Tides and Currents in Fanning Atoll Lagoon[1]

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AS PART OF the Fanning Island Expedition 1970, selected physical studies were conducted in the atoll lagoon. The major effort was the measurement of volume, salt, and heat transports through the three main atoll openings over a 24-hour period. In addition, lagoon and ocean tides were recorded, and a cursory survey was made of circulation in a small, reef-enclosed pond within the lagoon.

TRANSPORT STUDY

Fanning Island is a roughly oval atoll whose lagoon, although almost entirely enclosed, does exchange water with the surrounding ocean. Tidal flow in and out of the lagoon occurs at four locations and amounts to roughly 5 percent of the lagoon volume over a semidiurnal cycle. About 90 percent of this exchange takes place at English Harbor, through a channel with a maximum depth of approximately 8.5 m and a least width of 290 m. On the east side of the atoll, opposite English Harbor, is a shoal opening (Rapa Pass) which handles about 2 percent of the total exchange. A similar channel to the north (North Pass) accounts for roughly 5 percent. Air photos show one additional, meandering route which may or may not lead from the lagoon to the sea. This possible fourth opening, located about 5 km south of Rapa Pass, was ignored in our study.

Exchange between ocean and lagoon was monitored for 24 hours, starting at local noon on January 7, 1970. Current velocity, temperature, and salinity were recorded at each of the three passes.

Both North and Rapa passes were treated in simple fashion. In each case, a straight section was established by stringing a cross-channel line, along which bottom topography was measured. (At North Pass, there is, in addition to a main channel, an expanse of shoals which were uncovered at low water. This area was ignored—resulting in an estimated maximum local volume transport error of 13 percent.) A single station was chosen at a point along the section that appeared to be in the main flow (see Figs. 1 and 2). At this location, current velocity, temperature, and salinity were sampled each hour, within 0.5 m of the surface. Water level was read hourly from a tide staff mounted in a sheltered spot near shore. Figures 1 to 3 show the measurements. The various transports through these passes were computed by assuming the measured parameters to be constant over the channel cross sections.

Flow through English Harbor channel was sampled in far greater detail because it was expected to be overwhelmingly important in the total-exchange picture. It has been reported (U.S. Hydrographic Office, 1952) that currents in the channel exceed 5 knots. Taking measurements from a skiff would be very difficult at best in such a flow. Consequently, transports were monitored along a semicircular section enclosing the lagoon end of the channel and through which a more moderate flow could be expected. Figure 4 shows the section and a smoothed fathometer trace along it. Anchored buoys were emplaced at stations 1 to 6. The section was traversed continuously by a skiff which was made fast to each buoy in turn. Seventeen cycles of measurements were completed during the 24-hour study. At each buoy, current velocity, temperature, and salinity were measured at the depths shown in Figure 4. These data were integrated over the cross section to obtain transport figures.[3] Aver-

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[3] Details of all calculations, lists of instruments used, and a description of the buoy-anchoring method are given in Hawaii Institute of Geophysics Report 70-23.

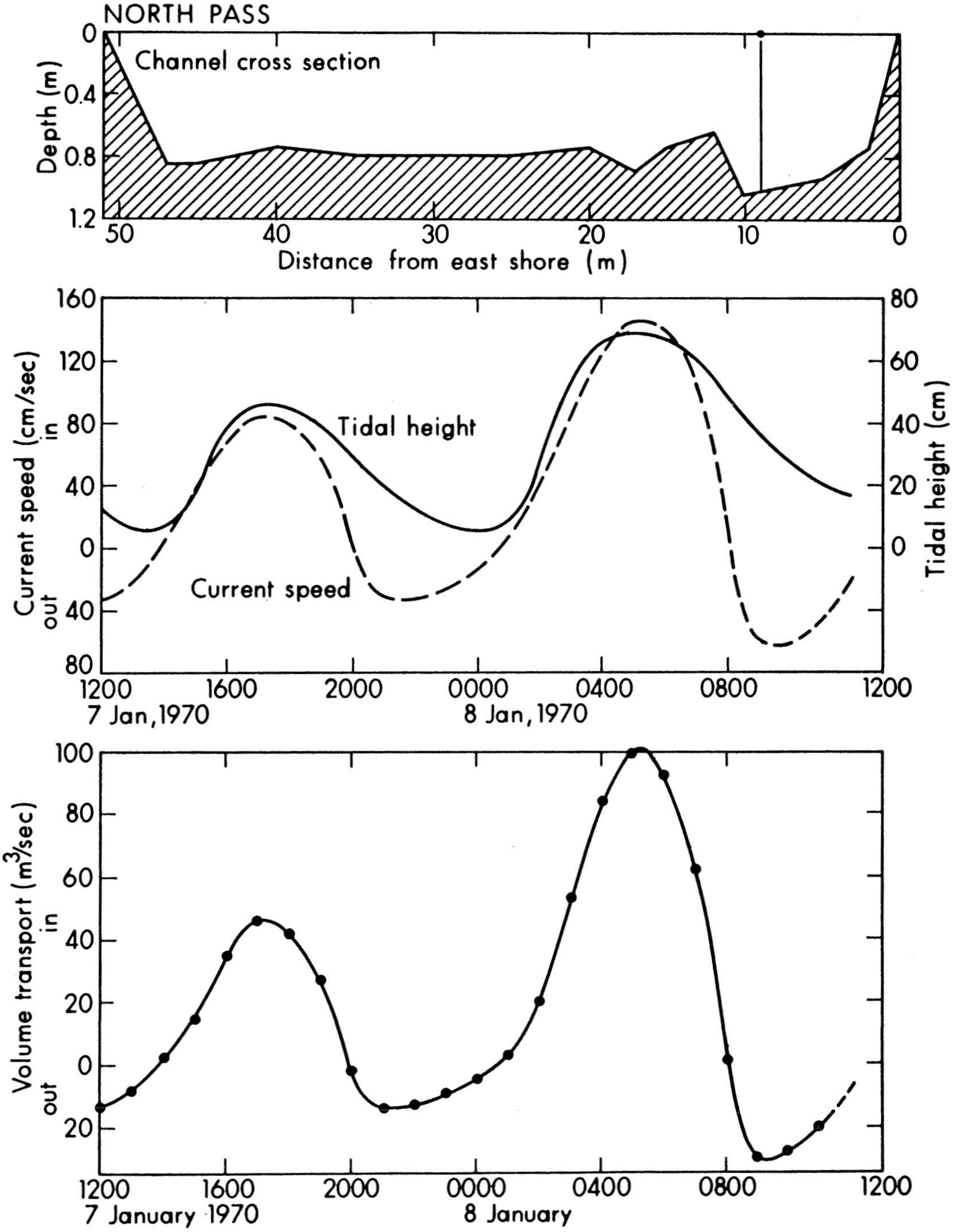

FIG. 1. Channel cross section showing station position (solid dot and vertical line), tidal height and current speed, and volume transport for North Pass during the 24-hour transport study. Dense patches of *Turbinaria* that nearly reach the surface at low tide are located between 20 to 40 m from the east shore. Cross-sectional depths are relative to a tidal height of 13 cm. Absolute sea level is arbitrary.

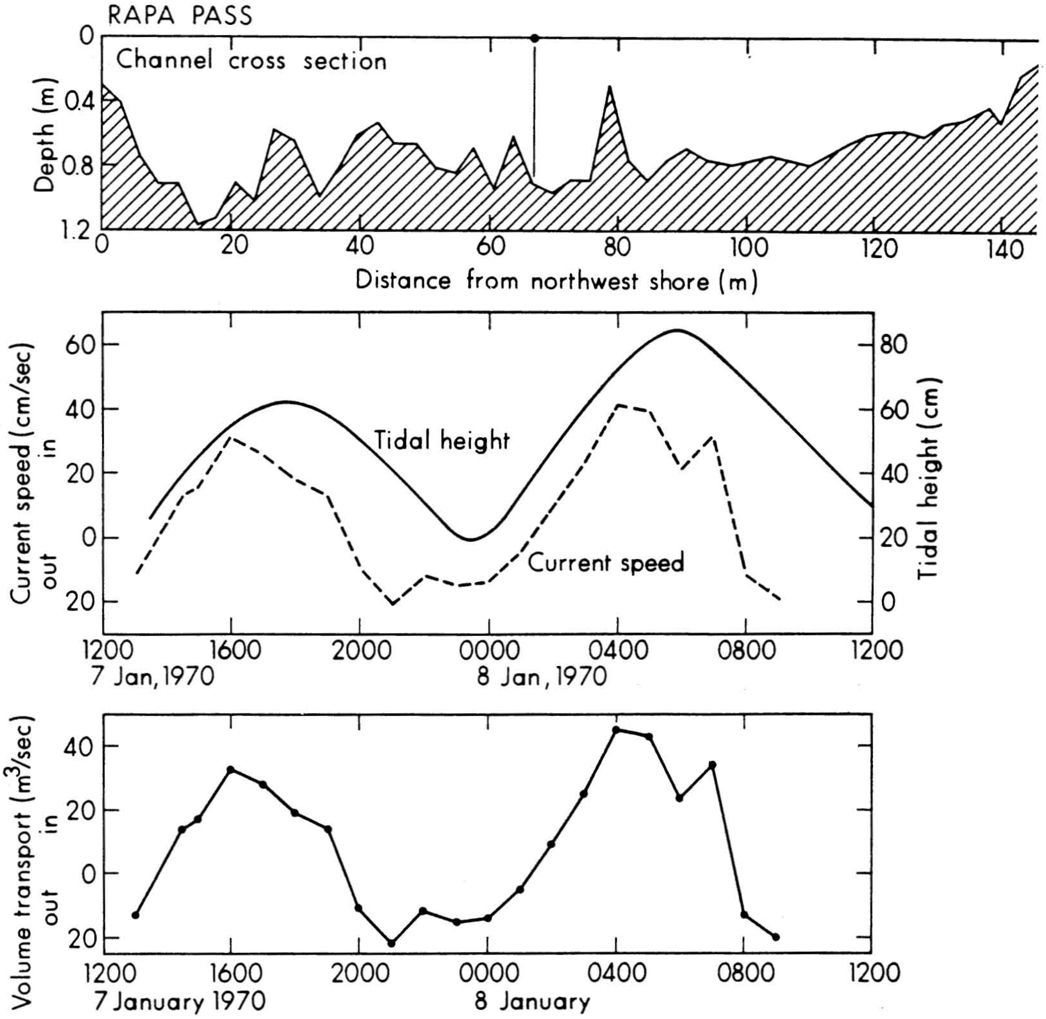

FIG. 2. Channel cross section with station position (solid dot and vertical line), tidal height and current speed, and volume transport for Rapa Pass during the 24-hour transport study. Cross-sectional depths are relative to a tidal height of 38 cm. Absolute sea level is arbitrary.

ages of all the temperature and salinity measurements at buoys 2, 3, and 4 for each measurement cycle are presented in Figure 5, along with the volume transport through the entire channel.

A recording current meter was later placed near the surface at buoy 3, the site of strongest flow. The resulting record is shown in Figure 6.

RESULTS OF THE TRANSPORT STUDY

Volume

Currents through the channel at English Harbor displayed an interesting pattern. During each period of inward flow, a jet developed and extended into the lagoon from the channel itself. The jet appeared at buoys 2, 3, and 4, where speeds exceeding 3 knots could be found. On either side of the base of the jet, eddying motion, which could be observed visually, appeared in the measurements of volume transport at stations 1, 5, and 6. During the ebb, however, there was outward flow at all locations across our section, funneling into the channel. Figure 7 illustrates these patterns in the volume transports at each buoy. The same jetlike flow also

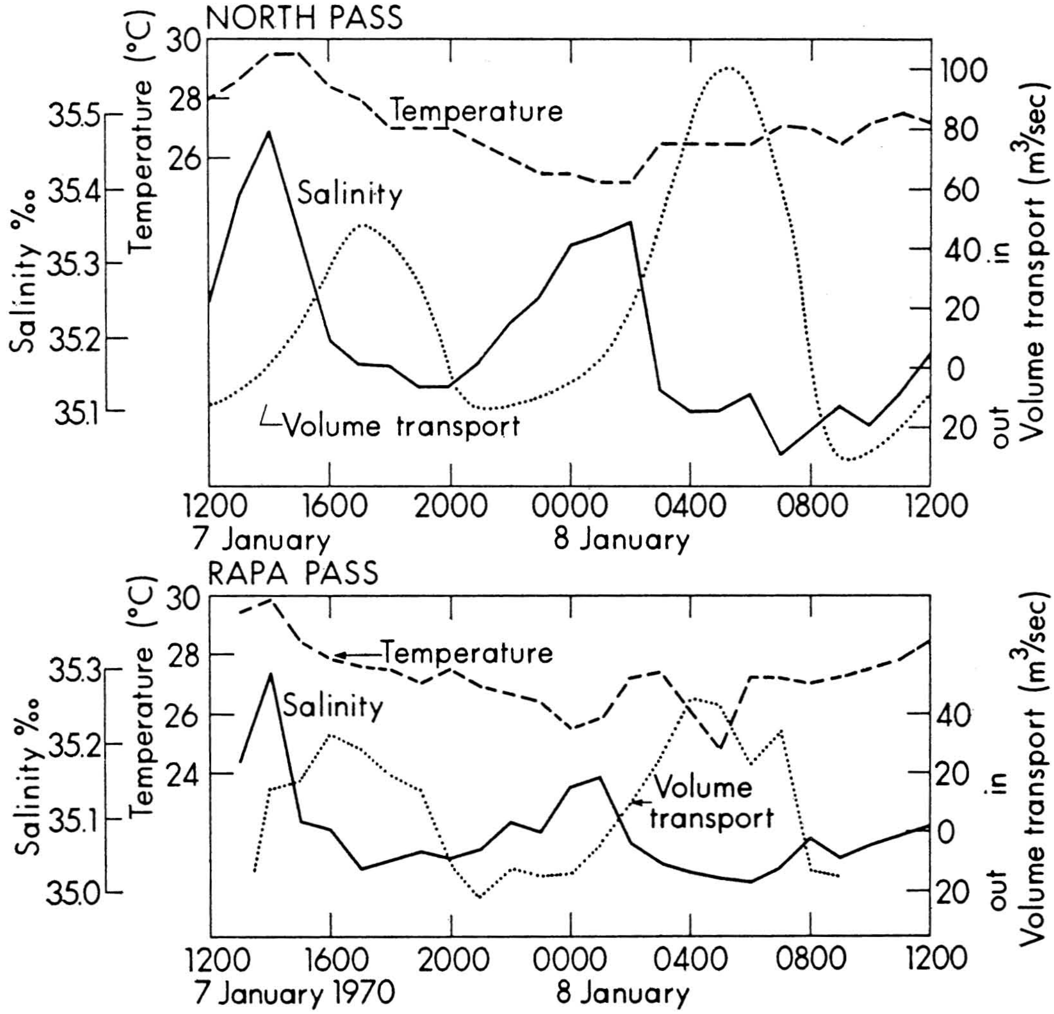

FIG. 3. Salinity, temperature, and volume transport for North and Rapa passes during the 24-hour transport study.

developed on the seaward side of the channel during ebb and could often be seen from shore. Another noteworthy feature of the current was its rapid reversal, with relatively short periods of weak flow between strong ebb and strong flood. This indicates that the lagoon has a nonlinear response to tidal excitation. The presence of nontidal overtones is seen in the current and lagoon tide records displayed together in Figure 6. As one would expect, the current shows strong relation to the tide's rate of change, but both processes clearly reflect nonlinear distortion.[4] The lagoon's response to the ocean tide would be an intriguing subject for further study.

The first semidiurnal cycle of transport studied coincided with a typical tidal excursion. During this period (1440 to 0120) 0.025 km^3 of water was computed to have entered the lagoon through the three passes. The computed out-

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[4] There probably is also some error in the relative phases of the curves. in Figure 6; the current should not lag the lagoon-tide derivative. We cannot find a timing mistake in either record and can only point out this discrepancy.

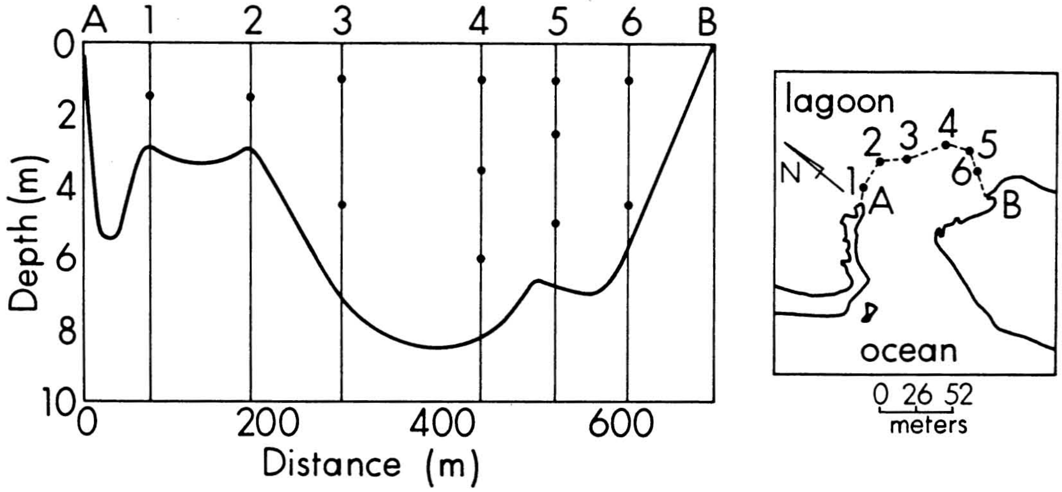


FIG. 4. Smoothed channel cross section (left) and buoy locations (right) for English Harbor channel. Depths (in meters) at which measurements were most often taken during the 24-hour transport study are indicated for each buoy.

flow was 0.026 km^3. The agreement between these numbers is gratifying, because the tidal records show no net change in lagoon water level over this particular period. Moreover, the measured exchange, 6 percent of the mean lagoon volume, agrees with the value estimated using tidal range and mean depth in the lagoon. In spite of these consistency checks, however, the transport figures calculated from our measurements should not be regarded as exact. Inaccuracies in current speeds, directions, and areas of channel cross sections lead to a volume transport uncertainty of ±15 percent.

There was a net inflow of water through North and Rapa passes during the first, semidiurnal tidal cycle monitored. The amount was 0.56×10^{-3} km^3, or 0.1 percent of the lagoon volume. Thus, there is an overall flow across the lagoon which must exit at English Harbor; this flow is probably driven by wind and wave transport over the windward and northern reefs.

Salt

During the first transport cycle, the computed total salt transport into the lagoon (90×10^7 kg) matched (within our limits of accuracy) the total salt transport out of the lagoon (91×10^7 kg).

At English Harbor channel, outflow (90×10^7 kg) also matched inflow (86×10^7 kg) within our limits of accuracy (see Fig. 8). Salinity followed no discernible pattern (see Fig. 5).

At North and Rapa passes, inflow exceeded outflow by 2.0×10^7 kg of salt (Figs. 9 and 10). Salinity in these passes decreased during flow into the lagoon and increased during outflow. Because these passes are shallow, solar heating may cause the levels of evaporation in the lagoon to exceed open-ocean levels, at least locally near the mouths of the passes. The higher salinity outflow could be partly caused by the mixing of incoming seawater with more saline lagoon water. However, this cannot be proven. If the ocean water merely flowed in and out of the lagoon, with no mixing, estimates show that local evaporation in the lagoon was sufficient to account for the observed salinity increase.

Heat

In the first transport cycle, during which net volume transport was zero, net heat transport (see Figs. 8 to 10) was also zero to within the accuracy of our measurements. Total inflow (68×10^{13} calories) was closely matched by outflow (66×10^{13} calories). There was a net inflow of heat at the small passes (1.6×10^{13} calories), but this reflected the particular phas-

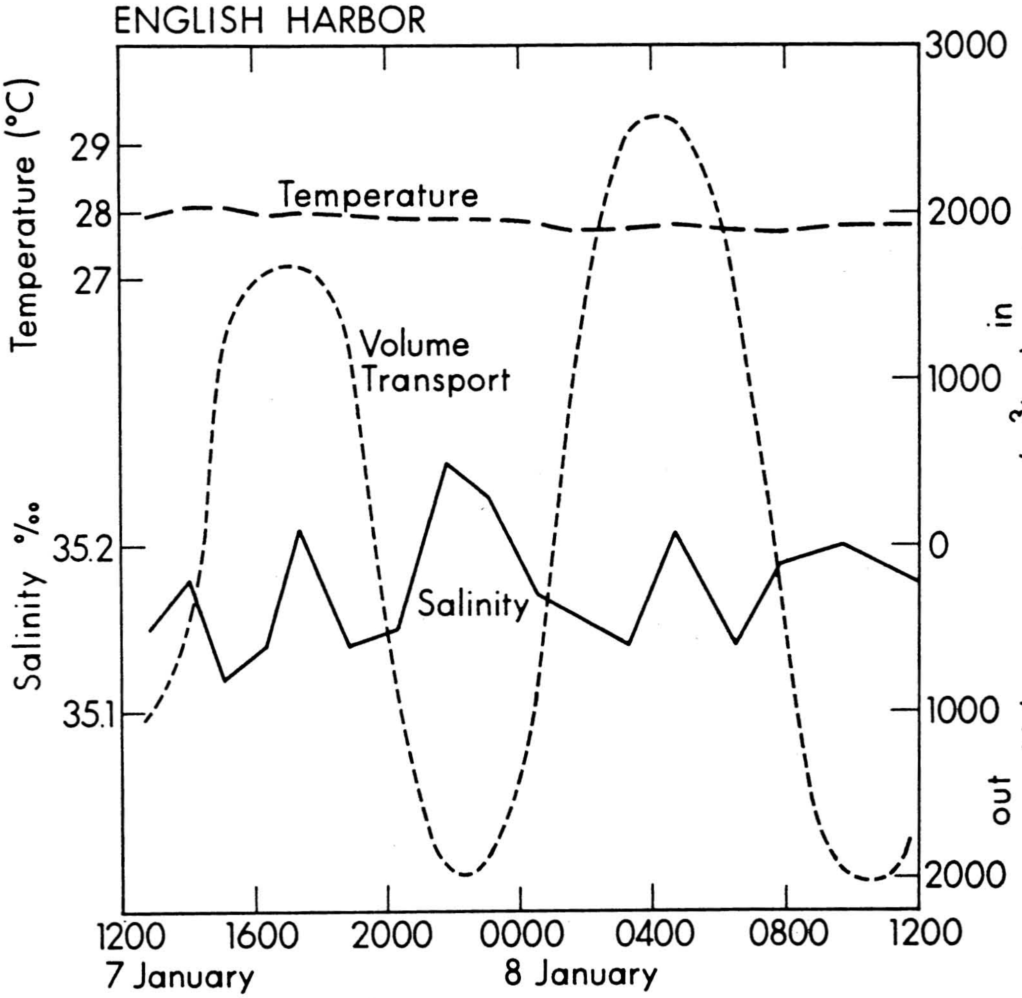


FIG. 5. Averages of the salinity and temperature measured at buoys 2, 3, and 4, English Harbor channel, and volume transport across the entire channel, during the 24-hour transport study.

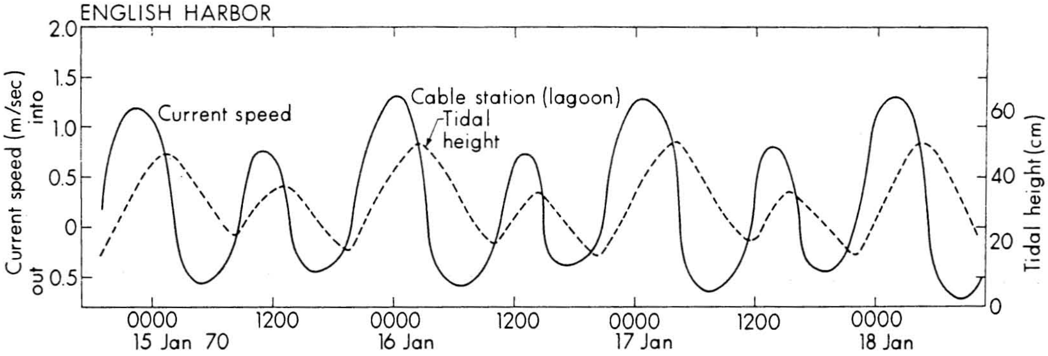


FIG. 6. Aanderaa current meter record at buoy 3, English Harbor channel, and lagoon tide. Absolute sea level is arbitrary.

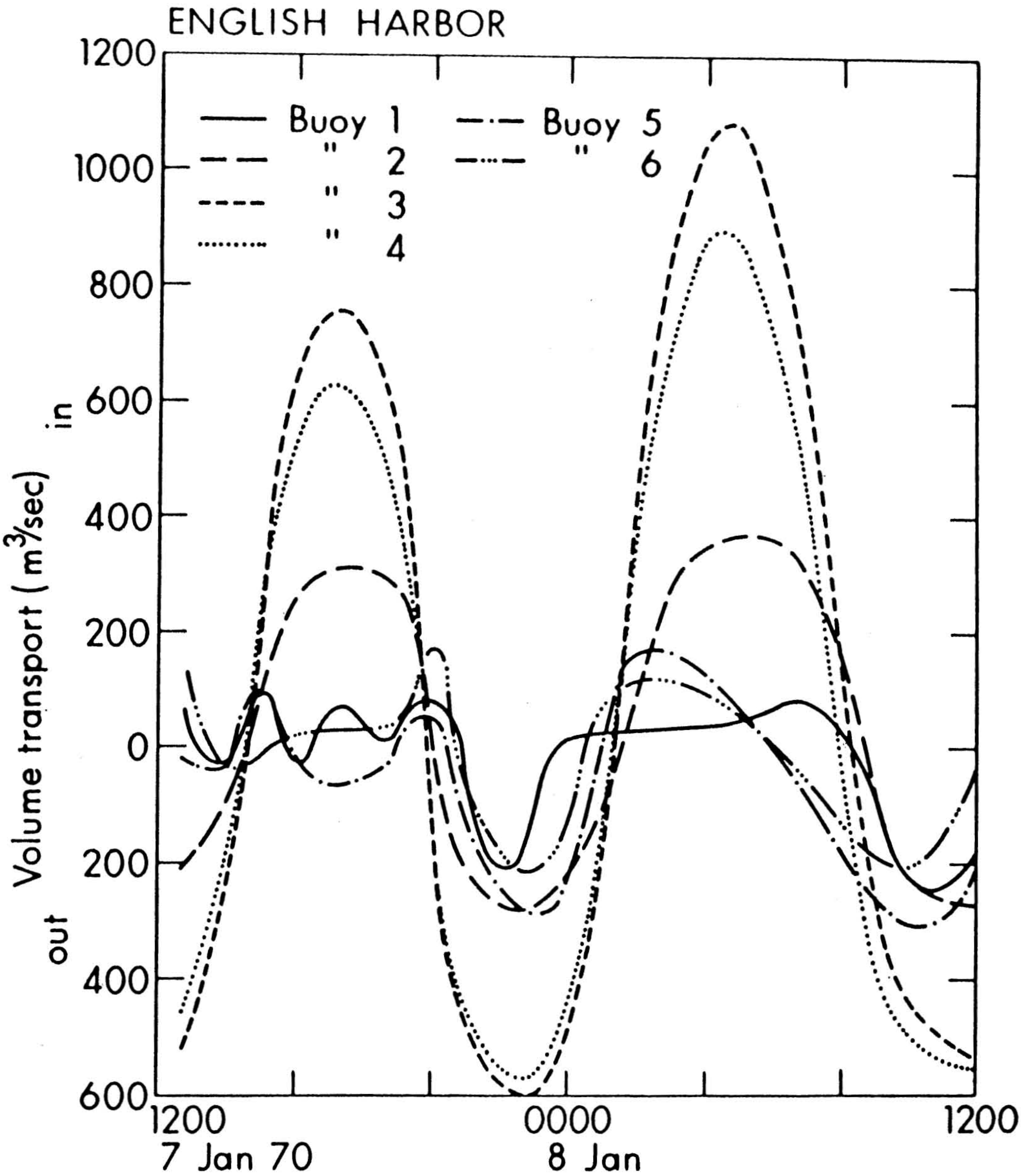


FIG. 7. Volume transports assigned to each buoy during the 24-hour transport study at English Harbor channel.

ing of the diurnal temperature curves with the semidiurnal current variations, and may have had no particular significance. It does seem strange, however, that the temperature variations were diurnal and did not show the effects of the tidal flows which appeared in the salinity curves. The disagreement in the periodicities of the temperature and salinity occurred at both passes. It seems likely that this illustrates the rapid response of temperature in this shallow-water environment to the large diurnal variation in the flux of radiant energy. The diurnal variation in evaporation was proportionately very much smaller, so that no diurnal salinity fluctuation is

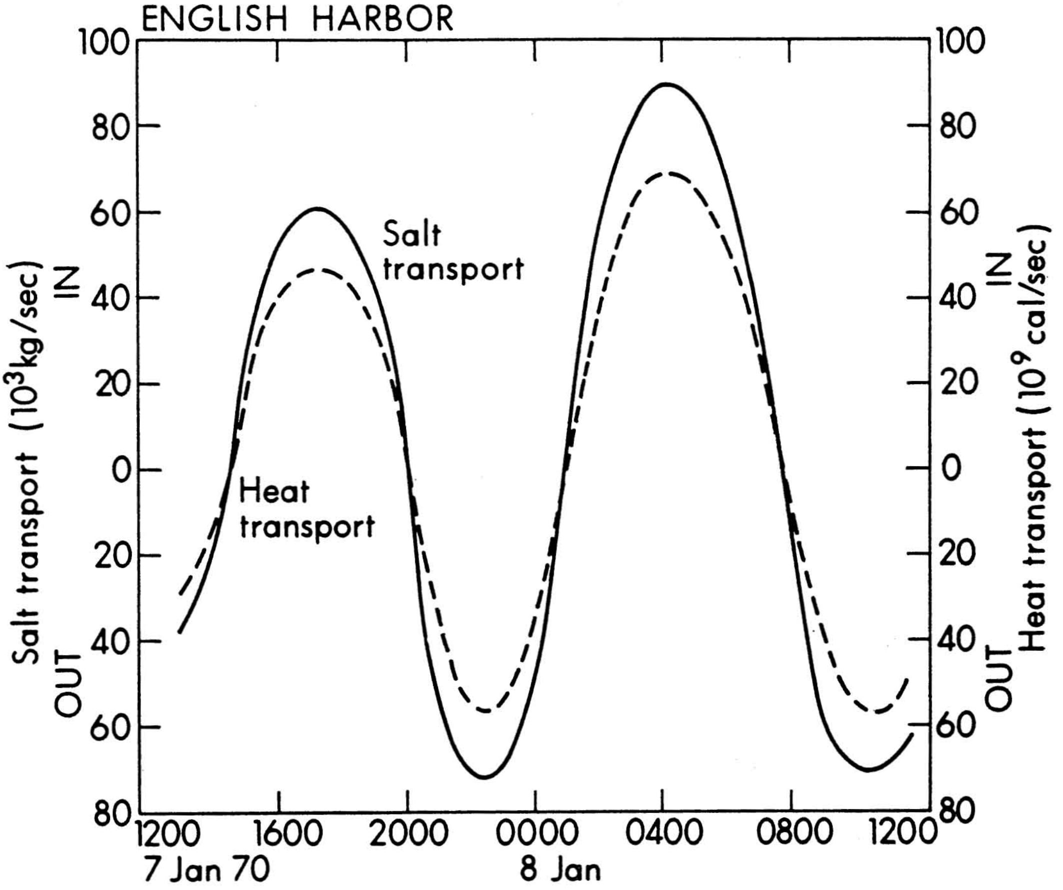


FIG. 8. Salt and heat transports at English Harbor channel during the 24-hour transport study.

obvious in the record. At English Harbor, there was no significant temperature variation. This agrees with other observations which indicate that the water which entered and left through the channel was essentially open-ocean water. Changes incurred by mixing with lagoon water were too small to be detected.

Mixing

Replacement of water in the lagoon appears to be a slow process. A major reason for this is the fact that the lagoon was divided into numerous, small ponds by interconnecting line reefs, many of which were almost uncovered at low water. Flow was thus restricted to a shoal surface layer and to meandering passes through the reefs. An exception was the area receiving flow through the channel at English Harbor. Lagoonward from the channel, the bottom was scattered with large coral formations, but these were isolated and did not seriously baffle the flow. The water here was relatively deep and quite clear. The clear water contrasted markedly with the extremely turbid water found throughout the rest of the lagoon, and the boundary between clear and turbid water appeared to be vertical and often only a few meters wide. This boundary was sometimes observed moving in response to tidal inflow and outflow through the channel. These facts, together with the temperature and salinity records from the transport study, indicate that very little mixing occurred between lagoon water and the water that participates in the predominant tidal exchange. Mixing is likely to be relatively more important very locally near North and Rapa passes where no topographic or turbidity boundaries were apparent and the water was shoal. Such mixing, because

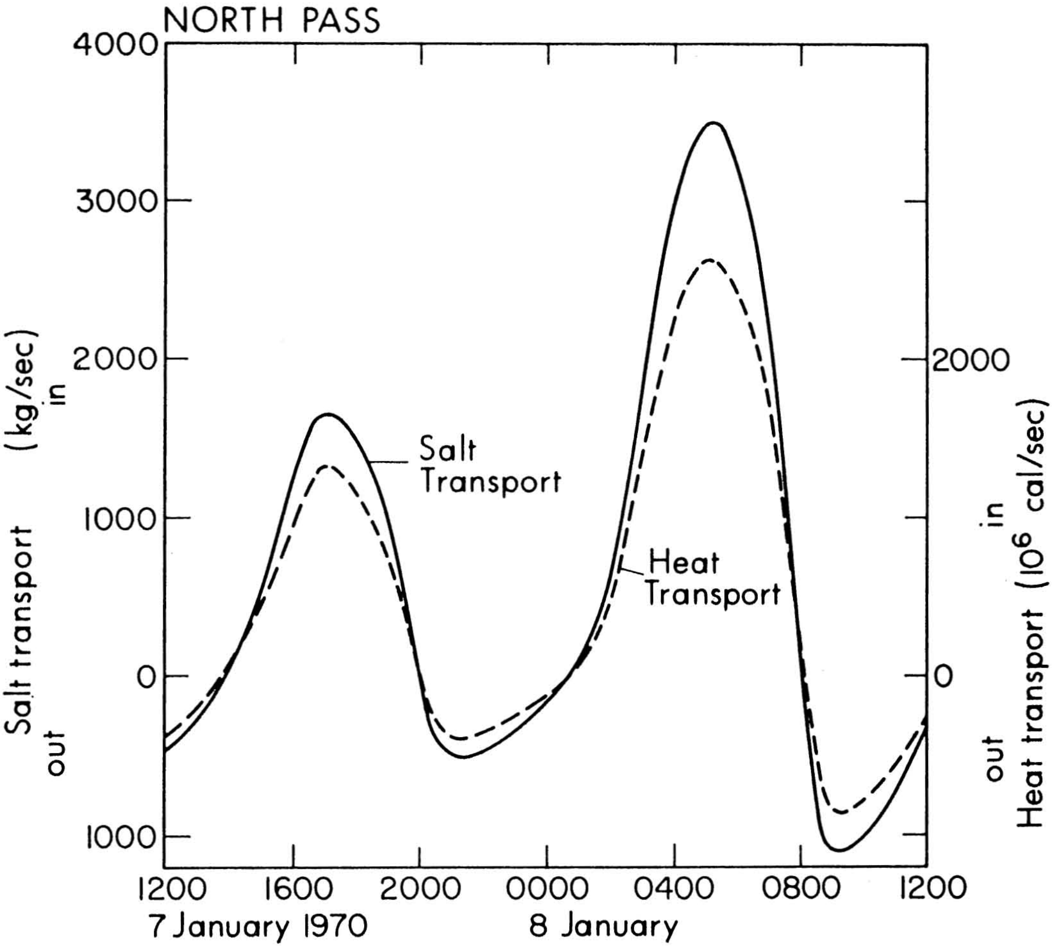


FIG. 9. Salt and heat transports at North Pass during the 24-hour transport study.

of the line reefs and because the volume exchange through these passes was relatively very small, would not greatly reduce lagoon-wide residence times.

One possible lower limit on residence time can be calculated by using the observed volume of net inflow through the two small passes. If this inflowing water is assumed to mix completely throughout the lagoon before exiting at English Harbor, then we have

$$\text{residence time} = \frac{\text{lagoon volume}}{\text{rate of net exchange}}$$

$$= \frac{.41\ \text{km}^3}{.56 \times 10^{-3}\ \text{km}^3/11\ \text{hr}} \approx 11\ \text{months.}$$

Tides

The main tidal records were kept near the Cable Station on the northwest side of the island; readings were taken in the lagoon and in the ocean. The ocean gauge was fastened to an outhouse piling a few meters seaward from the water's edge, while the lagoon record was obtained at the end of a small pier. The measurements were used to make daily predictions for biologists on the expedition who were involved in nearshore collecting. The tide curves, shown in Figure 11, are useful for examining ranges and phases. However, the records are not related to any common reference level. Moreover, the curves contain several interruptions occasioned by instrument malfunctions, and no

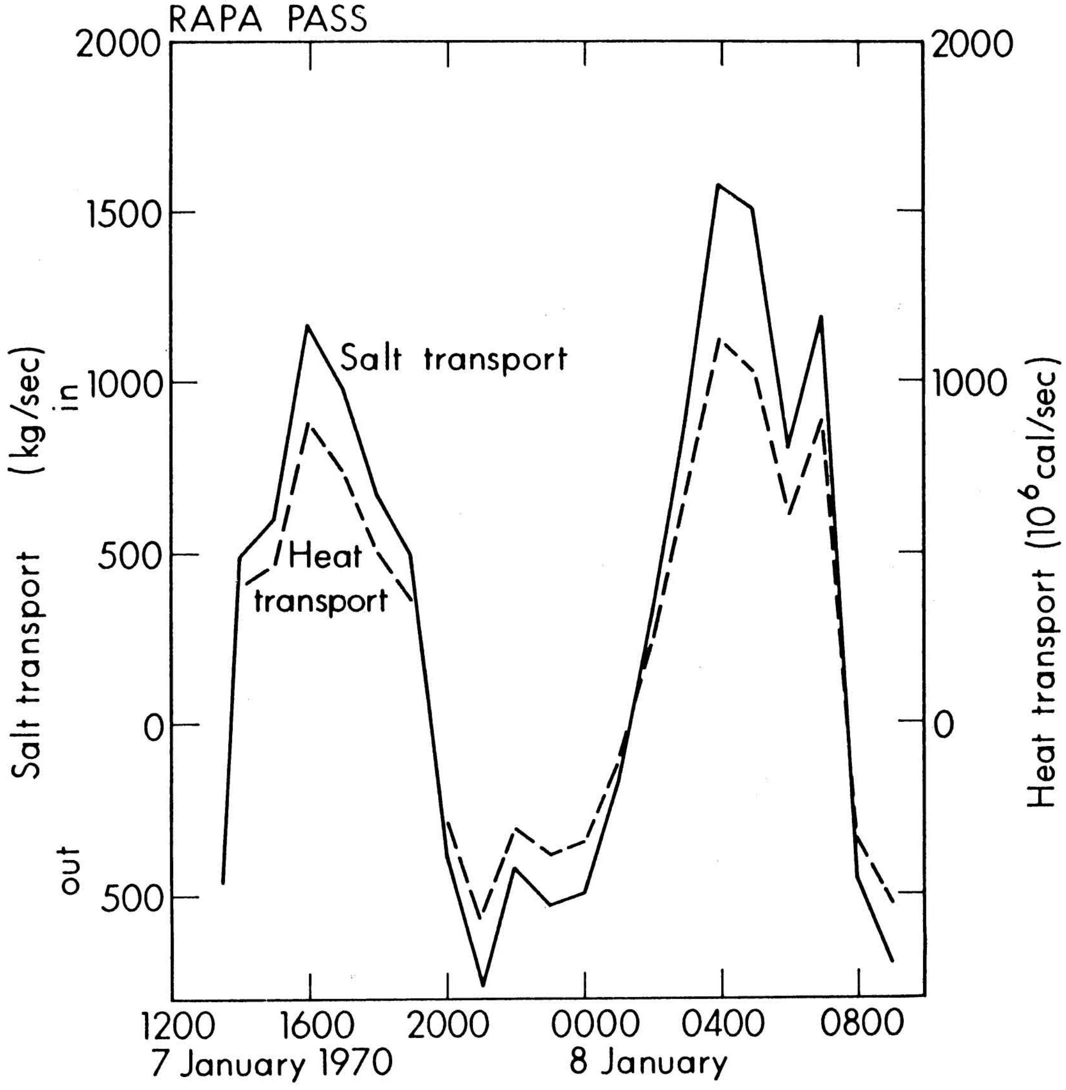


FIG. 10. Salt and heat transports at Rapa Pass during the 24-hour transport study.

attempt was made to maintain a constant zero-level between fragments of a given record.

The observed tidal range in the lagoon was typically 40 cm. This provided an immediate estimate of the volume of tidal flow. Half the tidal range was 5 percent of the mean lagoon depth estimated by the geologists, which implies that 5 percent of the lagoon volume took part in tidal exchange. Direct measurement of the volume transport through the passes confirmed this value. The range in the lagoon was roughly half that in the ocean outside.

The lagoon tide lags that of the surrounding ocean by a typical period of 1 hour, 40 minutes as shown in Figure 12. The figure also shows tides measured in North and Rapa passes during the transport survey and the tide outside the Cable Station. Although the measurements in the passes were taken roughly halfway between lagoon and sea, the curves appear to be about the same in phase and in range as the ocean tide measured at the Cable Station.

There is a temptation for practical reasons to see whether the ocean tide at Fanning Island is related in some simple way to Honolulu tides. The Honolulu tide is shown plotted against the Fanning Island tides in Figure 11. No relationship that could be used to give rough Fanning predictions based on Honolulu records is apparent. Semidiurnal phase lags, based on very scanty records, varied from 16 minutes to 1 hour, 42 minutes for high water and from —48 minutes to 2 hours for low water. The amplitudes were also quite different.

Suez Pond

A large part of Fanning Island Lagoon is subdivided into small ponds by interconnecting line reefs that reach nearly to the surface. A typical example, called Suez Pond in this paper, was chosen for intensive geological and chemical study; we attempted to provide some supporting information about water circulation. (See Roy and Smith in this issue of Pacific Science for a further description of the pond itself.)

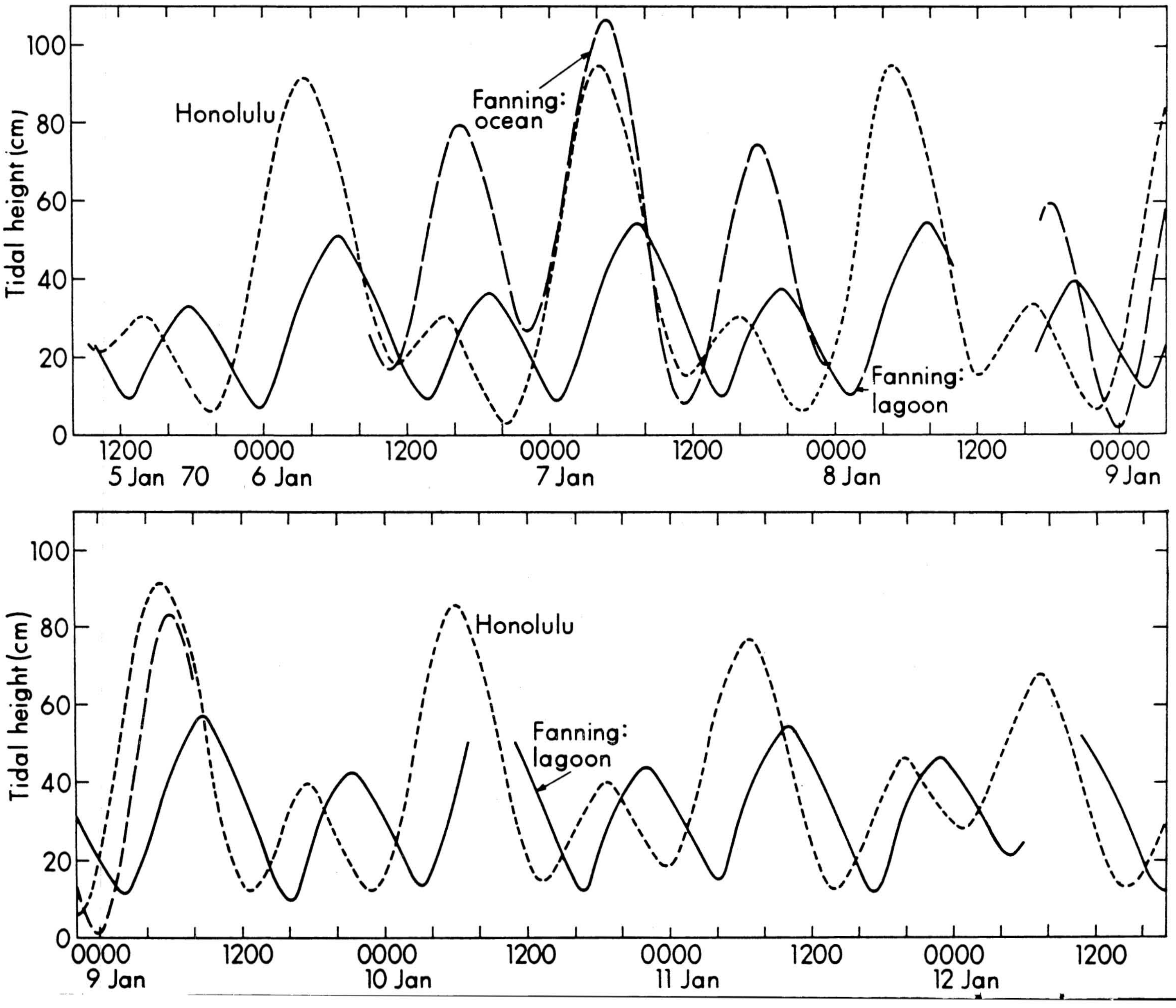
Water movements in the pond proved to be extremely complex and usually too weak to measure quantitatively with standard current meters. Winds, tides, and thermohaline forces all appeared to be important in the circulation. Furthermore, processes on the bordering reefs and in adjacent ponds seem to have had an influence as well. Our time and instrumentation were almost totally inadequate for the task of describing the circulation, and we are able to make only qualitative comments.

During much of the year Fanning Island lies in the southeasterly tradewinds, which blow across the lagoon at mean speeds of 10 knots from 135°. There are diurnal speed variations with afternoon winds being 10 to 20 percent stronger than morning winds (New Zealand Meteorological Service, 1956). Short, choppy waves up to 0.3 m high were generated within the lagoon itself. With exceptions to be noted later, surface flow across the pond and adjacent reefs was in the direction of the wind. Within the pond, the directly wind-driven layer was less than 1 m deep with speeds on the order of 0.1 knot. We found no simple pattern of return flow at depth; currents at 3 m were variable in direction with speeds too low to measure (< .05 knot). Sand from the tops of the adjacent reefs was found deposited almost exclusively along the windward boundary of the pond, indicating the directional consistency of the wind-generated waves and currents over the reefs, and supporting the finding that currents at depth are weak.

Tidal effects were superposed and sometimes masked by the wind-driven flow. Currents were measured at several locations on the shoal reefs bounding the pond, both during rising and during falling tides. At Suez, in a channel roughly 1 m deep and 5 m wide dredged through the leeward reef, an ebb flow moved against the wind at 0.1 to 0.2 knots. Tidal reversals were not detected at any other location. Tidal currents almost surely crossed the reefs at other places, and future measurements should include a study under conditions of no wind. To the north and west (and not communicating with the pond) is a meandering pass which can be followed through the reefs from the Cable Station to English Harbor. It is possible that this serves as a channel for overall southward flow in the area; the ebbing tide and the necessary return of wind-driven surface transport may be minimal in Suez Pond itself.

We attempted to trace subsurface flow with dye, but found this to be of limited value because of the high turbidity in the pond. On one occasion, however, we were able to detect subsurface movement against the wind. Dye introduced in a vertical streak near the windward edge of the pond broke into two patches. A surface patch moved with the 9-knot wind at a maximum estimated speed of 0.4 knot, and became too diffuse to see after about 40 minutes. A second patch, extending downward from about 0.5 m, moved up against the windward reef at an estimated speed of 0.06 knot and could not be seen coming to the surface. The dye may have moved downward, or it may have ascended very slowly and become too diffuse to detect in the surface flow. Dye injected as a point source in the same location at 3 m depth was never detected throughout 2 hours of observation.

Distributions of properties showed a complicated pattern of inhomogeneities. Salinity was sampled at depth at five locations during a 3-hour period. At four locations salinity increased by .01 to .03‰ from the surface to the bottom, and one station showed a decrease of .01‰.


Tidal height (cm)
0
20
40
60
80
100
Honolulu
Fanning: ocean
Fanning: lagoon
1200
5 Jan 70
0000
6 Jan
1200
0000
7 Jan
1200
0000
8 Jan
1200
0000
9 Jan
Tidal height (cm)
0
20
40
60
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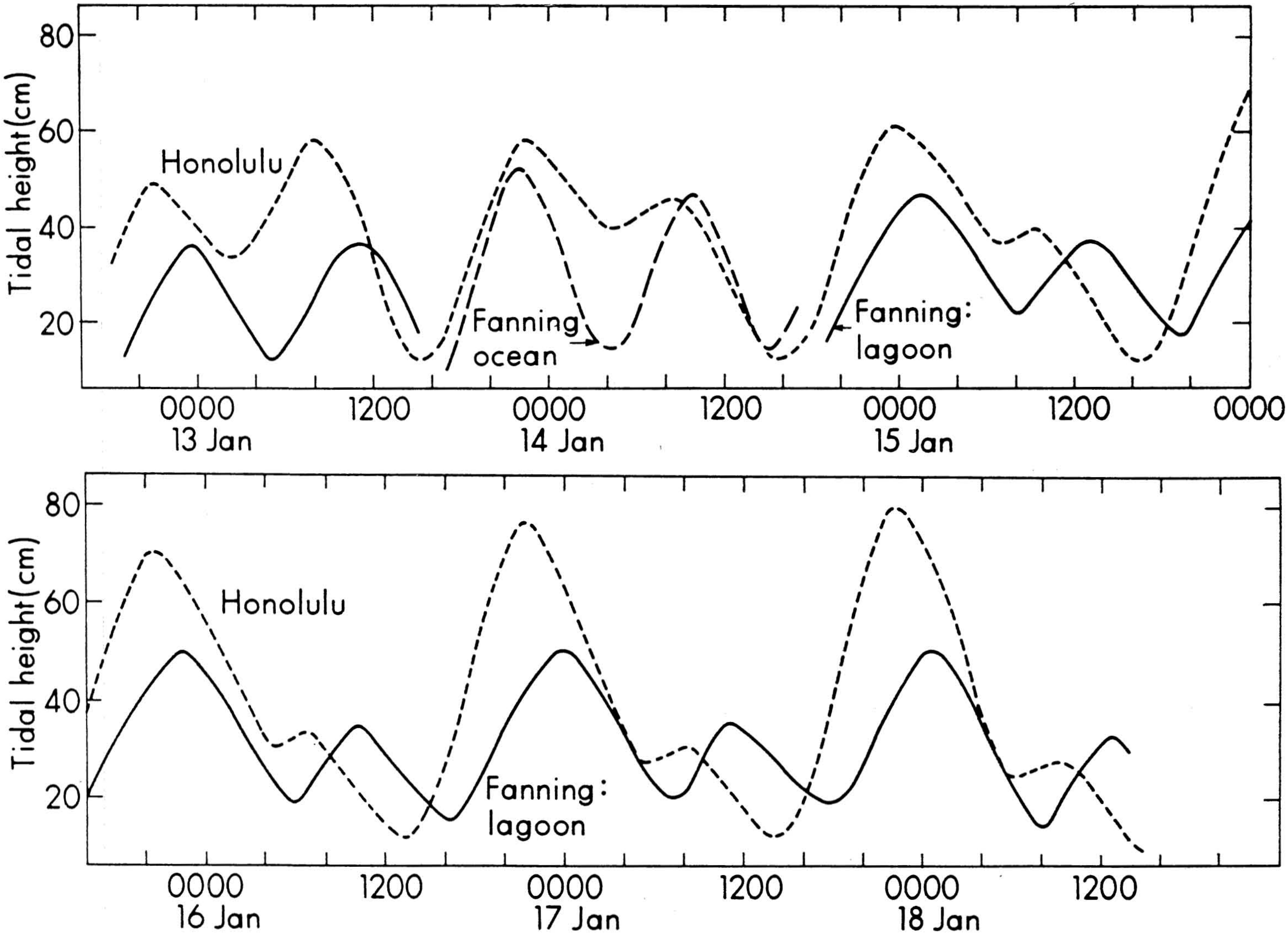

FIG. 11. Tidal height measured in the lagoon and the ocean near the Cable Station, Fanning Island, compared with tide at Honolulu (CGS record). Absolute sea level is arbitrary in the Fanning records.

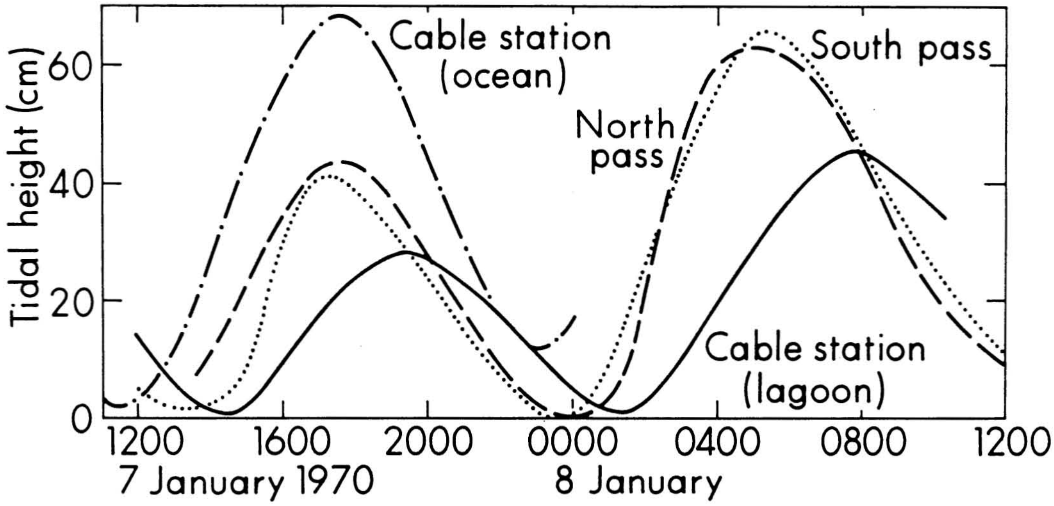

FIG. 12. Tidal heights at North and Rapa passes, and in the lagoon and the ocean near the Cable Station, during the 24-hour transport study. Absolute sea level is arbitrary.

Variations of .04‰ over distances of a few hundred meters occurred at all depths. One of the stations was repeated after 24 hours, and salinity had increased almost 0.3‰ at all depths. We found no water of this higher salinity in the pond on the previous day, so the rapid replacement of the 8-m water column at this station does indicate vertical movement. The salinity data indicate thermohaline circulation which was very irregular in space and in time. Probably patches of high-salinity water originated over the wide, shoal, boundary reefs; were advected into the pond; and, perhaps with nighttime cooling, gave rise to vertical circulations which can have small horizontal dimensions compared to the pond. Below about 3 m, the pattern of such circulation would be further complicated by the very irregular topography.

The distribution of extinction coefficients in the water column is shown in Figure 12, Roy and Smith, this issue. Several factors appeared. A patch of high turbidity, covering about one-third of the pond's area, was apparent at the surface and extended down to about 2 m. Within the patch, suspended load decreased with depth, indicating that the patch was quite recently formed. The horizontal distribution strongly implies that this highly turbid water entered the pond through Suez Canal during the falling tide and flowed out over the surface. Shallow tidal flow against the wind also appeared to bring turbid water from the leeward reef into the pond to the east of Suez. At depths between 2 m and 4 m additional horizontal patches of suspended load could be seen. They were less intense and had no apparent connection with those at the surface; they may have been remnants of surface patches in the process of settling. (Particulate matter of this size has a settling rate on the order of 1 m/day.) Below 4 m the turbidity became almost uniform horizontally, with an intensity that appeared to be close to an average value for the overlying water.

The salinity and suspended load data suggest some possible general conclusions about mixing in the pond. The uniformity of turbidity at depth, along with the settling rate of the particles, suggests that the pond had a mixing time of less than about 5 days. Salinity indicates that the mixing time certainly exceeded a few hours, and that at least part of the mixing was associated with diurnal, thermohaline processes. One might suspect that deeper portions of the pond are filled by relatively dense water that is renewed only infrequently by unusual events. However, there were no indications of stagnation; oxygen concentrations were close to saturation at all depths. Thus, there must be a fairly regular downward transport of buoyancy, indicating an external source of mixing energy. The most probable agent is the wind-driven flow, but we have insufficient measurements for proposing a circulation model which could explain the mixing and the observed distributions of properties.

Should members of a future expedition wish to obtain a comprehensive picture of physical processes in the pond, they would face a difficult task. We suggest from our experiences that they employ very sensitive current meters (responsive to 1 cm/sec or less) to see whether any average, overall patterns of movement can be discerned. Great effort would be required to ensure no motion of the meters themselves; they cannot simply be lowered from a single-anchored skiff. Hourly vertical profiles should be obtained at as many stations as possible (at least four on a line roughly parallel with the wind and through the center of the pond). We advocate this direct approach because the patchy and transient nature of property distributions would limit the value of these profiles for inferring motion unless they were based on very dense sampling. If a general circulation pattern were found, then temperature, salinity, and turbidity measurements could be planned to complement and take advantage of it. Such a plan should be designed to maximize the density of readings in both time and space; variations that occur rapidly and over short distances are to be expected. On-the-spot instrument readout would be extremely valuable.

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