Origin of Sustained Continuous Measurements of Surface Wind and Upper-Ocean Current and Temperature on the Pacific Equator

EQUA Project

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ABSTRACT: In 1976, a pilot experiment, called first Equatorial Mooring (EQUA-1), tested an innovative technique for anchoring a taut-line surface mooring at 0°, 150°W where the water depth is 4.5 km. The 36-day deployment contained a wind recorder and fixed-level current meters at 50 and 100 m in the Equatorial Undercurrent (EUC). The following year, in a second pilot experiment, named EQUA-2, a similar mooring was deployed at 0°, 125°W for 99 days. EQUA-2, with current meters at 10, 50, 100, 150, and 200 m, recorded a surge in EUC transport during April 1977 when 3-day-averaged eastward current speeds at 50-m depth reached 2 m s^{-1} . The associated eastward transport per unit meridional width over the 50–200-m layer was $190 \text{ m}^2 \text{ s}^{-1}$. Based on observations recorded in April 1980, the EQUA-2 pulse would correspond to a total EUC transport surge of about 38 Sv ($1 \text{ Sv} \equiv 10^6 \text{ m}^3 \text{ s}^{-1}$) and would represent an equatorially trapped first-mode baroclinic Kelvin wave. This paper describes EQUA Project observations and why and how I created the high-risk-of-failure opportunity to record pioneering time series measurements at the equator. The enduring legacy of the EQUA Project is the sustained maintenance of in situ surface wind and upper-ocean current and temperature measurements at numerous sites in the equatorial oceans, starting in the Pacific to improve forecasts of the El Niño and La Niña phenomenon. For example, the 40-yr records of surface wind and upper-ocean current and temperature measurements at 0°, 110°W and 0°, 140°W are some of oceanography's longest time series recorded far from land.

KEYWORDS: Ocean; Tropics; Atmosphere-ocean interaction; El Niño; Kelvin waves; Buoy observations

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The first moored-buoy time series measurements of surface wind and of currents and temperatures in the Pacific Equatorial Undercurrent (EUC) on the equator were recorded for 36 days in 1976 with the first Equatorial Mooring (EQUA-1). In 1977, the EQUA-2 time series length was nearly 3 times longer than in EQUA-1. The EQUA Project heralded the onset of long-period time series measurements of surface wind and other atmospheric variables and of current and temperature in, above, and below the EUC. Soon after the EQUA-1 and EQUA-2 observations were retrieved, I was buried by the demands of continuing the measurements, supporting technical staff, research and teaching, preparing proposals, and a young family. In 2014, I reviewed the EQUA Project in a presentation at the Lamont–Doherty Earth Observatory (www.ldeo.columbia.edu/~virginia/Mark70thSymposium/program.html) on the origin of time series measurements of surface wind and upper-ocean current and temperature on the equator.

Scientific motivation. The 1952 observational discovery of the EUC in the Pacific Ocean (Cromwell 1953) unleashed many expeditions (Cromwell et al. 1954; Knauss and King 1958; Knauss 1960, 1966; LeMasson and Piton 1968; Hisard et al. 1970; Colin et al. 1971) to determine the EUC's thickness (150–200 m), latitudinal width (1.5°S–1.5°N), longitudinal extent (the width of Pacific), core speed (1.0–1.5 m s⁻¹), and depth of core speed (200 m in the west Pacific and 75 m in the east Pacific). Direct observations of currents in the EUC were made with a current meter lowered from a ship and with subsurface floats tracked from a ship; indirect evidence of the flow was inferred from shipboard measurements of spatial distributions of temperature, salinity, oxygen, nitrate, and other variables. The strength of the EUC was not uniform along the equator and not constant with time at a site along the equator. Philander's (1973) excellent comprehensive review of the EUC provided the rationale for sustained current measurements in the EUC recorded simultaneously at widely spaced locations along the equator.

Many observations of the EUC preceded theoretical studies of the EUC (Arthur 1960; Charney 1960; Robinson 1960; Stommel 1960; Veronis 1960). However, theories of equatorially trapped waves (Blandford 1966; Matsuno 1966; Munk and Moore 1968; Lighthill 1969), in particular the equatorially trapped baroclinic Kelvin wave, preceded observations.

The equatorially trapped baroclinic Kelvin wave is an unforced wave mode of the linearized, time-dependent equations of motion on a beta plane in a stratified ocean. The meridional component of velocity is zero and only eastward propagation is a valid solution. The phase speeds for the first and second baroclinic modes are about 2.7 and 1.7 m s⁻¹, respectively (Yu and McPhaden 1999). The eastward component of velocity and thermocline displacement or sea surface steric height are maxima at the equator and symmetrical about the equator. Kelvin waves are important for baroclinic adjustment of an equatorial ocean to wind forcing. A cyclone close to the equator in the west Pacific is a source of strong westerly winds, which could deepen the thermocline through Ekman convergence and generate an energetic oceanic response, including downwelling Kelvin waves propagating to the east Pacific. An easterly wind burst would produce an upwelling Kelvin wave, which also would travel to the east Pacific.

Godfrey (1975), Wyrtki (1975), and McCreary (1976) hypothesized that equatorially trapped baroclinic downwelling Kelvin waves generated by an increase in surface westerly wind stress in the west Pacific would produce a deepening of the thermocline in the east Pacific that marks the onset of El Niño conditions. Earlier, Bjerknes (1966) had conjectured that the EUC might be connected to the development of an El Niño event. Rowntree's (1972) iconic study, building on Bjerknes's (1966) hypothesis, showed how an increase in sea surface temperature in the eastern equatorial Pacific, i.e., El Niño conditions, could disturb global atmospheric circulation and alter far-field conditions in a way that leads to floods and droughts. The 1972/73

El Niño had severely impacted global food prices (Caviedes 1975). The societal importance of improving skill of El Niño prediction increased the criticality of detecting equatorial Kelvin waves and interannual variations of the EUC.

By the mid-1970s it was apparent that a suitable platform for recording long-period measurements of surface wind and EUC currents and temperatures would substantially contribute toward generation of new knowledge and improved understanding of equatorial ocean science.

Technological motivation. The 1960s was a time of rapid changes in ocean observing technology when internal recording instruments became available for time series measurements of surface wind and ocean current and temperature. Platforms had to be engineered to support the new instruments for sustained in situ oceanographic measurements. In 1960, the Woods Hole Oceanographic Institution (WHOI) established the world's first moored buoy group (Winner 2010) that opened a new exploration era in ocean sciences. With regard to the EUC, one of the WHOI Buoy Group's initial successes occurred in 1963 in the Atlantic at 0°, 35°W, where moored current meter measurements of a 60-day interval were recorded at 155- and 405-m depths below a surface float (Stalcup and Metcalf 1966). The success at the equator was in contrast to the low success rate of surface moorings in the extratropical North Atlantic Ocean. Fofonoff (1968) had stated that WHOI Buoy Group "returns from surface float moorings [in 1965/67] ... are disappointingly low." With additional experience, successes became more numerous. Panicker et al. (1974) noted that WHOI Buoy Group's recovery of surface moorings were successful 54% of the time compared to about 90% for subsurface moorings.

In 1971, the WHOI Buoy Group deployed four surface moorings on and near the equator at 150°W, from which the longest record obtained in the EUC was 25 days at 100-m depth at 1°N, 150°W (Taft et al. 1974). At the equator where the EUC core speed would have been higher, the task was more challenging, as evidenced by the loss of the 0°, 150°W mooring only 2 days after deployment (Taft et al. 1974). During the 1974 Global Atmospheric Research Program (GARP) Atlantic Tropical Experiment (GATE) A-Scale Equatorial Experiment (Philander and Düing 1980), the Union of Soviet Socialist Republics (USSR) deployed slack-line surface moorings with current meters within the EUC (Weisberg 1980). The 82-day time series recorded by the USSR at 0° and 1°S along 10°W had four surface mooring deployments and recoveries at each location with 30 days being the maximum length of a single deployment at each site (GATE 1975). No taut-line surface moorings were deployed at or near the equator in GATE.

A deep-water taut-line surface mooring provides a better environment than a slack-line mooring for measuring the current, but is more challenging because of increased tension on the surface float. In a taut-line mooring, the untensioned length of mooring materials is less than the water depth, whereas in a slack-line mooring it is greater. Consequently, the area over which the surface float roams, called the watch circle, in response to wind and current is smaller for a taut-line mooring. A taut-line surface mooring strives to maintain a current meter aligned along the vertical with minimum horizontal and vertical displacements. In an ideal configuration in the absence of current and wind, the taut mooring line and instruments would be aligned vertically above the anchor. The speed and direction sensors are calibrated to measure the horizontal flow impinging perpendicularly on the vertically aligned instrument; a tilted speed sensor aligned at an angle from the vertical will record a lower speed than the true current. If the instrument is moving relative to Earth, it records the ocean current minus its own velocity. A vertical displacement of an instrument, in a region like the EUC with its large vertical current shear and temperature gradient, causes variations in the measured current and temperature related to the displacement; if the displacement is not known, the current and temperature measurements are assigned to an incorrect depth.

Along with their advantages, taut-line moorings present difficulties. For strong currents in the EUC a tautly moored surface float could be pulled beneath the sea surface if the anchor has adequate holding power. Otherwise, for strong currents the entire mooring would move, perhaps to a deeper site, which, with the anchor as a weight beneath the surface float, could cause the mooring line to break or, more likely, submerge the surface float. The toroidal surface float used in all our moorings rapidly loses buoyancy with depth of submergence (Richardson et al. 1963). The taut-line surface mooring consisted of wire cable and nylon line (see the “EQUA-1” section). If the mooring moves to a shallower site, the nylon rope would stretch less than before, producing a smaller downward force on the surface float, leading to a larger watch circle. A deep-water taut-line surface mooring represents a delicate balance of drag, gravitational, and tension forces; the drag force is related to the square of the ocean current.

The Pacific EUC is a particularly difficult region for taut-line surface moorings compared to the Atlantic. The core speed of the EUC in the Atlantic is about half as large as in the Pacific, i.e., 0.75 versus 1.5 m s⁻¹. The strength of the surface westward flow of the South Equatorial Current at the equator in the Atlantic is about half that in the Pacific. Thus, the drag force on a taut-line surface mooring on the equator is much greater in the Pacific.

The first section described the scientific and technological motivations for EUC measurements, the second section illustrates the preparation and historical context for the innovative EQUA Project, the third and fourth sections describe the novel EQUA-1 and EQUA-2 observations, and the fifth section presents concluding remarks on the legacy of the EQUA Project.

EQUA Project preparation

The origins of the EQUA Project can be traced back to my graduate student training when I was a research assistant for Professor Henry Stommel during September 1964–January 1969 at the Massachusetts Institute of Technology (MIT). One day in February 1965 Stommel suggested that I search for internal gravity waves in Massachusetts Bay, which presumably would form when the flood tidal current flowed over Stellwagen Bank. Discovering regularly occurring short-period internal gravity waves (Halpern 1971a,b) provided lessons on how to design and implement all facets of a multiyear oceanographic experiment (Halpern 1969), including chartering a ship and aircraft; purchasing a wide variety of items for a four-element array of surface buoy moorings instrumented with thermistor chains and current meters; analyzing time series observations and model results; preparing a proposal and budget; and hiring staff.

In 1969, I joined the Environmental Science Services Administration Pacific Oceanographic Laboratory (POL) [later named National Oceanic and Atmospheric Administration (NOAA) Pacific Marine Environmental Laboratory (PMEL)] in Seattle, Washington. The POL had about 20 people working on marine geology and geophysics, physical oceanography of Puget Sound, and other activities. The next year the National Science Foundation (NSF) International Decade of Ocean Exploration (IDOE) was established. I received IDOE funds to study wind-generated mixed layer deepening generated by the vertical shear of inertial oscillations trapped in the mixed layer. Building on experiences gained at MIT, I purchased equipment, hired staff, and established the Ocean–Atmosphere Response Studies (OARS) Group (Halpern 1974a). In 1971, the OARS Group used, for the first time, a class-I oceanographic research vessel (NOAA Ship *Oceanographer*) to deploy a taut-line surface mooring instrumented with a wind recorder, four current meters (depths of 8, 16, 26, and 46 m) and a thermistor chain in the northeast Pacific, where the depth is 2.7 km (Halpern 1974b). The deployment procedure followed the buoy-first, anchor-last method. For recovery, a coded acoustic signal was transmitted from the ship to an in-line instrument, named acoustic release, placed above the anchor. The acoustic signal triggered a jolt of electricity to pass through a fusible wire, causing it to melt and open a lever which released the mooring line above the anchor. The anchor remained on the ocean bottom. The backup floatation system

of about 40 hollow 0.4-m glass spheres, which were encased in plastic and located above the acoustic release, rises to the surface (R. Heinmiller 1970/71, personal communications; Heinmiller 1976). The backup recovery system would be used if the surface float was missing because it was stolen or sank to the bottom of the ocean.

During the next 5 years, the OARS Group gained further experience (and I gained additional confidence) with surface moorings instrumented for wind and upper-ocean current and temperature measurements. The IDOE Coastal Upwelling Ecosystems Analysis (CUEA) program supported these types of measurements in coastal- and deep-water regions off Oregon in 1972 (Halpern et al. 1974) and 1973 (Halpern 1976a,b, 1974c; Reed and Halpern 1975; Halpern and Pillsbury 1976; Hayes and Halpern 1976; Bryden et al. 1980), off Spanish Sahara (now called Western Sahara and administered by Morocco) in 1974 (Halpern 1977; Halpern and Reed 1976; Halpern et al. 1977; Fiúza and Halpern 1982), and off Peru in 1977 (Brink et al. 1980). In the 1974 GATE C-Scale Experiment (Halpern 1980a; Zenk et al. 1980), I was on the U.K. RRS *Discovery*, where Leach et al. (1985) used ribbon fairings to reduce hydrodynamic drag and vibration on a cable towing a salinity–temperature–depth recorder at a speed of approximately 4 m s^{-1} ; I recall this as the “aha” moment to consider an instrumented taut-line surface mooring with fairings in the Pacific EUC. In 1975 and 1976, the OARS Group participated in the NOAA Deep Ocean Mining Environmental Studies (DOMES) program (Halpern 1979; Hayes 1979). The third and final DOMES deployment at $8^{\circ}27'\text{N}$, $150^{\circ}45'\text{W}$ (Site A) in the North Equatorial Countercurrent in August 1976 provided the opportunity to establish EQUA-1 with equipment from the GATE program.

The current-, temperature-, and wind-measuring instruments in the EQUA Project had been used in CUEA, GATE, and DOMES. The AMF (or EG&G) model 610 vector-averaging current meter (VACM) (McCullough 1975; Tupper 1987), when developed in about 1971 at WHOI from a predecessor instrument called Geodyne 850 current meter, was the first current meter with internal capability for rapid determination of east–west and north–south current components from speed and direction measurements to adequately filter surface wave motion. The VACM contained an omnidirectional cylindrical Savonius rotor (Richardson et al. 1963) rotating about the vertical axis in response to water motion, a direction vane, a magnetic compass, and a thermistor; it measured speed and temperature continuously and direction in a nearly continuous manner. The rotation of the S-shaped rotor was caused by the drag difference between the advancing blade and returning blade. Magnets were equally spaced around the outer perimeter of the top plate of the rotor. As the rotor turned, a magneto-diode switch above it closed each time a magnet passed. Switch closures were counted, giving the rotation rate. At each eighth of a rotor revolution, vane and compass directions were measured, converted to Cartesian speeds, and added to previous values of east and north vectors. East and north vectors were recorded at specified intervals, which was 15 min in the EQUA Project. A thermistor, in which electrical resistance varied with temperature, was located on the end plate of the instrument case. For wind measurements, the OARS Group imitated a practice developed at WHOI and constructed the vector-averaging wind recorder (VAWR) by turning a VACM upside-down and replacing the Savonius rotor and direction vane with a balanced vane and a three-unshrouded-hemispherical-cup wind speed transmitter. For subsurface temperature measurements at a variety of depths the OARS Group constructed a multiconductor thermistor cable connected to a datalogger. Although this approach left all temperature measurements subject to a single point of failure, it was chosen over the alternative—independent temperature recorders on the mooring line—because it reduced the drag on the line.

EQUA-1

The *Oceanographer* deployed the DOMES Site A surface mooring and then transited to 0° , 150°W where it deployed the instrumented taut-line surface mooring EQUA-1 with a

VAWR and two VACMs. The operational plan was to remain close to the surface buoy for the approximate 3-week deployment; this was the best practice used in the GATE A-Scale Equatorial Experiment (GATE 1975; Bubnov et al. 1980). The plan was disrupted about 2 weeks after the mooring was installed when a crew member became seriously ill and the ship had to return to Honolulu. I received a ship-to-shore telephone call from Eugene Duley, OARS Group Mechanical Engineering Technician, about what to do with EQUA-1, i.e., recover the mooring or leave it on station. After a momentary hesitation, I decided to leave the mooring unattended until the ship would return from Honolulu. The purpose of the experiment was to record upper-ocean currents for at least 3 weeks. In addition, I thought the opportunity would not likely appear again. For several weeks I subsumed the fear of the consequences of losing a large amount of equipment. However, I silently welcomed the unexpected opportunity to extend the duration of the measurements. The mooring was recovered after 36 days, and just in time because one of the bolts holding the frame with the wind recorder was coming apart. EQUA-1 had recorded the longest continuous time series measurements of surface wind and EUC velocity and temperature at the equator. It was a gratifying success and an outstanding triumph for the OARS Group. I immediately began planning follow-on measurements of longer duration with additional instruments to demonstrate the reliability of the new mooring design.

Figure 1 shows a photograph of the EQUA-1 surface float during deployment on 5 August 1976 at 0°, 150°W. The fiberglass toroidal surface float had a 2.44-m outer diameter and a 0.91-m diameter of the hole. The interior was compacted foam, and the net displacement was 2,722 kg (Richardson et al. 1963). The surface float had a VAWR for wind speed and direction measurements at 3-m height, a datalogger to record temperature measurements at 1.8 m below the sea surface, a navigation light, and a NASA *Nimbus-6* satellite random access measurement system (RAMS) buoy transmit terminal (BTT) that yielded buoy locations at approximately 12-h intervals. Buoy locations were obtained by telephone from the NASA Goddard Space Flight Center.

The upper 1 km of the mooring had 1.11-cm-diameter wire cable to resist shark bites. The wire was precut in segments to insert 2-m-long vector-averaging current meters and other instruments at specific depths. The remainder of the distance to 50 m above the bottom had 3 km of 1.91-cm-diameter eight-strand plaited nylon rope. The bottom 50 m had chain above the anchor and wire with a backup recovery floatation system and acoustic release. The combined untensioned length of wire and nylon was about 90% of the 4.45-km distance between the sea surface and ocean bottom. All OARS surface moorings had larger diameter (i.e., stronger) wire cable and nylon line than those used by the WHOI Buoy Group (Heinmiller 1975). The approximate 10% nylon-rope stretch produced about 680 kg downward force on the surface float to minimize the watch circle. A multiconductor jacketed cable with 14 thermistors at various depths between 60 and 300 m was tied to the wire cable; temperature data were recorded in a datalogger inserted between wire cable segments. The effective diameter of the combined wire and

Fig. 1. Photograph of the EQUA-1 surface float on 5 Aug 1976 during deployment from the NOAA Ship *Oceanographer*. On recovery, barnacles coated the underside of the toroidal float. The stars on the surface float acknowledged the U.S. bicentennial. Image extracted from PMEL (1977, p. 29).

thermistor chain was about 2 cm. The current drag, which is proportional to the product of the square of the current speed, the cross-sectional area, and a drag coefficient, was reduced with a new technique. EQUA-1 was the first OARS taut-line mooring to use plastic fairings, each about 30 cm long $\times$ 5 cm wide, which encased both the wire cable and jacketed thermistor cable in the upper 300 m. The fairing reduced the drag coefficient. Fairings were also used on the wire cable between the surface float and current meter at 50-m depth. Each clip-on fairing was inserted manually. During deployment, the tedious work to pry open the fairings was painful and usually produced finger cuts and bruises.

Conventional wisdom in 1976 indicated that the interannual El Niño and La Niña phenomenon and the annual cycle were expected to produce variations of flow within the EUC. The amplitudes of these fluctuations were unknown at the time of the EQUA Project. The high currents of a Kelvin wave surge in the EUC were yet to be discovered. The EQUA-1 August–September 1976 time interval coincided with the onset phase of a very weak El Niño event (https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php).

EQUA-1 current speeds were less than those recorded by Knauss (1960) in April 1958. At 50 m, the average and maximum eastward speeds were 0.35 and 0.50 m s^{-1} , respectively (Milburn 1979). At 100 m, where the eastward flow direction was quite steady throughout the 36-day deployment, the average and maximum eastward currents were 0.85 and 1.0 m s^{-1} , respectively (Milburn 1979). EQUA-1 did not record unexpected observations and no lessons were learned to alter the design of EQUA-2.

EQUA-1 was the first expedition the OARS Group provided ship time for complementary measurements to improve interpretation of moored measurements. On 12 and 15 August 1976, a new vector measuring current meter (VMCM) (Weller and Davis 1980) was lowered from the *Oceanographer* located about 5 km from EQUA-1. VMCM speeds (Weller 1978), which were comparable with EQUA-1 data at 50 and 100 m, indicated the core speed and its depth were 1 m s^{-1} and 120 m, respectively. These observations were consistent with the design criteria for the mooring in which 1.5 m s^{-1} was the expected maximum core speed (Knauss 1960, 1966). Capturing the core speed and thickness of the EUC with VACMs would require instruments at additional depths. Five VACMs were used in EQUA-2. The VMCM, which became the gold standard for fixed-level current measurements from surface moorings, subsequently demonstrated the high quality of VACM measurements (Halpern 1987a).

EQUA-2

To confirm the reliability of the EQUA-1 technique for longer period measurements of surface wind and upper-ocean current and temperature, I established a follow-on surface mooring at 0°, 125°W with equipment from the GATE and DOMES programs. The essential design of the EQUA-2 mooring was unchanged from that of EQUA-1, except for additional current meters at 10-, 150- and 250-m depths to capture the westward flow in the South Equatorial Current above the EUC, EUC core speed, and the flow at the bottom of the EUC. The EQUA-2 mooring was deployed 7 months after EQUA-1 had been recovered. Swift demonstration of the technique was important because planning had begun for the NOAA Equatorial Pacific Ocean Climate Studies (EPOCS) and the National Science Foundation North Pacific (NORPAX) Programs, which proved to be sources of external funds for a variety of scientific studies of the EUC beginning in January 1979. In spring of 1977 when the *Oceanographer* sailed to the tropical northeast Pacific for geological and geophysical studies, I used the occasion to establish EQUA-2 at 0°, 125°W in water 4.5 km deep. At the time I could frequently access *Oceanographer* ship time. Similar to EQUA-1, EQUA-2 was supported by funds within the OARS Group.

When the *Oceanographer* began its journey from its home port in Seattle to recover EQUA-2, the *Nimbus-6* RAMS BTT locations showed that the mooring had moved 33 km from the deployment site at 0°0.1'N, 124°58.2'W to 0°0.6'S, 124°40.2'W during 13–19 April. The OARS

Group embraced state-of-the-art instruments and methods and, therefore, had volunteered in the demonstration of a new satellite positioning system. The satellite determination of the surface float's new location is credited with the recovery of EQUA-2. Had EQUA-2 not been recovered, it is questionable whether I would have continued equatorial moored measurements, which became, in 1979, a central component of the EPOCS Program (EPOCS 1979, 1982). For future OARS taut-line surface moorings the approximate 2,000-kg anchor system was strengthened with two additional 350-kg railroad wheels and a Danforth anchor for extra holding power in the soft bottom.

The surface float had instruments recording vector wind components at 3-m height and subsurface temperature at 1.8 m. Depths of VACMs were 10, 50, 100, 150, and 200 m. The VACM at 10 m and the 17-element thermistor chain did not operate. In preparing this paper, digital records of the measurements no longer existed. Paper copies of diagrams of time series, histograms, progressive vector displacements, and spectra, which had been computer generated with a package of graphical programs named VECPLOT (Holbrook and Halpern 1975), were found for the wind and 50- and 100-m current measurements. In addition, diagrams of 3-day-averaged east–west current component at 50, 100, 150, and 200 m and eastward transport per unit meridional width were accessed from a 1977 PMEL Annual Report (PMEL 1977).

At 50 m, 1-h-averaged eastward speeds were slightly higher than 2.0 m s^{-1} on 14, 15, 18, 19, and 20 April. At 100 m on those days, the eastward speed reached 1.8 m s^{-1} . These speeds were unexpectedly high compared to previous observations, e.g., Knauss (1960, 1966) and EQUA-1. The frequency of occurrence of eastward currents greater than 2 m s^{-1} will be examined in the “Currents” section. The enormous speeds dragged the mooring 33 km eastward along the equator, which represented an artificial westward speed of about 0.05 m s^{-1} . A tension recorder mounted below the buoy bridle measured mooring-line downward tensions of about 1,500 kg from 4 to 18 April with a 1,700-kg burst on 19 April (Halpern et al. 1984); after 20 April, the mooring-line tension averaged about 1,200 kg, which was the expected tension to keep the toroidal float about 50% submerged to prevent tipping. The 4,495-m water depth at the new position was 165-m shallower than at the deployment site. The shoaling bottom toward the east was fortuitous.

The EQUA-2 time interval of 4 April–11 July 1977 coincided with neutral conditions, i.e., the time interval did not represent an El Niño or La Niña event (https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php).

Wind. At the time of EQUA-2, the Wyrтки and Meyers (1976) climatological-mean monthly wind distributions over 2° latitude $\times$ 10° longitude regions were available; however, knowledge of variations of monthly and submonthly wind fields was nonexistent at 0° , 125°W and elsewhere along most of the equator. The EQUA-2 site was remote from a shipping route where surface marine observations would have been recorded. No adequate global numerical weather prediction (NWP) data product existed; one of the objectives of the 1979/80 Global Weather Experiment was development of global NWP analyses. The NASA *Seasat* satellite, which carried the first instrument to measure ocean vector winds, was launched on 27 June 1978, almost a year after EQUA-2 was recovered.

The 3-m height wind was fairly steady in speed and direction and represented the southeasterly trade wind, primarily toward the west with a small northward component (Fig. 2a). The mean and maximum 30-min averaged scalar speeds were 4.4 and 9.1 m s^{-1} , respectively, indicating, as in EQUA-1, the absence of storms. The westward and northward wind speed components increased from April to July 1977 (Fig. 2a), consistent with subsequent observations of the annual cycle (Halpern 1988).

Spectral energy levels (not shown) of the 30-min-averaged east–west and north–south components were similar and also similar to those recorded over November 1983–October

1984 (Halpern 1988). No spectral peaks appeared with magnitudes significant with 95% confidence.

Vertical motions of the surface-following float were expected to degrade the accuracy of EQUA wind data. In 1981, measurements recorded from a VAWR mounted on a surface float closely matched, to within 3.5%, those recorded with a VAWR mounted on a specialized spar buoy, which had negligible vertical motion (Halpern 1987c).

Currents. EQUA-2 currents were much stronger than those observed in EQUA-1, in part because EQUA-2 was deployed in April–July, at the maximum of the EUC annual cycle while EQUA-1, in August–September, was at the minimum (Halpern 1987b). At 50-m depth, eastward speeds above 2 m s^{-1} were a surprise. To estimate the likelihood of currents greater than 2 m s^{-1} , I analyzed current measurements recorded with the acoustic Doppler current profiler (ADCP) (https://en.wikipedia.org/wiki/Acoustic_Doppler_current_profiler) and archived at the Global Tropical Moored Buoy Array (GT MBA) Project (www.pmel.noaa.gov/gtmmba/pmel-theme/pacific-ocean-tao). ADCP measurements averaged over 5-m-thick layers and 1-h intervals were examined at 0° , 140°W and 0° , 110°W , which were equidistant locations closest to the EQUA-2 site because no ADCP data were recorded at 0° , 125°W . I arbitrarily chose record lengths at 140° and 110°W of 1 January 1997 to 31 December 2010 and 1 January 1996 to 31 December 2005, respectively, because they included the very strong El Niño event of May 1997 to June 1998 (https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php) and the multiyear data were fairly continuous. At 140°W , eastward speeds greater than 2 m s^{-1} occurred at 60–150-m depths; at 110°W , the depth range was 45–120 m. At 140°W , currents greater than 2 m s^{-1} were found 0.15% of the time at the 103.5-m mean depth of the EUC core speed. Similarly, at 110°W where the mean depth of the core speed was 77.5 m, currents greater than 2 m s^{-1} appeared about 0.18% of the time. Thus, currents greater than 2 m s^{-1} rarely happened and were extreme events. However, these sporadic events, when they happened, persisted for many hours concurrently over a substantial depth interval to significantly increase the drag force on the mooring line. At 140°W , eastward currents greater than 2 m s^{-1} were found 90% of the time during 4–6 April 1997 in the depth interval 97.5–107.5 m, where the depth-averaged speed was 2.1 m s^{-1} . Similarly, at 110°W , extreme currents occurred 99.6% of the time during

Fig. 2. EQUA-2 progressive vector displacement (PVD) diagrams of (a) wind measurements at 3-m height and (b) current measurements at 50- and 100-m depths. Note the different horizontal scales in (a) and (b). The PVD diagram is constructed by vector addition of 30-min-averaged displacements. An open circle is placed at the start of each day, and a larger distance between open circles indicates higher speed. The beginning of the PVD is illustrated with a plus sign at 0000 UTC 5 Apr 1977; the record length was nearly 99 days. The date is shown at 5-day intervals. The PVD curve represents the vector-averaged daily distance that the wind or current would have traveled at the buoy. The quasi-uniform daily direction over the 99 days indicates high steadiness. Since the data were measured at a single location, the PVD does not represent the path of a drifting object. This type of plot accentuates low-frequency events. Redrawn from VEC PLOT paper display.

14–18 April 1997 when the average current was 2.3 m s^{-1} in the depth interval 72.5–82.5 m. The maximum eastward current was 2.52 m s^{-1} (4.9 kt), which was recorded at 1200 UTC 16 April 1997 at 80 m at 110°W . At both sites, ADCP currents greater than 2 m s^{-1} were more abundant in April compared to other months. When EQUA-2 was deployed in April 1977, it was unforeseen that eastward speeds greater than 2 m s^{-1} would occur.

LOW-FREQUENCY VARIATIONS. At 50 and 100 m, the current direction was virtually constant toward the east throughout the measurement period; direction constancy or steadiness, which was defined by the mean vector current divided by the mean scalar speed (Singer 1967), was equal to about 0.99. The average daily current directions were primarily eastward with a small component toward the south (Fig. 2b). The directions of the wind and 50-m current were consistent with Philander's (1973) and Gill's (1975) ageostrophic model of the EUC, i.e., for a wind blowing from the southeast (Fig. 2a), the flow direction within the EUC would have an upwind component toward the southeast (Fig. 2b).

Progressive vector diagrams (Fig. 2b) showed a slight northward direction from 20 to 30 May and then southward from 7 to 14 June at 50 m and, to a lesser extent, at 100 m. The meridional current time series at 50 m (not shown) had several fluctuations with about 15–25-day time scale and 0.6 m s^{-1} crest-to-trough magnitude. The temporal pattern of the meridional current component was suggestive of oscillations with 20-day period, which Halpern et al. (1988) subsequently quantified as westward-propagating, equatorially trapped Rossby–gravity waves with maximum amplitude at 125°W compared to measurements at 152° , 140° , and 110°W .

HIGH-FREQUENCY VARIATIONS. Energy density spectra of the 50- and 100-m east–west and north–south current components (not shown) revealed 95% statistically significant peaks at the diurnal and semidiurnal periods. The semidiurnal period amplitude was about 25% larger than the diurnal-period amplitude.

EQUA-2 measurements of tidal currents generated a question about the influence of internal tidal vertical displacements on estimates of dynamic height computed from measurements of solitary vertical profiles of salinity and temperature. This question was of particular interest at the start of EPOCS in 1979. At 0° , 110°W , the average standard deviation of hourly measurements of dynamic height, 1.2 dynamic cm (Halpern 1980b), indicated that aliasing by tidal internal waves was negligible in determining horizontal gradients of steric sea surface height over distances more than 100 km.

KELVIN WAVE. Time series of 3-day-averaged eastward currents at 50, 100, 150, and 200 m revealed a surge on about 10–20 April (Fig. 3a), when the maximum speed at 50 m was 0.5 m s^{-1} higher than at 100 m. On 6 April, slightly before the start of the surge, the 50- and 100-m speeds were both 1.5 m s^{-1} . Eastward speeds at 50 m were higher than at 100 m from 8 April to about 30 May (Fig. 3a), which was likely caused by the annual upward migration of the EUC. Subsequent OARS moored measurements revealed that the depth of the EUC core speed is shallower in March–May than at other times of the year (Halpern 1987b; McPhaden and Taft 1988).

At any given longitude, the eastward transport per unit meridional width (ETMW) is equal to $\int \langle u(z) \rangle dz$, where $\langle u(z) \rangle$ is the time-mean eastward current [i.e., $\langle u(z) \rangle$ was greater than 0 m s^{-1}] in the depth layer dz . Figure 3b shows EQUA-2 ETMW time series estimated with 3-day-averaged currents at 50, 100, 150 and 200 m. At the time of the EQUA-2 deployment, the ETMW was considerably larger than the record-length mean value of about $147 \text{ m}^2 \text{ s}^{-1}$. A few days after deployment, the VACMs captured an ETMW surge from 9 to 23 April, reaching a maximum value of $190 \text{ m}^2 \text{ s}^{-1}$ on 18 April. From 23 April to 30 May and from 30 May to 9 July, ETMWs were relatively constant at about 147 and $130 \text{ m}^2 \text{ s}^{-1}$, respectively. The frequency of occurrence of ETMW greater than $190 \text{ m}^2 \text{ s}^{-1}$ was estimated with GTMBA ADCP currents. ETMWs

computed with 3-day averaged ADCP data from 50 to 200 m at 140°W and 45–195 m at 110°W (because insufficient data were recorded at 200 m) had exceeded $190 \text{ m}^2 \text{ s}^{-1}$ during 3.3% and 0.4%, respectively, of the time. At both sites, most occurrences happened in April 1977. Also, April, when EQUA-2 was deployed, was the most popular month for ETMWs greater than $190 \text{ m}^2 \text{ s}^{-1}$. A multiday surge in the depth-averaged EUC speed was unknown in 1977.

Because EQUA-2 measurements were at a single longitude, it was not possible to determine whether the ETMW surge represented an eastward-propagating Kelvin wave. However, the EQUA-2 ETMW surge in April 1977

had very similar features to the eastward-propagating equatorially trapped first baroclinic mode Kelvin wave that Knox and Halpern (1982) identified in current measurements at 152° and 110°W in April 1980. They had also shown a strong relationship between ETMW at the equator and total EUC transport measured with moorings on the equator and 72 km north and south of the equator. Using the Knox and Halpern (1982) tight linear regression, the maximum EUC total transport surge inferred from EQUA-2 measurements was about 38 Sv ($1 \text{ Sv} \equiv 10^6 \text{ m}^3 \text{ s}^{-1}$) or 39.5 Sv had the mooring not moved.

Dr. Eric Firing (2021, personal communication) found additional evidence that the EQUA-2 ETMW surge represented Kelvin wave dynamics. He informed me that Christmas Island (1°52'N, 157°24'W) (also known as Kiritimati Island) sea level data had a 4-week pulse with a 15-cm peak magnitude centered on 6 April 1977. If the sea level pulse was representative of the EQUA-2 current pulse, then the eastward propagation speed of the pulse was 3.4 m s^{-1} . The value was about 13% higher than that observed by Knox and Halpern (1982) with VACM measurements at 152° and 110°W and that estimated by Eriksen et al. (1983) from measurements of sea level at Canton (2°49'S, 173°43'W) and North Isabella (0°03'S, 91°28'W) Islands.

The early-1980s observations of downwelling first-mode baroclinic Kelvin waves enhanced the hypothesis of a Kelvin wave or succession of Kelvin waves promoting the onset of an El Niño event. The oceanographic community's attention then focused on the enigma of how the equatorial ocean would return to neutral and/or La Niña conditions before the onset of another El Niño event. Jin (1997) hypothesized that a reflection of the eastward-propagating downwelling Kelvin wave at South America would generate a westward-propagating Rossby wave to uplift the thermocline. In a novel concept developed in the last 10–15 years to explain the diversity of El Niño events, wind-generated downwelling Kelvin waves generated at various times of the year in the west equatorial Pacific would interact with ambient conditions, e.g., thermocline depth, in the central and eastern Pacific, which were changing because of global warming (Capotondi et al. 2020).

Concluding remarks

I often wonder whether the EQUA Project represented an example of the quotation, “Luck is what happens when preparation meets opportunity,” which has been attributed to the Roman

Fig. 3. (a) The 3-day vector-averaged values of east-west current components at 50, 100, 150, and 200 depths at 0°, 125°W. Redrawn from Fig. 3 in Halpern et al. (1984). (b) The 3-day values of the eastward transport per unit meridional width (defined in the “High-frequency variations” section). The accuracy of 3-day vector-averaged current measurements was about 0.01 m s^{-1} when compared with a higher-performance current meter (Halpern 1987a). Redrawn from Fig. 12 in PMEL (1977).

philosopher Seneca the Younger (4 BC–AD 65). The transformative EQUA-1 instrumented taut-line surface mooring design and implementation method was the product of 10 years of preparation. EQUA-2 confirmed the success of the EQUA-1 and produced unique datasets.

The EQUA Project developed a method to record long-period measurements of surface wind and upper-ocean current and temperature in the EUC. Today, the technique is essentially unchanged, including the diameters of the wire and nylon components of the mooring line. The upper-ocean wire length is 700 m (www.pmel.noaa.gov/gtmmba/moorings) compared to 1,000 m that I used. In addition to fixed-level current meters beneath taut-line surface floats, several equatorial sites since about 1995 have an upward-looking ADCP on a subsurface mooring with a pressure sensor at the buoy to record its vertical displacement as the mooring leans in the current (www.pmel.noaa.gov/gtmmba/sites/default/files/thumbnails/image/nxcurl.gif).

The quality of EQUA observations was subsequently evaluated in specialized experiments for wind (Halpern 1987c) and current (Halpern et al. 1981; Halpern 1987a). The robustness of the EQUA mooring design was proven in 1979–85 when the OARS Group lost only one mooring in a total of 56 and data return was greater than 90% (Halpern 1987b; Halpern et al. 1988). Other important EQUA Project discoveries included the first suggestion of a first mode baroclinic Kelvin wave in EUC transport, which was clarified only later, after Knox and Halpern (1982) obtained observations at two longitudes showing the zonal propagation of the phenomenon; the potential applicability of Philander's (1973) and Gill's (1975) ageostrophic model of the EUC; and first observations of hourly, daily, weekly, and monthly variations of surface wind and EUC velocities, which were necessary ingredients for planning the EPOCS and NORPAX oceanographic field campaigns.

In another far-reaching technical achievement, the EQUA Project's follow-on observations in 1982/83 advanced the development of ocean general circulation model (OGCM) simulations of upper-ocean zonal velocity and temperature fields in the EUC by confirming the first-ever OGCM replication of an El Niño event (Philander and Seigel 1985). The model–observation agreement promoted sustained current and temperature measurements in the EUC as valuable reference datasets for continued development of ocean-climate models (Tseng et al. 2016; Griffies et al. 2017).

The failure by the oceanographic and meteorological communities to detect in real time the onset of the 1982 El Niño event caused a sea change in studies of tropical Pacific ocean–atmosphere interactions. Forecasts of onset, maintenance, and dissipation of an El Niño event became a scientific priority because of important socioeconomic impacts. Consequently, real-time satellite transmission of moored measurements along the equator also became a priority for empirical forecasts and forecast-model initialization. Beginning in April 1983, vector wind components and temperature measurements at 0°, 108°W were transmitted in real time to the OARS Group via the Argos data collection and location system (an advanced and more capable system than RAMS) on board NOAA polar-orbiting satellites to usher in real-time monitoring of El Niño and La Niña oceanic conditions from surface moorings.

A long-lasting legacy of the EQUA Project was the knowledge that surface moorings could be deployed to monitor coupled upper-ocean and atmosphere variations in the equatorial Pacific for improved forecasting of El Niño and La Niña events. In 1984, my PMEL colleague, Dr. Stanley Hayes, proposed to EPOCS to deploy an array of slack-line surface moorings in the equatorial zone for real-time measurements of wind and subsurface temperature, which became the Tropical Ocean and Global Atmosphere (TOGA) Tropical Ocean–Atmosphere (TAO) Array (Hayes et al. 1991). Moored measurements of surface vector wind and subsurface temperature in the equatorial zone were a high priority for improved forecasting of El Niño and La Niña events (National Academies of Science, Engineering, and Medicine 1994; Halpern 1996). The importance of continuity for these measurements in the equatorial Pacific

is evident in the ongoing review of the sustainability of the TOGA-TAO Array, including its capability to support additional scientific themes (Smith et al. 2019).

The full scale of the impact of the EQUA Project can be evaluated only in hindsight. Davis et al. (2019), in their review of a century of progress of ocean observing systems, considered the EQUA Project to have initiated a new era of long-term taut-line surface moorings, including at extratropical ocean sites. The EQUA Project became the foundation for sustained measurements of upper-ocean current and temperature, surface wind and other variables on and near the equator in numerous field campaigns, including EPOCS (1979, 1982), NORPAX Hawaii-to-Tahiti Shuttle (Wyrski et al. 1981), Tropic Heat (Eriksen 1985), Seasonal Equatorial Atlantic Response/Francais Ocean-Climat en Atlantique Equatorial (Weisberg and Colin 1986), TOGA (Halpern 1996, McPhaden et al. 1998), TOGA TAO Array (Hayes et al. 1991), Prediction and Research Moored Array in the Tropical Atlantic (Bourlès et al. 2019), Research Moored Array for African–Asian–Australian Monsoon Analysis and Prediction (McPhaden et al. 2009), and the proposed Tropical Pacific Observing System (Smith et al. 2019).

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Data availability statement. The original digital datasets have been lost. The data described above were extracted from a 1977 annual report (source described in references), 1984 conference proceedings (source described in references), and paper diagrams and tables.

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