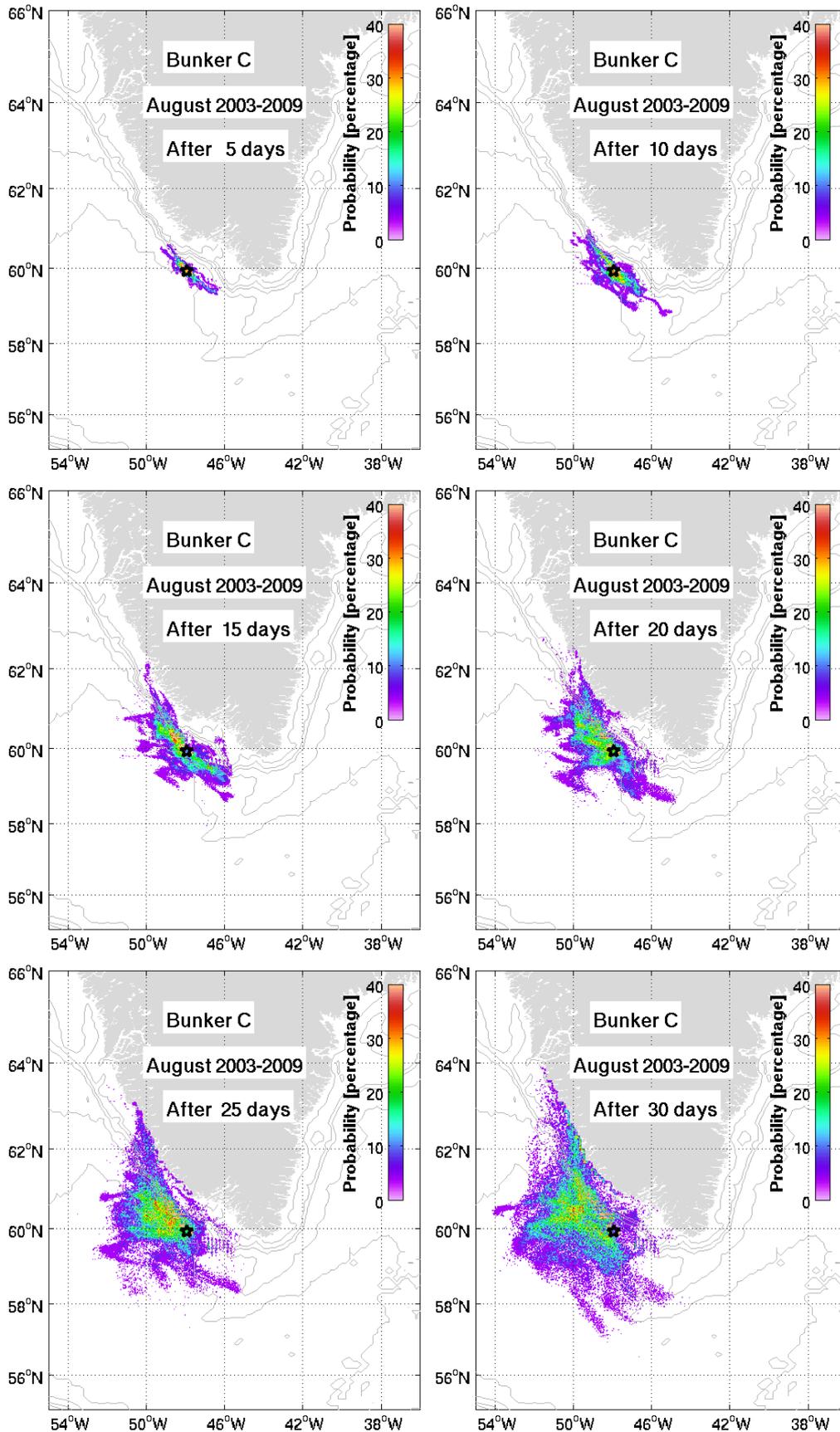


Figure 14. Probability maps (instantaneous) for oil type “Bunker C” after 5–30 days of simulation using 28 ensembles. The oil is released during August/September over a 10 day period from bottom. The colors represent the percentage of time a grid box was filled by oil. Ex. 10% time with oil after 15 days simulation is 1½ day with oil.

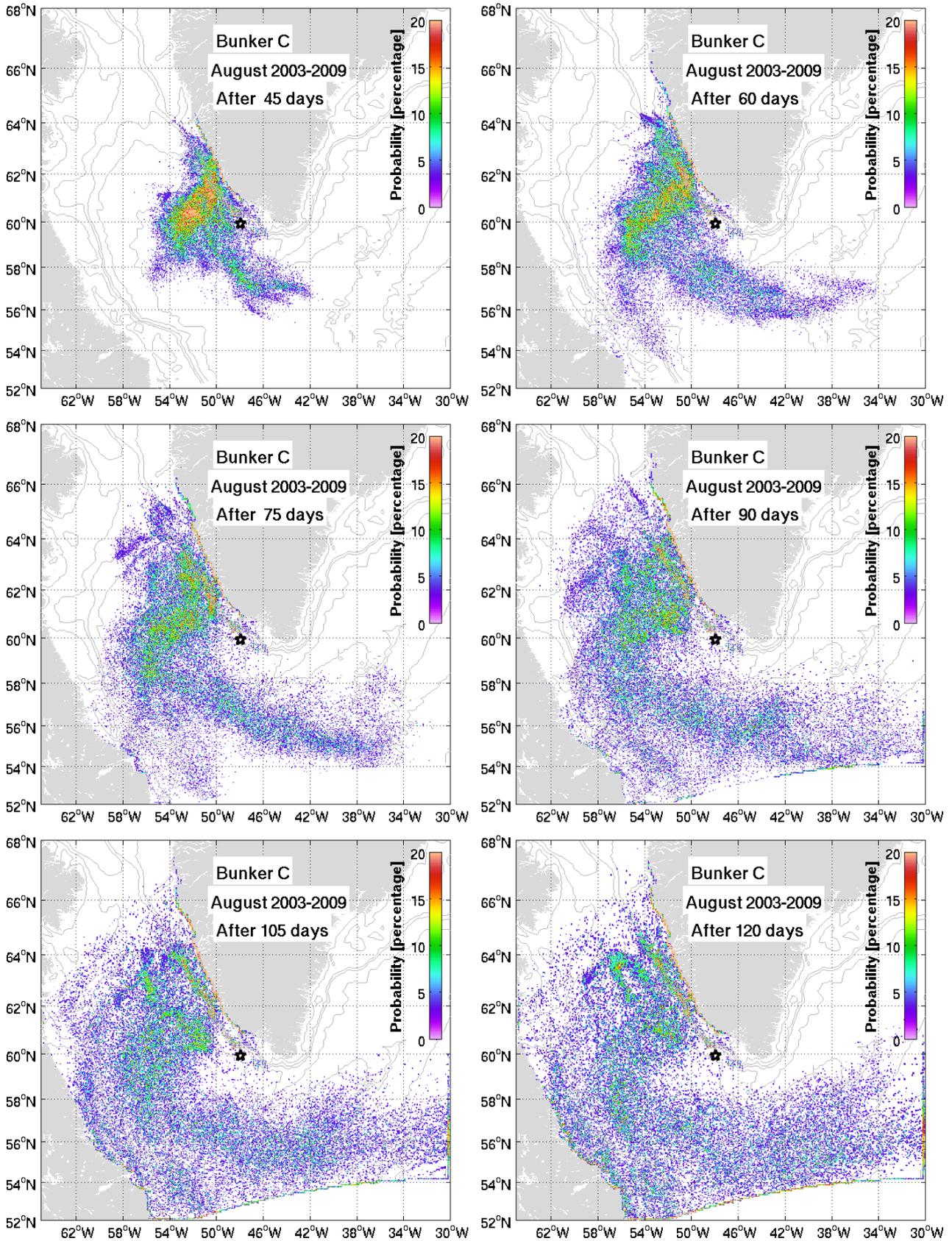


Figure 15. As previous figure but after 45–120 days of simulation. Note different color scale and different area. The high percentage at the bottom and right edge of the figure is an artifact due to oil escaping the extracted computation area.

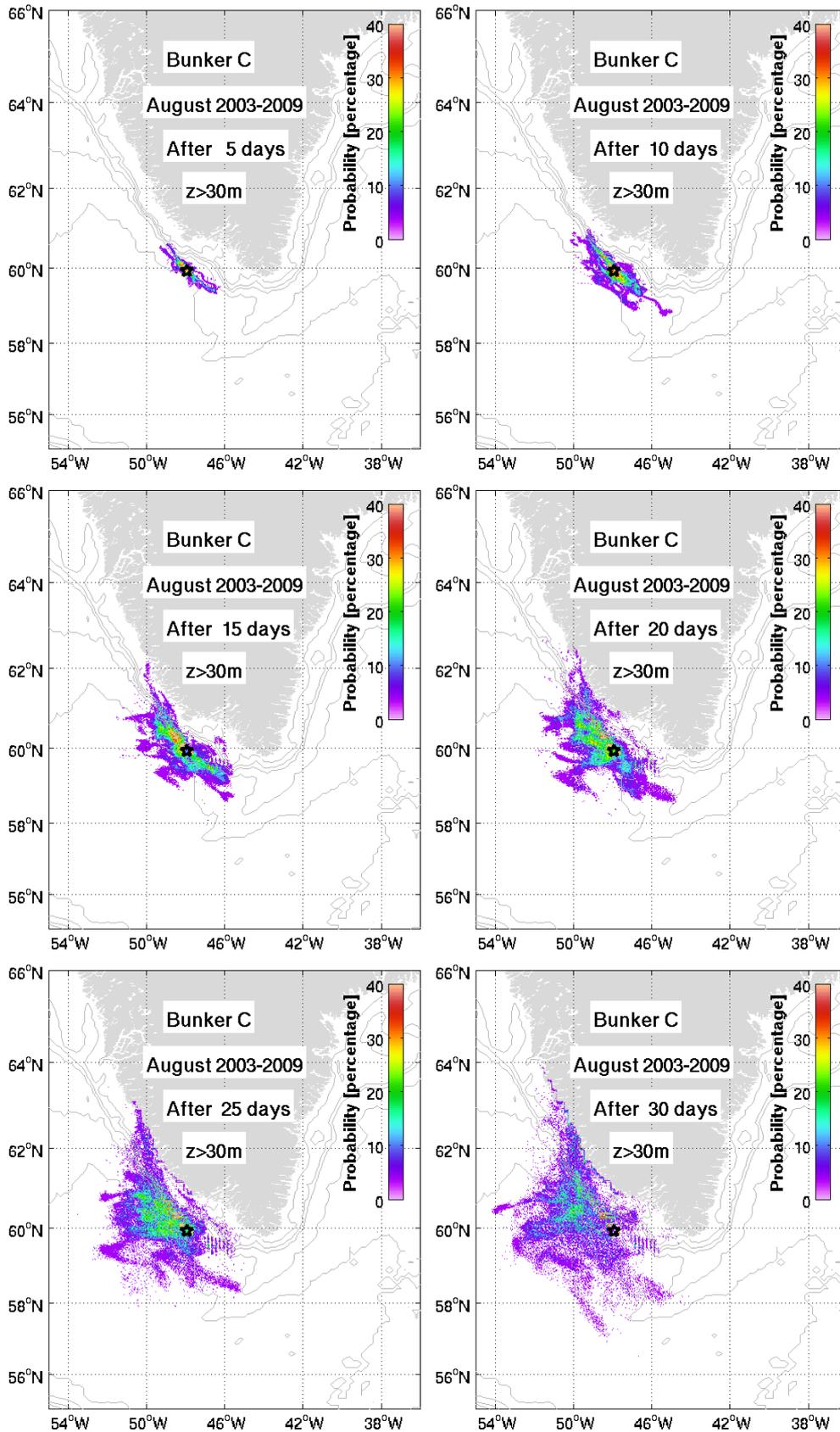


Figure 16. Probability maps (instantaneous and below 30 meters) for oil type “Bunker C” after 5–30 days of simulation using 28 ensembles. The oil is released during August/September over a 10 day period from bottom. The colors represent the percentage of time a grid box was filled by oil. Ex. 10% time with oil after 15 days simulation is 1½ day with oil.

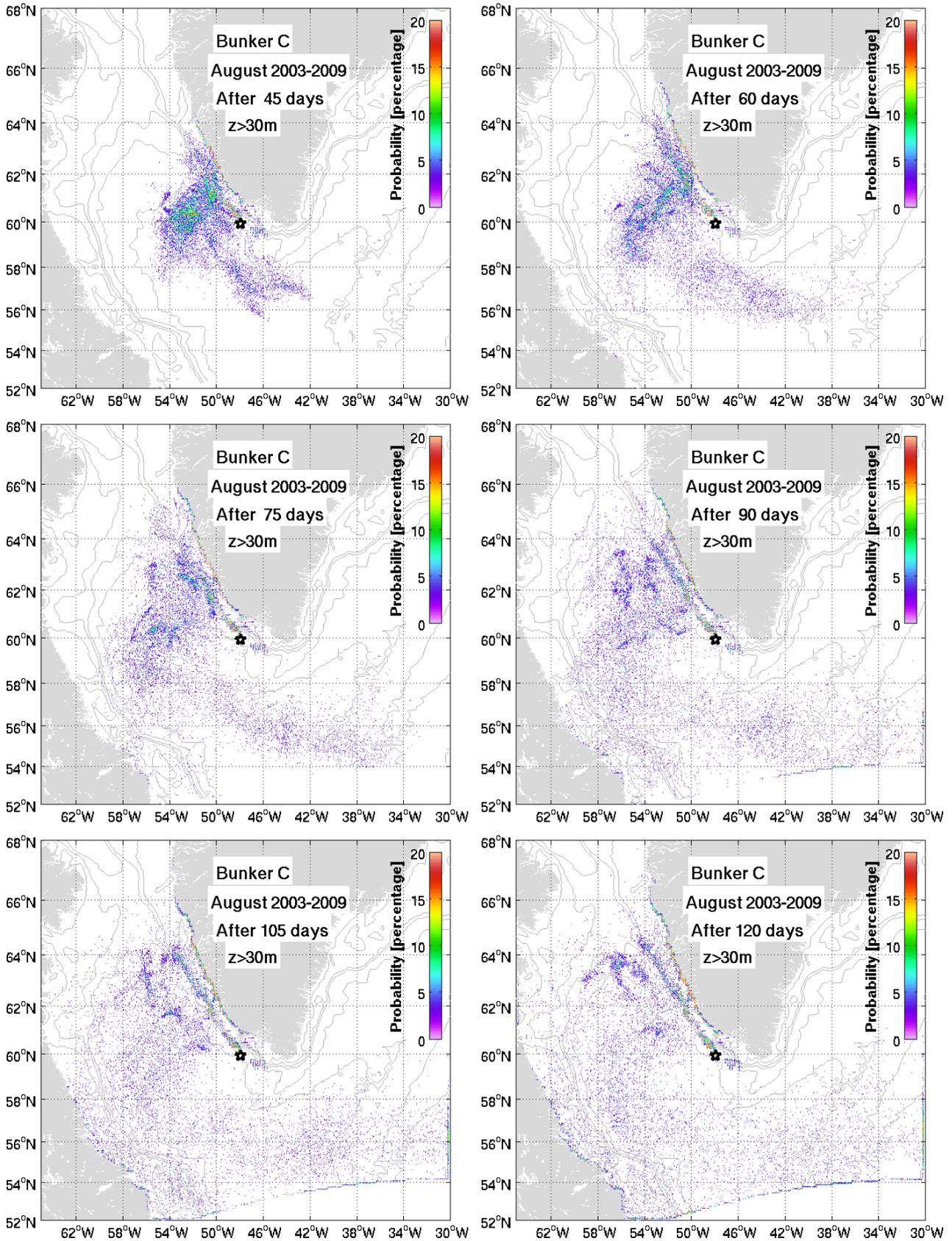


Figure 17. As previous figure but after 45–120 days of simulation. Note different color scale and different area. The high percentage at the bottom and right edge of the figure is an artifact due to oil escaping the extracted computation area.

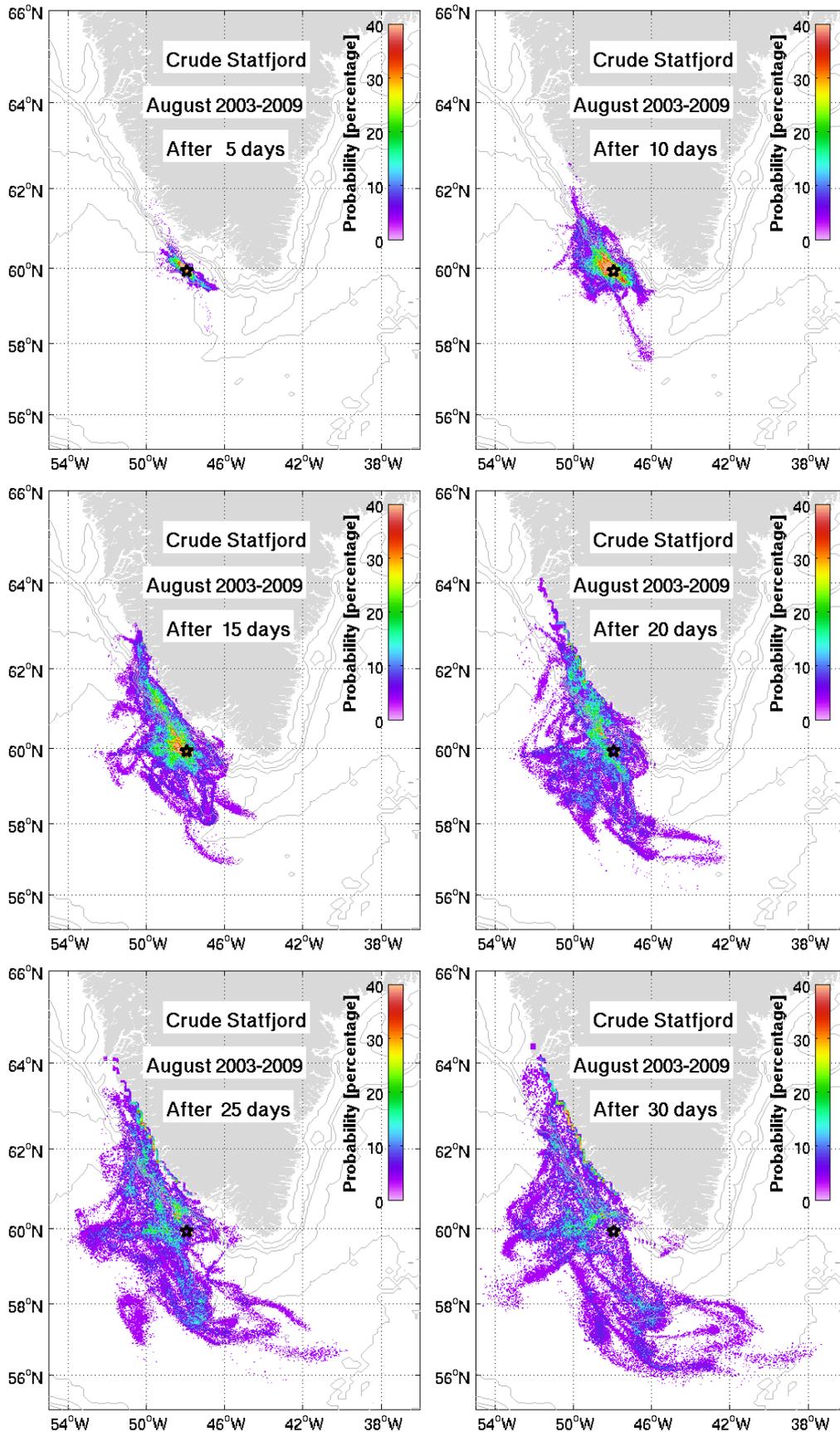


Figure 18. Probability maps (instantaneous) for oil type “Crude Statfjord” after 5–30 days of simulation using 28 ensembles. The oil is released during August/September over a 10 day period from bottom. The colors represent the percentage of time a grid box was filled by oil. Ex. 10% time with oil after 15 days simulation is 1½ day with oil.

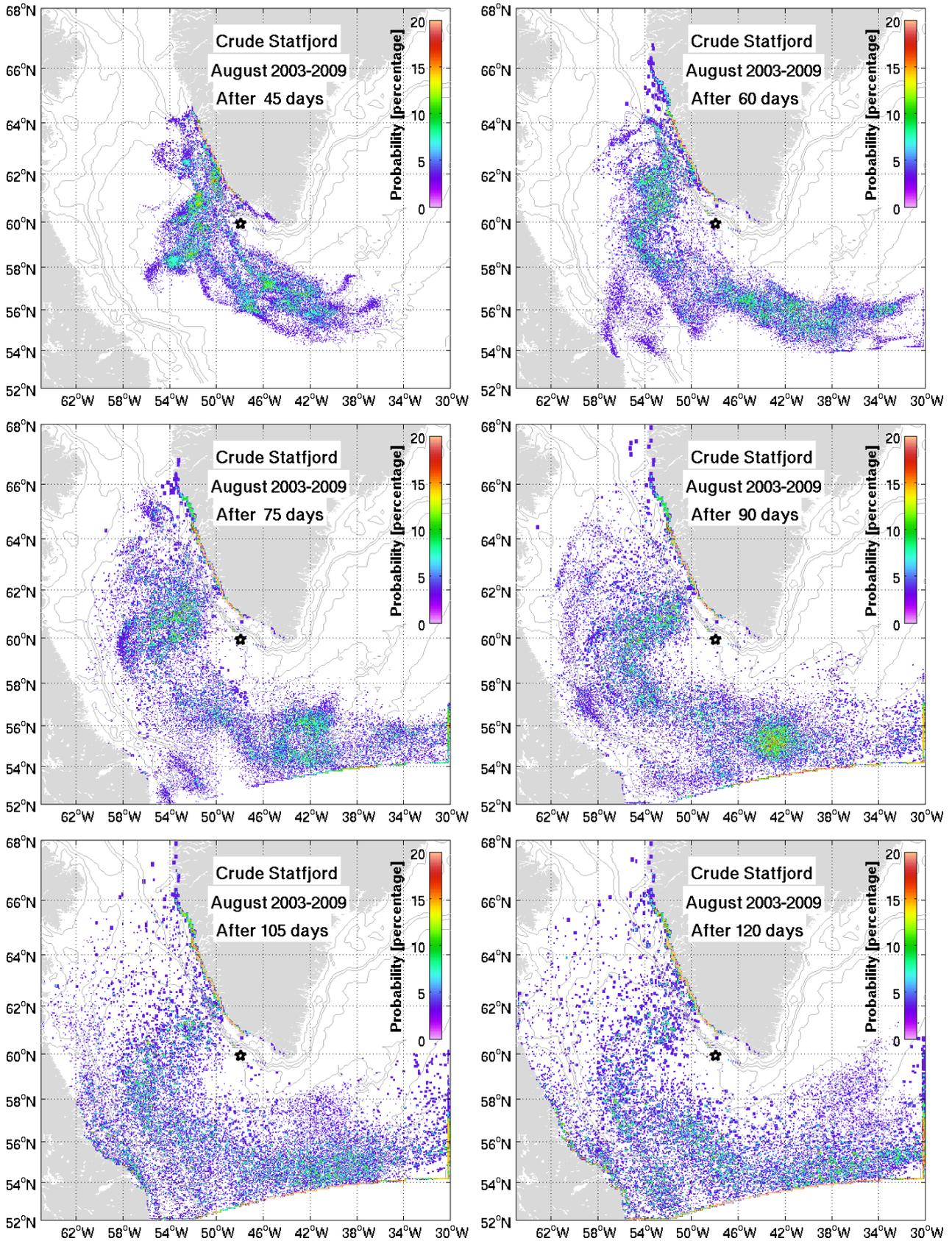


Figure 19. As previous figure but after 45–120 days of simulation. Note different color scale and different area. The high percentage at the bottom and right edge of the figure is an artifact due to oil escaping the extracted computation area.

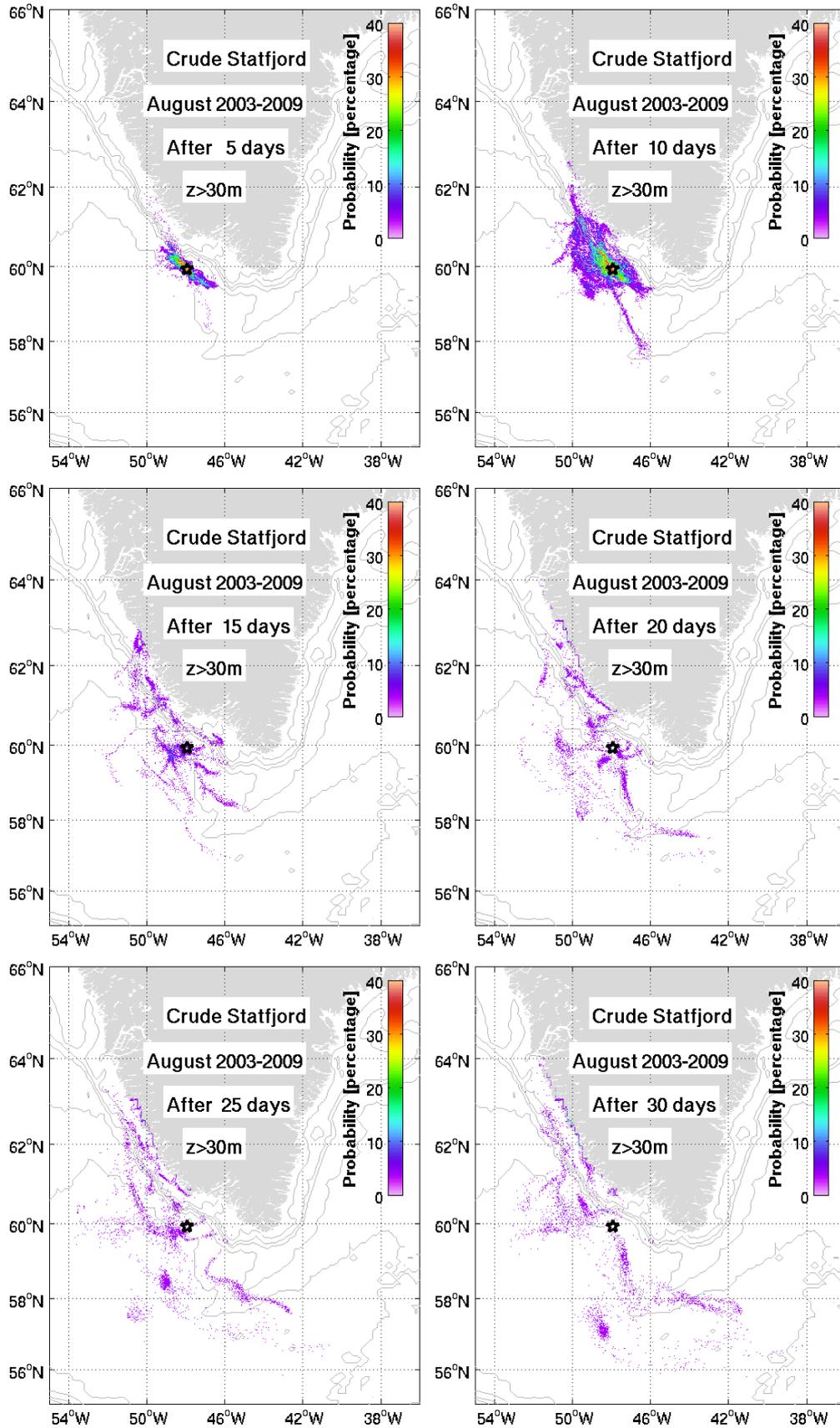


Figure 20. Probability maps (instantaneous and below 30 meters) for oil type “Crude Statfjord” after 5–30 days of simulation using 28 ensembles. The oil is released during August/September over a 10 day period from bottom. The colors represent the percentage of time a grid box was filled by oil. Ex. 10% time with oil after 15 days simulation is 1½ day with oil.

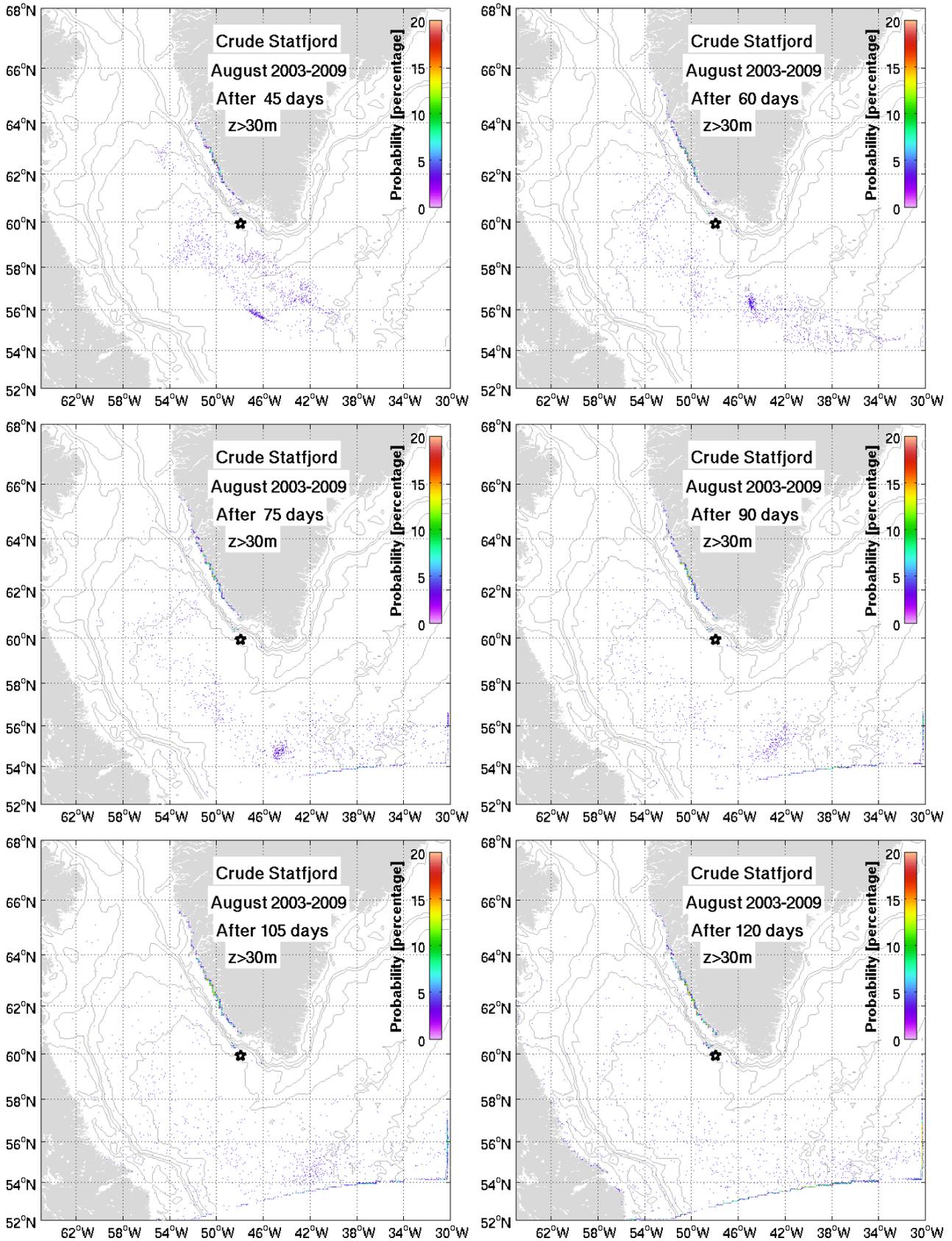


Figure 21. As previous figure but after 45–120 days of simulation. Note different color scale and different area. The high percentage at the bottom and right edge of the figure is an artifact due to oil escaping the extracted computation area.



Appendix C. Oil settling maps

Maps of the risk of oil settling below 30 meters are calculated based on the 28 simulation (7 years times 4 runs). If oil has settled on a specific day, oil will be present on the same location for the rest of the simulation. Therefore the probability can only increase with time.

These probability maps is shown for two oil types “Bunker C” and “Crude Statfjord”.

Note, the maps do not tell if the concentration of the settled oil is high or not. An estimate of the oil concentration can be estimated by combining the depth integrated oil thickness given in Appendix D and the standard deviation of depth given in Figure 4.

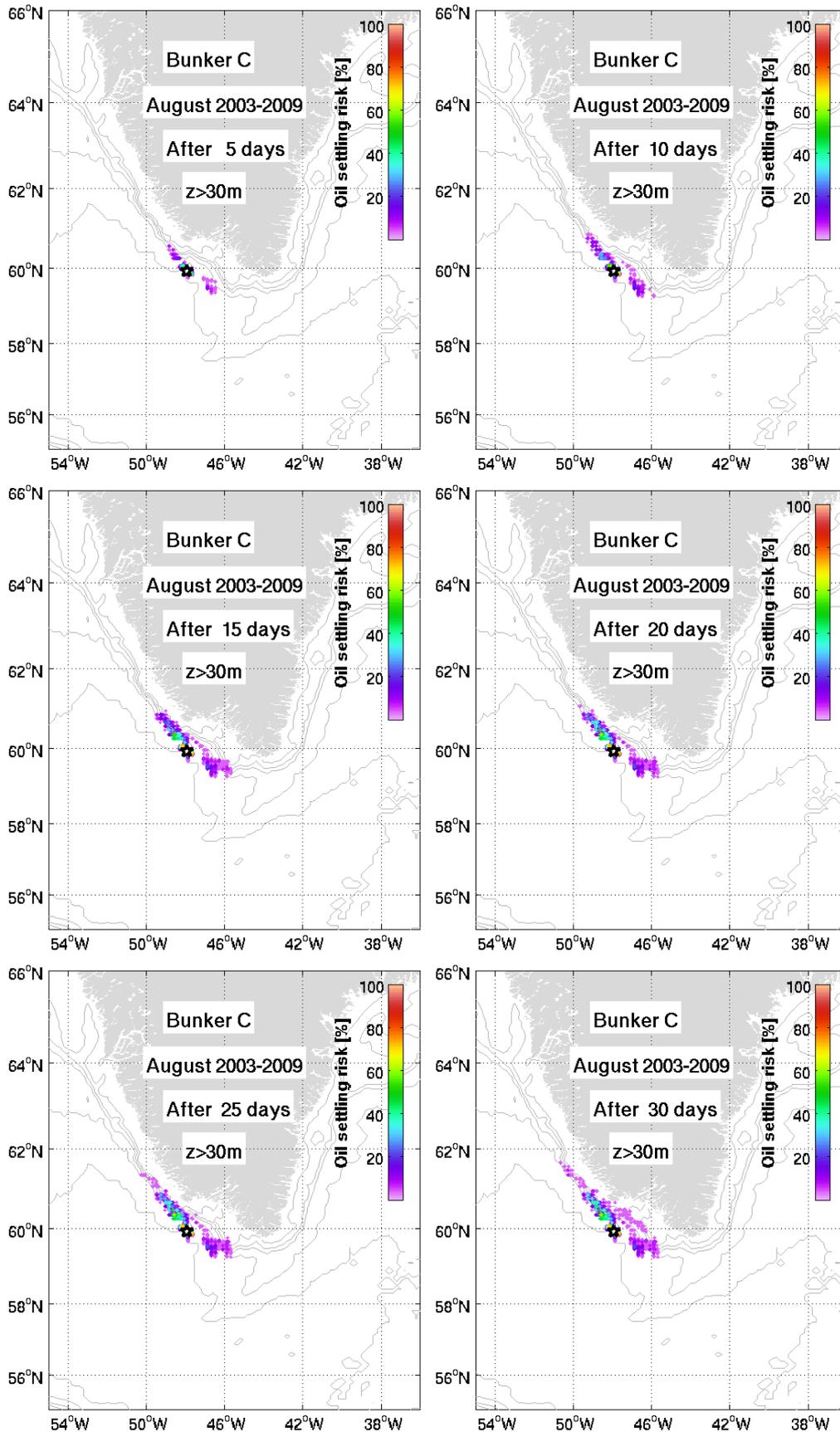


Figure 22. Probability maps for oil settling below 30 meters for oil type “Bunker C” after 5–30 days of simulation using 28 ensembles. The oil is released during August/September over a 10 day period from bottom. The colors represent the risk of oil settling based on 28 ensemble runs.

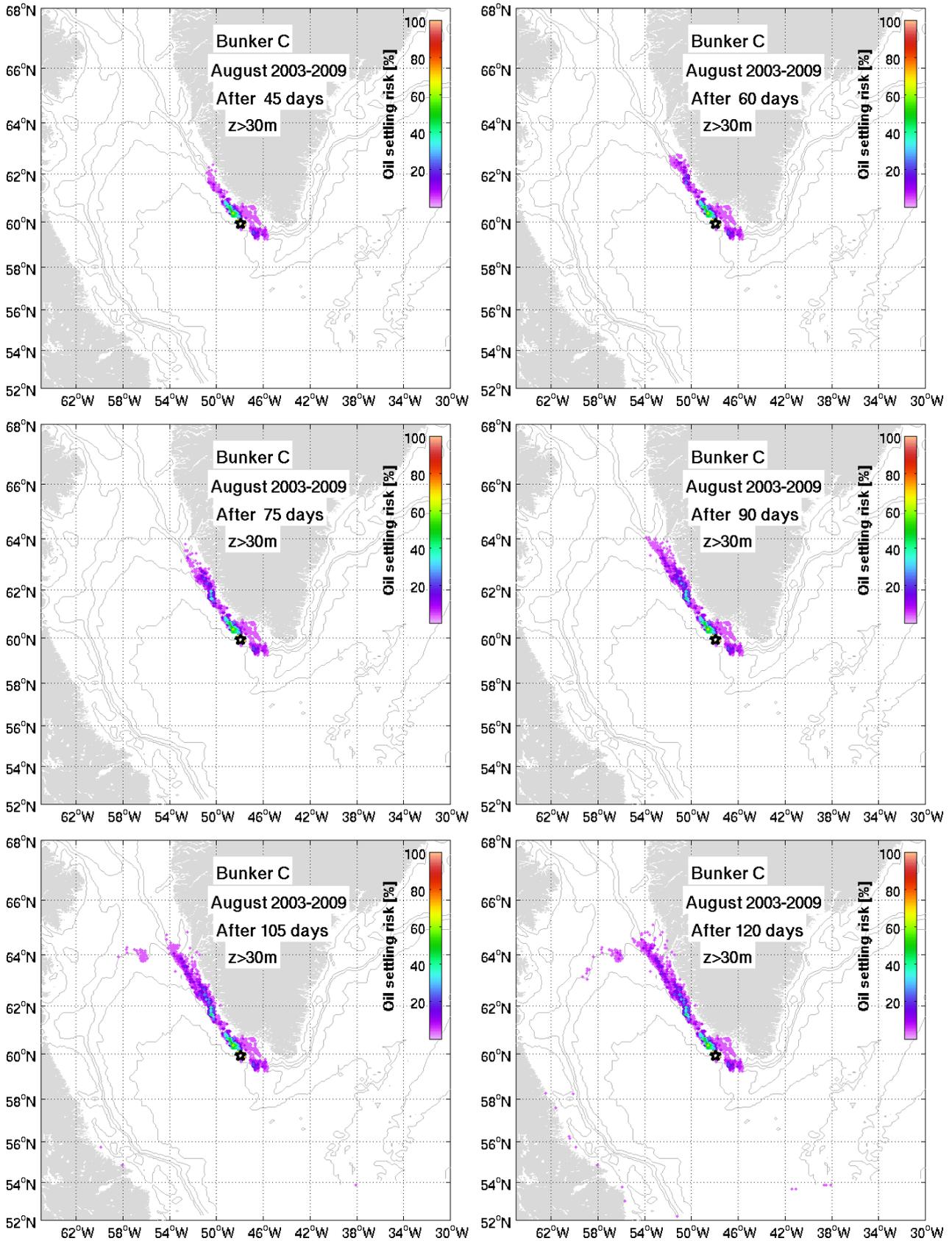


Figure 23. As previous figure but after 45–120 days of simulation. Note different color scale and different area. Particles at the bottom of the figure on deep waters is an artifact due to oil escaping the extracted computation area.

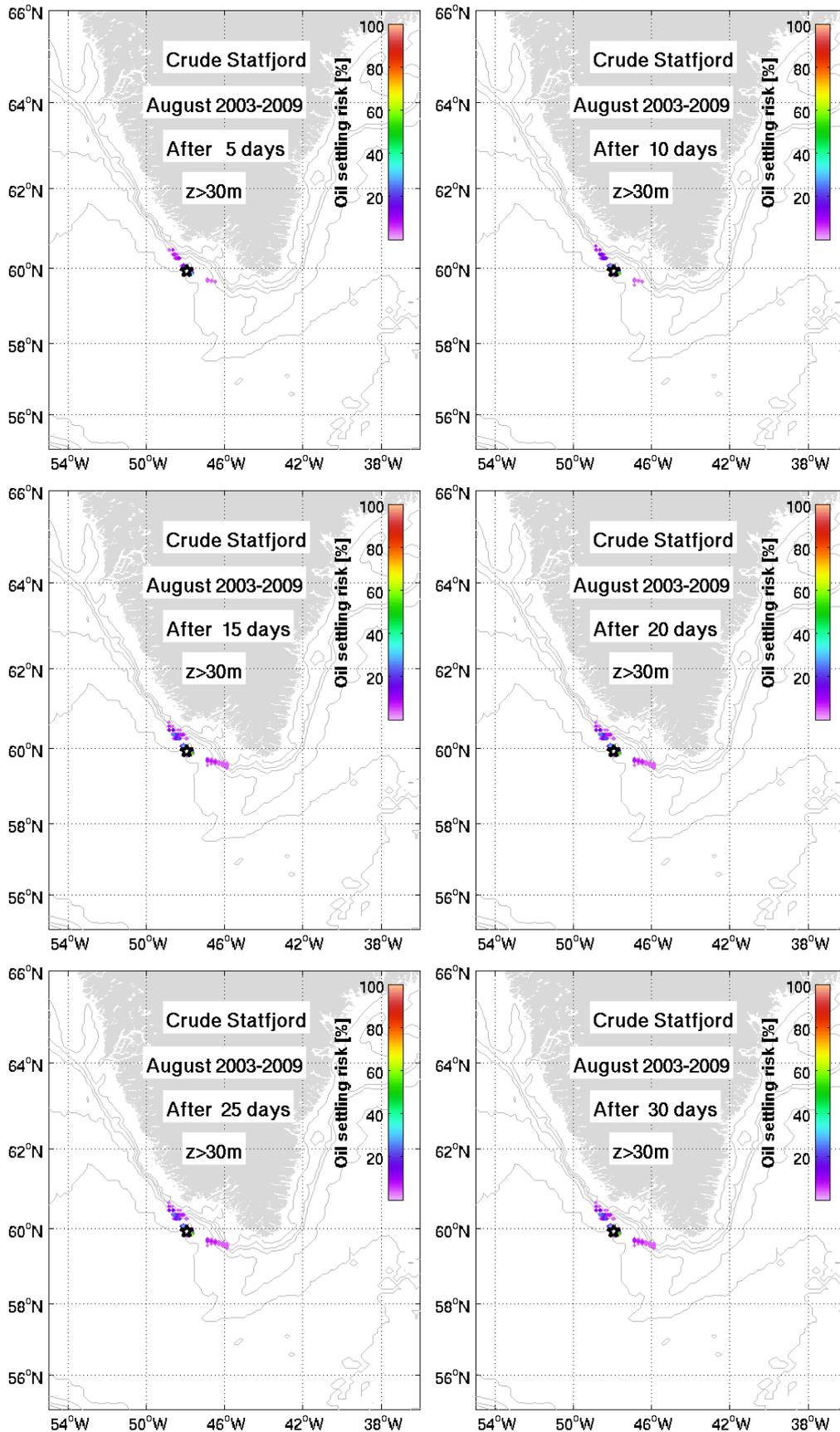


Figure 24. Probability maps for oil settling below 30 meters for oil type “Crude Statfjord” after 5–30 days of simulation using 28 ensembles. The oil is released during August/September over a 10 day period from bottom. The colors represent the risk of oil settling based on 28 ensemble runs.

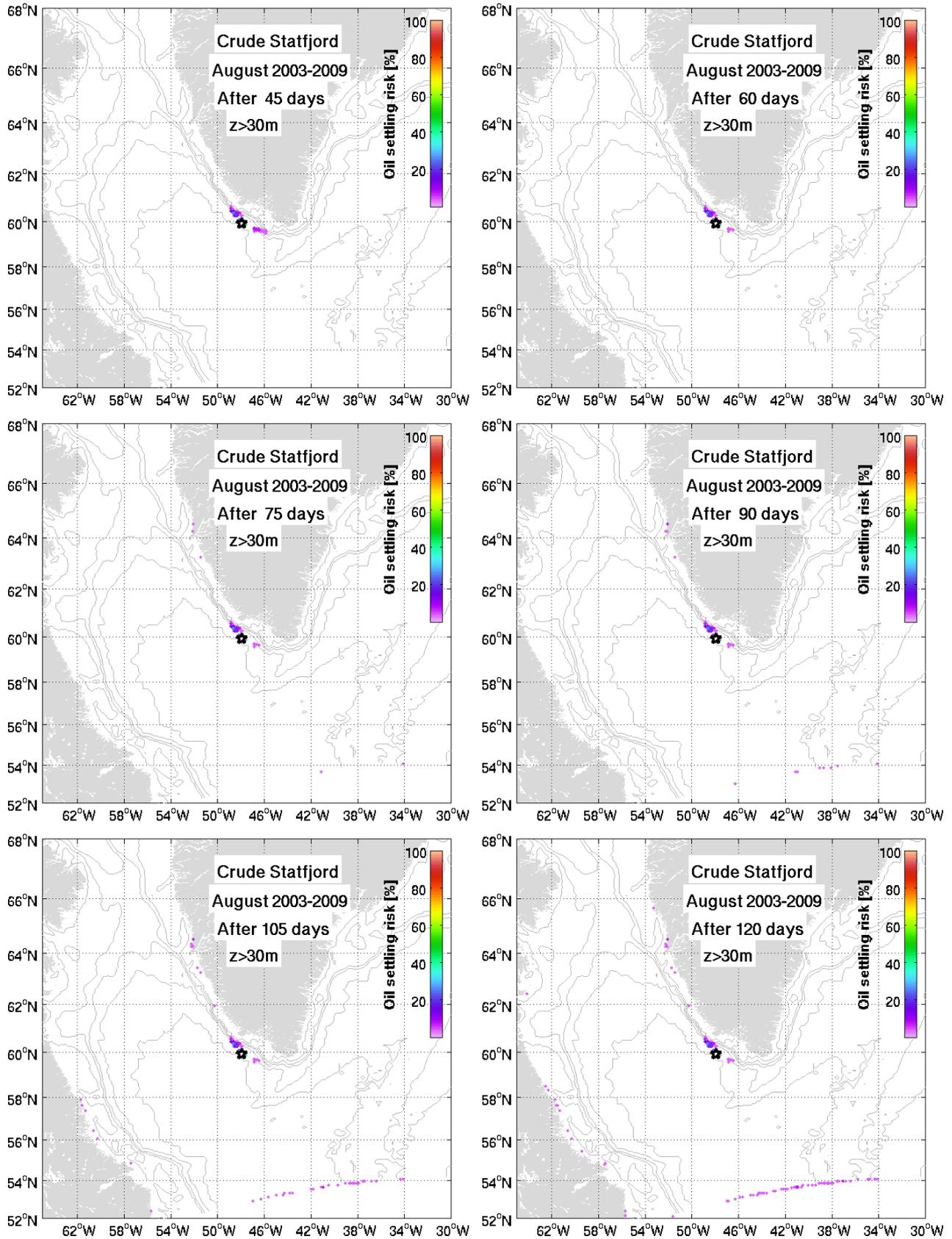


Figure 25. As previous figure but after 45–120 days of simulation. Note different color scale and different area. Particles at the bottom of the figure on deep waters is an artifact due to oil escaping the extracted computation area.



Appendix D. Accumulated thickness maps

The depth integrated oil thickness is calculated as the mean oil thickness in each grid cell for each of the 28 simulation (7 years times 4 runs). In these maps there are no information on which depth(s) the oil are located but only the total oil thickness as if it all was presence on the surface. If oil has settled on a specific day, oil will be present on the same location for the rest of the simulation preserving its oil composition and thickness. Therefore stranded oil is easily recognized.

These depth integrated oil thickness maps is shown for two oil types “Bunker C” and “Crude Statfjord” and for oil within the whole water column and for oil disperged below 30 meters depth.

An estimate of the oil concentration can be estimated by combining the maps and Figure 4 (standard deviation of depth).

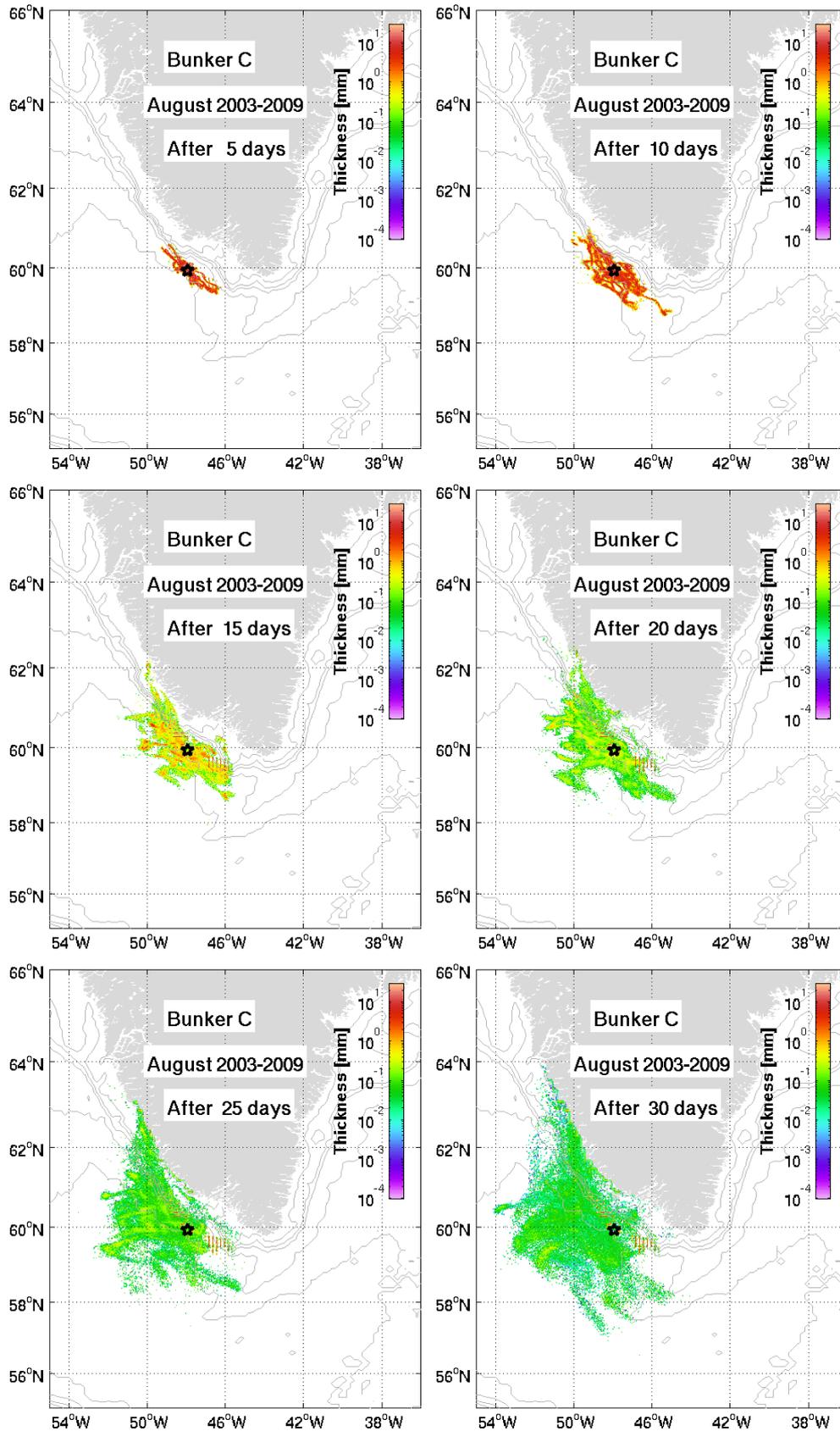


Figure 26. Depth integrated oil thickness for oil type “Bunker C” after 5–30 days of simulation using 28 ensembles. The oil is released during August/September over a 10 day period from bottom. The colors represent the depth integrated oil thickness [mm] of the oil in each grid cell as if all the oil was presence on the surface. Note the logarithmic color scale.

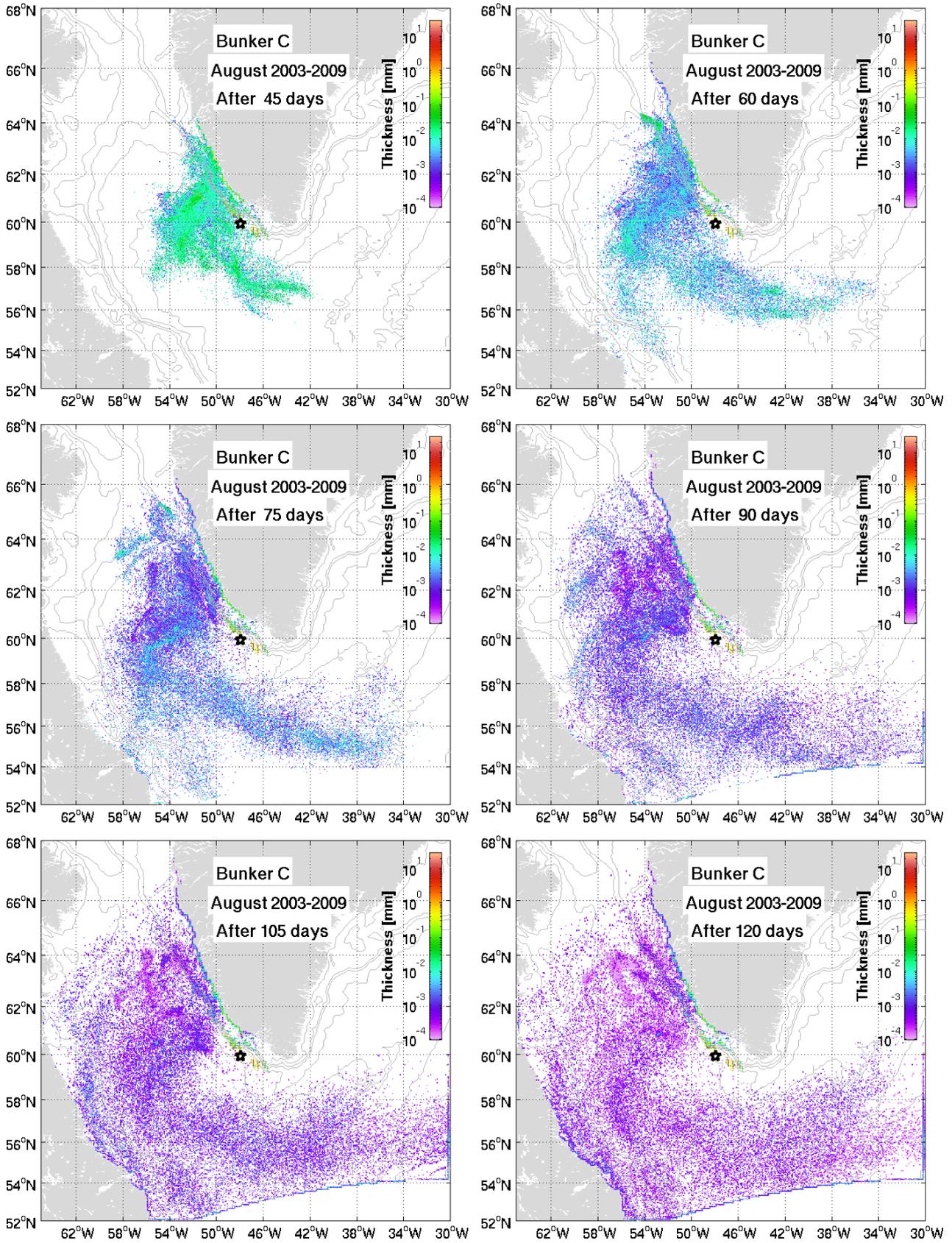


Figure 27. As previous figure but after 45–120 days of simulation. The high percentage at the bottom and right edge of the figure is an artifact due to oil escaping the extracted computation area.

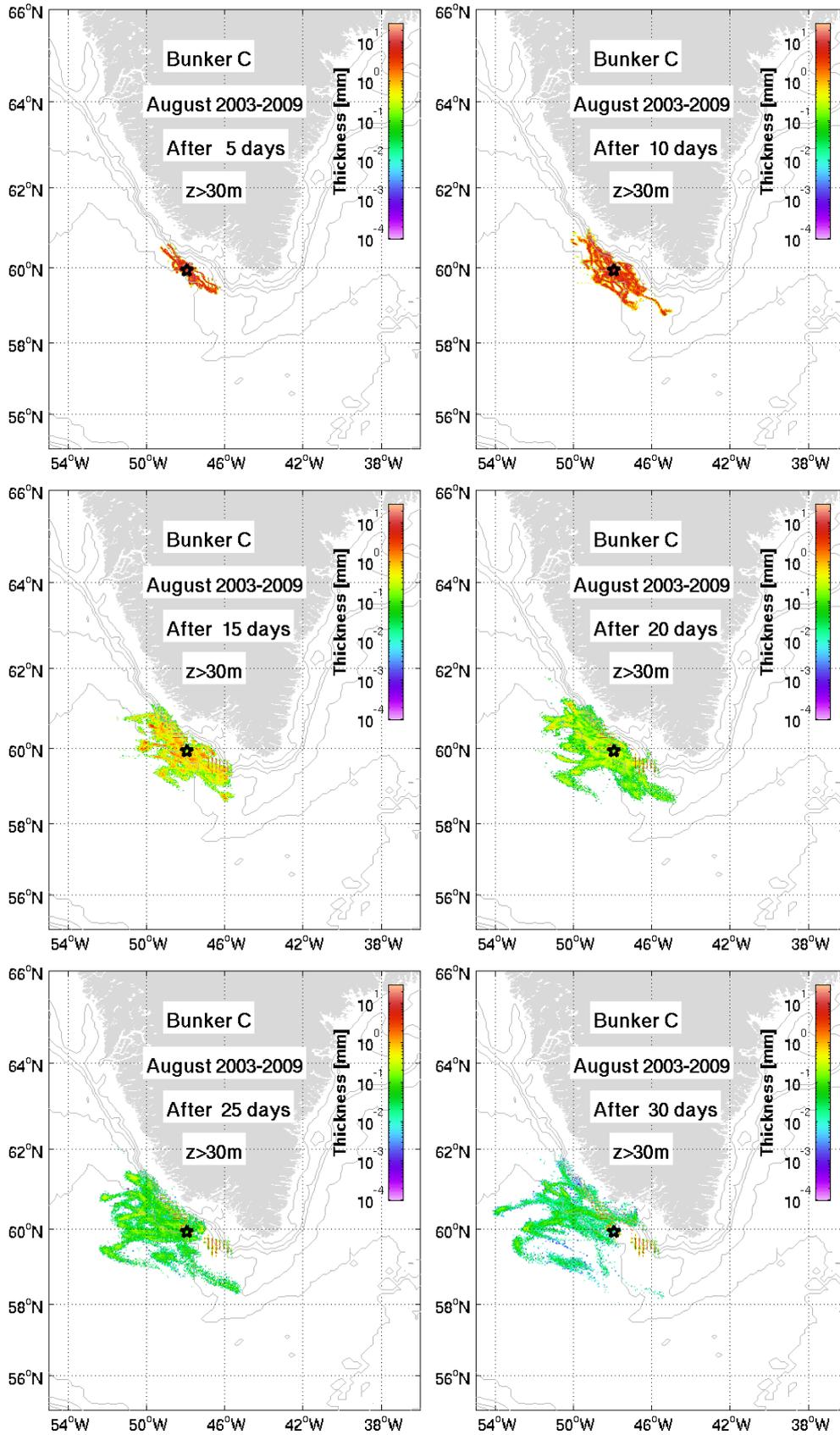


Figure 28. Depth integrated oil thickness (below 30m) for oil type “Bunker C” after 5–30 days of simulation using 28 ensembles. The oil is released during August/September over a 10 day period from bottom. The colors represent the depth integrated oil thickness [mm] of the oil in each grid cell as if all the oil was presence on the surface. Note the logarithmic color scale.

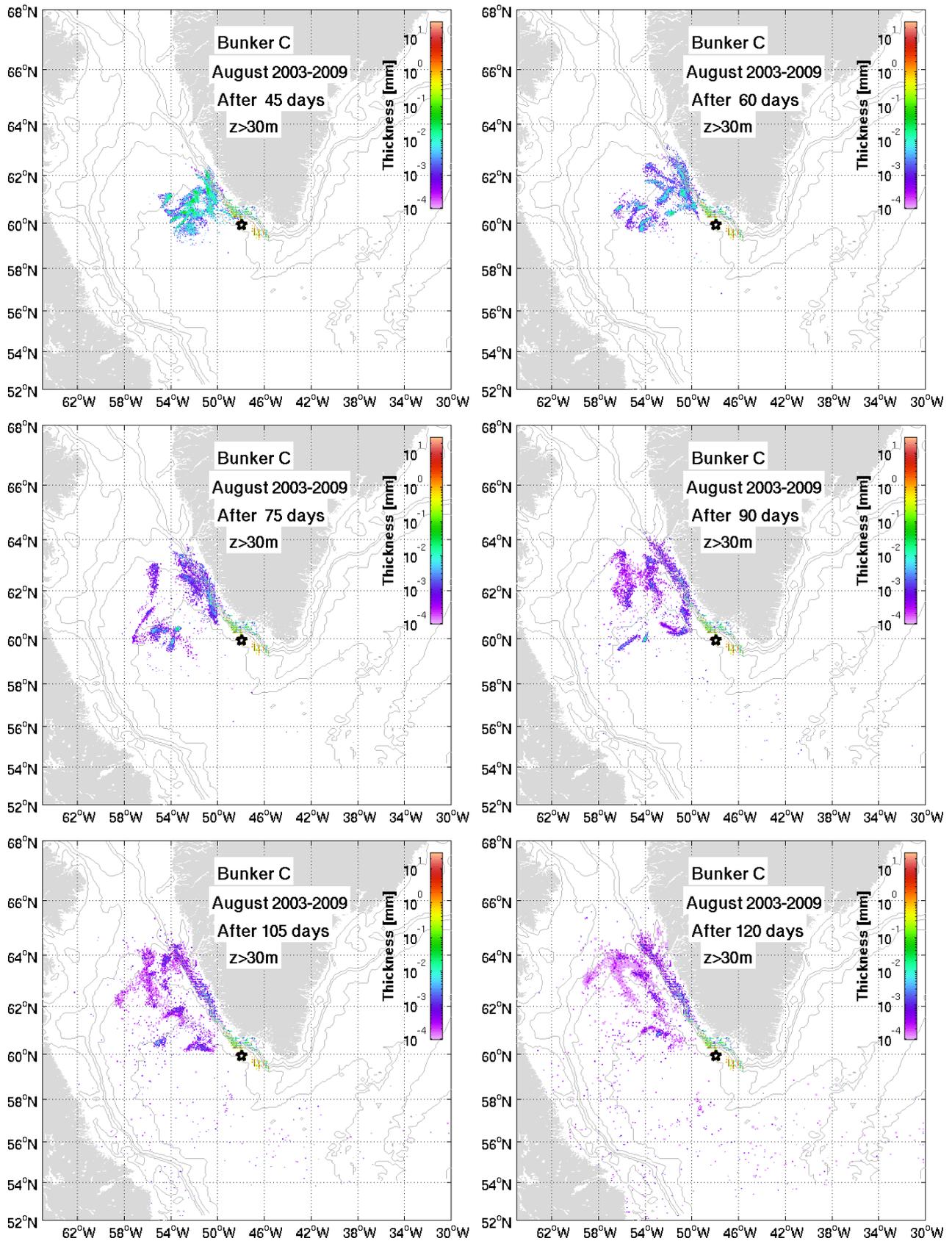


Figure 29. As previous figure but after 45–120 days of simulation.

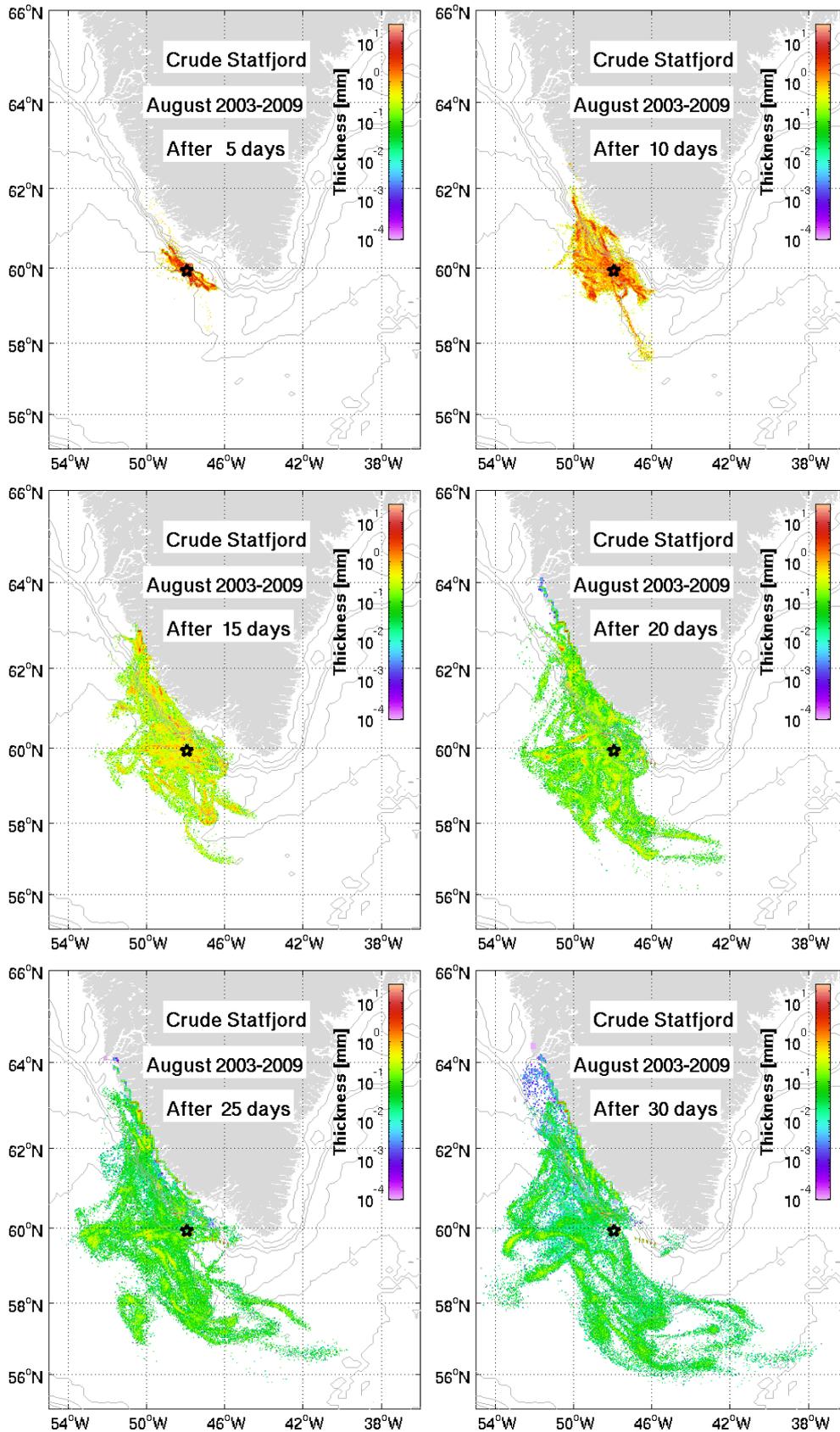


Figure 30. Depth integrated oil thickness for oil type “Crude Statfjord” after 5–30 days of simulation using 28 ensembles. The oil is released during August/September over a 10 day period from bottom. The colors represent the depth integrated oil thickness [mm] of the oil in each grid cell as if all the oil was presence on the surface. Note the logarithmic color scale.

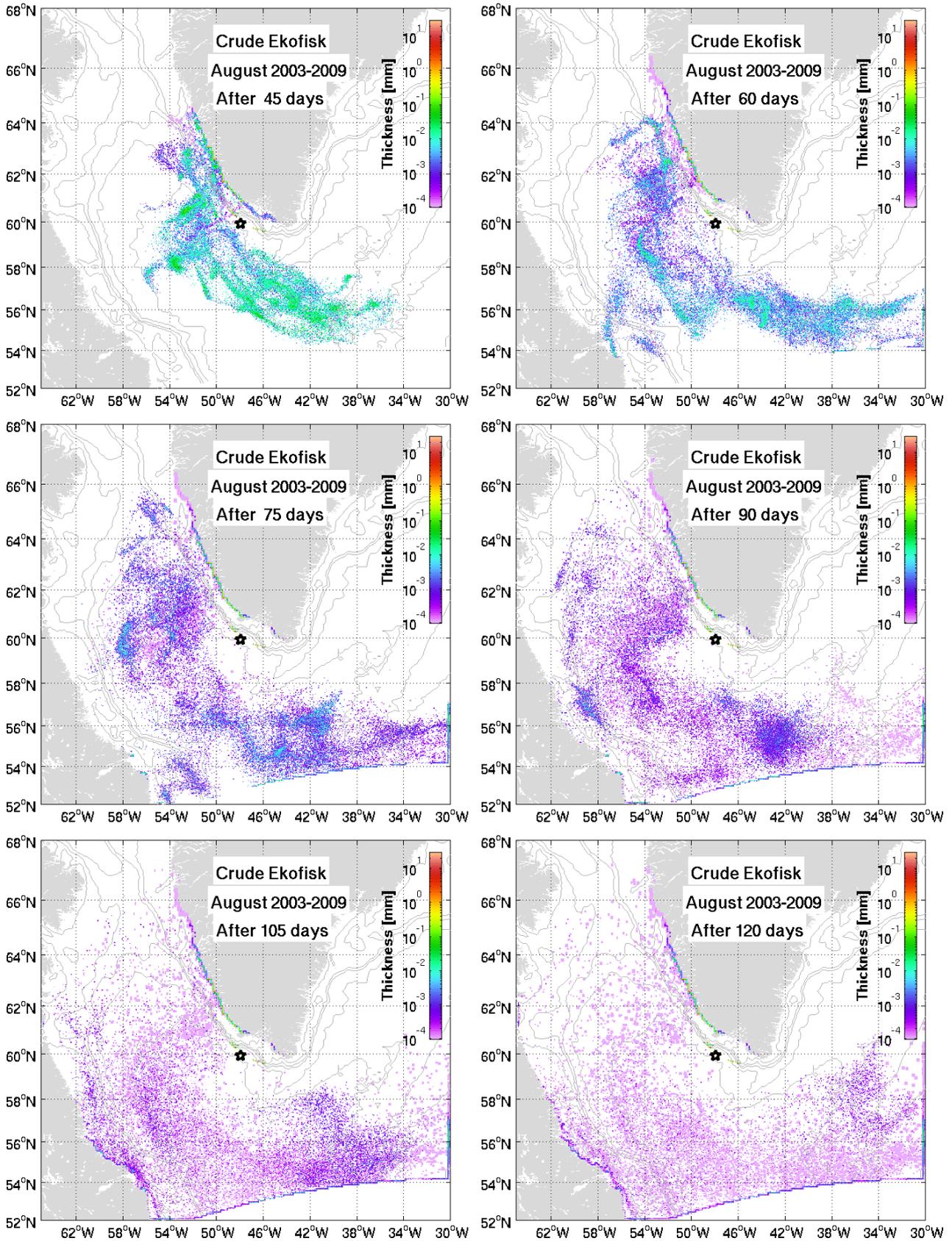


Figure 31. As previous figure but after 45–120 days of simulation. The high thickness at the bottom and right edge of the figure is an artifact due to oil escaping the extracted computation area.

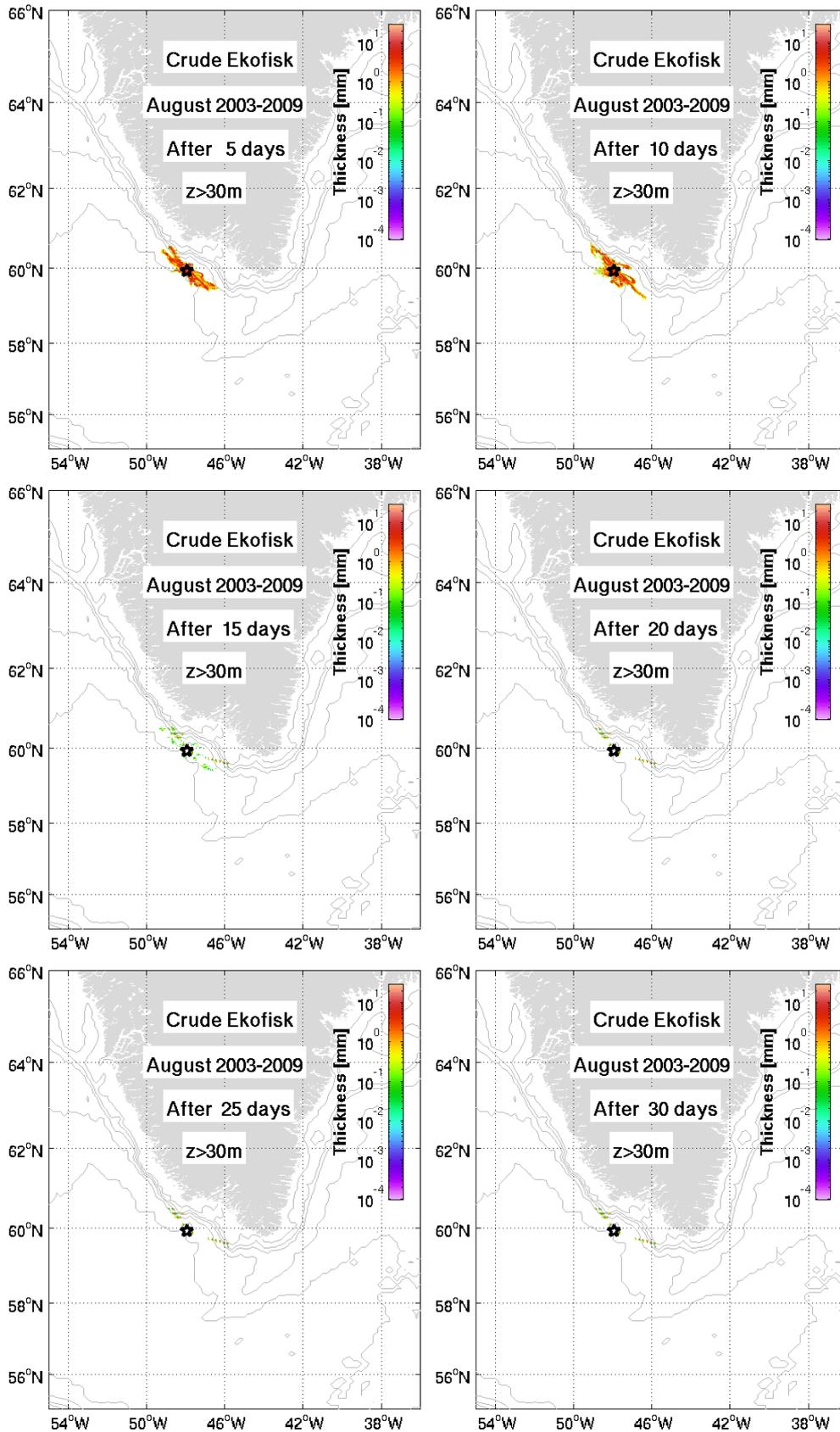


Figure 32. Depth integrated oil thickness (below 30m) for oil type “Crude Statfjord” after 5–30 days of simulation using 28 ensembles. The oil is released during August/September over a 10 day period from bottom. The colors represent the depth integrated oil thickness [mm] of the oil in each grid cell as if all the oil was presence on the surface. Note the logarithmic color scale.

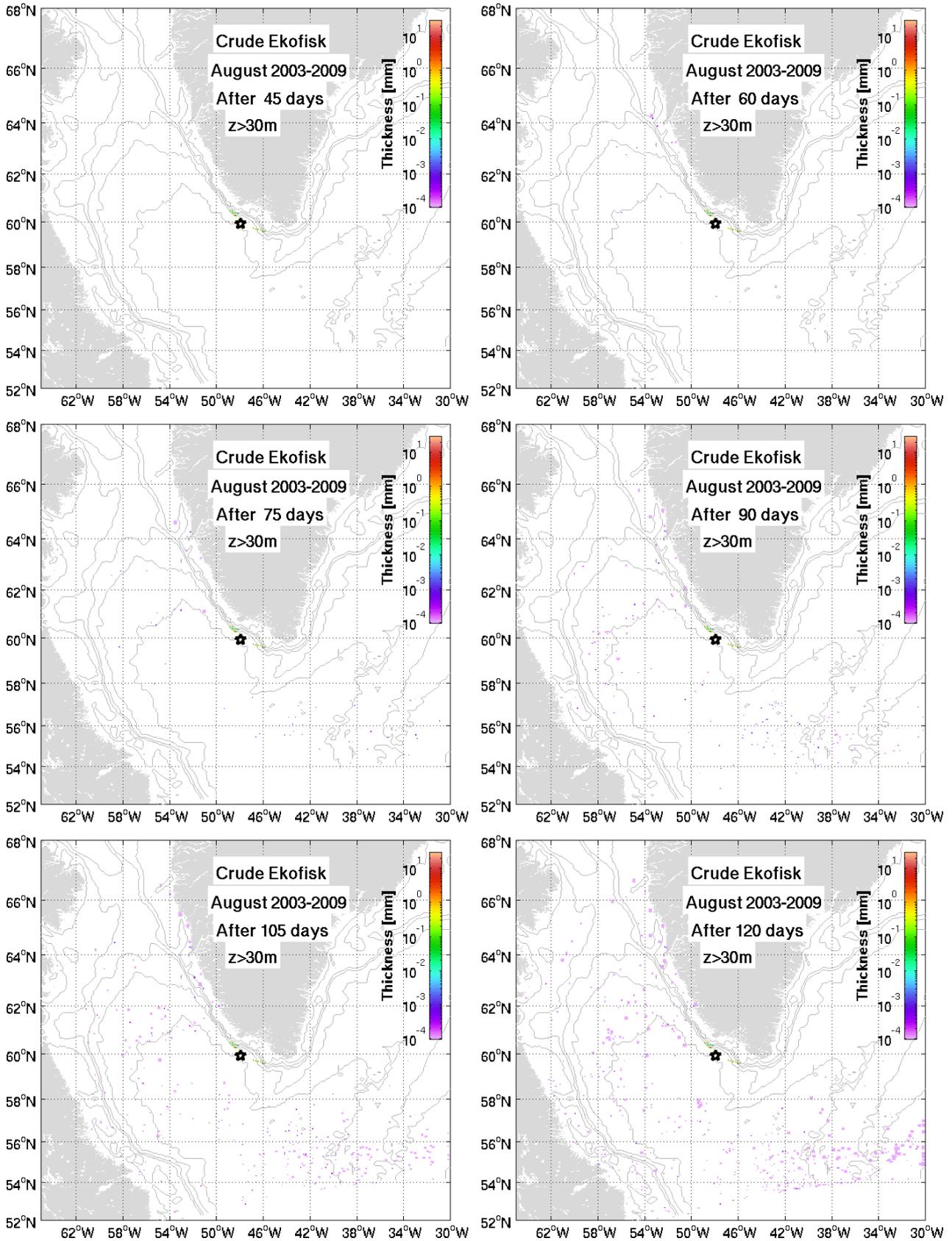


Figure 33. As previous figure but after 45–120 days of simulation.