Mediterranean Marine Science

Vol 24, No 2 (2023)

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doi: [10.12681/mms.30913](https://doi.org/10.12681/mms.30913)

Research Article

Mediterranean Marine Science
Indexed in WoS (Web of Science, ISI Thomson) and SCOPUS
The journal is available on line at http://www.medit-mar-sc.net
www.hcmr.gr
DOI: http://doi.org/10.12681/mms.30913

The impact of LNG offshore terminal on sea temperature and sea currents in the northern Adriatic Sea

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Contributing Editor: Elina TRAGOU

Received: 28 July 2022; Accepted: 8 May 2023; Published online: 20 June 2023

Abstract

The aim of this paper is to simulate the impact of a potential offshore LNG terminal on sea temperature (in autumn and spring/summer) and sea currents (in autumn/winter) at three different depths (at the sea surface, at 25 m depth and at the seabed) in the northern Adriatic Sea from 14 November 2015 to 06 August 2016 using the Regional Ocean Modelling System (ROMS) model. The location of the potential offshore LNG terminal Istria (in the northern Adriatic Sea) was selected using the visual PROMETHEE method. The potential LNG terminal uses seawater for LNG heating and the seawater cooled to a temperature of 9°C returns to the marine environment. Although the differences in sea temperature with and without the discharge fit within normal temperature ranges, the simulations show that the discharge changed the speed and direction of sea currents at the sea surface not only in the wider northern Adriatic, but in the entire Adriatic. This is probably due to the specific circulation in the Adriatic, where cold water affects the geostrophic balance, an important part of the circulation field that depends on density (a function of salinity and temperature). Atmospheric conditions in the broader vicinity of the LNG terminal would also be affected by redistribution of air-sea fluxes due to changes in surface temperature. Changes in circulation would alter environmental conditions by redistributing nutrients, oxygen, etc. Further multi-year simulations of changes in the circulation system are needed, but other physical parameters (density, salinity, river inflow...) should also be included in the simulations to determine the cumulative impact of a potential LNG terminal on the marine environment.

Keywords: LNG terminal; marine environment; sea temperature; sea currents; ROMS model; Adriatic Sea.

Introduction

In recent decades, global primary energy consumption has grown rapidly, led by natural gas and renewables. In 2019, the annual natural gas consumption was 3929.2 billion cubic meters and the share of gas in primary energy reached a record high of 24.2 % (BP, 2020). To meet the growing demand for primary energy, the share of natural gas in world energy consumption is expected to reach 25.9 % by 2030 (BP, 2016).

The Liquified Natural Gas (LNG) shipping market has developed rapidly since the early 2000s. In 2019, global LNG trade reached 354.73 million tonnes, while global liquefaction capacity was 42.5 million tonnes per year and global regasification capacity was 821 million tonnes per year. At the end of 2019, the global LNG fleet consisted of 5412 active vessels (IGU, 2020). The majority of existing regasification terminals are land-based (the ratio of existing onshore to floating regasification terminals was 5:1 in 2020), (IGU, 2020).

In maritime transport, LNG is carried in a liquefied state at atmospheric pressure, which allows for the transportation of larger volumes. Converting natural gas to its liquefied form (LNG) is a technical challenge because it must be transported at a much lower temperature, as its boiling point at atmospheric pressure is -162°C. The process of LNG production consumes a considerable amount of energy, which is stored in the LNG as cold energy (Semaskaite *et al.,* 2022). For the regasification of LNG at LNG terminals, seawater is normally used as a heating medium. During regasification, the LNG is transferred from the liquid phase (-162°C) to the gaseous phase (25°C) and the cold energy of 250 KW /t of the LNG is transferred to the seawater (He *et al.,* 2019). The chilled seawater used in the heat exchangers for LNG heating is discharged into the marine environment where it changes the temperature of the sea. Improper handling at LNG terminals can lead to accidents or pollution through pollutant discharges/emissions into the marine environment (Paltrinieri *et al.,* 2015; Aneziris *et al.,* 2014; Papadopoulou & Antoniou, 2014; Ramos *et al.,* 2014, Chan *et al.,* 2004). Current heat exchange technologies have numerous limitations and environmental impacts (Agarwal *et al.,* 2017).

Environmental sustainability has become an important issue in global maritime transport and international instruments such as the 2030 Agenda for Sustainable Development, the Paris Agreement under the United Nations Framework Convention on Climate Change and the Sendai Framework for Disaster Risk Reduction 2015-2030 play an important role in achieving sustainability goals (UNCTAD, 2019).

Considering the importance of interrelated issues such as growing energy consumption, global warming and loss of biodiversity, there is a lack of published information on the impact of LNG sea-born trade on the marine environment. Therefore, the aim of this paper is to simulate the impact of a potential offshore LNG terminal on sea temperature (in autumn and spring/summer) and on sea currents (in autumn/winter) at three different depths (at the sea surface, at 25 m depth and at the seabed) in the northern Adriatic Sea from 14 November 2015 to 06 August 2016 using the Regional Ocean Modelling System model (ROMS).

Malačič *et al.,* (2008) analysed the impact of a proposed onshore LNG terminal and a proposed offshore LNG terminal on sea temperature, salinity, ocean currents and circulation changes in the Gulf of Trieste using the Princeton Ocean Model (POM). The ROMS model used in this paper has already been used for temperature and salinity simulations (Janeković *et al.,* 2010.), simulations of dense water dispersion (Vilibić *et al.,* 2016) and simulations of the dispersion of invasive aquatic species (Kraus *et al.,* 2016) in the Adriatic Sea.

The Adriatic Sea is over 800 km long and about 200 km wide, with a surface area of about 138600 km^2 and a volume of about 35000 km^3 (McKinney, 2007). The basin can be divided into three sections: the northern Adriatic, the central Adriatic and the southern Adriatic with different characteristics, different latitudes and topographic gradients (Danovaro & Boero, 2019). The northern Adriatic Sea accounts for 5 % of the basin, has an average depth of about 35 m and a maximum depth of 75 m, and occupies the flooded seaward extent of the Po Plain (Trincardi *et al.,* 1996). The entire volume of the Adriatic Sea is exchanged into the Mediterranean Sea every three to four years, due to the combined contribution of rivers and submarine groundwater discharge (Danovaro & Boero, 2019).

Important features of the Adriatic Sea are: The Eastern Adriatic Current, which carries oligotrophic water from the eastern Mediterranean along the Croatian coast; the low tidal range; the large influence of the Po River, which is the largest source of freshwater and nutrients in the entire Mediterranean; the Bora winds in winter, which are involved in the formation of the dense waters of the northern Adriatic and initiate circulation in the eastern part of the Mediterranean; the longitudinal and transverse gradients of physical, chemical and biological properties, etc (Viličić, 2014).

The general circulation is cyclonic with a north-westerly flow along the east coast and a south-easterly return flow along the west coast, and the mean circulation shows seasonal variations according to the changing winds and thermal fluxes during the year (Orlić *et al.,* 1992; Cushman-Roisin *et al.,* 2001; Danovaro & Boero, 2019). The circulation of the Adriatic surface water is influenced by the inflow of freshwater, especially from the Po river, the inflow of Mediterranean water through the Strait of Otranto and wind stress (Orlić *et al.,* 1992; Cushman-Roisin *et al.,* 2001; Vilibić & Orlić, 2002; Danovaro & Boero, 2019; Dunić *et al.,* 2019).

The Adriatic circulation is modified by several large circulation cells with cyclonic or anticyclonic rotation directions (Artegiani *et al.,* 1997; Poulain *et al.,* 2001). In the northern region, apart from a cyclonic cell in the northernmost part of the region, which seems to be a permanent feature, several smaller cells with cyclonic or anticyclonic sense of rotation usually occur (Supić *et al.,* 2003; Djakovac *et al.,* 2015).

Geostrophic currents make an important contribution to the northern Adriatic circulation fields (Supić *et al.,* 2000; Krajcar *et al.,* 2003). Their distribution indicates the presence of large gyres in which organic material accumulates (Orlić *et al.,* 2013; Ciglenečki *et al.,* 2021). Changes in the density distribution can cause strong currents (Lyons *et al.,* 2007) that transport organic or inorganic material across the region (Kraus & Supić, 2015; Paliaga *et al.,* 2021). Geostrophic currents are generally less than 10 cm/s (Supić *et al.,* 2000; Orlić *et al.,* 2013). Geostrophic motions are primarily triggered by thermal differences, although the presence of low salinity water in the surface layer can significantly alter the density field (Lyons *et al.,* 2007).

Standard deviations of monthly averages of temperature, both in surface and bottom layers, based on long-term series at stations in the northern Adriatic, are up to 2°C (Supić & Ivančić, 2002),which implies long-term changes of monthly temperature in the range of 4°C.

According to Penzar *et al.* (2001), the lowest monthly mean sea surface temperature values are below 10°C and are measured in the northern Adriatic in February, and the highest monthly mean sea surface temperature values (below 24°C) are measured uniformly in the entire Adriatic area in August, with the exception of the Velebit Channel, where the highest monthly mean sea surface temperature values are around 20°C due to the strong influence of submarine freshwater springs and the Bora wind.

The northern part of the Adriatic is one of the most productive regions of the Adriatic and the entire Mediterranean. This is due to the shallow water depth and low water exchange with the rest of the Adriatic, as well as excessive nutrient input from the Po river (Degobbis *et* *al.,* 2000, Degobbis & Gilmartin, 1990). In general, the water of the Po river is confined to the Italian coast in winter and is distributed over the northern Adriatic Sea during the warm season (Krajcar, 2003). However, there are exceptions to this rule. There are winters when the waters of the Po flow eastwards, resulting in increased intensity of primary production in the northernmost part of the Adriatic. It seems that in years that start with such events, annual production is also high, suggesting that winter production can be a very important factor in total annual production (Kraus *et al.,* 2015). The Po discharge rate controls northern Adriatic primary production in the summer, while in the winter circulation plays a crucial role for primary production in the region (Kraus *et al.,* 2016).

Water temperature strongly influences other abiotic factors of the marine environment, such as currents (Lyons *et al.,* 2007), solubility of gases and nutrients (Hillel, 2005), density (Akbari *et al.,* 2017), etc. Moreover, sea temperature as well as dissolved oxygen concentration are crucial factors controlling marine productivity and habitat (Mathewson, 2003).

The aim of this paper is to simulate the impact of a potential offshore LNG terminal on sea temperature (in autumn and spring/summer) and sea currents (in autumn/winter) at three different depths (at the sea surface, at 25 m depth and at the seabed) in the northern Adriatic Sea from 14 November 2015 to 06 August 2016 using the Regional Ocean Modelling System (ROMS) model. The location of the potential offshore LNG terminal Istria (in the northern Adriatic Sea) was selected using the visual PROMETHEE method. The paper consists of the following chapters: Introduction, Materials and Methods, Results and Discussion and Conclusions.

Material and Methods

The first step was to select the optimal location for a potential LNG terminal. A set of preliminary and exclusion criteria was established for the entire Adriatic area. Three sites were selected as suitable locations for a potential LNG terminal using the multi-criteria expert evaluation method Visual PROMETHEE (Preference Ranking Organisation Method for Enrichment Evaluation) Beta version 0.93.1.1. Finally, the offshore LNG terminal Istria (45°00'N and 13°20'E) was selected as the optimal location in the northern Adriatic Sea

The potential LNG terminal is 300 m long, 46 m wide and 45 m high. The terminal is equipped with three membrane tanks, operates at a pressure of 70 to 100 bar and consumes 15300 m^3 of seawater for LNG heating. The seawater, cooled to a temperature of 9°C, is returned to the marine environment at a constant flow of 20 m^3/s at a depth of 20 m.

The impact of the potential offshore LNG terminal Istria on sea temperature and sea currents was simulated at three different depths in the northern Adriatic Sea from 14 November 2015 to 06 August 2016 using the Regional Ocean Modelling System (ROMS) model (Haidvogel *et al.,* 2000; Marchesiello *et al.,* 2003; Peliz *et al.,* 2003; Di Lorenzo, 2003; Dinniman *et al.,* 2003; Budgell, 2005; Warner *et al.,* 2005a, b; Wilkin *et al.,* 2005). The ROMS model was used according to Janeković *et al.* (2010). The ECMWF (*the European Centre for Medium-Range Weather Forecasts*) operational archive was used for surface forcing modification, Vilibić *et al.* (2016) for river inflow, and Janeković *et al.,* 2020 (the ADAM-ADRIA project) for boundary conditions at the Strait of Otranto (temperature, salinity, currents, and water height).

The changes in:

- sea temperatures at the sea surface, at 25 m depth and at the seabed in the northern Adriatic in autumn after 5 days, 15 days and 32 days of continuous discharge (started on 14/11/2015) and in spring/summer after 17 days, 45 days and 3 months of continuous discharge (started on 02/05/2016);
- sea currents at the sea surface, at 25 m depth and at the seabed in the northern Adriatic during the autumn-winter period after: 18 days, 1.5 months and 3 months of continuous discharges (started on 14/11/2015); and
- circulation, at 25 m depth and at the seabed in the autumn-winter period after: 18 days, 1.5 months and 3 months of continuous discharge (started on 14/11/2015) observed throughout the Adriatic.

Results and Discussion

Figure 1 indicates the differences in sea temperatures after 5 days (on 20/11/2015) of uninterrupted discharge (started on 14/11/2015) from the potential offshore LNG terminal Istria in the Northern Adriatic Sea at: a. the sea surface, b. 25 m depth, and c. the seabed, compared to the normal situation (without discharges) in November the (the autumn period).

The differences in sea temperatures compared to the normal situation in November are visible within a circle of 2 NM diameter from the location of the LNG terminal: -2.6^{o} C at the sea surface (lower temperature compared to the normal situation), +0.3^{o} C at 25m depth (higher temperature compared to the normal situation) and from -0.1^{o} C to +0.3^{o} C at the seabed. The highest temperature differences after 5 days of continuous discharge in November (autumn) compared to the normal situation are found at the sea surface, although the outlet of the cooled seawater is at a depth of 25 m.

Figure 2 indicates the differences in sea temperatures after 15 days (30/11/2015) of continuous discharge (started on 14/11/2015) from the potential offshore LNG terminal Istria in the northern Adriatic Sea at: a. the sea surface, b. 25 m depth, and c. the seabed, compared to the normal situation (without discharges) in November (the autumn period).

The differences in sea temperatures compared to the normal situation in November are: -1.5^{o} C at the sea surface near the LNG terminal (lower temperature compared to the normal situation), +0.4^{o} C at 25 m depth (higher temperature compared to the normal situation) and from -0.7^{o} C to +1^{o} C at the seabed.

The largest differences in sea temperatures after 15 days of continuous discharge in November (autumn) compared to the normal situation are found at the sea surface, where the sea temperature is lower than the temperature in the normal situation, while the temperature at 25 m depth is slightly higher than the temperature in the normal situation, although the outlet of the cooled sea water is at 25 m depth. The differences in sea temperature compared to the normal situation in November are visible over the entire area of the north-western Adriatic, especially at the sea surface and at the seabed.

Figure 3 shows the differences in sea temperatures after 32 days (16/12/2015) of continuous discharge (started on 14/11/2015) from the potential offshore LNG terminal Istria in the northern Adriatic Sea at: a. the sea surface, b. 25 m depth, and c. the seabed, compared to the normal situation (without discharges) in December (the autumn period).

The differences in sea temperatures compared to the normal situation in December are greater than after 5 days and after 15 days of discharge. They range from -3° C to +4° C at the sea surface, from -2° C to +2.4° C at 25 m depth and from -2° C to +2° C at the seabed and are visible over the entire area of the north-western Adriatic.

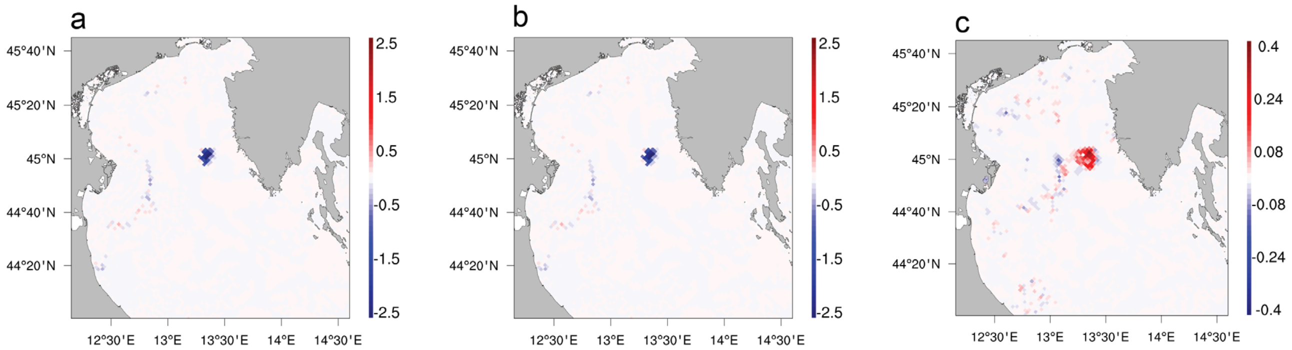

Fig. 1: The differences in sea temperatures after 5 days (on 20/11I2015) of continuous discharge (started on 14/11/2015) from the potential offshore LNG terminal Istria in the northern Adriatic Sea at: a. the sea surface, b. 25 m depth, and c. the seabed, compared to the normal situation (without discharges) in November (the autumn period).

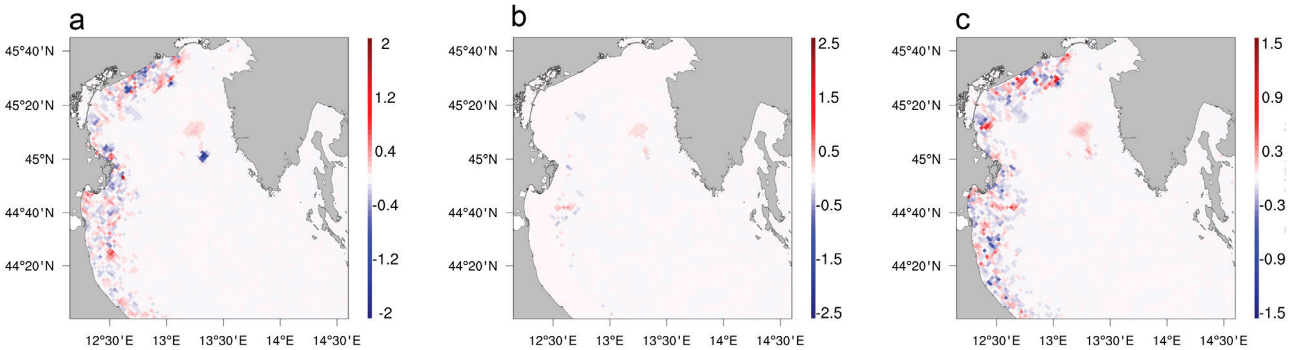

Fig. 2: The differences in sea temperatures after 15 days (30/11/2015) of continuous discharge (started on 14/11/2015) from the potential offshore LNG terminal Istria in the northern Adriatic Sea at: a. the sea surface, b. 25 m depth, and c. the seabed, compared to the normal situation (without discharges) in November (the autumn period).

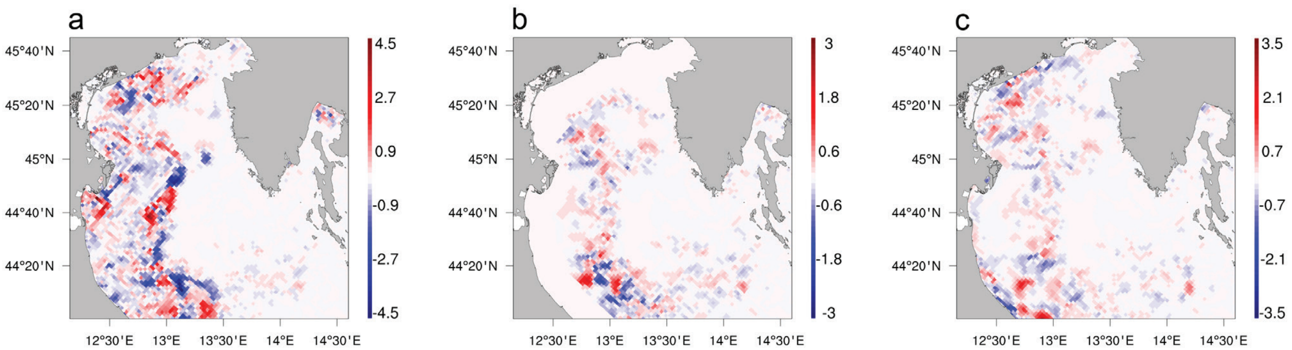

Fig. 3: The differences in sea temperatures after 32 days (16/12/2015) of continuous discharge (started on 14/11/2015) from potential offshore LNG terminal Istria in the northern Adriatic Sea at: a. the sea surface, b. 25m depth, and c. the seabed, compared to the normal situation (without discharges) in December (the autumn period).

Generally, the longer the period of discharge, the greater the difference in sea temperatures compared to the normal situation in autumn. The differences in sea temperature are visible over the entire area of the north-western Adriatic, even at places far from the LNG terminal location, except after 5 days of continuous discharge, when the differences in sea temperature compared to the normal situation in November are visible within a circle of 2 NM diameter from the LNG terminal location.

Figure 4 shows the differences in sea temperatures after 17 days (20/05/2016) of uninterrupted discharge (started on 02/05/2016) from the potential offshore LNG terminal Istria in the northern Adriatic Sea at: a. the sea surface, b. 25m depth, and c. the seabed, compared to the normal situation (without discharges) in May (the spring-summer period).

The differences in sea temperatures after 17 days of continuous discharge compared to the normal situation in May range from -1°C to +1°C at the sea surface and are visible over the entire area of the north-western Adriatic, while the differences in sea temperature at 25m depth and at the seabed are less visible and more spatially limited.

Figure 5 shows the differences in sea temperatures after 45 days (17/06/2016) of continuous discharge (started on 02/05/2016) from the potential offshore LNG terminal Istria in the northern Adriatic Sea at: a. the sea surface, b. 25m depth, and c. the seabed, compared to the normal situation (without discharges) in June (the spring-summer period).

The differences in sea temperatures after 45 days of continuous discharges compared to the normal situation in June range from -2°C to +1.7°C at the sea surface and at 25m depth and at the seabed and are visible over the entire area of the northern Adriatic.

Figure 6 shows the differences in sea temperatures after 3 months (06/08/2016) of continuous discharge (started on 02/05/2016) from the potential offshore LNG terminal Istria in the Northern Adriatic Sea at: a. the sea surface, b. 25m depth, c. the seabed, compared to the normal situation (without discharges) in August (the spring-summer period). Similar to June, the differences in sea temperatures after 3 months of continuous discharge compared to the normal situation in August range from -2°C to +1.7°C at the sea surface, at 25m depth and at the seabed, and are visible over the entire area of the northern Adriatic.

In the spring-summer period, the differences in sea temperatures compared to the normal situation at the sea surface are the greatest, ranging from -1°C to +1°C after 17 days of continuous discharge in May, from -2°C to +1.7°C after 45 days of continuous discharge in June, and from -2°C to +1.7°C after 3 months of continuous discharge in August. Nevertheless, large spatial distributions of sea temperature differences can be seen over the entire area of the northern Adriatic at all simulated depths.

The differences in sea temperature are visible in autumn and spring/summer in the whole northern Adriatic Sea, compared to the normal situation without discharges,

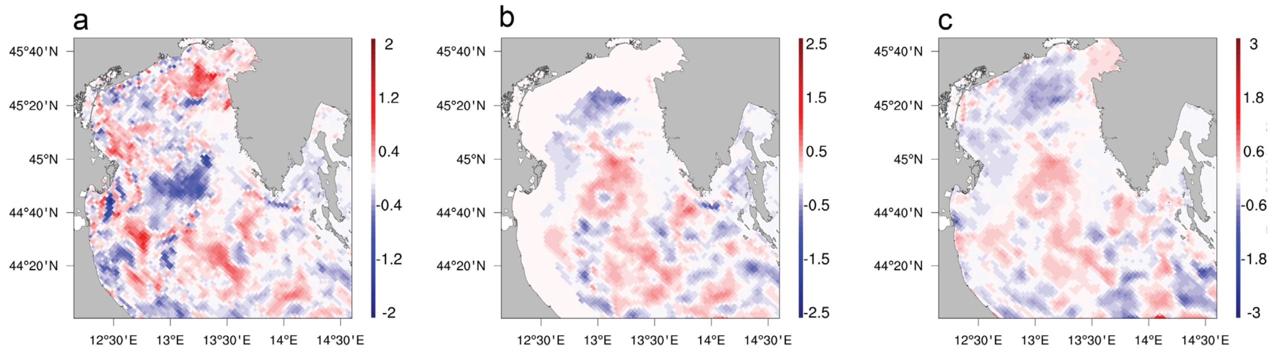

Fig. 4: The differences in sea temperatures after 17 days (20/05/2016) of continuous discharge (started on 02/05/2016) from the potential offshore LNG terminal Istria in the northern Adriatic Sea at: a. the sea surface, b. 25m depth, and c. the seabed, compared to the normal situation (without discharges) in May (the spring-summer period).

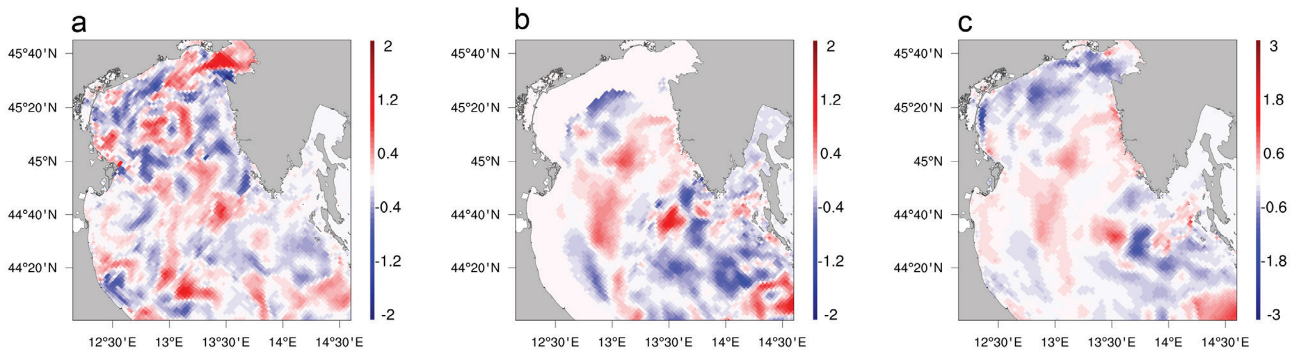

Fig. 5: The differences in sea temperatures after 45 days (17/06/2016) of continuous discharge (started on 02/05/2016) from potential offshore LNG terminal Istria in the northern Adriatic Sea at: a. the sea surface, b. 25m depth, and c. the seabed, compared to the normal situation (without discharges) in June (the spring-summer period).

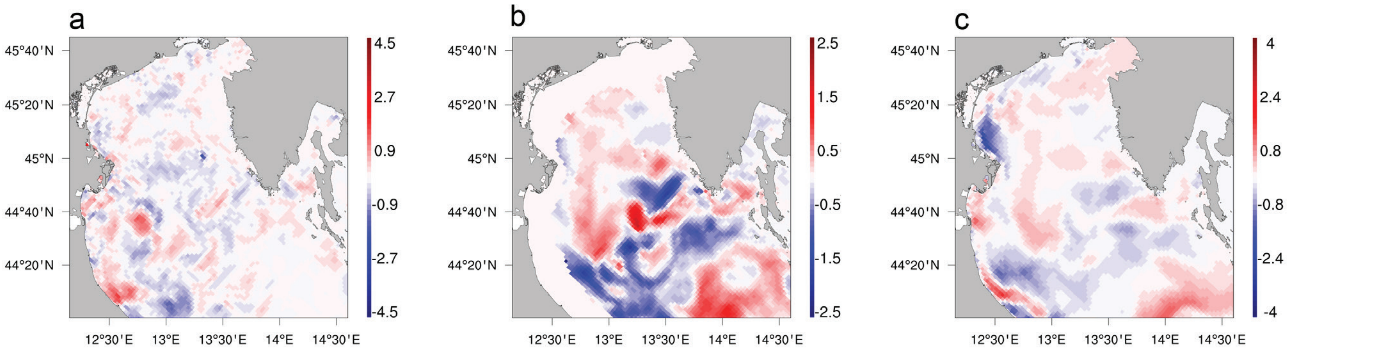

Fig. 6: The differences in sea temperatures after 3 months (06/08/2016) of continuous discharge (started on 02/05/2016) from potential offshore LNG terminal Istria in the northern Adriatic Sea at: a. the sea surface, .b 25m depth, and c. the seabed, compared to the normal situation (without discharges) in August (the spring-summer period).

except for the simulation after 5 days of continuous discharge in autumn, when the differences are concentrated in a circle of 2 NM diameter around the discharge point. The differences in sea temperature are more pronounced at the sea surface than at 25 m depth or at the seabed, but all of these differences lie within the normal temperature ranges of ±3^{o} C for the observed periods. These results are consistent with those found in the literature (Jelavić *et al.,* 2017; Ivančić *et al.,* 2010; Supić & Ivančić, 2002).

Figure 7 shows the surface currents of the northern Adriatic Sea without discharge compared to the currents with continuous discharge after 18 days, 1.5 months and 3 months. Figure 7 shows the sea currents at the surface: a. without discharge on 03/12/2015, b. after 18 days of continuous discharge on 03/12/2015, c. without discharge on 01/01/2016, d. after 1.5 months of continuous discharge on 01/01/2016, e. without discharge on 19/02/2016, and f. after 3 months of continuous discharge on 19/02/2016 in the Northern Adriatic Sea. Visible differences in the speed and direction of ocean currents were noted, especially in January after 1.5 months of continuous discharge.

Figure 8 shows the sea currents at 25 m depth: a. without discharge on 03/12/2015, b. after 18 days of continuous discharge on 03/12/2015, c. without discharge on 01/01/2016, d. after 1.5 months of continuous discharge on 01/01/2016, e. without discharge on 19/02/2016, and f. after 3 months of continuous discharge on 19/02/2016 in the northern Adriatic Sea.

The simulation of the sea currents at a depth of 25 m shows that there are no differences in the speed and direction of sea currents for all discharge scenarios compared to the normal situation without discharge.

Figure 9 shows the sea currents at the seabed: a without discharge on 03/12/2015, b after 18 days of continuous discharge on 03/12/2015, c without discharge on 01/01/2016, d after 1.5 months of continuous discharge on 01/01/2016, e without discharge on 19/02/2016, and f after 3 months of continuous discharge on 19/02/2016 in the northern Adriatic Sea.

The simulation of the sea currents at the seabed shows that for all discharge scenarios there are no differences in the speed and direction of sea currents compared to the normal situation without discharge.

While the simulations of the sea currents at 25 m depth and at the seabed show that there are no differences in the speed and direction of the sea currents for all discharge scenarios compared to the normal situation without discharge, the simulation of the sea currents at the sea surface shows visible differences in the speed and direction of the sea currents, especially in January after 1.5 months of continuous discharge.

Although the temperature differences with and without discharge fit into the normal temperature ranges, the simulations show that the discharge from the LNG terminal changed the speed and direction of the sea currents at the sea surface compared to the normal situation without discharge, not only in the vicinity of the discharge outlet, but also in the wider area of the northern Adriatic during the autumn-winter period.

Figure 10 shows the sea currents at 25 m depth: a. without discharges on 03/12/2015, b. after 18 days of continuous discharge on 03/12/2015, c. without discharges on 01/01/2016, d. after 1.5 months of continuous discharge on 01/01/2016, e. without discharges on 19/02/2016, and f. after 3 months of continuous discharge on 19/02/2016 in the entire Adriatic Sea. The simulation of the sea currents at 25 m depth on 19/02/2016 after 3 months of continuous discharge shows that the faster currents with a velocity of 0.8 m/s are concentrated in the south-western Adriatic near the Gargano peninsula and the Strait of Otranto.

Figure 11 shows the sea currents at the seabed: a. without discharge on 03/12/2015, b. after 18 days of continuous discharge on 03/12/2015, c. without discharge on 01/01/2016, d. after 1.5 months of continuous discharge on 01/01/2016, e. without discharge on 19/02/2016, and f. after 3 months of continuous discharge on 19/02/2016 in the entire Adriatic Sea area.

Like the simulation of the sea currents at 25 m depth, the simulation of the sea currents at the seabed shows the differences in the speed and direction of ocean currents only just after 3 months of continuous discharge on 19/02/2016. Faster currents, with a speed of 0.8 m/s, are concentrated along the Italian coast in the south-western Adriatic Sea, compared to the normal situation without discharges.

Simulations of the sea currents at 25 m depth and on the seabed for the entire area of the Adriatic show the dif-

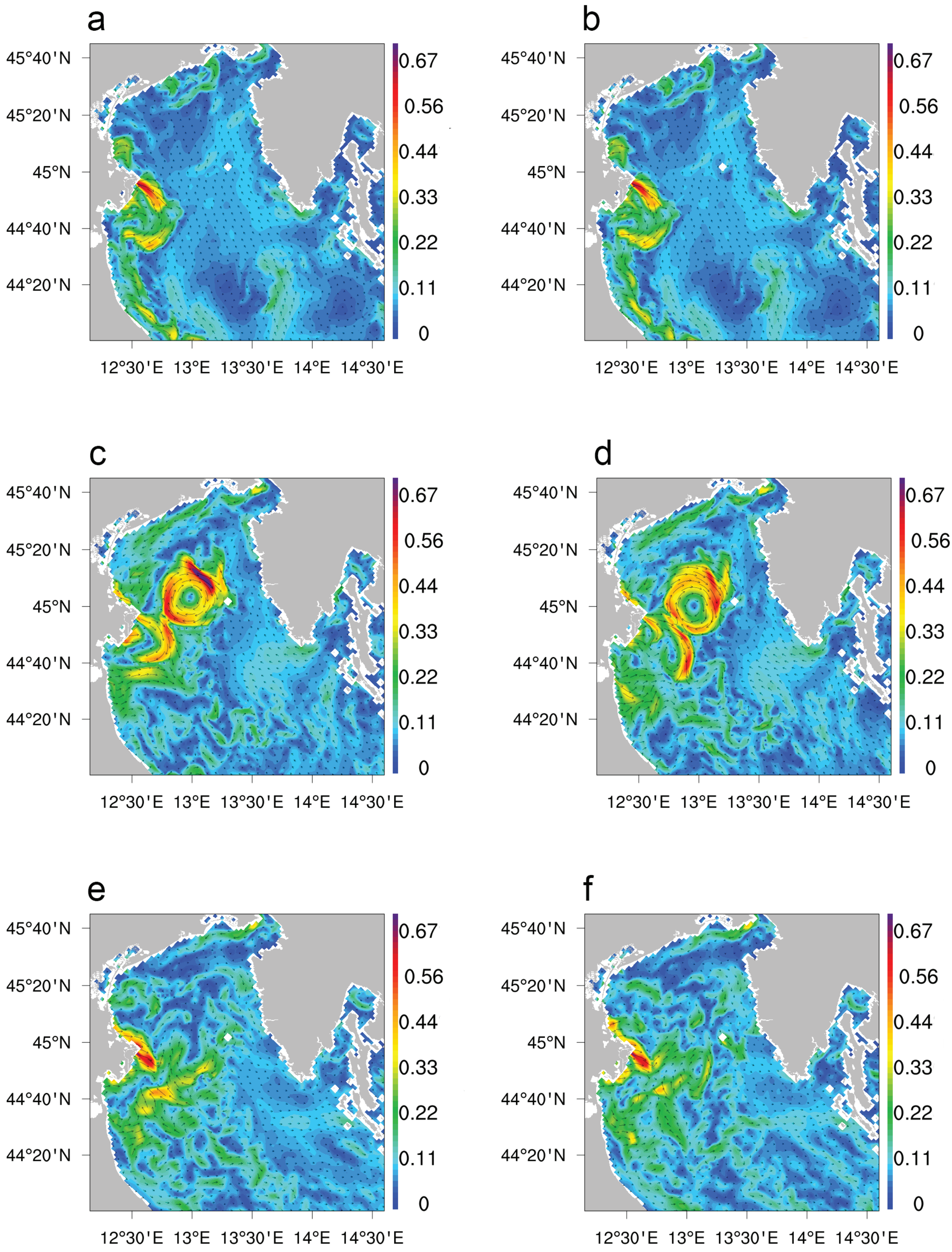

Fig. 7: Sea currents at the sea surface: a. without discharge on 03/12/2015, b. after 18 days of continuous discharge on 03/12/2015, c. without discharge on 01/01/2016, d after 1.5 months of continuous discharge on 01/01/2016, e. without discharge on 19/02/2016, and f. after 3 months of continuous discharge on19/02/2016 in the northern Adriatic Sea.

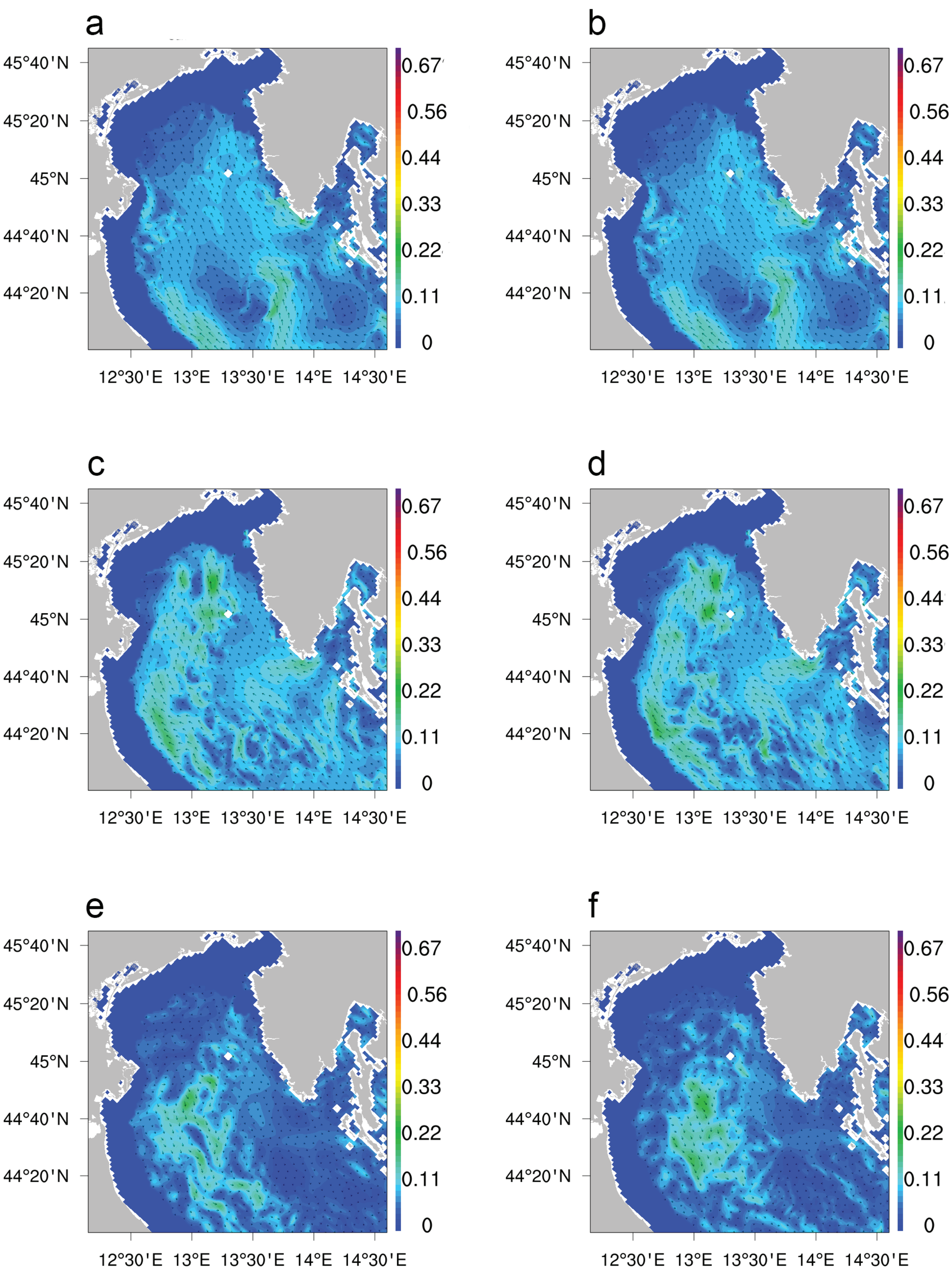

Fig. 8: Sea currents at 25 m depth: a. without discharge on 03/12/2015, b. after 18 days of continuous discharge on 03/12/2015, c. without discharge on 01/01/2016, d. after 1.5 months of continuous discharge on 01/01/2016, e. without discharge on 19/02/2016, and f. after 3 months of continuous discharge on19/02/2016 in the northern Adriatic Sea.

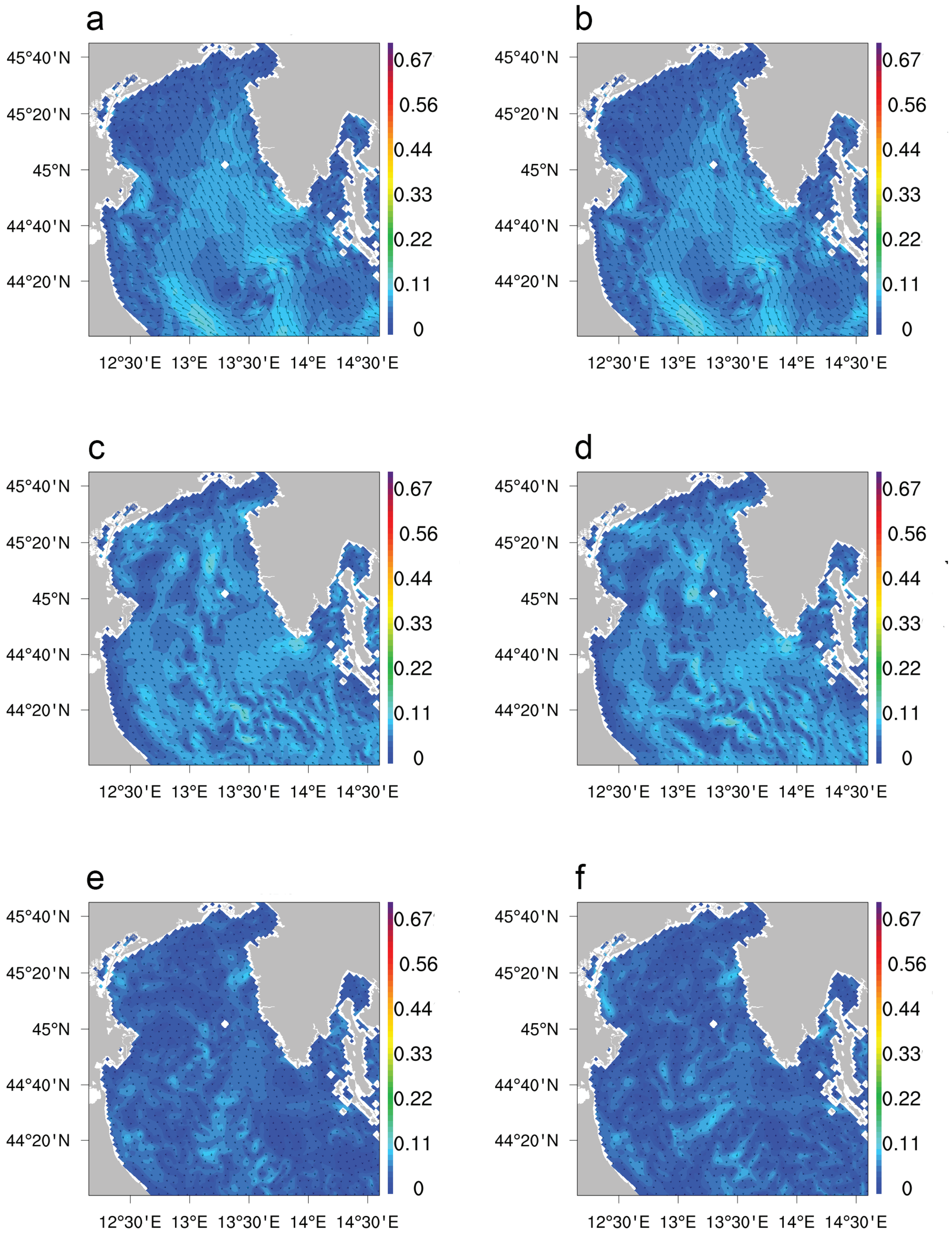

Fig. 9: Sea currents at the seabed: a. without discharge on 03/12/2015, b. after 18 days of continuous discharge on 03/12/2015, c. without discharge on 01/01/2016, d. after 1.5 months of continuous discharge on 01/01/2016, e. without discharge on 19/02/2016, and f. after 3 months of continuous discharge on 19.02/2016 in the northern Adriatic Sea.

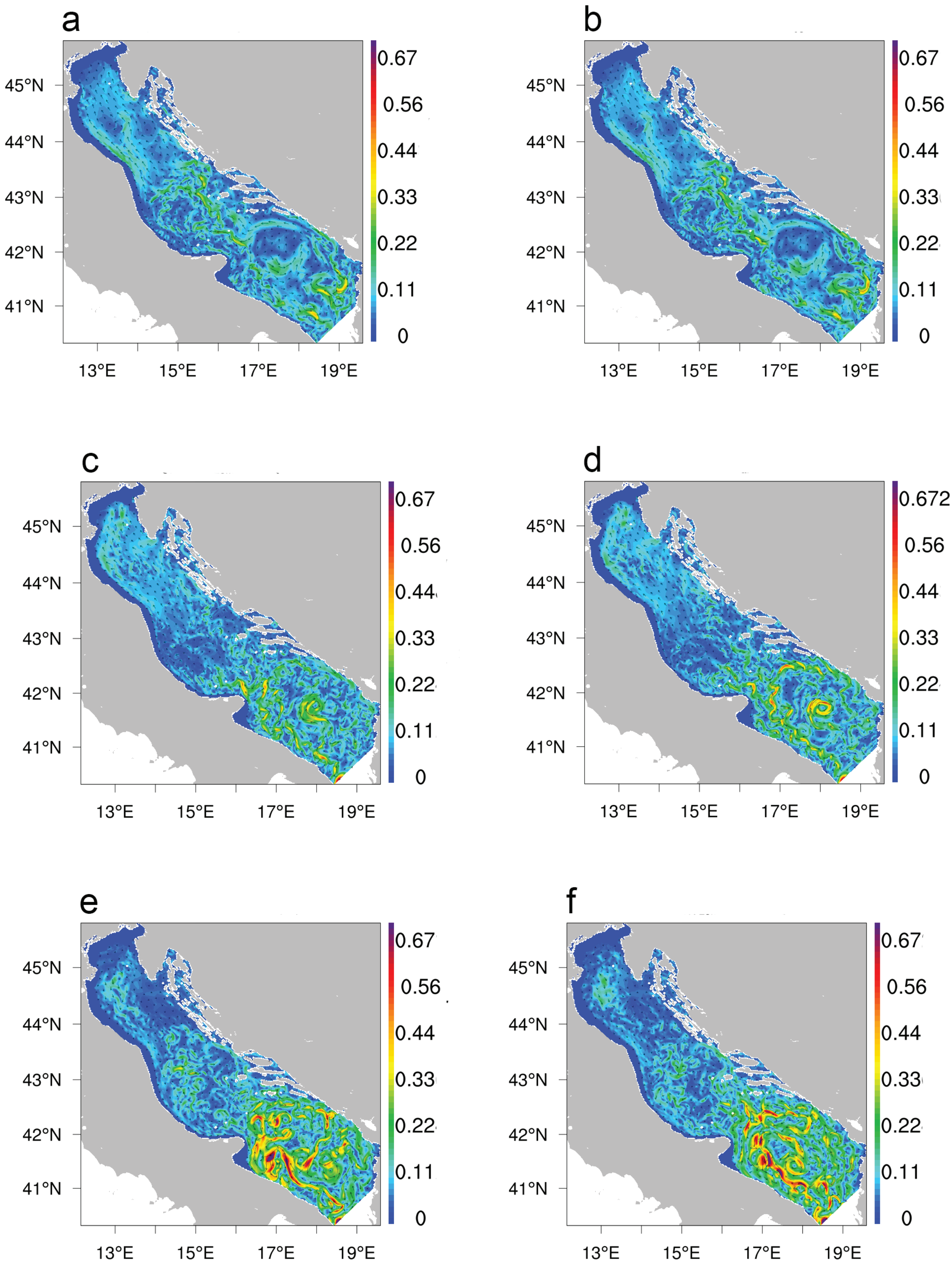

Fig. 10: Sea currents at 25m depth: a. without discharge on 03/12/2015, b. after 18 days of continuous discharge on 03/12/2015, c. without discharge on 01/01/2016, d. after 15 months of continuous discharge on 01/01/2016, e. without discharge on 19/02/2016, and f. after 3 months of continuous discharge on 19/02/2016 in the entire Adriatic Sea area.

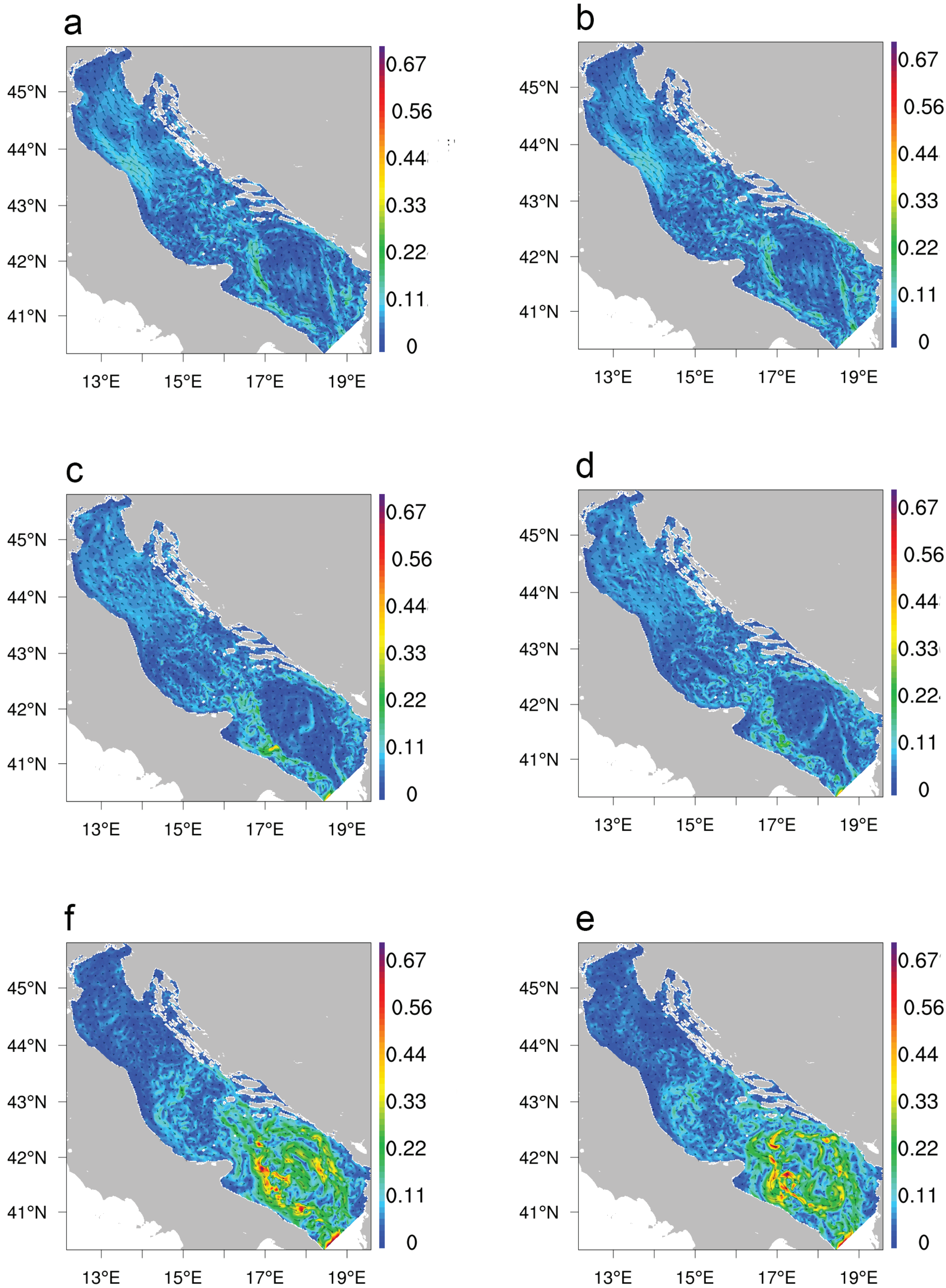

Fig. 11: Sea currents at the seabed: a. without discharge on 03/12/2015, b. after 18 days of continuous discharge on 03/12/2015, c. without discharge on 01/01/2016, d. after 1.5 months of continuous discharge on 01/01/2016, e. without discharge on 19/02/2016, and f. after 3 months of continuous discharge on 19/02/2016 in the entire Adriatic Sea area.

ferences in the speed and direction of the sea currents only just after 3 months of continuous discharge in February. Faster currents, with a velocity of 0.8 m/s, are concentrated along the Italian coast in the south-western Adriatic, compared to the normal situation without discharges.

The example of 20/05/2016 (Figure 12) shows that after 17 days of continuous discharge of cold water caused by the presence of LNG, changes in the circulation of the northern Adriatic Sea were caused by a geostrophic component in the current field. Changes in the temperature, salinity, and density fields resulted in changes in the total density of the 0-25 m water column, causing changes in the dynamic depth of the 25dbar surface. Under the condition of continuous discharge, the central part of the northern Adriatic region east of the Po delta is warmer, has higher salinity and density than in the case without discharge. When LNG is present, it is more likely that water from the Po delta is confined to the coastal area and does not spread across the northern Adriatic. In addition, changes in surface temperature caused by LNG discharge affect the distribution of air-sea heat fluxes. For example, colder areas with higher salinity in the central part of the northern Adriatic would gain more heat in the case of LNG (“disturbed”). This suggests that the redistribution of surface fluxes in the “disturbed” case would affect atmospheric conditions, presumably leading to changes in atmospheric circulation.

Note that the amount of heat released to the sea from the LNG terminal is very small compared to the total air-sea heat flux of the northern Adriatic. During regasification, the LNG is transferred from the liquid phase (-162°C) to the gaseous phase (25°C) and the cold energy of 250 KW/t of the LNG is transferred to the seawater (He *et al.,* 2019). The total work required to convert the liquid methane to gas and heat it by 200 K is about 5×10^{10} kJ in the 125000 m^3 tank (the usual capacity of the tank). The value, which we believe must be higher than the value of heat exchanged between the sea and the LNG terminal, since seawater is not used in the whole process of liquid gas heating (and is difficult to estimate), is small compared to air-sea heat fluxes. Monthly values of heat exchange between air and sea in the northern Adriatic region are up to 150 W/m^2 (Supić & Orlić, 1999) or about 4×10^{12} kW for a total area of the northern Adriatic of about 30000 km^2 or 4×10^{17} kJ per day. However, cooling in the sea region near the terminal leads to changes in the density fields and thus affects the geostrophic component of the currents. Changes in the circulation occur, as well as a redistribution of the temperature and salinity fields. Because of the interaction between air and sea, it is also expected that the changes in surface temperature induced by the presence of LNG will affect atmospheric conditions and possibly lead to changes in the wind regime in the area.

In the future, temperature increases would lead to some changes in the circulation patterns in the northern Adriatic (Dunić *et al.,* 2022). In contrast, while the number of LNG terminals is expected to increase, the response of these future density and current fields to the presence of the LNG terminal is beyond current knowledge. It can only be speculated that the induced currents, as a result of both climatic and anthropogenic influences, could significantly alter the existing Adriatic circulation patterns and wind regimes.

The amount of cold water released from the LNG terminal in the analysis herein is probably greater than in the real situation. However, even with a smaller amount of cold water, the circulation, at least near the LNG terminal, would change, which in turn would lead to changes in the ecosystem near the terminal or even in more distant locations. These changes cannot be predicted without detailed analysis. Further multi-year simulations of the changes in the circulation system are necessary, but other physical parameters (density, salinity, river inflow...) should also be included in the simulations to determine the cumulative impact of a possible LNG terminal on the marine environment.

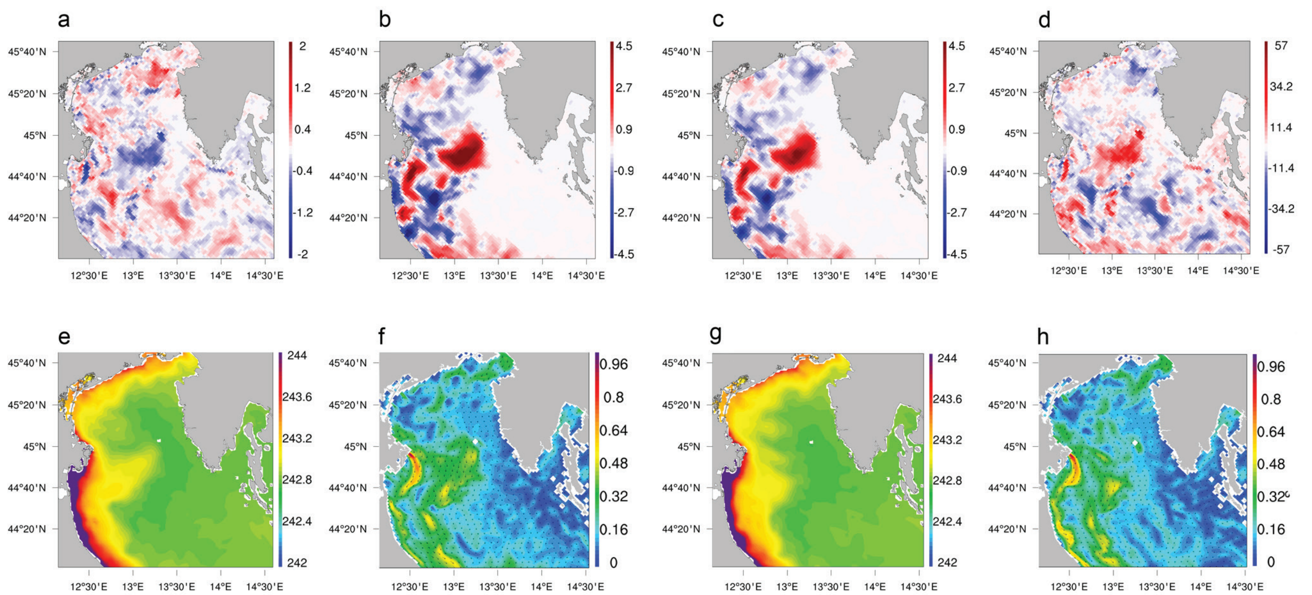

Fig. 12: The differences in a. sea temperatures, b. salinity, c. density and d. surface heat flux after 17 days (20/05/2016) of continuous discharge (started on 02/05/2016) from the potential offshore LNG terminal Istria. Dynamic depths of the 25 dbar surface and circulation are given for the undisturbed (e and f, respectively) and disturbed (g and h, respectively) cases.

Conclusions

The differences in sea temperature are visible in autumn and spring/summer compared to the normal situation without discharge over the whole northern area of the Adriatic Sea, except for the simulation after 5 days of continuous discharge in autumn, where the differences are concentrated in a circle of 2 NM diameter around the discharge opening. The differences in sea temperature are more pronounced at the sea surface than at 25 m depth or at the seabed, but all these differences fit within the normal temperature ranges of $\pm 3^{o}$ C for the observed periods. These results are consistent with those found in the literature (Jelavić *et al.,* 2017; Ivančić *et al.,* 2010; Supić & Ivančić, 2002).

Although the temperature differences with and without discharge lie within the normal temperature range, the simulations show that the discharge of the LNG terminal changed the speed and direction of the sea surface currents compared to the normal situation without discharge, not only in the vicinity of the discharge outlet, but also in the wider area of the northern Adriatic Sea. According to the example, which includes the distribution of the dynamic depths of the 25 dbar surface and the modelled circulation fields, the changes in circulation are due to the geostrophic component of the currents.

The simulations of the circulation over the whole area of the Adriatic Sea show changes in the circulation patterns after 3 months of continuous discharges from the LNG terminal at 25 m depth and at the seabed during the autumn-winter period. The observed changes in circulation patterns may cause significant changes in nutrient and oxygen distribution and thus affect the total annual production in the Adriatic Sea.

The winter production of the northern Adriatic is strongly influenced by circulation (Kraus *et al.,* 2015). Changes in the winter circulation can therefore affect the intensity of primary production in the region and perhaps even influence total annual production. As deep water forms in the northern Adriatic and spreads through the bottom layer in winter (Vilibić *et al.,* 2016), the observed changes in flow patterns at 25 m depth and at the seabed due to LNG terminal discharges may lead to significant changes in nutrient and oxygen distribution in the deep layers.

The amount of heat released to the sea from the LNG terminal is very small compared to the total air-sea heat flux of the northern Adriatic. However, changes in the surface temperature distribution are reflected in the spatial distribution of air-sea surface fluxes, which may lead to changes not only in the sea circulation but also in the wind regime of the area. Moreover, the warming trend would lead to some changes in the circulation patterns of the northern Adriatic in the future, while the number of LNG terminals is expected to increase. The response of density and current fields to the presence of LNG terminals is an interesting issue but it can only be speculated that the induced currents, as a result of both climatic and anthropogenic influences, could significantly alter the existing Adriatic circulation patterns and wind regimes. However, the data reported herein point to the importance of further studies in this direction, as well as continuous monitoring of the areas affected by the terminal (in the air and in the sea).

Acknowledgements

Support of the Croatian Science Foundation projects “Ecological response of northern Adriatic to climatic changes and anthropogenic impact” (EcoRENA, IP-2016-06-4764), and “Marine Rogoznica Lake as a model for ecosystem functioning in the changing environment” (MARRES, IP-2018-01-1717) is gratefully acknowledged.

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