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Modelling origin and transport fate of waste materials on the south–eastern Adriatic coast (Croatia)

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Abstract. The south–eastern parts of the Adriatic Sea coastline were severely polluted by large amounts of accumulated waste material in the second half of November 2010. The waste, reported by major news agencies, accumulated dominantly during 21 of November 2010 by favourable wind - ocean current transport system (the East Adriatic Current from south–east). In the study we analysed meteorological and oceanographic conditions that lead to the waste deposition using available *insitu* measurements, remote sensing data as well as numerical models of the ocean and the atmosphere. The measured data reveal that an intensive rainfall event from 7 till 10 of November 2010, over the parts of Montenegro and Albania, was followed by a substantial increase of the river water levels indicating a possibility of flash floods that could have splashed the waste material into a river and after to the Adriatic Sea (or to the sea directly). The currents that can bring this waste to Croatia could have been intensified by the strong wind from south–east. In order to test these two hypotheses we set a number of numerical drifter experiments with trajectories initiated off the coast of Albania during the intensive rainfall events following their faith in space and time. The numerical drifter trajectory experiments that resulted with drifters that reached the right position (south–eastern Adriatic coast) and time (exactly by the time the waste was observed) were initiated on 00 and 12 UTC of 10 November 2010, during the mentioned flash flood event.

1 Introduction

On the 21 of November 2010, a dramatic waste accumulation has been widely reported by public media (web news agencies, television, radio, daily papers) at the south–eastern coast of Croatia, particularly area of Pelješac Peninsula; islands Mljet, Korčula and Lastovo as well as in numerous inlets and beaches north–west of Dubrovnik (see map of the area in Fig 1). The heaps of waste were composed mostly of plastic packages, glass bottles, clothes and other typical floating municipal garbage while labels suggested that some part of the waste arrived from Albania. It is a country on the south–eastern Adriatic coast 100 km south–east of the area where waste accumulated. The labels are no proof that the waste originated from Albania. One can easily imagine a heap of waste accumulated on a sea shore anywhere on Earth with labels "Made in China" since it is well known for its massive production and export. This study describes a possible chain of events that lead to waste accumulation on beaches in south–east Croatia. It is not unusual that a few pieces of waste reach Croatian coast in a late autumn, however the event was several orders of magnitude larger than any other in previous years (according to the local officials, there were no reports in the media).

The meteorological conditions during October and November in southern Adriatic included several episodes of intensive precipitation that initiated flash floods in Montenegro and Croatia (there were no reports available for Albania). A flash flood event could have washed the waste to the sea (or first to a lake or a river that would eventually take it to the sea). There was no rainfall data from Albania available through standard international data exchange so remote sensing data and NWP model data were used to estimate which intensive precipitation events could have initiated a flash flood there. The high precipitation events that could have initiated flash flood in the area are identified by combination of in-situ and remote sensing data.

Numerical modelling studies that examine how a floating entity reached a certain position by means of atmosphere and sea driven currents have been done before (Beg Paklar et al., 2008; Döös et al., 2011; Liu and Weisberg, 2011). The subjects range from explanation of how floating sweet potato reached Polynesia from South America (Montenegro et al., 2008), spread of oil spills such as the one following the Deepwater Horizon disaster has received more attention (for a collection of articles see http://deep waterhorizon.nooa.gov/) as well as the floating debris that was washed to the sea by tsunami following the Tohoku 9Mw earthquake on 11 March 2011 (see http://www.marinedebris.noaa.gov/).

In our case we use meteorological and ocean models to explore how waste items, once washed to the sea, floated to the area affected by the accumulated waste. During this study we assume that strong south–easterly wind intensified the sea current system that was favourable to bring the floating waste materials. Previously, we also assumed that the waste was splashed into the sea by strong flash floods as a consequence of the severe torrential rain. These hypotheses are further investigated using all available meteorological, oceanographic and hydrological observational data as well advanced meteorological and oceanographic numerical models.

The next section describes the geographical characteristics of the area, meteorological and oceanographic conditions, measured data and models used in this study. Results of model simulations are presented in Section 3 and summarized in conclusions in Section 4.

2 Region, Data, and Models

2.1 Region

The Adriatic Sea is a narrow sea, connected to the Mediterranean only by the Otranto Strait at the southern part. Bathymetry varies over the basin, with the northern part as the shallowest, with mean depth of 35 m, the central and southern Adriatic are significantly deeper and divided by Palagruža sill (Fig 1). The central region reaches up to 280 m depth in Jabuka Pit. The southern region is the deepest, up to 1200 m in the South Adriatic Pit (SAP).

The Adriatic Sea surface flow is predominately cyclonic orientation (Cushman-Roisin at al., 2001) with distinct current regime of East Adriatic Current (EAC) flowing north–west along the eastern coast characterized with salty and warm water from the Ionian Sea. During the rain seasons EAC is further intensified with the outflow of the Albanian rivers creating region of fresh water (ROFI) dynamics (Burrage at al., 2008, 2009). In the central region the sea surface flow typically bifurcates east of the Palagruza Sill (eg. Wolf and Luksch (1887)) enhancing the cyclonic circulation in the southern Adriatic (Artegiani et al., 1997; Horton et al., 1997). On the other side of the Adriatic Sea there is a Western Adriatic Current (WAC) holding fresher and colder water along the western coast. It carries a signature of Po river outflow, the most important source of fresh water in the whole Adriatic Sea.

On the land, the area is surrounded by Apennines in the west, Dinaric Alps and high mountains of Montenegro and Albania along eastern coast while on the northern coast reaches low and flat Po valley. Mountains are much closer to the shore on the eastern side of the Adriatic Sea, with several peaks higher than 1.5 km located less than 10 km from the coast (Fig 1). Those mountains have a strong effect on the air flow and atmospheric dynamics (Mesinger and Strickler, 1981) and consequently define the sea current response as well.

Mediterranean cyclones often traverse the area (Horvath et al., 2009) from south. However cyclones often form in the Genoa Bay, at the north–west (Mesinger and Strickler, 1981) traverse the Tyrhennian Sea and continue to the east possibly supporting cyclone development and intensification in the Adriatic Sea at the east and Ionian Sea at the south (Alpert et al., 1990). These cyclones usually cross the Adriatic Sea but in a certain synoptic conditions can support development of a separate Adriatic cyclone (Horvath et al., 2008) and other mesoscale weather activity. In that case two of these cyclones can coexist forming a system of twin cyclones in which moist air converges and generates large quantities of available precipitable water (Lionello et al., 2006).

The intensive dynamics found in the area also supports strong wind (Horvath et al., 2011; Bajić et al., 2007; Branković et al., 2008) development with the most severe and gusty wind from north–east named bura (see Grisogono and Belušić (2009) for a review), as well the local wind from south–east referred as jugo (Jurčec et al., 1996). Strong bura or strong jugo can last for several days inducing strong response in the Adriatic Sea (Kuzmić et al., 2006; Dorman, et al., 2006). Onset, duration and spatial distribution of wind strength in a bura or jugo episode is controlled by an interaction of the synoptic and/or mesoscale forcing with local topography (Ivatek-Šahdan and Tudor, 2004; Pasarić et al., 2007; Tudor and Ivatek-Šahdan, 2010). The bura strength varies significantly in space and time forming usually several stripes of strong wind across the Adriatic Sea separated by areas of milder wind (Grubišić, 2004) related to mountain gaps and ridges upstream. On the other hand, jugo blows along shore, it is more steady and relatively warm wind related to a Genoa cyclone (Jurčec et al., 1996) or mesoscale cyclone above northern Adriatic (Brzović and Strelec Mahović, 1999; Brzović, 1999). Jugo can be associated with sirocco. However, the terms jugo and sirocco are not synonyms. The latter is a southern wind blowing from Sahara in advance of low pressure moving eastward across southern Mediterranean Sea. Jugo is SE wind over Adriatic, while in sirocco episodes, wind that brings the Sahara desert dust over Adriatic can be from south or south–west.

Climatologically, Southern Adriatic region is characterized with warm and dry summers and mild and wet winters (Zaninović et al., 2008). The area receives abundant precipitation amounts as Crkvice in Montenegro holds the maximum measured on the European continent (Magaš, 2002). Parts of the northern Albania is rich in precipitation but unevenly distributed in space and time. In those regions precipitation can be further intensified by increased aerosol concentration (Koren et al., 2012) usually advected to the Adriatic Sea area from the Sahara desert by the sirocco wind.

It is worth to say that wind forcing, when pronounced, dominate over all other forcing contributions and dynamically shape the sea surface currents system found in the Adriatic Sea. The surface wind jets and wakes of the bura wind have a profound effect on the surface currents (Orlić et al., 1994; Pullen et al., 2003), while jugo wind is well known to influence WAC flow reversals (Orlić et al., 2007; Poulain et al., 2004). It is therefore important to drive the ocean model with a high resolution wind field that resolves high resolution wind features that develop due to interaction of large scale dynamics with local mountains surrounding the sea.

2.2 Data

In order to test our hypothesis and numerical model results we used available remote sensing data and *insitu* measurements. For the meteorological part we used SYNOP, climatological and raingauge measurements from Croatia, Montenegro, Italy, Greece and Macedonia. At the time of the event (November 2010) there were no *insitu* measured data available from Albania through standard meteorological network, the data from airport did not contain measurements of precipitation. The hydrological analysis was based on the water level measurements on relevant major rivers in Montenegro and Macedonia used to confirm intensive precipitation as possible cause of the flush flood events. Since these rivers flow through Albania or along its border on their way to the sea, this is a good indicator of the state of the rivers in Albania.

Remote sensing data, used in this study, originate from Meteosat Second Generation (MSG), specifically from The EUMETSAT Network of Satellite Application Facilities (NWC SAF)[1]. Satellite derived precipitation data are used as provided from the Tropical Rainfall Measuring Mission (TRMM, Huffman et al. (2007)), in particular we used the diurnal accumulated precipitation data from the 3B42 product and 3 hourly precipitation intensity data from 3B40RT product. Precipitation can be enhanced by the presence of aerosols. The two sets of aerosol data presented in this study are the aerosol optical thickness (AOT) from Moderate Resolution Imaging Spectroradiometer (MODIS, Remer et al. (2008)) aboard Aqua satellite and Ozone Monitoring Instrument aboard NASA's Earth Observing System (EOS) Aura satellite (OMI, Torres et al. (2002),Veihelmann et al. (2007))[2]. The wind over the sea surface derived from MetOp ASCAT (Bentamy et al., 2012; Bentamy and Croizé-Fillon, 2012) was used to evaluate 10 meter wind field from the meteorological model.

2.3 Models

2.3.1 Atmospheric model – ALADIN

The numerical weather prediction (NWP) model data used in this study originate from the operational 8 km resolution forecast runs using ALADIN limited area model (Aire Limitée Adaptation Dynamique développement InterNational, ALADIN International Team (1997)) with a specific local 3D–var data assimilation (Stanešić, 2011). In autumn 2010, operational forecast run twice per day up to 72 hours in advance starting from 00 and 12 UTC analyses. The model forecast in 8 km resolution used initial and boundary conditions from global model ARPEGE (Action de Recherche Petite Echelle Grande Echelle, Cassou and Terray (2001)) run operationally in Meteo France. The operational high-resolution dynamical adaptation (Ivatek-Šahdan and Tudor, 2004) provides forecast of 10 m wind adapted to local and upstream topography (Horvath et al., 2011). Unfortunately, this method provides only wind field at high resolution, but not the other meteorological variables needed to force the ocean model. The meteorological model 10 m wind field is obtained by vertical interpolation from the lowest model level (17m above sea), see Geleyn (1988) for more details.

In order to simulate the mesoscale characteristics and development of the low pressure field, a 2km resolution forecast using the non-hydrostatic set-up of the ALADIN model and the full parametrization set, including radiation, microphysics and convection schemes (Tudor and Ivatek-Šahdan, 2010) was used to model the state of the atmosphere. The high-resolution forecast uses scale selective digital filter initialization Termonia (2008) and no data assimilation to initialize the model fields. It is coupled to the ALADIN 8 km resolution with 3 hour interval. This might be insufficient to prevent the fastest of the meteorological features to enter the domain unnoticed by the lateral boundary coupling procedure (Tudor and Termonia, 2010) and possibly miss or undersample a storm rapidly

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[1] products available on the http://www.eumetrain.org/

[2] The OMI and TRMM data are available from Giovanni web server interface (Acker and Leptoukh, 2007) on http://disc.sci.gsfc.nasa.gov

entering the domain through the lateral boundaries. Since the southern Adriatic is not very far from the southern lateral boundary of the high resolution domain, model could have underestimated a storm arriving from south through Otranto strait, however this would be a short duration event related to a flash flood but too short to affect the sea currents substantially.

2.3.2 Ocean model

The quality of simulated currents on the ocean surface depends on the wind field. Wind field over Adriatic is variable in both space and time, depends on surrounding topography and events with strong and severe wind are better forecast in high resolution NWP models (Ivatek-Šahdan and Tudor, 2004; Branković et al., 2008; Tudor and Ivatek-Šahdan, 2010). The ocean dynamics as a response to the atmospheric forcing was computed using REgional Ocean modelling System (ROMS, Shchepetkin and McWilliams (2005)) numerical model. ROMS model belongs to free surface, Boussinesq and hydrostatic approximation models that solves primitive equations using curvilinear finite difference grids. Model was forced with ALADIN meteorological model data (10m wind, 2m temp and relative humidity, sea level pressure, rainfall rate, short wave radiation and cloud fraction), climatological values for the Adriatic river run-offs and open boundary values with daily temperature, salinity, currents and sea level information from AREG (INGV) Mediterranean model. The advection scheme for tracers (temperature and salinity) is based on multidimensional positive definite advection transport algorithm - MPDATA (Smolarkiewicz and Margolin, 1998) while for momentum on 3rd order upwind scheme. More details of model implementation for the Adriatic Sea are described in Janeković et al. (2010). ROMS model time step was 120s while output frequency of needed current fields were every hour. Those hourly values were used for computations of drifter trajectories.

The sea surface currents, responsible for waste transport, are computed using 2 km resolution ROMS ocean model and were used for virtual drifter trajectory simulations. Drifters are set to the surface layer, without vertical dynamics, ensuring representation of floating waste material. For computing numerical drifer trajectories we used Roms OFfline Floats (ROFF) package (Carr et al., 2008), available for ROMS comunity (http://web.atmos.ucla.edu/ capet/Myresearch/my_research_floats.html).

3 Results and discussion

3.1 Atmospheric model results

To estimate the convective rainfall rate and precipitating clouds we used derived fields from the NWC SAF products focused on studied area and time, rain-gauge measurements and TRMM rainfall data. The NWC SAF precipitating clouds (PC, Thoss (2012)) field provides precipitation probabilities and the convective rainfall rate in mm/hour (CRR Rodiriguez and Marcos (2012)) is computed assuming that clouds being both high and with a large vertical extent are more likely to induce rain (see http://www.nwcsaf.org/ for more details). CRR gives estimate of intensive rainfall from convective clouds, but PC is useful estimate of rainfall from other types of clouds (eg. nimbostratus). According to the available rain-gauge measurements, 6 hourly PC and CRR fields and TRMM rainfall data, there were several heavy rainfall events in the month preceding 21 November 2010 that could have caused flash floods in the area of south–east Adriatic coast and inland.

We identify those events as four episodes: 23-25 October (E1), 2-3 (E2), 8-10 (E3) and 17-18 of November 2010 (E4).

The large scale synoptic conditions responsible for meteorological setup are described using ERA Interim (Dee et al., 2011) re-analysis fields. It turns out that on 24 of October 2010, low pressure system entered western Mediterranean from Atlantic, deepened and formed a cyclone, centred over Genoa bay. The next day the pressure decreased further and the associated southern wind strengthened from northern Africa to Adriatic causing intensive rainfall over the eastern Adriatic coast (E1). The cyclone moved south–east on 26 and initiated severe bura wind first on northern Adriatic and later spread over the whole Adriatic Sea by 27 of October 2010. An ensemble of trajectories initiated over south–east Adriatic on 12 UTC, 25 of October 2010 were used to test if this severe rainfall event was the one that flushed the waste to the sea. The results of these trajectory computations are described later in the text (as experiment 2 in Section 3.3.1)

Another cyclone from the 1 to the 4 of November 2010 (E2) moved from the Genoa bay south–eastward, causing strong jugo wind over the Adriatic Sea (Fig 6). The rainfall was the most intensive over the northern Italy and central Adriatic region with most of the rainfall above the Adriatic sea. Northern Adriatic received more than 100 mm of precipitation within 24 hours, while the rain was weak in the south–eastern region of our interest (Fig 2). Consequently, E2 case was omitted from further analysis as was too weak to initiate a flash flood in south–east Adriatic. In the following days, meteorological situation was stable with weak pressure gradient, low wind as well high pressure over western Mediterranean inducing moderate winds from north–west.

The weather changed again in the period from 7 till 10 of November 2010 (E3), dominated by a large scale cyclone (Fig 3) that arrived from the Northern Atlantic causing sirocco wind over Mediterranean (the colour of the wind vectors in Fig 3 indicates wind speed in m/s) that brought warm air and Sahara dust from the northern Africa (often found in rain gauges after intensive rainfall events), aerosols are also shown in Fig 3. Over Adriatic, the wind was strong to severe from south–west and south direction (Fig 6). The wind direction was well forecast by the model, but at Palagruža, Dubrovnik, Prevlaka wind speed was underestimated, while at Mljet and Biokovo the observed wind speed was correctly modelled. Pressure measurements reveal that during this event the Adriatic Sea was subject to a deep cyclone that last for several days (Fig 6) with a strong pressure gradient over the Adriatic sea.

The precipitation intensity was estimated using the PC and CRR fields that showed strong convection and rainfall in the afternoon and evening having periods with weak to moderate rain intensity in the night and early morning. The precipitating clouds covered much of the area, while the convective rainfall rate is far more localized and very intensive. It is important to note that PC and CRR fields were available on 6 hour interval, while heavy rainfall could have occurred outside the sampling interval and easily could have been missed. The 24 hourly precipitation exceeds 100 mm over northern Albania in TRMM precipitation estimates (shown as squares in Fig 4) and measurements at several rain-gauges in Montenegro for two consecutive days (rain-gauge measurements are shown as circles in Fig 4) as well as in the model forecast (shaded background in Fig 4). Measurements from the rain-gauges showed that rainfall during the E3 was the most intensive on stations in Montenegro (larger circles and stars on Fig 2) hence on south–east Adriatic coast and significantly more intensive than in other episodes in November 2010. For example, on 10 November 2010, there was 188.1 mm of rain measured at Cetinje and 143 mm measured at Golubovci station, both in Montenegro. Accumulated precipitation data are shown on maps for 9 and 10 November 2010 (for all available stations, circles in Fig 4). There are 3 intensive precipitation events before 21 November 2012, and measured precipitation exceeded 100 mm/24 hours in Montenegro only in the event 7 to 10 November 2012 (Fig 2. The forecast of the accumulated 24 hourly rainfall corresponds to the values measured on rain-gauges, although the model exaggerated slightly the rainfall on the coastline and underestimated the rainfall on several locations further inland (Fig 4). Wind measurements (Fig 6) show that wind in E3 episode was from south direction, more energetic and lasted longer than for other strong wind episodes during November 2010.

After E3, in the period from 11 till 15 of November 2010, the weather was mostly dry with weak to moderate wind and direction typical of the sea breeze diurnal cycle (Fig 6). In the next days a cyclone formed in the Genoa bay (15 of November 2010) supporting again strong jugo wind over the whole Adriatic Sea (Fig 5). Moreover, the wind strengthened (Fig 6) with prevailing direction from south–east as measured in Dubrovnik, Mljet and Prevlaka (Fig 7). Precipitation was intensive with peaks above 100 mm within 24 hours on 17 November (E4), but the maxima were localized on north–east Adriatic. The ALADIN model forecast had similar rainfall distribution, as a result, E4 was omitted from detailed analysis as a period favourable with respect to the flash flood. However, it is important as the wind field has driven the currents on the sea surface. During E4 wind was stronger on the coast (Dubrovnik and Prevlaka) than in the off-shore region (Mljet), as a consequence of channelling effect the coastal mountains (Fig 7). Model yields stronger wind above open sea (thiner arrows on regular grid in Fig 7) over southern Adriatic than MetOp ASCAT wind data (thicker arrows in Fig 7) for 16 November 2010, but the wind strength and direction are correct for 17 November 2010 (Fig 7). The global pressure gradient over the Mediterranean and Central Europe supported the wind regime from south and south–east over the whole southern Adriatic (Fig 5). Later, by 19 of November 2010, the wind changed direction to south–west. A cyclone moved from Atlantic south–east, to the western Mediterranean. The wind changed to strong and severe jugo wind on the 21 of November 2010.

Based on the analysis of available precipitation fields, it turns out that E3 episode was the one when intensive rainfall occurred over Albania and surrounding countries and was the most likely event that triggered a flash flood.

3.2 Hydrology

Annual river run-off distribution for the Albanian rivers usually varies for an order of magnitude during the year (embedded diagram in Fig 8) with one pronounced peak in November and another in January. Bojana river collects the water flowing from Drim river and Skadar lake and flows into Adriatic along the border between Albania and Montenegro.

The largest lake in the region, the Skadar lake, is filled by river Morača and Crnojevica in Montenegro and drained into Bojana river (the name is Bojana in Montenegro and Buna in Albania). Bojana river also receives Drim river as a major tributary on the way to the Adriatic Sea. Drim (Drim in Montenegro, Drin in Albania) river powers 3 hydroelectric power plants in Albania. Downstream it splits into two flows, the smaller one reaches the Adriatic sea directly, and the larger part flows into Bojana river.

The river water level measurements on the rivers in Montenegro that belong to the Adriatic Sea catchment (Fig rivers 8) increase substantially for the E3 episode. The water level surge is most intense for the rivers that fill the Skadar lake. The level of Bojana river raised as well during the same event. This is followed by a rise of 1.5 m in the water level of the Skadar lake. Bojana river level rose before the level of Lake Skadar, this could have happened due to an increase in contribution from the Drim river tributary. The water levels of Skadar lake and Bojana river stayed high until the end of November 2010.

Those measurements suggest that the event (E3) from 8 till 10 of November 2010 was capable of flushing the waste material into the Adriatic sea or any of the rivers in the area that flow into it.

3.3 Ocean model results

Ocean model results show (Fig 9) consistent development of strong surface north–west currents after strong jugo wind episodes and small eddies close to the eastern Adriatic coast in the periods of weak wind forcing. As stated before in the text, during the November 2010, we can find three periods of different wind conditions over the Adriatic Sea. The first one from 7 till 11, when strong south–east wind generated strong north–west current system in south–east Adriatic (Fig 9a) followed by a weak wind period when the sea-current transport was weaker (Fig 9b) and the ocean model formed a pool of colder water in south–east Adriatic in the area where Bojana river enters the Adriatic Sea. Finally, the period with moderate to strong south–east wind (Fig 9c) strengthened the north–west current. This was most likely responsible for waste transport and deposition.

3.3.1 Numerical drifter trajectories

The waste consisted of floating items, so its movement was computed as virtual floating drifters released in south–east Adriatic. Trajectories of virtual drifters were computed using ROFF package and surface currents from 2 km resolution ROMS run. The computation of the trajectories of the drifters stopped when they reached coastline for the first time. A number of numerical drifter experiments was set in which trajectories were initiated in south–east Adriatic on the 12 UTC, 19 (experiment 1) and 25 of October 2010 (experiment 2), and then sequentially at 00 and 12 UTC on each day starting from 8 till 12 of November 2010 (experiments 3 – 11). All virtual drifters were released within a polygon covering an area over southern Adriatic. The initial points of virtual drifter trajectories are separated by 0.01 degree ($\approx$ 1 km) along longitude and latitude (total 3071 drifters) and fill a polygon with longitude and latitude coordinates of south–west corner (19.1,41.0) and north–east corner (19.4,41.9) that cover a portion of south–eastern Adriatic Sea in the vicinity of coast of Albania and Montenegro (Fig 10). Furthermore we divided the polygon into 9 areas (A1,...A9) to better cluster track different regions, hence possible source origin. The drifters starting from different areas are plotted in different colours, as marked on the Fig 10. The longitude and latitude coordinates of south–west and north–east points of the polygons are

- A1: SW (19.1,41.0), NE (19.2,41.3) shown in red,
- A2: SW (19.2,41.0), NE (19.3,41.3) shown in green,
- A3: SW (19.3,41.0), NE (19.4,41.3) shown in blue,
- A4: SW (19.1,41.3), NE (19.2,41.6) shown in magenta,
- A5: SW (19.2,41.3), NE (19.3,41.6) shown in cyan,
- A6: SW (19.3,41.3), NE (19.4,41.6) shown in yellow,
- A7: SW (19.1,41.6), NE (19.2,41.9) shown in dark green,
- A8: SW (19.2,41.6), NE (19.3,41.9) shown in orange,
- A9: SW (19.3,41.6), NE (19.4,41.9) shown in gray,

A plot of drifter positions was done with 6 hourly interval for each experiment (not shown), and the summary trajectories are shown in Fig 10.

- In the experiment 1 the drifters were released at 12 UTC, 19 of October 2010 and were first pushed offshore into EAC. It turns out that a considerable number of drifters originated from regions A7, A8 and A9 reached Croatian coast and Mljet island already on 27 of October 2010. Drifters from regions A4, A5 and A6 reached Mljet channel by 3 of November, but were pushed back south–east in the following days. Those drifters continued further to the north–west and finally accumulated on the islands much further north–west than observed (Fig 10a). There were no reports of significant accumulation of waste on the Croatian coast that would be a consequence of this event. In that sense, we can reject the hypothesis that this rainfall event was the one that caused the flash flood that got the waste material to the sea.

- For experiment 2 the drifters were released at 12 UTC on 26 of October 2010. Soon the drifters were advected in the westward direction. When drifters entered EAC, they moved more to the north–west and were deposed on Mljet Island already on 9 of November 2010. However, several drifters starting from A6 region entered Mljet channel on 18 and later deposed on Pelješac on 21 of November (Fig 10b). Based on those results we can assume that it is possible but unlikely that the rainfall event on 26 October 2010 has initiated the chain of events that led to severe waste disposal in the region.

- Drifters initiated on 8 November (both 00 and 12 UTC – experiments 3 and 4) mostly arrived to south–east Adriatic Sea coast, the northern Albania and Montenegro as soon as on the 11 of November 2010 (Figures 10c and 10d) as a consequence of sea current system supported by strong southern and SSW wind blowing on 8 and 9 of November 2010. Furthermore, strong wind changed direction into NW on 12 and 13th of November 2010 generating currents that transported numerical drifters off the coast, resulting only with a small number of them (initiated from A4 region), to reach Mljet island and coastline north–west of Dubrovnik by 18 of November 2010. The rest of the drifters dominantly stayed in the south–east region, while only a small number of them moved north–eastward not entering Mljet Channel, but instead floated much closer to coast, at the end finally accumulated in the Koločep Channel and Ston bay area on 25 of November 2010.

- Quickest drifters initiated from A7, A4 and A8 regions at 00 and 12 UTC on 9 November 2010 (experiments 5 and 6) reached Mljet Island and entered Mljet Channel already on 17 and 18, while a majority of drifters from other areas accumulated in the Ston bay after 21 of November 2010 (Figures 10e and 10f).

- Small number of drifters from A7, A8 and A9 regions, released at 00 and 12 UTC on 10 November 2010 (experiments 7 and 8) reached Mljet, Dubrovnik and Koločep channel by 18, while other drifters initiated from the same area accumulate on the Croatian shores on 21 of November 2010 (Figures 10g and 10h). The drifters initiated further south lagged behind former ones and approached the affected area on 22 of November 2010. Those dates were the most commonly reported in the media as the onset of severe pollution at the Croatian coast.

- The last three sets of drifters, released at 00 and 12 UTC on 11 and 00 UTC on 12 November 2010 (experiments 9–11) were first pushed westward off the Albanian coast and stayed in the area off shore of Albania and Montenegro for a few days. Later they were transported into southward direction on 14 to 16 November 2012 (Fig 10i). Apparently, EAC was detached, at that time, from the shore and it's typical path. As a result, drifters from A1 and A2 regions arrived further north–westward than drifters initiated more to the north or closer to the coastline.

One should bear in mind that the drifter trajectories do not allow us to assign a single event in space and time as the moment when the waste was disposed to the sea. There is ambiguity in the position as a result of unresolved physics, imperfect meteorological model and initial conditions used to force ocean counterpart, missing dynamics in the ocean model introduced with a lack of wave–current interaction, spatial model resolutions in the narrow channels etc. However, the results do show that there is a possibility and is the most probably that the heavy rain on 9 and 10 of November 2010 washed the waste into the sea (or first to a river that carried it to the sea by that date). The computations further show that not all the numerical drifters initiated in south–east Adriatic inevitably ended on the coastline of south–east of Croatia. Surface sea currents enhanced by the wind forcing can carry the waste back to the shore, or to the closer coastline of Montenegro. Otherwise, different meteo–ocean conditions can push the waste off shore, and EAC can carry the waste to central or even north Adriatic, or in some cases back to the southern regions of the Adriatic Sea. However, none of the trajectories initiated in our experiments crossed the Adriatic Sea and approached to Italy, which is probably due to an absence of intensive bura events during the studied period.

4 Conclusions

The oceanographic and meteorological conditions that lead to a severe deposition of waste material on the south–eastern Adriatic Sea coast on 21 of November 2010, are studied using ALADIN – metorological and ROMS – ocean numerical models along with available measurements. We tried to answer what, where and when was the cause for the event, the initial points presented in this study were limited since the labels that indicated some of the items originate from Albania and the local current system is north–west.

Based on the meteorological simulations and satellite derived precipitation reveal several intensive rainfall events that could have initiated flash floods in Albania and presumably flush the waste material to the rivers and later to the Adriatic Sea. Moreover, measured and NWP model rainfall data shows that the rain was more intensive over the Albania in the event from 8 till 10 of November 2010 (E3) than in the other intensive rainfall events that occurred in the studied area during the 4 weeks before the reported waste accumulation.

Measured wind speed during the episode E3 was strong to severe from southern direction, however slightly underestimated by the operational ALADIN model forecast at several land locations. Improvements in the atmospheric model resolution could resolve those issues as noted in Signell et al. (2005). Since strong wind influences the surface currents that advect the drifters, this could have an impact on the computed trajectories of virtual drifters. It is interesting to note that based on the ASCAT estimated wind data, for the 16 of November 2010, ALADIN model wind speed was larger than the measured one (Fig 7). During the last studied period (E4), wind from observations as well from the model, was from south–east with weaker magnitudes than in the E3 period. In the E4 case the strongest wind was found over the open sea, in the south–east region of Mljet Island as well south of Dubrovnik (Fig 7). This event is a typical jugo wind episode which further enhanced the sea surface current system – responsible for transport of the waste material to the Croatian waters and finally to the shore on 21 of November 2010.

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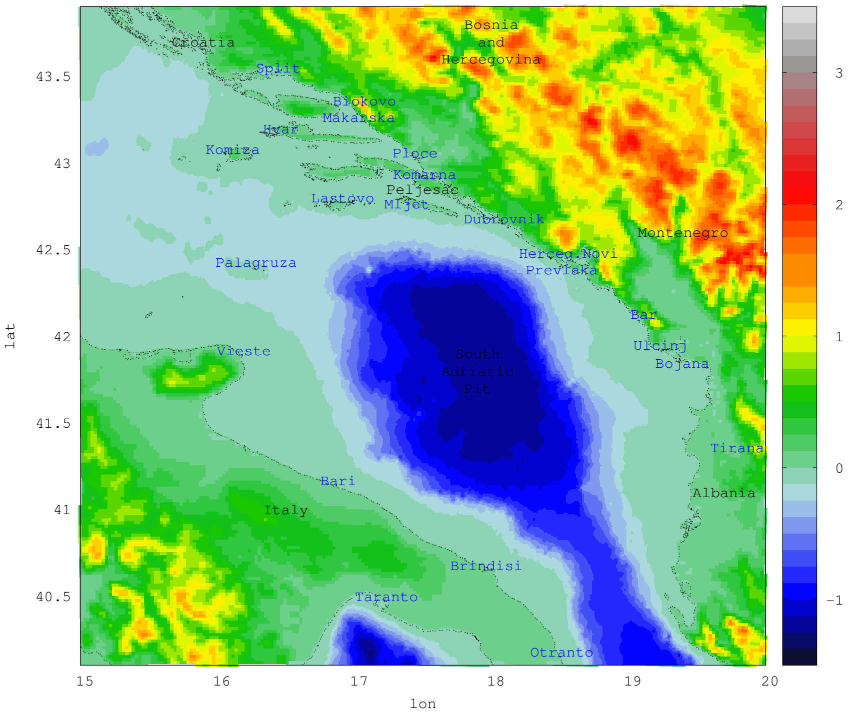

Figure 1. The South Adriatic region with locations of meteorological stations used in this study. The shaded background represents terrain height and sea depth in kilometres according to the scale on the right side. The "Bojana" mark shows position of the point where Bojana river enters the Adriatic Sea (this is also the border between Montenegro and Albania on the coast).

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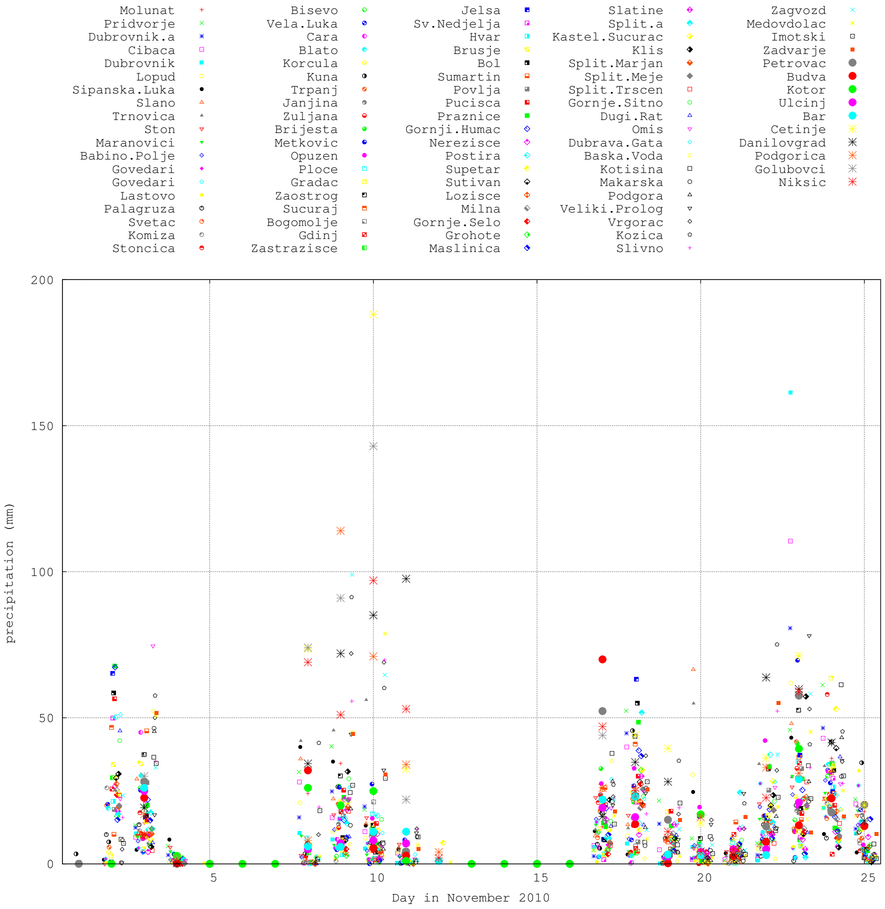

Figure 2. Measured accumulated 24 hourly precipitation on rain gauges in south–eastern Croatia (smaller symbols) and Montenegro (larger symbols) during November 2012. Precipitation shown for a certain day is measured at 6 UTC accumulated from the previous 24 hours. Only stations close to Adriatic are shown.

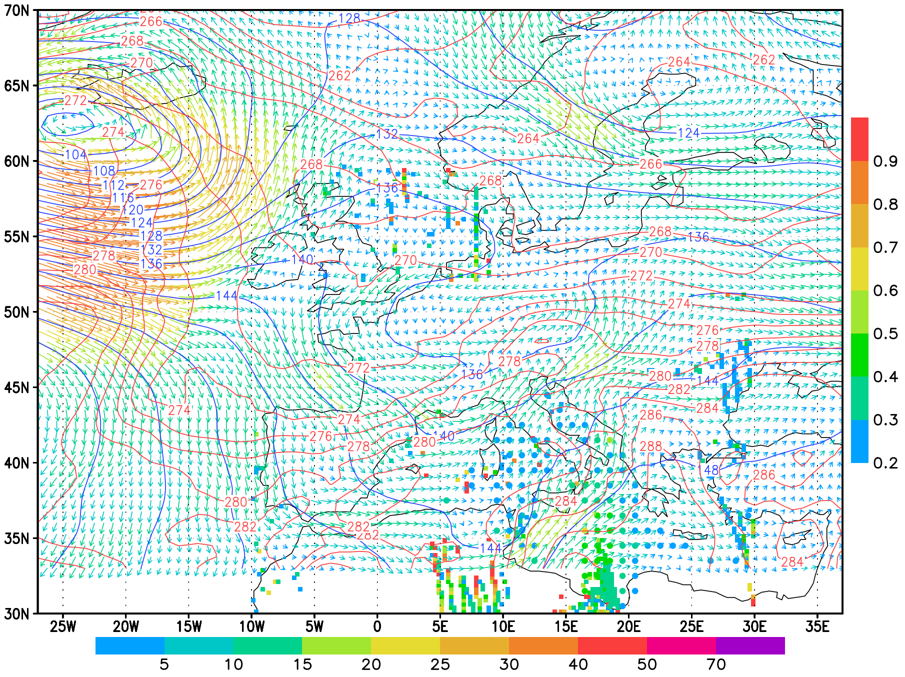

Figure 3. ERA Interim 850 hPa wind (colour of the vectors shows wind speed in m/s as on the colour bar below), geo-potential (blue isolines) and temperature (red isolines) with measured aerosol optical thickness at 12 UTC 7 November 2010 from MODIS (circles) and OMI (squares), AOT is shown in colour according to the colour bar on the right.

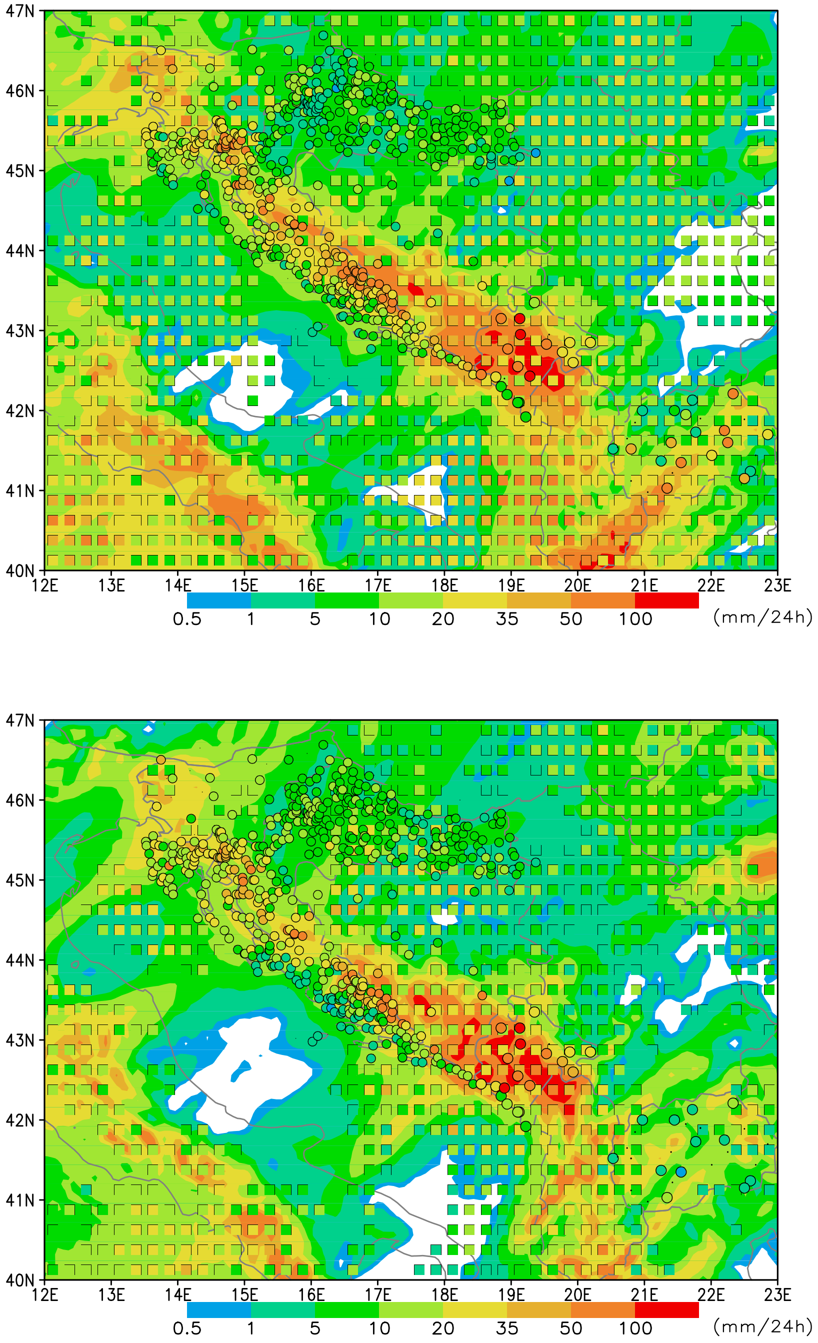

Figure 4. Measured accumulated 24 hourly precipitation on rain gauges in Croatia, Montenegro and Macedonia (circles), TRMM rainfall data (squares) and 8km ALADIN forecast data (shaded), the precipitation is accumulated for the period from 06 UTC on 8 until 06 UTC on 9 (top) and from 06 UTC on 9 until 06 UTC on 10 (bottom) November 2010. The corresponding rain-gauge data is shown in Fig 2 as measured on 9 and 10 November 2010.

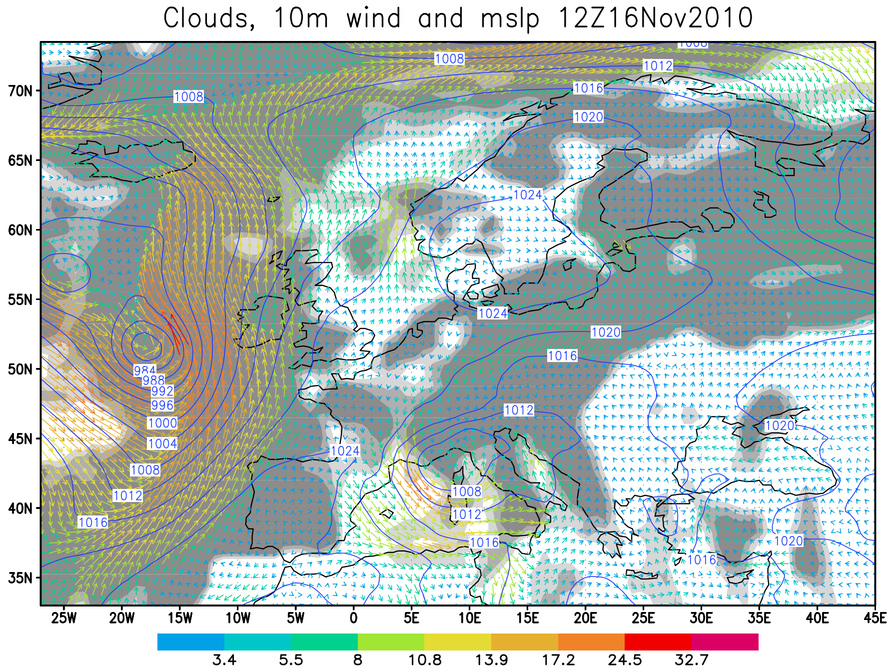

Figure 5. ERA Interim 10 m wind (colour of the vectors shows wind speed in m/s as on the colour bar below), mean sea level pressure (blue) and cloudiness (shades of gray) for 12 UTC on 16 November 2010.

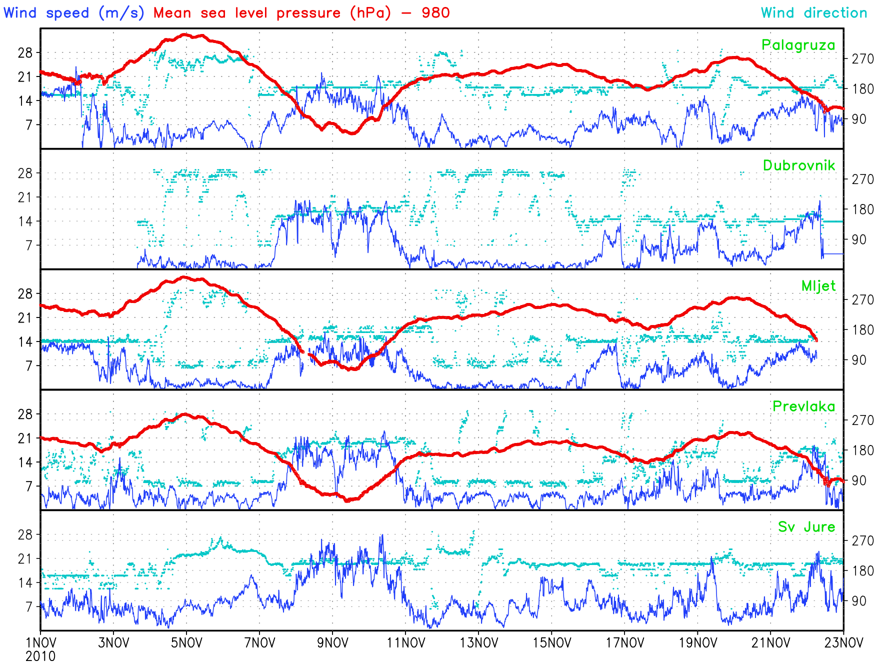

Figure 6. Measured wind speed (dark blue, scale on the left) and mean sea level pressure (red) reduced by 980 hPa (to fit the scale on the left) and wind direction (light blue in degrees from north clockwise, scale on the right) for November 2010 (Sv. Jure is marked as Biokovo in Fig 1).

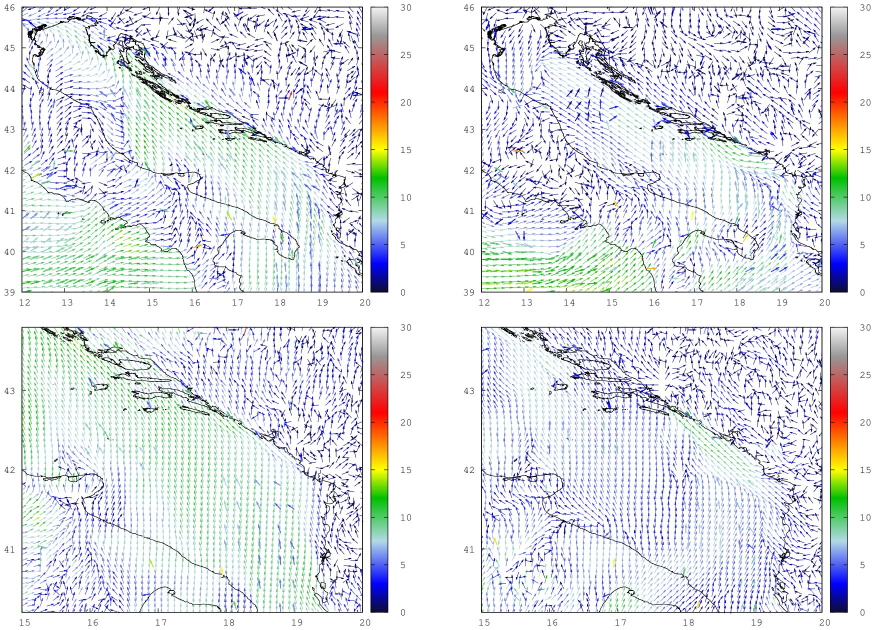

Figure 7. Forecast 10m wind in 8km (top) and 2km (bottom) resolution and measured wind speed and direction (arrows) from MetOp ASCAT data (above the sea surface), SYNOP and automatic stations for 12 UTC on 16 (left) and 12 UTC on 17 (right) November 2010. Colour of the vectors shows wind speed in m/s as on the colour bars. Model data are shown as thin vectors on a denser grid in the background, measured wind is shown as thicker vectors on the location of measurement.

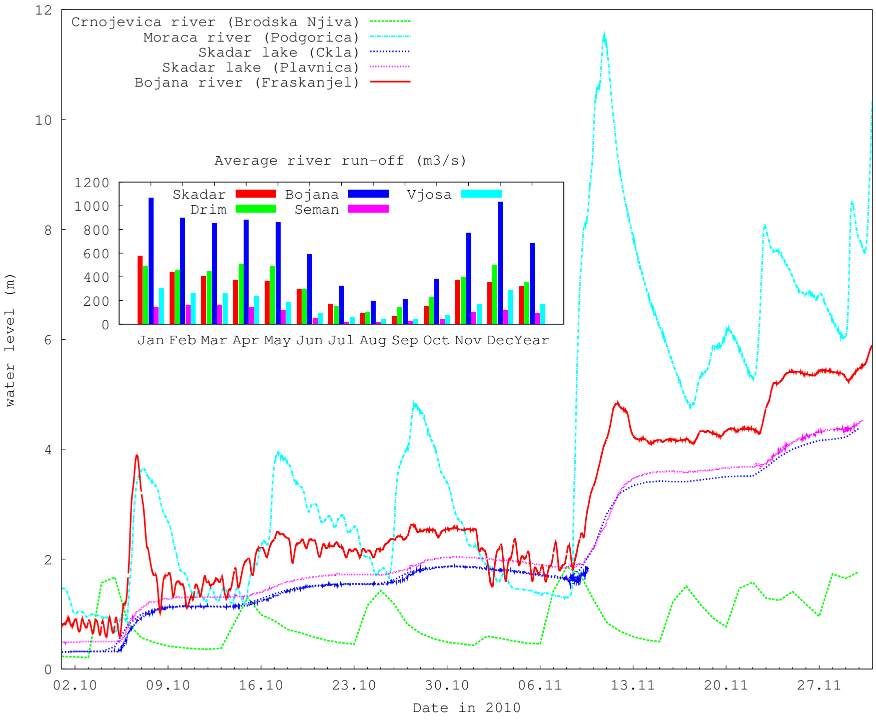

Figure 8. Measured water levels of rivers in Montenegro and Skadar lake in October and November 2010 and climatological river run-off of Albanian rivers (embedded figure). Moraca and Crnojevica rivers are tributaries to the Skadar lake, Bojana river takes the outflow from the Skadar lake and flows into the Adriatic sea at the position marked as Bojana in Fig 1.

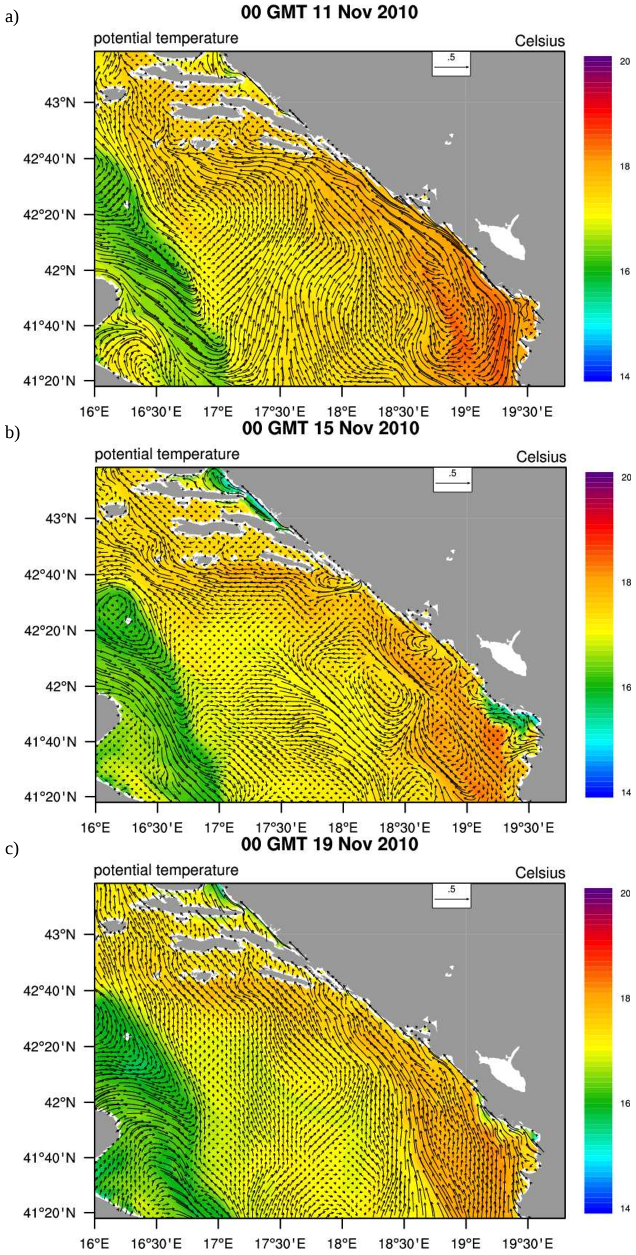

Figure 9. Surface currents (vectors) and sea surface temperature (shaded background) from ROMS for 00 UTC on 11 (a), 15 (b) and 19 (c) November 2010.

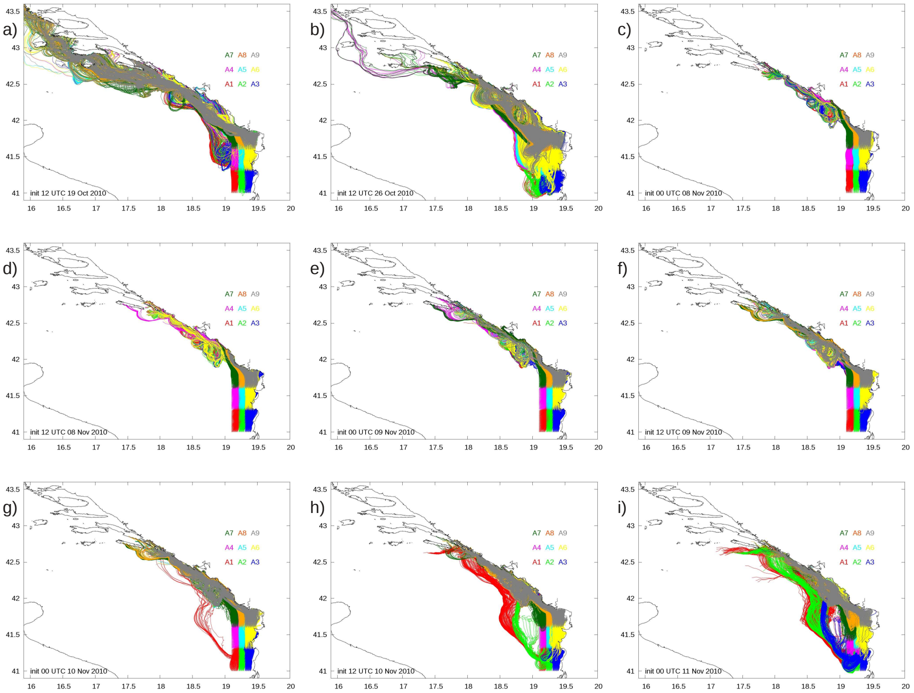

Figure 10. Trajectories of drifters released at 12 UTC 19 (a) and 12 UTC 26 October (b), 00 (c) and 12 (d) UTC 8, 00 (e) and 12 (f) UTC 9, 00 (g) and 12 (h) UTC 10 and 00 UTC 11 (i) November 2010. Trajectories initiated off different parts of a rectangle in south–east Adriatic are plotted in different colours.