Air Quality Climate in the Columbia River Basin

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Abstract

Aspects of climate that influence air quality in the Columbia River basin of the Northwestern United States are described. A few, relatively simple, analytical tools were developed to show the spatial and temporal patterns of mean-monthly mixing heights, precipitation scavenging, upper level and surface trajectory winds, and drought that inhibit pollution uptake. Also, potential changes in air quality from the effects of increasing greenhouse gases are discussed.

Keywords: Air quality, climate, air pollution, mixing heights, trajectory winds, pollution trajectories, pollution scavenging, drought, global change, Columbia River basin.

Summary

Several components of climate influence air quality in the Columbia River basin of the Northwestern United States. For example, stagnant air trapped below a persistent temperature inversion is common in the basin during winter. Stagnant conditions remain possible but are less frequent in summer. Midwinter rain in the basin occurs occasionally and allows effective scavenging of pollutants by liquid precipitation throughout the year. Pollution from the basin that reaches upper levels of the atmosphere most often will be transported by prevailing westerly winds toward states east of the basin. Northerly upper level winds, which transport pollutants to the Grand Canyon, occur less than 10 percent of the time. Surface winds usually transport pollution toward the west (offshore) in winter and toward the east (onshore) in summer. Also, during summer a diurnal pattern allows pollution to be lofted to upper levels during the day and follow downslope winds at night. Drought events in the basin, which reduce the susceptibility of many plants to pollution damage, are common but usually mild. Finally, a potential change in climate caused by increasing greenhouse gases may affect air quality in the basin. For example, higher mixing heights in the atmosphere may improve dispersion during summer but a decrease in storms may allow winter stagnation to persist for longer periods than normal. Increased summer drought in the central basin but less frequent drought in southeast portions of the basin may change the susceptibility of some plants to pollution damage. Also, a decreased snow cover may cause early discharge of pollutants held in the snowpack.

USDA United States
Department of
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Forest Service

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Bureau of Land
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Interior Columbia
Basin Ecosystem
Management Project
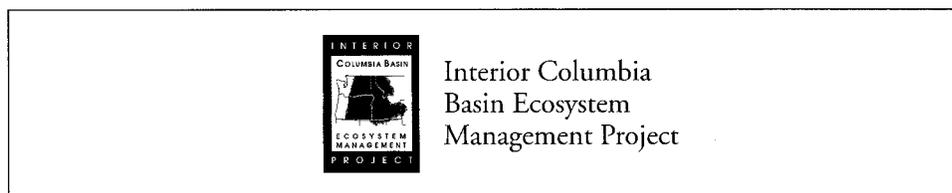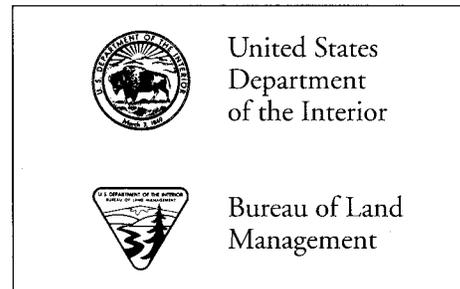
Although air quality in the basin generally is considered good, effects of air pollution on natural resources have been observed (Schoettle and others, in press). Also, rapidly growing population centers in and around the basin are increasing the need for abundant new energy resources, which will compound current pollution levels. Because the transport and deposition of pollutants are controlled to a great extent by atmospheric conditions, understanding related spatial and temporal climatic patterns plays a key role in developing effective means of managing air quality.

Climate patterns in the Columbia River basin are dominated by topographic features. Surrounding mountain ranges prevent frequent intrusion from progressing air masses and create an isolated, sometimes stagnant, basin atmosphere. Gaps through the mountains, however, allow a striking pattern of mixing that is unique to the basin. Figure 1 shows key features of the basin.

Components of Air Quality Climate

Mixing Height

Mixing height is a level in the atmosphere above which vertical exchange of air is inhibited. Low mixing heights mean that the air is generally stagnant with very little vertical motion; pollutants usually are trapped near the ground surface. High

mixing heights allow vertical mixing within a deep layer of the atmosphere and good dispersion of pollutants.

When a parcel of air is warmer than its surroundings, it will rise. When it is cooler than its surroundings, it will sink. One way to determine mixing height is to consider a parcel of air near the ground, whose temperature equals the daily maximum surface temperature. The parcel is lifted dry-adiabatically until it reaches the ambient air temperature, which is measured from a radiosonde observation (RAOB). The level at which the temperature of the lifted parcel equals the ambient air temperature is defined as the mixing height. Above the mixed layer, further lifting of the parcel will cause it to become cooler than ambient air temperatures.

Afternoon RAOBs were used to approximately coincide with the time of maximum daily surface temperature. Afternoon RAOBS occur near 0000 Greenwich Mean Time (GMT), which coincides with 1600 Pacific Standard Time (PST) and 1700 Mountain Standard Time (MST) in the Columbia River basin. Data included about 1,000 RAOBs taken from 1966 to 1989. Mixing heights were calculated by the Western Regional Climate Center. The stations analyzed included Quillayute, Washington (58 meters elevation), the only station on the Pacific coast; Salem, Oregon (61 meters), and Medford, Oregon (421 meters), between the coast and Cascade Ranges; Spokane, Washington
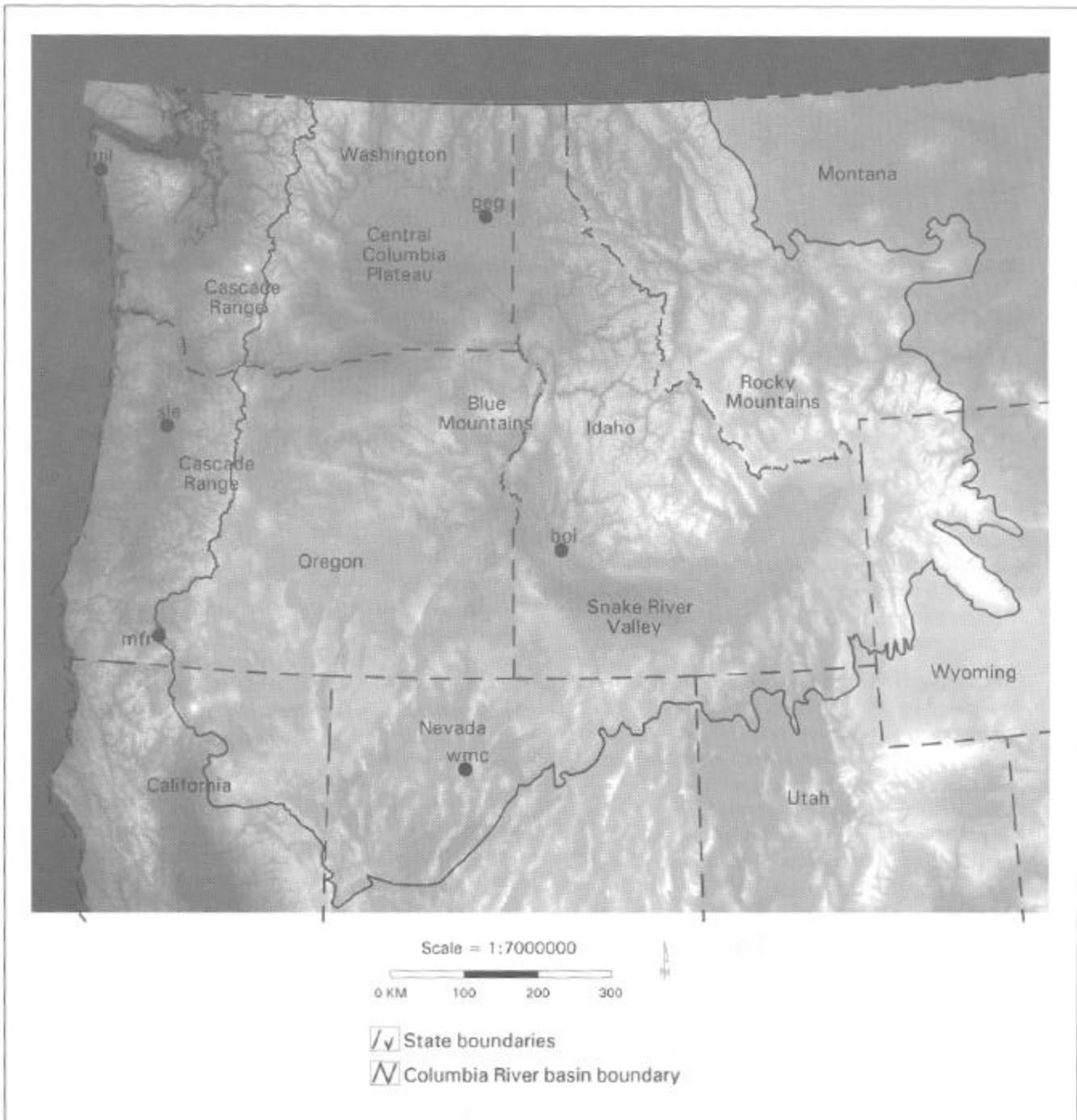
Figure 1—Topography of the Columbia River basin. Upper level observation stations are boi = Boise, geg = Spokane, uil = Quillayute, sle = Salem, mfr = Medford, and wmc = Winnemucca.

(722 meters) and Boise, Idaho (871 meters), inside the basin; and Winnemucca, Nevada (1310 meters), just south of the basin in northern Nevada.

In winter, mixing heights remain below about 300 meters in most places (fig. 2). During spring, Winnemucca begins to "mix out" first because the air is not constrained by basin topography (fig. 3). During summer (fig. 4) Winnemucca experiences consistently high mixing heights because the summer sunshine efficiently warms the inland continent. Within the basin, the mean summer mixing height is about 1800 meters at Spokane and Boise. The range of mixing heights, however, includes levels below 900 meters, especially at Boise where topographic constraints from the

Snake River valley are even more dominant than the overall basin topography. Stations west of the Cascade crest are influenced by frequent intrusions of marine clouds that increase atmospheric stability. This mostly is observed at Quillayute on the Washington coast. In autumn, mixing heights frequently drop below 900 meters at west-side and basin interior stations (fig. 5). They also begin to lower at Winnemucca.

To illustrate potential areal extent of stagnant air, constant height levels of 1000 meters and 1400 meters were plotted over the basin topography. The first plot (fig. 6) shows where stagnant air may occur if the mixing height is constant at 1000 meters, near the lowest summer mixing heights. Stagnant air is confined to the central plateau of
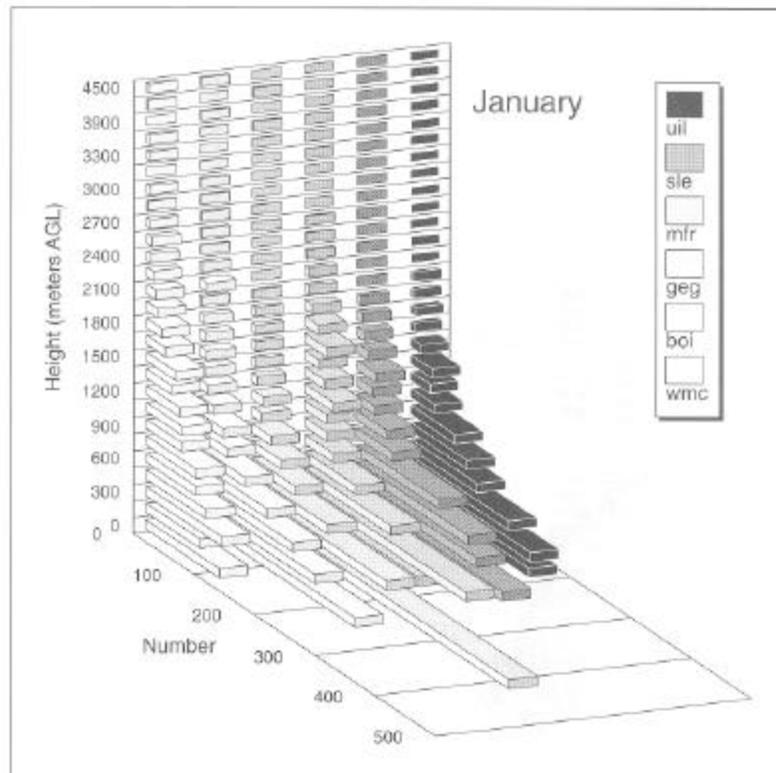

Figure 2—Distribution of mixing heights in January for Quillayute (uil); Salem (sle); Medford (mfr); Spokane (geg); Boise (boi); and Winnemucca (wmc). Height level categories are in increments of 150 meters above ground level (AGL). Mixing heights were calculated in feet AGL then converted to approximate values in meters.
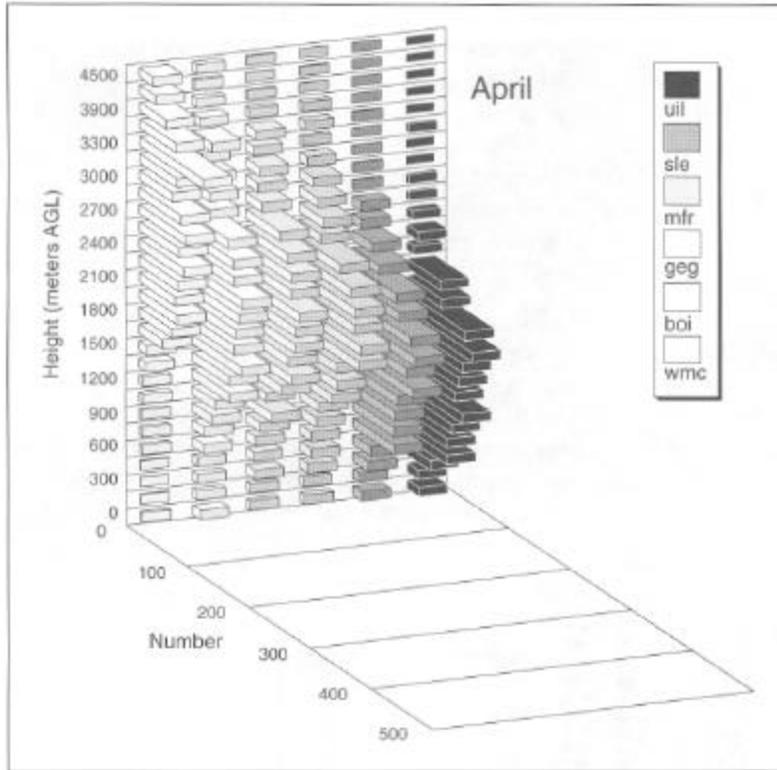
Figure 3-Distribution of mixing heights in April for Quillayute (uil); Salem (sle); Medford (mfr); Spokane (geg); Boise (boi); and Winnemucca (wmc). Height level categories are in increments of 150 meters above ground level (AGL). Mixing heights were calculated in feet AGL then converted to approximate values in meters.
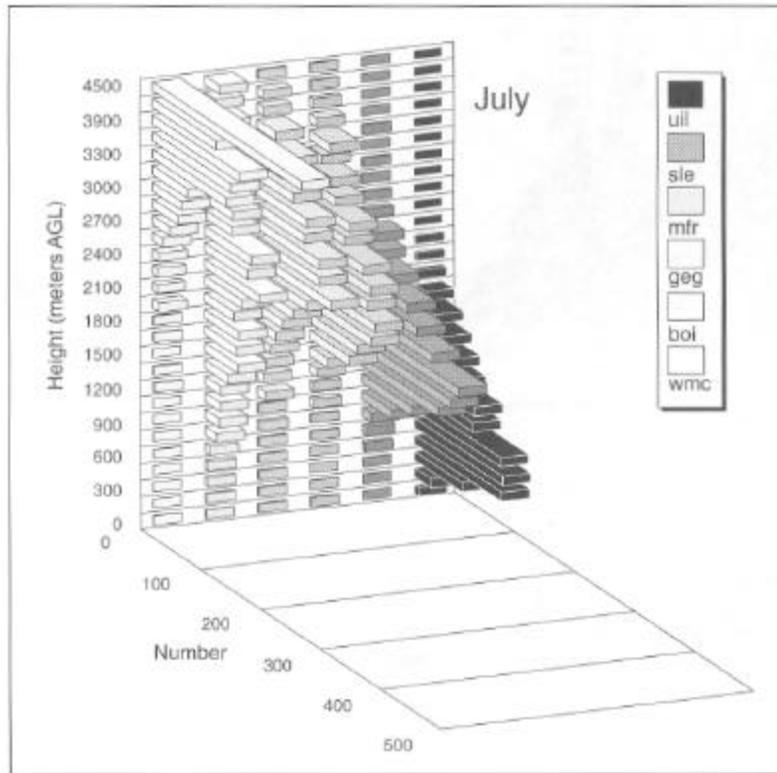

Figure 4-Distribution of mixing heights in July for Quillayme (ml); Salem (sle); Medford (mfr); Spokane (geg); Boise (boi); and Winnemucca (wmc). Height level categories are in increments of 150 meters above ground level (AGL). Mixing heights were calculated in feet AGL then converted to approximate values in meters.

Figure 5–Distribution of mixing height in October for Quillayute (uil); Salem (sle); Medford (mfr); Spokane (geg); Boise (boi); and Winnemucca (wmc). Height level categories are in increments of 150 meters above ground level (AGL). Mixing heights were calculated in feet AGL then converted to approximate values in meters.
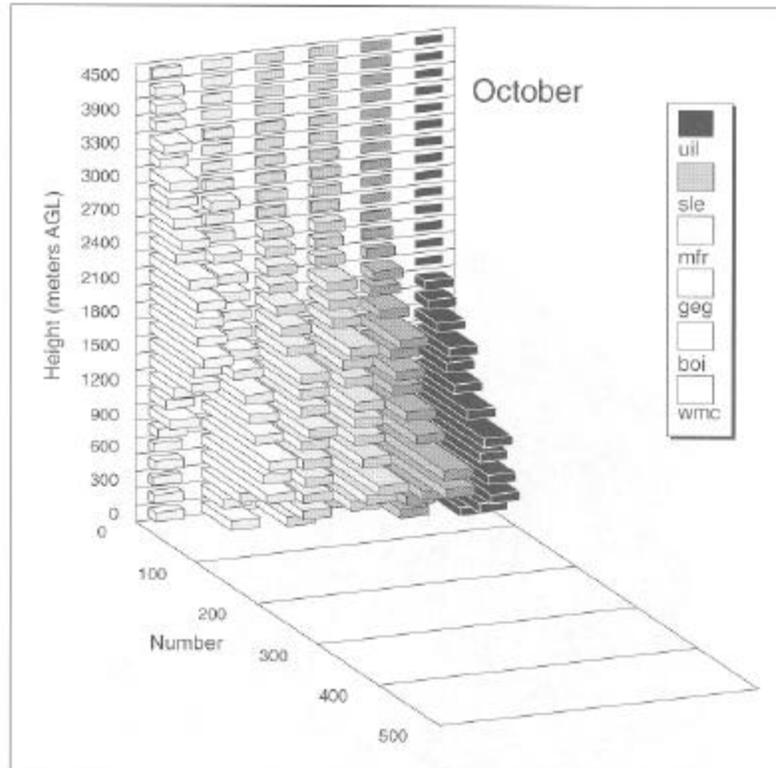
the basin and the lower Snake River valley. If the mixing height is constant around 1400 meters (fig. 7), there is relatively good dispersion in the central plateau of the basin. High basins and some high valleys in Oregon and western Montana may trap air, however, and cause pockets of stagnation.

Rain Days per Month

Airborne pollutants may fall out of the atmosphere by attaching to precipitating particles. Liquid precipitation (rain) is more efficient at scavenging gas and particles than is solid precipitation (snow, hail, etc.). A simple analysis of rain days per month therefore was conducted to help determine the frequency of wet deposition onto plants and into soils and snow cover.

To determine rain days in wildland regions, data were selected from all National Weather Service (NWS) cooperative observation station sites above 900 meters elevation. Days of rain were defined as those days with measured precipitation and mean temperatures greater than 5 °C. When near-surface air temperatures are above 5 °C, 100 percent of observed precipitation is rain (Ferguson 1994, Ferguson and Breyfogle 1994). Because mean temperature was used, there may be some periods during the day when temperatures are lower and snowfall may occur, but these should be rare. This definition omits days with cold rain, mixed periods of rain and snow, and purely snow.
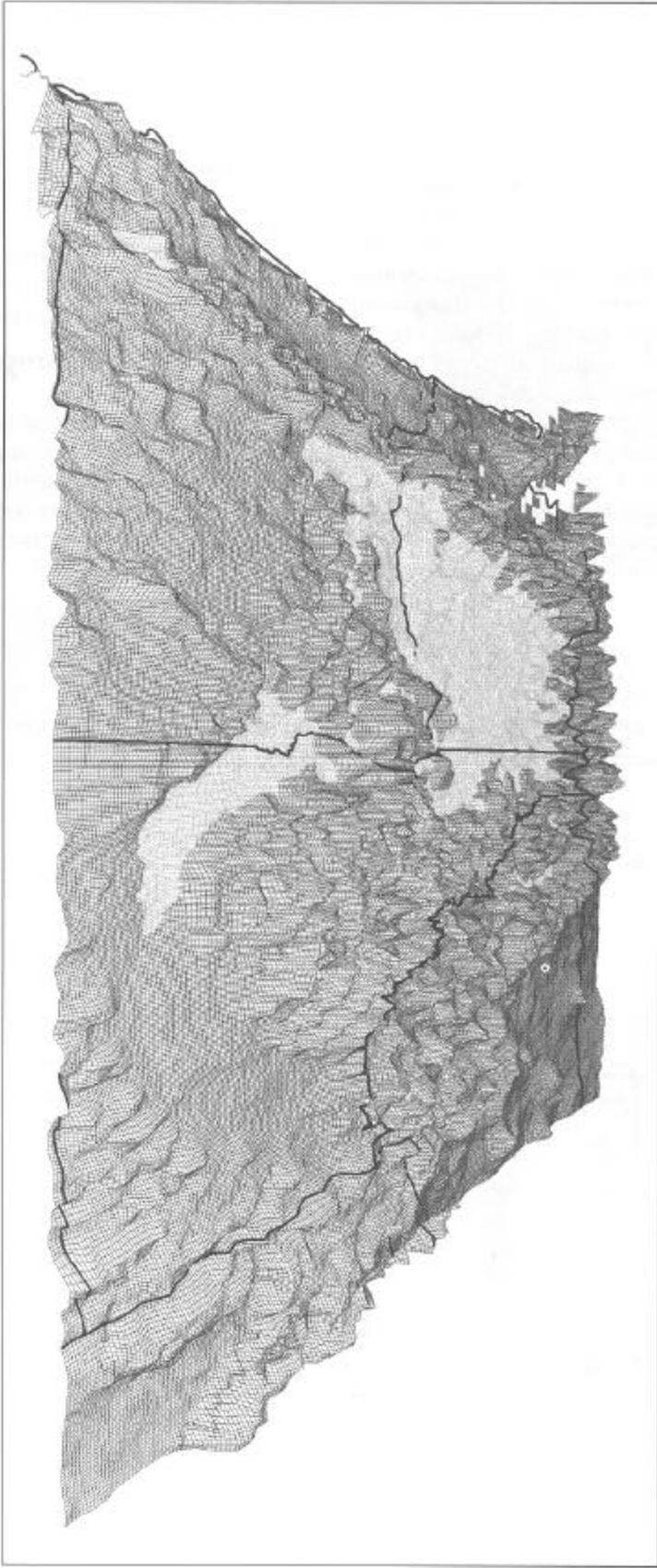
Figure 6—The area under a constant mixing height of 1000 meters is shown by light shading.
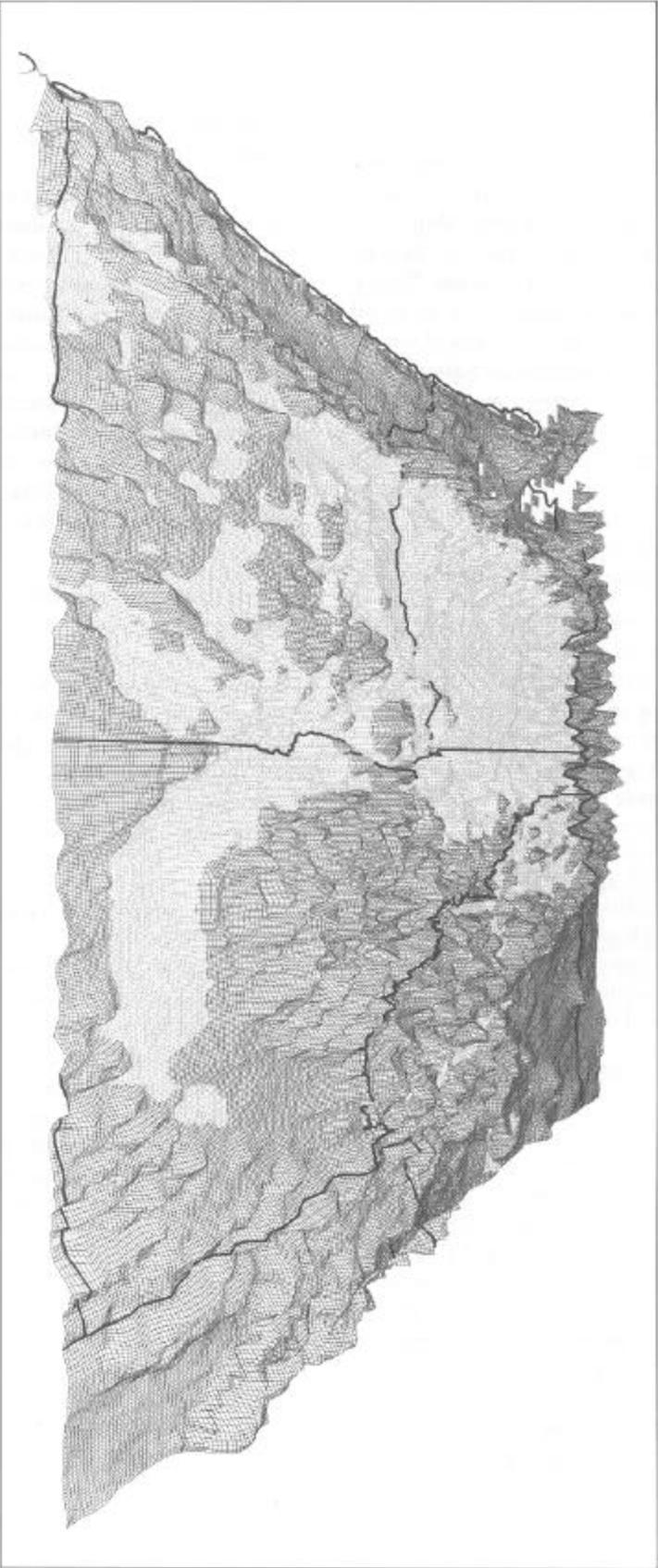
Figure 7—The area under a constant mixing height of 1400 meters is shown by light shading.

Only data from 1982, 1988, and 1989 were considered. These years were chosen by the Columbia River Basin Scientific Assessment Team as characteristic of cool and wet, warm and dry, and normal climatic conditions, respectively. A more complete analysis would benefit from a long period of spatially distributed observations, which were not available at the time of this study.

In January, there are few days of midwinter rain at elevations above 900 meters. Although significant precipitation occurred during winter 1982, most fell as snow with rain confined to lower elevations in eastern Oregon and western Idaho. Only a small amount of precipitation occurred in January 1988, so a similar pattern of rain days occurred, with some rain at higher elevations in central Idaho and western Montana. The normal year of 1989 (fig. 8) again showed few midwinter rain days; those that occurred were mostly at lower elevations.

The number of rain days per month becomes greater than snow days per month as seasonal temperatures increase. Slightly fewer stations observed rain during April in 1982 than in other years because snowfall continued through spring that year. In 1988, several stations throughout the basin experienced 50 to 75 percent days with spring rain. In 1989, most stations experienced at least 25 percent days with rain, which is typical of spring (fig. 9).

Summer precipitation in the basin is dominated by atmospheric convection. During wet years, such as 1982, a large number of stations experience more than 50 percent days with rain, especially in places where summertime convection dominates precipitation. In 1988, no station measured significant precipitation as dryness pervaded the basin. During a normal year (fig. 10) typical summer patterns of precipitation prevail with most rain days occurring in places where convection is common, such as eastern Idaho and western Montana.

During autumn, convection remains important in precipitation distribution. In addition, the signifi-cance of frontal and orographic precipitation begins to increase but snow also may occur. In 1982, most of the mountain sites showed more than 25 percent of the days with rain. Cooler than normal seasonal temperatures also may have caused days with snow. In 1988, a dry year, few stations measured more than a few days of rain. Most of those occurred in Idaho and western Montana where convection probably remained important. During a typical year (fig. 11), most stations observe about 25 percent of days with rain in October.

Upper Level Winds

Winds in the upper atmosphere may carry buoyant pollutants long distances. The Columbia River Basin Scientific Assessment team were interested specifically in the possibility of pollutants from the basin reaching the Grand Canyon. This could occur if upper level winds over the basin are strong from the north.

The distribution of wind speed and direction was calculated by the Western Regional Climate Center. Winds at the 700-hectoPascals (hPa) level were analyzed, because that level usually is above the influence of terrain surrounding the basin (about 3000 meters) and winds there are most likely to carry pollutants out of the basin.

At Spokane, the mean winter 700-hPa wind direction is westerly with a normal variation between SSW-W-NNW (fig. 12). Nine percent of the winds have a northerly component with speeds greater than 11 meters per second. Spring winds are highly variable with mean directions between SW and WSW. Twelve percent of the winds have a northerly component but all are less than 9 meters per second and most are less than 2 meters per second. A similar wind distribution occurs during summer (fig. 13) with a little more prefer-ence to SW and WSW directions. In autumn, prevailing winds begin to shift back to westerly. Four percent of autumn winds have northerly components greater than 11 meters per second.

Upper level winds at Boise have a slightly different distribution. This may be because the Snake River valley, which is oriented northwest to southeast, may influence the winds, even those well above the surrounding topography. Over Boise, winter winds prevail from the WNW and 15 percent have a strong (greater than 11 meters per second) northerly component (fig. 14). Spring winds prevail from the W, WNW, to NW, and 9 percent have strong northerly components. In summer, winds over Boise prevail from the WSW, and 14 percent of the winds have a northerly component, but all are less than 9 meters per second (fig. 15). In autumn, westerly winds dominate. Seven percent have a strong northerly component.

These results suggest that strong northerly winds are most common during winter when there is very little biomass burning. The northerly winds could scour away pollution trapped under the basin's frequent winter inversion, however. Whether the scoured components can reach the Grand Canyon or deposit along the way is unknown. Strong northerly winds are possible during spring and autumn burning seasons but are rare. Summer northerly winds usually are too weak to transport material for long distances.

Surface

Winds near Earth's surface are most efficient at transporting nonbuoyant or neutrally buoyant pollutants. They can carry smoke from burning biomass into nearby towns and cities. In addition, surface winds can carry pollutants from industrial sources into wildland areas.

Only a few observations are needed to determine the characteristics of upper level wind, because atmospheric patterns usually change slowly over space and time above the influence of topography. Near the ground surface, however, winds are strongly influenced by small undulations in topography. There are not enough observations of surface wind to show the true variation in wind.

A simple mesoscale wind model therefore was adapted to analyze the effect of surface wind on pollution transport.'

Surface wind during winter is controlled primarily by pressure gradient forces between a persistent region of high pressure over the continent and frequent low centers from approaching Pacific storms (fig. 16). This pressure gradient causes strong easterly winds to persist through the Cascade mountain passes. It also causes much of the stagnant air, which is trapped under the frequent winter temperature inversion, to be pulled against the eastern slopes of the Cascades. The passing storms also cause winds to accelerate over the higher ridge tops, especially in the Rocky Mountains. Converging winds are common, as in the lee of the Blue Mountains and around the head of the Snake River. Stagnant winds also occur, usually below the persistent inversions in the central Snake River valley and central Columbia plateau.

During summer (fig. 17), surface winds are dominated by downslope flows caused by cooling air that drains into the valleys at night. An onshore flow also prevails, causing weak to moderate westerly winds through the Cascade passes. Areas of weak convergence or stagnation occur most frequently in valleys and basins where the downslope winds are trapped by surrounding topography.

Drought

Drought stress causes plants to close stomata and become less susceptible to pollution. Drought in the Columbia River basin is common but tempered by an abundant source of moisture that spills over the Coast Ranges and through mountain gaps from the Pacific Ocean. Because most rainfall accumulates during winter and spring in the basin, and because much of the summer water resource relies on winter snowpack, the most severe droughts occur with abnormally low winter and spring rainfalls (Namias 1983).

'Ferguson, S.A.; Peterson, M.R.; Hayes, P.S.; Ruthford, J.: Surface wind patterns in the Pacific Northwest. Manuscript in preparation.
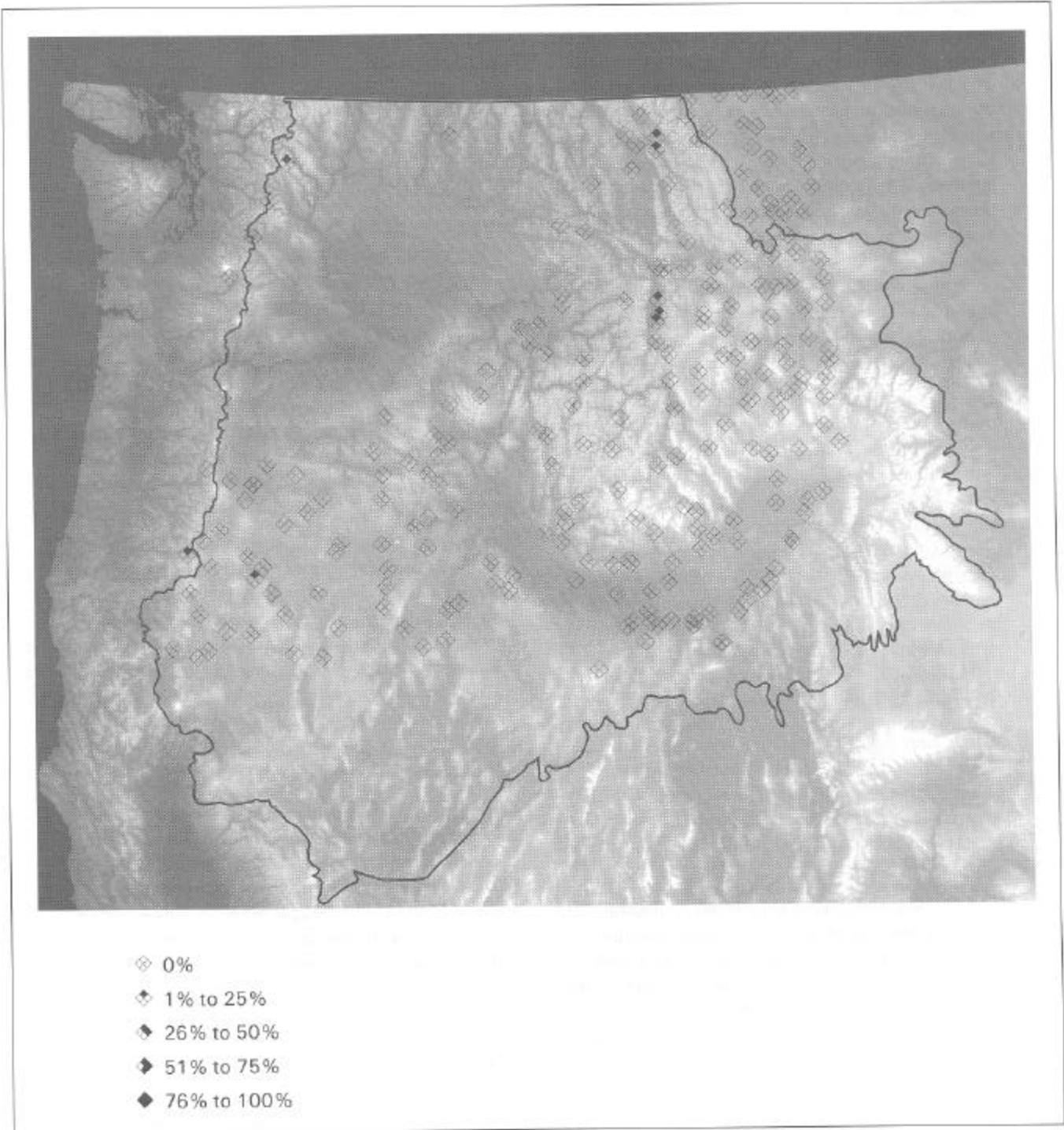
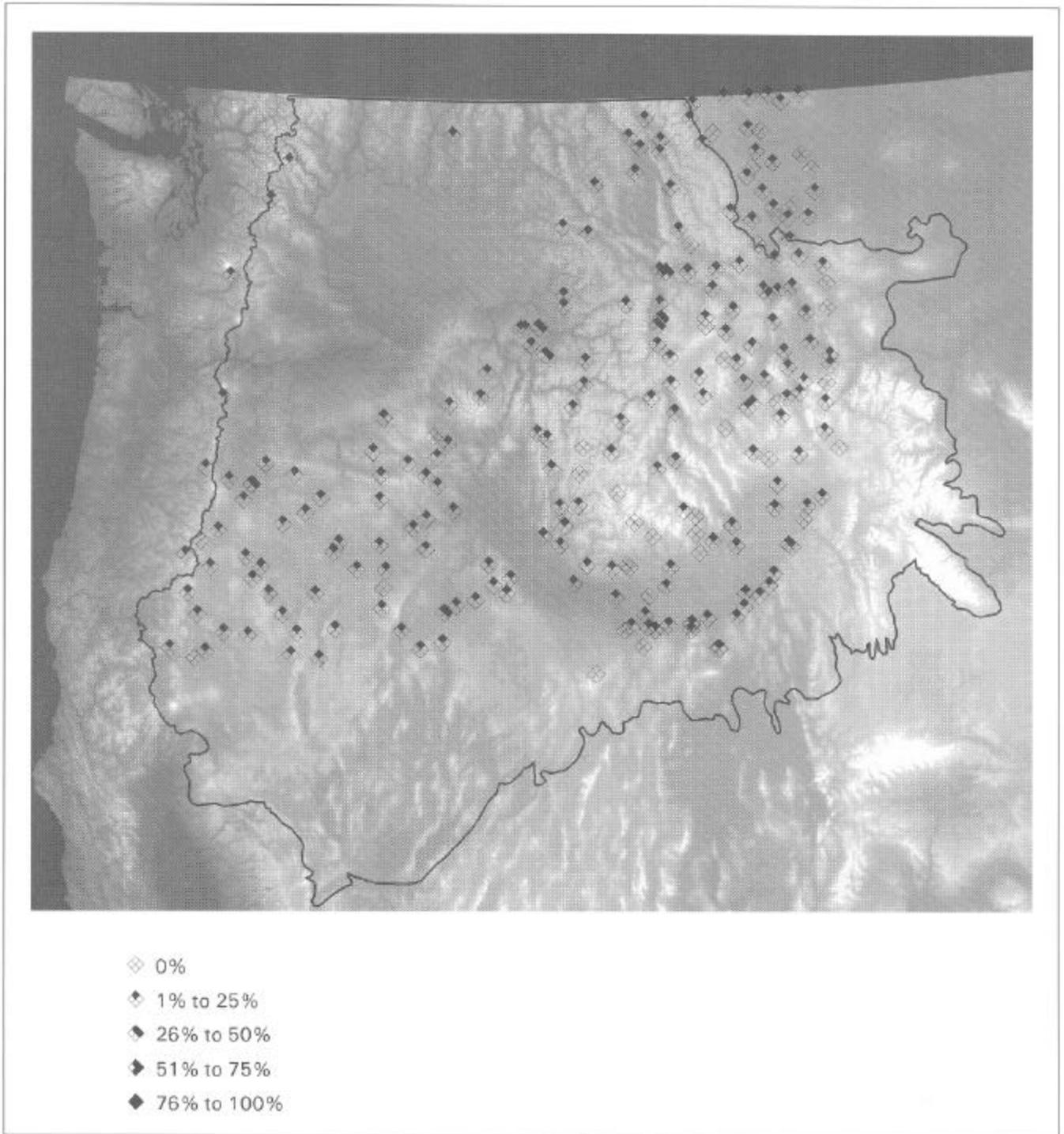Figure 8—Percentage of rain days per month, January 1989.

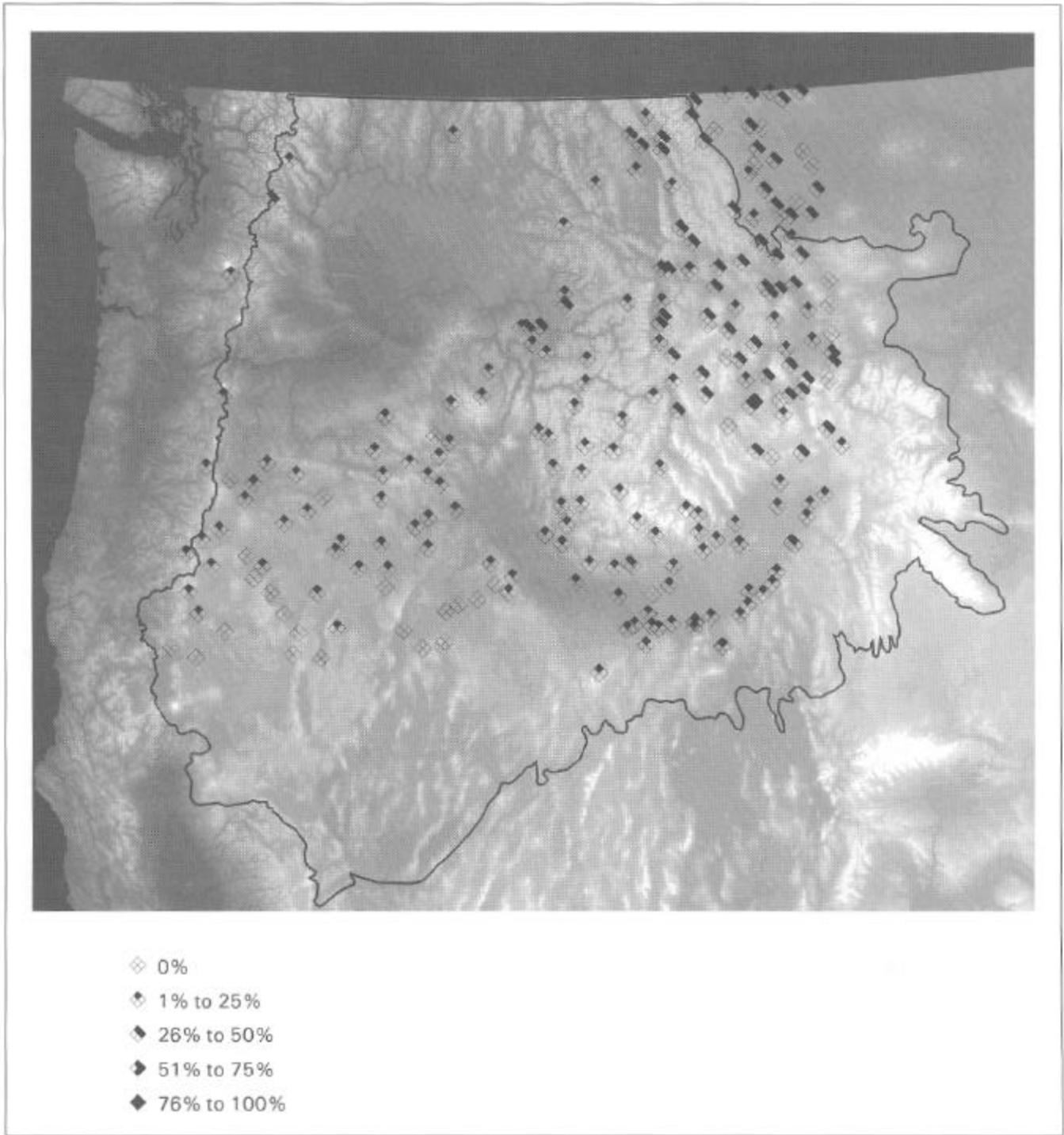Figure 9—Percentage of rain days per month, April 1989.

Legend:
- 0%
- 1% to 25%
- 26% to 50%
- 51% to 75%
- 76% to 100%

⬦ 0%
⬧ 1% to 25%
◆ 26% to 50%
◗ 51% to 75%
◆ 76% to 100%

Figure 10—Percentage of rain days per month, July 1989.
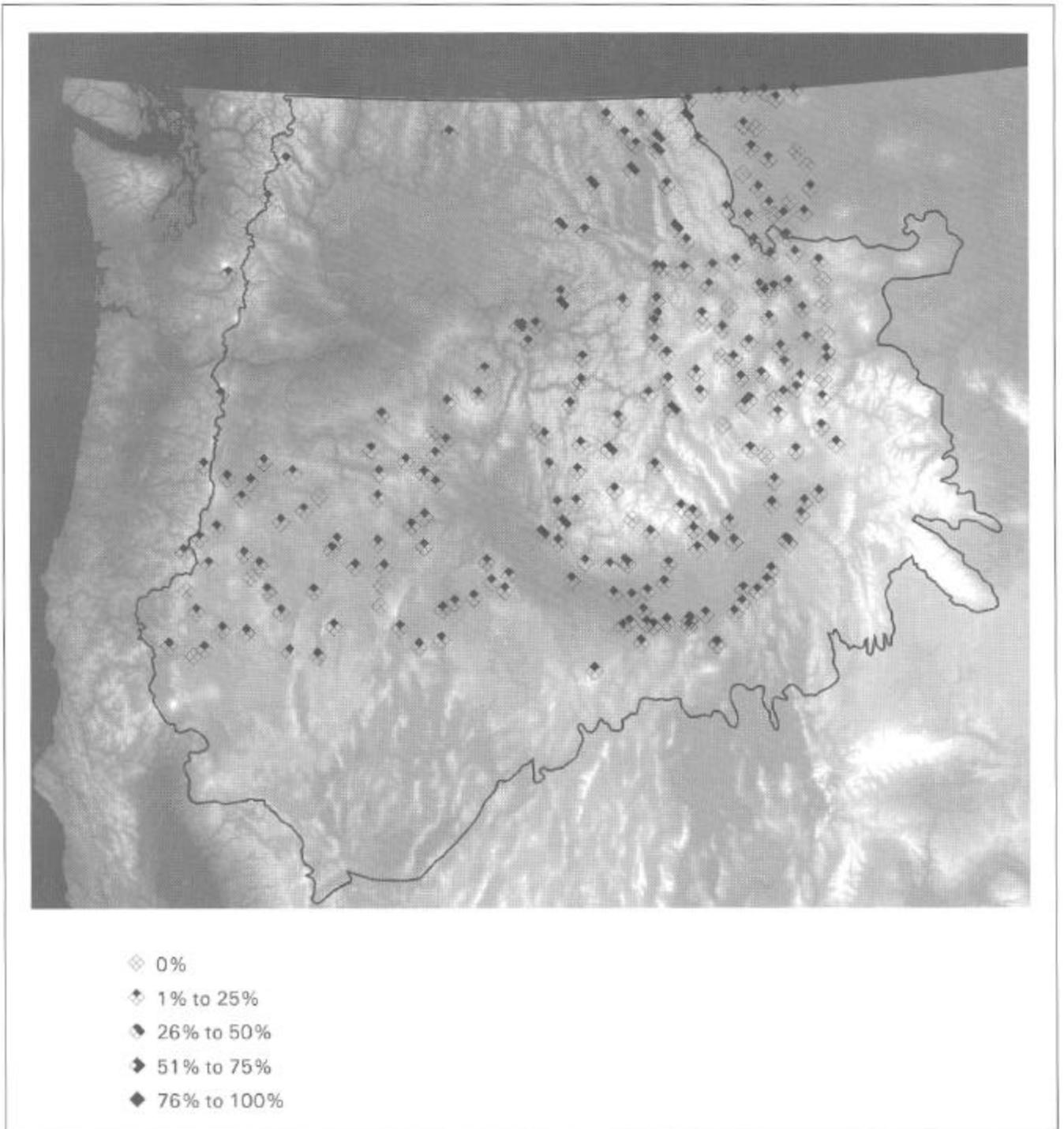
Figure 11—Percentage of rain days per month, October 1989.

Legend:
- ◇ 0%
- ◆ 1% to 25%
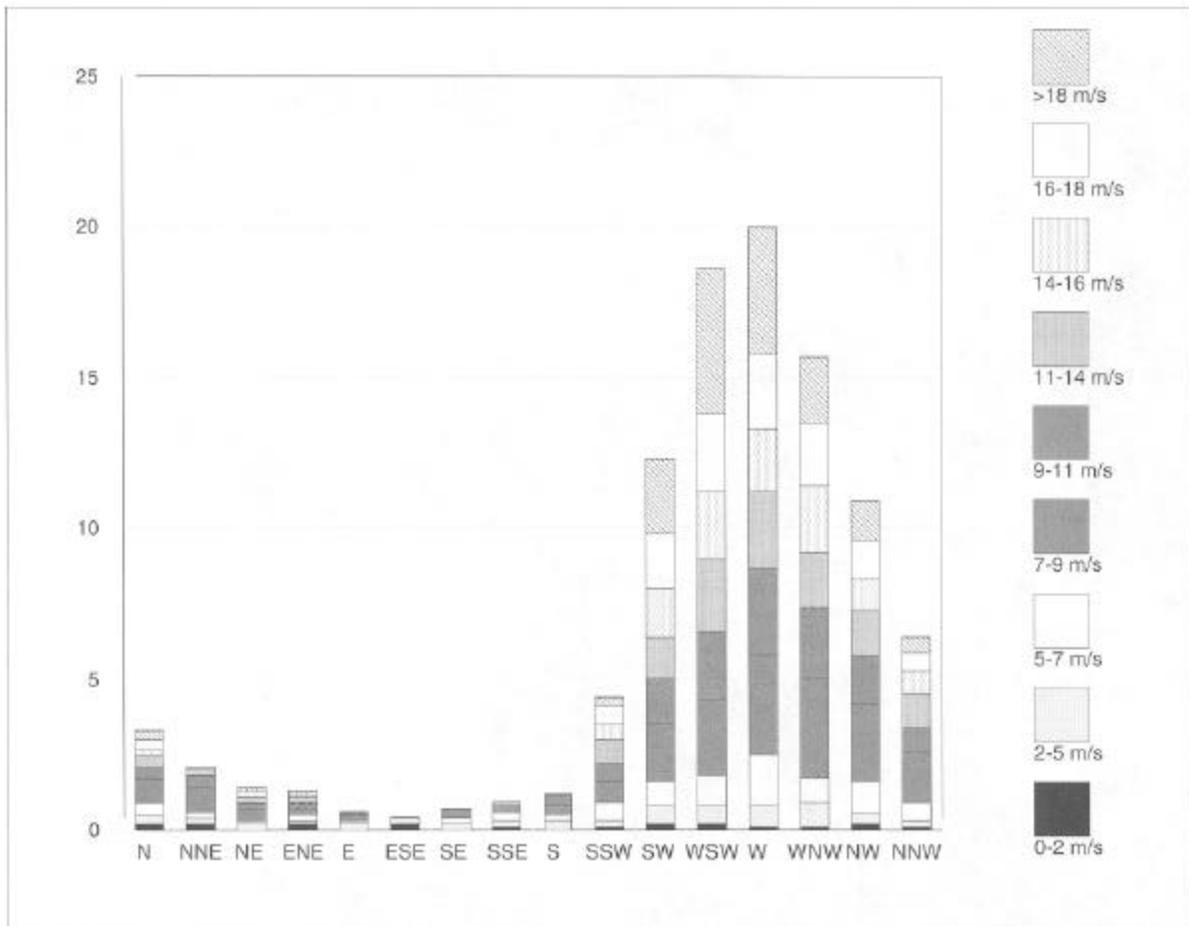- ◆ 26% to 50%
- ◆ 51% to 75%
- ◆ 76% to 100%

Figure 12—Distribution of winds at the 700-hPa level over Spokane during January. Speed categories were calculated in miles per hour then converted to approximate values in meters per second.
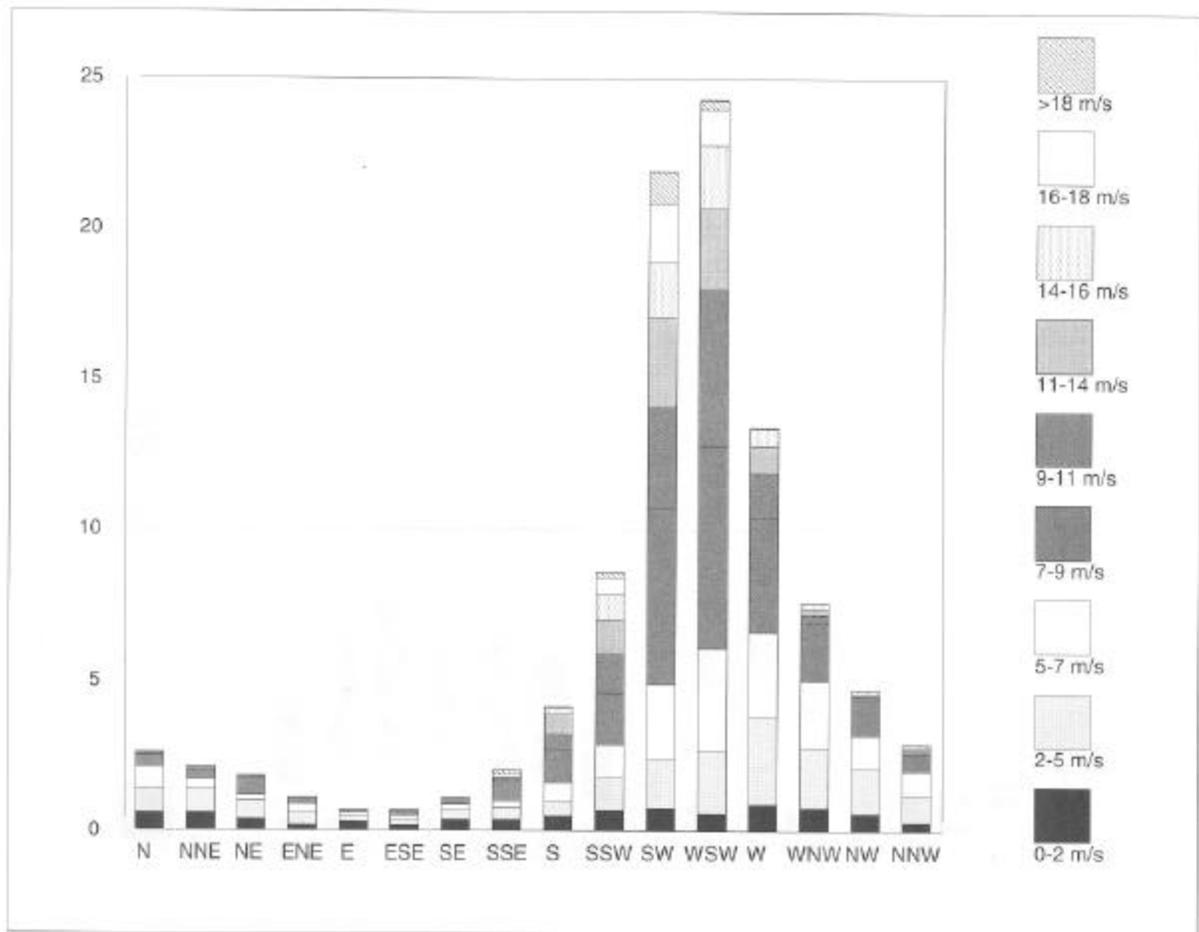
Figure 13—Distribution of winds at the 700-hPa level over Spokane during July. Speed categories were calculated in miles per hour then converted to approximate values in meters per second.
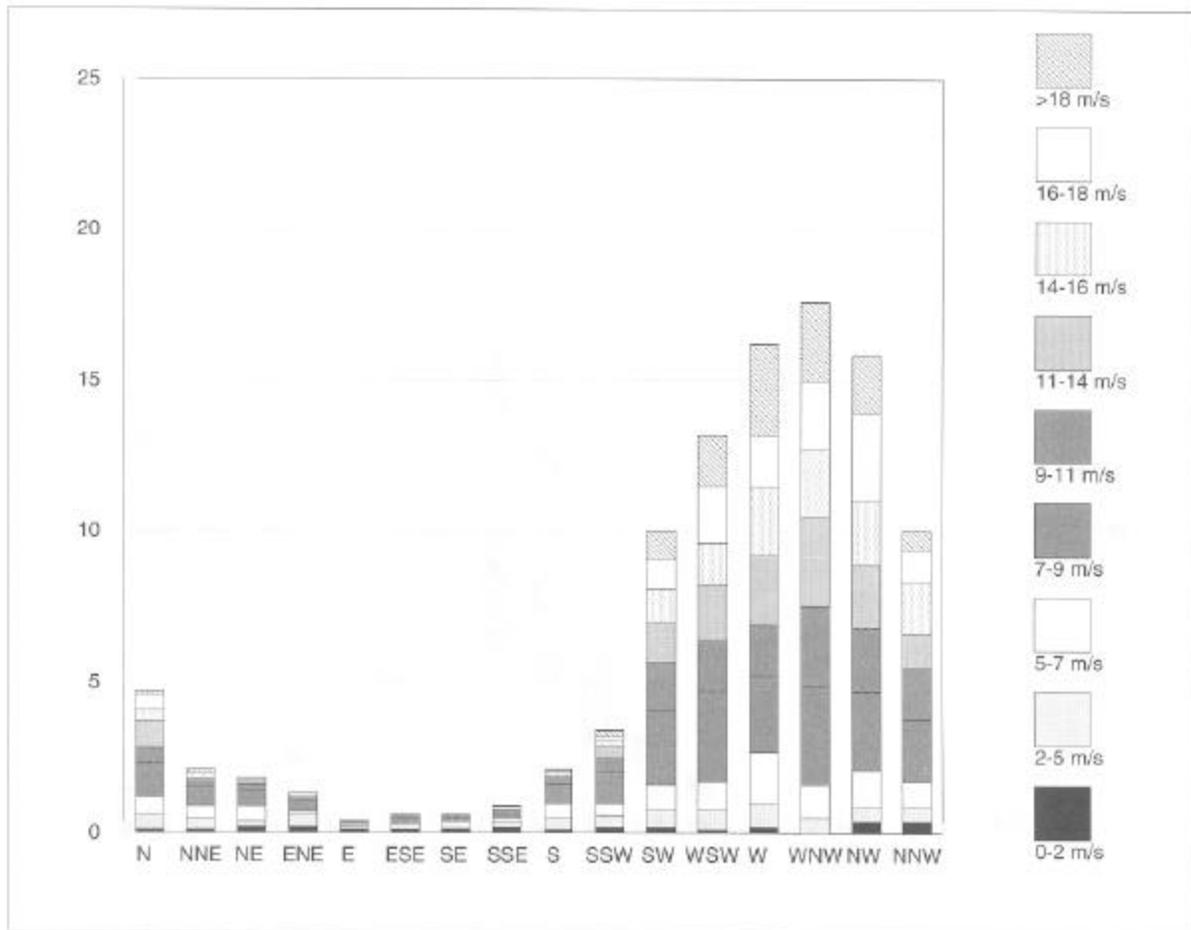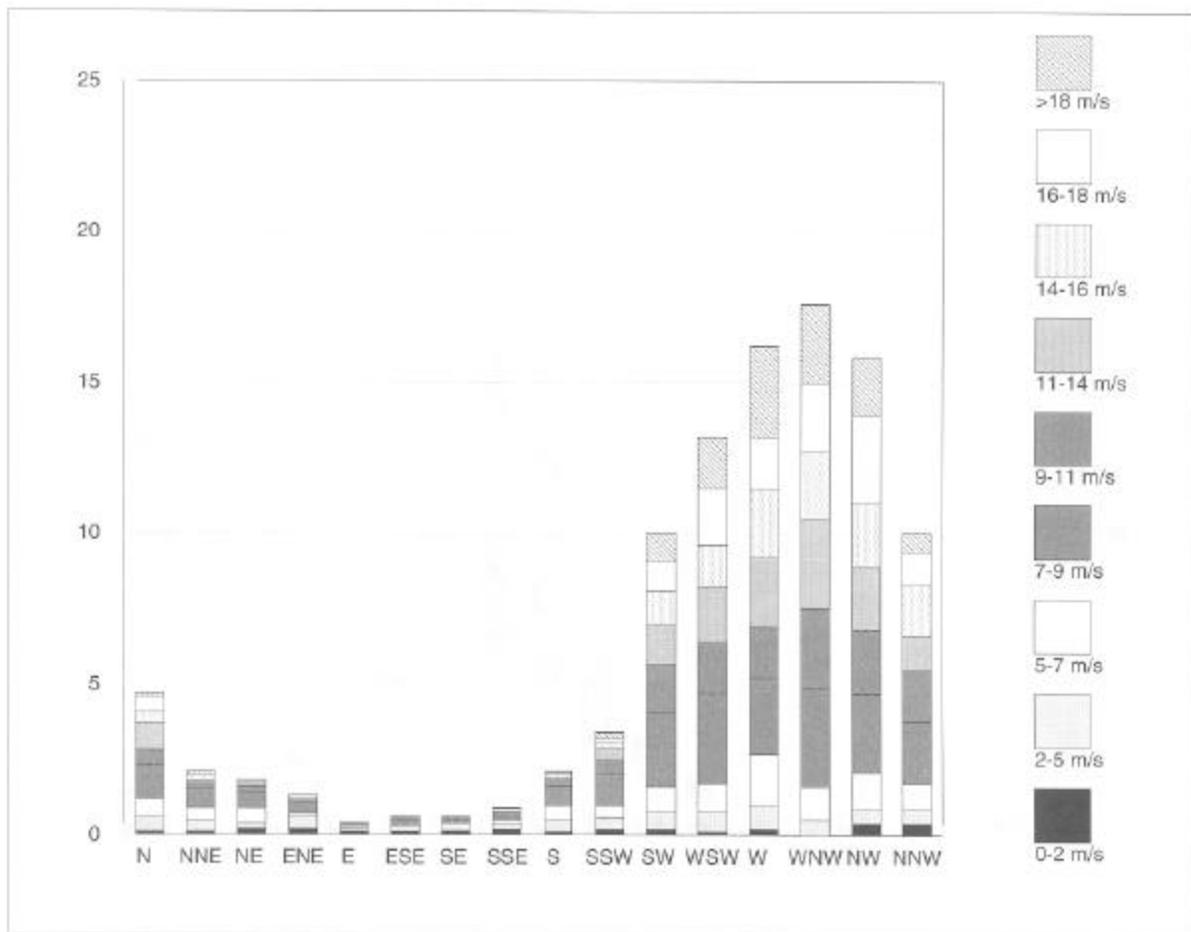
Figure 14—Distribution of winds at the 700-hPa level over Boise during January. Speed categories were calculated in miles per hour then converted to approximate values in meters per second.

Figure 14—Distribution of winds at the 700-hPa level over Boise during January. Speed categories were calculated in miles per hour then converted to approximate values in meters per second.
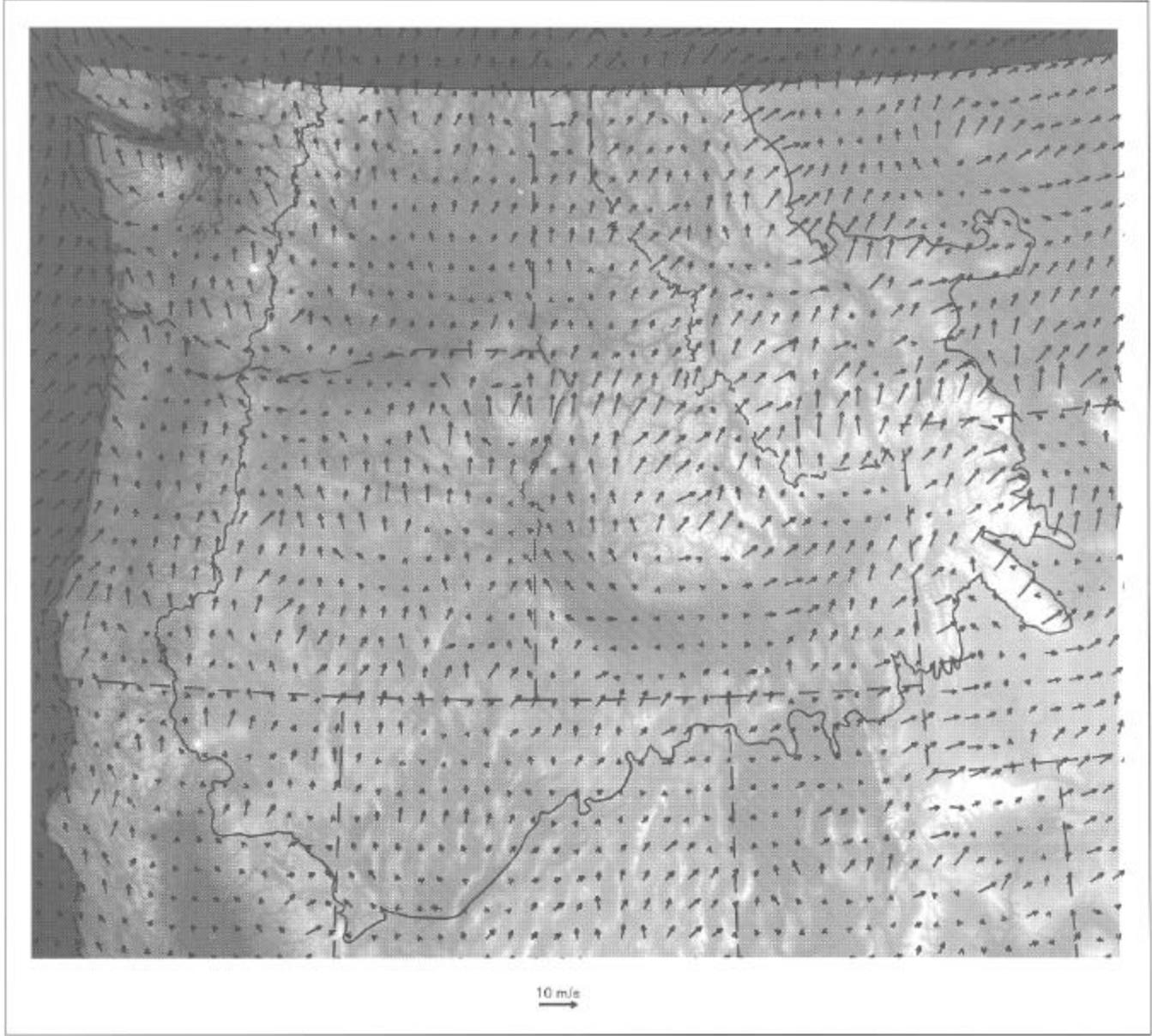
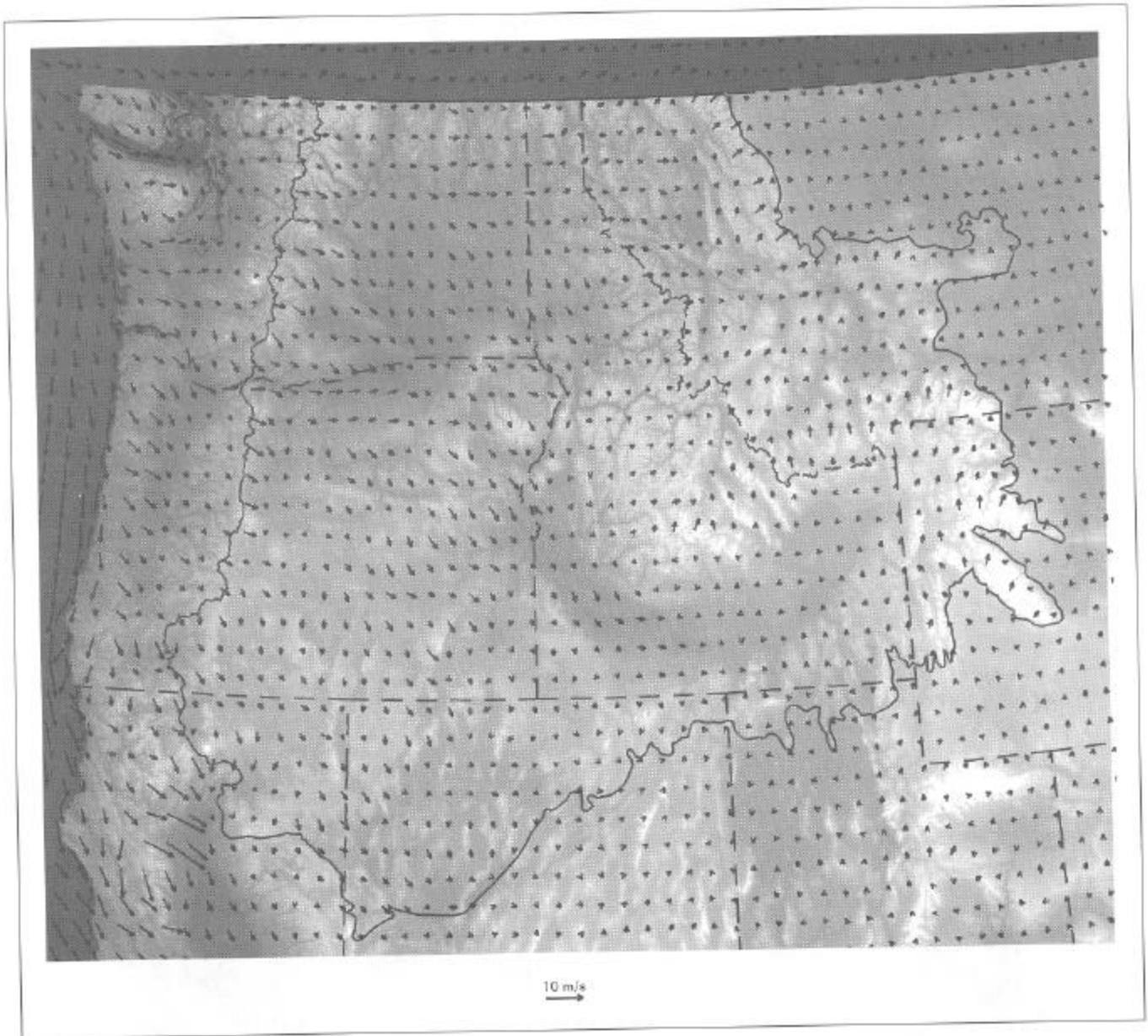Figure 16—The 30-year average of monthly-mean surface winds in January.

Figure 17—The 30-year average of monthly-mean surface winds in July.

a. Winter (Dec-Jan-Feb)

b. Spring (Mar-Apr-May)

c. Summer (Jun-Jul-Aug)

d. Autumn (Sep-Oct-Nov)

Less than 10
10 - 14
15 - 19
20 - 24
25 - 29
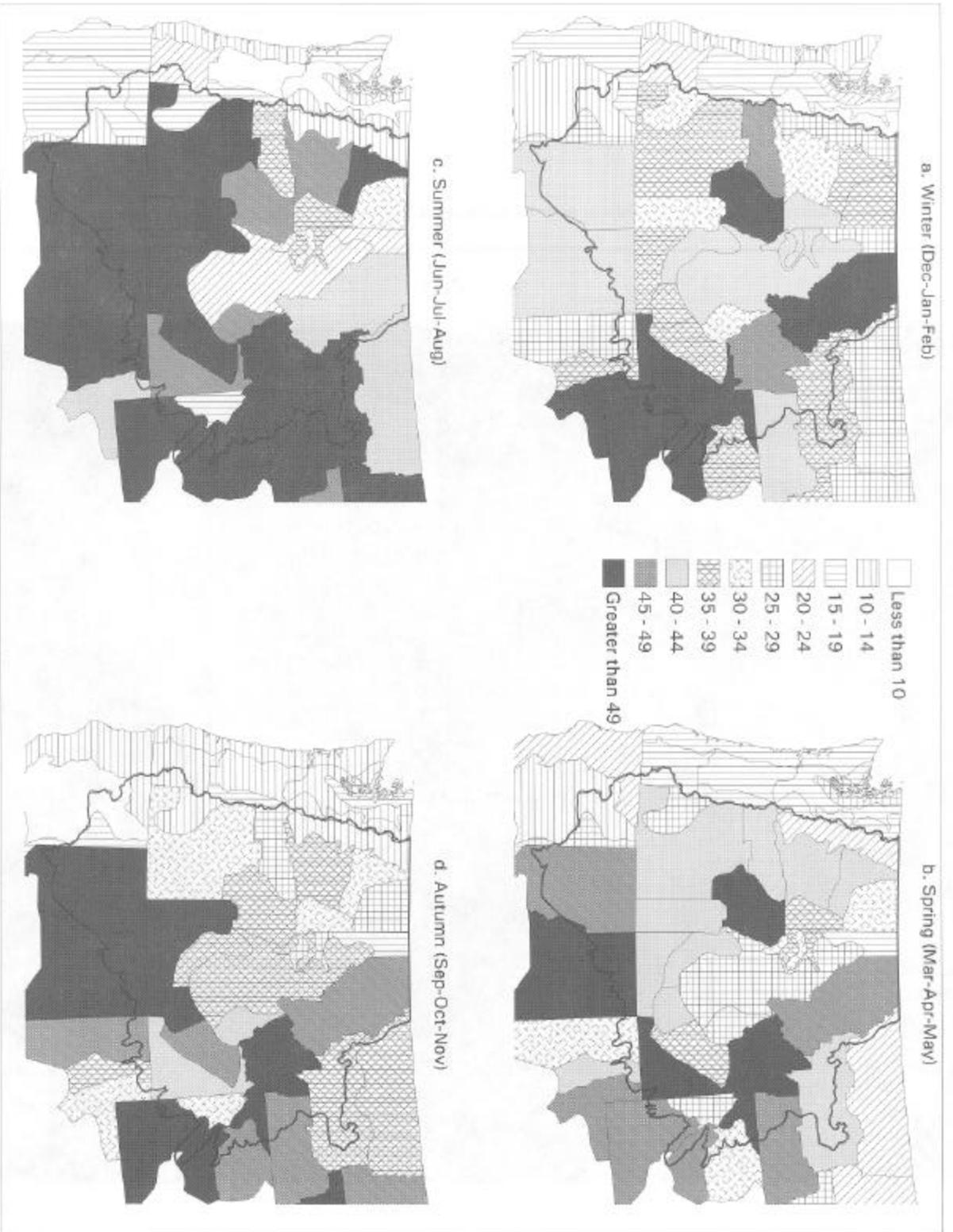30 - 34
35 - 39
40 - 44
45 - 49
Greater than 49

Figure 18—The Palmer drought severity index (PDSI) during summer. The number of months when PDSI was less than -3.0 in the period 1895-1994 are totaled for each climate division.

To help determine the spatial pattern of drought events, Palmer drought severity index (PDSI) data (Heddinghause and Sabol 1991, Palmer 1965) were obtained from the National Climate Data Center (NCDC). The index generally ranges from -6.0 to +6.0, with negative values denoting dry spells and positive values indicating wet spells. Drought frequency patterns for each season were created by counting the number of times from 1895 to 1994 that the PDSI was less than -3 (severe drought) in each climate division, a region specified by the National Weather Service. Maps of the drought frequency for each season are shown in figure 18.

During winter (fig. 18a), drought is most common in places having heavy winter precipitation only when the jet stream and related storm tracks are positioned optimally. For example, winter drought is common at the east end of the Columbia Gorge (the coastal barrier's most significant gap), the Blue Mountains (which rely on abundant moisture from the southwest), and some of the lower elevation inland areas in Idaho, western Montana, and Wyoming.

During the spring-and-summer growing season (fig. 18b and c), convective precipitation becomes important. Because convection is highly variable from year to year, those places that depend on convective precipitation have more frequent periods of drought. This includes most of the basin, except for some of the mountain areas near the Cascades, which benefit from spillover Pacific moisture, and places in northern Washington and Idaho, which collect moisture from a few storms that pass over Canada during summer. Winds at the head of the Snake River commonly converge, and this helps to enhance lifting and precipitation there.

In autumn (fig. 18d), the winter storm tracks begin to establish. This helps to relieve much of the northwestern and mountainous parts of the basin from further drought. The south and southeast portions, however, retain some reliance on the highly variable convective precipitation; these regions of the basin experience drought whenever autumn convection is minimal.

Implications of Global Change on Air Quality in the Basin

Atmospheric concentrations of greenhouse gases are increasing. Major carbon constituents that contribute to the greenhouse effect are increasing at the following known rate: carbon dioxide (CO_2)—-0.4 percent or 1.5 parts per million (ppm) per year; methane (CH_4)—-0.9 percent or 0.015 ppm per year; chlorofluorocarbons (CFCs)—4.0 percent or 0.015 ppm (Houghton and others 1990, 1992). A recent report by the USDA Forest Service, Pacific Global Change Research Program, summarizes the effective sources and sinks of greenhouse gases and discusses possible implications for management (Bytnerowicz 1997). For example, major sources for CO_2 are listed as decomposition, respiration, biomass fires, volcanic emissions, fossil fuel burning, and changes in land use. It also is recognized, however, that more nitrogen can produce a cofertilization effect in the terrestrial biomass, which leads to sequestration of additional carbon. In addition, a discrepancy in the global nitrous oxide budget is attributed to emissions from forest soils, but proper management practices could minimize this. The report also explains that sources of atmospheric methane include cattle, wetlands, and termites. Like CO_2 and nitrous oxides, CH_4 emissions can be changed by altering management practices.

Another implication of increasing greenhouse gases is their possible effect on global climate. Although uncertainty remains in the rate and magnitude of expected change, a general warming trend due to increasing concentrations of greenhouse gases is almost certain. A climate change scenario that considers the regional effect of doubling the global atmospheric concentrations of carbon dioxide ($2xCO_2$) on regional climate is discussed in Ferguson (1997). This report and

reports from the Intergovernmental Panel on Climate Change (Houghton and others 1990, 1992) are summarized below in a list of possible effects of global climate change on regional air pollution:

1. Greatest warming over high-latitude continents: less intense arctic influence and thus weaker temperature inversions during winter.

2. Continents could warm more than oceans: higher summer mixing heights.

3. Decreased snow cover: less intense winter stagnation and earlier seasonal discharge of pollutants held in the snowpack.

4. Increased convection over continents: more wet deposition in spring and summer with less frequent drought in southeast portions of the basin.

5. Decreased soil moisture during summer: greater summer drought, especially in the central basin.

6. Fewer, but stronger, winter cyclones: less frequent but more significant disruption of winter stagnation.

Conclusion

The Columbia River basin experiences air pollution patterns similar to typical basins. For example, temperature inversions, which can trap pollution in stagnant air near the ground, are common. The basin's topography and the influence of three distinct air mass types, (marine, arctic, and continental), however, create a unique pattern of climate that can influence the trajectories of polluting gases and particles. Winds through the mountain gaps can transport pollution into and out of the basin, or scour away stagnant air trapped in the basin. Rainfall is common enough to cause relatively efficient scavenging of airborne pollution during all seasons.

A few, relatively simple, analytical tools were used to show the general pattern of climate in the basin that influences air pollution. More comprehensive analyses are possible with mesoscale meteorological models and atmospheric dispersion and deposition models. These tools could help to show greater details in the timing and extent of stagnation periods, distance and concentration of pollution gases and particles, and pollution distribution patterns under different climate and management scenarios. Until more comprehensive tools become available at landscape-level scales, however, this cursory analysis may provide a reasonable foundation for understanding the strategic role of climate in controlling the impact of air pollution on natural resources.

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