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Research note

Infrared imagery of 'breaking' internal waves

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Abstract

Airborne infrared imagery is shown to provide preliminary evidence of surface thermal expressions associated with internal waves that become unstable and break over the continental shelf. These expressions include a narrow wave front that is warmer than the ambient; a wide, spatially intermittent 'wake' that is colder than the ambient; and $\sim O$ (10 m) diameter surface-renewal 'boils' that populate the wake. These thermal signatures might be useful in assessing the spatial distribution and structure of breaking internal waves.
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1. Introduction

Propagating internal waves (IWs) are a ubiquitous feature of the coastal ocean and are of broad interest because of their impact on vertical mixing, optical properties, transport of organisms, and acoustic signal propagation. Much has been revealed using imaging radars, which detect IWs through their effects on the surface wave field (e.g., Apel et al., 1985). These surface effects are pronounced when the pycnocline is relatively shallow and the IWs become nonlinear waves of depression. As an IW propagates, it can become unstable and break through either shear or convective instability (Thorpe, 1999). Breaking creates a turbulent flow and leads to dissipative energy losses (Moum et al., 2003). If the turbulence penetrates to the surface, then a breaking IW could leave behind it a turbulent surface wake. An ability to remotely sense such a wake would be helpful in assessing the frequency of occurrence and spatial scales associated with breaking IWs.

Recent studies suggest airborne high-resolution infrared cameras can image thermal expressions of IWs (Marmorino et al., 2004; Zappa and Jessup, 2005; Farrar et al., 2007). The physical mechanisms are not yet completely understood. One mechanism is IW-induced modulation of vertical mixing within the diurnal warm layer (Walsh et al., 1998; Farrar et al., 2007). In this 'warm layer' mechanism, entrainment at the base of the warm layer is reduced in the forward part of a wave, leading to enhanced solar heating of the near-surface water over the wave trough. Thus, a wave of depression should appear warm (or, bright) relative to the ambient water surface ahead of it. In contrast, turbulent mixing from IW instabilities should appear as a trailing signature that is cooler (darker) than the undisturbed ambient surface.

In this note, we examine airborne infrared imagery that appears to show evidence of such IW-induced turbulent mixing. The infrared data are supplemented in part with visible imagery, which can also reveal IWs through modulation of upwelling radiance from the water column (Weidemann et al., 2001; da Silva et al., 2002). The data were acquired as part of a pilot study and are limited in scope. Our interpretations are therefore preliminary and will need to be tested by additional studies—studies we hope will be encouraged by the results described here.

2. Study area and instrumentation

The study area is the southeastern part of the Strait of Juan de Fuca (Fig. 1). Infrared imagery was collected using a nadir-viewing midwave (3–5 μm wavelength) camera

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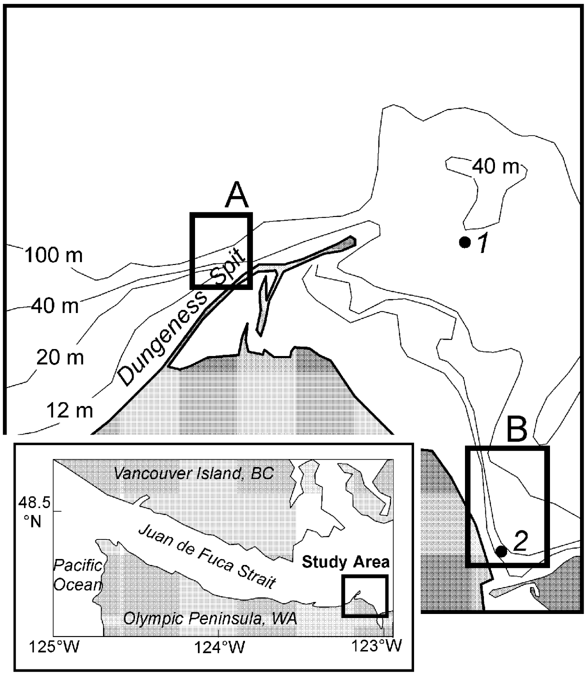

Fig. 1. Location of study areas (A, B) and in-water stations (1, 2).

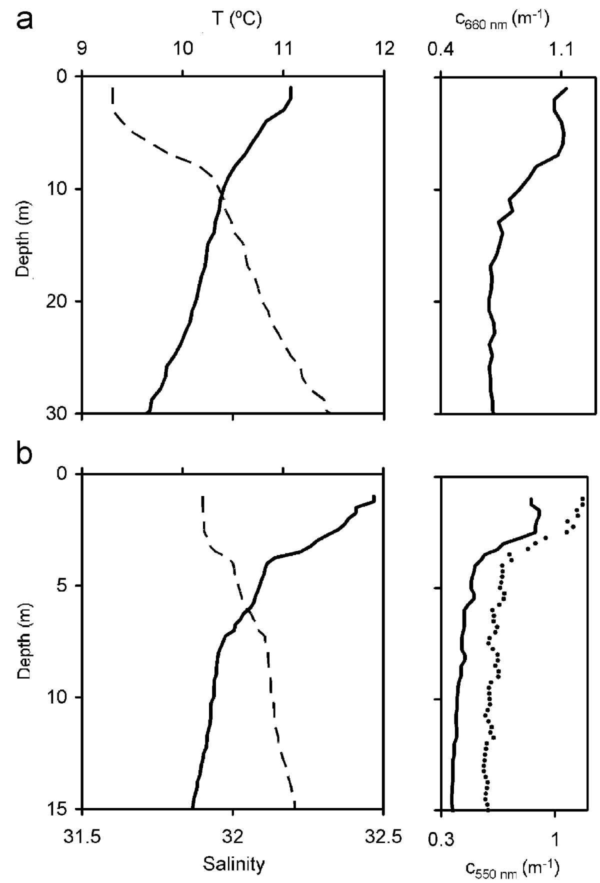

Fig. 2. Profiles of temperature (solid curve), salinity, and beam attenuation, c, at station 1 (a; 1101 LT 7 September) and station 2 (b; 1042 LT 12 September). Values of c are shown at wavelengths (a) 660 nm and (b) 550 nm. Dotted profile in panel (b) shows values of b_b/a_t, the ratio of backscatter (computed as in Weidemann et al., 2001) to total absorption, at 550 nm and multiplied by 10.

having a thermal resolution of ~0.02 °C. Aircraft altitudes of 600 m (area A) and 3 km (area B) yielded spatial resolutions of 1.4 and 7.0 m. In area A, simultaneous data were collected using a pushbroom-scanning visible hyperspectral instrument (PHILLS; Davis et al., 2002). Flights were done in early afternoon on 7 September (area A) and 13 September (area B) 2005. Meteorological conditions were similar on the two days: wind speed was low (~3 m/s), humidity high (~86%), air–water temperature difference positive (~2 °C), and surface solar radiation high (~685 W/m^2). Conditions inferred through use of a bulk-flux algorithm are: (1) there was a net upward sea-surface heat flux of ~O (10 W/m^2) and a correspondingly weak 'cool skin' of magnitude $\Delta T \sim O$ (0.04 °C); (2) there was a diurnal warm layer of thickness ~O (0.2 m) and temperature anomaly ~O (0.3 °C). In-water data collected at two stations (1 and 2; Fig. 1) can be used to approximate conditions in the study areas. These data show (Fig. 2) shallow stratification (pycnocline depth of ~6 and 2 m) and similar profiles of optical attenuation.

3. Results

An infrared image mosaic made from two successive passes over area B is shown in Fig. 3. A number of dark curvilinear bands, ranging up to ~100 m in width, can be seen to occur over the inner part of the shelf in varying water depths. The bands occur in several groups, or packets, which propagated shoreward (relative to ambient thermal structure) at a speed of 24±5 cm/s over the total sample period of 1.3 h (16 passes in all). The appearance of these signatures as multi-directional and partly intersecting is similar to sun-glint photographs and synthetic aperture radar imagery of topographically generated IWs in Georgia Strait, BC (Gargett, 1976; Hughes and Dawson, 1988). Though poorly resolved in these higher-altitude images, a dark band can be seen upon close examination to have a narrow, bright edge suggesting the leading part of an IW (or, for brevity, a wave front). The areas of darker shading thus trail behind the wave fronts, often extending to the next wave front in the packet. Relative to the ambient surface, the dark segments are 0.4±0.2 °C cooler. This thermal contrast is comparable to the wake from a motor boat (Fig. 3). The boat wake is relatively cool because turbulence in the wake mixes away any shallow thermal stratification (Peltzer et al., 1987); likewise, we argue that the cool, curvilinear bands are IW wakes.

Fig. 4 shows an infrared image mosaic made using three adjacent northward passes over area A. Imagery from the first and third passes (Fig. 4a and c) has been shifted slightly in latitude to create an approximately synoptic view of event A. This event is dominated by a dark area about 100 m in north–south extent that we interpret as an IW wake, as in the previous figure. Event A has an east–west extent of about 1 km and lies just inshore of the