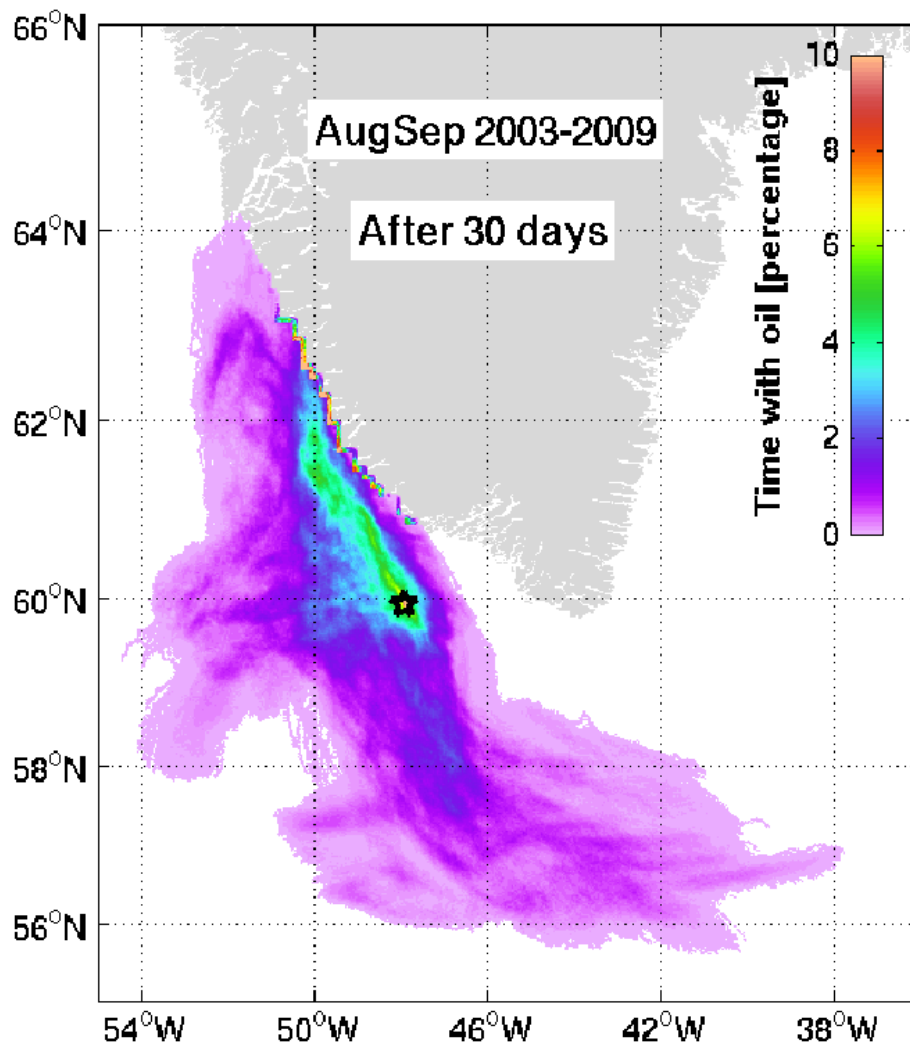




Technical Report 10-19

Ensemble oil drift modelling off Southwest Greenland

Mads Hvid Ribergaard, Stig Wilkenskjeld, and Jacob Woge Nielsen





Colophon

Serial title:

Technical Report 10-19

Title:

Ensemble oil drift modeling off Southwest Greenland

Subtitle:

Author(s):

Mads Hvid Ribergaard and Stiig Wilkenskeld, and Jacob Woge Nielsen

Other contributors:

Nicolai Kliem, Susanne Hanson

Responsible institution:

Danish Meteorological Institute

Language:

English

Keywords:

Oil drift, modelling, Greenland

Url:

www.dmi.dk/dmi/tr10-19.pdf

ISSN:

1399-1388 (online)

Version:

Website:

www.dmi.dk

Copyright:



Content:

Abstract	4
Resumé	4
1. Introduction	5
2. DMI oil drift model	6
Oil particles	6
Oil composition	7
Drift	7
The oil slick	7
Settling and emigration	8
Oil in ice-covered waters	8
Drift model output	8
Gridding	8
Slick thickness and oil concentration	9
Validity	9
3. Model setup	10
4. Simulations	11
5. Results	12
Downward mixing	13
Oil in ice	13
Oil thickness	13
Oil composition	13
Mean drift and spreading	13
Settling	13
Conclusion	14
References	14
Previous reports	14
Appendix A. An individual oil spill run	15
Appendix B. Probability maps	19
Appendix C. Maximum surface layer oil thickness	30



Abstract

An ensemble of one-month simulations of hypothetical oil spill off Southwest Greenland results in estimates of the region affected, the maximum skin layer thickness to occur and an estimate of the probability of finding oil at a given location.

Resumé

Et ensemble af månedslange simuleringer af hypotetiske oliespild i de sydvest grønlandske farvande resulterer i en vurdering af hvilket område der påvirkes, den maksimale opnåede tykkelse af oliefilm på overfladen samt et estimat af sandsynligheden for at finde olie i et given område.



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 into 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 and sites have been prescribed by the Danish National Environmental Research Institute in order to represent envisaged oil spill conditions. Two study periods in August/September and October/November have been selected. For each study period 4 runs have been performed for each the years 2003-2009 given a total ensemble of 28 runs.

The work has been funded by the Danish National Environmental Research Institute (NERI) as part of the cooperation between NERI 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.



2. DMI oil drift model

Since the 1990's, DMI has run an operational oil drift forecasting 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 generalised and set up DMOD for Greenland waters. The forcing fields in the present simulations are obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) model ERA Interrim 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 influences both weathering and the spreading processes. The environment is represented by water of constant temperature and density.

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).

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. The composition, and the physical properties of the oil, changes with time due to weathering processes (see below).

Drift

The oil particles drift passively with the ocean current. In a shallow 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 centimetres. 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.

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 decided 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. 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 downward mixing by surface waves is parameterized as a function of wind speed. The oil particles to be mixed down 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 this case of free or nearly free ice drift, 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 sea ice velocities into account, such that the ocean current equal ice velocity with 100% ice concentration. This has not been implemented in the present setup. However, the ice concentrations are very low and often absent throughout 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. The oil slick may thus be tracked as the average position of all particles, or by mapping out all particles geographically at any given time after the initial release. It should be noted that the mean position may end up on land, e.g. if a spill drifting past an island splits up in two branches. Also, in case of a continuous release of oil, taking place over several days, the mean position does not give an adequate description of the spill situation. In such cases, particle mapping is a better approach.

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 locates it in 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. When a surface slick of 1 mm thickness is mixed down, 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 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.

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). 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.

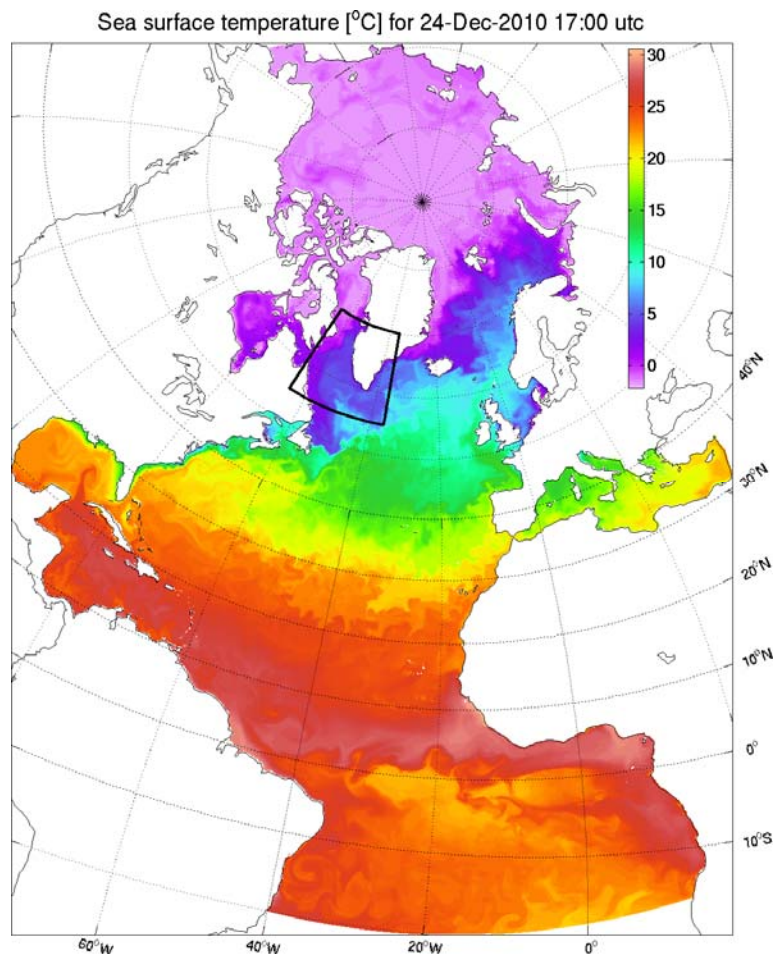


Figure 1. Model domain for the HYCOM-CICE ocean and sea ice model with modelled surface temperature valid at 24th December 17:00 UTC. The model has a horizontal resolution of about 10 km. Black box showing the sub-domain extracted for the DMOD oil drift model.

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.

The present ocean model setup 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 model domain still covers the entire Atlantic Ocean including the Arctic Ocean but now in an approximately 10 km horizontal resolution with 29 hybrid z and/or sigma vertical layers (Figure 1). 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 puts momentum into the surface currents. A new sea ice module (CICE) has been coupled to the ocean model HYCOM. Beside thermodynamic, CICE also calculates sea-ice drift which was lacking in the previous setup. The representation of the tides has been improved and 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)¹ 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 1 hour for surface quantities and 3 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 covers the region 65-36°W, 55-70°N with a latitude/longitude resolution of 0.2°/0.1°, respectively (approx. 10 km). The model has 13 layers, with layer interfaces located at 1, 5, 10, 20, 30, 50, 100, 200, 300, 500, 1000, 1500 and 2000 m depth. 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.

¹ <http://grdc.bafg.de>

4. Simulations

Five sites of hypothetical oil spills were given (Figure 2 and Table 1). These are located off Southwest Greenland off Julianehaab Bight. For each spill site we simulate a continuous spill of ten days duration, taking place at the surface. The oil slick is then tracked for a further 20 days, in order to simulate the spreading of the oil until concentrations are low and/or until the oil has settled on shore. The full simulation period is thus 30 days. The simulations are started day 1, 11, 21 and 31 in August and October from each of the seven years 2003-2009. Thus a total of 28 simulations are carried out for each position for each period (August-September and October-November) giving a grand total of 280 simulations.

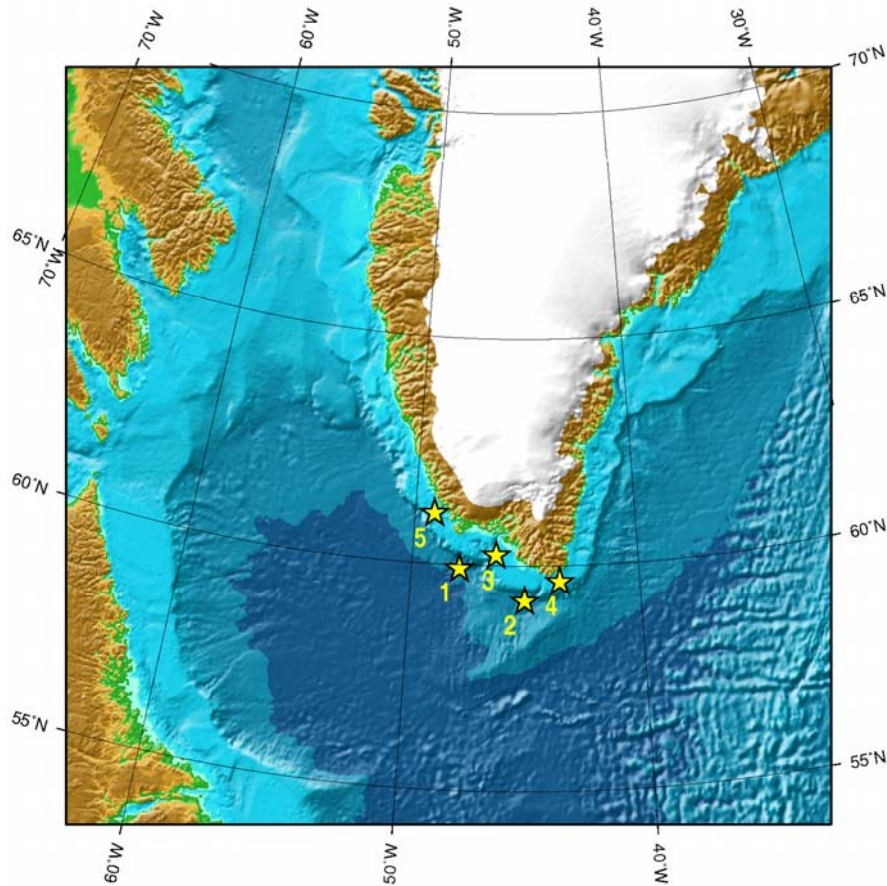


Figure 2 Map showing the bathymetry with yellow stars indicating the hypothetical spill positions.

Site no.	Longitude	Latitude	Depth (m)
1	47°53'44"W	59°55'40"N	3113
2	45°01'18"W	59°13'08"N	2019
3	46°17'22"W	60°14'29"N	157
4	43°29'22"W	59°39'05"N	190
5	49°07'53"W	61°07'38"N	150

Table 1. Oil spill sites and model depths.

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 1000 individual particles. A crude oil of type "Statfjord" with a density of 886.3 kg/m³ (a North Sea crude oil, see Table 2 for composition)



is chosen to represent oil in this region. This is a medium oil type which will evaporate about one third during the first 24 hours of a surface spill. The ambient water temperature is set to 2°C and the density of sea water is fixed at 1026 kg/m³ representing the shelf water during the autumn.

Fraction	1	2	3	4	5	6	7	8
Description	C ₆ -C ₁₂ Paraffin	C ₁₃ -C ₂₅ Paraffin	C ₆ -C ₁₂ Cyclo- Paraffin	C ₁₃ -C ₂₃ Cyclo- paraffin	C ₆ -C ₁₁ Aromatic	C ₁₂ -C ₁₈ Aromatic	C ₉ -C ₂₅ Naphtheno- Aromatic	Residual Incl. Hetero- cycles
Percentage	15	13	14	12	7	3.5	3.5	32

Table 2 Fraction of different compounds for the selected crude oil. The oil fractions 1,3, and 5 (36% in total) 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.

5. Results

A total of 280 oil spill scenarios have been simulated with 5 different release sites, 7 years (2003-2009) and 2 periods each with 4 spills started every 10th day (1st, 11th, 21st, 31st August/October).

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 includes 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 are 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 an example of an individual simulation to give the reader an idea of the very dynamic system off West Greenland. Moreover the simulation is plotted similar to the ensemble maps shown in appendix B and Appendix C for comparison of a single ensemble member.

Appendix B contains maps of the probability of finding oil at a given location. Shown is the probability accumulated after 5., 10., ..., 30 days of simulation. Only oil within the upper half meter is considered. The probabilities are grouped according to spill location and time period (August/September or October/November) giving in total 10 figures each consists of 28 simulations (four each year at each location in seven different years). 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.

Appendix C contains maps of the maximum oil slick thickness in the surface skin layer (0.5 m) attained at any time during the 30 days of simulation. The maximum thickness typically stems from



a few simulations resulting in “star shaped” maps. Moreover, as the maximum thickness is found in the start of the simulations, the central part of the figures are identical after 5, 10, ... 30 days..

Some general features of the oils spill simulations are discussed below.

Downward mixing

In calm weather all the oil stays in a skin layer at the surface, and the oil is mixed down only during periods of strong wind. A maximum of about 20% of the oil is temporarily mixed down. The average mixing depth is usually just a few metres, with a maximum of the order of ten meters. The maximum mixing depth of an individual oil particle is usually below 30 metres, depending on the wind period. Thus in practice no oil particles settle on the bottom in the present experiments.

Oil in ice

Southwest Greenland waters are usually ice free during autumn with only low concentration of sea ice when present at the end of the year. So in practice the present oil drift modelling experiments have been without sea ice.

Oil thickness

A typical skin layer thickness after 10 days is of the order of 0.5 mm. After 30 days the mean skin layer thickness has decreased by a factor of 10.

Oil composition

The total water content converges towards two thirds for all oil particles, except when they settle very quickly (the particle composition is then fixed). All volatile components, about 1/3 of the oil, evaporate during the first day or two after the oil has been released or has surfaced. The final volume is thus about double the spill size.

Mean drift and spreading

The mean drift varies a lot between the experiments. General the spreading is highest in October/November compared to August/September. This is to be expected, as the strengths and number of low pressure systems is in general higher during autumn compared to late summer. After 30 days, the slick typically covers an area of very irregular shape. In practice, the oil will form isolated patches within this area, with regions of high concentration interspersed with regions with no oil at a given time. This means that the area actually covered with oil is smaller than the indicated figured. The model gives no indication of how much smaller.

Settling

None of the oil particles settle on the sea bed when the spill is still taking place. After 30 days a significant amount of particles have settled along the coast in general. These are easily found, at their “probabilities” increased when they stay at a fixed position and still counts in the probability statistics. They thus pop up with higher probabilities than the surrounding water.



Conclusion

A total of 280 one-month oil drift simulations have been carried out. The simulations result in hourly tables of position and properties of a cloud consisting of 1000 oil particles. Proper averaging results in bulk spill time series. A careful gridding technique is applied, resulting in probability maps of oil and maximum oil slick thickness.

References

- Børresen, J.A., 1993: Olje på havet. Gyldendal.
- Christiansen, B.M., 2003: 3D Oil Drift and Fate Forecasts at DMI. *DMI Technical Report 03-36*, Danish Meteorological Institute, Denmark.
- Dai, A., Trenberth, K. E., 2002. Estimates of freshwater discharge from continents: Latitudinal and seasonal variations. *Journal of Hydrometeorology* **3**, 660-687.
- Dick, S., and Soetje, K.C., 1990. An operational oil dispersion model for the German Bight. *Deutsche Hydrographische Zeitschrift, Ergänzungsheft Reihe A*, **16**. Bundesamt Für Seeschifffahrt und Hydrographie, Hamburg.
- Nielsen, J.W., Kliem, N., Jespersen, M., and Christensen, B.M., 2006. Oil drift and fate modelling at Disko Bay. *DMI Technical Report 06-06*, Danish Meteorological Institute, Denmark.
- Nielsen, J.W., Murawski, J., and Kliem, N., 2008. Oil drift and fate modelling off NE and NW Greenland. *DMI Technical Report 08-12*, Danish Meteorological Institute, Denmark.
- Ribergaard, M.H., Kliem, N., and Jespersen, M., 2006: HYCOM for the North Atlantic Ocean with special emphasis on West Greenland Waters. *DMI Technical Report 06-07*, Danish Meteorological Institute, Denmark

Previous reports

Previous reports from the Danish Meteorological Institute can be found at:

<http://www.dmi.dk/dmi/dmi-publikationer.htm>



Appendix A. An individual oil spill run

In order to illustrate the very different behavior of the individual oil drift simulations, a specific run is shown starting from position 1 at the 1st of August 2003 (Figure 3). During the first five days the oil did take a steady drift towards west driven by remarkable (for the area) steady winds and currents. During the next 5 days timeslot a displacement towards south is experienced. Between day 10 and day 15, the drift shifted from south towards north, but still relatively slow drift velocities, which continues until about day 20. Then the forcing fields increases considerably and a northward drift of the order of 400 km in 10 days spread the oil slick along the Southwest Greenland coast from Julianehaab Bight to Nuuk.

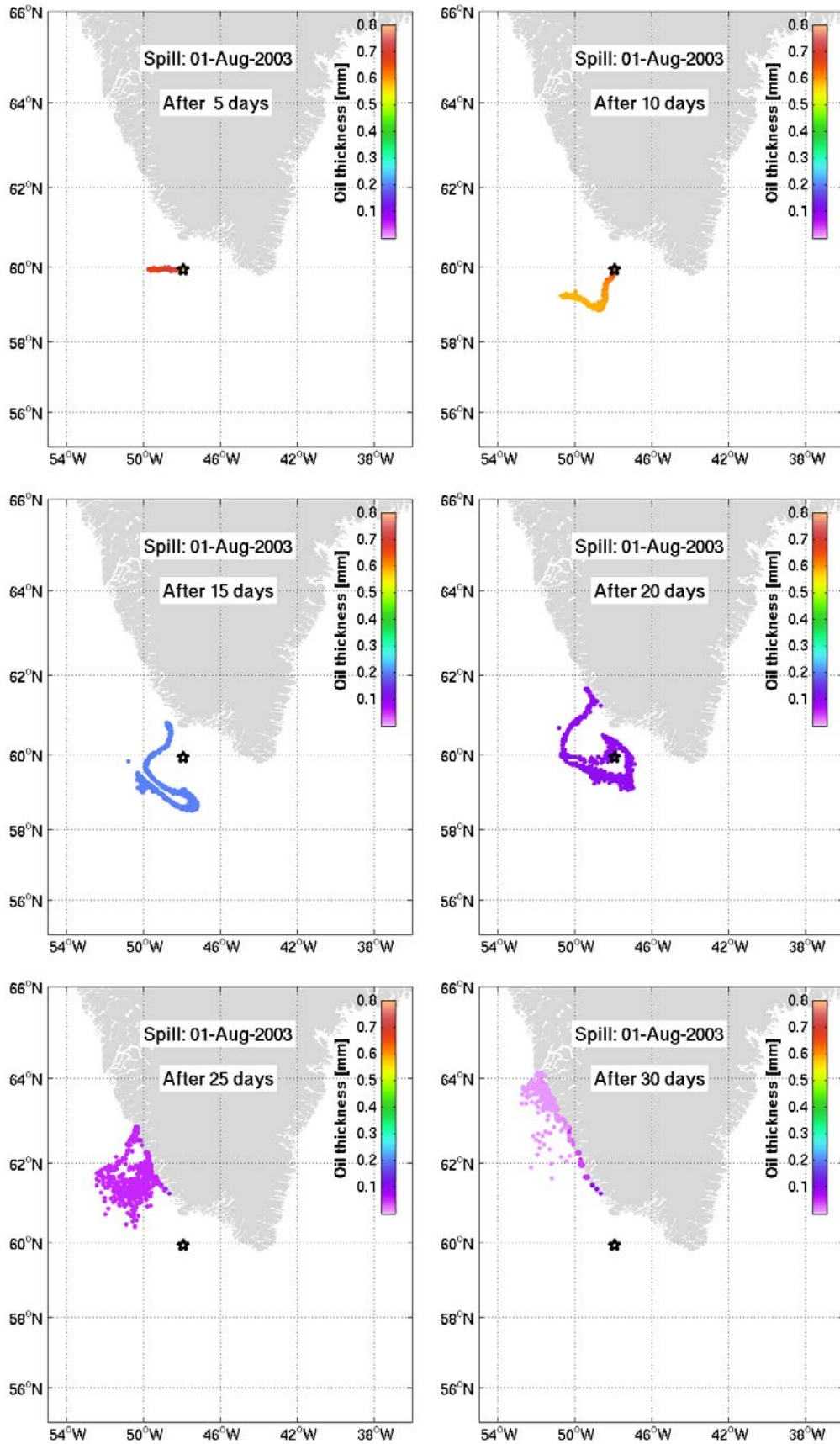


Figure 3. Simulated oil drift started 1st August 2003 from position 1. Snapshots are shown after 5-30 days of simulation. Colors are the *individual* thickness of each oil parcel – not necessary the total thickness.

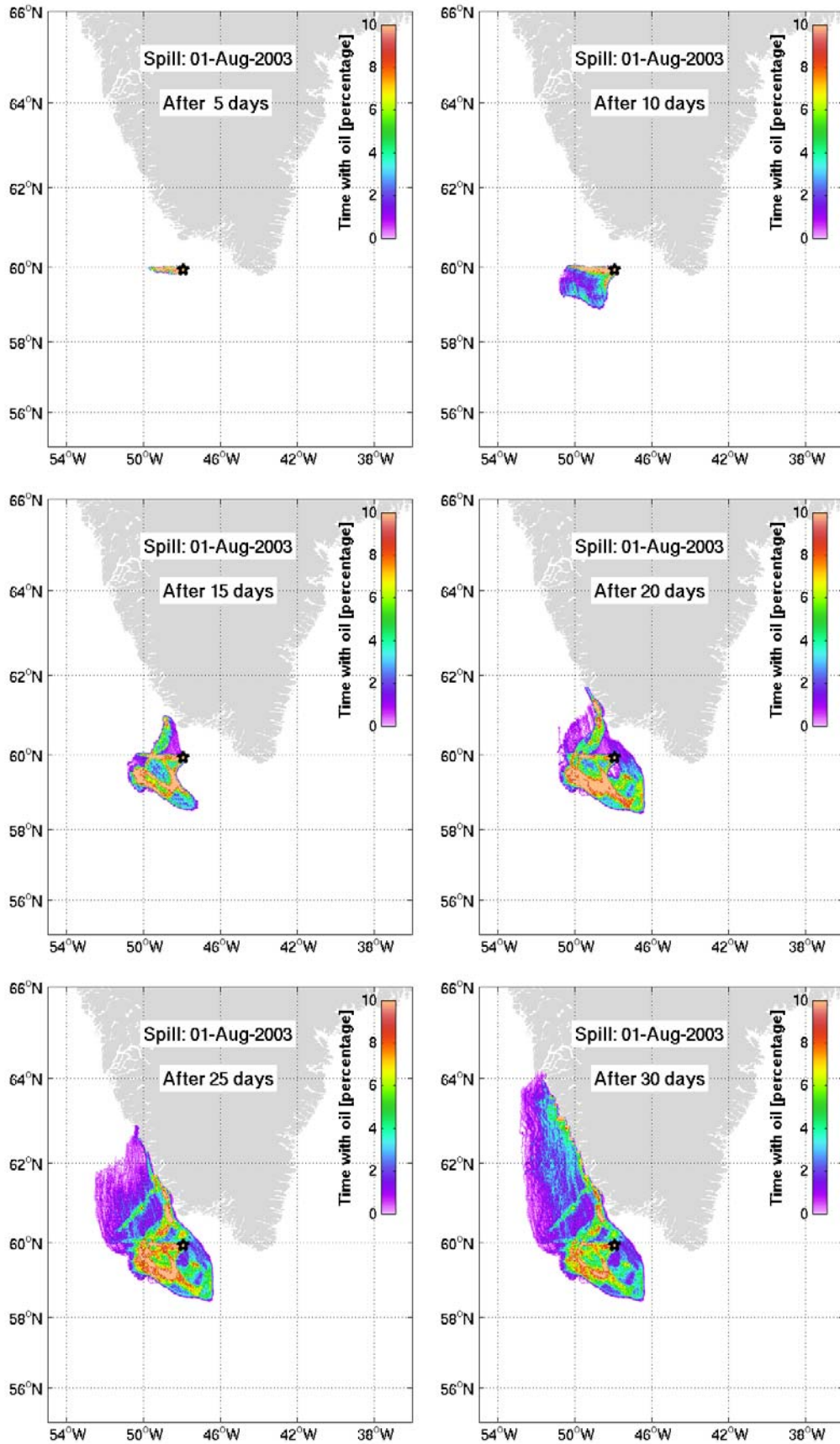


Figure 4. Simulated oil drift started 1st August 2003 from position 1. Snapshots are shown after 5-30 days of simulation. Similar to the ensemble probability maps in Appendix B but for a single simulation.

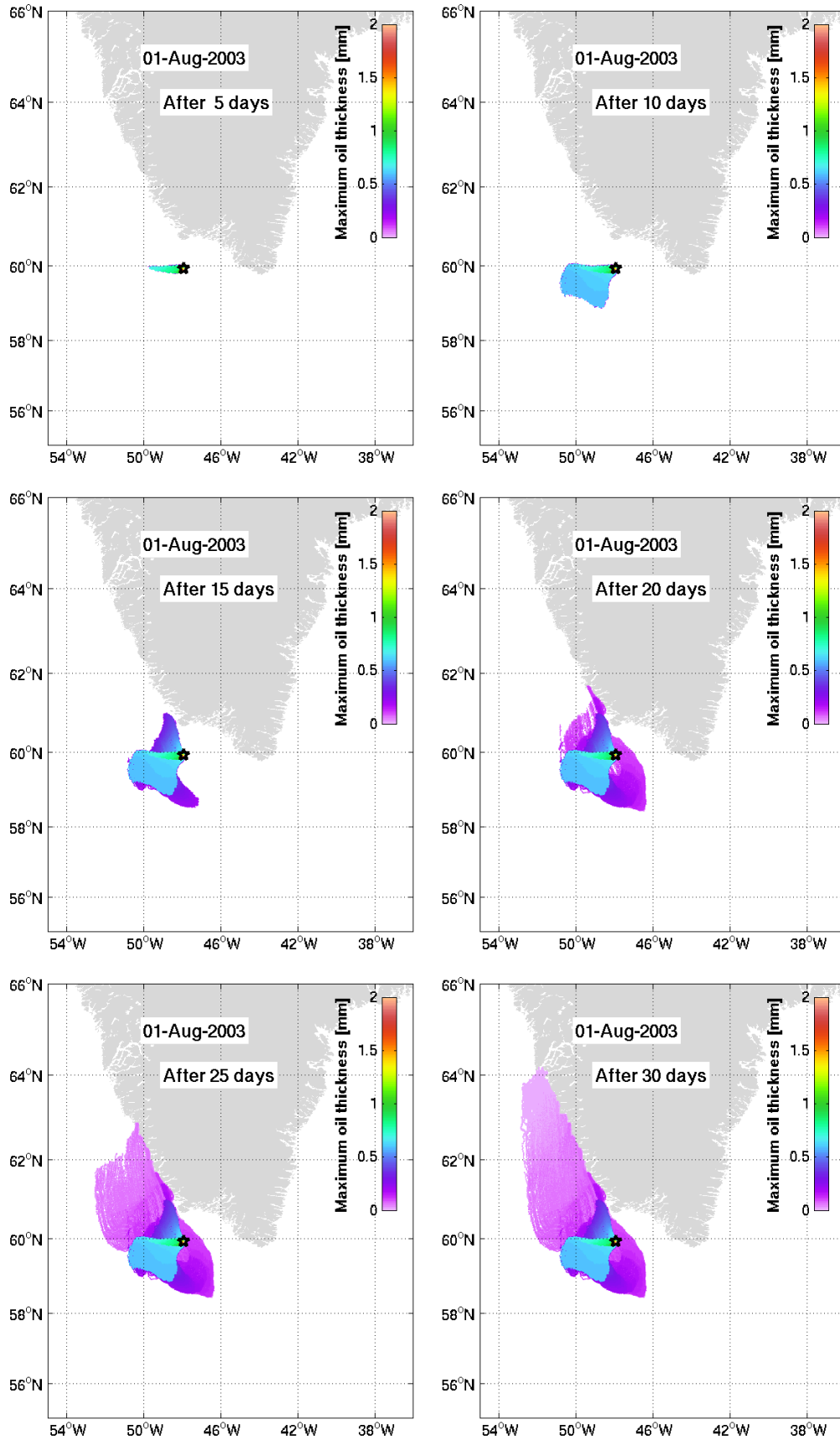


Figure 5. Simulated oil drift started 1st August 2003 from position 1. Snapshots are shown after 5-30 days of simulation. Similar to the ensemble probability maps in Appendix B but for a single simulation.



Appendix B. Probability maps

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 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.

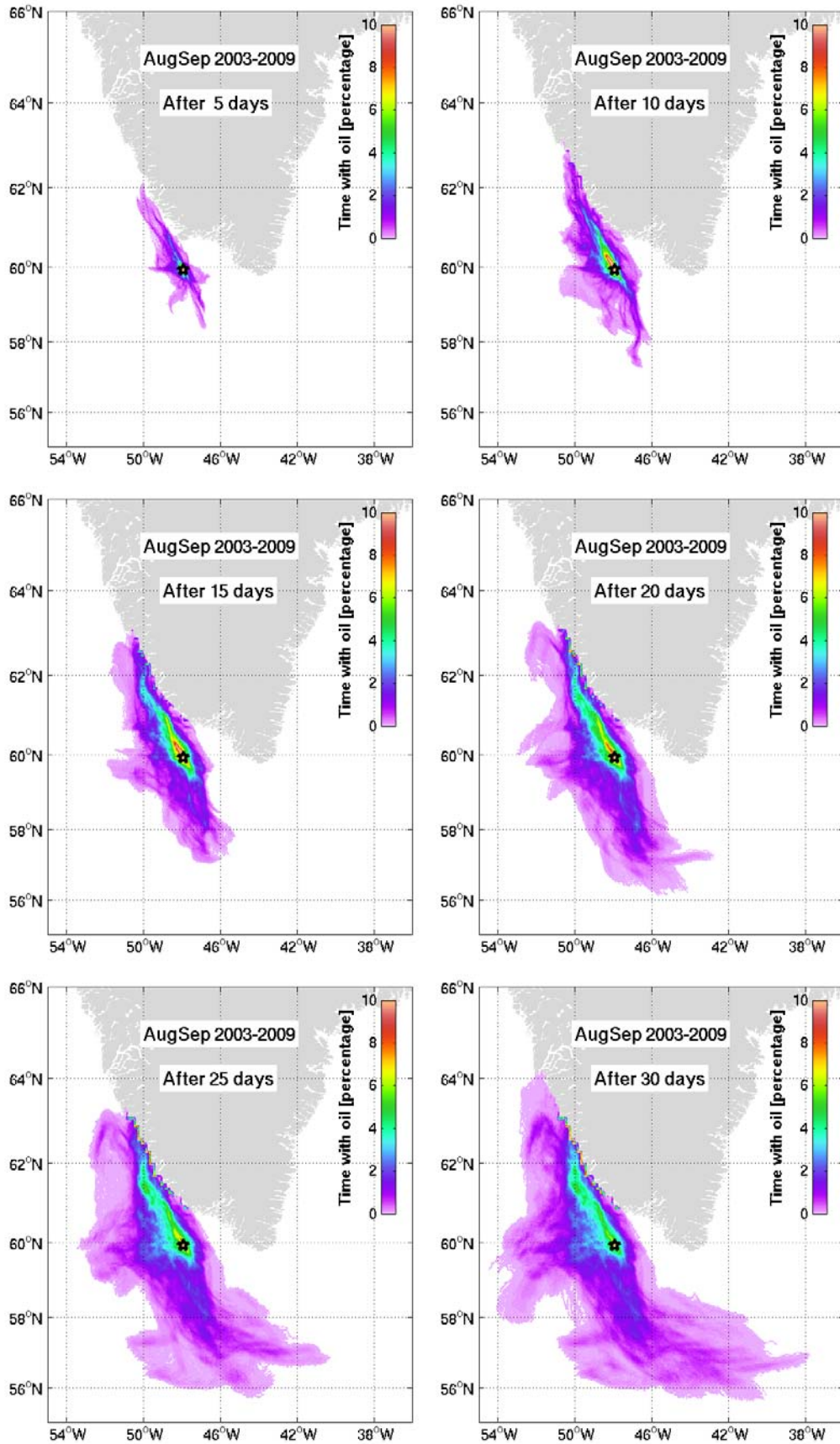


Figure 6. Probability maps for oil accumulated after 5-30 days of simulation using 28 ensembles for position 1 in August/September. The colors shows the percentage of time a gridbox were filled by oil. Ex. 10% time with oil after 15 days simulation is 1½ day with oil.

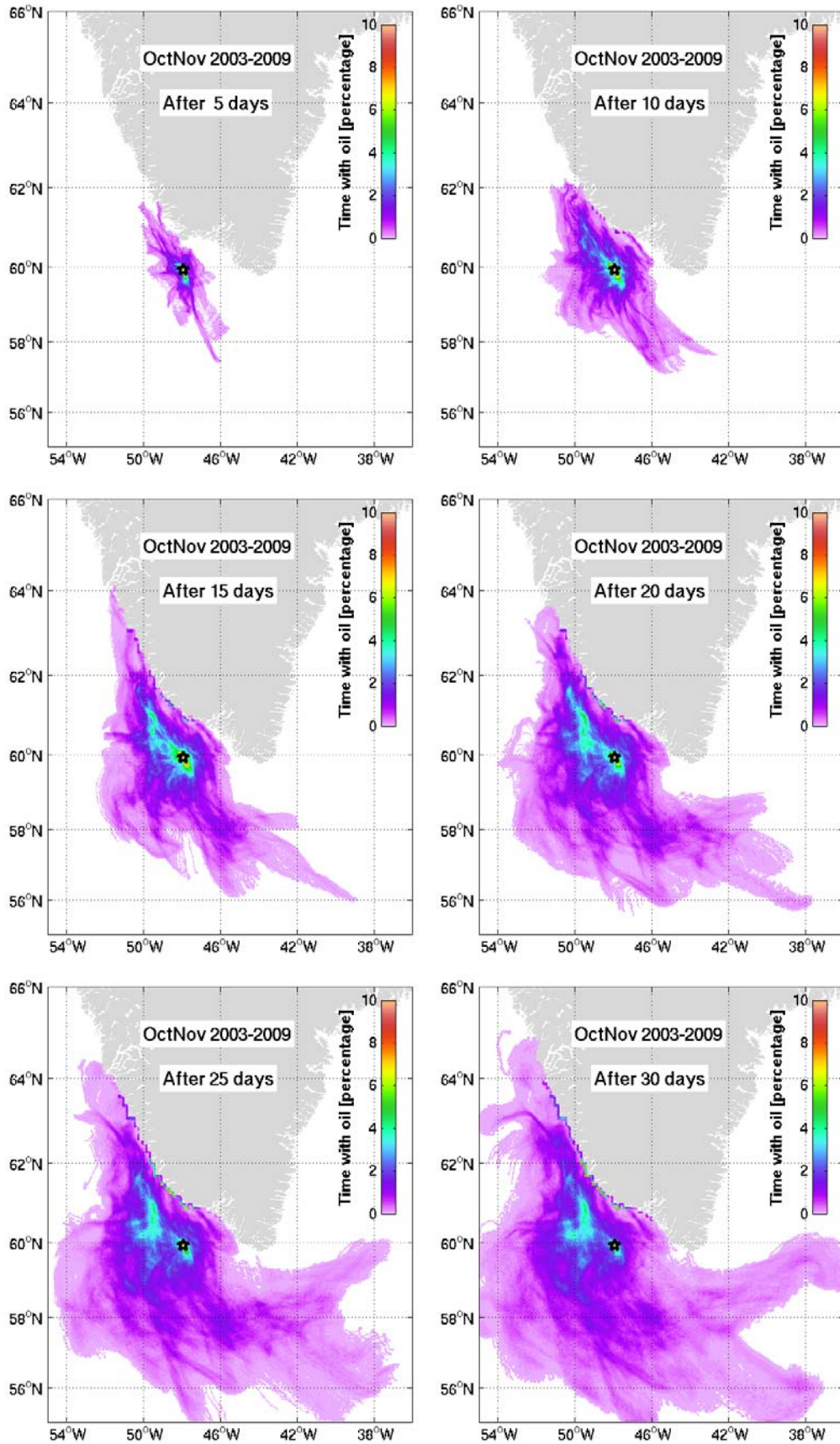


Figure 7. Probability maps for oil accumulated after 5-30 days of simulation using 28 ensembles for position 1 in October/November. The colors shows the percentage of time a gridbox were filled by oil. Ex. 10% time with oil after 15 days simulation is 1½ day with oil.

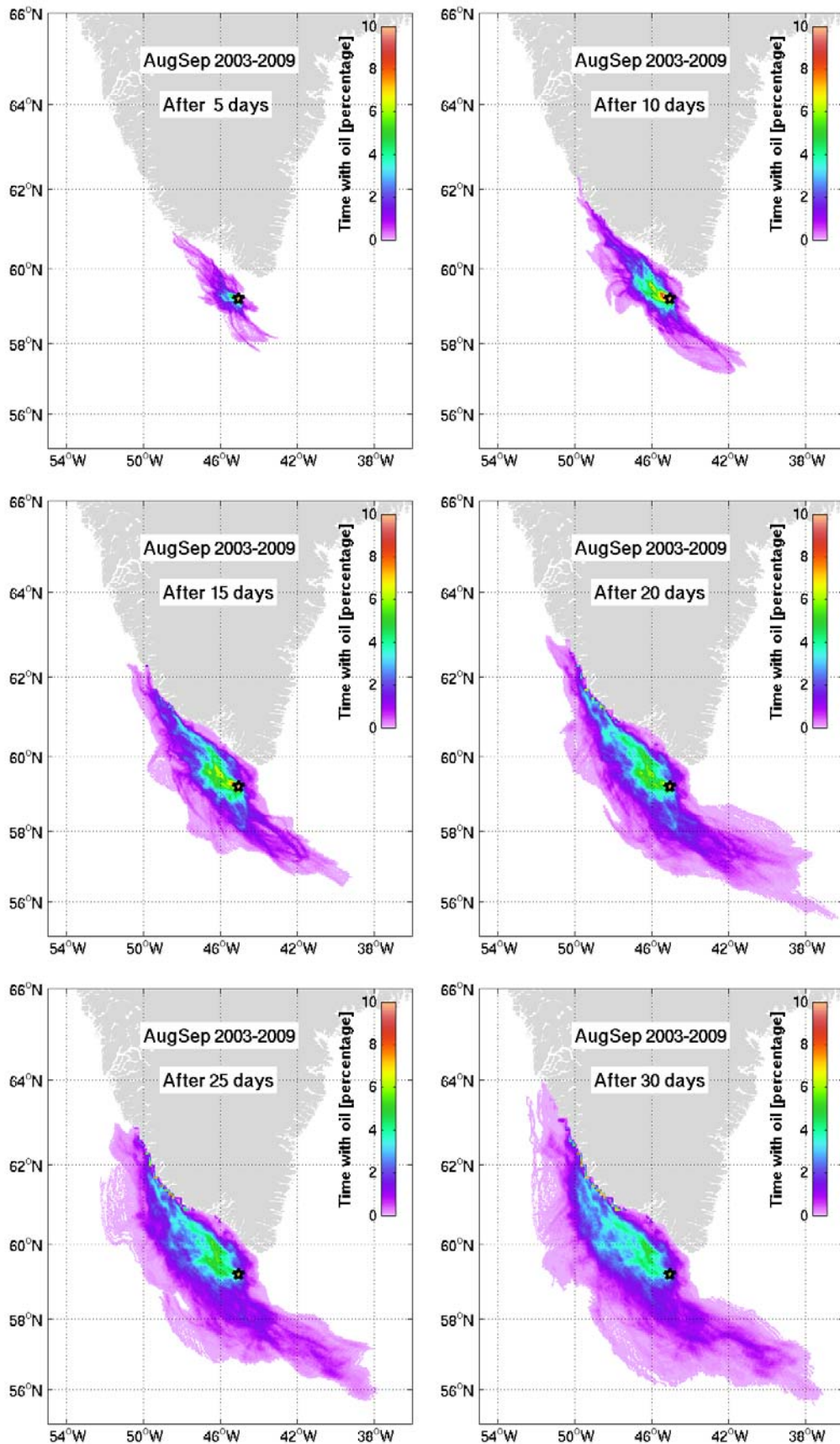


Figure 8. Probability maps for oil accumulated after 5-30 days of simulation using 28 ensembles for position 2 in August/September. The colors shows the percentage of time a gridbox were filled by oil. Ex. 10% time with oil after 15 days simulation is 1½ day with oil.

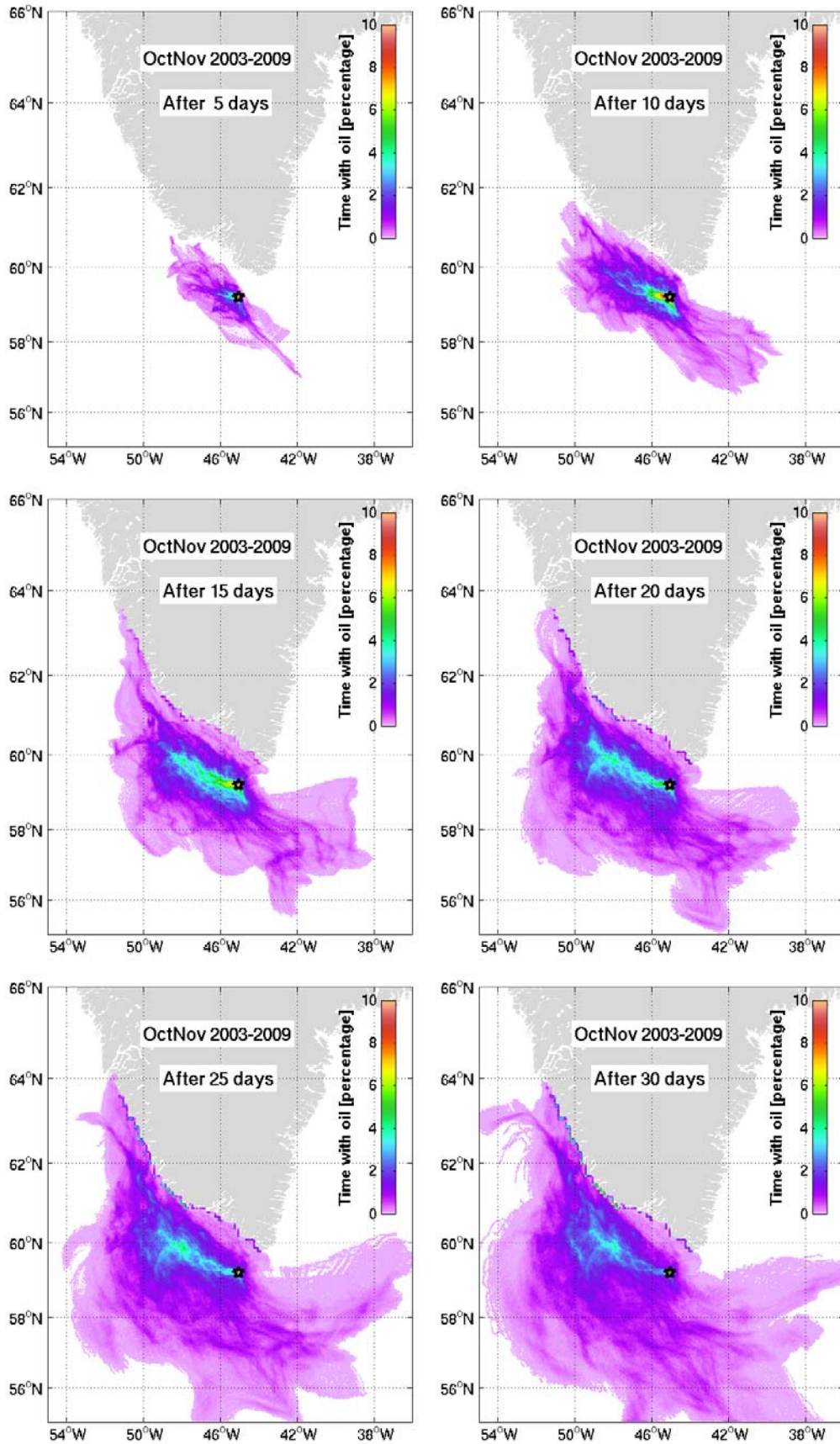


Figure 9. Probability maps for oil accumulated after 5-30 days of simulation using 28 ensembles for position 2 in October/November. The colors shows the percentage of time a gridbox were filled by oil. Ex. 10% time with oil after 15 days simulation is 1½ day with oil.

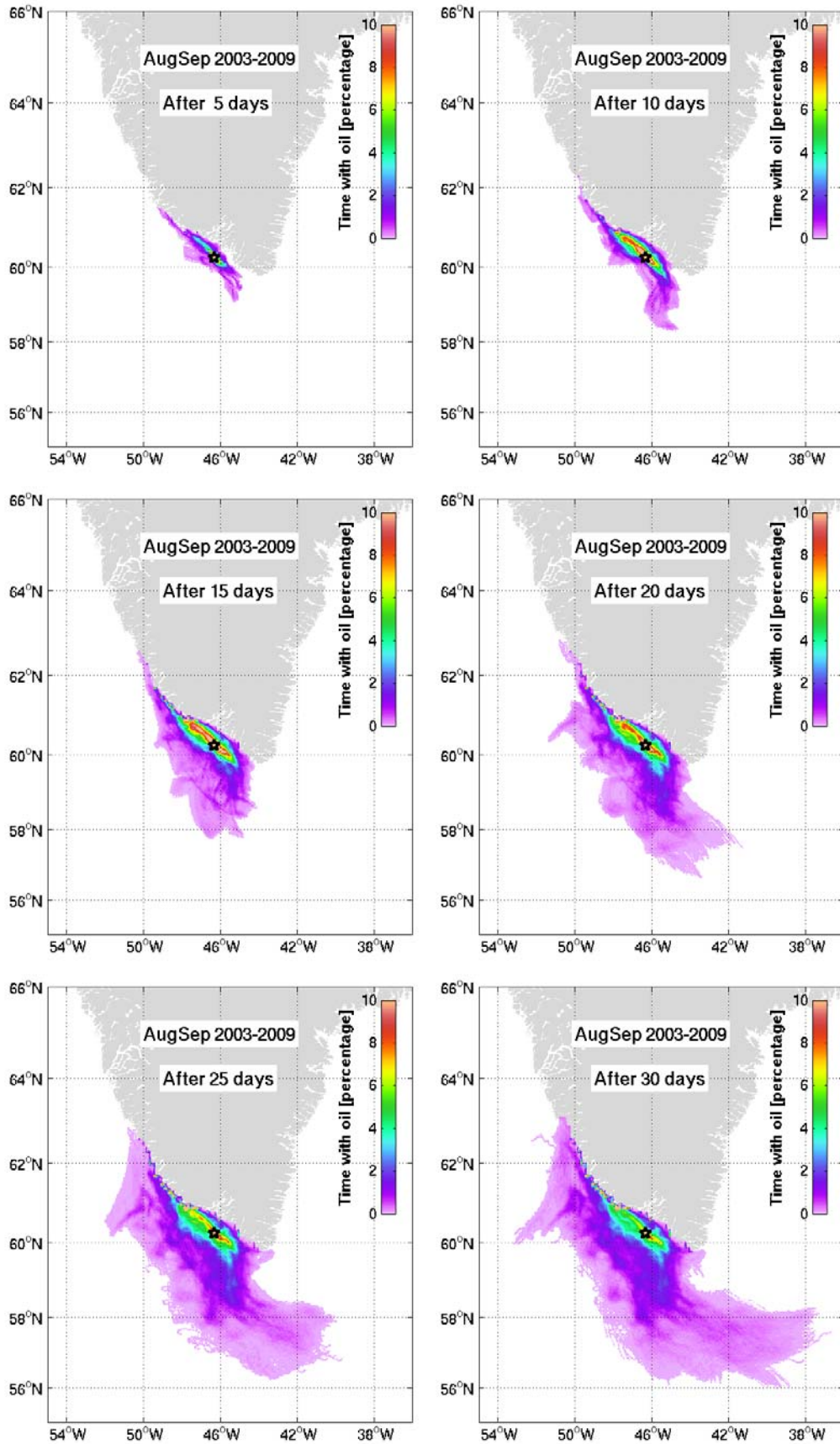


Figure 10. Probability maps for oil accumulated after 5-30 days of simulation using 28 ensembles for position 3 in August/September. The colors shows the percentage of time a gridbox were filled by oil. Ex. 10% time with oil after 15 days simulation is 1½ day with oil.

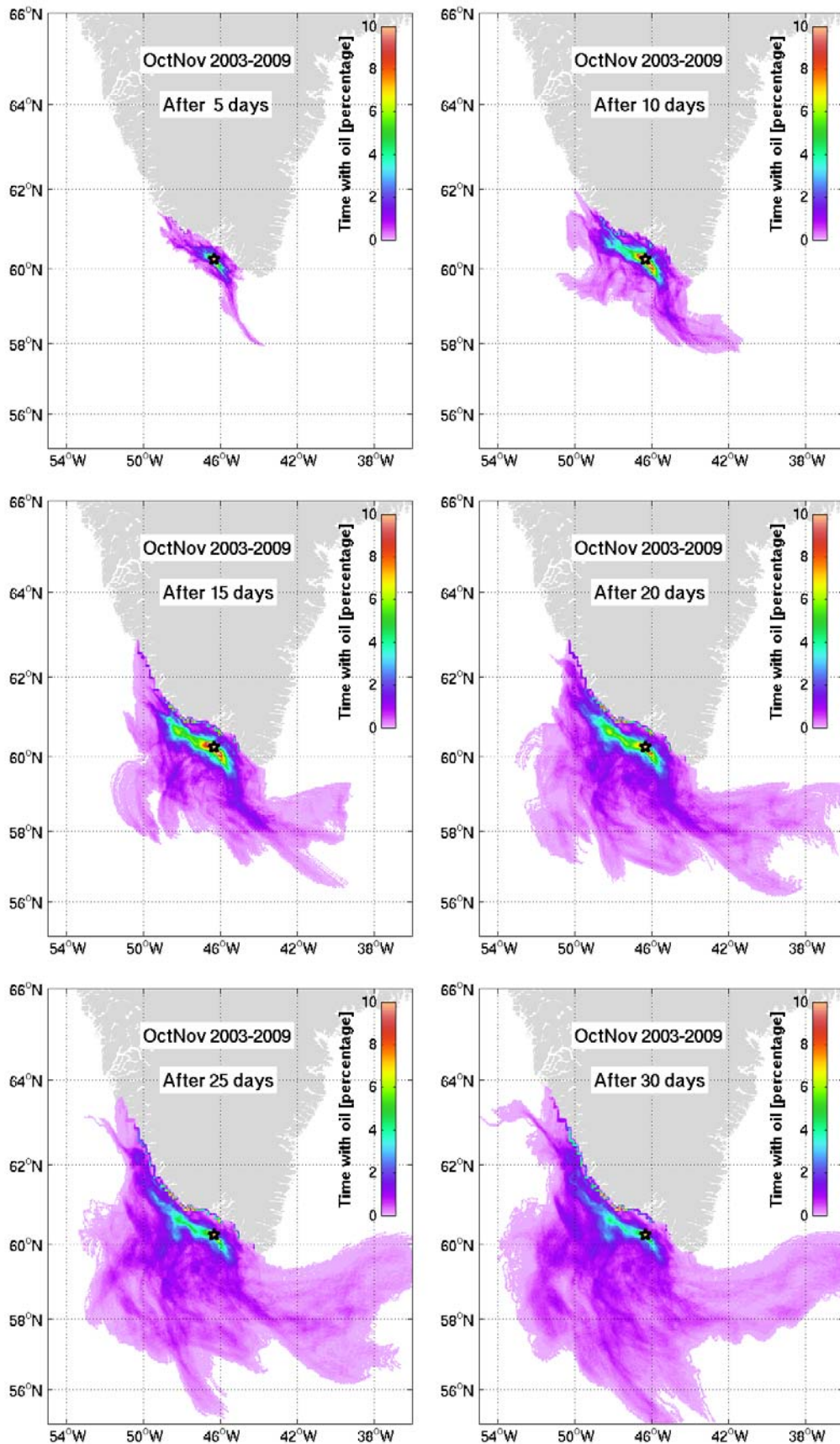


Figure 11. Probability maps for oil accumulated after 5-30 days of simulation using 28 ensembles for position 3 in October/November. The colors shows the percentage of time a gridbox were filled by oil. Ex. 10% time with oil after 15 days simulation is 1½ day with oil.

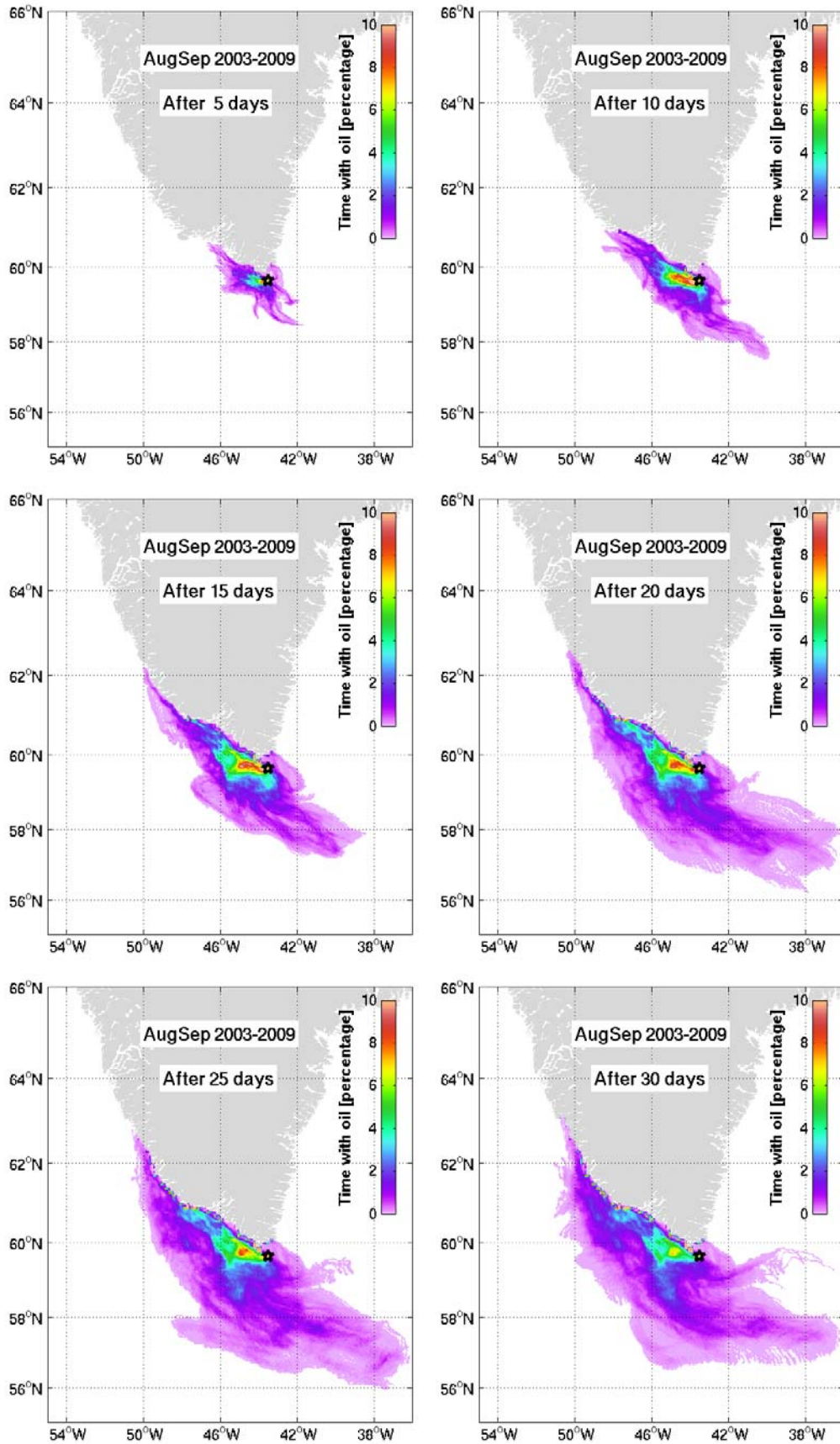


Figure 12. Probability maps for oil accumulated after 5-30 days of simulation using 28 ensembles for position 4 in August/September. The colors shows the percentage of time a gridbox were filled by oil. Ex. 10% time with oil after 15 days simulation is 1½ day with oil.

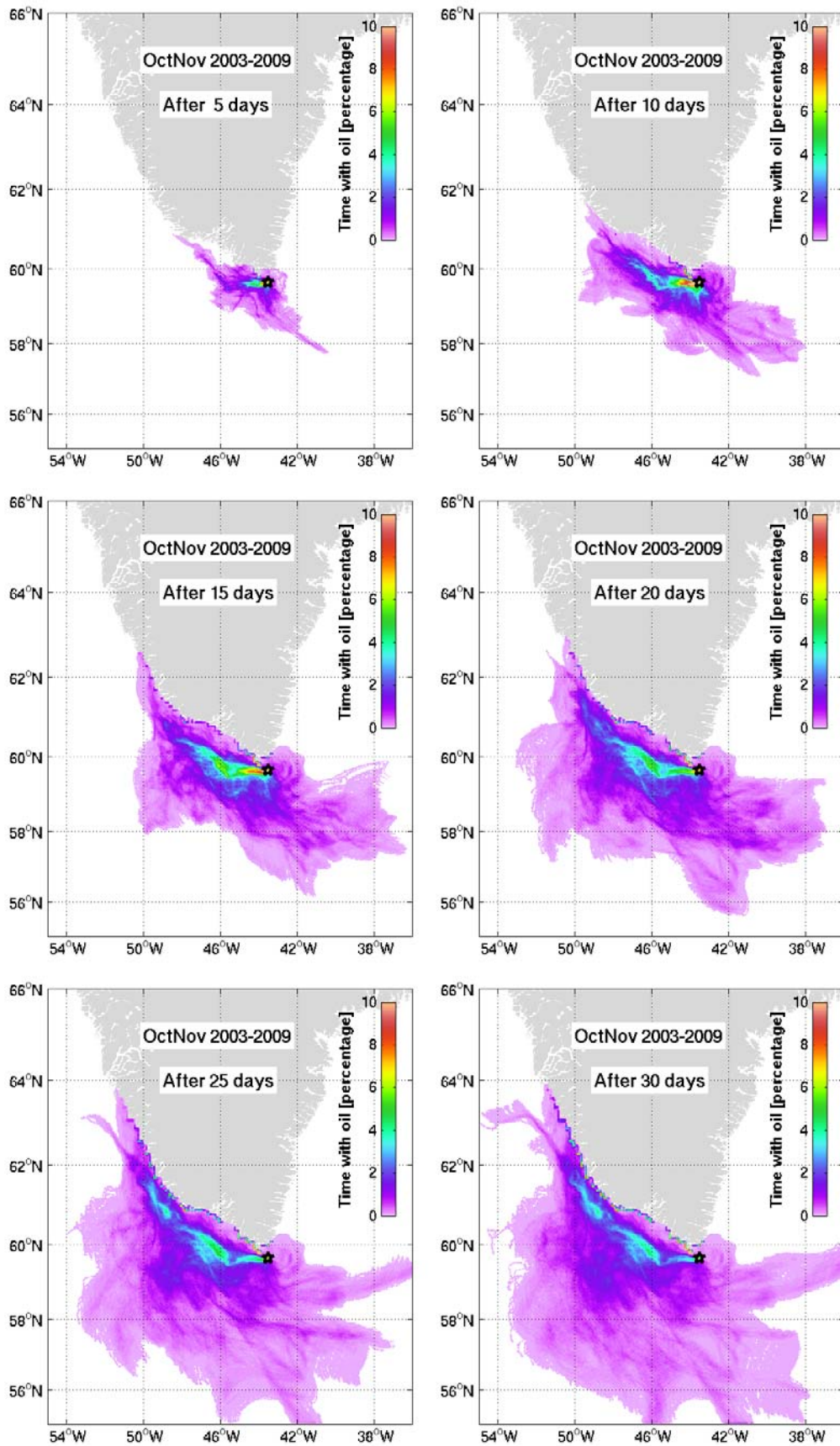


Figure 13. Probability maps for oil accumulated after 5-30 days of simulation using 28 ensembles for position 4 in October/November. The colors shows the percentage of time a gridbox were filled by oil. Ex. 10% time with oil after 15 days simulation is 1½ day with oil.

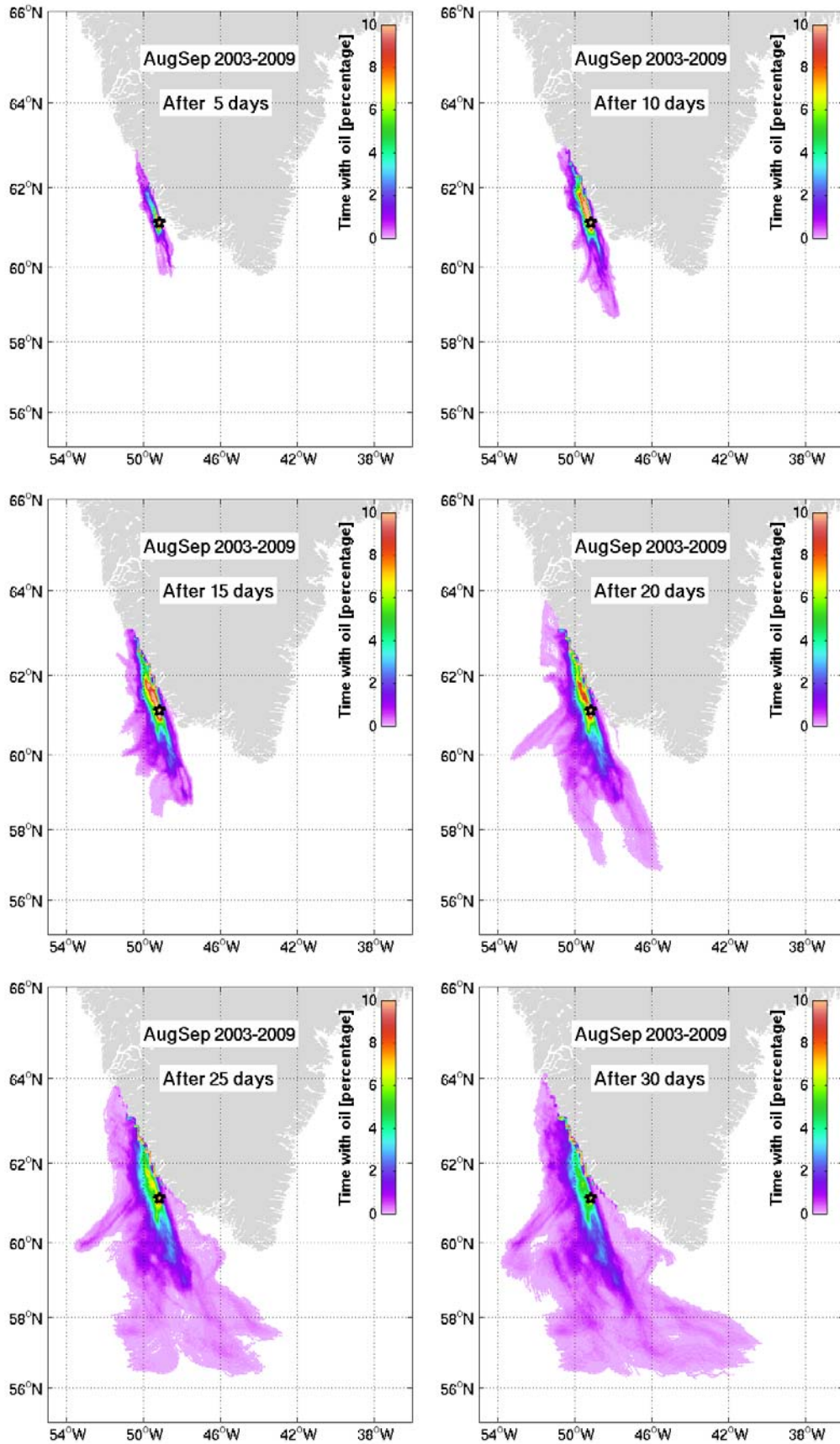


Figure 14. Probability maps for oil accumulated after 5-30 days of simulation using 28 ensembles for position 5 in August/September. The colors shows the percentage of time a gridbox were filled by oil. Ex. 10% time with oil after 15 days simulation is 1½ day with oil.

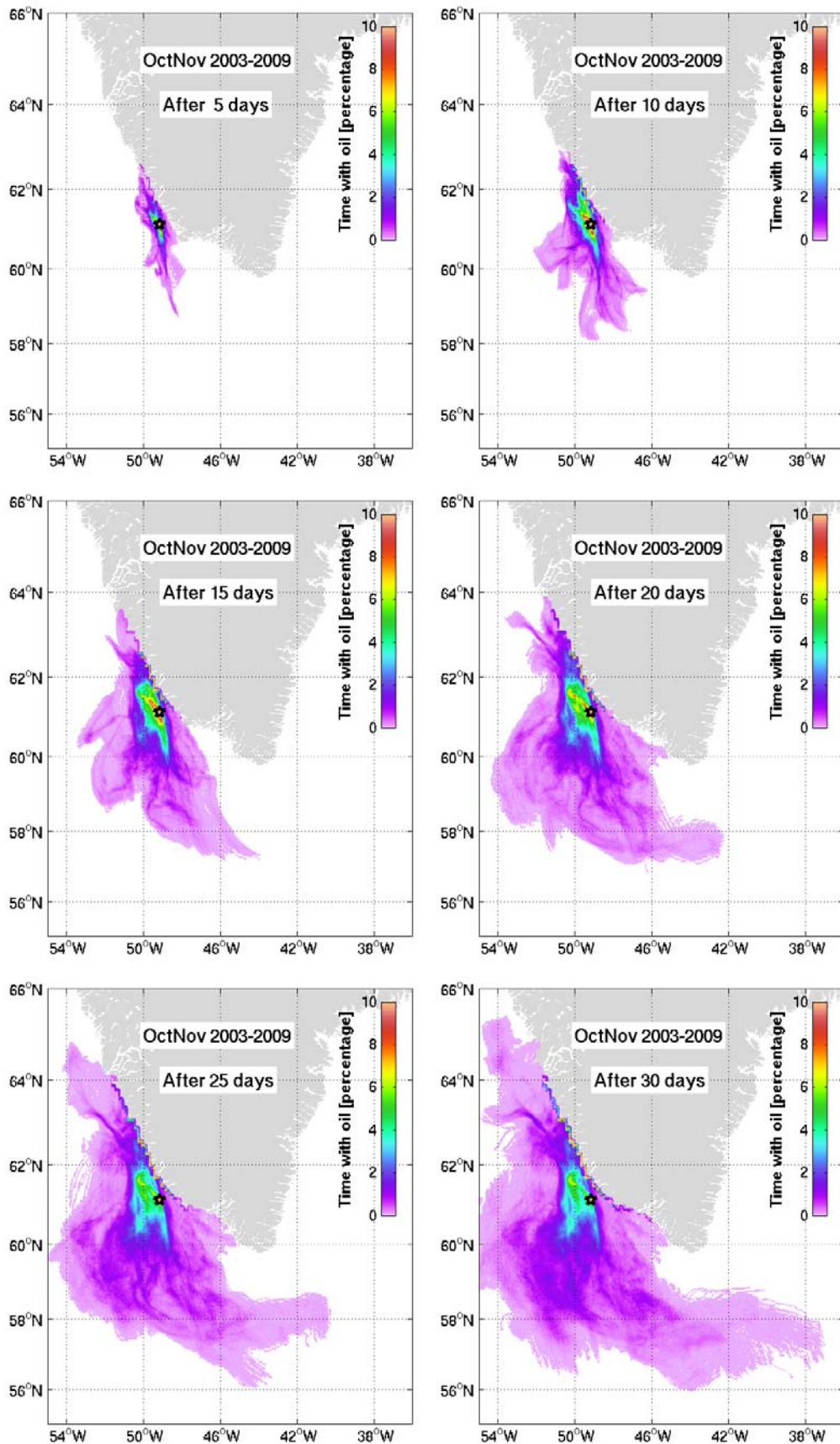


Figure 15. Probability maps for oil accumulated after 5-30 days of simulation using 28 ensembles for position 5 in October/November. The colors shows the percentage of time a gridbox were filled by oil. Ex. 10% time with oil after 15 days simulation is 1½ day with oil.



Appendix C. Maximum surface layer oil thickness

For each of the 7 spill sites, the maximum oil slick thickness in the surface skin layer attained at any time during the first 5, 10, ..., 30 days of simulation is mapped. Only surface spills are shown.

Note that the figures do not represent the oil slick at a given time, but shows the area that at any time during the simulation has been covered by oil. Also note the values sometimes exceed the colorbar scaling and the colours get saturated at the highest value.

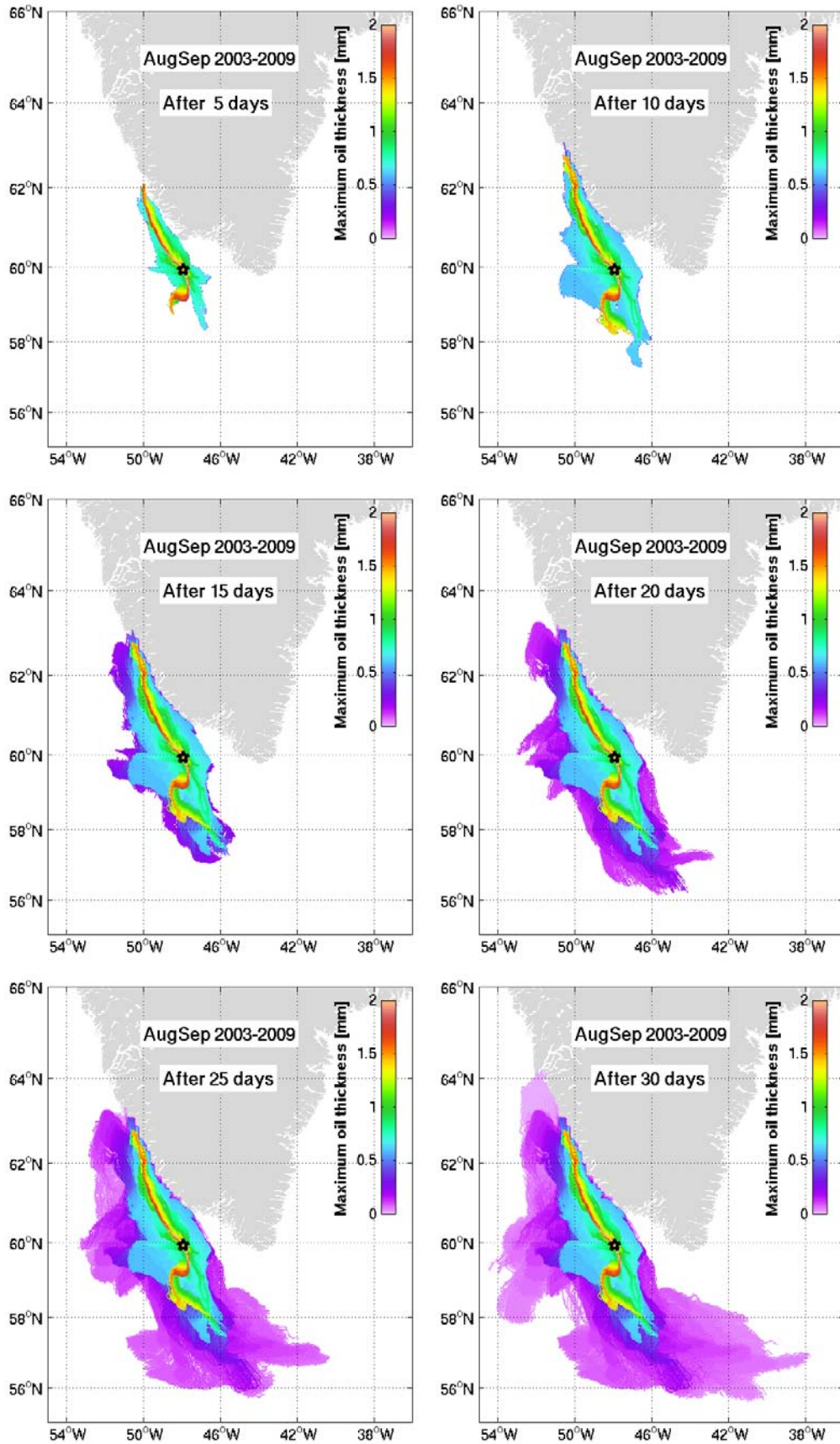


Figure 16. Maximum oil thickness after 5-30 days of simulation found in the 28 ensembles for position 1 in August/September.

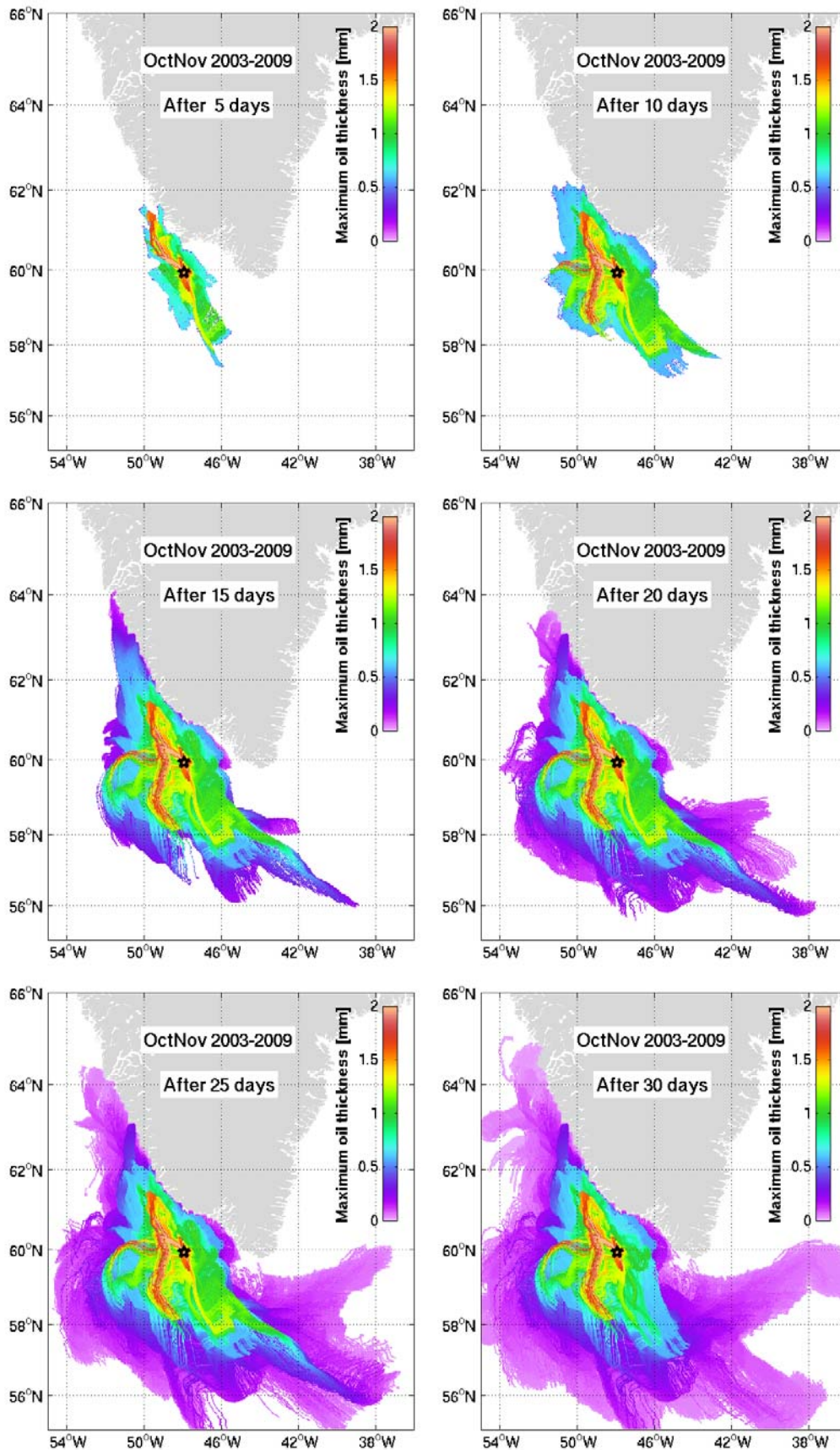


Figure 17. Maximum oil thickness after 5-30 days of simulation found in the 28 ensembles for position 1 in October/November. Only oil in the upper ½ meter is considered. Note some values beyond the color scale.

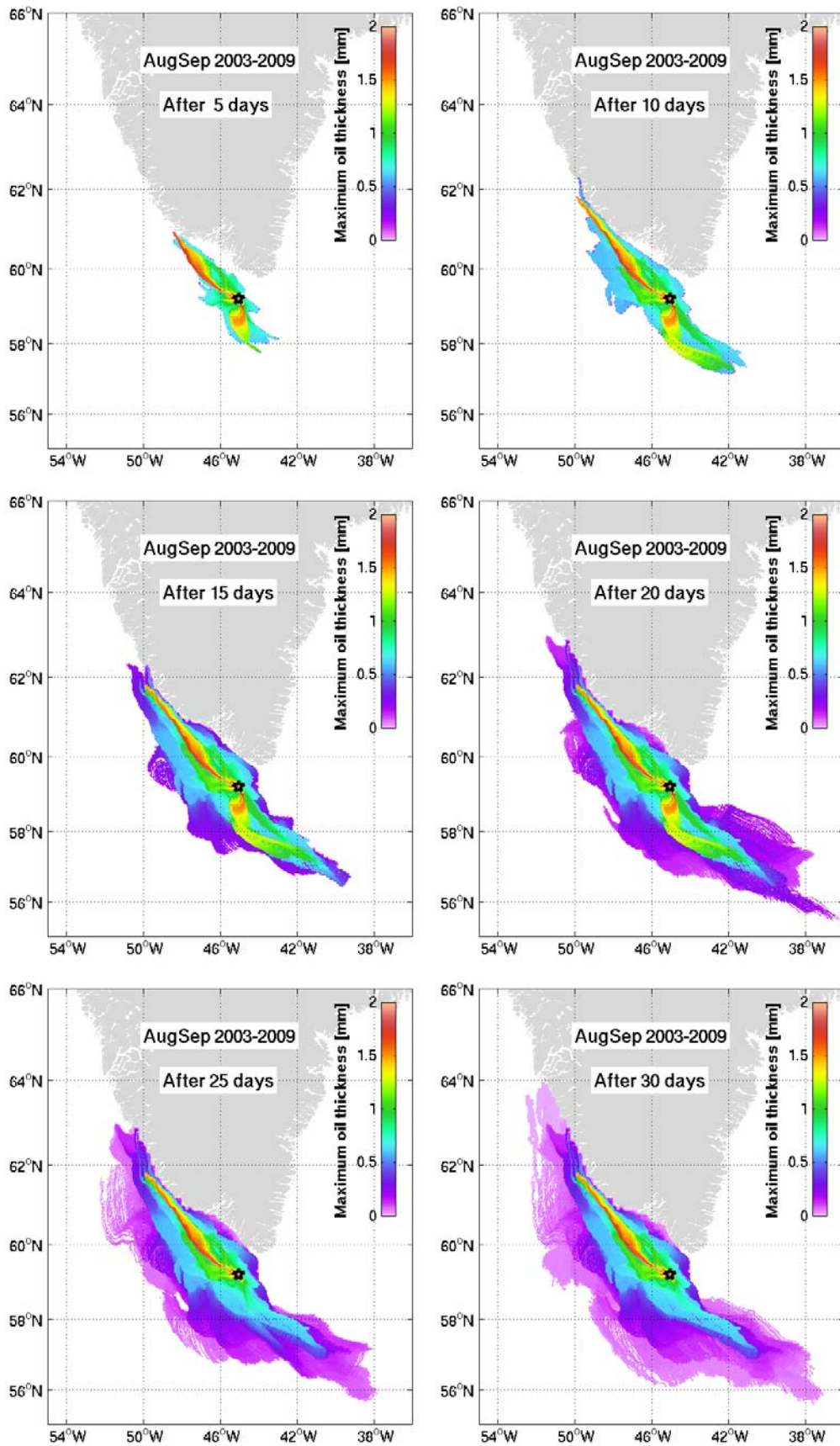


Figure 18. Maximum oil thickness after 5-30 days of simulation found in the 28 ensembles for position 2 in August/September.

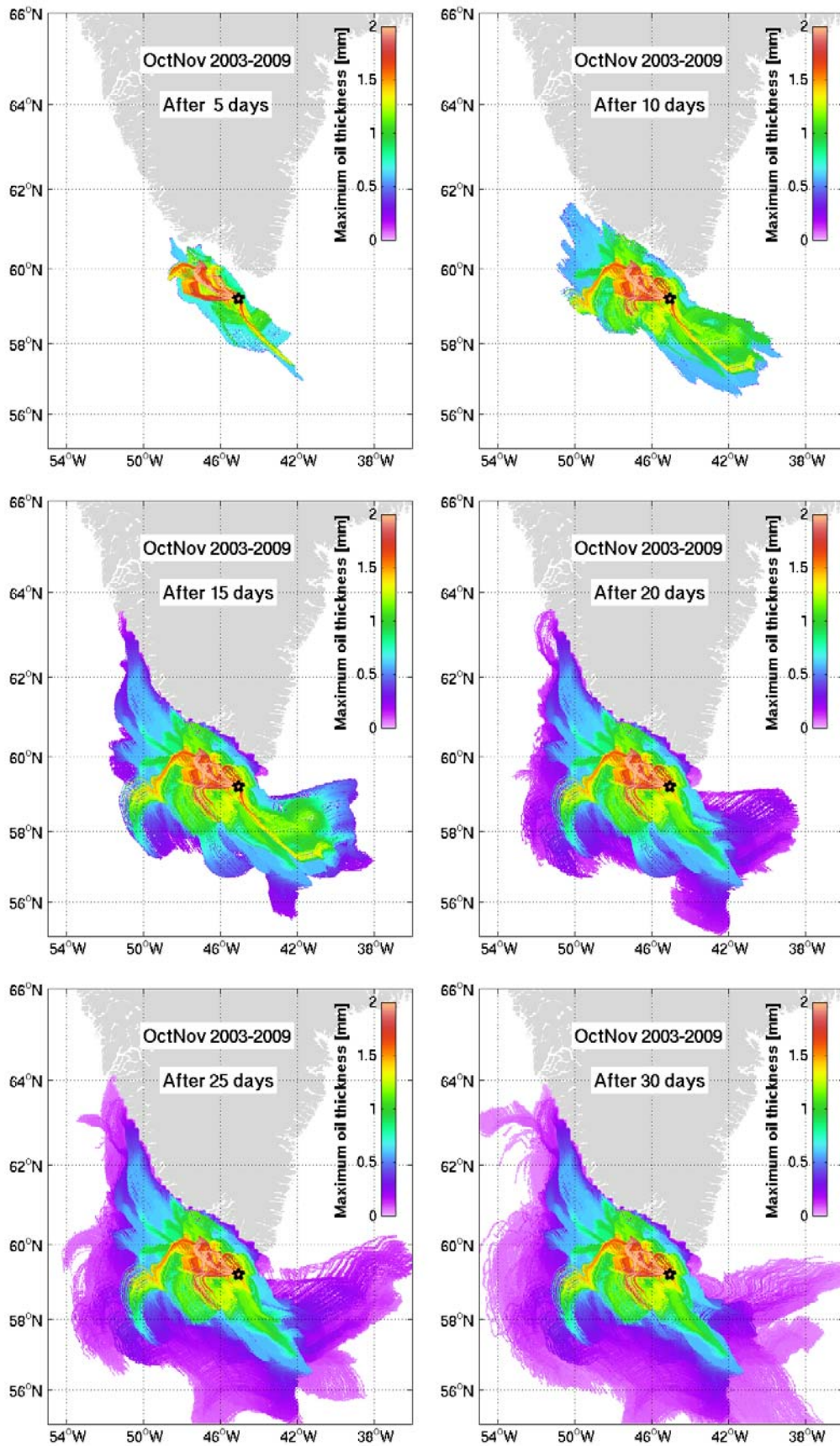


Figure 19. Maximum oil thickness after 5-30 days of simulation found in the 28 ensembles for position 2 in October/November.

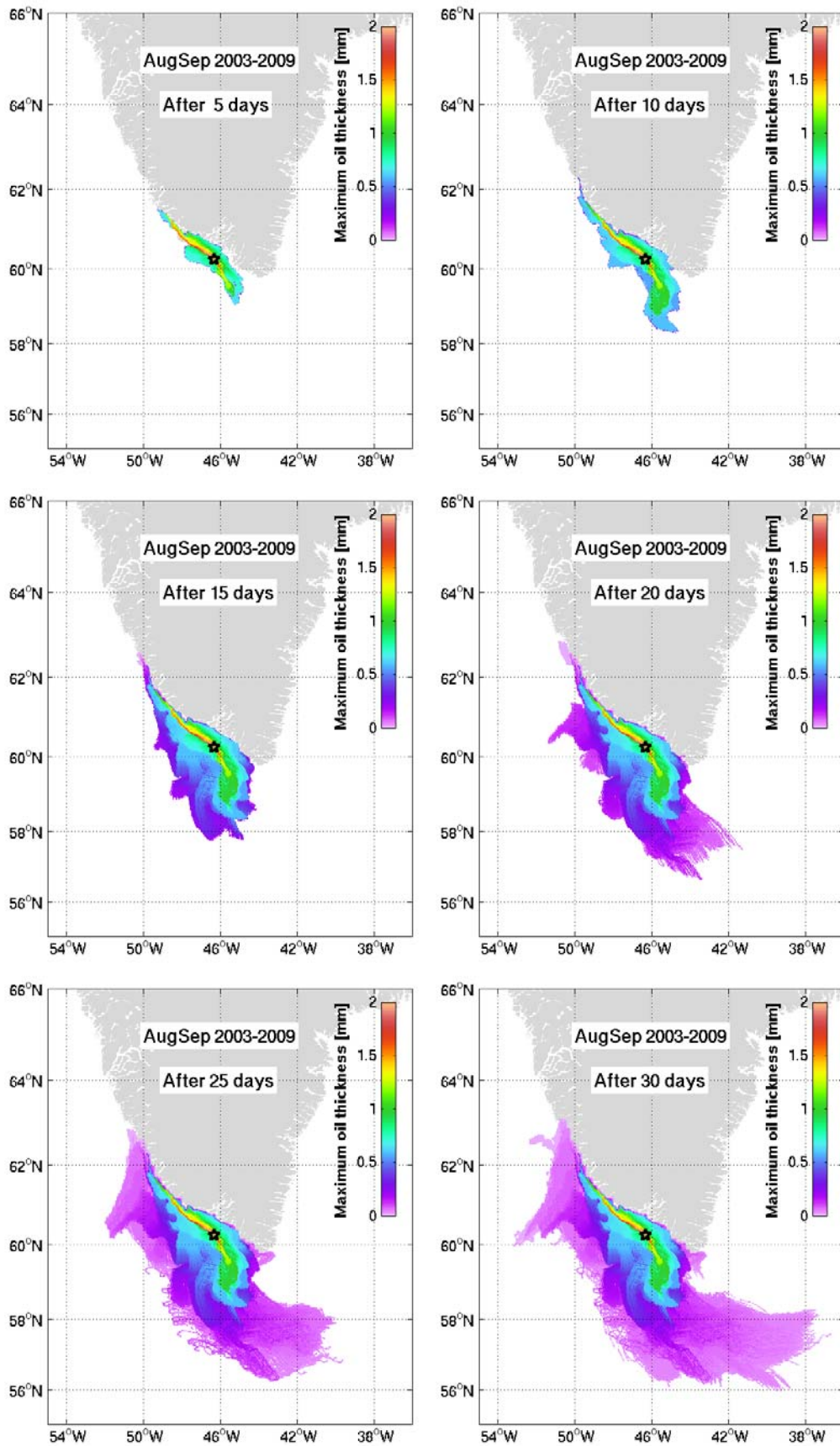


Figure 20. Maximum oil thickness after 5-30 days of simulation found in the 28 ensembles for position 3 in August/September.

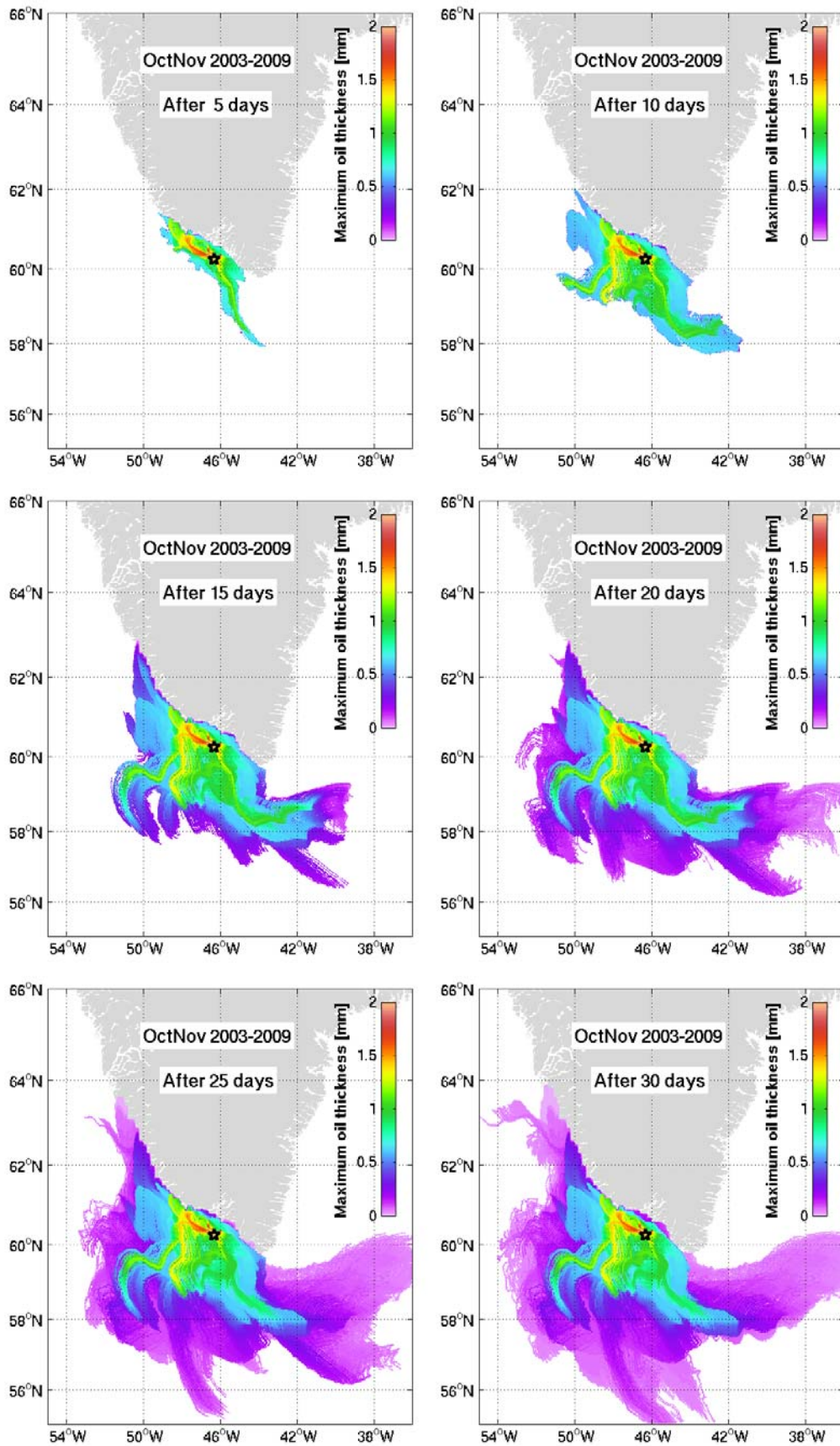


Figure 21. Maximum oil thickness after 5-30 days of simulation found in the 28 ensembles for position 3 in October/November.

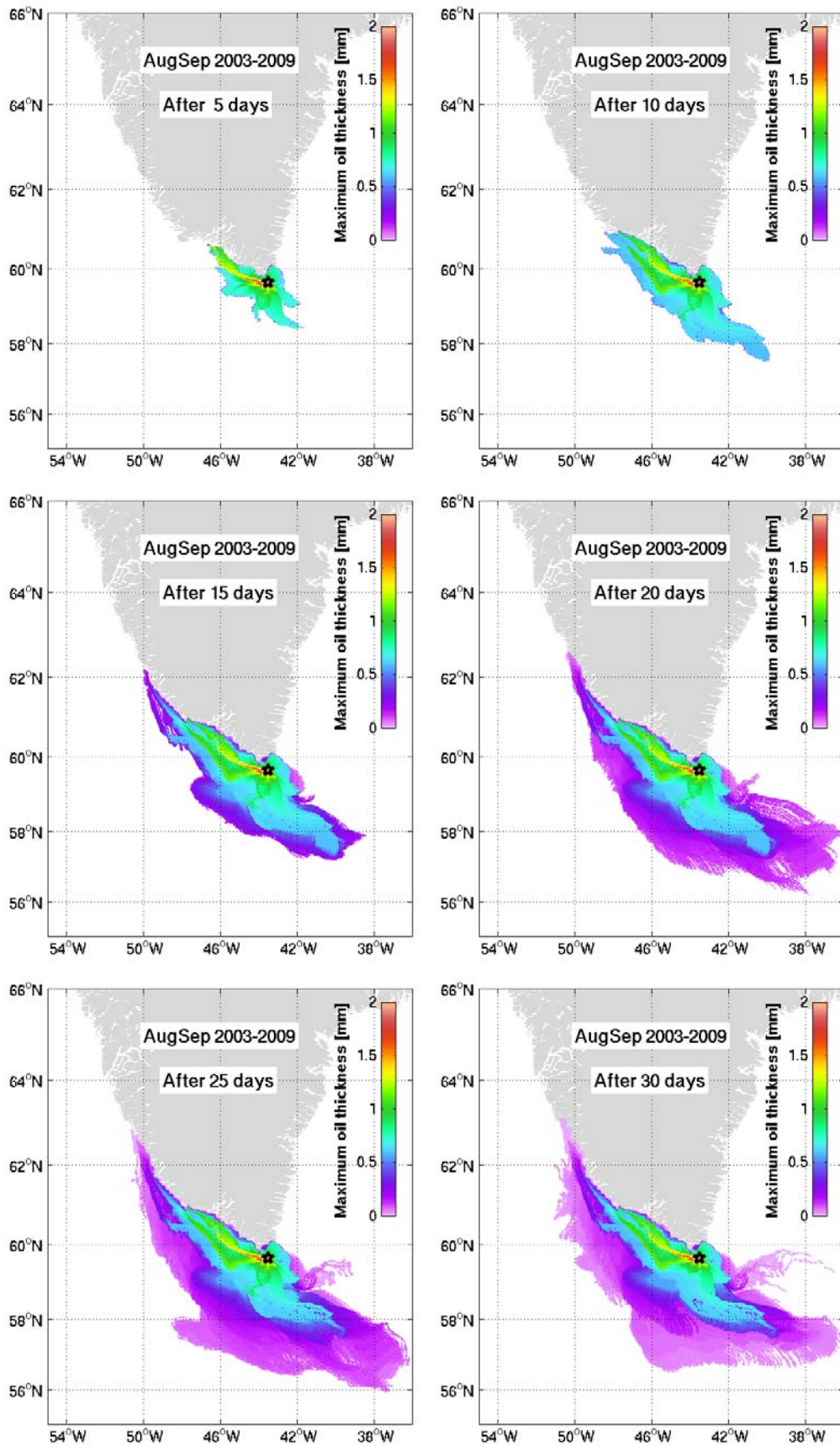


Figure 22. Maximum oil thickness after 5-30 days of simulation found in the 28 ensembles for position 4 in August/September.

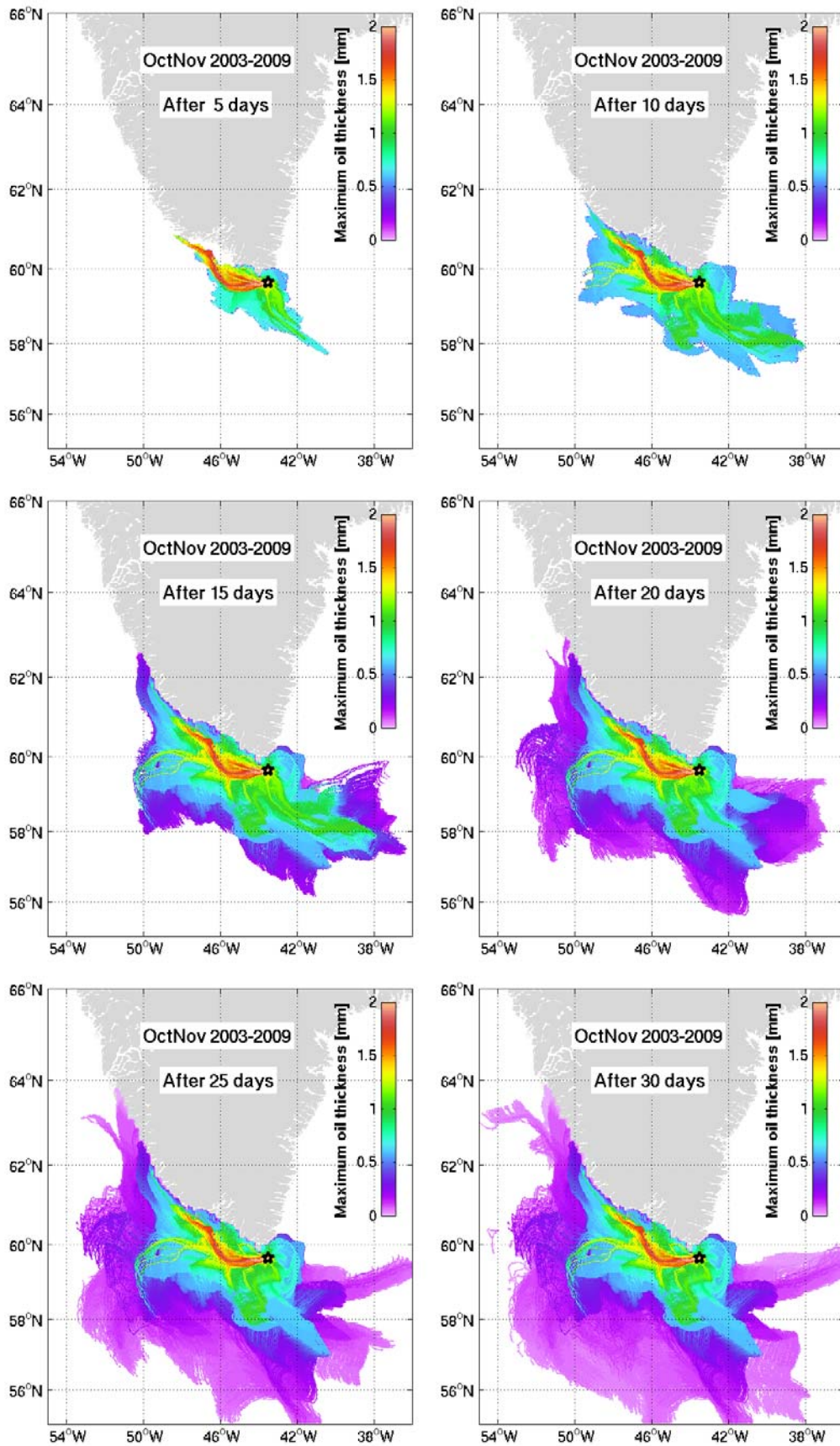


Figure 23. Maximum oil thickness after 5-30 days of simulation found in the 28 ensembles for position 4 in October/November.

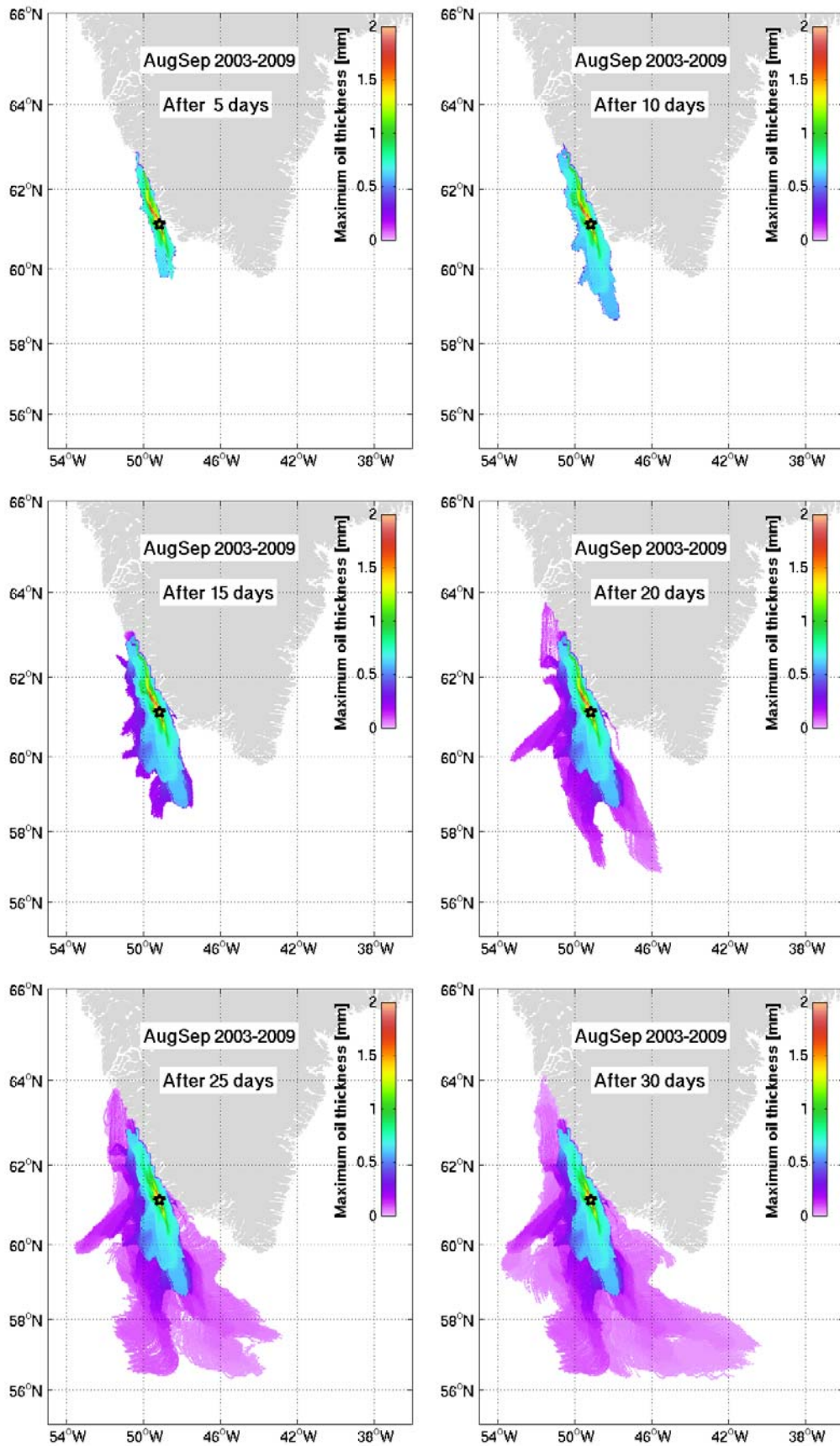


Figure 24. Maximum oil thickness after 5-30 days of simulation found in the 28 ensembles for position 5 in October/November.

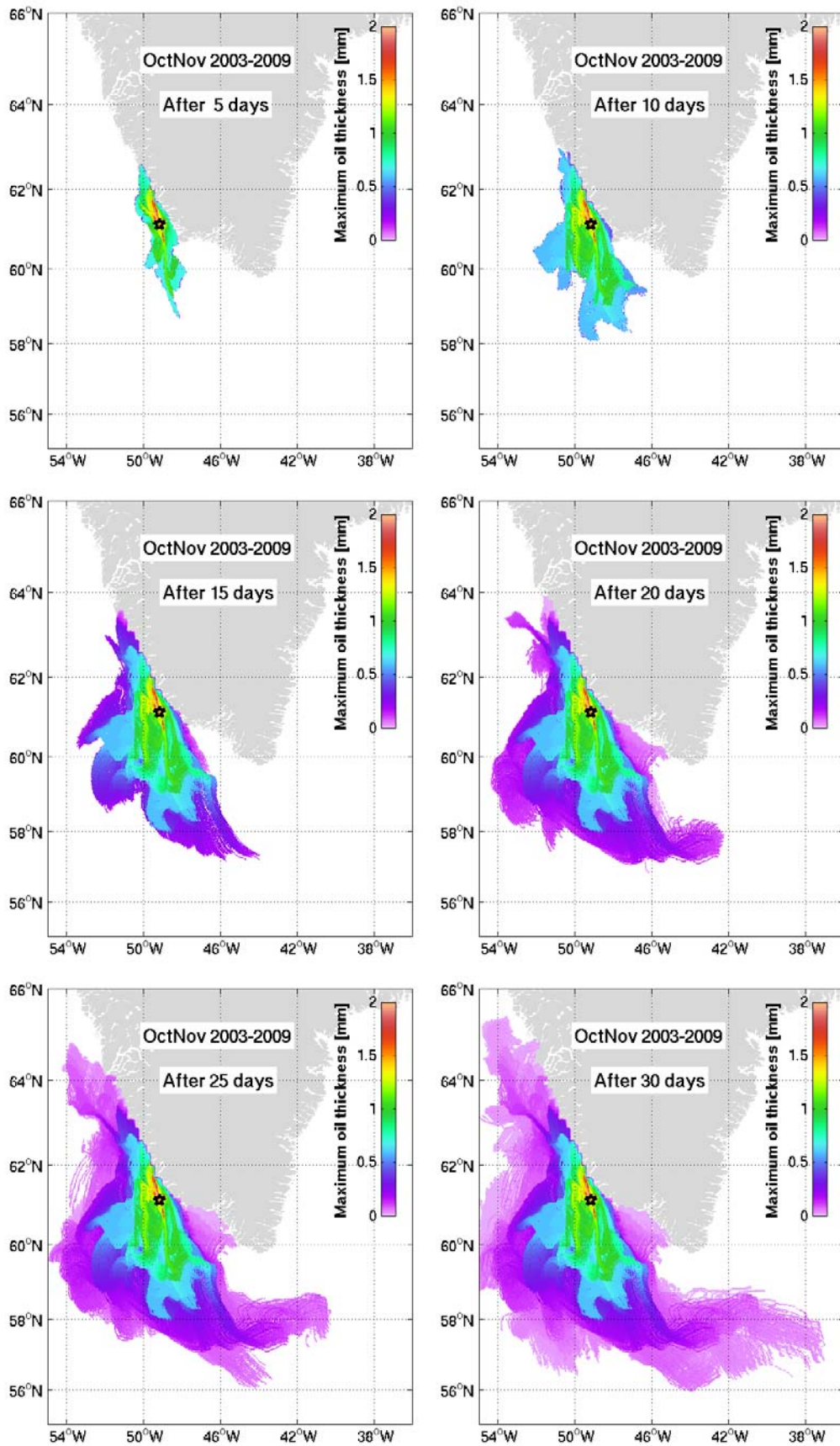


Figure 25. Maximum oil thickness after 5-30 days of simulation found in the 28 ensembles for position 5 in August/September.