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14A The ecological importance of larval dispersal

Radar-based tracking of pollutants/larvae in the Coral Sea

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Abstract. A Lagrangian approach is used in physical oceanography to follow a parcel of water as it moves along its flow path and changes shape. Buoyant particles can be tracked to understand and predict the movement of pollution, flotsam and biota on the sea surface. We used data from a high-frequency radar system to compute radar-based Lagrangian trajectories in the Capricorn/Bunker region of the Great Barrier Reef (GBR, Australia). This paper describes case studies for the tracking of flotsam from the Shen Neng I grounding on Douglas Shoal in 2010, and for the destination of coastal waters adjacent Gladstone at the time of a fish disease event in September 2011. Further, the movement of a passive buoyant particle can also be inferred from Lagrangian tracking, which is a valuable technique to study connectivity between reefs. Radar-based trajectories show that wind and tidal conditions greatly affect the advection and spread of particles near the surface in shallow areas of southern GBR, but larger scale processes may be dominant during particular occasions. Therefore, the timing of larval release is crucial to determine the degree of larval retention or advection. We have made a scenario calculation for intermittent release of particles from Heron Island (GBR) for the 2009 spawning to illustrate the capability of the methodology for connectivity research; we also discuss how to couple this with a behavioral model to predict migration paths of larvae.

Key words: Great Barrier Reef, Lagrangian tracking, HF radar

Introduction

The Lagrangian approach has a major advantage of describing precisely how fluid parcels (and neutrally buoyant particles) move and spread. It represents a cost-effective match for the probabilistic determination of the destination of floating particles (e.g. spilled oil, sediment plumes, pollutants and larvae) required for coastal management. Lagrangian techniques include both direct *in situ* observations of drifting buoys (drifters) and indirect computation of Lagrangian trajectories based on time series of either modeled or measured Eulerian current fields.

In this context, ground-wave high-frequency radar systems (HF radar) provide measurements of time series of the two-dimensional surface Eulerian current field that can be integrated to compute particle trajectories (radar-based trajectories) with a high temporal accuracy (minutes to an hour) and spatial resolutions, varying from 1-10 km depending on the operating frequency. The HF radar current data are usually averaged over approximately rectangular shaped cells of a few kilometers. Therefore, HF radar spatial averaging, similar to that used for hydrodynamic model smoothing, is implicit in the trajectories. In this case, drifter data serve as a guide for the accuracy of the radar-based trajectories.

Previous validation of the HF radar current measurements in the southern Great Barrier Reef (GBR) showed that current velocities measured with HF radar were typically within 5-8% of those measured with surface drifting buoys (Mantovanelli et al., 2011). Further, comparisons of GBR radar-based trajectories against surface drifter tracks showed generally a consistent direction and pattern between both methods (Mantovanelli et al., 2011).

Radar-based trajectories are particularly accurate within the first two days of tracking when relatively small separations (< 5 km) are observed between the radar-based and drifter paths. However, differences among these two methods increase over time because the comparison of individual particle tracks is subject to cumulative errors. Differences also appear near reefs and islands, indicating that some small scale processes (less than 4 km) are not resolved at the GBR HF radar resolution (Mantovanelli et al., 2011).

One of the biggest advantages of using of radar-based trajectories is that tracks of buoyant particles can be promptly computed in near real time for any starting position within the radar domain. Conversely, the use of Eulerian current fields estimated by 3D fine-spatial resolution (hundreds of meters) hydrodynamic models requires substantial computational power and time, extensive model calibration and large observational data sets for validation (Cetina and Connolly, 2011).

We present three case studies in which the GBR radar-based trajectories have been effectively applied to predict: (i) the flotsam destination when the Sheng

Neng I grounded on Douglas Shoal, (ii) the destination of coastal waters adjacent the Gladstone Harbour at the time of a fish disease event in September 2011, and (iii) a test of larval dispersal following a coral spawning event in November 2009. The potential destinations of particles during these three periods are presented.

Material and Methods

The southern GBR radar system applies a pair of high-frequency ocean radars (8.38 MHz; phased-array WERA) to remotely measure the ocean currents from land (Tannum Sands and Lady Elliot Island stations). The radar data are prescribed on a 4 km grid over an approximately 150 x 150 km domain, covering the Capricorn/Bunker groups and continental slope up to 400 m depth. The 2D surface current velocity vector can be computed by combining the radial velocity components obtained from the two radar stations (Mantovanelli et al., 2010).

Here we used the non-quality controlled radial data available in near real time (flagged in the IMOS portal with FV00_radial.nc suffix). These data were subjected to an *a posteriori* filtering procedure on the u- and v-components to remove outliers, which included the average (over 2-4 h) and the interpolation of the residual flow (total flow less the tidal signal) across small gaps (less than 6-12 h) (Mantovanelli et al., *submitted*).

The radar-based trajectories were computed using an Euler predictor-corrector scheme to solve the non-linear differential equation describing the motion of a particle in a two-dimensional velocity field at time steps of 10 minutes as:

$$d\mathbf{r}(t)/dt = v(t),$$

where $\mathbf{r}=(x,y)$ denotes the position of the particle on a Universal Transverse Mercator (UTM) grid and $v(t)$ is the Lagrangian velocity vector along the trajectory $\mathbf{r}$(t); both terms are time-dependent.

The Lagrangian velocity can be related to the two-dimensional Eulerian velocity field in a simple way: $\mathbf{v}(t) = \mathbf{u}[t,\mathbf{r}(t)]$, $\mathbf{u}$ being the Eulerian speed of a particle at the position $\mathbf{r}$ and time t (Piterbarg, 2001). The Eulerian speed can be decomposed into the u (east) and v (north) components, i.e. $\mathbf{u}$ = (u, v). A bilinear interpolator was used to obtain speeds of the u and v components from the time series of GBR HF radar surface current maps at every new position and corresponding instant of time. Additionally, Redfearn's formulae were used to project the tracking coordinates at each instant of time on a UTM grid. Wind speed and direction data were obtained from the Australian Bureau of Meteorology.

Results

Radar-based tracking of flotsam (April 2010)

The Chinese coal carrier Sheng Neng I ran aground on the 3rd of April 2010 in the southern Great Barrier Reef. The ship grounding damaged 19,087 m^2 of the Douglas Shoal reef (Marshall, 2010) and spilled 2.5 tonnes of oil (ATSB10 Transport Safety Report, 2011).

Radar-based trajectories were used to hindcast the destination of flotsam and any oil which may have escaped (after Heron et al., 2010). Simulations were started at the grounding site (Douglas Shoal, Fig. 1) and the same time on nine consecutive days after the incident (day 0), hypothesizing a continuous oil release.

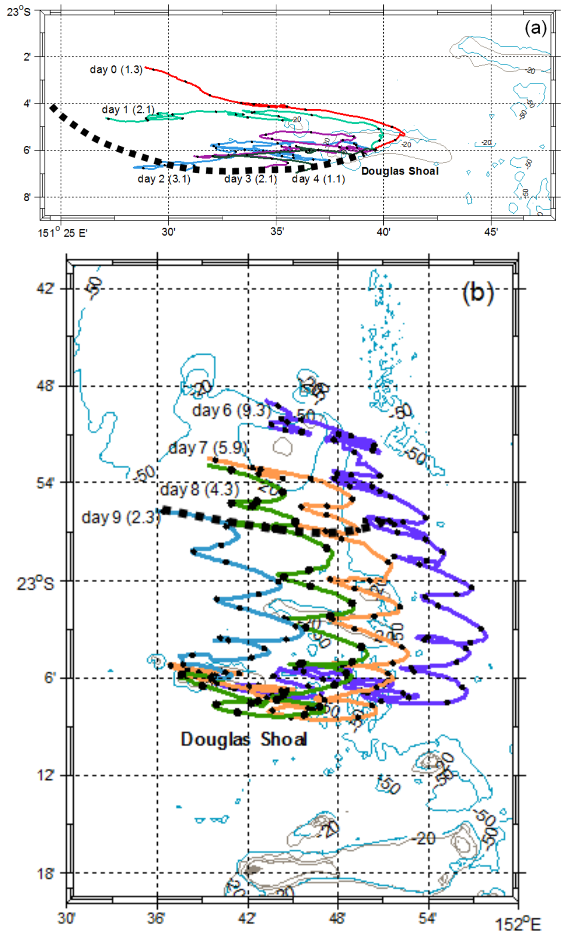

Figure 1: Radar-based trajectories starting at the Shen Neng I grounding site (Douglas Shoal) for days 0 to 4 (a) and days 6 to 9 (b). The black dots on each track mark 3 h intervals. The day after the incident and the total amount of time tracked are shown at the end of each tracking. The thick dotted line shows the estimated streak formation by the 'flotsam' (a) five days (to the south) and (b) 11 days (to the north) after the grounding (after Heron et al., 2010).

The radar-based surface tracks for days 0 to 4 (Fig. 1a) and days 6 to 9 (Fig.1b) could be followed for 1.3 to 9.3 days after releasing, with exception of the fifth day when the track was short because of gaps in the HF radar data.

Radar-based trajectories show that a large spreading of flotsam occurred around the place where the vessel went aground during the 11 days of the salvage operation (Fig. 1). The particles moved mainly to northwest on the day of the accident (day 0), to west on day 1 and to southwest on days 2 to 4 (Fig. 1a). Particle advection of ~ 21-26 km day^{-1} was expected within these first 4 days, under influence of moderate southeast winds (I, Fig. 2).

The surface circulation changed for days 6 to 11 after the incident; particle movement (~ 31-37 km day^{-1}) was toward the east first under mostly weak north to northwest winds (II, Fig. 1b and 2), and following, to the north-northwest under strong southeast winds (III, Fig. 2). Flotsam would likely form streak lines on the sea surface. The position of the slick line after 5.1 days of the accident had to be estimated because tracks were short for simulations of days 0 to 4 (Fig. 1a; after Heron et al., 2010). However, tracks simulated in the second period (days 6 to 9) were longer and a snapshot of the streak could be taken on the 11th day after the incident that shows a zonal spread of about 26 km. Fortunately, most of heavy fuel oil was effectively removed from the ship tank in the first few days of salvage.

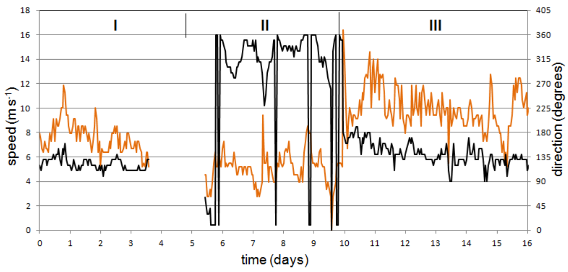

Figure 2: Wind speed (m s^{-1}, 10 m height; orange line) and direction (degrees; black line) measured at Heron Island weather station from day 0 to day 16 after the Shen Neng I incident. Three main wind conditions occurred during this period: (I) moderate SE winds (speeds of 5.2-12 m s^{-1}), (II) mostly weak N-NW (speeds of 0-9 m s^{-1}) and (III) strong SE (speeds of 5.2-16.4 m s^{-1}).

Radar-based tracking during a fish disease event (September 2011)

In September 2011, a fish disease event was reported near Gladstone. In response to this event, “the emergency fisheries declaration closed Gladstone Harbour and the surrounding area to all forms of commercial and recreational fishing for a period of 21 days between 16 September 2011 and 7 October 2011” (Gladstone Fish Health Scientific Advisory Panel, 2012).

Although the cause of the fish disease could not be identified, the incident has raised concern about the quality of estuarine and inner shore waters that could affect the adjacent GBR.

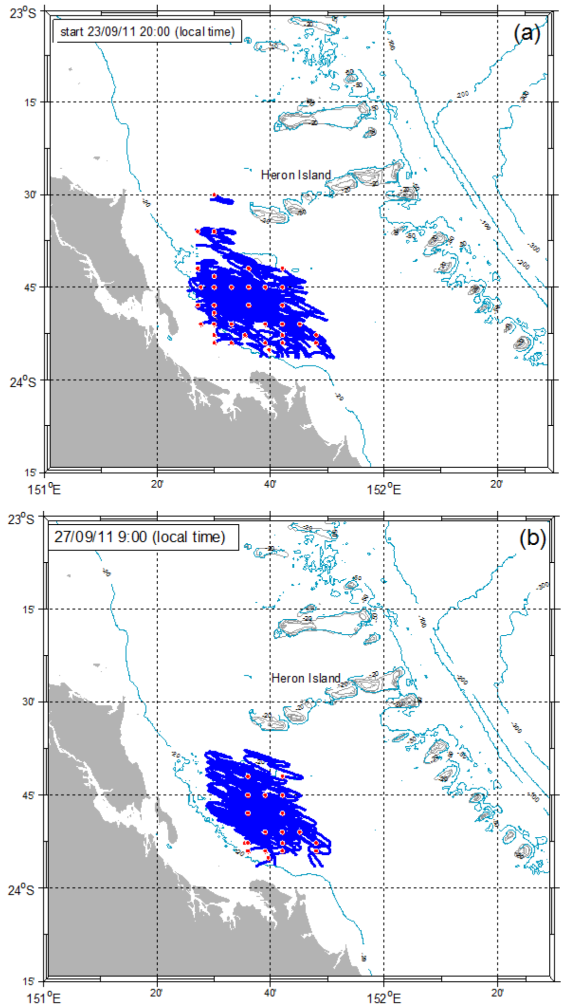

Figure 3: Radar-based trajectories starting in front of Facing Island (Gladstone, Australia) during ebb tides on (a) 23/09/2011 (20:00) and (b) 27/09/2011 (9:00). Starting locations of the tracks are shown with red dots.

Radar-based tracks were simulated starting during ebb tides on 23/09/2011 and 27/09/2011. The HF radar data were noisy during September 2011 and we used a longer average (8 h) and interpolation (24 h) of the residuals to allow longer simulations. A total of 23 tracks lasting between 1.1 and 7.4 days were followed on 23/09/2011 (Fig. 3a) and 20 tracks lasting 4.1-4.4 days are plotted for 27/09/2011 (Fig. 3b).

Mostly weak winds of constantly changing directions (3.6-9 m s^{-1}) prevailed during this week, and the particles were contained close to the shore during the analyzed periods.

Radar-based tracking during 2009 coral spawning
Many coastal benthic invertebrates and fish have a small, pelagic early life stage that can last from a few days to several months; the knowledge of population connectivity for these species requires an understanding of larval transport and dispersion (Pineda et al., 2007).

The movement and spread of passive buoyant particles (larvae) can be inferred from Lagrangian tracking. Even though the HF radar does not allow resolution of small scale circulation (< 4 km) around the islands, these simulations are valid to indicate the potential destination of the larvae that are not retained within the source reef and end up following the sub-mesoscale main flow. A residency time (around reefs) of about 0.5-6 days has been previously estimated considering different reef shapes and circulation regimes of GBR; most of the particles are flushed away from the source reef by 4 days (Cetina and Connolly, 2011).

The main *Acropora* spawning night around Heron Island was on the 26th of November of 2009 (Dr Selina Ward, *pers. comm.*). In this case study, we started radar-based trajectories for 7 consecutive nights following the spawning night; a few example tracks are presented in Fig. 4. Radar-based tracks show, in general, a southeast movement of particles, with some superimposed zonal dispersion caused by tides.

The larvae released at Heron Island could potentially reach the Bunker reefs located to the south in a few days. The longest tracking simulation for the first night of spawning predicted a maximum travelled distance of the particles (including the zigzags and loops) of about 140 km in 5 days (~23.5 km day^{-1}), with equivalent straight line displacement of 74 km east and 45 km south.

Interestingly, the change in wind direction from east to north, and subsequently to southeast did not alter the track directions as we would normally expect, and large scale processes may have dominated the circulation on this occasion. This atypical circulation condition will be subject of further study.

Summary and discussion

The southern GBR HF radar system accurately measures the two-dimensional ocean current field from the coast to over a hundred kilometers offshore. The HF radar time series of Eulerian current fields served as an input to an advective Lagrangian model used to track the destination of particles during three events: 2009 coral spawning, 2010 Shen Neng I grounding and 2011 fish disease event. The dispersion of particles is well represented by the measured HF radar data that include all of the oceanographic processes like diffusion and turbulence, wind stress, Stokes' Drift and shears (Heron et al., 2012).

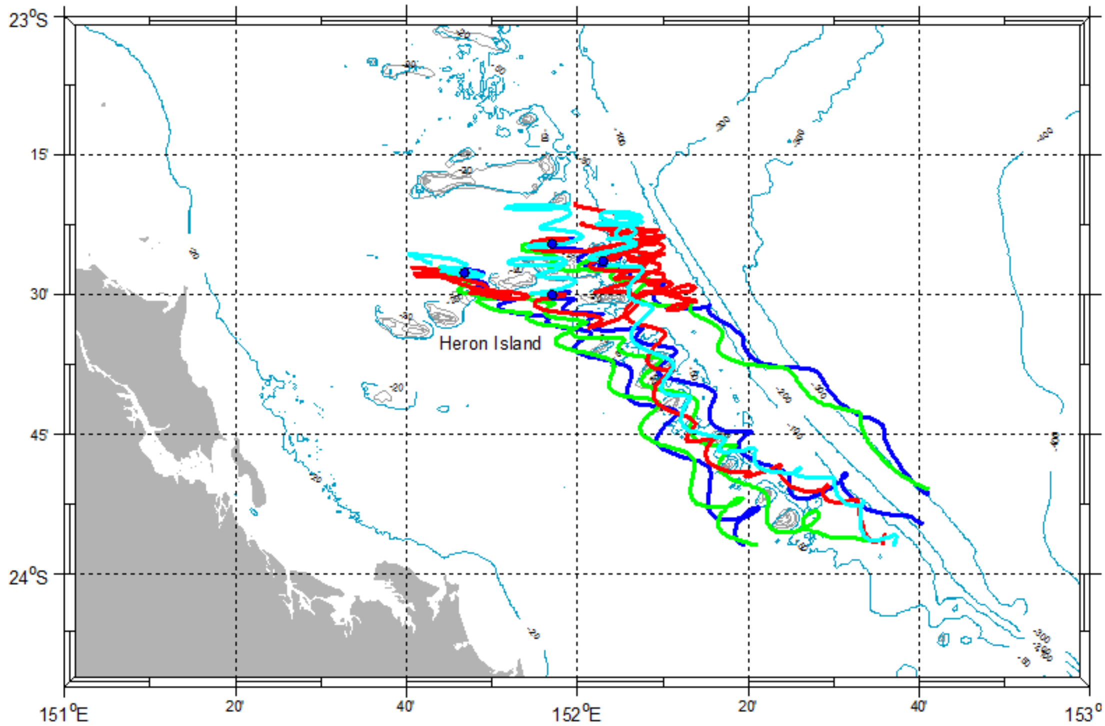

Figure 4: Radar-based trajectories starting at four locations (blue circles) around Heron Island in the southern Great Barrier Reef on the: (i) 26/11/2009 19:00 (blue line), (ii) 26/11/2009 23:00 (green line), (iii) 30/11/2009 23:40 (red line) and (iv) 04/12/2009 7:30 (cyan line).

Radar-based trajectories were valuable to hindcast the destination of pollutants and larvae in the southern GBR. However the existence of spatial and temporal gaps in the HF radar current field data prevents continuous tracking, and the radar-based tracking is limited to periods of time ranging from a few days to a couple of weeks (Mantovanelli et al., 2010, 2011). Radar-based trajectories can potentially be used for near-real time forecasting with some further improvement of the technique of filling unavoidable gaps present in the HF radar current field.

The resultant movement of particles in the shallow areas of the southern GBR was 'often and mainly' influenced by a combination of the wind and tidal forcing. These driving forces of surface circulation change in scales of hours to a few days. Therefore, the timing of particle releases is crucial to determine how fast larvae/pollutants can be dispersed and also the direction of the resultant movement of the particles. In the case of the 2009 spawning event at Heron Island, large scale physical forcing appears to have had major influence on particle paths. The determination of the nature of large-scale forcing requires further investigation.

Lagrangian particle tracking provided insight on the possible destination of larvae after a spawning event; incorporation of larval behavior in the model would add more realism to the predictions.

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