CLIMATE PATTERNS IN THE COASTAL ZONE

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Decadal climate changes are associated with the systematic variations in global patterns of atmospheric pressure, temperature, and sea surface temperature that persist from a year or two to multiple decades. These climate changes have major impacts on coastal processes, modifying wave climate, rainfall, river sediment flux, sand transport paths, coastal erosion, sea level and inundation. Understanding of the types and causes of climate change is in its infancy. *El Niño/Southern Oscillation (ENSO)* patterns that generate storms comparable to extreme seasonal events may occur every 3 to 7 years and appear to be associated with other longer period changes. The *Pacific/North American (PNA)* pattern of pressure anomalies and its sea surface temperature equivalent, the *Pacific Decadal Oscillation (PDO),* are associated with multidecadal periods of more intense El Niño type weather, alternating with decades of more intense *La Niña* weather, the complementary phase to El Niño. Similarly, a *North Atlantic Oscillation (NAO)* is associated with decadal changes in atmospheric pressure fields between Iceland and Portugal that alter North Atlantic wave climate and Caribbean hurricane tracks.

Background

The world-wide connection of weather patterns (teleconnections) was first addressed in detail by Sir Gilbert Walker (1928). He identified weather patterns with three global reversals in atmospheric pressure and temperature, the Southern Oscillation, the North Atlantic Oscillation, and the North Pacific Oscillation. Nile River floods, monsoon reversals in India, rice crop failures in Japan, and droughts in Australia were associated with these global reversals. Although there were little data at that time, Walker emphasized that ocean temperatures play a most important part in world weather. The advent of detailed global databases and rapid computer modeling in recent times has fueled a renewed understanding of the extent and duration of these climate events. Proxy records obtained from Greenland ice cores, tree rings, coral reefs, fish scales and ocean sediments show that abrupt fluctuations in climate have occurred throughout the Holocene. These shifts may occur within a few years and extend for decades to millennia (e.g., Meko, 1992; Cole *et al.*, 1993; 2000; Heusser and Sirocko, 1997; Soutar and Isaacs, 1974; Gupta *et al.,* 2003). These past events and the presently occurring climate changes are generally thought to be related to the extreme phases of the El Niño/Southern Oscillation (ENSO) phenomenon.

Hypotheses explaining the causes of unusual ENSO events are numerous and range from the extrusion of hot lava on the sea floor to variations in the intensity of the sun's radiations. Most climate modelers favor a complex set of changes in the interaction of the atmosphere and ocean that cause fluctuations in trade winds, monsoon intensity, and sea surface temperature (e.g., Somerville, 1996; Pierce *et al.*, 2000). Although the causes of climate change remain obscure, a clear pattern of atmosphere-ocean events associated with ENSO phenomena has emerged. It is this pattern that gives rise to three month forecasts of ENSO events. However, ongoing ENSO events are superimposed on a progressive rise in mean global temperature. Consequently, their effects are likely to be less predictable and perhaps more intense than previous events (Inman and Jenkins, 1997; Timmermann *et al.*, 1999; Fedorov and Philander, 2000).

Short-term climate patterns

The seasonal variations in the exposure of the hemispheres to the sun produce changes in the duration of daylight and the angle of the sun's irradiance. These effects modulate solar heating, resulting in variation of the earth's atmospheric pressure field which in turn induces seasonal climatic effects. Seasonal variations are enhanced by the higher convective effects of land and the greater concentration of land mass relative to water in the temperate latitudes of the northern hemisphere (Figure 1a, b).

On occasion, the typical seasonal weather cycles are abruptly and severely modified on a global scale. These intense global modifications are signaled by anomalies in the pressure fields between the tropical eastern Pacific and Malaysia known as the El Niño/Southern Oscillation (ENSO) (e.g., Diaz and Markgraf, 1992). The intensity of the oscillation is often measured in terms of the *Southern Oscillation Index (SOI)*, defined as the monthly mean sea level pressure anomaly in mb normalized by the standard deviation of the monthly means for the period 1951-1980 at Tahiti minus that at Darwin, Australia (Figure 1a, b, lower). A negative SOI (lower pressure at Tahiti, higher pressure at Darwin) is known as an *El Niño* or warm ENSO event, because of the arrival of unusually warm surface water off the coast of Peru at the time of Christmas, hence the term El Niño. Warm water also occurs along the coast of California, and both regions experience unusually heavy rainfall. A positive SOI is known as *La Niña* and it signals the occurrence of colder than normal surface water in the eastern Pacific, but stronger trade winds in the Pacific and southwest monsoons in the Indian Ocean with heavy rainfall in India and on the Ethiopian plateau (Inman *et al.*, 1996).

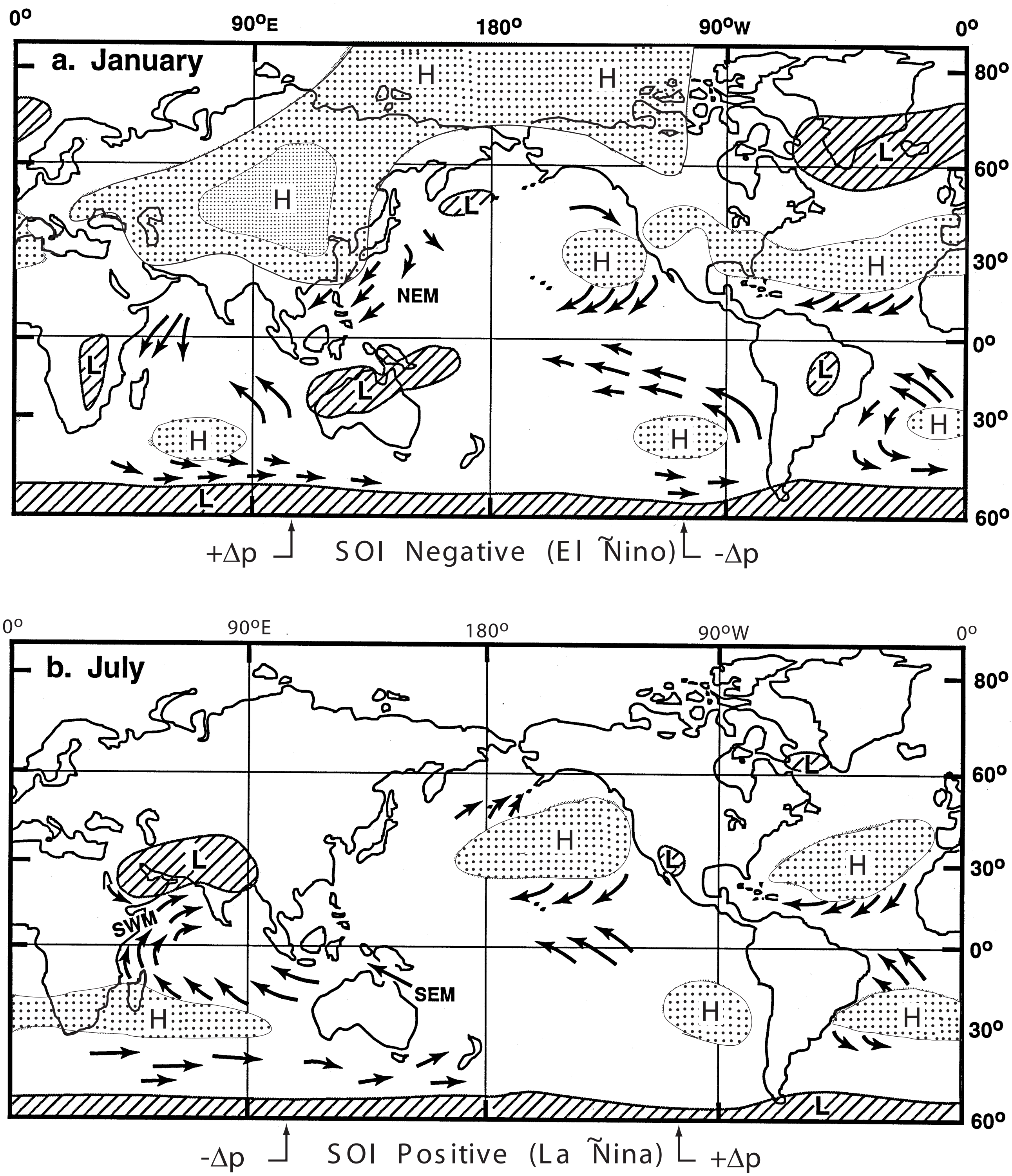

Figure 1. Seasonal pressure and winds for (a) January and (b) July. Contours of 1020 mb and 1000 mb are shown around areas of high (H) and low (L) pressure respectively. Prevailing winds are indicated by arrows: NEM, SEM, SWN designate northeast, southeast, and southwest monsoons. The pressure anomaly Δp is centered around longitudes 105° E and 105° W for negative and positive Southern Oscillation Indices (SOI) [modified from Inman *et al.*, 1996].

During El Niño events the combination of low pressure over the Pacific Ocean and the thermal expansion of warm water cause an increase in water level along the eastern Pacific Ocean. The water level increases by 20 to 30 cm during strong El Niño events and is depressed an equivalent amount during strong La Niña events. The water level increases lead to significant coastal inundation and sea cliff erosion during the intense storms that are common to El Niño events.

Decadal climate patterns

ENSO events occur with dominant spectral peaks at about 3 and 6 plus years. However these ENSO events are modified by climate changes that occur on decadal time scales of one quarter to one half century. These changes are often discussed in terms of two atmospheric patterns, the Pacific/North American (PNA) and the North Atlantic Oscillation (NAO), and a sea surface temperature pattern, the Pacific Decadal Oscillation (PDO). Both PNA and PDO are long period, multidecadal analogs of the seasonal variations of global pressure and temperature and are related to Walker's (1928) North Pacific Oscillation. NAO is a periodic intensification or relaxation of the January phase of the pressure variation (Figure 1a). These decadal climate patterns are disguised (aliased) by the interannual changes because they have the same structure and appear as extreme cases of the interannual patterns. This aliasing has delayed the general understanding and acceptance of these concepts.

The Pacific/North American (PNA) pattern is associated with an atmospheric dipole in pressure anomaly over the Pacific Ocean/North America region whose polarity reversals lead to wet and dry climate along the Pacific coast of North America (Wallace and Gutzler, 1981). High pressure anomaly over the North Pacific Ocean and low pressure anomaly over the North American continent result in dry (La Niña dominated) climate along the coast of central and southern California, while the opposite polarity in these dipole patterns leads to wet (El Niño dominated) climate (Figure 2a, b). Inman and Jenkins (1999) show that the twenty coastal rivers of central and southern California have streamflow and sediment fluxes during the wet phase of PNA (ca 1969-1998) that exceed those during the preceding dry phase (ca 1944-1968) by factors of 3 and 5, respectively. The sediment flux during the three major El Niño events of the wet phase averaged 27 times greater than the annual flux during the dry phase.

The Pacific Decadal Oscillation (PDO) is a long-lived sea surface temperature pattern with cool and warm phases similar in structure to the La Niña/El Niño phases of ENSO cycles (Goddard and Graham, 1997; Mantua *et al.*, 1997). Although the phase transitions of PNA and PDO may differ slightly in space and time, both events persist for decades and produce the most visible climate signatures in the North Pacific (Francis and Hare, 1994; Minobe, 1997). The El Niño dominated phase of the PDO cycle is characterized by a weakening of the trade winds that results in an eastward movement (slosh) of the warm pool of equatorial water normally contained in the western Pacific by the trades during La Niña conditions (Cole *et al.*, 2000). The sequence of events leading to and associated with the warm (El Niño) phase of the PDO is illustrated in Figure 3. It has been suggested that the breakdown from a prevailing La Niña to an El Niño occurs when brief bursts of westerly winds near the dateline begin the easterly transport of warm water. The positive feedback from the warm water further decreases the trade winds, beginning the transformation to an El Niño (e.g., Fedorov and Philander, 2000).

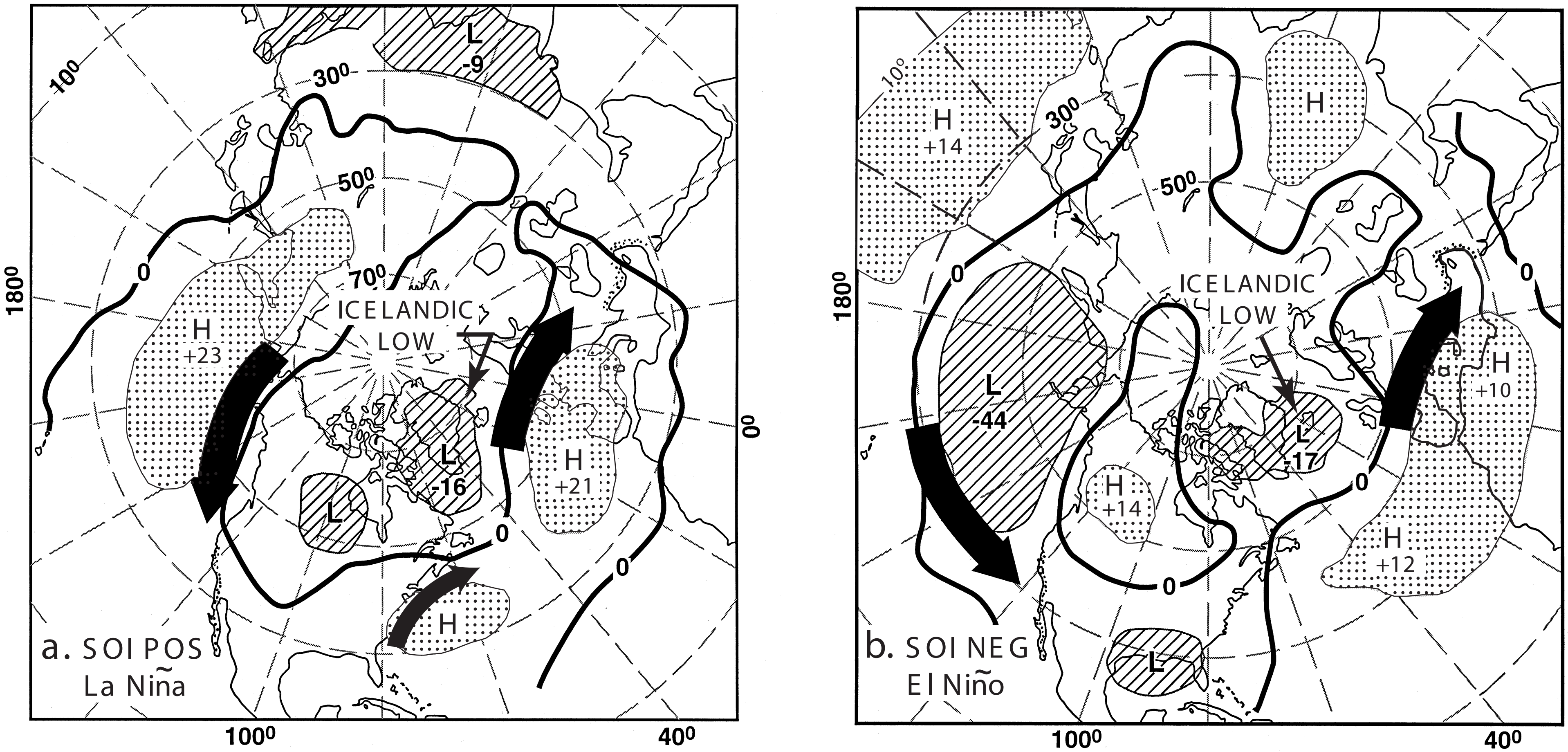

Figure 2. Storm track enhancement (arrows) associated with 700 mb atmospheric pressure anomalies during La Niña (a) and El Niño (b) dominated climate patterns [modified from Inman *et al.*, 1996; pressure data from Redmond and Cayan, 1994].

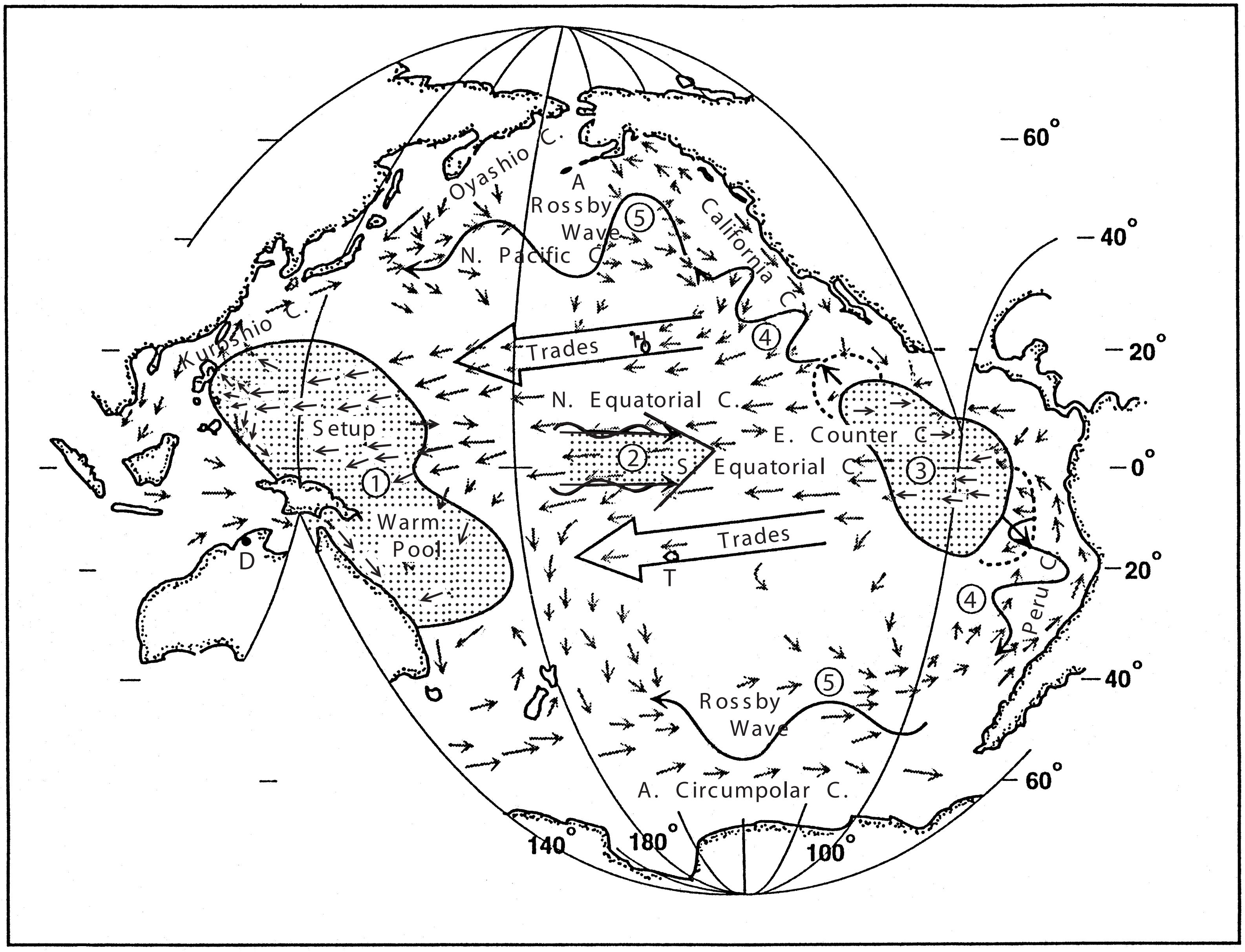

Figure 3. Schematic illustration of sequences leading to a fully developed El Ni̮no event. Numbers refer to (1) warm pool of water setup by trade winds, (2) eastward "slosh" (baroclinic Kelvin wave) of warm water released by relaxation of trade winds, (3) warm pool travels to eastern Pacific and (4) spreads poleward along continental margins (trapped barotropic Kelvin waves), and excites (5) westernly traveling planetary (Rossby) waves. D, T and H designate Darwin, Tahiti and Hawaii [modified from Inman *et al.*, 1996].

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The stronger trade wind systems during the cool (La Niña) phase of PDO are part of a general spin-up of the atmospheric circulation which causes the North and South Pacific Gyres to rotate faster. Both effects (wind and current) induce upwelling that maintains cold water masses along the west coast of the Americas, which sustains the typically cool dry coastal climate of these regions during the La Niña dominated periods of the PDO and PNA. In contrast, the strengthened trade winds of the La Niña period are associated with higher rainfall on the windward sides of Hawaii and other high islands in the trade wind belt. Higher than average rainfall occurred at Hilo and Lihue in the Hawaiian Islands during the La Niña dominated period 1943-1968, and lower average rainfall during the subsequent El Niño dominated period 1969-1998. However, the El Niño period included episodic Kona storms and the occurrence of hurricane Iniki.

The North Atlantic Oscillation (NAO) is an atmospheric dipole that retains its polarity with a low over Iceland and a midlatitude high that enlarges and contracts (Wallace and Gutzler, 1981; Hurrell, 1995). The Icelandic low remains more or less in place while the midlatitude high pressure anomaly changes in size, strength, and latitude (Figure 2). During La Niña the high pressure anomaly is stronger and centered over the Bay of Biscay and Spain; during El Niño the high expands but weakens and is centered around 30° North Latitude over the eastern North Atlantic and north Africa. Figure 2 shows that during La Niña events, storm tracks end near the Black Sea causing droughts in Israel; during El Niño the storm tracks end in Israel bringing rain and high waves. The biblical seven year floods on the Nile River are associated with La Niña intensification of the southwest monsoon over the Indian Ocean (Figure 1). These monsoons bring heavy rainfall over the high Ethiopian plateau that induces flooding on the Nile River.

The dipole systems of the PNA and NAO redirect the tracks of traveling storm fronts, causing changes in coastal wave climate. The strongest pressure gradients occur along the boundaries of the pressure anomalies of the PNA and NAO patterns and these boundaries indicate the prevailing storm paths. Figure 2a (La Niña) shows large areas of high pressure over the North Pacific and North Atlantic. These high pressure areas enhance storm tracks as shown by the arrows for waves approaching North America and Europe, with the prevailing North American storm tracts directed at the Pacific northwest and along the Atlantic east coast. In the eastern Pacific, the principal wave energy during La Niña dominated climate (1943-1977) was from Aleutian lows having storm tracks which usually did not reach southern California. Summers were mild and dry with the largest summer swells coming from very distant southern hemisphere storms. The wave climate in southern California changed with the El Niño dominated weather of 1978-1998. The prevailing northwesterly winter waves were replaced by high energy waves approaching from the west or southwest (Figure 2b), and the previous southern hemisphere swells of summer were replaced by shorter period tropical storm waves during late summer months from the more immediate waters off Central America. The east coast of North America is out of phase with the west coast for severe weather. Heavy rainfall and numerous, powerful Caribbean hurricanes and northeasters occur typically during La Niña years (Figure 2a). (see entry on *Energy and Sediment Budgets of the Global Coastal Zone*)

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Cross-references

Energy and Sediment Budgets of the Global Coastal Zone