Title

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Author

Winterhalder, Bruce

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CHAPTER TWO

The Ecological Basis of Water Management in the Central Andes: Rainfall and Temperature in Southern Peru

BRUCE WINTERHALDER
University of North Carolina, Chapel Hill

> *The noble proportions of the Peruvian Andes and their position in tropical latitudes have given them climatic conditions of great diversity. . . . The greatest variety of climate is enjoyed by the mountain zone. Its deeper valleys and basins descend to tropical levels; its higher ranges and peaks are snow-covered. Between are the climates of half the world compressed . . . with extremes only a day's journey apart.*
>
> –Isaiah Bowman, *The Andes of Southern Peru*

INTRODUCTION

The peasant farmer in the Andes studies the clouds with an interest that is palpable. Sufficient and timely precipitation determines the abundance of the harvest and therefore the degree to which the family's diet and income will be adequate for the coming year. Weather is as important as soil, seed, and labor in agricultural production, but it is less amenable to control. In the marginal agricultural lands of the high Andes its effects can be sharp and its pattern capricious.

In this paper I describe seasonal patterns of precipitation and temperature in the southern Peruvian portion of the central Andes. The analysis is based on data collected from various weather services in the mountains of southern Peru. It relies on concepts (predictability) that portray better than the standard ranges and averages how weather and climate actually affect agriculture and human adaptation.

As observed by Bowman (1968[1916]) and virtually every other geographer or anthropologist who has spent time there, the Andes confront the human ecologist with an astounding diversity of ecozones and environmental conditions. The agro-ecological regions encompassed within a transect across these mountains offers rich materials for comparative analysis. Although the data presented here indirectly may aid in the analysis of prehistoric and historic developments in the Andes, I focus on comparative features of climate as evident in the weather recorded over approximately the last twenty-five years.

In the context of the present volume, I envision irrigation as an attempt to mediate between the sometimes fickle patterns of weather and the always exacting schedule of agricultural crops. To understand irrigation design, management, and effectiveness, we must know how these are influenced by the quantity, patterning, and predictability of the precipitation that initiates the terrestrial portion of the hydrological cycle. Thus, our study of the clouds takes up some of the same issues that inspire the attention of the Andean peasant.

THE ANDEAN LANDSCAPE

From Juliaca (near the Peruvian end of Lake Titicaca), the road to Sandia heads northeast across the Altiplano. Past the town of Putina, it gently ascends an upvalley grade following a small river. Leaving the stream, the road banks abruptly upward through a series of switchbacks to a 4,650 meter crest. Here it offers a spectacular view northeast across the Carabaya basin. The vista is breathtaking, aesthetically and physiologically. This part of the Carabaya is known as the Ananea plateau. It is a high plain elevated even above the Altiplano. Far across the plateau to the northeast lies a single row of glaciated summits (the Cordillera Oriental, Nevado Nacarro, and Nevado Ananea), and beyond them, the great cauldron of the Amazon Basin. The broken line of peaks marks the sharp break between the flat, high puna and the steep eastern escarpment, the plunging descent of the mountains into the lowland tropical rain forests.

If one looks backward toward the southwest, toward the landscape just traveled, the road descends to the Altiplano through foothills of exposed sedimentary formations. The contorted stratigraphy is twisted into whorls of brown, red, and mauve that rise here and there above the peneplain, testimony to the immense pressures that folded and buckled the earth to create these mountains. Not visible, but in this same direction 250 kilometers distant, is the western edge of the Altiplano, the Cordillera Occidental. Beyond this chain of high snow covered ridges the western escarpment descends to the cool, coastal deserts that border the Pacific.

This spot above the Carabaya plain is a good geographical vantage from which to consider the climate of these mountains.

The central or tropical Andes form a massive barrier perpendicular to the prevailing easterly winds of the southern hemisphere. This positioning determines the large-scale features of their climate. Air that is moisture laden from the Atlantic and its trip across the Amazon Basin forms into fog and rain clouds as it ascends the slopes of the eastern escarpment. From April through August this upslope flow affects only the lowermost elevations, but as the humidity increases and winds intensify in September and October–coincident with the southward displacement of the seasonal trade winds (Sarmiento 1986:12)–the precipitation belts extend upslope and eventually lap onto and across the Altiplano. They reach as far to the southwest as the upper portions of the western escarpment. Beyond this point, nearly depleted of moisture and more retentive of the residual water vapor because of downslope movement, expansion, and warming, the winds quickly lose their capacity to release moisture. Precipitation attenuates in quantity and duration. At the lowest elevations on the western escarpment, coastal meteorological stations may go years without recording even a trace of precipitation.

By March the winds weaken. The clouds and precipitation retreat northeast. The Altiplano rainy season ends. The scattered bunch grasses of the high plains turn dry and brown. The night air becomes colder. In this tropical zone, seasonal changes of temperature depend more on cloud cover than on changes in solar insolation. Hence they coordinate with, in a sense are secondary to, the clouds and rain.

Within the compass of this broad pattern there is considerable and only partially predictable variation. The rains may come early or late, in regular or irregular monthly distribution, and in quantities varying from drought to flood. The deeply incised, topographically spectacular relief of the Andes complicates the pattern with localized rain shadow and orographic effects, and with exposure to frost from the downslope pooling of cold air. Incessant wind, intense radiation, thin soils and steep slopes further differentiate the landscape by reducing the physiological availability of water to plants. Desiccation threatens when the rains are too little, erosion when the rains are too much.

At the spring periods of transition (roughly, October and April), the seasonal pulse of rainfall onto the upper escarpments and central basins of the Andes is visible from the Carabaya overlook. One can look through the gaps between the peaks onto the top of the clouds boiling upward from the humid forests below. Occasionally, great tongues of fog will push through the passes and roll like a flow of white vaporous lava onto the plains. Depending on the season, these upwellings of cloud signal the advance or the hesitant retreat of the great pulse of moisture that gives birth to the high Andean rainy season.

GEOECOLOGY, HISTORY AND ADAPTATION

The natural elements of climate are prominent in Andean literature, perhaps partly because they are overwhelming to scientific visitors. The humans and the domesticated animals and plants inhabiting the zone push hard against real physiological limits set by climate and altitude. Compared to temperate zones, it is not a salubrious environment for the production of food, although some of the same qualities that make it difficult have been fashioned into the raw materials of human adaptation (Murra 1984).

Carl Troll (1960, 1968) introduced the term *geoecology* to describe the constellation of environmental features that dominate life in the southern hemisphere's tropical high mountains. He has comprehensively described their broad geographical outlines (see also Bowman 1968[1916]; Winterhalder and Thomas 1982; Molina and Little 1981). A key climatic observation is that of the *diurnal temperature climate* (Bowman 1968:19). By virtue of tropical latitude, the central Andes[1] experience minimum seasonal variation in temperature and day length. For instance, at 10° from the equator the summer-to-winter solar insolation difference is only 20 percent. At 50° from the equator it nearly is 400 percent (Sarmiento 1986:11). However, because of high altitude the mountain valleys and plateaus experience pronounced day-to-night thermal differences. The same clear, thin atmosphere that makes the overhead solar insolation intense during the day does little to impede the rapid radiative loss of ground level heat at night. Diurnal variation can be as great as 25°C during the dry season. During the wet season this effect is somewhat reduced. Moist air and cloud cover act to retain warmth, especially at night. Despite this, nighttime frosts can occur in any month of the year in high-elevation agricultural zones.

Prehistoric Patterns

Secular changes as well as short-term fluctuations in the mountain climate play a major role in archaeological explanations of Andean prehistory. Considering the long term, Kent (1987) notes that three types of prehistoric evidence–shrinkage of the Quelccaya glacial ice cap near Cuzco, retreat of Amazonian forests, and a shift of the diet of populations located along the southern shore of Lake Titicaca (Chiripa, Bolivia) toward greater dependence on lacustrine resources–converge to suggest a period of aridity on the Altiplano from 750 B.C. to A.D. 350. These environmental indicators parallel sociopolitical shifts in the highland polities of Tiwanaku and Pukara. These societies apparently contracted and consolidated their Altiplano realms while developing relationships of trade and exchange with settlements on the lower altitude ecozones of the two escarpments. Kent argues that the centralization of political control and its reorientation along a geographical axis of ecological diversity were both stimulated by prolonged drought.

Similarly, Cardich marshalls evidence in favor of the thesis that climate variations "rather than changes in settlement pattern, land tenure and other human and cultural factors were primarily responsible for major fluctuations in population density during pre-Columbian times" (1985:296-297). He correlates major events in the horizon/period framework of Peruvian prehistory with shifts between deterioration and amelioration of highland climate. By comparing archaeological evidence and historical observations with current distribution of crop zones, he shows that agriculture in the highlands previously has extended as much as 250 meters higher than the current limit at about 4,050 meters.[2] He notes the possibility that prehistoric fluctuations that depressed temperature caused a similar 250 meters magnitude shift *below* current levels. If so, the (500 meters) range of these changes would be enough to cause major dislocations of agriculture and population over much of the Altiplano. Like Paulsen (1976), Cardich attributes Inca expansion to worsening climatic conditions in the 15th century. According to the independent estimate of Schoenwetter (1973; see also Browman 1987a:7), conditions favorable to agriculture extended in the past to altitudes 350 meters above their current limits.

Paulsen (1976) and Isbell (1978; cf. Conrad 1981) have argued that Andean polities expanded to buffer short-term environmental perturbations. In this view, political evolution in the uncertain highland environment was driven by the need to encompass dispersed and therefore independently varying sources of production. The ability to control environmental zones on both of the escarpments was especially attractive. One can find elements of this argument underlying the "archipelago" model of Andean ecopolitical organization (Murra 1972; 1984). In addition, fluctuations of rainfall are among several hypotheses advanced to explain the extensive postcontact abandonment of terraced land in the Andes (Donkin 1979; Denevan et al. 1987; Guillet 1987a: 417; Malpass n.d.).

Whatever the eventual appraisal of these hypotheses linking climate change and political development, pre-Columbian Andean societies prospered because they developed unique political and technological means to wrest a living from their high altitude territories. According to Murra, this involved

> three distinct steps . . . two are essentially climatological and agronomic feats; the third, more complex, was expressed in the social structural and economic arrangements which handled the other two (1984:120).

The first of these steps was the achievement of high agricultural productivity and reduced risk in what appears otherwise to be a marginal and uncertain environment. The second was the use of strong solar insolation and the cold to freeze-dry meat and tubers for accumulation and prolonged storage. And the third was spatially integrative political and economic structures that coordinated the production and distribution of resources from dispersed, altitudinally differentiated ecozones–the "verticality" or "archipelago" model (Murra 1972; see also Orlove 1977).

Whether viewed as a prime mover of sociocultural development or as a resource available to peoples whose history ultimately was moved by other factors, hypotheses involving climate figure prominently in Andean history and prehistory.

Peasant Production

Nowhere is the impact of climate more evident than in the lives of contemporary Andean peasants. Although they make the observation in different terms, ethnographers working in the Andes routinely note the great immediacy of climate for agricultural production. Their texts often present vivid descriptions of the vagaries of severe drought, floods, and frost in the highlands:

> In 1956, 1957, and 1964 there were serious droughts; in 1962 there was a serious flood; and in 1960 and 1963 there were February floods followed by severe frosts and a premature end to the rainy season. In 1965 part of the pampa of Taraco (province of Huancané) was covered by several feet of water from the Ramis River, stranding hundreds of the Indians' conical huts, while flooding others; in the pampa of Ilave a bridge was closed because of the high water. In both cases, however, it was explained that these conditions were by no means as serious as those during the 1962 and 1963 floods (Dew 1969:39-40).

Major droughts are known from 1982-1983, 1964-1966, 1956-1957, and 1942-1944 (Browman 1987a; Brown 1987; Guillet 1987a). Their consequences can be severe. For instance, in the 1982-1983 drought, highland crop production fell by 60 percent to 70 percent (Browman 1987a: 7-8). Similar decrements in production are cited for Ilave by Brown (1987), caused not by a severe and seasonally prolonged drought but by irregular monthly distribution of rainfall (1976-1977) abetted by a hard February frost (see also Kent 1987:298). Monthly variation like this can be devastating. It has its greatest impact during the germination and seedlings period (Mitchell *intra*).

More general estimates of the risk and impact of drought and frost vary in their severity and manner of deposition. In the higher agricultural lands some part of the "crops are lost to frosts or droughts every third year on the average" (Browman 1987a:13). Bernabe Cobo (reported in Flores Ochoa 1987:278) reported in the seventeenth century that harsh climatic environment on the Altiplano resulted in a bad crop two years out of three. An economic review using data on sale and barter around Lake Titicaca notes that "fluctuations in harvest are influenced more by climate than by economic conditions" (Orlove 1986:95). Commenting on the same article, Guillet (1986:101) cites the importance of environmental factors such as droughts in an understanding of the agrarian crisis in the Andes.

The environmental dimensions of this agricultural risk are the subject of a statistical analysis by Lhomme and Rojas (1986). For three stations on the Bolivian Altiplano (Charaña, 4,057 meters; Copacabana, 4,018 meters; and La Paz, 3,632 meters) they have calculated the annual pattern of incidence of three types of agricultural risk: desiccation, frost, and hail.[3] The joint probability of at least one of these climatic insults falls below 50 percent for only three to four months (December through March) at Copacabana and La Paz. It remains above 90 percent year-round for Charaña. Agriculture at these altitudes is risky, and based on these stations, the difference between 4,000 meters and 4,050 meters is large. It is not surprising, then, that "the principle economic organizing strategy of Andean arid land producers is risk management" (Browman 1987a:2).

CURRENT KNOWLEDGE: A CLIMATE OVERVIEW

The central Andes derive key features from their tropical latitude, but it is altitude, exposure, and relief that dominate local climate patterns. Because extensive collection of weather data began only in the mid-1960s (see Tables 2.1, 2.2 and 2.3), detailed analyses of extant weather records are rare, and there are few analytical summaries of regional or local climates. Existing generalizations are broad-brush. Although lacking an extensive database, Johnson (1976) is the most complete review. It is the source of most of the following generalizations.

November through April is recognized as the rainy reason in the Southern Hemisphere mountains of Peru. Precipitation is increasingly concentrated in a seasonal burst in the central months of this period as one moves southeast down the axis and, coincidentally but to a lesser extent, west and across the central Andes. Depending on the location, the buildup of precipitation occurs gradually in October or November in a series of pulses, whereas the end of the season is more abrupt and typically occurs in April. Compared to Ecuador and Columbia, the Andes of southern Peru (at 12 to 18 degrees south latitude) experience to a greater degree the effects of "increased continentality and the transition to the extratropical zone" (Sarmiento 1986:31). For instance, they occasionally are subjected to prolonged cold spells because of northward outbreaks of polar air masses.

Eastern Escarpment

The Amazon Basin provides near-ideal conditions for saturating the easterly winds with water vapor. It offers unimpeded movement to the Atlantic trade winds, moisture soaked landforms, luxuriant vegetation, and warmth for transpiration and evaporation. Rainfall is substantial over the tropical basin but higher yet on the eastern flanks of the Andes, the first orographic barrier to the moisture laden winds. Thus, Pucallpa at 151 meters averages 146 centimeters of rainfall, whereas a short distance away, Yurac, which lies at 295 meters and adjacent to the Andean foothills, gets 490 centimeters (Johnson 1976:155). Rainfall diminishes abruptly beyond the initial mountain flanks and then more gradually as one moves upslope (a general pattern of tropical mountains; Lauer, cited in Sarmiento 1986:13).

There are two complicating factors that can reverse the trend: aspect and pronounced vertical relief. Lee slopes, and especially those in the deep valleys that lie perpendicular to the cross-Andean airflows, get their highest precipitation at the high-elevation ridges. These valleys may be quite xeric at lower elevations where rain shadow effects are most intense. In some higher altitude areas, massive outcrops of cordillera can intensify the local orographic blockage of airflows and lead to heavy localized precipitation immediately downslope from the topographic obstruction.

Temperature lapse rates (Johnson 1976:173) are given as 6.8°C/1,000 meters for the first 1,000 meters, 3.2°C/1,000 meters for the next 1,500 meters, and 6.5°C for

TABLE 2.1 WESTERN ESCARPMENT WEATHER STATIONS

Station	Abbr	Latitude & Longitude		Altitude (m)	Year	
					Start	Stop
Orcopampa	PRC	15° 16"	72° 21"	3779	1951	1984
Imata	IMA	15° 50"	71° 05"	4436	1935	1986
Yanque	YAN	15° 39"	71° 39"	3417	1951	1984
Cotahuasi	COT	15° 12"	72° 54"	2685	1964	1985
Cabanaconde	CAB	15° 37"	71° 59"	3287	1951	1984
Sibayo	SIB	15° 29"	71° 27"	3847	1947	1986
Angostura	ANG	15° 11"	71° 38"	4155	1962	1984
Crucero Alto	CRU	15° 46"	70° 55"	4400	1964	1985
Pulhuay	PUL	15° 05"	72° 26"	4600	1964	1984
Chinchayllapa	CHI	14° 56"	72° 43"	3950	1964	1986
Aplao	APL	16° 05"	72° 30"	510	1964	1986
Chuquibamba	CHU	15° 50"	72° 40"	2880	1954	1986
Pampa de Majes	PdM	16° 21"	72° 10"	1440	1950	1986
Punta Islay	ISL	17° 01"	72° 07"	43	1954	1976
Punta Atico	PAT	16° 14"	73° 42"	20	1954	1985
El Frayle	FRA	16° 09"	71° 11"	4015	1964	1986
Andagua	AND	15° 30"	72° 21"	3589	1951	1983
Huanca	HUA	16° 02"	71° 33"	3080	1964	1984
Arequipa	ARE	16° 22"	71° 33"	2520	1896	1984
Ayo	AYO	15° 41"	72° 16"	1956	1951	1984

Notes, Tables 1 through 3: Latitude is south; Longitude is west; Year/Start = year of the initiation of weather records; Year/Stop = last year in the recorded sample of weather records.

the elevations between 2,500 and 4,500 meters, with the lowered rate at intermediate altitudes apparently a result of inversions and the effects of pronounced topographic relief associated with deep valleys.

Altiplano

In the central portions of the Andes, the onset of the rainy season can vary by several months from year to year. Localized showers are common because much of the rainfall is convective in origin (often in the form of intense thunderstorms [Schwerdtfeger 1976]), and site-to-site variation in the pattern of precipitation is high. Compared to stations located to the northwest along the Andean axis, in southern Peru annual precipitation in the highlands is increasingly confined to the November through March period, totals are lower, and they are more variable (as

TABLE 2.2 EASTERN ESCARPMENT WEATHER STATIONS

Station	Abbr	Latitude	& Longitude	Altitude (m)	Year Start	Stop
Calca	CAL	13° 20"	71° 57"	2926	1965	1981
Cirialo	CIR	12° 43"	73° 11"	900	1968	1978
Quillabamba	QUI	12° 53"	72° 44"	950	1964	1981
Maranura	MAR	12° 57"	72° 40"	1500	1970	1978
Pisac	PIS	13° 26"	71° 51"	2971	1963	1983
Ccatcca	CCA	13° 37"	71° 34"	3700	1965	1983
Urubamba	URU	13° 18"	72° 07"	2863	1964	1986
Yucay	YUC	13° 19"	72° 04"	2830	1968	1983
Machu Picchu	MAC	13° 09"	72° 31"	2080	1964	1977
Huyro	HUY	12° 57"	72° 35"	1700	1964	1981
Occobamba	OCC	12° 48"	72° 20"	1700	1964	1982
Ollachea	OLL	13° 46"	70° 29"	2850	1964	1986
Quincemil	QUI	13° 12"	70° 46"	619	1959	1984
Tambopata	TAM	14° 13"	69° 12"	1280	1964	1987
San Gabon	SGB	13° 27"	70° 28"	820	1964	1987
Paucartambo	PAU	13° 16"	71° 37"	2830	1964	1982
Sina	SIN	14° 30"	69° 17"	3000	1963	1978
Cuyo Cuyo	CYO	14° 28"	69° 32"	3414	1963	1987
Limbani	LIM	14° 10"	69° 43"	3200	1964	1987

Notes, see Table 1.

measured by the coefficient of dispersion).

In general, mean maximum temperatures in the Andes have a modest and shallow peak during the months of September, October, and November. This period gets the enhanced warming which results from the southward track of the sun before the full onset of the rainy season introduces more frequent and continuous overcast. Between December and March the cloud cover reduces insolation and thus daytime high temperatures. To an even greater extent it mitigates nighttime lows by impeding the loss into space of long-wave radiation. Thus, daily minimum temperatures are lowest (and diurnal variation is at its greatest) during the dry season. Skies are clear and dry and nights are long, conditions that facilitate escape of long-wave radiation. Diurnal variation is least during the wet season. Pronounced, latitudinally induced seasonality begins to affect the region only in its southernmost extension.

TABLE 2.3 ALTIPLANO WEATHER STATIONS

Station	Abbr	Latitude & Longitude		Altitude (m)	Year	
					Start	Stop
Chuquibambilla	CHU	14° 47"	70° 45"	3910	1931	1987
Arapa	ARA	15° 08"	70° 07"	3880	1964	1987
Ayaviri	AYA	14° 53"	70° 36"	3900	1965	1987
Azangaro	AZA	14° 55"	70° 11"	3863	1964	1986
Huancane	HUA	15° 12"	69° 45"	3890	1964	1987
Huaraya-Moho	HUM	15° 23"	69° 29"	3881	1957	1987
Puno	PUN	15° 50"	70° 01"	3825	1964	1987
Cabanillas	CAB	15° 39"	70° 22"	3850	1964	1987
Ilave	ILA	16° 06"	69° 38"	3880	1964	1987
Salcedo	SAL	15° 53"	70° 00"	3852	1950	1971
Juliaca	JUL	15° 29"	70° 09"	3825	1966	1987
Santo Tomas	SNT	14° 27"	72° 05"	3660	1965	1972
Llally	LLA	14° 56"	70° 53"	3890	1964	1981
Lampa	LAM	15° 22"	70° 22"	3892	1964	1987
Pucara	PUC	15° 08"	70° 50"	3910	1970	1987
Nuñoa	NUN	14° 29"	70° 38"	4135	1963	1987
Acomayo	ACO	13° 56"	71° 42"	3250	1965	1983
Munami	MUN	14° 46"	69° 57"	3949	1965	1987
Putina	PUT	14° 55"	69° 53"	3920	1966	1987
Crucero	CRU	14° 20"	70° 02"	4460	1966	1987
Sicuani	SIC	14° 17"	71° 13"	3550	1957	1984
Progreso	PRO	14° 41"	70° 22"	3950	1964	1987
Anta	ANT	13° 28"	72° 09"	3435	1965	1982
Chinchero	CHI	13° 24"	72° 03"	3762	1954	1976
Orurillo	ORU	14° 44"	70° 31"	3920	1966	1987
Santa Rosa	SRS	14° 37"	70° 47"	4000	1966	1987
Ananea	ANA	14° 40"	69° 32"	4600	1963	1987
Antauta	ANT	14° 20"	70° 25"	4150	1963	1975
Granja Kayra	KAY	13° 34"	71° 54"	3219	1931	1986
Cuzco	CUZ	13° 32"	71° 58"	3399	1945	1984

Notes, see Table 1.

Western Escarpment

In central and southern Peru, the steep western escarpment is a transition region between the wetter highlands and the arid coastal zone. Already depleted of moisture during the ascent of the eastern escarpment and traverse of the Altiplano, the precipitation potential of the air is reduced by downslope warming and increased water retention capacity. On the ground, the availability of water is further diminished by evapotranspiration stemming from warmth and lack of cloud cover. In the lowest elevations, the high humidity of the cool coastal air produces dense low-level fogs (*garuas*) that blanket the zone from May through October. Between the elevations of 100 meters and 800 meters these fogs are dense enough to sustain unique moisture-capturing vegetation mats (*lomas*). These capture the airborne moisture to create a localized band of vegetation receiving the equivalent of 10 to 20 centimeters of precipitation.

Although El Niño episodes can result in sporadic, heavy precipitation on the north coast of Peru, they do not appear to have this effect south of Chimbote (about 9° south latitude). Temperatures along the littoral zone are cool because of the modulating effect of the cold oceanic Humboldt current. Peak annual temperatures on this escarpment are reached at about 1,500 meters. Above this, the lapse rate again becomes negative with increasing altitude.

AN APPLICATION

Regional patterns of irrigation are an excellent vantage from which to examine the climate patterns of the southern Peruvian Andes in greater detail. Other questions (for example, comparisons of sectorial fallowing systems, crop complexes, methods of subsistence risk reduction, the interaction of agriculture with pastoralism, and so on) could motivate a similar analysis, but irrigation is especially appropriate given the abundant comparative materials of the present volume. The following discussion presumes that a narrow analytical question can facilitate description of a complex data set that is relevant to a much broader range of problems. Patterning of meteorological conditions combined with information on agriculture should help one understand the distribution, types, and functioning of irrigation systems in this region.

I begin with a very simple observation. The agricultural terraces in the Colca Valley, located on the high western slopes of the southern Peruvian Andes, were built with an imbedded irrigation network (Denevan et al. 1987; Guillet 1987a). About 250 kilometers to the northeast, directly across the axis of the cordillera, lie the agricultural terraces of the Sandia Valley. These terraces, located high on the eastern Andean escarpment, were built without provision for irrigation. Today, irrigation remains common in the Colca Valley, and rain-fed agriculture remains standard in the Sandia Valley.

How might we explain this difference? Both escarpment regions have long histories of occupation and often were linked by their mutual incorporation into polities centrally located on the Altiplano (Goland 1988; Julien 1983). Both have an agricultural substratum of magnificent stone-faced terraces, built by peoples obviously sophisticated in agricultural engineering. Both share similar kinds of potential water sources: direct precipitation as well as melt from the snows and glaciers of adjacent summits. Until the recent impact of market production in the Colca, both have grown the same crops: Andean tubers in the highest elevations and maize at lower altitudes. The superficial facts and constraints of cultural development, landscape, and physical geography, as well as cropping regimes, do not appear to offer a ready answer to this inquiry.

Climatic differences appear more promising. Annual rainfall in the two regions differs substantially. It is 290 to 500 millimeters in the Colca Valley and about 600 to 900 millimeters at comparable elevations (3,000 to 4,000 meters) in the Sandia Valley. Here is an answer: the Colca is deficient in precipitation, and the Sandia region is not. But irrigation can serve functions besides that of simply augmenting precipitation. It would be premature to end the investigation with the most obvious possibility–that is, irrigation occurs where absolute amounts of rainfall otherwise are insufficient for crop production. Other meteorological or ecological conditions, such as the timing of precipitation or its predictability, or the moisture retention capacity of soils, also are of potential importance to our inquiry.

This question is like others that could be asked about the regional patterning of agricultural systems in the Andes: its resolution will require an ecologically sophisticated understanding of the highland environment (Winterhalder 1980). With that in mind, the following analysis approaches Andean climate from the perspective of agricultural systems, production risk, and, more generally, human adaptation.[4]

The Problem

I define irrigation as the collection, movement, and dispersal of water to enhance agricultural production. It can be distinguished from drainage, which entails the removal of excess water from an agricultural site. Irrigation can function to modify the timing, quantity, predictability, or quality of the water available for agriculture, relative to incident precipitation or subsurface sources. Understanding the rationale for irrigation and tactics of water management requires that we be able to distinguish among these functions and relate them to temporal and spatial qualities of the water source. The functions may not be entirely separable. For instance, if the total quantity of precipitation during the cropping season is marginal for agriculture, it may also be the case that crops will be unusually susceptible to irregularities in the week-to-week distribution of rains, to delays in their onset or to their premature conclusion.

Hypothetically, then, irrigation might have one or more of these beneficial effects:

(1) *Timing:* it can extend the period of water availability, at the initiation or conclusion of the usual period of precipitation (for example, to facilitate the growing

of more slowly maturing crops or perhaps to obtain multiple crops);

(2) *Quantity:* it can augment incidental precipitation to thresholds required by certain crops (just as drainage might be used to diminish retention of precipitation or subsurface moisture sources);

(3) *Predictability:* it might be used to more evenly distribute or otherwise manage irregular availability of water, by the day or longer time periods, through the provision of storage reservoirs or by drawing from unsynchronized sources; and, finally,

(4) *Quality:* it might be used to change the chemical composition of local water supplies or soils, by introducing, diluting, or flushing certain chemicals, or to change the local microclimate, by elevating humidity or reducing the possibility of damage from frost.

The function of timing implies that water must be available when other ecological and agro-economic conditions are salubrious. Temperature is especially important, but so also are market factors, household schedules, and competing activities that may reduce labor availability or raise labor costs. Water supplies must coincide with the thermally favorable period for crop production even if rainfall does not. Likewise, irrigation might be used to begin a crop early, before the normal seasonal onset of precipitation, to benefit from market conditions or so that the producer can take advantage of temporary labor opportunities.

Each of these four hypotheses about the function of irrigation implies that water is moved from a source to a favorable crop zone. In the process, irrigation might be used to disperse a concentrated source or concentrate a dispersed one. It can be adapted to the needs of food crops or used to enhance forage for livestock production (see Browman 1987b). The spatial extent of an irrigation network is not a defining feature: self-contained irrigation systems can cover many kilometers (Farrington 1980) or be so small as to be encompassed within the 100 or so meter radius of the ingenious Qocha systems of the Altiplano (Flores Ochoa 1987). Of course, irrigation and other forms of water management (for example, drainage, impounding) can entail other, nonecological factors, such as economic or political control, or even military tactics (see the papers throughout this volume). However, I will restrict my focus to its agro-ecological aspects. Using meteorological data, I will attempt to predict which of the above functions underlie the regional distribution and operation of some Andean irrigation systems.

THE SAMPLE

The data reported here were collected predominantly by the Servicio Nacional de Meteorología e Hidrología (SENAMHI) in Peru. They were photocopied or transcribed at SENAMHI offices in Lima, Cuzco, Puno, and Arequipa, during many visits extending over six years. The stations are located in the departments of Cuzco [n = ~~23~~, 52 percent of 44 stations listed], Puno [n = 29, 41 percent of 70 stations listed], and Arequipa [n = 20, 23 percent of 87 stations listed]. The station samples in each department were selected based on the quality and time depth of the records

error
n=20
or 45%

available and on their geographic and altitudinal representativeness. All stations recorded daily precipitation. Most also collected maximum and minimum temperature, and some recorded other measures, such as number of days with precipitation, relative humidity, vapor pressure, hours of sunlight, evaporation, wind direction, wind speed, and cloud cover.

The data were available and were coded in the form of monthly sums (precipitation) or averages (maximum and minimum temperature). Of greatest interest are total monthly precipitation (millimeters) and mean monthly maximum and minimum temperature (°C). The average duration of the records available from these stations is 19 years. In total, the sample represents 1,309 station-years of meteorological information. Most of the stations were established in the late 1960s. In the results that follow, three stations have been eliminated from the original sample because of spotty or suspect data. Tables 2.1 through 2.3 provide a partial description of the stations, organized by the three major biogeographical zones in southern Peru: the western escarpment, the eastern escarpment, and Altiplano. The data have been coded and analyzed on a microcomputer using Lotus 1-2-3 or Quattro "spreadsheet" software. All statistics were calculated with Systat.

ANALYSES AND METHODS

Some of the analyses will rely on familiar descriptive measures (for example, annual precipitation and mean monthly or annual maximum and minimum temperatures). These measures are of interest because of the paucity of published meteorological information for the southern Peruvian Andes[5] and because of the geographical comparisons possible with a regional data set. Two measures are novel and require some explanation.

Predictability

Predictability is a measure of the regularity of a periodic phenomenon, such as seasonal rainfall or temperatures (Colwell 1974; Stearns 1981). It refers to the statistical predictability of a phenomenon, as distinct from the cognitive ability to forecast its occurrence. Technically, predictability is the statistical certainty of the state of a phenomenon (such as quantity of rainfall) given information about time (for example, the month of the year). If, for the whole year, knowing the month or season allowed one to make a certain statement about the quantity of rainfall, then precipitation would be completely predictable.

Predictability can arise in two different ways, termed constancy and contingency. *Constancy* measures the evenness of the phenomenon at each time interval in the period of interest. Thus, if the same amount of rain falls in each month of the year for all years recorded, precipitation would be maximally predictable because of complete constancy. *Contingency* is best thought of as repetition of seasonal pattern. If the quantity of rainfall were different in each month of the year but in a pattern that was precisely the same every year, predictability would be maximal due to contingency. *Predictability* is an aggregate measure of regularity arising from the combined effects of constancy and contingency. It is measured on a scale of 0 to 1, as a sum of varying amounts of constancy and contingency (evenness and seasonality, respectively).[6]

To give an Andean example, monthly precipitation at the city of Cuzco has a predictability of 0.45. This implies that the distribution of monthly rainfall is highly irregular from year to year. Constancy at Cuzco is 0.12; contingency equals 0.33. Thus, the limited regularity of monthly precipitation at Cuzco is due predominantly to the repetition of a highly seasonal pattern. In general, predictability is most useful when applied comparatively to assess the relative differences in the regularity of meteorological or other conditions at differing sites.

Low predictability means that there is little regularity to a phenomenon. Surfeit or deficit or some state between occurs with little pattern. Environmental irregularities (especially drought, flooding, and frost) and the production risks they entail are paramount concerns of Andean peasants. Predictability is of obvious and immediate importance to the analysis of agricultural systems and production tactics, although it rarely has been assessed in human ecology studies (Winterhalder 1980). I have applied this measure in assessing two factors: monthly rainfall and monthly minimum temperatures.

Onset and Conclusion

The second novel measure refers to the onset and conclusion of the rainy and thermal seasons. These have been defined as follows:

Onset: the first month of the rainy season in which a majority of years recorded have rainfall greater than 64 millimeters; the first month of the thermal season in which a majority of years have mean minimum temperatures greater than 0°C.

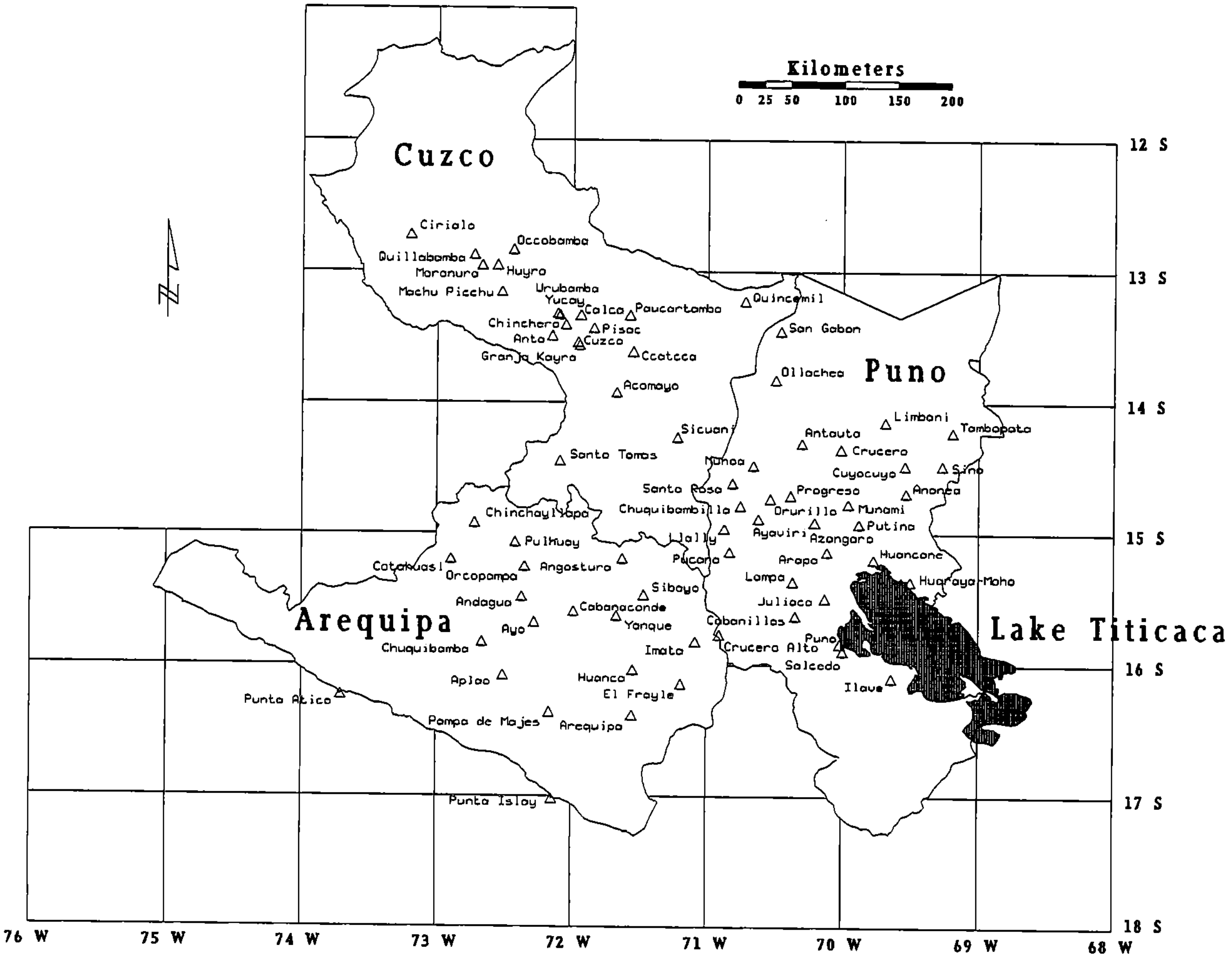
Conclusion: the last month of the rainy season in which a majority of years recorded have rainfall greater than 64 millimeters; the last month of the thermal season in which a majority of years have mean minimum temperatures greater than 0°C.

By these criteria Cuzco has a rainy season of 5 months, extending from November through March, and a thermal season of 12 months. The criteria used here–64 millimeters of precipitation and 0°C–are somewhat arbitrary from an agronomic perspective, but they provide a convenient index for regional, intersite comparisons.

RESULTS

I have organized the data in two formats. The first (Figure 2.1a) positions all 69 stations on a cross-Andes transect, oriented northeast to southwest perpendicular to the axis of the cordilleras. This places all the stations as if they occupied a single cross section of the mountains, stretching from the Amazon Basin across the Altiplano to the coast. It probably is the most general geographical comparison that

FIGURE 2.1a LOCATION OF SAMPLE WEATHER STATIONS.



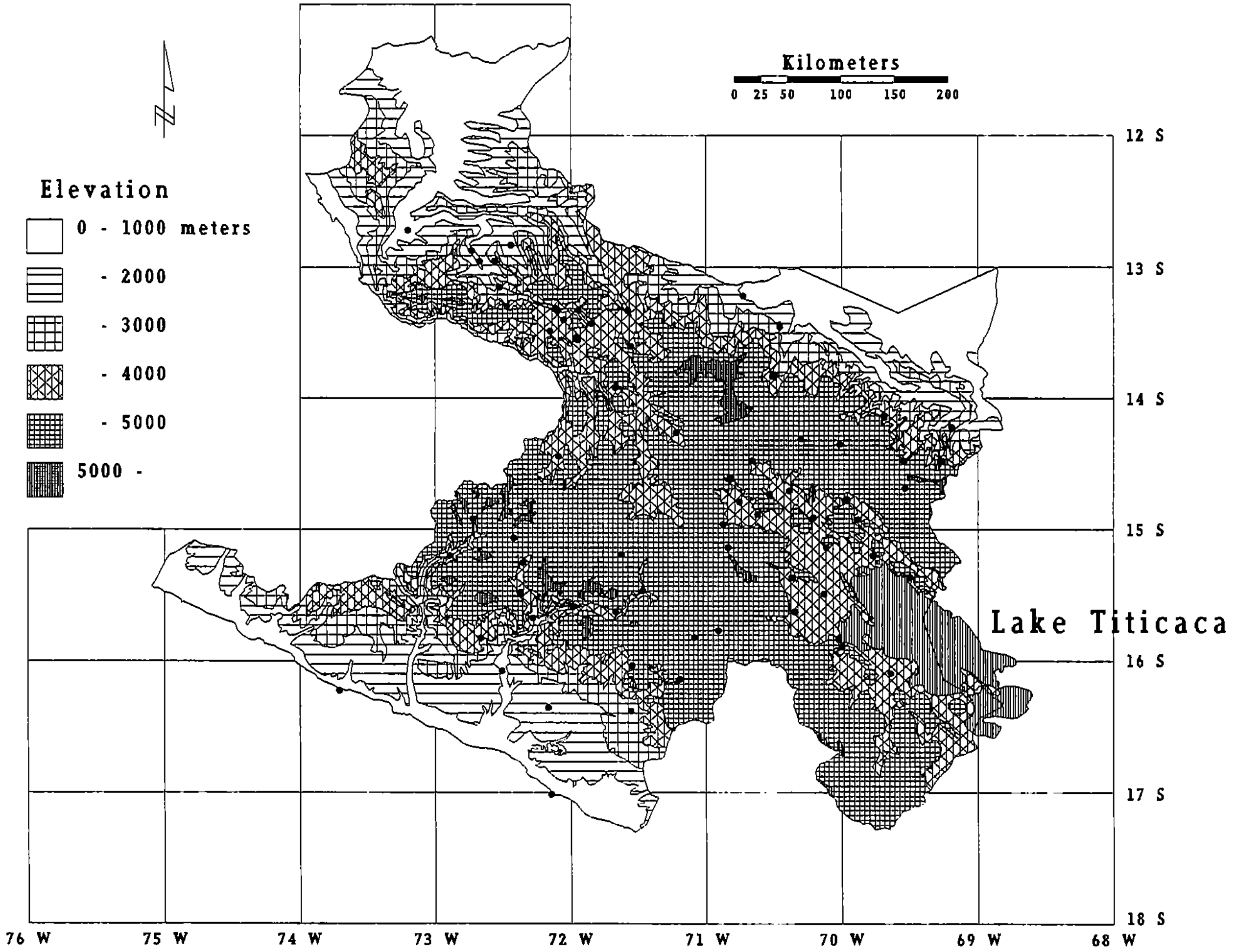


FIGURE 2.1b TOPOGRAPHICAL POSITION OF SAMPLE WEATHER STATIONS.

can be made with this data. The second format (Figure 2.1b) allows a more focused analysis. In it, I group data falling into the three geo-ecological zones of the Andes: the eastern escarpment, Altiplano, and western escarpment, using definitions as follows:

Eastern escarpment stations lie to the northeast of the divide of the Cordillera Oriental. They stretch from the headwaters into the lower reaches of the valleys draining into the Amazon Basin. The highest of these stations is Ccatcca at 3,700 meters, and the lowest is Quince Mil at 619 meters.

Altiplano stations occupy the interior basins and valleys between the eastern and western cordilleras. Most lie in the Titicaca Basin or the region surrounding Cuzco. The lowest is Granja Kayra, near Cuzco (3,232 meters) and the highest is Ananea (4,600 meters).

Western escarpment stations lie to the southwest of the divide of the Cordillera Occidental. These stations reach from sea level (Punta Atico at 20 meters) to 4,600 meters (Pulhuay).

All western escarpment stations lie within the department of Arequipa, whereas the departments of Cuzco and Puno both contain Altiplano and eastern escarpment stations. The data for stations in each of these zones are summarized in Tables 2.4 through 2.6.

Precipitation

Because of the visual density of the information in the tables, I will the discuss the results mainly by reference to a series of figures and regression analyses.

Figure 2.2 is a plot of the altitude of the transect stations. If the vertical scale were reduced, this figure would almost perfectly replicate the topographical cross section of the southern Peruvian Andes at the latitude of Lake Titicaca (see also Troll 1968:45; reprinted in Winterhalder and Thomas 1982). The saw-toothed character of the northeastern end of the transect reflects the tendency of eastern escarpment drainages to run for some distance parallel to the axis of the Andean chains. Thus, some stations set well into the province of the mountains nonetheless are situated at low elevations in valley bottoms. As noted earlier, the rain-bearing winds ascending this escarpment often must cross a series of valleys and ridges. In contrast, valleys on the western escarpment typically drain perpendicular to the mountains, directly and more or less continuously downslope. On this side of the cordilleras, elevation is better correlated with geographic position. The climatic impact of these topographic differences between the escarpments will become apparent below.

Figure 2.3 shows average annual precipitation along the transect. Some features of this data will be familiar from the earlier summary of central Andean meteorology: the very high precipitation of the eastern escarpment, montane zone; the high degree of variability on the middle and upper portions of the eastern escarpment; and the gradual and relatively continuous decrease of precipitation as one descends the western escarpment. An unexpected result is the very even distribution of precipitation across the Altiplano and into the Cordillera Occidental.

TABLE 2.4 WESTERN ESCARPMENT WEATHER DATA

Station	Avg P	Max P (mm)	Min P	Yrs (#)	Max T	Min T (°C)	P/C/M Precip	Onset Concl Rains	P/C/M Min Mon T	Onset Concl Thermal
Orcopampa	505.7	871.0	220.5	29			0.37/0.11/0.26	12 3		
Imata	569.3	893.3	182.8	34	12.8	-6.8	0.34/0.08/0.27	12 3	0.48/0.12/0.35	
Yanque	422.7	715.7	217.4	31			0.35/0.10/0.25	1 3		
Cotahuasi	297.9	577.6	110.1	13	22.4	8.3	0.44/0.12/0.32	1 3	0.36/0.25/0.11	7 6
Cabanaconde	399.0	807.7	105.2	33			0.49/0.25/0.24	1 3		
Sibayo	556.1	798.3	254.5	29	18.0	-1.6	0.35/0.06/0.29	12 3	0.56/0.05/0.51	11 4
Angostura	757.2	969.8	437.3	22	17.3	-10.1	0.41/0.07/0.34	12 3	0.59/0.08/0.51	1 3
Crucero Alto	579.2	914.9	230.7	17			0.40/0.10/0.30	12 3		
Pulhuay	631.6	1251.1	178.3	13			0.39/0.13/0.26	1 3		
Chinchayllapa	702.9	1021.5	189.3	20			0.36/0.13/0.23	12 3		
Aplao	6.8	13.6	2.0	12	26.9	11.8	0.68/0.55/0.13	0	0.64/0.23/0.42	7 6
Chuquibamba	173.0	389.0	36.5	9	16.0	6.1	0.61/0.38/0.23	0	0.68/0.48/0.20	7 6
Pampa de Majes	4.5	18.5	0.0	21	26.0	12.1	0.59/0.51/0.08	0	0.72/0.47/0.25	7 6
Punta Islay	6.7	21.2	0.0	6	20.7	16.4	0.73/0.59/0.14	0	0.66/0.40/0.26	7 6
Punta Atico	4.4	33.8	0.0	14	21.6	16.2	0.84/0.77/0.07	0	0.76/0.49/0.27	7 6
El Frayle	299.4	441.1	150.9	14	13.3	-4.2	0.43/0.11/0.31	1 2	0.50/0.18/0.32	1 3
Andagua	451.5	747.8	157.0	32			0.50/0.26/0.24	1 3		
Huanca	168.4	1039.4	40.7	17			0.55/0.34/0.21	0		
Arequipa	97.7	465.7	2.1	36	22.2	6.6	0.60/0.40/0.20	0	0.50/0.32/0.17	7 6
Ayo	87.1	203.1	26.4	31			0.48/0.29/0.19	0		

Notes, Tables 4 through 6: **Avg P** = Average annual precipitation; **Max P** = Maximum recorded annual precipitation; **Min P** = Minimum recorded annual precipitation; **Yrs** = number of complete years in sample; **Max T** = average monthly maximum temperature; **Min T** = average monthly minimum temperature; **P, C, M /Precip** = Predictability, constancy and contingency of monthly precipitation; **Onset Concl/Rains** = Onset and conclusion of the rainy season, 1 = January through 12 = December; **P, C, M/Min Mon T** = Predictability, constancy and contingency of monthly minimum temperature; **Onset Concl/Thermal** = Onset and conclusion of thermally favorable season for agriculture, 1= January through 12 = December.

TABLE 2.5 EASTERN ESCARPMENT WEATHER DATA

Station	Avg P	Max P	Min P	Yrs	Max T	MinT	P/C/M	Onset	Concl	P/C/M	Onset	Concl
		(mm)		(#)	(°C)		Precip	Rains		Min Mon T	Thermal	
Calca	514.3	668.5	357.3	14	22.1	5.6	0.44/0.12/0.32	12	3	0.46/0.13/0.32	7	6
Cirialo	1248.1	1631.7	887.5	10	31.1	19.6	0.48/0.15/0.33	11	4	0.91/0.81/0.10	7	6
Quillabamba	981.6	1312.0	667.3	16	30.6	16.7	0.50/0.23/0.27	10	4	0.57/0.46/0.10	7	6
Maranura	945.7	1246.9	792.6	7	29.4	17.5	0.52/0.22/0.30	11	3	0.77/0.54/0.23	7	6
Pisac	669.5	1414.3	219.8	18			0.37/0.08/0.29	12	3			
Ccatcca	594.7	718.3	499.3	15	15.3	1.1	0.49/0.11/0.38	12	3	0.56/0.19/0.37	9	4
Urubamba	391.4	592.4	70.6	20	22.2	6.2	0.38/0.12/0.26	1	1	0.59/0.15/0.44	7	6
Yucay	512.7	601.9	397.5	12	23.1	6.8	0.47/0.08/0.39	12	3	0.64/0.18/0.45	7	6
Machu Picchu	1996.3	2381.3	1571.3	11	22.3	9.9	0.58/0.28/0.30	8	4	0.63/0.44/0.19	7	6
Huyro	1766.5	2170.4	673.5	16	25.1	13.6	0.51/0.23/0.29	10	4	0.76/0.56/0.19	7	6
Occobamba	1863.5	3008.6	1301.3	15	25.9	12.9	0.52/0.25/0.27	9	4	0.57/0.47/0.10	7	6
Ollachea	1282.4	2574.2	829.4	19	17.9	6.9	0.37/0.12/0.25	10	3	0.54/0.39/0.15	7	6
Quincemil	7140.6	10024.3	5270.5	18	27.7	18.2	0.66/0.51/0.15	7	6	0.72/0.59/0.13	7	6
Tambopata	1526.3	1926.8	1280.0	23	25.0	14.7	0.58/0.35/0.22	9	4	0.77/0.55/0.23	6	6
San Gabon	5600.0	9115.2	3919.6	23			0.58/0.44/0.14	6	6			
Paucartambo	522.4	787.4	264.4	9	18.6	6.9	0.41/0.10/0.31	12	3	0.53/0.17/0.36	7	6
Sina	1720.3	2316.9	982.4	13			0.49/0.22/0.27	9	4			
Cuyo Cuyo	823.8	1696.5	536.0	16			0.50/0.21/0.28	12	3			
Limbani	951.0	1199.4	536.7	15			0.50/0.19/0.30	10	3			

Notes, see Table 4.

TABLE 2.6 ALTIPLANO WEATHER DATA

	Avg P	Max P	Min P	Yrs	Max T	MinT	P/C/M	Onset	Concl	P/C/M	Onset	Concl
Station		(mm)		(#)	(˚C)		Precip	Rains		Min Mon T	Thermal	
Chuquibambilla	691.7	1016.8	281.1	56	16.9	-2.7	0.46/0.14/0.32	12	3	0.55/0.18/0.37	12	3
Arapa	734.5	1302.1	435.0	21	15.9	2.4	0.38/0.11/0.27	12	3	0.72/0.26/0.46	9	5
Ayaviri	687.5	2164.2	333.9	17	16.0	-0.6	0.43/0.16/0.27	12	3	0.58/0.18/0.39	10	4
Azangaro	550.6	702.4	382.6	14	15.8	1.0	0.45/0.13/0.32	12	3	0.73/0.20/0.53	9	4
Huancane	681.5	1026.0	424.6	23	14.5	0.5	0.38/0.11/0.27	12	3	0.53/0.15/0.38	10	4
Huaraya-Moho	945.1	1383.3	615.4	20	14.5	2.9	0.43/0.11/0.32	11	4	0.74/0.26/0.49	8	5
Puno	724.3	1072.5	403.9	23	14.3	2.6	0.37/0.08/0.29	12	3	0.77/0.24/0.53	8	5
Cabinillas	652.8	852.7	218.9	21	16.7	1.6	0.43/0.10/0.33	12	3	0.66/0.11/0.55	9	4
Ilave	800.2	1192.4	335.3	14	14.6	1.1	0.36/0.10/0.26	12	3	0.62/0.14/0.47	9	4
Salcedo	658.3	1085.2	355.7	21	15.8	1.3	0.41/0.10/0.31	12	3	0.56/0.24/0.32	9	5
Juliaca	610.6	845.2	396.8	17	17.0	-0.7	0.42/0.13/0.29	12	3	0.60/0.09/0.51	11	4
Santo Tomas	742.4	1160.3	513.5	5			0.55/0.18/0.37	12	3			
Llally	751.0	1104.6	407.4	9	15.2	-1.5	0.44/0.09/0.36	12	3	0.66/0.24/0.42	12	4
Lampa	783.6	1620.7	522.7	20	16.3	-0.8	0.42/0.10/0.31	12	3	0.55/0.09/0.46	11	4
Pucara	794.1	1275.6	457.5	18			0.45/0.13/0.33	12	3			
Nuñoa	688.0	932.8	185.5	24			0.43/0.14/0.29	12	3			
Acomayo	880.0	1111.0	355.1	18	20.6	4.9	0.51/0.14/0.37	11	3	0.73/0.25/0.48	7	6
Munami	589.1	1044.2	320.6	18	16.0	0.6	0.43/0.15/0.27	12	3	0.51/0.31/0.20	9	4
Putina	683.3	880.6	445.7	21			0.44/0.13/0.31	11	3			
Crucero	906.1	1422.6	557.0	21			0.45/0.15/0.30	11	4			
Sicuani	597.1	960.5	122.5	20	19.4	2.6	0.38/0.12/0.26	12	3	0.50/0.24/0.26	8	5
Progreso	595.1	823.8	355.3	20	15.4	2.0	0.47/0.11/0.36	12	3	0.72/0.26/0.46	9	5
Anta	742.0	887.7	591.3	16	18.0	3.4	0.49/0.11/0.38	11	3	0.61/0.11/0.50	9	5
Chinchero	799.9	1113.8	420.5	12	20.4	6.8	0.42/0.11/0.31	11	3	0.28/0.09/0.20	7	6
Orurillo	750.8	1179.1	521.8	21			0.42/0.11/0.31	12	3			
Santa Rosa	1094.6	1383.8	757.8	9			0.52/0.13/0.39	11	4			
Ananea	658.6	874.0	486.9	21			0.47/0.17/0.30	12	3			
Antauta	709.1	1365.3	492.8	10			0.41/0.18/0.23	12	3			
Granja Kayra	676.7	923.2	477.7	21	24.8	3.8	0.47/0.09/0.38	12	3	0.68/0.25/0.43	8	5
Cuzco	745.0	982.1	389.5	35	19.7	4.3	0.45/0.12/0.33	11	3	0.67/0.21/0.46	7	6

Notes, see Table 4.

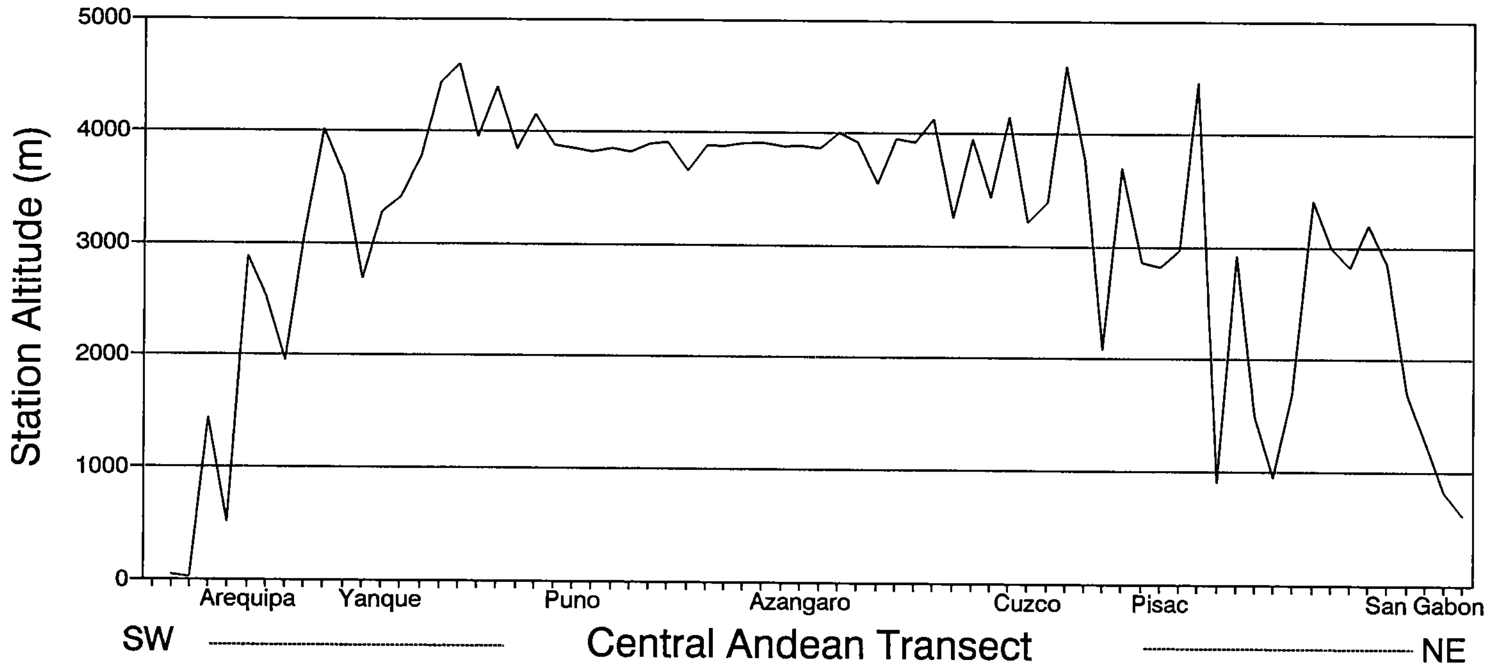
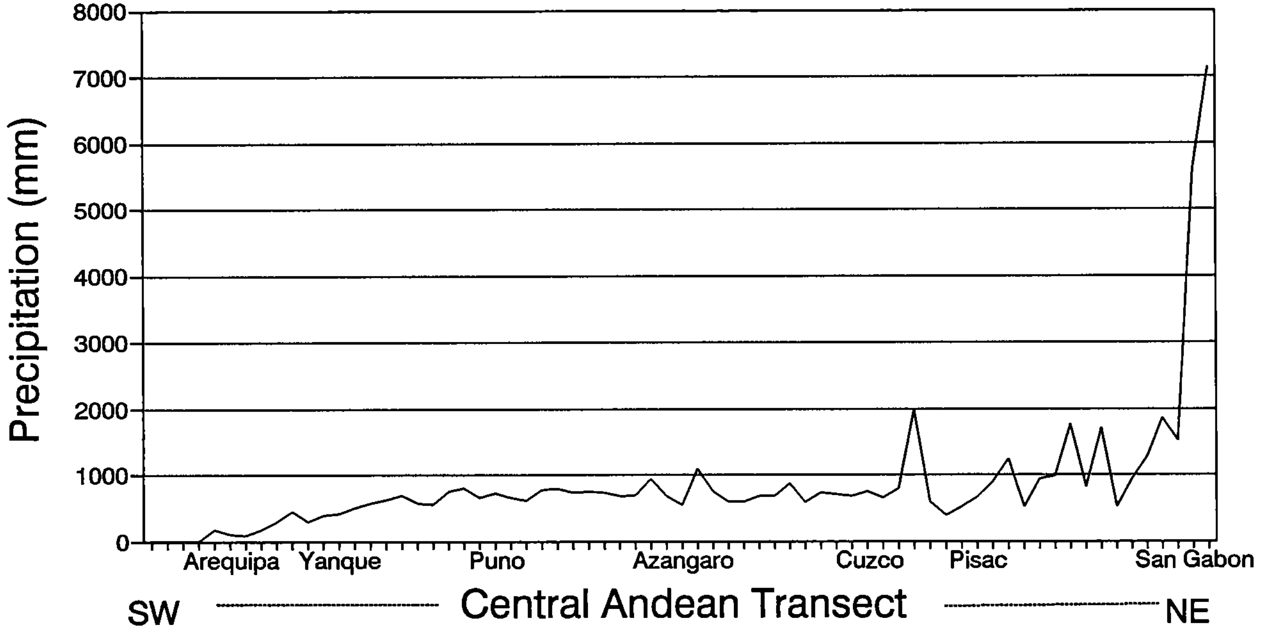


FIGURE 2.2 THE ALTITUDE OF THE SAMPLE STATIONS AS ARRAYED ON THE NORTHEAST (NE) TO SOUTHWEST (SW) TRANSECT ACROSS THE SOUTHERN PERUVIAN ANDES.

FIGURE 2.3 MEAN ANNUAL PRECIPITATION OF SAMPLE STATIONS AS ARRAYED ON THE NORTHEAST (NE) TO SOUTHWEST (SW) TRANSECT ACROSS THE SOUTHERN PERUVIAN ANDES.



The classic illustrations of Troll (1968; reprinted in Molina and Little 1981; Winterhalder and Thomas 1982) describe climatic zonation in the interior Andean basin going from northeast to southwest as "moist" and then "dry" puna belts.[9] Although these descriptive terms imply differences in the absolute amount of precipitation, the present data suggest that geo-ecologists need to look for other factors to explain these ecological zones–perhaps differing soils, temperature (acting to limit the physiological availability of water to plants), or the predictability of precipitation. With respect to the focal question of this inquiry, note that irrigation in the middle-to-upper altitude portions of the western escarpment can draw for a water source on the relatively high precipitation of adjacent Cordillera Occidental highlands.

Predictability of monthly precipitation (Figure 2.4) is high for the lowest stations of the eastern escarpment mainly because of constancy. At San Gabon and Quince Mil, for instance, it rains with fairly great regularity nearly year-round. Predictability diminishes gradually but with significant variation from the middle-upper altitudes of the eastern escarpment through the upper altitudes of the western escarpment. It increases dramatically as one moves downslope on the western escarpment, reaching peak values at the coast where with high predictability it seldom rains in any month of any year. From the perspective of our inquiry, irrigation to reduce irregularities in monthly precipitation would have its maximum benefit in the upper reaches of the western escarpment and on the adjacent Altiplano.

Greater resolution is possible if we examine this evidence by region. Precipitation as a function of altitude on the western escarpment is shown in Figure 2.5, along with two regression lines (see Table 2.7). A linear regression on this data has a Pearson correlation coefficient of $r = 0.87$, with an explained variance of $r^2 = 0.76$. However, visual inspection suggests that a polynomial regression [average annual precipitation = constant x altitude^2] might provide a better fit and it does ($r = 0.97$; $r^2 = 0.94$). The meteorological basis of this polynomial relationship between altitude and precipitation on the western escarpment is unclear, but the statistical concordance is striking. With the polynomial model, altitude alone accounts for 94 percent of the station-to-station variation in annual precipitation. The polynomial relationship depicted in Figure 2.5 again highlights the potential benefit of being able to capture by means of irrigation the moisture found in the highest zones of this escarpment. Relative to lower zones, precipitation occurs there in abundance.

The predictability, constancy, and contingency of monthly precipitation on the western escarpment is shown in Figure 2.6. Predictability decreases from about 0.8 to less than 0.4 as altitude increases. Constancy or evenness of the annual pattern declines even more sharply. By contrast, contingency increases upslope. At the uppermost stations, nearly all the limited regularity of monthly precipitation is caused by a pronounced seasonal pattern. As with amount of rainfall, there is a fairly regular relationship between predictability measures and elevation. Altitude alone explains 80 percent of the interstation variance in predictability ($r = 0.89$; Table 2.7).

Rainfall on the eastern escarpment has a less regular relationship to altitude (Figure 2.7), because of the effects of valley topography. A linear regression model

FIGURE 2.4 THE PREDICTABILITY OF MONTHLY PRECIPITATION AT THE SAMPLE STATIONS AS ARRAYED ON THE NORTHEAST (NE) TO SOUTHWEST (SW) TRANSECT ACROSS THE SOUTHERN PERUVIAN ANDES.

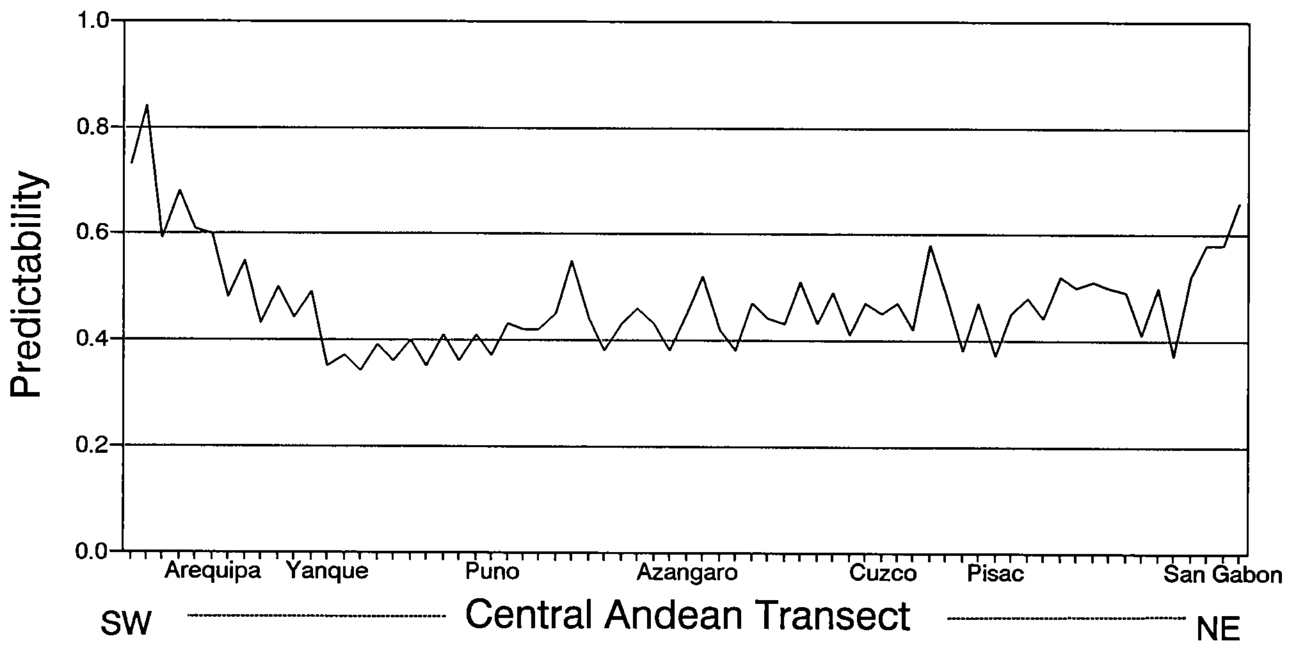


TABLE 2.7 REGRESSION ANALYSES OF CLIMATIC FACTORS ON ALTITUDE (MEASURED IN 1000s OF METERS), BY GEOECOLOGICAL ZONE

	Western Escarpment	Eastern Escarpment	Altiplano
AVERAGE ANNUAL PRECIPITATION			
n	20	19	30
r (Pearson)	0.874	0.627	0.036
r^2	0.764	0.393	0.001
Constant	-116.3	4107.6***	676.6*
Factor	154.0***	-1115.0**	14.0
MEAN MAXIMUM TEMPERATURE (°C)			
n	11	14	21
r (Pearson)	0.742	0.898	0.847
r^2	0.551	0.806	0.718
Constant	24.8***	33.3***	53.0***
Factor	-2.08**	-4.50***	-9.57***
MEAN MINIMUM TEMPERATURE (°C)			
n	11	14	21
r (Pearson)	0.943	0.978	0.616
r^2	0.890	0.957	0.379
Constant	17.6***	23.3***	24.5**
Factor	-5.24***	-5.90***	-6.07**
PREDICTABILITY OF MONTHLY PRECIPITATION			
n	20	19	30
r (Pearson)	0.893	0.624	0.168
r^2	0.798	0.390	0.028
Constant	0.752***	0.599***	0.536***
Factor	-0.088***	-0.048**	-0.0025
PREDICTABILITY OF MONTHLY MEAN MINIMUM TEMPERATURE (°C)			
n	11	14	21
r (Pearson)	0.617	0.674	0.130
r^2	0.380	0.454	0.017
Constant	0.693***	0.825***	0.856
Factor	-0.044*	-0.088**	-0.063

Note: *** Significant at 0.001; ** Significant at 0.01; * Significant at 0.05. All statistics used the MGLH module of Systat.

FIGURE 2.5 WESTERN ESCARPMENT: MEAN ANNUAL PRECIPITATION AS A FUNCTION OF ALTITUDE, WITH SUPERIMPOSED POLYNOMIAL REGRESSION (SEE TABLE 2.7).

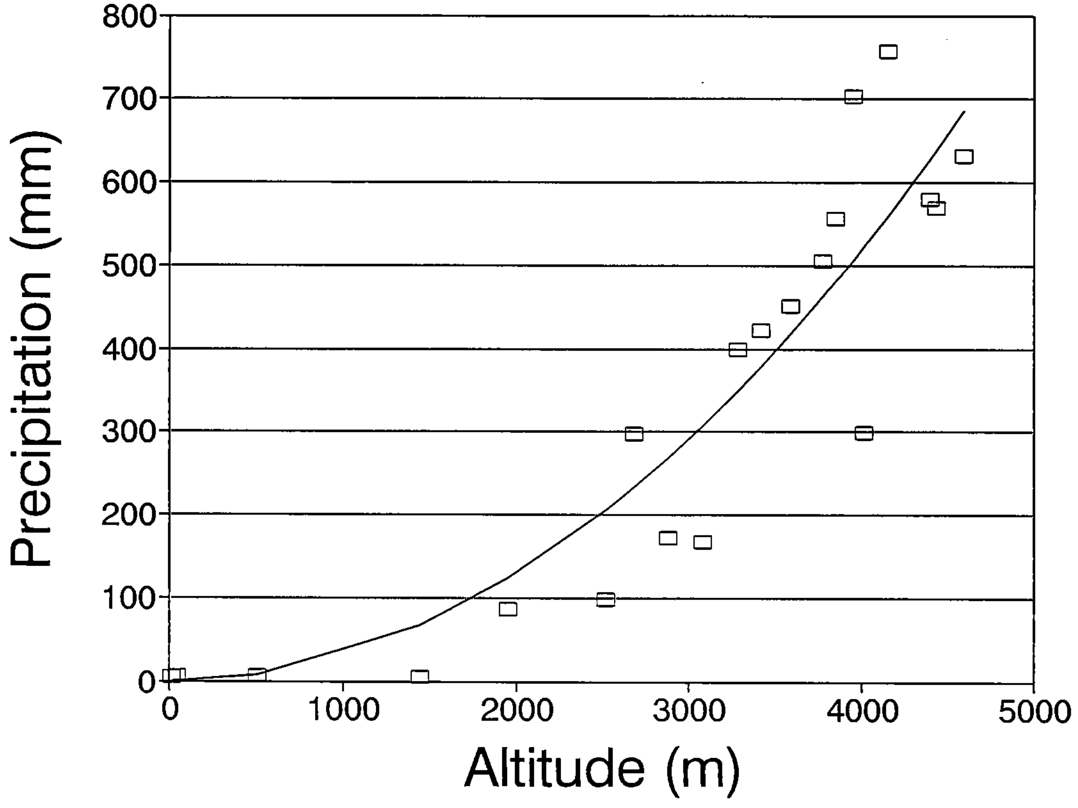


FIGURE 2.6 WESTERN ESCARPMENT: PREDICTABILITY (P), CONSTANCY (C) AND CONTINGENCY (M) OF MONTHLY PRECIPITATION AS A FUNCTION OF ALTITUDE, WITH SUPERIMPOSED LINEAR REGRESSIONS (SEE TABLE 2.7).

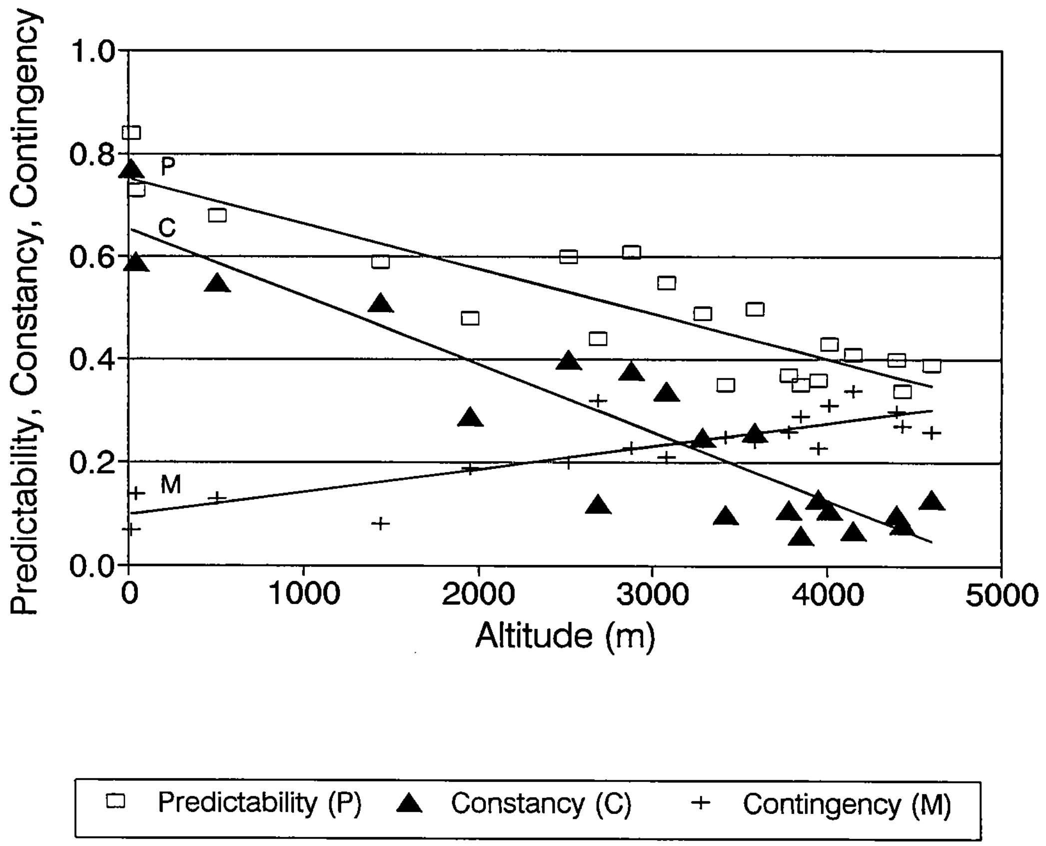
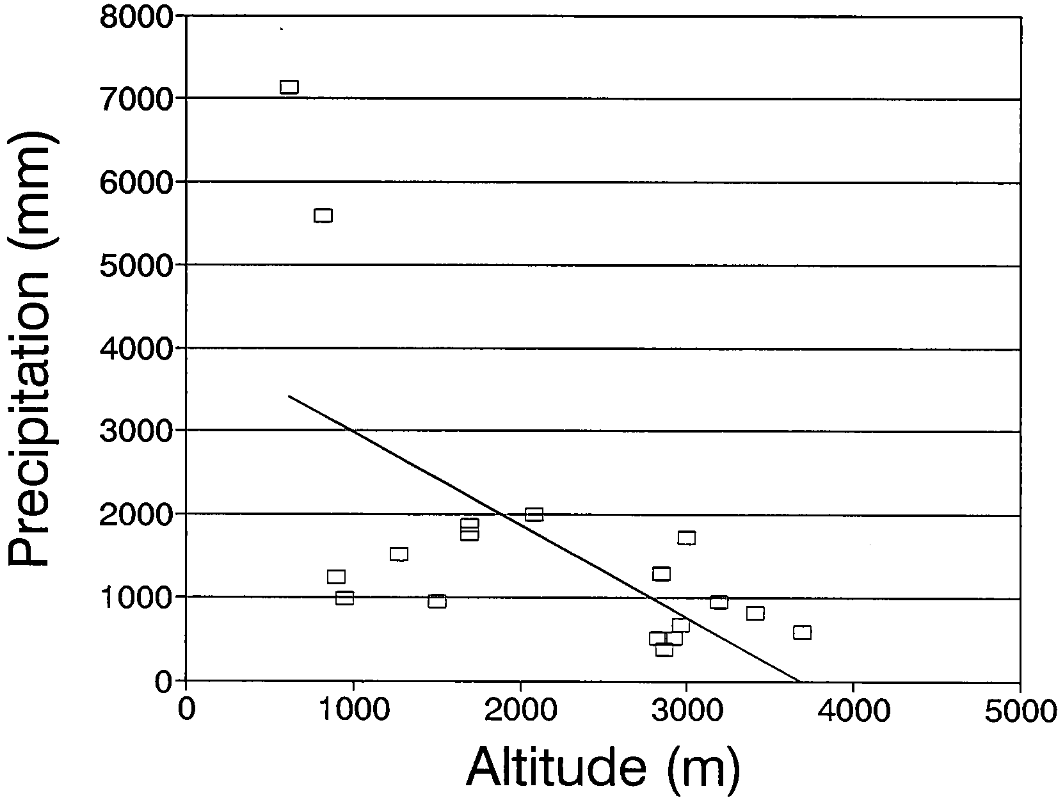


FIGURE 2.7 EASTERN ESCARPMENT: MEAN ANNUAL PRECIPITATION AS A FUNCTION OF ALTITUDE, WITH SUPERIMPOSED LINEAR REGRESSION (SEE TABLE 2. 7).



indicates that precipitation decreases upslope (r = 0.63; r^2 = 0.39), but visual inspection suggests that the very lowest stations on the mountain flanks (Quince Mil and San Gabon) are meteorologically distinct from the stations occupying the higher elevations.[10] Altitude accounts for less than 40 percent of the variance in precipitation among these eastern escarpment stations. Hence, although there is a weak overall trend toward lower rainfall as one moves upslope, rain shadow effects may cause localized reversal of this relationship in deep valleys. The high ridges, shoulders, and flanks of the valley may get more rainfall than the lower slopes and valley bottom, which are warmer because of low elevation and drier because of their isolation from the moisture bearing winds aloft.

Predictability of monthly precipitation on the eastern escarpment decreases upslope (r = 0.62; r^2= 0.39) as does the constancy component (Figure 2.8). As on the western escarpment, at the highest altitudes of the eastern escarpment nearly all the predictability of monthly precipitation is a result of contingency. However, the relationship of predictability to altitude is weaker on the eastern slopes than it is on the western slopes.

A comparison of the two escarpments shows that predictability of monthly precipitation decreases upslope *whether* the actual amounts of precipitation are falling (as on the eastern escarpment) or rising (as on the western escarpment). In either region irrigation to diminish irregularities in monthly distribution of rainfall is most likely at the higher altitudes of agricultural production.

Temperature

For the most part, annual mean minimum temperature follows the expected pattern on a transect across the central Andes (Figure 2.9): it drops for stations progressively higher on the two escarpments. However, it also appears to fall as one crosses the altiplano from the northeast to the southwest.[11] This decline in minimum temperatures may be more significant than is precipitation for the ecological zonation described by Troll (1968; see discussion above). If so, then it may be more apt to designate these vegetation zones by terms that refer to temperature rather than moisture, perhaps as the cool-dry and cold-dry punas. Viewed across the whole transect, predictability of minimum temperature shows no clear trend and has not been graphed.

A detailed look at the two escarpments gives evidence of an orderly relationship between altitude, temperature, and minimum temperature predictability. On the western escarpment, both mean maximum (r = 0.74; r^2 = 0.55) and mean minimum (r = 0.94; r^2 = 0.89) temperatures fall regularly with altitude (Figure 2.10). This relationship is especially strong for the minimum, which has a lapse rate of 5.24°C per 1,000 meters and an explained variance of 0.89. The range between the maximum and minimum temperatures increases as one moves upslope, but this effect would be reduced (and the correlation between mean max °C and altitude enhanced) if we eliminate the coastal stations from the mean maximum temperature data.[12] Both of these sea-level stations are "outliers" in the data set, their maximum temperatures unusually depressed because of proximity to the cold ocean currents.

FIGURE 2.8 EASTERN ESCARPMENT: PREDICTABILITY (P), CONSTANCY (C) AND CONTINGENCY (M) OF MONTHLY PRECIPITATION AS A FUNCTION OF ALTITUDE, WITH SUPERIMPOSED LINEAR REGRESSIONS (SEE TABLE 2.7).

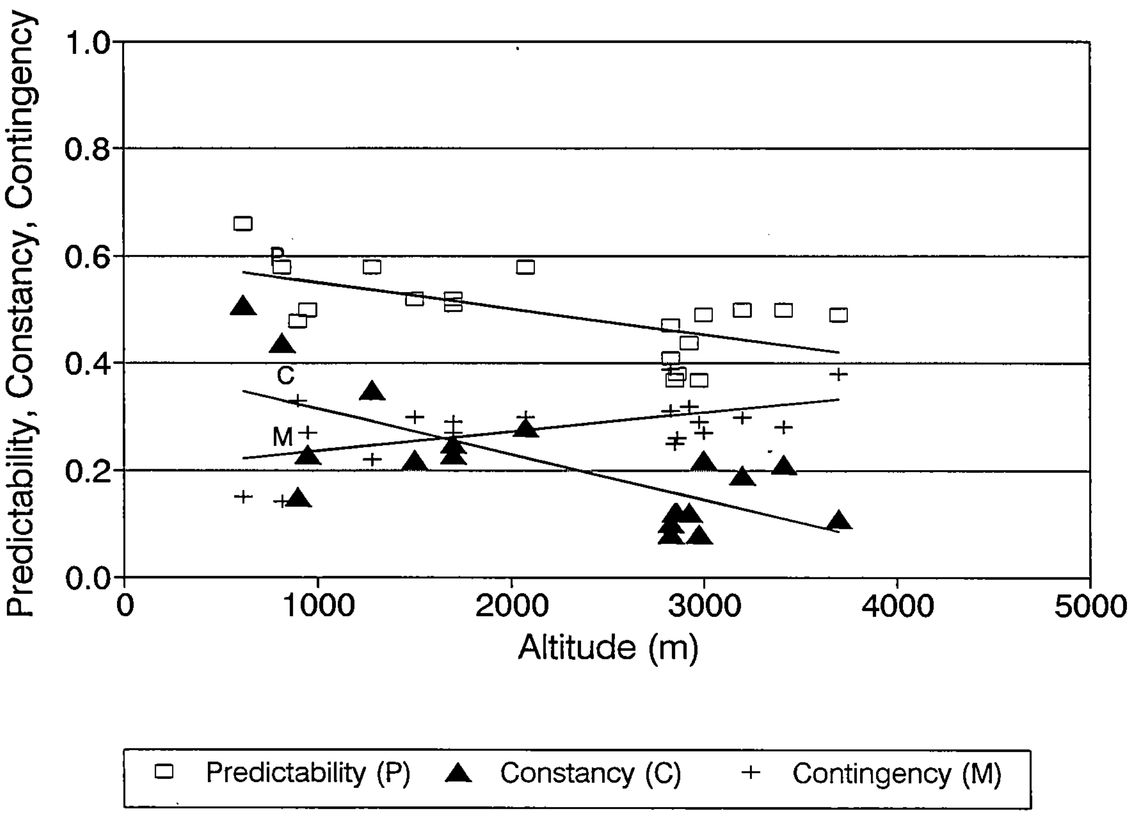


FIGURE 2.9 MEAN MINIMUM TEMPERATURE AT SAMPLE STATIONS AS ARRAYED ON THE NORTHEAST (NE) TO SOUTHWEST (SW) TRANSECT ACROSS THE SOUTHERN PERUVIAN ANDES.

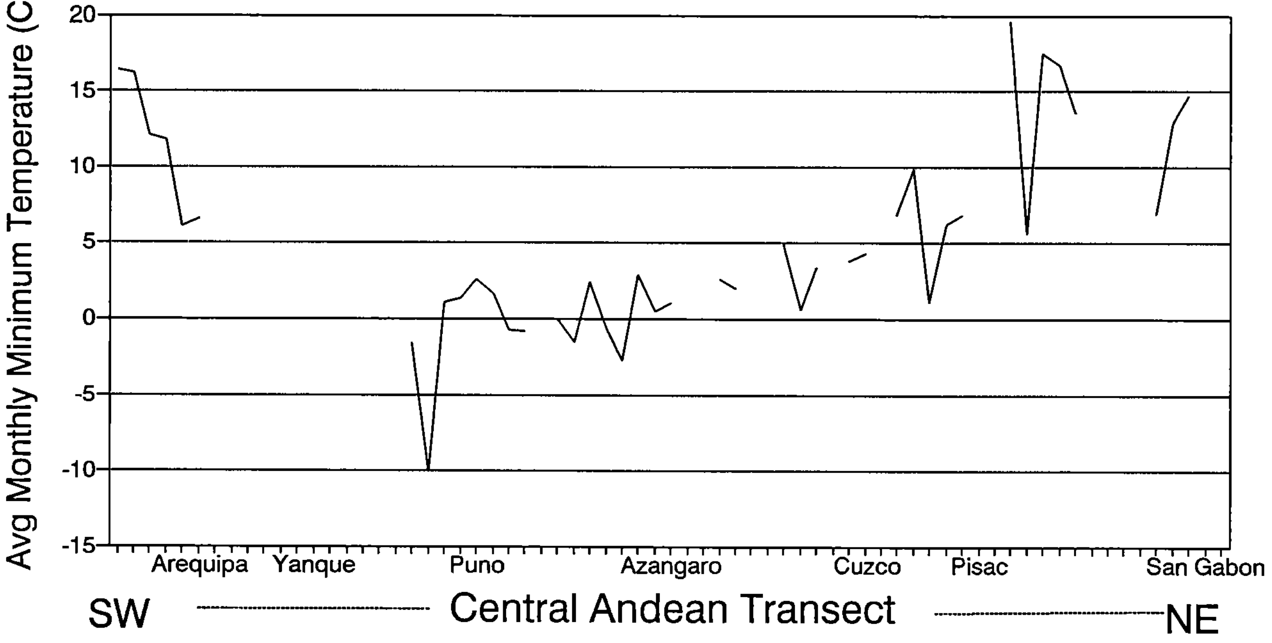


FIGURE 2.10 WESTERN ESCARPMENT: MAXIMUM AND MINIMUM MEAN MONTHLY TEMPERATURES AS A FUNCTION OF ALTITUDE, WITH SUPERIMPOSED LINEAR REGRESSIONS (SEE TABLE 2.7).

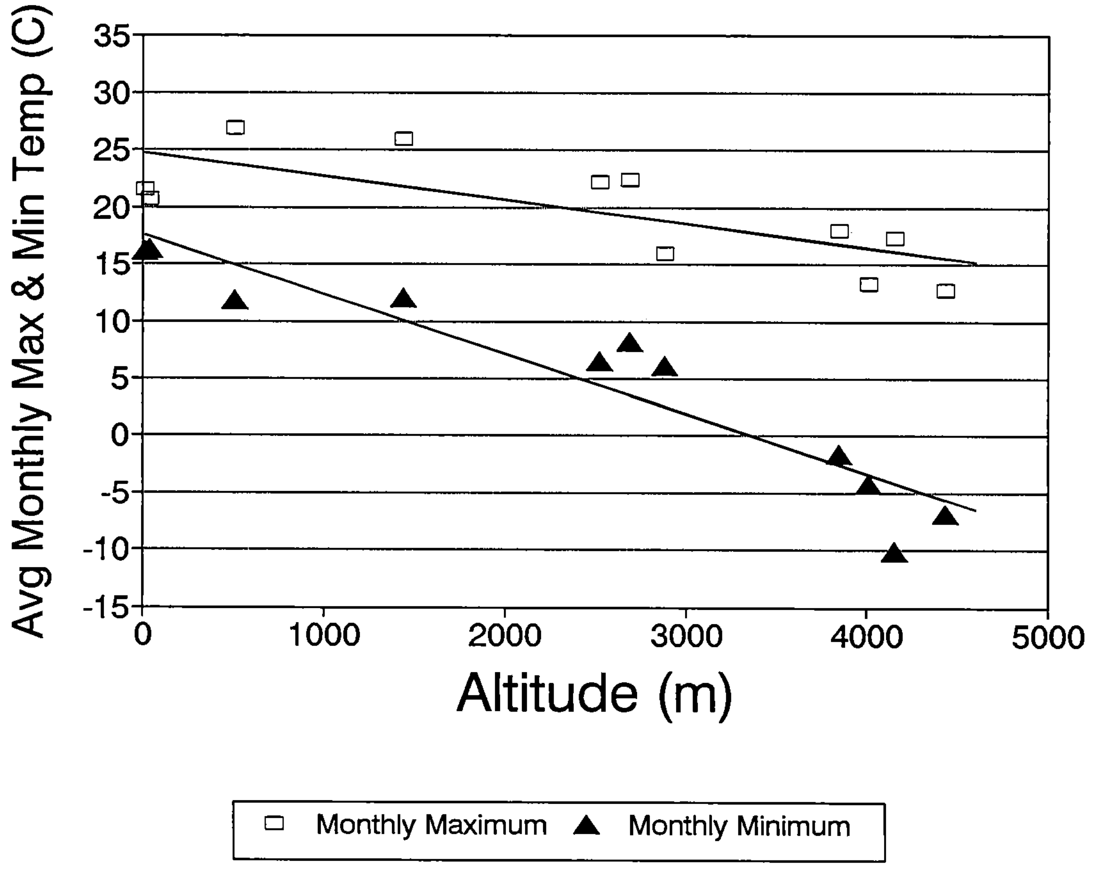
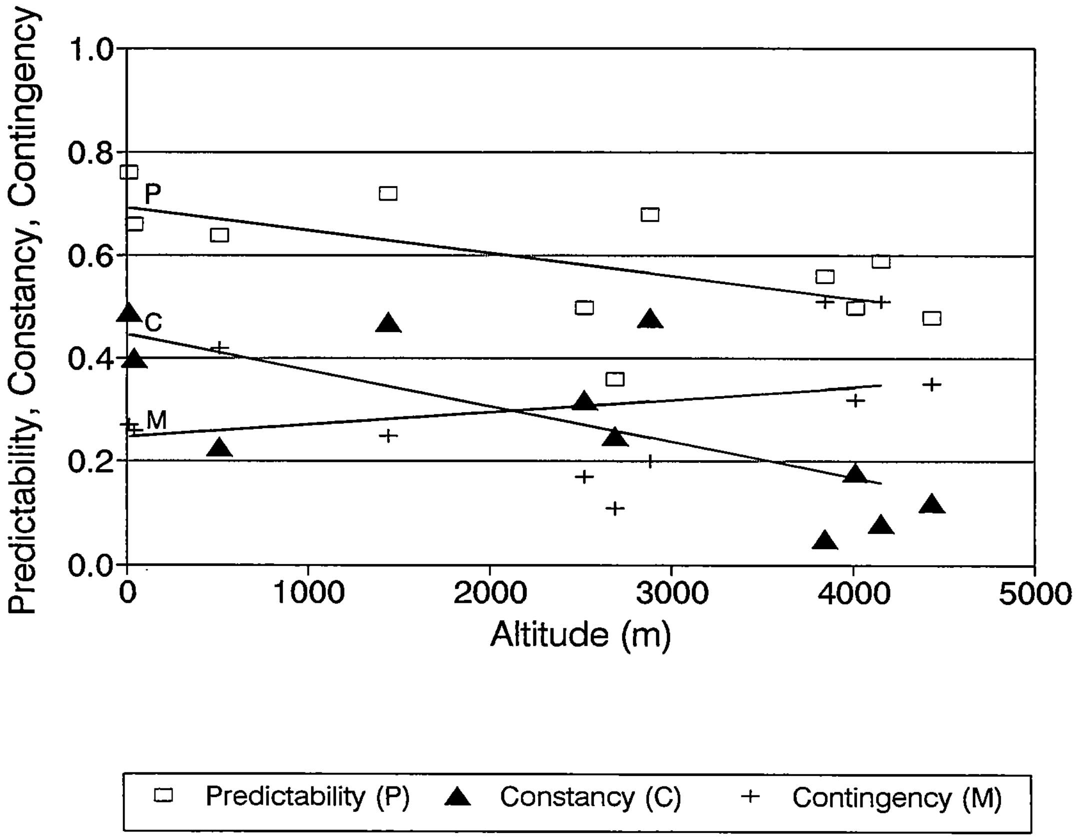


FIGURE 2.11 WESTERN ESCARPMENT: PREDICTABILITY (P), CONSTANCY (C) AND CONTINGENCY (M) OF MONTHLY MINIMUM TEMPERATURE AS A FUNCTION OF ALTITUDE, WITH SUPERIMPOSED LINEAR REGRESSIONS (SEE TABLE 2.7).



Predictability of minimum temperatures on the western escarpment also falls with altitude ($r = 0.62$; $r^2 = 0.38$), although altitude accounts for less than 40 percent of the variance in this measure (Figure 2.11; Table 2.7). Minimum temperatures are lower and less regular at the higher altitudes.

Much the same pattern of temperature relationships emerges on the eastern escarpment (Figure 2.12). Mean maximum ($r = 0.89$; $r^2 = 0.81$) and mean minimum ($r = 0.98$; $r^2 = 0.96$) temperatures fall with altitude in strong linear relationships. The lapse rates per 1,000 meters are 4.5°C and 5.9°C, respectively. The very high correlation coefficients in these data suggest that the irregular topography of this escarpment affects the relationship between temperature and altitude much less than it does the relationship between precipitation and altitude. The predictability of minimum temperatures diminishes upslope on the eastern escarpment ($r = 0.67$; $r^2 = 0.45$), from slightly less than 0.80 to approximately 0.50 at the highest altitudes (Figure 2.13; Table 2.7).

We can use the regressions from Table 2.7 to compare the eastern and western escarpments for altitude-adjusted minimum temperatures. At 1,000 meters, the western slopes average about 5°C colder than their eastern counter parts, whereas at 4,000 meters the difference is 3°C. Thus, at comparable elevations, minimum temperatures are significantly colder on the western escarpment. This difference may be partially because of the effect of moisture, as frosts generally begin at lower elevations on the slopes of dry mountains (Sarmiento 1986:13).

Onset of Rainy and Thermal Seasons

Figure 2.14 presents the second of the novel measures that I described earlier: onset and conclusion of the thermal and rainy seasons. On the northeastern end of the transect, the thermally propitious season lasts from July through the following June, the full 12 months of the annual cycle. Excepting stations adjacent to Lake Titicaca,[13] from the high northeastern slopes to the high southwestern escarpment the warmer thermal season drops from 10-12 to 4-5 months, mainly because it commences later and later in the year. This parallels the earlier observation of a fall in average minimum temperature along the same portion of the transect. In the middle to lower slopes of the western escarpment there is a rapid transition again to a 12-month thermal warm season.

The rainy season lasts for 12 months only at the lowest stations on the northeastern end of the transect. It diminishes, with the expected irregularities, as one moves up the eastern escarpment. It begins in November and lasts through March on the northeastern half of the Altiplano, and it begins somewhat later in December and lasts through March from the southwest Altiplano to the middle elevations of the western escarpment. It drops abruptly to zero for Arequipa and stations to the southwest. From the perspective of regional agro-ecosystems, it is important that on the eastern escarpment the rainy season is comfortably bracketed by relatively favorable thermal conditions. The coincidence of these two requirements for production, however, grows more restrictive along the transect until the middle levels of the western escarpment, where the lengthy thermal season is not

FIGURE 2.12 EASTERN ESCARPMENT: MAXIMUM AND MINIMUM MEAN MONTHLY TEMPERATURES AS A FUNCTION OF ALTITUDE, WITH SUPERIMPOSED LINEAR REGRESSIONS (SEE TABLE 2.7).

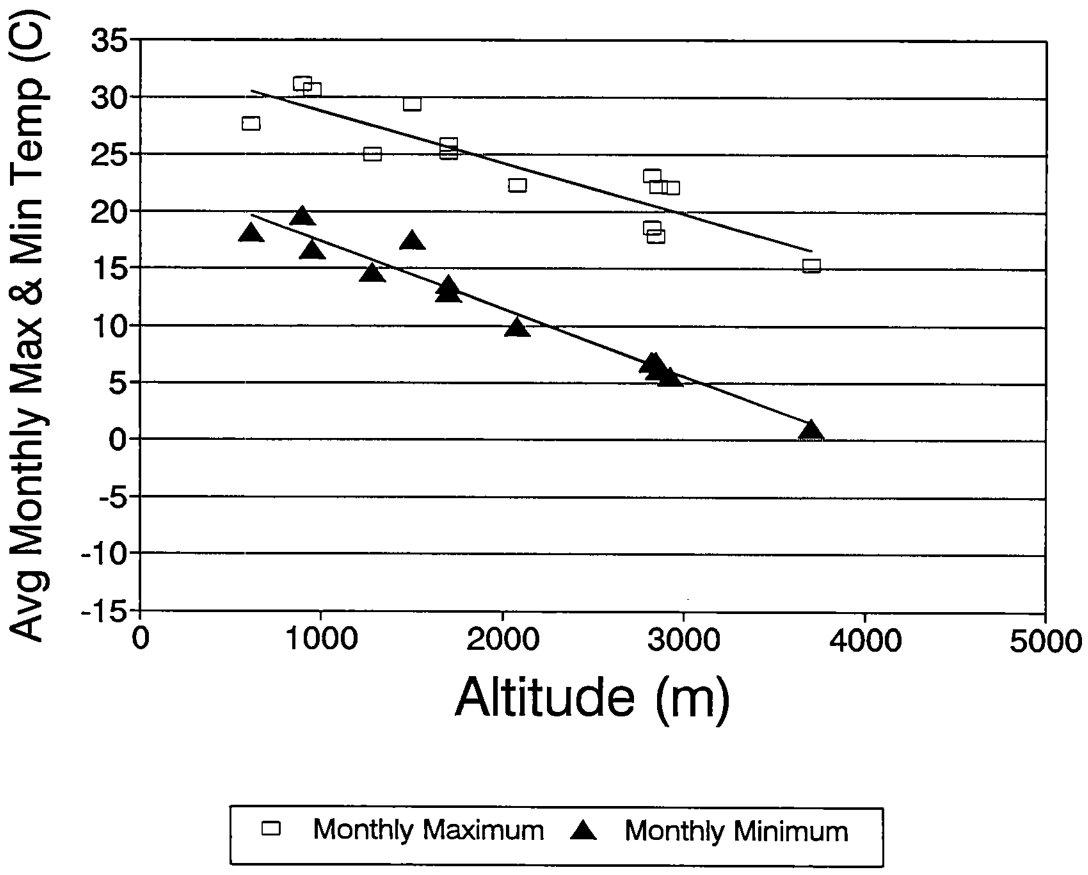


FIGURE 2.13 EASTERN ESCARPMENT: PREDICTABILITY (P), CONSTANCY (C) AND CONTINGENCY (M) OF MONTHLY MINIMUM TEMPERATURE AS A FUNCTION OF ALTITUDE, WITH SUPERIMPOSED LINEAR REGRESSIONS (SEE TABLE 2.7).

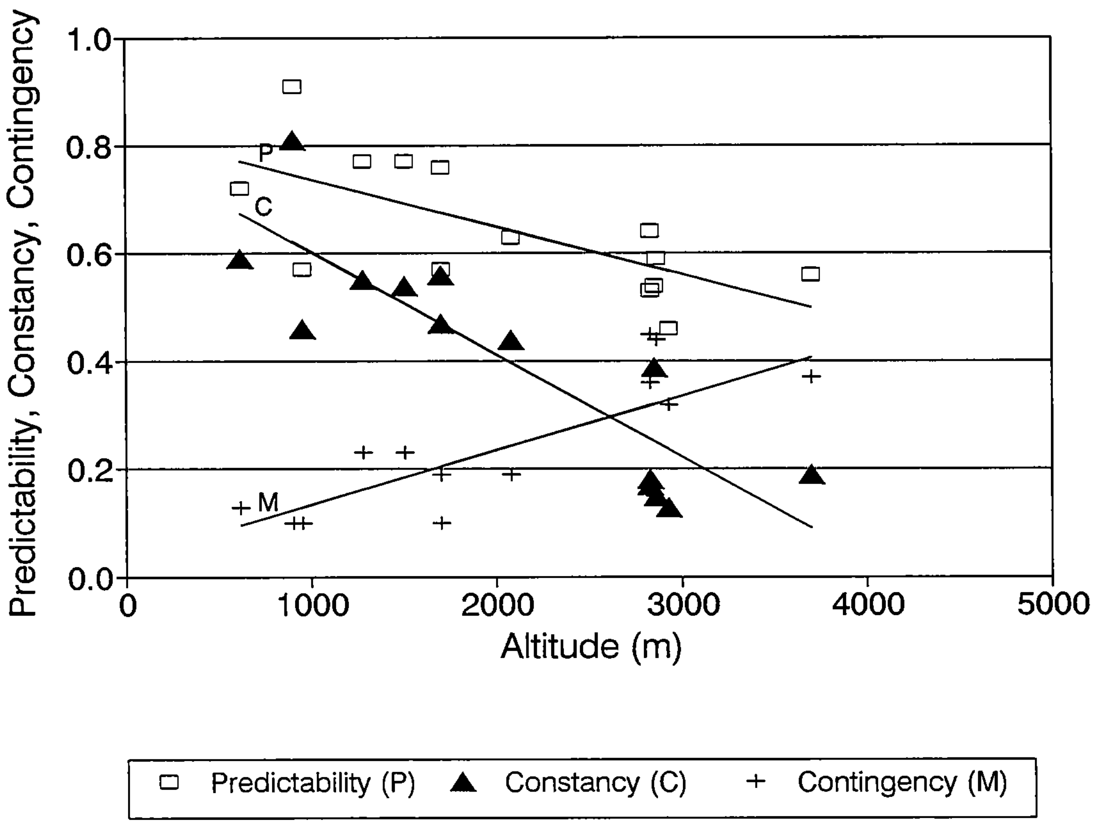
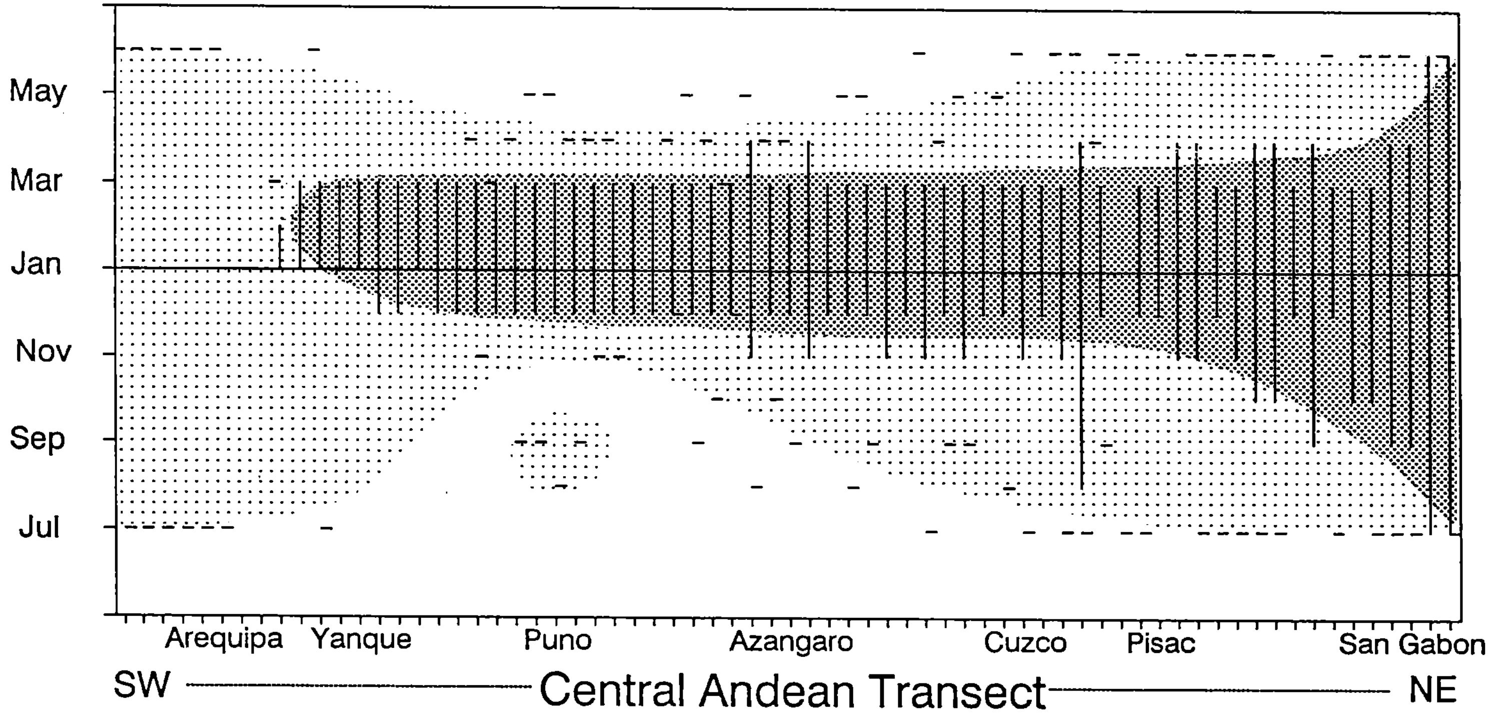
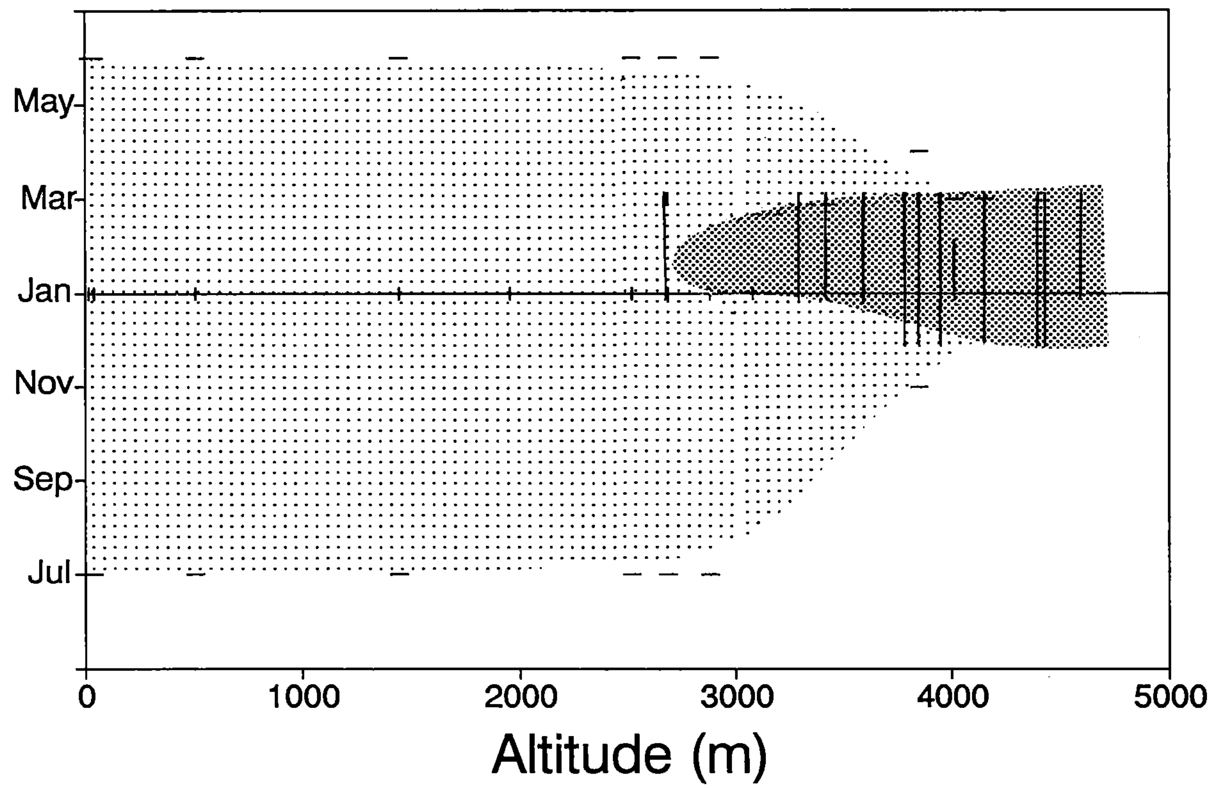


FIGURE 2.14 ONSET AND CONCLUSION OF THE RAINY (DARK STIPPLING) AND THERMAL SEASON (LIGHT STIPPLING) FOR THE SAMPLE STATIONS AS ARRAYED ON THE NORTHEAST (NE) TO SOUTHWEST (SW) TRANSECT ACROSS THE SOUTHERN PERUVIAN ANDES.



Note: The vertical lines represent the actual data points for duration of the rainy season; the horizontal, dashed lines the actual data points for the beginning and ending of the thermal season. The detached patch of light stippling isolates four stations that are located adjacent to Lake Titicaca.

FIGURE 2.15 WESTERN ESCARPMENT: ONSET AND CONCLUSION OF THE RAINY AND THERMAL SEASONS, AS A FUNCTION OF ALTITUDE.



Note: The vertical lines represent that actual data points for duration of the rainy season; the horizontal, dashed lines the actual data points for the beginning and ending of the thermal season.

complemented by a rainy season.

The western escarpment pattern is portrayed in greater detail in Figure 2.15. Note that the length of the thermal season expands from 4 months to nearly 12 months as altitude drops from 4,000 to 3,000 meters. But between these same elevations the effective rainy season drops from 3-4 to 0 months duration. Even without knowledge of past or present agriculture in the Colca Valley, we might predict irrigation in this zone. The abundant water of the highest elevations (Figure 2.5) need only be moved a short distance downslope to areas of favorable thermal conditions where it can augment the quantity and duration and ameliorate the irregularities of the quite limited rains.

SUMMARY

Average annual precipitation is highly variable from site to site on the eastern escarpment and is only partially correlated with altitude. It is nearly constant as one moves from northeast to southwest across the Altiplano. And it is almost completely explained in the statistical sense by altitude on the western escarpment. The amount of precipitation decreases upslope on the northeast side of the Andes. In contrast, it increases upslope on the southwest side. The predictability of monthly rainfall decreases with altitude on both escarpments. Contingency increases with altitude, but it fails to offset the stronger drop in constancy.

Monthly maximum and minimum temperatures diminish with altitude on both escarpments as does the predictability of minimum temperatures. Linear regressions of mean monthly maximum temperatures on altitude are quite similar on the two sides of the mountains, but mean monthly minimum temperatures are consistently higher on the eastern slopes (by 3° to 5°C). Predictability of minimum mean temperatures is higher at low elevations on the eastern escarpment than it is at low elevations on the western escarpment, but the regression lines for this factor are indistinguishable by 3,000 to 4,000 meters.

The *thermal season* constricts dramatically in the Altiplano portion of the transect. The *rainy season* drops from 5 or 6 to 3 or 4 months as one passes from the high slopes of the eastern escarpment across the Altiplano basin to the high slopes of the western escarpment. Favorable moisture and temperature conditions last only for a relatively brief seasonal period at the higher altitudes on the southwest end of the transect.

PROBLEM DISCUSSION

I have used a very focused question (Why is there irrigation in the Colca Valley but not in the Sandia Valley?) to motivate a broader analysis of climate in the southern Peruvian portion of the central Andes. It is appropriate that I return to that question to elucidate some of what has been learned from the data. I will focus on the zones between 3,000 and 4,000 meters on both escarpments.

I earlier hypothesized that irrigation might be used to alter the timing, quantity, predictability, or quality of water available for agriculture. I now can describe these postulated relationships in somewhat greater detail:

Timing: On the higher portions of the eastern escarpment a thermal season of 8-12 months amply brackets a rainy season of 4-6 months. In contrast, the rainy season on the western escarpment is 4 months or much less in the zones that are thermally adequate for agriculture. Irrigation to provide water before (and perhaps after) the normal rainy season would be of much greater benefit in the Colca area than in the Sandia area.

Quantity: According to the regressions established in Table 2.7, at 3,000 meters the Colca Valley gets 290 millimeters of precipitation and the Sandia Valley gets 900 millimeters. At 4,000 meters the difference is much less (518 millimeters in the Colca Valley; 609 millimeters in the Sandia Valley). Roughly speaking, the Colca gets half the incident precipitation of the Sandia Valley and would derive a much greater benefit from irrigation to augment the overall quantity of available moisture. The polynomial relationship of precipitation to altitude on the western escarpment makes the high elevation areas in the upper reaches of the Colca Valley relatively attractive water sources.

Predictability: The two escarpments do not differ greatly in the predictability of minimum temperatures or precipitation at these altitudes. Although month-to-month predictability is quite low in both zones and presumably influences agricultural tactics in a variety of ways (including irrigation management in the Colca Valley), it does not help explain the presence or absence of irrigation in the regional comparison.

Quality: Mean annual minimum temperatures are 3° to 5°C lower on the western escarpment than on the eastern escarpment. Another potential benefit of irrigation, the mitigation by damp soils of localized frost damage, would be of greater importance in the Colca Valley than in the Sandia Valley. Other potential aspects of water quality have not been discussed here.

A Summary of the Evidence

The validity of the climatological proposals developed here to explain the distribution of central Andean irrigation must be measured against empirical evidence of the agro-ecological function of irrigation in the prehistoric and contemporary periods. Unfortunately, most of the anthropological literature on Andean irrigation has focused on its sociopolitical organization and provides little information on its role in production. Quantitative data are sparse (Mitchell 1976). Nonetheless, the comparison given above supports the ecological approach, as do those few studies that provide the necessary information. In the Colca Valley, for example, irrigation "does seem to serve three functions: to extend the cropping season (for some crops); to increase predictability; and, to increase total water available for crops" (William Denevan, personal communication, 6 February, 1990). Treacy (1987:425) notes that Colca Valley farmers use irrigation to extend the cropping season at its initiation (August through November) to ensure that crops mature before they are killed by May and June frosts. For the same region, Guillet notes that irrigation is used in lower elevations to "lengthen the growing season for the long maturing maize" (1987b:82). Farrington states that "irrigation [in highland Peru] offers a valuable supplement to rainfall during the growing season and in places does serve to extend the cultivation year by enabling certain crops to be planted earlier" (1980:298).

Mitchell's (1976 and *intra*) work provides additional support. His description of irrigation in Quinua (located in the inter-Andean valley of Ayacucho) is one of the most complete in terms of the agro-ecological functions of the system. The major part of the food production in this community is based on two agricultural zones, one located in the upper altitudes and one in the lower altitudes of the lower montane savanna. In the upper zone, irrigation is used to extend the growing season immediately before the onset of rains (the September through December period). It is not used at the conclusion of the rainy season, which is limited by frost. The longer season is required to encompass the growing period of crops (especially maize) whose maturation is delayed by altitude. Further, the measured delivery of water before heavy rains allows root systems to develop past the point that they would suffer from rotting in more saturated soils. In the lower zone, irrigation is used to supplement the quantity of precipitation and to cover the intermittent dry periods during the normal period of the rainy season. Here, the overall amount of precipitation is inadequate, although the duration of the rainy season and the maturation period of the crops coincide and match the favorable thermal period. Thus, it is not necessary at this elevation to extend the cultivation interval. Use of water in the two zones is complementary because their agro-ecological requirements are successive in time.

Qualifications

Regional climatological analysis offers insight into one of the factors important in the origins, distribution, and functioning of Andean irrigation systems. Any complete explanation must include such additional considerations as differences in topography, soils, crops, capital, market conditions, and sociopolitical organization. Further, moisture availability to plants can be managed in other ways: by increasing the capacity of soils to retain moisture by adding organic matter, or by selecting crops with greater tolerance for desiccation. In my comparison of the Sandia and Colca valleys, these variables are more or less constant. But elsewhere in the Andes they are not. As Seligmann and Bunker have demonstrated (*intra*), people require both the technical and the political means to develop an irrigation system. Similarly, economic conditions in the contemporary Ayacucho Valley have discouraged the expansion of irrigation in spite of great need for additional agricultural land (Mitchell *intra*).

Even within its own terms, the large-scale of the comparison forces it to overlook significant local heterogeneity. Some of the regional variables, for example, also operate at much smaller scales. For instance, the local thermal conditions, upslope winds (Troll 1968:48), and rain shadows found in some of the deep valleys of the eastern escarpment create conditions similar to those characteristic of the western escarpment. Like the Colca Valley, the warm lower slopes of these valleys typically are xeric and might benefit from irrigation in their intermediate and lower elevations (Bowman 1968[1916]:154). The irrigation system of Quinua (Mitchell *intra*) is an example. The sources of Quinua's irrigation water are the springs and streams of the wet highland zones to the east of the valley.

At this point, climatological propositions concerning the regional patterning and functioning of Andean irrigation systems are somewhat tentative. I hope that raising these issues will motivate Andeanists to gather additional test data.

CONCLUSION

The Andean and general human ecology literature is filled with hypotheses about the effects of environment on the development and form of human adaptive systems. Despite this, ecological analysis in anthropology rarely has provided ecological information in the abundance, detail, and form needed to assess these proposals (Winterhalder 1980). The data often do not exist or are difficult to obtain. The analytical methods of the natural sciences often do not match the analytical needs of the human ecologist, and too often anthropologists have been content to propose but not test ecological explanations. The present essay has attempted to provide meteorological information with sufficient detail to assess the impact of climate on the distribution and function of highland irrigation systems.

Standing at the Carabaya overlook it is easy to appreciate the "noble proportions" (Bowman 1968[1916]) of the Andes and visualize the broad seasonal patterns of precipitation and associated changes of temperature to which they give rise. As Bowman notes, a diverse sample of the earth's climates can be found within a day's walk of a place like this. Significant changes also occur from day to night, week to week, and year to year, challenging the technical and managerial skills of the high altitude peasant who must deal with the resulting drought, flood, and frost. These spatial and temporal variations absorb the attention and organizational energies of Andean peoples. Both must gain the attention of human ecologists if we are to understand the ecological bases of phenomena like the regional distribution and functioning of irrigation systems. The geographical perspective must be matched to an analytical view that encompasses the local details of the weather, especially the short-term vagaries and predictability of precipitation and temperature.

NOTES

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1. The central Andes encompasses the tropical cordilleras of western South America from

southern Ecuador through Peru and into northwestern Bolivia, northern Chile, and Argentina (Brush 1982).

2. This corresponds, by his estimation of lapse rate on the Altiplano, to an average warming of about 2.5°C.

3. "Incidence" here is the probability of occurrence within consecutive ten day intervals, with crop damage assumed if precipitation is less than 0.5 times evapotranspiration, if minimum temperature drops below 0° C, or if hail is recorded.

4. This essay has been extracted from a monograph in preparation ("Climate predictability and patterning in the Central Andes of Peru"), part of a larger research project ("Production, Storage and Exchange in a Terraced Environment on the Eastern Andean Escarpment") funded by the National Science Foundation (BNS #8313190) from July 1984 to December 1987.

5. The key sources are the following: Drewes and Drewes 1957; Grace 1983; Johnson 1976; Winterhalder and Thomas 1982.

6. For precipitation, predictability is calculated using the base-2 log of monthly precipitation. This procedure eliminates the correlation between the mean and variance of rainfall, facilitating comparison among stations with differing average precipitations. The log transform is not used on minimum temperature calculations reported here.

7. The specific figure of 64 millimeters was chosen because it represents a natural break in the log transformed data; see note 6.

8. The position of each station on this transect was determined by measuring its distance from a line drawn parallel to the axis of the central Andes and passing through the northeasternmost station; the sequence is an ordinal ranking. The axis of the southern Peruvian Andes was determined to lie at an angle 64° west of North by visual inspection of a physical map of Peru; the transect was established at an angle of 26° east of North. With only a few exceptions, the transect ordering faithfully lumps together stations assigned to the three biogeographic zones (eastern escarpment, Altiplano, western escarpment).

9. Here is Troll's statement: "Because of this diagonally asymetric arrangement of the zones of humidity, the climato-vegetational zones of moist puna, dry puna, and thorn-and-succulent puna cross the Andes diagonally from NW to SE" (1968:46; see figure 17, p. 37, and figure 20, p. 47).

10. The polynomial model that fit so well on the western escarpment performs poorly on this eastern escarpment data [$n = 19$; without a constant, $r = 0.33$ and $r^2 = 0.11$; with a constant, $r = 0.56$ and $r^2 = 0.31$]. Similarly, a linear model, with the two low-altitude and very high precipitation stations eliminated gives a relatively poor fit [$n = 17, r = 0.48; r^2 = 0.23$; constant = 17772.9; coefficient = -291.0]. This model appears to be a better predictor at the upper altitude on this escarpment.

11. This may be due to minor differences of elevation. Stations on the northeastern end of the Altiplano portion of the transect are somewhat lower than those on the western end (Figure 2.2). There is a significant relationship between mean minimum temperature and altitude on the Altiplano (Table 2.7).

12. If the two coastal stations are eliminated from the sample, the linear regression of maximum temperature on altitude is much stronger [$n = 9; r = 0.91; r^2 = 0.83$; constant = 29.9; coefficient = -3.56]. This gives a lapse rate for mean maximum temperature of 3.56°C/1,000 meters.

13. Four stations make up a small isolated cluster on the southwestern end of the Altiplano segment of the transect. Their thermal seasons begin unusually early. They are centered immediately above "Puno" on the x-axis of Figure 2.14. In fact, all are on or near the margin of Lake Titicaca and presumably have their temperatures meliorated (see Figure 2.9) and growing season lengthened due to the proximity and thermal properties of the lake.

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