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Air Stagnation Climatology for the United States (1948-1998)

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1. Introduction

Due to the steady increase in urbanization over the last several decades, the air pollution problem has become more and more serious, and has attracted national and international attention. It has been observed that major air pollution episodes are usually related to the presence of stagnating anticyclones. Such anticyclones may linger over an area for a protracted period (4 days or more). During this period, surface wind speeds can fall to very low values. The near surface circulation is therefore insufficient to disperse accumulated pollutants, thereby causing distressful and possible hazardous conditions for the inhabitants of the area.

In this atlas, we define the meteorological state which is favorable to an air pollution episode as an air stagnation event. The air stagnation event identifies areas where air may be trapped by poor ventilation due to persistent light or calm winds, and by the presence of inversions. When air stagnation persists in a region, pollution can accumulate resulting in poor air quality.

Our definition for air stagnation events has been adapted from earlier works by Korshover (1960), and Korshover and Angell (1982). In their analysis, Korshover and Angell used the daily weather maps published by the National Weather Service. The present atlas uses the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) reanalysis (Kalnay et al. 1996) archive, which provides spatially and temporally consistent global analyses 4-times daily. A monthly air stagnation event data set is developed over the conterminous United States from 1948 to 1998. Detailed descriptions of circulation and rainfall data sets used, and analysis procedures, are found in section 2. In sections 3-5, monthly, annual, interannual, and trend characteristics of the air stagnation events are analyzed over the United States.

2. Data and Method

Atmospheric circulation variables used in this study are daily mean sea level pressure, daily 500 mb wind speed, and daily temperature inversion within the planetary boundary layer (below 850 mb level). These data are taken from 51 years of the NCEP/NCAR reanalysis/CDAS system (Kalnay et al. 1996). Daily gridded precipitation over the United States is provided by the Climate Prediction Center of the National Weather Service, as generated from original hourly station measurements (Higgins et al. 1996).

Following Korshover and Angell (1982), a horizontal pressure gradient technique is employed to determine the occurrence of air stagnation in the conterminous United States. Such a procedure is desirable because the sea level pressure gradient gives a more representative picture of the general flow pattern near the surface of the earth than does the surface wind analysis, which is influenced by complex conditions at the earth s surface and is essentially generated from numerical models of the boundary layer physics.

The method used herein to define conditions of air stagnation is completely objective, as compared to the partially subjective one used by Korshover and Angell (1982). The method involves delineating air stagnation conditions where, for at least 4 days, the sea level geostrophic wind speed is less that 8 m s^{-1}. In general, this would correspond to surface (anemometer level) wind speeds less than about 4 m s^{-1} (Brunt, 1941; Godske et al. 1957). In this study, we have checked that the ratio of wind speed between the sea level geostrophic wind and the wind at 10 m level above the ground is around 2.5 on average and is not geographically dependent. That is, an 8 m s^{-1} sea level geostrophic wind approximately corresponds to a 3.2 m s^{-1} wind at 10 m level, which is consistent with the results from previous studies.

The choice of 4 days duration and about 4 m s^{-1} wind speed is based on historical studies of the Donora, Pennsylvania smog disaster of 1948 (Fletcher, 1949; Willett, 1949; Hewson, 1951). The above criterion was relaxed by 10 percent if an inversion existed in the boundary layer ($dT/dz > 0$ below 850 mb). Air stagnation conditions so obtained were eliminated if there was precipitation (even a trace), or the wind speed at 500 mb exceeded 13 m s^{-1}. The latter wind speed criterion tended to limit the stagnation conditions to those with high pressure ridges at 500 mb. Generally, only warm core high pressure systems meet the criteria for air stagnation conditions, since cold highs do not persist long enough.

Once the criteria for defining air stagnation are determined, meteorological conditions are checked at each grid point on a 2.5º x 2.5º resolution over the United States. Every day each grid point will fall into either a stagnation day or non-stagnation day. The next procedure is to count whether there are 4 consecutive days or more of air stagnation conditions at each grid point. If so, those days are accumulated in each month at each grid point and are counted as an air stagnation case. Thus, if at a given grid point there were two stagnation cases during a given month, one of 4 days duration and one of 8 days duration, the total number of stagnation days during the month would be 12 at that grid point. These values of accumulated air stagnation days and cases for the month form the basic data base for the rest of the computations and discussions.

3. Annual Variations and Mean

In an annual mean sense, air stagnation events are most prevalent in the southern states (Fig. 1). The maximum occurrences of both air stagnation days (top panel) and cases (bottom panel) are in California, Nevada, Arizona, New Mexico, and Texas. There is a relative maximum in the central Gulf Coast states from Louisiana, Mississippi and part of Tennessee, to Alabama, Georgia and part of Florida.

The strongest center in Fig. 1 is near the border of California, Arizona, and Mexico, where the annual number of stagnation days and cases is around 80 and 12, respectively. These numbers mean that air stagnation conditions exist more than 20 percent of the time (top panel of Fig. 2). Another area where air stagnation occurs more than 10 percent of the time is in southern Texas close to the Mexican border. In the central Gulf Coast states, air stagnation conditions exist 5-10 percent of the time.

On average, an air stagnation case lasts about 5 days in the majority of areas (bottom panel of Fig. 2). The longest duration of air stagnation conditions occurs in southern California, the southern tip of Nevada around Las Vegas, western Arizona, and southwestern Texas.

From Figs. 1 and 2, it appears that air stagnation tends to occur in three separate zones, i.e., a western zone (125°W-110°W) including California, Nevada, and Arizona, a central zone (110°W-92°W) covering New Mexico and Texas, and an eastern zone (92°W-68°W) from Louisiana to Florida. Figure 3 shows the seasonal cycles of monthly mean air stagnation days and cases averaged over the west, central, and east zones of the U.S., as well as for the entire United States. It is clear that the largest amplitude is found in the west, and gradually decreases eastward, demonstrating the greater number of air stagnation days and cases in the west than in the east on average.

Most air stagnation events happen in an extended summer season from May to October (Fig. 3). This is the result of the weaker pressure and temperature gradients, and therefore weaker wind circulations during this period. In the eastern U.S. (the third panel from left, Fig. 3), there is a relative minimum of stagnation in July accompanied by relative maxima in May-June and August-October. The same feature was also found in the earlier study by Korshover (1976). This mid-summer decrease of air stagnation is due to the impact of the Bermuda high pressure system on the eastern United States. The Bermuda high is strongest in July, and hence the meridional wind in the Gulf states is a maximum then due to the increased pressure gradient, resulting in a relative minimum of air stagnation. Therefore, the Bermuda high is an additional and unique controlling factor for air stagnation conditions over the eastern United States, besides the seasonal cycle of minimum wind in summer and maximum wind in winter. Another unique feature of air stagnation in the eastern U.S. is its early onset in May (third panel from left, Fig. 3), compared to the onset in June in the west and central U.S. This results in a prolonged, but weaker air stagnation season in the eastern U.S.

The geographic distribution of the annual cycle of air stagnation days and cases is shown in Figs. 4 and 5 for the months May-October. In May, most of the stagnation occurs in the southwest U.S. and along the Gulf Coast (Figs. 4 and 5). The maximum center in the southwest U.S. expands both longitudinally and latitudinally with time, reaching a maximum of more than 16 days per month of air stagnation in July-August over southern California from the San Joaquin Valley to the Mexican border. The area of 4 days per month (one stagnation case per month) covers most of the west coast states in July-August. At the same time, from southeastern New Mexico to southern Texas there are more than 10 days per month of air stagnation with the maximum about 15 days close to the Mexican border. In the eastern part of the U.S., the maximum number of air stagnation days (August-October in Fig. 4) is less than 6 days per month (about one case per month). After August, the number of air stagnation days or cases per month decreases, quickly in the west and central U.S., and relatively slowly in the eastern U.S.

Figure 6 shows the root-mean-square (RMS) of stagnation days for the months May-October, representing a measure of the variability in the mean annual cycle discussed above. The magnitude of the RMS is on the order of 4-5 days in most areas. This indicates that the annual distributions of air stagnation days, as shown in Fig. 4, are more constant (mean is much larger than RMS) in the western and central U.S., and more variable (mean and RMS about the same) in the eastern U.S.

4. Interannual Variability and Trend

From the monthly accumulation of air stagnation days (only those days which satisfy the air stagnation criteria of 4 or more consecutive days are counted), a yearly accumulation is calculated to assess the interannual variability and long-term trend. Shown in Fig. 7 is the long term trend of air stagnation days. The positive trends are in southern California, central-south Arizona, the Pacific Northwest, most of Idaho, the Great Plains states, and south-eastern U.S. The negative trends are located over central California, the Great Nevada Basin, New Mexico, Texas, and the Mississippi River Basin.

Based on Fig. 7, five positive trend regions and five negative trend regions are selected to show their interannual variations, decadal or multi-decadal variabilities, and trends. The positive trend regions are Pacific Northwest (PNW), Southwest (SW) U.S., Great Plains (GP) states, Southeast (SE) U.S., and Florida (FL) (Fig. 8). The negative trend regions are San Joaquin Valley (SJV), Great Nevada Basin (GNB), New Mexico (NM), South Texas (STX), and Mississippi Basin (MB) (Fig. 8).

For the five positive trend regions, the area averaged yearly accumulation of air stagnation days are presented in Fig. 9. Also shown in Fig. 9 are the decadal/multi-decadal components and trends. In several regions, the linear trends are really residuals of a much larger decadal variation. For example, over the Great Plains, the first half of the record shows a large increase in stagnation, while the last half shows a decrease. Similarly, air stagnation over the southwest U.S. increases from the late 1940's to the mid 1960's, and increases again from the mid 1980's, with a decrease in between. The trend over the Southeast U.S. is negligible. The negative trends are generally larger in magnitude (Fig. 10). We have not observed an obvious relationship between air stagnation events in the United States and El Nino/Southern Oscillation (ENSO) episodes in the Pacific.

5. Monthly Features in Extended Summer

From section 4, we have shown that there is a clear geographic dependence of interannual variability in air stagnation days. To further elaborate on this aspect, the annually accumulated stagnation days are plotted for each state in the conterminous United States (Figs. 11-16). As shown previously, southern states generally have more stagnation days, i.e., California, Texas, Nevada, New Mexico, Arizona, Georgia, etc, and northern states have fewer stagnation days, i.e., North and South Dakota, Iowa, Maine, Minnesota, Vermont, etc. For the summer of 1998, the number of stagnation days broke records in three states, Georgia, Oklahoma, and Minnesota, and were exceptionally large in Alabama, Mississippi, South Carolina, Florida, and Tennessee.

Figures 17 to 67 show, in reverse order, the monthly distributions of air stagnation days for 6 summer months from May to October of each year from 1948 to 1998. Areas with heavy shading indicate more than 12 stagnation days per month, and with light shading, 4-12 days. Due to the restriction of 4 consecutive days in the definition of air stagnation, there is no value below 4 days per month in those figures.

6. Caveats and Future Work

There are a few caveats to consider while using the results in this atlas. As we pointed out earlier, the choice of 8 m s^{-1} of sea level geostrophic wind for 4 consecutive days is based on certain historical analyses and may not be optimal. Even though we have checked on the geographic consistency of the geostrophic wind method in defining air stagnation, the criterion for stagnation could still be somewhat different in the mountainous western U.S. The criteria to define an air stagnation case can be refined to be geographically dependent, by expanding the definition of stagnation to a range of wind speeds. In such a definition, not only the number of days of air stagnation but the strength of stagnation can be studied. It may be that the strength of stagnation is more important to an air pollution episode at some locations.

7. Acknowledgments

We wish to thank the many people involved in the reanalysis project for providing the scientific community with a homogeneous data archive suitable for studying climate variability and impact. Thanks also to Dian Gaffen, John Irwin, and K. Shankar Rao for reviewing the atlas and to Betty Wells for final formatting.

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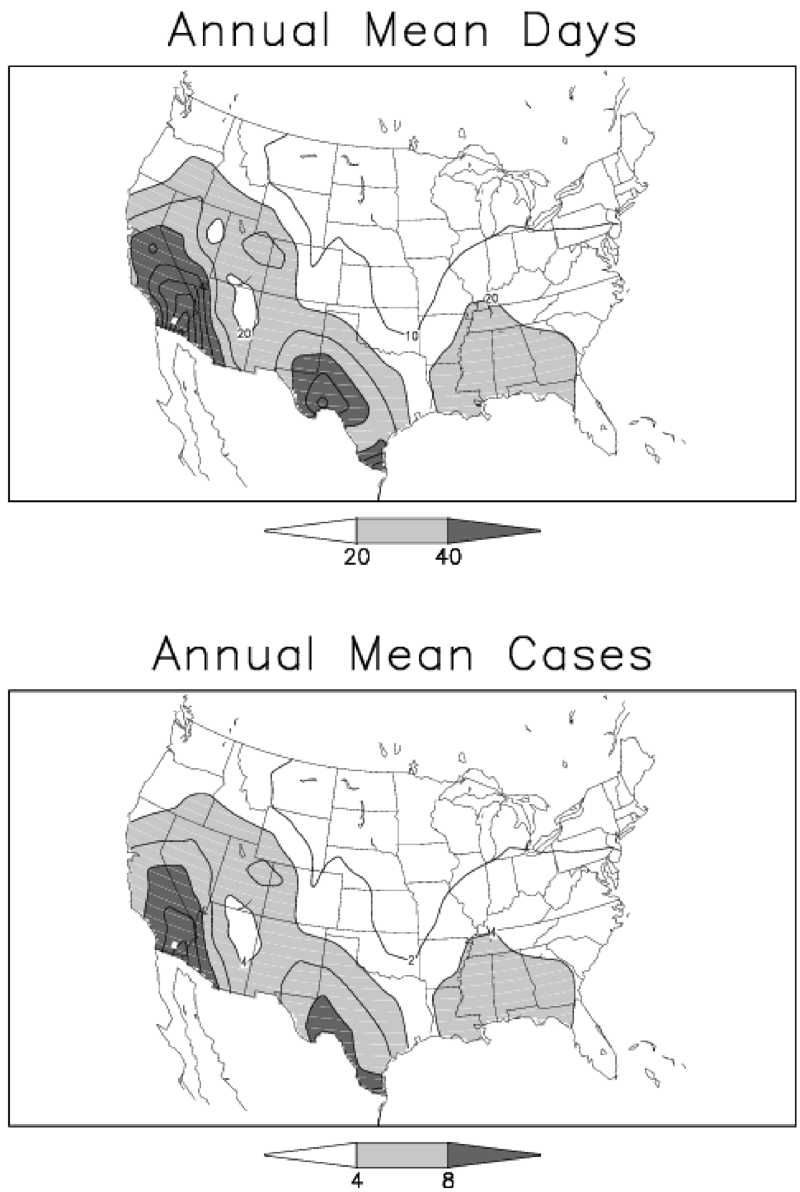


Figure 1, Air stagnation days (top) and cases (bottom) in a year, on average for 1948-1998. Light and dark shading represents regions exceeding 20 and 40 days per year in the top panel, and exceeding 4 and 8 cases per year in the bottom panel. Contour intervals are 10 and 2 for the top and bottom panels, respectively.

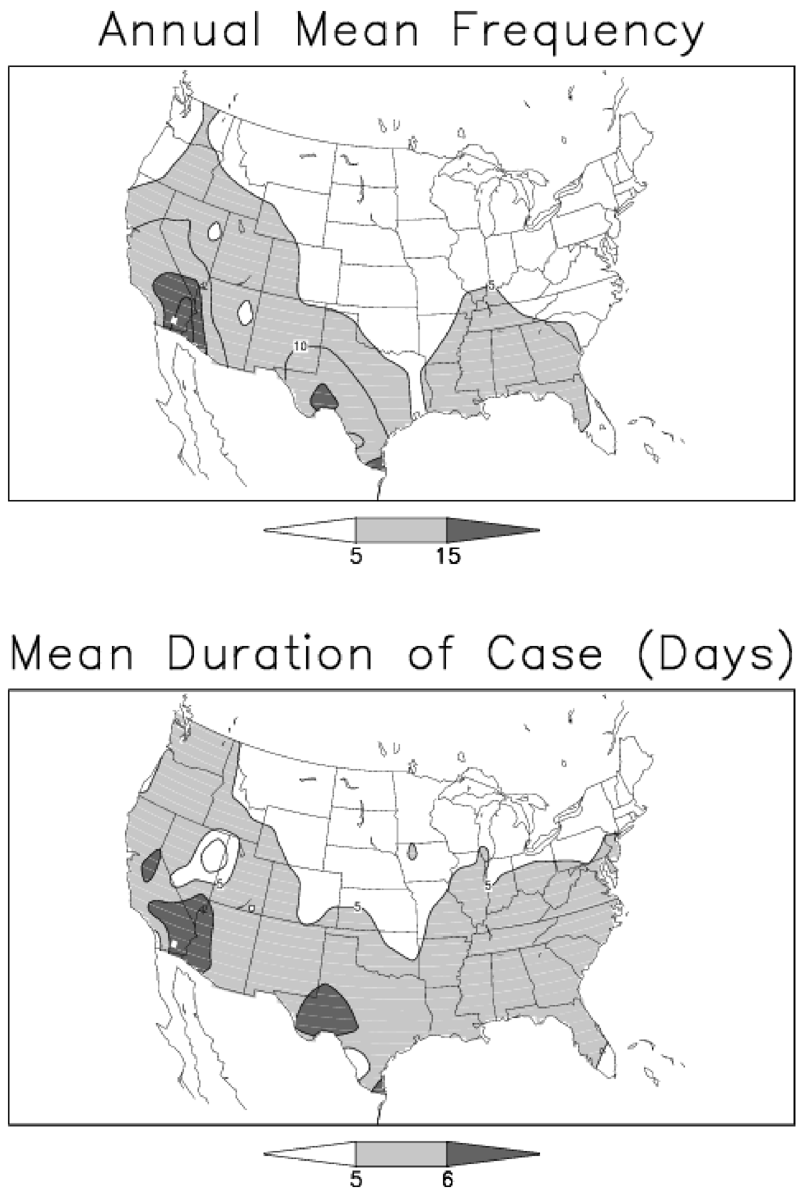


Figure 2. Annual air stagnation frequency (top) and mean duration of stagnation cases in days (bottom). Light and dark shading represents regions exceeding 5 and 15 percent of days per year with air stagnation (top), and exceeding 5 and 6 days per case (bottom). Contour intervals are 5 and 1 for the top and bottom panels, respectively.

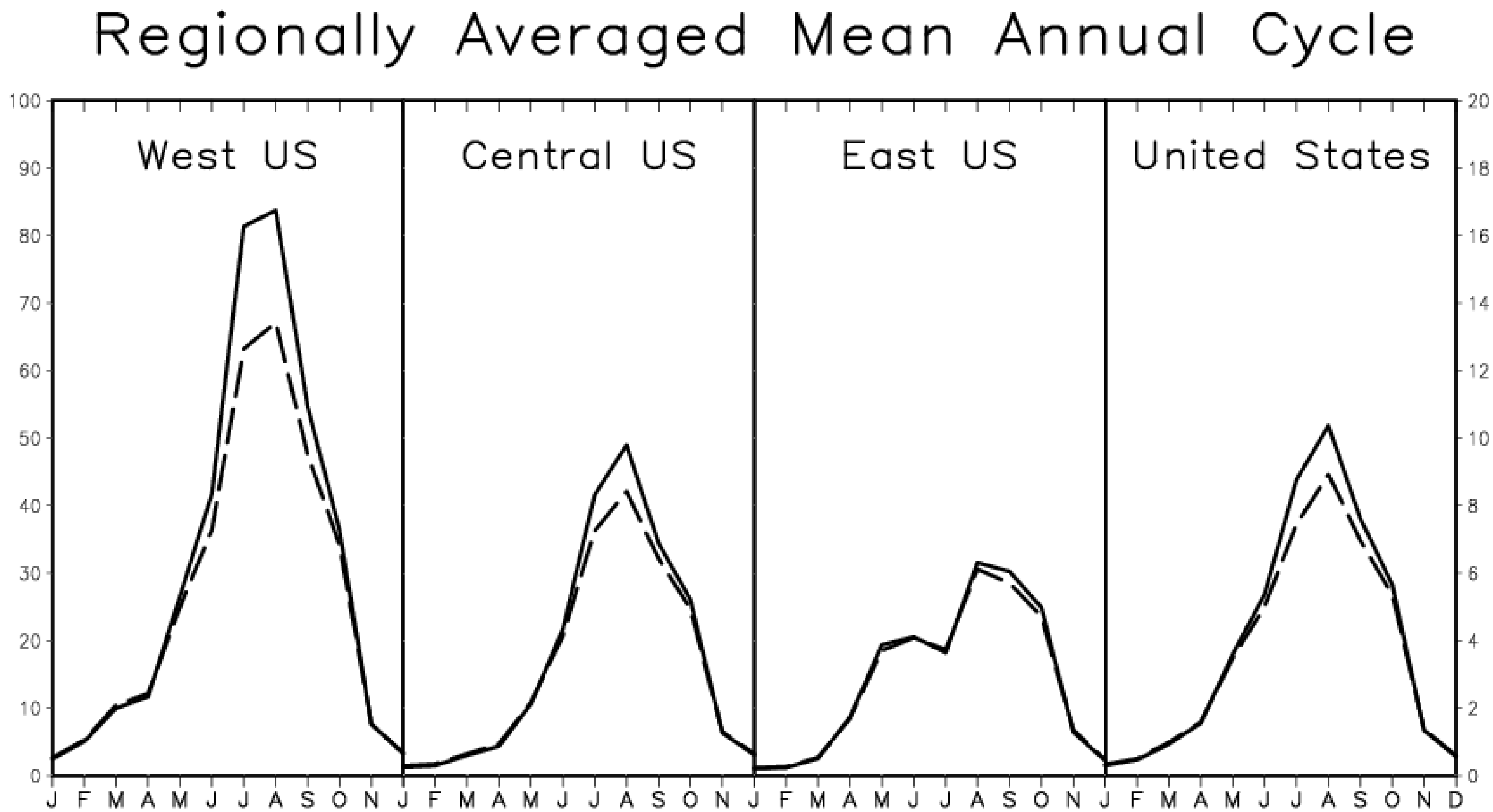


Figure 3. Regionally averaged mean annual cycle of air stagnation days (solid lines) and cases (dashed lines) in the western U.S. (125ºW-110ºW, first panel from left), in the central U.S. (110ºW-93ºW, second panel from left), in the eastern U.S. (92ºW-67ºW, third panel from left), and in the entire United States (fourth panel from left). Left (right) ordinate is for days (cases) per year on average, and the abscissa represents months from January to December.

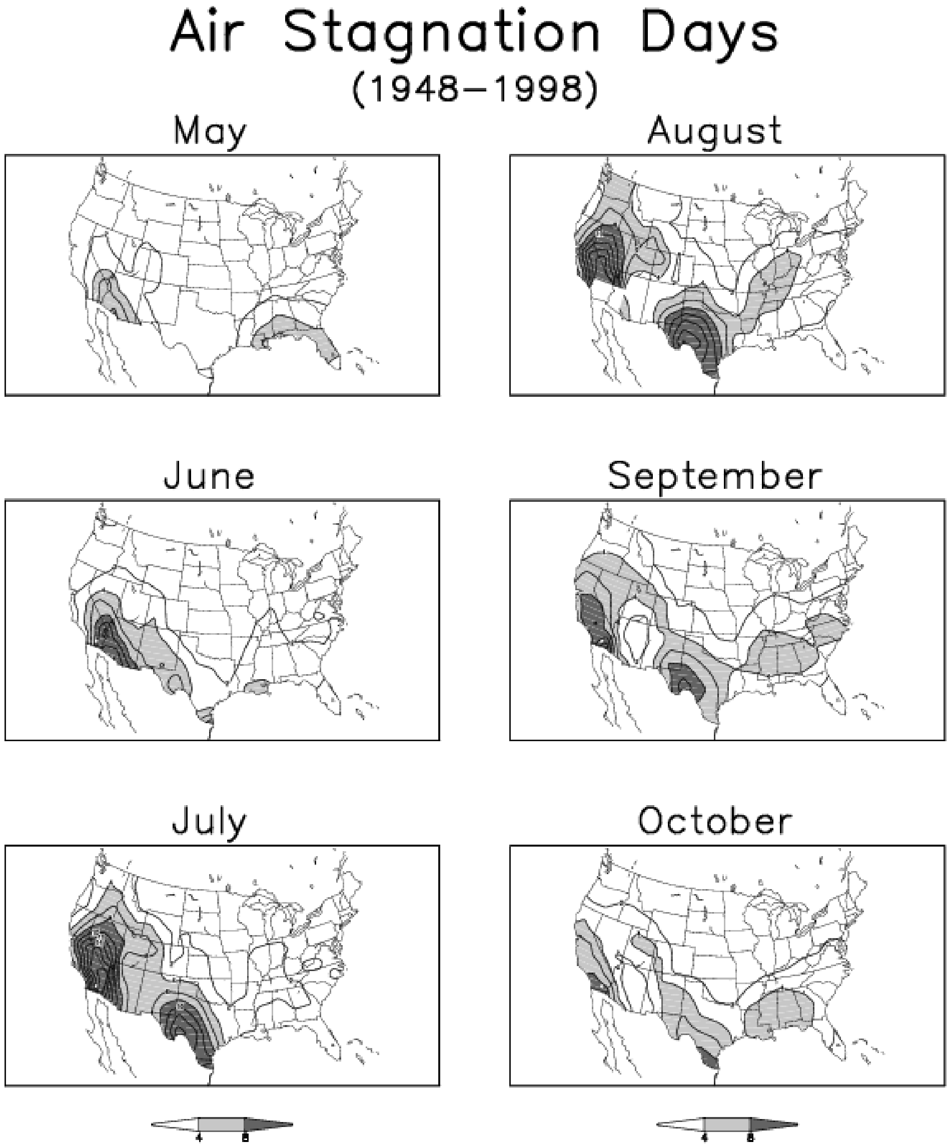


Figure 4. Mean number of stagnation days for the months of May-October, 1948-1998. Light and dark shading represents regions exceeding 4 and 8 days per month. Contour intervals are 2.

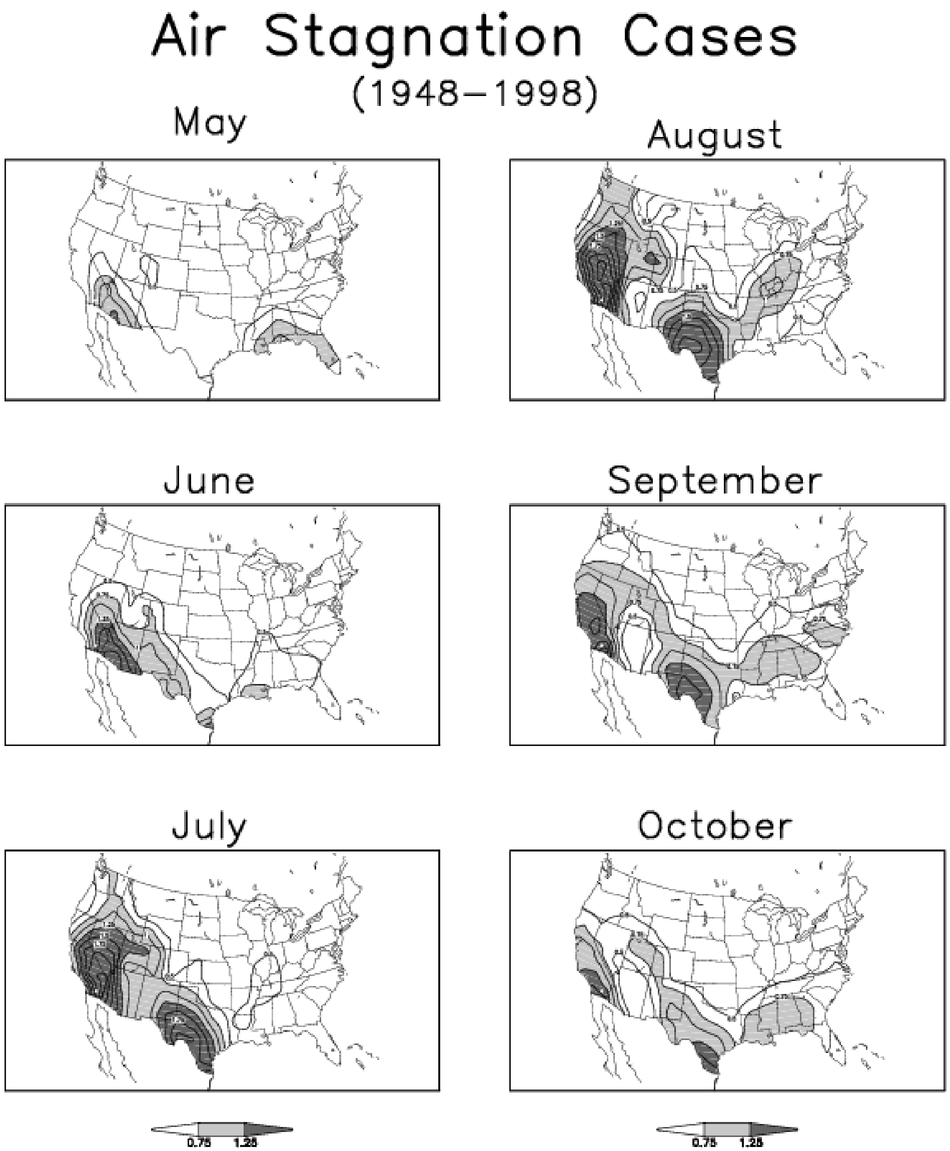


Figure 5. Mean number of stagnation cases for the months of May-October, 1948-1998. Light and dark shading represents regions exceeding 0.75 and 1.25 cases per month. Contour intervals are 0.25.

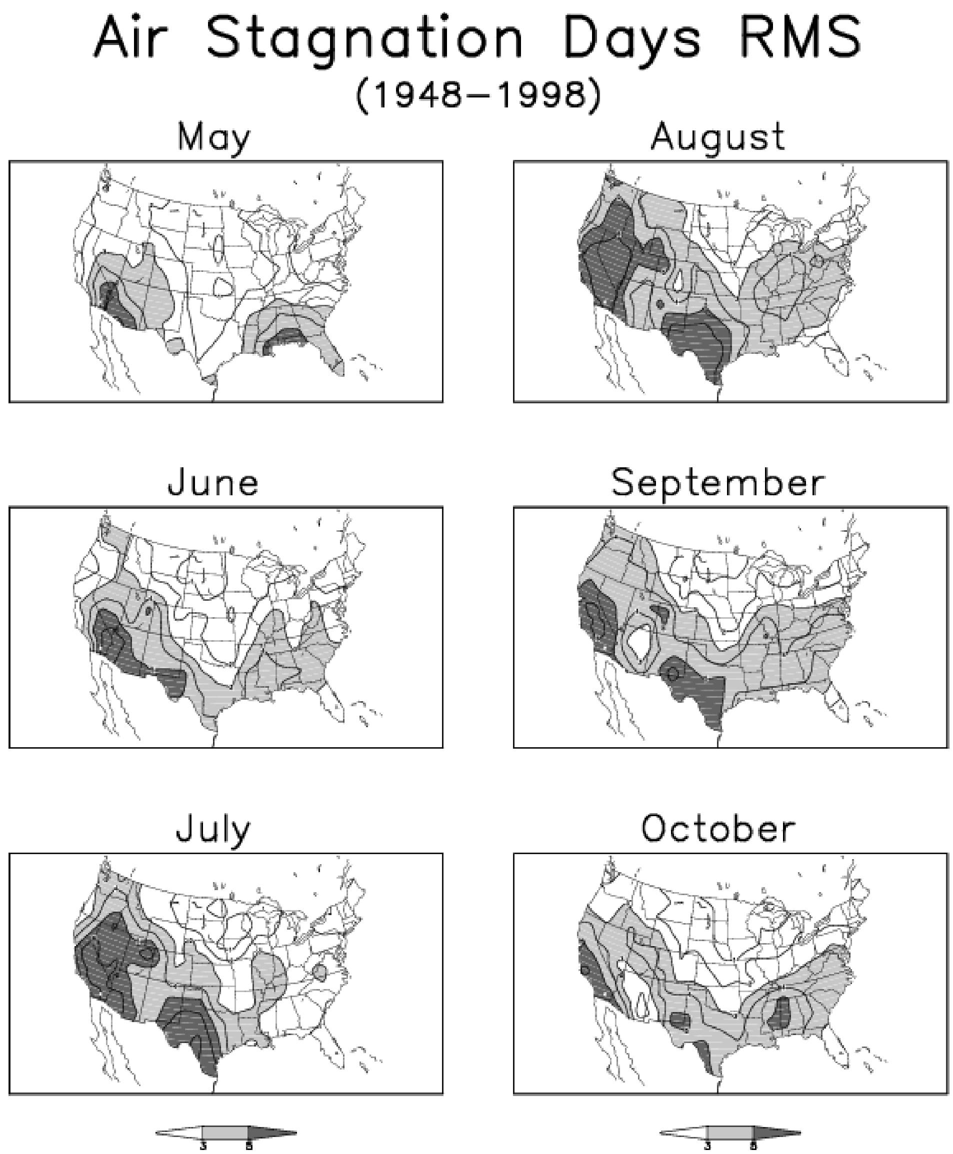


Figure 6. Root-mean-square (RMS) of annual mean stagnation days for the months of May-October. Light and dark shading represents regions exceeding 3 and 5 days per month. Contour intervals are 1.

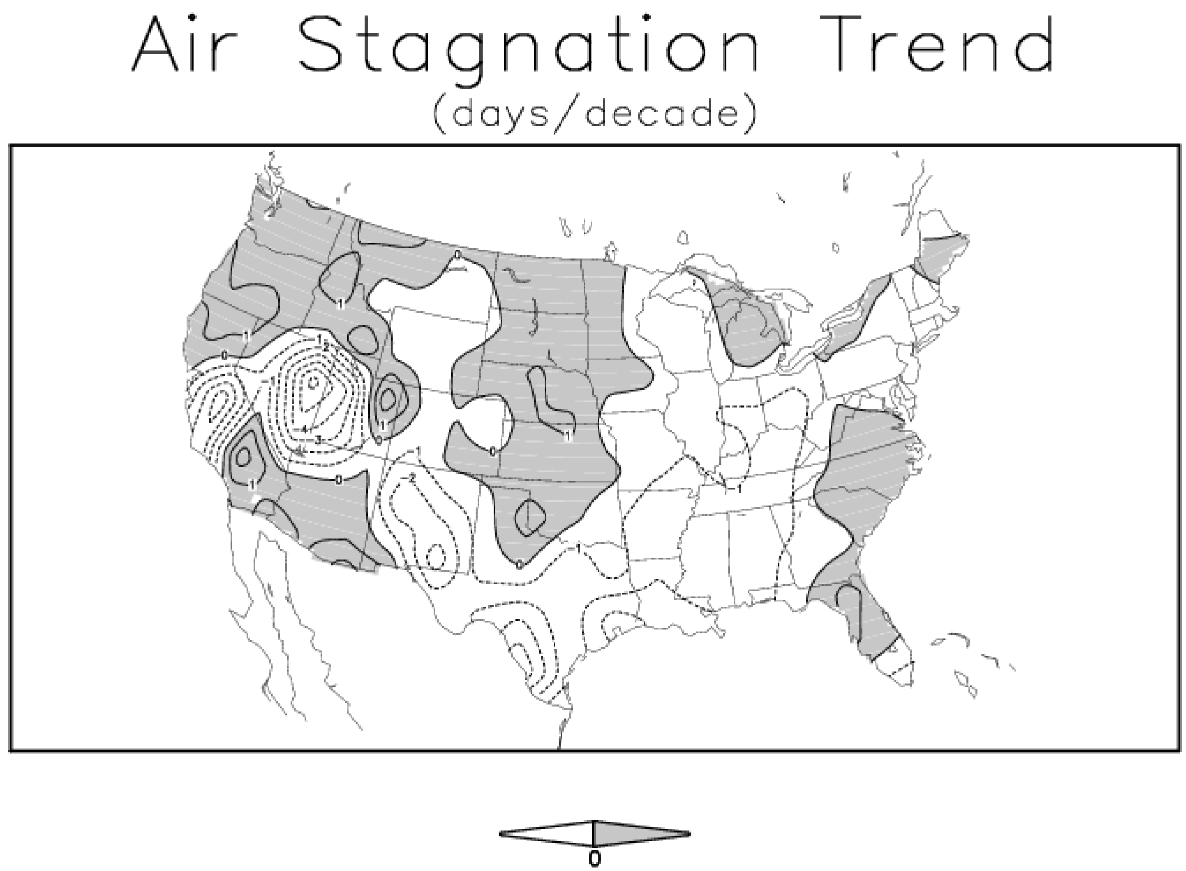


Figure 7, Trend in air stagnation days (unit: days per decade). Shading represents regions with positive trend. Contour intervals are 1.

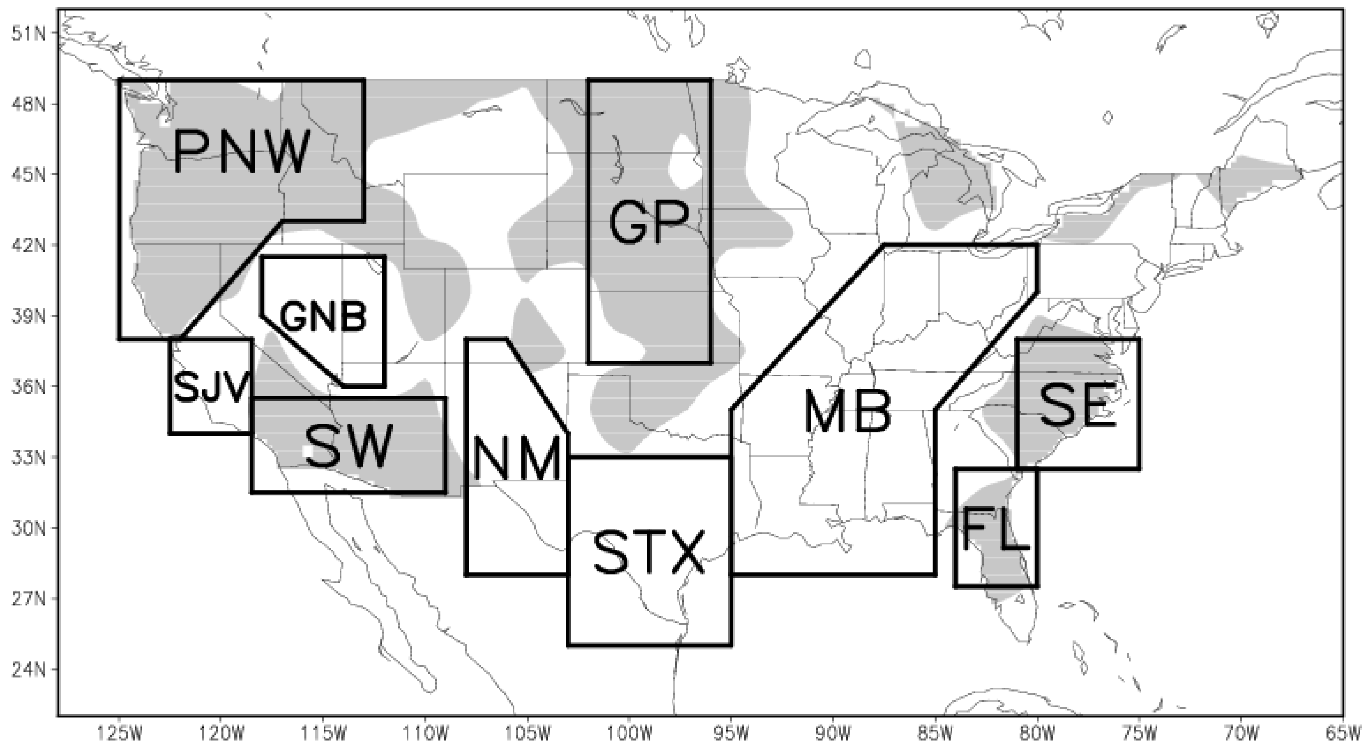


Figure 8, Regions of the United States over which the averages are done in Figures 9 and 10. Shaded areas denote the positive trend.

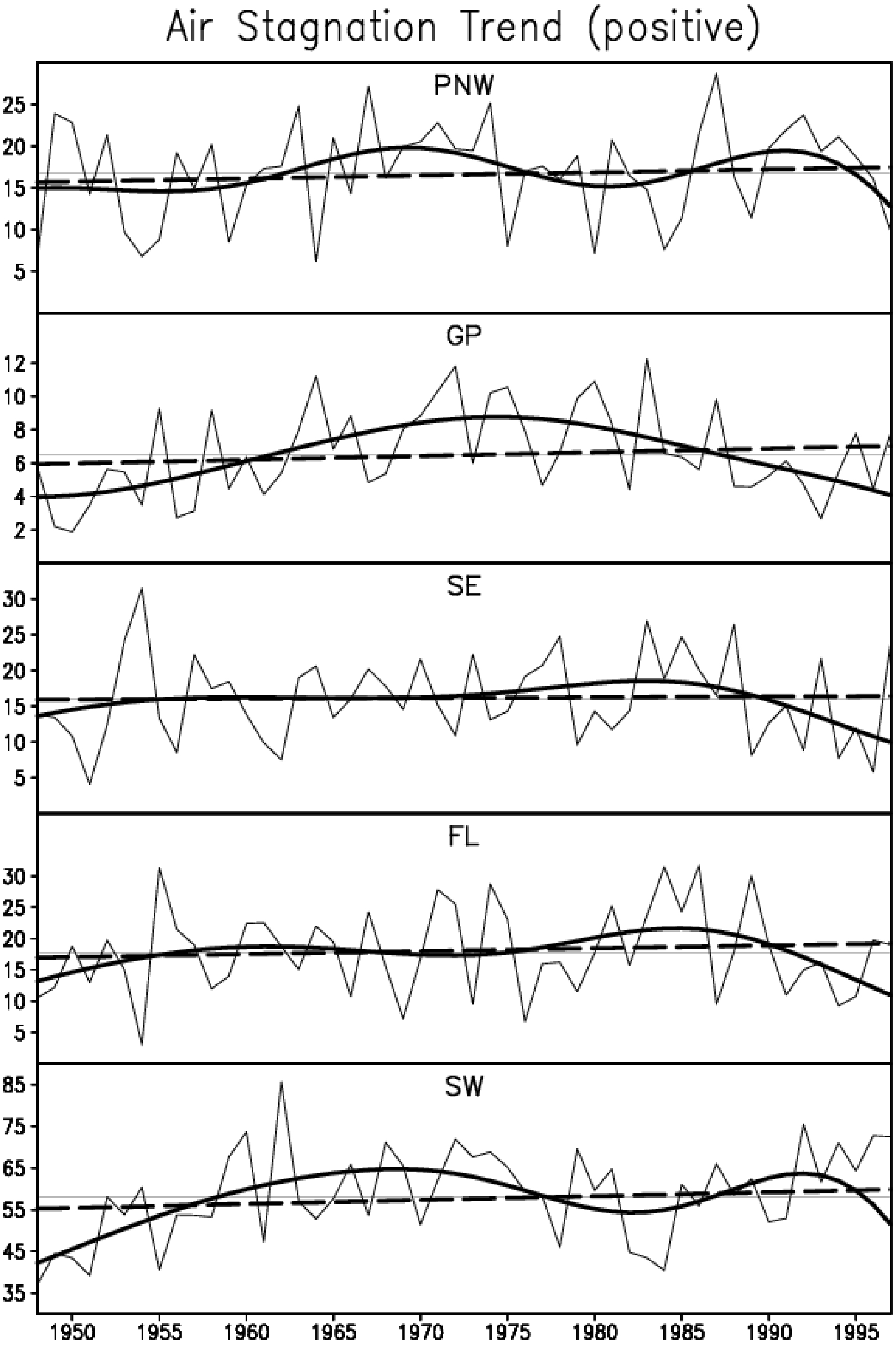


Figure 9, Annual accumulation of air stagnation days for the regions with positive trend. Light solid curve is for the yearly accumulation, smoothed heavy solid curve is for low-frequency component, and heavy dashed line for the trend.

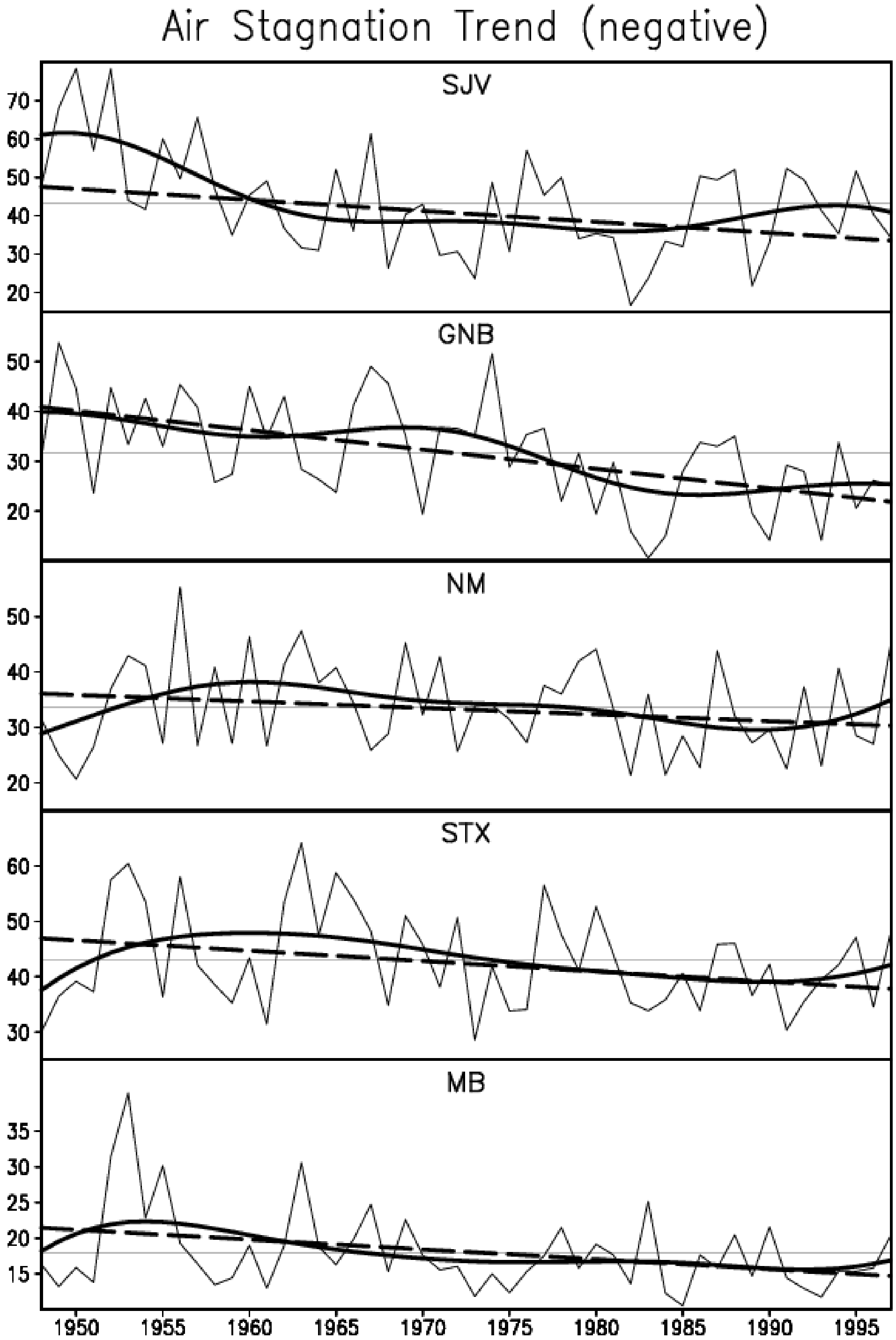


Figure 10, Same as Fig. 9 except for the regions with negative trend.

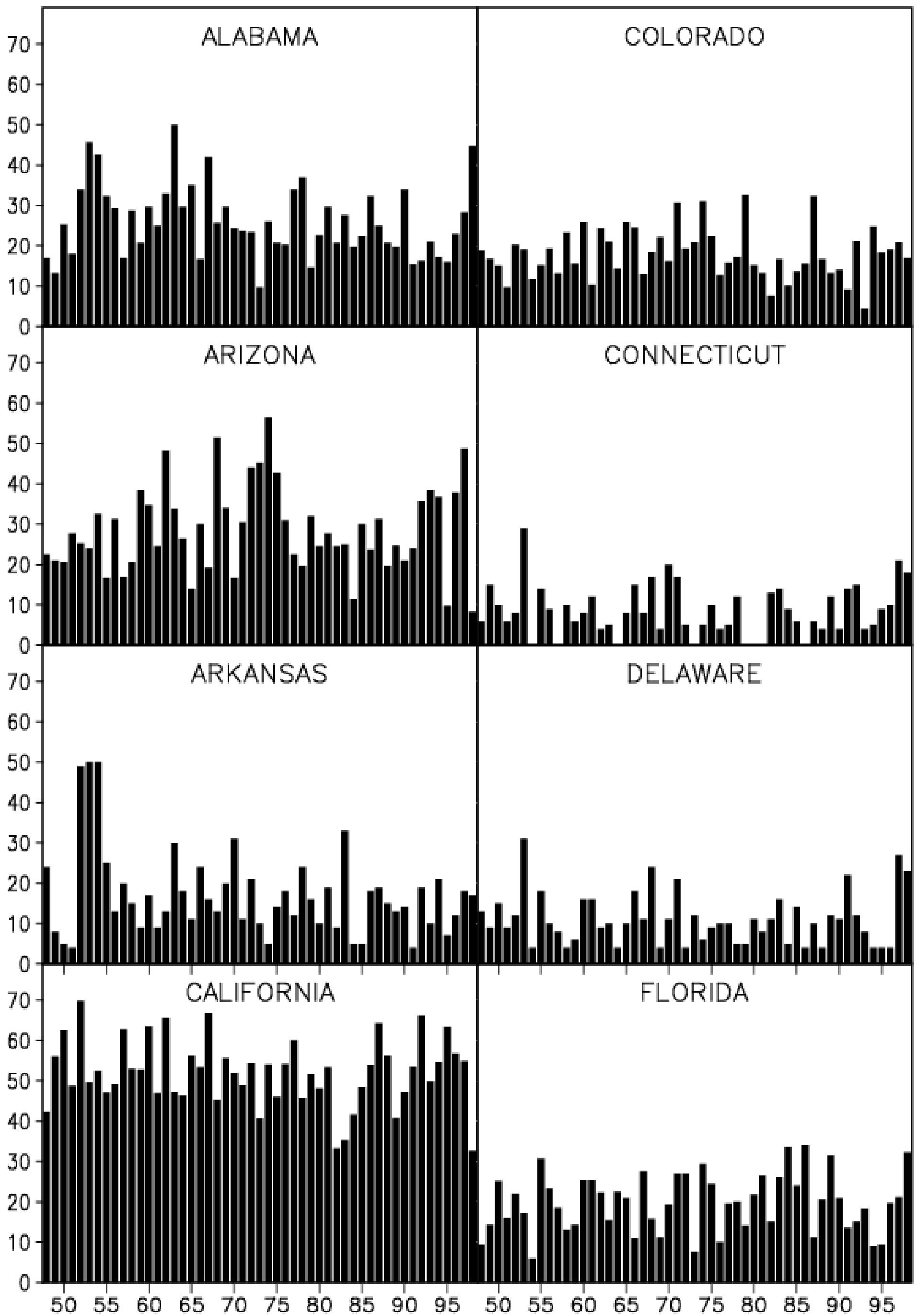


Figure 11, Annually accumulated air stagnation days for the states of Alabama, Arizona, Arkansas, California, Colorado, Connecticut, Delaware, and Florida.

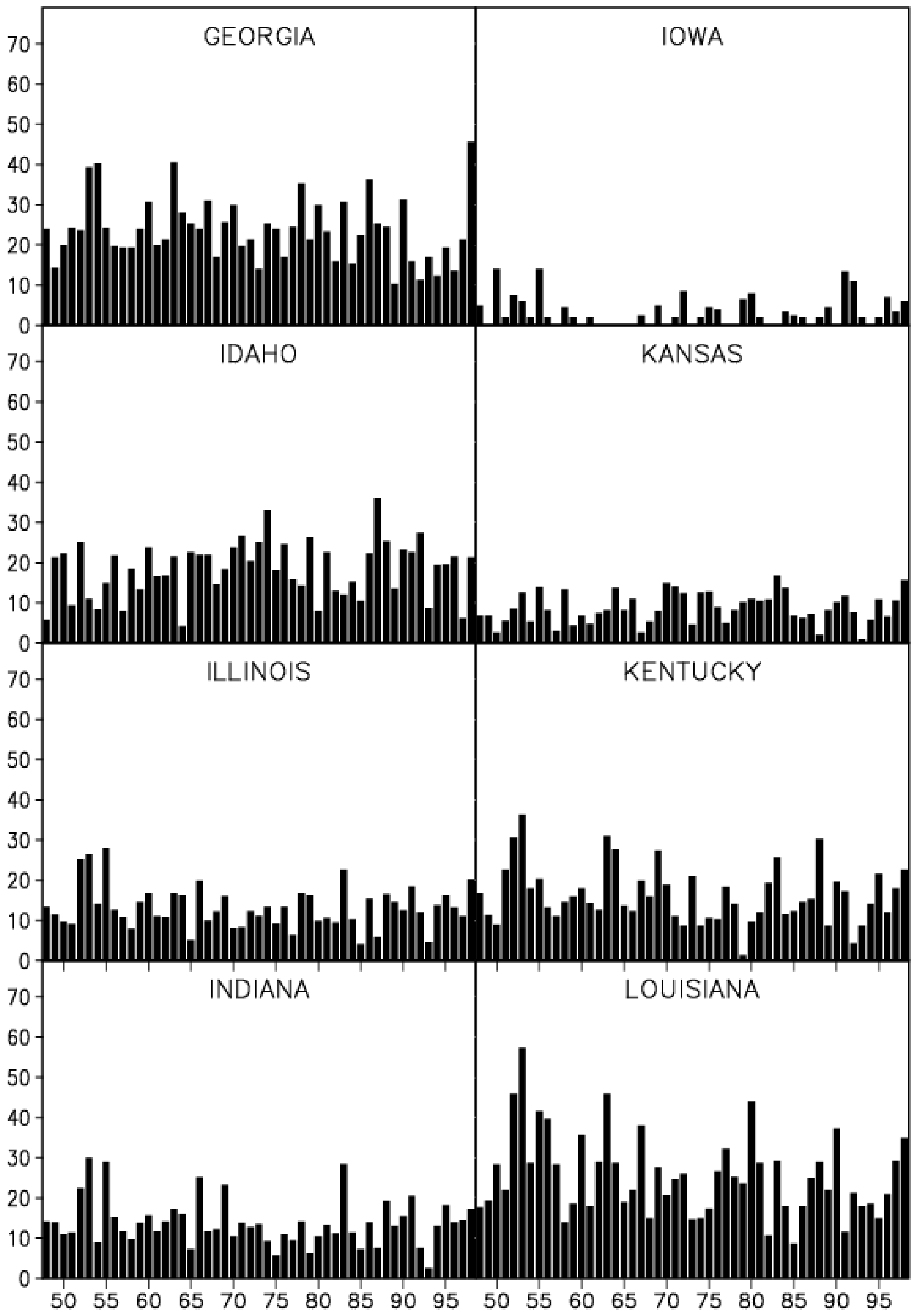


Figure 12, Same as Fig. 11, except for Georgia, Idaho, Illinois, Indiana, Iowa, Kansas, Kentucky, and Louisiana.

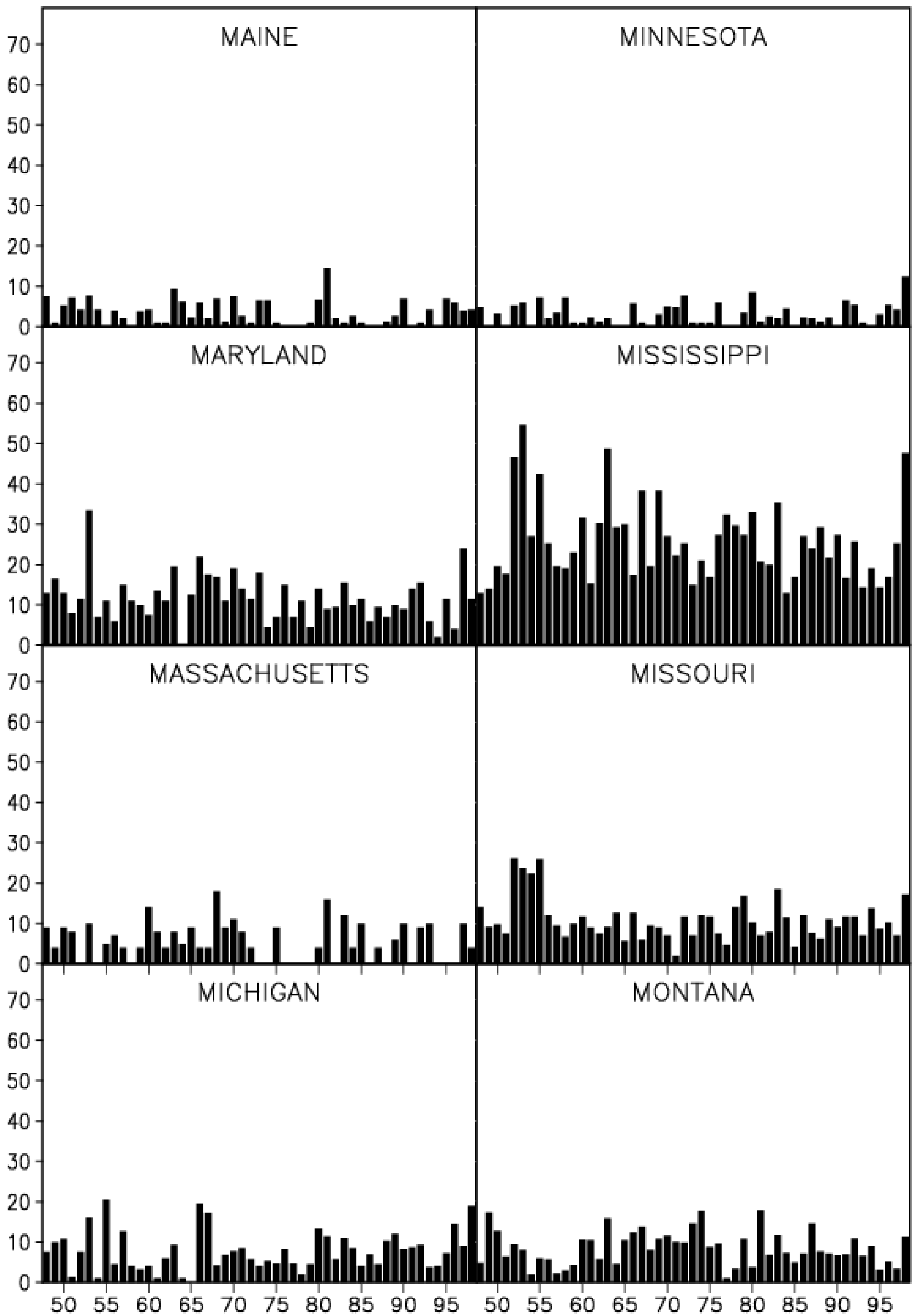


Figure 13, Same as Fig. 11, except for Maine, Maryland, Massachusetts, Michigan, Minnesota, Mississippi, Missouri, and Montana.

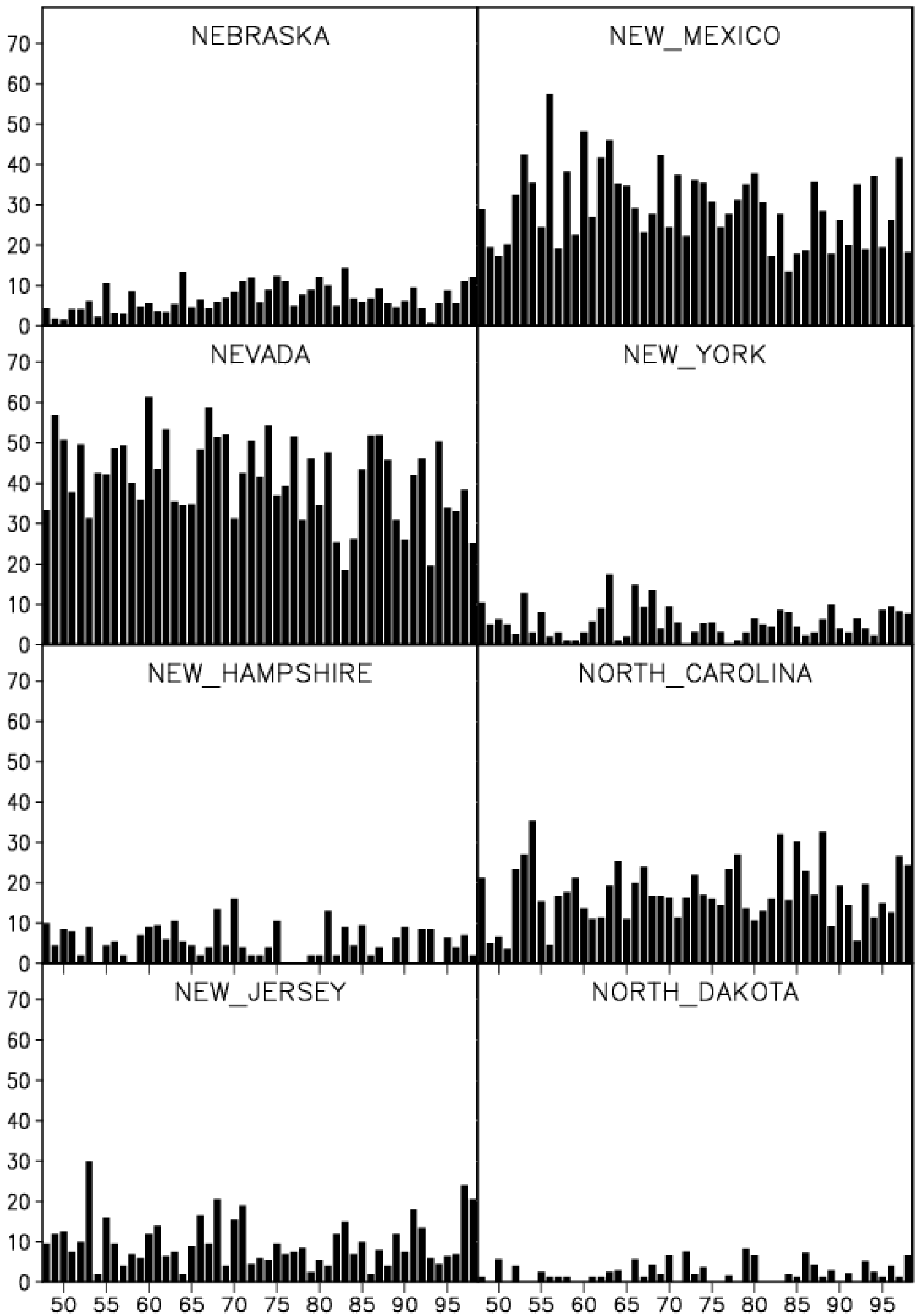


Figure 14, Same as Fig. 11, except for Nebraska, Nevada, New Hampshire, New Jersey, New Mexico, New York, North Carolina, and North Dakota.

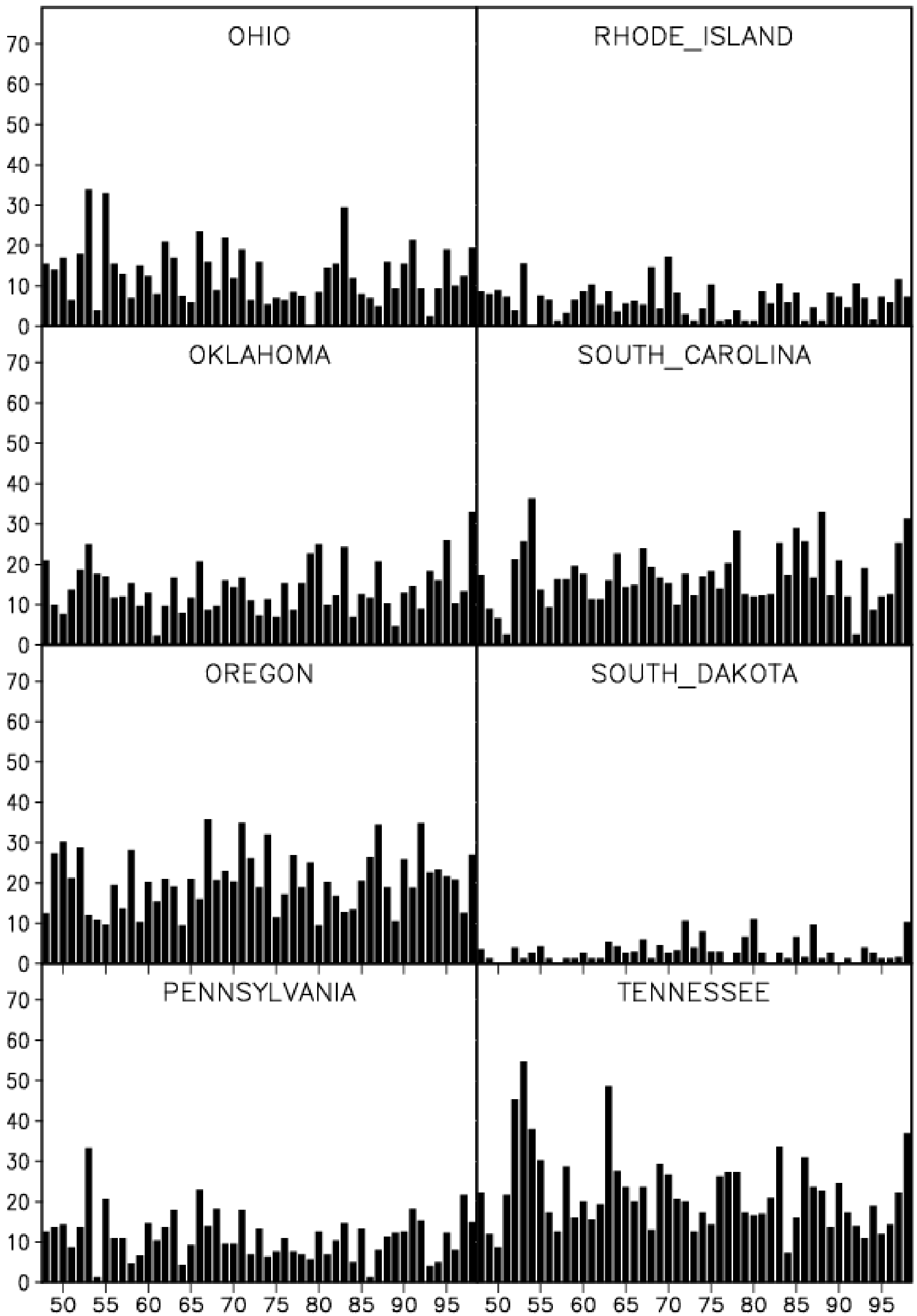


Figure 15, Same as Fig. 11, except for Ohio, Oklahoma, Oregon, Pennsylvania, Rhode Island, South Carolina, South Dakota, and Tennessee.

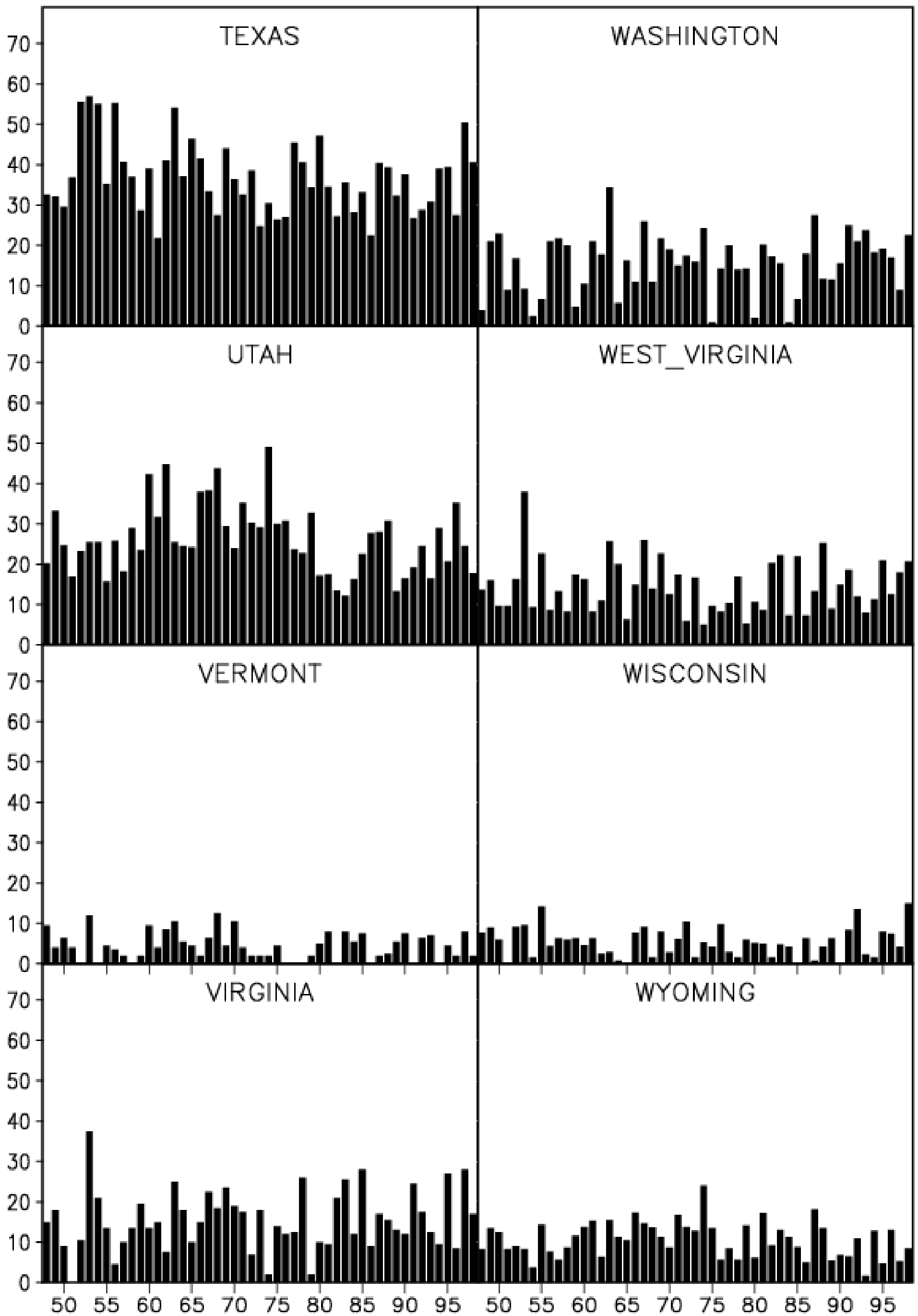


Figure 16, Same as Fig. 11, except for Texas, Utah, Vermont, Virginia, Washington, West Virginia, Wisconsin, and Wyoming.

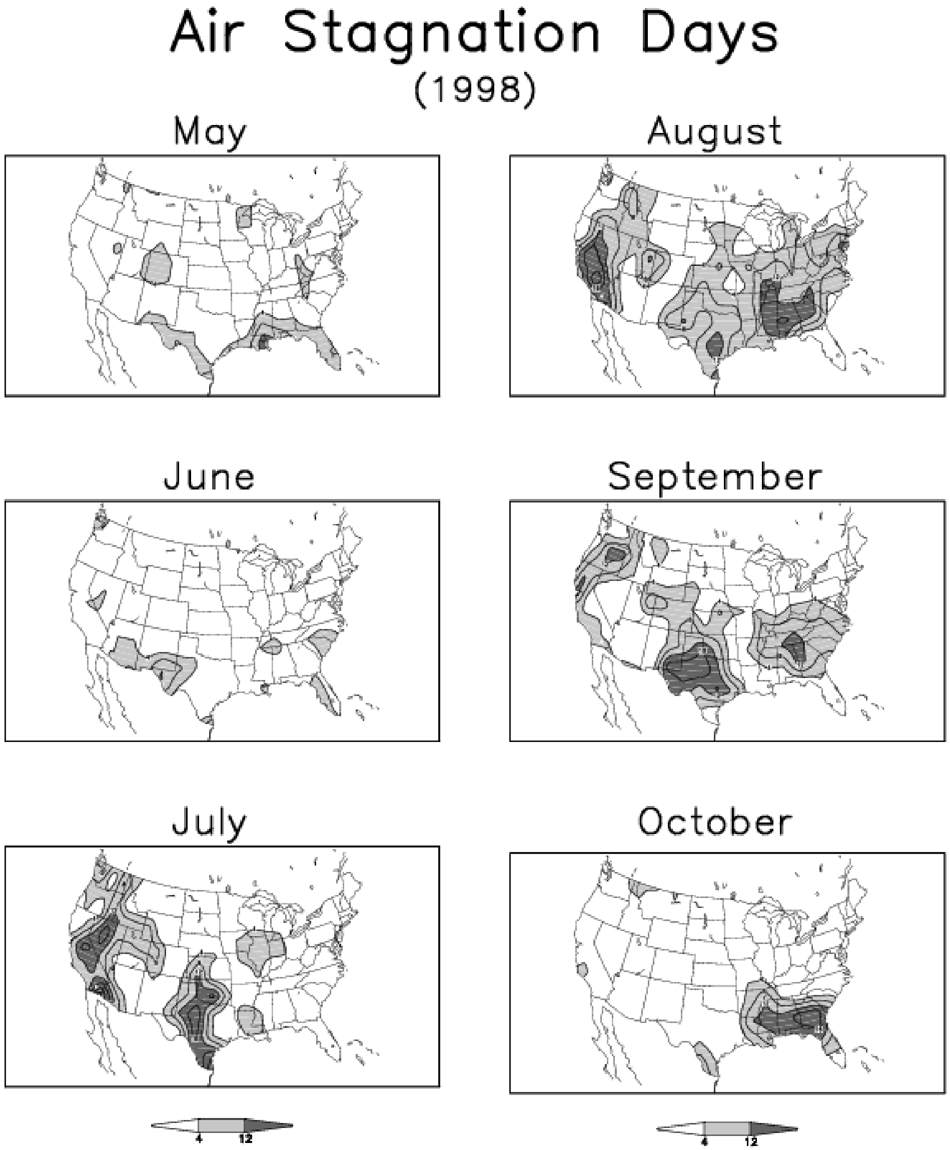


Figure 17, Air stagnation days for the months of May-October, 1998. Light and dark shading represents regions exceeding 4 and 12 days per month. Contour intervals are 4.

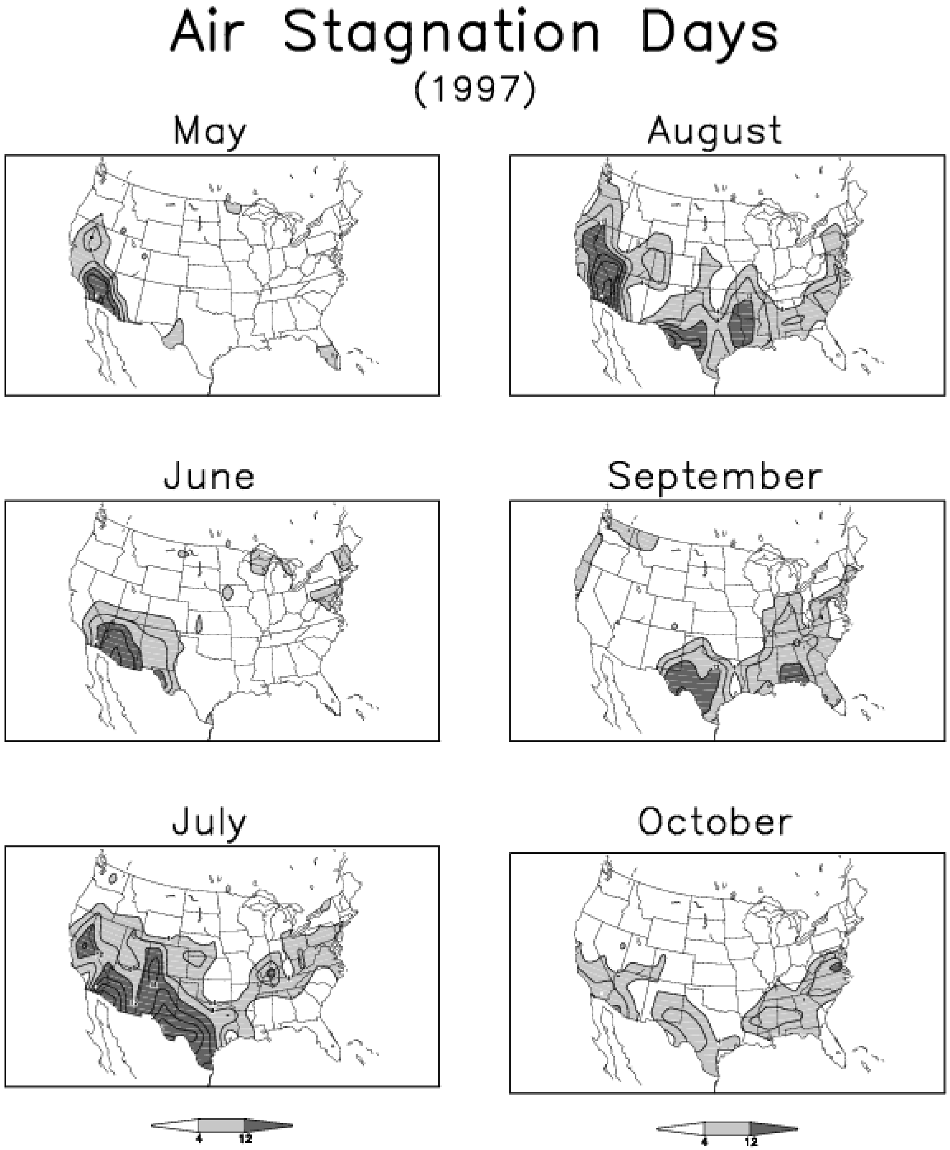
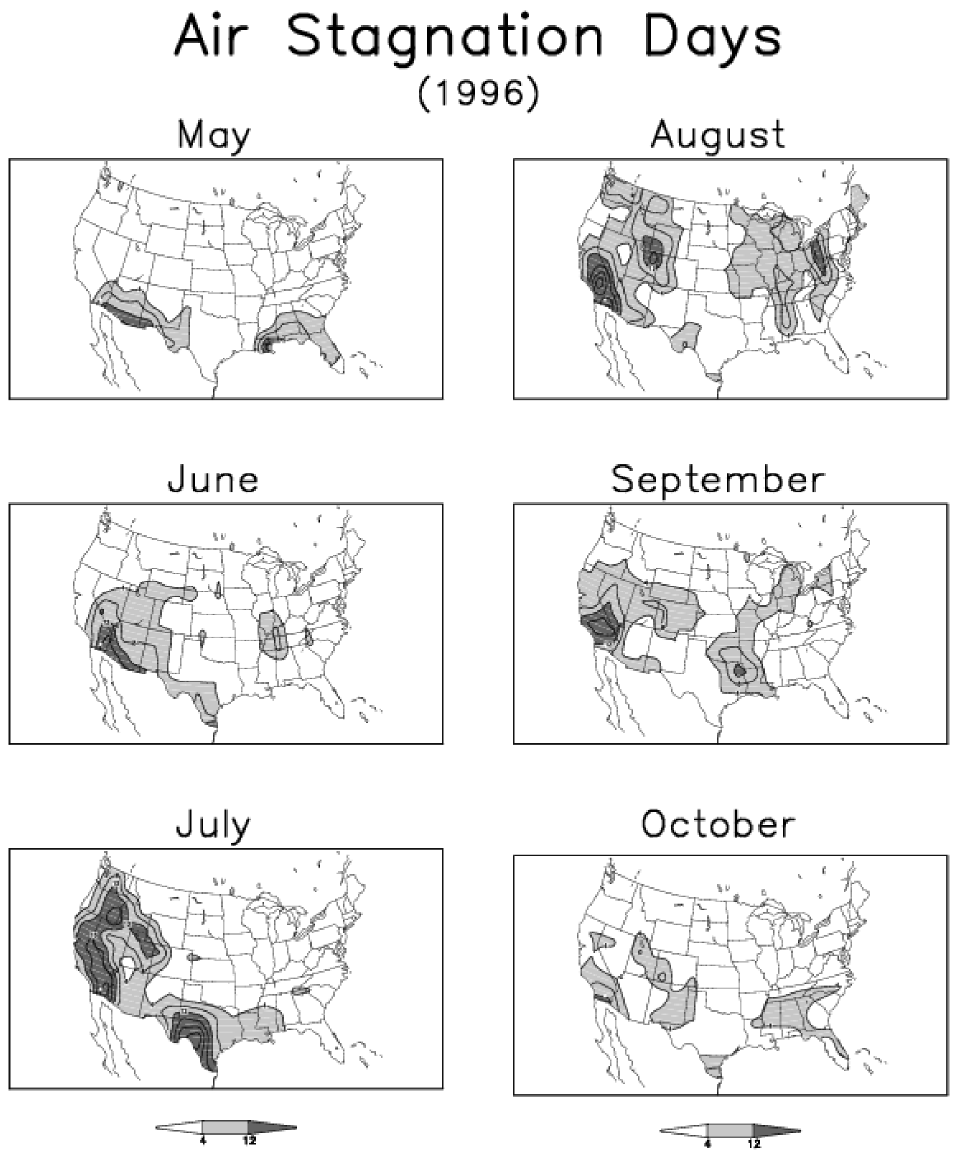


Figure 18, Same as Fig. 17 except for 1997.



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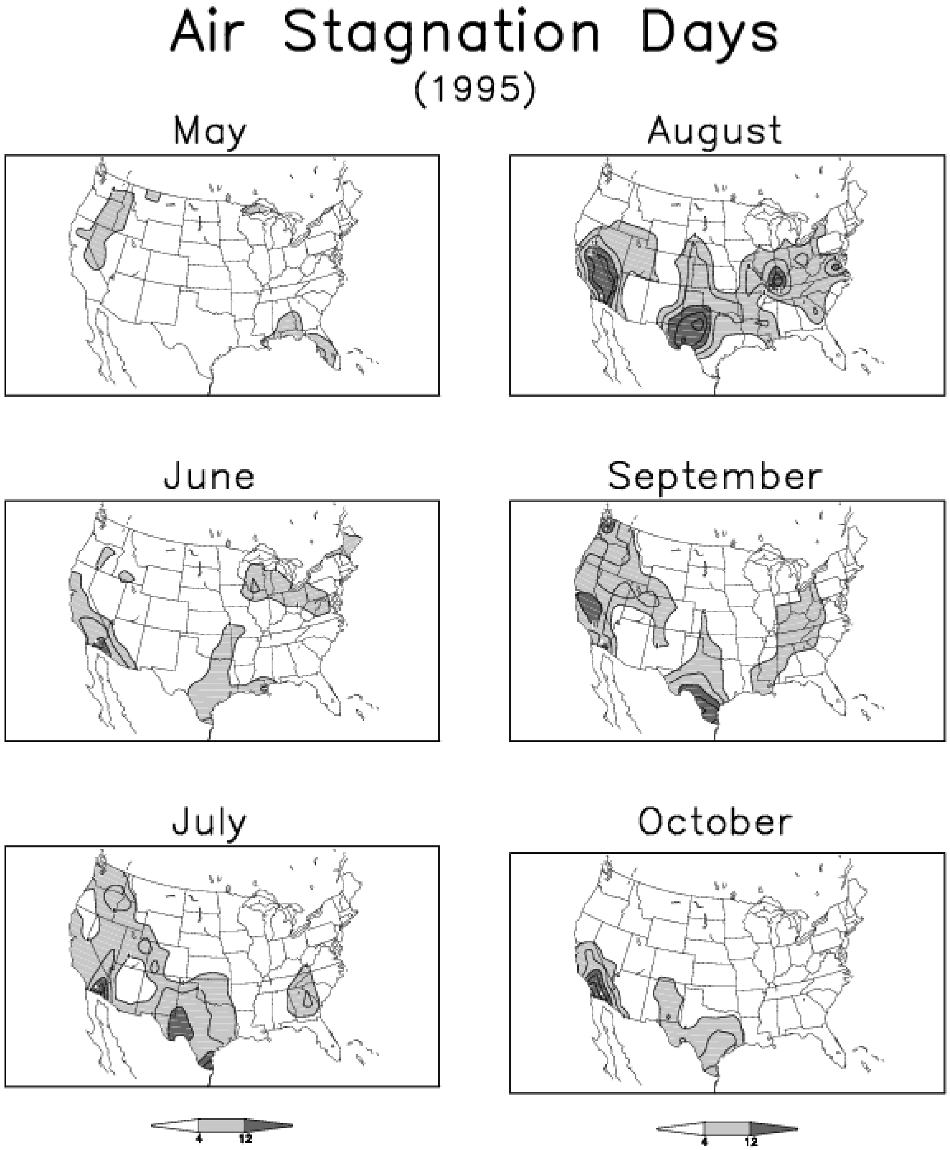

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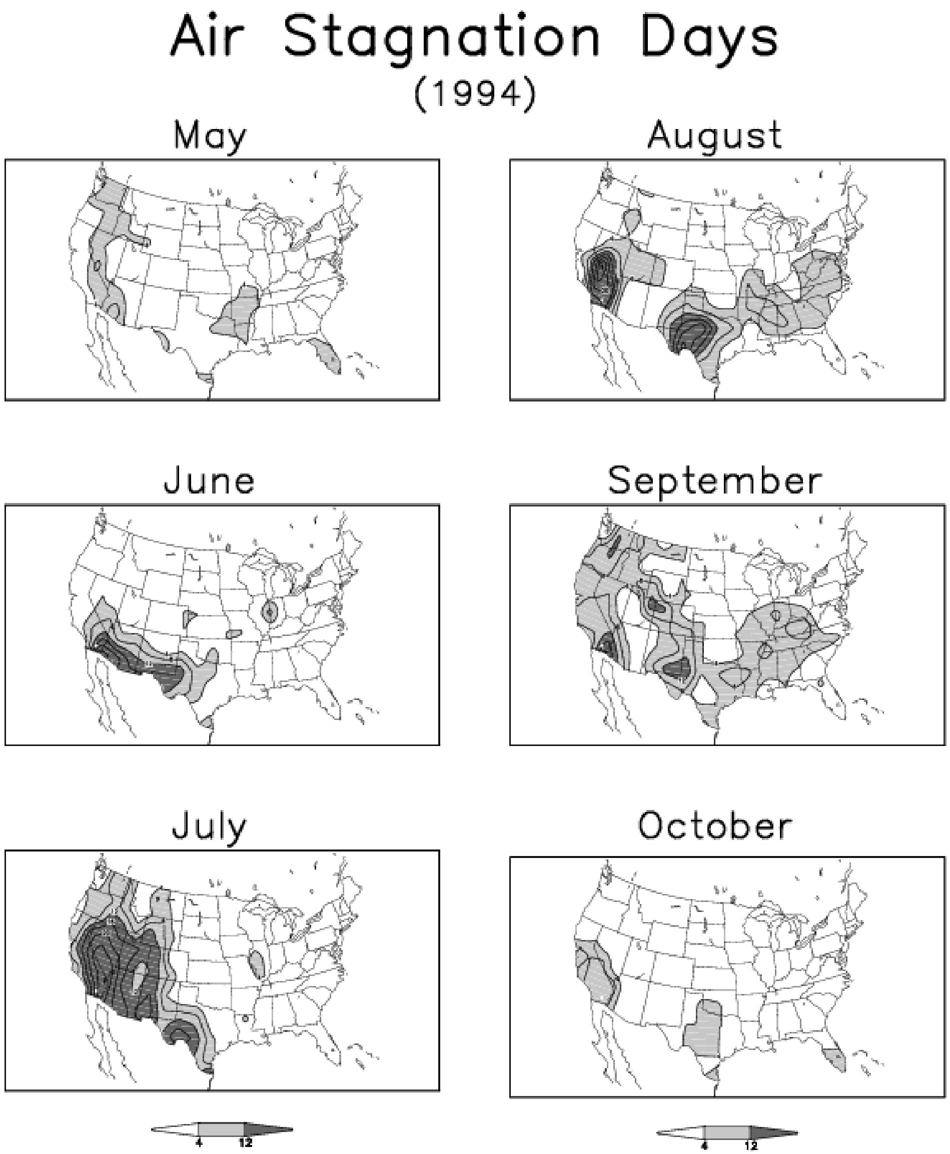
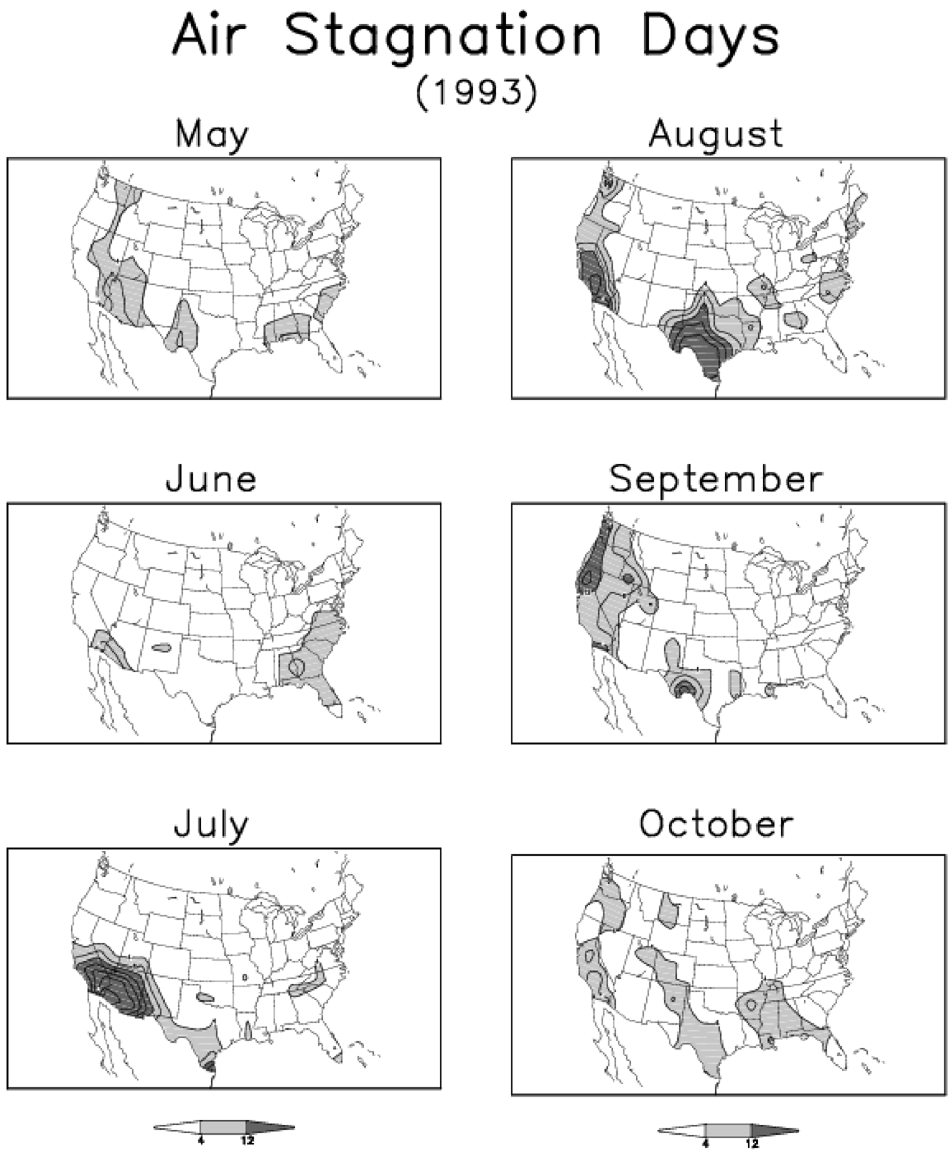


Figure 21, Same as Fig. 17 except for 1994.



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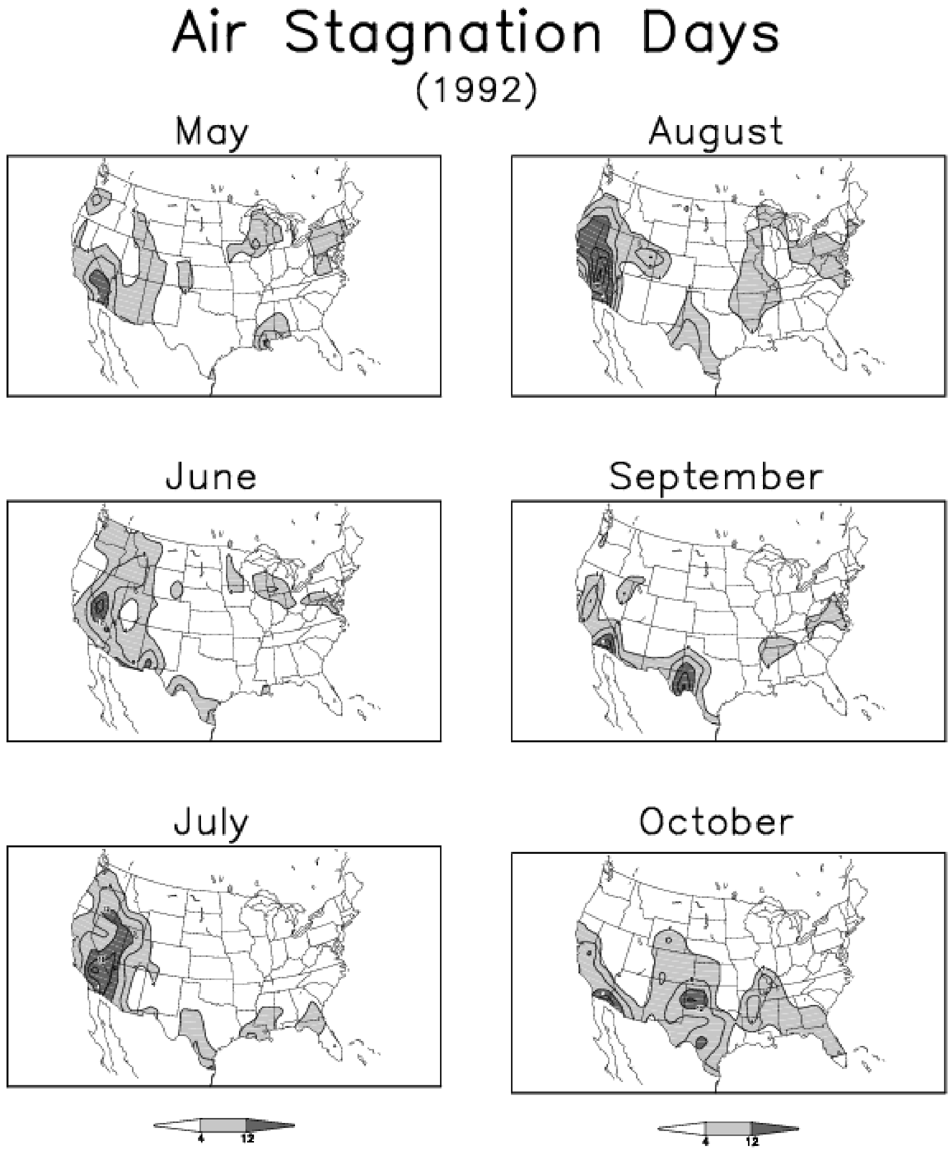
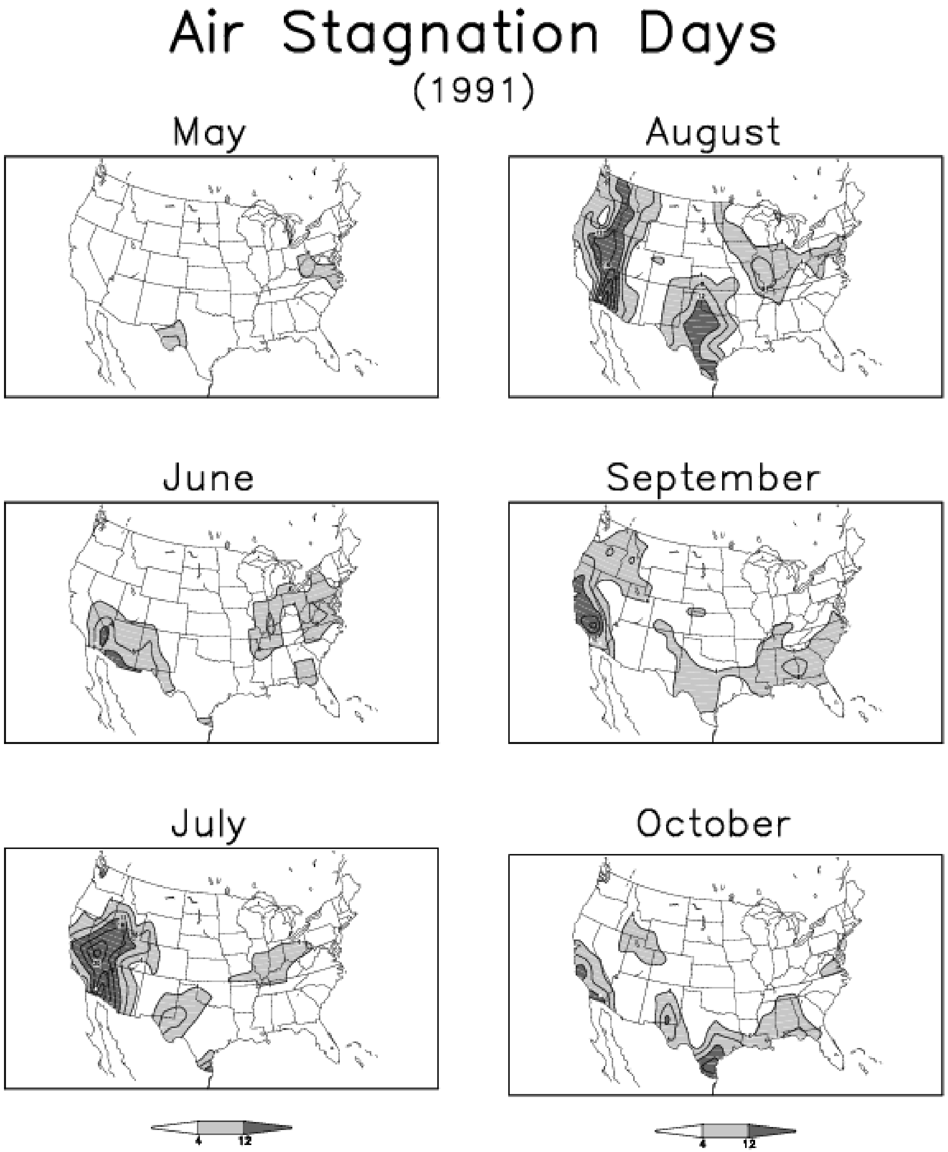


Figure 23, Same as Fig. 17 except for 1992.



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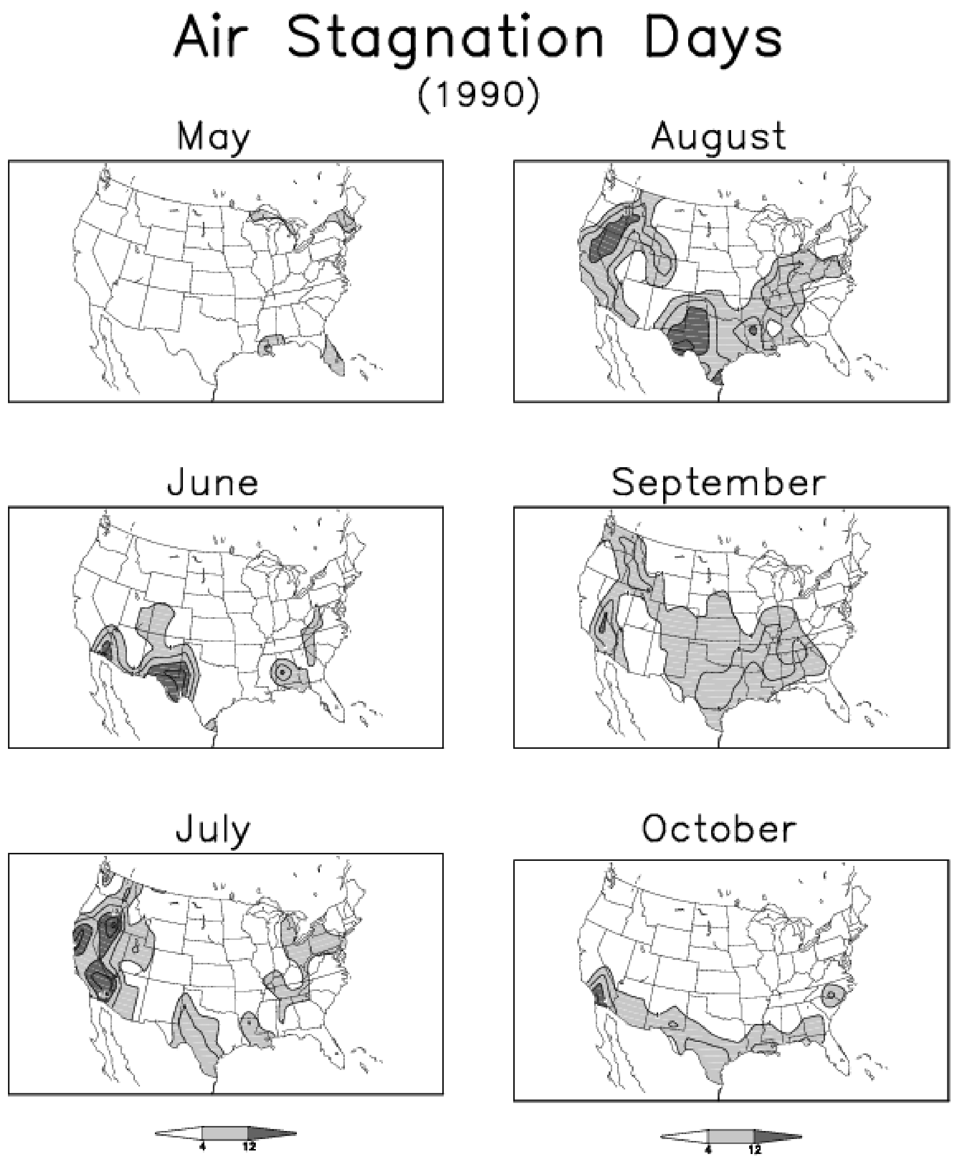

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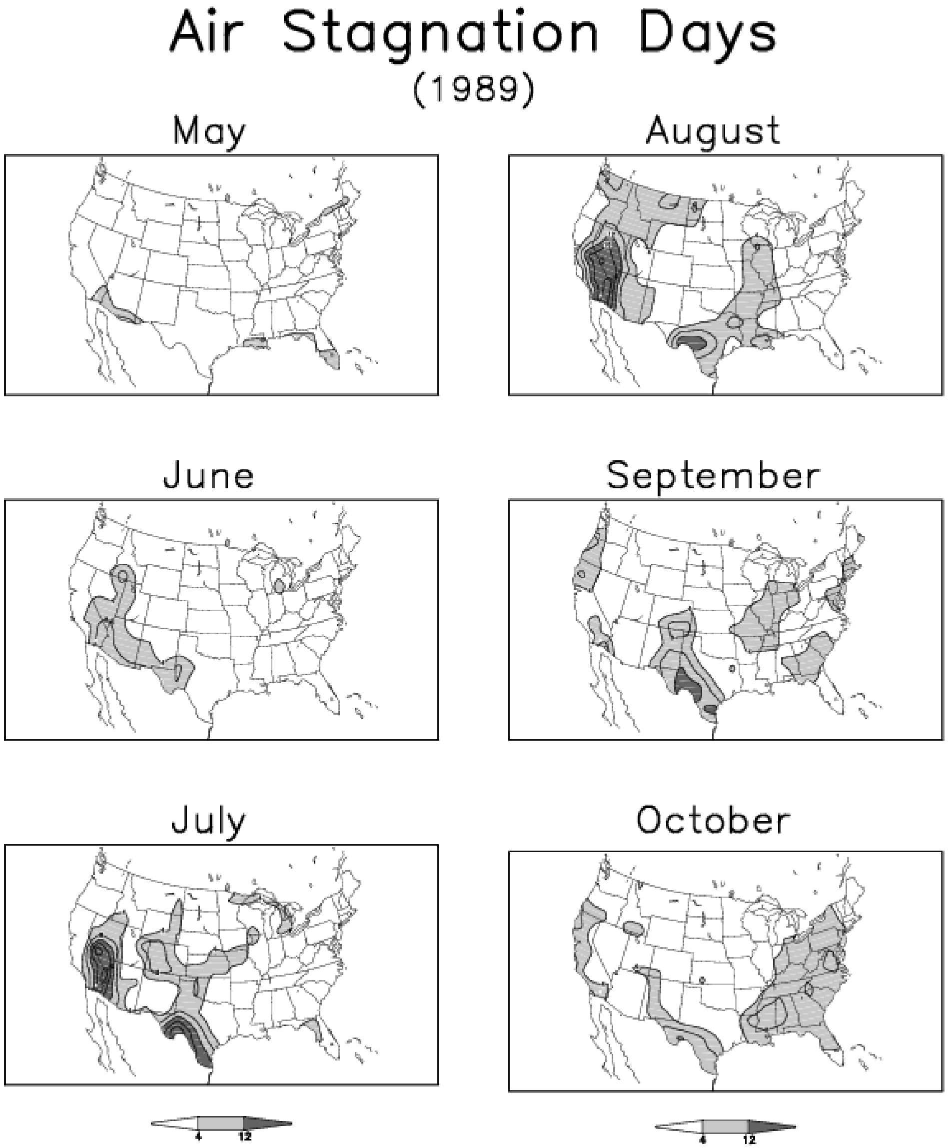

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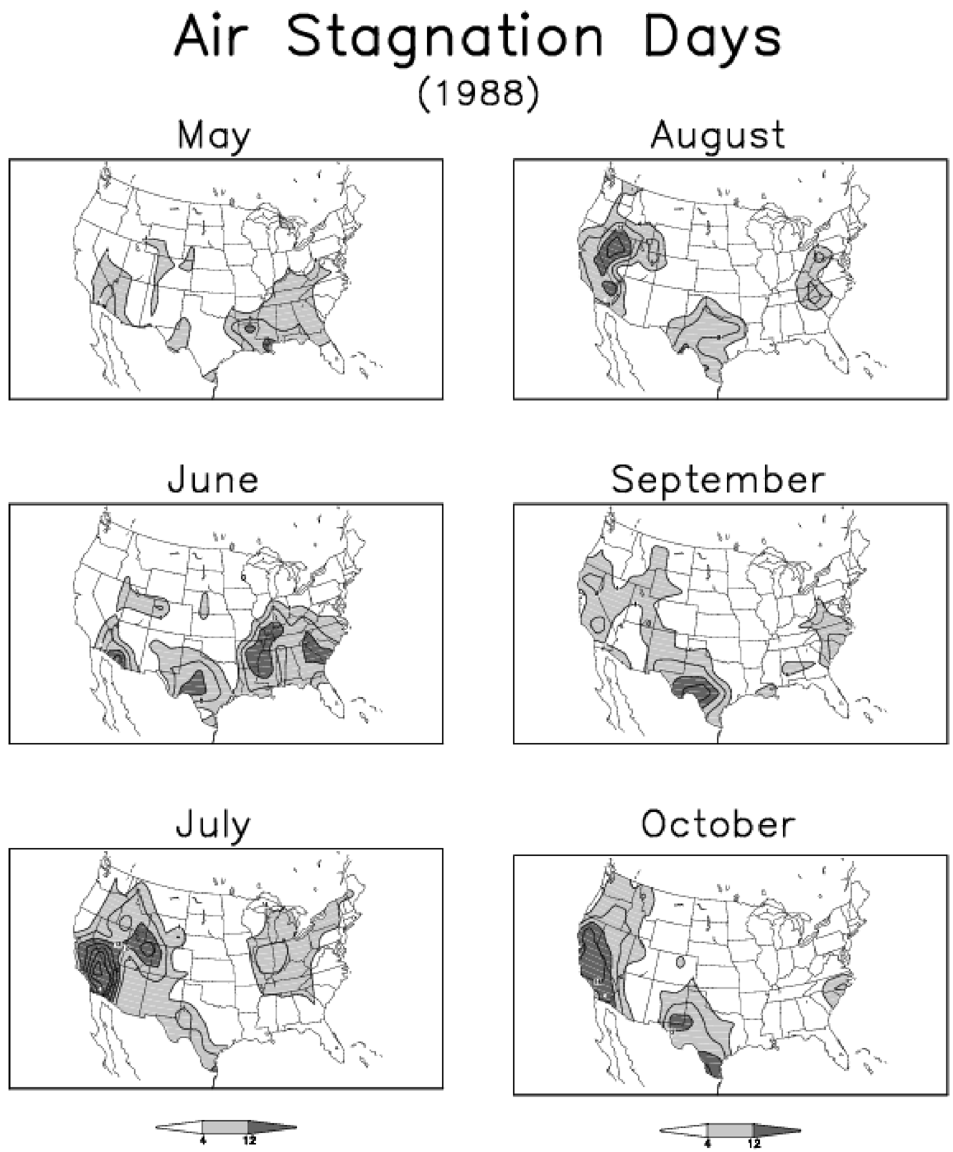


Figure 27, Same as Fig. 17 except for 1988.

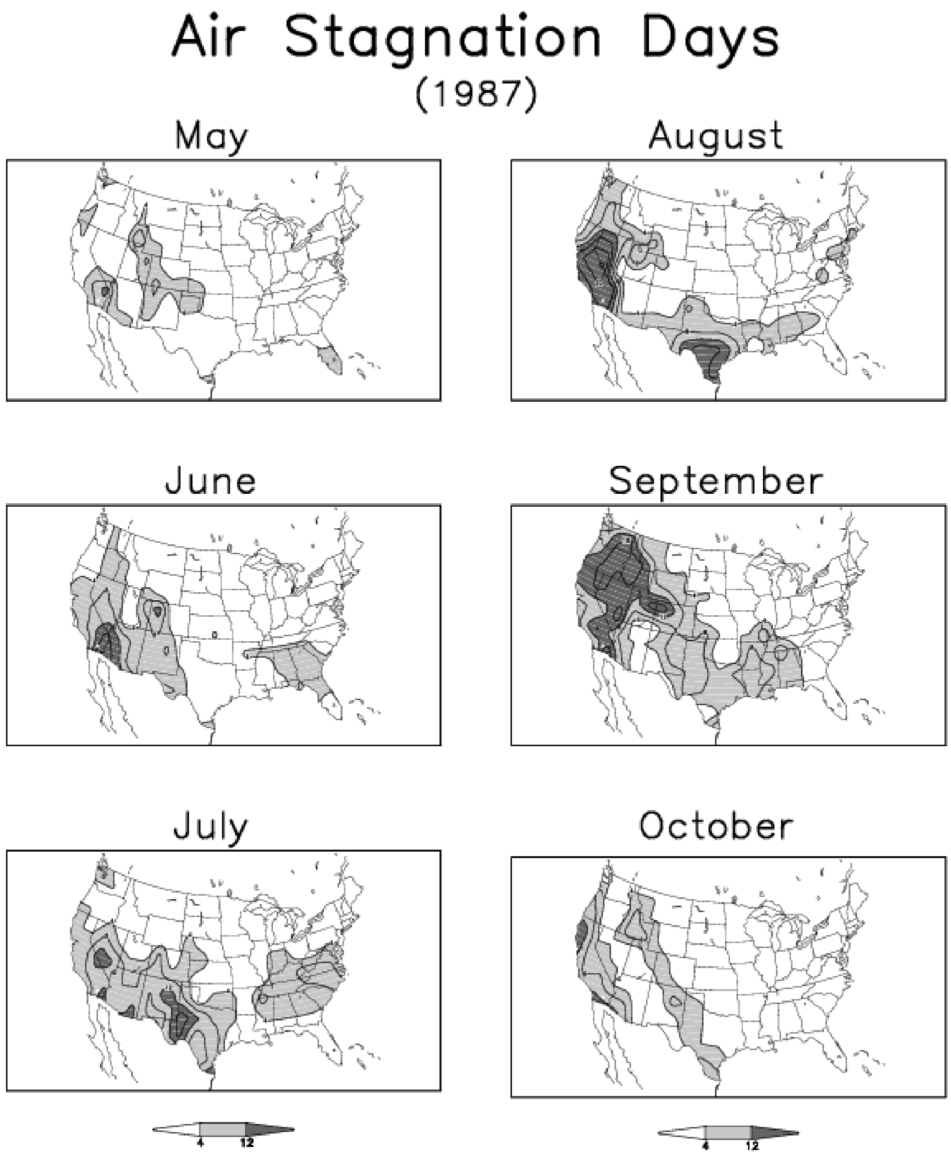
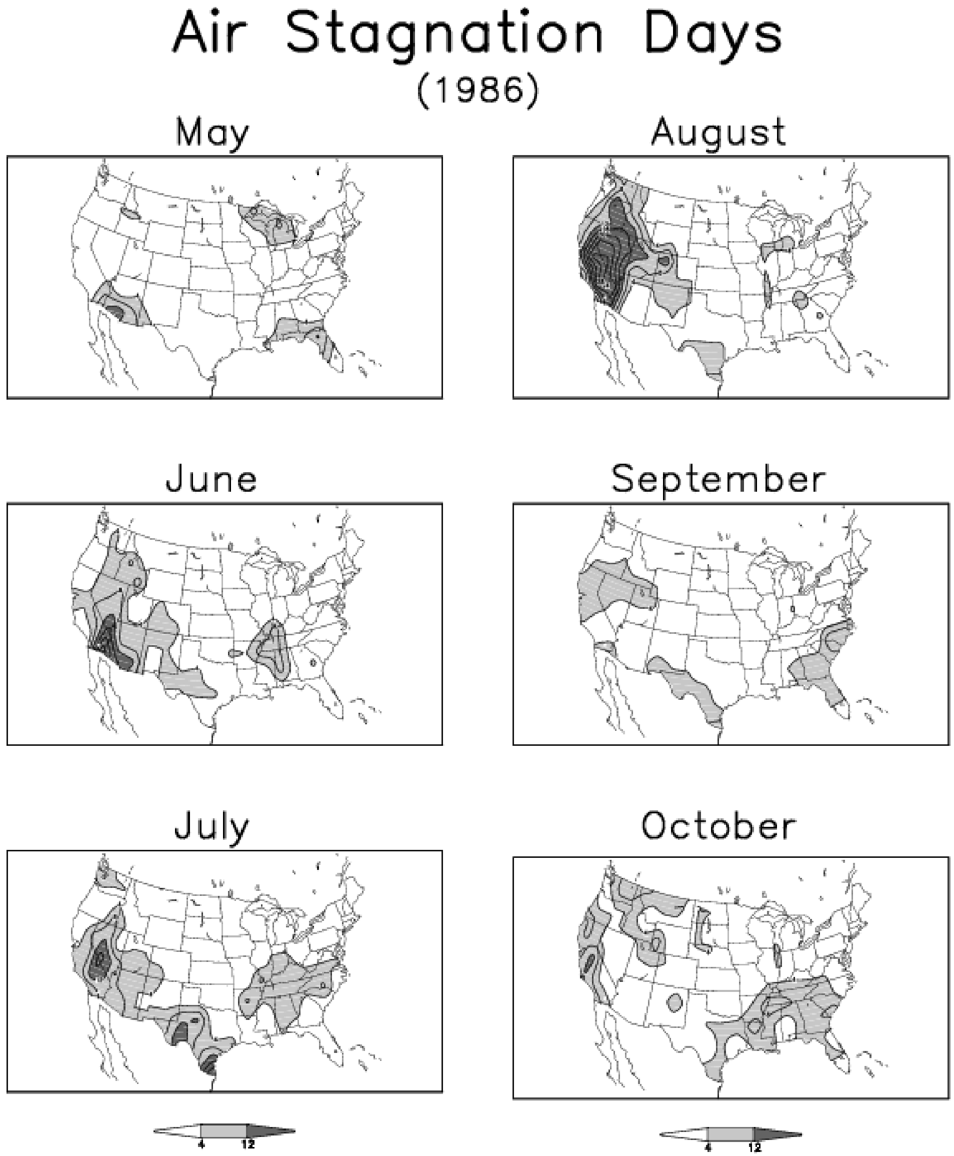


Figure 28, Same as Fig. 17 except for 1987.



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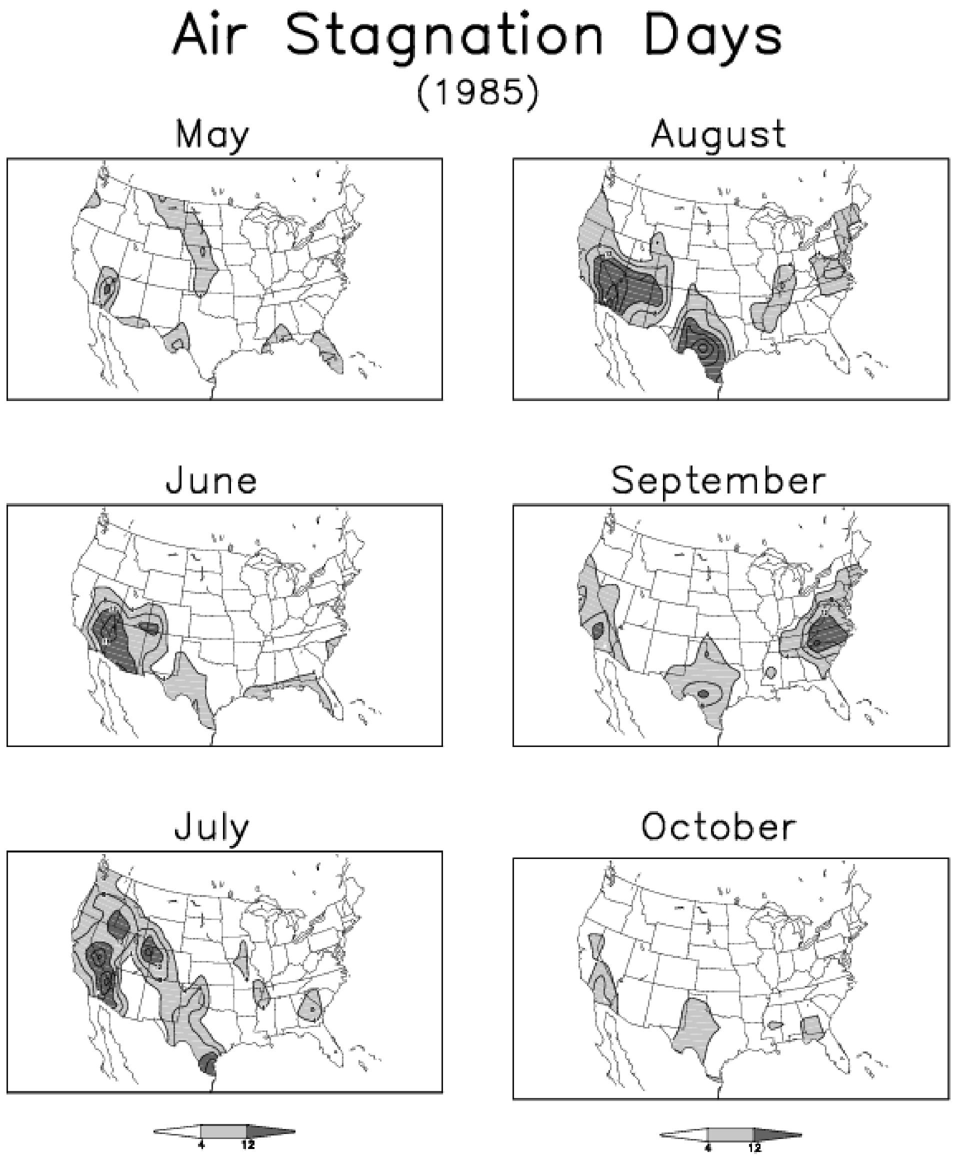

Figure 30, Same as Fig. 17 except for 1985.

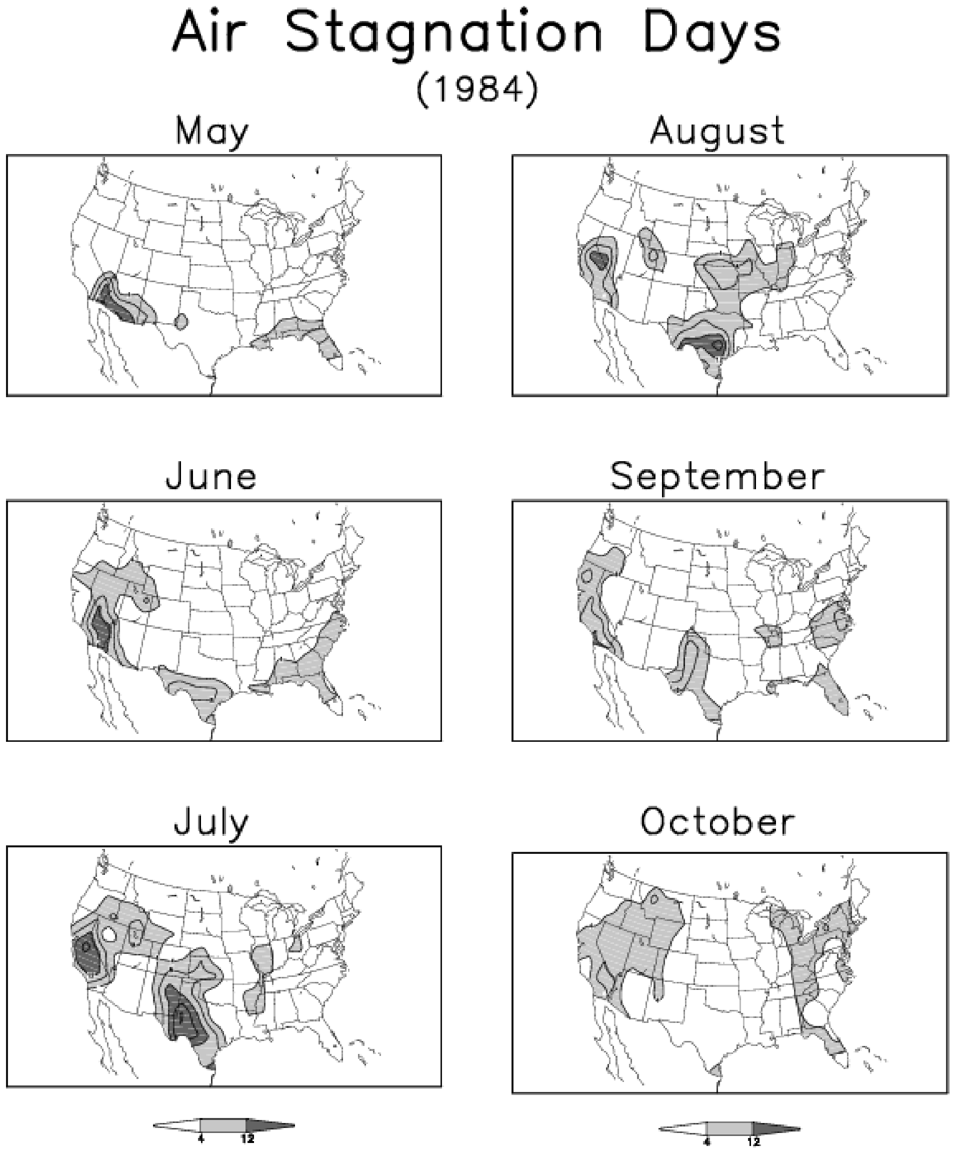

Figure 31, Same as Fig. 17 except for 1984.

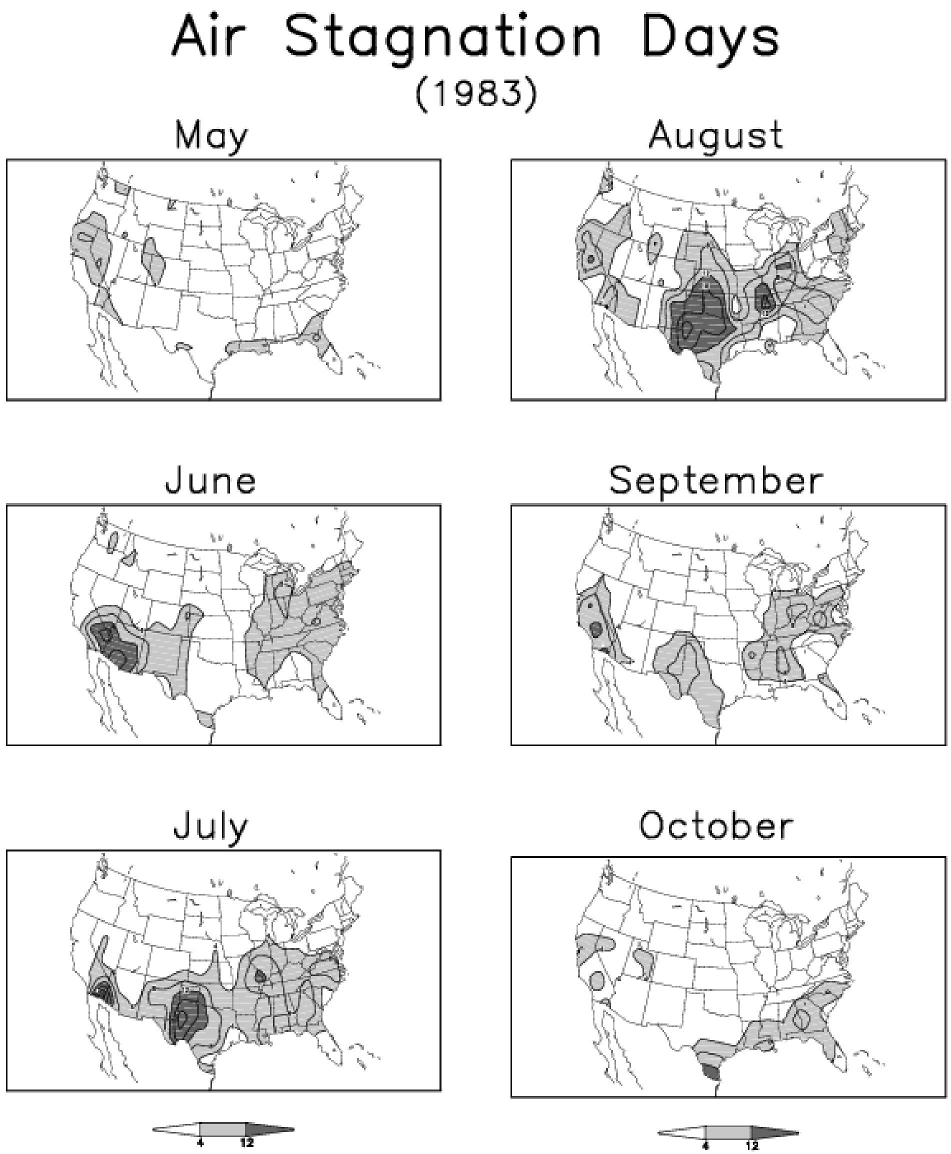

Figure 32, Same as Fig. 17 except for 1983.

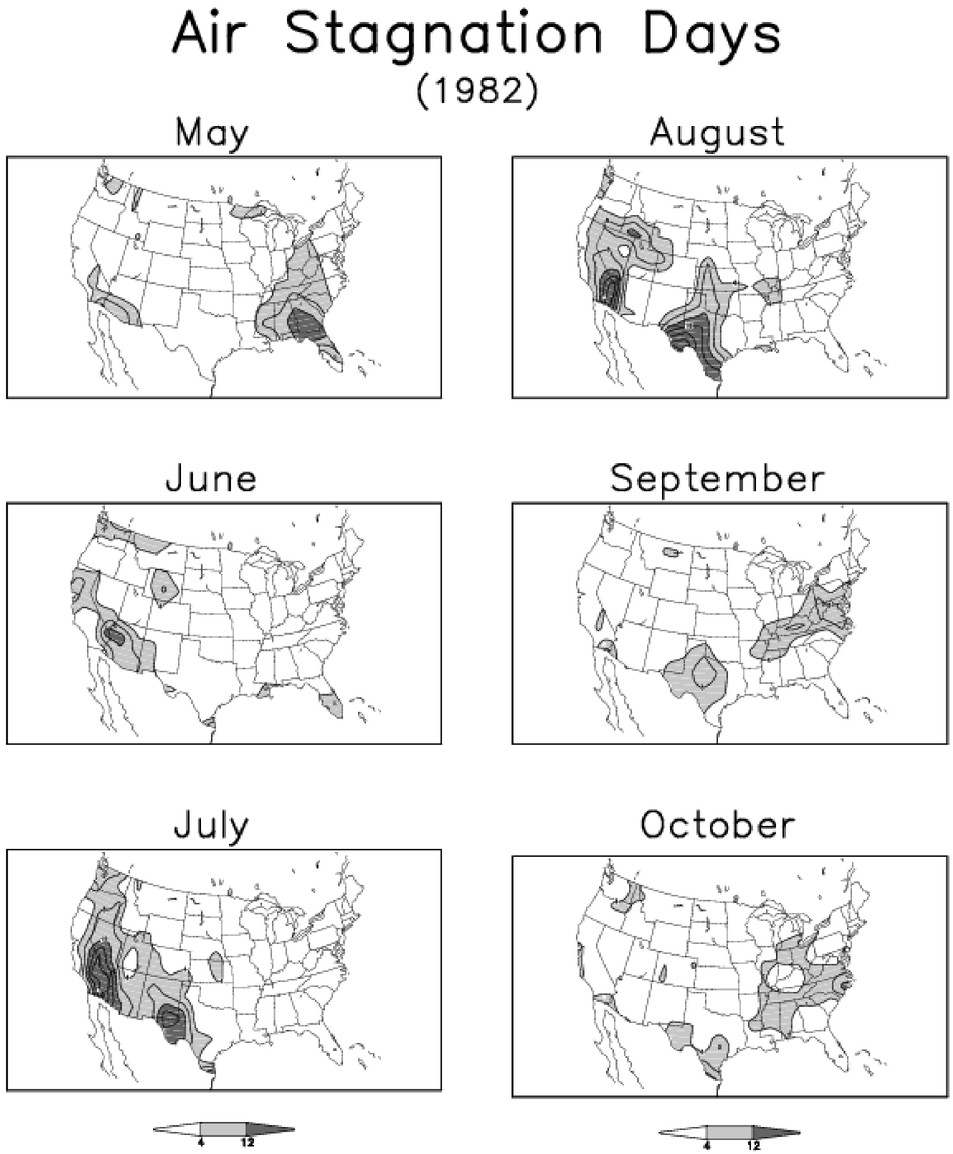

Figure 33, Same as Fig. 17 except for 1982.

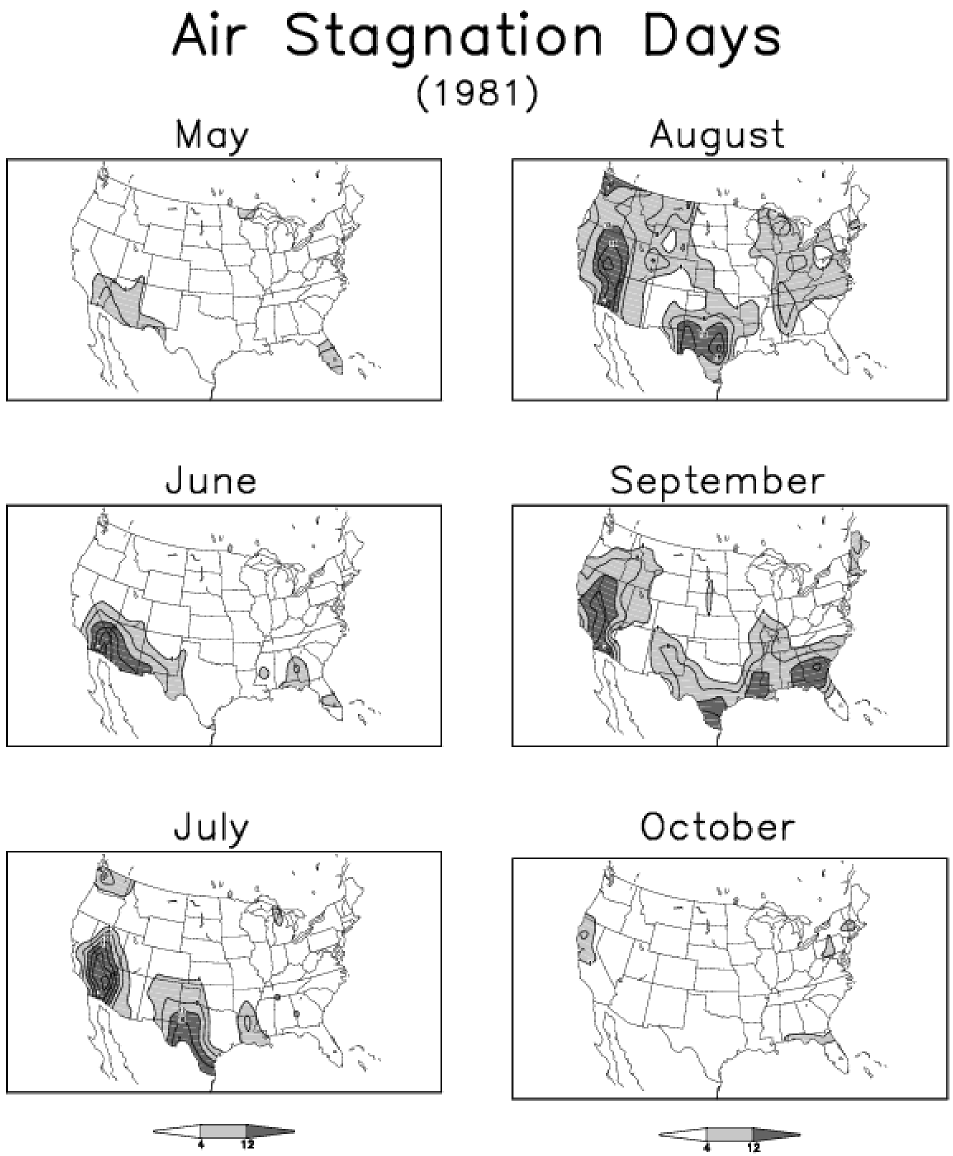

Figure 34, Same as Fig. 17 except for 1981.

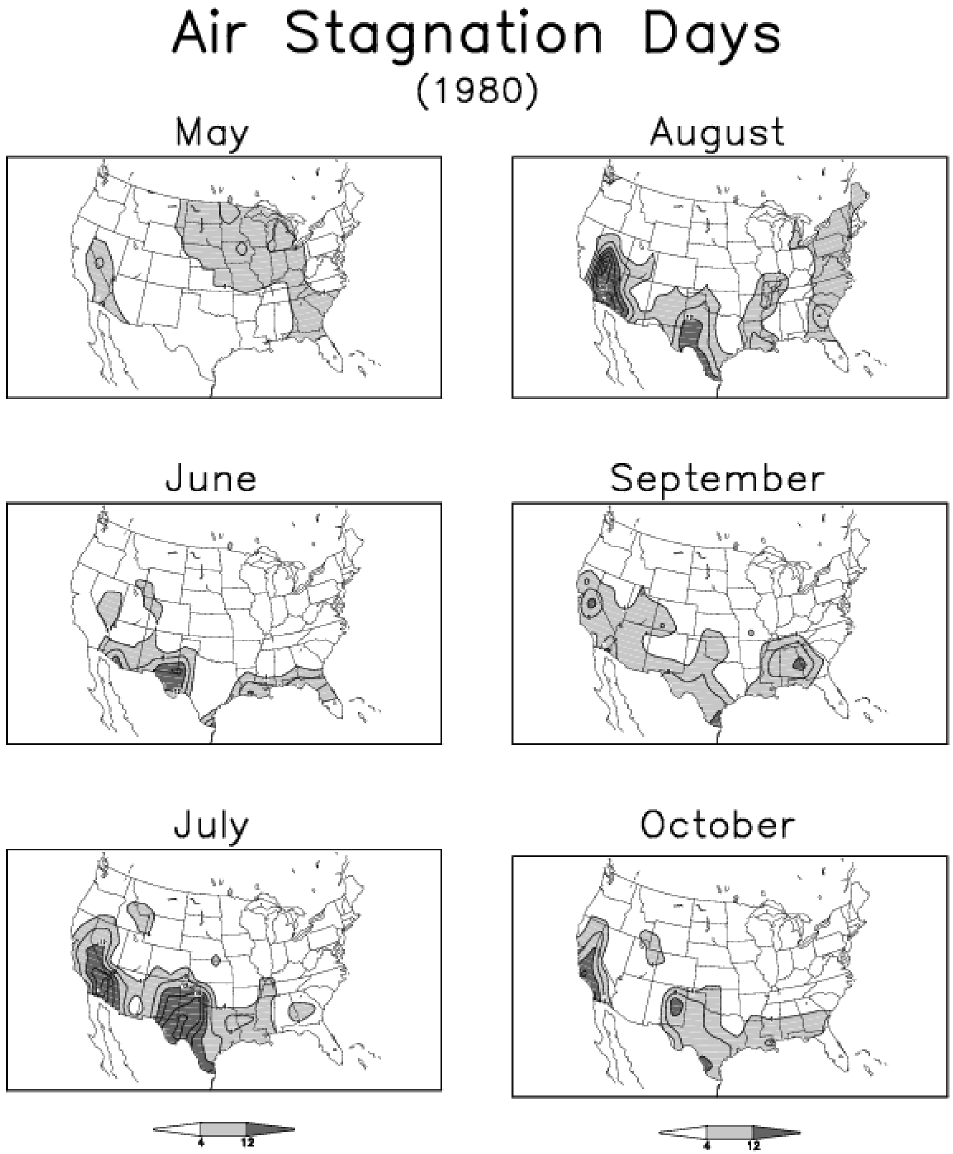

Figure 35, Same as Fig. 17 except for 1980.

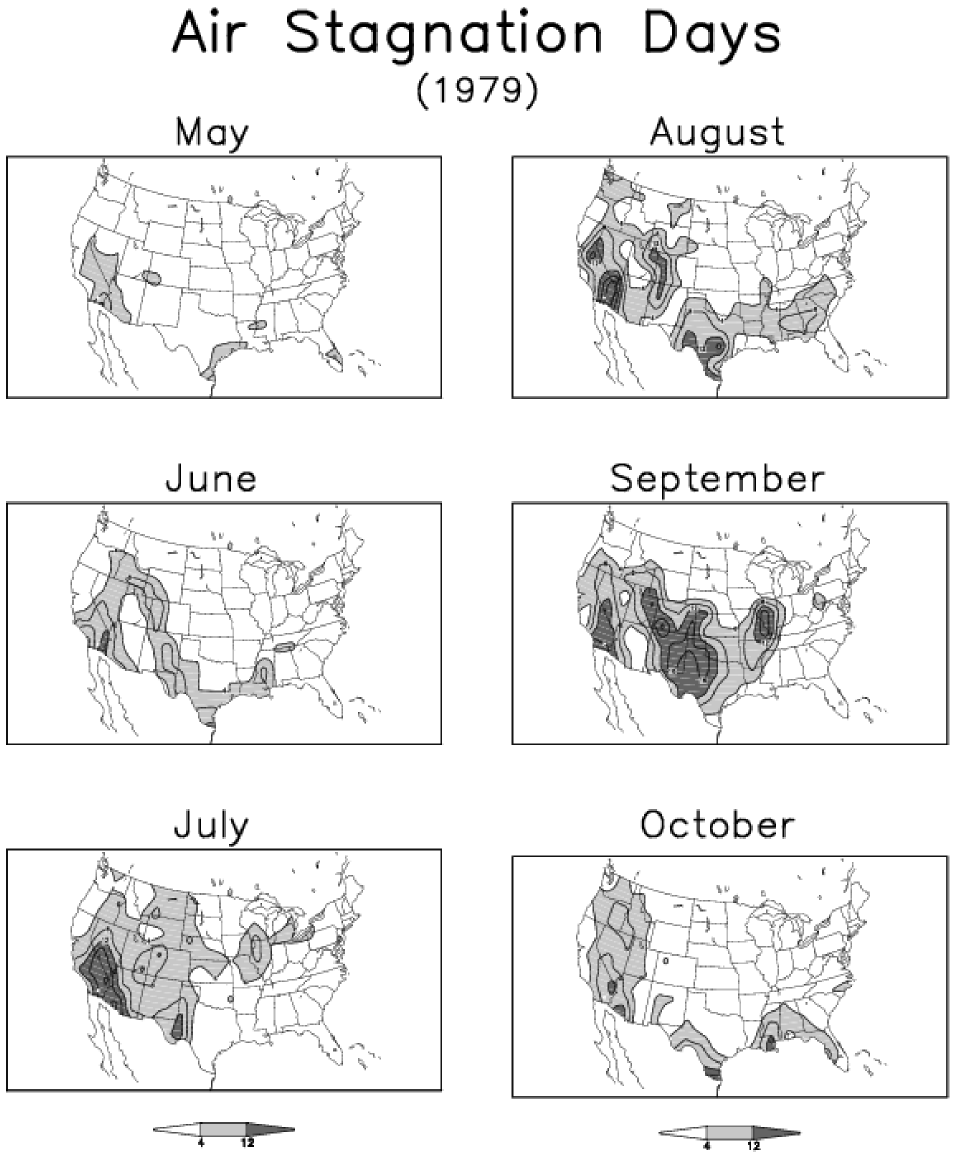

Figure 36, Same as Fig. 17 except for 1979.

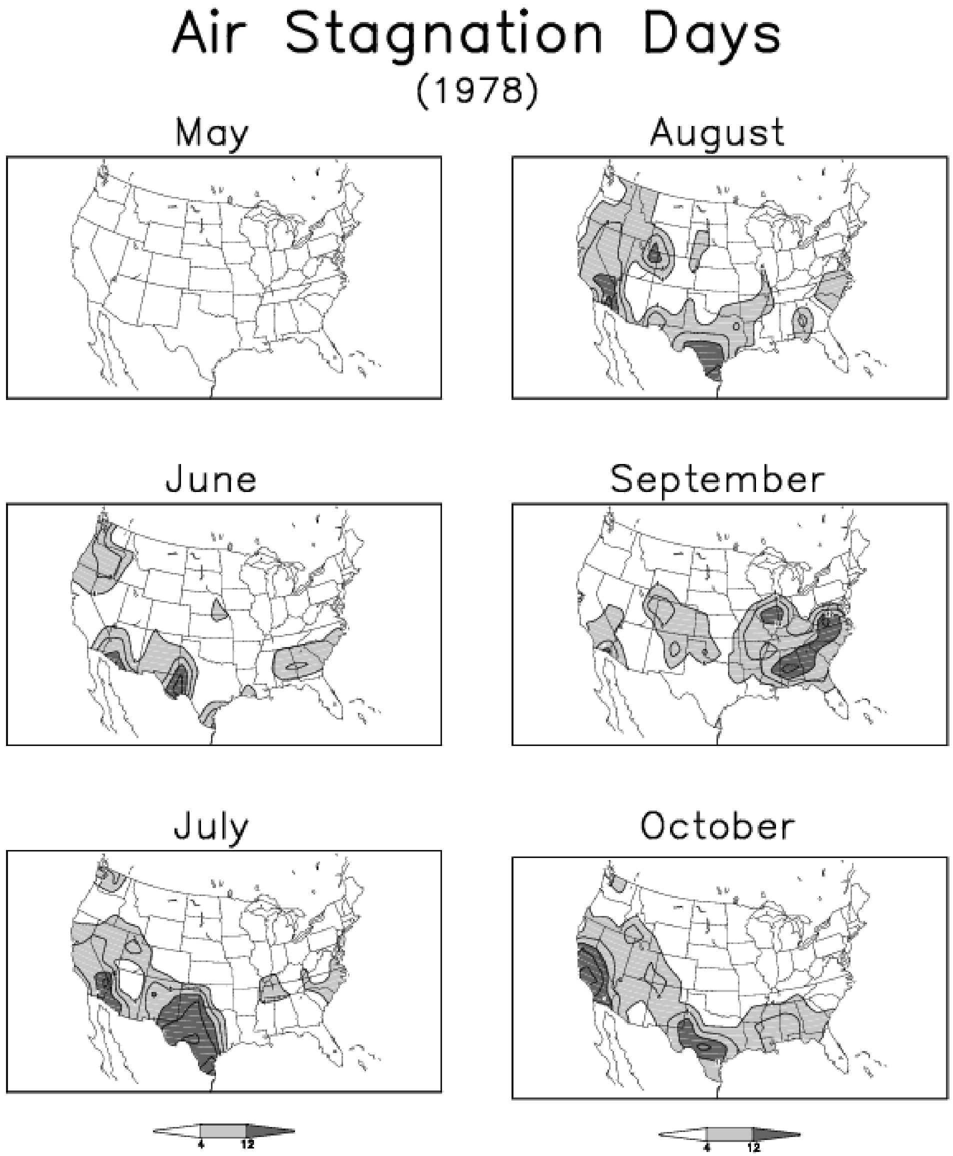

Figure 37, Same as Fig. 17 except for 1978.

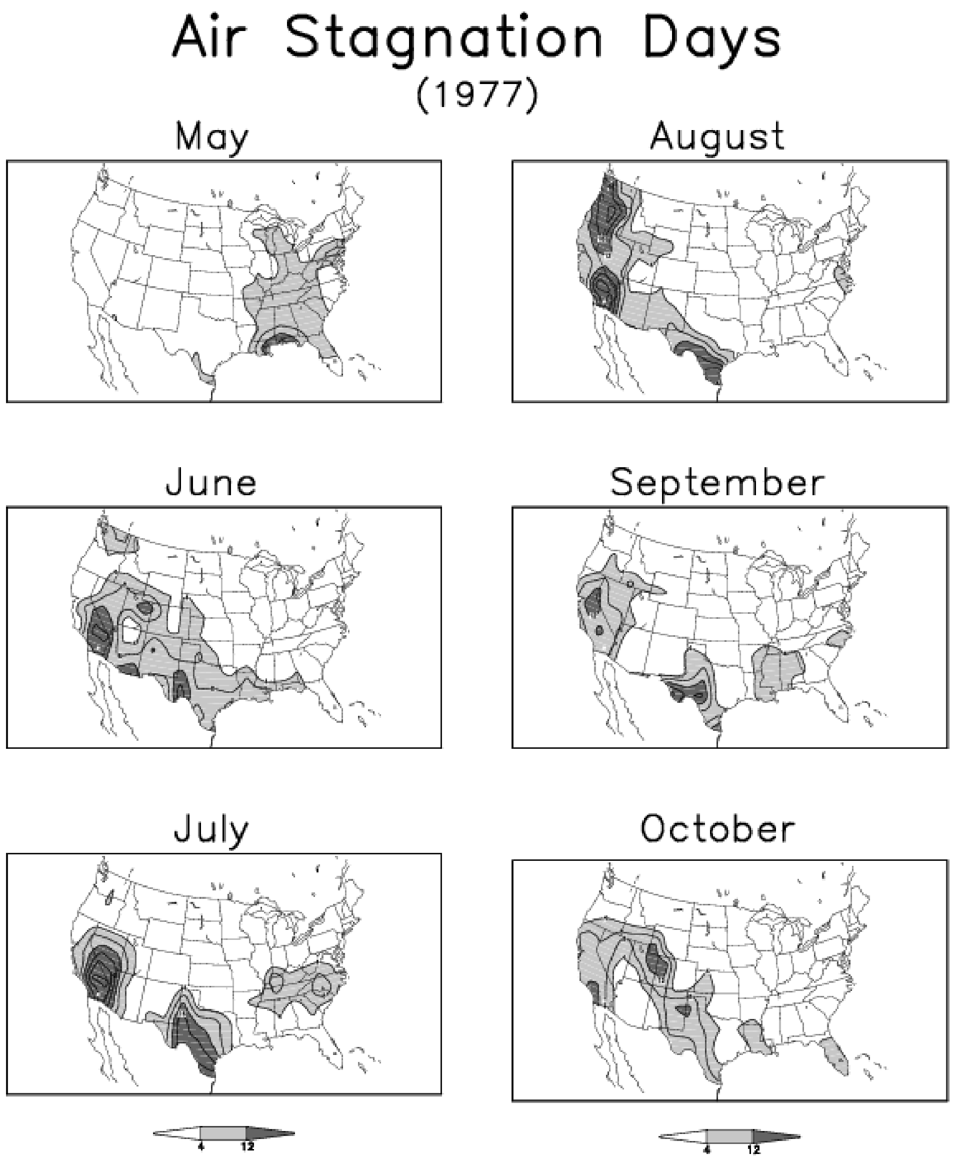

Figure 38, Same as Fig. 17 except for 1977.

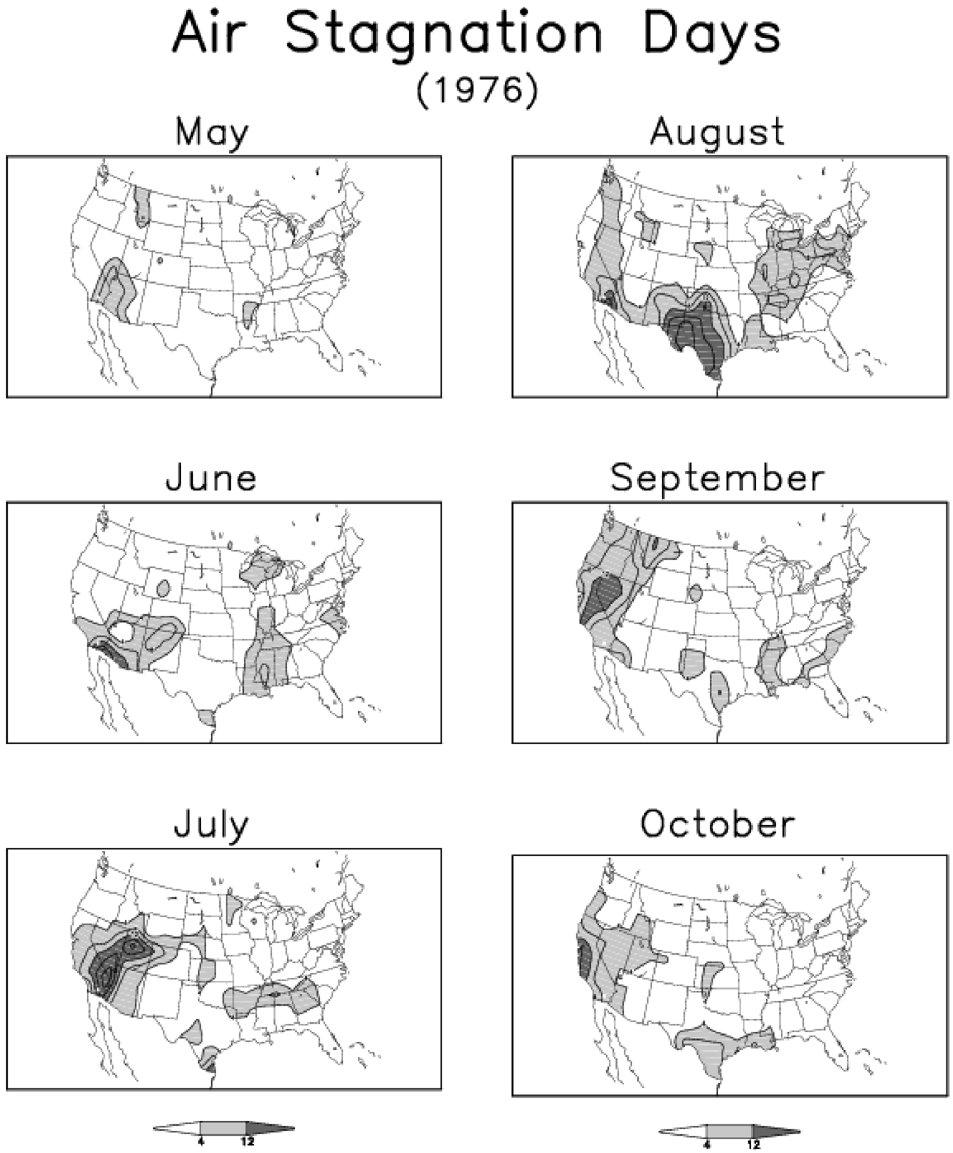

Figure 39, Same as Fig. 17 except for 1976.

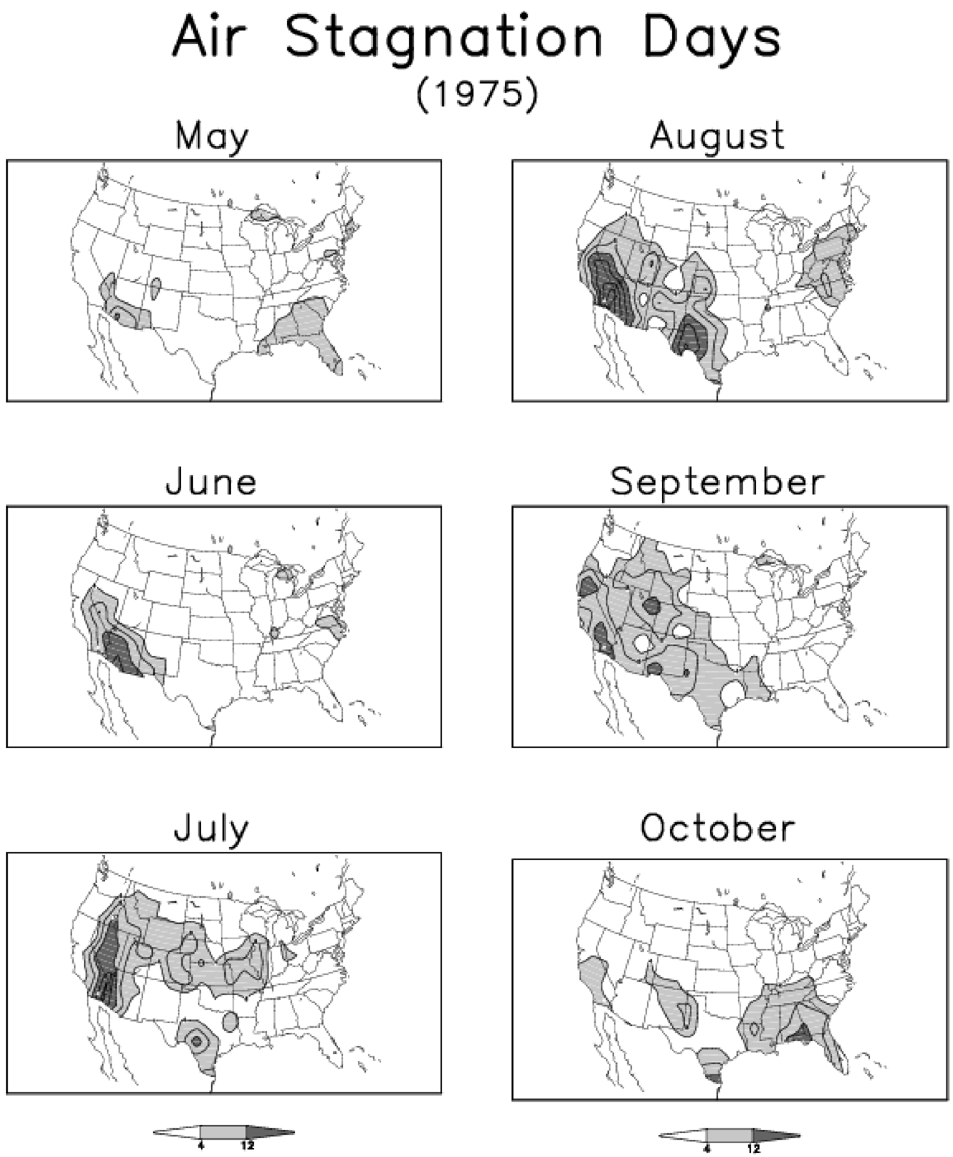

Figure 40, Same as Fig. 17 except for 1975.

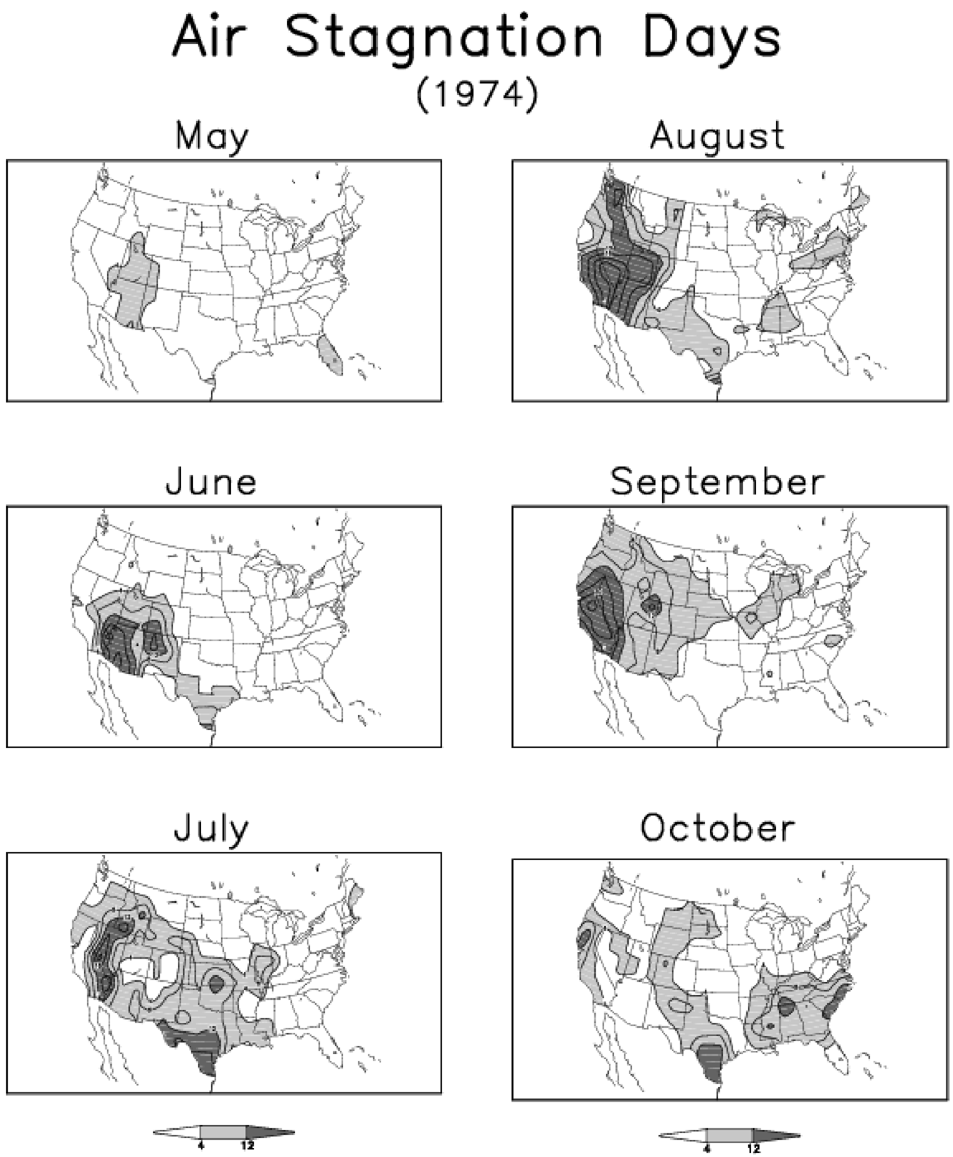

Figure 41, Same as Fig. 17 except for 1974.

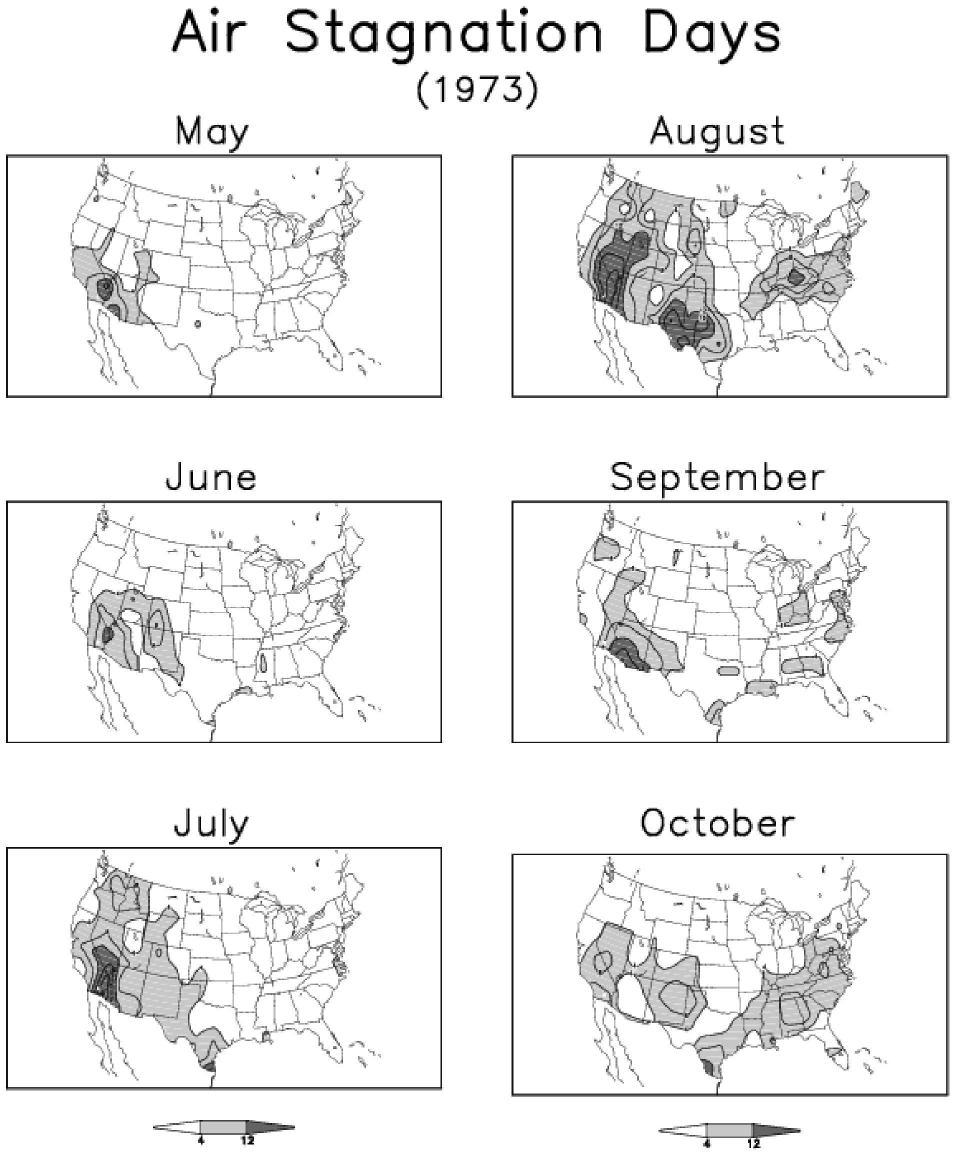

Figure 42, Same as Fig. 17 except for 1973.

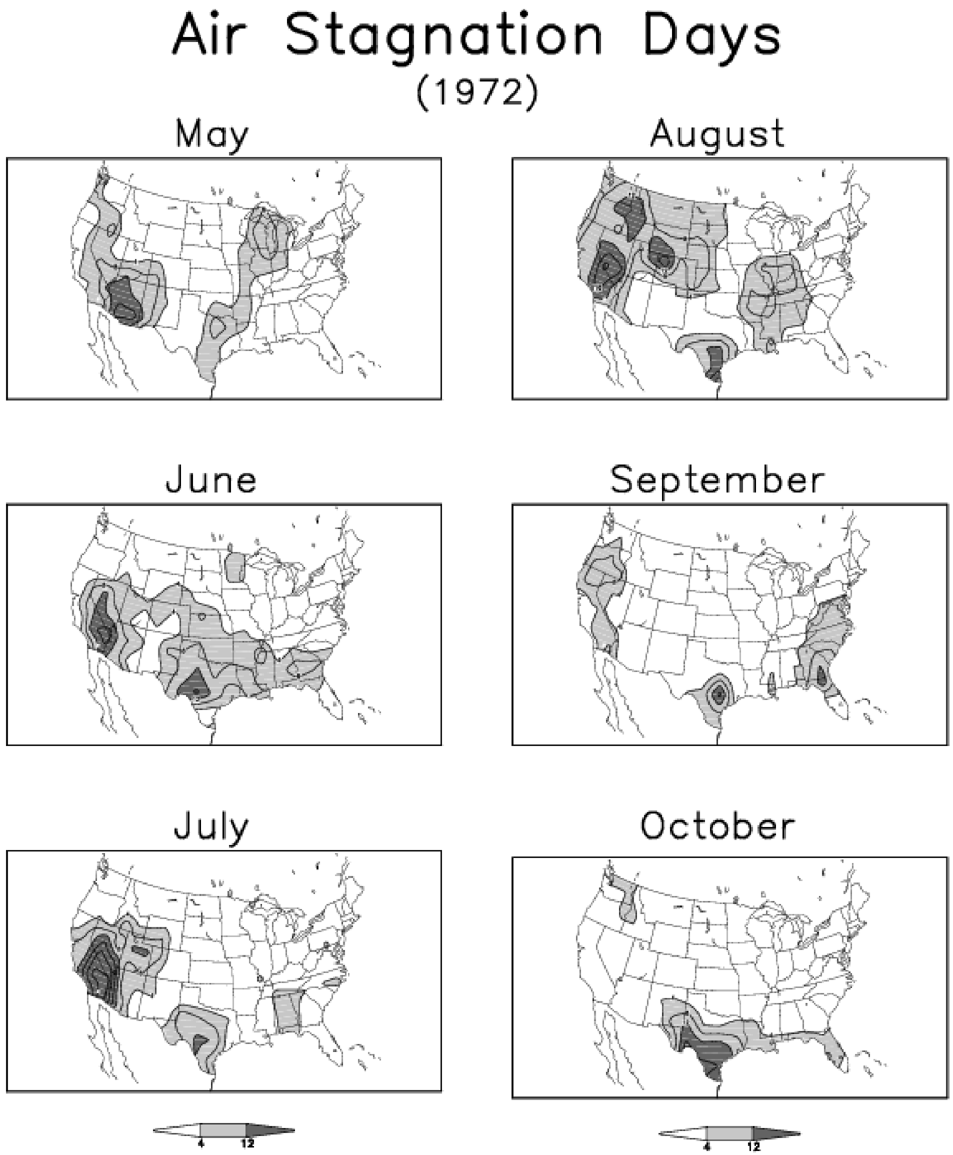

Figure 43, Same as Fig. 17 except for 1972.

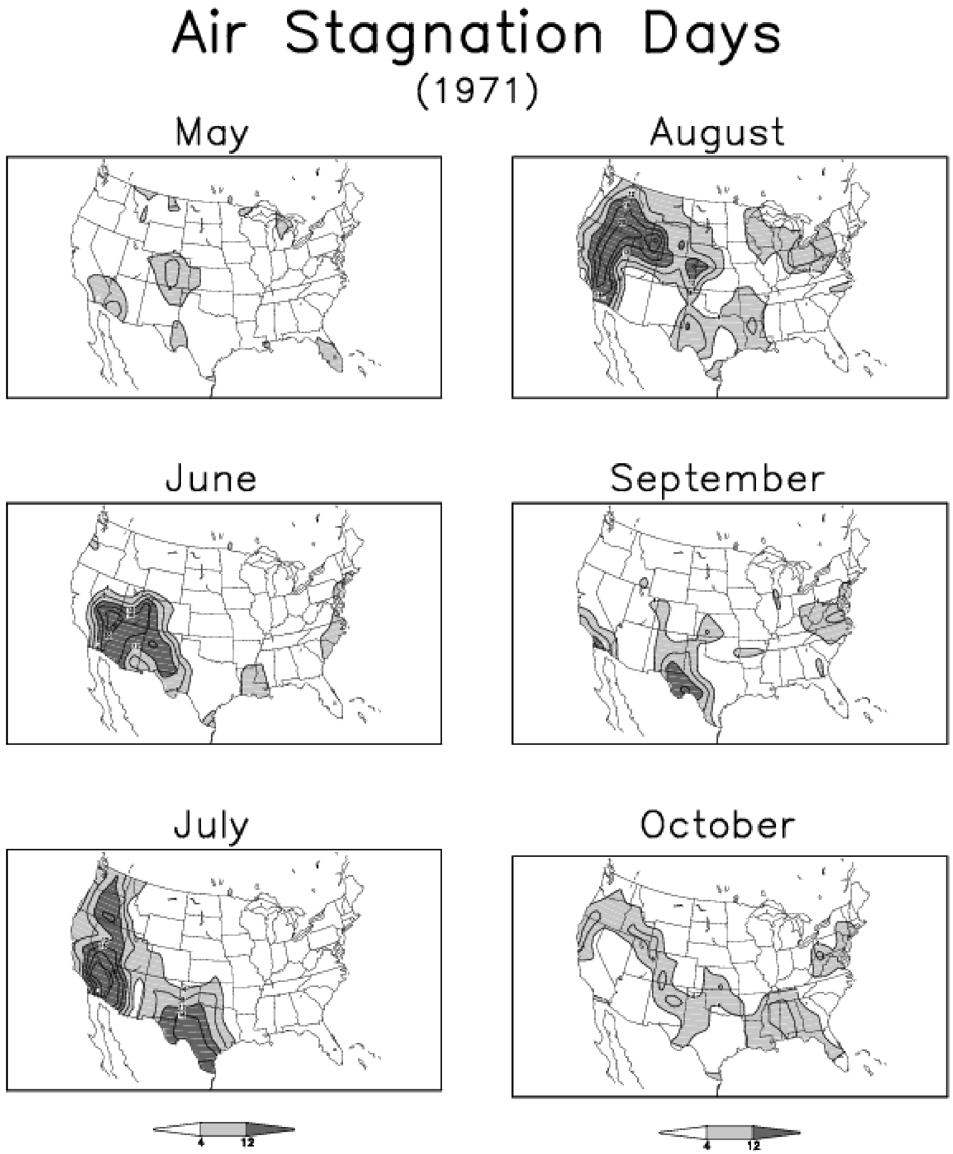

Figure 44, Same as Fig. 17 except for 1971.

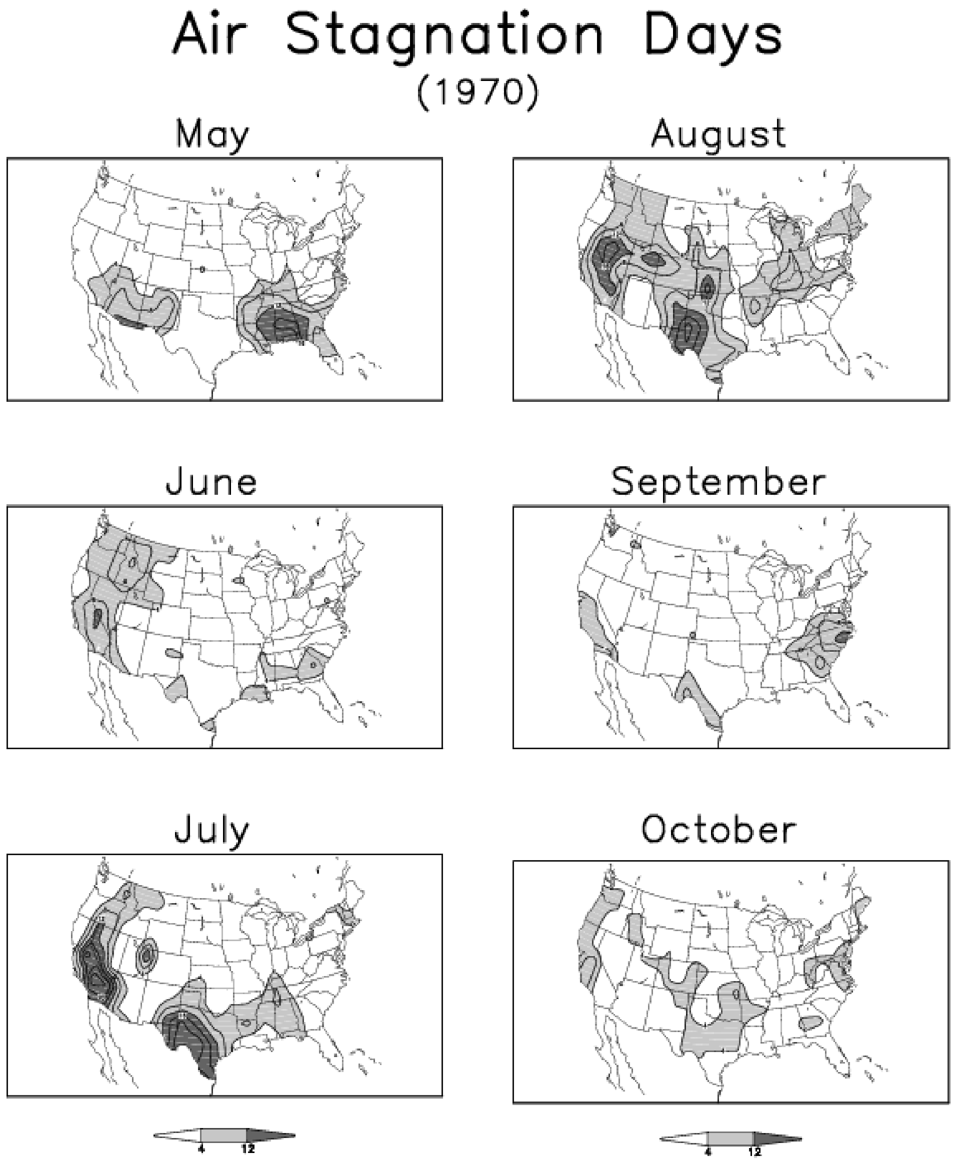

Figure 45, Same as Fig. 17 except for 1970.

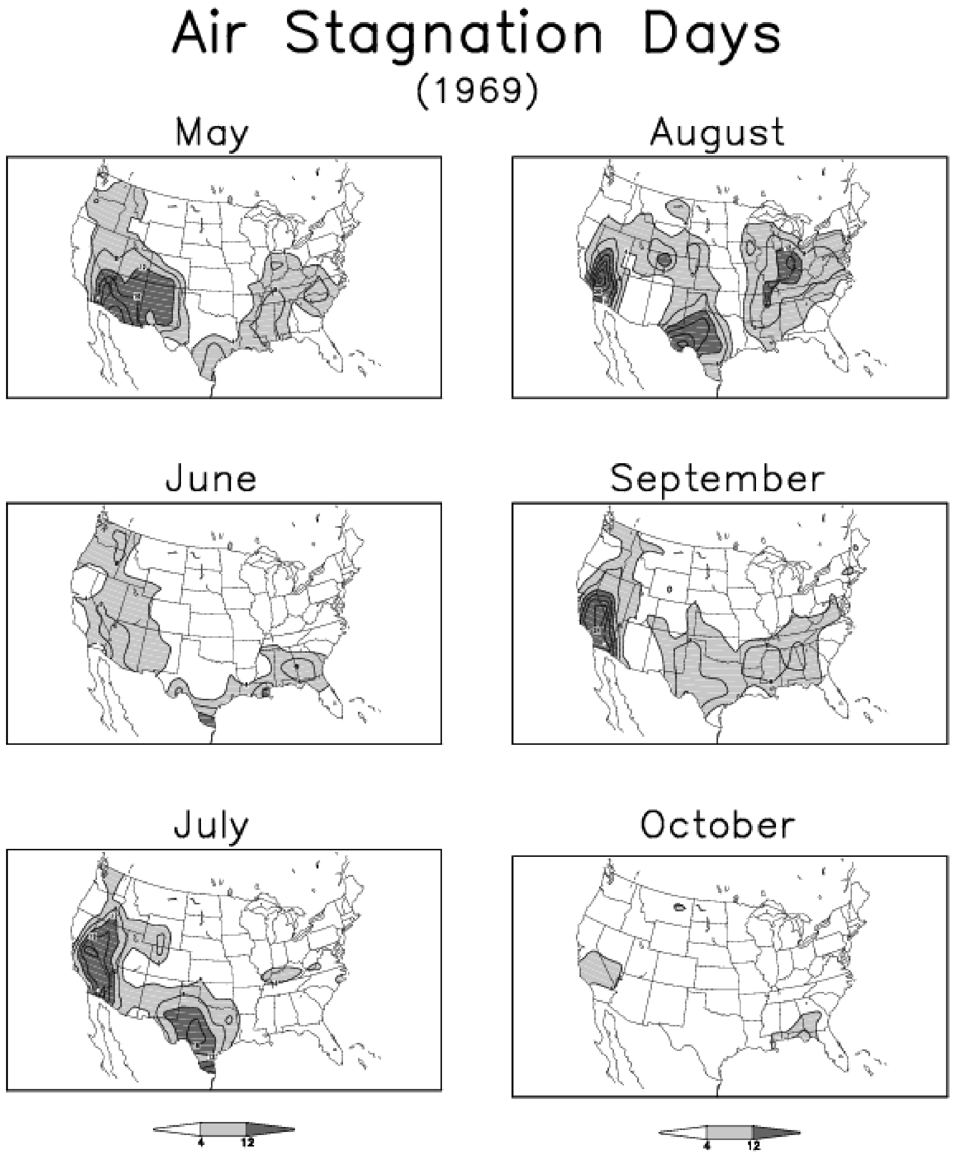

Figure 46, Same as Fig. 17 except for 1969.

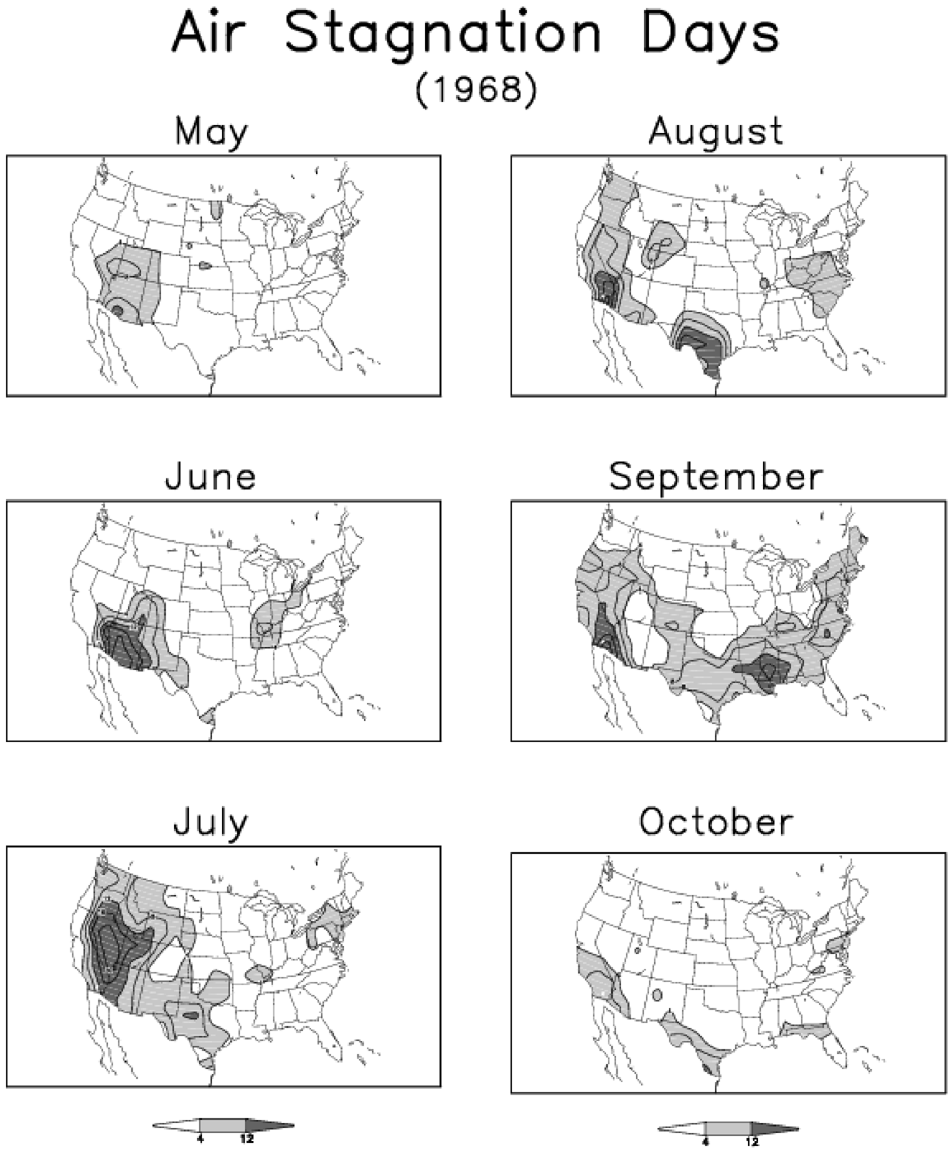

Figure 47, Same as Fig. 17 except for 1968.

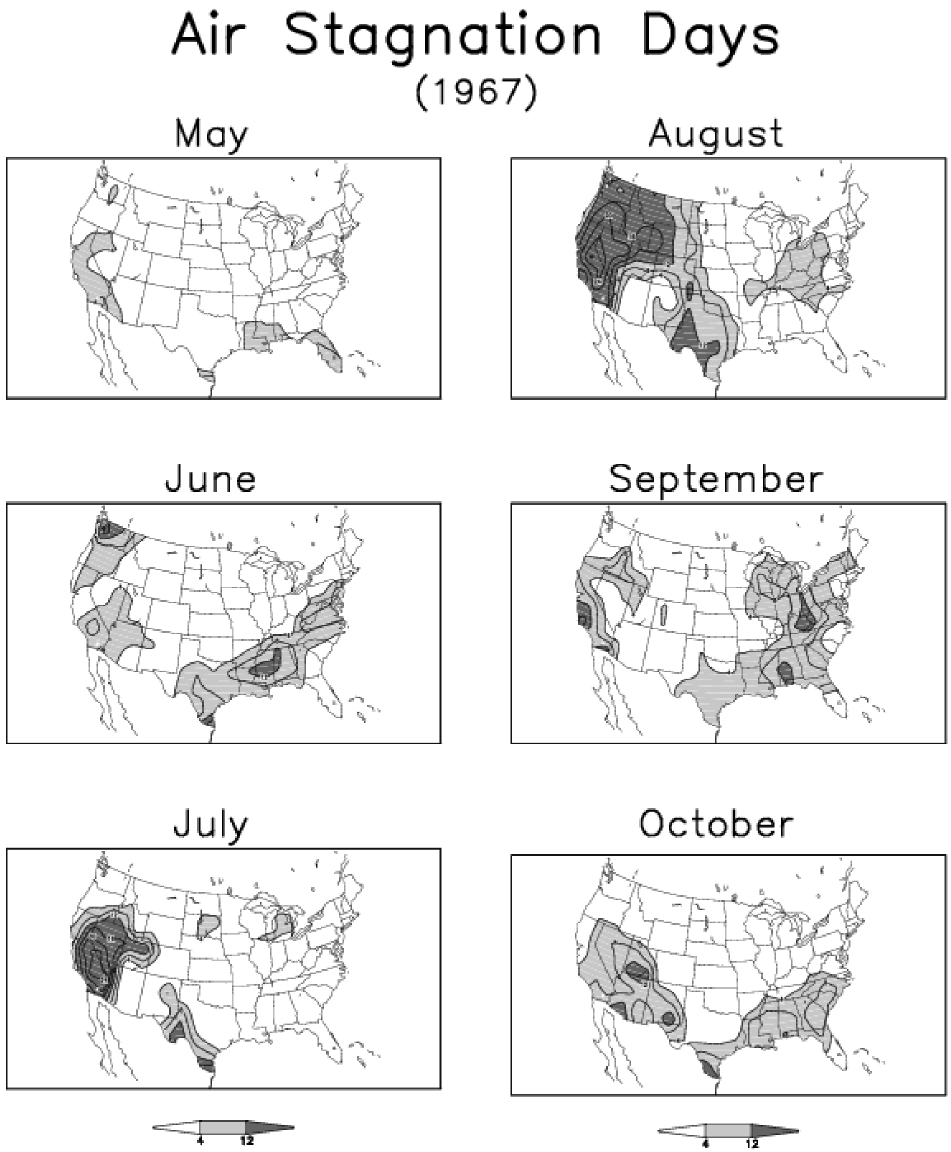

Figure 48, Same as Fig. 17 except for 1967.

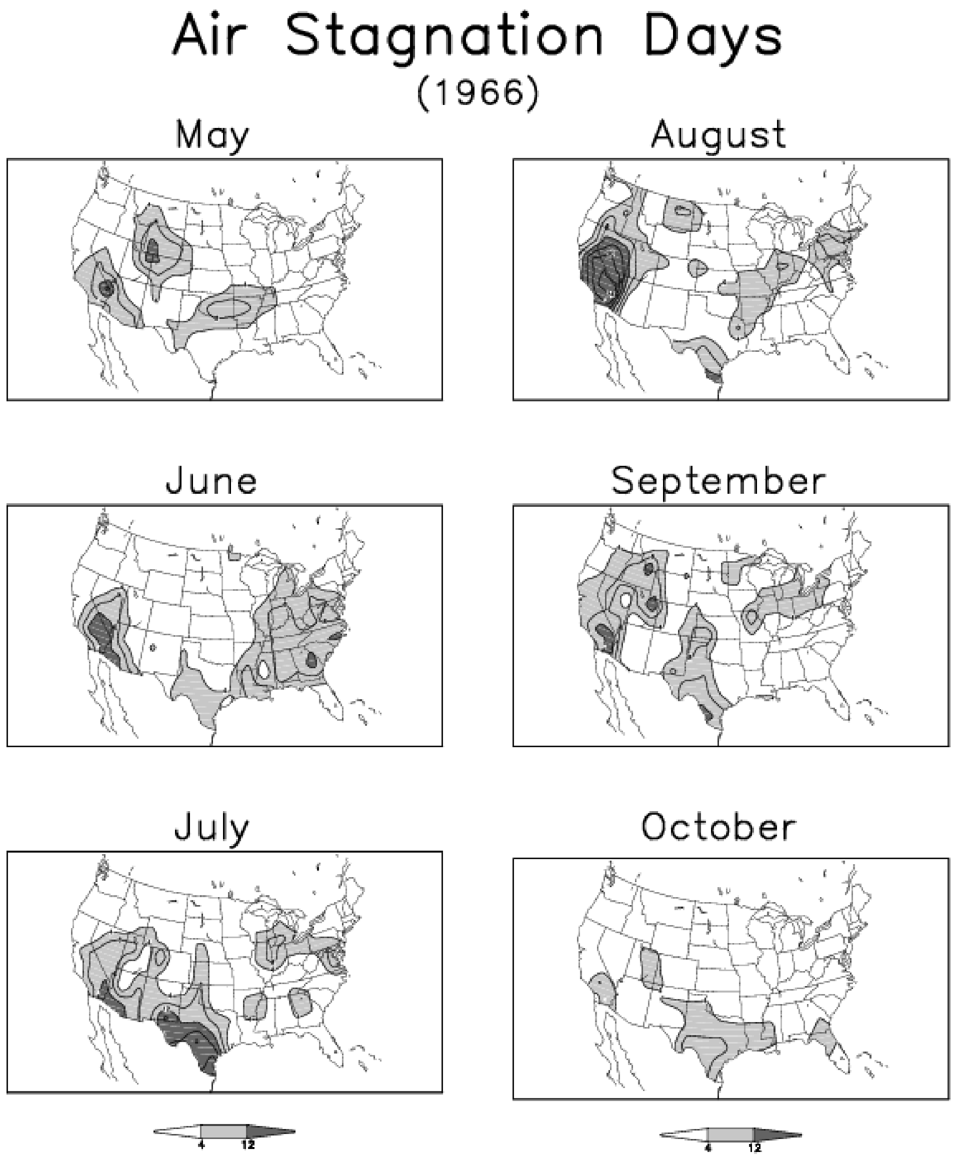

Figure 49, Same as Fig. 17 except for 1966.

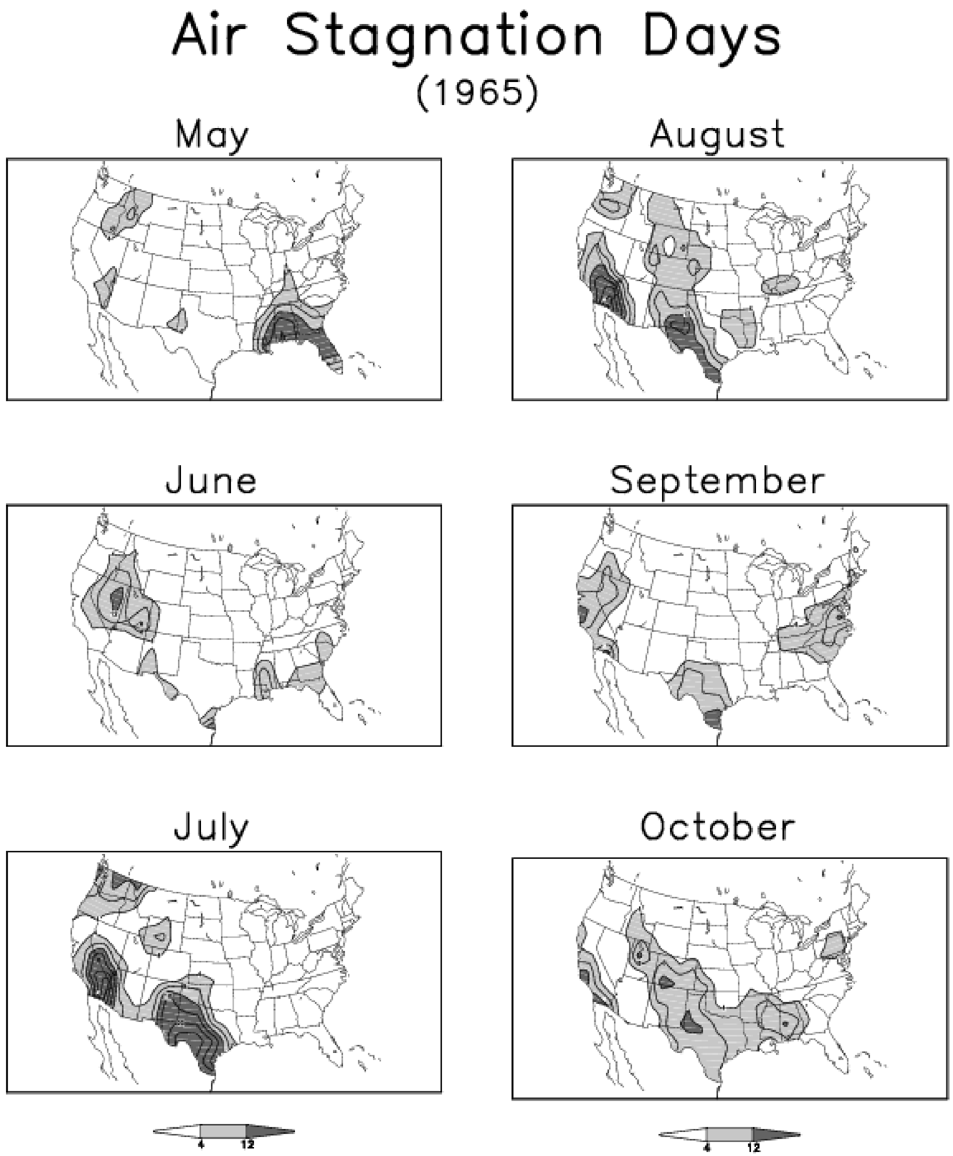

Figure 50, Same as Fig. 17 except for 1965.

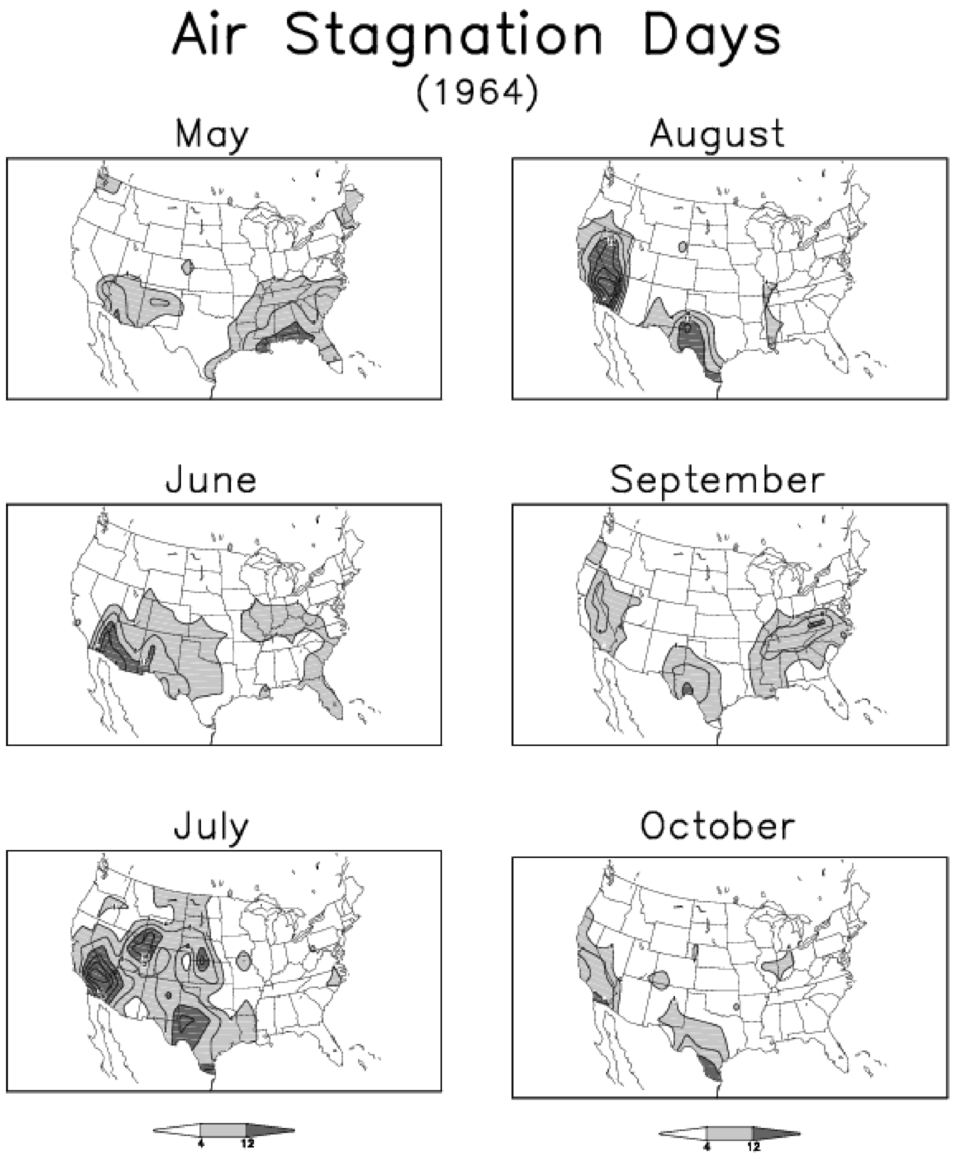

Figure 51, Same as Fig. 17 except for 1964.

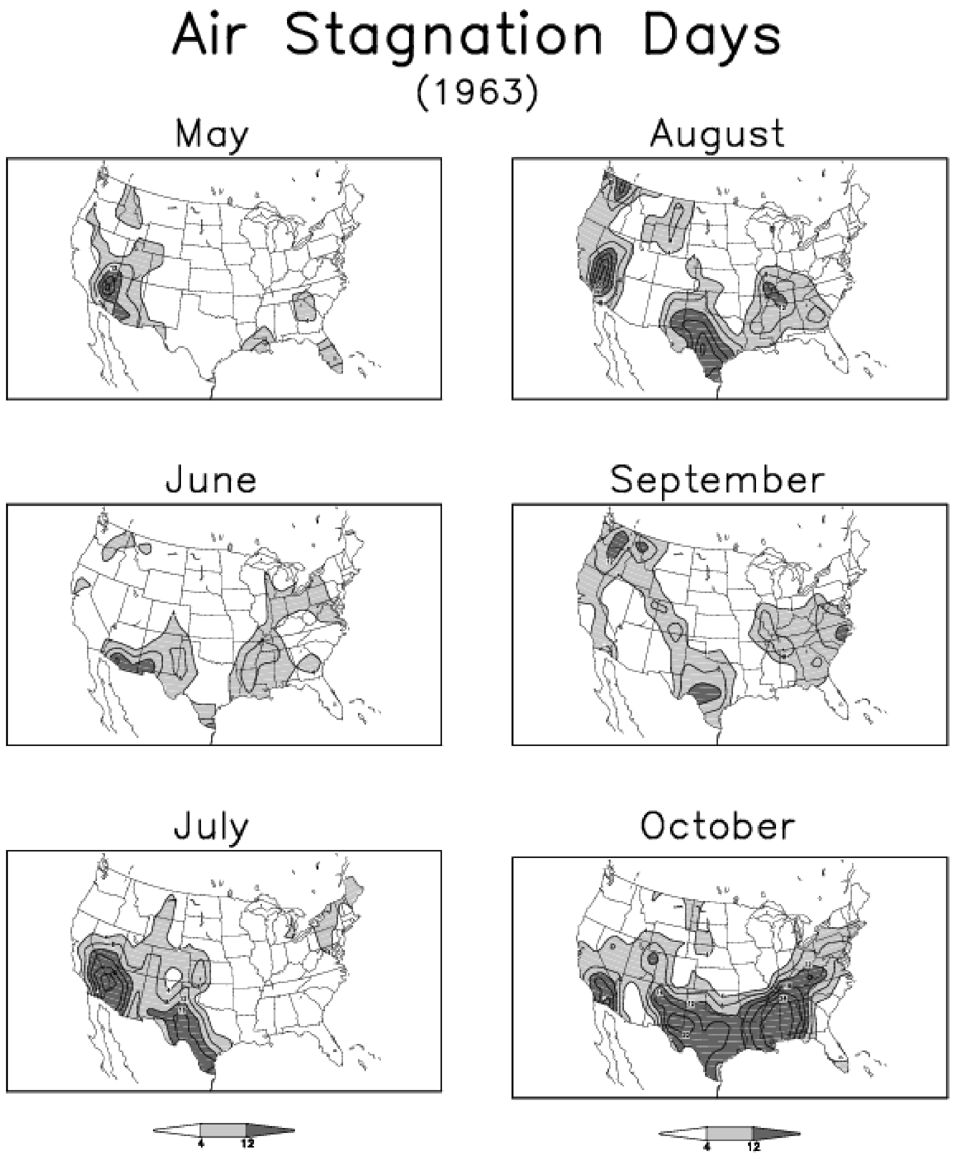

Figure 52, Same as Fig. 17 except for 1963.

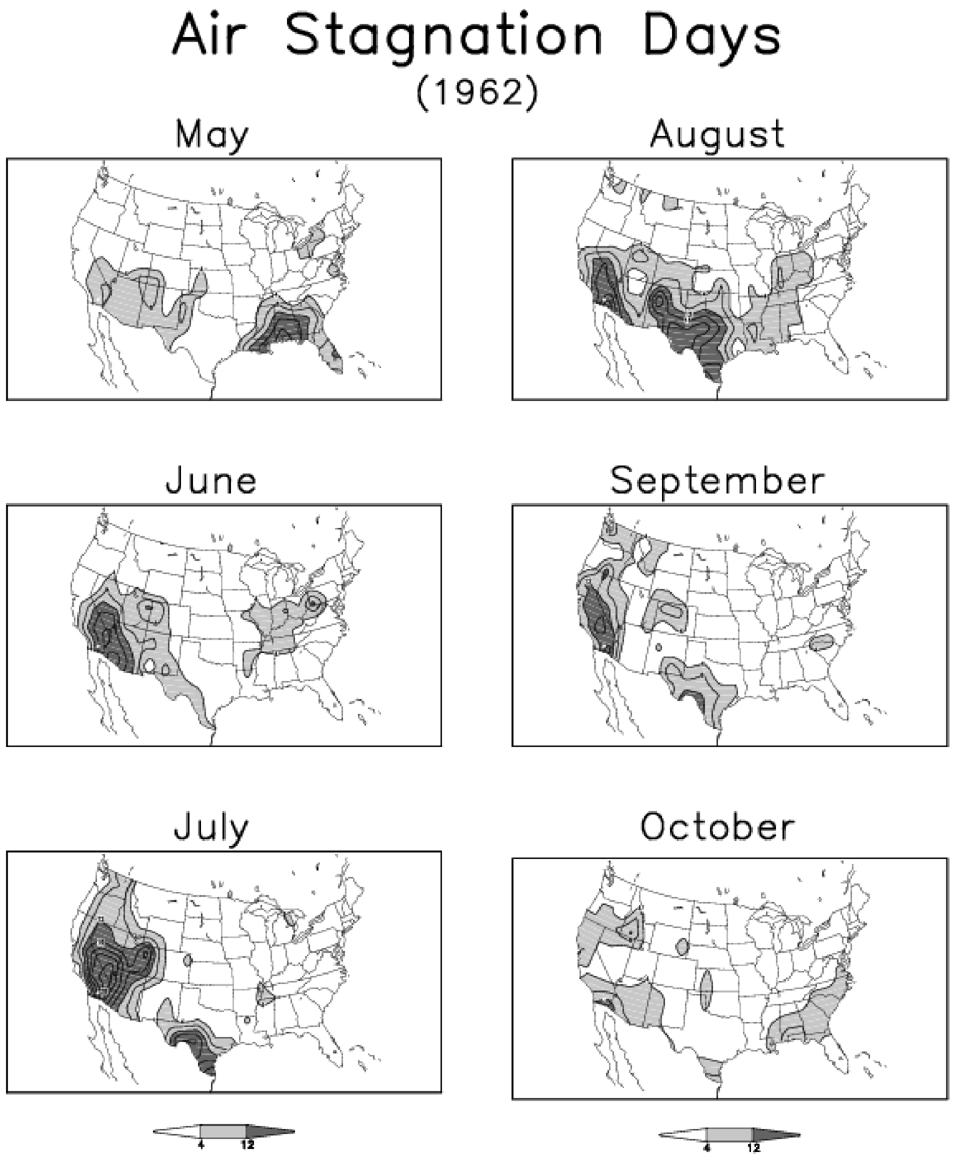

Figure 53, Same as Fig. 17 except for 1962.

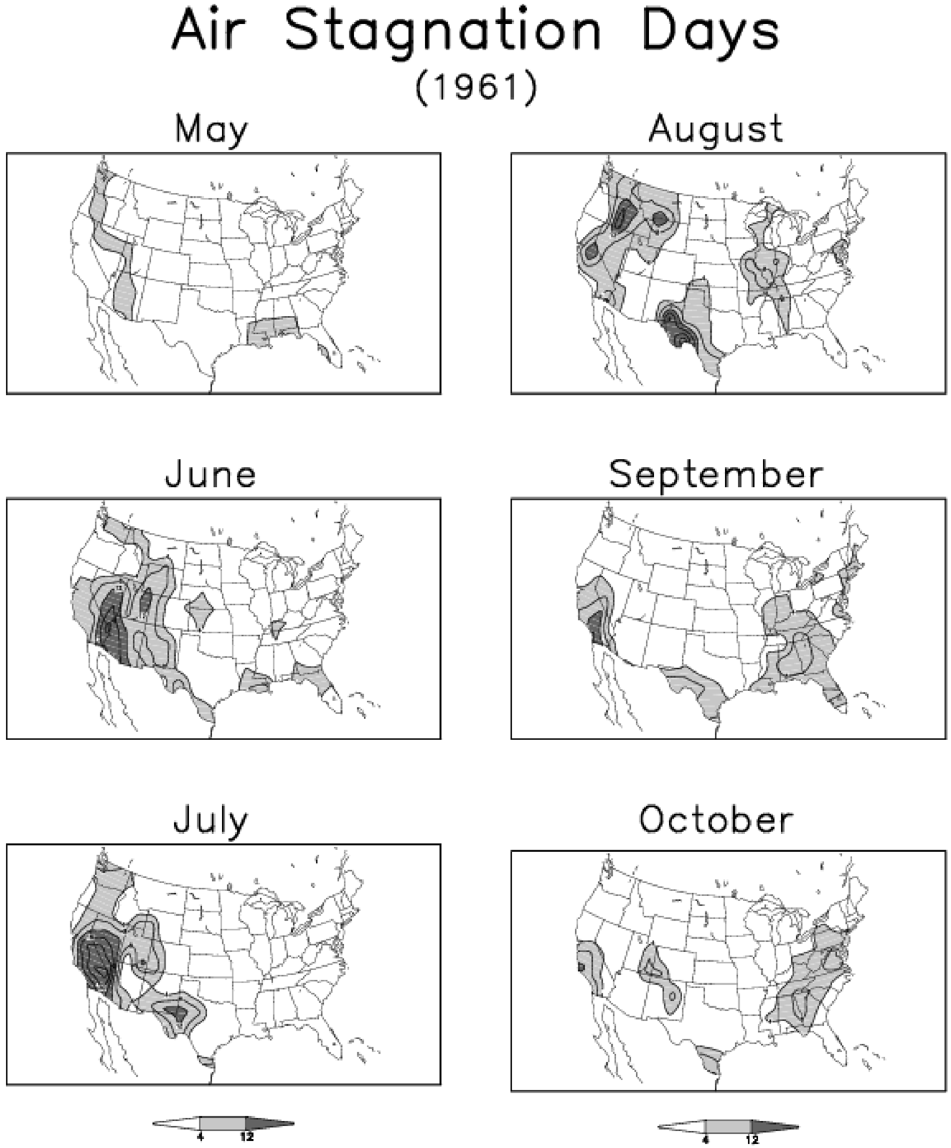

Figure 54, Same as Fig. 17 except for 1961.

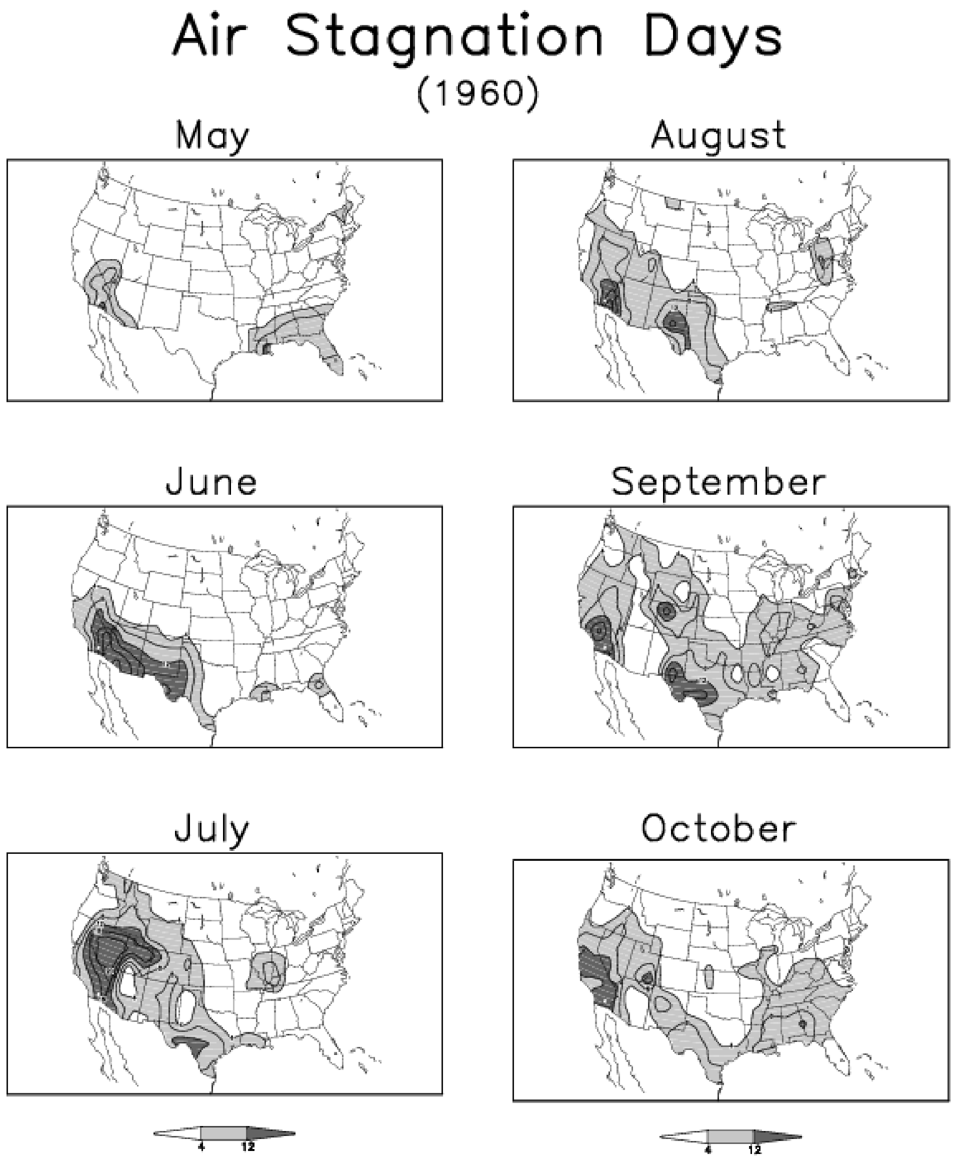

Figure 55, Same as Fig. 17 except for 1960.

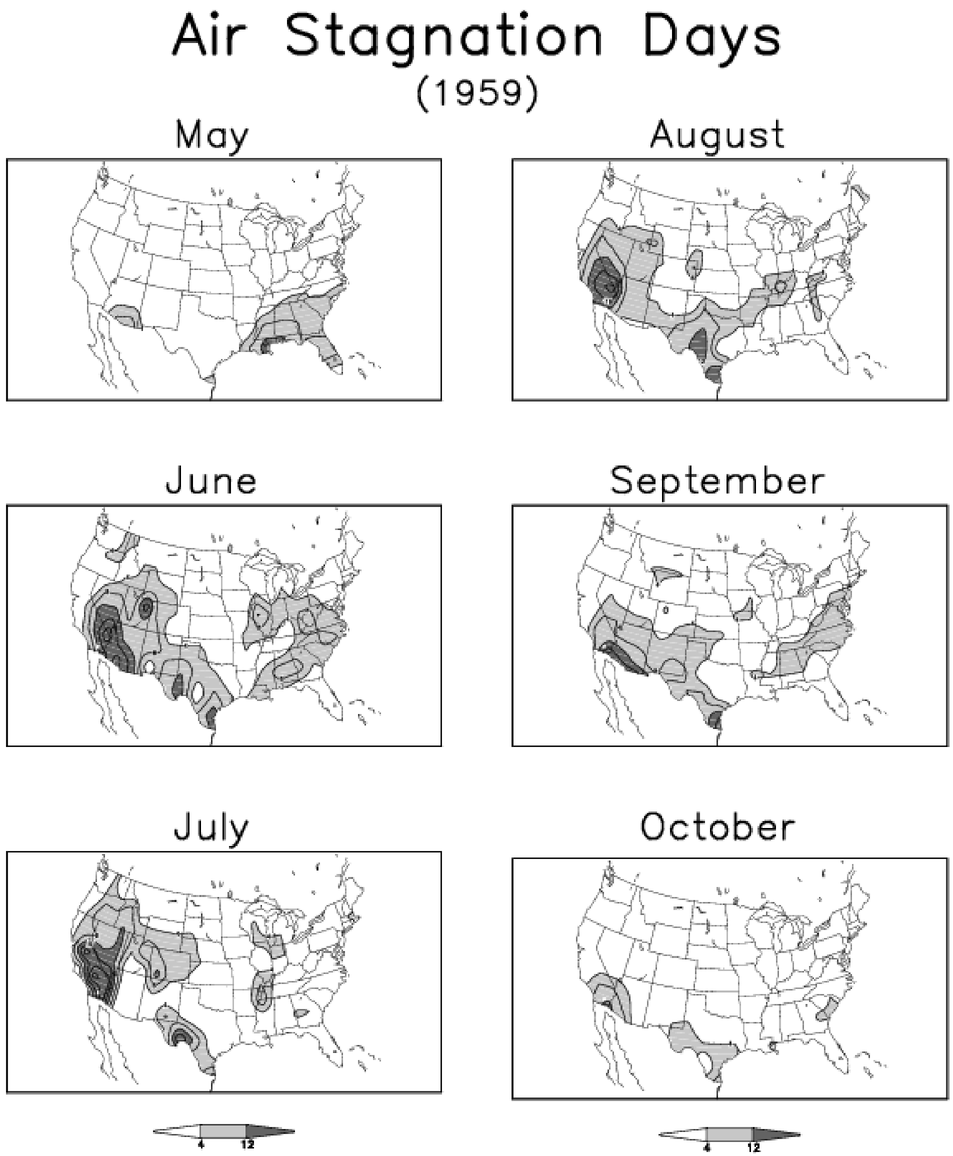

Figure 56, Same as Fig. 17 except for 1959.

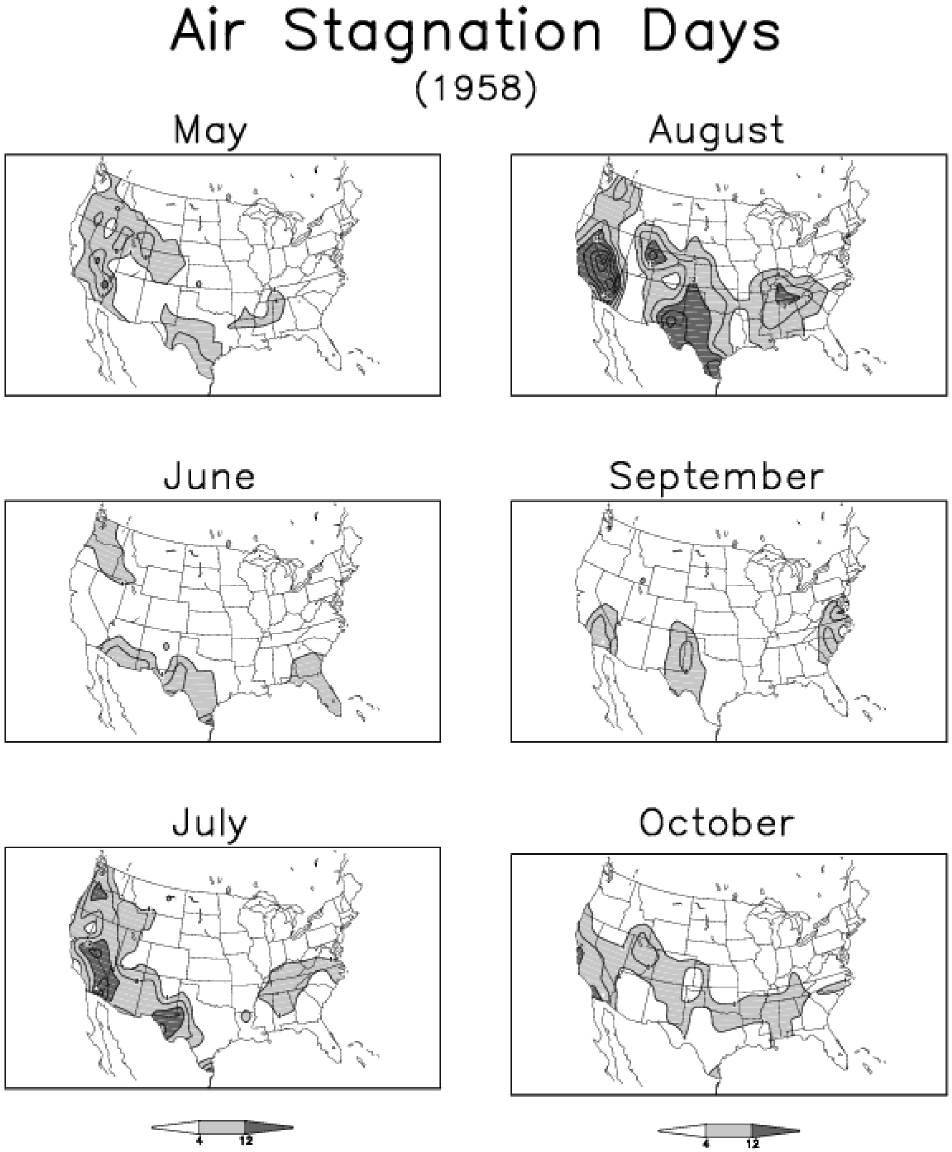

Figure 57, Same as Fig. 17 except for 1958.

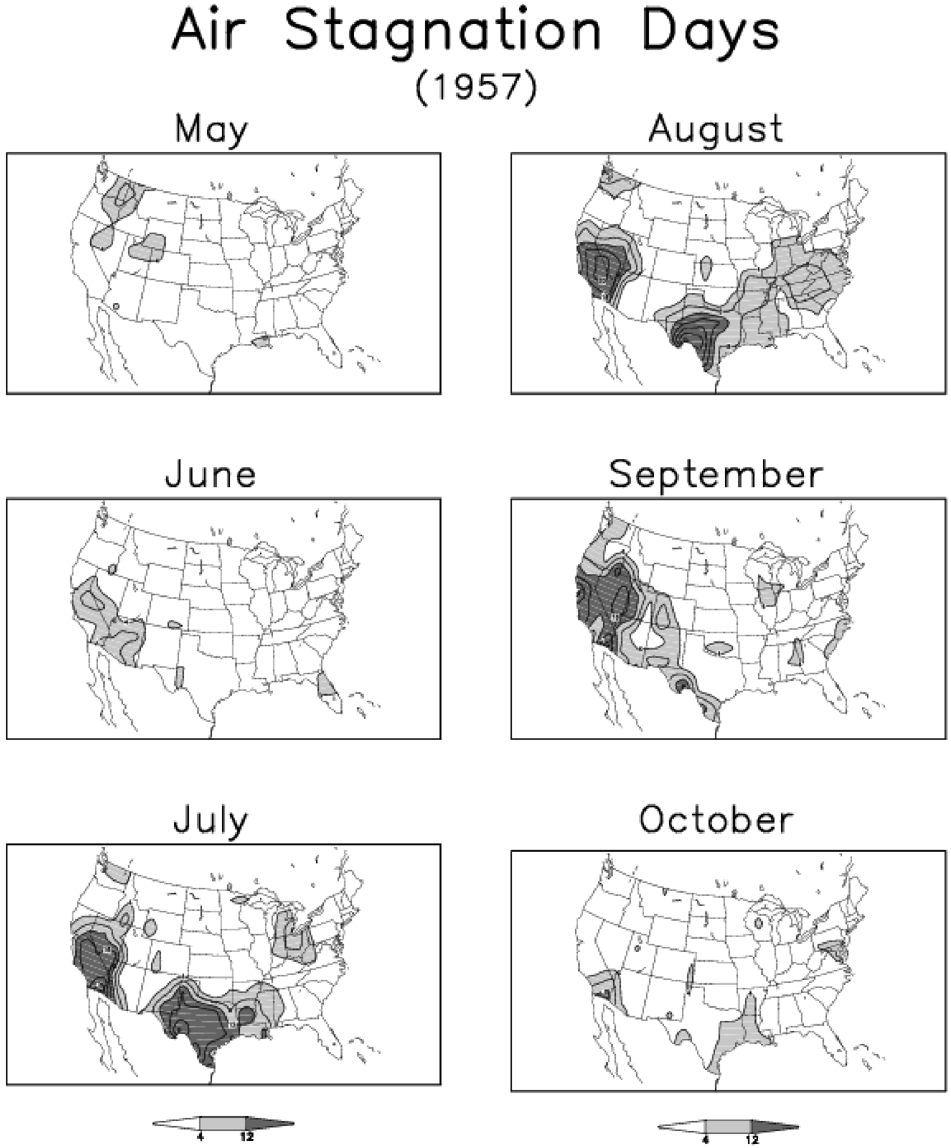

Figure 58, Same as Fig. 17 except for 1957.

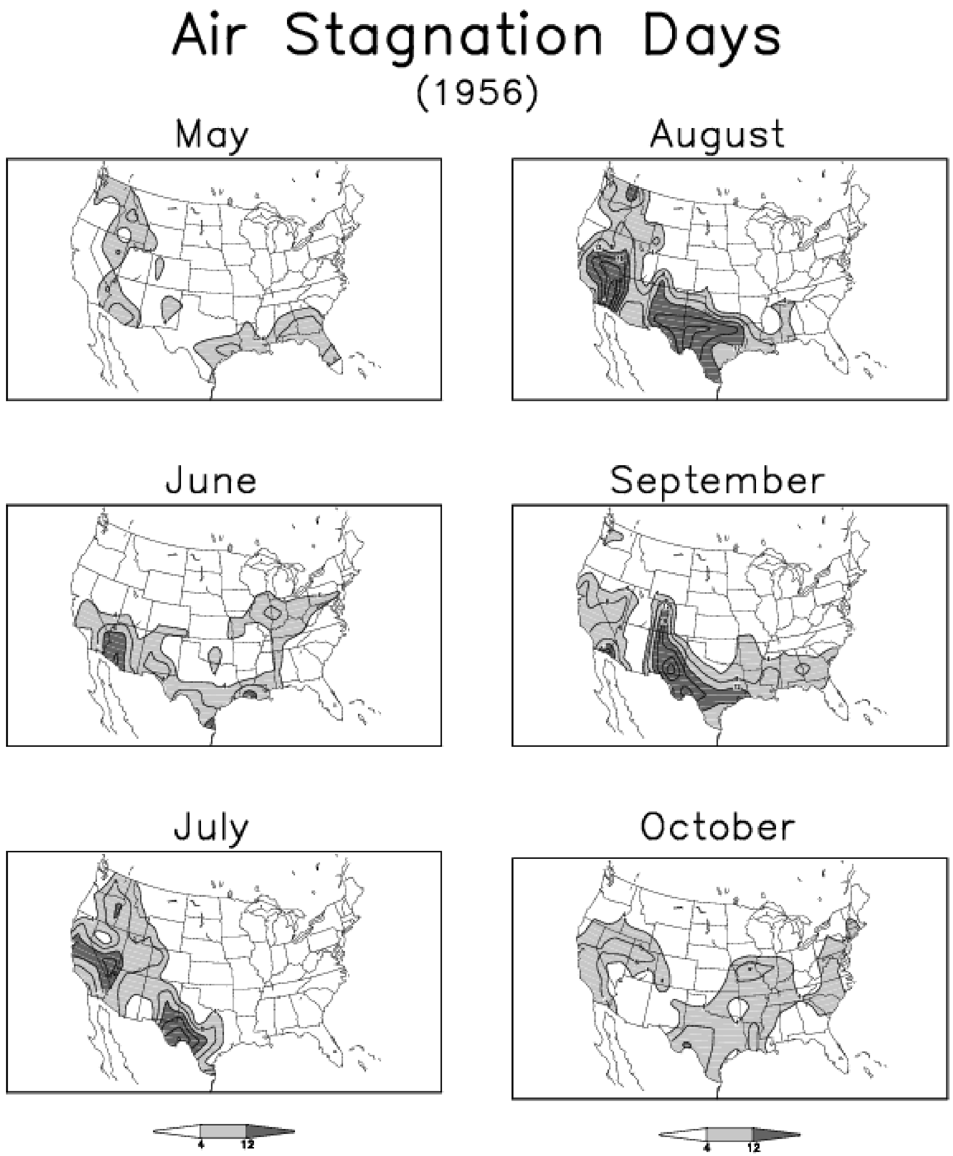

Figure 59, Same as Fig. 17 except for 1956.

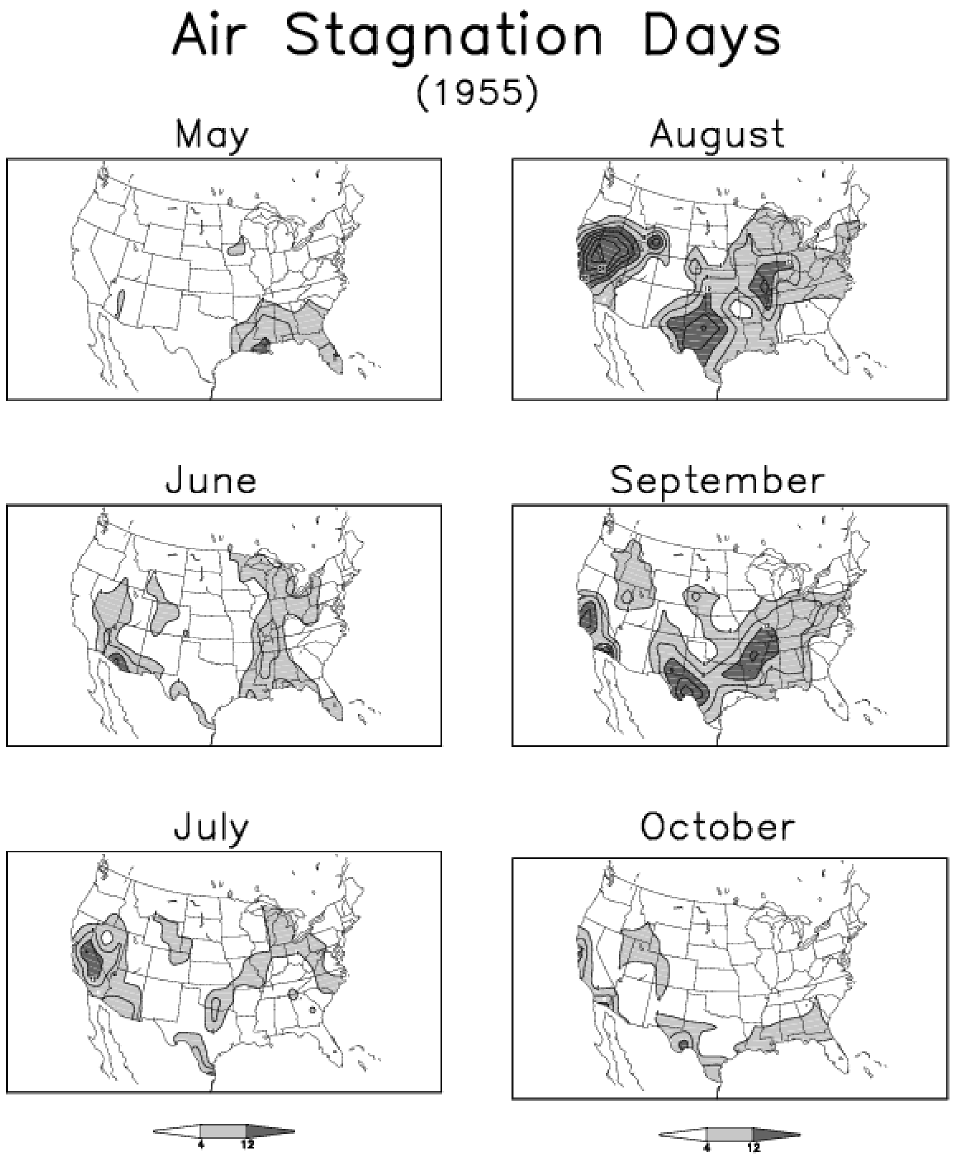

Figure 60, Same as Fig. 17 except for 1955.

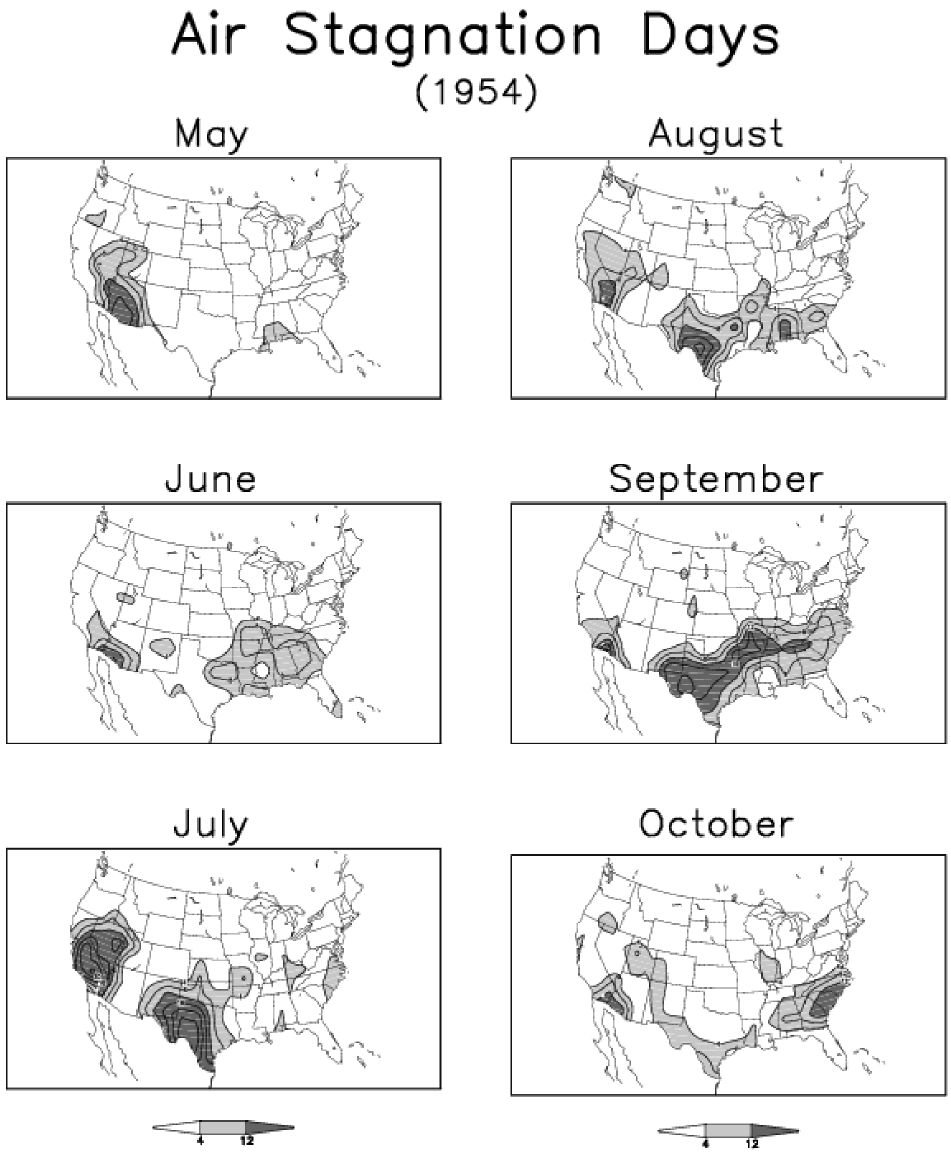

Figure 61, Same as Fig. 17 except for 1954.

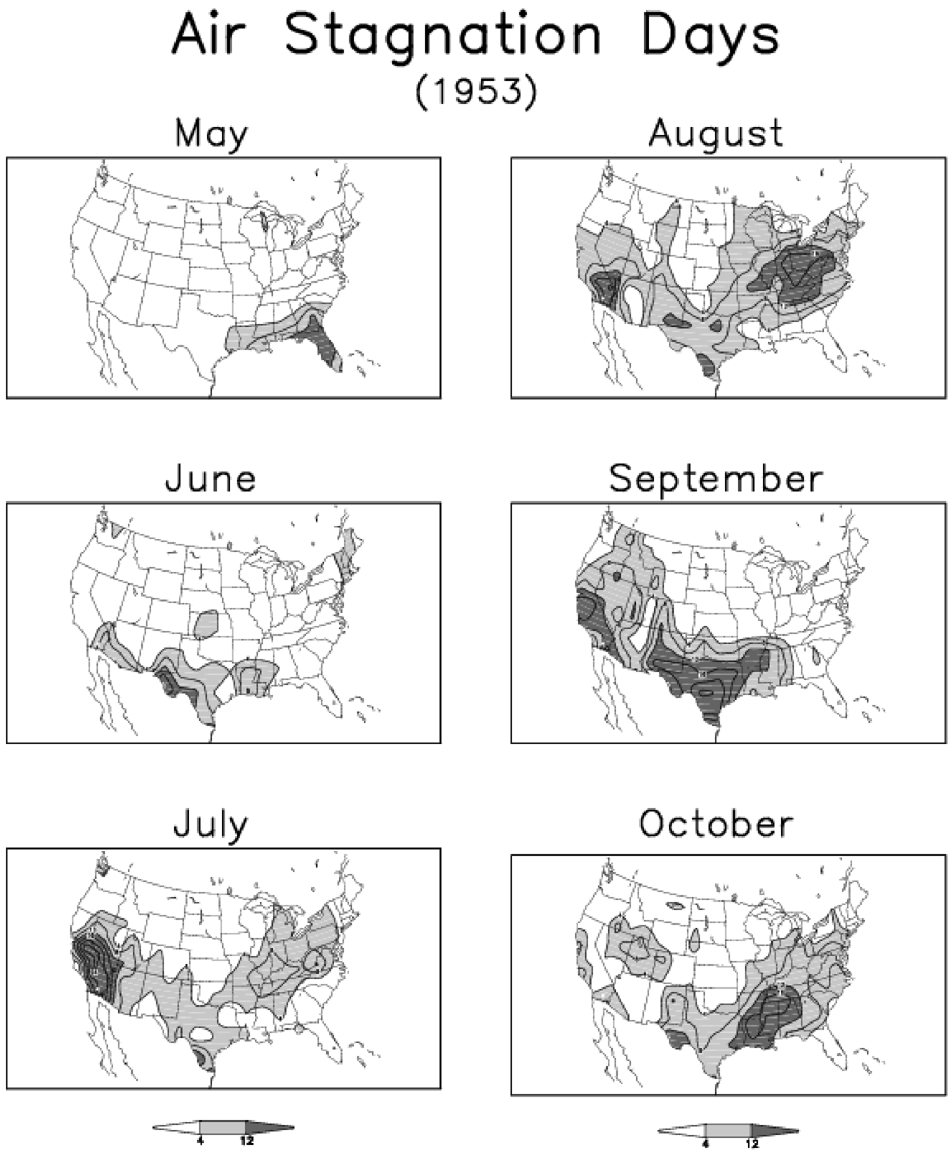

Figure 62, Same as Fig. 17 except for 1953.

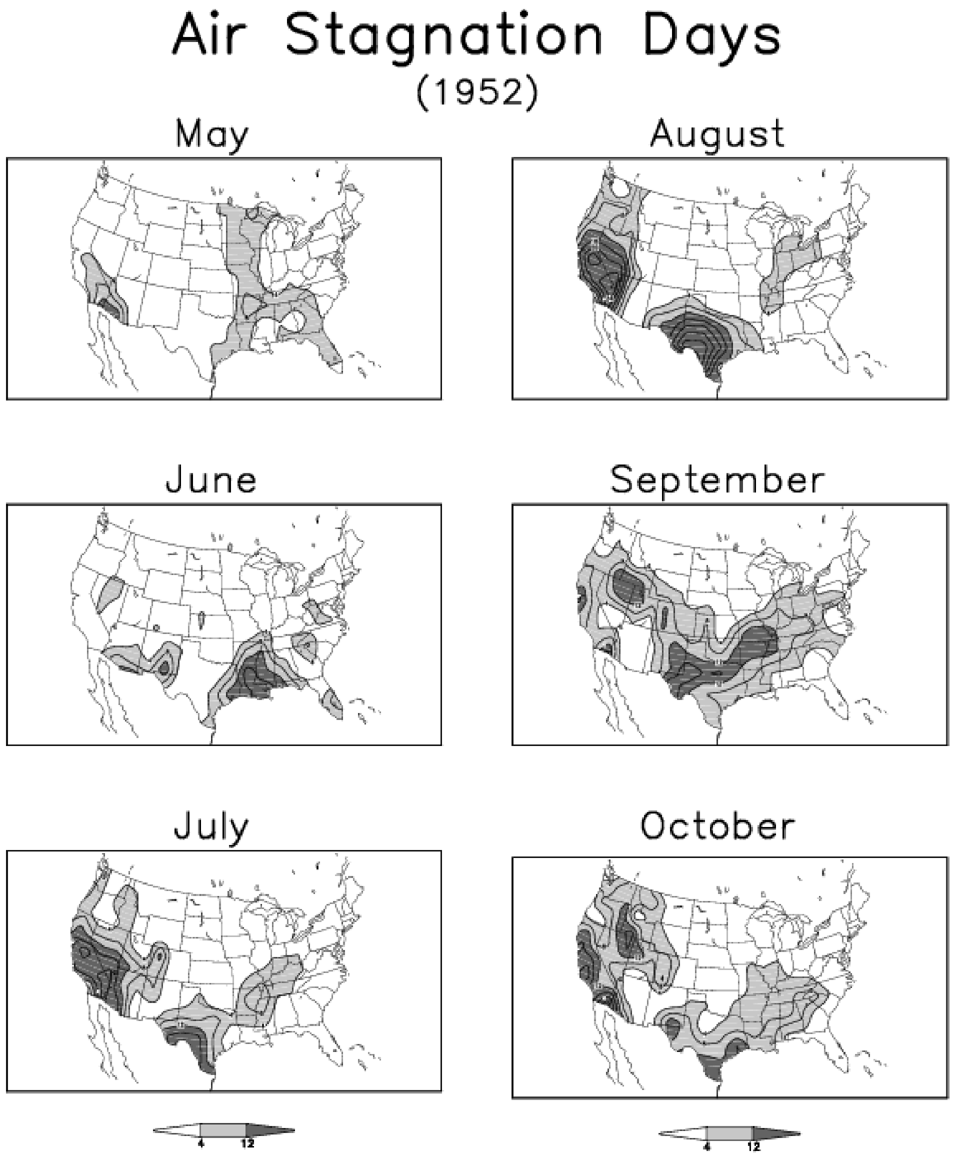

Figure 63, Same as Fig. 17 except for 1952.

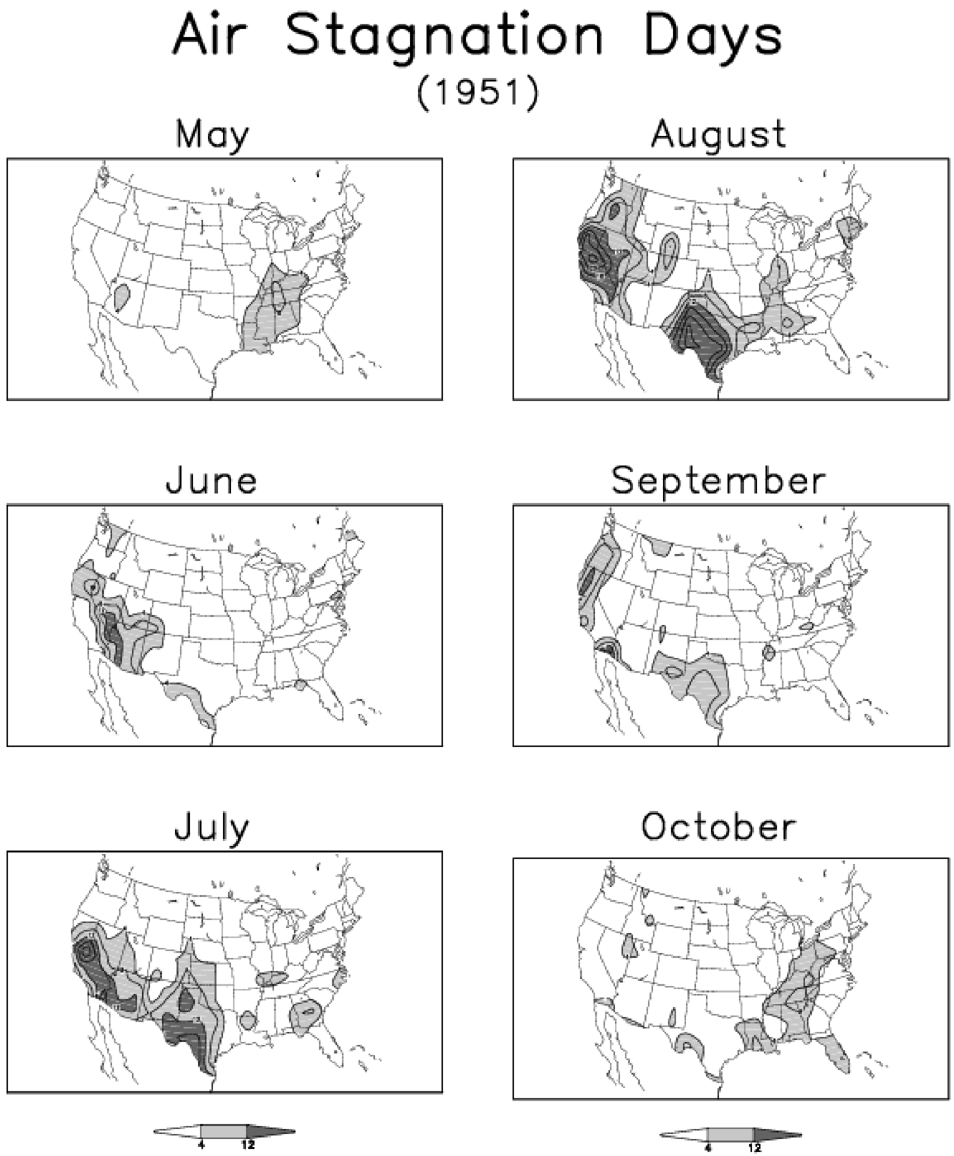

Figure 64, Same as Fig. 17 except for 1951.

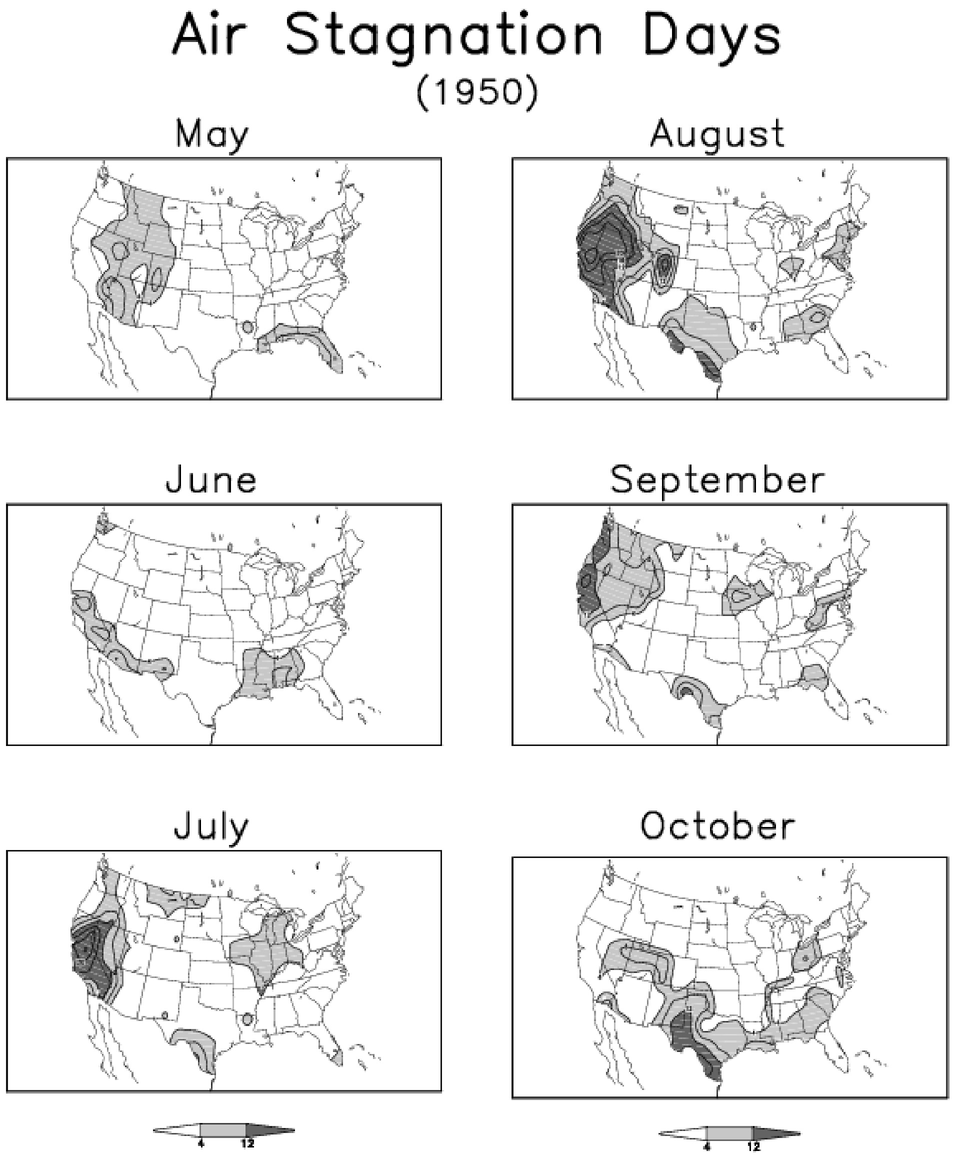

Figure 65, Same as Fig. 17 except for 1950.

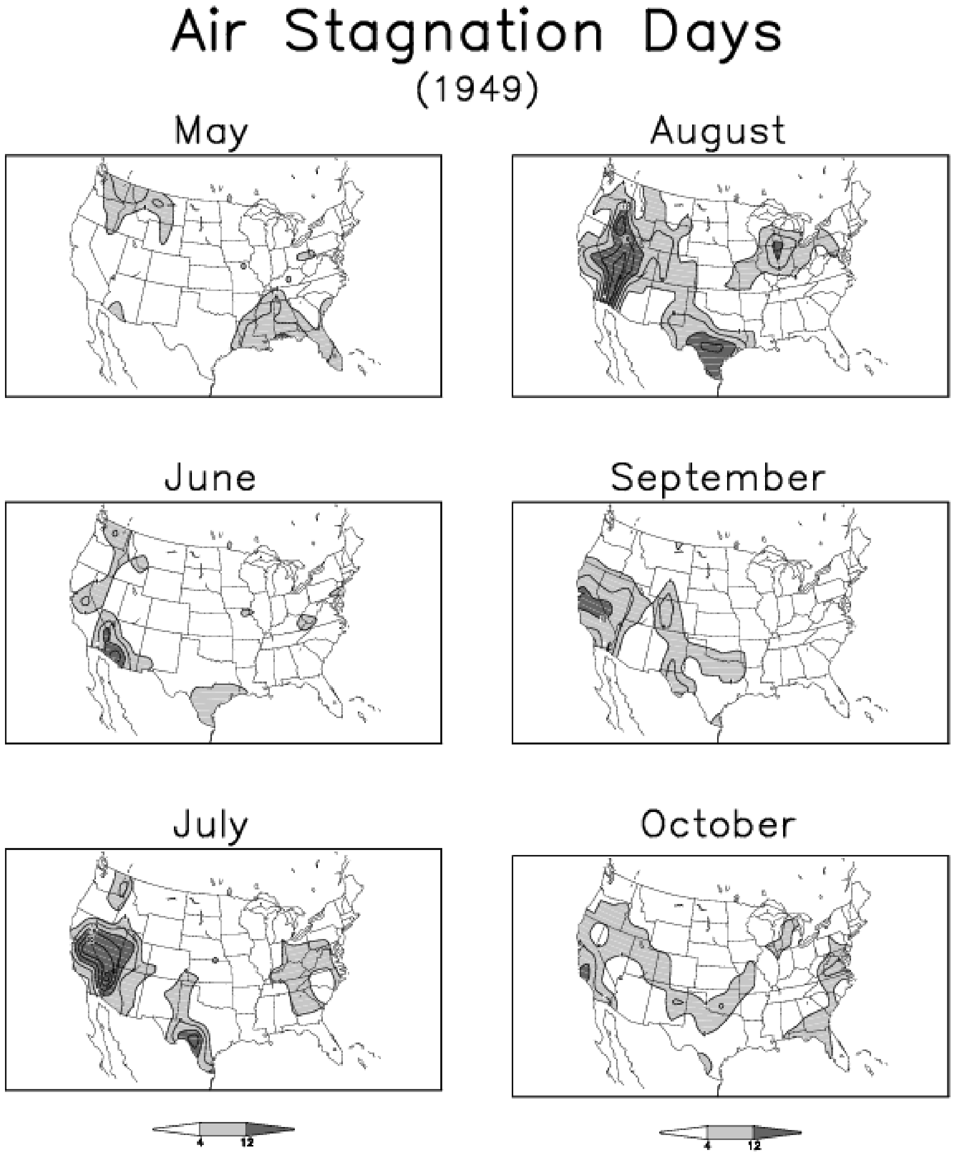

Figure 66, Same as Fig. 17 except for 1949.

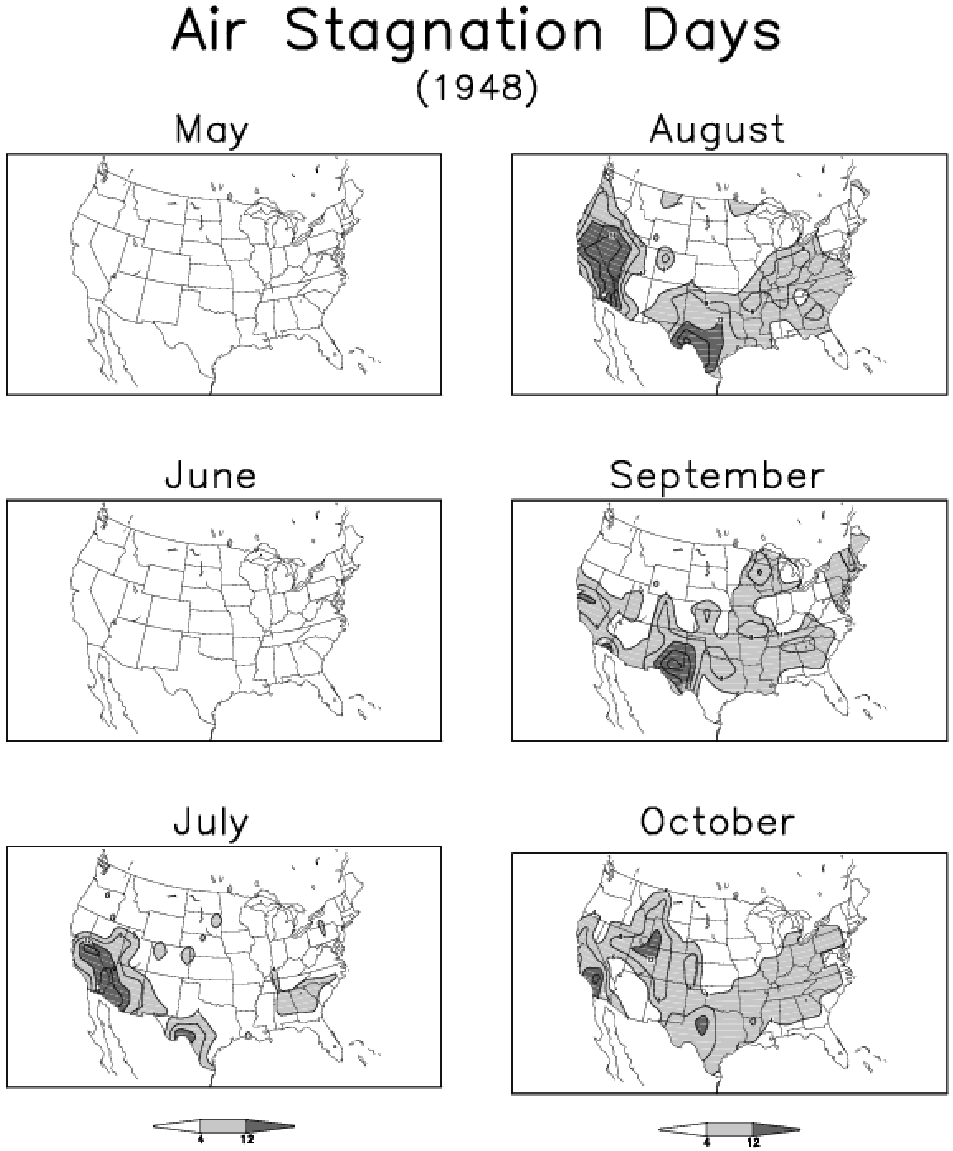

Figure 67, Same as Fig. 17 except for 1948.