Electronic Supplementary Material

Tracer transport and exchange processes in the Baltic Sea 2000 - 2009

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2. Description of Particle Paths

Gives the detail descriptions of particle paths in the Baltic Sea Basins and 11 major rivers enter the Baltic Sea

3. Figures

- Figure S1: Comparison of Particle release duration and particle numbers for the Bay of Bothnia and River Torne. Particles depths are shown by the colour scale.
- Figure S2: Particle tracking in the major basins of the Baltic Sea in the period 2000-2009. Particles depths are shown by the colour scale. The dark grey colour shows the paths covered by the particles.
- Figure S3: Particle tracking for the major rivers of the Baltic Sea. Particles depths are shown by the colour scale.

4. Description of Particle Paths

Please note that Figures 9 and 10 refer to the main manuscript.

5. Basins (S1-a to S2-j & Figures 9a-9j)

In the ***Bay of Bothnia***, the general mixing and particle migration characteristics are a large - scale anti-clockwise rotation of the deep and mid-depth layers. Figure 9a shows a typical path for one particle migrating north-westwards. The paths and time of arrivals are as follows:

- Initially, the particles move north-eastwards and north-westwards at a speed of 4 cm/s reaching the

Swedish and Finish shorelines after 90, and 210 days, respectively. The particles remain in the deeper layer for 305 days and then start to migrate upwards.

- A few particles move south-westwards that finally enter the Northern Quark after 515 days. These particles enter the deeper water of the Sea of Bothnia (≈-50m) after 1860 days and thereby split to westwards direction. Close to the end of the simulation time, a few particles enter the Kumlinge Sill and the northern part of the Archipelago Sea.

The analysis of particle distribution with the water depth indicates that about 45% of the released particles migrate upwards into the mixing and thermocline layers after the 10 years simulation period (see Figure 9a the 3D and histogram plots).

In the ***Sea of Bothnia***, particles remain within the northern part of the basin for 750 days following a general anti-clockwise circulation pattern that persists throughout the 10-year simulation period. Fig. 9b shows a typical path for one particle within the basin and the particle corresponding distributions with depth. The main particle paths are northwards within the basin and a limited southwards migration out of the basin as follows:

- Northwest migrating particles move further north and enter the Bay of Bothnia after 1115 days by passing through the Northern Quark
- Particles migrating south-westwards enter the Southern Quark after 585 days, reaching Åland Sea after 675 days. After 970 days they pass through the Gotska Sandö Sill and then enter the Western Gotland Basin after 1875 days.
- Particles moving south-eastwards pass through the Kumlinge Sill after 280 days and then enter the Archipelago Sea after 760 days. A few particles divert more eastwards into the Gulf Finland after 2015 days. After 2255 days they reach Ostrov Kotlin (60^{o}N and 29^{o}E) shorelines and travel close to the southern shorelines in the Gulf of Finland
- Particles migrating south-eastwards enter the Northern Gotland Basin after 1015 days. Most of the particles move further south entering the Eastern Gotland Basin after 1755 days and finally pass through Gdansk Sill after 3410 days. A few particles from the Northern Gotland Basin enter the Gulf of Riga having passed through Väinameri after 1755 days.

In comparison to the Bay of Bothnia, the particles not only migrate to most of the neighbouring basins, they also ascend further towards the surface water. About 50% of the released particles migrate upwards into the mixing and thermocline layers after the 10 years simulation period (see Figure 9b the 3D and histogram plots).

In the ***Åland Sea Islands***, the particles split into two main north and southwards directions. The general paths are as follows:

- The northward particles move close to the western Swedish shorelines. They reach the Archipelago Sea and the Sea of Bothnia after 90 and 100 days, respectively. Particles from the Sea of Bothnia move further north and enter the Northern Quark and finally the Bay of Bothnia after 900, and 1200 days, respectively.
- The southwards moving particles partly pass through the Åland Sill after 60 days and partly enter the Archipelago Sea after 90 days. Some particles from the Archipelago Sea divert eastwards and enter the Gulf of Finland after 900 days.
- The southwards moving particles from the Åland Sill enter the Northern Gotland Basin after 124 days. Thereafter, some particles move more west first passing through the Gotska SandÖ Sill and entering the Western Gotland Basin after 150 and 540 days, respectively.
- More particles from the Åland Sill re-enter the Northern Gotland Basin after 570 days. They then move southwards out of the Northern Gotland Basin entering the Eastern Gotland Basin after 1260 days.
- Particles from the Eastern Gotland Basin recirculate in a clockwise direction around the southern part of the Gotland Island and reach the Western Gotland basin after 540 days.

About 80% of the released particles migrate upwards into the thermocline and pycnocline layers after the 10 years simulation period (see Figure S-9c the 3D and histogram plots).

In the ***Archipelago Sea Islands***, the particles initially split at the release location, into three different northwest, southwest, and east directions. However, the principal particle paths are northwest and southeast. Figure 9d shows a typical path for one particle moving north-westwards and the corresponding particle distributions with depth. The paths are as follows:

- Particles moving north-eastwards reach the Archipelago Sea after 165 days and then enter the Kumlinge Sill after 500 days. After 720 days, some particles enter the Sea of Bothnia. Thereafter, the particles follow an anti- clockwise pattern that covers the entire Sea of Bothnia after 1245 days. Few particles exit the Sea of Bothnia through the Northern Quark and finally enter the Bay of Bothnia after 2190 days.
- Particles moving north-westwards enter the Åland Sill after 325 days and finally reach the Åland Sea after 640 days.

- The eastwards moving particles enter the Gulf of Finland after 165 days. A few particles enter the Gulf of Riga after 2190 days.
- Particles moving south-westwards first enter the Northern Gotland Basin after 340 days and then the Easter Gotland Basin after 730 days. Thereafter the particles are diverted more westwards entering the Western Gotland Basin along the southern shorelines of the Gotland Island after 115 days. The particles migrate further south and pass the Öland Island along its western shorelines after 1310 days. They then enter the Bornholm Sea after 1510 days through Hoburg-Midsjö Banks. Some of these particles cross the northwest part of the Arkona Basin exiting at the open-boundary after 1915 days.

About 80% of the released particles migrate upwards into the thermocline and pycnocline layers after the 10 years simulation period (see Figure 9d the 3D and histogram plots).

In the ***Gulf of Finland***, particles remain stationary for 30 days within the released point and thereafter migrate towards the northern and southern shorelines at a speed of 2.5 cm/s. Figure 9e shows a typical path for one particle moving north-westwards and the corresponding particle distributions with depth. The paths are as follows.

- The particles migrating north-westwards first enter the Archipelago Sea after 345 days and then the Åland Sill after 485 days passing close to the eastern Swedish shorelines. Particles reach the Åland Sea after 665 days. After 870 days particles move further into the Archipelago Sea passing its shallow islands. Particles having passed the Åland Sea, enter the Sea of Bothnia after 1245 days through the southern Quark and Kumlinge Sill.
- Particles exiting the Gulf of Finland first enter the Northern Gotland Basin and then split into west-southwards and east-southwards directions. The former enters the Eastern Gotland Basin after 1080 days. They then enter the Gotska Sandö Sill after 1300 days that finally reach the Western Gotland Basin after 1350 days.
- The east-southwards moving particles exit the Eastern Gotland Basin and then reach the eastern shorelines of Gotland Island after 1460 days. Thereafter, the particles follow a clockwise circulation pattern around the Gotland Island passing its southern shorelines. Part of these particles follow a new north-westwards path and finally reach eastern shorelines of the Öland Island after 1825 days.

About 45% of the released particles migrate upwards into the mixing and thermocline layers after the 10 years simulation period (see Figure 9e the 3D and histogram plots).

In the ***Northern Gotland Basin***, particles remain stationary within a narrow radius of 20km for 90days, and then start to spread in all four directions (NW-SW-SE-E) at a relatively high mean speed of 6 cm/s. Figure 9f shows a typical path for one particle and the corresponding particle distributions with depth. The paths are as follows.

- Particles moving in north-westwards direction pass through the Åland Sill and enter the Åland Sea after 180 days. A few particles migrate more eastwards entering the Archipelago Sea after 700 days. Particles from the Åland Sea pass through the Southern Quark and finally enter the Sea of

Bothnia after 910 days. After 1225 days, few particles enter the Northern Quark. The particles finally reach the Bay of Bothnia after 2155 days.

- The particles moving south-westwards partly enter the Gotska Sandö Sill after 310 days and partly reach Stockholm shorelines after 900 days. The former particles enter the Western Gotland Basin after 565 days with a speed of 5.4 cm/s. The particles move in the same direction towards the open boundary to the North Sea. They pass the Öland Island along its western shorelines after 850 days. They finally pass through Hoburg-Midsjö Banks, the Bornholm Basin, and Hamrare Strait, after 1395, 1730, and 1900 days, respectively. Few particles enter the Arkona Basin and exit the model domain after 2460 days.
- The particles moving south-eastwards partly enter the Bay of Riga and partly the Fårö Sill after 310 days. A few particles reach the northern shorelines of the Gotland Island and enter the Eastern Gotland Basin after 430 days with a speed of 10 cm/s and thereafter split around the island westwards and eastwards. The southwards moving particles remain close to the Gotland Island reaching its southern shorelines after 700 days. A few particles enter the Stople Channel and the Färö Sill after 1730 days. Particles passing through the Färö Sill reach the Bay of Gdansk after 2155 days. Finally, particle from the Stople Channel reach the Bornholm Basin after 3005 days.
- The eastwards moving particles enter the Gulf of Finland after 310 days in a northeast direction. After 990 days, they finally reach the entrance of the River Neva following a clockwise circulation pattern within the Gulf of Finland with a speed of 5.4 cm/s.

About 50% of the released particles migrate upwards into the mixing and thermocline layers after the 10 years simulation period (see Figure 9f the 3D and histogram plots).

In the ***Western Gotland Basin*** the particles spread into north and southwards directions covering most of the basins of the Baltic Sea. Figure 9g shows a typical path for one particle migrating north-westwards. The corresponding stages and time of arrivals are as follows:

- The northwards moving particles first enter the Gotska Sandö Sill after 75 days and then split further into northeast and northwest directions. The latter particles reach the Northern Gotland Basin after 135 days. Particles cross the Archipelago Islands and finally enter the Archipelago Sea after 515 with a speed of 4 cm/s. Some particles divert more eastwards entering the Gulf of Finland after 760 days. Northwest moving particles move further north reaching Stockholm shorelines after 135 days. Thereafter, they pass through the Åland Sill after 100 days and finally enter the Åland Sea after 255 days. The particles migrate further along the shorelines further north through the Southern Quark and after 575 days enter the Sea of Bothnia. After 1550 days, a few particles pass through the Northern Quark and finally enter the southern part of the Bay of Bothnia after 2940 days.
- The southwards moving particles reach the Eastern Gotland Basin after 850 days. Thereafter, the particles are diverted west towards the shorelines of the Gotland Island. They partly reach the southern end of the Island after 1270 days and partly enter the Gdansk Bay after 1980 days. Some particles pass through the Stople Channel and then enter the Bornholm Basin after 1395 days. They

then pass through the Hamrare Strait that finally entering the Arkona Basin after 1550 days. Finally, some particles exit the model domain through the open- boundary to the North Sea.

The analysis of particle distribution with the water depth indicates that about 55% of the released particles migrate upwards into the mixing and thermocline layers after the 10 years simulation period (see Figure 9g the 3D and histogram plots).

In the ***Eastern Gotland Basin***, the general particle paths are similar to those in the Western Gotland Basin that is northwards and southwards directions. Figure 9h shows a typical path for one particle migrating north-westwards. The corresponding stages and time of arrivals are as follows:

- The northwards moving particles rapidly (≈20 cm/s) split into northwest and northeast directions after a few weeks. The former particles reach Stockholm shorelines after 175 days and thereafter move further north. They pass through the Åland Sill after 515 days entering partly into the Åland Sea and the Archipelago Sea after 515 and 770 days, respectively. After 940 days the particles enter the Sea of Bothnia then reach the Swedish shorelines after 1075 days. The particles move further north first passing through the Northern Quark after 1100 days and then entering the Bay of Bothnia after 2735. The northeast moving particles enter the Northern Gotland Basin through Färö Sill after 175 days. Parts of these particles enter the Gulf of Finland after 545 days.
- The southwards moving particles split into southwest and southeast directions after a few days. The former particles reach the Gotland Island western shorelines after 285 days and then enter the Western Gotland Basin after 515 days. The particles then pass through the Hoburg-MidSjö Banks entering the Bornholm basin after 2000 days. The same particles then enter Arkona basin and through Hamrare Strait after 2885. The southeast moving particles enter into the Eastern Gotland Basin and the Gulf of Riga after 620 and 685 days, respectively. Part of these particles divert into of Bay of Gdansk after 2000 days. The rest first pass through the Stople Channel after 1460 days and then enter the Arkona Basin after 2180 days.

The analysis of particle distribution with the water depth indicates that about 65% of the released particles migrate upwards into the mixing and thermocline layers after the 10 years simulation period (see Figure S-9h the 3D and histogram plots).

In the ***Bornholm Basin***, the general particle paths follow two main north-eastwards north-westwards directions. Figure 9i shows a typical path for one particle migrating north-westwards. The corresponding stages and time of arrivals are as follows:

- North-eastwards migrating particles pass through Stolpe Channel (Figure1) and enter the Eastern and Northern Gotland Basins after 190 days and 545 days, respectively. Few particles enter the Gdansk Bay after 410 days. Some particles are diverted more to the east entering the Gulf of Finland after 1095 days.
- North-westwards migrating particles pass by the western coastlines of the Öland Island after 410 days and enter the Western Gotland Basin after 545 days. Thereafter some particles reach the Swedish coastlines. After 720 days the particles partly pass through the Åland Sill move further north and partly reach the Archipelago Sea after 1470 days. The particles migrate further

northwards entering the Åland Sea, Sea of Bothnia, and the Bay of Bothnia after 720 days, 1610 days, and 2525 days, respectively.

The analysis of particle distribution with the water depth indicates that 75% of the released particles migrate upwards into the mixing and thermocline layers after the 10 years simulation period (see Figure 9i the 3D and histogram plots).

The particles follow two different paths in the ***Arkona Basin***. An anti-clockwise circulation that crosses most of the lower basins of Baltic Sea around the Gotland Island and a north- westwards path that reaches the Bay of Bothnia. Figure 9j shows a typical path for one particle migrating northwards. The particle paths are as follows:

- The particles moving north-eastwards pass through the Hamrare Strait and the Stople Channel after 135, 165 days. They enter the Bornholm Basin and the Eastern Gotland Basin after 170 and 210 days. Some particles pass through the Fårö Sill after 695 days and enter the Northern Gotland Basin after 850 days. Thereafter, the path is spilt into west and northwest directions. Westwards moving particles enter the Gotska Sandö Sill after 860 days and continue towards the Western Gotland Basin (anti-clockwise rotation). The eastwards moving particles enter the Gulf of Finland after 2095 days.
- Particles from the Northern Gotland Basin pass through the Åland Sill and reach the Sea of Bothnia after 960 days. They pass through the Åland Sill and enter the Åland Sea after 1095 and 1185 days, respectively. After 1375 days some particles re-enter the Sea of Bothnia
- Particles from the Åland Sea move partly eastwards and enter the Archipelago Sea after 1295 days. The rest of the particles move more westwards reaching the northeast Swedish shorelines and the Bay of Bothnia and after 1475 and 1990 days, respectively.
- The north-westwards moving particles rapidly (10 cm/s) pass through the Hoburg-Midsjö Banks and the Öland Island after 135 and 360 days, respectively. They then reach the Gotland Island western shorelines after 375. Particles finally enter the Western Gotland Basin after 885 days.

The analysis of particle distribution with the water depth indicates that about 40% of the released particles migrate upwards into the mixing and thermocline layers. However, 40% of the particles migrate downwards into the deeper regions of the Baltic Sea i.e. below 45m (see Figure 9j the 3D and histogram plots).

Rivers (S3-a to S3-j & Figures 10-a to 10j)

From the ***Kemijoki River*** (Figure S3-a), the particles remain stationary close to the release point for 70 days. Figure 10a shows a typical anti-clockwise circulation path for one particle. The main paths are as follow

- The north-westwards moving particles follow an anti-clockwise circulation pattern covering a length of about 100 km. The circulation is in westward direction along the northern shoreline of the bay.

The southwards particles enter the northern part of the Bay of Bothnia after 68 days at speed of

9.6cm/s. They divert rapidly towards the central region of the bay and enter the Northern Quark after 1235 days at a speed of 3.5 cm/s. After 1835 days, they enter the Sea of Bothnia and the Swedish shorelines. Thereafter, more particles enter the Sea of Bothnia after 2340 days but remain within the upper part of the Sea. By the end of the simulation period only a few particles migrate further southwards. They pass through the Åland Sill and finally enter the Åland Sea. The particles remain in the surface water layer for the entire simulation time in both the Bay and the Sea of Bothnia. The analysis of particle distribution with the water depth indicates that about 85% of the released particles remain within the mixing layer and upper part of the thermocline layer after the 10 years simulation period (see Figure 10a the 3D and histogram plots). The general particle path released from the ***Torne River*** is similar to the Kemijoki River (Figure S3-b). However, the average migration speed is lower (2.5 cm/s) and the particles move along the northern shorelines for a longer period.

- After 888 days, particles start migrating south eastwards into the deeper regions of the Bay of Bothnia. Thereafter, particles circulate in an anti-clockwise direction within a closed region north of the Northern Quark. Some particles enter the Northern Quark after 930 but still remain within the region for 2160 days. Some particles enter the deeper layers of the Sea of Bothnia moving more eastwards. The anti-clockwise rotation is maintained throughout the simulation period above the Northern Quark.
- A few particles move further south passing through the Kumlinge Sill and Åland Sill after 3555 days. The main characteristic is the random migration from surface to the deeper layers (30-50m). This is an indication of the fresh river water mixing with the middle water layers within the basin.

The particle distribution with the water depth is similar to the Kemijoki River (Figure 10b, 3D and histogram plots).

The general particle paths from the ***Kalix River*** (Figure 10c) are similar to the Torne River. After 300 days, particles leave the shoreline and migrate into the deeper water layers for about 60 m, while moving rapidly southwest wards. The particles move out of the deep region of the Bay of Bothnia in north-westwards direction after 2070 days. Thereafter, the particles maintain a randomly varying circular motion close to the periphery of the basin. The three foregoing rivers have very similar particle paths and depth distributions.

From the ***Lule River*** (S3-c), the particles move south-eastwards at a speed of 1.5 cm/s entering the central region of the Bay of Bothnia after 65 days. The particles follow a large clockwise circulation pattern within the northern part of the bay for 720 days. They start migrating southwards and after 740 days enter the Northern Quark with an increased speed of 5 cm/s. The particles then enter the Sea of Bothnia after 1515 days with a reduced speed of 3.5 cm/s, approaching the Swedish eastern shoreline after 1825 days. A few particles pass the Southern Quark and the Kumlinge Sill after 2555 and 2810 days, respectively. Thereafter, a quasi-stationary clockwise circulation pattern is maintained. After 3000 days, the particles start to migrate into the deeper layers reaching a maximum depth of about 55 m. The plots in Figure 10d show a typical particle path and the depth distribution for one particle. In comparison with the River Kalix, the particles reach deeper layers but the particle concentration is still higher in the thermocline layer.

From the ***River Neva (***S3-d), the particles initially migrate in north-eastward and south- westwards directions within the Gulf of Finland at a speed of 5 cm/s. After 730 days, they start moving out of the Gulf with an increased speed of 15 cm/s along two different directions as given below

- The north-eastwards particles enter the Northern Gotland Basin after 910 days. They first pass through the Archipelago islands and then enter the Klumlinge Sill. These particles enter the Archipelago Sea after 1300 days.
- The north-westwards enter the Åland Sea after 1170 days through Åland Sill. Thereafter, they enter the Sea of Bothnia after 1470 days. By the end of the simulation time, particles reach the northern part of the Sea of Bothnia.
- The south-eastwards moving particles first enter the Eastern Gotland Basin after 1440 days and enter the Gotska Sandö Sill after 1537days. The particles move further west entering the Western Gotland Basin after 1840 days (8.5 cm/s). Thereafter the particles spread more southwards approaching the northern shorelines the Öland Island after 2705. They then pass through the Hoburg Midsjö Sill after 2800 days and enter the Arkona Basin.
- The southwards moving particles first enter the Eastern Gotland Basin after 1535 days. A part of the particles divert westwards and enter the Bornholm Basin through the Stople Channel after 2800 days. The rest of the particles continue to move south close to the shorelines and reach the shorelines of Latvia after 1965 days. Thereafter some particles enter the Bay of Gdansk through the Gdansk Sill after 2500 days.

The particle concentrations are highest in the mixing layer (≈10 m) and are about 80% (see Figure 10f).

From ***the River Narva*** (Figure S3-e), the particles initially migrate in north-eastward and south-westwards directions within the Gulf of Finland at a speed of 5 cm/s. After 730 days, they start moving out of the Gulf with an increased speed of 15 cm/s along two different directions of north and south. A typical particle path for one particle is shown in Figure 10e. The general particle paths are as follows

- The north-eastwards moving particles pass through the Archipelago islands and then enter the Klumlinge Sill. They then enter the Archipelago Sea after 1300 days.
- The north-westwards moving particles enter the Åland Sill after 1170. The particles then leave the Åland Sea and enter the Sea of Bothnia through Southern Quark after 2905 days (5 cm/s).
- The west-southward moving particles enter the Northern Gotland Basin after 910 days and then move along the shorelines of the Stockholm Archipelago and pass through the Åland Sill after 1915 days. Thereafter, they enter the Åland Sea after 2310 days and finally the Sea of Bothnia through the Kumlinge Sill after 2500 days. By the end of the simulation period, a few particles reach as far as the Northern Quark.
- The south-westwards moving particles enter the Gotska Sandö Sill after 1440 days. The particles then enter the Western Gotland Basin after 1815 days (8.5 cm/s). Thereafter they spread eastwards approaching the northern shoreline of the Gotland Island. The particles circulate between the Western Gotland Basin and the Northern Gotland Basin for 60 days. They then migrate towards the

Eastern Gotland Basin and enter the basin after 2385 days. The particles reaching the basin move southwards along two different directions. One group passes through the Ibre Strait reaching the Bornholm Basin after 2415 days. The second group enters the Bay of Gdansk after 2985 days.

The particle distribution with depth is quite different from the previous rivers (see plots in Figure 10e). There is a uniform distribution across the mixing and pycnocline layers with a particle concentration of 90%.

Particles released from the ***River Daugava** (*Figure S-10f) remain initially within the Gulf of Riga for a period of 400 days. shows a typical particle path for one particle. Their main particle paths are as follows:

- Westwards particles cross through the Fårö Sill and Gotska Sandö Sill after 640 days. They then divert southwards entering the Western Gotland Basin after 865 days and finally reaching the Swedish shorelines after 1040 days. A few particles from the Western Gotland Basin move southward close to the Gotland Island shorelines. They reach the Öland eastern shorelines after 1470 days. Thereafter, pass through the Hamrare Strait after 1660 days and then enter the Arkona Basin after 2400 days.
- South-eastwards particles approach the Lavonia shorelines after 865 days and then enter the Bay of Gdansk after 1730 days. Thereafter, they enter the Eastern Gotland Basin shorelines and then pass through the Stople Channel after 1365 days. Therefore, they enter the Bornholm and the Arkona Basins after 1390 and 1915 days, respectively.
- Northwards particles enter the Eastern Gotland Basin after 640 days. They then pass through the Åland Sill after 1915 and enter the Åland Sea and the Archipelago Sea after 2310 days. Few particles reach the Sea of Bothnia after 2500 days.

The particle distribution with depth is very similar to River Narva (see plots in Figure 10g). There is a uniform distribution across the mixing and pycnocline layers with a particle concentration of 90%.

The particles released from the ***River Venta*** (see Figure S3.g) over a large region of the Baltic Sea despite the relatively low flow discharge in comparison with the larger rivers such as Neman. Initially the particles follow a clockwise circulation pattern for a year. They then spread northwards into the northern basins and southwest wards into the lower basins. The main particle paths are:

- Particles enter the Eastern Gotland Basin after 30 days and reach the Bay of Gdansk through the Gdansk Sill after 1845 days.
- Particles enter the Western and Northern Gotland Basins through the Fårö Sill, after 640 and 890 days, respectively.
- Particles enter the Gulf of Riga and the Gulf of Finland after 640 and 1760 days, respectively.
- Particles enter the Åland Sea and the Archipelago Sea after 1300 days.
- Particles enter the Sea of Bothnia after 1350 days.
- The shorelines affected are Stockholm Archipelago, Estonia’s northern and Lithuania’s western shorelines.
- Some particles from the Eastern Gotland Basin move south-westwards. They pass The Stople

Channel and then enter the Bornholm Basin after 935 days. They finally reach the Arkona Basin after 1480 days.

The particle concentration is maximum (70%) within the mixing layer and the upper part of the thermocline layer i.e. ≈ 5-35m (see plots in Figure S3-g & Figure 10g).

The particles released from the ***River Neman*** (Fig.S3-g) initially move only south-westwards spreading to the lower part of the Eastern Gotland Basin, the Bornholm Basin, and the Arkona Basin. The pattern is maintained during 300 days. Fig. 10i shows a typical particle path for one particle. The general particle paths are as follows:

- Southwards moving particles enter the Gdansk Bay after 165 days at speed of 2 cm/s and pass the Gdansk Sill and enter the Bornholm Basin after 180 days. These particles continue westward crossing the Hamrare Strait after 360 days. They first reach the Swedish shorelines after 545 days and move along the shorelines southwards passing the Arkona Basin. They finally exit the model at the open-boundary after 925 days.
- The north-westwards moving particles enter the Eastern Gotland Basin after 300 days. Some of these particles reach the northern shorelines of the Gotland Island after 750 days. They pass through the Fårö Sill and finally reach the Stockholm archipelago after 1265 days. These particles continue to migrate northwards along the Swedish shorelines and pass through the Åland Sill after 1345 days and then enter the Åland Sea after 1450 days and the Sea of Bothnia after 1550 days.
- The northeast moving particles first enter the Northern Gotland Basin after 1045 days and finally the Gulf of Finland after 1125 days.
- The south-westwards moving particles follow a clockwise pattern just south of the Gotland Island. Some of the particles reach the Öland eastern shorelines after 1045 days. Thereafter, they enter the Western Gotland Basin after 1380 days.

The analysis of the particle distribution with depth indicates that about 90% of the released particle remain are within the mixing and thermocline layers (≈30m). Only 10% of the particles reach deeper layers i.e., below 50m.

The ***River Vistula*** (Figure S3-i) is the second largest river that flows into the Baltic Sea. The two main particle paths are north-eastwards and north-westward covering most of the Baltic Sea basins. To illustrate this Fig. 10k shows the typical paths for two particles instead of one as done for the previous cases. There is also a large scale anti-clockwise around the Gotland Island that originates from the north-eastwards particles. Particles remain initially within the Bay of Gdansk for 90 days. They then move north entering the Gdansk Sill after 120 days. Thereafter, the particles split into two distinct paths of north-eastwards and north-westwards directions. The north-eastwards particles follow the main paths below:

- They enter the Eastern Gotland Basin after 240 days. They then pass through the Fårö Sill and enter Northern Gotland Basins after 745 days.
- Particles from the Northern Gotland Basin pass the Archipelago Islands and the Åland Sill after

1145 and 1205 days, respectively. Few particles divert to the east entering the Gulf of Finland after 1365 days. Particles from the Åland Sill enter the Åland Sea after 1760 days and the Sea of Bothnia after 1795days. A few particles more further north reaching the northwest shorelines of the Bay of Bothnia after 2500 days.

The north-westwards particles follow the main paths below

- The particles are first diverted to the south. They cross the Stople Channel and enter the Bornholm Basin after 240 days. Some particles divert further southwest and enter the Arkona Basin after 358 days.
- Particles from the Bornholm Basin reach the Swedish shorelines after 395 days. Thereafter, the migration continues in the northwest direction. The particles pass the eastern shorelines of the Öland Island after 810 days. They then enter the Western Gotland Basin after 870 days.

Plots in Figure 10k show the 3D dependence with depth and the corresponding particle distribution for a single particle marked by the green colour. In analogy with the other rivers, the particle does not reach the deeper layers (>50m). About 90% of the released particles are within the mixing and thermocline layers (≈30m).

The general particle path for the ***River Oder*** (Figure S3.j) is north-westwards in similarity with the *River Vistula.* Initially, the particles move northwards entering the Bornholm Basin after 50 days. They then pass the Hamrare strait after 145 days close to the Swedish southern west shorelines. They enter the Bornholm Basin after 150 days. Thereafter, the particles split into norther-westward and north-eastward directions in analogy with the river Vistula. The former enters the Western Gotland having passed the Öland Island. The latter particles pass through the Eastern, and Northern Gotland Basins, the Åland Sea, the Archipelago Sea, the Sea of Bothnia, and the Bay of Bothnia. Figure 10j shows the main north-westward path for a typical particle. The particle distribution with depth is more skewed towards shallower depths than Rive Neman with about 90% of particles remaining within the mixed thermocline layers (≈30m). Complete sets of Particle Tracking surface plots for major basins and in the Baltic Sea

Map showing the Baltic Sea shorelines and the neighbouring countries (http://www.worldatlas.com/aatlas/infopage/balticsea.html)

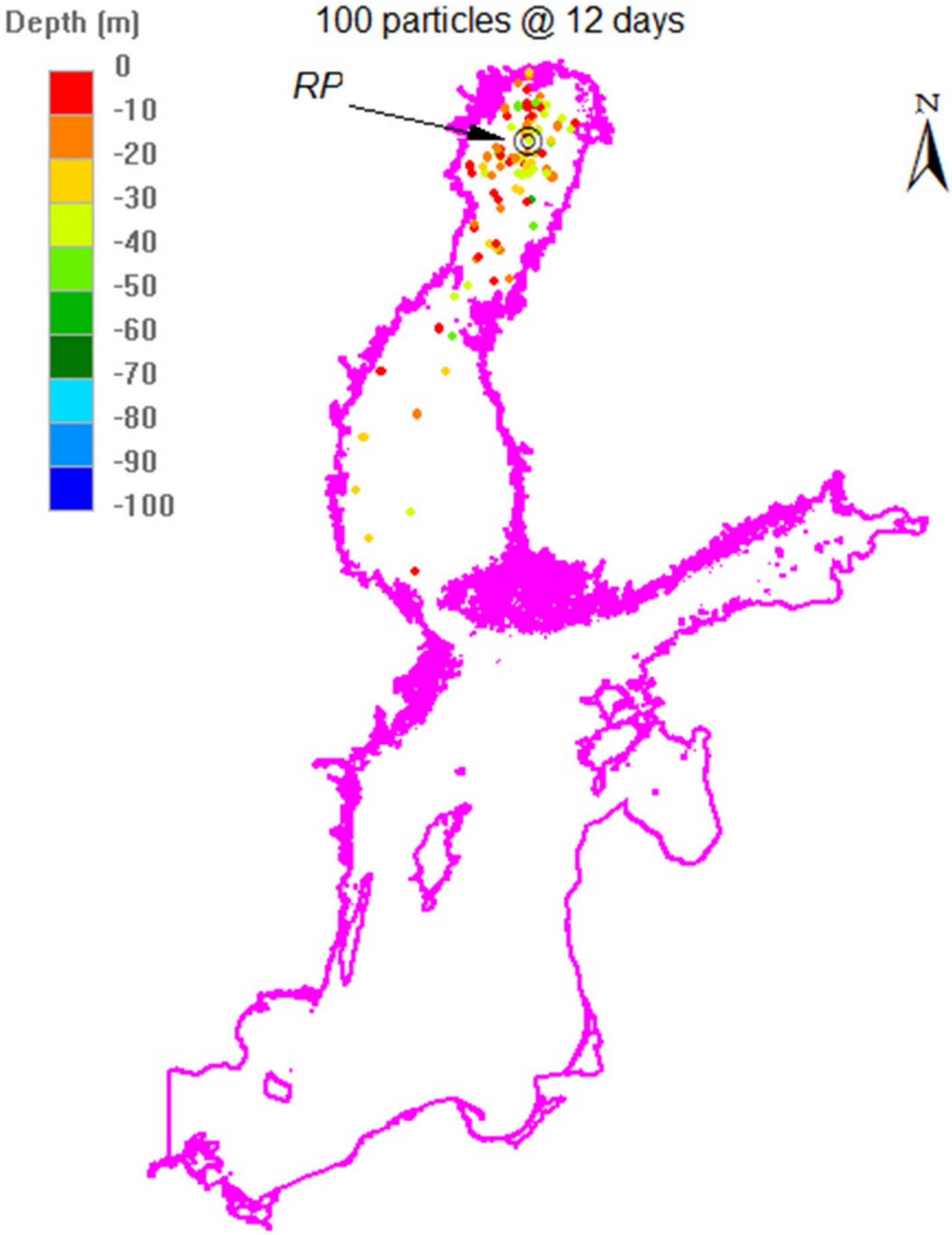

Figure S1.a: Particle positions of 100 particles released at a depth of 76m in the Bay of Bothnia during 12 days. Colour scale shows the particle depths.

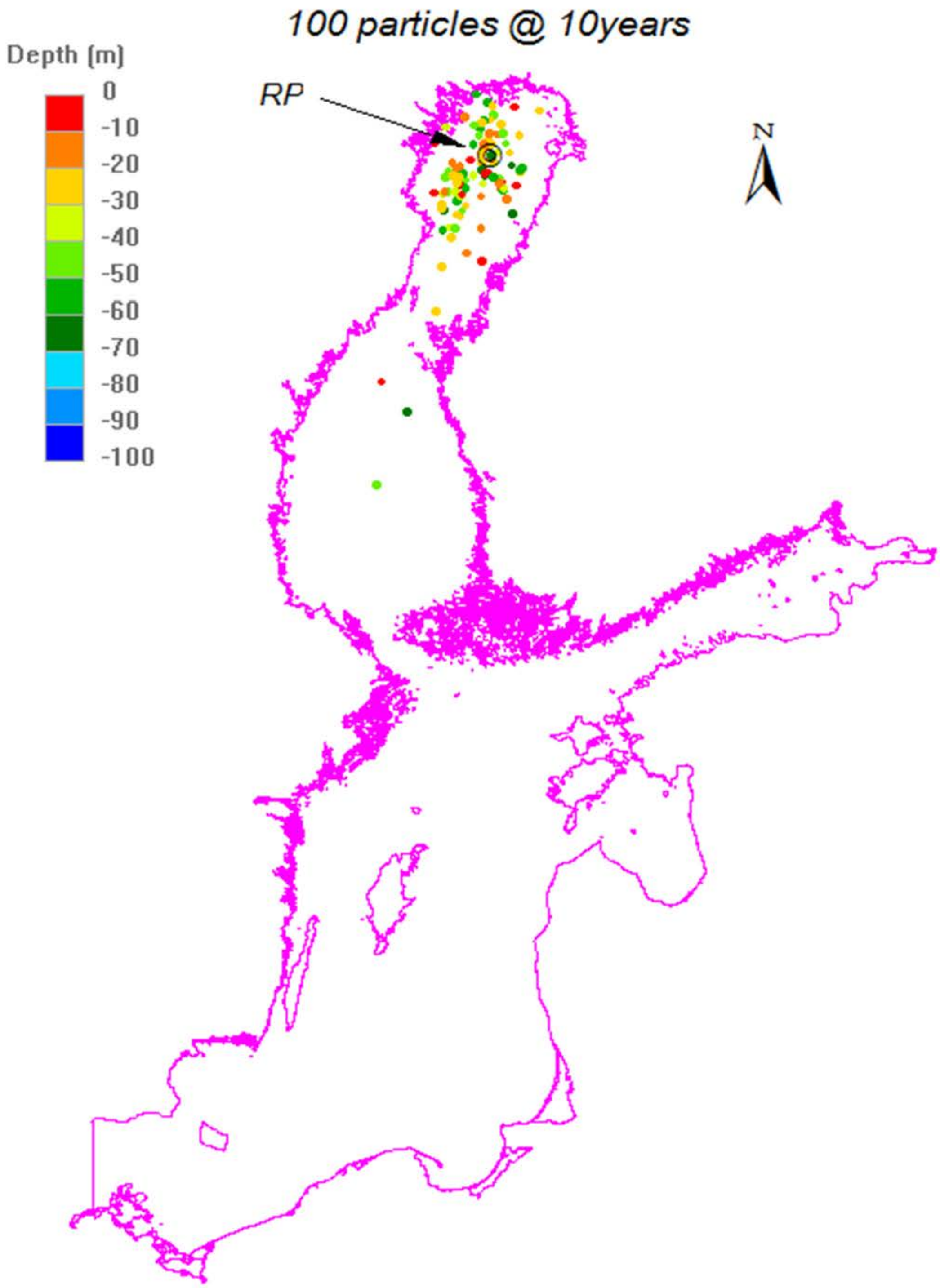

Figure S1.b: Particle positions of 500 particles released at a depth of 76m in the Bay of Bothnia in the period 2000-2009. Colour scale shows the particle depths.

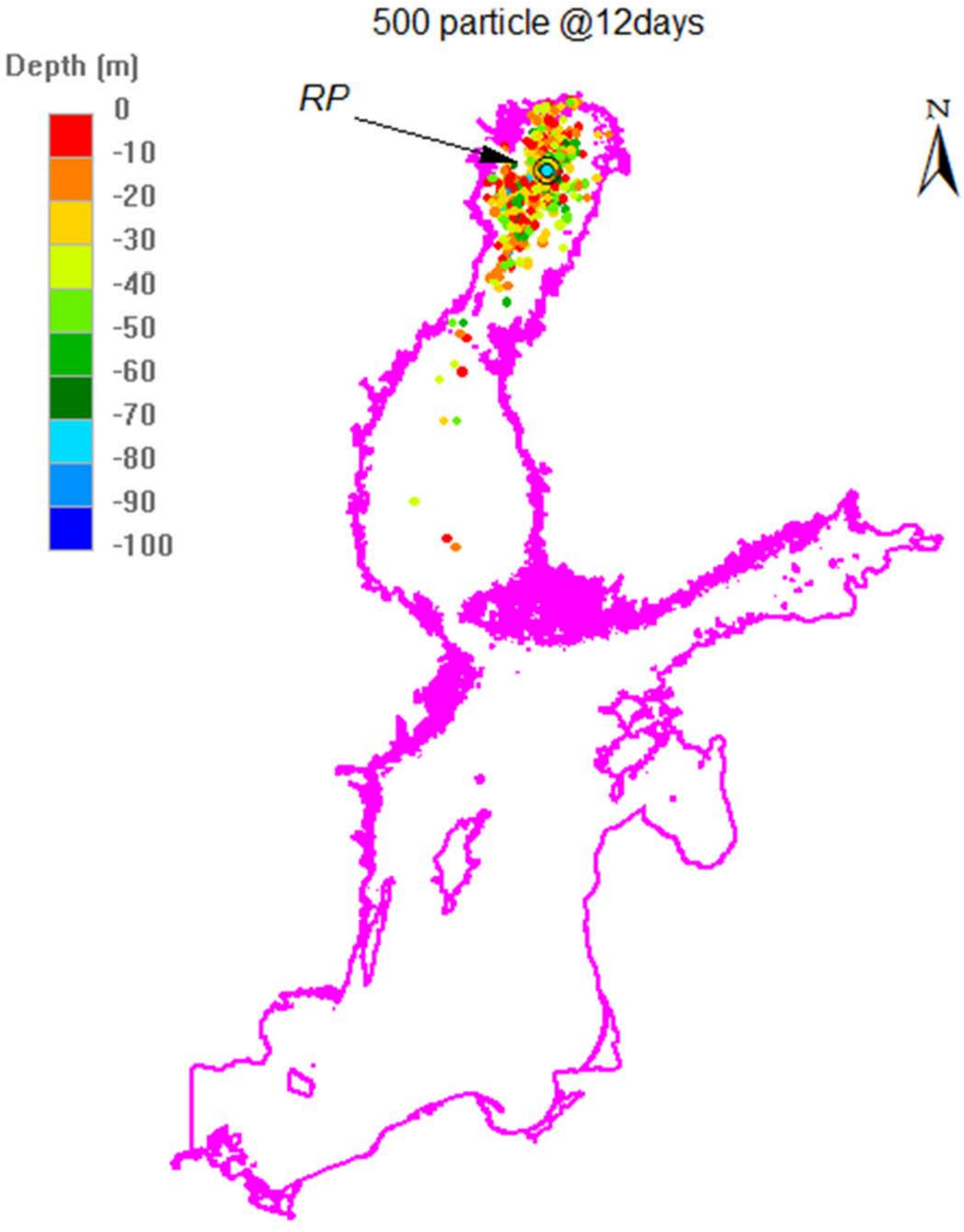

Figure S1.c: Particle positions of 500 particles released at a depth of 76m in the Bay of Bothnia during 12 days. Colour scale shows the particle depths.

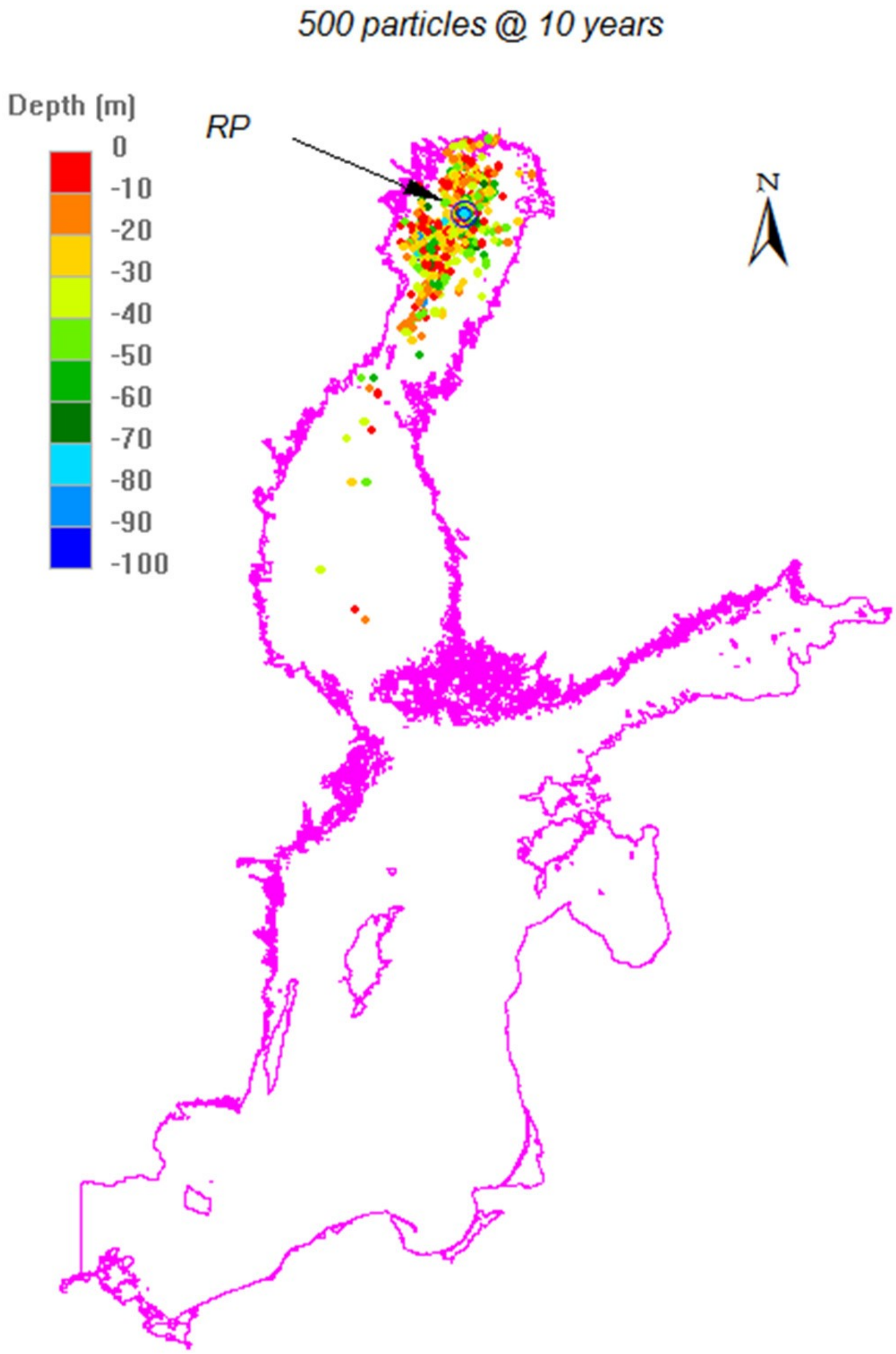

Figure S1.d: Particle positions of 500 particles released at a depth of 76m in the Bay of Bothnia in the period 2000-2009. Colour scale shows the particle depths.

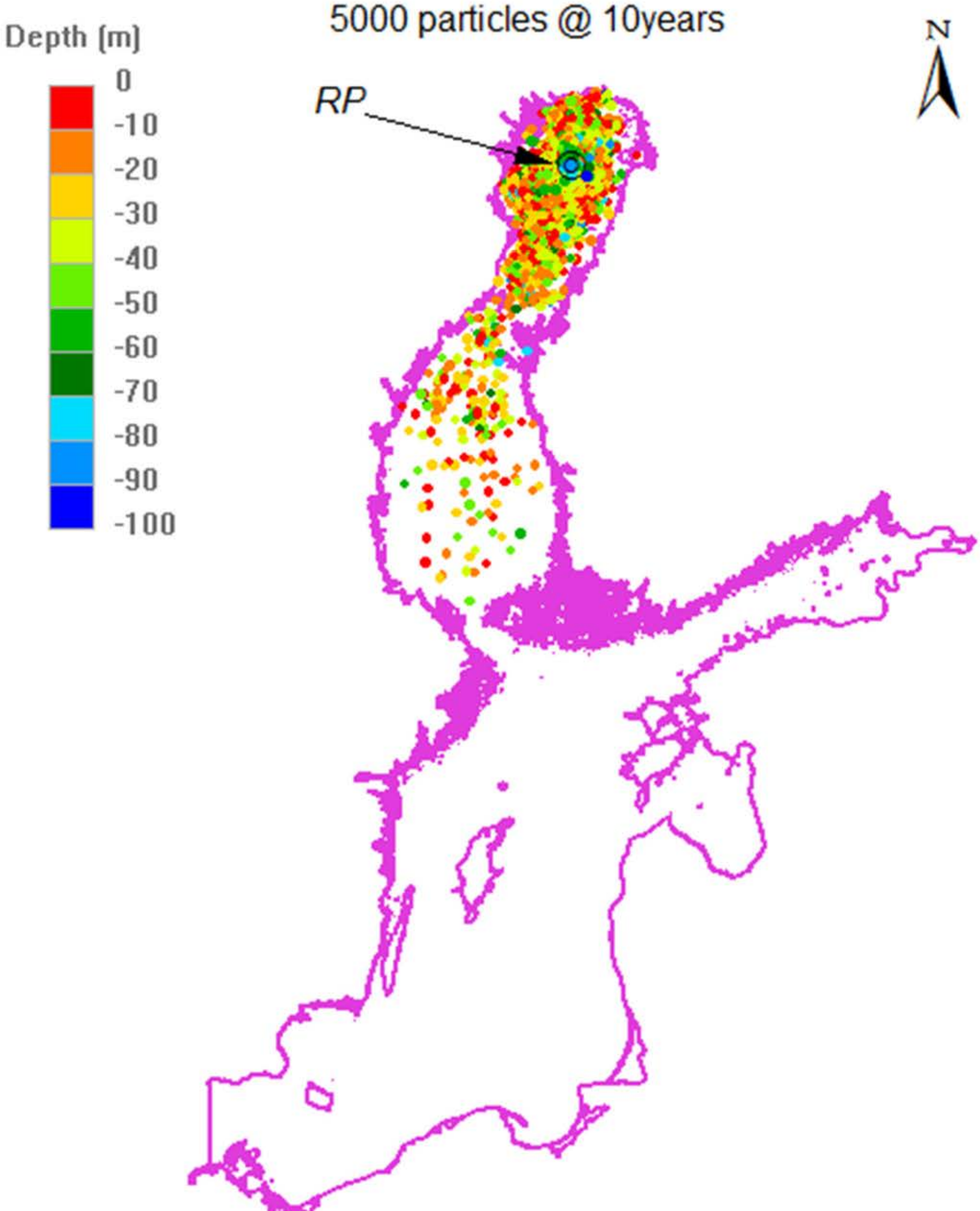

Figure S1-e: Particle positions of 5000 particles released at a depth of 76m in the Bay of Bothnia in the period 2000-2009. Colour scale shows the particle depths.

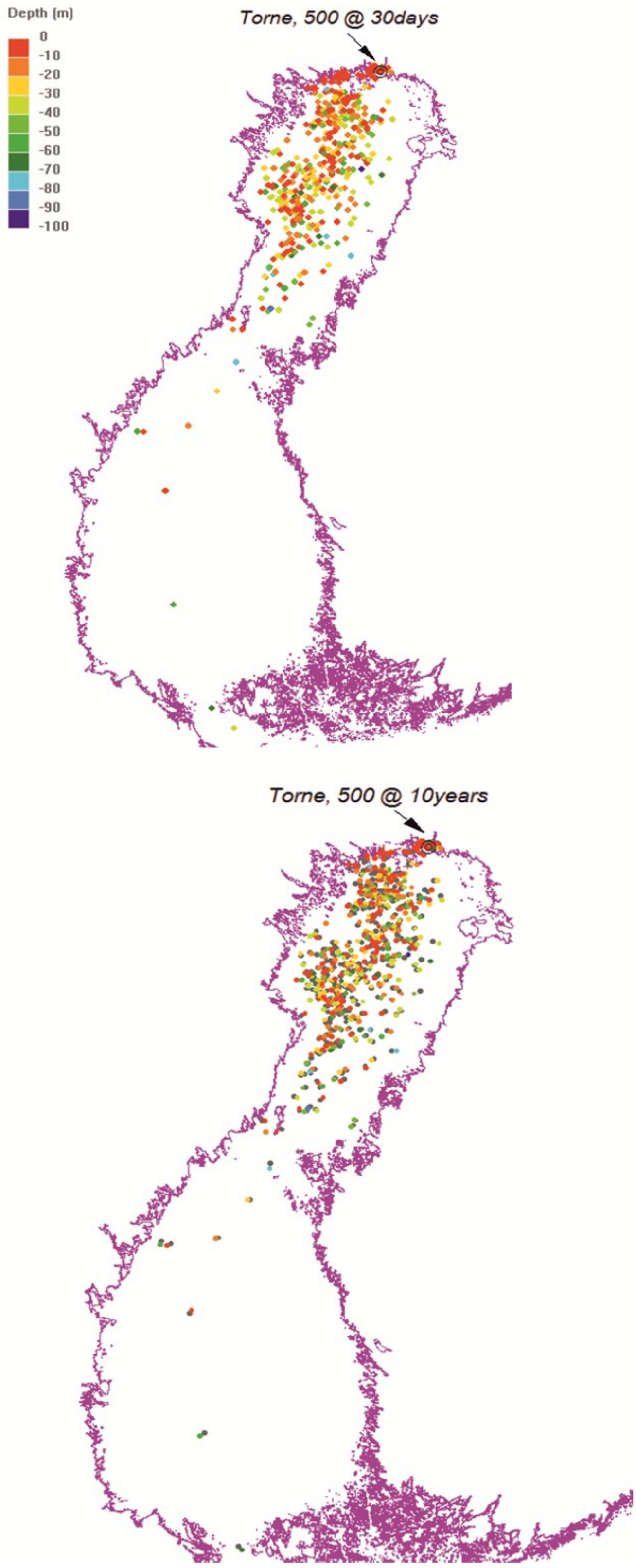

Figure S1.f: Comparison of particle positions of 500 particles released from River Torne during 30 days and 10 years. Colour scale shows the particle depths.

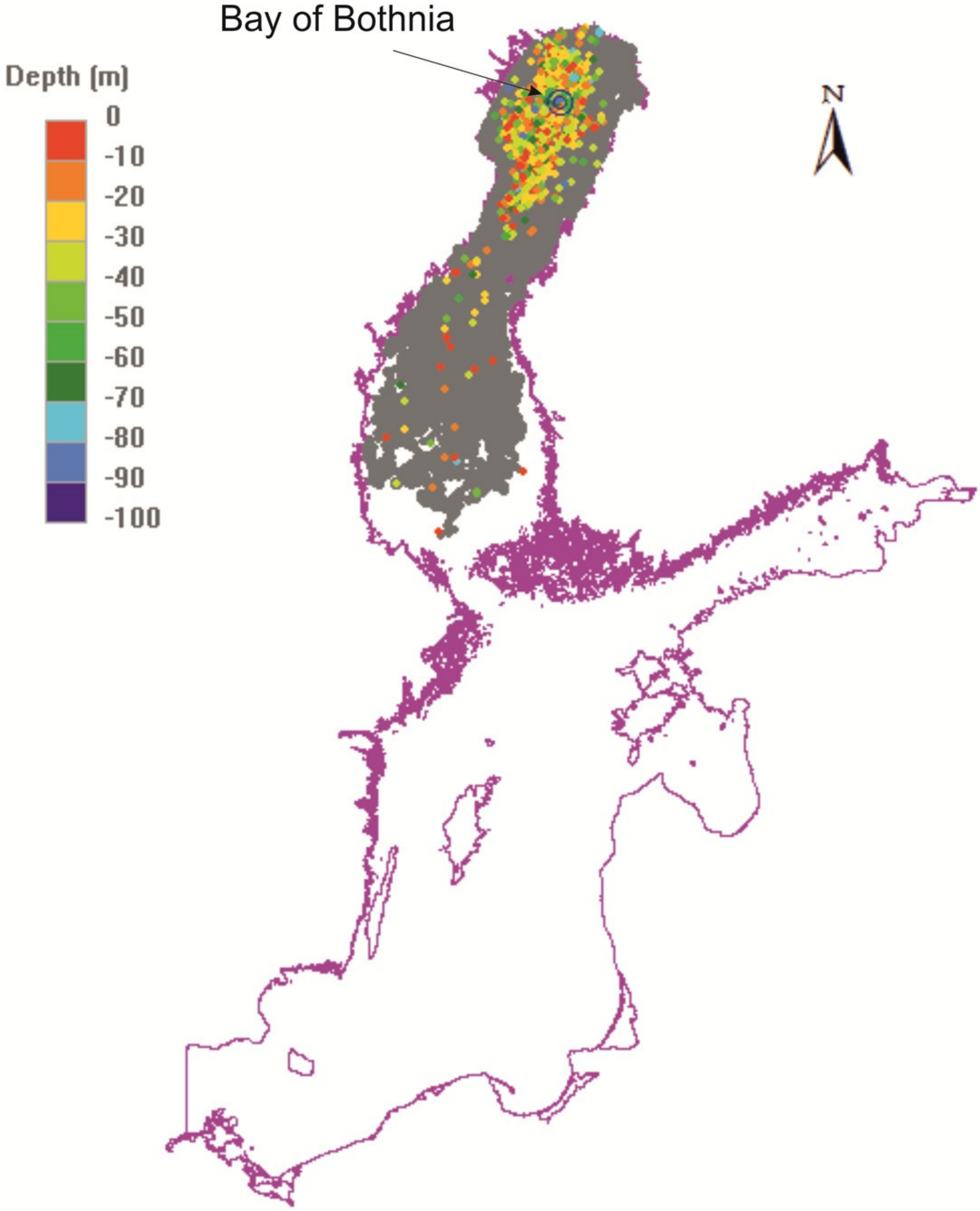

Figure S2-a: Particle tracer of 1000 particles released at depth of 76m in the Bay of Bothnia, period 2000-2009.

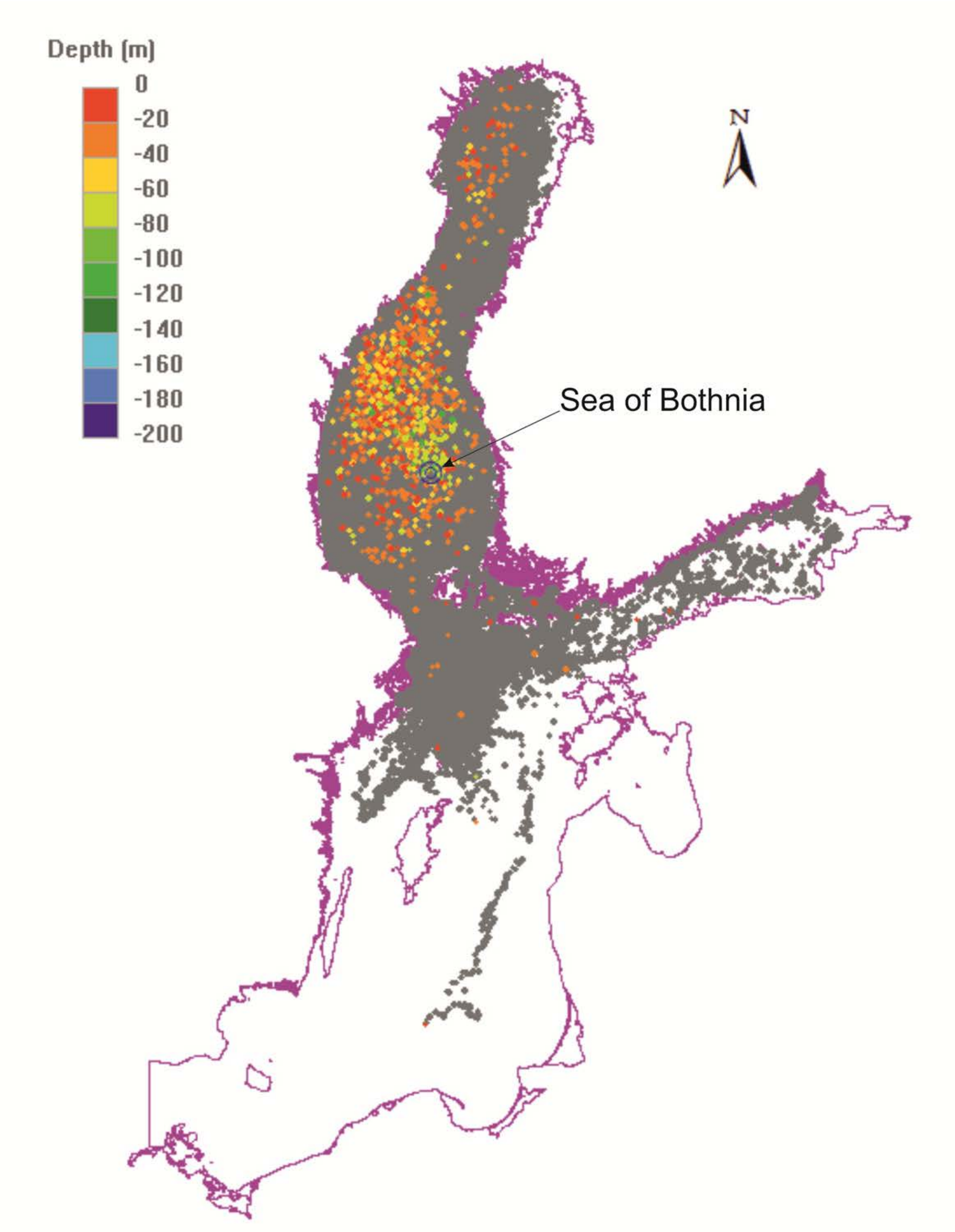

Figure S2.b: Particle tracers of 1000 particles released at depth of 94m in the Sea of Bothnia, period 2000-2009.

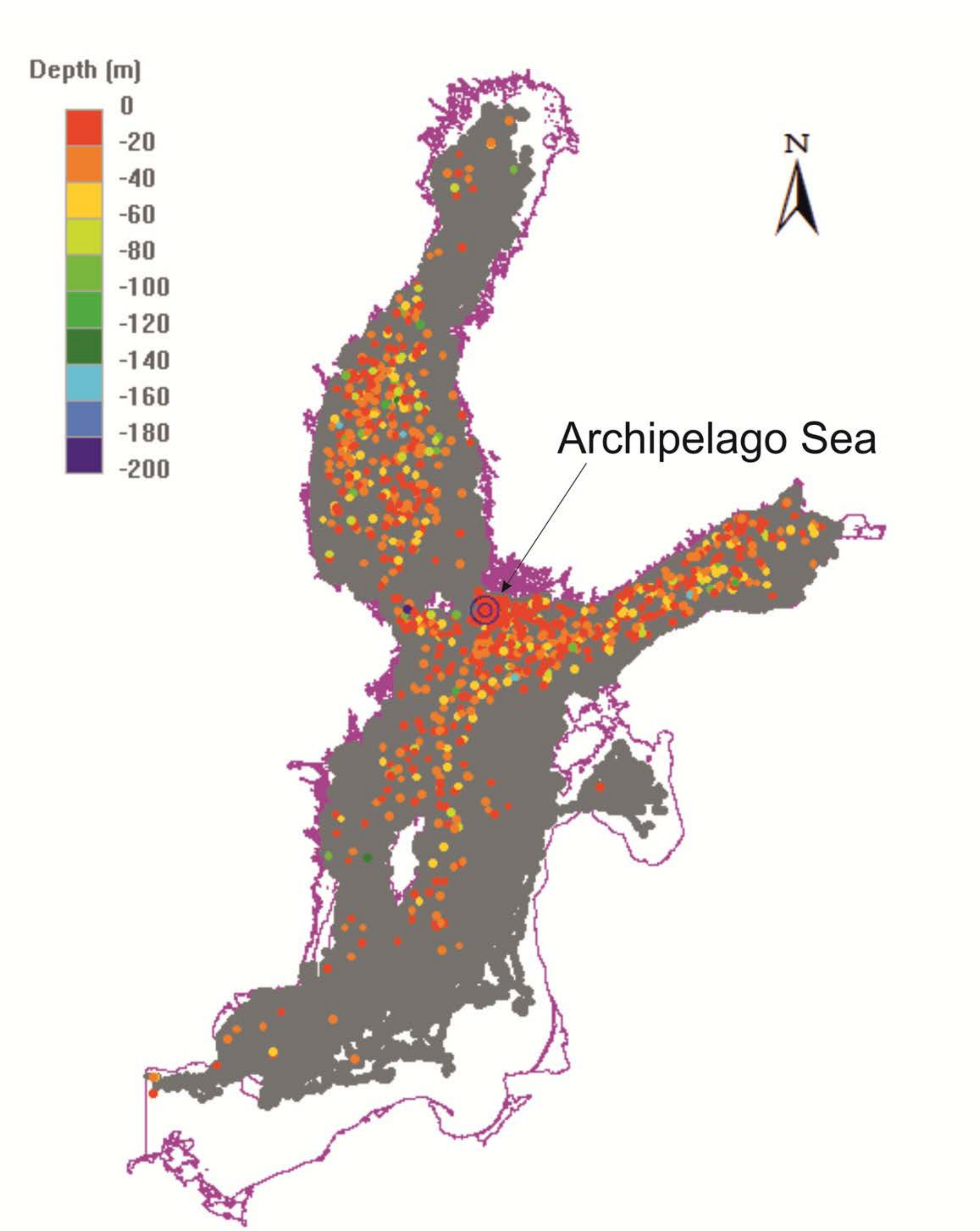

Figure S2.c: Particle tracers o 1000 particles released at depth of 36m in the Archipelago Sea, period 2000-2009.

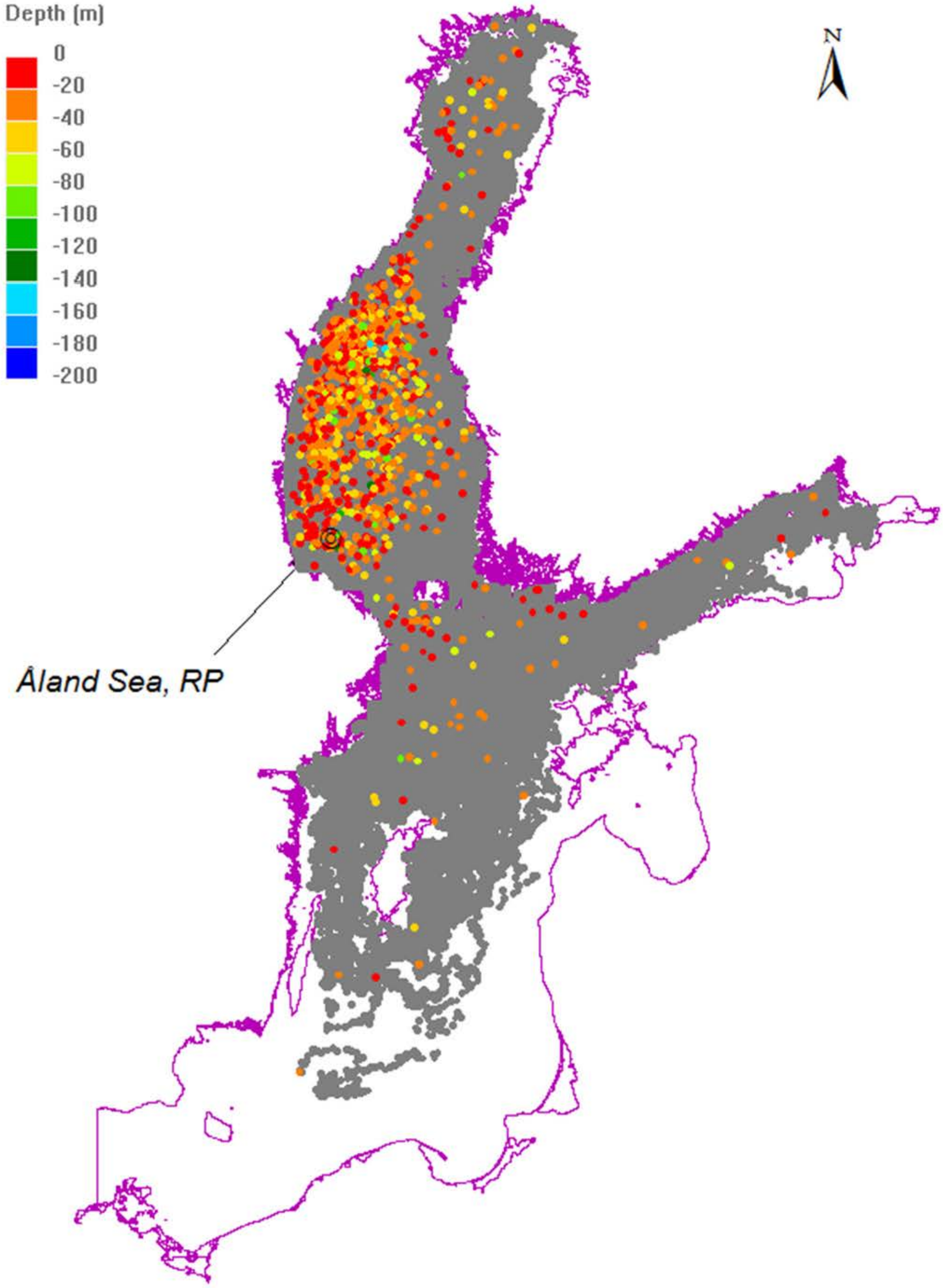

Figure S2.d: Particle tracers of 1000 particles released at depth of 28m in the Åland Sea, period 2000-2009.

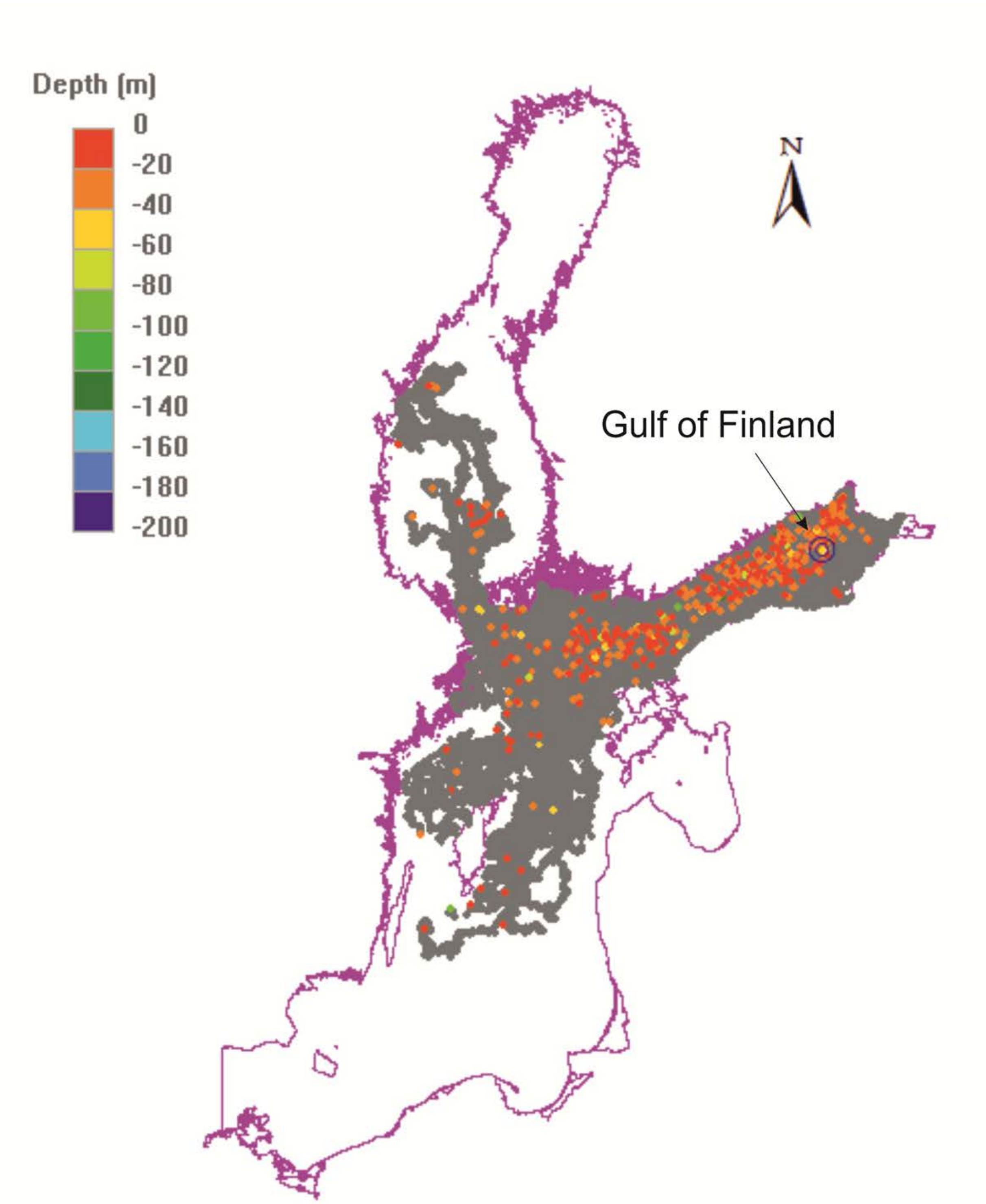

Figure S2.e: Particle tracers of 1000 particles released at depth of 52m in the Gulf of Finland, period 2000-2009.

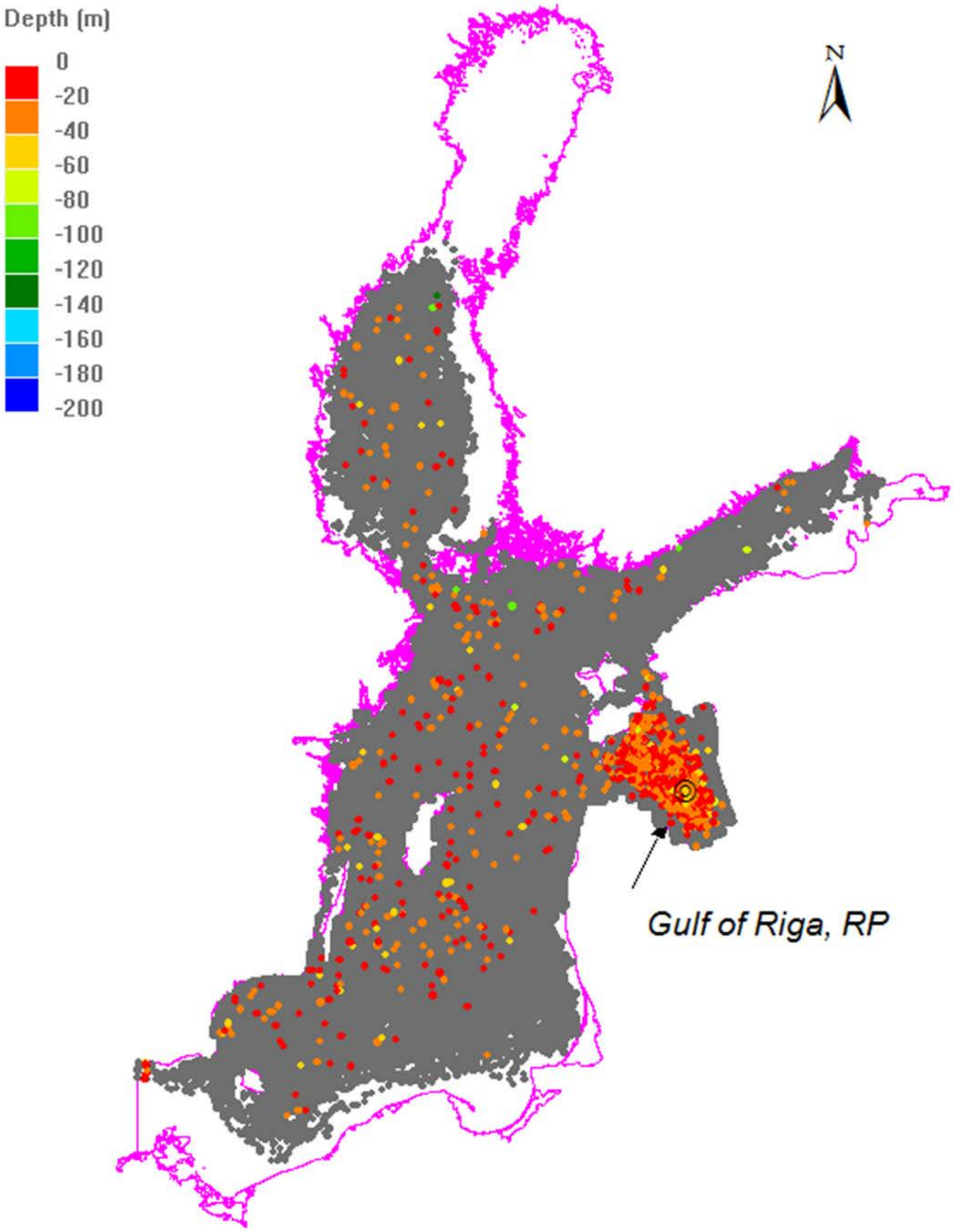

Figure S2.f: Particle traces of 1000 particles released at depth of 40m in the Gulf of Riga, period 2000-2009.

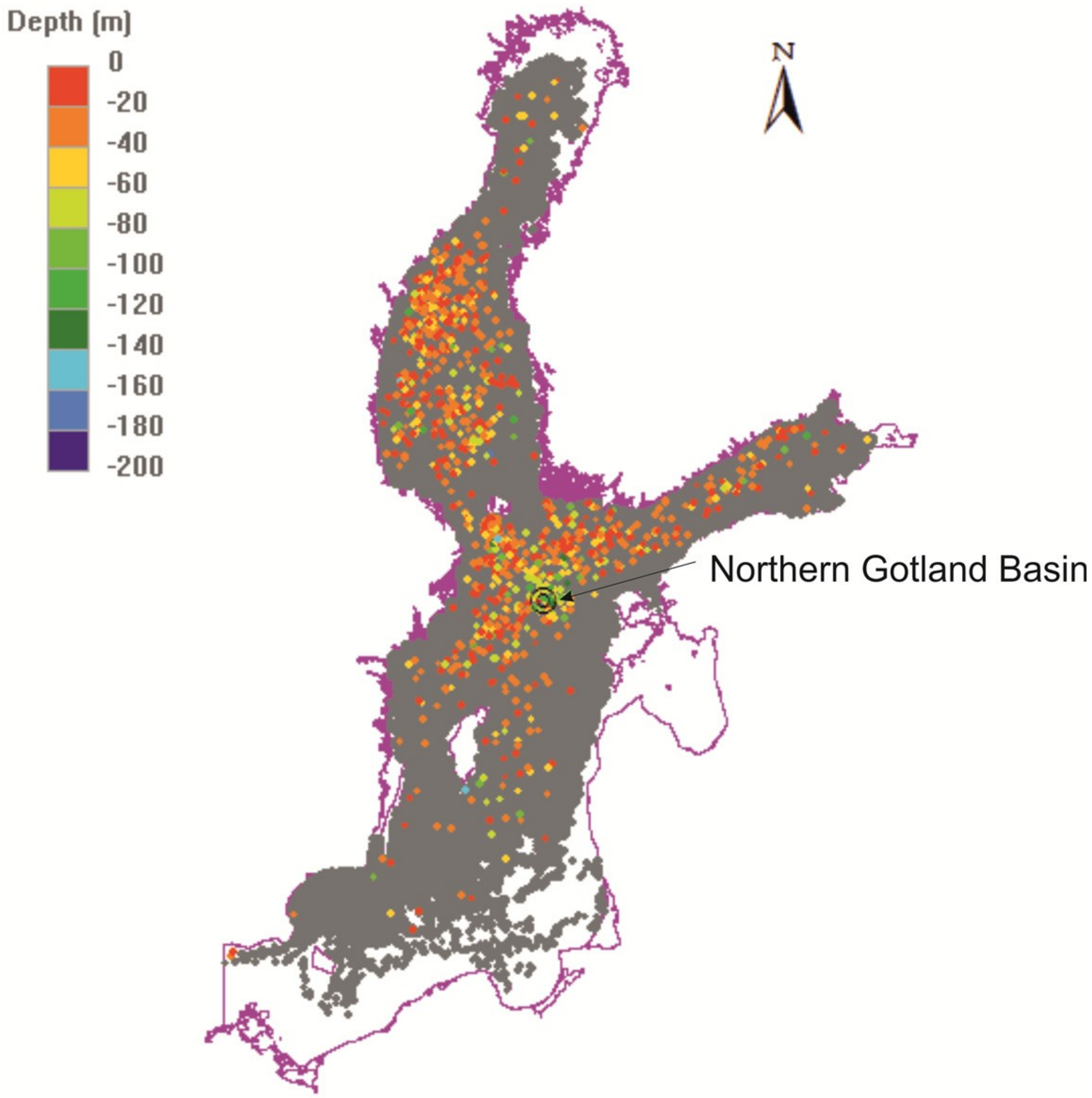

Figure S2.g: Particle traces of 1000 particles released at depth of 106m in the Northern Gotland Basin, period 2000-2009.

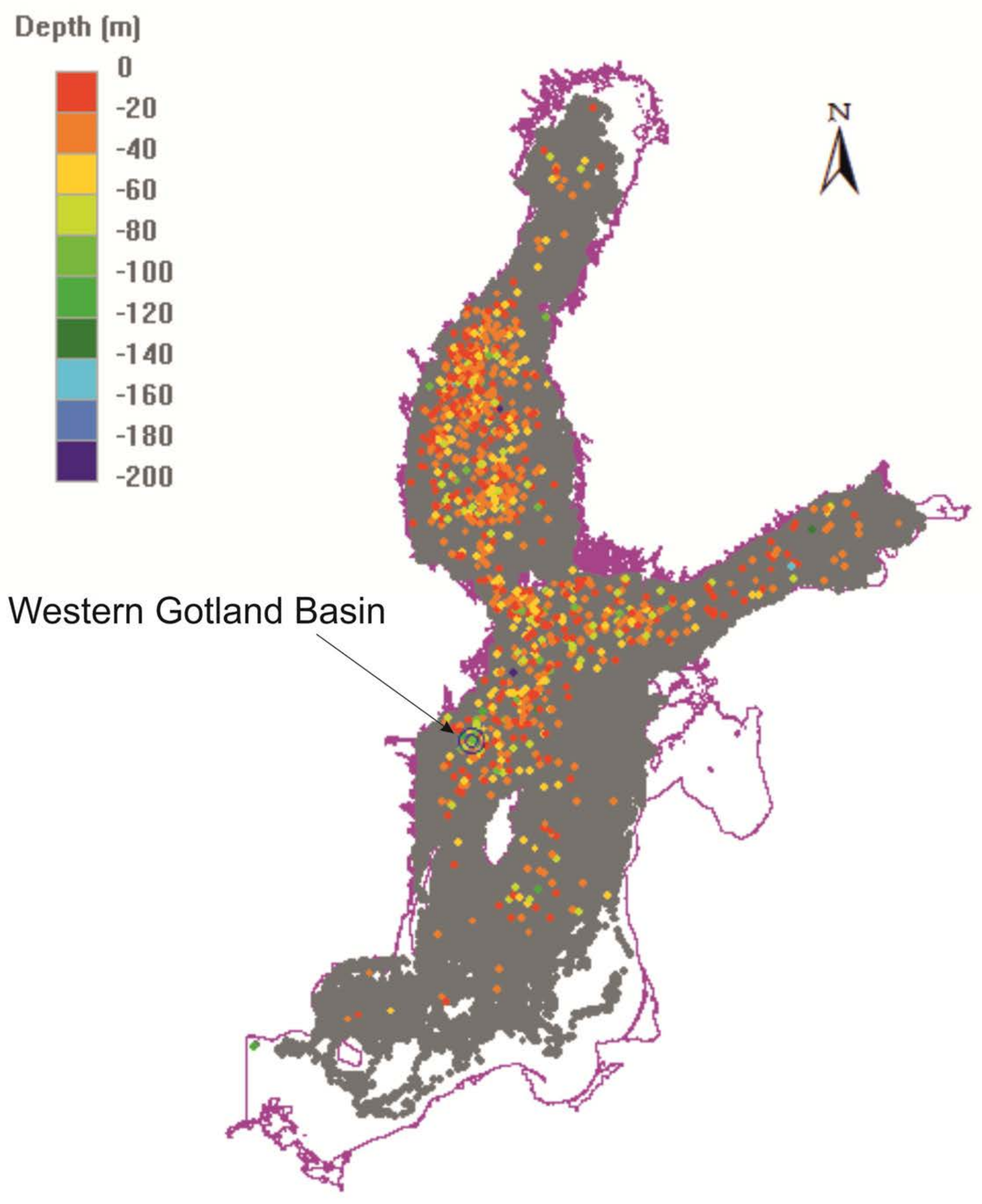

Figure S2.h: Particle traces of 1000 particles released at depth of 100m in the Western Gotland Basin, period 2000-2009.

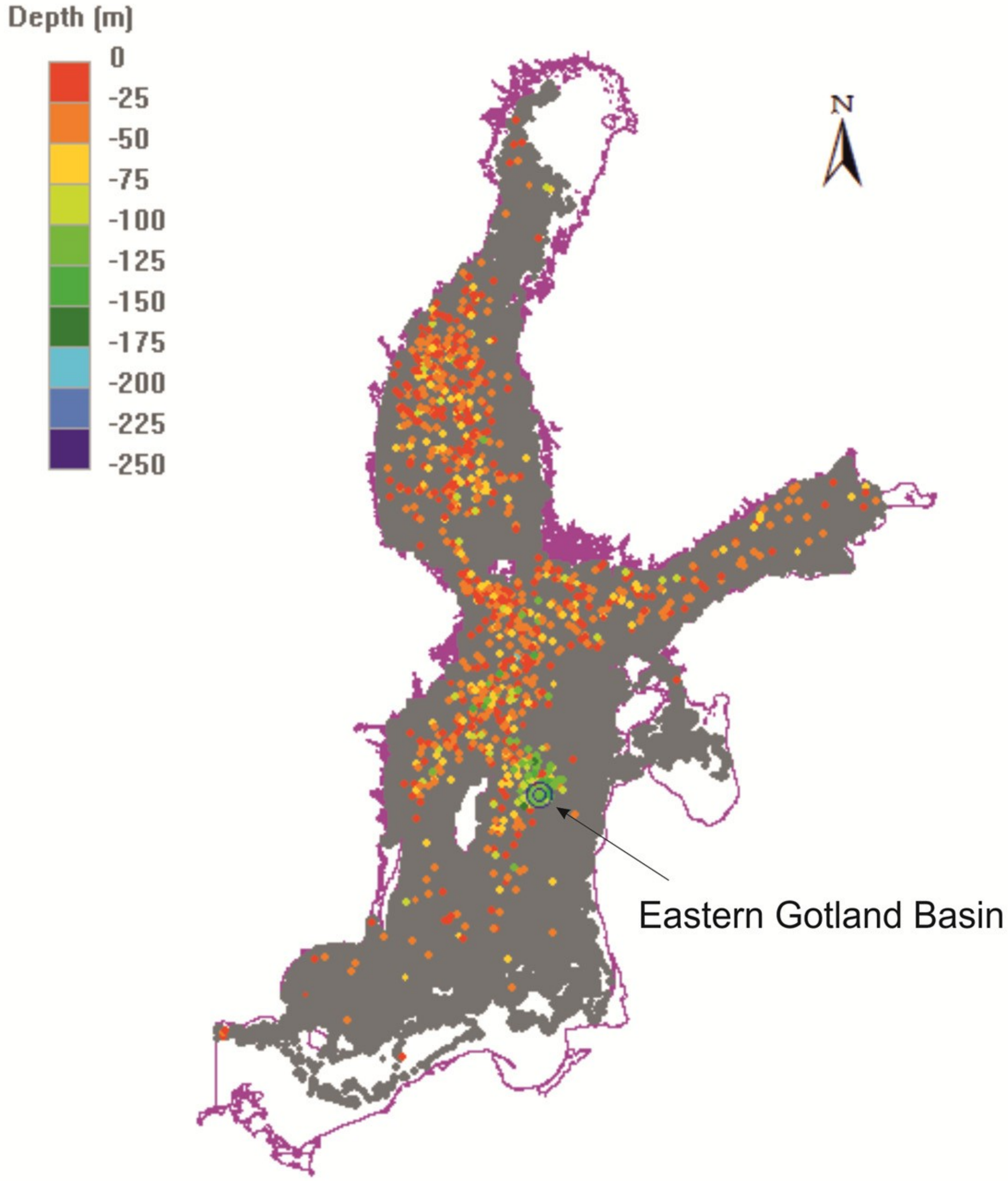

Figure S2.i: Particle tracers of 1000 particles released at depth of 124m in the Eastern Gotland Basin, period 2000-2009.

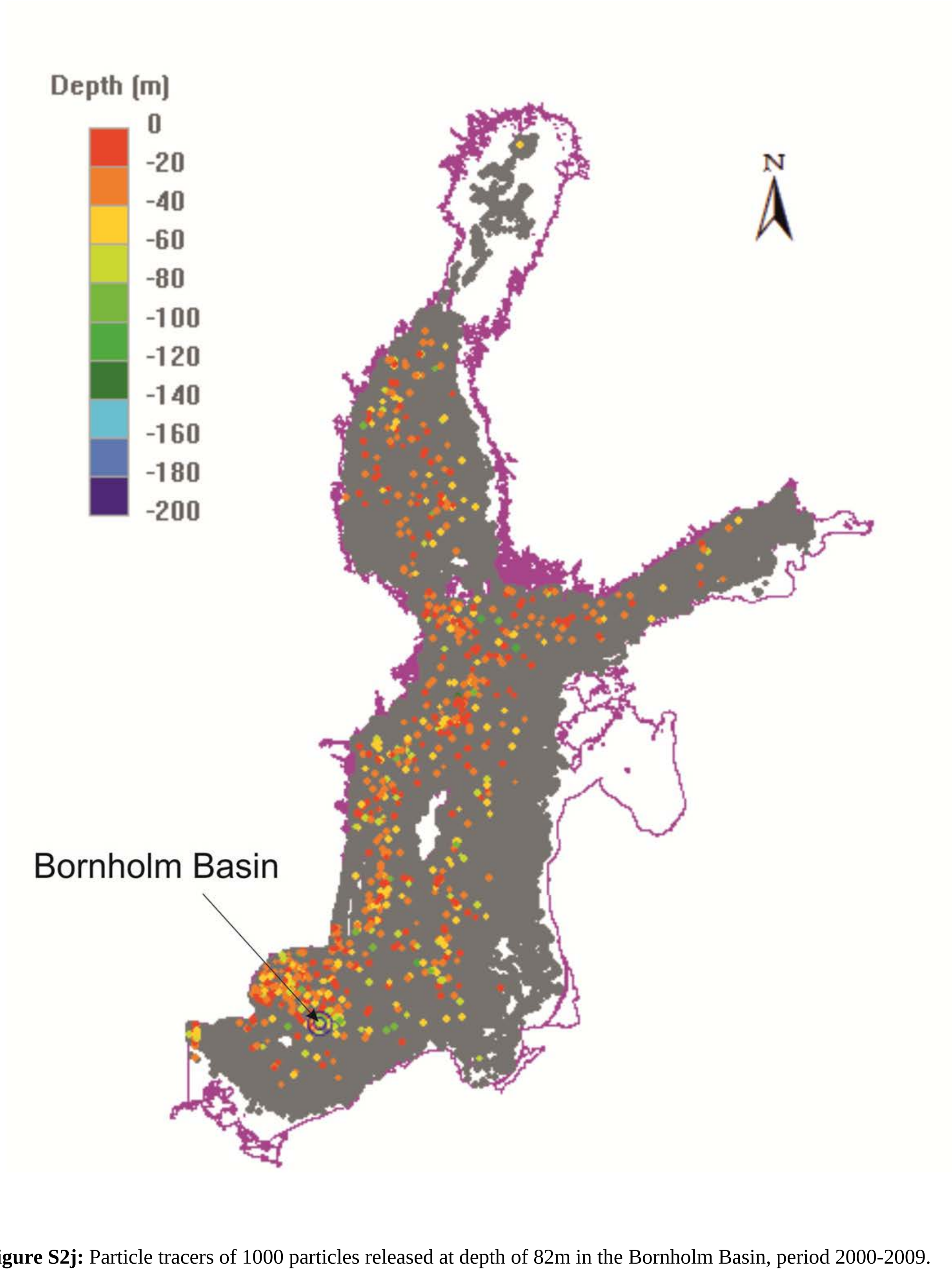

Figure S2j: Particle tracers of 1000 particles released at depth of 82m in the Bornholm Basin, period 2000-2009.

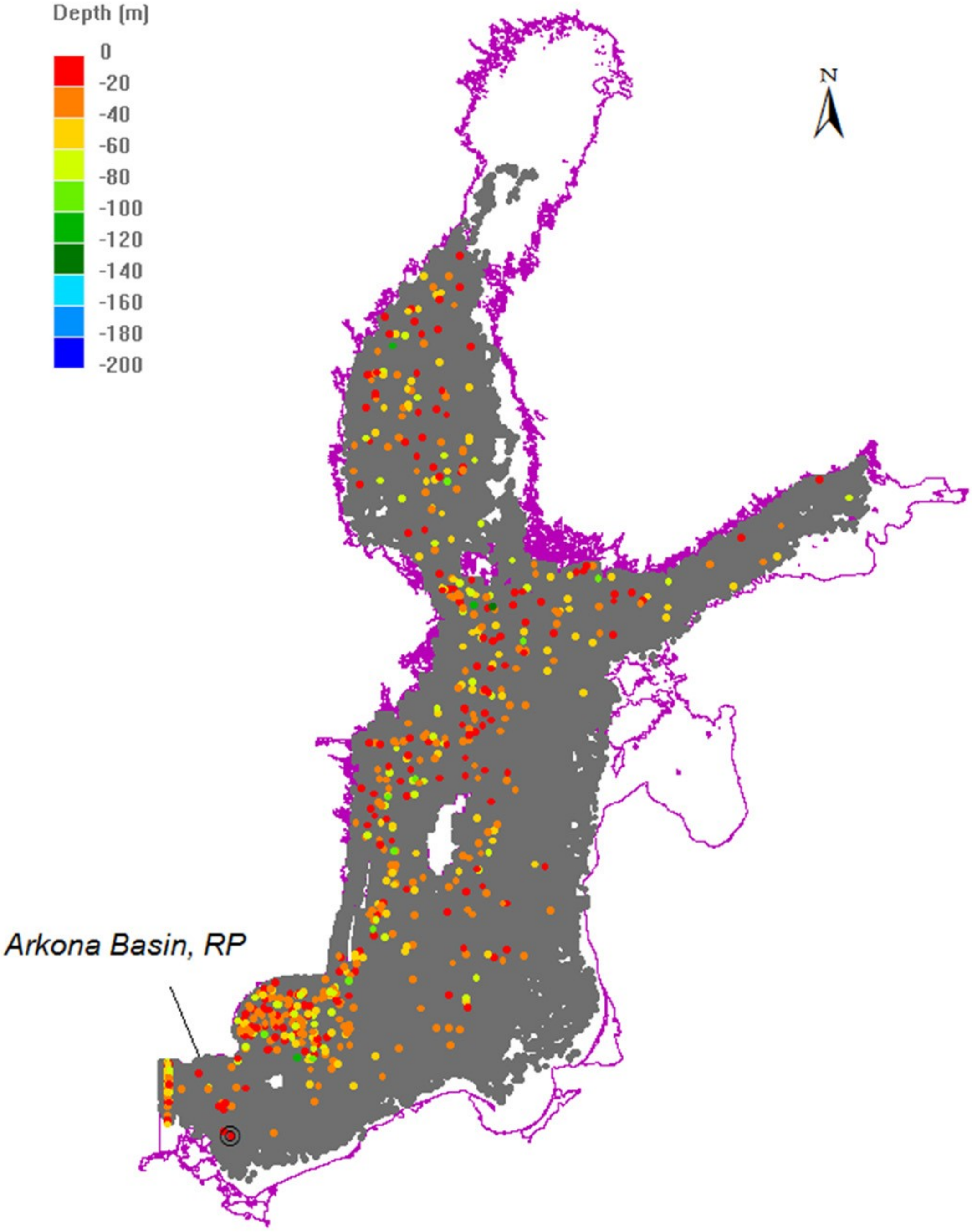

Figure S2.k: Particle tracers of 1000 particles released at depth of 16m in the Arkona Basin, period 2000-2009.

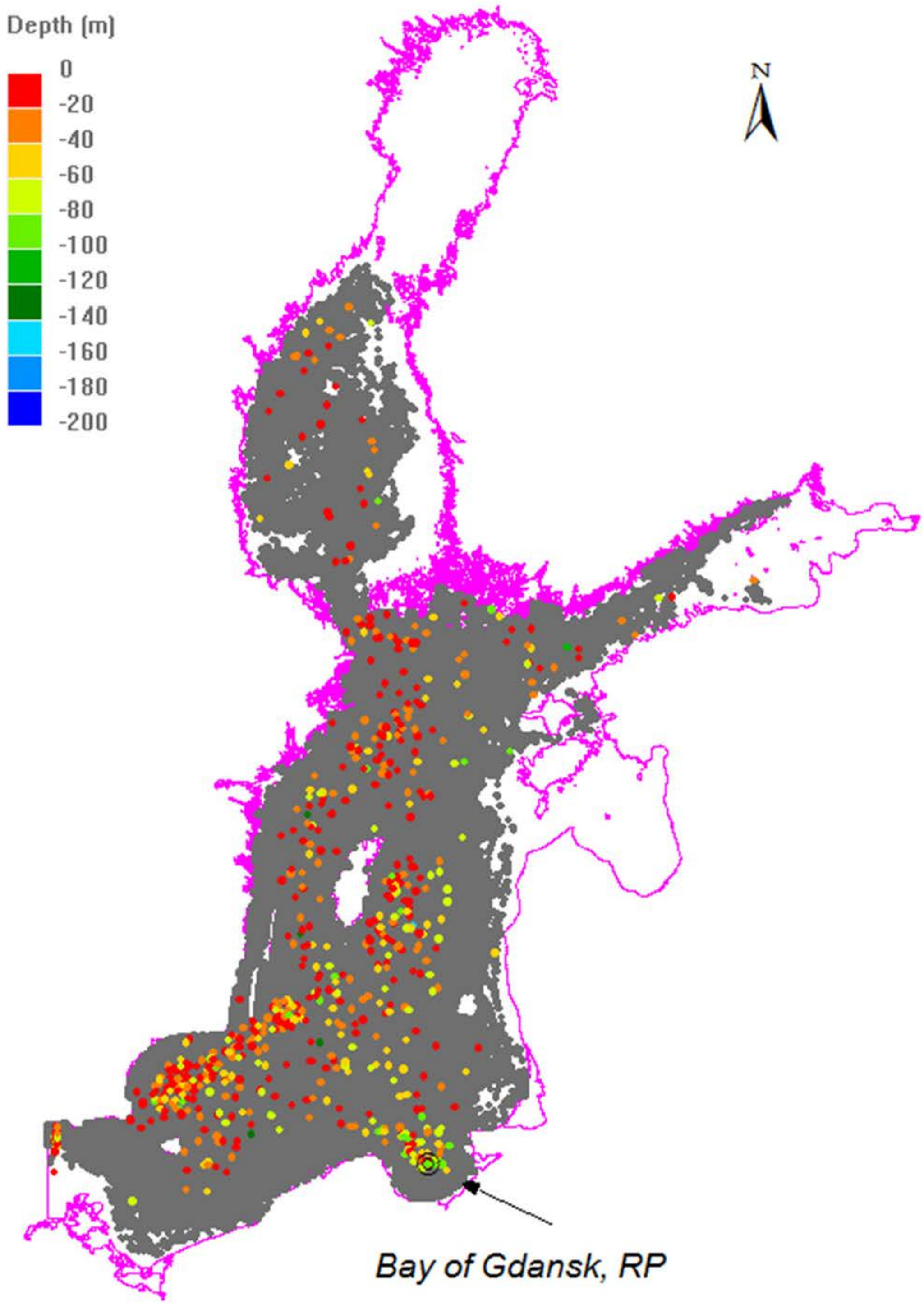

Figure S2.l: Particle tracers of 1000 particles released at depth of 82m in the Bay of Gdansk, period 2000-2009.

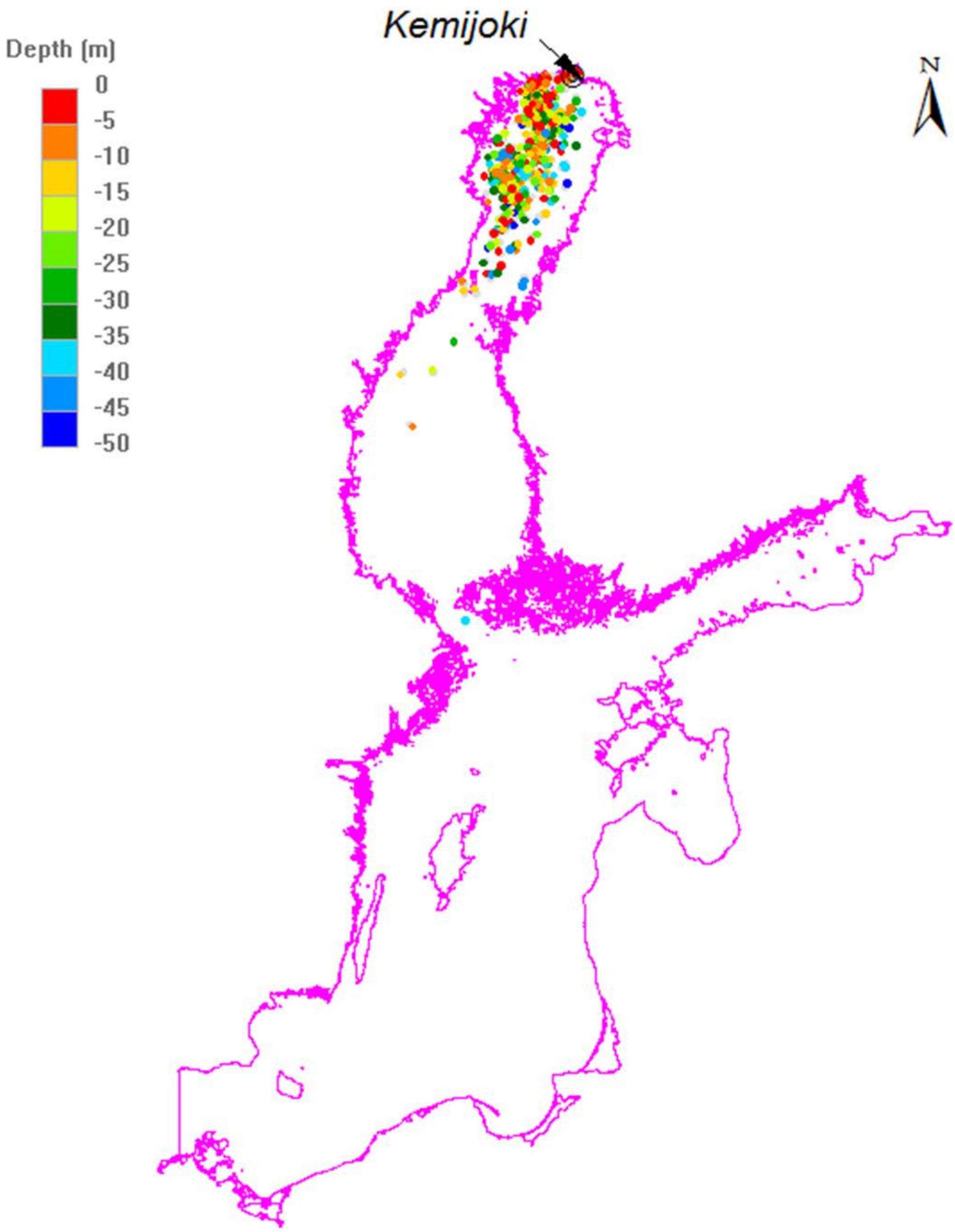

Figure S3.a: Particle tracers of 500 particles released from River Kemijoki during 30 day, January 2000.

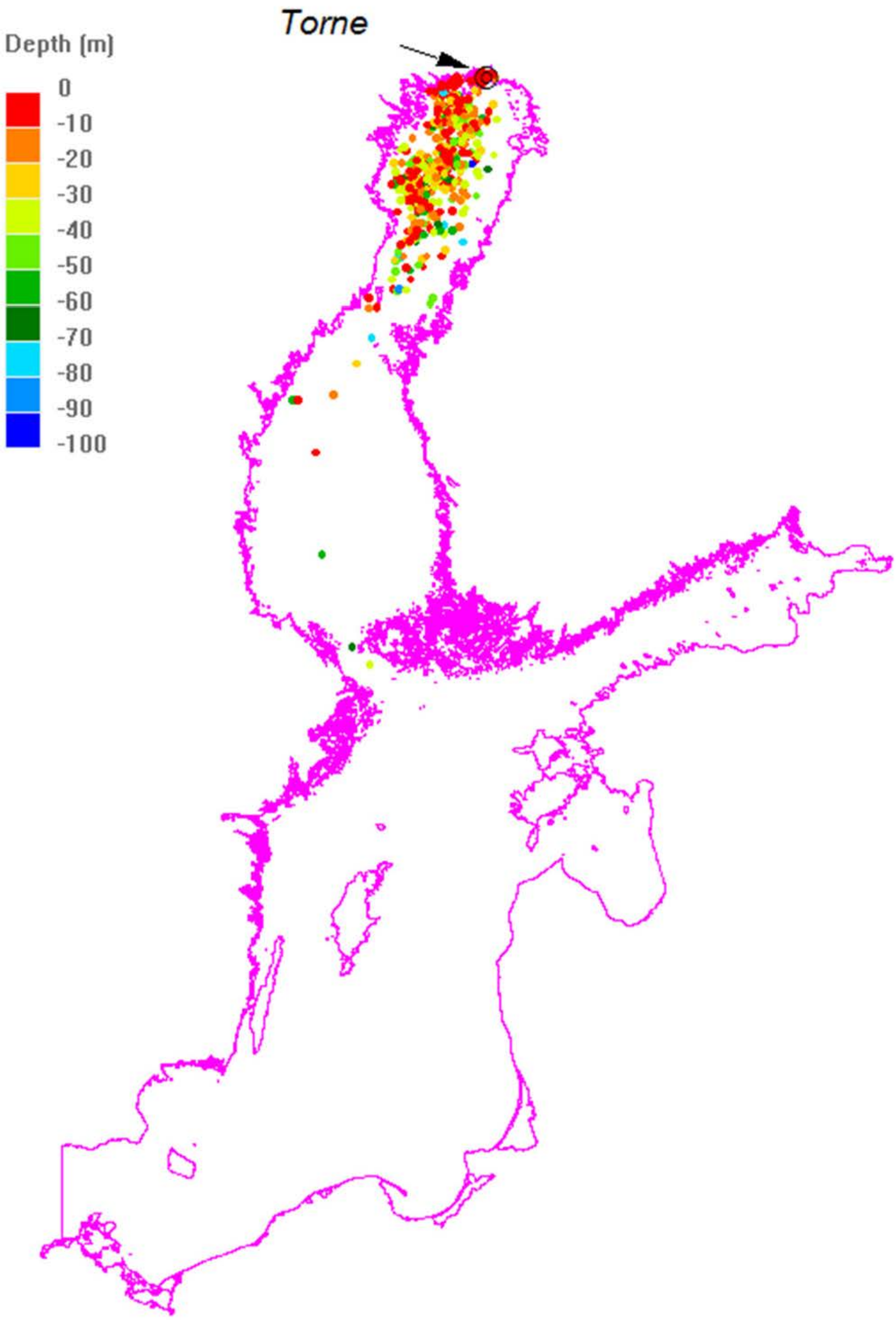

Figure S3.b: Particle tracers of 500 particles released at 5m from River Torne during 30 days, January 2000.

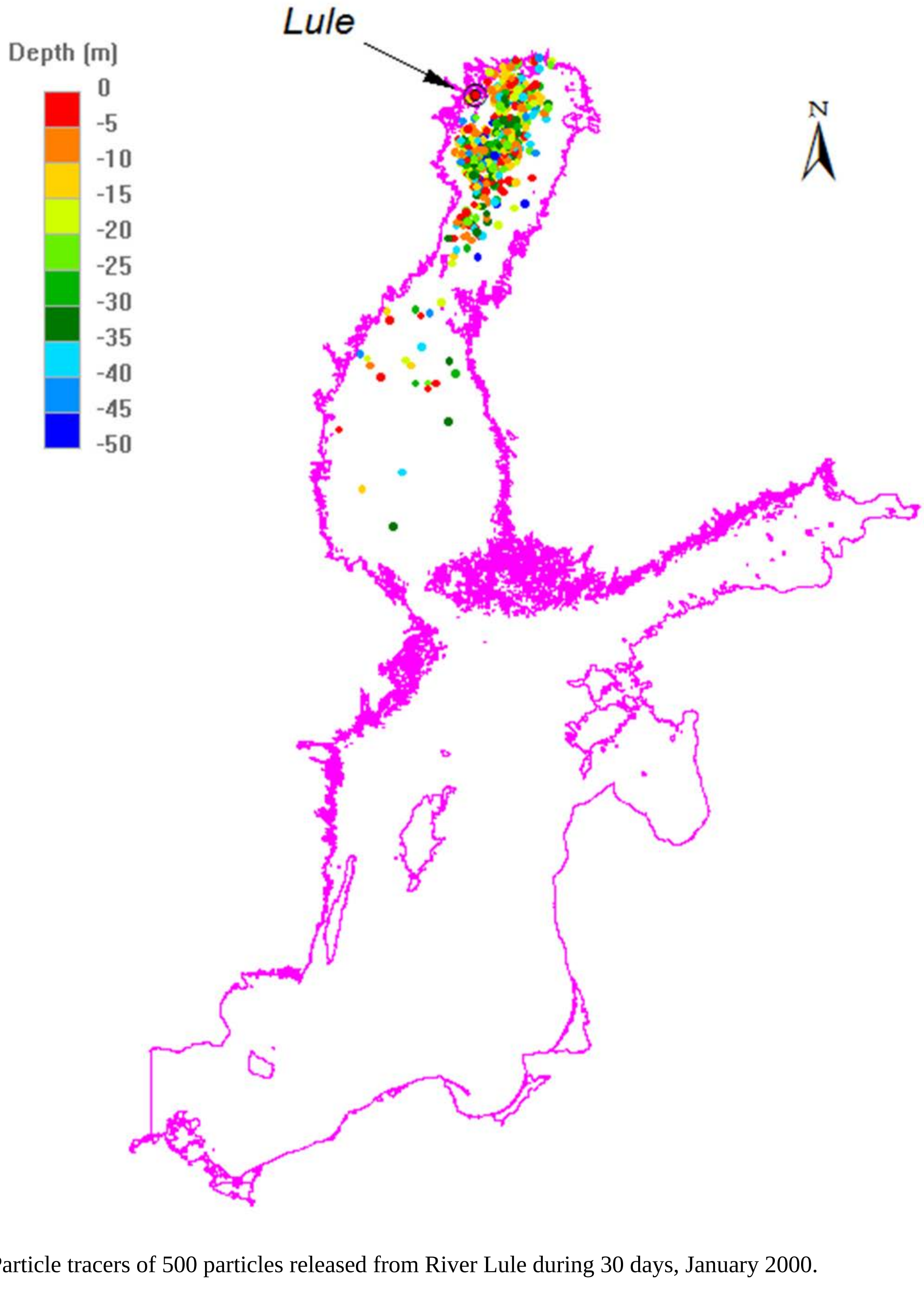

Figure S3-c: Particle tracers of 500 particles released from River Lule during 30 days, January 2000.

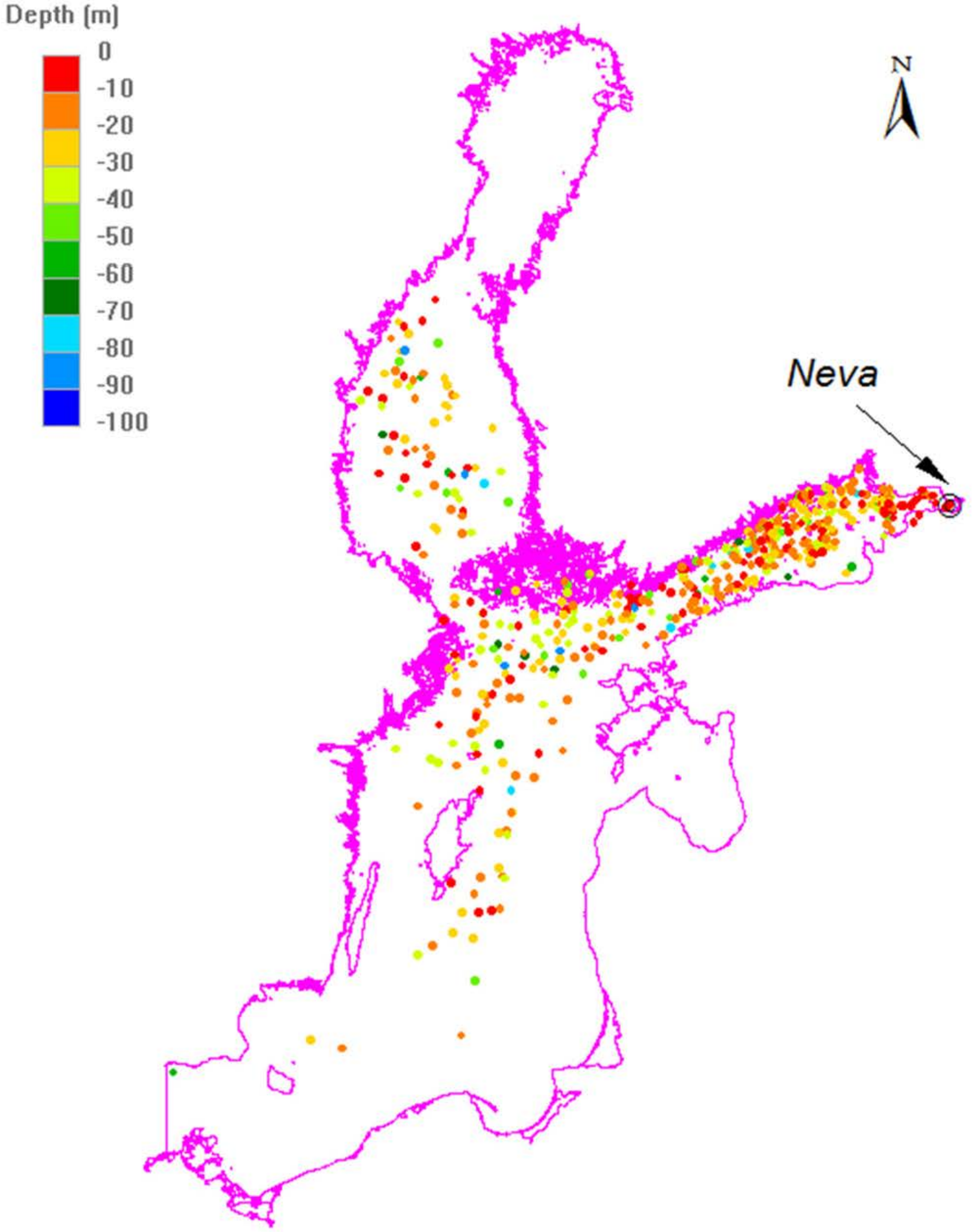

Figure S3.d: Particle tracers of 500 particles released from River Neva during 30 days, January 2000.

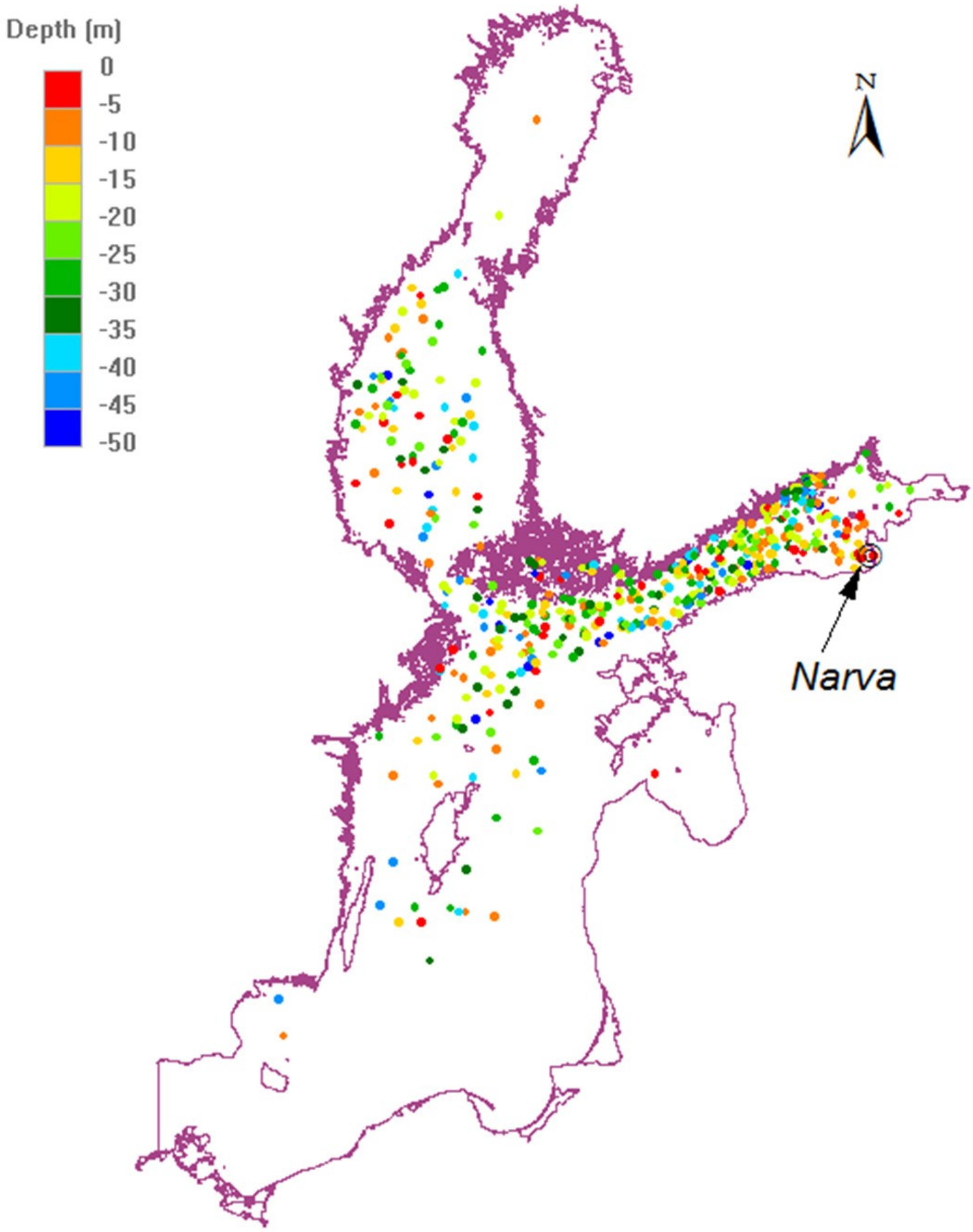

Figure S3-e: Particle tracers of 500 particles released from River Narva during 30 days, January 2000.

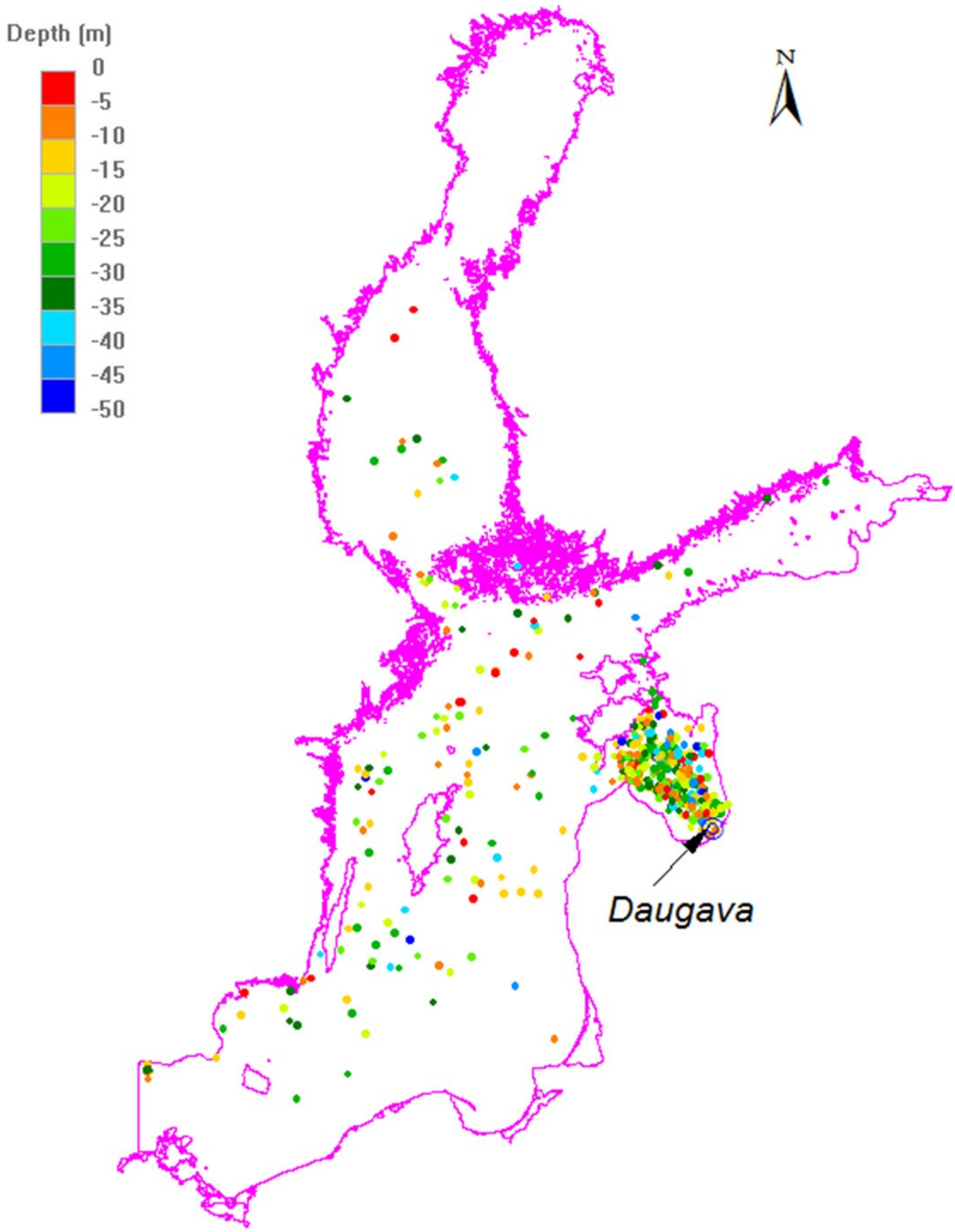

Figure S3.f: Particle tracers of 500 particles released from River Daugava during 30 days, January 2000.

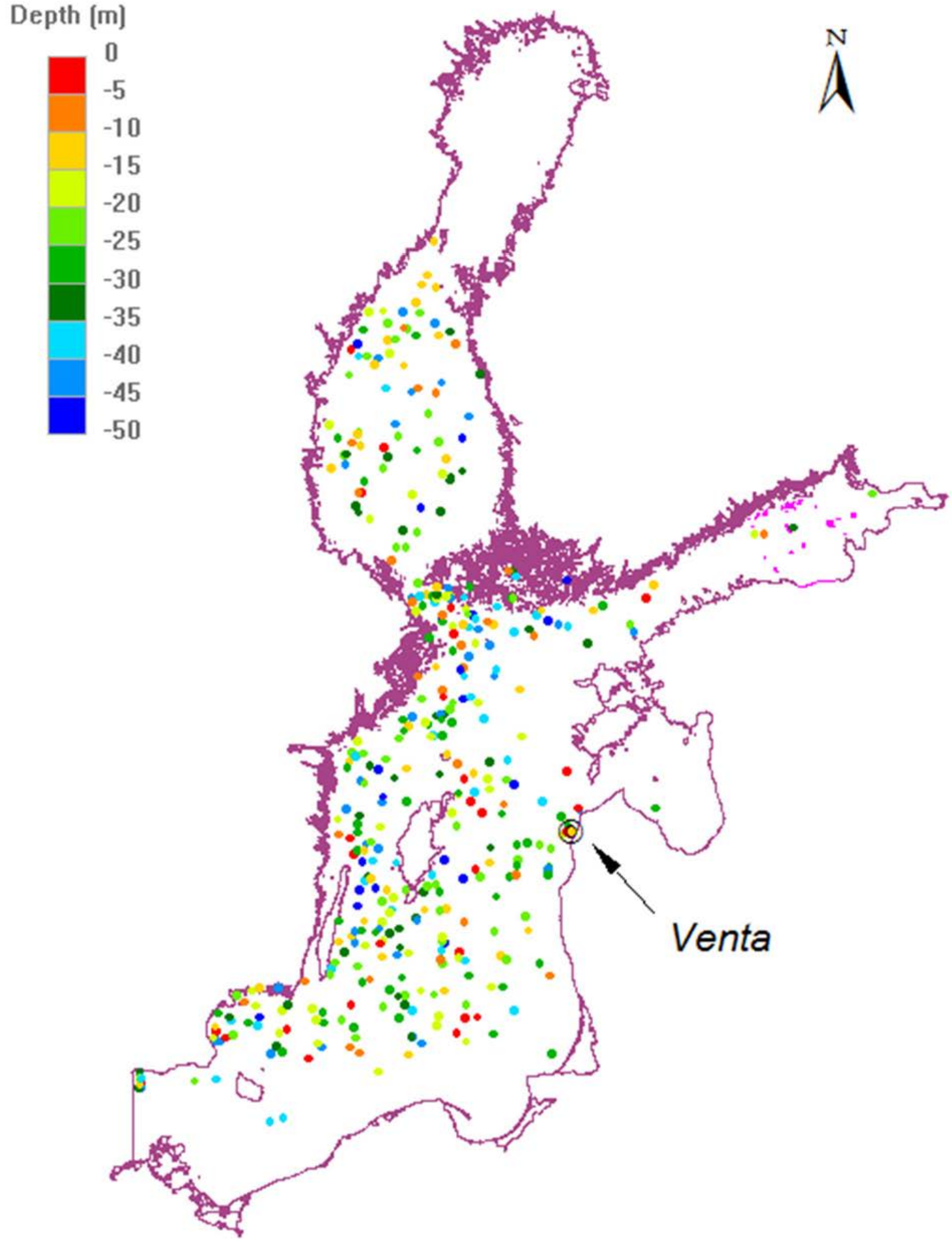

Figure S3.g: Particle tracers of 500 particles released from River Venta during 30 days, January 2000.

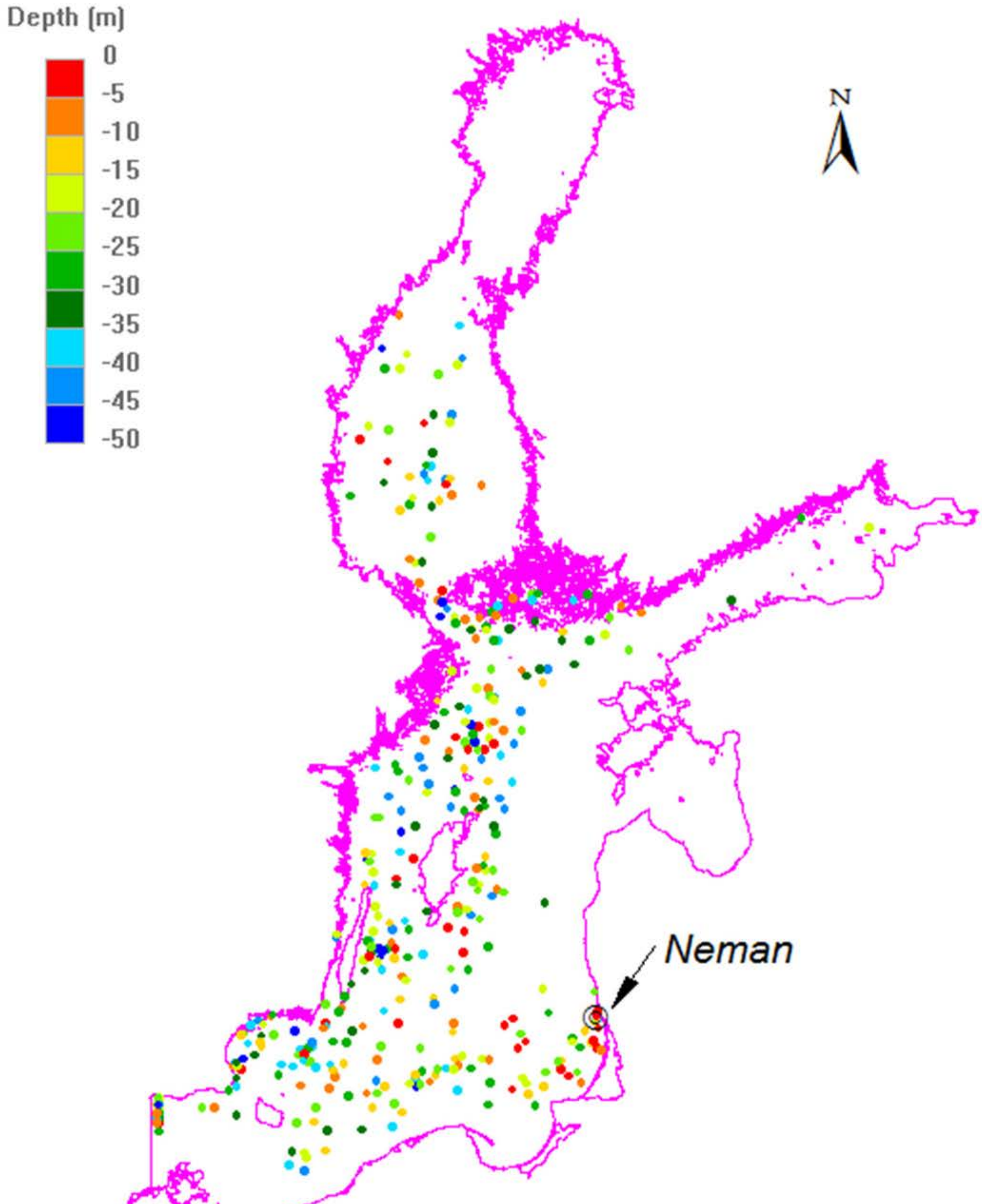

Figure S3.h: Particle tracers of 500 particles released from River Neman during 30 days, January 2000.

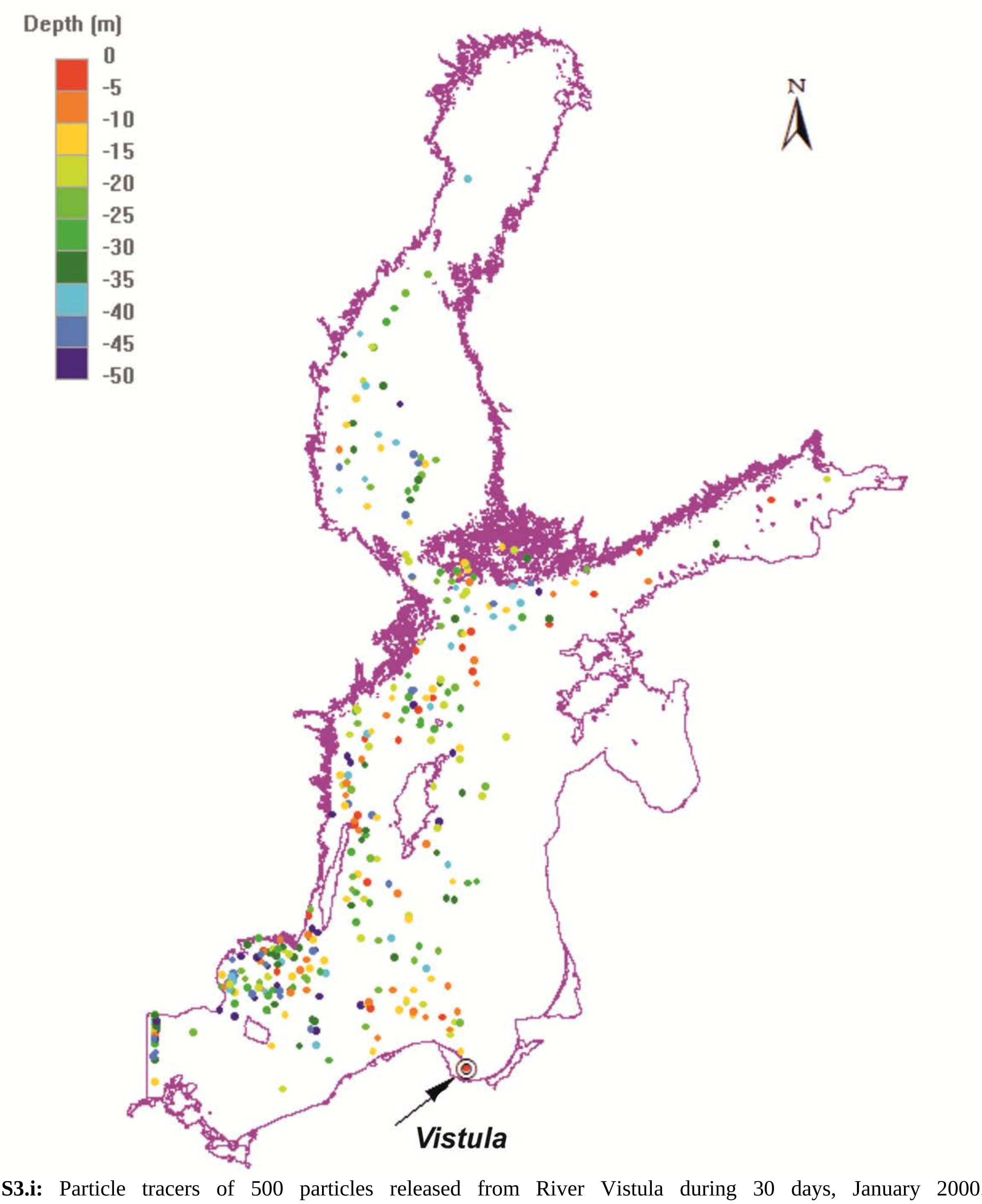

Figure S3.i: Particle tracers of 500 particles released from River Vistula during 30 days, January 2000.

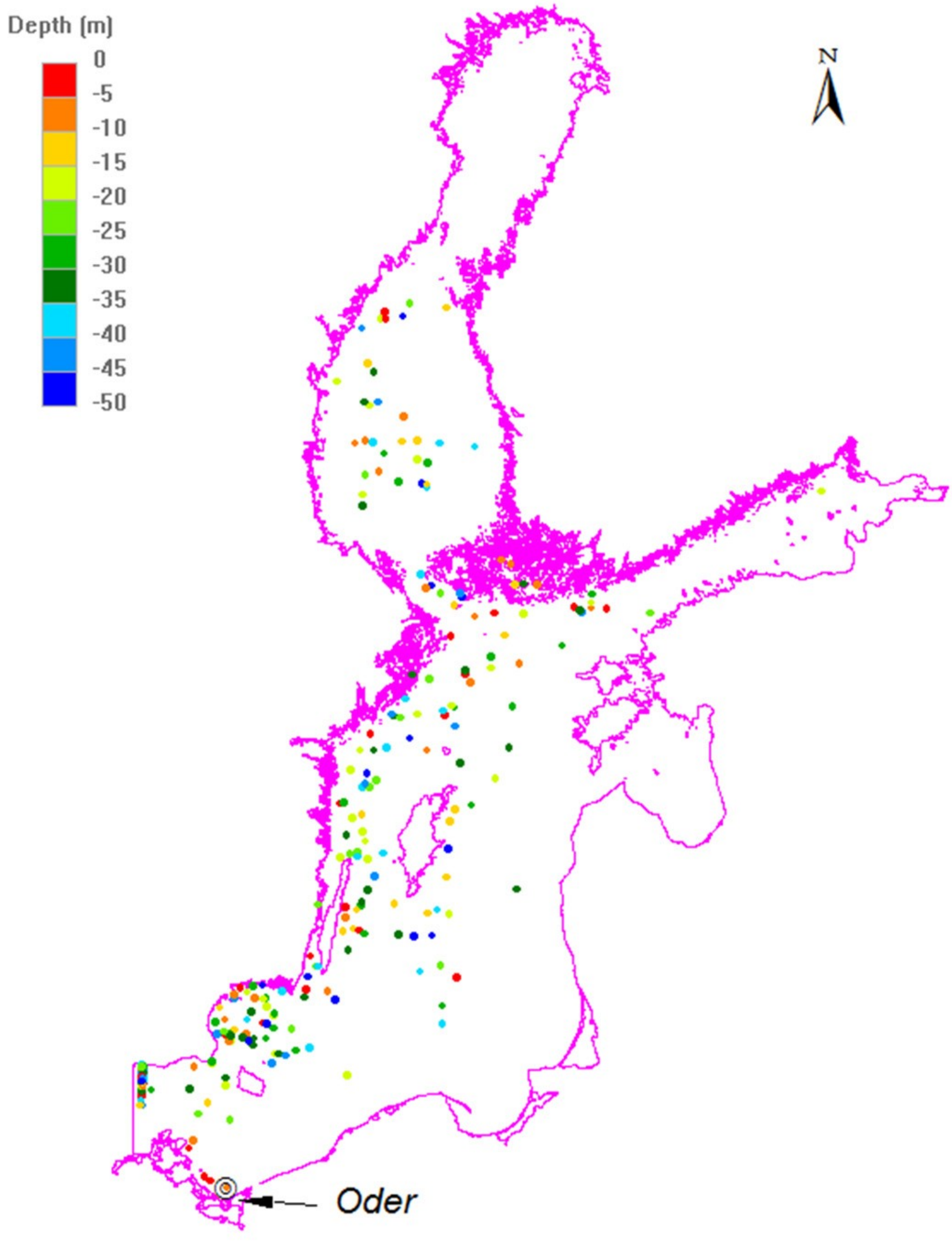

Figure S3.j: Particle tracers of 500 particles released from River Oder during 30 days, January 2000.

Appendix Particle Tracking

The movement of particles were determined by exploiting the equivalency between tracking particles and solving a mass transport equation for a conservative substance [64]. Following Dimou and Adams [56], a random-walk particle tracking scheme has been designed which calculates the displacement of particles as the sum of an advective deterministic component and an independent, random Markovian component which statistically approximates the dispersion characteristics of the environment. By relating the advective and Markovian components to the appropriate terms in a conservation equation, a technique has been designed where a distribution of particles will turn out to be the same as that concentration resulting from the solution of the conservation equation. In a three-dimensional environment, a conservative substance is transported under the influence of advection and dispersion processes. The solution for this transport problem is commonly based on the following mass balance equation:

$$h_1 h_2 \frac{\partial DC}{\partial t} + \frac{\partial\left(h_2 U_1 DC\right)}{\partial \zeta_1} + \frac{\partial\left(h_1 U_2 DC\right)}{\partial \zeta_2} + h_1 h_2 \frac{\partial\left(wC\right)}{\partial z} = \frac{\partial}{\partial \zeta_1}\left[\frac{h_2}{h_1} A_H D \frac{\partial C}{\partial \zeta_1}\right] + \frac{\partial}{\partial \zeta_2}\left[\frac{h_1}{h_2} A_H D \frac{\partial C}{\partial \zeta_2}\right] + \frac{h_1 h_2}{D}\frac{\partial}{\partial z}\left[K_H \frac{\partial C}{\partial z}\right] \tag{A-1}$$

in which C is the concentration; h_1 and h_2 are the metrics of the unit grid cell in the ξ_1 and ξ_2 directions, D is diffusion coefficient, U1 and U2 are the velocity components along the ξ_1 and ξ_2 directions, w is the velocity component in z-direction, AH is the momentum dispersion coefficient, and KH is the diffusion coefficient. Representing the conservative tracer concentration by a collection of particles, the transport problem can also be solved by particle tracking models and the displacement of a particle in a random-walk model is governed by the non-linear Langevin equation [59]:

$$\frac{d\vec{X}}{dt} = A\left(\vec{X},t\right) + B\left(\vec{X},t\right)Z\left(t\right) \tag{A-2}$$

in which $\vec{X}\left(t\right)$ is the particle trajectory vector $A\left(\vec{X},t\right)$ is the deterministic force that advects particles, $B\left(\vec{X},t\right)$ represents the random force vector that leads to particle diffusion, and Z(t) is a vector of the independent random numbers with zero mean and unit variance. A and B are defined by Equations 3 and 4 [65]

$$A = \begin{bmatrix} \dfrac{U_1}{h_1} + \dfrac{1}{h_1 h_2 D}\dfrac{\partial}{\partial \zeta_1}\left[\dfrac{A_H}{h_1^2} h_1 h_2 D\right] \\ \dfrac{U_2}{h_2} + \dfrac{1}{h_1 h_2 D}\dfrac{\partial}{\partial \zeta_2}\left[\dfrac{A_H}{h_2^2} h_1 h_2 D\right] \\ \dfrac{\omega}{D} + \dfrac{1}{h_1 h_2 D}\dfrac{\partial}{\partial \sigma}\left[\dfrac{K_H}{D^2} h_1 h_2 D\right] \end{bmatrix} \tag{A-3}$$

$$\frac{1}{2} B B^{\Gamma} = \begin{bmatrix} \dfrac{A_H}{h_1^2} & 0 & 0 \\ 0 & \dfrac{A_H}{h_2^2} & 0 \\ 0 & 0 & \dfrac{K_H}{D^2} \end{bmatrix} \tag{A-4}$$

$$\omega = W - \frac{1}{h_1 h_2}\left[h_2 U_1 \left[\sigma \frac{\partial D}{\partial \zeta_1} + \frac{\partial \eta}{\partial \zeta_1} \right] + h_1 U_2 \left[\sigma \frac{\partial D}{\partial \zeta_2} + \frac{\partial \eta}{\partial \zeta_2} \right] \right] - \left[\sigma \frac{\partial D}{\partial t} + \frac{\partial \eta}{\partial t} \right] \quad \text{(A-5)}$$

in which, D = Hη, η(x,y) is water surface elevation defined by Equation 6, and H(x,y) is the water depth.

$$\sigma = \frac{z - \eta}{H + \eta} \quad \text{(A-6)}$$