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5A Remote sensing of reef environments

Coastal Ocean Radars Applied to Coral Reef Science and Management

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Abstract. Coastal ocean radars provide detailed surface current maps and wind directions; some types of High Frequency radar also provide maps of wave heights. Radar range is dependent upon the radar frequency, extending up to 150 km from the shore. In the case of the Great Barrier Reef, this includes the continental shelf and some open water beyond. Detailed knowledge of the dynamics of the surface water opens the way for understanding much about localised environmental conditions, connectivity between sites and the movement of nutrients and pollution in the coastal ocean. Lagrangian tracking of buoyant particles can be achieved in the Great Barrier Reef lagoon within an accuracy (error) approaching 1 km per day of drift. This is a significant capability for search and rescue operations as well as reef science and management. A sequence of surface current maps has been shown to be useful for identifying areas where the currents are high enough to induce spontaneous turbulence throughout the water column. These areas are less vulnerable to coral bleaching because the heat from insolation is distributed through the water column rather than remaining at the surface. Spatial scales (i.e., range, resolution) for ocean radars are adjustable and it is shown that mapping of surface currents on a high resolution grid is possible with radars operating in the Very High Frequency band.

Key words: HF radar, surface currents, connectivity, coral bleaching, marine park management.

Introduction

High Frequency (HF; transmission frequency 3-30 MHz) ocean radars have become one of the most powerful technologies for mapping surface currents in coastal waters in near real-time. Crossed-loop and phased array systems are available commercially; these are different genres of the technology, and each has its stronger points in different applications (Heron et al., 2012). As well as surface currents, both systems can measure wind fields, while phased array systems also measure wave heights at reduced ranges. The Australian Coastal Ocean Radar Network (ACORN), part of the Integrated Marine Observing System (IMOS), incorporates both technologies. The deployment in the southern Great Barrier Reef, used in this paper, is a 12-element phased array system.

The equipment is located on the shore, generally on the back dune of a beach or on a cliff. Two stations are required to produce surface currents, because each one on its own measures only the component of the vector current towards (or away from) the radar station. Surface current values are normally presented on a rectangular grid as shown in Fig. 1. Here the arrows have their tails on the grid points and the length of the shaft is proportional to the speed of the current. The direction of the current at the grid point is that of the arrow. The operating range for the phased array system in Fig. 1 is up to 150km, but is reduced when radio interference, noise or echoes from the ionosphere or storms affect the signal.

The beauty of maps like Fig. 1 is that spatial relationships are easily identified. This map of surface currents exhibits divergences (upwelling), convergences (downwelling), vorticity (eddies) and jets. The applications of such data extend to particle tracking (pollution or bio-particles), location of upwelling and eddy zones, and search-and-rescue operations. The time resolution for phased array systems is 10 minutes, and for the crossed loop systems is 1 hour in the ACORN network.

Here we will provide an overview of radar resolution characteristics and then discuss three examples of the application of ocean radar data to coral reefs. The first is in tracking the movement of

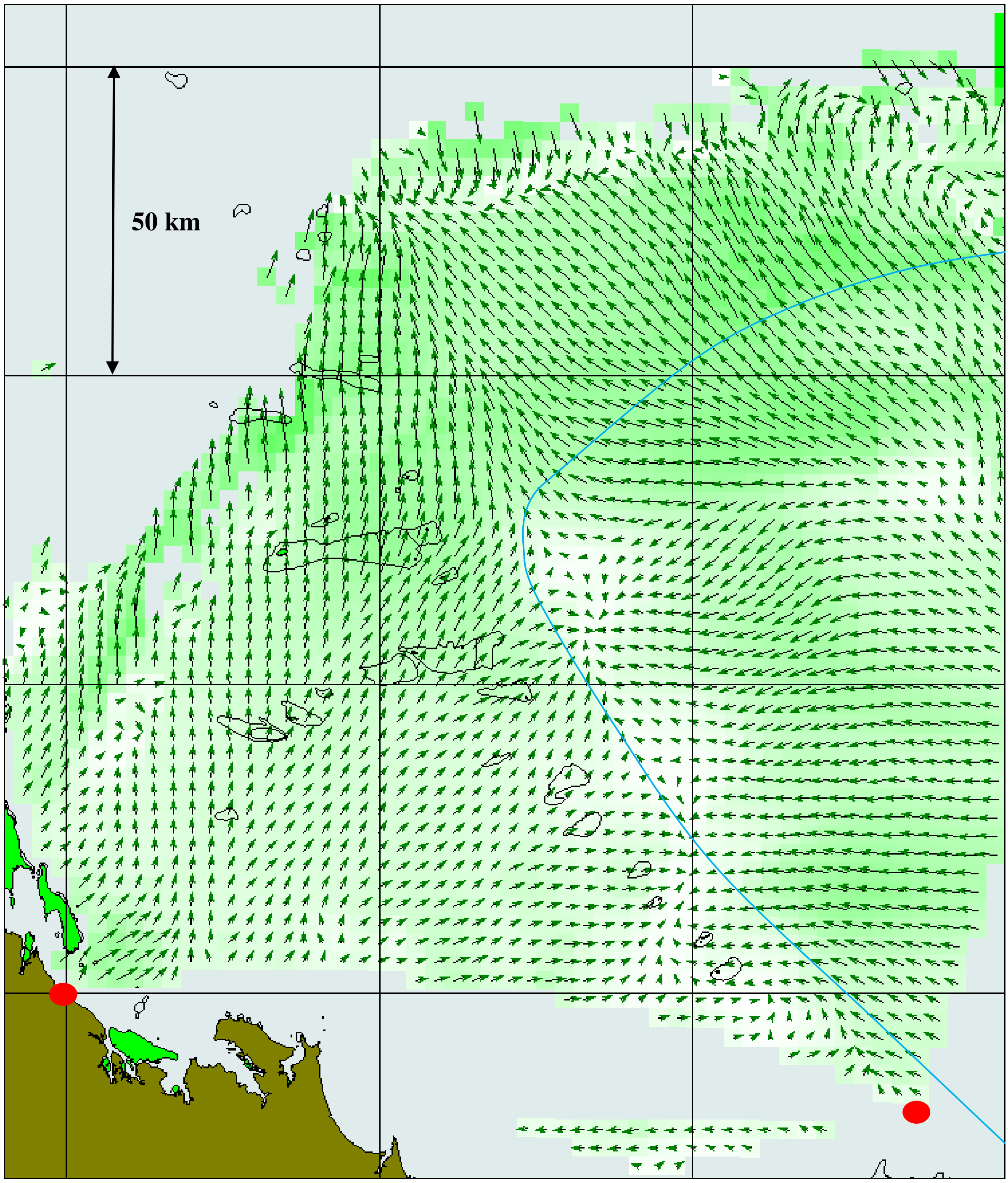

Figure 1. Surface current vectors on a 4 km × 4 km grid in the Capricorn/Bunker Groups in the Southern Great Barrier Reef. The radar stations are located at Tannum Sands and Lady Elliot Island (marked in red). The green shading is darker where the current speeds are higher. This is a raw sample without temporal gap filling or spatial smoothing, taken over a 10-minute interval. Values at the extremities are noisy and not reliable. The blue line indicates the location of the 400 m depth contour. The grey areas inside the mapped area appear when the analysis software could not reliably detect a Bragg peak – usually due to interference, noise, or abrupt shears.

water between reefs for nutrient, pollution and larvae transport. The second example uses radar currents to identify locations in the southern Great Barrier Reef region which are less likely to be affected by coral bleaching. Lastly, a demonstration of the capability of high-resolution, short-range ocean radars to map water dynamics within reef lagoon areas is provided.

Spatial Resolution

Spatial resolution is determined in polar coordinates of range and azimuth angle from the radar location. The range resolution is constant across the domain and is determined by the bandwidth allocated by the radio frequency regulating authority for each deployment. For the data shown in Fig. 1 the bandwidth was 33 kHz and the consequent range resolution is 4.5 km. The azimuthal resolution is defined for the radar system by design and can vary from about 5-25°. Once chosen, it is fixed for each radar installation. It means that the spatial resolution in the azimuth direction increases with range. The azimuthal resolution for the data in Fig. 1 is 8.5°. The native pixels are approximately square at a range of 30 km (4.5 × 4.5 km). At shorter ranges the azimuthal resolution is less than 4.5 km; at longer ranges it is greater than 4.5 km. In order to remove this complexity, the surface current data are presented on a 4 km × 4 km rectangular grid.

For different applications the spatial resolution can be controlled. For example, the lower resolution, long-range, crossed-loop systems deployed in ACORN have azimuthal resolution of about 18°, which results in an azimuthal cell dimension of 3.1 km at a range of 10 km and 31 km at a range of 100 km.

The short-range (up to 10 km) system, described later in the paper, achieves a spatial resolution of about 250 m to produce detailed maps of surface currents in a complex reef area.

Lagrangian Tracking

With mapped data, of the general quality shown in Fig. 1, taken every 10 minutes, it is conceptually easy to track a parcel of surface water over time and space. For a given starting location and time, we can interpolate on the 2D map to find the surface current at the point; and we can interpolate between 10-minute maps to get the surface current at the start time. Then we move in the direction and speed of that velocity vector to a new point, and iterate using the new map. Mathematically, this is risky because it is an integrating process where errors are cumulative and can become unacceptable. In practice, care is taken to avoid bad data, and gap filling is done by

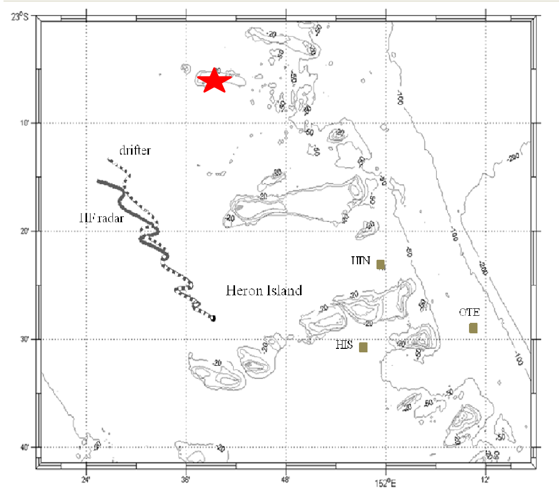

Figure 2. A surface drifter tracked by satellite follows the dotted line, while a track derived from HF radar data using the same starting location and time follows the solid line. The zigzags are due to the dominant 12-hour tide, and the trend towards the north west is due to the synoptic surface wind. The star marks Douglas Shoal, the site of a ship-grounding in April 2010.

first separating the part of the currents due to astronomical tides (for which we do not have to interpolate), and interpolating only that part of the signal that has unknown driving forces (e.g., wind, diffusion, mesoscale currents; Mantovanelli et al. 2011). The strength of this methodology is that the track produced is based on real data and has none of the assumptions of diffusion coefficients, wind effects or parameterisations that exist in hydrodynamic models. The main weakness is that it is restricted to buoyant surface particles (upper 1 m), and the area that can be used is limited to the extent of the area that the radars are covering at the time.

With the precautions discussed, particles have been tracked on the shelf for up to 4 days (with errors typically 2-4 km per day) to study spatial and temporal changes in diffusivity, and larval connectivity between reefs. Fig. 2 shows a test between a real satellite-tracked surface drifter, and a Lagrangian track derived from HF radar. A feature of interest in these data is the abrupt separation of the tracks after about 36 hours (zigzags are tidally-driven and occur at 12 hour intervals). Prior to that event, the tracks are very close (inseparable on the diagram), and afterwards there is a steadily increasing separation. This phenomenon is repeated when we consider two closely spaced drifters, or two radar tracked points which start closely spaced; and this is the focus of ongoing research: there is something in time or space that has caused a dramatic change in the horizontal diffusivity at the surface. Lagrangian tracking proved useful in tracking surface debris when the Shen Neng I ran aground in April 2010 at Douglas Shoal (marked with the red star in Fig. 2) (Heron et al. 2010).

Coral Bleaching

One of the main physical processes involved in coral bleaching is the stratification of the water column where warmer water at the surface forms a stable (density) layer above the cooler water below. Under conditions of stratification, the influx of solar heat remains in the surface layer, therein reinforcing the stratification. If the column is well mixed then the solar energy is distributed through a greater volume, and the temperature rise is reduced.

A simple link between water speed and depth, and turbulent mixing was described by Simpson and Hunter (1974) and applied to coral reefs by Di Massa et al. (2010). The Simpson-Hunter parameter is given by:

$$SHP = \log_{10}(h/U^3),$$

where h is the water depth and U is the water speed. The critical SHP value above which turbulent mixing dominates is determined mainly by the benthic rugosity and must be calibrated for each location. Di Massa et al. (2010) used data from an acoustic profiler moored on the shelf near Heron Island to calibrate the critical SHP at 2.2 for this area. On the basis of this, maps were produced showing the number of hours in a day that critical SHP was exceeded (Di Massa et al. 2011). This identifies areas that are less prone to coral bleaching for the benefit of management and planning of reef utilization.

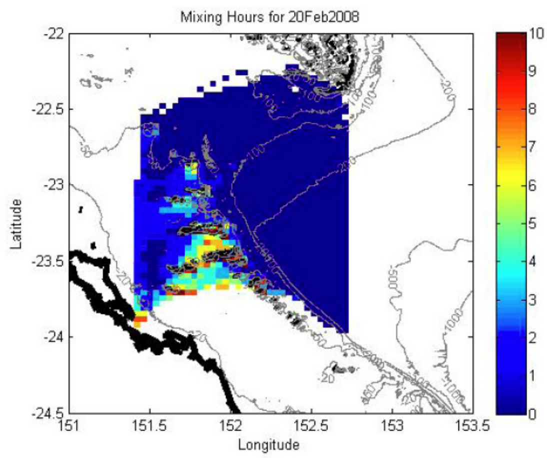

Figure 3. The number of hours on 20Feb2008 that the Simpson-Hunter Parameter exceeded the critical value for turbulent mixing. (after Di Massa et al. 2011)

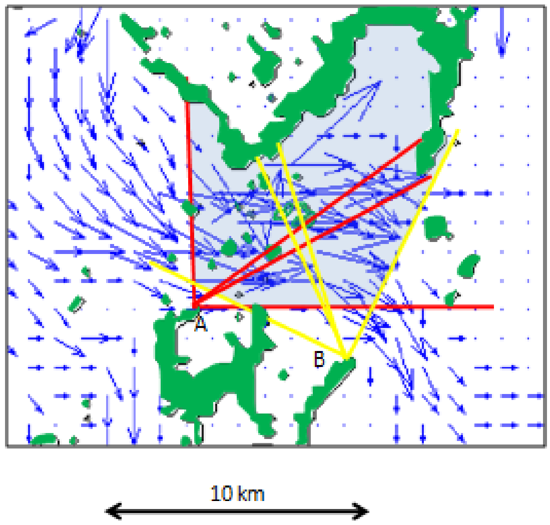

Figure 4. Model output (blue) on a 250 m grid in an entrance channel to the Palau Lagoon. Arrow tails are on the model grid points and only 1/16 of the arrows are plotted to avoid congestion on the picture. Emergent land is shown in green. Light blue shading indicates the area of coverage for ocean radar stations at locations A and B. The angular resolution for a 12-element phased array system is shown by the yellow and red sectors. Station A is at 134° 21.6' W, 7° 10.6' N.

High Spatial Resolution Ocean Radars

The parameters of spatial resolution can be controlled at the time of installation, and pixel sizes as small as 100 m can be achieved using VHF (Very High Frequency: 30-300 MHz) radars. This enables mapping of surface currents on lagoon scales.

An example is given to show how a high resolution phased array system could be usefully deployed in the Palau Lagoon in the tropical western Pacific Ocean. We use model output (Skirving et al. 2010) to design a layout using a 12-element phased array operating at 100 MHz with a bandwidth of 1.2 MHz. This gives range resolution of 250 m and azimuth resolution of 8.5°; at a range of 1.7 km the pixels would be symmetric with scale size 250 m.

The spatial sampling is shown in Fig. 4, superposed on the model output. Note that only 1 in 4 of the grid points in each of the east and north directions is plotted in order to make the diagram legible. The benefit of the ocean radar is that it automatically calibrates for parameterisations assumed in the model, and at ranges less than 1.7 km it can give more detail to validate the model.

Conclusion

Ocean radars map the surface current, incorporating all of the component phenomena like diffusion and turbulence, wind stress, Stokes' Drift and shears. The radar data provide an excellent validation for hydrodynamic models and enables calibration of the parameterisations of complex phenomena. Phased array radars have high precision, and it has been shown that buoyant parcels of water can be tracked for up to 4 days with accuracy in the order of 12 kilometres when compared with surface drifters. The spatially-broad nature of radar data has been utilized to determine areas of characteristically high current speeds where turbulent kinetic energy can destroy any stratification. These are areas where coral bleaching is less likely to occur.

VHF options for ocean radar are being developed for high spatial resolution and there is potential for increasing the understanding of water dynamics within coral lagoons.

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