Synthetic Aperture Radar scenes of the North West Shelf, Western Australia, suggest this is an underutilised method to remotely study mass coral spawning

ANNA K. CRESSWELL [1,2,3*], PAUL C. TILDESLEY [4] AND GEORGE R. CRESSWELL [4]

[1] *School of Biological Sciences, University of Western Australia, 35 Stirling Highway, Crawley WA, 6009, Australia*

[2] *CSIRO Oceans and Atmosphere, Indian Ocean Marine Research Centre, 64 Fairway, Crawley, WA, 6009, Australia*

[3] *The UWA Oceans Institute, University of Western Australia, 35 Stirling Highway, Crawley, WA, 6009, Australia*

[4] *formerly CSIRO Oceans and Atmosphere, Castray Esplanade, Battery Point Tas 7004, Australia (retired)*

* *Corresponding author: ✉ annacresswell@gmail.com*

Abstract

Corals reproduce during annual 'mass spawning' when gametes are released into the water column in near-unison. While mass spawning events have been well studied, there remain key questions about their timing, triggers and resilience. We report the second occasion to our knowledge in which a mass spawning has been captured serendipitously with satellite-borne synthetic aperture radar (SAR). SAR can collect information through cloud and in both day and night by detecting changes in ocean surface roughness, including, as we shown here, those caused by mass coral spawning, which creates slicks or films of spawn on the sea surface. We examined four SAR scenes of coral reefs on the North West Shelf, Western Australia, from a 10-day interval bracketing the expected time of mass spawning in March 2001. The scene from 19 March 2001 shows what we classify as a snapshot of mass coral spawn slicks, from reefs extending over an area of roughly 100 km. The locations of the slicks correlated spatially with underlying carbonate reefs. We suggest SAR monitoring of coral reefs at spawning time may be an underutilised method that can provide new information on this natural phenomena.

Keywords: Barrow Island, coral reproduction, coral reef, RADARSAT, remote sensing, SAR, monitoring, methodology

Manuscript received 29 December 2018; accepted 13 August 2019

INTRODUCTION

Understanding coral life cycles is becoming more important as ocean warming drives mass coral mortality events (Hughes *et al*. 2017). Reproduction in corals is a synchronised phenomenon, known as "mass spawning", where a large proportion of corals release gametes over only a few consecutive nights at certain times of the year (Simpson *et al.* 1991, Keith *et al.* 2016). The reproductive matter floats to the surface and in reefs of dense coral this often leads to coral spawn 'slicks' or 'films' on the water surface (Oliver & Willis 1987). Depending on weather conditions, these slicks can persist for several days, allowing the possibility of tracking both the extent and the movement of coral embryos and larvae following a mass spawning.

Satellite-borne SAR sends microwave pulses to Earth, and based on the return of echoes back to the satellite, makes an image, which can provide information on the surface from which it was reflected (Gens 2008). Roughened ocean surfaces scatter part of the SAR signal back to the satellite whereas a smooth ocean surface, where capillary waves are dampened, reflects the signal away (Gens 2008). When Jones *et al*. (2006) detected surface slicks in a SAR scene obtained with the Canadian Space Agency's RADARSAT of the Vulcan and Goeree Shoals in the Timor Sea on 16 April 1998 they interpreted these to be coral spawning slicks, the first documented by SAR. Their case was strong because the shapes of the slicks matched those of the underlying reefs, and the conditions were right to expect mass spawning in this region: autumn, 4½ days after full moon, shortly after sunset, an ebb tide one hour before low tide with wind speed 4.6 ms^{-1}.

Coral spawn slicks are composed of coral eggs and embryos and their breakdown products, and can form dense, highly viscous patches (Oliver & Willis 1987). SAR has commonly been used to detect natural hydrocarbon seeps and oil spills in the ocean (Tian *et al*. 2015), the principles of which may be applied to coral slicks (Jones *et al*. 2006). There are challenges associated with detecting slicks, mainly linked to the wind and swell conditions at the ocean surface. Harahsheh *et al*. (2001) assign optimum wind speeds for oil slick detection to be between 3 and 6 ms^{-1}, given that wind speeds less than this will cause minimal difference in backscatter between slicks and calm seas, and wind speeds greater are likely to cause disintegration of slicks (Ivanov 2000; Brekke & Solberg 2005).

In Western Australia mass coral spawning was first recorded in the Dampier Archipelago (Simpson 1985). In this region corals generally spawn around the third quarter of the moon (*i.e.* one week after full moon) on neap, nocturnal, ebb tides (Rosser & Gilmour 2008, Baird *et al*. 2011, Gilmour *et al*. 2016). In some cases where the full moon falls near the edge of the spawning window only some corals will have mature gametes and spawn, whereas others will delay spawning until the following full moon, resulting in a 'split-spawning' (Gilmour *et al.* 2016).

There are still questions about the timing of coral spawning, geographic variation in spawning season and the environmental triggers (Rosser & Gilmour 2008, Baird *et al.* 2011, Gilmour *et al*. 2016, Keith *et al*. 2016). Recently, remote sensing has been recognised as an important tool for the interdisciplinary assessment of coral reef processes (Hedley *et al.* 2016). Here, we present four SAR scenes of the waters around the Barrow and Montebello Islands, which bracket the time of an expected coral spawning event in March 2001. SAR has not previously been used in targeted studies of coral spawning events, and we discuss the utility of this method for adding to the knowledge base on coral spawning.

METHODS

Four SAR scenes were obtained over a ten-day interval in March 2001 as part of Project 250 of RADARSAT-1 of the Canadian Space Agency/Agence spatiale canadienne (Parashar *et al.* 1993). They were initially acquired to investigate oceanic internal waves in the region (Jackson 2004, fig. 3). The scenes are "ScanSAR Wide", i.e. 500 km square with a resolution of 100 m, and cover the region around the Barrow and Montebello Islands, part of a group of islands to the northwest of the Australian coast at ~21°S (Fig. 1). The date and times of the scenes, as well as whether the satellite was in ascending or descending orbit, are as follows: 17 March (05:44, descending), 19 March (18:50, ascending), 24 March (05:40, descending) and 26 March (18:46, ascending). The SAR scenes were interpreted visually; generally, white areas due to high backscatter of the reflected signal indicate roughened water surfaces, and black or low backscatter areas indicate smooth surfaces (Gens 2008). Images required interpretation with reference to additional factors as low backscatter can be indicative of windless, smooth water surfaces (Gens 2008), oil slicks (Nunziata *et al*. 2013) and phytoplankton blooms (Wu *et al*. 2018) amongst other things (Harahsheh *et al*. 2001).

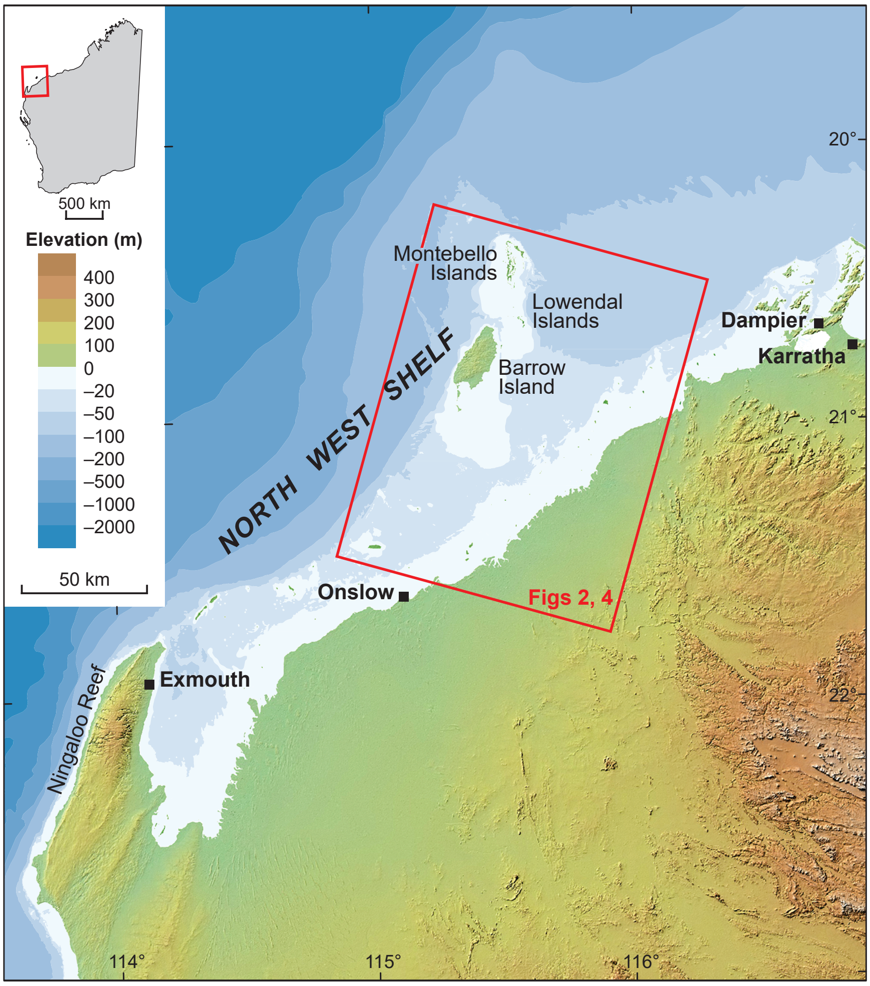

Figure 1. The North West Shelf of Australia showing the region covered by the RADARSAT SAR scenes examined for this study. The coastline and isobaths from 100–1000 m are from the General Bathymetric Chart of the Oceans (GEBCO) https://www.gebco.net/ and the 20 m isobath was copied from the Australian National Bathymetric Map Series.

In order to narrow the classification to coral spawn we followed the advice of Jones *et al*. (2006) to increase the accuracy of interpretation. Ancillary data—bathymetry, current velocities, wind speeds and directions—were investigated alongside the SAR scenes. We examined the scenes with reference to the expected time and days of coral spawning in 2001, the proximity to underlying carbonate reefs, and the states of the tides and winds. We also checked for any historical reports of oil spills at the time of the SAR scenes.

With reference to the time, moon phase and tide, a spawning event was expected 7–10 days after the full moon on a neap, nocturnal, ebb tide (Gilmour *et al*. 2016). Tide data for the time of the SAR scenes was sourced for Barrow Island from http://tides.mobilegeographics.com. Tides in the region are semidiurnal and the magnitude varies around the islands with a maximum spring tide on the east coasts of >4 m compared with <2.5 m on the west coasts of the offshore islands (Richards & Rosser 2012).

Wind measurements from the Barrow Island Airport were obtained from the Australian Bureau of Meteorology for the times of the SAR scenes. We considered the locations of the subtidal and intertidal carbonate reefs as indicators of a coral population, overlaying spatial data from SAR scenes illustrated by the Western Australia Department of Environment and Conservation (2007, fig. 3).

All references to time are in Western Standard Time, WST (Coordinated Universal Time, UTC + 8 hours), with local time in the study region being WST-20 minutes.

RESULTS AND DISCUSSION

The four SAR scenes (Fig. 2) and information on wind, moon phase and time of day (Fig. 3), suggest that a mass spawning event can be captured using SAR. The 17 March 2001 scene (Fig 2a), six days after the full moon, was captured at dawn on what was a strong ebb tide with Barrow Island airport recording a 9 ms^{-1} southwesterly wind. This is equivalent to five on the Beaufort Scale (Mather 2005), which translates to “Fresh breeze. Moderate waves (1.8 m), many whitecaps”. Although the time of the lunar month, the tide and time of day satisfied Gilmour’s *et al.* (2016) conditions for mass coral spawning for the region, no coral spawn slicks were detected. However, the strong wind and breaking waves would likely have demolished any coral spawn slicks that may have been present.

The 19 March 2001 scene (Fig. 2b), ten days after full moon at neap tide (weak ebb), was captured at

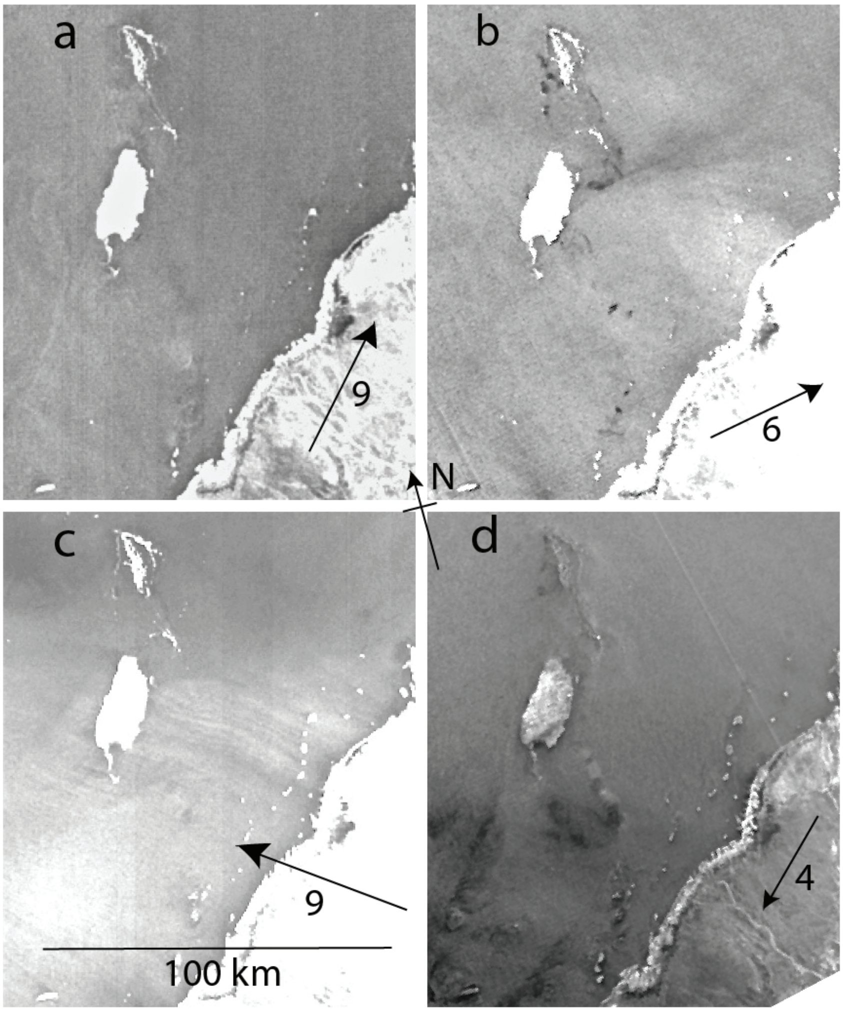

Figure 2. The RADARSAT SAR scenes from the Montebello and Barrow Islands region for a) 17, b) 19, c) 24 and d) 26 March 2001. The vectors represent the winds (ms^{-1}) measured at Barrow Island Airport at the times of the satellite passes.

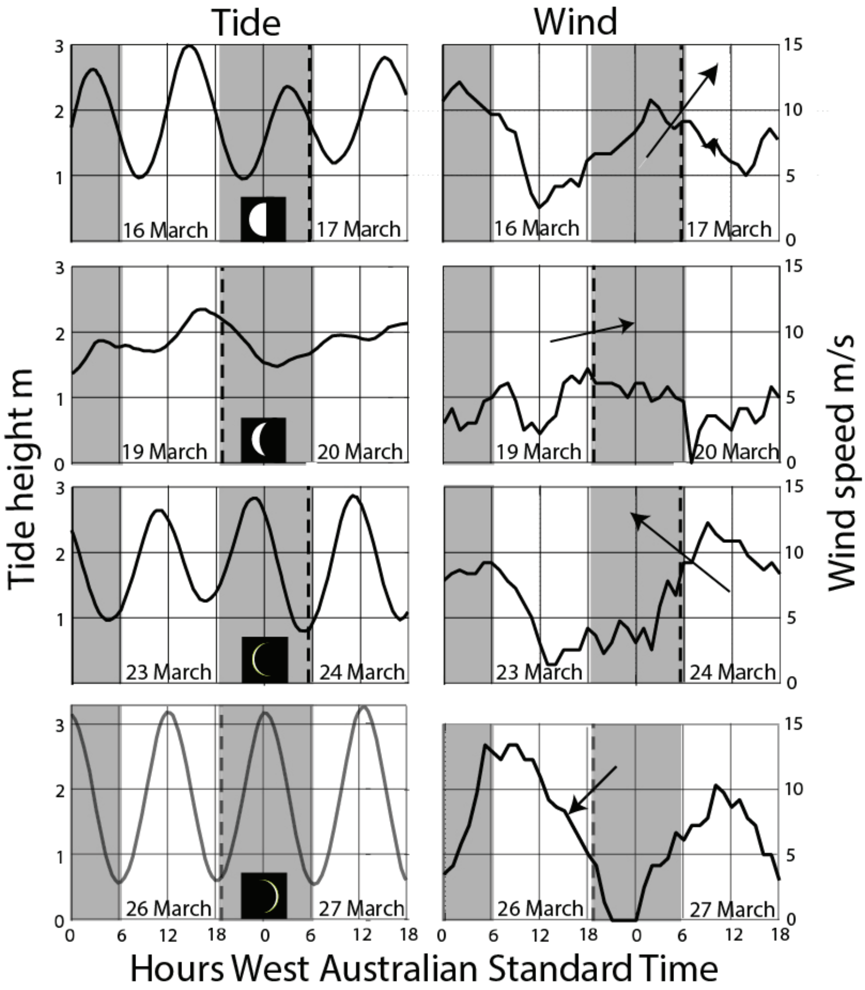

Figure 3. Predicted tide at Barrow Island and wind speed measured at Barrow Island airport around the times of the RADARSAT SAR scenes, which are marked with vertical dashed lines. The shading indicates night, the small black boxes show the phases of the moon, and wind vectors at the times of the scenes are added at the intersections of the dashed lines with the 10 ms^{-1} grid lines.

early twilight and a 6 ms^{-1} westerly wind was recorded, equivalent to four on the Beaufort Scale—"Moderate breeze. Small waves (1 m), some whitecaps." Gilmour's *et al.* (2016) conditions for mass coral spawning—phase of the moon, tidal conditions and time of day (early evening)—were satisfied and the wind speed fell within the optimum range for slick detection (Harahsheh *et al*. 2001). These factors in combination with low backscatter shown by black areas near the islands, and between there and the NW Australian coast, indicate slicks. Slicks appear to have originated from multiple reefs across the study region.

The 24 March 2001 scene (Fig. 2c) was captured just before dawn, at new moon and low water with a 9 ms^{-1} southeasterly wind, equivalent to five on the Beaufort Scale, as was that for the 16 March scene. Roughened waters, some aligned with the wind direction, can be seen between the northwestern Australia coast and Barrow Island. As with Figure 2a, there appear to be no regions of smooth water or slicks, in keeping with the strong winds.

The 26 March 2001 scene (Fig. 2d) was captured just after sunset at new moon at low water with a 4 ms^{-1} northeasterly wind, equivalent to three on the Beaufort Scale—"Gentle breeze. Large wavelets (0.6 m), crests begin to break". The gentle breeze may be the reason for the extensive smooth areas in the southwest part of the scene. To the west of the Montebello Islands localised areas of low backscatter are likely due to calm water surfaces, as in this region coral spawning has not been documented to continue for this many days after the full moon (Gilmour *et al*. 2016, Simpson *et al.* 1991).

The complex distribution of subtidal and intertidal reefs around Barrow and the Montebello Islands is represented in the yellow and green overlay on the 19 March 2001 scene in Figure 4b, as this was the scene that showed strong evidence of coral spawn slicks. There appears to be a strong relationship between the reefs and the dark pixels (low backscatter) of the SAR image. We suggest these dark pixels represent a mass coral spawning in progress on the evening of 19 March. The slicks are more distinct in some locations, particularly west of the Montebello Islands, east of Barrow Island and at the subtidal reefs further south. Eastward from Barrow Island is a fan of water that is smooth relative to its surroundings, as shown by the darker pixels. We speculate that this may be due to coral spawn being carried eastward by current and/or wind, though it could also be a result of smooth water in the windward lee of the land. Dark pixels on the eastern sides of two small reefs west of Barrow Island can be interpreted as having a similar origin. Along part of the southeast coast of Barrow Island there is also smooth water, possibly from coral spawn or from being in the lee of the island.

Aerial photographic surveys are one method that has historically been used to quantify the extent of coral spawn slicks, which appear as pink or white patches on the water surface (Oliver & Willis 1987). The advantage of SAR over photography is that it can collect data at night (coral generally spawn in the evening), and through cloud cover (Gens 2008). However, there are potential problems associated with false positive detections. Smooth water, oil spills, phytoplankton blooms (Wu *et al.* 2018), in particular *Trichodesmium* spp. slicks (Oliver & Willis 1987), and natural carbon seeps all have the potential to give a false positive for coral spawn (Gens 2008). Low wind speeds may cause pseudo slicks which would be indistinguishable from coral spawn, as Figure 2d showed, whereas high wind speeds can cause coral spawn to be quickly dispersed thus not forming slicks that can be detected by SAR (Brekke & Solberg 2005).

Nevertheless, our study, along with that of Jones *et al*. (2006), suggest it would be worthwhile to trial SAR as a method for targeted studies of coral spawning on a large scale, if measures can be taken to remove the likelihood of false positives through consideration of the weather, tide, and predicted coral spawning time. Combining SAR with data such as in situ documentation of coral spawning, and monitoring of oil slicks or phytoplankton blooms that could confuse the SAR interpretation would allow this method to be used more accurately. Alternatively, or additionally, optical satellite (e.g. from Landsat (https://landsat.gsfc.nasa.gov/)) or airborne imagery, in daylight hours if cloud was absent, would help to confirm SAR identifications (Hedley *et al.* 2016).

SAR may be particularly useful to assess remote or difficult to access coral reefs where monitoring coral spawning can be logistically and/or economically challenging. In the years since the SAR scenes of the present study were collected, SAR technology (and remote sensing satellite technology more generally) has advanced. There are now more than 15 space-borne SAR systems in operation for a diverse range of applications, with continued advances in the capability to collect ecological information (Moreira *et al*. 2013). This includes the Sentinel-1 satellite (https://sentinel.esa.int/web/sentinel/missions/sentinel-1/data-distribution-schedule), which has freely distributed SAR scenes. There are various ways SAR acquisition could be adapted to directly target coral spawning. The SAR scenes interpreted in this study were the “ScanSAR Wide” option, but higher resolution, smaller scenes could be

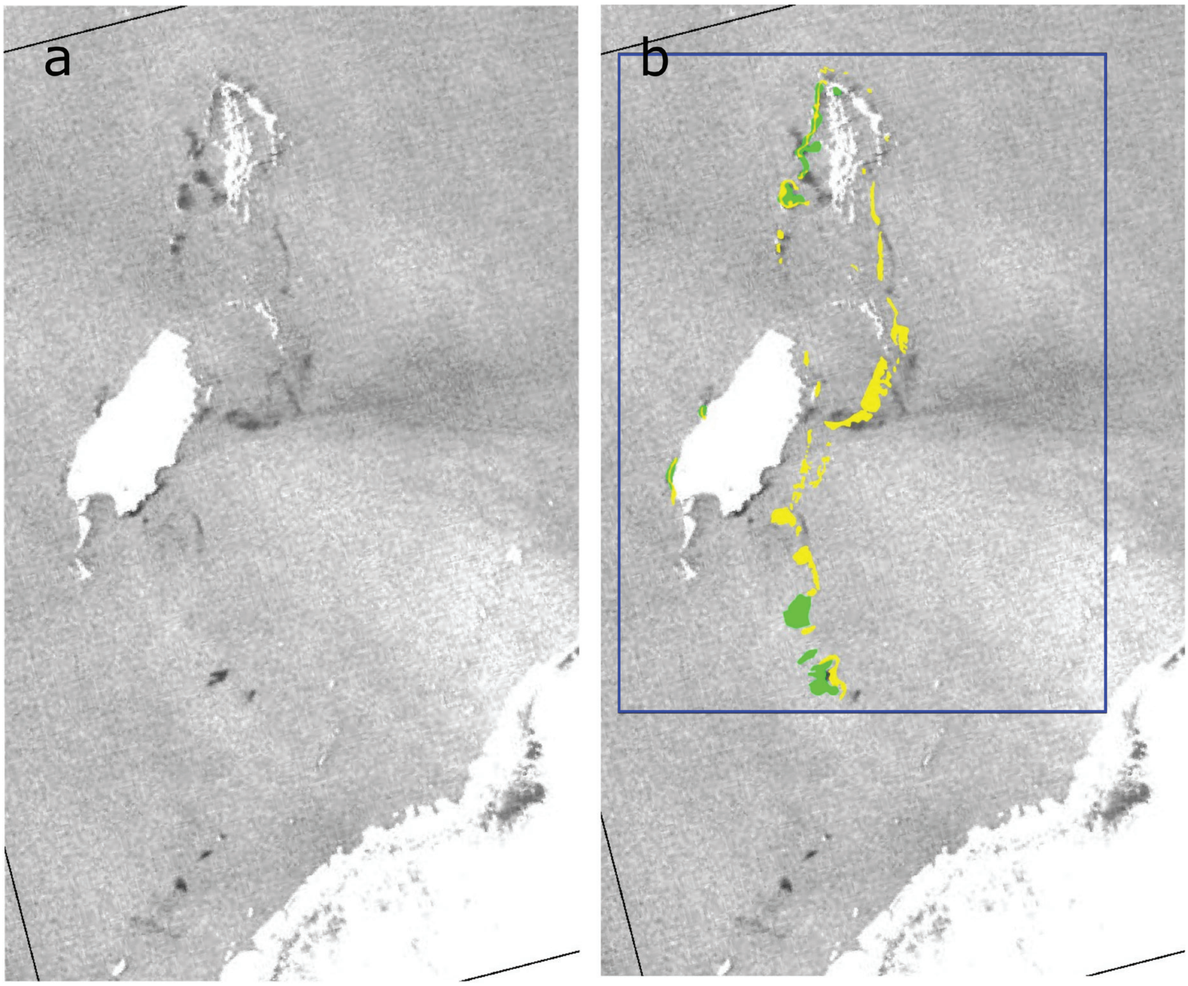

Figure 4. a) RADARSAT SAR scene for 19:50 hrs WST 19 March 2001; b) with yellow and green overlays showing the positions of subtidal and intertidal reefs, respectively. Note, the spatial data for reef locations are smaller than the SAR scene, indicated by blue outline.

collected in the future. There are likely to be issues with satellite location lining up with the timing and location of coral spawning in cases where the satellite overpass does not align with the targeted reef(s). Ideally, several satellite passes each day could capture the evolution of coral spawn slicks. However, access to a number of SAR satellites would be required to achieve this, as the return frequency of an individual satellite is generally every few days, as was the case in the present study. With a greater number of satellites operating SAR, this becomes more possible. Nonetheless, targeting a large reef system such as the Great Barrier Reef, or being flexible with location, would allow higher likelihood of capturing the event.

CONCLUSIONS

Of the four SAR scenes we examined, that for 19 March 2001 captured a mass coral spawning event off north Western Australia that was synchronised at reefs extending over 100 km. This is, to our knowledge, the second time SAR has serendipitously captured mass coral spawning. This suggests that if targeted, SAR can be a method to provide important synoptic information on the timing, extent and surface longevity of coral spawn slicks, which would increase our understanding of this phenomenon. New information could be applied in many fields, including modelling studies focused on reproduction, connectivity and dispersal in coral reefs, as parameters surrounding the extent and timing of mass spawning events are important for such models (Wood *et al.* 2014). It could also directly benefit managers; for example, in situ monitoring in north Western Australia is used to detect spawning events on reefs in areas of dredging and industrial development, yet Styan & Rosser (2012) suggest that current practices often miss significant mass spawning events. We do not suggest SAR as a replacement to existing monitoring, rather as a complementary tool, with limitations discussed above. Greater availability of SAR, including freely available images from Sentinel-1, promises to continue to allow better connections between field observations of spawning events with satellite-borne imagery.

ACKNOWLEDGEMENTS

The SAR scenes were collected as part of Project 250 of RADARSAT-1 of the Canadian Space Agency/Agence spatiale canadienne. PCT and GRC were employed by CSIRO at that time. We acknowledge the BHP-CSIRO Industry−Science Ningaloo Outlook Marine Research Partnership and the University of Western Australia Jean Rogerson Postgraduate Scholarship for supporting AKC at the time of writing. Dr Susan Blackburn and other anonymous reviewers provided valuable comments on the manuscript. We thank the Australian Bureau of Meteorology for their service.

CONFLICT OF INTEREST STATEMENT

On behalf of all authors, the corresponding author states that there are no conflicts of interest.

REFERENCES

Baird A, Blakeway D, Hurley T & Stoddart J 2011. Seasonality of coral reproduction in the Dampier Archipelago, northern Western Australia. *Marine Biology* **158**, 275–285.

Brekke C & Solberg A H S 2005. Oil spill detection by satellite remote sensing. *Remote Sensing of Environment* **95**, 1–13.

Parashar S, Langham E, McNally J & Ahmed S 1993. RADARSAT mission requirements and concept. *Canadian Journal of Remote Sensing* **4**, 280−288.

Department of Environment and Conservation 2007. Management plan for the Montebello/Barrow Islands marine conservation reserves 2007–2017. Marine Parks & Reserves Authority and Western Australia Department of Environment and Conservation Perth, WA, Management Plan No. 55.

Gens R 2008. Oceanographic Applications of SAR Remote Sensing. *GIScience & Remote Sensing* **45**, 275–305.

Gilmour J, Speed C W & Babcock R 2016. Coral reproduction in Western Australia. *PeerJ* **4:e2010** doi:10.7717/peerj.2010

Jackson C R 2004. Australian Northwest Shelf. Pages 509–518 *in* Global Ocean Associates, compilers, *An Atlas of Oceanic Internal Solitary-like Waves* (2nd edtion). Office of Naval Research, Alexandria Virginia, USA.http://www.internalwaveatlas.com/Atlas2_PDF/IWAtlas2_Pg509_Australia_NW2.pdf

Hedley J, Roelfsema C, Chollett I, Harborne A, Heron S, Weeks S, Skirving W, Strong A, Eakin C & Christensen T 2016. Remote sensing of coral reefs for monitoring and management: a review. *Remote Sensing* **8**, 118.

Harahsheh H, Essa S, Shiobarac M, Nishidaid T & Onumad T 2001. Operational satellite monitoring and detection for oil spill in offshore of United Arab Emirates. Pages 658–663 *in* O Altan, editor, *XXth International Society for Photogrammetry and Remote Sensing Congress, Technical Commission VII*, July 12–23 2004, Istanbul, Turkey. https://www.isprs.org/proceedings/XXXV/congress/comm7/papers/130.pdf

Hughes T P, Kerry J T, Álvarez-Noriega M, Álvarez-Romero J G, Anderson K D, Baird A H, Babcock R C, Beger M, Bellwood D R & Berkelmans R 2017. Global warming and recurrent mass bleaching of corals. *Nature* **543**, 373–377.

Ivanov A 2000. Oil pollution of the sea on Kosmos-1870 and Almaz-1 radar imagery. *Earth Observation and Remote Sensing* **15**, 949–966.

Jones A T, Thankappan M, Logan G A, Kennard J M, Smith C J, Williams A K & Lawrence G M 2006. Coral spawn and bathymetric slicks in Synthetic Aperture Radar (SAR) data from the Timor Sea, north-west Australia. *International Journal of Remote Sensing* **27**, 2063–2069.

Keith S A, Maynard J A, Edwards A J, Guest J R, Bauman A G, Van Hooidonk R, Heron S F, Berumen M L, Bouwmeester J & Piromvaragorn S 2016. Coral mass spawning predicted by rapid seasonal rise in ocean temperature. *Proceedings of the Royal Society B* **283**, 20160011

Mather J R 2005. Beaufort wind scale Encyclopedia of World Climatology. Springer, pp156–157 doi: https://doi.org/10.1007/1-4020-3266-8_28

Moreira A, Prats-Iraola P, Younis M, Krieger G, Hajnsek I & Papathanassiou K P 2013. A tutorial on synthetic aperture radar. *IEEE Geoscience and remote sensing magazine* **1**, 6–43 doi:10.1109/MGRS.2013.2248301

Nunziata F, Gambardella A & Migliaccio M 2013. On the degree of polarization for SAR sea oil slick observation. *ISPRS Journal of Photogrammetry and Remote Sensing* **78**, 41–49.

Oliver J & Willis B 1987. Coral-spawn slicks in the Great Barrier Reef: preliminary observations. *Marine Biology* **94**, 521–529.

Richards Z & Rosser N 2012. Abundance, distribution and new records of scleractinian corals at Barrow Island and Southern Montebello Islands, Pilbara (offshore) bioregion. *Journal of the Royal Society of Western Australia* **95**, 155–165.

Rosser N L & Gilmour J P 2008. New insights into patterns of coral spawning on Western Australian reefs. *Coral Reefs* **27**, 345–349.

Simpson C J 1985. Mass spawning of scleractinian corals in the Dampier Archipelago and the implications for management of coral reefs in Western Australia. *Western Australian Department of Conservation and Environment Bulletin* **244**, 35 pp.

Simpson C J, Pearce A & Walker D 1991. Mass spawning of corals on Western Australian reefs and comparisons with the Great Barrier Reef. *Journal of the Royal Society of Western Australia* **74**, 85–91.

Styan C A & Rosser N L 2012. Is monitoring for mass spawning events in coral assemblages in north Western Australia likely to detect spawning? *Marine Pollution Bulletin* **64**, 2523–2527.

Tian W, Bian X, Shao Y & Zhang Z 2015, On the detection of oil spill with China's HJ-1C SAR image. *Aquatic Procedia* **3**, 144–150.

Wood S, Paris C B, Ridgwell A & Hendy EJ 2014. Modelling global coral connectivity. *Global Ecology and Biogeography* **23**, 1–11.

Wu L, Wang L, Min L, Hou W, Guo Z, Zhao J & Li N 2018. Discrimination of Algal-Bloom Using Spaceborne SAR Observations of Great Lakes in China. *Remote Sensing* **10**, 767.