CHAPTER 21

The Effects of a Kona Storm on the Molokaʻi Reef: November and December 2001

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On the average, heavy rains affect the southern slopes of Molokaʻi once or twice each winter, usually as part of a Kona storm, a seasonal, tropical storm with winds coming from the "kona" (or leeward) side of the islands. In November 2001, such a storm occurred, the first in a four-year period. Runoff of sediment was heavier than normal, as evidenced by road closures. Large quantities of plant debris and soil that had accumulated on the hillsides through normal weathering processes were washed down through gulches to the coast. Culverts carrying water and debris beneath Highway 450 (King Kamehameha V Highway) quickly became clogged, as often occurs during a Kona storm, and gravel, sand, and mud washed onto the road. Muddy sediment poured over the coastal terrace, into the water, and onto the reef. The U.S. Geological Survey (USGS) had a set of instruments on the reef, as well as two cameras on land to photograph changes in ocean turbidity (fig. 1). The USGS conducted follow-up high-resolution aerial surveys on November 29 and acquired satellite images (Landsat TM) from that same day. What follows is our analysis of the storm and its short-term effect on the reef and some speculation about how such storms affect the reef over longer time periods.

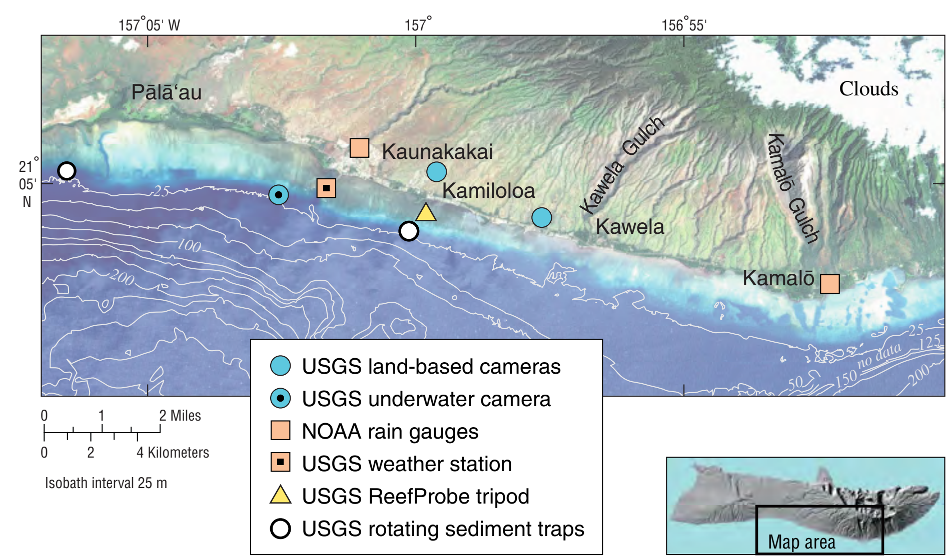

Figure 1. Aerial photograph of central south Molokaʻi and the adjacent reef, showing the locations of the U.S. Geological Survey instruments and cameras and the National Oceanic and Atmospheric Administration rain gauges that recorded information during the November 27, 2001, Kona storm. Much of the sediment delivered to the coast in the storm was discharged from Kawela and Kamalō Gulches and other drainages.

The Storm of November 27, 2001

Rain began falling on Molokaʻi late on November 26, 2001, reaching a maximum rate of more than 2 cm/hr (0.8 in/hr) between 4 and 5 a.m. on November 27 and tapering off that afternoon (fig. 2). Total rainfall for the storm was nearly 10 cm (4 in) at Kaunakakai (National Weather Service Hydronet System, http://www.prh.noaa.gov/hnl/hydro/hydronet/hydronet-data.php, last accessed April 29, 2008). The rain gauge at Kamalō was not functioning during the storm, but by comparison with other storms (fig. 3), rainfall there was likely twice as high as at Kaunakakai, probably reaching levels near 20 cm (8 in). The previous three years had been relatively dry with little rainfall (fig. 3), and the high rainfall rate in the November 2001 storm overwhelmed possible infiltration rates and resulted in rapid transport of gravel, sand, and mud in large quantities down the steep slopes of south-central Molokaʻi. Overland flow and massive deposition on Highway 450 resulted in road closures and direct flow of muddy water onto the central Molokaʻi reef flat (fig. 4).

Long-term rainfall records at both Kaunakakai and Kamalō show that these areas typically experience one or two months of heavy rainfall each winter, usually from Kona storms such as the one on November 27, 2001 (fig. 3). The previous wet winter was 1996–97, although the Kaunakakai gauge also recorded more than 15 cm (6 in) of rain in the summer of 1998.

Wind and Waves During the Following Month

USGS instruments recorded wind speed and direction, as well as wave heights and periods (calculated as wave stress) on south Molokaʻi throughout the fall and winter of 2001; these values are shown in figure 5. The winds show a pattern that is typical for the period during and following a Kona storm (fig. 5*A*). Before and during the storm, winds blew towards the north

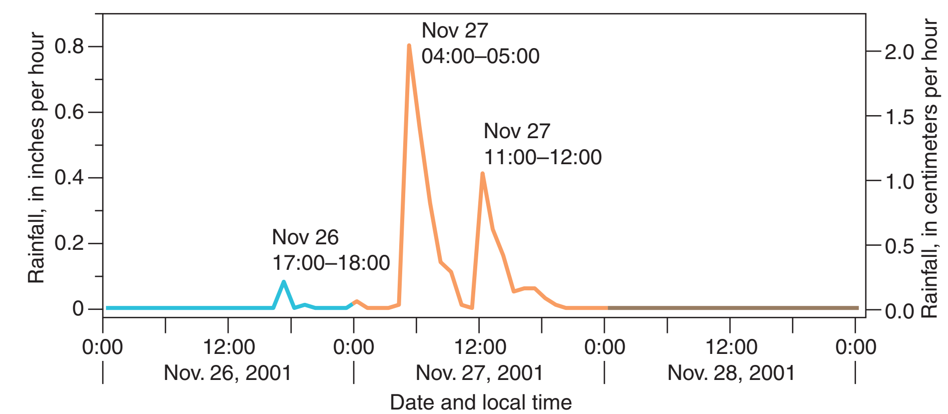

Figure 2. Rainfall amounts recorded hourly during the November 2001 storm by the rain gauge at Kaunakakai, Molokaʻi (source: National Weather Service Hydronet System, http://www.prh.noaa.gov/hnl/hydro/hydronet/hydronet-data.php, last accessed April 29, 2008).

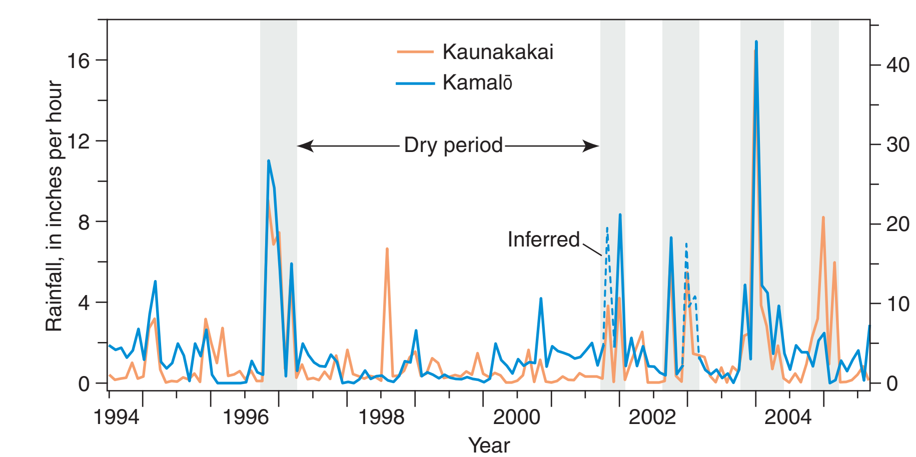

Figure 3. Monthly rainfall amounts for Molokaʻi between July 1994 and September 2005 as recorded by the rain gauges at Kaunakakai and Kamalō (source: National Weather Service Hydronet System, http://www.prh.noaa.gov/hnl/hydro/hydronet/hydronet-data.php, last accessed April 29, 2008). The rain gauge at Kamalō stopped working at times, including during the November 2001 storm. As in the December 2001 storms, rainfall at Kamalō is inferred to be nearly twice that at Kaunakakai. Note that, on average, each winter has a period of heavy rainfall (shown by gray bars), except for the four winters preceding the November 2001 storm. The lack of heavy rain for four years may have led to a heavier-than-normal soil buildup, and consequently to heavier-than-normal sediment runoff.

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and northwest at speeds greater than 10 m/s (22.4 mph). Immediately after the storm, on November 28, the winds decreased in speed and shifted to a typical trade-wind pattern, with winds blowing dominantly toward the west. In the days that followed, from November 28 to about December 1, trade winds were variable in intensity. From about December 1 through December 15, trade winds were consistently strong, as is typical during the trade-wind season, attaining speeds of 10 m/s (22.4 mph) to 15 m/s (33.6 mph) during the day and relaxing at night. This pattern of wind speeds and directions is important to the fate of sediment on the reef.

Wave stresses for November and December 2001 (fig. 5*B*) were calculated from wave heights as recorded by a wave gauge deployed at 10-m (33 ft) water depth on the fore reef off Kamiloloa (see Storlazzi and others, this vol., chap. 11). The measurements show high stresses starting before November 27, peaking that day, and steadily decreasing for the following two days. Short bursts of high stress occurred sporadically throughout December, but never to the same level as recorded on November 27 and 28. This, too, is important to the fate of sediment on the reef.

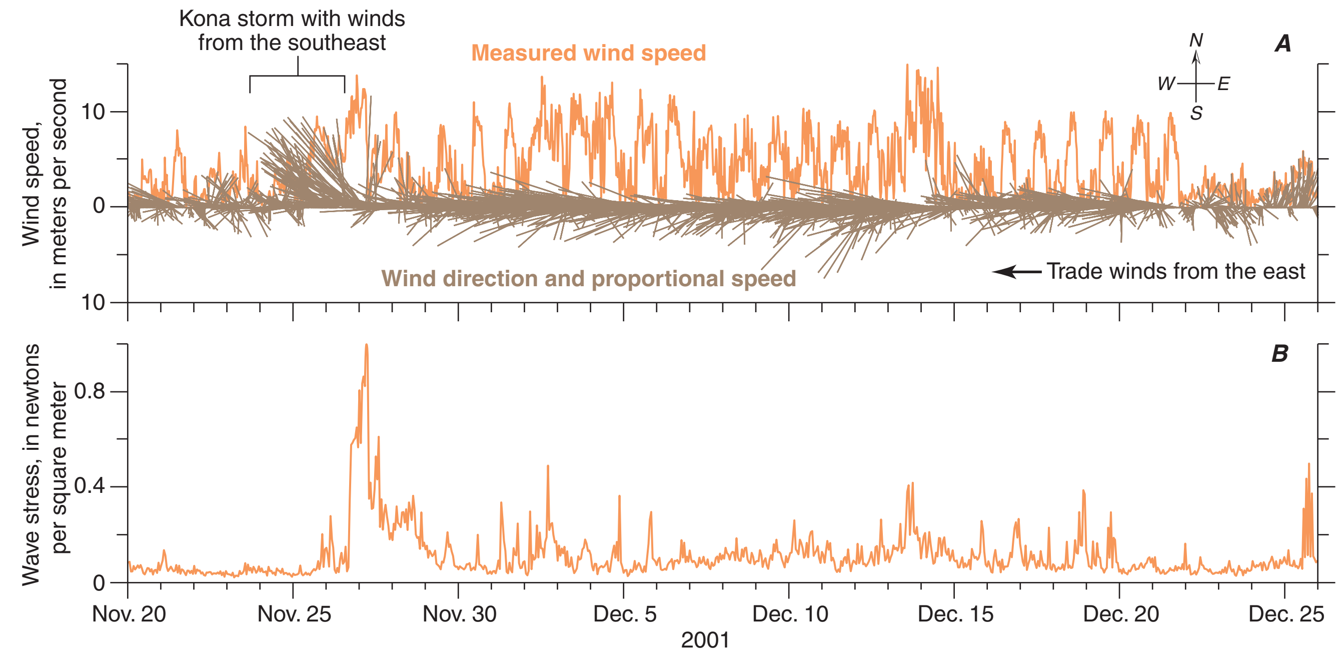

Figure 5. Physical forcing during the November and December 2001 storms on Moloka'i. *A*, Wind speed and direction for the months of November and December 2001, as recorded by the U.S. Geological Survey weather station on the Kaunakakai Wharf. The brown lines point in the direction that the wind was blowing, and their lengths gives the proportional wind speed. Measured wind speed is shown in orange. Note the Kona wind pattern (blowing strongly north and northwest) on November 26 and 27, followed by trade winds blowing to the west that increase in strength after the storm. *B*, Wave stress (a measure of force per unit area) as recorded by the wave gauge at 10-m (33 ft) depth offshore Kamiloloa. Note that waves are strong (high stress values) during the storm on November 27 and subside significantly following the storm's passage.

Figure 4. Sediment transport and deposition resulting from the November 2001 storm on Moloka'i. *A*, Highway 450 near mile marker 7, showing sediment deposits on roadbed. Closures such as this are common along this stretch of road and typically occur about once a winter. *B*, Overland flow of sediment across Highway 450 and onto the reef flat near mile marker 6.

Sediment Plumes on the Reef Flat

Critical information about the timing and extent of sediment plumes on the reef flat was provided by comparing satellite images (fig. 6), turbidity measurements (fig. 7), land-based photographs (fig. 8), and aerial photographs for the days before, during, and following the storm. The ReefProbe (see Ogston and others, this vol., chap. 20, for a description of this oceanographic instrument) was positioned on the reef flat about 5 km (3 mi) west of Kawela Gulch, one of the major sources of flood sediment to the coast. Salinity measurements at the ReefProbe show a large decrease in salinity on November 27 (fig. 7), immediately after the storm, as fresh water flowed across the reef flat and downwind to the west. Interestingly, the fresh-water pulse was not accompanied by a maximum in turbidity levels. Previous studies by Ogston and others (2004), detailed in chapter 20 of this volume, found a strong correspondence between tide stage and turbidity. During high tides, water on the reef flat becomes deep enough for waves to form there and to resuspend fine-grained sediment; thus there exists a strong diurnal signal to the values of suspended sediment on the reef flat. During the five days following the heavy rains of November 27, turbidity rose sporadically, or spiked, several times because of the coincidence of large offshore wave energy and high tide. Turbidity values (fig. 7) during those five days were equal to or slightly higher than values that typically occur on the reef flat during normal (nonstorm) periods of high tides and moderate trade winds (Ogston and others, 2004; Storlazzi and others, 2004; Presto and others, 2006). This indicates that much of the sediment discharged in the 2-day storm was deposited near the discharge points at Kamalō and Kawela to form deposits of terrigenous (land-derived) sediment along the shoreline and on the inner reef flat.

Following the Kona winds (blowing towards the northwest and north) that accompanied the rain on November 27, 2001, the winds gradually returned to a trade-wind-dominated pattern on November 28, 29, and 30 (fig. 5*A*). Satellite imagery, instrument data, and cameras mounted on a water tower on land captured this pattern convincingly (figs. 6, 7, and 8). Photographs taken from November 27 through 30 show that at the ReefProbe site at Kamiloloa the turbidity levels were apparently low (relative to the Kawela site) and that winds were also variable, as evidenced by the palm tree fronds hanging

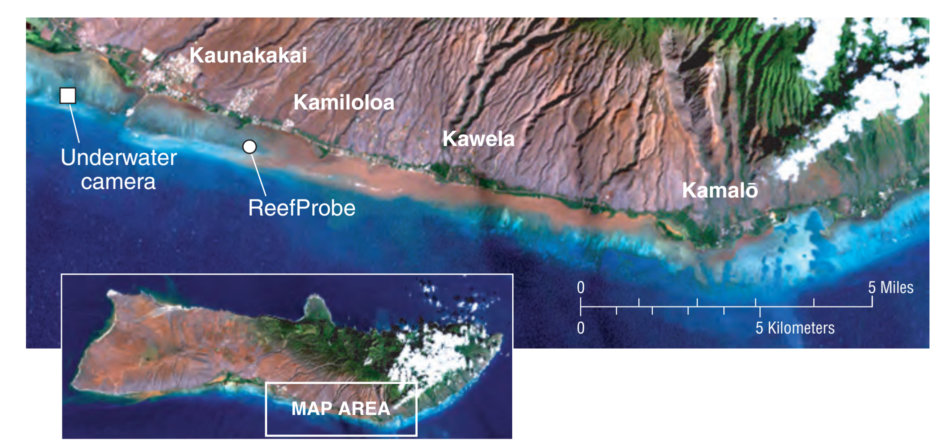

Figure 6. The Landsat satellite passed over Moloka'i on November 29, two days after the heavy rainfall, and provided this image of highly turbid waters on the fringing reefs of south Moloka'i. Note that at this time the muddy waters were concentrated on the reef flat from Kamalō to Kawela and farther west but had not yet reached the ReefProbe instrument site at Kamiloloa.

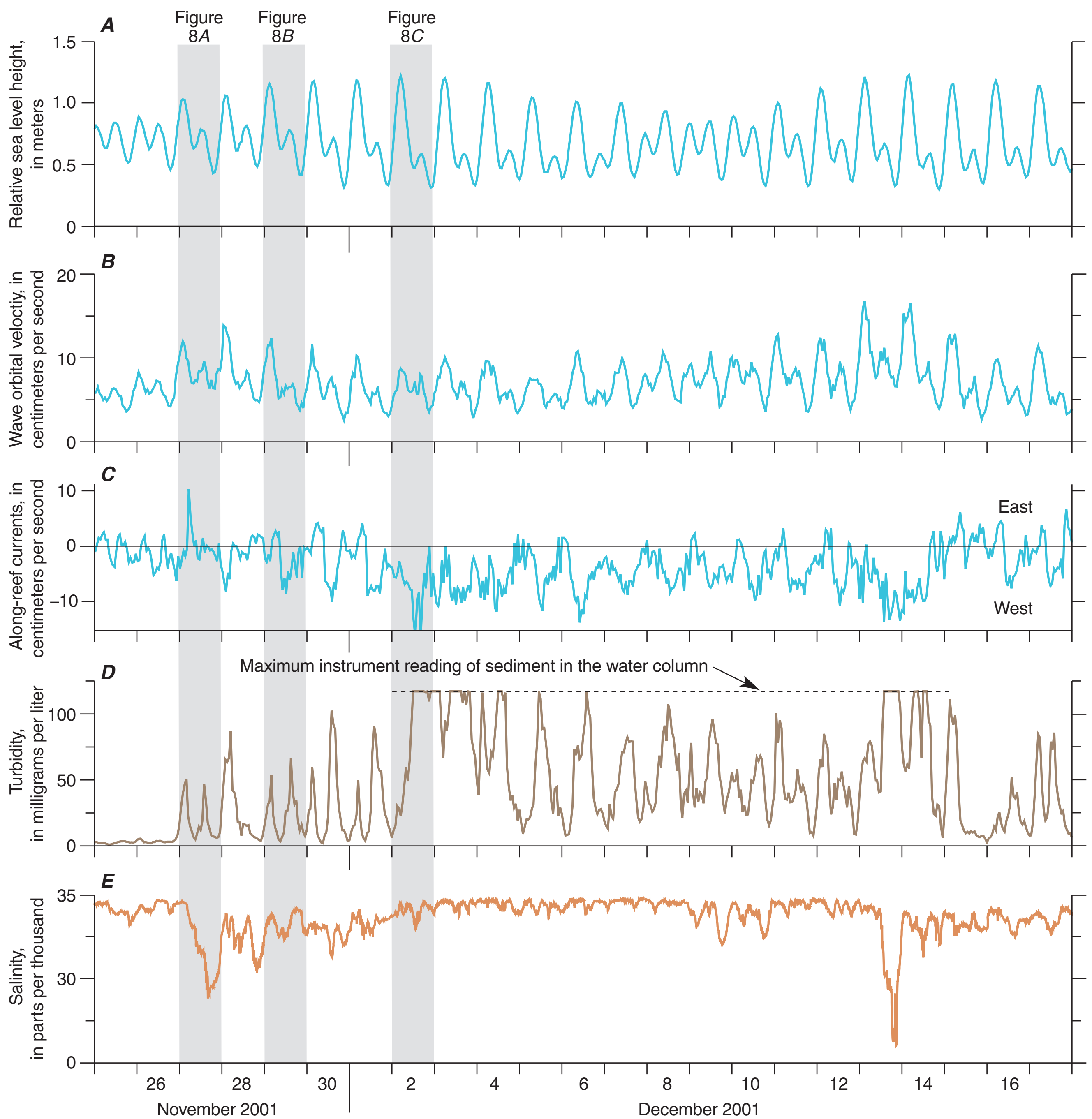

Figure 7. Tides, waves, currents, turbidity, and salinity for the period of November 25 to December 18, 2001, as recorded at the ReefProbe on the reef flat off Kamiloloa, south Moloka‘i. Note the marked drop in salinity that occurred shortly after the rainfall on November 27, and again on December 13. Of particular interest is the lag in turbidity after the November storm. Typical daily values of turbidity were seen in the 4 days following the flood event until about December 2; at that time strong along-reef currents appear to have transported large quantities of sediment in the water column, resulting in maximum values of turbidity. Note that on December 14 there is another rain period, marked by the low salinity, yet trade winds were strong and there was no lag in turbidity. Photographs representing the time periods marked by the gray bars can be seen in figure 8. *A*, Sea surface height, or tidal stage. *B*, Wave orbital velocities. *C*, Along-reef (parallel to shore) currents (negative values show flow to the west.) Currents were measured at 0.2 m above the bed. *D*, Turbidity. *E*, Salinity.

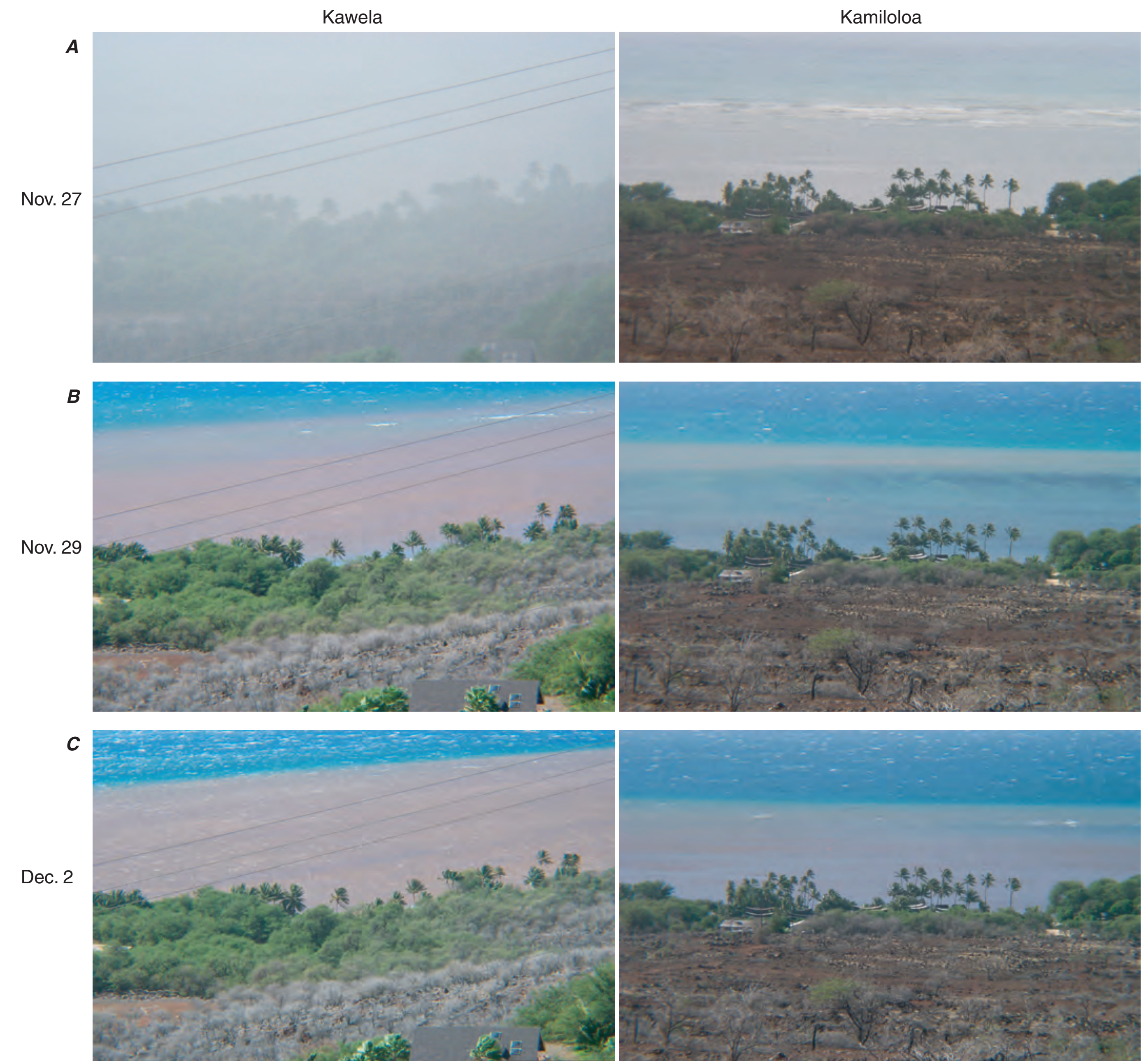

Figure 8. Photographs looking south taken from cameras mounted on water towers on the south coast of Moloka‘i show the westward movement of sediment-laden water under the influence of strong trade winds. A pair of photographs is shown, one from Kawela and one farther to the west at Kamiloloa, for each of the three mornings of November 27 (*A*, the day of the rain), November 29 (*B*), and December 2 (*C*), 2001. The reddish-brown mud is present in the water at Kawela on November 29 and finally at Kamiloloa on December 2 after several days of strong westward-blowing trade winds.

straight. Trade-wind strength gradually increased from November 29 through December 1 and reached maximum speeds on the afternoon of December 2. The steady and strong winds that started at the very end of November likely resulted in erosion of flood sediment that had been deposited near the shoreline at Kawela and other source areas farther east. The trade-wind-induced waves and currents then resuspended and transported the muddy flood sediment westward toward Kaunakakai. The pulse of muddy sediment moving westward along the reef flat is clearly shown by the maximum turbidity levels that were recorded at the ReefProbe site starting December 2 and by the land-camera images at Kamiloloa (fig. 8).

Satellite images (Landsat Thematic Mapper, or TM) with 30-m resolution and aerial images with 0.6-m resolution were collected on November 29, 2001, to detect and map the distribution, concentration, and total amount of suspended sediment over the south Molokaʻi reef. Two large suspended-sediment plumes were evident on November 29 (fig. 6), one on the west end of the south coast and a much larger one along the south-central coast, and their suspended-sediment concentrations (SSC), determined from water samples collected from the upper 0.5 m, ranged from 30 to 410 mg/L. These values were used to develop a model relating digital values from the satellite images to SSC, and the amount of suspended sediment in the upper 0.5 meter of water was then computed. Calculations using the TM images show that the total amount of suspended sediment in the upper 0.5 m of water on November 29, 2001, was approximately 1,500 tons (Chavez and others, 2004).

The significance of this series of events to the health of the reef is twofold. First, it is now evident that even a moderate amount of rain results in substantial transport of mud, sand, gravel, and associated debris directly from land to the reef flat. Second, the mud component is not moved entirely or even mostly in a plume across the reef flat and into deeper water. Rather, most of the mud is stored along the shore and inner reef flat near its on-land source. There it becomes a long-lasting source of turbidity as trade-wind waves resuspend the deposits nearly every day and slowly move the particles westward by means of trade-wind-driven currents.

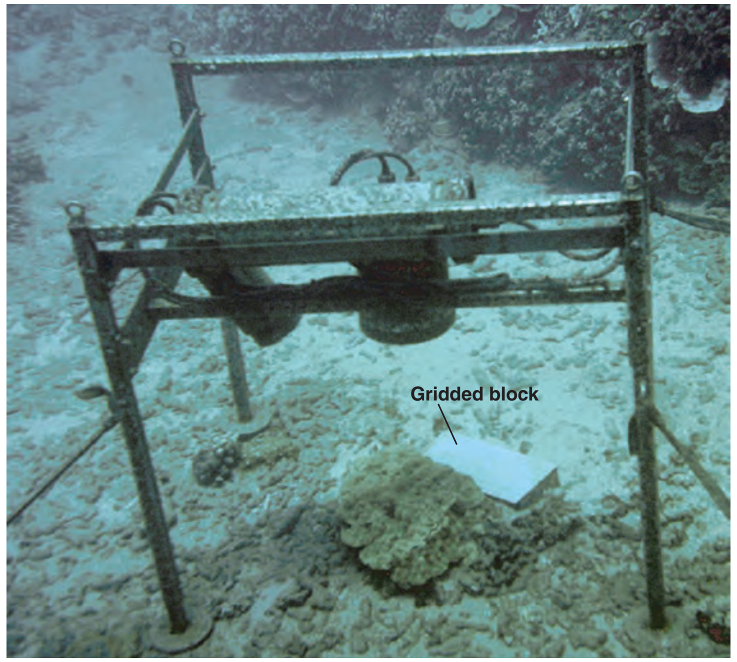

Figure 9. Bottom-mounted underwater camera on the fore reef west of Kaunakakai Harbor, Molokaʻi. The camera was located at a water depth of 12 m in a groove between two coral spurs (one visible in background). The camera took an image every four hours of the colony of *Porites lobata* (lobe coral) and a gridded concrete block, both beneath the frame. Scale is indicated by the size of the block (20.3 × 40.6 cm; 8 × 16 in).

Was the Fore Reef Affected by the Sediment Discharge?

The fore reef off south Molokaʻi is a magnificent reef with luxuriant coral cover hundreds to thousands of acres in extent (see chapters 5 and 9 of this volume for a discussion of the coral and benthic habitats, respectively, found along the south Molokaʻi reef). An important question is how much of the high load of sediment that washes onto the Molokaʻi reef flat is transported across the reef crest and onto the fore reef. Again, the storm of November 27, 2001, provided us an opportunity to learn more about that process during a large Kona storm, the typical kind of event that causes heavy rains on south Molokaʻi. Before the storm, instruments had been placed on the fore reef, as well as on the reef flat. The instruments on the fore reef included a rotating sediment collector with a wave gauge attached (see Bothner and others, this vol., chap. 19, for details about the instrument) and an underwater camera station (fig. 9) that recorded images of sediment collecting on a flat surface and the seabed six times daily. The data from these two systems show that sediment deposition on the fore reef is a complicated process and is not simply the result of plume fallout after heavy rainfall onshore.

Using a time series of photographs of the sea floor on the fore reef just west of the Kaunakakai Wharf, it was possible to document the timing of high-turbidity events and thus relate them to the events that were occurring along the coast. The pictures in figure 10 show that, starting on November 27 at 4 a.m. and continuing for the next 24 to 36 hours, the amount of suspended sediment was so high that visibility was greatly reduced in water that is normally quite clear, probably because of local sediment resuspension. Importantly, the water began to clear late on November 28. The satellite image obtained on November 29 shows that even by that date sediment plumes had not moved a significant distance along the reef flat, let alone onto the fore reef. Thus the high level of turbidity here was related to waves and not to plume fallout. However, at other locations along the reef, closer to discharge points, plume fallout may have generated turbid water.

If sediment plumes had not reached the fore reef by November 27 and 28, then what caused the distinctive high levels of turbidity observed by the underwater camera? One possible, and likely, source is wave action. On November 26 through 28, large waves hit the south Moloka‘i coast. Bottom shear stresses from waves such as occurred on those dates are capable of resuspending sand and mud particles that lie in areas normally too deep or protected from wave disturbance. Thus it is likely that the large southerly swell arriving at south Moloka‘i on November 26 was responsible for resuspending large volumes of sediment and causing high levels of water turbidity before the products of the on-land rainfall could be dispersed to the fore reef.

Additional evidence supporting such a scenario was provided by sediment collected in traps that had been placed on the reef flat and the fore reef before the storm. In addition to the rotating sediment trap described above, single 0.5-m tube traps (10-cm diameter) were placed at various locations on the reef for a three-month period (November 15, 2001, to February 14, 2002). Single tube traps from both ends of the island (Hale O Lono and Pūko‘o) were completely filled during this three month fall-winter period, but analysis of the sediment in the traps indicates that its source was chiefly from local reef areas, with only a small (~10 percent) amount contributed from land (Bothner and others, 2006). The evidence for this is that the material filling the traps is about 90 percent calcium carbonate, which can only be derived from the reef, and is coarse (nearly 80 percent sand).

The time-series trap sample number 3 at Pālā‘au (fig. 11) was collected during the storm period and was full of sediment. Because the sampling period was 4.5 days, and because the runoff and large waves occurred at nearly the same time within this period, which process was most responsible for the high sample volume is difficult to determine. That is, how much of the sediment collected was contributed by wave-induced resuspension of sediment on the fore reef, and how much was contributed by direct settling from sediment plumes emanating from the coast?

The nature of the sediment filling the tubes provides some answers. Trap sample number 3, which included the storm period, had about the same (or lower) amount of terrigenous sediment as prestorm samples (about 24 percent). At Kamiloloa, another rotating sediment trap showed that the terrigenous sediment there increased from approximately 34 percent in prestorm samples to 39 percent in poststorm samples during periods with similar wave conditions. This increase is relatively small and does not indicate massive sedimentation from plume fallout. The sediment tube trap on the fore reef off Kamiloloa had a distinctive layer corresponding to the storm, but even that layer is unlikely to result solely from plume fallout. It is composed of only 27 percent terrigenous sediment, and therefore more than two-thirds of it was derived from the reef itself. Furthermore, 60 percent of the sediment in that layer is sand, which is not easily transported by surface currents. The composition of sediment caught in these tube traps is persuasive evidence that wave resuspension, not sediment discharge from streams, is the key factor causing turbidity on the reef. Recent work (Bothner and others, 2006) shows a strong relation between sediment collection and wave stresses, even in periods of no runoff.

How Kona Storms Generate Turbidity on the Moloka‘i Reef

Our study of the November 27, 2001, Kona storm on south Moloka‘i has demonstrated that such events contribute sediment and turbidity to the reef flat and fore reef, but they do it in a complex manner. The waves that accompany the weather fronts are a major factor in resuspending both terrigenous and reef-based sediment and transporting it on the reef, where it deposits on corals and other benthic organisms and inhibits photosynthesis. Heavy rains produce floods in intermittent streams and gullies as well as overland flow at the coast. In the November 2001 storm, large amounts of terrigenous sediment were deposited along the coast and on the reef flat, where they became available as a source for later resuspension. These events and resulting conditions are summarized in figure 12.

The sequence of natural processes that occurred before, during, and following the November 27, 2001, Kona storm provide a solid basis for understanding the natural cycle of ridge-to-reef sedimentation in this environment. These processes are neither unusual nor extreme, and they most likely represent events that happen one or more times annually. The conditions that led to high sediment mobility and high turbidity on the reef in November and December 2001 were as follows:

- On land: A high rate of rainfall (10 cm, or 4 in, within 24 hours) led to high water and sediment runoff onto the reef. The high

Figure 10. This series of bottom photographs (taken with the underwater camera near Kaunakakai Harbor, see figure 9) shows the timing of periods of turbidity on the fore reef that can be compared with the land-camera images of the reef flat shown in figure 8. The images show clear water and a sediment–free block surface at the time of deployment in mid-November 2001. Black lines on the concrete block are 2 cm apart. Before the rain event in late November, the block had become covered by sediment. The water became very turbid beginning at 4 a.m. on November 27, as rains just began onshore, and remained turbid for approximately the next 24 hours. This interval coincides with the period of large waves that accompanied the storm. By November 29, the water is relatively clear again, there is less sediment on the block surface, and what sediment is present appears coarser than before the storm.

sediment runoff was likely exacerbated by land-use practices and a preceding dry period (~3 years). The sediment reached the coast and inner reef by means of gullies and overland flow, and much of it was deposited near the discharge points at the coast.

- On the reef: Waves were high before and during the heavy rainfall, then dropped back to normal levels. During the storm, large storm waves caused resuspension of previously deposited sediment, leading to turbidity on the fore reef. Winds were onshore; trade winds were mild to nonexistent and only slowly became reestablished in the days following the storm. The return to trade-wind conditions following the storm caused renewed resuspension and along-reef transport of flood sediment.

These conditions led to a decoupling of sedimentation on the reef flat and on the fore reef off central Moloka‘i. The reef flat was characterized by initial high levels of deposition at coastal deltas and adjacent areas. Following the storm, trade winds became reestablished, leading to daily resuspension and high turbidity. Macro algae and silt increased markedly for at least six months after the storm (Stamski and Field, 2006).

On the fore reef, the storm was characterized by high wave stresses and onshore winds, resulting in temporary high turbidity and temporary deposition. Because periodic high wave stresses subsequently resuspended and transported the sediment, there was apparently no significant long-term storage of fine-grained terrestrial sediment on the fore reef.

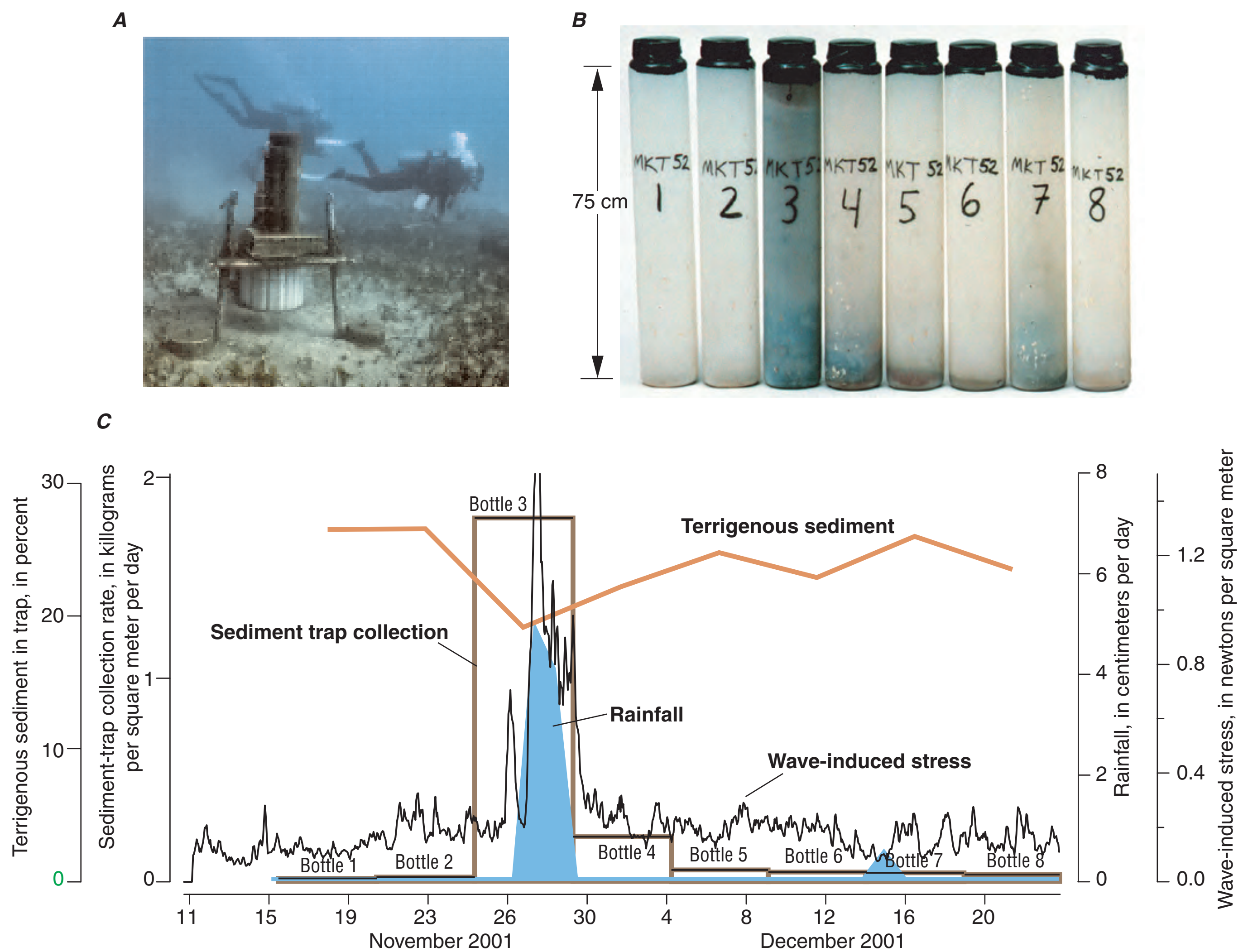

Figure 11. Sediment-collection data from the rotary sediment trap at Pālā‘au, Moloka‘i. Each tube from the rotating sediment trap on the fore reef represents 4.5 days of sediment collection (see Bothner and others, this vol., chap. 19). *A*, The sediment trap in place on the sea floor (photograph taken on the fore reef off Kamiloloa). *B*, The Pālā‘au sediment-collection tubes aligned in chronological order. Tube number 3 represents the time period of the Kona storm. *C*, Sediment-collection rate for each tube plotted against rainfall (blue), wave stresses (black), and percent noncarbonate in the collected sediment (orange). Although the high rate of sediment collection (as shown by the filled tube number 3) corresponds with the heavy rainfall, it also correlates with the period of high wave stress. The lack of significant change in the amount of terrestrial sediment (noncarbonate) in the tubes indicates that wave resuspension was the significant factor in filling the tubes, not fallout from flood plumes.

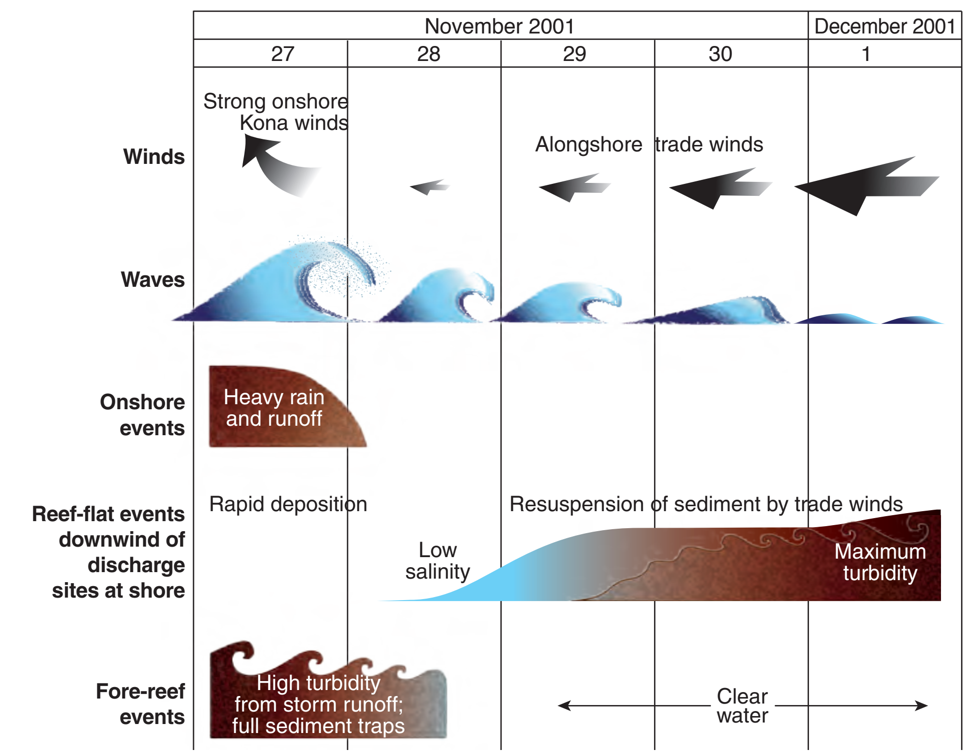

Figure 12. Schematic diagram summarizing the series of events in late November 2001 that influenced turbidity and sediment transport on the south Moloka‘i reef off Kamiloloa. The timing of observations of turbidity on the reef flat and the adjacent fore reef are important, as they document that the two settings are somewhat independent, or decoupled, in the short term. Rainfall and wave stress were both at maximum values on November 27. Although it took several days for terrestrial sediment to have an impact on the reef flat, wave-induced turbidity was immediate on both the reef flat and the deeper fore reef. On the reef flat, sedimentation and maximum turbidity came later than on the fore reef, as terrigenous flood deposits were gradually and increasingly resuspended by trade-wind waves, transporting sediment west along the reef flat by means of trade-wind currents.

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