not dissolve sodium metasilicate as suggested by Provasoli *et al.* I found that sodium metasilicate introduced Al into the culture medium as a contaminant at relatively high concentrations (> 30 μg/liter). I also added Al to the cultures in the form of a Titrisol $AlCl_3$ standard solution.
8. J. B. Mullin and J. P. Riley, *Anal. Chim. Acta* **12**, 162 (1955).
9. R. M. Dagnall, R. Smith, T. S. West, *Talanta* **13**, 609 (1966).
10. M. Stoffyn, thesis, University of Brussels (1975).
11. D. W. Menzel, E. M. Hulburt, J. H. Ryther, *Deep-Sea Res.* **10**, 209 (1963).
12. I thank F. T. Mackenzie for the critical review of this report. I am also indebted to J. B. Jordan of the Institute of Marine Resources who kindly supplied the diatoms. Supported by NSF grant EAR 76-12279.
* Present address: Bedford Institute of Oceanography, Dartmouth, Nova Scotia B2Y 4A2, Canada.

4 August 1978; revised 2 October 1978

Heat Storage in the Oceanic Upper Mixed Layer Inferred from Landsat Data

Abstract. *From the spacing of internal wave packets generated by tidal flow over topography, one can determine their propagation speed. The propagation speed depends upon the density anomaly and depth of the upper mixed layer. Attributing the density anomaly to temperature only, one can calculate the heat storage in the upper oceanic layer. On the basis of Landsat images of the New England continental shelf, the heat storage calculated from satellite data has been compared with available in situ observations. The data show that the method may have merit and is deserving of further refinement.*

The amount of heat stored in the upper ocean during the warm season is governed by the balance between incoming solar radiation and exchanges of heat with the atmosphere and the water layers below the upper heated layer. Horizontal advection in both the atmosphere and the ocean also affects the state of the upper warm layer in the ocean at a geographical location. The amount of heat stored in the upper warm layer and the depth of the layer affect biological productivity, and the heat available for direct participation in the formation of atmospheric disturbances affects weather development. In addition, the heat stored in the upper ocean during the warm season may be a useful climatological variable. The continuous observation of the upper warm layer over a large area is an expensive and difficult effort, since observations are affected by the internal tides, which must then be observed.

We have found a method for estimating the heat stored in the seasonal upper warm layer, using information available in Landsat images. Tidal flow over topography produces internal wave packets (*1*, *2*). These internal waves cause horizontal convergences and divergences in the velocity field of the sea surface, which, in the presence of capillary waves or short gravity waves, will stretch and compress these surface waves, creating bands of variation of surface roughness above the internal waves (*3*). Internal waves in the upper layers of the ocean can therefore generate surface signs that are discernible in satellite images (*4*).

Figure 1 shows a contrast-enhanced Landsat image from the region of the northeastern American continental shelf. Two wave packets are visible, apparently being emitted from the same location at successive tidal periods. The spacing between successive wave packets is the distance traveled per tidal period. Dividing the distance by the period of the semi-diurnal lunar tide (M_2), which is approximately 12.4 hours, yields the propagation speed of the wave.

For an idealized stratification where the ocean is composed of two homogeneous layers, the boundary between them being a sharp pycnocline, the wave propagation speed of an interfacial internal wave is

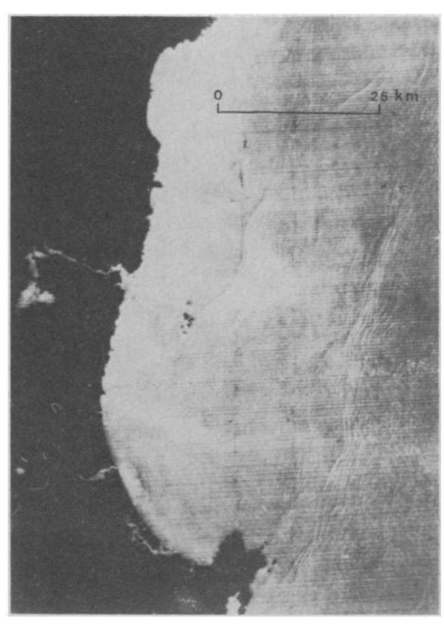
$$c^2 = g\ \Delta\rho\, h/\rho_2 \qquad (1)$$

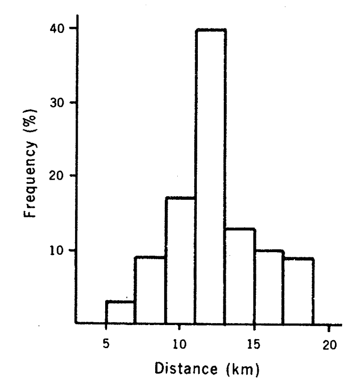
where c is the propagation speed, g is the acceleration of gravity, $\Delta\rho$ is the density difference between the upper and the lower homogeneous layers, ρ_2 is the density of the lower layer, and h is the depth of the upper layer. Equation 1 is based on the assumption that the wavelength is much longer than h and that the lower layer is much deeper than the upper layer. Typically, the wavelengths seen in satellite images range from 400 m to 2 km, h is typically 10 m, and the total depth varies from 20 to 200 m.

The density anomaly, $\Delta\rho = \rho_2 - \rho_1$, is due to temperature and salinity differences (ΔT and ΔS) in the two layers, according to the approximate relation

$$\Delta\rho = \rho_2\,(\alpha\Delta T - \beta\Delta S) \qquad (2)$$

where α is the coefficient of thermal expansion and β is the fractional increase in density per unit increase in S at con-





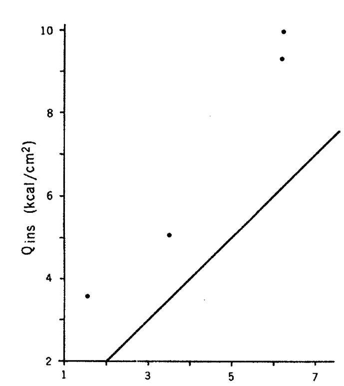


Fig. 1 (left). Enlargement of Landsat image 1364-14550 taken on 23 July 1973. We can see two wave packets north of Cape Ann; the waves propagate shoreward. Fig. 2 (top right). Frequency distribution of distance between the wave packets corrected by the multiples of a fundamental minimum distance (78 observations). Fig. 3 (bottom right). Comparison of heat storage computed from satellite pictures (Q_{sat}) and of heat storage computed from in situ measurements (Q_{ins}). For perfect agreement, the points should lie on the line shown.

0036-8075/79/0216-0653$00.50/0

stant T and pressure. The effect of T is dominant on the North American eastern continental shelf, typically being ten times larger than the effect of S. For this idealized situation, the extra heat, Q, stored in the upper layer is

$$Q = \rho_1 c_p h \, \Delta T \simeq c^2 \rho c_p / g\alpha \quad (3)$$

where c_p is the specific heat of seawater at constant pressure, and where we have used Eqs. 1 and 2 and ignored the effect of S on ρ and the effect of variations in ρ on c_p per unit volume. For more complicated density stratification, one can still take the square of the propagation speed to be approximately proportional to the heat storage.

We measured the wave packet spacings in enhanced Landsat images for the period June through August in 1972, 1973, and 1974. We found that, plotting histograms of packet spacing, there appear to be at least three dominant spacings but these are apparently multiples of a fundamental, minimum spacing. But remembering that internal wave groups are only visible in surface images in the presence of capillary waves or short gravity waves (which only occur when there is wind), we interpreted the finding to mean that there is only one wave packet spacing in a given location in a 2-month period. Doing this, we assumed that the observation of a multiple of the minimal group spacing simply means that one has missed some groups since they are not visible because of an absence of surface ripples which can be modified by the velocity field of the internal waves. On the basis of this hypothesis, we assumed that there was a single wave packet spacing and obtained the histogram shown in Fig. 2, including all the wave packets measured. This interpretation may give an overly favorable result, since it suppresses variations from the mean larger than the mean (such values are modified by the subtraction of a multiple of the mean).

Since the data suggest that there is a single predominant wave spacing, one may wonder why. If, as suggested by the Landsat data, internal waves propagate all over the continental shelf area in a variety of directions, their presence provides a smoothing mechanism for variation in the propagation speed. At a locality with smaller propagation speed there would tend to be an accumulation of wave energy, associated with large wave amplitude and wave breaking. Wave breaking causes mixing, leading to a deepening and cooling of the layer with no change in wave propagation speed at first. But a cooler surface layer will absorb more heat from the atmosphere and lose less heat through evaporation and radiation. Eventually, a local discrepancy in propagation speed will be smoothed out.

With these crude assumptions we have calculated the heat stored in the upper heated layer and compared the results with the in situ observations made from ships in the area within 2 weeks of the time of the satellite observations (Fig. 3). The results indicate that the heat storage estimated from satellite data is smaller than the results of calculations based on in situ observations. One reason for this is that, as found by Halpern (*2*), the wave packets propagate into the region when the layer depth is a minimum during the tidal period, whereas the in situ data contain an unknown contamination from internal tides. The internal tide amplitude of the seasonal thermocline can amount to half its mean depth, as shown by Halpern's observations.

Our method thus provides a way of estimating the upper ocean heat storage uncontaminated by the internal tides. The preliminary results are sufficiently encouraging to warrant further exploration and attempts at refinement of the method.

ERIK MOLLO-CHRISTENSEN
AFFONSO DA S. MASCARENHAS, JR.*
*Department of Meteorology,
Massachusetts Institute of Technology,
Cambridge 02139*

References and Notes

1. M. Rattray, Jr., *Tellus* **12**, 54 (1960).
2. D. Halpern, *J. Mar. Res.* **29**, 116 (1971).
3. A. E. Gargett and B. A. Hughes, *J. Fluid Mech.* **52** (part 1), 179 (1972).
4. C. Sawyer and J. R. Apel, "Satellite images of ocean internal wave signatures" (Publication S/T 2401, National Oceanic and Atmospheric Administration, Washington, D.C., 1976).
5. This work was supported by the U.S. Office of Naval Research under contract N00014-75-C-0291. A.S.M. was supported by a fellowship from the National Research Council of Brazil.
* On leave from the Oceanographic Institute, University of São Paulo, Brazil.

14 September 1978

Hydraulic Transients: A Seismic Source in Volcanoes and Glaciers

Abstract. *A source for certain low-frequency seismic waves is postulated in terms of the water hammer effect. The time-dependent displacement of a water-filled subglacial conduit is analyzed to demonstrate the nature of the source. Preliminary energy calculations and the observation of hydraulically generated seismic radiation from a dam indicate the plausibility of the proposed source.*

Some of the most enigmatic seismic waves are those of low frequency (1 to 5 Hz) associated with both volcanoes and glaciers. These waves are routinely recorded by earthquake seismographs to distances of a few hundred kilometers (*1*). Typically, the signals recorded exhibit emergent onsets and have either weakly developed or no seimic phases that can be ascribed to compressional (*P*) and shear (*S*) waves. Generally, the signals are unusually monochromatic. When associated with volcanic activity, they are classified as "B-type" earthquakes (*2*). Events of the same character in glaciological investigations are termed "type-II" icequakes (*3, 4*).

The B-type earthquakes are monitored as a means of predicting volcanic eruptions; however, their origins are unknown (*5*). The type-II icequakes are assumed to be associated with the movement of glaciers (*1*). Microearthquake investigations on glaciated volcanoes have shown that the type-II and B-type signals cannot be differentiated from one another (*5*). We propose a source mechanism that suggests a hydraulic origin for both types of waves. We develop the hydraulic source in terms of the familiar water hammer phenomenon that is generally associated with piping systems.

According to Minakami (*2*), B-type earthquakes are of shallow focus (less than 1 km) and are associated with active vents. These tremors are inferred to be a result of magmatic activity. Matumoto and Ward have suggested that volcanic earthquakes are caused by stress concentrations that result from the transport of magma (*6*).

Relatively high-energy, type-II glacier signals have been recorded at the University of Alaska's high-gain seismic station (SCM) in southern Alaska (*1*). The recorded waves had weakly developed *P* phases and well-developed, nearly monochromatic *S* wave trains. Hypocentral determination showed them to be of shallow focus with their epicenters near the Harvard Glacier, Alaska. The events described were monitored at stations up to 420 km from their sources and in some instances had Richter magnitudes of 2.0 to 2.5.

Local microearthquake surveys made