Rapa Nui: a climatically constrained island?

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Conjectures versus Facts

Climatic variability that aggravated periods of dryness on Rapa Nui has been invoked as a reason for vegetation degradation, the loss of crop land and the subsequent breakdown of the social order resulting in the decline of a once flourishing culture (Mann et al. 2008). In the contemporary debate many authors argue that Rapa Nui is a prime example of how, when human-induced stress is added at a time of naturally-based stress, the result can be ecological crisis, environmental deterioration, and social collapse (see Hunt & Lipo 2006). To make their point on Rapa Nui, most environmentalists use climate similes taken from neighboring South Pacific islands, or construct climatic generalizations of the island devoid of empirical support, thus demonstrating a poor grasp on the peculiarities of the atmospheric circulation and ocean dynamics in the southeastern Pacific. Inappropriate climate generalizations and incorrect assumptions have been favored by a scarcity of long-term meteorological series and comprehensive ocean observations.

To dispel equivocal notions of climate and rebut unfounded assumptions, this article starts by first establishing the actual patterns of precipitation, temperatures, and winds using updated climatological information. Departing from an empirically-based characterization of Rapa Nui's climate, the actual magnitude of contemporary climatic variation is assessed. It is a central premise of this study that the physical processes and circulation mechanisms underlying the island's contemporary climate can be utilized to reconstruct the climate of the past, and, in this manner, also shed light on the impact of former climatic crises for which only indirect proxy evidence exists.

Data

Detailed meteorological series from the archives of the Servicio Meteorológico de Chile (Chilean Meteorological Service) for 1970/80-2000, and monthly precipitation data from 1950-2000 issued by NOAA, U.S. Department of Commerce, were used to characterize the climate of the island. The patterns of precipitation seasonality and rain variability were tested by comparing the cumulative probability distributions applied to a thirty-one year monthly rainfall record (1970-2000). Since the major climate modulator in the Pacific realm is the pseudo-periodicity known as El Niño-Southern Oscillation (ENSO), the inter-annual variability was examined under the three phases of ENSO: the "warm phase" or El Niño, the "cold phase" or La Niña, and the "neutral phase" when none of the first two conditions appeared. Probabilities of monthly rainfall occurrences in each of these three populations were calculated. In this way, surpluses (large monthly totals) or deficits (smaller totals) under the three phases could be identified. Moreover, since droughts have been invoked as a reason for the cultural demise, the rain episodes during these months or groups of months were examined in order to differentiate between "dry" and "wet" months or seasons.

The probability distribution of air temperatures (1970-2000) was also scrutinized under each phase. Further, to ascertain whether the climate was more benign in the past – as often assumed – or perhaps more stressful to tropical crops, monthly absolute minimum temperatures were assessed. The analysis was complimented with a review of the dominant winds and velocities in order to discern how cooler temperatures and drying winds may have reduced the extent of cultivated fields and curtailed the production of edible vegetables.

The phase of ENSO to which the monthly values of the climatic variables corresponded was determined based of the Southern Oscillation Index (SOI) compiled by the National Center for Atmospheric Research (NCAR). For a finer determination of the ENSO phases as they apply to Rapa Nui, the sea-surface temperature anomalies in the El Niño regions 1+2 and 3 in the Pacific were consulted since these regions fall within latitudes 100-140°W, where oceanic conditions dominate that have a bearing on the climate of the island (NOAA/Climate Prediction Center 2010).

Droughts and Deluges

The climate of Rapa Nui has been characterized as oceanic, high-insolation, with humid autumns and winters, and scorching dryness in summer (Hajek & Espinoza 1988). The rainfall extremes are muffled by long-term averages, making it difficult to study inter-annual variability. The yearly distribution of rainfall displays a unimodal distribution, with 34% of the annual total in the April-May-June triad – the southern autumn. The lowest amounts occur at the end of the southern spring. After this dry period, precipitation rises through the southern summer to culminate in the mid-autumn rainy peak (Figure 1). Neighboring islands in East Polynesia such as Pitcairn, Rapa and Mangareva (Figure 2) differ in that

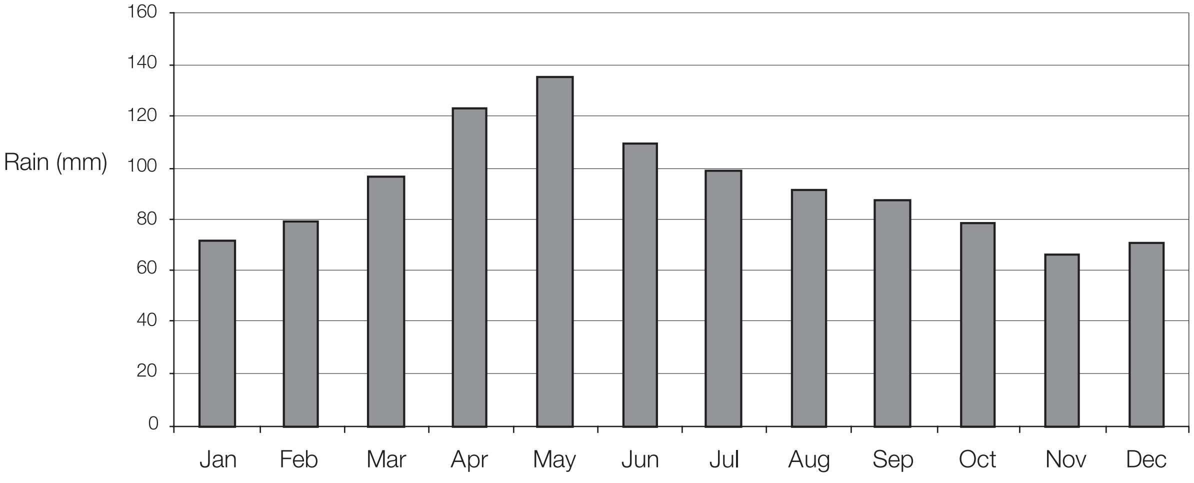

Figure 1. Mean monthly precipitation on Rapa Nui.

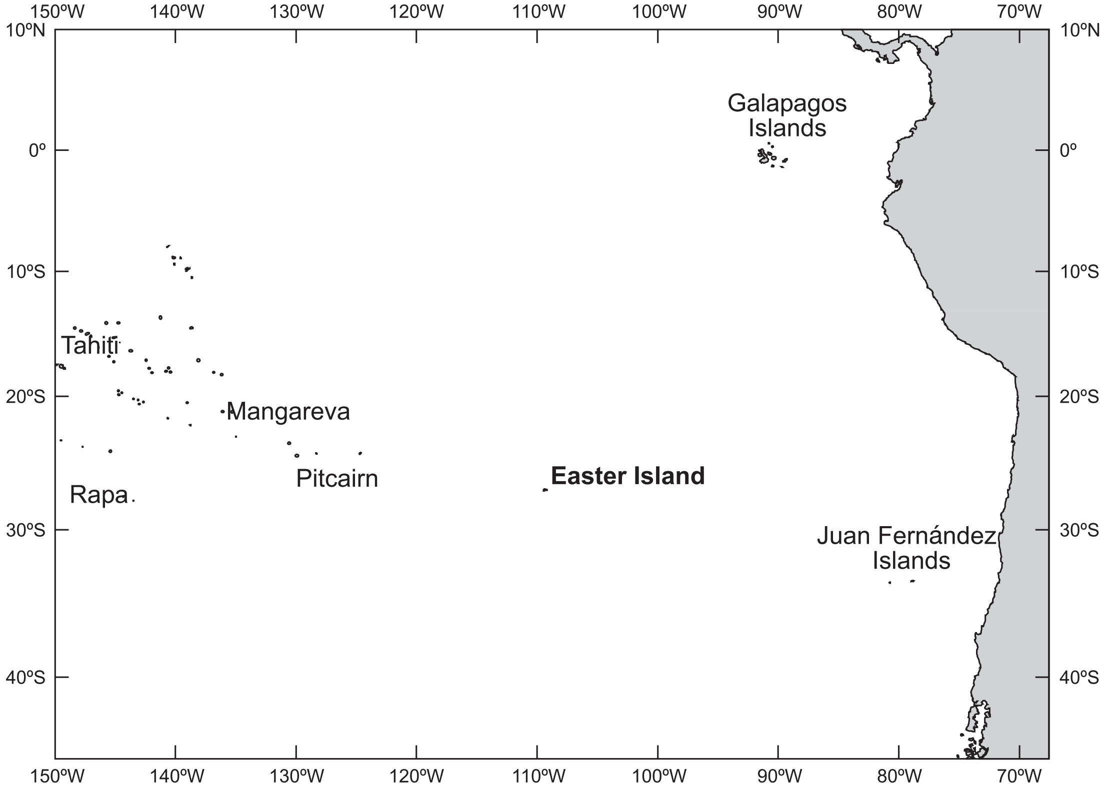

Figure 2. Location of Easter Island and neighboring islands in the southeast Pacific.

they have larger annual totals and three – or even four – peaks indicating multiple rain-generating mechanisms that include summer convection, cyclones or frontal passages in winter, and zenithal rains in spring (Figure 3). On the contrary, the distinctive winter maximum on Rapa Nui is caused by subtropical frontogenesis in autumn and early winter as is typical in the extra-tropical southern Pacific, including the Juan Fernández Islands, close to the central coast of Chile.

Although the role played by fronts and traveling depressions over the southeastern Pacific and the central coast of Chile has long been stressed by Chilean climatologists (Peña & Romero 1976; Romero 1985*),* other research has tended to ignore them and persists in reciting unsubstantiated explanations for climate variability on Rapa Nui, relying on the assumption that they are similar to those of neighboring islands (MacIntyre 2001), and even to distant north-equatorial

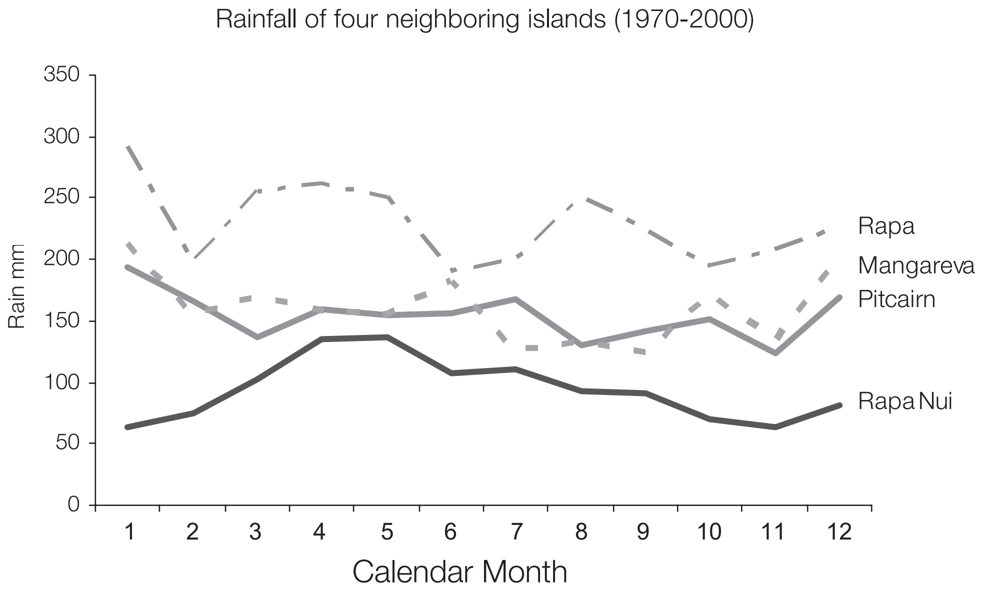

Figure 3. Annual rainfall of Rapa Nui and neighboring southeastern Pacific Islands.

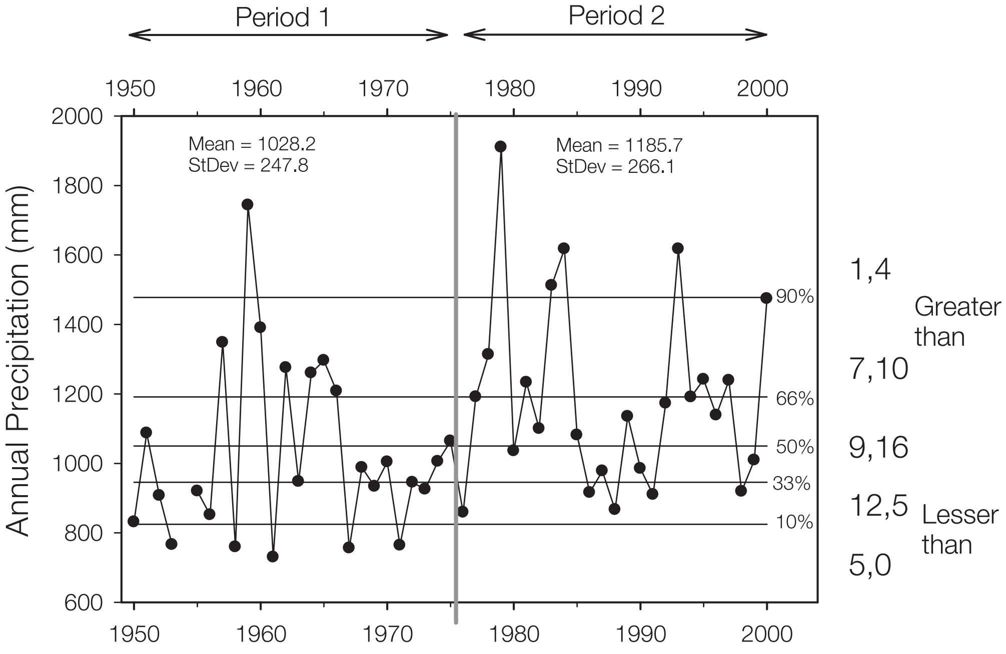

Figure 4. Total annual precipitation on Rapa Nui, 1950-2000.

islands such as Palmyra (Stenseth & Voje 2009). Spurious associations over distance are extended to inter-annual rainfall fluctuation, which itself is a crucial issue for endorsing or rejecting the theses of catastrophic past droughts or deluges. The complexity of climate regimes in the central and southeastern Pacific – which arise from regionally varying rain control mechanisms – has been properly noted by Allen (2006), but continues to be overlooked by ecologists writing about Rapa Nui. A partial reason for the existing misconceptions comes from the absence of meteorological series long enough to detect low frequency and long-term variations. Only the official World Meteorological Organization data on Rapa Nui from 1950 to 2000 offers clues as to the rain variability over time, which, as shown in Figure 4, reveals active year-to-year variability. Furthermore, two long-term periods emerge: one, from 1950 to the early 1970s, has a low annual mean (1028mm), and 248mm standard deviation; while the second period from the mid-1970s to 2000 exhibits a higher annual mean (1185mm), and a slightly larger standard deviation (266mm). Such a distinct break in climatic trends around the mid-1970s has been detected in many regions in the world (Graham 1994; Wang 1995; Mason 1996; Power et al. 1999; Chavez et al. 2003; Meehl et al. 2009).

During the first 25-year period, fifteen years show precipitation below the long-term median, while during the second period, only nine years were below that level. The contrast is more accentuated as the long-term historic level of interest (10, 33, 66 and 90%) becomes more extreme. This finding coincides with the increase in heat and precipitation over oceans since the mid-1970s reported by Levitus et al. (2000), and with the noted frequency of warm ENSO events in the South Pacific (Intergovernmental Panel on Climate Change [IPCC] 2007). Even though there are several years in the first period which fell within the low third of all records, caution must be exercised in calling these occurrences "prolonged droughts" because the monthly records show normal winter rain levels, and the usual low precipitation that characterizes the spring months, as depicted in Figure 1. Moreover, a simple empirical analysis of the lengths of "runs" of consecutive "dry" periods below variously defined critical thresholds (Figure 5), starting at the median and decreasing at 10 percentile increments of the long run annual precipitation totals, indicates a fair frequency of consecutive dry years prior to the climatic shift, rather than following it. Since averaged annual totals do not reveal the *monthly* or *seasonal* variability needed in studies of climate oscillations, fine-grained monthly or seasonal analyses allowed us to pinpoint the months or seasons in which rain deficits occurred and to establish whether some of these periods can be qualified as prolonged droughts.

Many authors have used the term "drought" loosely to define scarcity of rainfall on Rapa Nui. None have employed any of the existing hydro-meteorological indices (i.e., De Martonne, Palmer, Penman, or Walter-Gaussen) to objectively establish whether low annual amounts of rain or lack of precipitation during the vegetation growth period or excessive surface evaporation constitute the "droughts" according to the authors' meanings. The closest approximation to creating an objective measure of the term was attained by Hajek and Espinoza (1988), who draw a Walter-Gaussen's ombrothermal climate diagram of Rapa Nui (see their figures 9 and 10, 1988: 77-79). It emerges from the diagram and comments that, notwithstanding the high insolation and evaporation, no month evidences a sufficient deficit of humidity (rain) to justify qualification as a drought.

To approach this question, we subjected the rainfall data to triad analysis (Table 1). Over the years, March-April-May (MAM), April-May-June (AMJ) and May-June-July (MJJ) turned out to be the wettest regardless of ENSO phase. During strong El Niño events – like those of 1972-73, 1981-82, 1992, and 1997-98 – the autumn rains continued into the mid-winter June-July-August (JJA) triad, signaling the persistence of the summer oceanic warming and high air humidity. In those years no traces of a rainless southern spring or summer are evident to support the contention that El Niño years are dry throughout the seasons (Daude 2008; Mann et al. 2008). Diminished rainfall occurs during the high insolation months of November, December, and January, when no fronts or transient depressions affect the island, and convective rains are scant. Strong sun radiation and cloudless skies convey an impression of lasting aridity. When it is argued that drought means scarce precipitation during the rainy season, a review of the years with annual precipitation below 900 mm – considered dry years in Figure 4 – reveals that the shortages happened during spring and early summer and not in the winter semester. Some deficits of precipitation during the annual peak (AMJ triad) during cold La Niñas of the 1950-1975 sub-period coincide with the spread of cold ocean waters and dry air that were frequent in that period (Philander 2004). However, since 1975 there have been no deficient AMJ triads, instead, conditions turned wetter in consonance with recent global warming. Table 1 illustrates that not all warm events cause increased precipitation, nor do they cause diminished rainfall to support the drought hypothesis. On the other hand,

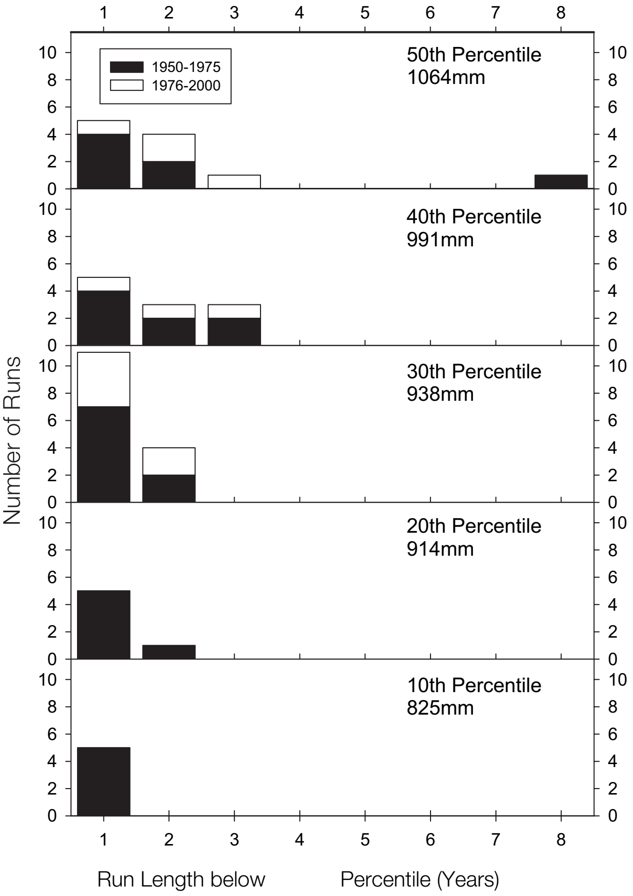

Figure 5. Frequency of the lengths of periods of consecutive years in which total annual precipitation was below various defined levels. The periods are identified as occurring before or after the global climate shift in the late 1970s.

not all cold ENSO events equal dry years. And, since the "neutral" years are a mix of the two, no distinct patterns of extra humidity or dryness can be discerned in looking at either the rainy or the dry triads of these years.

It can be posited that total monthly values do not mean much when rain is concentrated in a few downpours that – due to the high insolation and soil porosity – evaporate quickly. A list of the number of days per month with precipitation amounts above 1mm addresses this issue. Throughout the year, and in each ENSO phase, the number of such events is larger during the rainy months of late autumn and winter, and lesser (but not considerably so) in the dry months of spring and summer (Table 2).

In other words, dryness is not indicative of a low number of rain events; it is a common occurrence during the period of maximum insolation and heightened anti-cyclonic subsidence. Still, during cold phase years an increased number of rain episodes occur in the early spring and summer months, an observation that counters the generalization that during all warm ENSO phases the invasion of tepid waters and humid air increase the levels of rains in the southeastern Pacific. Rains during "neutral" phases are regular throughout, reflecting the prevailing mix of intermediate ocean and air masses, conditions that do not create extremes in the distribution of events per month. As a whole, this examination confirms that the months of the annual rainfall peak also have a higher number of rain episodes than the low-rain summer months. Unusually large numbers of rain events in early spring (September and October) and at the height of summer (January and February) during cold La Niña phases may represent the last signs of an ebbing El Niño episode and the transition into the subsequent cool phase, according to the "canonical sequence" of El Niño proposed by Cane (1983) and Wyrtki (1985). Once again, the opinion that devastating droughts are caused by El Niño or La Niña is not substantiated by this analysis as none of the phases exhibit a monthly number of rain episodes low enough to qualify as prolonged periods of aridity; the same conclusion was arrived at by Genz and Hunt (2003).

Year	*Surplus*	*Deficit*	Year	*Surplus*	*Deficit*
1950		OND	*1975*		AMJ
1951			1976		JFM
1952			1977	MAM	
1953		OND	1978	MAM	
1954			1979	AMJ	
1955			1980	OND	
1956	NDJ		1981	AMJ	
1957	AMJ		**1982**	MAM	
1958	AMJ		**1983**	MJJ	
1959	MAM		*1984*	AMJ	
1960	AMJ		*1985*	MAM	
1961		AMJ	1986	JAS	
1962		SON	1987	AMJ	
1963	AMJ		*1988*		MJJ
1964	OND		*1989*	MAM	
1965	NDJ		1990	JJA	
1966	AMJ		1991	AMJ	
1967		MAM	**1992**	MAM	
1968	MJJ		1993	MAM	
1969		AMJ	1994	MAM	
1970	FMA		1995	AMJ	
1971		AMJ	*1996*	JJA	
1972	MJJ		1997	MAM	
1973	FMA		1998	MAM	
1974	MAM		*1999*	AMJ	
			2000	OND	

Bold: El Niño years *Italics*: La Niña years Normal: Neutral years

Table 1. Triads with surpluses and deficits of rainfall (1950-2000).

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
El Niño	*7.8* ^{C}	9.6 $^{\mathrm{Cn}}$	*10.2* ^{N}	**14.2**	12.6	*9.2*	**13.8**	12.0 $^{\mathrm{cN}}$	*8.2* ^{cN}	*7.6*	*8.2*	*6.6*
Neutral	8.5 $^{\mathrm{C}}$	*9.0* ^{Cw}	12.9 $^{\mathrm{cW}}$	*10.9*	*11.3*	**12.3**	*12.0*	*8.7* ^{W}	8.8 $^{\mathrm{W}}$	8.4	8.5	**10.9**
La Niña			*8.8* ^{n}	12.2	**13.3**	10.3	12.0	12.2 $^{\mathrm{w}}$	**11.0** $^{\mathbf{w}}$	**9.2**	8.7	9.3

In **bold** the highest number in each of the three ENSO phases; values in *italics* are the minima. Superscripts indicate statistically significant differences in values. Upper case at the 0.05 level and lower case at the 0.10 level of significance. The letters indicate significant differences with N = neutral years, C= cold phase years, and W = warm phase years.

Table 2. Mean number of rain episodes with more than 1mm per day in each month (1980-2000).

Dryness is not the result of scarce rain events but is a seasonal recurrence during the high-sun period, which is typical of sub-tropical oceanic islands located in the realm of cold eastern boundary currents (Glantz 2001).

The Pulses of El Niño and La Niña

Since the effects of the ENSO phases on the climate of South Pacific islands were first observed in the early 1970s, significant research has focused on elucidating how these phases operate. In anthropological investigations the phases of ENSO have been mentioned as elicitors of strife and social complexity (Field 2004) with plausible effectiveness. But in other cases the utilization of this concept has been marred by a lack of understanding of its meaning. Until now the analyses of rain and air temperatures of Rapa Nui and their relationship with ENSO have been based on annual or monthly averages that hide substantial variability. Fine-grained data at our disposal has allowed us to establish the monthly and seasonal effects of the *pulses* of ENSO imbedded in the atmospheric and oceanic mechanisms that determine the island's inter-annual variability.

With the purpose of clarifying the magnitude of the relationship, probabilities of occurrences of monthly rain and temperature values from 1970-2000 were calculated. This period is well suited for this type of inquiry, for it includes very warm ENSO episodes in 1972, 1976, 1982, 1983, 1987, 1992, 1993, and 1997 as well as cold events in 1974, 1984, 1989, and 1999. It was expected that the signatures of these pronounced phases would express themselves in rainfall surpluses or deficits. The neutral years should contain a mixture of humid and dry months, and as such should include values similar to those registered during warm and cold ENSO episodes. During the months of maximum precipitation (April, May and June) the observations for the three phases are distributed along the whole array of measured values (see upper overall diagrams in Figure 6a-b-c). Only when the sub-samples are separated by ENSO phases do particular traits emerge (lower diagrams); most cold phase years yield rainfall totals of less than 100mm per month, with a large representation of La Niña values and only a few El Niño values. The wettest months are generally those of neutral years, and not those of warm phase years, given the warmer and wetter conditions in the South Pacific during the autumn and winter months following an El Niño event. Thus, the largest rainfall during the annual peak seems to be *independent* of each of the two opposite ENSO phases. It is also interesting that in June (Figure 6c) – the beginning of the southern winter – the three populations are neatly separated from each other, with cold-phase Junes being the driest, and warm- and neutral-phase Junes the rainiest. Moreover, the largest values of precipitation have fallen during neutral and warm phases, but never during cold phases. The rainiest seasons on Rapa Nui, like those of 1982-83, 1992, 1994 and 1997, occurred during El Niño events. Thus, the assumption that El Niño brings less autumn and winter precipitation to Rapa Nui is not sustained by this finding.

When the distributions of monthly rainfall in the three driest months (October, November, and December; OND triad) are regarded according to ENSO phase (Figure 7a-b-c, lower), a revealing characteristic surfaces – Octobers and Novembers of warm phase years are the driest, followed by those of neutral phases. Perhaps for this reason previous studies have often construed them as droughts, frequently associated with warm ENSOs. Contradicting this view, cold phase OND triads – even when cold seas dominate – exhibit higher precipitation, with the exception of Decembers of neutral phases which tend to be wetter than those of the other phases (Figure 7c).

At the height of the southern summer the picture is particularly complex (Figure 8a-b-c). In January, the highest rainfall occurs during cold phase months and the lowest during El Niño. February's rain distribution shows no discernible pattern; still, the lowest rain amounts fall during cold ENSO phases and the highest during warm phases, announcing the autumn precipitation peak when warm sea temperatures are widespread in the southeastern Pacific.

High precipitation in February and March of warm phases occurs in concomitance with stormy weather over the rest of the South Pacific tropical islands during the summers of El Niño. This is another significant yet unmentioned difference between Rapa Nui and its tropical neighbors, namely the absence of low-latitude cyclones so common on other islands at the height of warm phases punctuated by strong El Niño occurrences (Dupont 1984).

In addition to the pulses of ENSO, other periodicities have been recognized in the Pacific realm (Trenberth et al. 1998). Among them are the Pacific-North America (PNA), the Western Pacific (WP), the Tropical/Northern Hemisphere (TNH), and the Inter-Decadal Pacific Oscillation (IPO). The latter refers to shifts of cold and/or warm waters in the eastern and western quadrants of the northern Pacific, with opposite associations with El Niño and La Niña affecting the central and southeastern Pacific. IPO phases can be up to 20 and 30 years in duration. The quantified expression of IPO is the *IPO Index* developed by Mantua and Hare (2002). During the twentieth century the IPO phases were stimulated by the global warming trend; thus, from the mid-1930s to the mid-1940s, and from the 1980s to the 1990s, when powerful warm ENSO episodes occurred, IPO was particularly energized, while in the 1950s, early 1960s, and end of the 1970s cold IPO phases prevailed. Earth scientists, biologists, anthropologists and archaeologists have keenly applied the decadal cycle to explain variability in their real and proxy time series (Linsley et al. 2000; Salinger et al. 2001; Moy et al. 2002).

Given the relatively short span of the reliable meteorological observations of Rapa Nui and the absence of coral carbon δ^{18} isotope series, it is indeed adventurous to advance any solid statement concerning the influence of IPO

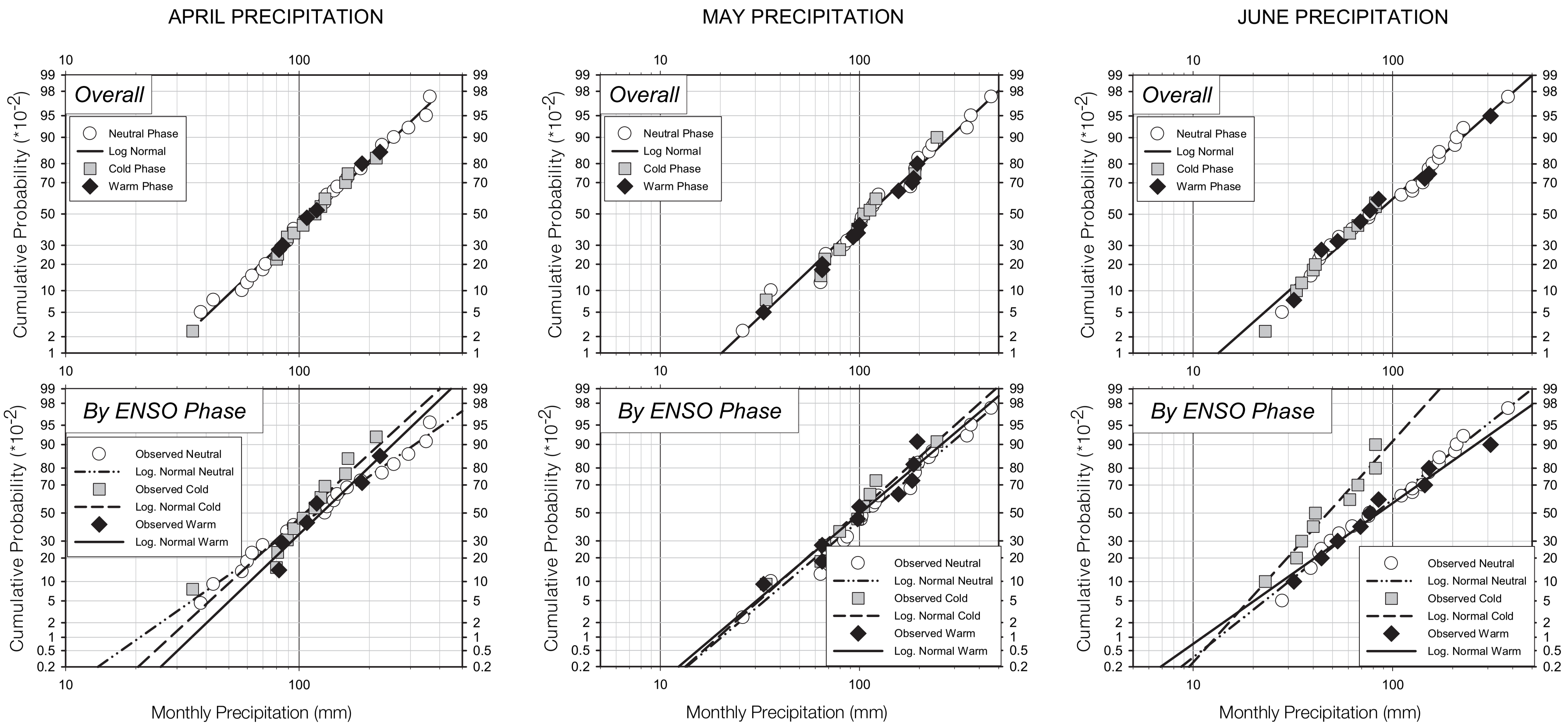

Figure 6. Probability distributions of rainfall totals for (a) April, (b) May and (c) June under the three phases of ENSO. Distributions are plotted jointly in the upper diagrams and separate by phase in the lower diagrams. Diamonds represent warm phases, squares cold phases, and open circles neutral phases.

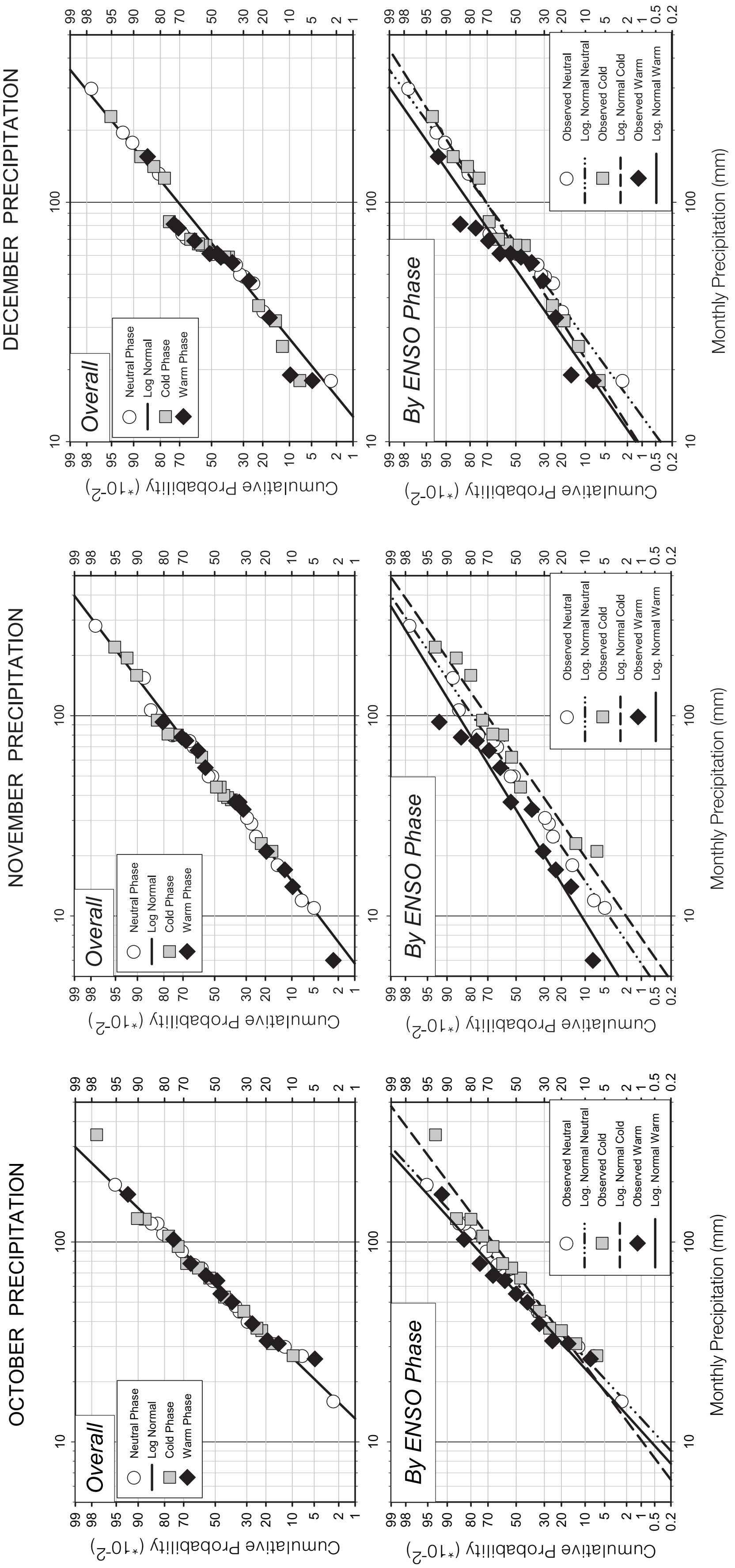

Figure 7. Probability distributions of rainfall totals for (a) October, (b) November and (c) December under the three phases of ENSO. Symbols as in Figure 6.

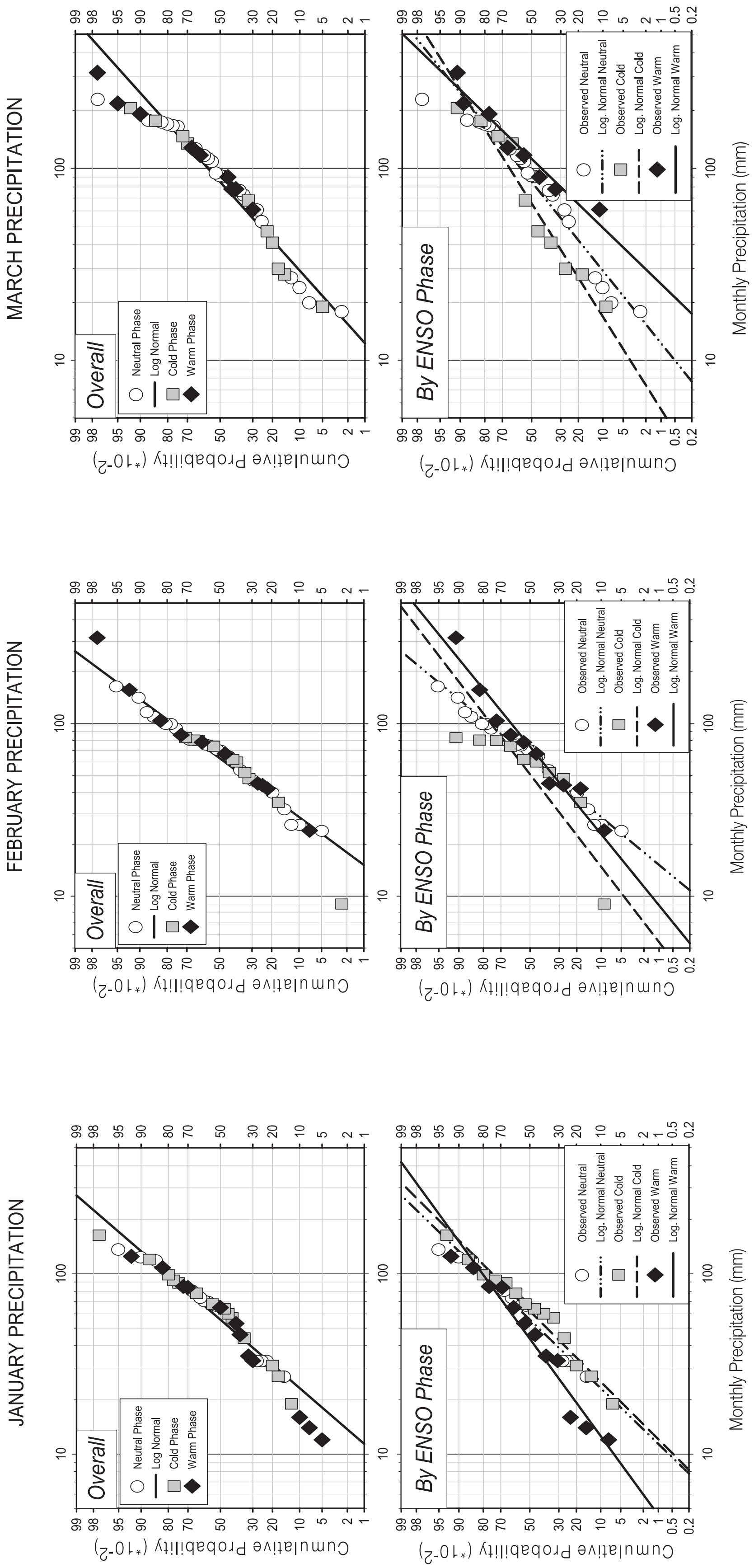

Figure 8. Probability distributions of rainfall totals for (a) January, (b) February and (c) March under the three phases of ENSO. Symbols as in Figure 6.

on the sea and temperatures, or precipitation variability, as has been attempted regarding other Pacific islands. If any clue is to be extracted from the existing meteorological series, the low precipitation years of the 1950s, end of the 1960s, and late 1980s coincided with negative (cold) IPO indices, while the wet mid-1980s and early 1990s were in-phase with raised (warm) IPO indices. Further, the warmest spike of IPO during the 20th century occurred in the early 1940s, a period when El Niño was coeval with decisive weather-influenced moments in world history from 1939 to 1942 (Caviedes 2001).

The Implications of Rapa Nui's Subtropical Location

In the ongoing debate about the ecological effects of climate variability on Rapa Nui, it has been overlooked that this is a "subtropical island" in the middle of a vast maritime realm. Being a subtropical island means that – unlike on tropical islands – the insolation and thermal regime are subject to seasonal changes, whose amplitudes are moderated by the "maritime" setting. Whatever pulse or periodic variability exists in the ocean and atmospheric system is modulated by this latitudinal component. It follows that, when the effects of extreme temperatures on the cultivars introduced by the Polynesian colonists on Rapa Nui are studied, one must be knowledgeable about the limiting role played by low temperatures on exotic cultigens in a subtropical island (Figure 9).

When ecological interpretations are made concerning the implications of extremely high or low air temperatures, it is appropriate to consider how they vary under the phases of ENSO, especially because, as demonstrated in the examination of monthly precipitation, these phases have a bearing in the variability of climate on the island. At the end of the southern summer in March (Figure 10a), the warmest air temperatures are registered in concomitance with the seasonal warming of the subtropical ocean. Higher temperatures have been recorded in neutral years and, to a lesser degree, during warm phase years. Nevertheless, some of the warm phase Marches have been cooler, but others have been exceptionally warm, as during the strong El Niños of 1972-73, 1982-83, 1992, and 1997 (NOAA-Earth Research System Laboratory 2006). As expected, the cooler Marches coincide with cold La Niña sea conditions in the southeastern Pacific.

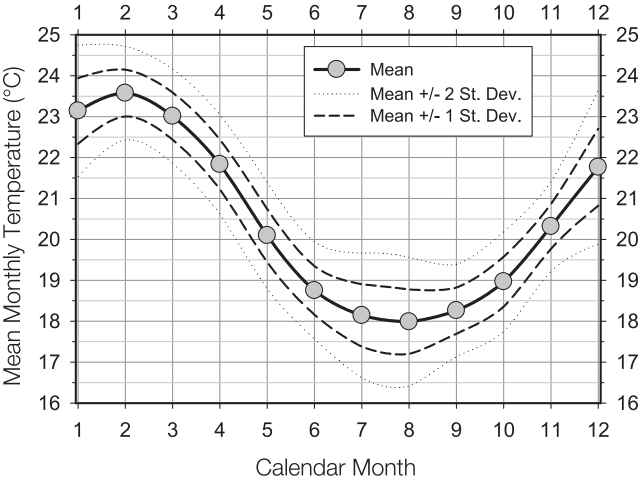

Figure 9. Mean monthly air temperatures plus and minus one and two standard deviations as a measure of inter-annual variability.

At the onset of the southern winter (June solstice), when the air circulation over the sub-tropical South Pacific is energized by frequent frontal passages and cyclogenesis, temperatures are cooler during the neutral and cold ENSO phases. Only in Junes of strong warm phases are the air temperatures seasonally elevated, due to the lingering effect of the summer warming typical of extreme El Niño episodes (Figure 10b).

At the beginning of the southern spring (September equinox) air temperatures on the island are cooler during the cold ENSO phases, with the exception of September 1999 when the highest temperature of the series was registered (see upper right outlier of Figure 10c). The overall warmest September air temperatures occur during "neutral" years' situations, indicating that that month's thermal regime is not ruled by any extreme ENSO phase, but by ocean conditions that normally transit ("neutral" years!) from the previous cool winter into the temperate semester of the subtropical Pacific. When considered under the three phases of ENSO, the air temperatures of December (Figure 10d) exhibit anomalous cool temperatures during warm phases – except in 1968 – and warmer temperatures during neutral phases. Strangely, temperatures during cold phase Decembers are not the coolest and they tend to occur in the triad of lowest precipitation and highest insolation. Warm air temperatures and cooler seas, during a time of year when normally the initial signs of a developing El Niño in the southeastern Pacific become noticeable (Wyrtki 1985), is an indication that the coupling of low annual rainfall and highest annual insolation, added to cold seas, results in dry weather conditions due to the stabilization of the lower atmosphere. This conjunction leads to the belief that *all* El Niño events cause scant precipitation, which are mistakenly referred to as droughts.

These findings prove that high air temperatures on Rapa Nui are not exclusively registered during warm ENSO phases, as generally assumed. Conversely, high temperatures do also occur during the cold and neutral phases. These unconformities defy many accepted views and reveal a dependency on very peculiar oceanic and atmospheric circumstances in the surroundings of Rapa Nui that is not totally understood. Why these special conditions arise is a matter discussed at the end of this article.

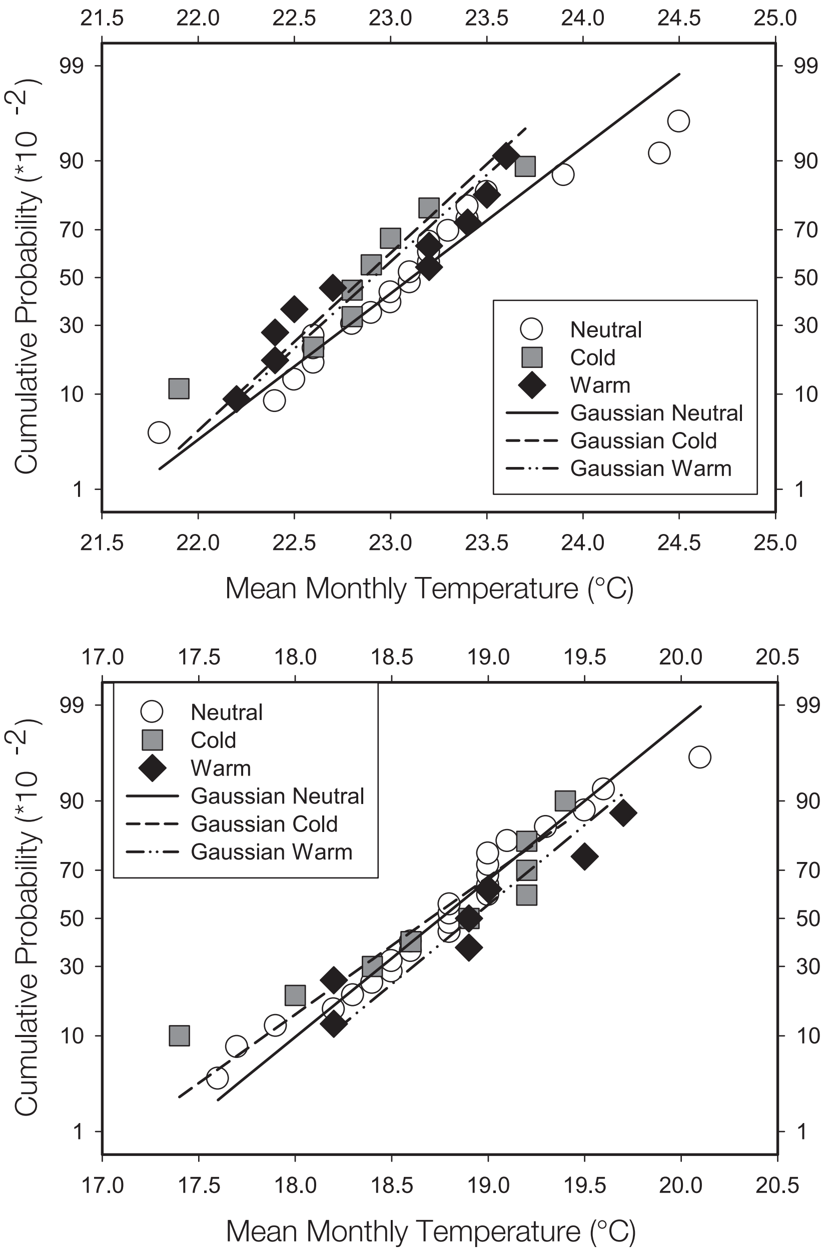

Figure 10a-b [top and bottom]. March and June mean monthly temperatures grouped by ENSO phase. Diamonds denote warm phases, squares cold phases, and empty circles neutral phases.

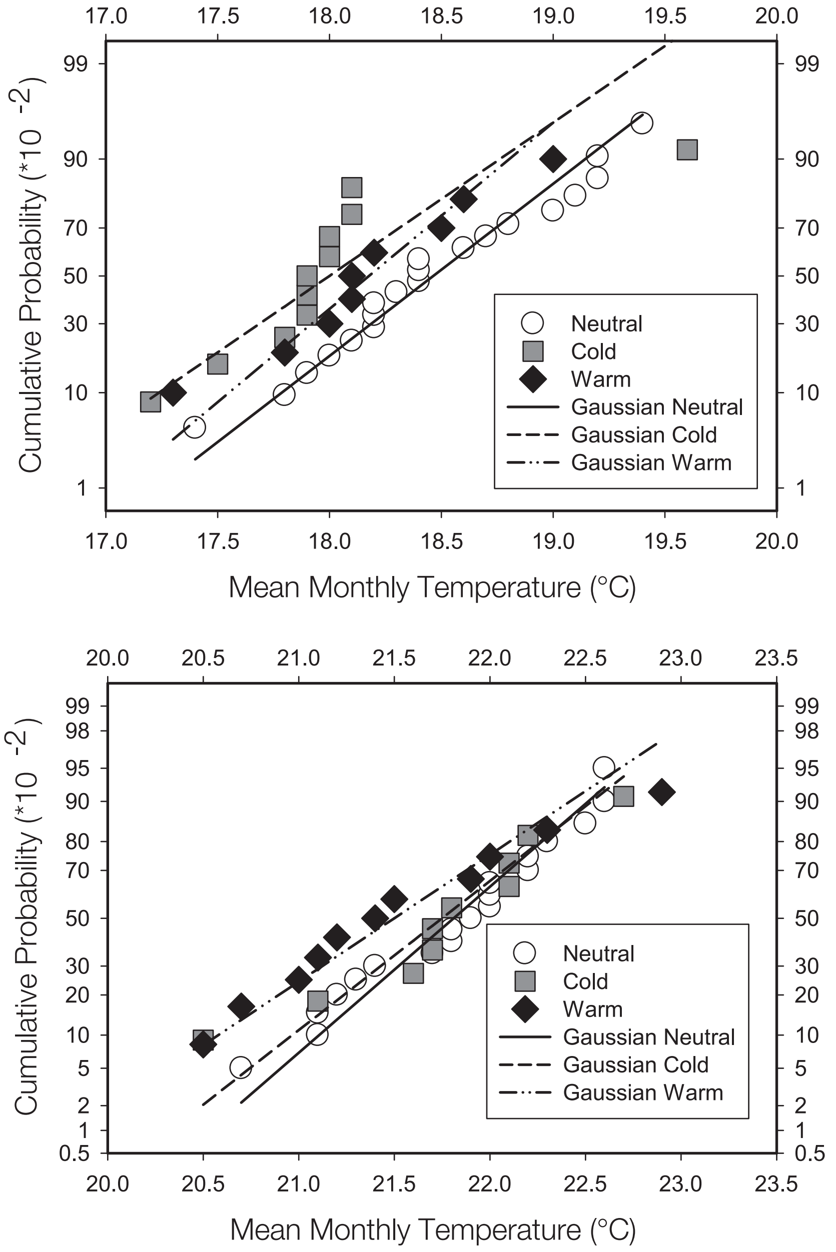

Figure 10c-d [top and bottom]. September and December mean monthly temperatures separated by ENSO phase. Diamonds represent warm phase, squares cold phases, and empty circles neutral phases.

Minimum Temperatures as an Ecological Constraint

A key implication of the sub-tropical location of Rapa Nui and the attendant low-sun elevation in winter is the occurrence of minimum temperatures that impose – and may well have imposed in the past – severe limitations on the tropical plants brought by the Polynesian colonists from their warmer homelands. Critical low temperatures seriously hampered the acclimatization of exotic cultivars. Root crops, like taro and yam, and tubers such as sweet potatoes did well, along with low-temperature tolerant sugar cane and bananas (Louwagie et al. 2006), but the sensitive breadfruit and paper mulberry tree, for example, did not flourish under the winter conditions of the island (Barthel 1978; Yen 1988; Stevenson et al. 1999; Flenley & Bahn 2003).

The ecological implications of minimum temperatures are well illustrated by the calendar of agricultural activities that pointedly reveal the adaptation of cultivated plants to seasonal conditions. Thomas Barthel (1978) compiled the only known calendar of prehistoric Rapa Nui cultivators. From it one learns that sweet potatoes, for example, were planted in March and April, probably to take advantage of the first rains of the year. In May, the beginning of the "cold season", planting was suspended until the end of July "because nothing grows (*tupu meme*)" (Barthel 1978: 52). Annuals were put out in August and tended through spring as solar radiation increased and rain lessened. After the harvest in October a thanksgiving festival (*hakakio*) was celebrated and the cleaning of banana fields started. November and December were a time for community festivities and for active fishing and surfing, because agricultural activities were hampered by "problems with drought" (Barthel 1978: 52). This sequence clearly exposes the limitations imposed by changeable seasonal rains, or a lack thereof, and by the cold winter conditions on planting.

Before assessing the control exerted by winter temperatures it is necessary to note that during the winter solstice the sun at noontime stands on Rapa Nui at a 50° angle above the northern horizon – too low an inclination for tropical plants used to an overhead sun position. During this time of year the northward shift of the mid-latitudinal frontal zone that brings rainfall to the island also takes place, while over the ocean cool and dry winds from the southeast intensify.

The monthly minimum temperatures of the 1980 to 2000 period and their amplitude are graphed in Figure 11. Temperatures in the lower quintile (7.0°C to 11.0°C) are registered exclusively during the southern winter months, reflecting low sun inclination, heightened precipitation and increased cloud cover. The 11.0°C temperature was chosen as a cutoff because it is the upper value of the lower quintile, which, considering the dominance of southeasterly winds, further depresses the minima when the wind chill is taken into account. In fact, June, July and August experience mostly southeasterly flows (Hajek & Espinoza 1988). *Rapa Nui*

Abs. Min. °C	Month-Year	Direction	Frequency	Knots
7.2	7-1997	SE	20 / 88	8
8.0	7-1989	SE	18 / 85	8
8.2	8-1997	NW	34 / 92	11
8.5	7-1994	E	18 / 89	11
8.6	8-1993	N	22 / 91	11
8.7	9-1993	N	21 / 87	19
9.2	7- 1996	SE	27 / 98	9
9.4	10-1996	E	25 / 88	8
9.4	5-1998	SE	24 / 83	10
9.5	8-1988	SE	27 / 92	13
9.5	7-1991	E	23 / 93	9
9.6	8-1994	E	31 / 97	8
9.7	8-1980	SE	27 / 59	10
9.7	9-1997	SE	27 / 97	12
9.8	8-1995	SE	29 / 91	10
9.9	6-1992	E	38 / 95	10
9.9	10-2000	SE	28 / 87	11
10.0	8-1983	SE	30 / 90	11
10.0	10-1984	E	19 / 88	12
10.0	9-1990	SE	31 / 89	10
10.0	8-1996	SE	26 / 87	9
10.2	7-1988	E	29 / 82	7
10.2	10-1994	SE	30 / 86	10
10.3	8-1984	E	27 / 89	7
10.3	6-1995	N	10 / 81	7
10.4	8-1982	W	19 / 82	15
10.4	6-1987	E	22 / 75	10
10.5	9-1986	SE	22 / 90	10
10.6	6-1996	S	22 / 85	7
10.6	10-1996	E	25 / 92	8
10.6	10-1997	E	34 / 89	8
10.8	9-1983	NE	16 / 92	8
10.8	10-1983	SE	33 / 88	11
10.8	9-1987	N	17 / 90	10
10.8	7-1993	E	22 / 89	8
10.8	9-1983	NE	16 / 82	8
10.9	6-1991	W	28 / 90	16
10.9	7-1999	E	22 / 75	10
11.0	6-1989	SE	28 / 87	11
11.0	9-1991	SE	23 / 74	13

Bold: El Niño years *Italics*: La Niña years Normal: Neutral years

Table 3. Absolute minima, date, wind direction, frequency, and velocity.

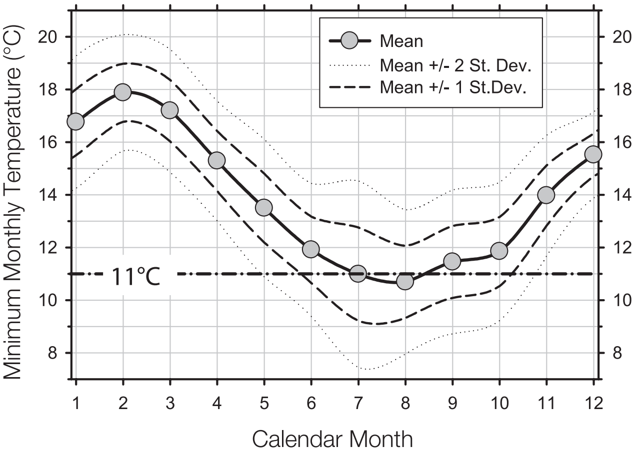

Figure 11. Monthly minimum temperatures and amplitude (1 and 2 standard deviations). The 11°C line represents the critical lower boundary for sensitive tropical cultivars.

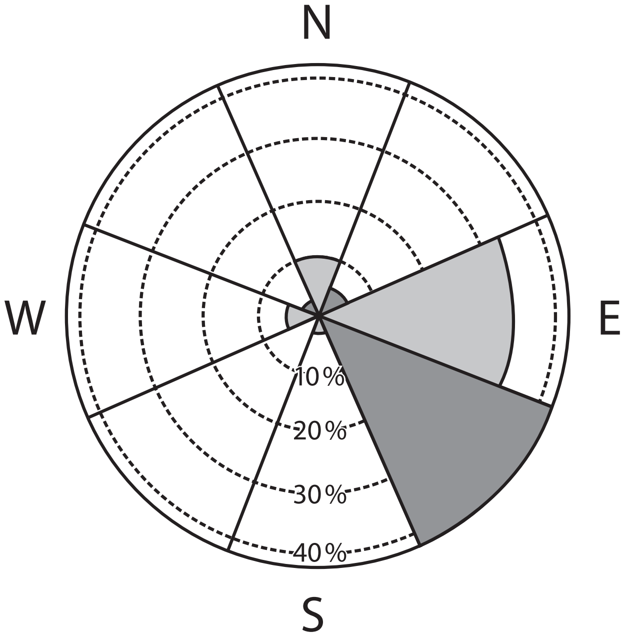

Figure 12. Direction of the most frequent winter winds on Rapa Nui.

Journal readers who review numerous articles dealing with archaeological work on the island will be surprised – as we certainly were – to see researchers in wind breakers or winter gear that seem out of place on a Polynesian island.

Table 3 synthesizes the meteorological conditions under which temperatures below 11.0°C were recorded from 1980 to 2000. Note that these minima occurred under all three phases of ENSO, that is, regardless of the thermal conditions of the ocean. Nearly 75% of the low temperatures were related to southeasterly and easterly winds sweeping over the open ocean between the coast of Chile and Rapa Nui (Figure 12). During the winter months, the flow of southeasterly winds is interrupted by northerly or northwesterly wind outbreaks associated with passing fronts and transient depressions (Hajek & Espinoza 1988). But the southeasterly winds, blowing over the cold waters of the southeastern Pacific, and unabated by any physical barrier, affect the east coast and the unprotected southeast slopes of the island unimpeded.

Winds from the SE and E are particularly intense during the winters of neutral years and cold La Niña episodes, while northerly and northwesterly flows increase in frequency during El Niño events. Powerful outbreaks of northwesterly and northerly winds during El Niño have been cited as decisive contributors to the Polynesian seafarers' ability to reach Rapa Nui against the prevailing ocean currents and southeasterly winds (Caviedes & Waylen 1993). The impact of the seasonal northwesterly and westerly winds is felt mostly along the steep west coast of the island, their effect on lowering temperatures being secondary, as shown in Table 3.

The relevance of dominant winds for the island's vegetation distribution is underscored by the location of crop land and patches of woody species on protected leeward locations and inside deep sheltered ravines. Shrubs and recently introduced arboreal species tend also to cluster in flat-bottomed basins (*hondonadas*) in the central part of the island, while they are less frequent along the exposed southern coast (Figure 13). This treatment of the relationship between rainfall and temperatures with ENSO phases, complimented by the review of minimum temperatures and dominant winter winds, provides a basic frame of reference for understanding the limiting ecological conditions encountered by Polynesian colonizers on Rapa Nui: and those were challenging at the least. Research by Ladefoged et al. (2010) synthesizes the limitations imposed by winds, soil water retention, and limiting temperature conditions that forced Rapanui dwellers to develop gardening alternatives suited to site and terrain attributes to cope.

The advances made in prehistoric Rapa Nui environmental reconstructions and farming practices have led to the acknowledgement that catastrophic climatic variability and reckless spoilage did not prompt the cultural decline of Rapa Nui, but that – from the beginning of settlement – the natural conditions were less propitious in this Polynesian enclave than in the colonizers' tropical homelands. The meteorological evidence presented in this paper prompts us to concur with Louwagie (2004) that Rapa Nui's colonizers settled on a subtropical island whose supporting potential was more restricted than in other larger Polynesian outposts. So, what they achieved under those adverse circumstances is really remarkable. Trying to explain the reasons for their ultimate demise by resorting to doubtful or insufficiently documented natural catastrophes of the past (e.g., Nunn 2000, 2003) introduces the bias of accepting them as undisputable tenets to explain cultural break-up and social upheaval.

Figure 13. View of Rapa Nui's southern coast looking north-east. Far on the horizon is the Poike Peninsula and the summit of Maunga Terevaka is off to the left, just out of the picture. (Photo by C.N. Caviedes).

Discussion

Improper characterizations of the climate of Rapa Nui have led to erroneous assessments of its ecological potential. The detailed examination of precipitation, temperature and winds has brought to the fore weather features that had remained vague when averages or incomplete time series were utilized. Rapa Nui is still considered by many authors to be just another "tropical island" in the South Pacific and this misnomer has predisposed many researchers to faulty interpretations of its environmental foundations. The analysis of rainfall distribution throughout the year as well as the monthly mean and minimum temperatures of the island offer concrete proof of the differences between Rapa Nui and its tropical counterparts. Careful inspection of the minimum temperatures and their relationships with cold southern winds offer an insight into the difficulties faced by tropical cultivators to secure and expand the fields of staples needed to support a growing population. It is not necessary to explain famines and ensuing social turmoil (e.g., Nagarajan 2006) by invoking "catastrophic droughts" when it is clear that the limited supporting capacity of the tiny island was due to its restrictive climatological and geological bases.

Another point that has been improperly investigated is the role of the ENSO phases – the main pace-maker of long-term climate in the South Pacific – on the inter-annual variability of precipitation, temperatures and winds on Rapa Nui. The meteorological records used in this article cover the second half of the twentieth century and document in finer detail the last three decades, a period in which major fluctuations affected the world's climate, one of them being the repeated and brisk variations of El Niño-Southern Oscillation. Since ENSO is berthed in the South Pacific, it follows that its variations have implications for the atmospheric-oceanic systems operating around Rapa Nui, and more so when its influence on climates around the world has increased since the late 1970s.

Tracing the imprint of ENSO phases on rain amounts and air temperatures on the island is, however, not a simple task. As attested by the analyses of monthly rainfall and air temperatures, warm seas and increased humidity during the warm phases, and cool waters and dryness during the cold phases, are not as explicit as one would expect. Only under very accentuated warm phase conditions is there a marked increase of humidity on Rapa Nui, and La Niña does not always bring dryness on the island. What are the reasons for this lack of consistent association?

First, there is a problem with the location of the stations where the air pressure is measured to calculate the *Southern Oscillation Index*, i.e., the standardized difference between sea-level pressures at Darwin, northern Australia, and Pape'ete, Tahiti. These stations are located 4,800 miles apart. Now, considering that Rapa Nui lies 2,900 miles *southeast* of Tahiti (the eastern pole of the Southern Oscillation) it is easy to grasp that air pressure, surface winds, and oceanic conditions must be different for both. Moreover, with Rapa

Nui lying at the core of the South Pacific anticyclone, it does not reproduce the pressure differences between Darwin and Pape'ete. Its location further east than the eastern pole of the Southern Oscillation, and at subtropical latitude, explains the inconsistencies between Rapa Nui's humidity and temperature values and those of "neighboring" Pacific islands.

Second, at latitude 27°S and longitude 110°W, Rapa Nui is subject to ocean and atmospheric controls different to those of tropical South Pacific islands. In fact, while its tropical counterparts experience year-round warm seas, the waters of Rapa Nui reflect their proximity to the *subtropical oceanic front* – i.e., the encounter zone of tepid tropical waters and the cooler masses known as SPESMW, or "South Pacific Eastern Subtropical Mode Water" (Hanawa & Talley 2001). In the southeastern Pacific, between longitude 105°W and the South American coast (long. 75°W), the Subtropical Oceanic Front runs diagonally to the northeast due to the intrusion (plume) of the cold Peru Current from the west (Tsuchiya & Talley 1998). It must be borne in mind that the SPESMW, the Subtropical Oceanic Front, and the Peru Current are parts of the gyre known as the Eastern Pacific Boundary Current, which is a closed circuit (Clarke et al. 2001). Depending on the eastward expansion of the heated ocean during the warm phases of ENSO (El Niño), or its contraction during the cold phases (La Niña), Rapa Nui's regime of rainfall and air temperatures are affected, or not, by these anomalies. But – as stated previously – not all El Niños or La Niñas have similar effects: only during extreme El Niños and very severe La Niñas are the widespread weather conditions exactly opposite. Geodating based on Sr/Ca isotopes at Rarotonga (Cook Islands, 21°S, 175°W) have established that most El Niños display cooler sea conditions (Linsley et al. 2008) than in tropical locations *east* of longitude 150°W, which constitute the prime El Niño regions 1, 2 and 3. These disagreements have their reasons in the long-established and conventional identification of El Niño as the positive ocean anomalies recorded within a 5°N-5°S band of waters at both sides of the Equator. Since this arbitrary band runs more than 20 degrees north of Rapa Nui, it is understandable that the effects of equatorial ocean variations are neither identical, nor simultaneous on that distant subtropical island (NOAA/Climate Prediction Center 2010: 5).

Finally, let us return to the question of the applicability of an actualistic model to interpret past climatic variations. The analysis of half a century of data can provide helpful hints about conditions in the past, particularly when one considers that 1950 to 2000 was a period of convulsive variability elicited by contemporary global warming. These oscillations exacerbated the frequency and magnitude of extreme ENSO events, probably in the same manner in which similar cooling and warming influenced oceanic and climatic variability in the not-documented past. It can be argued that the oscillations of 1950-2000 are similar to the ones experienced by the Polynesian settlers on Rapa Nui. Sound climate reconstructions (Mann et al. 1999; Briffa & Osborn 2002) suggest that the global climate of the millennium from A.D. 1000 to 2000 was punctuated by cooler and warmer events similar to those of the 20th century, but not as intense because there was no upward trend as in the present. Palynological investigations of lacustrine sediments on Rapa Nui have revealed vegetation assemblages (Azizi & Flenley 2008) that differ from those of the tropical rain forests of other Pacific islands, and are more attuned with the moderate maritime climate of Rapa Nui today. Such evidence does not support the claim that the collapse of Rapa Nui's culture was owed to catastrophic droughts, coupled with wanton deforestation. Robust palynological research (Dumont et al. 1998; Butler & Flenley 2010) indicates that the island in the past was not significantly drier than at present, and that – on the other hand – it lacked the large arboreal species of the humid forests of neighboring islands (Banack 1991). In a study of charcoal residues, Orliac and Orliac (2005) cautiously cite no more than three mid-size arboreal species. By far, the most imposing species on Rapa Nui was the now-extinct Rapa Nui *coquitos* palm (Mieth & Bork 2006), a relative of central Chile's *Jubaea spectabilis* that grows in a mesophytic ecosystem. Past vegetation assemblages suggest a climate whose variability oscillated within the bounds of contemporary maritime subtropical climates (Trenberth & Smith 2006), but that was never drier. The interplay of air masses, ocean dynamics, rain processes, air temperature factors, and wind variability on Rapa Nui is still not fully understood as to furnish definite answers to the question of whether the environmental decay of Rapa Nui was caused by climate change, human intervention, or disruptive biological pests. In this context, the present article is to be considered as a qualified contribution to the debate about the effects of climate variability on the culture that once flourished on Rapa Nui.

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References

Allen, M.S. 2006. New ideas about late Holocene climate variability in the central Pacific. *Current Anthropology* 47:521-35.

Azizi, G. & J.R. Flenley. 2008. The last glacial maximum climatic conditions on Easter Island. *Quaternary International* 184:166-176.

Banack, S.A. 1991. Plants and Polynesian voyaging. In *Islands, plants and Polynesians. An introduction to Polynesian ethnobotany*. P.A. Cox and S.A. Banack (eds.):25-40. Portland: Dioscorides Press.

Barthel, T.S. 1978. *The Eighth Land: Polynesian discovery and settlement of the Easter Island*. Honolulu: University of Hawai'i Press.

Briffa, K.R. & T.J. Osborn. 2002. Blowing hot and cold. *Science* 295:227-228.

Butler, K.R. & J.R. Flenley. 2010. The Rano Kau 2 Pollen Diagram: Palaeoecology Revealed. *Rapa Nui Journal* 24(1):5-10.

Cane, M.A. 1983. Oceanographic events during El Niño. *Science* 222:1189-1194.

Caviedes, C.N. 2001. *El Niño in History*. Gainesville: University Press of Florida.

Caviedes, C.N. & P.R. Waylen. 1993. Anomalous westerly winds during El Niño/Southern Oscillation events: The discovery and colonization of Easter Island. *Applied Geography* 13:123-134.

Chavez, F.P., J. Ryan, S. Lluch-Cota & M. Niquen. 2003. From anchovies to sardines and back: multidecadal change in the Pacific Ocean. *Science* 299:217-221.

Clarke, A., J. Church & J. Gould. 2001. Ocean processes and climate phenomena. In *Ocean Circulation and Climate.* G. Siedler, J. Church, and J. Gould (eds.):11-30. San Diego: Academic Press.

Daude, J.H. 2008. *Mega El Niño et déforestation de Île de Pâques.* Quebec: Edition priveé.

Dumont, H.J., C. Cocquyt, M. Fontugne, M. Arnold, J-L. Reyss, J. Bloemendal, F. Oldfield, C.L.M. Steenbergen, H.J. Korthals, & B.A. Zeeb. 1998. The end of moai quarrying and its effect on Lake Rano Raraku, Easter Island. *Journal of Paleoliminology* 20:409-422.

Dupont, J.-F. 1984. Where the exception confirms the rule: The cyclones of 1982-1983 in French Polynesia. *Disasters* 8:34-47.

Field, J.S. 2004. Environmental and climatic considerations. A hypothesis for conflict and the emergence of social complexity in Fijian prehistory. *Journal of Anthropological Archaeology* 23:79-99.

Flenley, J.R. & P. Bahn. 2003. *The enigmas of Easter Island: Island on the Edge*. Oxford: Oxford University Press.

Genz, J. & T.L. Hunt. 2003. El Niño/Southern Oscillation and Rapa Nui prehistory. *Rapa Nui Journal* 17:7-14.

Glantz, M.H. 2001. *Currents of Change: Impacts of El Niño and La Niña on Climate and Society.* New York: Cambridge University Press.

Graham, N. 1994. Decadal-scale climate variability in the Tropical and North Pacific during the 1970s and 1980s – Observations and model results. *Climate Dynamics* 10:135-162.

Hajek, E. & G.A. Espinoza. 1988. Meteorología, climatología y bioclimatología de las Islas Oceánicas Chilenas. In *Islas oceánicas chilenas: Conocimiento científico y necesidades de investigación*. J.C. Castilla (ed.):55-84. Santiago: Ediciones Universidad Católica de Chile.

Hanawa, K. & L.D. Talley. 2001. Mode waters. In *Ocean Circulation and Climate.* G. Siedler, J. Church, & J. Gould (eds.):11-30. San Diego: Academic Press.

Hunt, T.L. & C.P. Lipo. 2006. Late colonization of Easter Island. *Science* 311:1603-1606.

Intergovernmental Panel on Climate Change. 2007. *IPCC Fourth Assessment Report: Climate Change 2007.* Geneva: IPPC.

Ladefoged, T.N., C.M. Stevenson, S. Haoa, M. Mulrooney, C. Puleston, P.M. Vitousek & O.A. Chadwick. 2010. Soil nutrient analysis of Rapa Nui gardening. *Archaeology in Oceania* 45:80-85.

Levitus, S., J.L. Antonov, T.P. Boyer, & C. Stephens. 2000. Warming of the world ocean. *Science* 287:2225-2229.

Linsley, B.K., Wellington, G.M. &D.P. Schragg. 2000. Decadal sea surface temperature variability in the subtropical South Pacific from 1726 to 1997 A.D. *Science* 290:1145-1148.

Linsley, B.K., P. Zhang, A. Kaplan, S.S. Howe & G.M. Wellington. 2008. Inter-Pacific decadal climate variability from multicoral oxygen isotope records in the South Pacific Convergence Zone region since 1650 A.D. *Paleooceanography* 23:PA2219 1-16.

Louwagie, G. 2004. Palaeo-environment reconstruction and evaluation based on land characteristics on archaeological sites. Case study 1: Verrebroek "Dok" and Doel "Duerganckdok"; Case study 2: Easter Island. Unpublished PhD Dissertation, University of Ghent.

Louwagie, G., C. M. Stevenson & R. Langhor. 2006. The impact of moderate to marginal land suitability on prehistoric agricultural production and models of adaptive strategies for Easter Island (Rapa Nui, Chile). *Journal of Anthropological Archaeology* 25:290-317.

Mann, D., J. Edwards, J. Chase, W. Beck, R. Reanier, M. Mass, B. Finney, & J. Loret. 2008. Drought, vegetation change, and human history on Rapa Nui (Easter Island). *Quaternary Research* 69:16-78.

Mann, M.E., R. Bradley, & M.K. Hughes. 1999. Northern hemisphere temperatures during the past millennium: inferences, uncertainties, and limitations. *Geophysical Research Letters* 26:759-762.

MacIntyre, F. 2001. ENSO, climate variability, and the Rapa Nui. Part I. *Rapa Nui Journal* 15(1):17-26.

Mantua, N.J. & S.R. Hare. 2002. The Pacific decadal oscillation. *Journal of Oceanography* 58:35-44.

Mason, S.J. 1996. Climatic change over the Lowveld of South Africa. *Climatic Change* 32:35-54.

Meehl G.A, A. Hu, & B.D. Santer. 2009. The mid-1970s climate shift in the Pacific and the relative roles of forced versus inherent decadal variability. *Journal of Climate* 22:780-792.

Mieth, A. & H.-R. Bork. 2006. The dynamics of soil, landscape and culture on Easter Island (Chile). In *Soils and societies. Perspectives from environmental history*. J.R. McNeill and V. Winiwarter (eds.): 273-320. Isle of Harris: White Horse Press.

Moy, C.M., G.O. Seltzer, D.T. Rodbell, & D.M. Anderson. 2002. Variability of El Niño/Southern Oscillation activity at millennial timescales during the Holocene epoch. *Nature* 420:162–65.

Nagarajan, P. 2006. Collapse of Easter Island: lessons for sustainability of small islands. *Journal of Developing Societies* 22:287-301.

Nunn, P.D. 2000. Environmental catastrophe in the Pacific islands around A.D. 1300. *Geoarchaeology* 15:715-714.

Nunn, P.D. 2003. Revising ideas about environmental determinism: human-environment relations in the Pacific Islands. *Asia Pacific Viewpoint* 44:63-72.

NOAA-Earth Research System Laboratory. 2006. *Comparison of Different El Niño and La Niña Events*. http://www.esrl.noaa.gov/psd/enso/enso.different.html

NOAA/Climate Prediction Center. 2010. *ENSO Evolution, Status and Prediction*. July 2010.

Orliac, C. & M. Orliac. 2005. La flore disparue de l'Ile de Pâques. *Nouvelles de l'Archéologie* 102:29-33.

Philander, S.G. 2004. *Our affair with El Niño: How we transformed an enchanting Peruvian current into a global climate hazard*. Princeton: Princeton University Press.

Peña, O. & H. Romero. 1976. Rutas ciclonales en el Pacífico Sur: situaciones de primavera y verano. *Revista del Pacífico Sur* 5:113-127.

Power, S., T. Casey, C. Folland, & V. Mehta. 1999. Inter-decadal modulation of the impact of ENSO on Australia. *Climate Dynamics* 15:319-324.

Romero, H. 1985. *Geografía de los Climas. Geografía de Chile.* Vol. XI. Santiago de Chile: Instituto Geográfico Militar.

Salinger, M.J., J.A. Renwick & A.B. Mullan. 2001. Interdecadal Pacific oscillation and South Pacific climate. *International Journal of Climatology* 21(14):1705-1721.

Stenseth, N.C. & K.L. Voje. 2009. Easter Island: climate change might have contributed to past cultural and societal changes. *Climate Research* 39:111-114.

Stevenson, C.M., J. Wozniak, & S. Haoa. 1999. Prehistoric agricultural production on Easter Island, Rapa Nui, Chile. *Antiquity* 73:801-812.

Trenberth, K.E. & L. Smith. 2006. The vertical structure of temperature in the tropics: different flavors of El Niño. *Journal of Climate* 19:4956-4973.

Trenberth, K.E., G.W. Branstator, D. Karoly, A. Kumar, N. Chau, & C. Ropelewski. 1998. Progress during TOGA in understanding and modeling teleconnections associated with tropical sea surface temperatures. *Journal of Geophysical Research* 103:14291-14324.

Tsuchiya, M. & L.D. Talley. 1998. A Pacific hydrographic section at 88°W: water property distribution. *Journal of Geophysical Research* 103:12899-12918.

Wang, B. 1995. Interdecadal changes in El-Nino onset in the last four decades. *Journal of Climate* 8:267-285.

Wyrtki, K. 1985. Water displacements in the Pacific and the genesis of El Niño cycles. *Journal of Geophysical Research* 90:7129-7132.

Yen, D.E. 1988. Easter Island agriculture in prehistory. The possibilities of reconstruction. In *First International Congress: Easter Island and East Polynesia. Volume I: Archaeology*. C. Cristino, P. Vargas, R. Izaurieta and R. Budd (eds.): 50-81. Santiago de Chile: Instituto de Estudios Isla de Pascua, Universidad de Chile.

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