



HOKKAIDO UNIVERSITY

Title	Along-coast shifts of plankton blooms driven by riverine inputs of nutrients and fresh water onto the coastal shelf: a model simulation
Author(s)	Hoshiba, Yasuhiro; Yamanaka, Yasuhiro
Citation	Journal of oceanography, 69(6), 753-767 https://doi.org/10.1007/s10872-013-0206-4
Issue Date	2013-12
Doc URL	https://hdl.handle.net/2115/57453
Rights	© The Oceanographic Society of Japan and Springer Japan 2013, The final publication is available at link.springer.com
Type	journal article
File Information	Hoshiba and Yamanaka_J02013.pdf



Along-coast shifts of plankton blooms driven by riverine inputs of nutrients and fresh water onto the coastal shelf: A model simulation

Yasuhiro Hoshiba^{1*} and Yasuhiro Yamanaka²

¹Graduate School of Environmental Science, Hokkaido University, Sapporo, Japan

²Faculty of Environmental Earth Science, Hokkaido University, Sapporo, Japan

*Corresponding author. E-mail: h-dragon@ees.hokudai.ac.jp

Keywords: coastal ocean; biogeochemical cycles; 3-D modeling; riverine input; nutrient supply; phytoplankton bloom; color tracer

Abstract:

Rivers transport nutrients and suspended sediment matter (SSM) as well as fresh water from land to coastal regions, where the biological productivity is high. In the coastal area, the buoyancy of fresh water leads to the formation of horizontal anticyclonic gyres and vertical circulations, which affect the variation of biological production such as plankton blooms. However, the primary production caused by the three-dimensional dynamics have not been quantitatively discussed, and observations can hardly capture the daily temporal variations of phytoplankton blooms. We developed an ocean general circulation model (OGCM) including a simple ecosystem model, to investigate the three-dimensional and temporal changes in phytoplankton blooms caused by riverine input such as flooding. The distribution patterns of nutrients and phytoplankton differ significantly from that of fresh water. The phytoplankton maxima shift from the downstream (right-hand side of the river mouth) to the upstream regions (left-hand side of the river mouth). The shift that occurs is categorized by the different nitrate origins: (1) river-originated nitrate is dominant in the downstream region; (2) subsurface-originated nitrate is dominant in the upstream region, and is transported by upwelling associated with vertical circulation and horizontal anticyclonic gyre; and (3) regenerated nitrate is dominant in the upstream region. The total primary production in phytoplankton blooms is maintained not only by river-originated nitrate but also by subsurface-originated nitrate that is 1.5 times larger than the river-originated. Several case studies (*e.g.*, including SSM) were conducted in this study.

1. Introduction

Nutrients and suspended sediment matter (SSM) are derived from river discharge (Le *et al.*, 2006; Usui *et al.*, 2006). River discharge has influence on coastal areas, where biological productivity is high (Costanza *et al.*, 1997). Fresh water is supplied as a buoyant input into large areas of the shelf seas adjacent to estuaries. Simpson (1997) termed these as regions of freshwater influence (ROFI) and classified into them four types: open coast, corner source, gulf and gulf with sill. Open coast ROFI, assumed in this study, is the simplest situation that the estuarine discharge enters the sea on a straight coast. In ROFI, freshwater inputs induce horizontal river plumes with anticyclonic gyres due to geostrophic adjustment, and vertical circulation composed of the surface water flows from the coast to offshore and a subsurface counter-flow with upwelling occurs near the coast (Rattray and Hansen, 1962). The strength of circulation depends on the density difference between the river derived fresh water input and the coastal sea water. These horizontal and vertical flows transport nutrients and SSM from the river mouth into ROFI. ROFIs in the subarctic regions have seasonal changes in nutrients in the surface water, which are abundant from winter to spring but depleted from summer to autumn (Kudo *et al.*, 2007; Yoshimura and Kudo, 2011). Phytoplankton blooms occur due to regularly large amounts of riverine discharge by snowmelt and/or a few days pulse of riverine discharge due to heavy rains (*e.g.*, Agboola *et al.*, 2009). The Tokachi River, for example of the subarctic rivers, the second largest discharge in Hokkaido, had steady large amounts of discharge in spring (April to June) and two pulses of discharge in August and October in 2006 (Figure 1), and the river mouth of 1 km width. The daily mean discharge on 19th August, 2006 amounted to 1865 m³/s.

Fresh water from the river is muddy due to SSM (*e.g.*, sand, silt, and other terrestrial inorganic particles). The relationship between river discharge and turbidity is well known as the empirical L-Q equation: the SSM concentration from the river is larger as the flux of river discharge becomes larger. When SSM in fresh water mixes with the sea water, SSM particles aggregate due to the pH difference between the river and the sea water, and are removed from the sea water as settling sediment particles (Kusuda, 2003). The rate of removal from the water as settling sediment particles is larger with larger particle-size of SSM, according to Stokes' law. High turbidity (*i.e.*, SSM concentration increases with freshwater flux) tends to shade sunlight and prevent phytoplankton from photosynthesis, when the freshwater flux is larger (Kaiser *et al.*, 2005).

There are a lot of previous studies discussing the physics of horizontal anticyclonic gyres (*e.g.*, Garvine, 2001; Nof and Pichevin, 2001; Pimenta *et al.*, 2011), but limited quantitative studies focusing on the primary production increased by gyres. The relationship between the vertical circulation and primary production has been studied using a box model (Yamamoto and Hashimoto, 2007). Observations of phytoplankton blooms in ROFI have been also conducted (*e.g.*, Beman *et al.*, 2005; Agboola *et al.*, 2009; Yoshimura and Kudo, 2011). However, box models cannot represent three-dimensional dynamics, and observations can hardly capture the daily temporal variations of phytoplankton blooms.

In this study, we applied an OGCM with simple ecosystem model to investigate three-dimensional and temporal variations of plankton bloom caused by flooding in spring in ROFI. In the next section, we describe the model settings and methods. In section 3, we present the results such as the horizontal distribution of salinity and

current field, nitrate, phytoplankton and zooplankton in the control case. In section 4, we discuss our results in several cases as well as the control case. In section 5, we have the conclusions.

2. Model and Method

2.1 Model

The model used in this study is an OGCM, the Center for Climate System Research (CCSR) Ocean Component Model (COCO) version 4.0 (Hasumi, 2002). We dealt with fresh water and nutrient flowing from a river into the ocean which has the simplified rectangular domain on f-plane (about 43°N, Figure 2). The domain was large enough not to affect the river plume. The horizontal grid sizes are approximately 1 km (x-direction) and increasing from 1 km near river mouth to 20 km far from the river mouth (y-direction). The model has ten vertical layers with thickness increasing from 10 m at the surface to 40 m at the bottom. The depth to the ocean floor varied from 30 m near shore to 200 m for the offshore (Figure 2). In this study, when we look offshore from the river mouth, we call the left-hand side ‘upstream’ and the right-hand side ‘downstream’ the same as in previous studies (*e.g.*, McCreary *et al.*, 1997; Yankovsky, 2000; Magome and Isobe, 2003). The downstream is the propagated direction of the Kelvin wave. We used the Quadratic Upstream Interpolation for Convective Kinematics with Estimated Streaming Terms (QUICKEST; Leonard, 1979) and the Uniformly Third-Order Polynomial Interpolation Algorithm (UTOPIA; Leonard *et al.*, 1993) as the vertical and horizontal tracer advection schemes, respectively. The diffusion coefficient along and across the isopycnal was set to $1.0 \times 10^6 \text{ cm}^2/\text{s}$ with a

maximum slope of 0.01. The horizontal diffusion coefficient was set to 1.0×10^6 cm^2/s and the vertical diffusion coefficient was $0.5 \text{ cm}^2/\text{s}$. These values are defaults in the model (COCO ver.4) except the vertical diffusion coefficient. The somewhat large coefficient relative to the default value (about $0.1 \text{ cm}^2/\text{s}$; Tsujino *et al.*, 2000) was determined due to the effects of vertical mixing in coastal regions. A biharmonic friction with a Smagorinsky-like viscosity (Griffies and Hallberg, 2000) was used for momentum with a scaling constant $C = 3.0$ in their notation. Effects of tide and background flow were not considered. There are some studies investigating the effects of tide and background flow on river plumes. In the ROFI of Tokachi River, for instance, wind-driven flow and Oyashio flow have influences on the temporal and spatial variations (Lihan *et al.*, 2008). Tide also horizontally suppresses the river plume spreading and propagating towards the upstream (Isobe, 2005), and vertically advances mixing between riverine low and marine high density waters (Rattray and Hansen, 1962). Before applying the realistic simulation, we introduce a simple simulation such as no tides and background flows, as a first step, in order to focus on the response of ecosystem and biogeochemical cycles to river flows. The initial salinity was assumed to be constant (33.5 g/kg) throughout the region, and the initial temperature was constant horizontally (Figure 4 (e)).

We incorporated a simple ecosystem part, based on the four-compartment version in Yoshikawa *et al.* (2005), into OGCM (Figure 3). The four state variables are composed of nutrient assumed to nitrate, phytoplankton, zooplankton and detritus. The concentrations of components are calculated by individual biological processes (*i.e.*, photosynthesis, grazing, etc.) as nitrogen fluxes, except physical processes of diffusion and advection. The biological parameters used in this study are summarized in Table 1,

most of which were based on those in Yoshikawa *et al.* (2005). The time step of the hydrodynamic model was 2 minutes. After a spin-up of 10 years with the ecosystem model, we used the distributions of nitrate, phytoplankton, zooplankton and detritus as initial conditions of the experiments driven by river input (Figure 4 (a)-(d)). The 10 years were enough that the distributions of NPZD became a quasi-steady state due to the diffusion and the ecosystem cycle in the model.

In all experiments except experiment #4 (Table 2), we put the freshwater input as 2,000 m³/s (the peak discharge rate from Fig. 1), with the same surface temperature, into river mouth region of 20 km × 3 km for the first 2 days and no discharge for the other 98 days. Nitrate concentration of 1.0 mg/l, a typical value representative of rivers in Hokkaido, Japan (Tachibana *et al.*, 2001; Ileva *et al.*, 2009), in the fresh water was also used. In experiment #4, we put the freshwater input as 100 m³/s for 40 days with a nitrate concentration of 1.0 mg/l, which is the same total freshwater volume and nitrate amount discharged as in the other experiments but a long-term input, and no discharge for the other 60 days. We confirmed that the results in the two experiments using an averaged discharge of 100m³/s instead of no discharge as the initial condition or the averaged discharge instead of no discharge after high discharge as another follow-up condition and were almost the same as those in the experiment #1 (not shown).

In experiment #5, we also give SSM input given by an empirical equation for the Tokachi River, Hokkaido (T. Irino, *personal communication*),

$$[SSM] = 0.00331 \times MF^{1.685} \quad (1)$$

where [SSM] (g/m³) is the concentration of SSM, MF (m³/s) is the mass flux of freshwater input. SSM is transported as a passive tracer and is gradually removed from the sea water according to the following equation:

$$\frac{\partial[\text{SSM}]}{\partial t} = (\text{Adv.}) + (\text{Dif.}) - \frac{1}{\tau}[\text{SSM}] \quad (2)$$

where (Adv.) and (Dif.) represent advection and diffusion terms as physical processes, and τ is the removal time for SSM. SSM is faster removed as its size is bigger. Following Kusuda *et al.* (1978), aggregated clay particles (0.2 to 0.5 mm diameter) in salty water have precipitated at the sinking speed of 0.2 to 0.5 mm/s. As this sinking speed is approximately equivalent to the removal time of $\tau = 0.5$ to 2.0 days, we conducted four parameter studies as $\tau = 0.5, 1.0, 1.5, 2.0$ days. The effect of shading sunlight due to SSM was included as follows: light intensity (I) at the depth z is

$$I = I_0 \exp\left(-\int_0^z \kappa dz\right) \quad (3)$$

$$\kappa = \alpha_1 + \alpha_2 [\text{PHY}] + \alpha_{\text{SSM}} [\text{SSM}] \quad (4)$$

where I_0 is the isolation at the sea surface, imposed as the boundary condition, and α_{SSM} (Table 1) is the coefficient of shading light due to SSM.

2.2 Numerical experiments

We conducted five experiments for 100 days (Table 2). In experiment #1 (hereafter referred as the control case), we initiated the model with freshwater and nutrient inputs for two days but no SSM input. Experiment #2 (no flux-case) without all inputs was conducted as the base line condition, and we discussed most of simulation results as differences from those in the no flux-case. Experiment #3 was designed to clarify the direct effect of river-originated nutrient comparing with Experiment #1. Experiment #4 demonstrates the different pattern of river input, *i.e.*, long-term input of 40 days instead of two days. In experiment #5, we dealt with SSM to demonstrate the shading

effect by SSM.

3. Results

The buoyant inflow from the river mouth forms an anticyclonic gyre due to geostrophic adjustment. The horizontal salinity distributions with current velocity in the surface layer (5 m depth) in the control case are shown in Figure 5 (a). The buoyant water in the anticyclonic gyre continues downstream as a coastal current trapped against the wall as a Kelvin Wave (*e.g.*, Bowden, 1983). The anticyclonic gyre spreads and propagates towards the upstream region with time. Propagations of river plumes to the upstream area have been reported in various river systems (*e.g.*, the Changjiang River; Beardsley *et al.*, 1985, major Siberian rivers in the Arctic; Weingartner *et al.*, 1999, the Mississippi River; Walker *et al.*, 1994, the Ganges River; Murty *et al.*, 1992, the La Plata River; Piola *et al.*, 2008, some rivers in the Suo-Nada in Japan; Magome and Isobe, 2003). The Figure 1 in Matano and Palma (2010) showed chlorophyll-a observed by satellite propagating to the upstream. The prerequisite condition of propagating to the upstream occurring is that the width of the river mouth is smaller than the internal deformation radius calculated from the density difference between the river and the sea waters. The width of the river mouth is 3 km in this study, which is smaller than the radius (~ 10 km). Propagating to the upstream generally does not occur if the river mouth width is wider than the internal deformation radius (*e.g.*, the exp.1 of Chao and Boicourt, 1986; the width of the river mouth is 15 km). The gyre propagating can be explained by the method of mirror image (Kubokawa, 1991). McCreary *et al.* (1997) also explains that the proceeding to the

upstream results from the downward frontal current generated by geostrophic adjustment, and the upward coastal jet established by Kelvin-wave propagation from the plume nose thinning the layer within the plume. The strength of shifting depends on the outflow amount from the river mouth, the density difference between the river and the sea waters, topography around the river mouth, and so on. There are a lot of previous studies related to this shifting of anticyclonic gyres (*e.g.*, Chapman and Lentz, 1994; Yankovsky, 2000). The flow of gyres determines both distributions of salinity and nitrate (Figure 5 (b)). Both distributions are similar until Day 6. Nitrate-rich freshwater spreads from the river mouth, bends to the right, and is transported to the downstream while being trapped against the coast. However, the distribution pattern of nitrate gradually becomes different from that of salinity as time progresses. Nitrate maxima tend to locate in the upstream region rather than the river mouth. This is because upwelling, forced by vertical circulation, occurs in the upstream region due to the anticyclonic gyre. The upwelling supplies nutrient-rich water from the subsurface layer to the surface (Figure 6 (a), (b)). As an advantage of the three-dimensional model, we can obtain upwelling in the upstream region as a combination of horizontal anticyclonic gyre and vertical circulation. The horizontal anticyclonic gyre transports coastal surface water to the offshore in the upstream region where upwelling forced by vertical circulation is formed. Therefore, upwelling occurs mainly in the upstream region, and the coastal upwelling region spreads to the upstream with horizontal anticyclonic gyre propagating toward the upstream region (Figure 7).

Phytoplankton bloom occurs (Figure 5 (c)), which is maintained by nitrate supplied from the river at its first stage and from the subsurface layer at its subsequent stage, as discussed in the next section. This shift of nutrient supply causes a location shift of

phytoplankton maxima from the downstream to the upstream regions (hereafter we call this ‘Downstream-to-Upstream shift (D-U Shift)’). Zooplankton bloom follows phytoplankton bloom with D-U Shift (Figure 5 (d)).

4. Discussion

4.1 Introducing nitrate colored by its origins

To clarify the dynamics of D-U Shift, we introduced nitrates categorized into three origins from the river, the subsurface layer, and via regeneration (hereafter we term these as river-originated nitrate, RO-nitrate; subsurface-originated nitrate, SO-nitrate; and regenerated nitrate, R-nitrate, respectively). RO-nitrate is the river nutrient input integrated over time (*i.e.*, there is no RO-nitrate as initial condition). Net primary production (NPP) is also divided into three components, RO-NPP, SO-NPP and R-NPP, in proportion to the three origins of nitrates in nutrient uptake.

Total nutrient uptake occurs as a sequence of RO-NPP, SO-NPP and R-NPP with time (Figure 8 (a)). This time sequence is categorized into three stages by the primary origin of nitrate: RO-nitrate as the first stage (Day 0 to 7), SO-nitrate as the second stage (Day 8-19), and R-nitrate as its final stage (after Day 20). RO-NPP and SO-NPP decrease gradually in order, and are replaced by R-NPP. After Day 40, total NPP consists only of R-NPP.

D-U Shift can be explained by the shift of nitrate origins as the geographically different sources. D-U Shift is observed in total NPP (Figure 9 (a)). The maximum of total NPP located in downstream region is mainly made up of the RO-NPP in the first stage (Day 2 and 6 in Figure 9 (b)), which is caused by nitrate-rich freshwater spreading

from the river mouth and transported to downstream by the anticyclonic gyre. There is a small area where the SO-NPP is less than that in the no flux-case in the first stage (the purple-colored region in Day 2 in Figure 9 (c)), due to the spread of discharged water without phytoplankton near the river mouth. In the second stage (after Day 6), the SO-NPP mainly appears in the upstream region. The bloom in the upstream region is dependent on SO-NPP associated with upwelling, as discussed in the previous section (Figure 10). In general, the R-NPP gradually increases where the concentration of phytoplankton is high. Therefore, the distribution of R-NPP follows the plankton bloom with D-U Shift (Figure 9 (d)): the R-NPP maxima are located in the downstream region in Day 10, and shifts to the upstream region in Day 22. As a result, D-U Shift is induced by the different nitrate origins: RO-nitrate in downstream at the first stage, SO-nitrate at the second, and SO- and R-nitrates in the upstream region.

The accumulated RO-, SO-, and R-NPP until Day 40 are 0.84, 1.26, and 1.42, respectively, to the total amount of river nitrate input. It is interesting that SO-NPP is 1.5 times larger than RO-NPP, *i.e.*, NPP in ROFI is maintained not only by RO-nitrate but also by SO-nitrate which is transported by vertical circulation, also with R-nitrate.

4.2 The case of freshwater flux without nutrient input

Even without a nutrient input, a phytoplankton bloom occurs caused by the vertical circulation (Figure 8 (b)), although the NPP maximum is less than that in the control case. Note that SO-NPP is also smaller than that in the control case, because the vertical circulation is the same as the control case but the phytoplankton concentration

is lower. R-NPP is also less than that in the control case. The R-NPP is greater than the SO-NPP after Day 26 (Figure 8 (b)).

We found no local maximum NPP in the downstream region without nutrient discharge from river. That is, the local maximum of NPP is located in the upstream region all the time with a gradual propagating towards the more upstream region with time (Figure 11 (a)). Total NPP almost consists of SO-NPP until Day 14 (Figure 11 (a), (b)). High R-NPP domain appears after Day 10 due to R-nitrate increased by biological production where NPP is high at that time or was 4-5 days before that time, and propagates with time in the upstream region (Figure 11 (c)). Comparing these results with those in the control case, the phytoplankton bloom in the first stage of D-U Shift is made by nutrient-rich water input from the river mouth. Even without nutrient input, however, vertical circulation and anticyclonic gyre make propagation of NPP distributions in the second stage of D-U Shift.

4.3 The difference between long and short durations of river discharge

Rivers in the subarctic zone often have flooding due to snowmelt and heavy rain in spring. D-U Shifts in the long-term input case are much slower than that in the control case (Figure 12 (a), (b)). In the case of long-term input, river input keeps a quasi-steady large flow until Day 40. The anticyclonic gyre expands bigger and propagates toward a more upstream region than those in the control case. In the near coast upstream region, the gyre has the along coastal flows to the upstream (*e.g.* Figure 9 in McCreary *et al.*, 1997), and therefore river water is transported towards the upstream region via turned to the left at the river mouth ('initial left turn'). Total NPP

is slowly increasing in the long-term input case (Figure 8 (c)), compared with that in the control case. The steady river input produces a gradual increase in RO-NPP, and the development of vertical circulation leads to a gradual increase in SO-NPP. Therefore, the phytoplankton maxima are smaller than that in the control case, but the duration of bloom is longer.

NPP is higher in upstream region than that in downstream, and high NPP domain is spreading towards a more upstream region with time (Figure 12 (a)). The initial left turn transports RO-nitrate to the upstream region, where NPP increases. As a result, the total accumulated NPPs in the long-term input case are higher in the upstream region (red-shaded) and lower in the downstream region (blue-shaded) than those in the control case, although these differences are small, about 5~7 % at most (Figure 12 (c)).

4.4 Introducing Suspended Sediment Matter (SSM) from river

What kind of impact does SSM have on the marine ecosystem in ROFI? SSM is introduced with freshwater input from river, and removed SSM from the water column for 1 day, as an example of the middle removal time of parameters (0.5 to 2 day). High concentrations of SSM tend to shade sunlight and prevent phytoplankton from photosynthesis, as mentioned in the introduction.

During the first week (Day 0 to Day 8), NPP in SSM case is significantly lower than that of the no flux-case (Figure 8 (d)). This is because river-originated water with SSM spreads over the sea surface near the river mouth and covers phytoplankton already existing in the subsurface water. As a result, NPP in SSM case is low due to the effect of shading sunlight. The shift of the maximum peak of phytoplankton

concentration to the upstream is delayed compared to that of the control case (Figure 13 (a), (b)), and the maximum peak arrives at the upstream region on day 24 (not shown). D-U Shift also occurs in the SSM case, but the shift differs from the control case as follows. As shown in Figure 8 (d), phytoplankton mainly utilize RO-nitrate, and do not exhaust it until the concentration of SSM is very low (Figure 14). Therefore, the duration of the first stage in D-U Shift is extended by around 4 days, and the situation of the high phytoplankton concentration in the downstream region is also kept for more days (Figure 13 (a)). Sunlight shading occurs due to high concentration of SSM (Day 2 and Day 6 in Figure 14 (a)). The surface concentration of phytoplankton is lower than that of the no flux-case near the river mouth and in the downstream region (Day 2), and the relatively low region (*i.e.*, the concentration of phytoplankton is lower than that of the no flux-case) spreads towards a more downstream region in Day 6. In Figure 14 (a) during Day 2 to Day 6, the domain where light reaches deeper (A-region; yellow~green) occurs surrounded by high shading domain (B-region; blue~purple), because the subsurface clear water comes due to strong upwelling. After Day 14, the small shading domain remains close to the river mouth associated with the high concentration of SSM in river water. The area where the phytoplankton concentration is higher than $0.25 \mu\text{gchl-a/l}$ (light red in Figure 13) is smaller than that in the control case, but the bloom duration is longer and D-U Shift is delayed, as increasing rate of NPP in the surface is also slow.

We estimated how the removal time of SSM from sea water impacts the phytoplankton bloom in ROFI. As SSM removal time increases, NPP decreases because SSM inhibits photosynthesis. Thus when τ in equation (2) is longer, SSM settles out much

later, the time to recover from the low NPP is delayed more, and the peak of the plankton bloom is delayed (Figure 15).

5. Conclusion and Remarks

In this study, we incorporated a simple ecosystem into an OGCM to investigate three-dimensional and temporal variations of plankton bloom in ROFI. Nutrient-rich river discharge drives phytoplankton bloom in ROFI. River also indirectly supplies nutrients with saline water from the subsurface to the surface by vertical circulation driven by the freshwater input.

The direct and indirect nutrient supplies produce the shift of phytoplankton maximum concentration from downstream to upstream regions (D-U Shift). D-U Shift is categorized into three stages by the different nitrate origins as follows: (1) phytoplankton increases using river-originated nitrate in downstream, (2) after river-originated nitrate is exhausted, phytoplankton increases mainly using subsurface-originated nitrate in the upstream region, where nitrate is supplied by the upwelling as a part of vertical circulation associated with horizontal anticyclonic gyre, and (3) after subsurface-originated nitrate is also exhausted, NPP (Net Primary Production) is kept high by regenerated nitrate in upstream region.

In the case of freshwater input without nutrient, the maximum peak of phytoplankton concentration in the downstream part of D-U Shift does not occur, although a weak phytoplankton bloom occurs. Nutrient-rich water input has a significant impact on phytoplankton bloom in the first stage of D-U Shift. The buoyant flows due to

freshwater input play an important role in the second stage. The vertical circulation by buoyant flows generates the upwelling from the nutrient-rich subsurface layer.

Recent simulation studies of global warming scenarios suggest that freshwater flux from rivers in the world would have greater fluctuations in magnitude (*e.g.*, Nijssen *et al.*, 2001). Future studies are needed to investigate how variations of freshwater flux change plankton blooms by flooding in upstream regions of ROFI.

Effects of tide and background flow were not included in this study. If tide was included, the D-U Shift would have a shorter distance but this phenomenon remains. This is because tide horizontally suppresses river plume spreading and propagating towards the upstream (Figure 13 in Isobe, 2005). Tide also vertically advances mixing between riverine and subsurface waters. If tide was included, NPP would be higher. As the sensitivity of tide and background flow much depends on each region, we need the observation data *in situ* about tides and background flows in order to conduct more realistic simulations in specific ROFI.

Acknowledgements

We deeply thank to Dr. Genta Mizuta of the Faculty of Environmental Earth Science, Hokkaido University for helping with the model settings and discussions. We are very grateful to Dr. Atsushi Kubokawa, Dr. Isao Kudo and Dr. Tomohisa Irino of the Faculty of Environmental Earth Science, Hokkaido University for discussing the physics of river plumes, advising on biogeochemical cycle in ROFI and providing the information on empirical coefficients in Tokachi River, respectively. We would also like to thank to Dr. Yutaka Isoda of the Faculty of Fisheries Sciences, Hokkaido University for

392 discussing the physics of ROFI. Yasuhiro Hoshiba was supported by the Grant-in-Aid
393 for the Global COE Program from MEXT and by Development of mitigation and
394 adaptation techniques to global warming in the sectors of agriculture, forestry, and
395 fisheries as a research assistant. Yasuhiro Yamanaka was also supported by Core
396 Research for Evolutional Science and Technology (CREST), Japan Science and
397 Technology Agency (JST).

398

References

- Agboola, J. I., S. Yoshi and I. Kudo (2009): Seasonal change of riverine nutrients and distribution of chlorophyll a in Ishikari Bay, subarctic oligotrophic coastal environment of Japan. *La mer*, **47**, 1-17.
- Beardsley, R. C., R. Limeburner, D. Hu, K. Le and G. A. Cannon (1985): Discharge of the Changjiang (Yangtze River) into the East China Sea. *Cont. Shelf Res.*, **4**, 57–76.
- Beman, J. M., K. R. Arrigo and P. A. Matson (2005): Agricultural runoff fuels large phytoplankton blooms in vulnerable areas of the ocean. *Nature*, **434**, 211-214.
- Bowden, K. F. (1983): Physical Oceanography of Coastal Waters. *John Wiley*, 302 pp.
- Chapman, D. C. and S. J. Lentz (1994): Trapping of a coastal density front by bottom boundary layer. *J. Phys. Oceanogr.*, **24**, 1464–1479.
- Chao, S.-Y. and W. C. Boicourt (1986): Onset of estuarine plumes. *J. Phys. Oceanogr.*, **16**, 2137–2149.
- Costanza, R., R. d’Arge, R. de Groot, S. Farber, M. Grasso, B. Hannon *et al.* (1997): The value of the world’s ecosystem services and natural capital. *Nature*, **387**, 253-260.
- Garvine, R. W. (2001): The impact of model configuration in studies of buoyant coastal discharge. *J. Mar. Res.*, **59**, 193-225.
- Griffies, S. M. and R. W. Hallberg (2000): Biharmonic friction with a Smagorinsky-like viscosity for use in large-scale eddy-permitting ocean models. *Mon. Wea. Rev.*, **128**, 2935–2946.
- Hasumi, H. (2002): Sensitivity of the global thermohaline circulation to interbasin freshwater transport by the atmosphere and the Bering Strait throughflow. *J.*

423 *Climate*, **15**, 2516-2526.

424 Ileva, N. Y., H. Shibata, F. Satoh, K. Sasa and H. Ueda (2009): Relationship between the
425 riverine nitrate-nitrogen concentration and the land use in the Teshio River
426 watershed, North Japan. *Sustain. Sci.*, **4**, 189-198.

427 Isobe, A. (2005): Ballooning of river-plume bulge and its stabilization by tidal currents.
428 *J. Phys. Oceanogr.*, **35**, 2337-2351.

429 Kaiser, M. J., M. J. Attrill, S. Jennings, D. N. Thomas, D. K. A. Barnes, A. S. Brierley,
430 J. G. Hiddink, H. Kaartokallio, N. V. C. Polunin and D. G. Raffaelli (2005):
431 Marine Ecology: Processes, Systems, and Impacts. *Oxford Univ. Press*, 501 pp.

432 Kubokawa, A. (1991): On the behavior of outflows with low potential vorticity from a
433 sea strait. *Tellus*, **43A**, 168-176.

434 Kudo, I., T. Yoshimura, C. W. Lee, M. Yanada and Y. Maita (2007): Nutrient
435 regeneration at bottom after a massive spring bloom in a subarctic coastal
436 environment, Funka Bay, Japan. *J. Oceanogr.*, **63**, 791-801.

437 Kusuda, T. (2003): Aquatic environment in estuaries (*in Japanese*). Journal of Japan
438 River Association 'KASEN', **680**, 20-26.

439 Kusuda, T., K. Koga and Y. Awaya (1978): Aggregation of clay particles in salty water
440 (*in Japanese*). *Journal of Water and Waste*, **20**, 295-300.

441 Le, V. S., T. Yamashita, T. Okunishi, R. Shinohara and M. Miyatake (2006):
442 Characteristics of suspended sediment material transport in the Ishikari Bay in
443 snowmelt season. *Applied Ocean Res.*, **28**, 275-289.

444 Leonard, B. P. (1979): A stable and accurate convective modeling procedure based
445 upon quadratic upstream interpolation. *Comput. Methods Appl. Mech. Eng.*, **19**,
446 59-98.

447 Leonard, B. P., M. K. MacVean and A. P. Lock (1993): Positivity-preserving numerical
 448 schemes for multidimensional advection. *NASA Tech. Memo.* 106055, 62 pp.
 449 Lihan, T., S. Saitoh, T. Iida, T. Hirawake and K. Iida (2008): Satellite-measured
 450 temporal and spatial variability of the Tokachi River plume. *Estuar., coast.*
 451 *shelf sci.*, **78**, 237-249.
 452 Magome, S. and A. Isobe (2003): Current structure and behavior of the river plume in
 453 Suo-Nada. *J. Oceanogr.*, **59**, 833-843.
 454 Matano, P. R. and E. D. Palma (2010): The upstream spreading of bottom-trapped
 455 plumes. *J. Phys. Oceanogr.*, **40**, 1631-1650.
 456 McCreary, J. P., S. Zhang and S. R. Shetye (1997): Coastal circulations driven by river
 457 outflow in variable-density 1½-layer model. *J. Geophys. Res.*, **102**,
 458 15535-15554.
 459 Murty, V. S. N., Y. V. B. Sarma, D. P. Rao and C. S. Murty (1992): Water
 460 characteristics, mixing and circulation in the Bay of Bengal during southwest
 461 monsoons. *J. Mar. Res.*, **50**, 207–228.
 462 Nijssen, B., G. M. O'Donnell, A. F. Hamlet and D. P. Lettenmaier (2001): Hydrologic
 463 sensitivity of global rivers to climate change. *Climatic Change*, **50**, 143-175.
 464 Nof, D. and T. Pichevin (2001): The ballooning of outflows. *J. Phys. Oceanogr.*, **31**,
 465 3045-3058.
 466 Pimenta, F. M., A. D. Kirwan and P. Huq (2011): On the transport of buoyant coastal
 467 plumes. *J. Phys. Oceanogr.*, **41**, 620-640.
 468 Piola, A. R., S. I. Romero and U. Zajaczkovski (2008): Space-time variability of the
 469 Plata plume inferred from ocean color. *Cont. Shelf Res.*, **28**, 1556–1567.
 470 Rattray, M. and D. V. Hansen (1962): A similarity solution for circulation in an estuary.

471 *J. Mar. Res.*, **20**, 121-133.

472 Simpson, J. H. (1997): Physical processes in the ROFI regime. *J. Mar. Systems*, **12**,
 473 3-15.

474 Tachibana, H., K. Yamamoto, K. Yoshizawa and Y. Magara (2001): Non-point
 475 pollution of Ishikari River, Hokkaido, Japan. *Water Sci. and Technol.*, **44(7)**,
 476 1-8.

477 Tsujino, H., H. Hasumi and N. Suginohara (2000): Deep pacific circulation controlled
 478 by vertical diffusivity at the lower thermocline depths. *J. Phys. Oceanogr.*, **30**,
 479 2853-2865.

480 Usui, T., S. Nagao, M. Yamamoto, K. Suzuki, I. Kudo, S. Montani, A. Noda and M.
 481 Minagawa (2006): Distribution and sources of organic matter in surficial
 482 sediments on the shelf and slope off Tokachi, western North Pacific, inferred
 483 from C and N stable isotopes and C/N ratios. *Mar. Chem.*, **98**, 241-259.

484 Walker, N. D., G. S. Fargion, L. J. Rouse and D. C. Biggs (1994): The great flood of
 485 summer 1993: Mississippi River discharge studied. *EOS Trans. AGU*, **75**, 409.

486 Weingartner, T. J., S. Danielson, Y. Sasaki, V. Pavlov and M. Kulakov (1999): The
 487 Siberian Coastal Current: A wind and buoyant-forced Arctic coastal current. *J.*
 488 *Geophys. Res.*, **104**, 29697–29713.

489 Yamamoto, T. and T. Hashimoto (2007): Estuarine circulation and primary production
 490 (in Japanese with English abstract). *Bull. Coast. Oceanogr.*, **44**, 137-145.

491 Yankovsky, A. E. (2000): The cyclonic turning and propagation of buoyant coastal
 492 discharge along the shelf. *J. Mar. Res.*, **58**, 585–607.

493 Yoshikawa, C., Y. Yamanaka and T. Nakatsuka (2005): An ecosystem model including
 494 nitrogen isotopes: perspectives on a study of the marine nitrogen cycle. *J.*

495 *Oceanogr.*, **61**, 921-942.

496 Yoshimura, T. and I. Kudo (2011): Seasonal phosphorus depletion and microbial
497 response to the change in phosphorus availability in a subarctic coastal
498 environment. *Mar. Chem.*, **126**, 182-192.

499 A-line data home page by Fisheries Research Agency, Hokkaido and Tohoku Institute.
500 http://hnf.fra.affrc.go.jp/a-line/data/nutri/Data_aline0001-0710.csv.
501 Accessed 28 September 2012

502 Tokachi River discharge from Water Information System. Ministry of Land,
503 Infrastructure and Transport, Japan.
504 [http://www1.river.go.jp/cgi-bin/DspWaterData.exe?KIND=7&ID=3010812811](http://www1.river.go.jp/cgi-bin/DspWaterData.exe?KIND=7&ID=301081281107070&BGNDATE=20060131&ENDDATE=20061231&KAWABOU=NO)
505 07070&BGNDATE=20060131&ENDDATE=20061231&KAWABOU=NO.
506 Accessed 14 September 2012

507

508

509 Table 1. Biological parameters.

$V_{\max}$	Phytoplankton Maximum Photosynthetic Rate at 0°C	0.5	/day
K_{NO_3}	Phytoplankton Half Saturation Constant for Nitrate	2	$\mu\text{molN/l}$
k	Phytoplankton Temperature Coefficient for Photosynthesis	0.0693	/°C
I_{opt}	Phytoplankton Optimum Light Intensity	104.7	W/m^2
M_{p0}	Phytoplankton Mortality Rate at 0°C	0.04375	$1/\mu\text{molN/day}$
k_{Mp}	Phytoplankton Temperature Coefficient for Mortality	0.0693	/°C
R_{p0}	Phytoplankton Respiration Rate at 0°C	0.03	/day
k_{R}	Phytoplankton Temperature Coefficient for Respiration	0.0519	/°C
γ	Phytoplankton Ratio of Extracellular Excretion to Photosynthesis	0.135	(nodim.)
G_{Rmax}	Zooplankton Maximum Grazing Rate at 0°C	0.3	/day
k_{G}	Zooplankton Temperature Coefficient for Grazing	0.0693	/°C
l	Zooplankton Ivlev Constant	1.4	$1/\mu\text{molN}$
P_{Z}^*	Zooplankton Threshold Value for Grazing	0.04	$\mu\text{molN/l}$
α	Zooplankton Assimilation Efficiency	0.7	(nodim.)
β	Zooplankton Growth Efficiency	0.3	(nodim.)
M_{z0}	Zooplankton Mortality Rate at 0°C	0.0585	$1/\mu\text{molN/day}$
k_{Mz}	Zooplankton Temperature Coefficient for Mortality	0.0693	/°C
α_1	Light Dissipation Coefficient of Sea Water	0.04	/m
α_2	Self Shading Coefficient	0.04	$1/\mu\text{molN/m}$
α_{SSM}	Shading Coefficient due to SSM	0.6	m^2/g
S_{DET}	DET Sinking Velocity	20	m/day
V_{DN0}	Remineralization Rate of DET to Nitrate at 0°C	0.2	/day
K_{DN0}	Temperature Coefficient for DET Remineralization to Nitrate	0.0693	/°C

510 All values are based on those of Yoshikawa *et al.* (2005), except α_{SSM} is newly
511 introduced in this study.

512

513

514 Table 2.

Experiment No.	1	2	3	4	5
Name	control	no flux	only fresh water	long-term input	SSM
Freshwater input	Yes	No	Yes	Yes	Yes
Nutrient input	Yes	No	No	Yes	Yes
SSM input	No	No	No	No	Yes
Duration of discharge	2 days	-	2 days	40 days	2 days

515

Figure Captions

Fig. 1 River discharge at Moiwa near the river mouth of the Tokachi River in Hokkaido, Japan observed in 2006 (Ministry of Land, Infrastructure and Transport, Japan: <http://www1.river.go.jp/>).

Fig. 2 Horizontal geography and vertical topography used in the model. The width of the river mouth is about 3km, the depth of ocean floor varied from 30 m near shore to 200 m in the offshore area. The dashed area shows the area drawn in figures 5, 6, 8, 9, 11, 13, 15 and 16.

Fig. 3 Schematic view of interactions among the four components. The symbol NUT indicates the nitrate concentration, PHY phytoplankton, ZOO zooplankton and DET detritus.

Fig. 4 Initial vertical distributions of (a) NO_3^- , (b) PHY, (c) ZOO and (d) DET after Spin-up (see text for details), and (e) Temperature, T, as annually averaged at stations A1 and A2 near coast of Hokkaido measured by Fisheries Research Agency, Hokkaido Institute (FRA (2011.10.3), A-line data homepage, <http://hnf.fra.affrc.go.jp/a-line/>). PHY is drawn as chlorophyll-a unit multiplied by the nitrogen-chlorophyll ratio of 1:1.325 (from nitrogen unit used in the model).

Fig. 5 In the control case, the horizontal distributions of (a) salinity, (b) nitrate, (c) phytoplankton and (d) zooplankton in the surface layer (5 m depth), with current

velocity field whose vectors are drawn at intervals of five grids. Red line in (b) Day 14 shows the location of the vertical nearshore-to-offshore section detailed in Fig. 6.

Fig. 6 (a) Nitrate distribution and vertical circulation along the section shown as the red line in Fig. 5 (b) (Day 14). (b) The previous (Day 0) and post (Day 14) vertical nitrate distributions at the point near the coast along the vertical section shown in Fig. 6 (a).

Fig. 7 Simulated image of the river-plume front, upwelling region, and induced flow by horizontal anticyclonic gyre in the surface layer in the control case, respectively. The black contour shows the salinity of 34.5 g/kg at the depth of 10 m on 12 day. The regions surrounded by color contours (red; 7 day, orange; 12 day, purple; 17 day) show vertical upwelling at the depth of 10 m of over a speed of 0.001 cm/s. The arrow shows the main stream of horizontal gyre on 12 day at the depth of 5 m. Upwelling region spreads to the upstream with horizontal anticyclonic gyre propagating toward the upstream.

Fig. 8 (a) Time series of normalized Net Primary Productions, NPPs, driven by river input in the calculation domain, that is, NPPs in the control case subtracted by that in the no flux case. NPPs are categorized into three origins: river-originated (solid line), subsurface-originated (dashed line), and regenerated (dotted line) and normalized by the nitrate input, *i.e.*, nitrate of 1.0 mg/l in fresh water of 2000 m³/s in Day 1 in the control case. (b) Same as (a) except those in the only freshwater case. (c) Same as (a) except those in the long-term input case. (d) Same as (a) except those in the SSM case.

564

565 Fig. 9 Horizontal distributions of the NPPs driven by river input in the surface layer (5
566 m depth): (a) NPP, (b) River-originated NPP, (c) Subsurface-originated NPP and (d)
567 Regenerated NPP subtracted by that in the no flux-case, with current velocity field at
568 intervals of five grids. Red line in (c) Day 18 shows the location of the vertical
569 nearshore-to-offshore section detailed in Fig. 10.

570

571 Fig. 10 SO-NPP distribution subtracted by that in the no flux-case and vertical
572 circulation along the section shown as the red line in Fig. 9 (c) (Day 18).

573

574 Fig. 11 Same as Fig. 9 except NPP, Subsurface-originated NPP and Regenerated NPP
575 in the only freshwater case.

576

577 Fig. 12 Time series of NPP in (a) the long-term input case, (b) the control case, along
578 the coast with 1.5km distance with contour of velocity along the coast (solid and dashed
579 lines are toward upstream and downstream, respectively). (c) the ratio of NPP as
580 $(NPP_{\text{long-term}} - NPP_{\text{control}})/(NPP_{\text{long-term}} + NPP_{\text{control}})$ accumulated from Day 0 to Day 50,
581 where NPP_{control} is NPPs driven by river input in the control case and $NPP_{\text{long-term}}$ is
582 NPPs driven by river input in the long-term input. Red shaded area shows the NPP in
583 the long-term input is higher than that in the control case (blue shaded shows lower
584 values than the control case).

585

Fig. 13 Horizontal distributions of phytoplankton driven by river input in the surface layer (5 m depth) in (a) the SSM case and (b) the control case subtracted by that in the no flux-case, with current velocity field at intervals of five grids.

Fig. 14 Same as Fig. 13 except those in the depth of 20 % of the surface insolation. White colored area shows that light intensity on the floor has over 20% to the surface insolation.

Fig. 15 Time series of normalized NPP driven by river input in the calculation domain, changing in the SSM removal time: $\tau=0.5, 1.0, 1.5$, and 2.0 days.

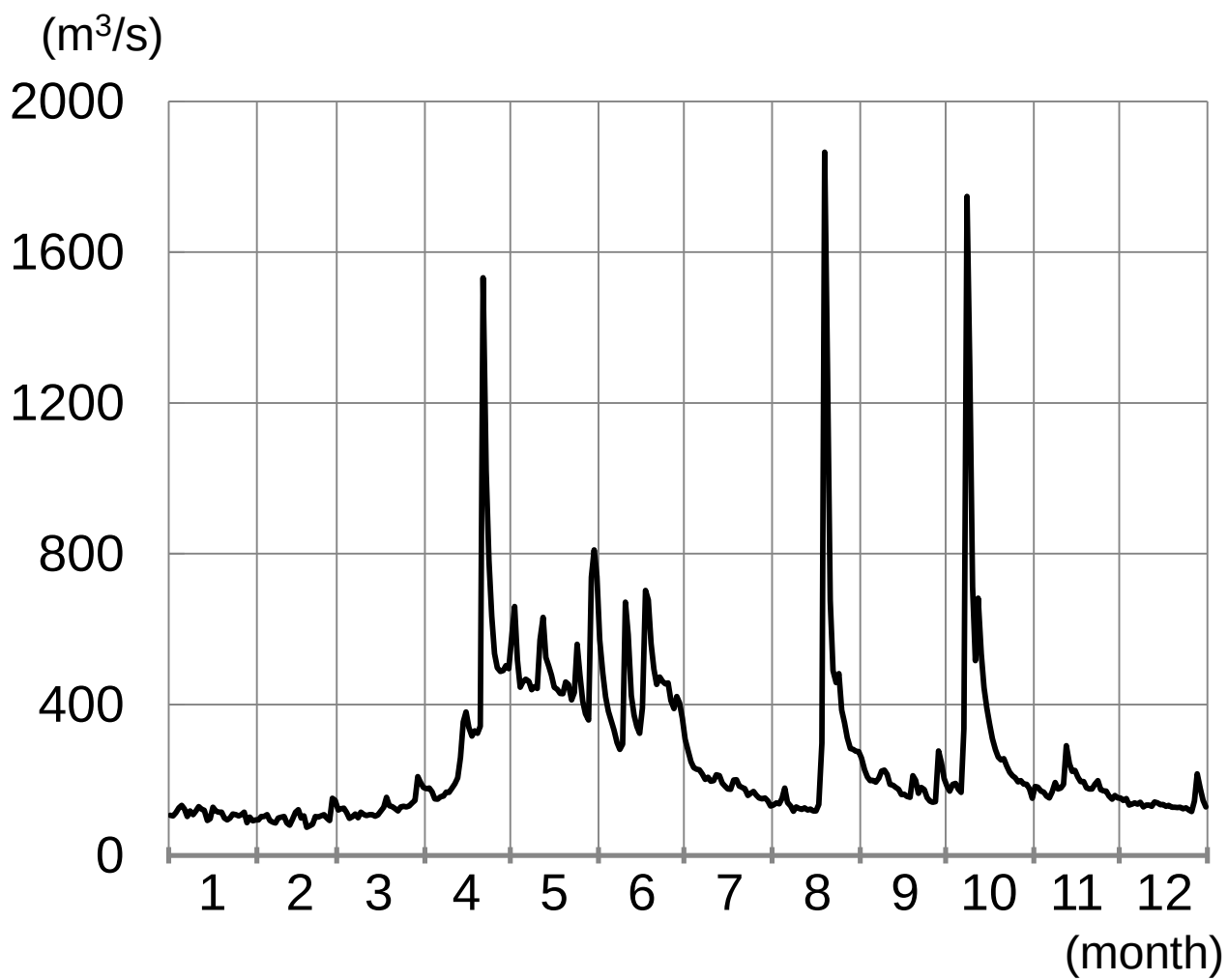


Fig.1

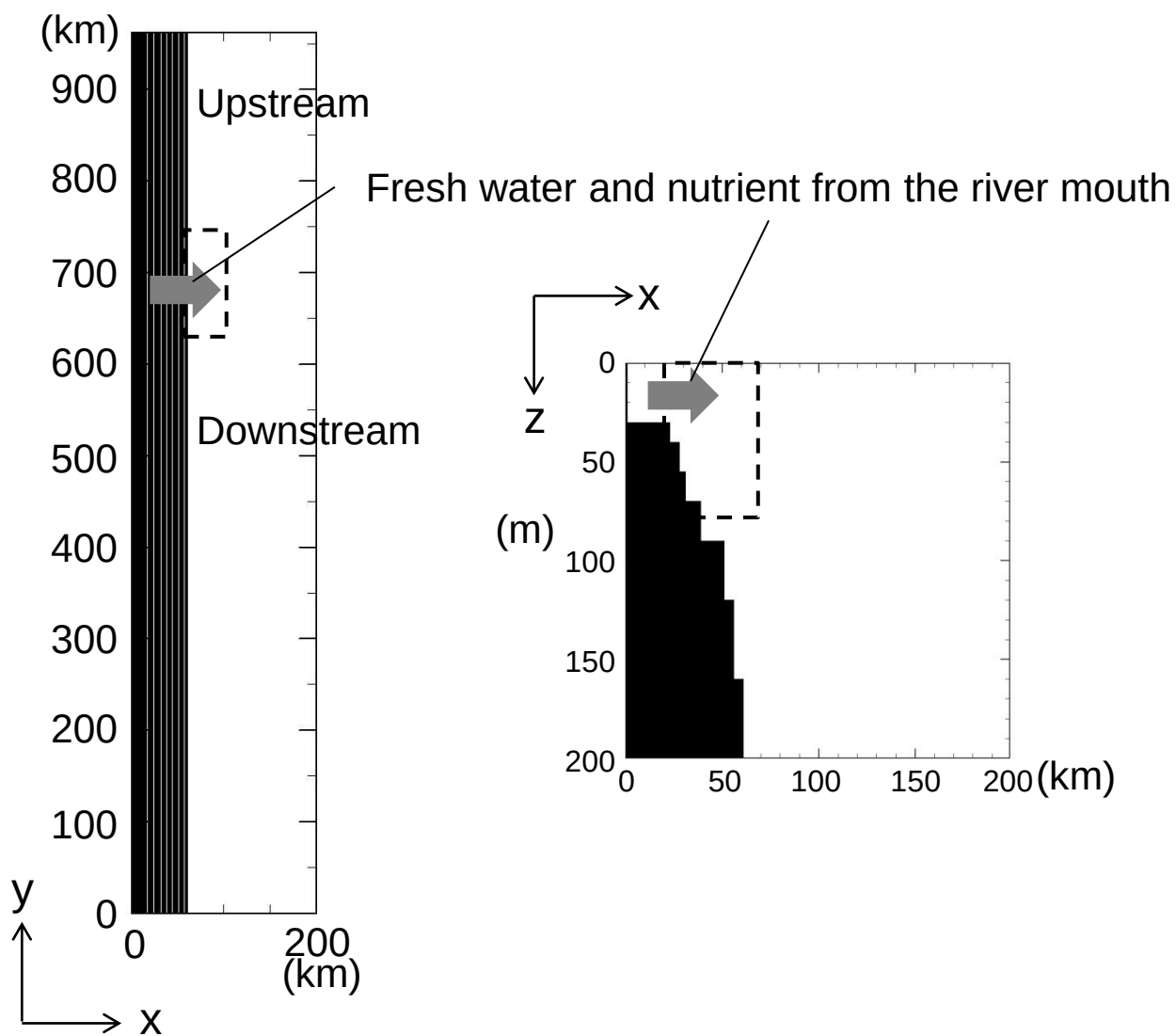


Fig.2

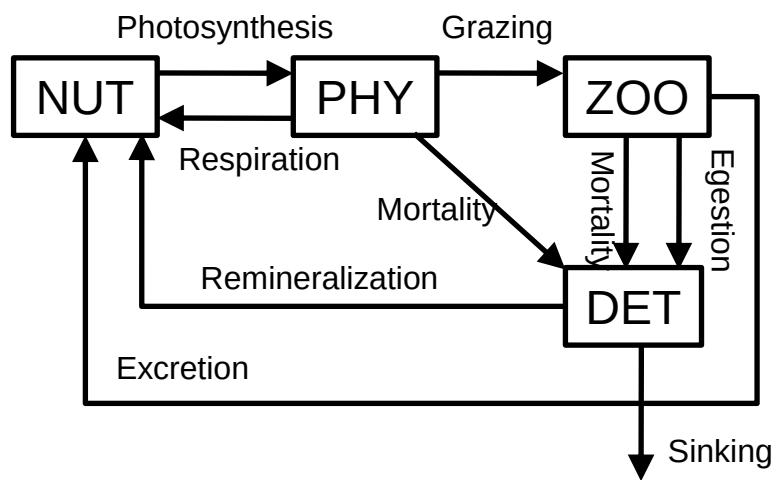


Fig.3

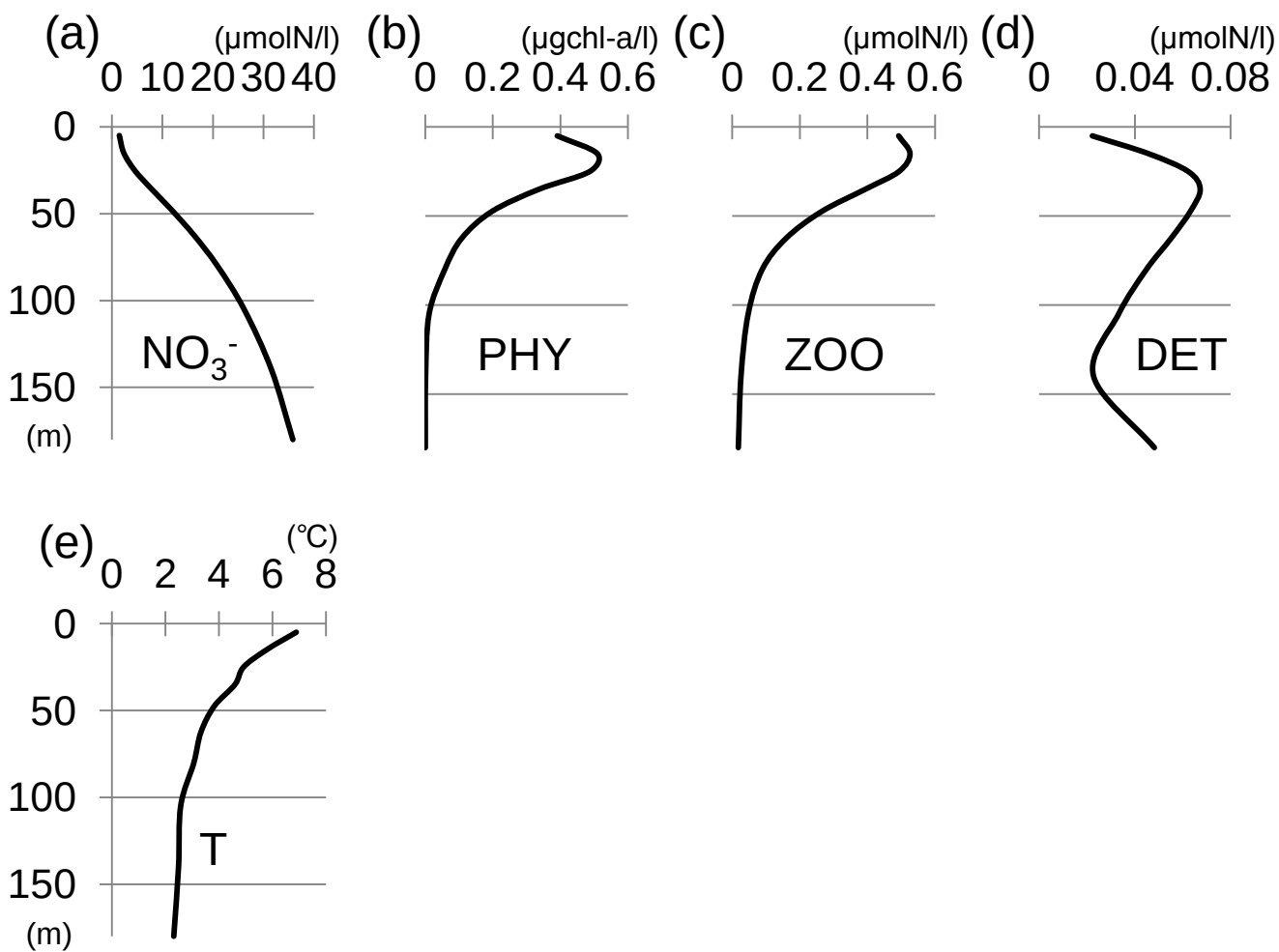
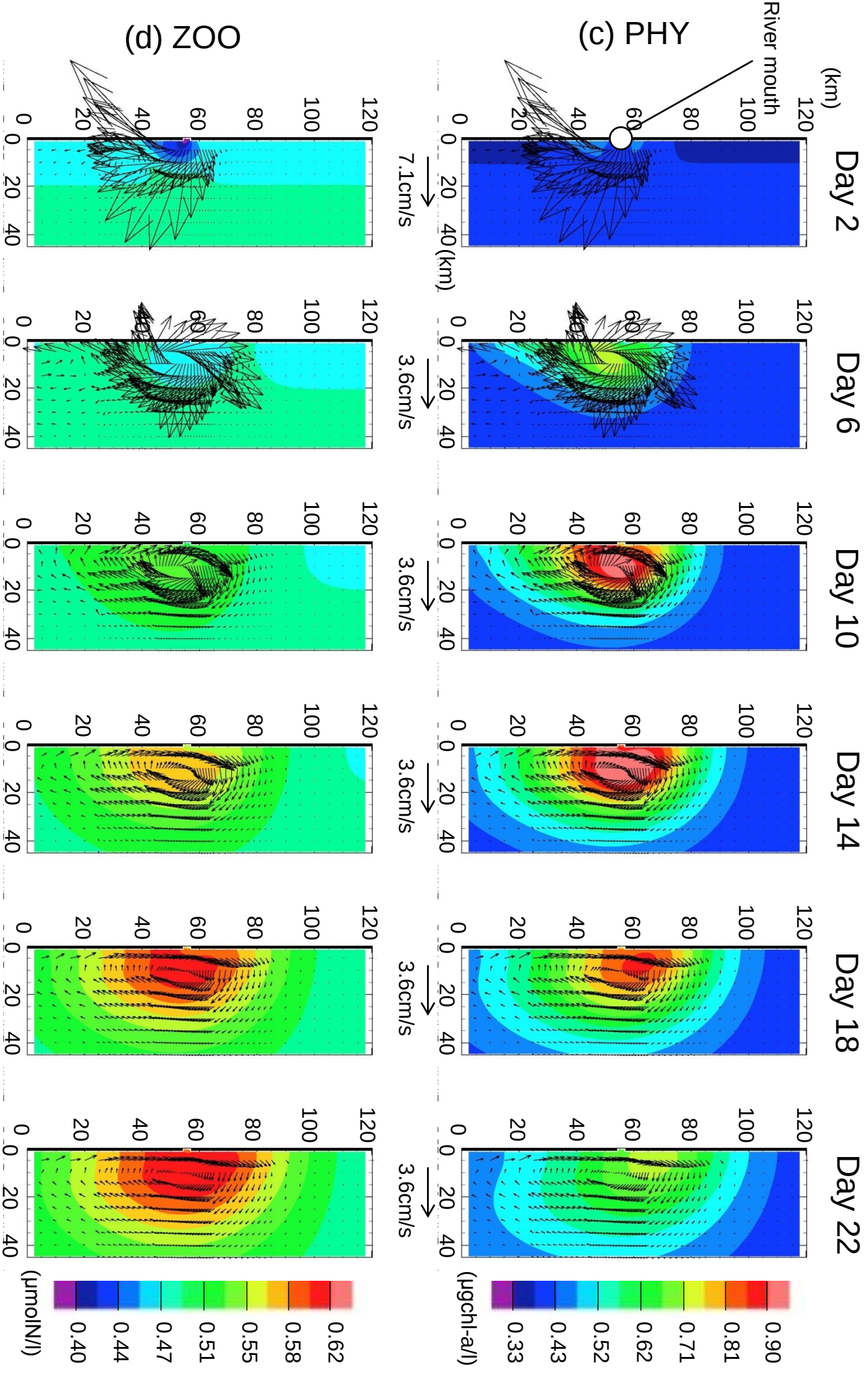


Fig.4



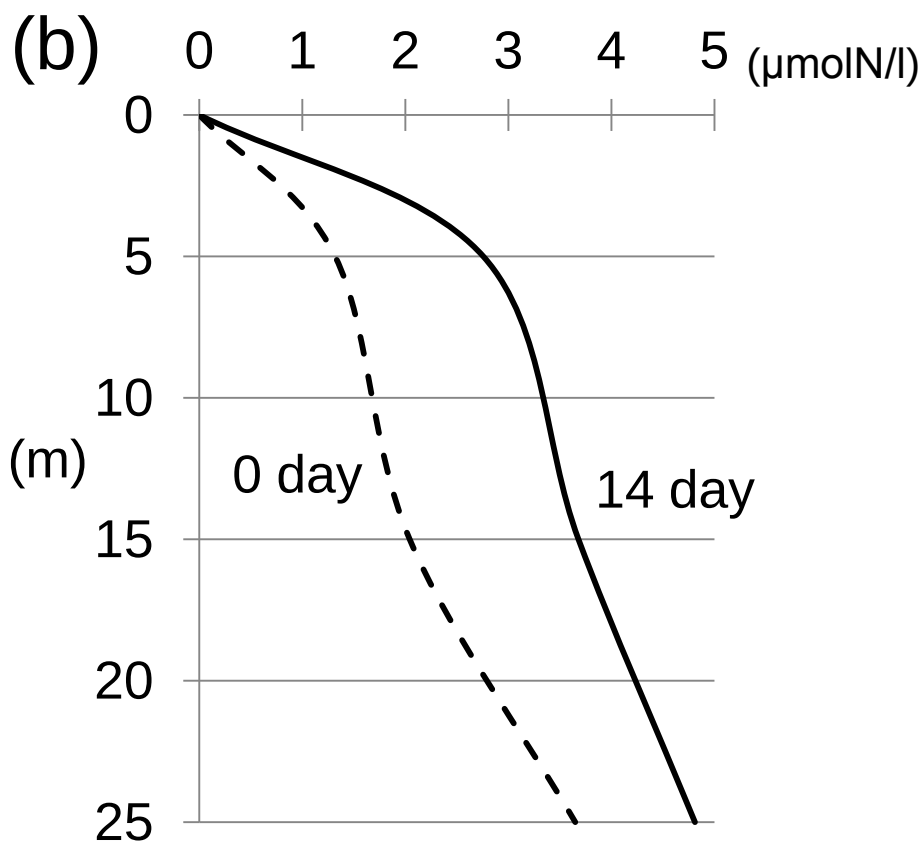
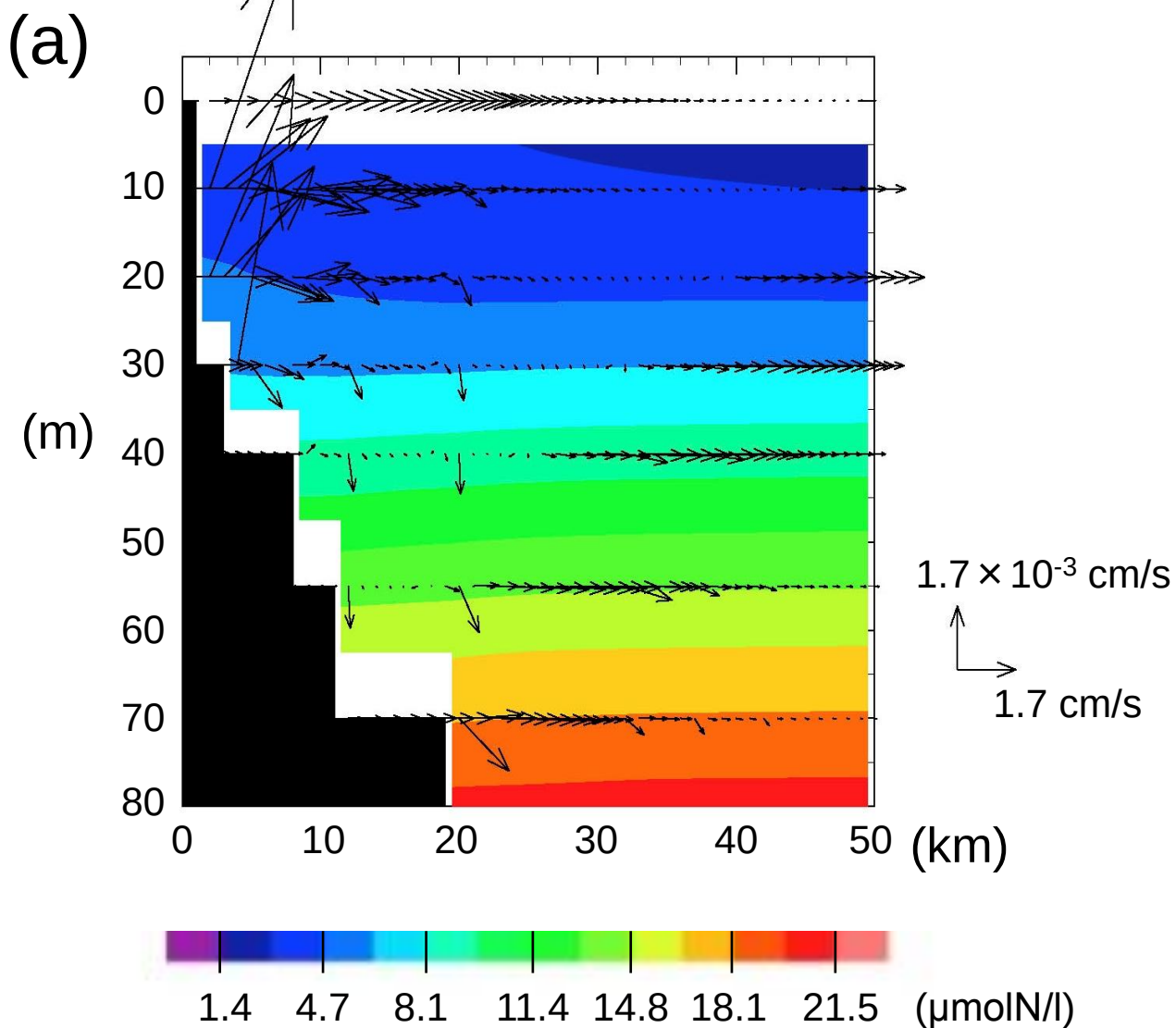


Fig.6

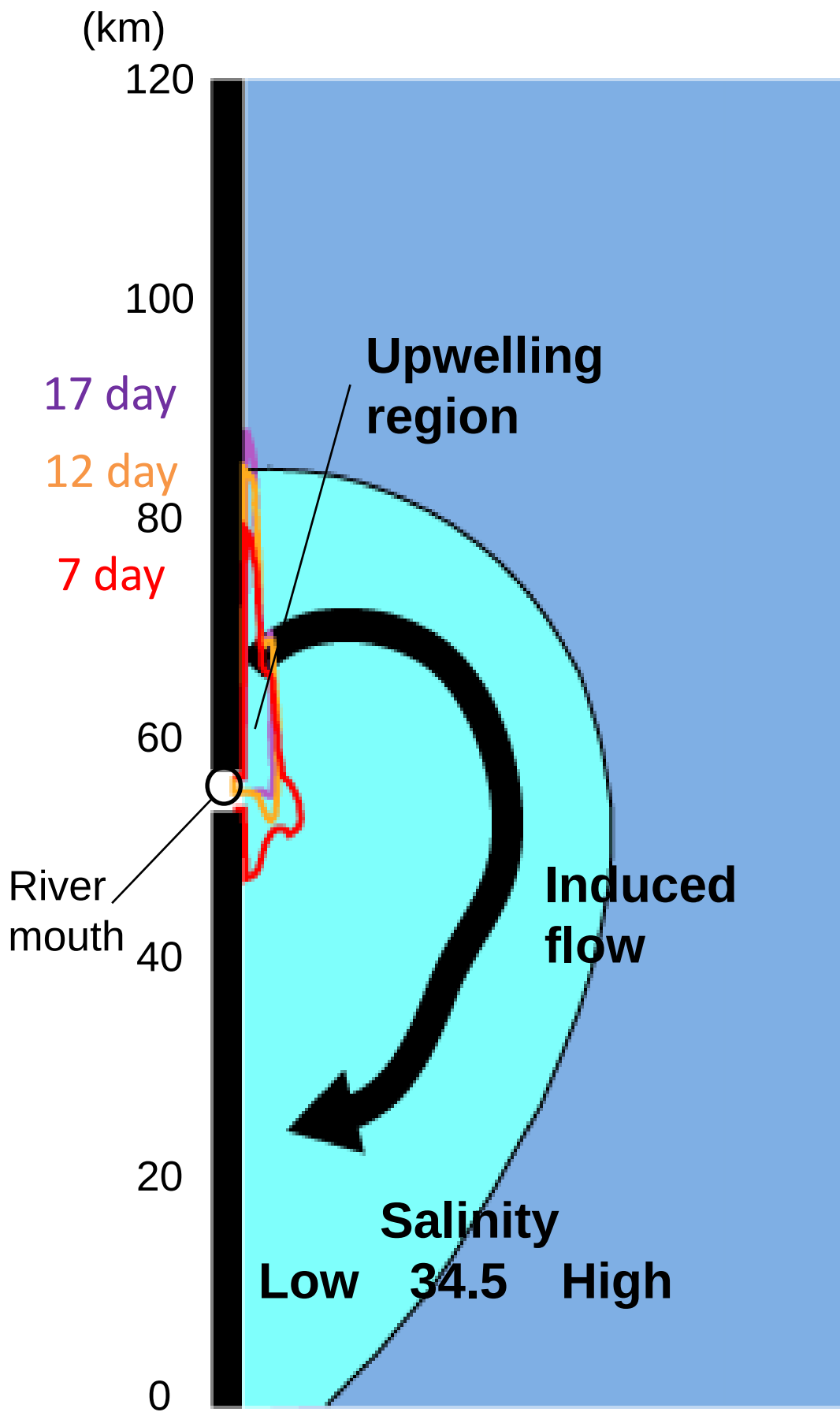
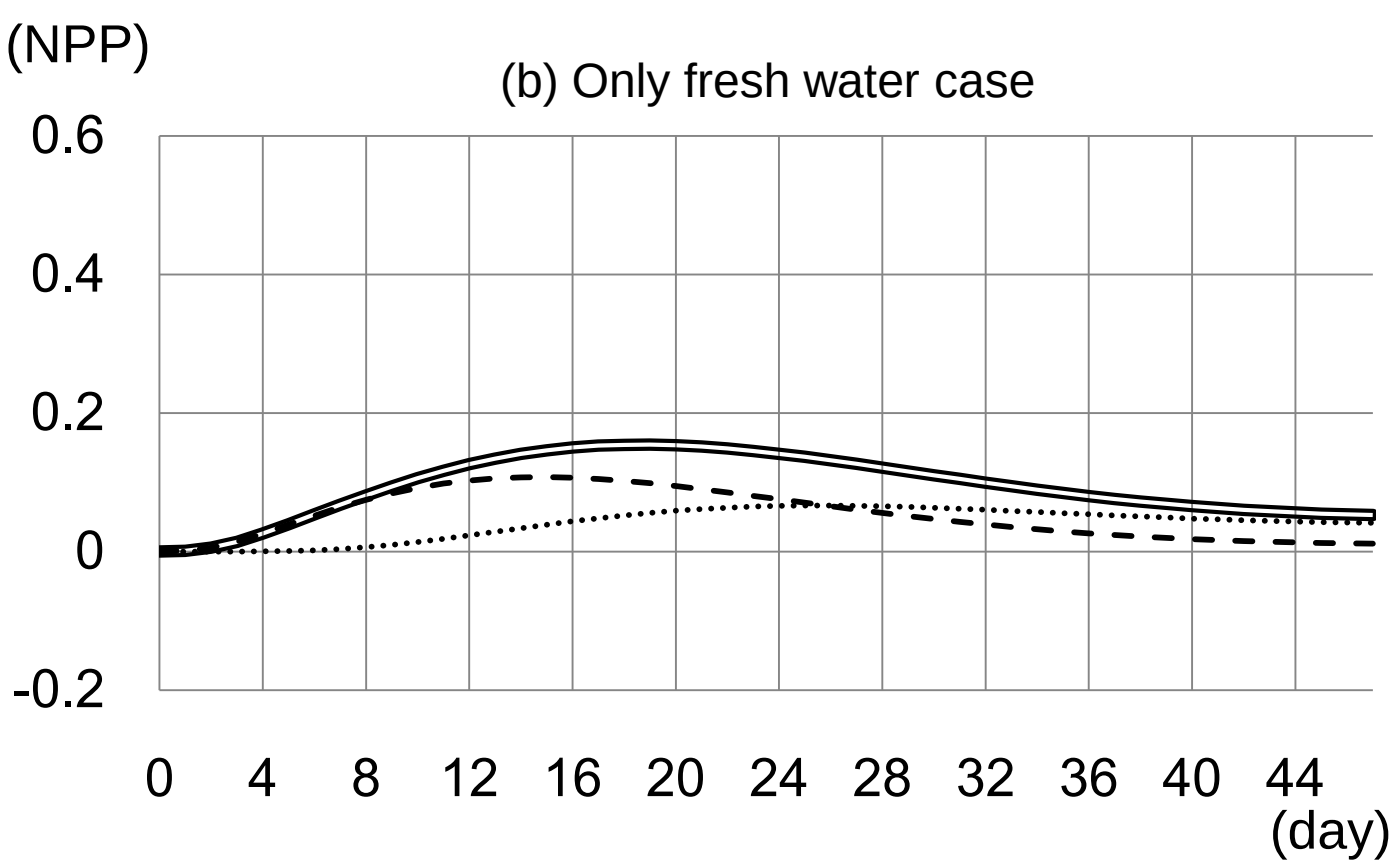
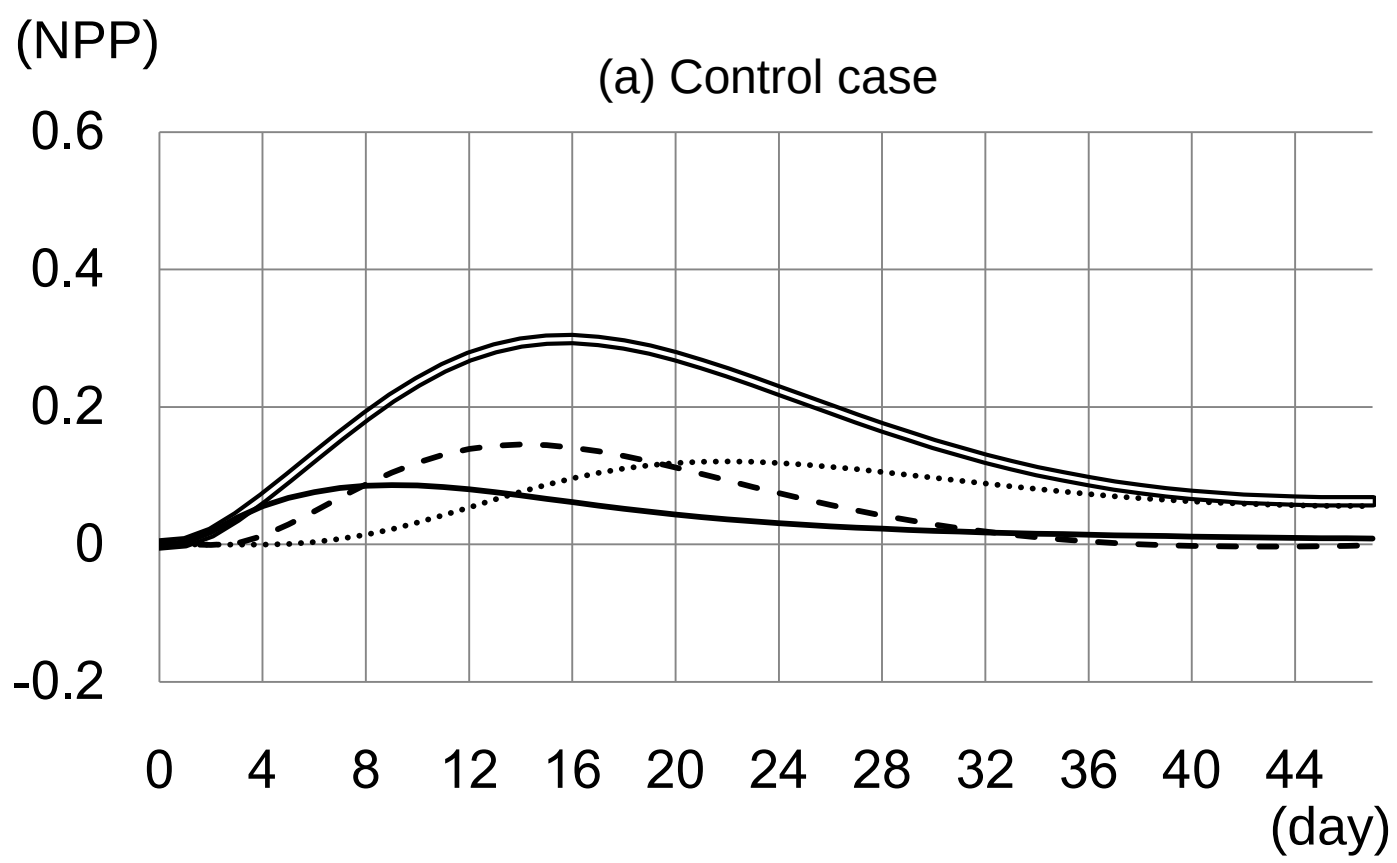
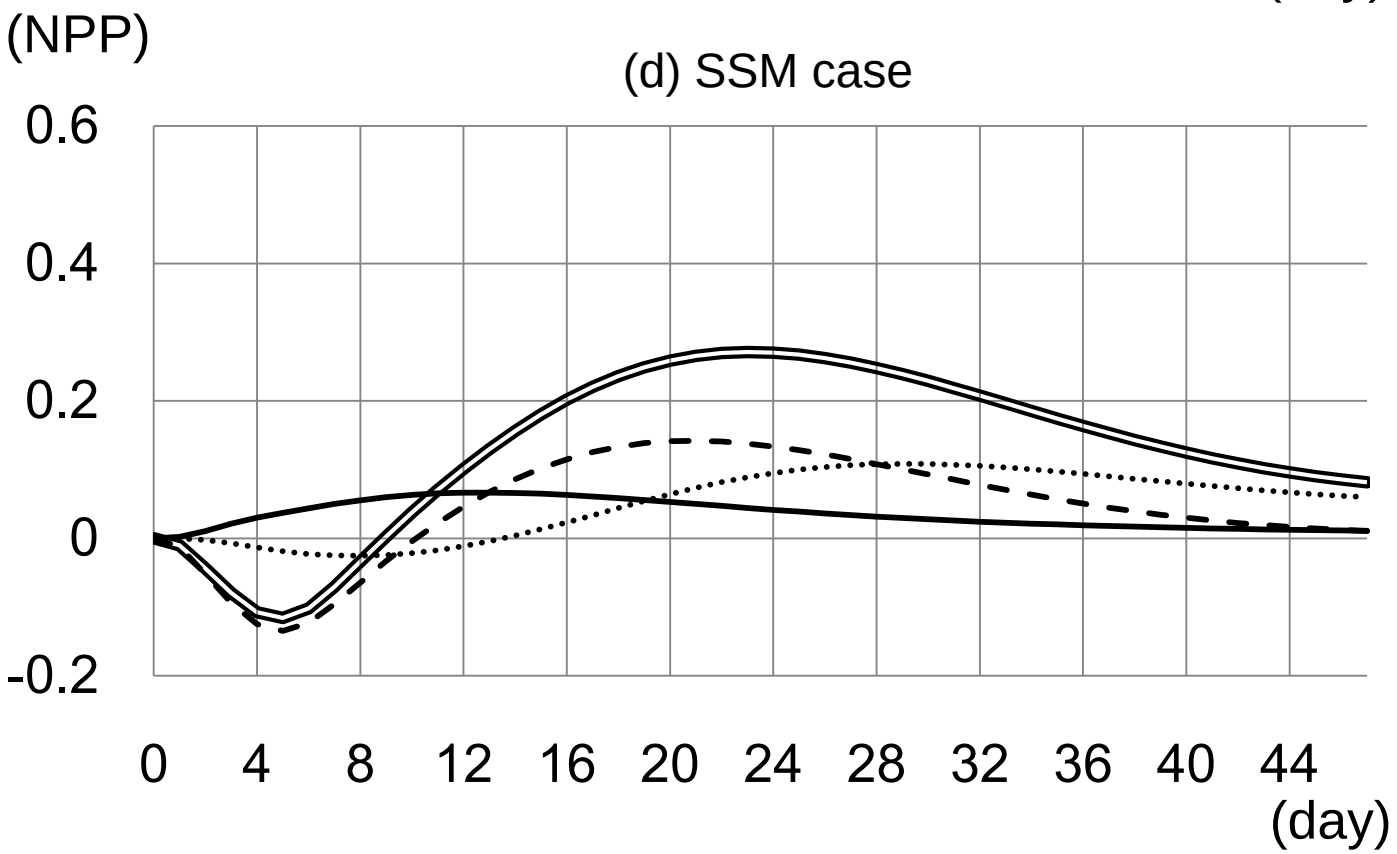
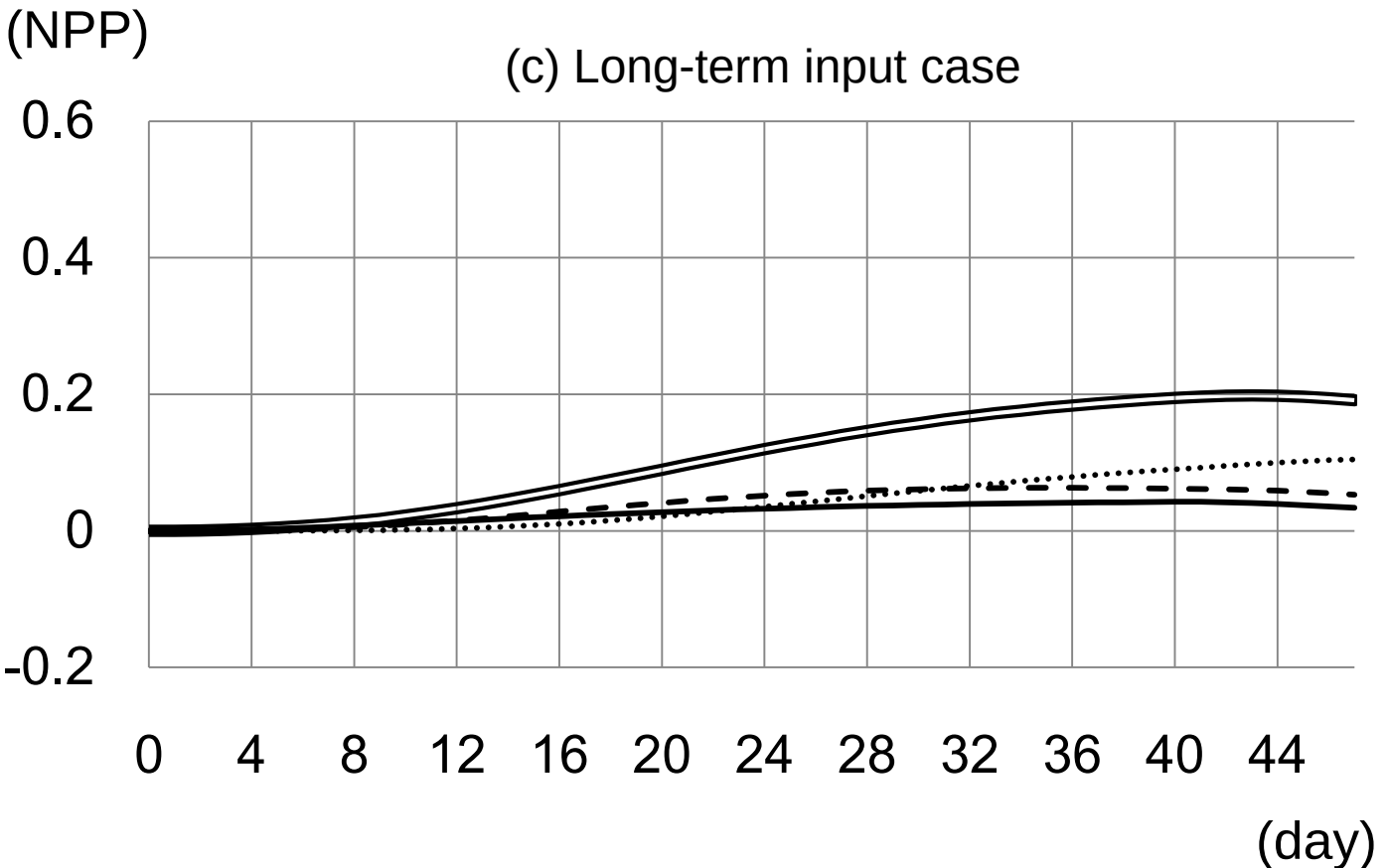


Fig.7



— River-originated NPP - - Subsurface-originated NPP
..... Regenerated NPP ══ NPP

Fig.8 (1)



— River-originated NPP - - Subsurface-originated NPP
..... Regenerated NPP ═ NPP

Fig.8 (2)

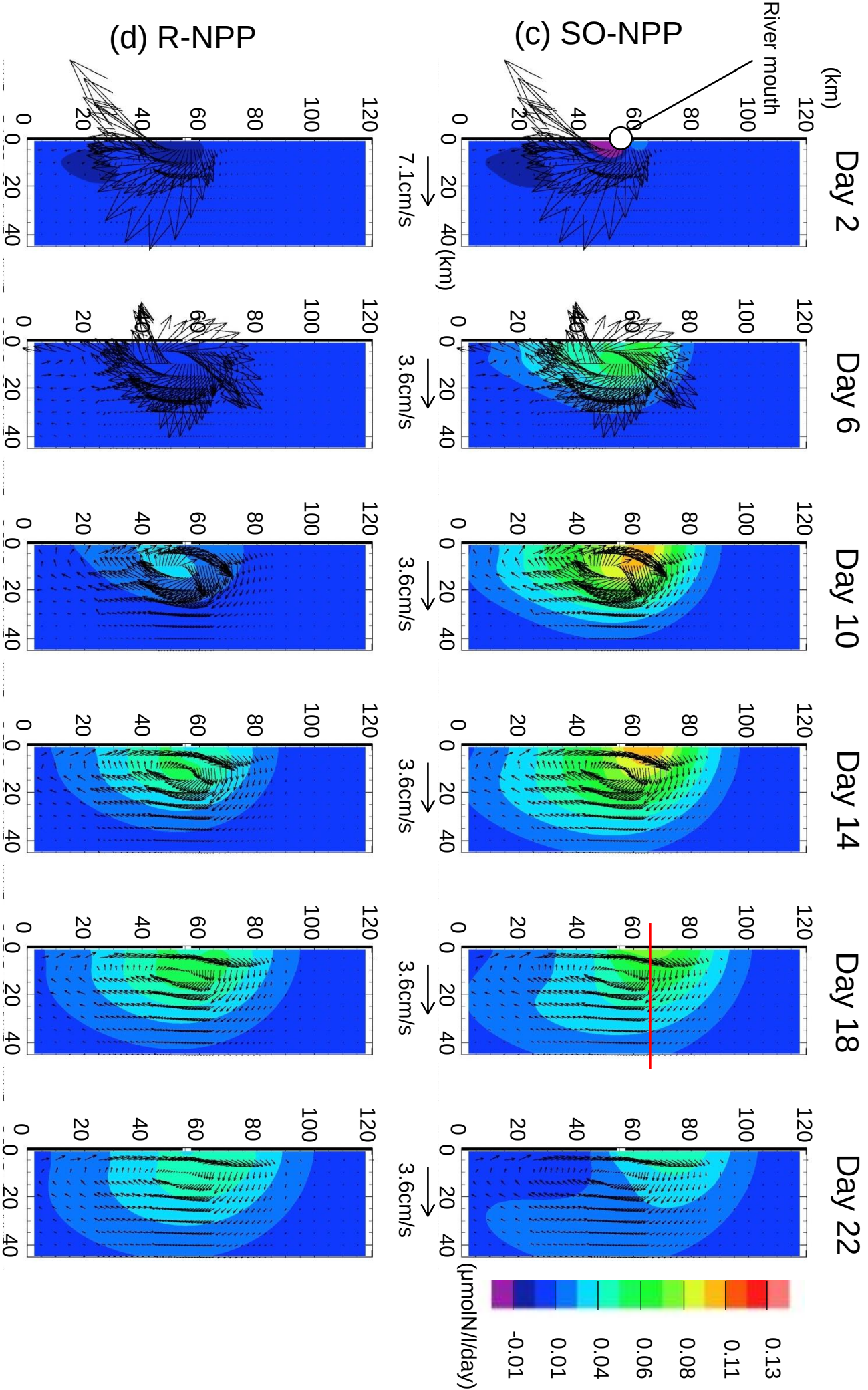


Fig.9 (2)

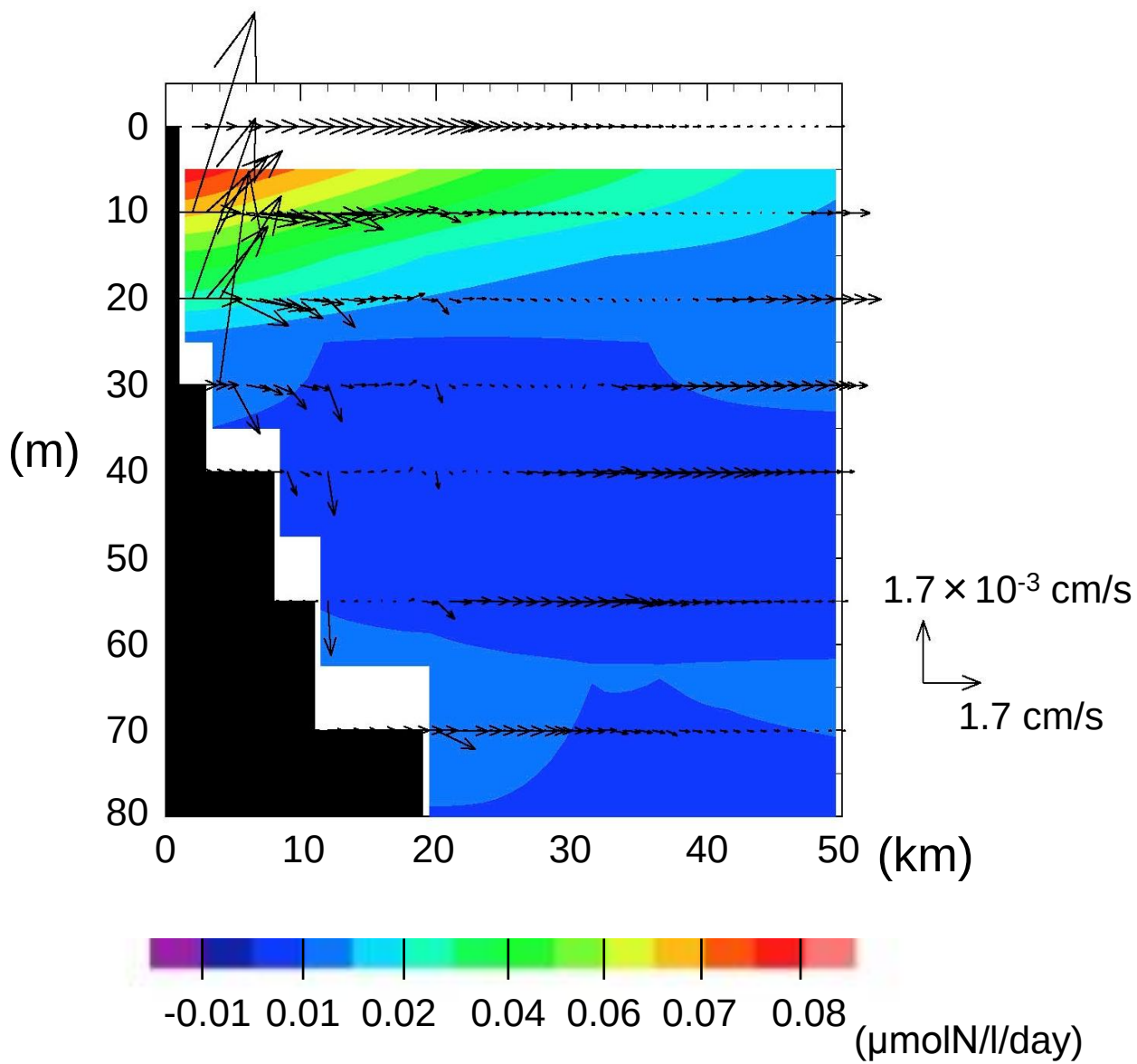


Fig.10

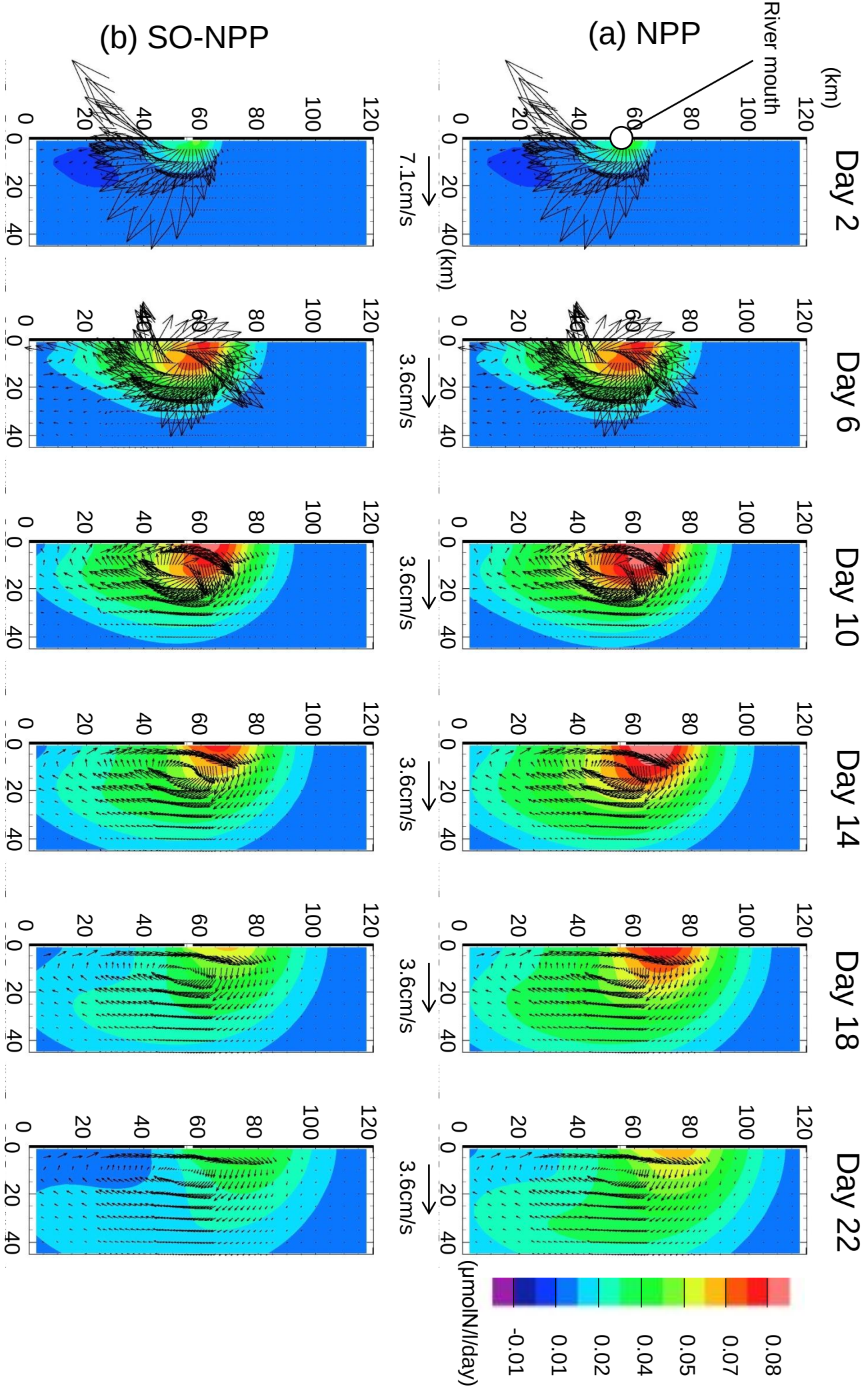


Fig.11 (1)

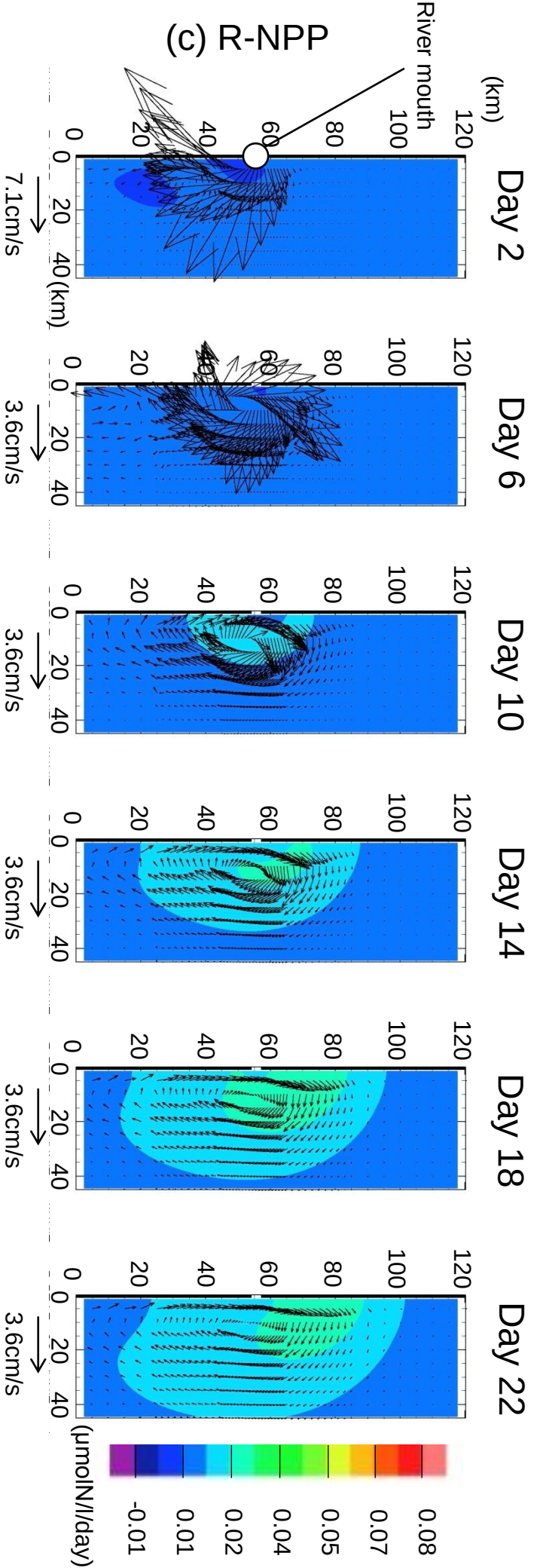
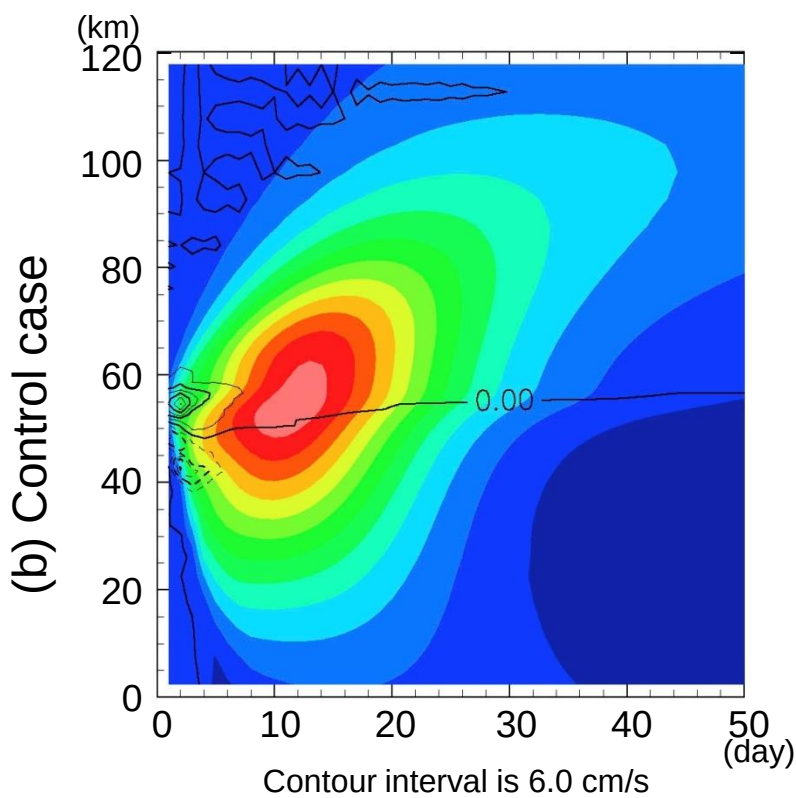
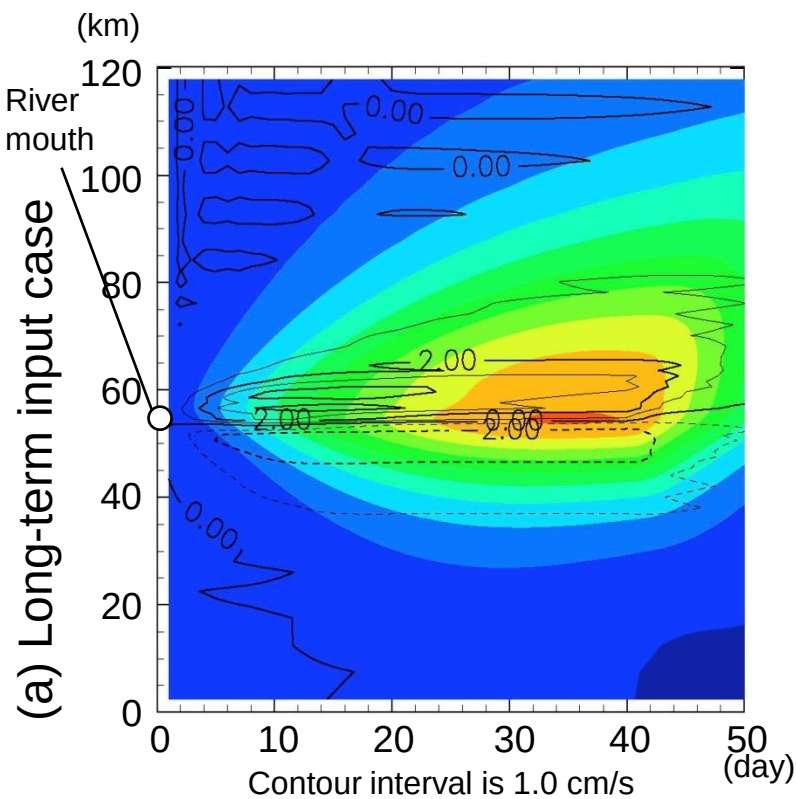


Fig.11 (2)



(c) Comparison of the NPP-amounts between the control and the long-term input cases

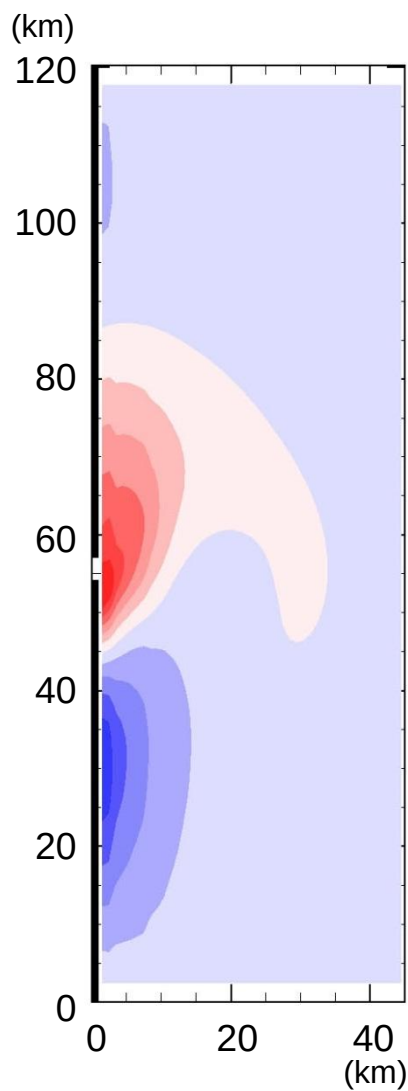


Fig.12

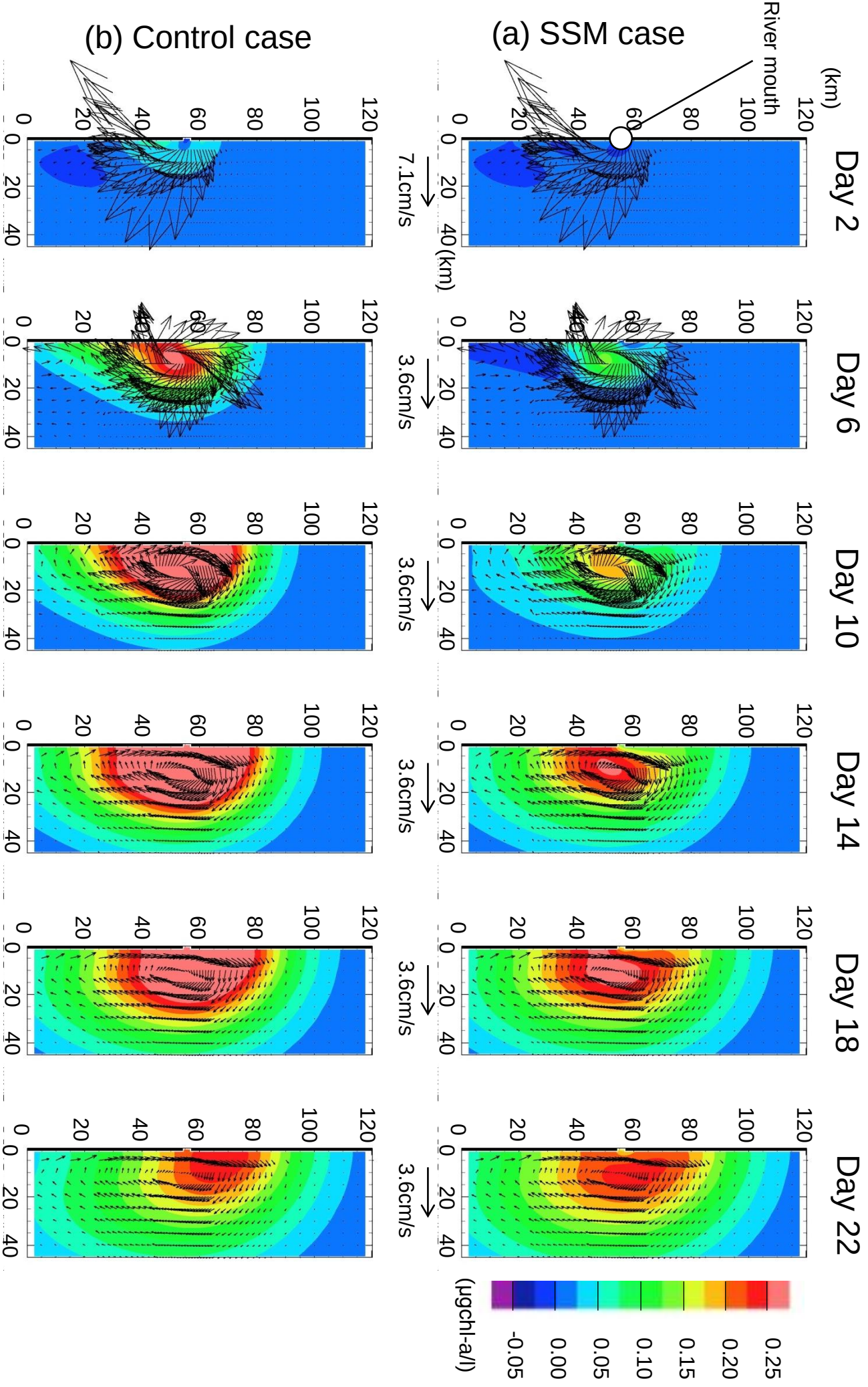


Fig.13

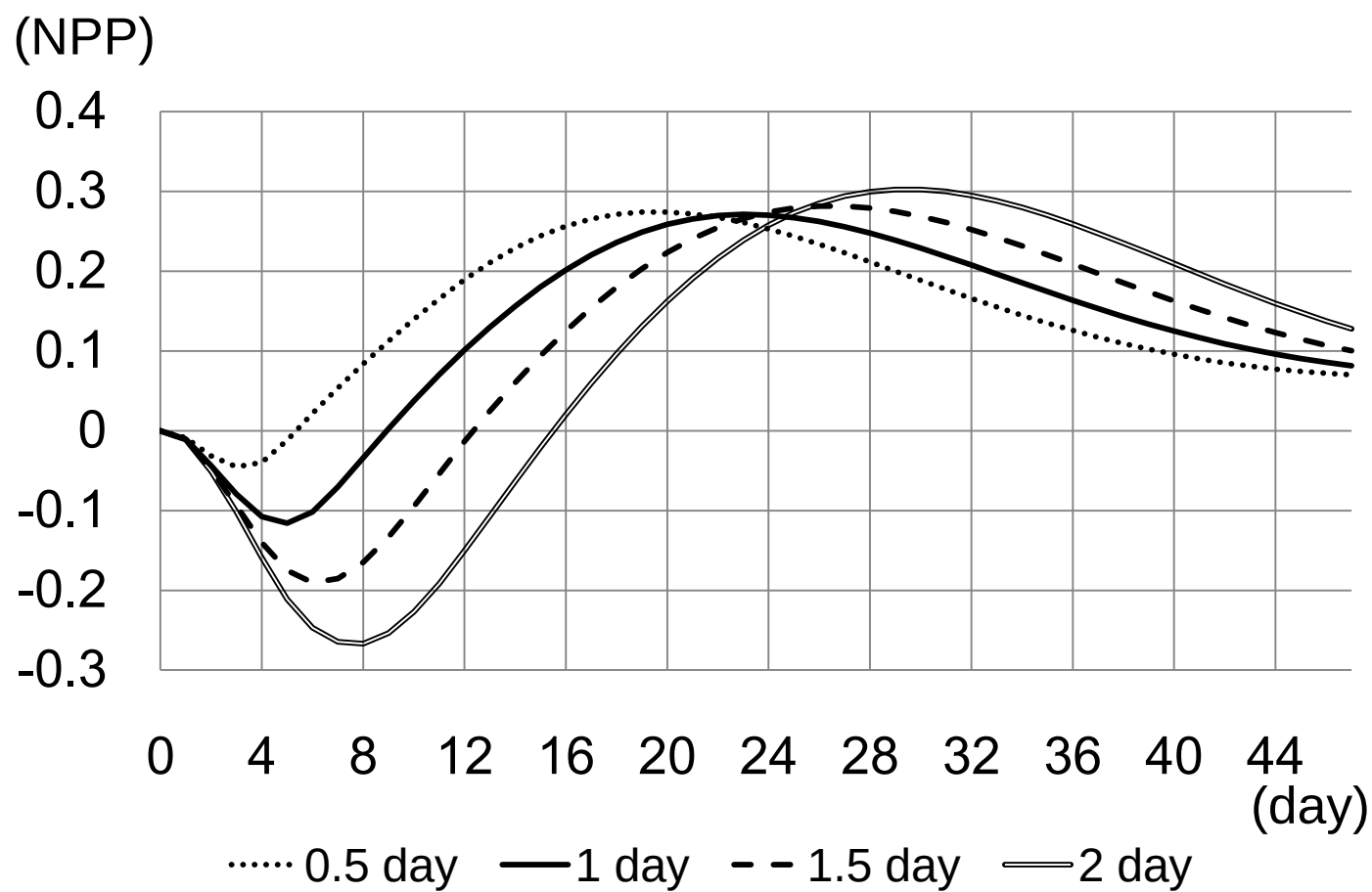


Fig.15