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Final technical report:
Lagrangian Tracer Transport & Dispersion in Tidal Inlets
Grant number: N00014-11-1-0246

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1 LONG-TERM GOALS

Our *long-term goals* include developing and field-testing numerical models of shallow water breaking waves and wave-driven processes, including currents, and tracer transport and dispersion. Improved prediction of the fate of terrestrial runoff pollution and other substances (e.g. fine sediment, chemicals) sometimes present in very shallow water.

2 OBJECTIVES

The objective of this project, to measure mixing and transport in a small tidal inlet, was achieved in the RIVET 1 experiment. During RIVET 1, we measured transport and dispersion from within the New River Inlet to 2-3 km offshore and alongshore, at different tidal stages. Analysis of this diverse data set of waves, currents, stratification, Lagrangian drifter, and dye-tracers has begun.

3 RIVET I Observations

RIVET-I observations were collected from May 1-21 with instrument deployment in late April and recovery in late May. During the observation period, summaries of recent observations and upcoming activities were regularly posted to http://blogs.iod.ucsd.edu/RIVET, a community blog that we created. Our diverse data set is in the process of being quality controlled and will be shared freely with all investigators by the start of FY13.

3.1 New River Inlet Bathymetery

The New River Inlet N.C. (Fig. 1) was surveyed three times by the USACE FRF. The inlet is approximately 1 km wide at the mouth and has strong currents and at times large waves. The inlet opening is oriented to 148 deg and here we use a coordinate system where $x = 0$ is in the mouth and $+x$ is offshore. The inlet has two channels. One relatively deep channel is on the Topsail (South-West) side of the inlet, becoming quite shallow (1-2 m depth) at $x > 0$ m, before opening up to the ocean at $x = 700$ m and $y \approx 0$ m. This "new" channel was dredged by the USACE a few weeks prior to the experiment. The second "old" channel originates about 1 km up the inlet ($x \approx -1000$ m), and runs along the Camp Lejeune (North-East) side of the inlet where it opens to the ocean about 800 m in the $+y$ direction. Both channels have strong currents and both openings are hazardous to small boat traffic.

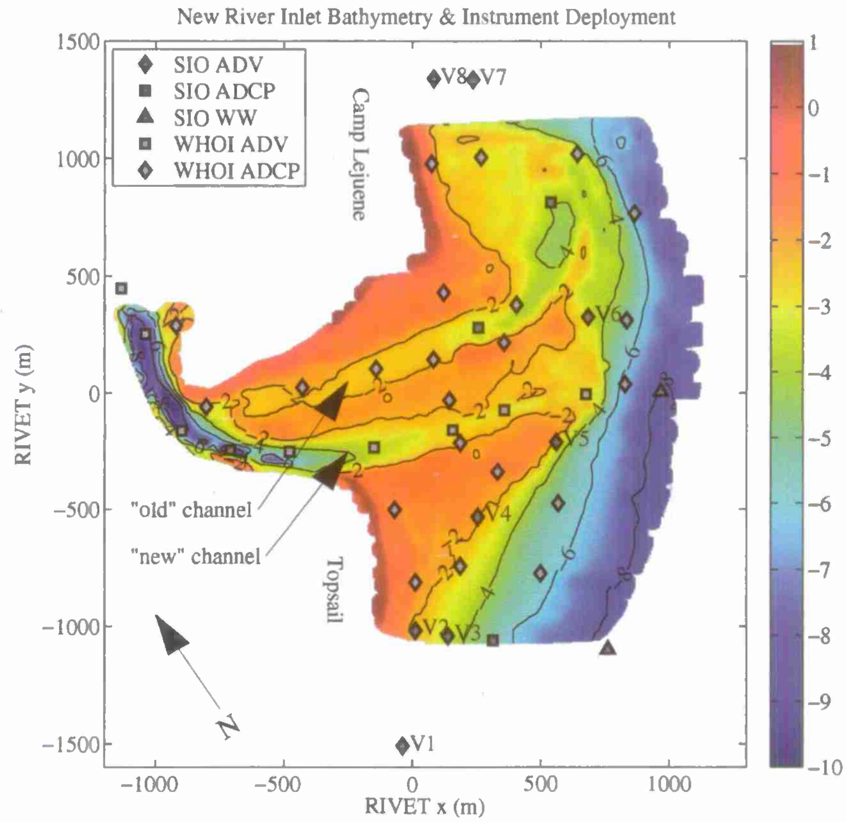

Figure 1: Map of New Rivet Inlet NC bathymetry (from the ASACE FRF) in the RIVET coordinate system with the SIO (Feddersen/Guza) and WHOI (Raubenheimer/Elgar) ADV, ADCP, and wirewalker (WW) instrument locations as noted in the legend. The TopSail side of the inlet is below and the Camp Lejuene side is on top. SIO ADV locations are marked V1-V8. All locations also had a co-located pressure sensor and many locations also had a co-located Rhodamine WT dye fluorometer. Dye was released either near $x \approx -600$ m and $y \approx -300$ m, or about 1.2 km further up the inlet towards the Inter-Coastal Waterway.

3.2 In Situ Fixed Observations

The inlet was heavily instrumented during RIVET-I. The majority of instrumentation at the inlet mouth was deployed by WHOI (Raubenheimer/Elgar) and by the proposal PIs at SIO (Fig. 1). Instrumented locations were chosen in collaboration with the goal of mapping along the two inlet channels and also mapping fluxes out of these channels. Wave and current observations were collected at 8 ADV+P locations and 4 ADCP locations (Fig. 1). In addition, currents and stratification observations were collected at 2 wirewalker+ADCP moorings (triangles, Fig. 1).

3.3 GPS-Tracked Drifters

Thirty-five GPS-tracked drifters were deployed on 8 days of May, specifically May 1, 2, 3, 4, 14, 15, 16, & 17 and collected data at 1 Hz. An average of approximately 140 drifter hours of data was collected per day. During ebb, drifters were released within the inlet, from near the mouth to near the inter-coastal waterway in a variety of release strategies. Unless wave conditions made recovery too dangerous, drifters generally flowed out the inlet and were recovered 1-2 km from the mouth of the inlet. Flood tide releases occurred outside the inlet in typically 5 m water depth ringing the inlet, and drifters then typically flowed into the inlet. More specifics on the drifter release experiments and visualizations can be found on the blog here. In combination with the fixed observations, the Lagrangian drifter data set is a rich resource for understanding inlet/ocean exchange and tracer transport, dilution, and dispersion.

3.4 In Situ Dye and Temperature Observations

Day in May	Type	Duration (hr:min)	Tide	Amount (gal)	Location	Wind	Waves
06	C	0:57	Ebb	30	Deep Channel	strong	large
07	C	2:19	Ebb	30	Deep Channel	strong	large
08	C	2:25	Ebb	30	Deep Channel	light	moderate
11	P	-	Ebb to Flood	20	near-ICW	calm	none
12	P	-	Ebb	20	near-ICW	calm	none
19	C	5:54	Flood	30	Deep Channel	onshore	large
20	C	1:12	Ebb	24	mid-Inlet	light	small

Table 1: Summary of RIVET-I dye releases at New River Inlet: Release type is listed as C for continuous and P for point release.

On 7 days during RIVET-I, between 20–30 gallons of Rhodamine WT dye was released within the New River Inlet either instantaneously or continuously from 1 to 6 hours during various tide stages (Table 1). These dye releases created a plume that evolved in a variety of ways depending on the tide stage, release duration and location, wave and wind field.

During dye releases, dye concentration was measured at 15 SIO or WHOI current meter locations (Fig. 1) with co-deployed WetLabs fluorometers. For example, the two point releases (May 11 & 12) had a burst of dye flow past the fluorometer at V4 (see location in Fig. 1) on the ebb tide. Vertical profiles of dye concentration (together with temperature and salinity) were measured at the two SIO wirewalkers (triangles in Fig. 1). Two dye-sampling jetskis were used to make surface maps of dye and temperature both within and outside the inlet (*e.g.*, Fig. 2). Our small boat made CTD+Dye casts inside and outside the inlet within the dye plume, and using a towed fluorometer/temperature array measured vertical dye profiles outside of the inlet in > 5 m water depth (see Fig. 3). In addition, on most dye release days, the SIO-MPL group (PI: Terrill) measured the sub-surface dye plume outside of the inlet with their AUV (example images can be found here.

3.5 Airborne Dye and Temperature Observations

During RIVET I, 5 days of airborne observations were collected in conjunction with Rhodamine WT dye releases from May 6-12th. These airborne observations were made by the Prof. Ken Melville lab as part of their airborne remote sensing recharge facility and funded (approximately 100K) with internal UC (CA state) funds. The airborne observations included, (1) a hyperspectral pencil-beam imager that measures light-intensity at many wavelengths, (2) a multispectra camera system, (3) a day-time capable infrared (IR) sensor, and (4) lidar measurements for surface gravity waves. Example airborne temperature and dye observations are shown in Fig. 4.

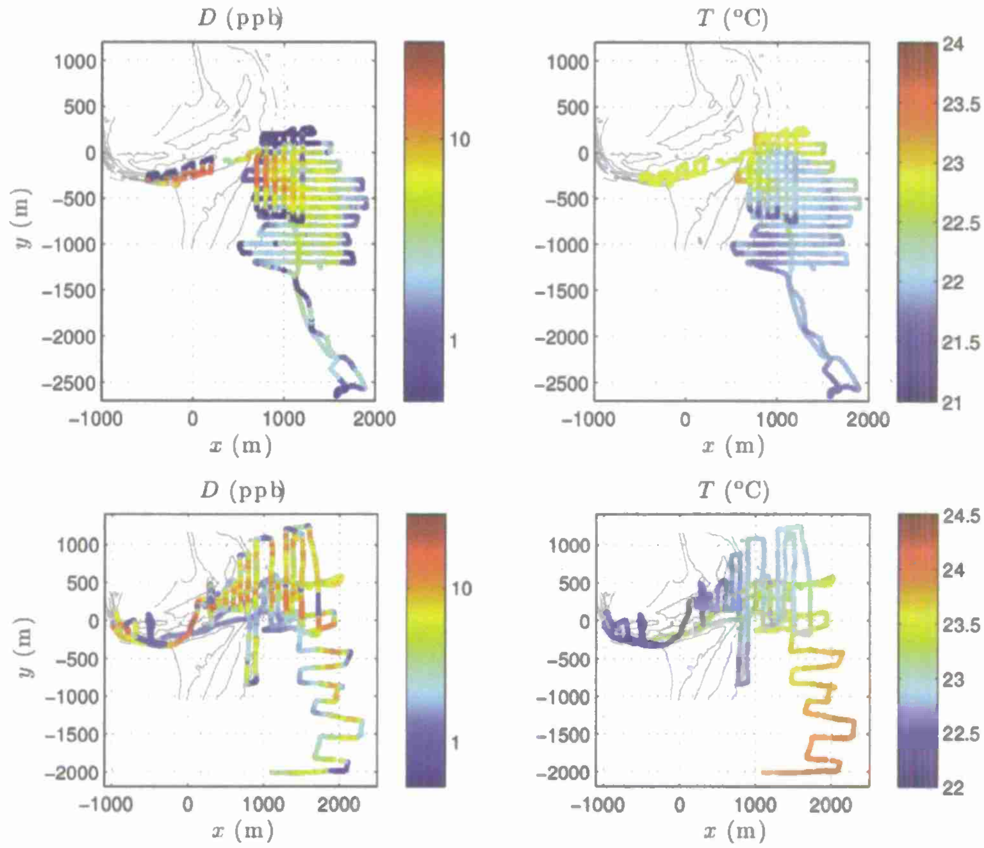

Figure 2: Surface dye (left, ppb) and temperature (right, °C) observations from (top) May 6th and (bottom) May 8th at the New River Inlet NC measured by a SIO-CCS dye and temperature mapping jetski. On May 6th, dye was continuously released near (x,y)=$(-400,-250)$ m and on May 9th, dye was point released at (x,y)=$(-1000,400)$ m. Note how the jetskis were able to map out the dye plume structure outside of the inlet mouth and the downstream dilution as well as the temperature between the warmed inlet and the ocean.

3.6 Example Comparison between Dye Days

It is instructive to examine the differences in the dye evolution between two days, in particular May 6th and May 12th (Fig. 2 & 3). On May 6th, dye was continuously released over one hour inside the inlet (Table 1) and was advected in a narrow plume largely out the main channel. The dye plume then turned, spread, and propagated downcoast $(-y)$ direction in an alongshore plume about 500 m offshore of the mouth of the main channel (Fig. 2top,L). Offshore of the channel mouth, the plume was $\approx$ 5 m thick and well mixed (Fig. 3top).

In contrast, the point release on May 12th (Table 1) had dye spread out across the inlet and propagate out in both old and new channel as well as over the shoals (Fig. 2bottom,L & Fig. 4). Within the inlet, the dye was observed to be well mixed (not shown). However, offshore of the inlet mouth, the dye remained concentrated in the upper 1 m of the water column (Fig. 3,right) corresponding to the sharp near-surface thermocline. On May 12th, the winds were weak and the waves were very small, which reduced the vertical mixing in the water column relative to May 5th. May 11th also had weak wind and waves and had similar thin surface dye layer (see this photo). The lateral spreading with a extremely sharp front of warm inlet

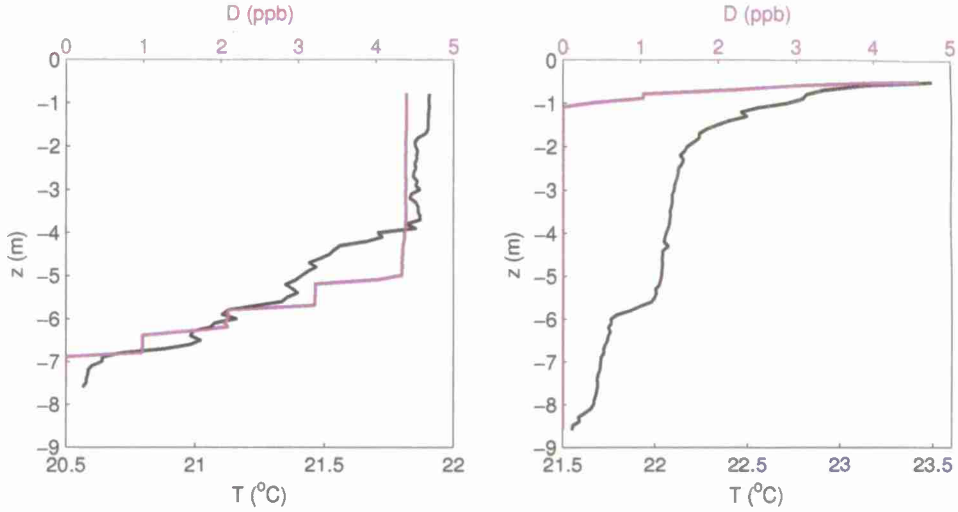

Figure 3: Example sub-surface dye (pink) and temperature (black) profiles from small-boat CTD+F casts on (left) May 6th and (right) May 12th. The May 6th cast was taken at 1516 EDT at $(x, y) = (1340, -303)$ m and the May 12th cast was taken on 1315 EDT at $(x, y) = (1230, -232)$ m. Both casts have similar maximum $D = 4.5$ ppb. However, note that on May 6th the dye is well mixed to $z = -5$ m, whereas on May 12th, dye is only found above $z = -1$ m. The depth at which dye is well mixed is consistent with the location of the thermocline.

water (Fig. 4,left) indicates that the colder, saltier ocean water subducts under the warm,fresh inlet water with very little vertical mixing (Fig. 3,right). Understanding the mechanisms that lead to drifter and dye transport, spreading, and mixing will be the focus of our analysis.

3.7 Future Analysis

Our analysis will use drifter and dye observations to quantify the dilution, horizontal spreading across the ebb delta, and vertical structure of tracers released in the inlet. A variety of analyses will be performed appropriate to either dye or drifter data.

3.8 Dye Analysis

The seven dye release experiments at the New River Inlet all showed a wealth of new and interesting information from which novel research should be based upon. The first task will be to ground truth the airborne hyper- and multi-spectral observations of dye using the in situ dye observations. This work will commence shortly and will be the topic of a presentation (by Lenain et al.) at the Fall AGU meeting, with a subsequent publication planned for *J. Atmos. Oceanic Tech.*

The next task will be to do control volume budgets of dye flux out and returning into the inlet. Understanding how much tracer (*e.g.*, sediment, pollution, nutrients) leaving an inlet on ebb tide comes back on flood, and under what conditions, is of great scientific interest. For example, on the May 11th dye release, the tide switched from ebb to flood before all the dye left the inlet and a significant fraction of dye mass was pulled back up the inlet as discussed (with corresponding aerial photos) in our blog post. The dye that was pulled back up the inlet during flood, was then later observed to come back out the inlet in low dye concentration on the subsequent ebb. For example, note the low broad dye peak 12 hrs (0.5 days) after the primary

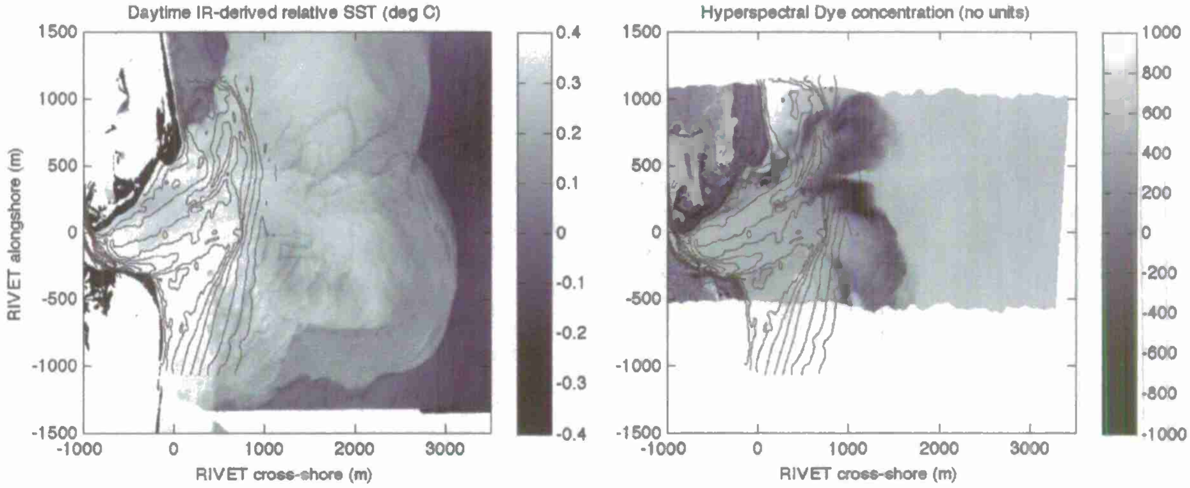

Figure 4: Airborne IR-based temperature (left) and uncalibrated dye (right) observations at New Rivet Inlet on 14:09 12 May with bathymetery contours underneath The temperature observations (left) are relative and clearly show the warm inlet water plume advecting offshore with a sharp $\approx 0.5°C$ temperature gradient at the front. Black colors (negative counts) indicate elevated Rhodamine WT dye concentrations. Note the ring of elevated dye concentration exiting the inlet mouth preferentially through the 2 inlet channels.

peak on May 11 at V4 (near time 11.8 days in Fig. ??). The fluorometer and current meter deployment plan was specifically designed to make these inlet flux measurements.

The subsequent analysis component will focus on the mixing of dye-rich warm inlet water with the colder and saltier dye-free ocean water. Over the dye release experiments, our observations show that the vertical mixing of dye, temperature, and salinity offshore of the inlet was highly variable, depending on tide stage, wind, and wave conditions (*e.g.*, Fig. 3). The two wirewalkers, the small-boat CTD casts, and the SIO-MPL Remus observations will be used to study the vertical mixing of dye, temperature, and salinity from the inlet mouth to farther offshore. In particular, the abilities and deficiencies of two-equation turbulence models (k-ϵ, Mellor-Yamada, k-ω) will be rigorously examined as our observations provide a very challenging test for such models.

3.8.1 Drifter Analysis

This analysis will focus on transport, dispersion, mixing and ocean/exchange. Thus, the observed drifter data set will be used to quantify the surface velocities and dispersion. In particular, during many ebb tide releases, drifters "fanned" out across the inlet opening much like the dye. Quantifying this dispersion is one goal of the proposed analysis. In addition to the purely observational analysis, in collaboration with graduate student Julie Chen and Prof. Tom Hsu at the University of Delaware, observed and modeled drifter transport and dispersion will be compared. Portions of this analysis will be the topic of work to be presented at the upcoming 2012 AGU Fall meeting.

For this analysis, simulated drifters will be advected by modeled velocity fields computed using the NearCoM model forced by observed tides and waves. This will provide important model Lagrangian transport and dispersion verification. In a separate analysis, the model is presently being compared to the observed Elgar/Raubenheimer Eulerian velocities. Preliminary Lagrangian drifter comparisons have begun with simulated drifter tracks having been computed for some of the drifter release days (Fig. 5). Fig. 5 shows releases at two tide phases: ebb (Fig. 5a) and slack-to-flood (Fig. 5b). Two differences between the

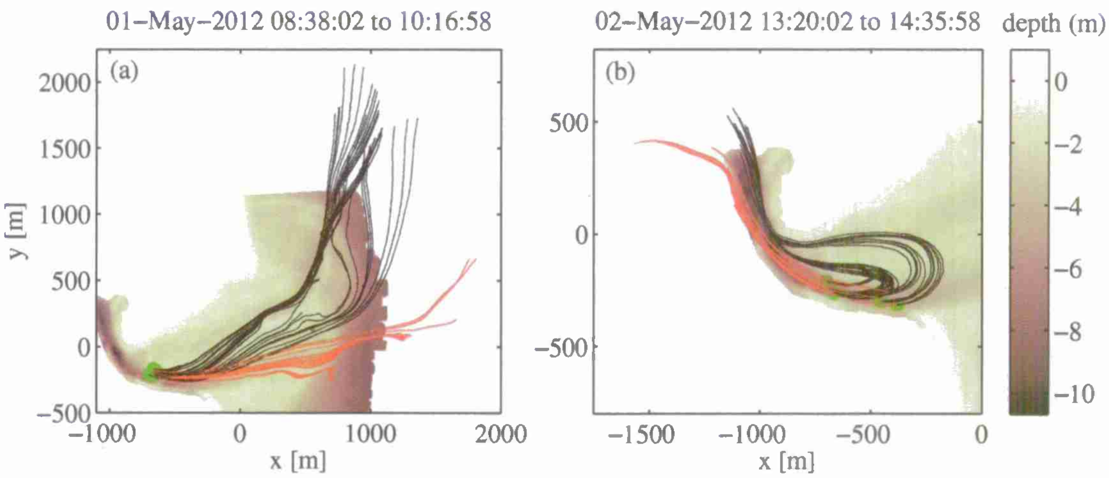

Figure 5: Observed (black) and modeled (red) drifter tracks on two different days and at two different tide phases: ebb (a) and slack-to-flood (b). Green dots indicate the release locations for the 35 drifters. Note the different cross- and alongshore extents in the two panels. The surveyed bathymetry is colored and depths are indicated. The modeled drifter tracks were computed from NearCoM velocity field data provided by Hsu and Chen of the University of Delaware.

observed and simulated drifter tracks are apparent: 1) observed drifters feel a much larger mean alongshore velocity ($+y$ direction) than the simulated drifters feel (Fig. 5a) especially further offshore, and 2) there is a slight phase difference between modeled and observed drifter velocities with modeled drifter velocities leading observed (Fig. 5b) – notice that unlike observed drifters, simulated drifters do not feel any ebb flow during this release. Understanding the differences between observed and simulated drifter data is important for determining the physics important to tidally driven Lagrangian transport and dispersion.