On the Incidence of Tornadoes in California

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ABSTRACT

Climatological analyses of tornado occurrence in the state of California for the period 1950–1992 are presented. In constructing these analyses, the official historical record of California tornadoes was supplemented and corrected with tornado reports from other sources. In corroboration of the results of the few previous studies of California tornadoes, the distribution of tornadic events across the state is found to be very uneven; in particular, a relatively small area of south-coastal California has an incidence of tornadoes (per unit area per unit time) comparable to regions within the midwestern United States. Other subregions of the state with an enhanced incidence of tornadoes are also identified; these include a large portion of the Central Valley (which comprises the Sacramento and San Joaquin Valleys), the north-central coastal region (including the San Francisco and Monterey Bay areas), and a part of the vast southeast desert region. Annual and diurnal distributions of tornadoes in each of these areas are examined. Tornadoes in the southeast desert region are found to occur primarily during the warm season, while those in the other three identified subregions occur primarily during the cool season. Peak incidence generally occurs during the afternoon, though the diurnal distribution is complex in the two coastal regions. The average tornado in California is weaker and has a shorter path width and pathlength than the average tornado in the contiguous United States; however, the preferential occurrence of tornadoes in areas of California that are moderately-to-densely populated makes them a source of significant concern.

1. Introduction

a. Overview

Studies of tornadoes in the United States have generally focused on those occurring to the east of the Rocky Mountains. This is not surprising, given that meteorological conditions conducive to formation of severe thunderstorms and tornadoes occur more frequently over portions of the central and eastern United States than anywhere else in the world. In fact, it is so commonly assumed that the eastern escarpment of the Rocky Mountains represents the western edge of the region of the United States prone to significant tornadic activity that it is fairly common to entirely ignore the region of the United States to its west (e.g., Kelly et al. 1978).

When such studies do include the western United States and follow the usual approach of tabulating tornado occurrence by state over some interval of time (e.g., Pautz 1969; Kessler and Lee 1978; Rasmussen and Andrews 1986), they yield an incidence per area per time ratio that is much smaller for those states west of the Continental Divide than for the rest of the nation. In such an analysis, it is implicitly assumed that the tornadic events are evenly distributed across each of the individual states. Unlike the midwestern states, however, the western states contain significant topographical variation and can be divided into subregions with vastly disparate climates.

In determining tornadic incidence in the western United States, one needs to consider whether or not there are subregions that experience a significantly higher incidence of tornadoes than is indicated by statistics compiled on the scale of the states themselves. In fact, the few relatively detailed climatological studies of tornadoes thus far conducted that have either contained or focused on the western United States have revealed a few small regions that do indeed appear to experience significantly greater tornado activity than the rest of the region (Pautz 1969; McNulty 1981; Rasmussen and Andrews 1986; Grazulis 1991). Two of these regions are within California: the Los Angeles area, and the Central Valley of California (which comprises the Sacramento and San Joaquin Valleys), with the former generally given as the subregion of the western United States with the highest tornadic incidence.

b. California tornadoes

Thus far there have been only a few climatological studies of California tornadoes. These studies supported the preceding findings and showed that most of the tornadoes in California were comparatively weak and
small and had relatively short pathlengths. The vast majority of California tornadoes were of F0 or F1 intensity; events of F3 intensity were exceedingly rare, and there were no documented events of greater than F3 intensity.

The geographical distribution of California tornadoes was considered by Goodridge et al. (1979) and Hales (1983, 1985). The former presented a plotted distribution of California tornadoes that occurred over a period of approximately 12 years and thereby identified two regions of significantly enhanced incidence: primarily the Los Angeles area, and secondarily the Central Valley from the southern end of the Sacramento Valley south through the central San Joaquin Valley. Hales (1983, 1985) mapped the locations of California tornadoes that occurred during the period 1962–1983 and thereby identified three subregions of the state of significantly enhanced incidence. Two of these (the Central Valley and the coastal plains of southern California) expanded upon regions noted above; in addition Hales identified the deserts of southern California as a third region of enhanced toradic activity. Using Hale’s tornado data for the 2600-km² rectangular subregion of highest tornado incidence within the greater Los Angeles Basin area, and normalizing to the area of a local 1° lat × 1° long grid box, we find that the corresponding tornadoic incidence would be approximately 110 for the 22-year period, or 5 per year. This is approximately a factor of 5 greater areal rate of incidence than that implied by McNulty (1981) for the Phoenix area, the subregion of the western United States that appears to have the next greatest tornadoic incidence. Remarkably, it is also comparable to corresponding values over much of the midwestern United States (e.g., Pautz 1969).

There is evidence that California tornadoes, on average, are of smaller size and have shorter pathlengths than those in the Midwest. Considering the period 1950–1971, Smith and Mirabella (1972) documented 48 California tornadoes in which the damage exceeded $50. Numerical values of pathlength were available for 28 of these tornadoes, while 26 of them had numerical values of path width. From these they found a median pathlength of 0.62 miles (1.0 km) and a median path width of 43 yards (39.3 m). Despite the fact that these values are based on only a limited subset of all of the tornadic events in California, the difference between them and the corresponding values given for Iowa tornadoes [4 miles (6.4 km) and 170 yards (155.4 m), respectively] is striking. That a small number of California tornadoes are large and/or traverse comparatively long paths is indicated by the significant degree to which the mean values of these parameters exceed the median values. Using data from Smith and Mirabella, the mean pathlength is 1.9 miles (3.1 km) and the mean path width is 91.4 yards (83.6 m). Qualitatively similar values were found by Goodridge et al. (1979). They documented 116 tornadoes in California during the period January 1951–April 1979; for 45 of the events, numerical values of both pathlength and path width were given. These resulted in an average pathlength of 3.115 km and an average path width of 116 m. However, the lists of California tornadoes given by these two studies had significant differences. Twenty-eight of the tornadoes listed by Goodridge et al. for the period 1950–1971 were not listed by Smith and Mirabella, while seven of the tornadoes listed by the latter did not appear on the list of the former. And, for some of the tornadoes that were listed by both sources, values of pathlength and path width differed. Grazulis (1991) developed a database of just the strongest of California tornadoes (all of F2 intensity); these had an average pathlength of 3.66 miles (5.89 km) and an average path width of 114.5 yards (104.7 m).

Relatively good agreement is found between the results of different studies of the intensity of California tornadoes. Of the 48 tornadoes considered by Smith and Mirabella (1972), eight were rated as F0 on the Fujita intensity scale, 32 as F1, and 8 as F2. None were considered to be of greater than F2 intensity. A somewhat lower average intensity was found by Braun and Monteverdi (1991) in an analysis of California tornadoes for the period 1950–1988 using National Severe Storms Forecast Center (NSSFC) data records. Out of a total of 138 California tornadoes identified for this period, 44 were of intensity F0, 34 were of intensity F1, 19 were of intensity F2, and 2 were of intensity F3 (with no F-scale designation available for 39 of the events). Grazulis (1991) considered only those tornadoes of F2 or greater intensity but compiled a particularly complete database of such events. He considered the period from 1880 to 1989 and, unlike previous investigators, went to considerable effort to supplement the tornado databases readily available from Storm Data and the NSSFC data record through a thorough analysis of other sources of information, particularly historical newspaper articles. Over this period of more than 100 years he was able to document only 26 cases of F2 intensity, 13 of which occurred between 1954 and 1983, and no cases of greater than F2 intensity. All but 6 of these tornadoes occurred either in the southern portion of Los Angeles County (10 total) or the Central Valley (10 total). The former region, in particular, had a remarkable number of such events (10) over an area of significantly less than 5271 km² (i.e., all of these 10 tornadoes occurred within an area less than half of that of Los Angeles County).

Other climatological characteristics of California tornadoes have received less study. Thus far only Goodridge et al. (1979) have examined the annual and diurnal distributions of California tornadoes. Using 150 recorded tornadoes in California, the department found peaks in the tornado incidence both during January–April and in November, with significantly fewer events during the summer. They stated that 83% of the recorded tornadoes occurred between 10 a.m. and 6
P.M., with a maximum 2-h incidence of 31% between 1 P.M. and 3 P.M. Although the department indicated that the information used in its study was derived from Storm Data for the period 1959–1979 and the Climatological Data National Summaries for the period 1950–1958, we found that the department’s list of California tornadoes for these time intervals did not entirely agree with those in the source publications. It is also unclear where the department obtained some of the quantitative information on various tornado characteristics that it presented.

To this point, however, no studies have yet examined the annual and diurnal distributions of California tornadoes by individual subregion of enhanced incidence. There is no a priori reason to assume that the statewide statistics accurately reflect each of California’s geographically and climatically disparate subregions. The primary goal of this paper, then, is to examine the climatological characteristics of tornadic activity in each of California’s subregions.

To undertake such an analysis, however, a large and accurate database of tornadic events is needed. Previous studies have been based largely on the reports in Storm Data (1959 and thereafter) and Climatological Data National Summaries (1958 and prior) over relatively limited time periods. However, we were led to question the accuracy and completeness of these reports. Hales (1983), for example, noted while cataloging tornadic events in the Los Angeles area for the 22-year period 1962–1983 that there was a 9-year gap (1968–1976) during which no tornadoes were reported. He found, though, that there were six episodes of one or more tornadoes each during the period 1962–1967 and seven such episodes between 1976 and 1983. He thus tactfully concluded that “it appears that the nine year gap resulted from other than meteorological reasons.” In addition, we found cases of tornadoes well documented by journal articles that never appeared in Storm Data (e.g., Bluestein 1979; Carbone 1982, 1983). On the other hand, some of the reports that are in Storm Data appear questionable. Many of the reports therein originated with sightings made by meteorologically untrained members of the general public. In a number of cases, neither photographic documentation nor a professional damage survey was ever undertaken. In some cases the presence of localized wind damage was incontrovertible, but its cause remained uncertain.

Our research, then, also involves the development of a uniquely comprehensive database of tornadoes in California, over the extended period 1950–1992. Our general methodology follows that used by Grazulis (1991) in developing his database of “significant” tornadoes.

2. Data and methodology

We began our climatological analysis of California tornadoes with the construction of the best possible database documenting these events. We chose for our investigation the period 1950–1992. Use of 1950 as the initial year was motivated by the rather dramatic decrease in the number of reported tornadoes in California per year prior to that time. Even so, we found that the number of tornadoes reported per year in general increased significantly with time over the period of our database. In constructing the database, we began with Storm Data (NOAA 1959–1992) as our primary data source for the period 1959–1992 and a similar listing in Climatological Data (NOAA 1950–1958) for the period 1950–1958. Our initial intention was to compile our database directly from these monthly publications, but in attempting to do so, several problems quickly became apparent.

First, we were led to question the accuracy of some of the tornado reports given in Storm Data. For California, these published reports represent a simple compilation of those individual event reports submitted by the Weather Service Forecast Offices (WSFOS) in San Francisco (Redwood City) (for northern California) and Los Angeles (for southern California). These reports often originated with tornado sightings made by meteorologically untrained members of the general public. Especially in a place such as California where much of the population has never seen a tornado, such reports seem intrinsically questionable in the absence of corroborating information such as photographs or a professional damage survey. For many California tornadoes, neither of these was available. In some cases, the report of a possible tornado originated with reports of localized wind damage, but again in the absence of additional supporting information it can be difficult to tell if the damage resulted from a tornado, from a microburst, or from straight-line winds.

We also questioned the completeness of the record contained in Storm Data. Particularly in the case of short-lived tornadoes in rural areas, there may simply be an absence either of a sighting or of any indicative damage or damage reports. On the other hand, we have found a number of well-documented reports of tornadoes in California that never appeared in Storm Data. A few of these came from journal articles; many more derived from newspaper stories. Examples of the former are provided by the damaging tornado that occurred near Sacramento on 5 February 1978 (Carbone 1982, 1983) and the tornado that occurred near Bishop (in the Owens Valley east of the Sierra Nevada) on 7 August 1978 (Bluestein 1979). Examination of articles from newspapers throughout California revealed a number of heretofore unrecorded tornadic events. In addition to eyewitness descriptions of individual tornadoes, many of the articles were accompanied by photographs of the damage. And for some of the tornadic events that were recorded in Storm Data, newspaper articles yielded useful additional information, including, in a few cases, a photograph of the tornado itself.
In addition, we compared the record of California tornadoes kept by the NSSFC with the Storm Data reports. Theoretically, the former is derived entirely from the latter, but we noted discrepancies between the two. Some were relatively easy to account for, such as an error in the direction of time conversion [e.g., in converting between Pacific standard time (PST) and central standard time]. Others, such as pathlength information that appeared in the NSSFC log but not in Storm Data, or reports that appeared in one but not the other, seemed more difficult to explain.

Given all of the preceding, we took the following approach to developing our database. We first compiled a list of all California tornadoes reported in Storm Data from January 1950 until April 1991 (the most recently available issue of Storm Data at the time we initially developed our database). Records from the WSFOs in Los Angeles and San Francisco were then used to extend this list through December 1992. Tornadic events described in Storm Data were divided into two data files: 1) where either it was stated that the tornado was confirmed or that the descriptive information was sufficiently compelling as to indicate little doubt that the tornado occurred, and 2) where either it was stated that the tornado was unconfirmed or where descriptive information was entirely lacking or indicative of uncertainty as to whether or not the tornado had actually occurred.

The first data file was then supplemented with those cases of tornadoes not appearing in Storm Data but for which we were able to find well-substantiated accounts in either journal articles or newspaper reports. A particularly careful search of various California newspapers was undertaken for the period extending from 1968 to 1976, as during this 9-year time interval we found only one officially reported tornado in the south-coastal region of California. Even with this search, our database still almost certainly underrepresents the actual number of tornadoes for the south-coastal region for at least this period. The second data file was supplemented with tornadic events that were not given in Storm Data but that were listed in the NSSFC log or in other publications [e.g., Windstorms in California (Goodridge et al. 1979)] or in various unofficial listings of tornadoes that we obtained.

Those in the first data file were considered valid and put on the list to use in our climatological analyses. Those in the second data file were checked further, wherever possible, through the use of archived newspapers. Where such additional information was both available and compelling in indicating the likelihood of there having indeed been a tornado, the report was switched to the first list.

In determining times and locations of individual events, all available data were used. In some of the cases, specific values of these parameters were not available or varied depending on the source. A best estimate was then used based on the information available. If the uncertainty in time of occurrence exceeded \( \pm 75 \) min, the time of the event was considered to be unknown.

3. Results

a. Climatological analyses of California tornadoes on the statewide scale

Following the approach described above, we have thus far ascertained as valid a total of 242 tornadoes in California during the period 1950–1992. The spatial distribution of these 242 events is given in Fig. 1; this figure also shows the approximate boundaries of regions of enhanced incidence. Locations of landfall of the 32 of these tornadoes that initiated as waterspouts are shown in Fig. 1b. Foremost among the four identified regions of enhanced tornadic activity, both in total number of tornadoes and in number per area, is the south-coastal region with a total of 99 tornadoes (40.9\% of the total). The area of enhanced incidence within the Central Valley contains 69 of the tornadoes (28.5\% of the total). The north-central coastal region contains 31 of the events (12.8\% of the total). Twenty-six events (10.7\% of the total) occurred in the southeast desert region. Only 17 tornadoes (7.0\% of the total) occurred outside these four regions, even though less than 50\% of the total land area of the state is contained in these four areas. Much of the area of the state outside the four identified regions is sparsely populated though, so the true incidence may be underrepresented. With the exception of the identification of the north-central coastal area, these results are in qualitative agreement with those of Hales (1985). Our much more extensive database, however, does reveal comparatively greater detail about the distribution of events within each of these regions. As will be discussed later, this is of particular significance in the south-coastal region.

The distribution of California tornadoes by decade shows a general increase in incidence over the years of this study (Fig. 2). The total number of tornadoes for just the first 3 years of the present decade already substantially exceeds the total number of tornadoes reported during either of the first two decades of the study period. The apparent increase in incidence probably reflects both the overall increase in population of the state and also the increased fractional area of the state containing a significant population. In addition, there has been some increase in awareness of tornadoes in California. Thus, in recent years it is likely that a higher percentage of the tornadic events actually occurring have been reported. It is also interesting that there is no significant trend apparent in the distribution of tornadoes between different regions of the state, with the exception, perhaps, of a relative increase in events in the desert regions of the state. This probably reflects habitation of previously uninhabited or sparsely inhabited regions.
The annual distribution of California tornadoes by month of the year is presented in Fig. 3a. This analysis, which includes all of the tornadoes in our database, shows that most California tornadoes occur during the period extending from late fall to early spring. In fact, 80.2% of the tornadoes (194 of the 242 events) occurred during November–April, with March having significantly more tornadoes than any other month (55 tornadoes, or 22.7% of the total); similarly, 29 of the 32 tornadoes that initiated as waterspouts occurred during this same period. The state thus experiences its maximum tornadic activity during the cool season. This stands in contrast to the annual distribution of tornadoes for the contiguous United States. In considering the average number of tornadoes for each month of the year based on 28,820 tornadoes that occurred from 1953 through 1990, Storm Data (NOAA 1990) shows that 67.3% occur during the period April–July with 42.6% of the average annual total occurring during the 2-month period May–June. Of course, the annual distribution of precipitation in California is also different from that for much of the rest of the contiguous 48 states; California receives most of its precipitation during the winter half of the year.

The distribution of all California tornadoes by time of occurrence (Fig. 3b) indicates a peak incidence during early afternoon hours. This would generally be just past the time of day of greatest surface heating during the cool season months. Secondary peaks also appear during the midmorning and predawn hours.

Most California tornadoes have relatively short pathlengths and path widths. Of the 242 tornadoes in our database, 109 have numerical values given by Storm Data for pathlength and 97 have values reported for path width. Based on these subsets, the average pathlength is 1.5 miles (2.4 km) and the average path width is 98.0 yards (89.6 m). This pathlength is shorter than the corresponding values from Smith and Mirabella (1972) and Goodridge et al. (1979), while the path width is approximately comparable. However, as noted by Schaefer et al. (1986), the percent of reports that contain length, width, and intensity information has increased markedly in more recent years, and most of this increase has been in information reported for
small tornadoes. It should also be noted that average values for both pathlength and path width diminish markedly if only the middle 80% of the values of each are considered; here the average pathlength of California tornadoes is 1.0 mile (1.6 km) and the average path width is 69.4 yards (63.5 m). For all United States tornadoes that occurred between 1 January 1950 and 1 January 1983, the average pathlength was 7.1 km and the average path width was 117 m (Schaefer et al. 1986).

The average California tornado is also fairly weak. Of the 242 tornadoes in our database, 144 have been assigned F-scale values by either Grazulis (1991), Storm Data, or the NSSFC tornado log. Where these sources yielded different F-scale values for a particular event, priority was given based on the order in which these sources are listed here. Of the subset of tornadoes with F-scale values, one (0.7%) was of F3 intensity (given in the NSSFC log, but neither listed as a tornado of greater than F1 intensity by Grazulis nor given an F-scale rating by Storm Data), 23 (16.0%) were of F2 intensity, 50 (34.7%) were of F1 intensity, and 70 (48.6%) were of F0 intensity. Thus, only 16.7% of these tornadoes were of greater than F1 intensity. In contrast, Kelly et al. (1978) found that 38.3% of tornadoes occurring within the contiguous United States during the period 1950–1976 were rated F2 or greater. For this same period, 26.7% of the tornadoes in California with F-scale values were of greater than F1 intensity. We have thus far made no attempt to assign F-scale intensity values to the additional events we documented from whatever descriptive information was available; it is our impression, however, that the vast majority of the supplementary events that we documented through the use of newspaper accounts were of less than F2 intensity. It thus seems likely that the average strength of tornadoes in California is less than that of all tornadoes in the contiguous United States.

Concern over the strong tornadoes that do occur in California is enhanced, however, by their preferential occurrence in either the heavily populated south-coastal region or in the moderately populated Central Valley. Seven of the F2 tornadoes, including all such events in California in the month of November, occurred in the former, while 10, including all such events in California in April and May and 2 of the 5 events in March, occurred in the latter. The single documented event of F3 intensity occurred in the area of Blythe in the southeast desert region on 16 August 1973. A detailed geographical analysis of California tornadoes of greater than F1 intensity is presented by Grazulis (1991).

The overall distribution by month of occurrence of the 24 tornadoes of greater than F1 intensity (Fig. 4a) is basically similar to that for all California tornadoes except for the deemphasis of the winter months in
comparison to the months of November, March, and April. Five of these tornadoes occurred in November, 5 in March, and 4 in April. However, only 3 occurred during the 3-month period December–February.

An analysis of California tornadoes of greater than F1 intensity by time of occurrence (Fig. 4b) yields a distribution similar to that for all tornadoes in that maximum incidence occurs during the hour starting at 1300 PST. This peak, however, is significantly sharper in the case of these more intense tornadoes. The distribution also differs from that for all tornadoes in that there is a complete absence of any of these more intense tornadoic events during the predawn hours.

b. Climatological analyses of tornadoes in the south-coastal region

From examination of Fig. 1 it is immediately apparent that the south-coastal region is the portion of the state that has the greatest incidence of tornadoes (per area per time). As this is an area of complex topography, and as it has been suggested that topography plays a significant role in the formation of tornadoes in this region (e.g., Hales 1985), we next consider a much more detailed spatial analysis of the tornadoic events in this part of the state (Fig. 5).

In this limited region there have been a remarkable number of tornadoes; we have thus far ascertained as valid a total of 99 tornadoes in the south-coastal region during the period 1950–1992. Even though much of the nonmountainous part of this region is heavily populated, the greatest incidence of tornadoes occurs almost precisely in the area of highest population density. Such a result stands in apparent contradiction to the findings of Elson and Meaden (1982), who suggested, based on a study of tornadoes in the area of London, that weak tornadoes are suppressed and dissipated in urban areas. In the present case it is possible, though, that if the same area was rural rather than urban, the number and intensity of tornadoes would be even greater.

The greatest incidence within the south-coastal subregion occurs in the area bounded by the box in Fig. 5. The area enclosed is 4225 km$^2$, and the number of events within this subdomain over the period 1950–1992 is 58. This leads to a tornadic incidence of $3.19 \times 10^{-4}$ tornadoes km$^{-2}$ yr$^{-1}$, or 3.19 tornadoes (10 000 km$^2$)$^{-1}$ yr$^{-1}$. This is qualitatively similar to the tornadic incidence for the state of Oklahoma. According to Storm Data (NOAA 1990), Oklahoma experienced 1969 tornadoes during the period 1953–1990. Oklahoma subtends an area of approximately $1.811 \times 10^5$ km$^2$. If we assume an even distribution of these tornadoes throughout the state, we find a statewide average incidence of 2.86 tornadoes (10 000 km$^2$)$^{-1}$ yr$^{-1}$, or only 89.7% of that of the indicated subdomain of the south-coastal region of California.

Some caveats are needed, however, in interpreting such a comparison. First, a tornado in Oklahoma is likely to be larger and longer lived than one in the south-coastal region (or, for that matter, any region) of California and to have a greater pathlength. So if, instead, the respective spatially and temporally averaged areas of tornadoic events were compared, that for Oklahoma would be significantly greater than that for the south-coastal region of California. Second, as discussed earlier, a not insignificant number of tornadoes are probably never officially recorded. As noted in Dockery (1977), an exhaustive survey of severe storms in Iowa in 1974 revealed many more tornadoes (by a 3:1 ratio) than are listed in official storm data compilations. And, in the present study we have undertaken considerable effort to supplement the official records of tornadoes in California using other sources of data. So in the sense that the comparison does not involve a similarly enhanced database of tornadoes in Oklahoma, the value for California is comparatively inflated. Finally, although the distribution of tornadoic events over the region occupied by the state of Oklahoma is far more uniform than that over the region of California, some spatial variation does exist, and this is not taken into account in the preceding comparison. Nonetheless, this comparison does indicate that the tornadic incidence in a densely populated and heavily urbanized subregion of southern California is signifi-
Fig. 5. Distribution of tornadoes in the south-coastal region for the period 1950–1992. Elevation contours are indicated as follows: thin dotted line is 304.8 m (1000 ft), thin solid line is 762 m (2500 ft), heavy solid line is 1524 m (5000 ft), and heavy dotted line is 2286 m (7500 ft). Dark shaded regions have an elevation in excess of 3048 m (10 000 ft). Key locations referred to in the text are identified. The box superimposed on the figure is 65 km in length on each side and indicates the approximate area of greatest tornadic incidence.

cant, even when compared with that for a region far more commonly thought to experience significant tornadic activity.

Of the 24 tornadoes of greater than F1 intensity (out of the 144 tornadoes in our database that have been assigned F-scale values), 7 occurred in the south-coastal region. Five of these 7 tornadoes occurred in the month of November on 2 tornado days. All seven of these more intense tornadoes occurred within the small subsection of this region comprising extreme southwestern Los Angeles County and the adjacent extreme northwestern part of Orange County. A similar finding is evident in the geographical analysis of California tornadoes of greater than F2 intensity presented by Grazulis (1991).

Within the south-coastal region, mesoscale variation is also apparent in the general distribution of tornadic events. One cluster of tornadoes lies along a line extending to the north from the Palos Verdes Peninsula. Another line of tornadoes extends to the northeast from the southeastern end of this peninsula, and a third cluster of tornadoes is situated to the west of the northwest end of the Santa Ana Mountains. It also appears that a cluster of tornadoes could be defined as consisting
of those events in the vicinity of—and along—the coastline itself. A more thorough understanding of the spatial distribution of tornadoes within the southcoastal region will require analysis of the meteorological conditions associated with each of the events and, in particular, study of the interaction between the low-level flow and the topography. The present analysis suggests, however, that there should be further investigation of the following possible significant topographical influences: convergence to the lee of the Palos Verde Peninsula (which has a peak elevation of 451.7 m) and Santa Catalina Island (which has a peak elevation of 648.3 m); vortex generation by flow past these two obstacles; the possible presence of a topographically induced convergence zone—in the case of an offshore low pressure center or trough—between the low-level flow channeled to the north-northwest by the alongshore mountains and that funneled westward through the gap between the Chino Hills and the Santa Ana Mountains; and, finally, convergence induced by differential surface friction in the vicinity of the coastline.

Most tornadoes in the south-coastal region occur during the cool season (Fig. 6a). This coincides with the period during which this region receives most of its annual precipitation. Eighty-three of the 99 tornadoes (83.8%) occurred during the period November-March, with March being the single month with the greatest number of tornadoes (22 tornadoes or 22.2% of the total). A relative minimum in monthly incidence occurs in December. The number of tornado days, however, was much higher in the months of January, February, and March (13, 11, and 13, respectively) than in either November or December (6 and 7, respectively).

Twenty-three of the tornadoes in this region began as waterspouts (not shown). Five of these tornadoes occurred in November and 5 in December, while 4 occurred in February and 4 occurred in April. One of these tornadoes was of F2 intensity, 4 were of F1 intensity, and 6 were of F0 intensity; the remaining 12 events had not been assigned an F-scale value by Grzulis (1991), Storm Data, or the NSSFC log. There were also a large number of waterspouts that did not move onshore and that were therefore not considered in the present study.

The diurnal variation of tornadic events for this region (Fig. 6b) appears complex; although maximum incidence is in the early afternoon, tornadoes have occurred throughout the day and night. Secondary peaks in incidence are evident during the midmorning and predawn hours. The former appears to be a consequence of the subgroup of tornadic events that initiated as waterspouts. Of the 23 tornadoes in this region that started as waterspouts (not shown), 10 occurred between 0900 and 1200 PST, 4 between 1300 and 1500 PST, and 3 between 0100 and 0300 PST. No more than two waterspouts moved inland during any other 2-h period. Such an explanation would also be entirely consistent with the absence of such a peak in the diurnal distributions for the Central Valley and the southeast desert regions. The secondary peak in incidence during the predawn hours is, if not an artifact of limited sample size, even more intriguing. A possible hypothesis would be that decoupling of the surface layer at night, as it cools, from the flow above it would have the effect of enhancing the vertical wind shear.

c. Climatological analyses of tornadoes in the southeast desert region

In contrast to the other regions of enhanced tornadic incidence in California, most tornadoes in the southeast desert region occur during the warm season (Fig. 7a). Also unlike much of the rest of California, the southeast desert region receives a significant fraction of its annual precipitation during the summer months. In Needles (situated along the Colorado River just south of the southern tip of Nevada), for example, the month with the highest average precipitation is August, while in Imperial (in the Imperial Valley, CA), August is on average the second wettest month (NOAA 1985). Although a significant percentage of the annual precipitation also occurs during the cool season, the summer precipitation is much more convective in nature, as it
is associated with episodic intrusions of tropical moisture into the region. These intrusions occur when the Southwest Monsoon circulation, which typically brings more significant summertime precipitation to Arizona than to California, shifts westward (Tubbs 1972), or when surges of moisture move up the Gulf of California and into the southeast desert regions of California itself (Hales 1972, 1974).

In this region, then, 76.9% (20 out of 26) of the tornadoes occurred during the period June–September, with September being the single month with the greatest number of tornadoes (7, or 26.9% of the total). The distribution of tornado days is virtually identical to that for the tornadoes themselves; we show only a single day on which more than one tornado occurred in this region. This may, however, in part reflect the sparse population of this region; additional tornadoes on a given tornado day could well have gone unreported.

The diurnal distribution of tornadoes for this region (Fig. 7b) indicates maximum incidence during the afternoon hours. In fact, 65.4% (17 out of 26) of the tornadoes occurred between 1300 and 1700 PST, which indicates that the period of maximum incidence occurs just past the time of greatest surface heating. Our database contains no tornado reports for the period of time between 2200 and 0900 PST.

d. Climatological analyses of tornadoes in the Central Valley

In the Central Valley, the tornadic incidence in the months of March and April greatly exceeds that during the rest of the year (Fig. 8a). During this 2-month period, 59.4% (41 out of 69) of the tornadoes occurred, while during the 6-month interval December–May, 89.9% (62 out of 69) of the tornadoes occurred. The annual distribution of tornado days is very similar to the annual distribution of tornadoes.

As in the coastal regions of California, virtually all of the precipitation in the Central Valley occurs in the cool season. The period of maximum precipitation, however, is earlier in the season than the time of maximum tornadic incidence. Tornadic activity increases dramatically in the late winter and early spring, yet by this time the storm track has typically begun to shift northward with the region therefore receiving diminishing precipitation. This delay in peak tornadic activity would seem to indicate that low-level diurnal heating contributes significantly to producing conditions conducive to tornado formation. Although diurnal heating continues to increase as the spring season progresses, the decline in tornadic activity after April is consistent with the lack of precipitation received after this time, as the storm track has by then shifted too far northward.

![Graph showing tornado occurrences by month in the Central Valley.](image-url)
to bring significant cyclonic activity into this region of California.

Of the 69 tornadoes in our database for this region, 48 have been assigned F-scale values by Grazulis (1991), *Storm Data*, or the NSSFC tornado log. Of these, 10 were of F2 intensity. Five of the F2 tornadoes occurred during the month of April and 2 occurred during March. Although the F2 tornadoes in the south-coastal region all occurred within a small subsection of this region, those in the Central Valley occurred at disparate locations. Three of these tornadoes occurred in the northern portion of the Sacramento Valley, 1 occurred in the southern part of the Sacramento Valley, 2 occurred in the northern portion of the San Joaquin Valley, and 4 occurred in the central San Joaquin Valley.

The spatial distribution of the Central Valley tornadoes (Fig. 1) contains some interesting features. As mentioned above, there is a noticeable absence of tornadoes in the southern portion of the San Joaquin Valley, even though this region is significantly populated, and thus, is an area where any tornadoic events that did occur would likely be reported. Although definitive interpretation will await thorough analysis of the meteorological conditions associated with Central Valley tornadoes, two plausible limiting factors on the occurrence of tornadoes in this area are apparent. First, the southern end of the valley is distant from the primary source region of low-level moist marine air—the San Francisco Bay Area. This air ventilates into the valley largely through the break in the Coast Range in the northeastern Bay Area. The southern end of the San Joaquin Valley is farther from this source of marine air than any other part of the Central Valley, and thus may be too far away for the marine air to penetrate except on rare occasions. Second, the southern end of the San Joaquin Valley is comparatively narrow and it is surrounded by high mountains. Thus under otherwise favorable meteorological conditions, orographically induced subsidence in this area may preclude tornadoic development.

Also apparent is the lack of tornado reports from the west sides of both the Sacramento Valley and the San Joaquin Valley, and the approximately linear orientation of the reports along the east side of the San Joaquin Valley. The latter appears to be at least in part a consequence of population distribution; most of the significant population centers in the San Joaquin Valley are aligned with California State Highway 99; this route (not shown) is practically traced out by the tornado reports. The relative lack of tornado reports from the west sides of the valleys is a bit more ambiguous. Although this is a more lightly populated part of the Central Valley, there is a significant interstate highway (Interstate 5) that goes along the west side of the San Joaquin Valley, and thus, significant traffic goes through this area. Also, as marine air ventilates into the Central Valley from the San Francisco Bay Area, it tends to first travel across the valley towards the Sierra Nevada, and then due to the barrier effect of these mountains it flows to the north and south along the east sides of the valleys, thus perhaps diminishing the actual frequency of occurrence of tornadoes along the west sides of the valleys. In addition, if there is flow aloft with a westerly component, then there may be some subsidence induced to the lee of the coastal mountains, which would also diminish the probability of tornadoes occurring there.

The diurnal distribution of Central Valley tornadoes (Fig. 8b) appears qualitatively quite similar to that for the southeast desert region (Fig. 7b). Here again, the distribution is unimodal, with a peak incidence at close to the typical time at which the maximum temperature would be observed. Thus the diurnal cycle in tornadoes appears to approximately follow the diurnal cycle in instability. Of the 64 tornadoes for which time of occurrence could be ascertained with an uncertainty of not more than 75 min, only four occurred between the hours of 1900 and 1000 PST.

e. Climatological analyses of tornadoes in the north-central coastal region

Analysis of the annual distribution of tornadoes for the north-central coastal region (Fig. 9a) shows that 29 of the 31 tornadoes occurred during the period December—April, with a maximum incidence in the month of February. It is interesting to note that peak tornadoic incidence for the north-central coastal region occurs earlier in the wet season than that for the Central Valley, even though the median latitudes of the tornadoes in each of these two regions are similar. The implication, then, is that diurnal heating plays less of a role, on average, in the north-central coastal cases than the Central Valley cases.

It is also instructive to compare the annual distribution for the north-central coastal region with that for the south-coastal region (Fig. 6a). The most striking difference between the distributions for the two regions is the much larger occurrence in November (i.e., earlier in the wet season) in the south-coastal region than in the north-central coastal region. Intuitively, one might well expect just the opposite, as the wet season starts earlier along the coast as one progresses to the north. It would thus seem reasonable to presume that the secondary peak in incidence (and primary peak in incidence of tornadoes of greater than F2 intensity) that appears in the month of November in the south-coastal region is a consequence of the topography of the area. It may be that the occasional lingering presence of warm sea surface temperatures from summer until well into fall in the vicinity of the southern California coast contributes to the potential for positive buoyancy of the atmosphere. In examining the comma cloud associated with the occurrence of 7 tornadoes in the Los Angeles Basin on 9 November 1982, Reed and Blier
4. Summary and discussion

Certain subregions of California have been found to experience tornadic activity that significantly exceeds the statewide average. In descending order of tornadic incidence per area per time, these are the south-coastal region, the Central Valley, the north-central coastal region, and the southeast desert region. The south-coastal region, in particular, experiences a remarkably high incidence of tornadoes. In the subsection of this region with the greatest incidence of tornadoes, the number of tornadoes per area per time is comparable to the statewide average value for Oklahoma. Although most of these tornadoes are of less than F2 intensity, their occurrence over a heavily populated and highly urbanized area makes them a legitimate concern.

Significant differences were found when annual distributions of tornadoes for the state of California as a whole were compared with those for the individual regions of enhanced incidence. On the statewide scale, approximately 80% of the tornadoes occurred during the period November–April, with more tornadoes having occurred during March than any other month. With the exception of the southeast deserts, the individual subregions of the state also experienced maximum tornadic activity during the cool season, but the distributions within the cool season varied. In the south-coastal region, in excess of 80% of the tornadoes occurred during the period November–March, with March being the single month with the greatest number of tornadoes. In the Central Valley, almost 60% of the tornadoes occurred during the 2-month period March–April, while almost 90% occurred during the period December–May. This region also received more tornadoes of greater than F1 intensity than any of the other subregions. Eight out of the 10 such tornadoes thus far documented in the Central Valley occurred during the 3-month period March–May. In the north-central coastal region, approximately 94% of the tornadoes occurred during the period December–April, with February being the single month with the greatest number of tornadoes. Unlike the south-coastal region, which has experienced significant tornadic activity—and 5 of its 7 F2 tornadoes—in the month of November, the north-central coastal region has only had 1 tornado during this month. The southeast desert area, in marked contrast to the rest of the state, received most of its tornadoes during the summer months. Over 75% of the tornadoes occurred during the period June–September, with September being the single month with the greatest number of tornadoes.

The diurnal distribution of tornadoes for the state as a whole shows maximum incidence during the afternoon hours. This is also true of the individual subregions of the state with enhanced tornadic activity, but secondary aspects of the distributions varied. In both the Central Valley and the southeast deserts, very few tornadoes occurred at times other than during the af-
ternoon hours. For the former, approximately 81% of the tornadoes occurred during the afternoon hours, while for the latter, 73% of the tornadoes occurred during the afternoon hours. No tornadoes have yet been observed in the southeast deserts during either the late-night hours or the first part of the morning, and only approximately 5% of the tornadoes in the Central Valley have occurred at these times. In contrast, the two coastal regions of enhanced incidence have more complex diurnal distributions. In both, the overall distributions are broader, and both show a secondary peak in incidence in the predawn hours of the morning. In fact, 34 of the 40 tornadoes that have been documented in California between 0000 and 0900 PST have occurred in these two regions.

The preceding findings on the incidence of tornadoes in California indicate the importance for future research on several topics. First, there needs to be further study of the underlying causes of the significant variations in tornadoic activity documented in the present investigation. Second, study is needed of the meteorological conditions associated with tornadoes. And finally, investigation is required of the dynamical mechanism(s) through which these tornadoes form.

Related to the first of these topics is the question of how accurately the geographic distributions of tornadoes presented in Figs. 1 and 4 represent the true tornadoic incidence. With the exception of the southeastern desert region, the areas of enhanced tornadoic incidence are also those that are more densely populated. In support of the veracity of the present findings, though, is the fact that tornadoic events have not been reported from all of the more heavily populated areas of the state. Virtually no tornadoic activity has been observed in the far southern portion of the San Joaquin Valley, for example, despite significant inhabitance of portions of this region (e.g., the area around Bakersfield) throughout the period of this study. Similarly, few or no tornadoes were reported in the central Sacramento Valley, the southern California coast and coastal valleys to the northwest of the Los Angeles Basin, and the Imperial Valley in the low deserts of southern California, despite the presence of a significant population in each of these areas.

Also, most of the areas of the state that are more sparsely inhabited are also mountainous, and there is reason to believe that mountainous regions do not in general have the tornadoic incidence of less-mountainous areas due to the increased surface roughness of such environments; this may be particularly true of the comparatively weak tornadoes that predominate in California. Dessens (1972) found from a laboratory study that increased surface roughness tends to have a damping effect on vortex formation. Support for the true representativeness of the documented relative infrequency of tornadoes in the mountainous regions of California is provided, for example, by the absence of tornado reports from the area of Lake Tahoe where there is a sizable population over a significant area, as well as by the lack of reports from the well-populated parts of the foothills of the Sierra Nevada and the more significant hills and mountains of the south-coastal area. Reduced tornadoic activity in areas of California characterized by rougher terrain is consistent with the documented relative minima in tornadoic activity in the Flint Hills region of eastern Kansas and over the Ozark Plateau (Kelly et al. 1978). Finally, although detailed analyses of the synoptic weather situations associated with the occurrence of tornadoes in California are still in progress, it seems quite reasonable to presume that the areas most prone to developing the low-level instability typically associated with tornadoic development will be those with ready access to comparatively moist and mild lower-tropospheric air. These will be the coastal areas of the state—and the interior valleys to which maritime air has relatively easy access—during the winter, and the southeast desert regions—which at times in the warm season receive moist and unstable air from the Gulf of California—during the summer.

Little work has thus far been done to address the questions concerning the meteorological conditions associated with tornadoes in California and the dynamical mechanisms responsible for their formation. The complexity of the climatology of California tornadoes indicates the likelihood of occurrence in association with diverse meteorological conditions. Such variation is, in fact, indicated by the few case studies that have so far been performed.

Some California tornadoes appear to form in an environment characterized by small convective available potential energy but strong vertical wind shear in the lower troposphere. A study by Hart et al. (1985) of the 1 March 1983 F2 tornado in Los Angeles indicated occurrence in association with cloud tops of less than 5500 m and strong vertical wind shear, and within a significant mesoscale cloud band that appeared similar to the comma clouds studied by Reed and Blier (1986a, b). The Los Angeles Basin tornado outbreak of 9 November 1982, which included a total of 7 tornadoes, 2 of which were rated F2 in intensity, also occurred in association with a comma cloud. Here again there was evidence of strong directional and speed shear in the lower troposphere (Reed and Blier 1986b). In both of these cases, however, the surface lifted index (LSI) indicated less instability than would commonly be expected in association with an F2 tornado. Using San Diego sounding information (the closest available sounding), Hales (1985) calculated an LSI of 0 for the March case and −4 for the November case. Blier and Batten (1993) analyzed an outbreak of three F1 tornadoes that occurred in the northern part of the San Francisco Bay region on 2 December 1992. They found that this tornadoic event also occurred in association with weak vertical instability but strong lower-tropospheric vertical wind shear. Interestingly, rather similar conditions appear to be found with tornadoes occurring
in association with landfalling hurricanes (McCaul 1991). In examining three tornado episodes in California that occurred in December 1992 in low buoyancy–moderate shear environments. Monteverdi and Quadros (1994) showed that associated values of 0–2-km storm-relative helicity were large enough to be consistent with rotating updrafts and mesocyclones, despite the fact that bulk Richardson numbers were very low.

Other California tornados occurred in conjunction with very different meteorological conditions. Bluestein (1979), for example, found that a small tornado that occurred in the Owens Valley in the southeast interior of the state was associated with weak synoptic-scale forcing and weak vertical wind shear, and with an environmental thermodynamic structure similar to the “inverted-V” (Beebe 1955) or type IV (Miller 1972) tornado sounding found during the summer months in the western plains. In contrast, the F2 tornado in the northern Sacramento Valley described by Braun and Monteverdi (1991) was associated with significant vertical instability and was clearly supercellular in nature, while the Central Valley tornado of 5 February 1978 investigated by Carbone (1982, 1983) was coincident with an inflectional instability (presumed to initiate through a barotropic instability mechanism) along a sharp surface cold front. Thus, the climatological aspects of California tornados documented in the present investigation represent the amalgamation of individual events that occurred under a wide range of meteorological conditions and that would seem to encompass a similarly wide range of dynamical mechanisms of formation.

5. Concluding remarks

In addition to documenting the spatial and temporal distributions of California tornados, we have demonstrated that their incidence in certain regions of the state is far higher than would commonly be suspected. This is particularly true for part of the south-coastal region of California and, to a somewhat lesser degree, for portions of the Central Valley. The tornadic incidence of the former is comparable to that of regions in the heart of the “tornado belt” of the midwestern United States. As the southern California tornados form in an environment that is very different from that of their midwestern counterparts, there is significant scientific motivation to better understand the meteorological conditions in which (and the physical processes through which) they develop.

Additional motivation is provided by the dense inhabitation of south-coastal California. The greatest concentration of tornadic events occurs in the most densely populated parts of Los Angeles and Orange Counties. In terms of the 1 April 1990 population, these two counties ranked first and fifth, respectively, of all counties in the United States (Hoffman 1992). Although the average intensity, size, and longevity of tornados in California appear to be significantly less than corresponding values for tornados to the east of the Continental Divide, any tornado presents a potential potential hazard, especially if it occurs in a highly urbanized area. Documentation found in the present investigation indicates that in numerous prior California tornadic events a slight change in the time or location of the tornado could have led to far more devastating consequences.

Remarkably, there have thus far been no deaths recorded as a consequence of tornados in California. As the population of the state continues to increase, however, so does the attendant risk. In both official and news media accounts of California tornadic events, we have noticed a striking reluctance toward the use of the word “tornado.” And, on those comparatively infrequent occasions when the word is used, it is typically prefaced by an adjective such as “rare.” Whether this is politically motivated or stems from a prevailing disbelief that parts of California can have an appreciable incidence of tornados is unclear. However, the need to better understand these events should be strikingly apparent.

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