LETTER OF INTRODUCTION

In the mid 1960s, the United States Weather Bureau's State Climatologist for California, C. Robert Elford, produced a series of papers which catalogued climatological data for several counties in the state—including weather summaries for Los Angeles County. The official Weather Bureau records for 1931-1960 were used in his analyses.

Since the 1960s, sweeping changes have occurred in the monitoring and collection of weather data in the Los Angeles metropolitan area. In addition to thirty-five more years of basic climatological data, these changes—which include vast improvements in meteorological equipment and the proliferation of new environmental study sites—have led to an overwhelming need for a new and broadly-based official survey of Los Angeles climate.

As we approach the beginning of a new century, a number of government and private agencies now maintain weather monitoring equipment in the Los Angeles area. The leading government agencies now involved in weather data collection include the National Weather Service, Federal Aviation Administration, National Aeronautics and Space Administration, Department of Defense, US Army Corps of Engineers, City of Los Angeles Department of Water and Power, South Coast Air Quality Management District, State of California Department of Water Resources, and Caltrans. In addition, educational institutions, private corporations and citizens also are engaged in weather and climate data collection for a variety of reasons. As a direct result of all these data collection activities, both the climatological database and the knowledge of meteorological processes within the Los Angeles basin have greatly expanded.

The study offered in this publication was conducted by members of the National Weather Service Forecast Office in Oxnard, California which serves the Los Angeles area. Our goal was to assemble the latest available climatological data from as many reliable sources as possible for the city of Los Angeles and surrounding communities. Our effort was designed to provide a comprehensive view of Los Angeles climate, in a form and scope never before attempted in a publication of this type. Much of this work is original and is presented here for the first time.

We hope and trust that readers will find *The Climate of Los Angeles, California* to be both useful and informative, not only as a data source, but as an important document that broadens the understanding of weather and climate systems that affect southern California.

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1. AN OVERVIEW OF LOS ANGELES CLIMATE

Los Angeles is noted for its moderate weather. Under the modified Köppen classification system, Los Angeles climate is categorized as *Mediterranean.* This climate type is characterized by pronounced seasonal changes in rainfall—a dry summer and a rainy winter—but relatively modest transitions in temperature.

In the dry season, the eastern Pacific high pressure area—a semi-permanent feature of the general hemispheric circulation pattern—dominates the weather over much of southern California. Warm and very dry air descending from this Pacific high caps cool, ocean-modified air under a strong inversion, producing a *marine layer.* This marine layer is the prominent weather feature for the Los Angeles Basin for much of the year—especially from late spring through early fall.

Daily variations in the strength of the Pacific high result in variations in the depth and coverage of the marine layer, which typically thickens and advances inland during the night and early morning hours, before retreating to the sea or "burning off" to hazy sunshine around midday. Surface pollutants trapped under the marine inversion result in smog—the infamous L.A. mixture of smoke and fog.

Due to the dominance of the stable marine layer, significant precipitation is rare between May and October. Any rain that does occur at this time of year is usually the result of isolated thunderstorms associated with subtropical moisture.

During the remainder of the year—from November through April—the eastern Pacific high pressure ridge is displaced and Los Angeles finds itself on the southern margins of the northern hemisphere polar jet stream. With cold air aloft, the marine layer breaks down and is no longer dominant. Pacific storms, sometimes fed with subtropical moisture, often push cold fronts across California from northwest to southeast. These storms and frontal systems account for the vast bulk of the area's annual rainfall. Such rainy season storms are migratory, with wet and dry periods alternating during the winter and early spring with considerable irregularity in timing and duration.

Average annual precipitation for the Los Angeles area is highly variable and terrain-dependent, ranging from twelve inches at the ocean to about twice that in the foothills. At downtown Los Angeles, the average seasonal rainfall is 14.77 inches. The annual average high temperature for the city is 75•F, while the average low is 57•F.

Winds are generally light, with frequent afternoon sea breezes of 10 to 15 miles per hour. While severe weather is uncommon, strong offshore winds, known as *Santa Anas*, can reach hurricane strength below passes and canyons. Also, passing winter storms can bring southeast winds to gale force. However, for the most part, damaging winds tend to be rare, or highly localized.

2.THE CITY OF LOS ANGELES: A BRIEF HISTORY

[We found] a delightful place among the trees on the river. There are all the requisites for a large settlement.

—Fr. Juan Crespi
August 2, 1769

Perhaps no city in modern times has been so universally envied, imitated, ridiculed, and, because of what it may portend, feared.

—Encyclopedia Britannica, 1997

Less than 250 years ago, a primitive aboriginal village near the center of an obscure coastal plain on the west coast of North America was visited for the first time by European colonials. That agreeable Spanish campsite is now called Los Angeles. Today, the city has a population of 3.5 million people in an area of 464 square miles—extending from the south coast port of San Pedro through the sprawling San Fernando Valley to the northwest.

The Los Angeles metropolitan district, the second largest in the United States, is home to almost nine million people. The Los Angeles/Long Beach seaport is by far the largest in the United States, and the third largest in the world. In fiscal year 1997, the value of shipping imports through this busy seaport amounted to $80 billion. Los Angeles International Airport (LAX) moves more air cargo than any airport in the country—ranking third in the world in that category. If the Greater Los Angeles Area were an independent nation, it would have the world's twelfth largest economy.

The modern history of Los Angeles dates from the 1700s. A Native American settlement known as *Yang-na* existed on the banks of what is today the Los Angeles River. In August 1769, a Spanish expedition headed by Gaspar de Portola camped at what was to become downtown Los Angeles. A dozen years later, in 1781, forty-four Spanish settlers established a secular village—the first civil colonial town in California—at the old Spanish campground. The town was called *El Pueblo de Nuestra Señora, La Reina de Los Angeles.* It was referred to by locals as *El Pueblo* [The Town].

In the spring of 1822, word reached *El Pueblo* that Mexico had won its independence from Spain. Between 1839 and 1845, approximately 4,000 square miles of land surrounding *El Pueblo* were divided into 70 *ranchos*, each containing many thousands of acres. This led to a land boom, a developing cattle market, and an increase in the presence of Yankee traders.

In January 1847, after a brief skirmish, American John C. Fremont took possession of the Los Angeles area for the United States. The City of Los Angeles was incorporated into the State of California on April 4th 1850.

The city grew quickly. From a population base of 1,250 in 1835, the number of inhabitants grew to 11,000 at the time of the first official weather observation in 1877; to 50,395 in 1890; and to 320,000 in 1910. A nearby harbor, the railroad, aerospace and above all, the automobile, contributed to a dizzying growth rate. The world's first freeway, the Pasadena Freeway (I-110) was dedicated on December 30, 1940. There are now twenty major freeways in the Los Angeles area and 10.5 million registered motor vehicles.

Part of the elixir that attracted huge numbers of people to the Los Angeles Basin was the Mediterranean climate regime. An early drawback to the city's expansion was the lack of available water to support a large population. In the early twentieth century, shrewd businessmen and politicians arranged to import large amounts of water from the Owens and Colorado River valleys. That made the increase in population and human activity nearly inevitable, with the pace of growth continuing unabated ever since.

Diversity is Los Angeles' middle name. Its cultural, racial, and political diversity are universally acknowledged. And the diversity of Los Angeles extends to its geography and climate as well.

Los Angeles County has 70 miles of seacoast. The City of Los Angeles sits on a 20 to 40 mile wide coastal plain bounded on the north and east by relatively high mountains; on the south and west lies the Pacific Ocean. Elevations within the city range from sea level at its Pacific beaches to 5080 feet at Mt. Lukens. Some of the mountains in the San Gabriel Range north of the city exceed 10,000 feet in elevation (Figure 5). Transitions between vegetation and climate zones, highly dependent upon elevation and distance from the ocean, can be striking.

The diversity theme extends to Los Angeles' weather, which is normally about as benign as the inside of a shopping mall. However, the area has a lesser-known history of winter storms that can produce amazing rainfall rates and flooding. In fact, the 24-hour record rainfall for the entire state of California, 26.12 inches, occurred in the foothills of the San Gabriel Mountains, just a few miles north of downtown Los Angeles.

3. WEATHER RECORDS AT LOS ANGELES

Weather records for southern California can be traced as far back as 1849, when regular weather observations began at San Diego. Later, in 1867, routine weather observations were also started both at Santa Barbara and Ventura. Some weather observations exist for Los Angeles prior to 1870, but these records are incomplete. In those early years, the *Los Angeles Star* used a bookstore thermometer at 13 Spring Street to report temperatures, until the federal government established an official weather station.

In 1870, Congress authorized the War Department to set up a standardized national weather reporting network. However, it was not until seven years later that the US Army Signal Corps opened the first federal weather station at Los Angeles. The observation site was 37 feet above the ground, on the roof of the Ducommon Building at the corner of Main and Commercial Streets.

At 4:50 a.m. on Sunday July 1, 1877 Sergeant C. E. Howgate took the first official weather observation for Los Angeles. The weather was overcast with light fog and a temperature of 59•F. The observation was recorded neatly in ink (Figure 7) and telegraphed to Washington D.C.—the next day—since the telegraph office was closed on Sunday.

In late January 1881, the weather station was moved to the roof of a five-story building in the 300 block of North Main Street. There it remained for almost eight years until November 1888, when it was moved again—this time to the roof of the seven-story Wilson Building on South Spring Street.

Because of a scandal within the War Department, national responsibility for weather services was transferred from the Army to civilian authority. The Weather Bureau was established as part of the Department of Agriculture in 1890.

The Los Angeles Weather Bureau Office moved twice more, with instrumentation ascending to the roof of the 18-story Post Office and Courthouse Building at 312 North Spring Street in March 1940. According to official Weather Bureau records, this site was so far above the city that weather measurements, particularly rainfall catch, were adversely affected. To remedy this, all meteorological instruments were re-sited to ground level in May 1948, remaining there until the Civic Center office closed July 1, 1964.

The Los Angeles downtown site became a US Weather Bureau co-operative station in 1964 when automated weather equipment was set up on the roof of a three story downtown building on Ducommon Street. Although officially known as the Los Angeles Civic Center (Station 04-5115), it was no longer located at the Civic Center Courthouse Building. It had moved 3/8 mile east of the Civic Center to the Department of Water and Power offices. In October 1987, the instruments were again moved, this time to the roof of a three story parking garage at 500 Ducommon Street. This automated station measured temperature, humidity and rainfall data and transmitted coded information once each hour.

On June 30, 1999 the National Weather Service, in partnership with the University of Southern California, commissioned an impressive new array of meteorological instruments at downtown Los Angeles. The Automated Surface Observation System (ASOS) on the University Park Campus at USC employs state-of-the-art technology to monitor the weather on a continuous basis, 24 hours a day.

Since its establishment in 1877, the Los Angeles downtown weather record, commonly called the *Civic Center* record, has been produced from eight different locations, ranging from four feet to over 220 feet above the ground. Due to these frequent moves and poor rooftop siting, the city center weather record lacked the consistency in siting, exposure and instrumentation that is the hallmark of other climatological sites in the Los Angeles area. Pasadena, Pomona, Long Beach, Burbank and other cities have first-rate, stable weather records which date from the turn of the century or earlier.

Now, the new official observation site at USC promises a stability for local climate records, along with the improved representative nature of a rare ground-based location within a major downtown metropolitan area. These qualities will result in homogeneous climate records for the city in the twenty-first century.

Primarily to encompass the geographically large and diverse Los Angeles metropolitan area, and partly to offset the climatologically-challenged record from downtown Los Angeles, the scope of this paper was broadly established. The authors included representative climatic data from several key sites within the City of Los Angeles, and added some stations immediately adjacent to the city and within the southern part of the County of Los Angeles. All of these weather stations have maintained outstanding data quality through the period of record.

Please note that this text employs English units of measurement exclusively. This is the system that was in general usage in the United States throughout the twentieth century.

4. TEMPERATURE

The Los Angeles Basin is bound by

mountain ranges to the northwest through the northeast, and to the southeast, and by the Pacific Ocean from the south through the west. Beyond the mountains to the north and east lies the Mojave Desert. Due largely to cool ocean waters and modified marine air, temperatures in the basin area are generally comfortable for most of the year—with freezing conditions being quite rare.

With its proximity to the ocean and the desert, in addition to its variable terrain, the Los Angeles Basin frequently experiences a broad range of daily temperatures. On a summer afternoon it is not unusual for temperatures to range from the mid 60s at the beaches near Santa Monica to over 100 degrees at Canoga Park in the San Fernando Valley—a forty degree temperature difference within a distance of only fifteen miles. The wide spectrum of daytime temperatures over a relatively small area makes temperature forecasting surprisingly difficult. Terrain, distance from the ocean, and an ever-changing marine layer can result in wildly fluctuating temperatures on a day-to-day basis. Also, large areas of the basin can experience daily temperature ranges that exceed average seasonal ranges from the coldest to the warmest months.

When a relatively warm and dry airmass moves over a cool body of water, the layer of air in direct proximity to the water's surface is modified—the air is both cooled and moistened. This modified layer of air is the *marine layer.* Being cooler and relatively dense, the marine layer settles over the Los Angeles Basin as a surface-based laminar intrusion, from one hundred up to as much as several thousand feet thick—the extent of the inland intrusion usually being dictated by the terrain contour corresponding to the marine layer's depth. The unmodified warm airmass above the marine layer creates a temperature *inversion*—a layer of air in which temperatures warm with increasing height (Figure 11). The inversion is thermodynamically very stable, preventing significant vertical air currents (mixing) upward within the atmosphere.

Sunshine tends to break up the marine layer, as strong insolation and local winds can vertically mix the lowest layers of the atmosphere above the basin. The extent of this breakup depends on the strength of the layer and the angle of the sun. After dark, the lowest layer of the atmosphere again cools and the marine layer typically re-forms.

The marine air is associated with relatively cool and constant temperatures, low clouds, fog and haze. These are persistent elements in Los Angeles weather, particularly during the late spring through early fall, when warm and dry air aloft from areas of dominant high pressure strengthens the inversion. In the winter and spring months, the marine layer is frequently disrupted by frontal passages—when cool air from the northwest mixes out the marine inversion—or by strong offshore wind patterns, which push the marine layer out to sea.

Sea surface temperatures (SST) are also a factor in the strength of the basin marine layer. At the point of contact with the Los Angeles County littoral, SSTs range from the mid 50s in spring to the low to mid 70s by early fall. During the late spring and early summer, strong northwest winds cause an increase in upwelling—where cold waters from the depths of the ocean are brought to the surface—resulting in lower SST readings and a strengthened marine layer. In addition, some beaches—such as Cabrillo Beach—are influenced by current-driven upwelling and maintain cooler SST readings all year.

Cool coastal waters in the immediate proximity of a diurnally heated coastal plain result in daily sea breeze and land breeze oscillations typical of coastal climates worldwide. Over the Los Angeles Basin, the sea breeze is typically from the west or southwest at 10 to 15 miles per hour. Afternoon sea breezes tend to reinforce the marine layer, cool surface temperatures and reduce pollutants.

Inland areas, particularly the San Fernando and San Gabriel Valleys do not exhibit pronounced sea breeze effects; the marine layer is less dominant at these locations. Afternoon sea breezes, modified by overland trajectories, reach these locations later in the day, if at all. The sea breeze in the San Fernando Valley is actually an east or southeast wind, bending around the coastal hills. This valley wind is sometimes neutralized by a dry front — a eastward moving mass of hot air descending from higher terrain in the western San Fernando Valley.

The most extreme temperature contrasts across the Los Angeles area occur during the afternoon in a very warm summer pattern with a shallow marine layer—less than 1,000 feet deep. In this situation, temperatures in the warmest valleys can be more than forty degrees higher than those at the beaches. On average however, the difference in daily high temperatures peaks in July, when Los Angeles International Airport (LAX) averages twenty degrees cooler than Canoga Park at Pierce College. Average daily high temperatures are much more uniform during the winter months, with immediate coastal sites averaging about three degrees cooler than the inland valley locations.

The average annual temperature at downtown Los Angeles, based on the current standard climatological 30-year period of record (1961-1990), is 66.0••. Daily maximum temperatures average 67.7•• in January and 84.0•• in July. Daily average minimum temperatures are 48.9•• in January and 63.3•• in July. The all-time record high temperature for the downtown weather station is 112•• set June 26, 1990. The all-time record low is 28••; which was established on February 6, 1883; equaled on January 7, 1913; and tied again on January 4, 1949. For the official National Weather Service stations across the Los Angeles Basin, the highest temperature of record is 116•• at Canoga Park in the San Fernando Valley, set August 24, 1985. The lowest temperature of record is 18••; also at Canoga Park, on February 6, 1989.

In January, soil temperatures in the Los Angeles area, measured at a depth of about six inches, range from 46 to 51 degrees inland and from 53 to 56 degrees along the coast. By early August, soil temperatures climb to between 75 and 84 degrees in all areas.

Seasonal temperature patterns across the Los Angeles Basin show remarkably consistent relative trends from year to year, despite great differences in absolute values from station to station. For statistical comparison, the authors analyzed 50-year temperature records from coastal, inland and valley locations. Fifteen-day statistical running means were computed for each day of the year, then cross-checked with manually recorded temperature data and a concurrent analysis of Western Region Climate Center data.

Individual station data all show that the lowest average daily temperatures—52.2• • inland to 55.4• • coastal—occur between December 30th and January 3rd. The corresponding diurnal minimum–to-maximum temperature ranges are 24.5• • inland and 18.2• • coastal. All station records also indicate that the highest average daily temperatures of the year—77.5• •inland to 70.3• •coastal—occur between July 30th and August 15th. The diurnal ranges for that period are 38.2• • inland and 12.7• • coastal. In addition, there is a second heat maximum that occurs in all records from August 31st to September 4th. The early August maximum reflects the peak of mid-summer insolation, while the early September maximum marks the beginning of seasonal offshore wind flow patterns.

There is another seasonal periodicity that is reflected in all basin temperature records—a dramatic and pronounced cooling that occurs in each record between November 3rd and 15th. This cooling is especially dramatic with regard to average daily high temperatures, which drop 5.8• •inland and 2.8• •coastal during that period. This cooling is apparent in other climatic records in coastal California, but the exact cause is unknown.

Warming conditions in springtime are less dramatic and much more diffused than the November chilling, and less definable within the overall record. Inland, significant warming occurs during early April and again in early May. However, all stations wait until mid-June for the strongest seasonal warming. This occurs from June 6th to 25th, when average daily temperatures rise by 4.9• • inland and 2.5• •along the coast.

While it can get hot on the coastal plain, extended periods of hot weather are quite uncommon near the beaches, where cooling sea breezes have a more direct influence. Streaks of very hot weather, with temperatures exceeding 100• •, have run to fourteen days duration at Canoga Park (August 1992), but to only four days at coastal LAX (September 1963).

The average number of days on which temperatures climb to 90• • or higher at LAX is only five—although it is not unusual for the temperature to remain below 90• • at the beaches for the entire summer. Further inland, at downtown Los Angeles, temperatures reach 90• •or more about 25 times per year—but strings of 90• •+ days rarely last for more than a week at a time. During the worst heat wave on record, from August 31 to September 7, 1955, downtown Los Angeles reached or exceeded 100• •on eight consecutive days (Tables 3, 4).

It is noteworthy that temperatures have reached 90••or higher in every month of the year at downtown Los Angeles.

In direct contrast, cold weather is very uncommon in the Los Angeles area. The all-time low temperature record for downtown Los Angeles is 28••; a temperature that barely qualifies as a "hard freeze". That twenty-eight degree benchmark has been reached three times in downtown L.A. since records began in 1877.

Cold continental air is almost invariably blocked by the mountains that ring the Los Angeles Basin. While nighttime temperatures in late spring and summer are relatively cool for such a southerly latitude, the scarcity of extreme cold is apparent in the long-term record. In the continental United States, only southern Florida has a lower frequency of occurrence of freezing temperatures than downtown Los Angeles.

In most winters, inland valley temperatures drop below freezing at least once—but only on rare occasions do minimum readings drop to more than a few degrees below freezing, or remain below freezing for more than a few hours. The average number of nights on which temperatures drop to or below freezing range from one in every ten years (or more) at the ocean to between 2 and 4 nights per year inland. The coldest valley locations, Canoga Park in the San Fernando Valley and Pomona in the San Gabriel Valley, average 18 and 24 freezing dates per year, respectively.

The coldest weather pattern for southern California occurs when a deep low pressure trough in the western United States forms in conjunction with a very high amplitude ridge across the northeastern Pacific Ocean and the Canadian Yukon. The last severe cold outbreak in the Los Angeles area occurred in December 1990, when temperatures dropped below freezing across a major portion of the coastal plain, and into the low to mid 20s over inland valleys. Temperatures stayed below freezing for up to eight hours at some valley locations, resulting in significant damage to plants and commercial agriculture.

All-time minimum temperatures on the coastal plain are mostly in the mid to upper 20s. Most valley locations have recorded minima in the lower 20s, while the record low for the entire Los Angeles Basin is 18••at the Canoga Park site.

The last occurrence of freezing temperatures at downtown Los Angeles was January 21, 1979—the last time freezing temperatures were reported at LAX was December 21, 1968.

Long-range temperature trends in the Los Angeles Basin reflect substantial warming over the entire period of record, which spans more than 100 years. However, this is not necessarily the result of global warming; there are other factors that must be considered. First, as was earlier discussed, numerous moves of the official observation site have produced a climate record that is homogeneous neither in siting nor in instrumentation. More significantly, recent research by a highly-regarded climatologist, Jim Goodridge, revealed that non-urban weather stations in California have seen virtually no temperature change over more than a century of records. This strongly suggests urbanization as the real cause of the increase in annual average temperatures across the Los Angeles Basin over the past 100 years.

5. AIR QUALITY

Today, air quality is an important element of meteorological study throughout the world. In southern California, air quality has been monitored, studied, and regulated to an extent unprecedented in the history of the earth. As a result of extensive research, great strides have been made in reducing air pollution in the Los Angeles Basin.

The basin is ringed by mountains, except open to the west and south where the cool marine layer from the Pacific Ocean can envelope the densely populated coastal plain before being confined by the mountain slopes. This marine layer, capped by warm air aloft, traps particulates and gasses—man-made and natural—within about a quarter to a half mile above the earth. Thus, across some 1,600 square miles of basin lies a huge volume of trapped, stable air weighing some 200 million tons. Pollution within this pool of air becomes a problem when it affects the environment directly, or the health of persons living within it. Today, it is recognized that *smog*, the combination of smoke and fog that typifies Los Angeles weather, has a history that is older than the city itself.

In the prehistoric record there is evidence, verified by examinations of ocean sediment cores, of huge fires that occurred in and around the Los Angeles Basin up to two million years ago. Presumably, the atmosphere was sometimes laden with thick smoke from lightning-caused fires. In more recent times, the Native American population used fire extensively in their daily activities. Early Spanish explorers noted a thick smoky haze in the harbors when they first visited the Los Angeles area. In addition, natural pollution sources, Popular opinion held that industrial smoke and emissions were responsible for most of the air pollution in the Los Angeles Basin—in much the same manner that the infamous smokestack industries had polluted the big industrial cities of the eastern United States. Investigations in the late 1940s and early 1950s established that the origins of Los

primarily oil and gas seepage from beneath the ocean floor, have also contributed to an air pollution problem over the years.

With the rapid industrialization of the basin in the late nineteenth and early twentieth centuries, Los Angeles developed serious problems with smog. By 1903, the haze had become so thick that on one occasion persons in the city mistook a smoggy darkness for an eclipse of the sun. Beginning in 1905, the Los Angeles City Council passed legislation to curtail smoke emissions. But the measures proved ineffective, overwhelmed by the massive and mainly unregulated growth of industry and population.

After World War II, the smog problem was so bad that it began to affect commerce, industry, and the general health of the population to an extent that could no longer be ignored. Special interests could no longer block the necessary studies and regulations aimed at pollution clean-up. Moreover, a series of well-publicized killer smogs occurred in Belgium (1930); Donora, Pennsylvania (1948); and London, England (1948 and 1952) which underlined the potential health hazards associated with severe air stagnation and pollution episodes.

Angeles area pollution were multi-causal. However, the chief culprit was ozone produced by photochemical reaction in the lowest levels of the atmosphere. Driven by sunlight, ozone is produced by hydrocarbons and nitrogen oxides emitted mainly from oil refineries and the incomplete combustion process within automobile engines.

Smog, and particularly the ozone component of Los Angeles area smog, is harmful to human health. The lungs are the primary target of ozone—which damages cells in lung tissue, causing edema (swelling) and lowering the ability of the immune system to fight disease. Asthma, emphysema and chronic bronchitis are worsened by the presence of ozone. Children and the elderly are especially vulnerable to ozone concentrations in excess of the federal standard (0.12 ppm). Numerous studies have shown measurable damage to human and animal tissue and shortened life span due to increases in ozone concentration. Additionally, ozone damages plants and destroys certain manufactured materials, such as rubber.

There were a number of other sources of pollution in mid-twentieth century Los Angeles. Backyard incinerators, numbering more than 300,000, belched forth intermittently without controls. The oil industry estimated that 120,000 gallons of gasoline evaporated into the area atmosphere from all sources each day. Citrus growers operated more than one million smudge pots, burning used motor oil and old tires, in a mistaken belief that black smoke helped keep winter minimum temperatures above freezing.

Smog was recognized as a problem created by science and industry—and people turned to science and industry for a solution. One proposal called for the connection of all commercial and industrial emissions to a network of massive exhaust pipes, which would transport the smog above the San Gabriel Mountains, dispersing the offending particulates above the basin's atmospheric inversion. Energy requirements made this idea unfeasible. Another suggestion was made to spray a chemical (*diethylhydroxylamine*) over Los Angeles each summer to short-circuit the ozone and smog formation process. However, it was determined that the chemical was itself a pollutant, so that proposal was dropped.

Over the past half-century, pollution and ozone levels have been markedly reduced over the entire Los Angeles Basin. This result was accomplished through anti-pollution agency efforts and strict enforcement of controls.

On October 14, 1947 Los Angeles County supervisors established the nation's first Air Pollution Control District. The district required air pollution permits of major industries. Recognizing that air quality management was a regional and not just a county responsibility, three other counties joined Los Angeles to form the South Coast Air Quality Management District (AQMD) in 1977.

Air quality markedly improved over the Los Angeles Basin during the last two decades. By the late 1990s, Los Angeles no longer had the nation's dirtiest air. Moreover, peak ozone levels at downtown Los Angeles reached 0.68 parts per million (ppm) in 1955 before declining almost two thirds by the mid 1990s.

It should be mentioned that large scale meteorological processes can themselves greatly impact pollution levels in the Los Angeles Basin. Specifically, the global *El Niño* episodes of 1982-83 and 1997-98 were accompanied by much-reduced levels of atmospheric toxicity at Los Angeles. *El Niño* events are usually accompanied by increased atmospheric instability, better vertical mixing and cleaner air across southern California.

The reductions in air pollution in general and ozone in particular came through strict controls on commercial, public, and residential emissions, including incineration sources. But the most effective anti-pollution measures were controls on automotive exhausts, including catalytic converters, which were required beginning in 1975. In addition, a system of vehicle smog inspections was put in place by the City of Los Angeles before 1980.

Regulatory measures have sometimes been unpopular with both industry and with citizens. But the effect of the regulations, which have set standards for laws in other parts of the world, has been remarkable. Toxic air pollutants have been markedly reduced over the past several decades. The number of stage one ozone alerts issued by AQMD plummeted from 121 in 1977, to zero in the summer of 1999. In fact, 1999 had the cleanest air quality measurements ever recorded at Los Angeles since records began.

AQMD officials have set new goals to improve air quality even further. The agency estimates that federal clean air quality standards can be met in Los Angeles by 2010.

6. PRECIPITATION

Data Acquisition

A discussion of rainfall data and patterns applicable to the Los Angeles Basin needs to be qualified by the following caveats: First, a published rainfall measurement is only an approximation of site-specific precipitation accumulating within a vertically-oriented conical apparatus mounted approximately four feet above the ground. Second, automated and rooftop-sited rain gauges collect and register significantly less rainfall than their manual and surface-based counterparts due to wind updrafts near buildings and wind circulations within the measuring devices. Third, tipping bucket gauges, in common use in the latter half of the twentieth century, were often nothing more than guides to approximate rainfall totals; their measurements were affected by wind gusts, irregular maintenance, detritus accumulating within the system, fog, dew, and by systemic difficulties in the recording of very heavy precipitation events.

Significantly, the Los Angeles Civic Center rain gauge has been automated since 1964, and has been mounted on a rooftop location for most of the time since 1877. In fact, the Los Angeles Civic Center site used during the 1990s was criticized for under-reporting rainfall. Recent comparisons with ground level standards and adjacent gauges showed a catch shortfall of approximately ten percent of the reported rainfall total for the Civic Center site during those years.

Fortunately, other rainfall gauges across the Los Angeles Basin have been very well-sited, and exhibit the reliability necessary for long-term climatic study. The National Weather Service recognizes the excellent century-long records which When viewed serially, historic seasonal rainfall totals in the Los Angeles area display an almost aggravating randomness. However, when a statistical smoothing method is employed, there appears to be an underlying periodicity in these precipitation statistics. This long-term pattern, approximating a thirty-year cycle, has been noted by Goodridge, Michaelson and others who have studied historic and pre-historic climatic data dating back hundreds of years.

This portion of the study is concerned with the historic period of record, which dates from about 125 years, and the thirty-year (operational) climatological averages exist at Pasadena, Long Beach, Mount Wilson, and Pomona, among others.

In California, annual precipitation is generally described in terms of seasonal rainfall, computed by the National Weather Service from the first of July through the 30th of June. This data acquisition method allows a cohesive projection of the entire winter rainy season. Daily rainfall values are reported from midnight to midnight, except at manned stations where gauge readings are taken at other times, as specified. Precipitation averages are normally based on standard National Weather Service thirty-year normals (1961-1990), or the entire period of record, as identified.

For the purposes of this study, precipitation values are expressed in inches of water.

Precipitation Patterns

ending in 1990.

Two striking features of Los Angeles rainfall are its seasonal nature and its reflection of orographic effects.

Over the entire Los Angeles Basin, excluding mountain locations, the average annual precipitation ranges from less than 12 inches at the immediate coast to more than 20 inches at the foothills. The normal seasonal rainfall measured at downtown Los Angeles is 14.77 inches.

On average, 92% of the seasonal precipitation falls between November 1st and April 30th. This percentage is roughly the same for all stations, regardless of elevation or distance from the ocean.

That it doesn't rain much in the summer in Los Angeles is borne out by statistics furnished by the L.A. Dodgers Baseball Club. The Dodgers have had only sixteen home games rained out in 41 years of baseball—over 3,300 games. The team averages only 0.39 rain-outs per year. Fully half of the rain-outs have occurred in the month of April, and none have ever occurred during the months of June or July.

In a semi-arid climatic type with strong seasonal and periodical variability, "average" precipitation is seldom realized. If achieved, "average" is only a transitional state between extremes of wet and dry, flood and drought. Angelinos must be prepared for extreme rainfall patterns because dry and wet cycles are both inevitable.

Seasonal rainfall variability was strongly demonstrated once again in Los Angeles during the 1998 calendar year. LAX received 352% of normal rainfall in the first six months of 1998 but only 63% of normal in the second half of the year. The end of a very wet *El Niño* episode and the transition to a dry *La Niña* circulation was responsible for the change.

Seasonal precipitation patterns, computed through running means on a daily basis for each day of the year, are very consistent for all weather stations in the Los Angeles Basin. Generally, the chance of having measurable precipitation on any given day increases to between 20 and 25 percent from January 10th-13th; again from February 6th-10th; and for a third time from March 4th-8th. These maxima are present in all basin weather records, and reflect average rainfall accumulations ranging from 0.10 inches per day at the ocean to 0.17 inches of rain near the foothills. There is a smaller seasonal peak which occurs in the autumn, between November 14th and18th. These autumn and winter precipitation maxima may suggest some type of intra-seasonal periodicity in the arrival of north Pacific storms into southern California.

An index of the variability within historic precipitation data at Los Angeles is seen in the large standard deviations observed within the *complete monthly rainfall* data (Tables 8, 14 and 17) in the second section of this paper.

Statisticians have revealed a periodicity underlying the apparently random nature of year-to-year precipitation data within the historical record (Figure 13). This regularity is seen most clearly in the application of a nine-year rolling mean, which is based on an 18.6 year lunar cycle (Goodridge, 1998). Goodridge believes that these data may reflect changes in sea surface temperatures at 30N/130W and may, furthermore, be related to changes in the solar constant.

On a longer term, the100-year change in rainfall rates within California in general and Los Angeles County in particular is practically nil; however, there was an apparent increase in the number of heavy precipitation events in the last two decades of the twentieth century.

COOL SEASON PRECIPITATION

Winter Rains

Precipitation episodes in Los Angeles, with a few notable exceptions, are largely caused by extratropical disturbances approaching California from the west or northwest during the winter season. In wintertime, southern California is on the southern margin of the northern hemisphere jet stream and receives from ten to thirty of these north Pacific weather systems per year.

Classical synoptic surface analyses show cold maritime polar air masses dropping southward from the Gulf of Alaska during the winter and early spring months. These cold air intrusions interact with relatively warm water in the eastern Pacific, and with other moisture sources streaming toward California from the west or south. With upper air support, surface waves can develop along the frontal boundary of cold air and move over southern California. The cold air may trigger enough atmospheric instability to generate "cold core" thunderstorms, which on occasion can spawn a funnel cloud or small tornado.

As a winter storm approaches southern California from the west, moist subtropical air may become entrained within the system and—depending on the continuity of the eastward movement of the storm—produce copious amounts of moisture across the coastal plain and mountains adjacent to Los Angeles. In such events, the transverse and coastal ranges of Los Angeles County act as a continental catcher's mitt, capturing huge amounts of water within the Los Angeles Basin. The flow of moisture from the southwest is associated with some of the heaviest rainfalls in southern California. Due to its origins near the Hawaiian Islands, this southwesterly flow of moisture into California is sometimes called the *Pineapple Connection.*

Despite evidence to the contrary, there is a common misconception—even among some Californians—that "it never rains in southern California". A study of record rainfall events that occurred in the state during the 1900s gives an interesting insight into this myth.

Jim Goodridge has studied extreme rainfall events that have occurred in California since 1900. In the years from 1900 to 1943, a clear majority of severe storms that occurred in California also affected southern California: Of the twelve years with very heavy precipitation and flooding listed in his study during this period, all but four impacted southern California.

However, from 1943 to 1992—a period of almost fifty years—extreme rainfalls occurred in southern California on only five occasions, although central and northern California were affected in fourteen separate years. This time span covered an era of incredible growth within the Los Angeles Basin—and the concurrent flood control construction project which tamed the flood-prone Los Angeles River. With a lessening of the threat of floods, and very few major storms through five decades, it is no wonder, then, that southern California developed a reputation for dry and benign climate.

Since 1992, however, that "shopping mall climate" reputation has begun to tarnish—or, perhaps *rust* is the better term. Beginning in that year, the decade of the nineties turned decidedly soggy. In fact, heavy rainfall events were noted in the basin during the years 1992, '93, '95, '97, and '98—helping to make the decade of the nineties the wettest since the 1930s and early '40s

It is interesting to note that the heaviest rainfalls recorded within the State of California have occurred on the mountain slopes of Los Angeles County. California's greatest 24-hour rainfall, 26.12 inches, occurred at Hoegees—below Mount Wilson on the slopes of the San Gabriel Range—on January 23, 1943. This rainfall is 6.73 standard deviations higher than the mean for that station and has a return period of 11,000 years (Goodridge, 1997).

In fact, the mountains which drain into the Los Angeles Basin have the highest probable 24-hour maximum precipitation
(December 1889)
■One season - 38.18 inches
(1883-84)

Geography acts in other ways to add to winter precipitation within the district. The mountains surrounding the Los Angeles Basin contain and reinforce the marine layer—a shallow pool of ocean-modified air that frequently exists over the basin. Elliott and Hovind describe the marine layer as causing Pacific cold fronts to behave locally like occlusions, producing 12 to 24 hours of steady light

rates to be found anywhere in the continental United States—with *theoretical maxima of more than 48 inches near Mount Wilson!*

Short duration maximum rainfall rates are remarkable in the Los Angeles area. The heaviest rainfall observed within the Los Angeles County historic record occurred on January 4, 1995, when 2.60 inches of rain fell in one hour in the Long Beach area at Signal Hill. In the San Gabriel Mountains, where heavy orographic rains would be expected, the record hourly rainfall is a more modest 2.00 inches, set January 4, 1926 at Opids Camp, north of Mount Wilson. (Another storm in the same location produced 0.65 inches of rain in *one minute* in April of that year.)

Following are the record maxima rainfall statistics for downtown Los Angeles:

■One hour - 1.87 inches
(November 19, 1967)
■One 24-hour period - 7.36 inches
(Dec 31-Jan 1, 1933-34)
■One month - 15.80 inches

precipitation, consisting of small droplets. During the approach of a frontal boundary, the pre-existing marine layer typically merges with middle troposphere features, producing continuous precipitation which continues until frontal passage.

Almost all significant precipitation occurring within the Los Angeles area can be attributed to the general winter pattern dynamics previously described. However, there are other weather types which are less frequently observed, but nonetheless important.

Snow

In southern California, much of the winter precipitation falls as snow above 8,000 feet elevation. About 80 inches of snow falls annually in parts of the San Gabriel Mountains. When augmented by snow-making equipment, this is sufficient to support several ski areas within a short drive from the Los Angeles Basin. However, all of these ski slopes are at elevations above 5,500 feet. While the ski season is relatively short compared to other parts of the nation, snow cover in the highest elevations of the San Gabriel and San Bernardino Mountains is not unusual during much of the year. It is not uncommon to have a mountain snowfall in October. In 1995, a rare June snowfall occurred. In that event, Mount Wilson reported 1.5 inches on Father's Day, a record for the month.

Snowfall is infrequent below 4,000 feet elevation, but not exceptionally rare. Such events can occur several times during a winter season. The primary Minnich (1986) reports that snow levels drop into the intermediate elevations of the mountains during the course of a normal winter season, and that the usual 2,500 foot average decrease in snow levels which occurs between November and April is accompanied by a concurrent 9•F drop in offshore sea surface temperatures (SST).

The primary correlation that was noted by Minnich is the inverse relationship between total seasonal precipitation and areal snow cover. Seasons with heavier precipitation totals correlate with higher snow levels; drier years, with more cold impact of low snow levels is on tourists and residents traveling to and from mountain resorts, and on travelers driving over the higher mountain passes. In particular, Interstate 5 at Tejon Pass reaches a height of 4,183 feet, and is sometimes closed for several hours due to snow and ice. This can snarl freeway traffic badly on the major north-south route that connects southern California with the rest of the state.

Snow levels down to the floor of the basin are extremely rare. Since statehood, measurable snowfall has occurred at downtown Los Angeles only three times: On January 12, 1882; on January 15, 1932; and on January 9, 1949. The 1932 snowfall was the heaviest of these at two inches. In the 1949 event, only 0.3 inches of snow was recorded downtown, but three inches was common at higher elevations within the city. The 1949 snowfall was, of course, heavily reported by the media, with photos of Glendale College students hurling snowballs at each other (Figure 18).

air advection, produce light snow over a wide area and at lower elevations.

Tornadoes

The south coastal region of California, including the Los Angeles Basin, has the greatest incidence of tornadoes in the state. In the period from 1950 to 1992, the basin had 99 confirmed tornadoes. According to Blier and Battan (1994), this area has a tornadic incidence similar to that of the State of Oklahoma. However, these researchers go on to point out that the size, severity and duration of

California tornadoes is less than those common to the plains states, and the tornado count in the Golden State may be inflated due to inaccuracies within the database. Nevertheless, the fact that tornadoes occur with great frequency in a very densely populated urban area makes the occurrence of tornadoes in the Los Angeles Basin particularly relevant.

Severe storms researcher John E. Hales, Jr. (1983) stated that “a tornado can hardly find a place to touch down around Los Angeles that won’t hit something”. That assertion notwithstanding, there is no record of a Los Angeles tornado ever causing a fatality.

Unlike their plains counterparts, southern California tornadoes occur mainly in the winter. Of the 99 tornadoes that were reported in the Los Angeles Basin between 1950 and 1992, the vast majority—83—occurred in the months November through March. March had the highest number of incidents, with 22. The fact that few tornadoes occur in the Los Angeles Basin during the warm season is In conjunction with topographic features which set up favorable cyclonic, low-level wind patterns, Hale further identified a number of synoptic weather features—more common to the cool season—that are associated with the strongest of the tornadoes that he studied. These include:

• •Closed cyclonic circulations from the surface to 500 millibars (mb).

• •A west-southwest oriented, 120 knot or stronger, 300 mb jet that crosses the coast near San Diego. The tornadoes always form on the cyclonic side of the jet.

primarily due to the stabilizing effect of the marine layer, and the lack of dynamic forcing during the warmer months.

Roughly a quarter of the tornadoes listed by Blier and Battan originated as waterspouts over either Santa Monica Bay or San Pedro Channel. There were many more waterspouts that never made landfall; these were not included in the tornado count.

The cause of many, if not most, Los Angeles Basin tornadoes seems to be linked to the terrain layout of the basin. Hales specifically mentioned the natural curvature of the shoreline and the location of the coastal mountains. Due to frictional and barrier flow effects, a convergent cyclonic wind pattern is established in the vicinity where most L.A. tornadoes occur. Blier and Battan discussed several features that require further investigation, including convergence to the lee of the Palos Verdes Peninsula and Santa Catalina Island.

• •A dewpoint at San Diego of 51••or greater.

• • The 500 mb temperature on the Vandenberg sounding -5•• (-20•C) or colder.

• •A mean cold front position on the California/Arizona border. Usually, tornadoes occur well behind the surface cold front.

• •A time of occurrence between 1200 and 1500 PST, coincident with maximum solar heating.

• •A strong increase in wind speed with height—similar to wind profiles in the central United States.

In the 1997-98 *El Niño* episode, the Pacific storm track was located over southern California for much of the winter season. This produced a number of days in which Hale's criteria were approximated over the Los Angeles Basin and adjacent waters. In that season, there were over twenty days in which either waterspouts, funnel clouds or tornadoes were reported—including 30 separate sightings. Two tornadoes touched down within the City of Long Beach.

WARM SEASON PRECIPITATION

There are three main warm-season rain producers for the Los Angeles Basin. These are: (1) Light rain or drizzle from a deep marine layer, (2) monsoonal thunderstorms, and (3) showers or thunderstorms from the occasional tropical storm.

Marine Layer Drizzle

When the marine layer reaches several thousand feet in depth, air parcel cooling and droplet growth will occur within the marine layer stratus. Drizzle or light rain, with small droplets measuring approximately .02" in diameter, can occur during these periods. This type of precipitation can result at any time of year, but is most likely during the relatively stagnant period of weather which is typical from late May through mid October.

Thunderstorms

A mass of warm, moist subtropical air occasionally overlies the Los Angeles Basin during the mid to late summer. The subtropical airmass originates in Mexico, then moves northwesterly into Arizona about the first week in July. The humid, sultry air, with its characteristic high dewpoints, frequently pulses into southern California deserts and occasionally extends into the coastal plain. During these periods, thunderstorms form mostly over the mountains of southern California in the afternoons, then occasionally meander over the coastal lowlands during evening and nighttime hours.

The mean number of days per year on which thunderstorms occur (i.e. days on which thunder is heard, regardless of precipitation) is 4.1 in the downtown Los Angeles area.

Because they are an infrequent visitor to the heavily populated southern California coast, thunderstorms are very notable when they do occur. Even when they produce only light precipitation, they can be a source of serious inconvenience by wetting an area that had been dry for weeks, or even months. Also, they may cause shifting surface winds with local gusts to 50 miles per hour or more. This combination, more or less innocuous in other parts of the United States, is actually dangerous in Los Angeles. The inevitable result of even small summer thunderstorms is a rash of highway accidents, freeway traffic jams and local power outages.

During one afternoon in the spring of 1999 when scattered thunderstorms occurred across the Los Angeles Basin, a cluster of traffic accidents was reported, including one 70-car pileup on Interstate 10.

Tropical Storms

The average number of tropical storms in the eastern Pacific Ocean is 16.7 per year, of which about seven develop into hurricanes. Only once in the twentieth century did an eastern Pacific tropical storm directly impact the Los Angeles area with gale force winds and heavy rain. About once every two years, however, eastern Pacific tropical storms or hurricanes indirectly impact southern The 1939 tropical storm had other repercussions for Los Angeles. The Weather Bureau Forecast Office in San Francisco had been completely surprised by the storm. Largely in response to this tragedy, the Weather Bureau decided to establish a new forecast office for southern California. In February 1940, the first forecast office in southern California was opened in the Lockheed Terminal at Burbank Airport.

The heaviest property damage caused by the remains of a tropical storm occurred in September 1976, when heavy rains from the remains of Tropical Storm Kathleen caused $160 million in agricultural and urban flooding damages.

California with residual rains and/or heavy surf.

A tropical storm crossed the Los Angeles County coastline in 1939. In the event, a tropical depression had developed off the coast of Panama on September 15th. The storm quickly grew into a hurricane. The lowest pressure (28.67") occurred on September 22nd, when the storm was centered approximately 300 miles southwest of Cabo San Lucas. On Sunday, September 24th the dying storm crossed Catalina Island, where southeast winds gusted to 50 miles per hour. The storm came ashore near San Pedro. Torrential rains fell Monday morning and again Monday night across the Los Angeles coastal plain. The Civic Center received 5.62 inches of rain and Mount Wilson reported 11.60 inches. Forty-five lives were lost at sea, and property losses were placed at $2 million.

The *El Niño* Effect

El Niño is one of several major ocean-atmosphere teleconnection patterns that influence the weather around the globe. In fact, for southern California, it is arguably the most significant of all such patterns. Due to its importance, it has been extensively studied by researchers since the 1960s. With the success of certain predictors related to these studies, the popular media have linked the Spanish name with rainy episodes in California to an almost tiresome extent.

There is now little doubt that inter-annual variation in rainfall patterns in southern California is related to sea surface temperature (SST) anomalies in the Pacific Ocean. Equatorial eastern Pacific SST maxima are the signature of the initialization of an *El Niño* pattern. Eastern Pacific SST maxima seem to cause the strengthening and southward shift of the northern hemisphere jet stream. The result is usually above normal rainfall for southern California.

The authors compared twenty-three *El Niño* events of various magnitudes (as identified by the National Oceanic and Atmospheric Administration) with the Los Angeles Civic Center rainfall record. It was determined that above normal rainfall at Los Angeles occurred in 78% of the *El Niño* years, with precipitation during the Heavy rainfall seasons in the Los Angeles area are almost always followed by unusually dry years. Heavy seasonal rainfall, defined by the authors as 25 or more inches of rain (• • 1.5 standard deviations above the mean), occurred ten times during the 122-year period of record. In nine of the years following heavy rainfall, precipitation was below normal. The averages are impressive: Wet years averaged 30.48 inches of rain or 202% of normal. The years following the wet seasons averaged only 10.49 inches of rain or 69% of normal. Thus there is a strong suggestion of a significant oscillation in the seasonal dynamics controlling southern California precipitation.

FLOOD CONTROL

The Los Angeles County Drainage Area comprises a 1,459 square mile watershed which flows to the Pacific Ocean mainly through the Los Angeles River and the San Gabriel River. The Los Angeles River is approximately 55 miles long and has an aggregate tributary system which is 225 miles in length. Stream slopes

selected years averaging 134% of normal. Statistical sampling techniques employed within this study reflected some uncertainty; a blind data sampling method has produced similar results.

However, it should be noted that strongly positive *El Niño* anomalies have invariably produced heavy rainfall in southern California. Of the four strong *El Niño* anomalies recorded in the past century, all resulted in seasonal rain totals in excess of 30 inches at the Civic Center, with an average of 215% of normal.

range from extremely steep, 200 feet per mile or more in the mountains, to about three feet per mile over the coastal plain.

Due to steep terrain, runoff from the mountains concentrates quickly. Runoff from urban watersheds is generally uncontrolled and is characterized by high flood peaks of short durations, because a high percentage of the rain falls on impervious cover. Hydrographs illustrate that Los Angeles area flood events are typically of less than twelve hour durations (Figure 20). The lower Los Angeles River will respond to heavy rain by rising from 2/3 channel capacity to full in less than an hour, and reversing to 2/3 channel capacity within two hours. Such events have been noted recently, in 1980, 1993 and 1995.

Through historic times, and as evidenced in a variety of pre-historic sources, the Los Angeles area has been periodically pounded by heavy rains and inundated by floods. Some of the heaviest rains ever recorded on the west coast of North America occurred near Los Angeles as a result of the high transverse orographic barrier catching a moist subtropical airflow. Historical references highlight eight major floods across the coastal plain in the Los Angeles area between 1815 and 1876. From 1884 to 1938, nine more floods wreaked havoc. In the latter half of the twentieth century, enormous public work projects were completed which served to mitigate flood damage in the Los Angeles area.

Prior to 1915, little was done to control flooding within the county. To the contrary, uncontrolled growth and economic development did much to exacerbate a growing urban flood problem, which in fact had become one of the worst in the United States.

Through the early twentieth century, the Los Angeles River, at 55 miles long, was the county's major (and most capricious) drainage. The Los Angeles River had a long history of meandering almost at random across the coastal plain, emptying into the Pacific Ocean at various places from Santa Monica to Long Beach.

Flood destruction and loss of life awakened the growing population of the Los Angeles Basin to the need for flood control. The Los Angeles County Flood Control District was established in 1915, and Congress authorized the U.S. Army Corps of Engineers to work on the Los Angeles River problem at about the same time.

The river posed major difficulties: An intermittent and swampy slough in the late summer, it became an unpredictable and raging torrent during periods of heavy rain. In flood stage, the river was gorged with huge volumes of water, strong current velocities, large debris loads, and unstable channels. As the population of the Los Angeles area grew rapidly in the early twentieth century, each flood produced increasing damage to the district, and scores of lives were lost. Flood control had become absolutely essential.

Between 1917 and 1965, the huge public works projects undertaken by the Corps of Engineers and its partners bore fruit. With great leaps forward in technology and in ecological sensitivity, a series of catchment basins and concrete or stone-lined channels controlled the Los Angeles River, its tributaries, and other streams within the district. The cost was high — over two billion dollars in federal and local funds for the entire project — but great benefits were realized. There were no more catastrophic floods after the 1950s, in spite of the sharp upward trend in urbanization and an increase in the number of heavy rainfall events late in the century. In addition, valuable recreation land was set aside for the public trust as a result of construction of catchment basins along channels.

The last major flood destruction in Los Angeles occurred on March 2, 1938. Forty-nine lives were lost. A major rainfall event occurred in 1969, in which an estimated $1.5 billion in damage was saved by flood control projects. Other heavy rains in 1983, 1992 and 1998 were well-handled by the complex system of drainages, catchments and bridges built by the Corps of Engineers within the Los Angeles area.

Turhollow (1975) rightly suggests that "early Spanish settlers probably would not recognize these 'new' rivers, like the Los Angeles, but no doubt would appreciate the modifications."

The current Los Angeles County Drainage Area flood control system is one of the world's largest and most extensive flood protection infrastructures. This flood protection includes:

- 15 flood control reservoirs
- 5 flood control basins
- 143 debris control basins
- 225 stabilization dams
- 33 storm water pumping plants
- 470 miles of open, improved channel
- 2,400 miles of underground drains
- 75,000 catch basins

The Corps of Engineers estimates that the value of damages prevented by the system in storms during its lifetime has already reached $3.6 billion.

Projects now underway in the lower Los Angeles River will expand the channel capacity from 133,000 cubic feet per second (cfs) to 182,000 cfs, which would approximate a 133-year flood (Plates 1-5).

Heavy rain still poses a flooding threat in the Los Angeles Basin, but the greatest problems are now associated with urban flooding, ponding of water in poorly drained areas, and high outflow of water, mud and debris below canyons draining higher terrain.

Drought

A dictionary defines *drought* as "an extended period of dry weather, especially one injurious to crops." But *drought* is a subjective term, with different meanings for different users; there is no standard or official meteorological definition.

The common meaning of the word hardly applies to southern California, where extended periods of dry weather occur every year, from May through October, as part of the normal Mediterranean climatic regime.

Los Angeles' annual rainfall, less than fifteen inches, is only about one-third of the precipitation received each year at New York City. Moreover, the Los Angeles area, with its large population, always operates under a water deficit, which has been made up mostly by water imports through a massive aqueduct system, established in 1913.

Water for the Los Angeles metropolitan area is currently purchased from northern California, the Sierra Nevada, and the Colorado River. Local water sources, such as reservoirs and ground water, make up a shrinking or unstable portion of the total water supply. The market for partially or totally desalinated ocean water may grow in the future in response to continued economic and population growth in the area.

The driest rainfall season at the Los Angeles Civic Center was 1960-61, when only 4.85 inches of rain were recorded. On an intra-seasonal basis, the greatest number of consecutive days without measurable rain was 219, from February 18th to September 24th, 1997. It was this "drought" that was effectively broken by the *El Niño* episode of 1997-98.

A number of dry cycles are easily observed within the historic rainfall record of Los Angeles. Dry periods seem to occur about every thirty years, beginning at about the time of the Civil War. There are clusters of dry seasons—years with less than ten inches of rainfall—around, or just before 1870, 1900, 1930, 1960 and 1990 (Figure 13). There is some suggestion that droughts, like heavy rainfalls, are related to changes in the solar constant, to SST changes in the equatorial Pacific, or to some other heat transfer mechanism in the oceans. Future studies may help to better understand these relationships.

7. LOS ANGELES CLIMATE AND STORM HISTORY

Prehistoric (Paleoclimatology)

Paleoclimatological data are lacking over the United States in general, and over the southwest in particular. To complicate matters, some of the studies of prehistoric weather in the region have been contradictory. Moreover, global and North American climatic patterns and dynamics are not necessarily reflected in Los Angeles Basin. Los Angeles has always been a modifier of world climatic change by virtue of its encapsulated topography, and by its unusual maritime interface. A brief overview of Pleistocene and recent climatic change globally—and in the Los Angeles area—illustrates this relationship.

The Quaternary Period (i.e., the past one million years) has been distinguished by two remarkable events: (1) Glacial-interglacial climatic oscillation, and (2) the increasing dominance of the Earth by hominids.

During the past 130,000 years, the global climate has swung broadly from warm interglacial to cold glacial and back to warm. Within this framework, there have been many sharp oscillations in global and regional temperature and rainfall patterns.

Between 130,000 and 110,000 years ago (ya) the climate of southern California may have been much like today, perhaps even warmer. About 110,000 ya a very rapid shift occurred (in the space of a few decades) which plunged the planet into glacial conditions. Following the initial chilling, a gradual and uneven cooling continued until about 70,000 ya. This marked one of two glacial maxima in the past hundred millennia.

From 60,000 to 30,000 ya, there was an intermittent warming trend, but temperatures did not moderate to the relatively mild levels of the present interglacial.

Beginning about 30,000 ya there was a major cooling trend which culminated in the Last Glacial Maximum (LGM) at 21,000 ya. This very cold stage lasted for about 4,000 years.

At the time of the LGM, it is suggested that Los Angeles area climate was cooler than now by an average of about 4-9•F, This local cooling was much less dramatic
During the LGM, vegetation in the Los Angeles area was similar to what is found today on the Monterey Peninsula. Stands of closed-cone pines predominated, with redwoods at higher elevations. The LGM was characterized by alpine glaciation at highest elevations, and permanent ice was believed to exist at elevations above 6,500 feet in the Sierra Nevada in east-central California. At the close of the LGM, large glacial lakes existed in the Mojave River drainage, and elsewhere in southern California.

Approximately 14,500 ya, a rapid transition to a warmer and wetter Earth occurred. This change is now thought to have happened quickly, in the space of only a few years. The moderating trend was interrupted by the Younger-Dryas cooling between 12,800 and 11,500 ya. The effect of Younger-Dryas on Los Angeles area climate is uncertain. However, at the end of that interval, global warming again occurred rapidly, most of it within the space of only 15 years.

Between 9,000 and 6,000 ya, during the

than that observed elsewhere on the North American continent, much of which was buried under thousands of feet of ice.

With the southward suppression of the jet stream over the north Pacific during the LGM, it is believed that the Los Angeles Basin received from 25 to 100% more rainfall than at present. Recent research points more toward the lower end of this estimate. In any case, the cooler climate is certainly indicative of more effective moisture and lower evapotranspiration rates.

so-called “Holocene optimum”, Los Angeles weather was mild and somewhat wetter than today, except that a strong cool and dry spike occurred within the record about 8,200 ya which lasted for one or two hundred years.

From 6,000 to 3,000 ya, Los Angeles climate was slightly warmer and drier than at present. At 2,600 ya, strong global cooling occurred in phase with a 1,500-year temperature cycle. Following that event, the climate across southwestern California has remained more or less the same as at present, except for occasional warm/cool spikes.

A climatological anomaly occurred between 1,500 and 1,400 ya which caused a sharp irregularity in world climatic patterns. An unknown singular event may have precipitated the climate shifting circa 540 Christian Era (CE). At any rate, the latter half of the sixth century CE was marked by *El Niño* circulations of unprecedented strength and persistence. There is an assumption of very strong rains and flooding across southern California during that period. However, we are not aware of any core data which support these conclusions.

Investigations into ocean bottom sedimentation and tree ring patterns have indicated wet and dry cycles, and even statistically wet single-season outliers, within the framework of the past five or six hundred years. Such surveys are considered quite reliable because of historical cross-referencing.

Using such techniques, Michaelson and Haston (1988) have identified two years, Recent research by Schimmelmann, et al. (1997) suggests an extreme precipitation event occurring in southern California in approximately **1605**. These heavy rains occurred in a region which had experienced years of drought in preceding years. This extreme rainfall caused massive erosion and unusually heavy sedimentation within the Santa Barbara Basin. These very heavy stream flows predate European settlement in the area, thus no written record exists. Nevertheless, confidence is high that such events did occur.

Historic Storms

Flooding in the Los Angeles Basin was mentioned by Spanish missionaries as early as the eighteenth century. But from the time of the establishment of the civil settlement at Los Angeles in 1781 until the second decade of the nineteenth century, rainfall rates were remarkably low in the area. Then in **1815**, a massive flood cut a channel across what is now the downtown district, re-routing the Los Angeles River westward, where it emptied into the Pacific Ocean south of Santa

1565 and **1568**, in which rainfall was very heavy throughout southern California. The 1568 event is suspected of approaching extreme values.

The first decade of the seventeenth century was notable for exceptionally cold conditions worldwide. Beginning in 1600/01, a cluster of volcanic events occurred. Strong El Niño conditions developed in 1604 in the eastern Pacific Ocean, displacing storm tracks into southern California.

Monica, at Ballona Lagoon. A decade later, an **1825** storm returned the Los Angeles River to its present channel, which now flows southward into the Pacific Ocean at San Pedro Bay.

From December 24, **1861** to January 31, **1862** almost continuous heavy rainfall deluged all of California. Heaviest rains were recorded at San Francisco—which averaged almost an inch of rain per day for 30 days, in what was computed to be a 37,000 year event (Goodridge, 1997). In Los Angeles, measurable rain occurred on thirty consecutive days. Flooding and massive mudslides occurred throughout Los Angeles County, destroying property and roadways.
Immediately following the flooding, In the fall of 1862, a severe drought settled into Los Angeles County. No significant rains fell again in Los Angeles until the fall of 1864. This drought doomed the embryonic cattle and livestock industry within the basin.

Almost 26 inches of rain fell at Los Angeles in February and March **1884**. The 1883-84 rainfall season was the wettest in recorded history, with 38.18

inches recorded downtown. There was some loss of life in the February and March floods, and a great deal of property damage. Fifty houses were washed away in floods.

The heavy rains of January 25-26, **1914** were followed by a second and larger storm three weeks later. Large areas of the basin were flooded by the Los Angeles River,. This flooding led directly to the establishment of the Los Angeles County Flood Control District in 1915.

In January **1916** Los Angeles was on the northern fringe of the storm that drenched San Diego County with its all-time record rainfalls. Los Angeles was spared the worst of the disaster, but still received nearly eleven inches of rain between January 14th and 28th, and widespread flooding occurred within the district.

Beginning December 31, **1933** and continuing into New Year's Day **1934**, very heavy rains caused destructive flooding and mudslides across Los Angeles County from Malibu to Covina. Fourteen weather stations in the Los Angeles area reported record maximum two-day rainfalls, with two locations recording 1,000-year events. A rain gauge located on the slopes below Mount Wilson recorded almost fifteen inches of rain on New Year's Day. Glendale and Montrose—along the La Crescenta delta cone northwest of Pasadena—were severely affected by a huge debris flow. The effect of the heavy canyon outflows of mud, debris and boulders was exacerbated by a fire which had burned over the district during the previous summer. In all, the flooding left more than forty persons dead and destroyed or damaged 500 homes. The City of Pasadena measured 6.21 inches of rain on that New Year's Day in 1934, but the Tournament of Roses Parade went ahead as scheduled.

The storm of March 2, **1938** produced another astounding precipitation and flooding event in Los Angeles County. This flood was the most destructive and violent of the twentieth century. Leading up to the March rains, Los Angeles had received about ten inches of rain in February. On March 2nd—with the ground already saturated—five to seven inches of rain fell across the basin. Rainfall in the surrounding mountains was much heavier. Seventeen mountain gauges recorded ten inches or more of rain—with a few receiving up to 18 inches. Stream flows recorded by gauging stations within the San Gabriel Mountain watershed were phenomenal. Forty-nine persons were killed and millions of dollars of destruction was reported. Turhollow wrote that

> *...the City of Los Angeles endured a 2-day nightmare in which the break-down of rail, telephone, highway and mail services left the city with the radio as the sole means of communications. Over an emer-gency national hook-up, Mayor Frank L. Shaw...reassured the world that: 'The sun is shining over southern California today and... Los Angeles is still smiling.'*

Less than five years later, in **1943**, it rained extremely hard on January 22nd and 23rd. The greatest 24-hour rainfall in California history occurred in this storm when 26.12 inches fell at Hoegees, below

Mount Wilson. Fifteen weather stations in the transverse ranges received storm totals exceeding twenty inches—Hoegees had a storm total of 36.34 inches—while many more stations in the foothills and valleys of Los Angeles County reported a one hundred-year event. Goodridge (1998) stated that the area encompassing a 100-year or more return period covered 11,000 square miles, and extended from Santa Barbara County to Riverside County.

Southern California received heavy

Flood control projects completed before 1968 mitigated property damage in Los Angeles. When the 1969 *El Niño* rains finally ended, Frank G. Bonelli of the Los Angeles County Board of Supervisors stated that "the overall flood control system prevented one of the worst catastrophes in the history of Los Angeles." To the north, across Santa Barbara County and San Luis Obispo County, losses and damage from these heavy rains had been much more severe.

In the month of February **1980**, thirteen inches of rain fell after an abnormally wet January. The Los Angeles River slightly overflowed the levees at the lower end of the river at Wardlow Road. The 129,000 cfs river gauge measurement at that location was the highest recorded since records began in 1928. This 40-year flood event broke through a barrier that was supposed to withstand a 100-year flood, which caused the Corps of Engineers to re-evaluate flood protection for the lower Los Angeles River.

The January 4, **1995** storm caused about six million dollars damage, mostly as a result of urban flooding from record rainfalls in the south portion of the Los

precipitation through the **1968-69** season, particularly during January and February, when almost 23 inches of rain fell at downtown Los Angeles. A low pressure trough had anchored off the southern California coast, setting up a steady-state subtropical moisture flow across the district. During this event, almost three hundred rain gauges recorded the highest-ever 60-day rainfall totals.

Angeles Basin. Between 3:00 and 4:30 p.m. on January 4th, the area in south Los Angeles County between Long Beach and Carson was deluged with up to 3.40 inches of rain, while a gauge near LAX received only 0.12 inches and the Pomona area reported 0.55 inches. Two hundred structures were flooded and one hundred vehicles abandoned. Flood control facilities operated at peak capacity at many locations for short periods of time during the event, but the Los Angeles River did not approach capacity because intense rainfall occurred over only a relatively small portion of the lower drainage basin.

In **1998**, another strong *El Niño* episode produced the wettest February of all time at downtown Los Angeles, with 13.68 inches recorded during the month. Over nineteen inches fell at Montebello Fire Station, just east of the downtown weather station. In the Los Angeles metropolitan area, seasonal rainfall records were established at six key area stations, including Chatsworth with an incredible 44.19 inches. For the entire 1997-98 rainfall season, precipitation over the whole district averaged a whopping 230% of normal. With such huge numbers, it was somewhat surprising to note that the only flooding reported was of the urban and small stream variety—more nuisance than disaster. Several reasons are offered to explain the lack of problems associated with this very heavy rainfall season:

• •Ample warning, well in advance, of the strong probability of heavy winter rains was provided by the National Weather Service and the media. This prompted extra vigilance in the removal of debris from storm basins and flood channels. When rains did occur, the National Weather Service, using latest technologies, communicated warnings to emergency officials. This, in turn, led to appropriate action-response.

• The rains were spread fairly evenly over the course of the 1997-1998 season.

• Adequate long-term flood control measures by the U.S. Army Corps of Engineers and their partners were largely completed and in place.

8. LOS ANGELES BASIN WIND PATTERNS

California lies within the "prevailing westerlies" zone of the northern hemisphere. The eastern north Pacific high pressure area is the dominant large-scale meteorological feature, affecting the entire state of California, especially during the summer and early fall. This high pressure area, reflected in surface and upper air circulations, produces a broad northwest wind flow across California. This wind flow is modified to a more westerly direction by continental influences as the maritime air nears the California coast.

Two major regional influences result in further adjustments in the broad scale wind pattern in southern California's coastal zones: (1) The blocking influence of the high mountains which ring the district, and (2) the "edifying" effect of the California bight on the predominant northwest flow.

The transverse ranges divide Los Angeles County into semi-desert and coastal sections and further isolates the Los Angeles area from the rest of California, and vice-versa. The mountains reinforce the predominant sea breeze and land breeze patterns across the coastal plain.

There are a plethora of data, in general remarkably consistent, that have been produced by various agencies to analyze surface and low-level wind patterns across the Los Angeles Basin. The South Coast Air Quality Management District (AQMD) and the California Air Resources Board regularly monitor wind data over southern Los Angeles County. Historic wind data consist principally of Weather Bureau, National Weather Service and FAA airport wind data. These data are stored at the National Climatic Data Center in Asheville, N.C. In addition, most area airports maintain wind rose diagrams, reflecting predominant wind speeds and directions. These diagrams were carefully prepared by federal authorities from the 1930s until the 1950s.

As is often the case with climatological data which span more than half a century, there are some incongruities in National Weather Service and FAA airport wind records. Sometimes data problems occurred because of changes in exposure and equipment at official sites, but also because of differences in methods of wind speed evaluation. For example, the Weather Bureau used six different sites and various types of equipment in measuring wind at downtown Los Angeles. In 1964, wind data evaluation for downtown was transferred to AQMD. Then, the National Weather Service ended its participation in the program altogether in 1974.

Moreover, the LAX wind tower was relocated in 1960 and lowered from 59 feet to 20 feet above ground level. Interestingly, the average annual wind speed at LAX promptly increased from 6.6 mph to 7.9 mph. And in 1996, the United States government changed the official period of evaluation of wind speed from one minute to two minutes.

There are more than fifty official government wind monitoring sites in the Los Angeles area. The National Weather Service and FAA together operate about two dozen of these. A large number of wind sensors have been installed since 1990 by various agencies, public and private, in addition to a proliferation of wind monitoring equipment owned by private citizens. Only a few of these wind gages archive wind data on a continuous basis, although most instruments report once-hourly or peak winds.

General Wind Patterns

For downtown Los Angeles, the predominant wind direction is from the west-southwest for most of the year. The average annual wind speed is 6.2 mph. But there are significant diurnal and seasonal exceptions to this normal.

Generally, most of the Los Angeles Basin experiences light and variable gravity or land breezes during the night and morning hours. Winds then reverse to onshore sea breeze patterns during the late morning or afternoon hours, depending on distance from the ocean and local topography. The direction of this onshore wind flow varies from west-southwest (at LAX and downtown) to south-southeast (at Long Beach, El Monte and Pasadena) to southeast or east (at Van Nuys and Burbank). Afternoon sea breezes normally range from 10 to 15 mph, but can be enhanced by increases in onshore pressure gradients.

At downtown Los Angeles, strongest mean monthly wind speeds occur in March, with lightest winds usually recorded in August and September. A peak wind (one minute average) of 49 mph was recorded from the north during a Santa Ana windstorm in January 1946. Wind gusts to 70 mph or more have a return period of more than 100 years, while winds can gust from 55 to 60 mph once in 25 years. (Some studies have suggested greater return periods.) Strongest winds, from a northerly direction, occur in winter as a result of Santa Ana katabatic conditions. More rarely, strong southeasterly winds gust to 50 mph or more as a result of the transition of a north Pacific winter storm across the district.

The average annual wind speed at LAX is 7.5 mph, the highest value at any official weather station (excluding beach sites) within the Los Angeles Basin. Average monthly winds are highest at LAX in April, at 8.5 mph, and lowest in December, at 6.6 mph.

Winds are less strong at Long Beach Airport, where the annual average wind speed is 6.3 mph.

Two wind patterns occurring over south coastal California, the Catalina Eddy and the Santa Ana winds, are locally famous effects of a special combination of terrain and atmospheric pressure gradients. Phenomena similar to these occur in a few other areas of the world, but nowhere do they affect such a large number of people and almost nowhere else do they so impact local climatic conditions.

Catalina Eddy

From April or May through October, the normal west or northwest wind pattern along the southern California coast is sometimes interrupted by southerly coastal winds, increasing the depth of marine layer and raising the bases of the stratus clouds over the basin.

The low level winds are reflective of a mesoscale vortex which establishes itself near Catalina Island east of the primary northwesterly wind flow offshore. Evident on satellite loops, this *Catalina Eddy* circulation is nature's air conditioner and air purifier for the Los Angeles Basin. It occurs in contradiction to the basic geostrophic wind but, paradoxically, is caused by the geostrophic wind in an interaction with topography.

Such eddy circulations are not unique to
Although Catalina Eddy circulations can occur at any time of the year, they are

Lightest annual average winds across the basin include Pasadena at 3.1 mph, Reseda with 3.0 mph, and San Dimas at only 2.2 mph.

southern California; they have been observed to the south of Vancouver Island, British Columbia, and on coastal sections of Oregon and Washington.

Between Point Conception and the Mexican border, the California coastline extends in a more eastward or south-eastward direction, forming the Southern California Bight. Strong winds blowing from the northwest along the central California coast cause a lowering of pressure to the south and east of Point Conception. This tends to turn the winds to a more westerly direction as they head across the inner waters toward the Los Angeles area. When the northwest flow is strong enough, a low-level vortex called a Catalina Eddy is formed. This cyclonic circulation causes further turning of the low level wind field, and westerly flow into the Los Angeles Basin becomes southerly (Figure 31a).

Considerable cyclonic rotation is established in the lowest layers of the atmosphere above the basin, with a sharp increase in the force of southerly and southeasterly surface winds, and considerable mixing up to 5,000 feet above the surface. The south to southeast wind flow is especially significant, averaging 10-20 mph at Torrance, Long Beach, and across the San Fernando Valley.

most common from April through early October, with a maximum frequency in

May and June. This seasonal distribution is largely due to the lack of strong broad-scale weather makers, such as low pressure systems and fronts, which tend to have a deleterious effect on eddy circulations. Certain atmospheric conditions increase the likelihood that an eddy will form. At the surface, high pressure building across the Pacific toward northern California will increase the strong northwesterly low-level flow along the central coast, essential to the development of an eddy. Additionally, surface low pressure located in southern or central Nevada will also assist in the eddy's development. An upper level trough of low pressure along the west coast of the United States will often provide just enough upward air motion to help spin up an eddy circulation.

The process that sets up a Catalina Eddy is analogous to that which initiates a *sundowner* (downslope wind event) in Santa Barbara; indeed the sundowner and Catalina Eddy are closely related cousins and frequently occur together. Sundowner winds near Santa Barbara cause a secondary pressure minimum there, which is the result of mountain wave activity. This serves to intensify the Catalina Eddy circulation further.

Eddy circulations generally last for 3 to 5 days, or as long as synoptic conditions are stable. The demise of the eddy circulation can be caused by a sufficient decrease in northwesterly flow along the central coast, the disruption from a strong synoptic scale weather system, the deepening of the marine inversion to 6,000 feet, or a combination of all three.

Santa Ana Winds

Santa Ana winds are one of the principal signatures by which Los Angeles weather is known. Santa Anas are offshore winds—usually warm—blowing from the mountains to the coast, and occurring principally in the fall and winter. They are a type of downslope (foehn) wind which occur in many other regions of the planet. But perhaps nowhere else do such winds impact so many people with so much force, and possess such extensive opportunity for damage and destruction.

Fortunately, destructive Santa Ana winds are rare. For most Angelinos and for the great majority of Santa Ana events, the effects of these offshore wind conditions are benign and even welcome. The Santa Ana condition is usually one of warm temperatures when the rest of the United States is in the grip of winter. For most of the district, Santa Anas are marked by light coastal winds, clean air and low humidity.

There is much contradictory information in circulation with respect to Santa Ana winds. An excellent treatment of the technical aspect of Santa Ana winds was authored by Ivory Small in 1995 and is referenced elsewhere in this study. A fine historical perspective of Santa Ana winds was presented by Art Lessard, Don Gales, and Don Lust in 1988.

The name *Santa Ana* was applied to Los Angeles' offshore winds over 100 years ago, with an early article describing "Santa Anas" appearing in the *Los Angeles Evening Express* on November 15, 1880.

On November 21, 1880 one Charles L.

Moore of Compton wrote to a relative describing a recent Santa Ana wind episode:

We have had some terrible Santa Anna [sic] wind storms which at Santa Anna [sic] blew orange trees out by the roots and stripped cornfields leaving them bare and scattering the corn over other mens [sic] farms. I am told they have their houses propped up with poles.

It is likely that the Santa Ana name (variously spelled "Santa Anna" or "Santana") derives from Santa Ana Canyon in Orange County from which the winds sometimes blow with considerable force.

An Associated Press account of a strong windstorm which occurred about Christmas Day in 1901 popularized the Santa Ana winds on a national scale. The wire service's exaggerated account of the winds, and the alleged damage caused by them, resulted in an understandable reaction in the city of Santa Ana. Following this incident, the Santa Ana Chamber of Commerce tried, without success, to have newspaper editors refrain from using the name "Santa Ana" in connection with area's winds. Notwithstanding the city's objections, the U.S. Weather Bureau published a Climatology of California in 1903 which referred to the winds as "Santa Ana", and that designation has remained in common use throughout the twentieth century.

Santa Ana winds are a type of katabatic or downslope winds, generally warm and dry, broadly affecting the Los Angeles Basin with the strongest impact felt below passes and canyons of the coastal mountains.

Offshore winds from the northeast or east must reach 30 mph or more below passes and canyons to reach minimum criteria for Santa Ana wind advisories. More typically wind speeds are in the 40 to 55 mph range, and in extreme cases winds can gust locally to over 100 mph.

An understanding of Santa Ana winds begins with a review of the principles of fluid dynamics, which have been vigorously adapted since 1885 to explain the structure of downslope winds. Jakob Bernoulli's equation relating fluid pressures and velocities has been used in discussions of winds channeling through topographic gaps and canyons. Canyon winds are evidently part of the Santa Ana process.

Hydraulic flow models used in fluid dynamics to describe open channel flow over a barrier were adapted by Long (1953) in a mainly successful application to atmospheric analysis. Horel (1992) states that recent investigation indicates that much of observed downslope wind phenomena can be explained by utilizing the "hydraulic jump" concept. In this model, a breaking wave forms in the airflow on the lee side of a mountain barrier where strongest winds occur as lee waves.

Another factor in the establishment of a Santa Ana wind regime may be the vertical propagation of waves through the atmosphere. Upper atmosphere investigations since the 1970s have suggested the presence of lee waves rotating vertically through a dynamically layered troposphere. These studies appear to be confirmed by recent computer applications at the University of California Santa Barbara.

An indicator of lee wave formation and activity is the rapid hydrostatic lowering of surface pressure during the maximum surface wind occurrence in the affected areas. Rapid increases in surface pressure across the Los Angeles Basin invariably signal the end of the Santa Ana winds, irrespective of diurnal or synoptic scale pressure tendencies.

Some combination of canyon wind (Bernoulli effect) and hydraulic jump or reflective breaking wave is involved in the process that generates Santa Ana winds. The synoptic scale event that initiates this process is the formation of a dome of high pressure over the Great Basin.

High pressure areas build in the fall and winter over the Great Basin as cold air translates into that region from Canada. When the surface pressure gradient reaches or exceeds ten millibars as measured from Tonopah, Nevada to LAX, wind gusts can reach 70 mph in the mountains and below passes and canyons near Los Angeles. If in addition to strong gradients from the Great Basin, pressure gradients increase to eight millibars or more from San Francisco to LAX, a general Santa Ana condition will ensue that will affect most of the Los Angeles Basin. In this event, winds may gust to 40 mph or more at LAX and at downtown Los Angeles.

Santa Ana winds typically affect southern California via three main sources: (1) The Santa Clara River Valley, impacting the San Fernando Valley, Malibu Hills and Ventura County; (2) Cajon Pass, affecting Fontana, Santa Ana, eastern and southern Los Angeles County; and (3) Banning Pass, which affects southern Orange County (Figure 31b).

Santa Anas may last from one day to up to a week or longer. They occur most often in the fall and winter, with a frequency of occurrence peaking in the month of December.

Santa Anas affect the Los Angeles Basin very unequally; winds tend to channel in “the usual places” below specific passes and canyons. Within these channels, winds tend to come in gust clusters, letting up from time to time and blowing fiercely at other times. Strong winds may blow in one neighborhood, while a few blocks away there are only gentle warm breezes.

In the extreme, Santa Ana winds represent a potential threat to public safety. The winds can spread destructive fires, take roofs off of houses, and uproot trees. They can carry clouds of dust, lowering visibilities, and they can pose serious dangers for motorists, pilots, farmers, and mariners.

In November 1961, flames driven by Santa Anas at speeds in excess of 100 mph resulted in a loss of hundreds of homes in the exclusive Bel Air district of Los Angeles.

9. MISCELLANY

Relative Humidity

Humidity is an indicator of the amount of water vapor in the air. Relative humidity is a ratio between the amount of water vapor actually in the air, at a given temperature and pressure, and the amount of water vapor which the same parcel of the air could hold if it were saturated. This is expressed as a percentage.

Moist conditions are common in Los Angeles. The relative humidity averages 63 percent at downtown Los Angeles on an annual basis. The average daily maximum relative humidity is 75 percent, generally occurring in the early morning hours around sunrise. The average daily minimum relative humidity is 53 percent, normally occurring in the early afternoon.

Humidity readings are higher than the annual average, by 10 to 20 percent, during the time from June through early October. Lowest levels of the atmosphere tend to be drier in the Los Angeles area during the winter season; relative humidity levels are generally 10 to 20 percent below average annual levels from November through April. The relative humidity frequently ranges between 90 and 100 percent during late night and morning hours in the summer and early fall.

Dry air with very low relative humidity is infrequently observed at surface weather stations within the Los Angeles Basin. Relative humidity values of less than twenty percent occur mainly with offshore Santa Ana winds, when dry desert air enters the basin from the northeast. These conditions are most likely to occur from October through April, with an annual frequency of about 10 to 15 days. On rare occasions, relative humidity readings of less than five percent have been measured with reliable instrumentation across the Los Angeles Basin.

Evapotranspiration

The term evapotranspiration refers to the total transfer of moisture from the soil to the air over a field growing a well-established crop. Some of the water loss is by evaporation from the surface of the soil, while other moisture is carried upward and transpired from the leaves and other surfaces of plants.

At Los Angeles, the average annual evapotranspiration is 47.5 inches. The average daily evapotranspiration rate is 0.13 inches, with a range from 0.04 inches per day in December to 0.23 inches per day in July.

Average annual evaporation, as measured from a standard four-foot pan, is estimated to be about 70 inches per year, but the rate is highly variable due mainly to surface wind irregularities. Approximately two thirds of total annual evaporation occurs in the months from May through October.

Clouds and Fog

The City of Los Angeles is a mostly sunny place. The city averages 185 clear days per year, with "clear" defined as zero to three tenths of the sky covered by clouds.

At downtown Los Angeles, dense fog—with visibilities of 1/4 mile or less—occurs on an average of approximately 17 days per year. Thick fog commonly results from a shallow intrusion of marine air over the coastal plain. Dense fog is generally a nighttime phenomenon, and tends to dissipate quickly during morning insolation.

Dense fog—thick enough to suspend aircraft operations—is most likely to be observed at LAX from November through January, with each of these months averaging about six days on which heavy fog occurs for part of the day. Downtown the situation is different, as heavy fog occurs most frequently in September and October, which average three days each with dense fog.

The months with the most persistent low cloud cover are May and June. June averages just nine clear days at LAX, versus a maximum monthly normal of fourteen days in November. Downtown, the average number of clear days ranges from 11 in May to 22 in August.