TOSCA project

Deliverable D3.4.1
"Basic Lagrangian algorithm to compute transport based on HF and drifter data"

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Contributors: CNR-ISMAR, LSEET

CP3: Analysis of past dramatic events and of different applied methodologies. Preparation and Development of tools & instruments

CP3.4: Implementation of assimilation procedures for the prediction of Lagrangian tracers and oil spill.

- **Partners involved:** DISAM, LSEET, UIB IMEDEA, ICM-CSIC, UAGEAN
- **Duration:** 01/09/2010 to 31/08/2012
- **Deliverables:**
  - 3.3.1: Basic Lagrangian algorithm to compute transport based on HF and drifter data
  - 3.3.2: Advanced prediction algorithm based on data assimilation and models

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I. Introduction

Project description: "A basic, state of the art "Lagrangian" algorithm will be first implemented to compute transport by marine currents using data from HF (High Frequency) radars and drifters. This algorithm will be used for the first products for state authority, i.e. dispersion and probability maps from a given source during the measurement period"

One of the main goals of TOSCA is to provide reliable tools for the prediction of transport and dispersion to be used by public authorities in case of accidents at sea. These tools will allow a joint use of measurements from HF radar and drifters together with model results, in order to provide optimized estimates of currents and their associated transport. Here we present an algorithm that will be used to merge information from HF radar data and drifters.

The rational is the following. HF radars provide a unique source of velocity data over extended coastal regions, making them the instruments of choice to monitor coastal waters and to provide current information in case of accidents. It is important to keep in mind though those radar velocity measurements are relative to the very upper part of the water column and that they typically differ from actual in-situ measurements of transport for various reasons, such as resolution, coverage or influence of sea state. Typical differences between in situ and radar measurements are of the order of 5-10 cm/sec, and can go up to 20 cm/sec in some conditions. For this reason, it is important that HF radar data are complemented, compared and eventually corrected using instruments such as drifters, which directly sample current transport.

For practical applications, in case of accidents at sea, it is highly advisable to have a plan where drifter data are launched in the area of interest, and the drifter information are used together with the radar data. The algorithm presented here allows to perform a "blending" between the two types of data, providing maps of optimized current and transport.

A first version of the algorithm able to correct ("reconstruct") velocity fields using Lagrangian data was already available to the partners (CNR-ISMAR and LSEET), and it has been used as a basis for the development. The algorithm, called LAVA (LAgrangian Variational Analysis) is based on a variational approach and was developed in collaboration between CNR-ISMAR, LSEET University of Toulone, LOV CNRS, RSMAS University of Miami (Molcard et al., 2003; Taillandier et al., 2006a). The algorithm has been thoroughly tested and previously applied to correct velocity fields from numerical models, in the framework of Lagrangian data assimilation. The algorithm has now been customized for TOSCA applications, where the velocity fields are provided by HF radar data. A first series of tests have been made using historical data collected during the MREA/POET 2007 experiment in the Gulf of La Spezia (Molcard et al., 2009), where the LSEET WERA radar was used in VHF mode.

In the following, a brief description of the LAVA approach is provided in Section II together with a brief review of previous applications. The TOSCA customized algorithm is discussed in Section III, while the results from the test case are shown in Section IV.

II. Background on the LAVA algorithm and previous applications

The LAVA algorithm is based on a variational approach (Taillandier et al., 2006a), and previous implementations have been performed in the framework of assimilation of Lagrangian data in numerical models. The crucial step consists in correcting the velocity field at the level where the instruments are transported by the currents (i.e. at the surface for drifters and in the interior ocean for Argo floats), by requiring minimization of the distance between observed positions and positions of numerical trajectories launched in the model (Molcard et al., 2003, Taillandier et al., 2006a). The local correction along the trajectory is assumed to be characterized by some basic correlation scales in time and space that characterize the Eulerian persistence of the flow, and the correction is performed over time sequences that are required to be shorter than both the Eulerian and Lagrangian time scales (Molcard et al., 2003a). Further details on this procedure are provided in Subsection 2.1 below.

2.1. Formal description

Drifter (or float) data positions $\mathbf{r}^{obs}$ and velocity fields from models or radar $\mathbf{u}^{bck}$ are blended together to reconstruct 2D flows. As a priori characterization, the circulation structures to be corrected have a length scale R and a time scale T, and a Lagrangian time scale T_L.
Considering such scaling (R, T, T_L) constant over a well-defined domain (shelf or offshore), the reconstruction consists in computing time-independent sequential velocity corrections $\Delta\mathbf{u}(t_o)$ for successive sampling sequences $[t_o, t_o+\tau]$ in the neighborhood of drifter trajectories. Note that the sequence duration τ is chosen about T_L for a consistent sampling of the corrected structures, and T_L is typically shorter or of the same order as T. Each single-time velocity field is then reconstructed as

(1) $\mathbf{u}^{est}(t) = \mathbf{u}^{bck}(t) + \Delta\mathbf{u}(t_o)$, where $t_o \in [t - \tau/2, t + \tau/2]$

The methodology is based on the resolution of an inverse problem for each single sequence $[t_o, t_o+\tau]$. It evaluates a velocity correction $\Delta\mathbf{u}$ which minimizes the misfit between trajectories simulated inside ($\mathbf{u}^{bck}+\Delta\mathbf{u}$) and observed positions $\mathbf{r}^{obs}$ (Taillandier et al., 2006). This minimization problem is solved using a variational approach formulated by the following procedure:

Stage 1: the prediction of the position $\mathbf{r}^{obs}(t_o+\tau)$ is performed by a trajectory simulation using the non linear equation

(2) $d_t\,\mathbf{r} = \mathbf{u}(\mathbf{r}(t), t)$, $t \in [t_o, t_o+\tau]$, with $\mathbf{r}(t_o) = \mathbf{r}^{obs}(t_o)$

where d_t is the first order derivative in time. This position prediction can be written as $\mathbf{r}(t_o+\tau) = \mathbf{H}_{NL}(\mathbf{u})$. The distance between observed and simulated positions is then expressed by the cost function

(3) $J = ½\,(\mathbf{r}^{obs}(t_o+\tau) - \mathbf{H}_{NL}(\mathbf{u}))^T \cdot (\mathbf{r}^{obs}(t_o+\tau) - \mathbf{H}_{NL}(\mathbf{u}))$

where ^{T} denotes the vector transpose, which components are assumed independent and associated to Gaussian homogeneous errors.

Stage 2: the optimal velocity correction $\Delta\mathbf{u}$ is estimated by minimizing J using a steepest descent procedure, along the gradient

(4) $\nabla J = -\mathbf{B} \cdot \mathbf{H}^T \cdot (\mathbf{r}^{obs}(t_o+\tau) - \mathbf{H}_{NL}(\mathbf{u}))$

where $\mathbf{B}$ is the background error operator, $\mathbf{H}$ the tangent linear operator associated to $\mathbf{H}_{NL}(\mathbf{u})$, and $\mathbf{H}^T$ its adjoint operator. $\mathbf{B}$ is built on finite iterations of the diffusion equation (Derber and Rosati, 1989; Weaver and Courtier, 2001) in the aim to spread each along-trajectory velocity correction around its neighborhood. Note that the number of iterations specifies the characteristic length R. **H** is defined by the perturbation equation associated to Eq.(2),

(5) $d_t\, \delta\mathbf{r} = \delta\mathbf{r}(t)\cdot\mathbf{u}(\mathbf{r}(t), t) + \mathbf{r}(t)\cdot\delta\mathbf{u}(\mathbf{r}(t))$, $t \in [t_o, t_o+\tau]$ with $\delta\mathbf{r}(t_o) = \mathbf{0}$

which involves a time-independent velocity increment $\delta\mathbf{u}$ taken along the simulated trajectory.

2.2. Results from previous applications

The LAVA reconstruction method has been first thoroughly tested using the twin experiment approach in models of increasing realism (Taillandier and Griffa, 2006), and then applied to in-situ data sets.

Two main applications have been performed using drifter data and model results. The first one considers surface reconstruction in the Adriatic Sea using drifters in the upper 1 m and outputs of the ROMS model (Taillandier et al., 2008). The analysis focuses mostly on the impact of the velocity correction on the exchange between the boundary current and the interior. The results are qualitatively consistent with indications from satellite data, but a true quantification using independent data is lacking. The issue of independent data testing has been addressed in a more recent application in the Pacific Sea off Taiwan (Chang et al., 2011), where data from 30 Surface Velocity Programme (SVP) drifters drogued at 15 m and 28 sonobuoys with instrument chains were used in the framework of an operational exercise (LWAD07), together with the outputs of an NRL (Naval Research Laboratory) data assimilating model EAS-16 (East Asian Seas). The velocity fields of the EAS-16 model are corrected using the data from the drifters, and the corrections are statistically propagated from the drifter depth to the water column using the statistics of the (uncorrected) EAS-16 fields. The correction tends to widen the extension of the Kuroshio meander, sharpening the front in the region of interest. Data from sonobuoy trajectories are then used to provide an independent data set to test the correction results. Synthetic sonobuoy trajectories are computed using the velocity fields in the first 30 m with and without the correction and they are compared with the observed one. A visual example is shown in Fig.1, clearly showing the improvement of the trajectories in presence of correction. At the quantitative level, the error is decreased with a gain of approximately 50%.

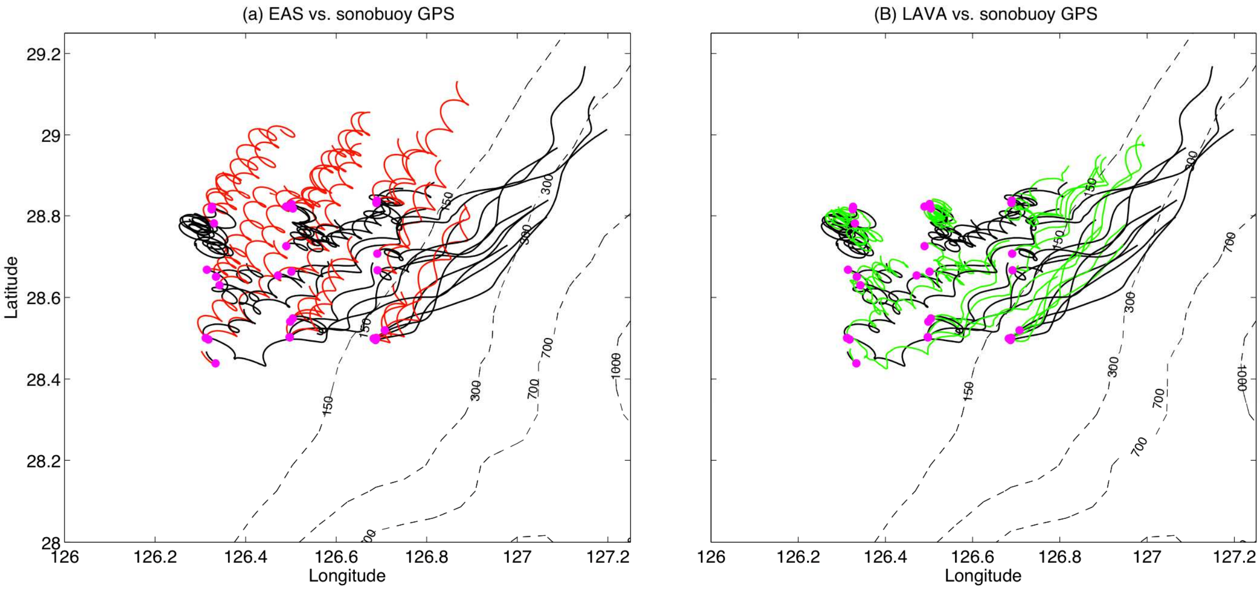

Fig.1 Modeled sonobuoy trajectories in the LWAD07 region using the EAS-16 (red, left panel) and LAVA corrected (green, right panel) model velocity fields, compared to observed in-situ data (black) for two days after deployment. Adapted from Chang et al. (2011).

The LAVA method has also been used in the framework of a complete data assimilation scheme in terms of sequential re-initialization. In this case not only the velocity field is correct at the level of drifter or floats, but the whole set of model variables are consistently corrected, so that the model can be re-initialized and integrated using the corrected state. Technically, this means that other steps are performed after the velocity correction. First of all the correction is statistically projected in the water column using results from data if available or otherwise from the model itself. Then the other variables of the model, i.e. the water mass properties (temperature T and salinity S) and the sea surface height (SSH), are adjusted using some simplified dynamical requirements such as geostrophy and mass conservation (Özgökmen et al., 2003).

The assimilation procedure has been applied to the assimilation of Argo floats (Taillandier et al., 2006b) in the Mediterranean Sea as part of the MFS (Mediterranean Forecasting System) project. Argo floats (MedArgo) are programmed to drift at a parking depth of 350 m, resurfacing at approximately 5 day intervals, and providing information on their position and on TS (Temperature and Salinity) profiles. Lagrangian assimilation uses the position information to correct the drift at 350m. An example of results obtained assimilating MedArgo floats in the region close to the Balearic Islands is shown in Fig.2. Results without assimilation (left panel) can be compared with results with assimilation (right panel). The brown lines indicate the observed drift of one float during 10 days, the arrows indicate velocity vectors and the color indicate the salinity field S. As it can be seen, the assimilation of the Argo float data induces a jet along the eastern coast of the island that was not present without assimilation, in keeping with the observed float drift. Notice also that there are differences also in the S fields between the two panels, due to the dynamical adjustment performed during the assimilation. The Lagrangian assimilation of MedArgo has been recently performed in the framework of a multivariate system, i.e. together with the assimilation of all the variables that are part of the MFS observing system, including T,S profiles from MedArgo data and XBT and satellite SSH and SST (Taillandier et al., 2010).

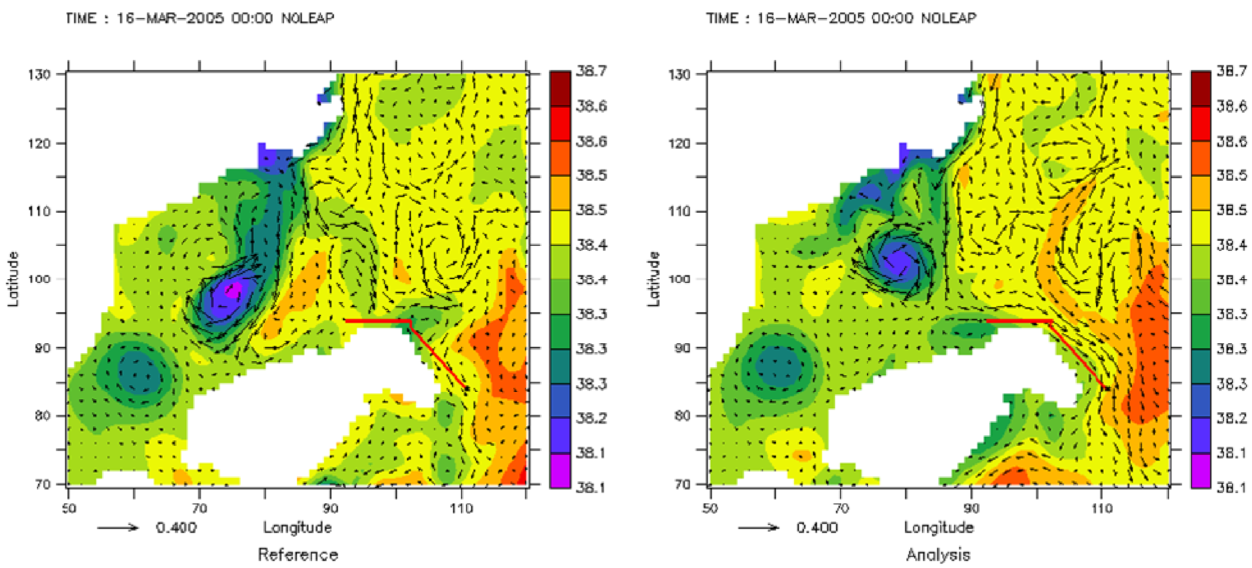

Fig 2. Left (right) panel shows an example of OPA model results in the Balearic Sea without (with) assimilation of Argo float trajectories. Arrows indicate vector velocities, color the salinity field and the superimposed brown-orange lines indicate the observed 10 day drift of the assimilated float. (Adapted from Taillandier et al. 2006b)

III. Algorithm characteristics and customization for TOSCA applications

The basic LAVA algorithm written by V. Taillandier has been customized for TOSCA focusing on:

- applications in a restricted coastal area
- applications for velocity fields from HF radar.

In the following we briefly describe the main characteristics of the algorithm in terms of input and output fields and parameters, referring to the MREA/POET application (Section IV) as an example.

3.1. Input fields and main parameters

The following fields and parameters have to be provided as inputs to the algorithm:

- Grid and mask data: they define the domain of applications in terms of geographical grid coordinates. For the MREA/POET example, the domain is situated in the Gulf of La Spezia, and it consists of a 50 x 54 matrix with a resolution of 250 m

- Velocity data: they define the velocity data from HF radar on the grid and are provided at time interval dt. For the MREA/POET example, the data are provided by VHF WERA with dt=1800 sec (half hour)

- Drifter data: they define the geographical coordinates of the drifter positions at the same time intervals dt as for the radar data. For the MREA/POET example, two drifter trajectories are used.

- Space scale: it defines the typical Eulerian scale R used to correct the velocity field. An estimate can be provided by the typical Rossby radius of deformation in the area. For the MREA/POET example R is set to R=1 km, consistent with an estimate of the Rossby radius from hydrological measurements.

- Time scale: it defines the time τ over which the correction is performed, in terms of number of iterations dt. τ must be equal or smaller than the Eulerian and Lagrangian time scales in the area, i.e. of the persistency time of the structures and of the particle velocities respectively. For the MREA/POET example, given the high velocity variability, τ is chosen to be 3 hours, i.e. 6 dt.

- NOTICE: the values of R and τ can be chosen to be different in different regions of the domain, for instance if the domain is characterized by dynamical areas such as shelf and offshore. This is set trough a matrix "Shelf" that defines the various regions. At the moment, the algorithm is set for only 2 of such regions, with a linear transition area in between. For the MREA/POET example, since the domain is characterized by approximately constant depth of 20 m, Shelf is set to a constant and R and τ are single valued.

- NOTICE: the code also allows to pre-filter the radar and/or drifter data for instance for tidal or inertial motion, in case one chooses to correct only the subinertial mesoscale component of the flow. For the MREA/POET example, the filter is not applied and the complete velocity field is corrected.

3.2. Output fields

- Corrected (reconstructed) velocity data provided at time interval dt.
- Synthetic drifter trajectories computed using the original and corrected velocity field.

IV. Results from a test case with historical data (MREA/POET 2007 experiment)

In the framework of the experiment MREA/POET during summer 2007, a WERA radar system in very high frequency (VHF) mode has been operated by LSEET in the small coastal area of the Gulf of La Spezia (range of 7 km, resolution of 250 m) and the velocity fields have been compared with surface drifter data launched in collaboration between OGS, ISMAR-CNR and LSEET (Molcard e al., 2009). The drifters have been launched in clusters of 3-6 units, aimed at investigating the significant time and space variability of the flow. The first two clusters showed an excellent qualitative agreement with the radar data, with quantitative differences in radial velocity characterized by RMS of less than 5 cm/s, definitely on the lowest side of the RMS values reported in the literature. The third cluster on the other hand showed a more marked difference, possibly because of the rough sea state.

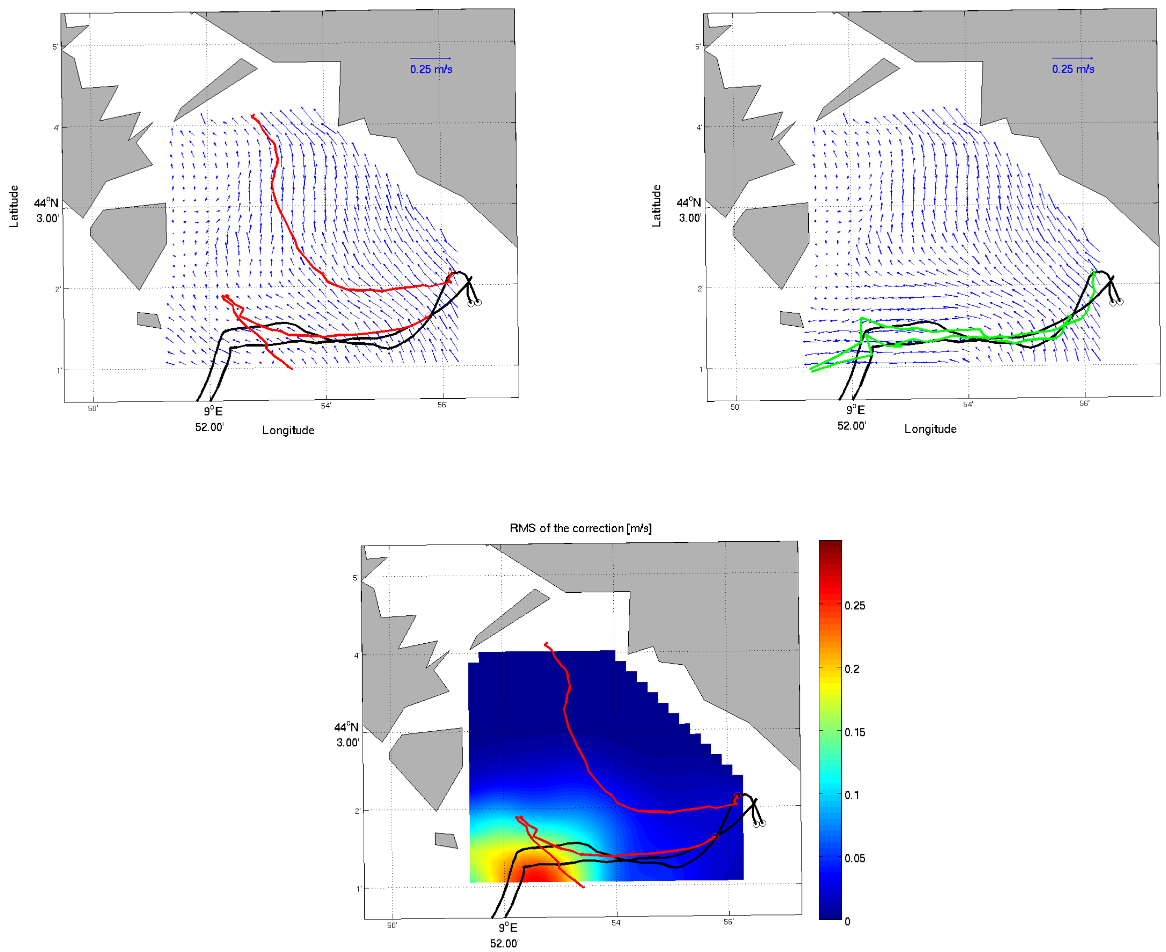

Fig.3 Observed trajectories (black lines) for the drifters in the third cluster of the MREA/POET 2007 experiment superimposed to the average radar velocity (top-left panel) and the average assimilated velocity (top-right panel). Synthetic (LAVA corrected) trajectories are in red (green). The bottom panel shows the RMS of the velocity field with and without assimilation

Results from this third cluster have been used here to test the performance of the LAVA algorithm applied to radar data. Trajectories from the two drifters in the third cluster are shown in black in the top-left panel of Fig.3, for the period from 22/06 11:00 to 23/06 7:00. They are superimposed to the 15-hr average velocity from the radar (blue arrows) for the period from 22/06 13:30 to 23/06 4:30, i.e. when at least one of the two drifters stays in the area spatially covered by the radar. Synthetic trajectories computed from the radar via fourth-order Runge-Kutta time integration are shown in red on the same picture. The comparison between real and synthetic trajectories shows a clear difference, indicating that the radar data differ from the in situ velocity sampled by the drifters. This is evident for example for the easternmost drifter: according to the radar, its trajectory is toward northwest, while in reality it moves toward southwest.

In the top-right panel of Fig.3 we show the LAVA application: corrected LAVA trajectories are in green and are superimposed to the average assimilated velocity. The assimilation of the two trajectories induces a westward jet in the bottom-left corner of the domain where the spatial distribution of the RMS is large (Fig.3, bottom panel).

V. Outlook and future plans

The results of the test case are very encouraging and they indicate that LAVA can be a very useful tool in enhancing transport prediction, blending radar and drifter results.

Future plans for the TOSCA implementation include the following steps:

- the algorithm will be first tested using TOSCA data by approximately January 2012, thanks to LSEET-ISMAR first experiments in December 2011 in the Toulon area;
- after that, a "beta" version of the algorithm will be made available to the other partners, to be tested with past data and/or acquired on recent/upcoming experiments. This is expected to provide useful feedbacks for the algorithm;
- for the final TOSCA configuration, all partners will use common formats for the radar and drifter data, leading to a unified strategy for the common use of the algorithm for local authorities. Scripts for creating these common formats will be made available.

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