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# Satellite Observations of Internal Waves on the Australian North-west Shelf

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*Abstract*

This paper describes the results of a search of the existing Landsat (1 and 2) imagery catalogue for tidally generated internal waves over the continental shelves of Australia and New Zealand. The only area where such waves were observed was the Australian north-west shelf where they were found in abundance from the North West Cape to the latitude of Darwin. Wavelengths were in the range 300–1000 m with typical speeds of 0·5–1 m $s^{-1}$, and spacing between wave packets of 25 km.

## Introduction

Bands of sea-surface roughness over continental slopes have been observed in imagery from the Landsat (formerly Earth Resources Technology Satellite) satellites for several years, and these have been identified with internal waves on the shallow thermocline, generated by the tide at the shelf edge (Apel *et al.* 1975). Such waves may only be found where a shallow seasonal thermocline exists to support them, generally in the spring and summer. They have been observed (by satellite and other means) in many parts of the world, particularly off the United States east coast north of Cape Hatteras (Sawyer and Apel 1977); recently a spectacular example in the Andaman Sea has been documented in detail (Osborne and Burch 1980).

The satellites Landsats 1 and 2 produced pictures in four channels of visible or near infra-red light, of which channel 6 (700–800 nm) was generally the best for observing the internal wave bands. The area covered by each picture is approximately 180 by 180 km, with a resolution of 75 m. The internal waves on the thermocline are made visible by the effect of the associated convergence and divergence patterns producing rough/smooth bands on the free surface. Two mechanisms have been advanced to account for this. Firstly, if the water is covered by a surface film of organic matter (which is a common occurrence in biologically active areas), variations in the thickness of the film cause substantial variations in surface tension and consequently in surface-wave damping; the flow patterns associated with internal waves produce such variations, and travelling bands of rough and smooth water have been identified with internal waves in these conditions in light winds (Ewing 1950; Lafond 1962). The second mechanism does not require surface films and concerns the effect of the internal waves directly on the surface-wave field; the surface roughness is increased (decreased) in regions of convergence (divergence) due to radiation stress effects (Gargett and Hughes 1972). Observations made by airborne synthetic aperture radar (Elachi and Apel 1976) suggest that both mechanisms may operate simultaneously. However, our knowledge of the circumstances under which each mechanism may be expected to work is vague, and in any particular satellite observation it is not known *a priori* which mechanism is responsible. Whether or not such waves will be observed by satellite therefore depends on a number of factors—a generation mechanism (see below), a seasonal thermocline, a suitable surface film or wind-wave field or both, and, possibly, an appropriate solar angle of incidence.

No observations of such internal waves made by satellite in the Australia–New Zealand region have yet been described, and in order to find out whether this was due to an absence of waves or to a failure to look for them, a search was undertaken of the available Landsat pictures of the area. With the help of Dr Constance Sawyer of the Pacific Marine Environmental Laboratories, National Oceanic and Atmospheric Administration, Seattle, an inspection was made of the existing Landsat pictures from October to March inclusive using the 70-mm film collection at those laboratories compiled by Dr John Apel. No slicks having the characteristic internal-wave packet signature could be found, except in the Australian north-west shelf area.

**Observations**

Twelve Landsat pictures were found with characteristic internal-wave features. The dates, locations and identification numbers of these are given in Table 1. These pictures

**Table 1. Details of Landsat pictures with characteristic internal-wave features**

| No. | Location[A] | Date | I.D. No. |
|---|---|---|---|
| 1 | 24°34′S., 114°18′E. | 11.xi.1973 | 1476-01483-6 |
| 2 | 20°09′S., 114°40′E. | 11.xi.1973 | 1476-01481-6 |
| 3 | 18°52′S., 119°13′E. | 13.xi.1972 | 1113-01331-6 |
| 4 | 17°26′S., 119°35′E. | 13.xi.1972 | 1113-01325-6 |
| 5 | 15°54′S., 121°29′E. | 30.xi.1972 | 1130-01264-6 |
| 6 | 15°48′S., 121°29′E. | 7.xi.1973 | 1472-01240-5 |
| 7 | 14°29′S., 123°10′E. | 29.xi.1972 | 1129-01203-6 |
| 8 | 13°03′S., 123°38′E. | 29.xi.1972 | 1129-01201-6 |
| 9 | 13°01′S., 126°22′E. | 27.xi.1972 | 1127-01084-6 |
| 10 | 12°57′S., 125°04′E. | 23.x.1972 | 1092-01140-6 |
| 11 | 11°36′S., 123°52′E. | 29.xi.1972 | 1129-01194-6 |
| 12 | 11°31′S., 125°24′E. | 23.x.1972 | 1092-01133-6 |

[A] Location of centre of Landsat picture is given.

were mostly taken in October and November 1972; the standard policy with Landsat was apparently to cease recording pictures when suitable cloud-free coverage of a particular area was obtained, unless requested otherwise. The locations where internal waves (or wave-like features) were observed on these pictures have been drawn on standard navigational charts in Fig. 1. This has been done by enlarging each picture to the scale of the appropriate chart and tracing the features; there is a small amount of distortion because the charts are in Mercator projection, yielding errors in position generally less than $\pm 2$ km. Four representative pictures (Nos 1, 4, 8 and 11 in Table 1) are shown in Fig. 2 and described below; their locations are indicated on the charts in Fig. 1.

Picture 1 (Fig. 2*a*) shows two characteristic groups of internal waves north-east of the North West Cape; these are aligned approximately parallel to the shelf edge, represented by the 183-m (100-fm) contour. Their shape suggests on-shore propagation, and this is consistent with the common observation that the largest waves travel fastest, leading the group. These waves have lengths ranging from 700 to 300 m. Other features which also appear to have oceanic internal wave character may be seen further north.

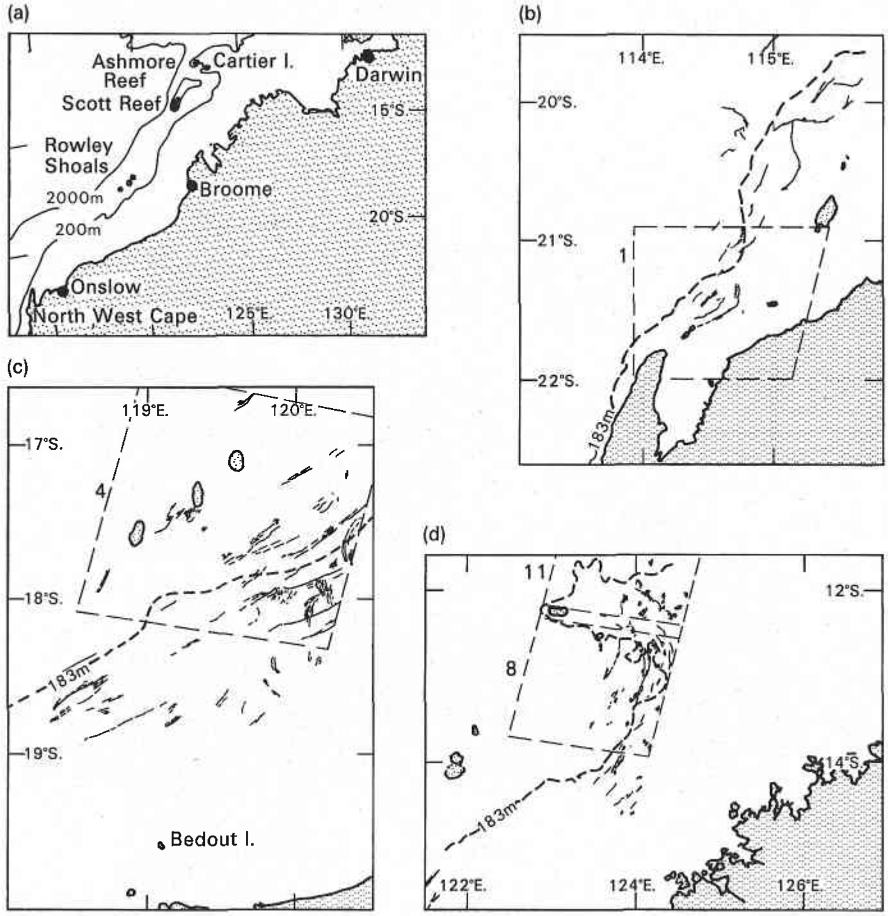
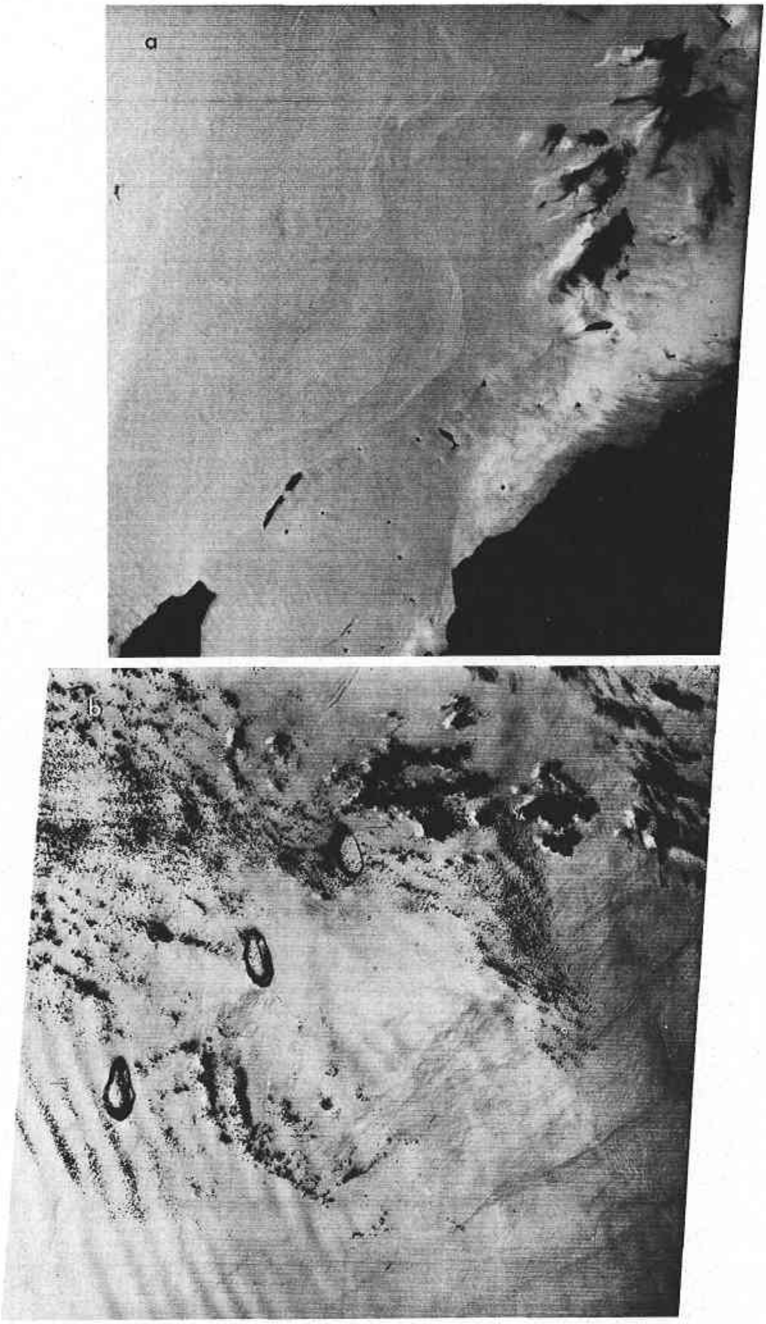



**Fig. 1.** (*a*) Study area. (*b*)–(*d*) Locations of internal waves and wave-like features, traced on standard navigation charts for the north-west shelf region. 183-m (100-fm) contour line is shown. Areas denoted 1, 4, 8 and 11 are those photographed by Landsat satellites, given in Fig. 2.

Picture 4 (Fig. 2*b*) shows three (at least) bands of internal waves propagating shoreward in a direction away from the three reefs known as Rowley Shoals. The wavelengths of the small-scale internal waves are again 300–700 m, and the mean distance between the bands is approximately 24·5 km. If we assume that a band is generated near the shelf edge every M2 tidal cycle with a period of 12·4 h (the largest local tidal constituent), we obtain a propagation speed of $0 \cdot 55$ m $s^{-1}$. It is noteworthy that Admiralty chart No. 1048 contains the following statement along the 183-m line due east of Rowley Shoals: 'During strength of tide, heavy rips were experienced on edge of bank about 2 cables in width, at a mile's distance resembling heavy breakers'.

To the right of the picture there are a number of semicircular packets of waves which indicate propagation towards the west; these may be due to scattering of the above-

**Fig. 2**




mentioned waves from bottom topography, although no irregularities in the latter were visible on the chart.

Pictures 8 and 11 (Figs 2*c* and 2*d*) overlap, both showing Ashmore Reef, and were taken by the satellite on the same pass. Wavelengths in these pictures range from 200 to

**Fig. 2.** (contd)

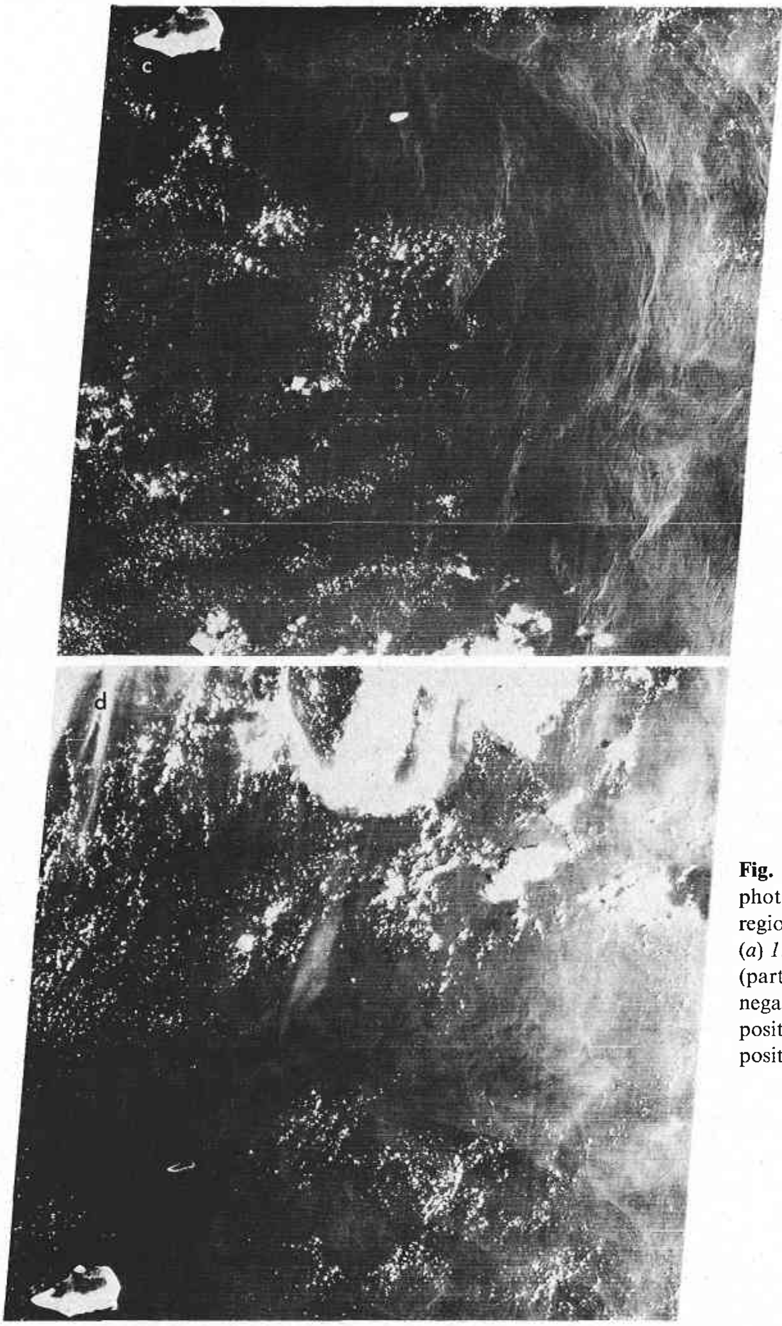



**Fig. 2.** Satellite photographs for the regions shown in Fig. 1: (*a*) *1*, negative print (part only); (*b*) *4*, negative print; (*c*) *8*, positive print; (*d*) *11*, positive print.

1000 m. Picture 8 is remarkable for the number of internal waves on the right where whole areas appear to be completely covered with them. As in picture 4 three (at least) major bands of internal waves may be distinguished, although here they have the shape of circular arcs, with mean spacings of 33 and 44 km for the inner and outer two respectively. Assuming M2 period, these give band speeds of 0·74 and 0·99 m $s^{-1}$ respectively in these regions. The shallow region to the east of Ashmore Reef in picture 11 (Fig. 2*d*) shows a confused pattern of waves, possibly due to waves generated at the shelf edge both to the north-west and south-west, but it also suggests a substantial degree of scattering from bottom features.

## Discussion

The above observations of internal waves contain information about the thermal stratification and the tides. The internal waves generally fit the familiar picture of tidal generation at the shelf edge producing a non-linear train of waves propagating onshore, with no similar waves visible in the deeper water. This generation mechanism has yet to be fully described, although it has been demonstrated in the laboratory by Maxworthy (1979), and a survey of the existing *linear* model is given in Baines (1981). The necessary ingredients—substantial tides and a sufficiently wide continental shelf (for sufficient on–offshore flow at the shelf edge and wave visualization)—are certainly present on the north-west shelf; a third requirement—suitably stratified shelf water—is probably met from October to April, on average, although the absence of pictures for months other than October and November makes this uncertain. Significant stratification on the shelf is usually absent from May to September, so that the tidal motion would be barotropic during this period. When the stratification exists, the phenomena shown in the pictures should be repeatable and to some extent predictable, as are all tidal phenomena.

The satellite observations may (in principle at least—it has yet to be done) be used to estimate the substantial baroclinic currents associated with the internal waves. Observations of the wave speeds (as above) may also be used to estimate the heat storage of the shelf waters (Mollo-Christensen and Mascarenhas 1979). In addition to these physical aspects, internal tides may have a significant effect on biological processes (Kamykowski 1974), producing (among other things) patchiness of biological constituents. Satellite observations such as described here enable the estimation of the potential significance of such processes.

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## References

Apel, J. R., Byrne, H. M., Proni, J. R., and Charnell, R. L. (1975). Observation of oceanic internal and surface waves from the Earth Resources Technology Satellite. *J. Geophys. Res.* **80**, 865–81.

Baines, P. G. (1980). On internal tide generation models. *Deep-Sea Res.* (In press.)

Elachi, C., and Apel, J. R. (1976). Internal wave observations made with an airborne synthetic aperture imaging radar. *Geophys. Res. Lett.* **3**, 647–50.

Ewing, G. (1950). Slicks, surface films and internal waves. *J. Mar. Res.* **9**, 161–87.

Kamykowski, D. (1974). Possible interactions between phytoplankton and semi-diurnal internal tides. *J. Mar. Res.* **32,** 67–89.

Gargett, A. F., and Hughes, B. A. (1972). On the interaction of surface and internal waves. *J. Fluid Mech.* **52,** 179–91.

Lafond, E. C. (1962). Internal waves. Part I. In 'The Sea'. (Ed. M. N. Hill.) Vol. 1, pp. 731–51. (Interscience: New York.)

Maxworthy, T. (1979). A note on the internal solitary waves produced by tidal flow over a three-dimensional ridge. *J. Geophys. Res.* **84,** 338–46.

Mollo-Christensen, E., and Mascarenhas, A. Jr (1979). Heat storage in the oceanic upper mixed layer inferred from Landsat data. *Science* **203,** 653–4.

Osborne, A. R., and Burch, T. L. (1980). Internal solitons in the Adaman Sea. *Science* **208,** 451–60.

Sawyer, C., and Apel, J. (1977). Satellite images of ocean internal-wave signatures. Natl Ocean. Atmos. Adm. (U.S.) Publ. S/T 2401.

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