QUATERNARY PALEOCLIMATOLOGY OF THE PACIFIC COAST OF NORTH AMERICA[1]

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We will now deal in a field where facts are disputed and theories are a dime a dozen. A few points in regard to the climate of the past in western North America, however, are reasonably well established.

As a background for a consideration of recent secular changes in climate we may profitably spend a brief—very brief—time reviewing facts and interpretations of climatic changes in this region during Cenozoic time. The earlier periods will be rushed over; increasing emphasis will be accorded data that are accumulating on the more recent, largely Postglacial events, particularly over the past few millenia; in greatest detail, over the past few centuries.

LONG-TERM TRENDS

In western North America, despite enormous fluctuations, there has been, up to the present time, a fairly general climatic trend, which paleobotanists in particular have worked out in some detail. Through all or much of the Tertiary and Quaternary periods the trend in general has been toward cooler temperatures and greater aridity. Harking back momentarily more than a million years, we note that the trend toward aridity seems to have been rather consistent and extensive through Tertiary time. During late Pliocene time the downward trend toward aridity seems to have been reversed, and during Pleistocene time the surface-water supplies fluctuated widely on four main and various minor occasions. During each ice advance the long-term trend toward cooler weather was accelerated, to be reversed during each of the three Interglacial periods, when, in contrast, the trend toward aridity was resumed. With fluctuations again, this combination of drought and warmth characterizes the Recent period, whether or not we class it as Interglacial.

Throughout these complex trends there seems to have been a tendency toward increased fluctuation, from period to period, from year to year, and from season to season; also from region to region. This circumstance, plus the accentuation of some trends along with the temporary reversal of other gradients during Quaternary time, renders difficult and dubious any definite prediction as to future trends. In view of the past, perhaps the highest plausibility can be accorded the hypothesis that climate will change. My own feeling is that there is a very strong possibility, if not a probability, that the trend toward greater aridity will continue, with fluctuations of course.

The complexity of the climatic trends renders difficult not only future predictions, but also an understanding of the causes of past changes. In broad terms, particularly for Tertiary and Pleistocene history, the trends seems to have been largely worldwide, but, as I shall indicate later, some of the more recent fluctuations seem to have been negatively correlated in different regions of the earth.

The trend toward greater aridity in western North America has commonly been attributed to the elevation of the western mountains, which captured rainfall and produced rain shadows to the eastward, but there is some evidence that this was not the only factor. Interglacial aridity could hardly be so explained. Fluctuations in aridity during Recent time seem to have affected coastal regions and offshore islands, as well as the interior of western North America. And at least some of the changes were simultaneous in the diverse regions. Some factor other than local land elevation seems to have been involved.

Though other and broader factors have doubtless operated, it seems obvious that climatic conditions in the West have been greatly influenced by the massive land elevation that began in the Miocene, gained impetus in the Pliocene, and reached a crescendo in early Pleistocene. An important point of vital climatological bearing that has often been neglected is that not only the mountains but also vast plateaus were greatly elevated. In all probability the Great Plains and the Columbia Plateau were elevated, along with the vast Colorado Plateau. The Range and Basin Province, primarily of the Great Basin, was apparently subject not only to the internal ups and downs of fault blocks, but also to a general uplift of perhaps 2,000 or 3,000 feet. There are reasons for believing that in Pliocene time the Great Basin was essentially part of the coastal plain, standing at less than 1,000 feet elevation and draining to the Pacific. One reason that we have advanced to justify this view is that Pliocene fish fossils in the Great Basin represent coastal-plain types.

Though there are conflicting theories, and some would have the major trends of climate alternating in different regions, especially during the Pleistocene, it seems rather obvious now that in general the major climatic trends of Tertiary and Pleistocene times were essentially simultaneous over the earth, at least over Eurasia and North America. Early Tertiary times seem to have been rather uniformly warm and moist over the world, even toward the poles. There were, apparently, no polar ice caps, and, in seeming response, deep ocean temperatures dropped to only about 10°C, according to Emeliani's data from benthic foraminifera. Low elevation of the continents presumably contributed to the uniformity of conditions, but was probably not the only factor. The free passage of currents through the Panama Strait may have played a part. In any event, the Arcto-Tertiary Geoflora reached far south in the West. The warmth of the North Pacific presumably permitted interchange between temperate faunas on the two sides.

[1] Contribution from the Scripps Institution of Oceanography.

Cooling appears to have continued over the world through late Tertiary, as did desiccation prior to late Pliocene, when there appears to have occurred a reversal that in due time probably led to the first major accumulation of ice. The Panama Strait was closed by the elevation of the isthmus. The Madro-Tertiary Geoflora progressed northward taking over areas previously covered by the Arcto-Tertiary Geoflora.

Enormous fluctuations in precipitation and in temperature, involving the four major glacial periods of the Pleistocene, with their various substages, seem to have been world-wide. Paleontological and paleotemperature studies of bottom sediments confirm the picture in general, but emphasize the multiplicity of substages. Recent paleontological evidence, advanced by Claude W. Hibbard of the University of Michigan, confirms the picture: small fossil mammals of the Great Plains appear to represent all four of the successive cold periods of the Pleistocene, plus, on present evidence, two of the three Interglacial periods. Carbon-14 datings of the recession of the last ice cap about 11,000 years ago, bespeak essential simultaneity over the northern continents and northern oceans. And there is some evidence, as from faunal displacements in the sea, that Wisconsin (Würm) events were simultaneous in the Northern and Southern Hemispheres.

EXTREME COLD IN WISCONSIN TIME?

There are strong indications that the last (Wisconsin) ice stage was one of extreme and far-reaching cold—perhaps emphasizing the long-term trend toward cooler weather. The fact that the continental ice sheet did not advance as far as had the previous glaciers, and the fact that each major ice sheet was less extensive than the preceding one, may well reflect the long-term trend toward greater aridity. The extent of each ice sheet may have depended less on the degree of cold than on the available precipitation. Decreased moisture would have led to less accumulation of ice and less southward flow of the continental ice sheet.

If the Wisconsin was arid, it was dry of course only in comparison with early Tertiary and other ice age periods. Precipitation must have been heavy to have produced the vast ice cap (though less vast than previously) to have formed simultaneously montane glaciers well toward and, some think, almost to the Mexican border; to have produced ponds and marshes in now dry regions on the Great Plains; and to have filled many Western basins with great inland seas. The northern part of the Range and Basin Province had almost as much water as land, and even to the southward at least semipermanent lakes covered the playas. There is much evidence also of increased stream flow, along the coast as well as in the interior. The widespread pimple-mound topography may be interpreted as reflecting greater moisture as well as extreme cold.

Evidence of world-wide coldness during Wisconsin time is rampant. In the East the boreal forest seems to have advanced to the Gulf of Mexico, and the northern biota seems to have been forced into refuges in Florida and Mexico, from which redispersal took place in early Postglacial time. Anadromous fishes were able to move southward through seas now too warm for them: a small salmon became landlocked in Formosa; trout got to Sinaloa, the Atlas Mountains, and the Near East; sticklebacks moved into streams of northwestern Baja California. Disjunct populations of northern freshwater fishes in New Mexico and even in northeastern Mexico almost surely got there in cooler, Wisconsin time. Cool-water mollusks occupied ponds and lakes about which man existed at about the close of the Wisconsin period. The mammoth reached the Valley of Mexico. In New Zealand, I have heard, littoral mollusks dated at about 20,000 years have been dredged, from presumably Pleistocene submarine terraces, farther north than these cool-water species now occur.

It was presumably during Wisconsin time that certain marine plants and animals that now occur in temperate waters to either side crossed the then materially cooled waters of the tropics. One such organism is the giant kelp *(Macrocystis)*, which occurs as the same variants of the same species in Peru and Chile as in California. Another is the Pacific sardine, which is virtually indistinguishable in our waters and in Peru. I have computed that a drop in sea-surface temperature of about 3°C in winter and perhaps 8°C in summer would allow these and distributionally similar species to regain connection off the coast of Middle America, and I am assuming that the seas were cooled about that amount in Wisconsin time. Oxygen-18 temperature estimates from organisms in sea-bottom cores are in essential agreement.

The widespread extinction of large mammals in late Pleistocene time may also be attributed in part at least to extreme cold in Wisconsin time, forcing dispersal far southward into less favorable ranges, and in part to the following period of aridity.

Another line of evidence indicative of the southward extent of Pleistocene cold is furnished by the to-be-sure somewhat controversial pimple-mound or Mima-mound topography. These rather well-aligned mounds cover many thousands of acres in the western half of the United States, from near Canada to the Mexican border, and even, I am told, into the mountains of Sonora. Similar mounds in the far north are attributed to the freezing and thawing of the soil cover overlying permafrost. Farther south, I believe, they were formed by similar seasonal freezing and thawing of waterlogged soil overlying impervious hardpan.

Sea-temperature estimates by the oxygen-18 method from Wisconsin-period mollusks should eventually give us a sounder picture of reduced sea temperatures during that period—and air temperatures were no doubt very closely correlated. But the Wisconsin deposits were laid down when the sea-level was much reduced and, in my belief, the general trend of land elevation (or sea-level depression) has not proceeded far enough since the time of deposit to reveal the fossils of this period. Most of the cold-water fossilmollusk faunas already exposed at low elevations along the coasts of Southern California and Baja California I believe to be of Illinoian age. From mollusks of one such deposit in northwestern Baja California an oxygen-18 temperature estimate of only about 12°C has been obtained, I have heard.

Great secular fluctuations in sea temperatures—and hence of coastwise air temperatures—are indicated by the Pleistocene faunal assemblages in all temperate regions. Some of these assemblages are indicative of colder-than-present temperatures, others of warmer. Recent claims of mixed cool- and warm-water faunas are in part at least, based on erroneous and doubtful data; and the oceanographic explanation offered does not seem to hold water. Recently I have sampled on Guadalupe Island, only 240 miles south of San Diego, a warm-water late Pleistocene fauna, including reef coral, and mollusks that now inhabit tropical waters extending from the Gulf of California to beyond Panama. With modern isotope methods and other more intensive and critical methods, we should eventually be able to seriate and in part date these findings, and get definite temperature estimates.

POSTGLACIAL TRENDS IN TEMPERATURE

About 7,000 years ago (by carbon-14 determination from shell) the Indians of Santa Rosa Island, California, were feeding chiefly on red abalones *(Haliotis rufescens)*, a species that is available inshore only where the coastal water (and air) is cold. Hence a trace of Glacial cold was presumably persisting. Later the warm-water black abalone, *Haliotis crackerodii* was chiefly consumed.

I have obtained oxygen-18 estimates that indicate, in agreement with faunal data, that the sea-surface temperature along the coast of northwestern Baja California was somewhat warmer than that of the present about 4,000, about 2,500, and about 300 years ago. These estimates were obtained on shells of surf-zone mollusks from Indian middens, from which I also have obtained carbon-14 datings from charcoal and/or shell. But between the 2500-year and 300-year B. P.* datings I have evidence of a cooler-than-present period. Oxygen-18 temperature estimates lie below the present growing-season mean, and the dating is about 900 years ago. In this period the Indians over a long stretch of the Baja California coast fed heavily on the giant chiton *Cryptochiton stelleri*, which now, except for extremely rare deepwater strays off Southern California, is confined to the cold-coastal region from near Pt. Conception in California to Japan. No trace of it has been found along the coast from which it was abundantly harvested about a millenium ago.

A point of prime interest in this connection is that at about the same time it is thought that coastal Greenland had become attractive to and was inhabited by Scandinavians—when Greenland was green. This is one of the bits of evidence of negative correlation in regional temperature regimes. Temperature, like money, may be present in adequate amount but not evenly distributed.

* Before present.

Coming closer to the present, we have evidence of a warm period, along the southern half of the California Coast, just about a century ago, after which this region became cooler while arctic amelioration was proceeding in the far north; again, the ambient temperatures of this coast and of the far north seem to have been negatively correlated. I was led into this interpretation of a warm period approximately a century ago by the faunal evidence. The first zoological survey of the West Coast worthy of that designation, conducted by the naturalists of the Pacific Railroad Survey of 1853-57, disclosed at San Diego a fish fauna of a warmer-water affinity than that of the present—about like that of Turtle Bay, and even of Magdalena Bay (near the middle and southern parts of the Baja California peninsula). And at Monterey this early survey found a fauna containing San Diegan elements that do not now occur in the colder waters of central California. Some of these southern forms at each port were sedentary types not very subject to northward dispersal in isolated warm seasons such as we are now discussing. A seahorse, for example, was one of the fishes taken then, but never recently, at San Diego. Other faunal data keeps fitting into the picture.

To check the indications of warm water in the southern half of California about a century ago, I made a short journey into meteorology. First I showed an extremely high correlation between sea and air temperatures near San Diego. Then I analyzed the weather data, which very fortunately began at San Diego in 1849 and very soon afterward at Monterey. There was indeed a definite trend toward cooler temperatures at these localities through the second half of the nineteenth century, notably in the late-spring and early-summer months, which are of most significance to the fishes.

The weather data for San Diego seemed to indicate a continued cooling trend until about 1910, after which the monthly plots seemed to show a slight rise. But this rise may be attributed at least in part to the effect of urbanization, which, as certain meteorologists have shown, yields temperatures in built-up cities that are somewhat too high for the region. The most marked rise toward the end of the years analyzed is definitely attributable to the moving of the weather station to Lindbergh Field, for test runs showed the temperature there to be about 1.0° F. higher than at the Federal Building, where the weather station had previously been located.

POSTGLACIAL TRENDS IN MOISTURE

There is now, of course, no shadow of a doubt that during the Pluvial period, which accompanied the last Glacial period, the rainfall from the Great Plains to the Pacific Coast and from the ice cap to Middle America must have been vastly greater than at present, and the evaporation must have been much less. Together these factors caused rivers to flow full and basins to fill with great lakes. I have reviewed this evidence in some detail and will not repeat it here.

Evidence has been presented to indicate considerable desiccation through the still moist and cool early ("anathermal") portion of Recent time, which was followed by the warm and dry altithermal period (or climatic optimum), around the middle of Postglacial time. A "Little Pluvial" period then is thought to have followed, during which Pluvial lakes and streams were somewhat re-established. Archeological and tree-ring data suggest a severe drought in the thirteenth century.

Obviously there have been marked fluctuations in water supply during Postglacial (Recent) time, but throughout most of the period water was probably much more abundant than it has been over the last few centuries. Archeological and physiographic evidence is replete with indications of more abundant water, at many times during the Postglacial period and at many places from the Pacific Coast to the Great Plains. Indications accumulate of past human populations too large to have been supported by the amount of surface waters presently available. Midden remains are found of fishes and other water-limited animals that could not now exist in the region, and in places the remains of plants indicate vegetation of a more humid period. My own studies keep uncovering confirmatory indications of greater humidity at various dated times in the Postglacial sequence.

In fact, I have for some years thought that the drought of the past three decades has been the most severe of any since the Pluvial period. I have found evidence of the extirpation during this period, as a result of the drought, of wholly isolated fish populations that must have persisted since Pluvial time. Except for isolated introductions by man, fishes occur only in waters that they have at some time reached by normal dispersal.

The "march of the desert" seems to have been continuing right up to the present. In fact I am becoming more and more impressed with the apparent recency of the desert conditions over the southwestern United States. To be sure the desert biota is too distinctive to have suddenly evolved, but the deserts may well have merely been dispersed, with their characteristic biota, northward from some ancient center in Mexico.

Some of the evidence for the recency of the deserts in the Southwest is physiographic. Recent gullying—very striking through the region—is very likely due in part to drought, which has destroyed ground cover. More pointed evidence, in the extreme desert regions of the Colorado Desert and the Colorado Delta, is furnished by the structure of the *bajadas* (the alluvial apron around desert mountains). Typically, sections of *bajada* even against the mountains show fine sediment throughout the greater part of their height. Occasional gravel or cobble streaks tell of flash floods. But the fine sediments are typically capped by desert shingle. Furthermore, secondary fans topping older *bajada* slopes are composed of very coarse rock fragments. The plausible explanation is that over long periods of time until very recently—unfortunately we do not yet have datings—the desert mountains were smooth-topped and largely covered with a mantle of soil, which, from time to time, probably at an accelerating rate, eroded away, to be deposited at the base of the mountains. The abundance of large herbivores until late Pleistocene and early Post-Pleistocene time, and the oncoming drought may have together caused the erosion. Shift of rainfall from a rather even distribution to one of limited but torrential precipitation may have been a major factor. Whatever the cause, the soil on the mountains was largely eroded away, so that subsequent weathering has attacked and broken down the bare rock faces that are now so characteristic of the arid Southwest. I believe that the naked-rock mountain landscape of the West is of much more recent origin than has generally been thought, and that the seas of playa sediments that surround the *Inselbergen* have often accumulated much more rapidly than has generally been assumed. Some radiocarbon dates of buried levels of human habitation in the Southwest confirm this view.

This rapid development of arid landscape may be observed in certain places where the ground cover is being destroyed. Bare rock exposed by landslips in New Zealand mar the mountain slopes that are overgrazed by sheep. The landscape of Santa Rosa Island off California has been transformed over the last two or three decades from one of gentle soil-covered contours to one in which bare rock exposures are becoming more frequent. The soil veneer keeps slipping off to expose these scars. The reason I believe to be a combination of drought plus the foraging and trail-making of many large introduced mammals—elk, deer, and boar, as well as cattle, horses, and sheep. The landscape is beginning to change from one resembling that of the Alleghanies to one beginning to approach that of the desert mountains. What is now happening before our eyes on Santa Rosa Island I believe represents what happened in late Pleistocene or early Recent time over vast areas in the Southwest, very likely from the same causes—drought and over grazing.

The past and present distribution of animals offers much evidence corroborating the view of increasing aridity. For example, the woodchuck over the past few millenia ranged through northern Arizona well south of the range to which it is now limited by reduced moisture and higher temperatures. Fish mummies from caves in Nevada indicate a permanent lake in the Humboldt Sink, in the last few millenia. Now bone-dry canyons in southern Nevada show campsites, pictographs, petroglyphs, and other evidences of human occupation when these water courses contained water. Such evidence abounds throughout the Southwest. My own investigations yield conclusions consistent with the general view.

We are now accumulating evidence of a rather heavy population on the coast of Southern California about 7,000 years ago, in areas where the present water supply would not be adequate. Similar evidence stems from sites dated at about 5,000, 4,000, 3,000, and 2,500 years B. P.

Some of the evidence of more ample water relates to much more recent time. Very extensive middens, predominantly of small Pismo clams, over a long stretch of the Baja California coast, have been dated from a warm period, about 300 years ago, that must also have produced more surface water; carbon-14 dating and oxygen-18 paleotemperature estimates are involved. A rather extensive habitation site on North Coronado Island has been dated at less than 400 years, but there is now not enough fresh water on the islands to supply more than a family or two, and not enough brush to provide fires for any length of time for more than a very few people. But the site carries much evidence of fire, and more rainfall would surely have been needed to grow the wood that was used. Large populations of relatively recent date (to judge from a few radiocarbon tests and from the types of artifacts) existed at points along the Baja California coast, as about San Felipe, Turtle Bay, and San Ignacio Lagoon, where the present available water could not have supported the people.

Evidence of former, much-greater-than-present precipitation in the desert of Southern California was recently obtained on "Fish Creek," in the Fish Creek Mountains on the west slope of the Salton Basin. I went there with archeologists specifically to check on the former fish life of this creek. Some small fish still persisted in water holes in this creek prior to the great flood of 1916, which filled the stream bed with sediment. Since then the rainfall has been insufficient to produce permanent water, in recent years none at all; except for very rare flash floods, the stream bed is bone dry. We travelled up this dry bed by Jeep for about 14 miles, through the defile in Split Mountain, to reach an extensive ancient village site that was already known. On the surface were remains of mountain-sheep horns, suggesting better grazing and more water in former times. Digging in the abundant hearths yielded not only mammal, bird, and lizard bones, but also many fish bones. These represented the humpbacked sucker *(Xyrauchen texanus)* and the bonytail (*Gila robusta elegans*) — species that abounded in Lake LeConte, the vast inland sea that existed until about 300 years ago in the Salton Sink, and that was formed, at least in part, by inflow from a distributary of the Colorado River. These species formed a major—probably the major—part of the diet of the thousands of Indians who lined the shores of the ancient lake. But it was the adults of these large fishes that were caught and eaten about the lake, whereas most of the fish that were eaten at the Fish Creek site far back in the hills were young. The wholly plausible conclusions are that these young fish were caught locally in Fish Creek, and that they had grown from spawn deposited there by big fish that had found sufficient water in the creek to swim up from the ancient lake. To yield such a flow must have required rainfall about equal to that of the coast—say ten inches a year, as contrasted with probably less than five in the same watershed today. The date from charcoal in the hearths is 1,000 B. P.

Surprising as such a rapid decrease in rainfall may appear to be, we may regard the estimate as not at all improbable. The depopulation of the Old World deserts over the past few millenia suggests that the increase in aridity has been very widespread, at least at comparable latitudes.

Other dates of habitations in the desert region over the past few hundred years, about Clark Dry Lake and elsewhere, also suggest that more water was available until very recently, even within the past two to four centuries.

The last few centuries, though almost surely not so excessively arid as the present, have I believe approached the present in desert drought. There has perhaps been no great recovery from the great drought of the thirteenth century (about 700 years B. P.). A bit of physiographic data, for which I am largely indebted to George M. Stanley, bears on this point. The main shore bars of the last stage of Lake LeConte, which I estimate from radiocarbon datings and other evidence to have lasted from at least about 1,000 years B. P. to about 300 years ago, are remarkably unbroken, even where consisting largely of fine sediment in the even sweeps across canyon mouths. Much rainfall during the past 300 years, after the desiccation of the lake, would surely have formed ponds behind the bars, and these ponds on overflowing would have cut much more extensively than they did through these bars (which stand at 45 feet above sea-level). The recession lines representing temporary levels as the lake disappeared also bespeak great aridity about 300 years ago, for they are spaced (or were before the Age of Jeeps) about five feet apart (about half the present rate of evaporation). Earlier Pluvial conditions almost surely yielded enough inflow from the drainage basin to hold the lake levels, without contribution from the Colorado River, but the local rainfall must have been greatly curtailed over the past few centuries.

About five feet higher than these last-formed bars, which give evidence of about three centuries of notable drought, Dr. Stanley found, as remnants only, other bars, representing an earlier lake level. These earlier bars possibly date from a much more ancient, separate lake stage, but my present hypothesis is that they date from an early period during the last lake fill, possibly from about the time Fish Creek provided breeding grounds for the lake fish (1,000 years B. P.). Greater rainfall, in this view, was more responsible than great antiquity for the major destruction of the earlier bars. Archaeological, radiocarbon, and physiographic evidence indicates that in the interval between 1,000 and 300 years ago sedimentary deposits were rapidly formed behind the lake bars, as a result of heavy erosion, before the bars were reworked into the last formation, which has so well resisted erosion during about three centuries of drought.

Historical data confirm the view that the Southwestern deserts have been extremely arid over the past two centuries. Earlier evidence, from the explorers of the coast, dating back more than 400 years, is unfortunately confused. Cabrillo and Vizcaino wrote of forests on Pt. Loma and near Santa Barbara where none have existed more recently, but historians argue over the translations and the meaning. Early Spanish maps of the Central Valley of California show vast expanses of freshwater lakes, ponds, and sloughs, but it is possible that the map maker passed through during a brief flooding. I am inclined to the view, however, that these early observations reflected greater rainfall.

CONSISTENCY IN WEATHER PATTERN

Through all these major fluctuations in climate the general geographic pattern seems to have been maintained throughout the Pacific Coast and Southwestern regions. There have no doubt been north-and-south shifts, as well as general changes in intensity—of rainfall, temperature, wind direction, etc.—but the gradients have been maintained.

The illuminating researches of Axelrod indicate that the pattern was already established in early Tertiary time and persisted throughout that period. Pluvial conditions were graded from north to south in much the same pattern as today, though everywhere the effective precipitation was probably more than twice that of the present. The same pattern almost surely persisted during the greatly reduced rainfall of Postpluvial time.

Along the coast we find evidence of the long duration of the temperature pattern, as indicated by faunal assemblages and some oxygen-18 estimates; and, as I have noted, air temperatures are very strongly correlated with sea temperatures. Though time correlations are questionable, the evidence from Pleistocene deposits strongly indicates a southward increase in temperature with a break near Pt. Conception. Where the coast seems relatively stable, in northwestern Baja California, Pleistocene deposits that I believe will prove to be Illinoian seem to reflect the regions of upwelling that are so striking today; if so, prevailing winds were probably similar to those of the present.

In the middens also we find evidence of the persistence of the temperature pattern. Thus the faunal assemblages of relatively recent middens on the northern Channel Islands show a marked gradient from cold-water types at the western end of San Miguel Island to warm-water types at the southern side of Santa Cruz Island, over a stretch where there is today a gradient of about 10°C in summer sea-surface temperature and a corresponding gradient in the littoral fauna. The region in Baja California where the occurrence of the cold-water *Cryptochiton* in middens indicates, along with isotope determinations, a colder-than-present period about 900 years ago, is precisely the area where upwelling induces today incongruously cold coastal sea-surface temperatures (and cool, moist air). Even within this area the actual points where *Cryptochiton* is found in the middens are those where upwelling is intense (and where ecological conditions were favorable). Other mollusks in the middens confirm the picture. We can feel sure that roughly a millenium ago the winds were predominantly northerly, as now, and that they were, for some reason, sufficiently more intense or persistent to cause even greater upwelling then than now.

Long persistence in available water supplies is indicated by the evidences of especially large aboriginal populations where surface water still remains, or would now exist if the climate turned somewhat more moist. There are many indications through the arid West of ancient and often more or less continuous populations about springs that still flow, or along streams or lakes. Other populations existed, at times as early as 10,000 to 25,000 or more years ago, where streams or lakes are now intermittent, but would contain more or less permanent water if the rainfall were moderately increased. Similar indications can be cited for coastal sites. For instance, radiocarbon dates of approximately 3,500, 3,900, and 7,300 years B. P. have been obtained from camp or village sites along Batiquitos Lagoon in San Diego County, California, right beside a present-day cattail marsh. Along the northern Baja California coast ancient habitation signs dated at about 900 and 2,500 to 3,000 years B. P. tend to be concentrated near the mouths of streams that are still more or less permanent.

POSSIBLE PREDICTIONS

It is obvious that we can venture predictions of future climate only with great uncertainty. Past changes, however, lead us to believe that the climate will almost surely fluctuate widely, perhaps rather abruptly. It is almost certain that the fluctuations, however great or abrupt, will be superimposed on a geographic pattern much like that of the present.

As to temperature, I see no clear suggestion of what we may expect. We have some indication of negative correlation between temperatures along the Baja California coast and in the far north about 900 years ago, and rather definite indication of the cooling of the southern half of California during the recent arctic amelioration. There are suggestions that cool periods as well as warm periods over the past few thousand years were more moist than the present. The general trend since Wisconsin time has been toward warmer weather, but with great fluctuations, and this trend is contrary to the longer-term trend toward cooler conditions. The apparent recency of the evolution of desert conditions in the American Southwest suggests at least continued heat in this area.

As to aridity I feel rather strongly that the long-term trend toward dryness has been continuing, perhaps with acceleration. If so, the trend may well continue into the future. At least, we ought to be prepared, on the existing incidence, to meet the very strong possibility, if not probability, of even increased aridity in the Southwestern regions, including Southern California and Baja California. It would be most unwise to plan otherwise.

DISCUSSION

Isaacs: As I remember, in his book *Two Years Before the Mast,* Dana told about trees on Point Loma.

Schaefer: Dana and some of the others were left on the beach to cure hides and they had to go out to cut the wood. He described it as brush or small trees.

Isaacs: I always thought the storms he described were exaggerated. He was in a small ship and I have always thought that they were probably ordinary storms as we now experience, but some time ago I picked up an edition of *"Two Years Before the Mast"* that I had never seen before. An epilogue in it records a conversation that Dana had with a ship's captain in San Francisco in 1859. Dana came back to this coast in 1859, and in this conversation, the ship's captain said that the storms off Point Concepcion had stopped some time ago. They had not seen anything like them since. I now feel that it is quite possible that these were storms of some significance. I have often wondered about the storms because he described them in quite vigorous terms, as being much more severe than the storms around Cape Horn.

Hubbs: I will have to look into this historical evidence.

One of the things I particularly want to do is to get some botanist to identify the charcoal fragments from ancient hearths so that we can reconstruct the vegetation of various regions at the determined times. There is promise, I think, of our being able to reconstruct the past oceanography, climate, and human occupation.

Namias: Do you have any ideas as to what produces weather regime?

Hubbs: Are you asking me?

Namias: You made a prediction that it would be drier.

Hubbs: Well, over enough millenia, it will be.

Charney: The changes of which you speak are probably part of a word-wide pattern. It would be interesting to see if one could find the same thing, say, on the west coast of Africa.

Hubbs: I have not looked into this, but when Ahlmann was at Scripps, he mentioned that there is some evidence that in Portugal there was cooling during the period of Arctic amelioration.

Charney: The reduction of temperature contrast in the past would probably have weakened the westerlies. This would have slowed down the ocean circulation.

Hubbs: The general pattern has probably long remained the same, because the locations of upwelling are such that if we had had south winds instead of northwest winds, the pattern would have been reversed, so that it would be cold where it is now warm, and warm where it is now cold. However, the evidence from remains of fauna in kitchen maidens is such that reversals could not have taken place along the coast of California and western Baja California since late Pleistocene time.

Charney: What is hard for me to imagine, is how the small change in the same weather pattern could produce enough additional rainfall in the arid regions to enable you to measure it.

Namias: In the climatic pattern of this last winter, we have had storm activity spreading into the southwest with surprising frequency. The smallest disturbances would trigger rains in Arizona and Mexico, for instance. This condition was associated with very warm air in the Labrador area (Fig. 8). The normal temperature contrast between the subtropics and the polar regions was reduced. This increase in precipitation at lower latitudes probably extended over the southern North Atlantic and possibly into the British Isles, Spain and Portugal.

Fleming: Hubbs, what do you mean by this aridity?

Hubbs: Less water for people to drink is the main thing.

Fleming: Do you actually mean to imply that there would be less evaporation from the oceans, too?

Hubbs: That of course goes right with it, and the change has been both in the evaporation and the rainfall.

Fleming: I cannot imagine that there is much change. I would assume that the long-term average evaporation over the ocean must remain relatively constant. Although, obviously, we have had a short term change in the last two years.

Namias: Why should it remain constant?

Fleming: Evaporation amounts to just about a meter of water per year. The thing that brought this to mind, first of all, was this statement made that during the Pleistocene there must have been tremendous changes in the amount of precipitation. Of the estimates I have been able to get out of my geological friends, the total amount of ice accumulated during the glacial period would result in about a millimeter of water evaporated from the ocean per year. This, incidentally, is about the same rate the sea level has risen in the last fifty years. This great change of the evaporation precipitation balance, which gave rise to the glaciers and their subsequent melting therefore resulted from an imbalance of only about 1/1000 of the mean annual evaporation. It reflects a very small annual change in the distribution of water between land and ocean. The change over millenia is, of course, conspicuous, and is essentially a very sensitive thing. I question whether you have to invoke this idea of large changes in precipitation patterns. Certainly you can, but can it be world wide?

Charney: These temperature changes we are speaking of, 2 or 3 degrees decrease in the south and 2 to 3 degrees increase in the north, would produce 10 to 15 percent changes in the wind pattern. Such changes in the mean westerly winds would in turn produce large shifts in the semi-permanent centers of action, and probably even larger changes in the wind-driven ocean circulation patterns.

Hubbs: What would this circulation change then do to north-south temperature gradient?

Fleming: Would it increase it in terms of the ocean as an equalizer?

Charney: I don't know the answer to that. A decrease of wind would perhaps reduce the intensity of the ocean circulation and hence the heat transported northward by the oceans. This change in transport would have to be compatible with the reduced north-south temperature gradient in the atmosphere. The oceanic heat transport across latitudes is usually considered to be small compared with that of the atmosphere, but do we actually know this?

Saur: It is on the order of 10 percent at mid latitudes, according to Jung.

Charney: I have heard this; but does anyone believe it? The oceans certainly transport heat from equatorial to polar regions. The question is: how much do they transport?

Saur: How much? Jung's figures are fairly good, I believe.

Charney: How did Jung arrive at them?

Saur: He took the Atlantic stations and used, I think, latitudinal sections of stations across the Atlantic, balanced each one for the current, and constructed a pattern of currents for the whole Atlantic on the basis of a geostrophic circulation. He also used salt transports in establishing the pattern.

Charney: But how did he know what the deep currents were?

Saur: He took a section of stations and adjusted his levels of no motion till there was essentially no net mass transfer through the section.

Comment: Isn't it so that there is an infinite number of solutions to this problem? Any current assumed will give you the surface topography that will also satisfy continuity, so nobody really knows what the deep currents are unless you measure them. Is he trying to get something for nothing here?

Fleming: But one thing that you do know, is that the heat transfer of that part of the ocean is negligible.

Charney: But do we know this?

Fleming: You can at least set certain limits on it in terms of the heat budget. You can consider how much water sinks from the surface in the higher latitudes and rises at the Equator, and you can set upper limits. We might have violent circulation in the deep ocean, but this will not give you net flux of heat. This water may be circulating very rapidly in the deep water, but it will not give you any net flux across latitudes. Thus the deep currents are not important in the heat budget.

Saur: I agree to your argument that although we do not know accurately how fast the currents are going in the deep ocean, that would not be very important here. We can set some sort of limits.

Charney: Well, put it this way: we know that the atmosphere plus the oceans receive a certain amount of excessive heat in the southern equatorial regions, and deficient heat in the polar regions, therefore this heat has to be transported either by the atmosphere or the ocean. There is no other way. What part of this transport is carried by the oceans? If we had an accurate idea, for example, of how much the atmosphere transferred, exactly how much was coming in and going out, we could then ascribe the difference to the oceans, but we do not have that idea. I think Jung's figure does not contradict anything we know. The oceanic transport could be twice as great as the atmosphere or half as great.

Saur: His figure for oceanic heat transport is twice that given in *The Oceans,* but he still attributes more heat transport to the atmosphere than to the oceans.

Charney: There is probably no point in trying to speculate because in a few years we will be able to get numbers. A difficulty, of course, is, or will be, that a proper climatic theory must consider the atmosphere and the oceans as a coupled dynamical system. A change that takes place in the atmospheric circulation will produce a change in the ocean surface temperatures and thereby produce changes in the atmosphere.

Hubbs: Sometime it would help to have paleotemperature data from Japan at the same periods we are getting it over here. Are there any, Takenouti?

Takenouti: No.

Hubbs: That would be a very interesting thing to do in Japan. If we obtained the same data 1000 years ago here, and 1000 years ago there, it would be extremely interesting comparing them.

Fleming: Three hundred miles off Washington Coast we get into a band of non-calcareous sediments. What is interesting in making a time reference is that we can find this band of non-calcareous sediments, which is an indication of warmer water conditions, extending all the way up the Gulf of Alaska, where there it is about a foot or 18 inches of non-calcareous sediment material. Considering a reasonable rate of sedimentation, this appears to represent a few thousand years. Definitely there must have been some change in the character of the circulation and of the temperature from roughly 50° to 55° or 56° N. We are going to try to get some carbon-14 dates from that layer.

Hubbs: Oxygen-18 determinations too would be tremendously significant. The deposit might be interglacial.

Fleming: Another thing we have that makes a good marker, is the ash fall, ash layers that occurred about 6000 years ago. They constitute a very useful sort of marker.

Hubbs: Apparently the volcano that went off with a big bang was Mount Mazama. There were Alaskan volcanoes too. The ash falls certainly could help.