Satellites Reveal the Influence of Equatorial Currents and Tropical Instability Waves on the Drift of the Kon-Tiki in the Pacific

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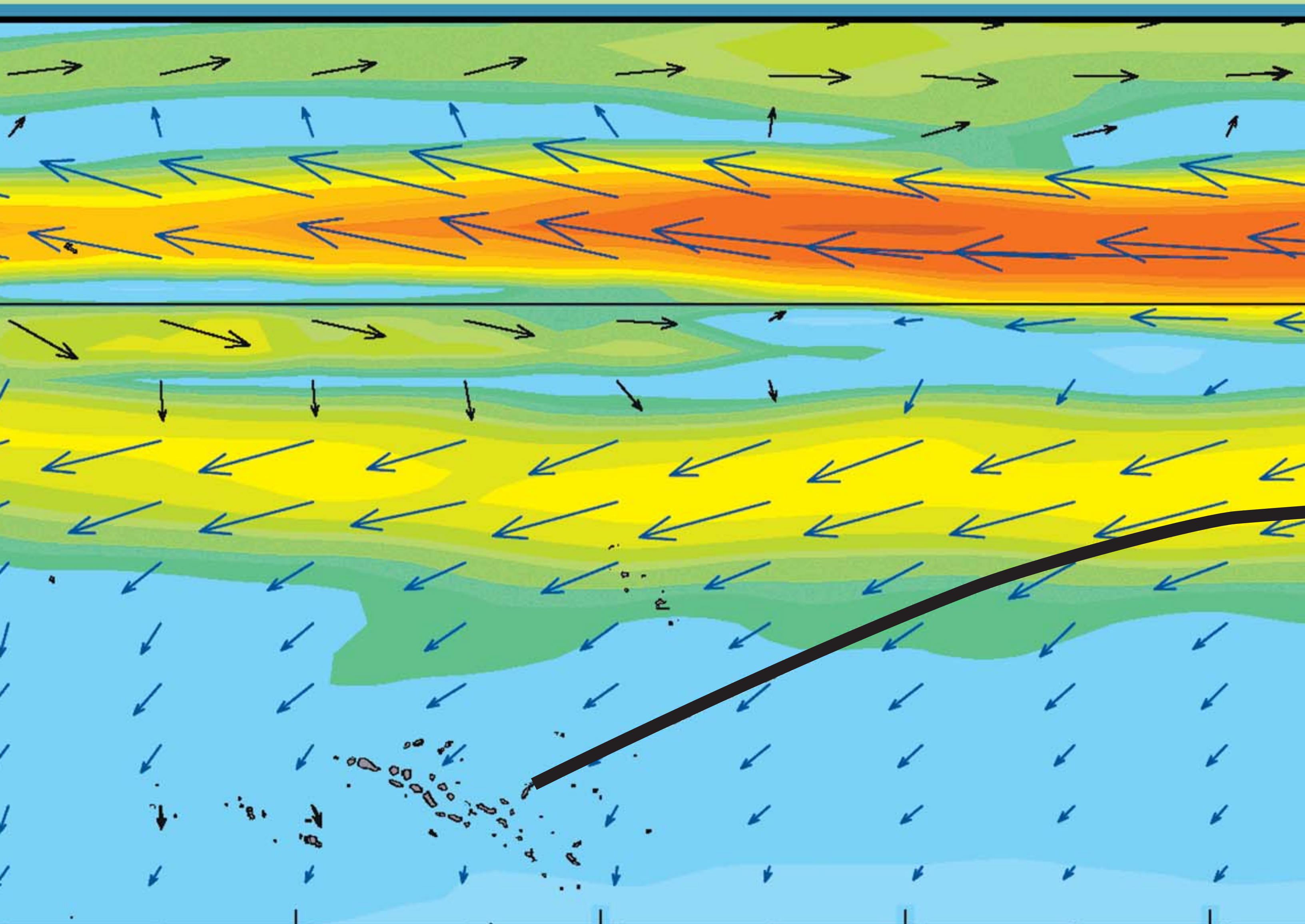
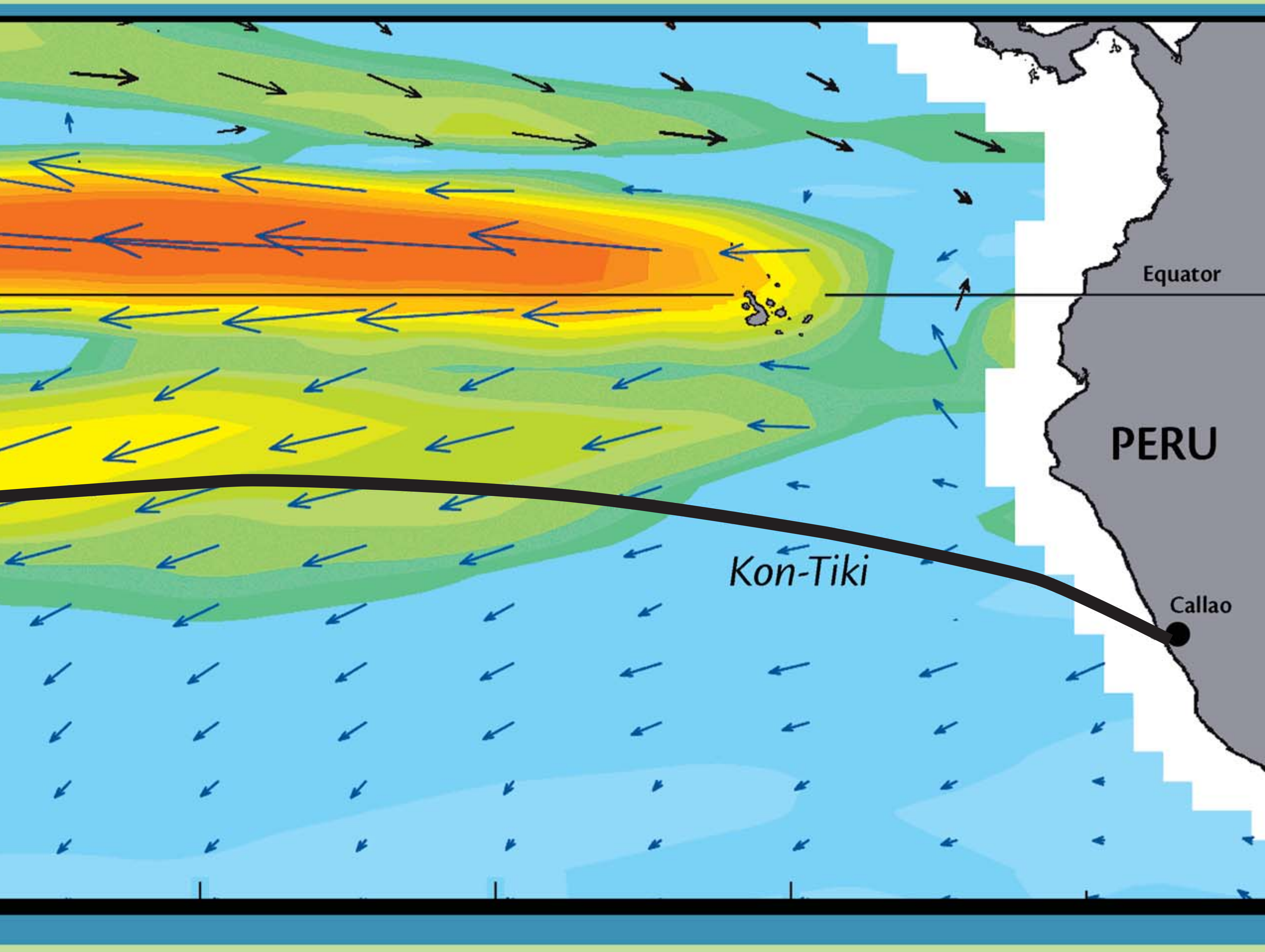


VOYAGE OF THE *KON-TIKI*

A raft drifting on the ocean is at the mercy of the elements. When a sailor describes this experience, one begins to understand the meaning of "*in situ*," of being in touch with the water. The senses feel the wind, waves, rain, humidity, and temperature and recognize the change in the patterns of swell, clouds, flying fish, and sea birds. Thor Heyerdahl (1950) described these events vividly as he and five companions crossed 7,700 kilometers of the equatorial Pacific on *Kon-Tiki* in 1947. Detractors predicted that they would be lost at sea. It is of interest to investigate modern, *in situ*, and satellite ocean measurements to determine why and how the voyage succeeded.

The *Kon-Tiki* was constructed from wooden balsa logs in an attempt to duplicate Peruvian rafts described by early Spanish explorers in the sixteenth century. The native rafts were equipped with sails and an unusual steering system that made them effective in carrying large cargoes along the western coast of South America. Heyerdahl (1950) proposed that such rafts allowed the natives to sail from South America to the Polynesian Islands. To test this hypothesis, the *Kon-Tiki* was launched from Callao, Peru on April 28, 1947 and on August 6 landed at Raroia atoll, part of the Tuamotu atolls (Figure 1a). Olle Nordemar directed an Oscar winning documentary of this voyage.



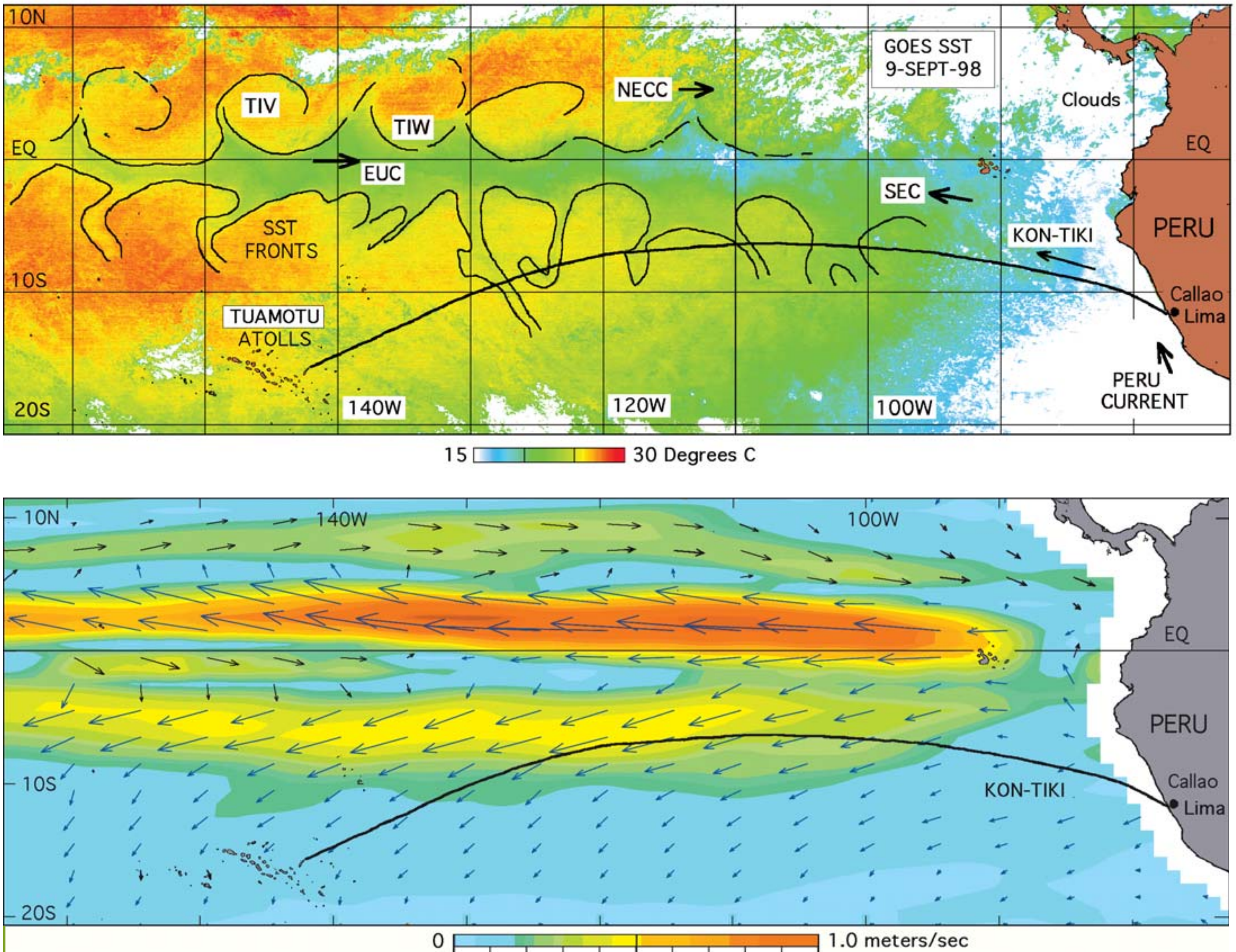


Figure 1. (a) The warmest composite of GOES satellite sea surface temperatures on 9 September 1998 shows the equatorial cold tongue (green) surrounded by warmer (red) waters. The temperature fronts outline the westward propagating tropical instability waves (TIW) and vortices (TIV). (b) The mean current vectors for a 10-day interval centered on 10 September 1998. The South Equatorial Current (SEC) flows westward on both sides of the equator and maximum westward flow occurs north of the equator. The North Equatorial Counter-Current (NECC) flows eastward between latitudes 5°N and 10°N. The eastward flow near the equator (160°W-140°W) may be the surfaced Equatorial Under-Current (EUC). The *Kon-Tiki* raft crossed the Pacific in mid-year of 1947 and was deflected southward by mysterious currents described by Heyerdahl.

Heyerdahl provided the following descriptions of the ocean currents encountered by the *Kon-Tiki*: "There was not one day on which we moved backward toward America, and our smallest distance in twenty-four hours was 9 sea miles, while our average run for the voyage as a whole was 42.5 sea miles in twenty four hours." The maximum distance achieved by the raft for one day was 71 sea miles (128 km). This relentless westward drift was a result of the persistent trade winds, as well as the South Equatorial Current (SEC), which intensifies seasonally between April and December.

During the voyage, Erik Hesselberg, the navigator of the *Kon-Tiki*, noticed that mysterious surface currents occasionally diverted the raft southward. Heyerdahl comments: "The currents could run like invisible rivers branching out all over the sea. If the current was swift, there was usually more swell, and the temperature of the water usually fell one degree. It showed its direction and strength every day by the difference between Erik's calculated and his measured position." The observation of the decrease in surface water temperature during these southward surface currents was intriguing since a change of that magnitude is now detectable by satellites using infrared and microwave sensors.

In 1947, the origin of the mysterious southward currents described by Heyerdahl was unknown. Today, we have a better understanding of the currents in the Equatorial Pacific and their variability from improved modeling approaches and new observational techniques. For illustration, satellite data from El Niño and La Niña of 1997-1998 are used here as a proxy for environmental conditions encountered by *Kon-Tiki*. This period is especially well documented and provides examples of westward propagating tropical instability waves, the surfacing of the eastward flowing equatorial undercurrent, and an unprecedented phytoplankton bloom that traveled along the equator. This article will show that the source of the southward deflections encountered by Heyerdahl on *Kon-Tiki* probably originated along the equator due to the interactions of swift eastward and westward currents (Figure 1b).

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EL NIÑO, LA NIÑA AND THE EQUATORIAL COLD TONGUE

The departure of *Kon-Tiki* at the end of April 1947 was fortuitously well timed for the voyage. The equatorial winds and currents have seasonal and inter-annual cycles. The annual cycle of equatorial currents and winds produces a cold tongue that extends westward from South America to the central Pacific from May to January. The cold tongue is shown during mid-June for each year between 1982 and 2003 in satellite sea-surface temperature (SST) maps (Figure 2). During June, the raft was at the midway point of the voyage. The persistence and extent of the cold tongue can be attributed to several factors as described by Wyrtki (1981) and McPhaden et al. (1998). The cold waters of the Peru Current that flow along the coast of South America (Figure 1a) turn to the west along the equator and flow past the Galapagos Islands. The annual cycle of westward trade winds increases equatorial upwelling due to Ekman divergence that brings cold, nutrient-rich waters to the surface. The trade winds also result in the establishment of surface currents, counter-currents, and undercurrents as illustrated in Figure 1b; Weisberg (2001) provides an observer's view of these equatorial currents. The interactions among these currents create instabilities and vortices that produce intense areas of upwelling and downwelling along the cold tongue. Qiao and Weisberg (1995) provide a comprehensive review of these instabilities and make a case for their origin. Although the dynamics of the equatorial currents are quite complex, the appearance and duration of the equatorial cold tongue is a proxy for winds and currents favorable for westward travel by *Kon-Tiki*.

Every three to seven years, the equatorial ocean currents and temperatures are altered as part of the inter-annual El Niño-Southern Oscillation (ENSO). During El Niño events, the currents weaken and sometimes reverse direction, with the westward extent of the equatorial cold tongue diminishing, and sometimes disappearing entirely. At least five significant El Niño events have occurred since 1982 (Figure 2), and the El Niño of 1997 to 1998 is especially well documented (Wilson and Adamec, 2001; Delcroix et al., 2000; McPhaden, 1999; Chavez et al., 1999). Historical records (1925 to 1986) of coastal ocean temperatures, river discharge in Peru, and sea-level pressures analyzed by Deser and Wallace (1987) show that an El Niño occurred in 1948. A raft launched during an El Niño could have been driven back towards South America or been stranded in the equatorial ocean. Therefore, by undertaking the voyage in mid-1947, the *Kon-Tiki* avoided an El Niño and encountered favorable conditions for westward drift both on a seasonal and an inter-annual basis.

EQUATORIAL PACIFIC CURRENTS

The Eastern Equatorial Pacific currents consist of the westward South Equatorial Current (SEC), the eastward North Equatorial Counter-Current (NECC),

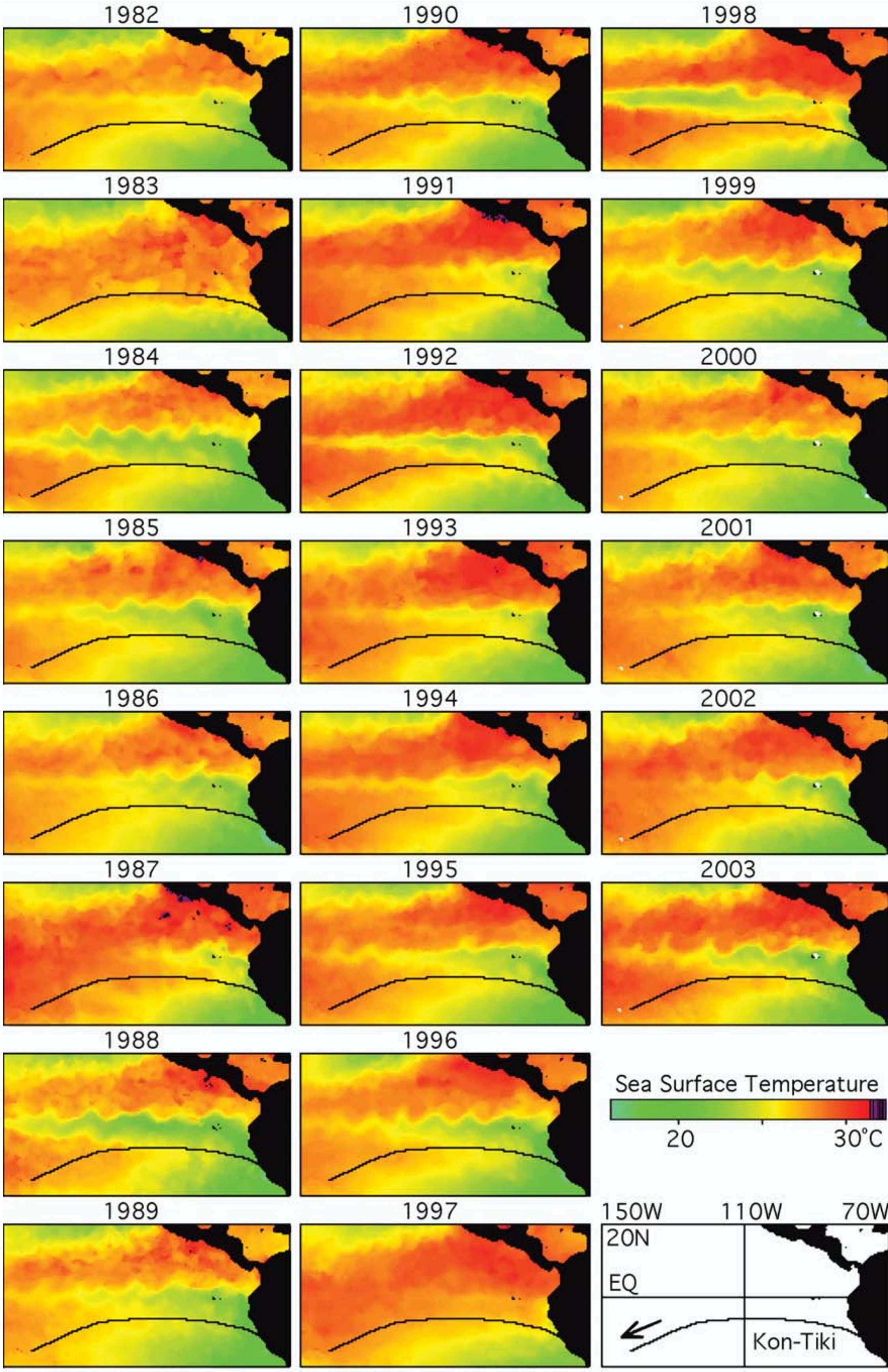

Figure 2. Weekly AVHRR (Advanced Very High Resolution Radiometer) sea surface temperature images in mid-June from 1982 to 2003 shows the equatorial cold tongue and tropical instability waves. *Kon-Tiki* departed Peru on 28 April and landed in Polynesia on August 6, 1947 (black line is *Kon-Tiki* path). The cold tongue is diminished during El Niño years: 1982, 1987, 1991, 1997, and 2002. A strong La Niña appeared in 1983, but the cold tongue was delayed until July. By undertaking the voyage in mid-1947, the *Kon-Tiki* avoided an El Niño and encountered favorable conditions for westward drift both on a seasonal and an inter-annual basis.

and the subsurface eastward Equatorial Under-Current (EUC) (Figure 1b and Figure 3). The equatorial currents have been studied intensely during the last thirty years due to the increased interest in predicting El Niños (Johnson et al., 2001; Weisberg and Qiao, 2000; McPhaden et al., 1998; Halpern et al., 1988; Feldman et al., 1984). A buoy array now monitors currents and temperatures at fixed locations across the equatorial Pacific (more information available at www.pmel.noaa.gov/tao). The Ocean Surface Current Analysis Real-time (OSCAR) project uses winds derived from satellite scatterometers (NASA QuikScat) and sea level estimated from altimeters (TOPEX/Poseidon) to analyze the combined wind-driven and geostrophic currents in the tropical Pacific (Bonjean and Lagerloef, 2002) (more information available at www.oscar.noaa.gov).

The current vectors in Figure 3 show the variability of the speed and direction of the equatorial currents. The most favorable westward currents for the *Kon-Tiki* occur during La Niña, while adverse eastward flow occurs during El Niño. During each year, eastward flow can occur at the NECC north of 5°N latitude, near the equator with the surfacing of the EUC, and due to tropical waves described below. Less conspicuous in Figure 3 are the southward current vectors from June to September south of the equator. Although the OSCAR currents are coarse (10-day averages, 100 km intervals), these currents' vectors are sometimes aligned with the narrow, southward-directed SST fronts (Figure 4). The speed of these currents can increase by a factor of two at the fronts (Legeckis et al., in press). It is proposed that the cur-

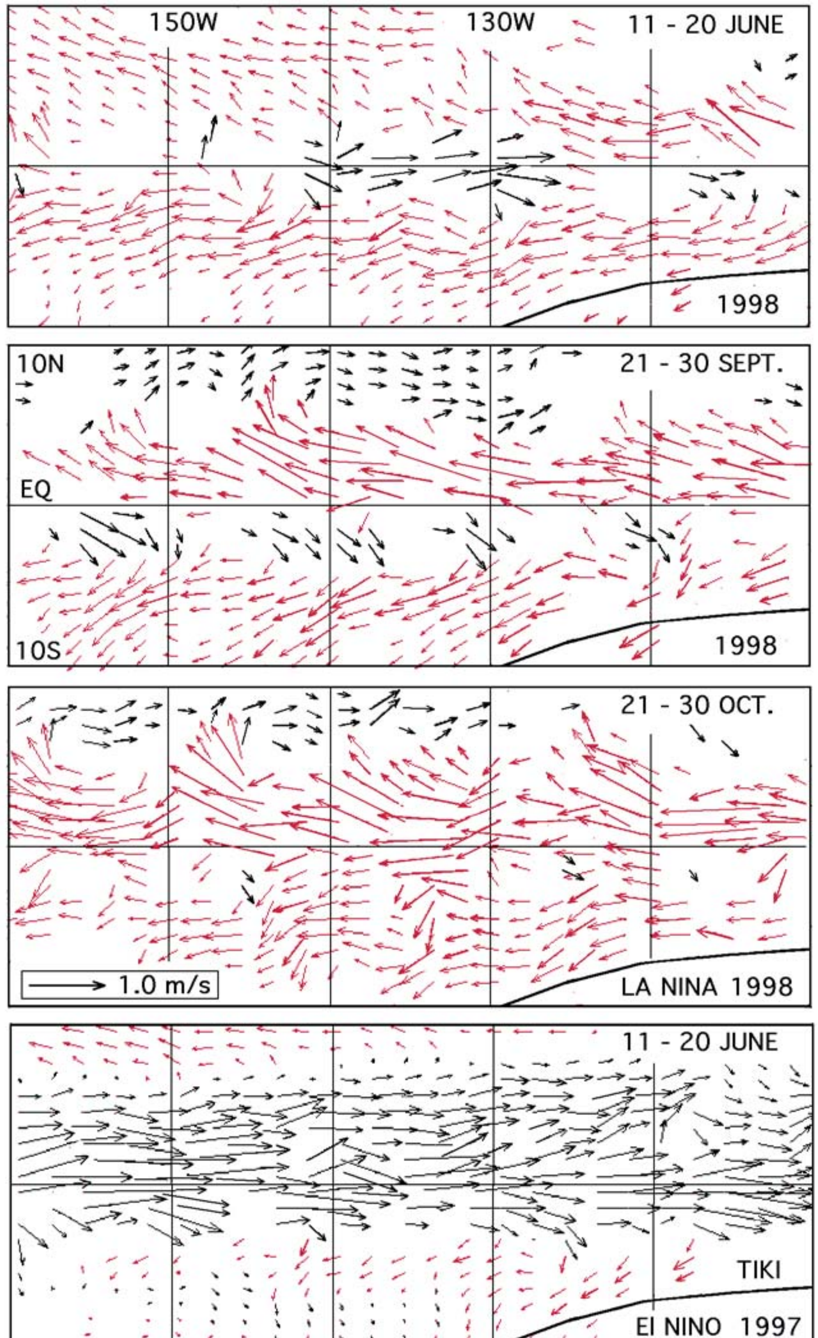

Figure 3. Surface current vectors from the OSCAR analysis during June, September, and October of the 1998 La Niña. During 1997 El Niño, strong eastward flow (black) occurs along the equator and the weak westward currents (red) south of the equator would have slowed down the drift of *Kon-Tiki* toward Polynesia.

rents along these narrow SST fronts diverted the *Kon-Tiki* southward.

TROPICAL INSTABILITY WAVES AND VORTICES

A unique wave-like pattern of equatorial SST is generated by the instability of equatorial currents and the waves are therefore called tropical instability waves (TIW) (Qiao and Weisberg, 1998; Philander, 1990; Cox, 1980; Legeckis, 1977). The TIW are very long (1000 km) and appear to move westward (Figure 4). The waves are seasonal in appearance and disappear with the equatorial cold tongue (Figure 2). Each year, as the cold tongue forms, the TIW grow in amplitude and an anti-cyclonic, clockwise rotating vortex, with a diameter of about 500 km, is formed north of the equator at the leading edge of each TIW (Figure 4). The tropical instability vortex (TIV) is advected westward by the SEC (Kennan and Flament, 2000).

Although the TIW have been monitored north of the equator since 1975, the weaker SST gradients and increased cloud cover south of the equator have limited infrared observations. In 1997, the all weather TRMM (Tropical Rainfall Measuring Mission) Microwave Imager (TMI) began to provide a nearly continuous view of SST patterns within 38 degrees of latitude around the globe (Wentz et al., 2000). Continuity was made possible because the microwave measure-

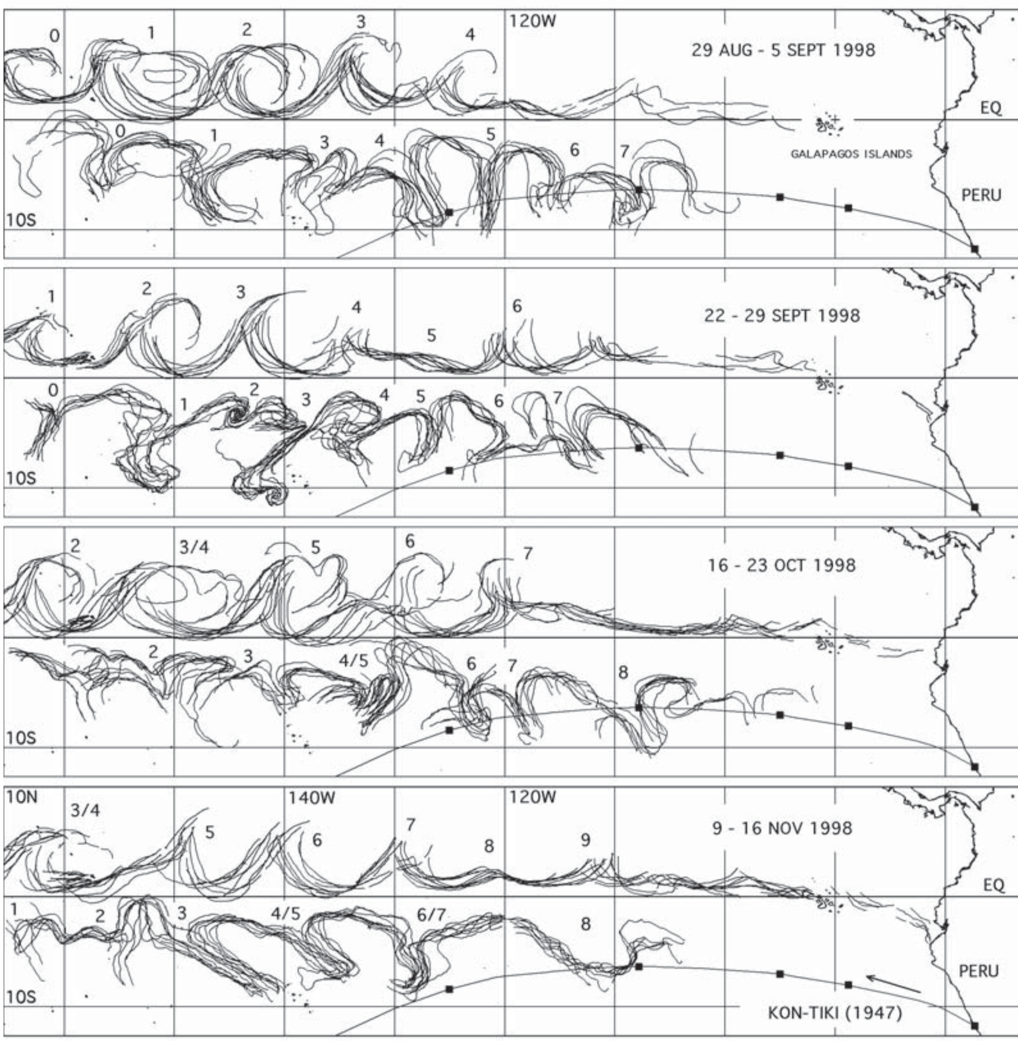

Figure 4. Eight-day composites of GOES SST fronts show the formation and westward propagation of tropical instability waves (TIW) on both sides of the equator. The numbers identify wave crests (0 to 9) tracked in image animations. Some of the waves appear to merge together (TIW-north 3/4 and TIW-south 4/5 and 6/7) as the TIW respond to changes in the speed of equatorial currents. Thor Heyerdahl related how *Kon-Tiki* was often deflected southward by mysterious currents of cooler water.

ments penetrate clouds, except in areas of rain. During the La Niña of 1998, the TMI revealed for the first time that TIW and TIV occur and propagate westward on both sides of the equator (Chelton et al., 2000). Although the spatial resolution of TMI is coarse (50 km), it was obvious that distinct TIW SST fronts protruded south of the equator and could have intersected the path of *Kon-Tiki*.

In 1996, higher-resolution (~ 5 km) SST measurements became available every 30 minutes from the Geostationary Operational Environmental Satellite (GOES) (Wu et al., 1999). The composites of SST fronts in Figure 4 reveal a nonsymmetric pattern of TIW fronts around the equator in 1998. The TIW fronts north of the equator retain a clockwise rotation pattern for months at a time and move westward steadily at 53 cm/sec (Legeckis et al., 2002). The TIW fronts south of the equator do not appear to exhibit a preferred rotational pattern. Instead, these fronts tend to extend far to the south while propagating westward. The phase speed of these southern TIW fronts between latitude 1°S and 3°S was estimated to be 21 cm/sec (August-October) and 36 cm/sec (October-November). Although microwave SST analysis by Chelton et al. (2000) yielded the same TIW phase speeds (~50 cm/sec) on both sides of the equator, a new analysis by Chelton et al. (2001) re-estimated the southern phase speed at 25 cm/sec during August to September and noticed an abrupt increase in phase speed in early October, similar to our analysis. We attribute this increase in the southern TIW phase speed to an increase in the speed of the SEC during October to November as monitored by OSCAR.

The TIW fronts south of the equator are more difficult to track because these fronts appear to merge and combine to form new wave patterns with different wavelengths (Figure 4). This occurred at least three times during 1998 and was especially noticeable during October when the orientation of the SST fronts shifted from southwest to southeast. This corresponded to an increase in the speed of the westward currents along the equator. Time-series of GOES SST fronts reveal that rapid changes of the TIW amplitudes can result in rapid southward extensions of narrow bands of colder equatorial waters. These fronts, and their associated currents, can reach the Marquesas Islands (140°W and 10°S) and initiate periodic phytoplankton blooms (Signorini et al., 1999; Legeckis et al., in press). Although direct measurements of the narrow southward currents along the SST fronts are yet to be made, the patterns of SST fronts suggest the presence of currents that would have deflected the *Kon-Tiki*.

OCEAN COLOR AND THE EQUATORIAL UNDERCURRENT

In 1997, the NASA Sea-viewing Wide Field-of-View Sensor (SeaWiFS) started making global measurements of surface ocean color (chlorophyll) (McClain et al., 2002; Dickey, 2001). In 1998, SeaWiFS provided the first large-scale view of the surfacing of the EUC and the simultaneous westward propagation and eastward advection of an equatorial phytoplankton bloom (Chavez et al., 1999). Ryan et al., (2002) analyzed the equatorial current's dynamics during 1998 and attributed the eastward displacement of the bloom to advection by the surfacing of the EUC. It will be shown below that the chlorophyll-rich upwelled equatorial waters may have also been diverted southward and into the path of the *Kon-Tiki*.

The equatorial patterns of chlorophyll are illustrated in Figure 5 by merging the eight-day composites of SeaWiFS chlorophyll concentration with the daily positions of GOES SST fronts between June and August of 1998. This unprecedented SeaWiFS sequence shows that the EUC appears at the surface as a narrow, sinusoidal, wave-like pattern (wave peaks A-E) of chlorophyll-rich waters centered on the equator. At the same time, the TIW wave-like patterns (1-5) form in the east at the GOES SST fronts north of the equator. Initially, the EUC and northern TIW wave patterns meet at longitude 120°W and both propagate westward. While their wavelengths are comparable (1000 to 1300 km), the wave-like patterns of chlorophyll within the EUC propagate westward at a mean speed of 30 cm/sec, much slower than the TIW (53 cm/sec). As the EUC wave patterns grow in amplitude, they begin to merge with the TIW SST fronts and, by August, the EUC wave pattern is no longer distinct from the TIW fronts. These transient EUC wave patterns depend on the complex shear of the zonal currents as described in current meter measurements by Qiao and Weisberg (1998) and will have to be evaluated further by numerical models.

While the EUC wave-like patterns appear to move westward, the phytoplankton bloom also appears to be displaced to the east (Ryan et al., 2002). For example, the leading edge of the chlorophyll pattern in Figure 5 moves from 122°W to 112°W between day 193 and 209, a speed of about 70 km/day (0.8 m /sec). This

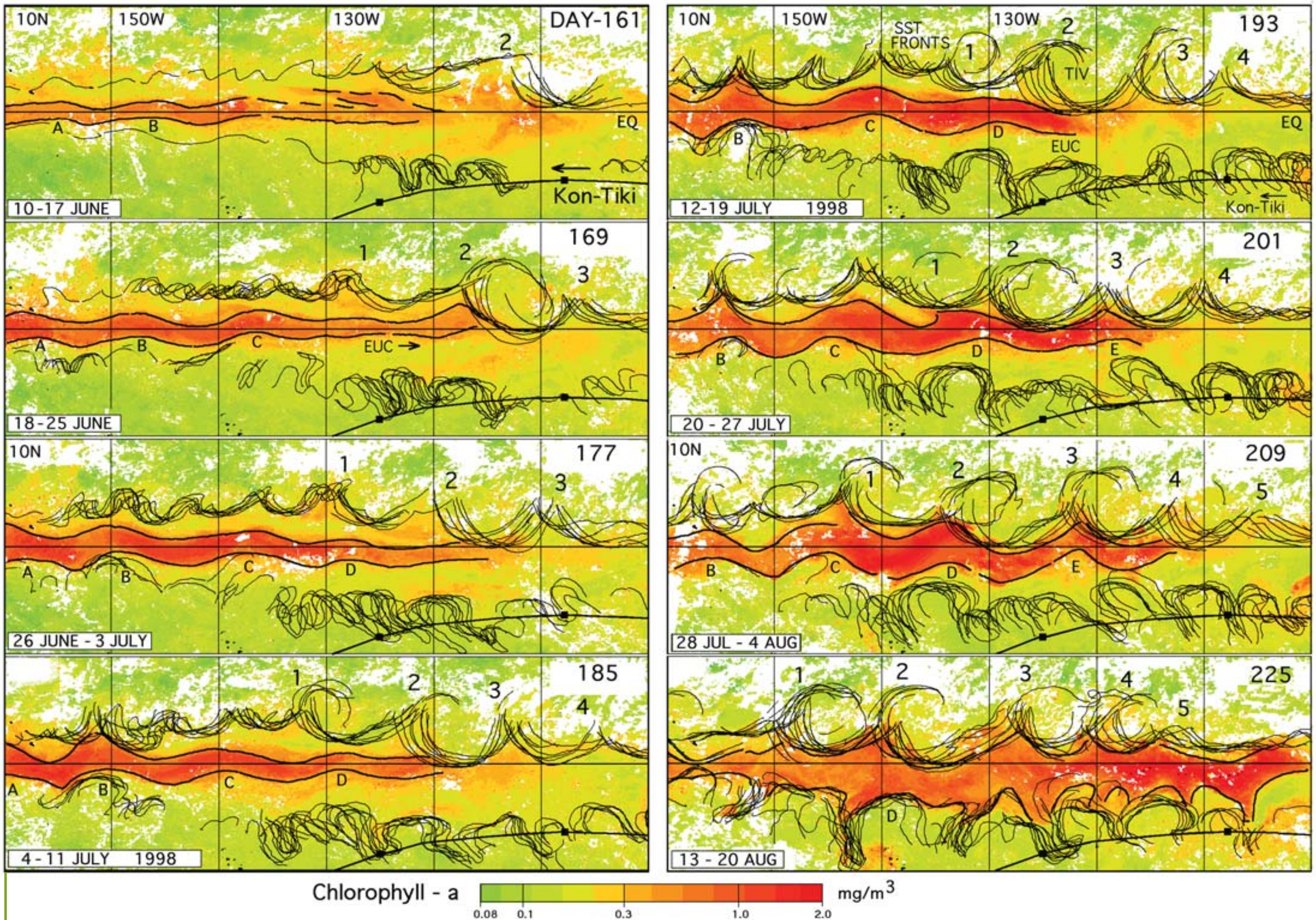

Figure 5. Daily positions of GOES SST fronts superimposed on eight-day composites of SeaWiFS chlorophyll concentration. The EUC (A-E) and TIW (1-5) wave-like patterns propagate to the west while the bloom is advected to the east by the EUC. The phytoplankton bloom diminished in intensity by September but the TIW SST fronts persisted until February 1999.

eastward equatorial flow also appears in the OSCAR analysis from June to September in Figure 3. While model results by Cox (1980) initially showed that the shear between the SEC and the NECC contributed to the formation of TIW, more recent analyses and observations point out the greater contribution of the EUC. Based on *in situ* observations at longitude 140°W and the equator, Qiao and Weisberg (1998) suggest that the shear between the SEC and the EUC is important for the development of TIW. Numerical models by Masina and Philander (1999) also show that the EUC plays a dominant role in the energetics of TIW. The chlorophyll images in Figure 5 illustrate that the track of the *Kon-Tiki* encounters the SST and color fronts frequently. In fact, the equatorial chlorophyll patterns are sometimes diverted as far as latitude 13°S along the GOES SST fronts. Because most of the SST fronts became indistinct south of about latitude 8°S, the chlorophyll images provide an additional clue that the equatorial waters are advected far to the south by currents that originate near the equator.

SUMMARY

The search for the explanation of the narrow currents that deflected *Kon-Tiki* southward started in the summer of 2002 while one author (Legeckis) was sitting at the edge of the ocean in Wildwood, New Jersey, casually reading about Heyerdahl's Pacific adventures. A single sentence relating mysterious currents to changes in water temperature and the corresponding roughness of the sea surface was puzzling. It was assumed that these changes were somehow related to the TIWs. It is of interest to note that finding the connection only became possible due to the steady improvement in the quality of satellite and *in situ* observations. In 2005, Olav Heyerdahl will attempt to duplicate his grandfather's voyage on a new raft. The eyes of many satellites will follow his quest but the currents, winds, and waves will still be controlled by Mother Nature.

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