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Turbidity Currents Generated by Hurricane Iwa[1]

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Abstract

Off southwest Oahu, Hawaii, an array of current sensors recorded four successive episodes of downslope displacement associated with high-speed near-bottom currents of up to 200 cm/s and elevated water temperatures. These episodes coincided with the maximum storm effects of hurricane Iwa. Sensors from four moorings recorded increases in depth of as much as 220 m, implying downslope movement of as much as 2.4 km at speeds up to 300 cm/s. A succession of slope failures at or above the 110-m shelf break, each resulting in a turbidity current event, is the favored explanation.

Introduction

Current measurements on coastal slopes and in submarine canyons have resulted in an increasing number of observations of low-speed turbidity currents. Although current speeds as high as 750 cm/s, calculated from cable breaks following the 1929 Grand Banks earthquake, appear possible [1], actual measurements in submarine canyons show lower current speeds of 50–75 cm/s to be more common [2,3]. Current speeds as high as 190 cm/s have been observed [4], and speeds of 200–250 cm/s have been estimated from submersible observation [5]. All but one of the submarine canyons where turbidity currents have been observed are at the mouths of rivers where large quantities of sediment are discharged. The turbidity current speeds are sufficient to suspend and transport sediment [6,7], and sediment has been deposited on the current sensors [2,8,9].

The initiation of low-speed turbidity currents has been linked to surface waves [8,10], winds [4,11], and storm surges in rivers [9,12] that resuspend or destabilize accumulated sediment. The sediment and water then form a suspension that cascades down the canyon slopes. In all the above cases, the sediment is terrigenous. This paper presents observations of several episodes of downslope flow off Kahe Point, Oahu, Hawaii (Fig. 1). The bathymetry at Kahe Point [13] indicates a broad (4-km-wide) reentrant unrelated to a river mouth. The sediment is a calcareous ooze rather than terrigenous.

Setting

Previous Work

The Kahe Point area is the focus of a number of intensive oceanographic studies performed as part of the Ocean Thermal Energy Conversion (OTEC) program of the U.S. Department of Energy. The Hawaiian Electric Company (HECO) has a shore-based power plant nearby and has performed further studies as part of its Environmental Impact Statement (EIS) and to maintain its National Pollution Discharge Elimination System (NPDES) Permit.

The deep-water bathymetric map (Fig. 1), seaward of 100 m water depth, was derived from a detailed survey using both 12- and 3.5-kHz profiling systems and a minisparker system [13]. An orthogonal survey grid with trackline spacings of 500 m positioned by shore-based radar-frequency transponders was used for this survey. A steep escarpment below a depth of 110 m and about 1 km offshore lies upslope from a probable bedrock slump marked by the rectangular reentrant in the slope contours; this feature is similar to others mapped off Hawaii [14]. This bedrock feature forms a

[1]We dedicate this work to Gil Van Dyke, who lost his life in an accident during deployment of the current meter moorings.

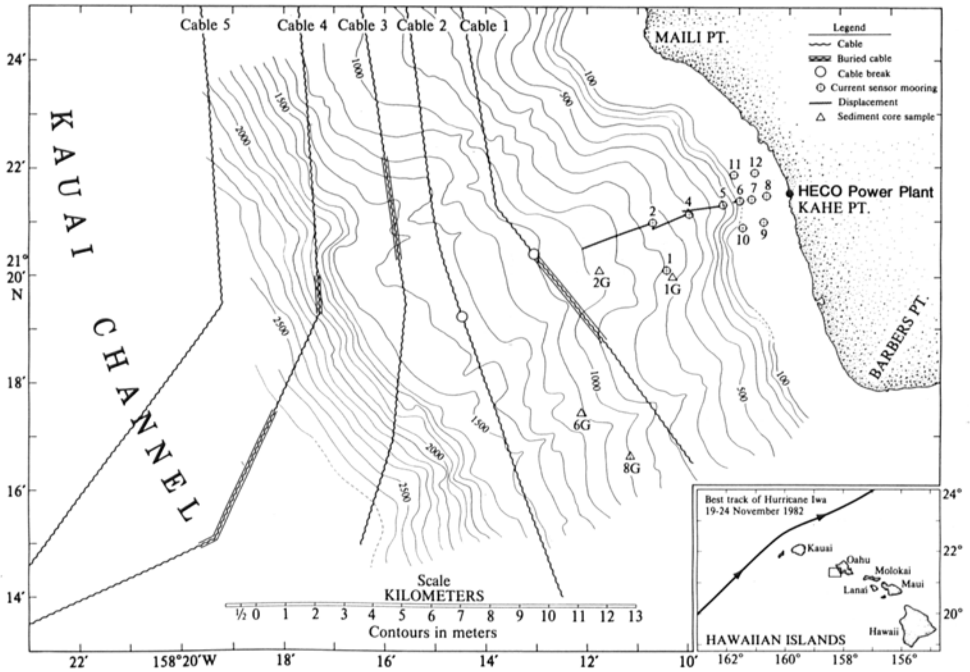

Figure 1. Bathymetric map of study area [14] with locations of current sensor moorings, buried and/or broken communication cables, and sediment cores. Cable damage and mooring movement are indicated. Inset shows the study area within the Hawaiian Islands and the track of hurricane Iwa.

broad channel for the offshore transport of surficial sediments. Based on high-resolution geophysical data, the sediment cover below the 110-m escarpment appears to be generally greater than 15 m. Eight sediment cores were attempted, and four of these (Fig. 1) recovered sufficient sediment (1.75–5.50 m) for geotechnical analyses [15].

Observers on the University of Hawaii submersible *Makali'i* examined the slope to a depth of 365 m [16]. In the nearshore area, they found a 10-m escarpment between depths of 50 and 60 m. The shelf-edge escarpment at 110 m drops about 100 m to a depth of 215 m with slopes of 60°–80°. The top of the scarp consisted of carbonate rocks. The observers on the *Makali'i* noted numerous shallow (<10-m) sand-filled channels in the escarpments at both 50- and 100-m depths. These sand-filled channels, several meters wide, were more common along the shallower escarpment. At the base of the scarp, observers recorded a 30°–60° talus slope of large carbonate boulders up to several meters across and a debris apron with slopes of 10°–30°. A submersible dive with the DSV *Turtle* [17] resulted in visual observations along a path in proximity to the current sensor moorings (Fig. 1) from a depth of about 1,000 m to just above the escarpment at 110 m. Observations from the DSV *Turtle* generally confirmed the *Makali'i* report and showed slopes below the debris apron graded from 10° down to 5°.

Current Meter Program

Near-bottom currents off Kahe Point have been measured in two programs. In April 1982, four near-bottom current sensors were deployed at water depths of 90, 400, 600, and 730 m [18]. Only the sensor from 730 m was recovered as intended 2 months after deployment. Measurements from this sensor showed current speeds of greater than 40 cm/s in more than 2% of the 10-min observation periods, and average and maximum speeds of 17 and 61 cm/s, respectively. Summary speed statistics for a shorter record from the prematurely released 600-m sensor were approximately 15% lower than for the 730-m sensor. The sensors from 90 and 400 m were not recovered.

The current measurement program that included the hurricane Iwa episode began on 22 September 1982 with continuous deployment of sensors [19] (Fig. 1). The near-bottom currents observed in this program rarely exceeded 30 cm/s and showed a strong diurnal tidal component directed principally on-offshore. The program calls for continued deployment of current meters until late 1984.

Current sensors that were redeployed on 20 November 1982 were operating during the hurricane episode; initial deployment positions are plotted in Figure 1, with deployment and recovery information summarized in Table 1. The sensors were Aanderaa RCM-4 and RCM-5 current meters which use Savonius rotors for sensing current speed. The integrated current speed was recorded at 5-min intervals along with instantaneous values for current direction, water temperature, and water pressure. Intercalibration of time between sensors was better than one-half of the 5-min recording interval.

The deep-water moorings (locations 1, 2, 4, and 5 in Fig. 1) consisted of a chain-anchoring element, a timed release/explosive bolt system, the current sensor, and a buoyancy module. The weight in water of the entire assembly was ap-

Table 1. Current sensor deployment (20 November 1982) and retrieval (14 December 1982) information [21]

Current sensor mooring	Water depth (m)	Sensor depth (m)	Retrieval information
1	781	771	Recovered
2	766	756	Recovered[a]
4	614	604	Recovered[b]
5	424	414	Recovered[c]
6	119	109	Recovered[d]
		61	
7	79	69	Not recovered
		41	
8	24	19	Not recovered
9	30	25	Recovered[e]
10	76	66	Recovered
		38	
11	76	66	Recovered
		38	
12	30	25	Recovered[f]

[a]Surfaced 14 December 1982; recovered 23 February 1983 in Kauai Channel.
[b]Surfaced 23 November 1982; recovered 26 November 1982 at Barbers Point, Oahu.
[c]Retrieved 1.2 km seaward of deployed location.
[d]Retrieved 0.1 km seaward of deployed location.
[e]Recovered 28 March 1983, between Kahe and Maili Points, Oahu.
[f]Recovered 7 December 1983 at Kahe Point, Oahu.

proximately 30 kg. If a static friction factor of 1 is assumed [20] and a horizontal drag load calculated from the frontal area of the mooring assembly, the moorings could begin to slide in a current of approximately 1 m/s [21]. Mooring 6 (at a water depth of 100 m) used a concrete clump anchor giving a total weight in water of approximately 100 kg. The principal buoyancy module was above a second current sensor 50 m above the bottom giving a smaller near-bottom frontal area. Bottom currents sufficient to move this mooring would thus be somewhat faster. The shallow moorings (locations 7–12 in Fig. 1) used concrete clump anchors and were to be recovered by divers.

Hurricane Iwa: Surface Effects and Cable Breaks

The "best track" of the center of hurricane Iwa (National Weather Service, 1983) is shown in the index map of Figure 1. The eye passed over or close to the weather station at the Pacific Missile Range, Barking Sands, Kauai, 150 km from Kahe Point, Oahu. A minimum barometric pressure of 973 millibars was recorded at 1800 HST. The hurricane was estimated to be moving to the northeast at about 20 knots. At Barking Sands, maximum wind speeds of 50–70 knots were observed. At Barbers Point, Oahu, 5 km south of Kahe Point, sustained wind speeds peaked at 37.4 knots with gusts to 52.1 knots during the 1900 HST hour. Hindcast calculations for Kahe Point [21] gave a significant wave height of 5 m (average of the highest third of the wave heights in the wave field) and a maximum wave height of 9 m.

During hurricane Iwa, six deep-water communication cables off the west coast of Oahu sustained damage (Table 2). Four of these cables were damaged offshore of Kahe Point. Figure 1 shows the cables, breaks in the cable as located by the metering station, and cable unretrievable by the cable repair ship C/S *Enterprise*. The retrieval operation consists of grappling for the cable to either side of the damaged area, as located by the metering station, and then pulling the cable on board until the cable is recovered or parts from tension. Cable 2 was completely recovered with significant effort, and the break ends showed the classic neck-down diameter associated with a tension break. Tension meter monitoring of the cable loads during retrieval attempts and abrasion of recovered damaged cable segments suggest that the unretrieved cable was buried by sedimentary material (Capt. J. H. Neal, C/S *Enterprise*, 1983, personal communication).

Results

Recovery of the deployed moorings gave the first indications of near-bottom events during the hurricane (Table 1). Sensors from moorings 1, 10, and 11 were recovered as planned on 14 December 1982 and were found at the deployed locations. The sensor from mooring 4 had surfaced early (23 November 1982) during the peak of the hurricane and was recovered on the beach at Barbers Point, Oahu (Fig. 1) on 26 November 1982. The sensors from moorings 5 and 6 were recovered on 14 December 1982, 1.2 km and 0.1 km further offshore, respectively, than the point of deployment. The sensor from mooring 2 apparently surfaced when intended but was not located until mid-February 1983, when it was found floating in the Kauai Channel. The sensors from locations 12 and 9 were found on the beach in March 1983

Table 2. Submarine cable descriptions and estimated outage times on 23 November 1982 [21]

Cable no.	System	Estimated (time) outage (HST)	Remarks
1	Hanauma Bay-Makaha[a]	1920	Broken
2	California-Makaha[a]	1950	Broken
3	Guam-Makaha[a]		Damaged
4	Johnston Island-Makaha[b]	2000	Damaged
5	New Zealand-Keawaula[c]	1940	Damaged[d]
6	Vancouver-Keawaula[c]	1940	Broken[d]

[a]Hawaiian Telephone Company/AT&T.
[b]Military.
[c]Compac.
[d]Damage occurred 15 km north of Kahe Point.

and December 1983, respectively. Sensors from locations 7 and 8 have not been found (as of 15 February 1984).

We will deal primarily with measurements from current sensors deployed at moorings 2, 4, 5, and 6. These sensors were deployed along a line from the top of the 110-m escarpment to a depth of 760 m (Fig. 1). The sensors were periodically moved downslope during a four hour period on 23 November 1983, during the height of hurricane Iwa. The downward displacements recorded by the pressure sensors are plotted in Figure 2. For moorings 2, 4, and 5, the depth changes occur as a series of steps 15–45 min apart. The initial movement occurs at later times with greater depth, at 1845, 1900, and 1930 hours Hawaii Standard Time (HST) for moorings 5, 4, and 2, respectively.

Initiations of successive episodes of downslope movement of the three deeper moorings also appear to record an advancing downslope current: for moorings 5, 4, and 2, the initiations of activities for the second episode occur at 1930, 1940, and 1955 hours HST; for the third episode, at 2000, 2005, and 2010 hours HST; and for the fourth episode, at 2025, 2030, and 2035 hours HST (2030 hours HST is the first interval where the measurements at mooring 4 become unreliable, probably because the sensor was released and began to surface). For mooring 6, originally placed near the top of the escarpment, movement episodes at 1925 and 1955 hours HST are recorded. These times are later than the initial episode at the deeper meters, and we think that these episodes at position 6 are related to the second and third episodes at the greater depths.

Current-sensor records show high downslope water-flow speeds during the intervals when the moorings were displaced (Fig. 3). At moorings 5, 4, and 2, initiation of movement corresponds to the start of high-speed pulses. In the current episodes observed at mooring 5, there is a periodicity on the order of 1 h. There is little activity prior to the first motion of the mooring. At mooring 4, there are intermittent periods of high current speeds in the 1.5 h prior to the first displacement of the sensor. These measurements are difficult to explain and do not correspond to depth or temperature fluctuations.

Temperature measurements show anomalously high values during the downslope movement of the moorings (Fig. 4). Because the sensors are moving to greater depths, the temperature is expected to proceed from warmer to colder. However, for moorings 5, 4, and 2, downward motion is accompanied by *increased* temperature. An expected temperature can be calculated using: (1) the observed temperature measured immediately before downward movement is observed; (2) the gradient of temperature versus depth normally observed at this temperature during November [22]; and (3) the observed depth change. The observed temperature is initially 2°–4° C warmer than expected. This difference decreases when sensor motion ceases and currents decrease. Only mooring 6 shows displacement to colder water not accompanied by a

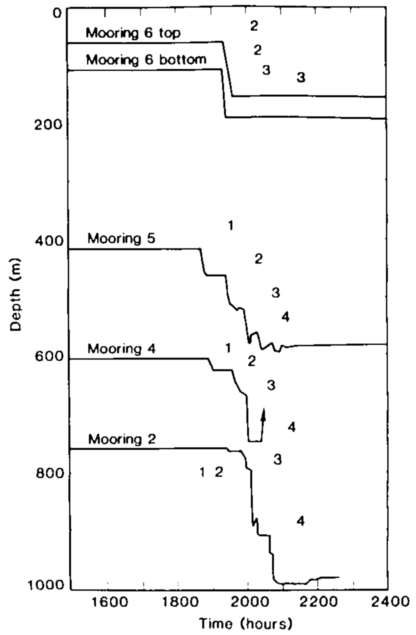

Figure 2. Depth versus time (HST) for the sensors on moorings that moved downslope. The reference numbers above each record designate times interpreted as the passing of turbidity current fronts. The sensor at mooring 4 is thought to have released and surfaced at the time designated 4.

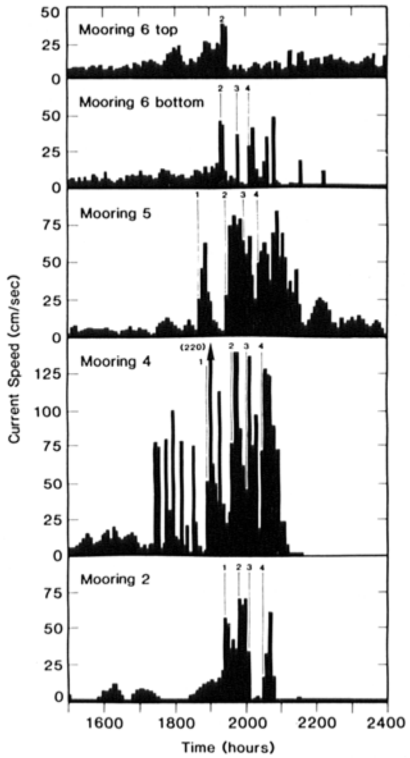

Figure 3. Current speed versus time (HST) for the sensors on moorings that moved downslope. The reference numbers above each record are as for Figure 2.

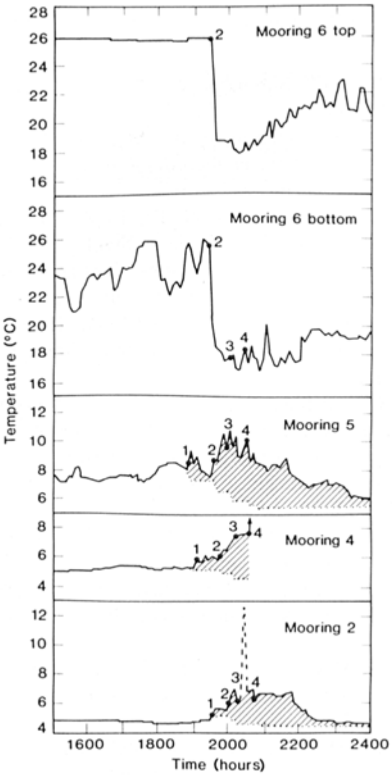

Figure 4. Temperature versus time (HST) for the sensors on moorings that moved downslope. The reference numbers are as for Figure 2. The expected ambient temperature at the observed depth is indicated as a broken line for moorings 5, 4, and 2. The resulting anomalies are the shaded areas between the expected and the observed temperatures. The observed temperature of 12.6 °C at 2020 hours HST is of questionable accuracy.

period of warm flow. The upper sensor is initially in the mixed layer at 26° C and drops below the thermocline to a depth where temperature undergoes a 5° C tidal fluctuation. The bottom sensor on mooring 6 drops from just below the 26° C mixed layer to a depth where temperature undergoes a 3° C tidal oscillation. The tidal oscillation and noise produced by internal waves could mask warm water flow at this sensor.

Using the maximum observed temperature at each mooring and the gradient of temperature normally observed in the area, and assuming no mixing with cooler water during downslope flow, we can give a conservative estimate of the depth from which water originated. At mooring 5, water is estimated to come from at least 100 m above the initial depth of 416 m, at mooring 4 from at least 200 m above the initial depth of 607 m, and at mooring 2 from at least 300 m above the initial depth of 760 m.

From the arrival times at successive moorings and assuming continuity of flow between mooring positions, we can estimate the frontal speed of the turbidity current. The third event travels about 3 km between moorings 6 and 2 in 15 min. This implies downslope speeds on the order of 300 cm/s (6 knots).

The results from mooring 6, initially at the top of the escarpment, are significant in our analysis. Two sensors are on the mooring, at 10 and 55 m above the bottom. When the mooring moved around 1920 hours HST, the shallow sensor recorded an onshore current, as if the mooring were being dragged through water moving more slowly offshore, while the near-bottom sensor recorded an offshore current, as if the mooring were moving with a faster current. Later current pulses with temperature fluctuations were recorded at the near-bottom sensor, but no such events were recorded 55 m above the bottom.

Observations at moorings 1, 10, and 11 limit the lateral extent of the downslope events. These moorings were recovered where deployed and showed no downslope movement, no anomalous temperatures, and relatively high currents during the hurricane but no extreme currents.

It is probable that some combination of phenomena associated with hurricane Iwa initiated the downslope motion. There was no indication of seismic activity around the time of the current sensor movement (Tsunami Warning Center, 1983). At Kahe Point, the major current sensor downslope movement occurred between 1800 and 2100 hours HST, coincident with the peaks in storm-related effects. The times (Table 2, 1920–1950 hours HST) and locations (Fig. 1) of damage to communication cables also indicate a linked series of events. The concurrent damage 15 km north of Kahe Point to two of the cables suggests that the events at Kahe Point were not singular.

Four additional pieces of anecdotal evidence point towards turbidity currents as the cause of movement of the sensors. First, upon retrieval of mooring 5, a significant amount of turbid water flowed out of the polyethylene protective cover structure around the glass buoyancy spheres. To our knowledge, this phenomenon has not been previously described. Second, sediment was found on the sensor from mooring 2, after it had been floating for three months prior to its eventual recovery. We think that the 9-m decrease in depth of mooring 2 approximately 1 h after episode 4 represents a readjustment after burial or entanglement with the anchor. Third, during a subsequent redeployment of current meters, a limited 12-kHz resurvey of the bottom in the region of the shelf break detected no major changes in bathymetry. Fourth, the C/S *Enterprise*, during cable repair work, collected some bathymetric data from the neighborhood of the cables and detected no significant differences between the collected data and published hydrographic charts.

On a subsequent DSV *Turtle* dive on 21 July 1983, the third author observed bottom features consistent with sediment movement in the deep-water region between 850 and 250 m. There were several small scarps and ridges, all 2 m high, running parallel to the depth contours [23]. Surveys from surface vessels would not be expected to detect these features. The scarps and ridges existed within 100 m from where smooth bottom had been observed before the turbidity current episodes [17].

Conclusions

A succession of slope failures at or near the upper slope escarpment that in turn resulted in turbidity currents is an explanation consistent with all observations. We hypothesize that the sequence of events was as follows: four of the slope failures generated turbidity currents carrying a mixture of sediment and water downslope at frontal speeds of 300 cm/s or greater (i.e., speed of meter displacement is minimum). The first turbidity current sequentially moved deeper current sensor moorings (5, 4, and 2) and then broke or buried the submarine telephone cables. The second carried with it mooring 6, initially anchored just below the top of the escarpment, and resulted in the second turbidity current episode. Slope failure is postulated because the recorded current speeds alone were not sufficient to move this heavily anchored mooring unless it had been precariously situated. The second turbidity current then proceeded to move moorings 5, 4, and 2. The third turbidity current also moved all four moorings. The fourth turbidity current, detected as a current pulse at mooring 6, traveled downslope, moved mooring 5, caused mooring 4 to release, moved mooring 2, and horizontally buried or entangled mooring 2's current sensor. The sensors at moorings 5 and 6 experienced additional later current pulses, accompanied by temperature increases, but these pulses were insufficient to cause additional movement. Finally, the sensor on mooring 2 freed itself, but damage had incapacitated the current and direction sensors.

The data allow alternative explanations of the dominant mechanisms of action and initiation. Turbidity currents may have been generated by storm-induced flow [4] in the absence of any slope failure. Sediment mass movement or debris flows may have occurred down the entire slope coupled with a turbidity front. We consider these explanations less likely than successive slope failures, near the escarpment, that generated turbidity currents down the slope. Further investigations will try to resolve these uncertainties.

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