Lagrangian applications of the coastal surface currents using high-frequency radar in California

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***Abstract*— The hindcast and near real-time Lagrangian applications of the coastal surface currents measured by high-frequency (HF) radar are presented. The hourly surface current maps created by HF radar network along the California coast are applied to the coastal river plume, the oil spill experiment, and the oil spill and ocean outfall tracking.**

I. Introduction

The surface current measurement using backscattered signals of the high-frequency (HF) radar has been the one of the populating oceanographic observational methods ([1], [2], [3], [4]). The HF radar network in California delivers the near real-time hourly surface current map to cover 1–150 km from the coastline, builds the infrastructure of the regional coastal ocean observing systems – Southern California Coastal Ocean Observing Systems (SCCOOS) and Central & Northern California Ocean Observing System (CeNCOOS), and helps to incorporate with other in-situ observations and the numerical ocean modeling efforts. Moreover, it leads the various applications in the education, oceanographic research and the environmental policy decision making. For example, the Lagrangian trajectory model using HF radar-derived surface currents has been applied to the coastal river plume, water quality, oil spill, search and rescue, and biological larvae spreading ([5], [6], [7], [8]). We present several field experiments to apply the Lagrangian simulations and the results to compare with the other in-situ observations including remote sensing data.

II. Observations

A. Study Domain

An example of the surface current maps created by the California HF radar network is shown on the Google map for the southern California (Fig. 1A) and San Francisco Bay (Fig. 1B), of which spatial resolutions of the surface current map are 6 and 0.5 km, respectively. The initial starting locations of the Lagrangian data-driven model (section II-C) are shown as white dots in Fig. 1: Tijuana River plume (a in Fig. 1A), 2 NM southwest of Point Loma for the oil spill experiment (b in Fig. 1A), Orange County Sanitation District (OCSD) discharge (c in Fig. 1A), Hyperion Discharge (d in Fig. 1A), Santa Barbara Channel Oil Platform (e in Fig. 1A), Oakland Bay Bridge (a in Fig. 1B), San Francisco Bay Mouth (b in Fig. 1B)

B. Surface Currents

The surface vector current map is the optimal solutions of the multiple radial current maps, which are the scalar current maps in the radial direction. The vector current calculation has been addressed with least-squares fitting ([9]) and optimal interpolation ([10]). The radial current map can have missing data due to the intrinsic characteristics in the direction finding algorithm ([11], [12]), so they affect the quality of the vector current map as well. The missing data in the surface current map can be completed several statistical and mathematical methods such as normal mode analysis ([13]), open boundary modal analysis ([14]), and objective mapping

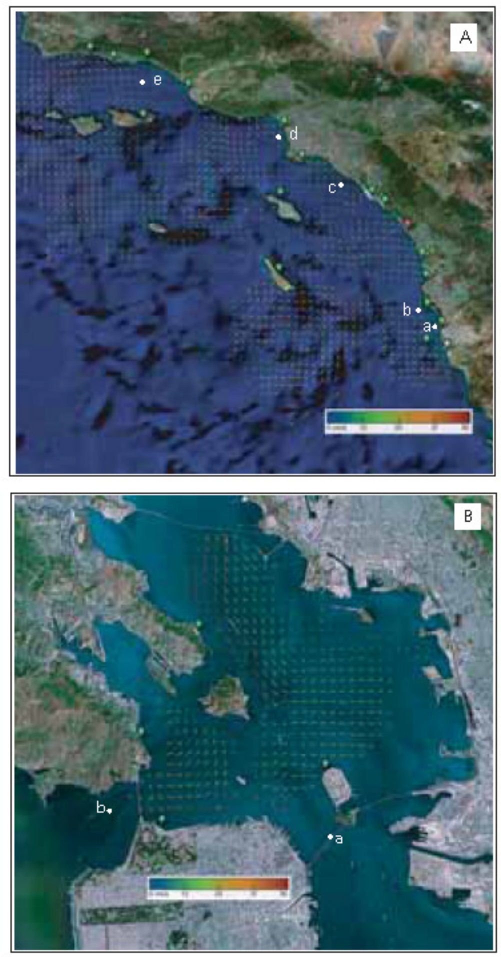

Fig. 1. An example of the surface current map created by the California HF radar network is superposed on the Google map (courtesy of http://www.cordc.ucsd.edu). A. Southern California (6 km grid resolution): (a) Tijuana River plume. (b) 2 NM southwest of Point Loma for the oil spill experiment. (c) OCSD Discharge. (d) Hyperion Discharge. (e) Santa Barbara Channel Oil Platform. B. San Francisco Bay (500 km grid resolution): (a) Oakland Bay Bridge (oil spill). (b) San Francisco Bay mouth (oil spill). The initial releasing locations of the Lagrangian data-driven model are indicated with white dots, and the status of HF radar site is shown with colored balloons as green (online), yellow (temporary delay), red (temporary shutdown), and gray (offline).

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([15]). Optimal interpolation and objective mapping are used for the vector current calculation and gap filling in this analysis. The resolution of surface current map depends on the operating frequency (f_o) of the radar (Table I).

Classification	f_o (MHz)	Resolution (km)
Long	4–6	6
Mid	12–14	2–4
Short	24–26	1–2
Very-short	40–45	0.5

TABLE I

THE RESOLUTION OF THE VECTOR CURRENT MAP IN TERMS OF THE THE RADAR OPERATING FREQUENCY (f_o).

C. Lagrangian Trajectory Model

The Lagrangian trajectory model using random walk is developed using the forward time integration of the objectively mapped surface currents ([15]):

$$x(t) = \int_{t_0}^{t} \left(u(t') + \epsilon^u\right) \mathrm{d}t' + x(t_0) \approx \sum_k \left(u(t_k) + \epsilon^u\right) \Delta t + x(t_0), \quad (1)$$

$$y(t) = \int_{t_0}^{t} \left(v(t') + \epsilon^v\right) \mathrm{d}t' + y(t_0) \approx \sum_k \left(v(t_k) + \epsilon^v\right) \Delta t + y(t_0), \quad (2)$$

where $\mathbf{x}(t) = [x(t)\, y(t)]^\dagger$ and $\mathbf{u}(t) = [u(t)\, v(t)]^\dagger$ denote the location of the particle and the surface currents at the particle location at a given time (t), respectively (t_0 is the initial time of the simulation). ϵ^u and ϵ^v are the random variables with zero mean and RMS of ϵ. The diffusion parameter (ϵ) implies the turbulent scheme and is assumed to be the uncertainty in the HF radar measurements ($\epsilon = 5\ \mathrm{cm\,s^{-1}}$) ([16], [10], [17], [18]).

III. RESULTS

A. Tijuana River Plume Tracker

The environmental challenges in the U.S–Mexico border region with regards to impaired water quality resulting from local discharges have drawn attention in a broad audience. The understanding of the fate and transport of the discharged Tijuana River plumes (a in Fig. 1A) including the spatial and temporal scales of the physical processes has been limited. The near real-time Tijuana River plume tracker was developed and has provided timely decision for beach closure of the city of San Diego, which is available on the web (`http://sdcoos.ucsd.edu/data/particles/IB/`).

Continuously released particles at the Tijuana River mouth at every hour are tracked for three days and the age of particles are shown as color (top of Fig. 2). The number of particles in the nearcoast cell, which is the area within 1 km from the coastline, are presented as histogram (bottom of Fig. 2). The plume tracker was evaluated with the shoreline fecal indicator bacteria (FIB) samplings provided by San Diego County Department of Environmental Health using receiver operating characteristic (ROC) analysis ([19]). The accuracy of the plume tracker model shows approximately 70%.

B. San Diego Oil Spill Experiment

The oil spill experiment on November 8, 2005 at 2 NM southwest of Point Loma, San Diego (b in Fig. 1A) had done using multiple observations: dye dispersal and plume transect sampling vessels, GPS tracked drifter, and HF radar-derived surface currents. A strong north and northwestward wind was observed during the experiment, and we observed that the drifter moved faster than the dye. The surface transport of the dye was simulated with the time integration of the surface currents maps. The particles in the hourly map and 10-minute sampled drifter tracks are superposed with color-coded by the local time (Fig. 3). The simulated results agreed with the dye observations, which shows the northward transport.

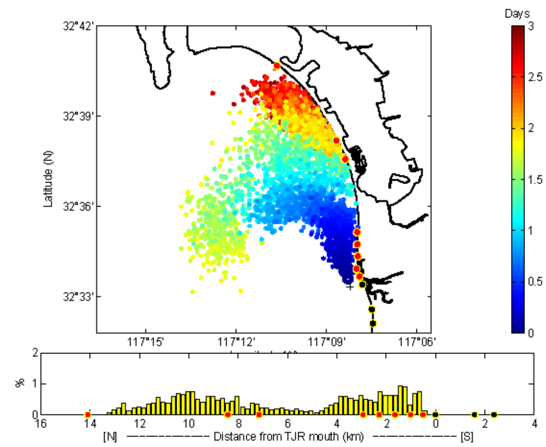

Fig. 2. Top: A snapshot of the Tijuana River plume track model and the nearshore risk map. The particles released at the Tijuana River mouth (a in Fig. 1A) continuously at every hour are tracked during three days, and are counted within 1 km bin from the coastline. Bottom: The relative number to the total number of particles is plotted as the histogram along the coast.

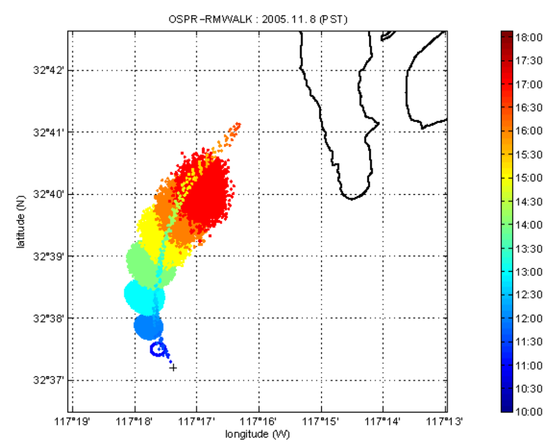

Fig. 3. The drifter tracks and the Lagrangian particle trajectory using surface currents on November 8, 2005. The colorbar indicates the local time (PST).

C. Orange County Sanitation District (OCSD) 2007

Orange County Sanitation District (OCSD) routinely reduces flow through and shuts down the 120-inch outfall in order to perform necessary maintenance and to facilitate construction projects. For the temporal shutdown of the main outfall, OCSD developed the contingency plans to avoid discharges through the 78-inch outfall and/or use of the emergency overflow to the Santa Ana River. As a part of the contingency plans, both routine ocean outfall operations and the advent of any unplanned or planned discharges to OCSD's 78-inch ocean outfall or to the Santa Ana River need to be monitored.

OCSD planned a maintenance on the 120-inch outfall on May 18

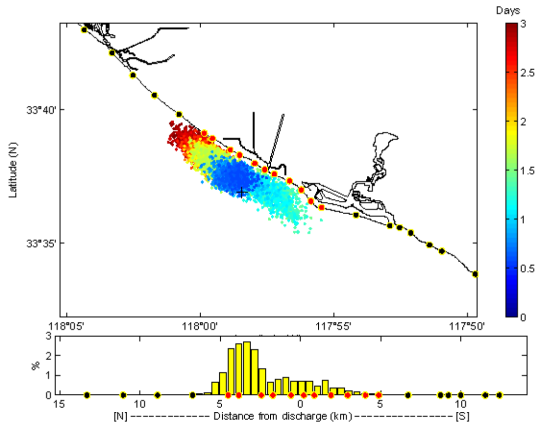

Fig. 4. Top: A snapshot of the OCSD plume track model and the nearshore risk map (May 25 1730, 2007 (PST)). The particles released at the OCSD discharge (c in Fig. 1A) continuously at every hour are tracked during three days, and are counted within 1 km bin from the coastline. Bottom: The relative number to the total number of particles is plotted as the histogram along the coast.

0500, 2007 (PST), and had to release the effluent to the nearshore discharge if the maintenance was not completed. A snapshot of the plume tracker for the OCSD discharge is shown in Fig. 4. The particle trajectory highly depends on the alongshore flow.

D. Hyperion Discharge

During November 28–30, 2006, the Hyperion sewer discharge, which runs under the ocean and through which Los Angeles' processed wastewater, was diverted from the 5-mile pipe to the shorter 1 mile outfall to allow inspection of the longer outfall pipe. The discharge is typically 300–350 million gallons per day (MGD), with a total estimated volume of discharge to approach 875 million gallons. The satellite images of the chlorophyll-a (Chl-a) and nLw-551 in the study area are used for qualitative verification of the offshore surface transport, which is provided by MODIS/Aqua (`http://seadas.gsfc.nasa.gov/DOCS/MODISA_processing.html`). A snapshot of the particle trajectory and the remote sensing data at the nearly coincided time are shown in Fig.5. The particle trajectory is stretched offshore and the Chlorophyll-a/nLw-551 images show the similar features.

There was a report on the smelly event in spite of the offshore surface transport. The Santa Ana River flow owing to overnight rainfall was suggested for the potential source, so the trajectory simulation for two sources was done. The surface transport by the river flow was heading onshore as opposed to the transport of the Hyperion discharge (Fig. 6). Therefore the reason on the smelly event could be explained at some levels with the Santa Ana River flow.

E. San Francisco Bay Oil Spill

The intermediate fuel oil (8,000 gallons) on November 7 0830, 2007 (PST) was spilled near Oakland Bay Bridge in the San Francisco Bay. Owing to the limited spatial coverage of HF radars, the Lagrangian surface transports were simulated at two locations: Oakland Bay Bridge and San Francisco Bay mouth (Figs. 1B-a and 1B-b). The particles released during the first 12 hours were tracked for seven days, and a series of the snapshots of the tracked particles are shown in Fig. 7. The trajectory simulation results are compared with the records of eye witnesses and reports on the spreading of oil slicks.

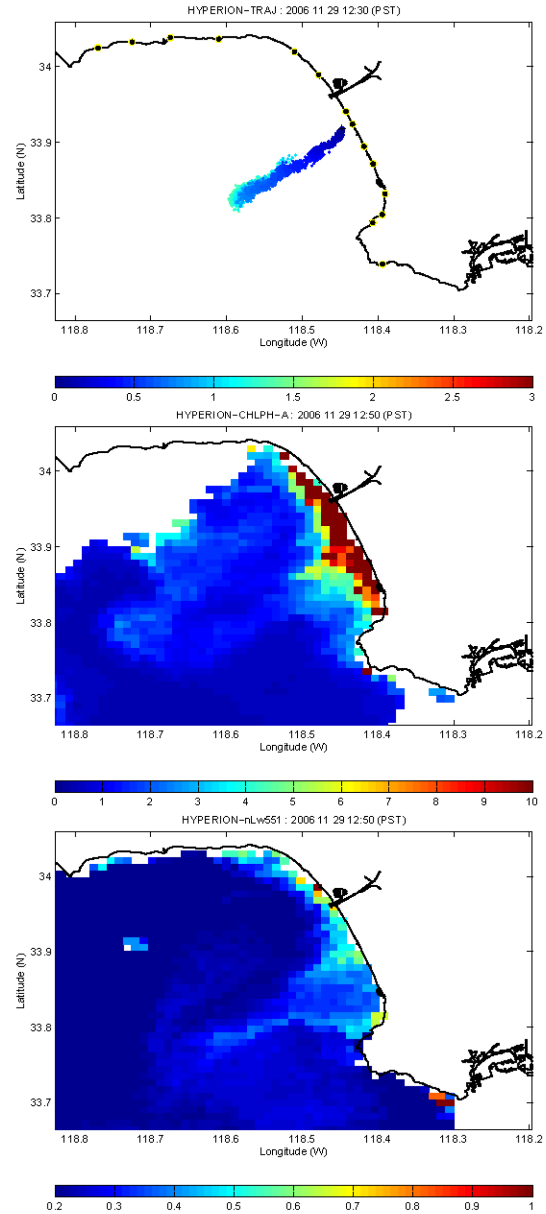

Fig. 5. The trajectory simulation of the Hyperion discharge (d in Fig. 1A) and its comparison with the remote sensing data. (a) The plume track model on November 29 1230, 2006 (PST). (b) MODIS-A Chlorophyll-a (mg m^{-3}) (c) MODIS-A nLw-551 (mW cm^{-2} um^{-1} sr^{-1}). Both remote sensing data are taken on November 29 1250, 2006 (PST).

F. Santa Barbara Channel Oil Platform Oil Spill

The oil spill occurred at the one of oil platforms (Platform A) in the Santa Barbara Channel on December 7 0700, 2008 (PST). The particle trajectory simulations are calculated for the different initial releasing schemes, and are presented with the oil slick boundary (red curve) on December 8, 1130 (PST) shown in Fig. 8. The simulation agrees with the quadrant where the oil slick was spread.

IV. Conclusions and discussions

Lagrangian data-driven model using surface currents created by HF radars along the California coast has been applied to the coastal water plume, the oil spill experiment, and the oil spill and ocean outfall

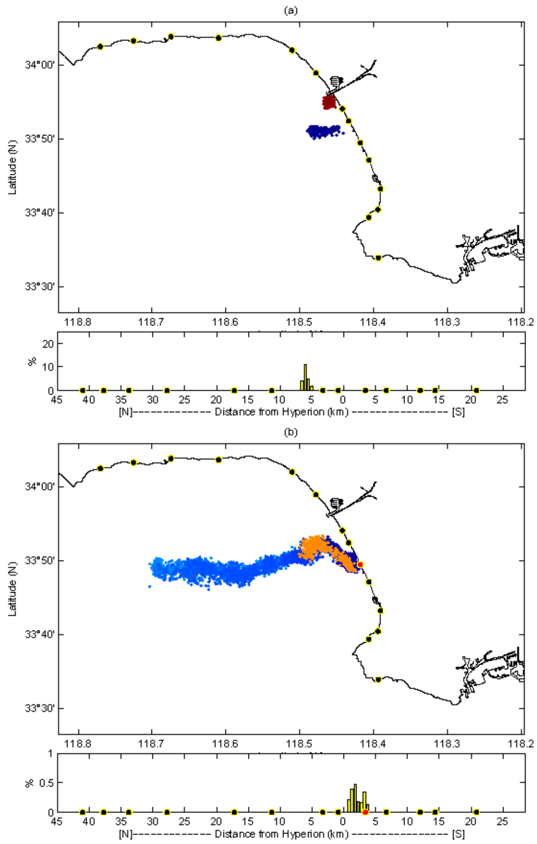

Fig. 6. Two snapshots of the trajectory simulation for two sources – Santa Ana River (red) and Hyperion discharge (blue). (a) November 28 0830, 2006 (PST). (b) November 30 1430, 2006 (PST).

tracking in both near real-time and hindcast modes. Although the verification with other in-situ observations is limited, the trajectory model using random walk provides the general overview of the surface transport and can increase the monitoring capacity. These applications would be substantiated in the the national network ([20], [21]).

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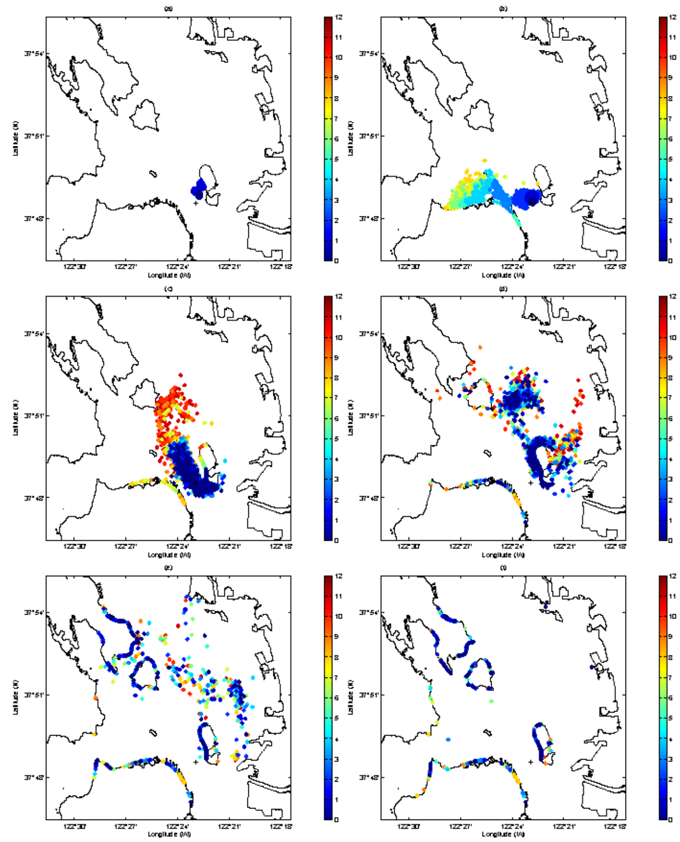

Fig. 7. A series of snapshots of the Lagrangian trajectory simulation for San Francisco Bay oil spill. (a) 3 hours later (November 7 1030 (PST)). (b) 10 hours later (November 7 1730 (PST)). (c) 20 hours later (November 8 0330 (PST)). (d) 50 hours later (November 9 0930 (PST)). (e) 100 hours later (November 11 1130 (PST)). (f) 160 hours later (November 13 2330 (PST)).

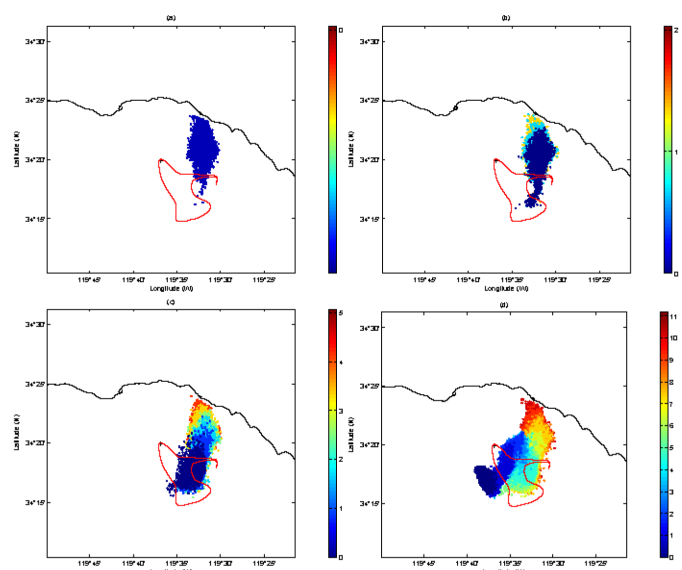

Fig. 8. Snapshots of the Lagrangian trajectory simulation for Santa Barbara Channel oil spill superposed with the oil slick boundary (red curve) on December 8 1130, 2008 (PST) with the varying release duration: (a) 1 hour. (b) 3 hours. (c) 6 hours. (d) 12 hours

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