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U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
Environmental Data Service

Terrain and Climate

ROBERT W. SCHLOEMER

SILVER SPRING, MD.

April 1971

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TERRAIN AND CLIMATE

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551.3		External geodynamics
	.053	Weathering

CONTENTS

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ABSTRACT

The effects of interaction between the atmosphere and terrain in producing climate are discussed in general terms. Large, intermediate, and small-scale interactions are considered separately. The basic meteorology of the major interactions, together with aspects of their effects on and application to civilization are presented. Finally, geophysical factors resulting in terrain changes and differences are examined.

INTRODUCTION

Long ago man in the tropics learned to seek shade from the hot sun and in the middle latitudes to seek and build on the south facing slopes in order to avoid the harsh blasts of northerly winter winds. He learned to sail under the protecting shelter of offshore islands and peninsulas. He sought the slopes of mountains to plant his crop--to avoid frost damage and take advantage of the increased rainfall. In winter he migrated to the valleys with his cattle to avoid the snows and winds of the high mountains. His trails skirted the hazards of flood plains.

Climatic effects of terrain have produced different types of soils and vegetation. For example, in middle latitudes variations in trees between north and south slopes of a moderate hill may be as diverse as those over hundreds of miles of latitudinal distance in level country.

The principal meteorological elements to be considered in relating climate to terrain are solar radiation, paths of storms or characteristic winds, and sources of moisture. In addition, due attention must be given to the characteristic profile of temperature through the atmosphere (normally decreases with height), and differences in rates of heating and cooling of surrounding land and water.

The principal terrain features to be considered are height and orientation in relation to meteorological parameters, degree of local variations in height, and the land-water relations.

In order to keep the discussion of reasonable length, we will limit examples of the contiguous 48 States. This will eliminate discussion of the largest scale of orographic effects such as prevail in Southeast Asia under monsoon conditions and the impact of islands on oceanographically controlled flow.

LARGE-SCALE RELATIONS

There are many excellent textbooks that can be referred to for details which establish the many characteristics of weather patterns. In general terminology, weather is the day-to-day sequence of events, whereas climatology is description, analysis, interpretation and application of the sum total of weather over a period of time. A few fundamental concepts applicable to meteorology will suffice here to provide sufficient understanding for the purposes of this paper.

First, the sun is the source of energy that drives the atmospheric heat engine. The latitudinal migration of the overhead sun due to the tilt of the earth's axis relative to the plane of the ecliptic results in changes in heating intensity over the surface of the earth (fig. 1) with the changing seasons. This results in a regular north-south migration of the patterns of atmospheric circulation.

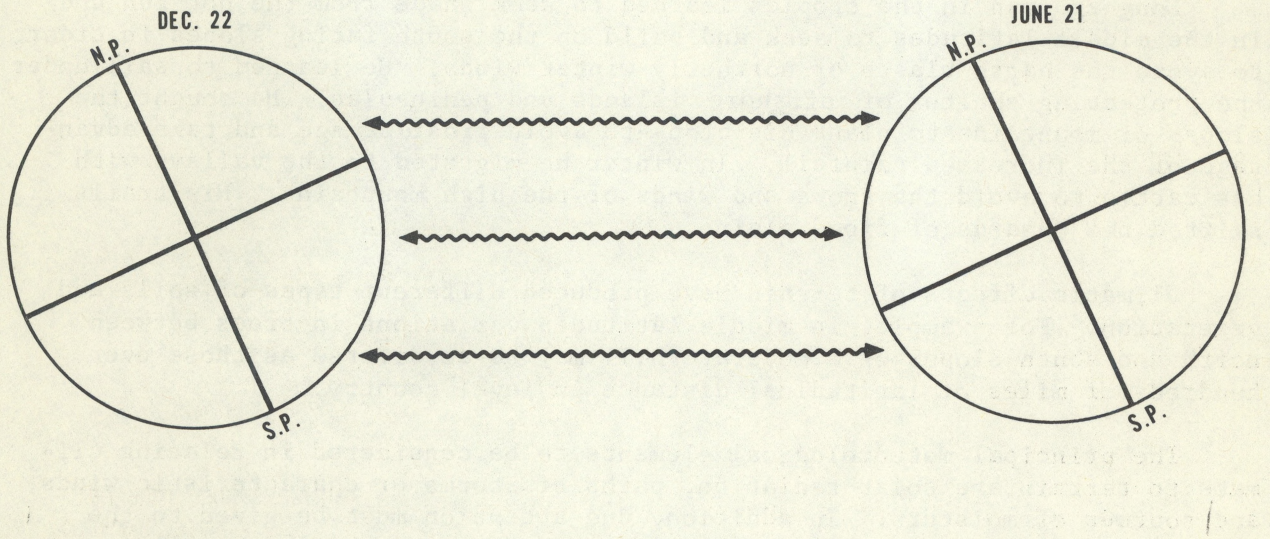

Figure 1.--Seasonal change in angle of incidence of solar radiation.

Secondly, there is a continuing attempt within the atmosphere to redistribute the heat. Thus, there is an interchange between atmospheric layers and the surface, and between lower latitudes and higher latitudes. The vertical heat distribution is diagramed in figure 2. The latitudinal heat exchange is shown in figure 3.

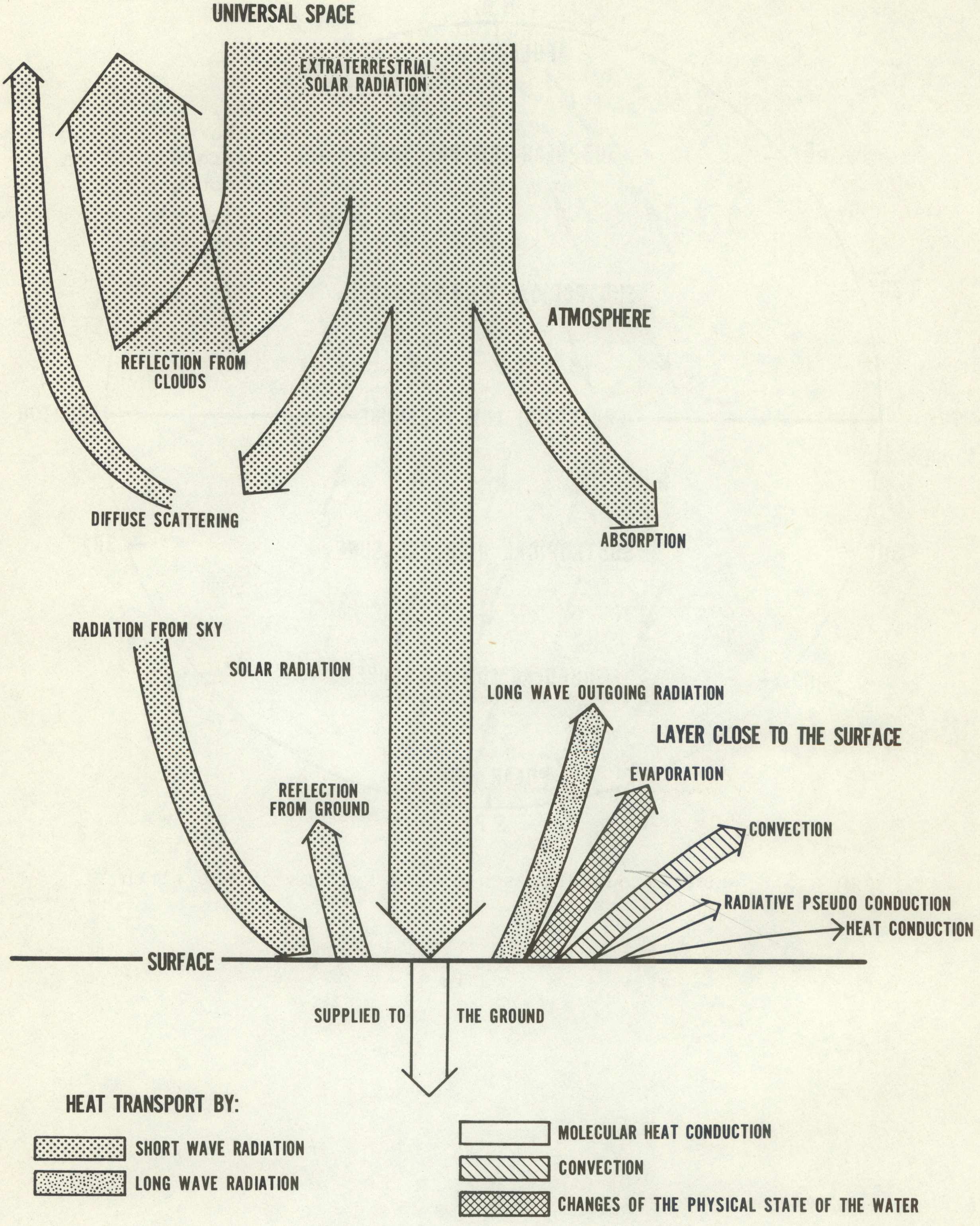

Figure 2.--Heat transfer in the atmosphere during summer noon. Width of arrows shows amount of heat transfer.

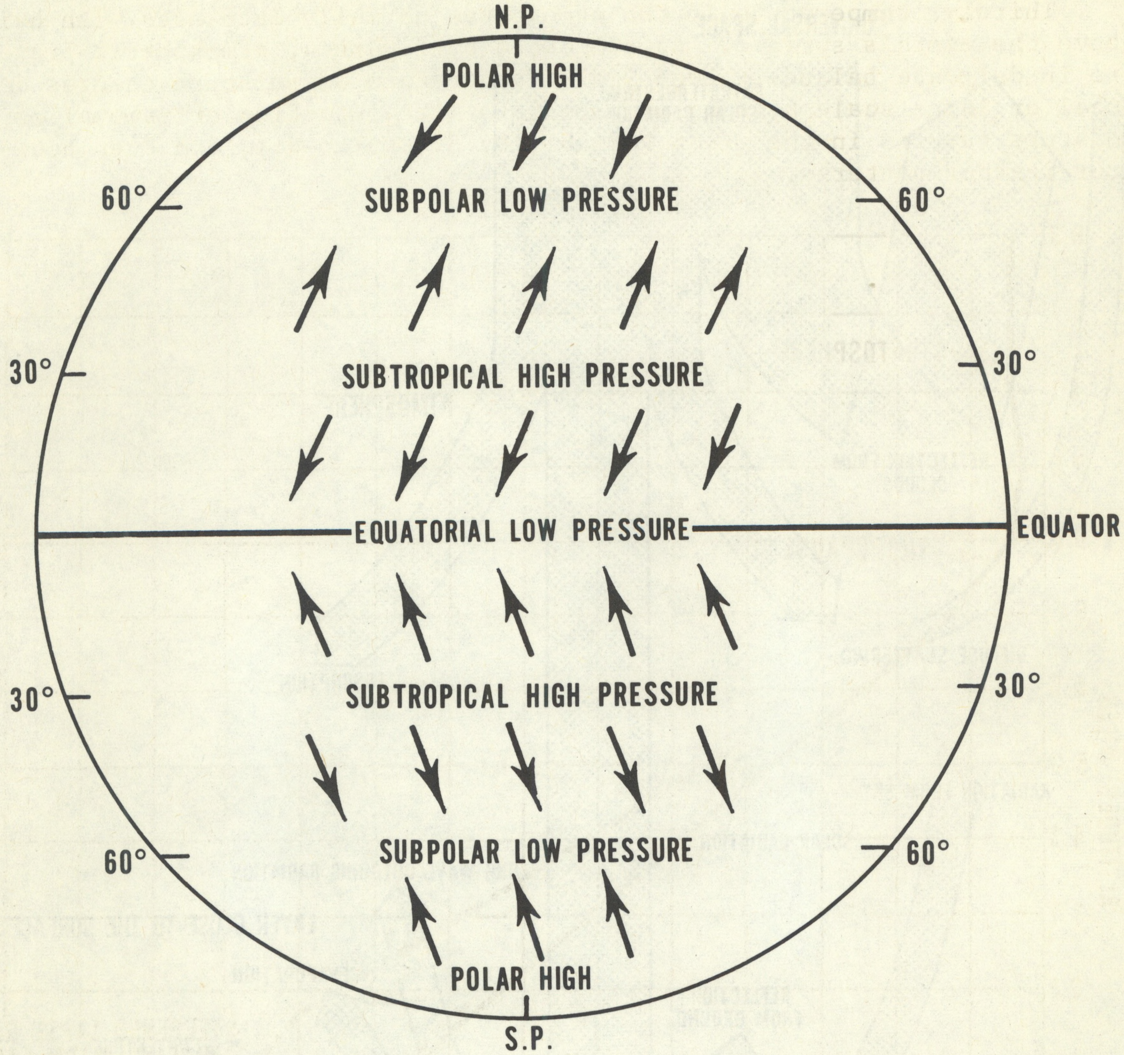

Figure 3.--Generalized large-scale wind systems of the earth.

Thirdly, temperature in the atmosphere normally decreases with height above the earth's surface. As suggested by figure 4, atmospheric properties are in delicate balance. Even small temperature or moisture changes due to local or large-scale heating or cooling or the injection or removal of moisture results in the great variability of day-to-day, and even hour-to-hour weather patterns.

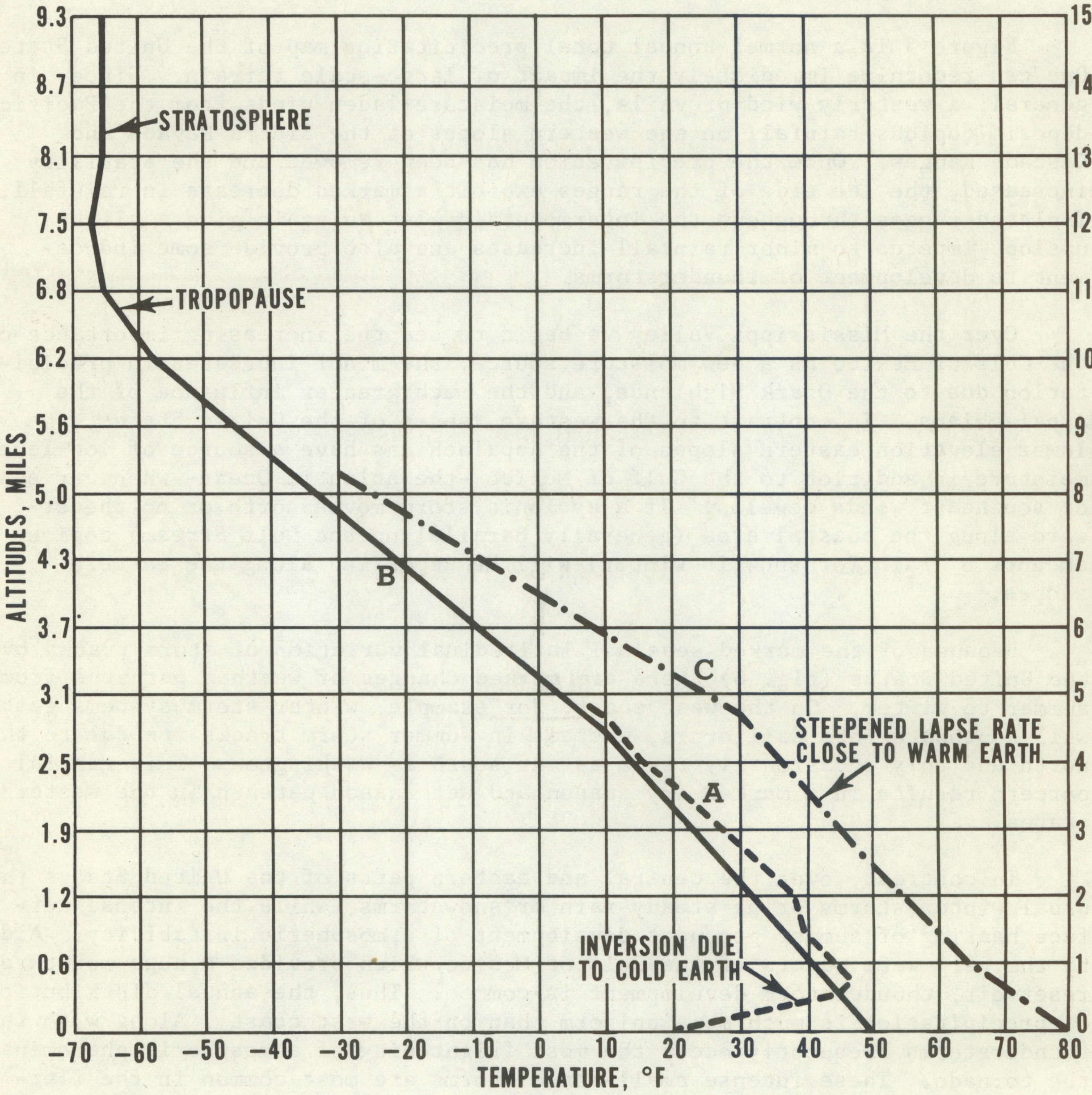

Figure 4.--Typical temperature variations with altitude. A. During a cold, clear night. B. Midlatitude average. C. During a hot, sunny day.

The activity within the atmosphere is fundamentally an attempt to maintain a balance of heat and mass. Heated air at the surface of the earth is replaced by adjacent colder air and is forced to rise, producing clouds and rainfall. In middle latitudes, where this imbalance is greatest, large masses of cold air plunge southward replacing warmer air masses and resulting in repeated cyclonic storms. These, along with visitations of hurricanes, are the principal weather producers in the United States.

Figure 5 is a normal annual total precipitation map of the United States. One can recognize immediately the impact of large-scale terrain. Since, in general, a westerly wind prevails, the moisture-laden winds from the Pacific deposit copious rainfall on the western slopes of the Sierra Nevada and Cascade Ranges. Once the precipitation has been removed and the stability increased, the lee side of the ranges exhibit a marked decrease in rainfall. Isolated ranges throughout the intermountain plateau again give a slight upslope impetus to minor rainfall increases and also provide some inducement to development of thunderstorms.

Over the Mississippi Valley we begin to see the increasing importance of the Gulf of Mexico as a new moisture source, the minor increases in precipitation due to the Ozark Highlands, and the much greater influence of the Appalachians. In contrast to the western ranges of the United States, the lower elevation eastern slopes of the Appalachians have a source of low-level moisture in addition to the Gulf of Mexico--the Atlantic Ocean--whenever east or southeast winds develop. If a cyclonic storm moves north or northeastward along the coastal area (generally paralleling the Gulf Stream) copious amounts of rain (or snow in winter) will be deposited along the eastern slopes.

Because of the marked seasonal latitudinal variation of storm tracks over the United States (fig. 6) there are marked changes of weather patterns from summer to winter. On the west coast, for example, winter storm systems reach well southward into California, whereas in summer storm tracks are far to the north and only occasionally reach as far south as Washington. This general pattern results in a marked dry season and wet season pattern in the western states.

In contrast, over the central and eastern parts of the United States the usual winter storms bring steady rain or snowstorms, while the intense surface heating of summer produces development of atmospheric instability. Aided by the very warm waters of the Gulf of Mexico, which provides a huge moisture reservoir, thunderstorm development is common. Thus, the annual distribution of precipitation is much more uniform than on the west coast. Along with the thunderstorms frequently occur the most frightening of atmospheric phenomena, the tornado. These intense small-scale storms are most common in the flatlands of the midwest and south, since rough terrain such as in West Virginia will tend to suppress the storms.

There are some favored areas for redevelopment of storm systems, partly due to surface configurations and partly due to access to new moisture sources. A very common area for such occurrences is off the south coast of Greenland. Typical of such areas in the United States is the Cape Hatteras

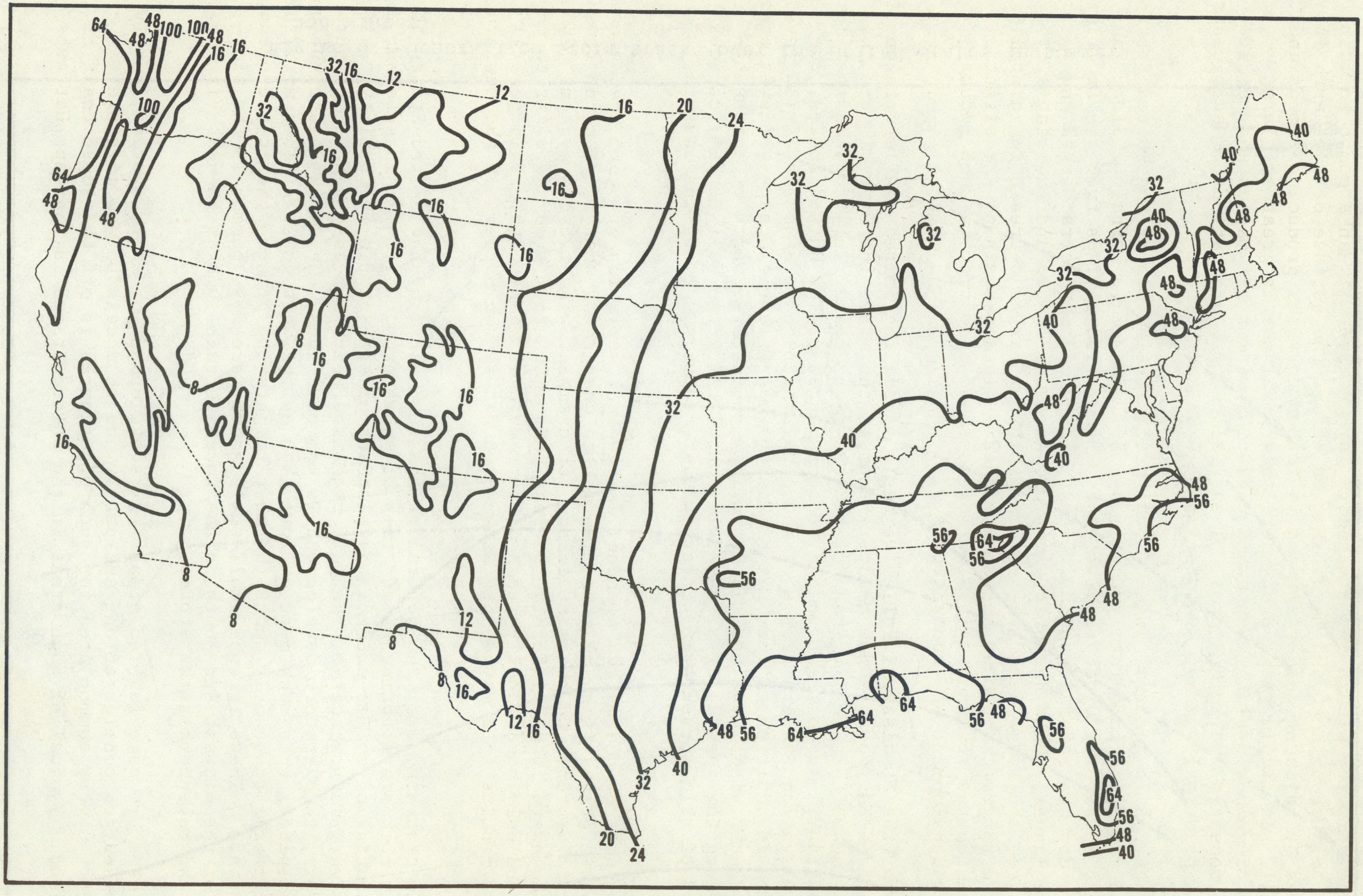

Figure 5.--Normal annual precipitation in the United States (inches).

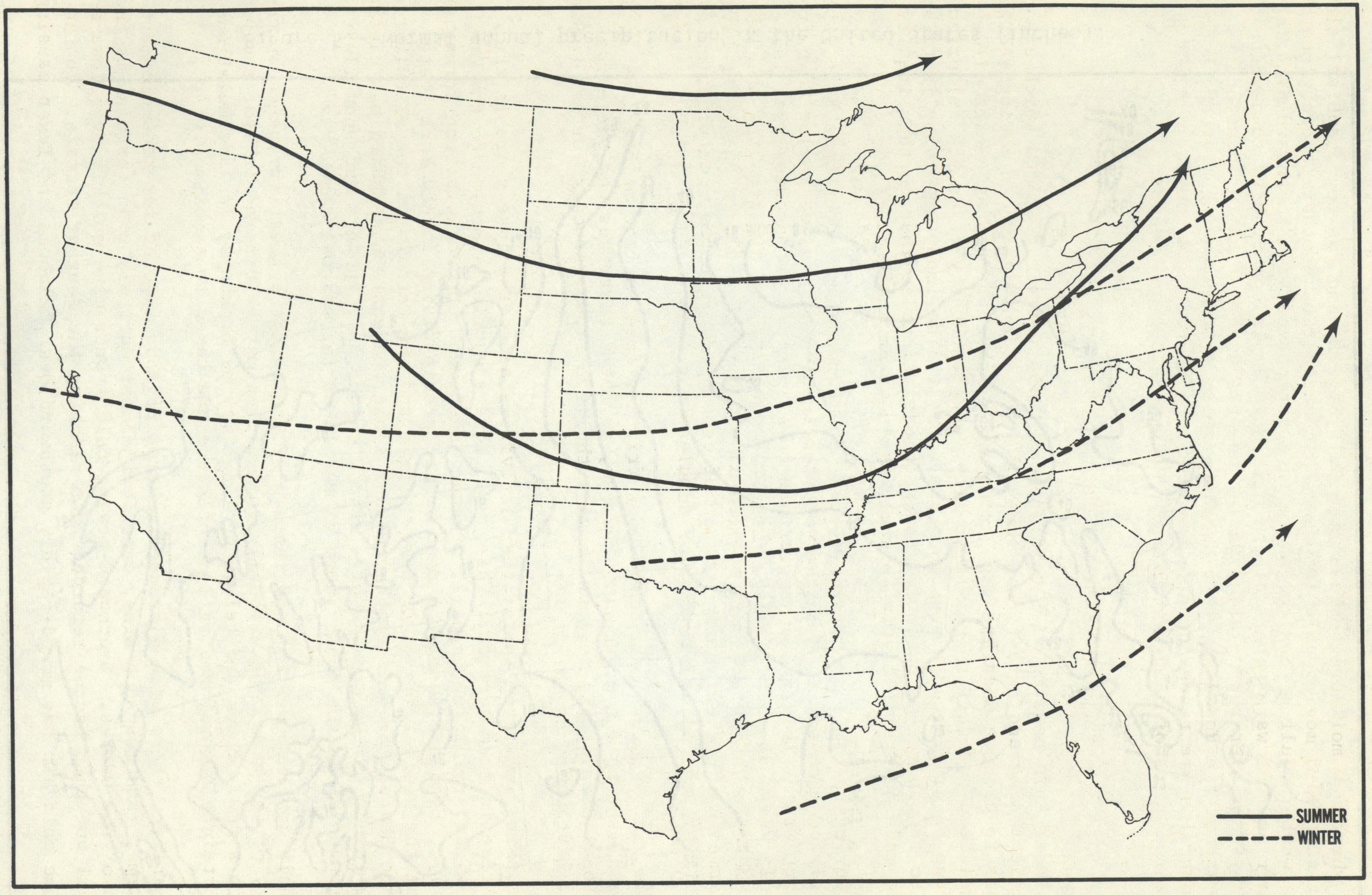

Figure 6.--Generalized storm tracks over the United States in summer and winter.

area, where new moisture sources (the Gulf Stream) and the topographical slowing of southward moving cold fronts both contribute. Another favored location is the western Gulf of Mexico, where interactions between southward plunging cold air and the warm waters of the Gulf have ample opportunity to develop storm systems over the relatively flat coastal area. A third location is just east of the Rockies, where decadent storm systems moving eastward over the mountains are rejuvenated by new moisture sources and their interaction with the sources of cold air from the Plains States and Canada.

INTERMEDIATE-SCALE EFFECTS

Under this heading will be discussed those terrain features which are of sufficient size and extent that they have sufficient impact on moving weather systems to produce moderate-size anomalies in the general pattern of climate. As indicated earlier, there are so many such features that only a selection of them can be discussed in even moderate detail. The important thing is to be able to recognize the potential for such deviations so that further inquiry can be made before initiating planned projects or analyses.

During the fall and winter months, the temperatures over Lake Erie will normally be much warmer than the cold continental air masses moving down from the northwest. This and other factors come into play to produce what is commonly known as the snowbelt. Meteorologically, the air crossing the lake is warmed from below and much additional moisture is added to the lower layers. The warmed air rises rapidly because of density differences, contributing to instability and the development of cumulus type clouds.

As the air moves over the almost friction-free surface of the lake it has no impediment to its movement. However, as the air strikes the shoreline, frictional drag at the surface impedes the free flow, inducing further tendency toward lifting of the air.

A third impact on the weather activities along the lake shore is the rapid rise in land surface. This, too, adds a vertical impulse to the onshore winds, resulting in still greater inducement to precipitation formation (fig. 7). Figure 8 shows the mean annual precipitation in New York State showing the similar impact of Lake Ontario and the terrain on the distribution over the State. Even after the weather along the eastern seaboard has cleared as the result of the passage of a strong cold front, showers and snow flurries will linger along the south shore of the lakes for several days.

This combined weather and terrain situation has a great influence on the economy of the area. Occasionally communities may be "snowed in" for several days in a row. Power and telephone lines may be broken by ice accumulations, and certainly highway and rail maintenance are taxed to a maximum.

Earlier, there were discussed several regions favored for redevelopment of storms. Another such area, dependent almost entirely upon terrain, is the Region of the Ozarks. Southward-moving cold fronts move quickly over Iowa and Missouri but then become retarded upon reaching the rougher terrain. In the meantime cold air has moved rapidly southward over Oklahoma and Texas causing

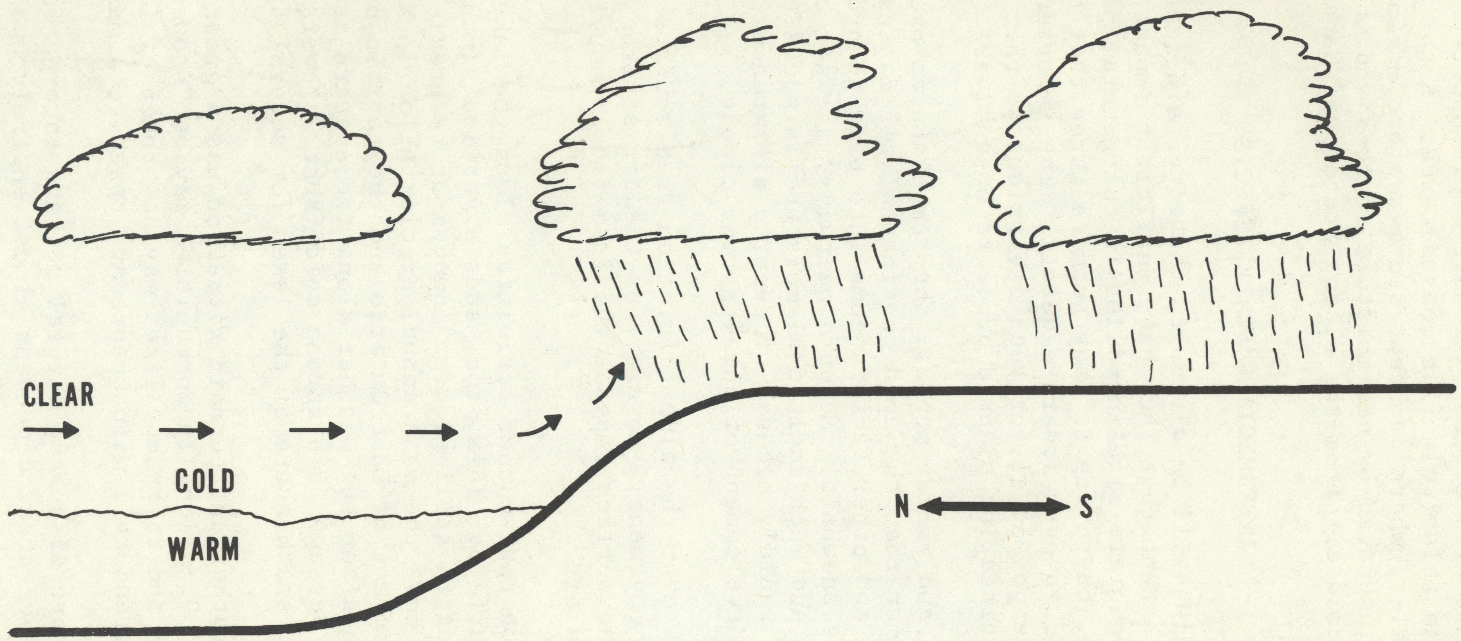

Figure 7.--Generalized wind and weather profile near south shores of lakes in winter.

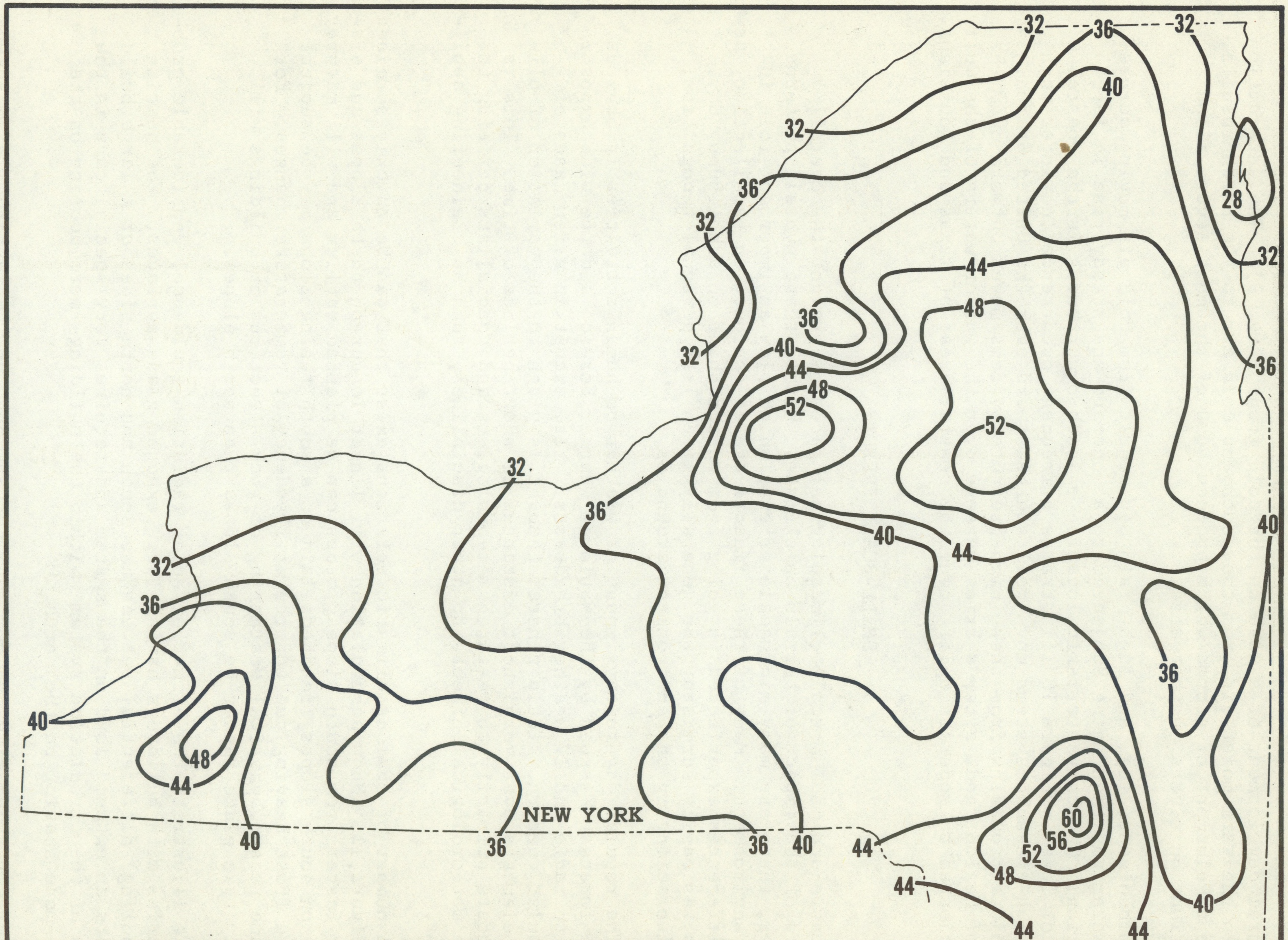

Figure 8.--Mean annual precipitation in New York State (inches).

a natural development of a wave on the cold front (fig. 9). The interaction between the warm moist air from the south and cold air to the north results in the development of storms which produce some of the most severe flood situations on rivers in that area.

Cloudiness, fog, and light rain can result from cold air moving across warm water and then being subjected to a moderate and steady rise in land elevation. One characteristic location of such occurrences is the coastal areas of Texas. Figure 10 illustrates a frequent occurrence in winter when cold high-pressure systems move well southeastward over the United States. The cold air outflow from these high-pressure systems moves outward over the Gulf of Mexico, and, after a brief passage over the warmer waters of the Gulf, is subjected to moderate uplift over the coastal areas of Texas and Louisiana.

SMALL-SCALE EFFECTS

Large-and medium-scale climatological patterns present the overall picture of the impact of terrain on climate. Within these overall patterns, however, there are many microscale effects which play an important role in man's environment. Many of these impacts are as obvious, on recollection, as the differences experienced in going from sun to shade on a hot sunny day. Others, as easily surmised, but generally given less personal recognition, are also acting in the environment around us.

The regular day-to-day impact of weather on human activities is obvious in the forecasts issued by the National Weather Service and the wide exposure given to radio and TV weather broadcasts. Yet, except in a few cases of particular concern, little general thought is given to the variation of climatic elements over very short distances or short periods of time. This is of concern primarily to research meteorologists and specialists desiring to relate meteorological effects to other disciplines, such as engineering applications.

A number of obvious climatic relations exist that can be quickly surmised from figure 11. Snow accumulation will linger longer on north slopes and disappear faster from south slopes, crops can be planted earlier and will mature faster on south slopes, roadbeds laid on a south facing slope may be subject to more frost heaving due to greater frequency of temperature changes. For the same reason, physical weathering of rock structures or buildings will usually take place faster on south slopes than north slopes.

To illustrate the effect of solar radiation incidence, considerable problems arise with buildings having large exposed glass surfaces. The heating (or cooling) differential between the south and north sides of a large building puts an extreme load on the system and requires very special care in the design of the circulation system within the building--more cooling on the south--more heating on the north.

Buildings themselves become an important part of the terrain. Wind speeds in open country may be as much as 15 to 25 percent higher than the turbulence-producing environment of a large city complex. This fact has recently become

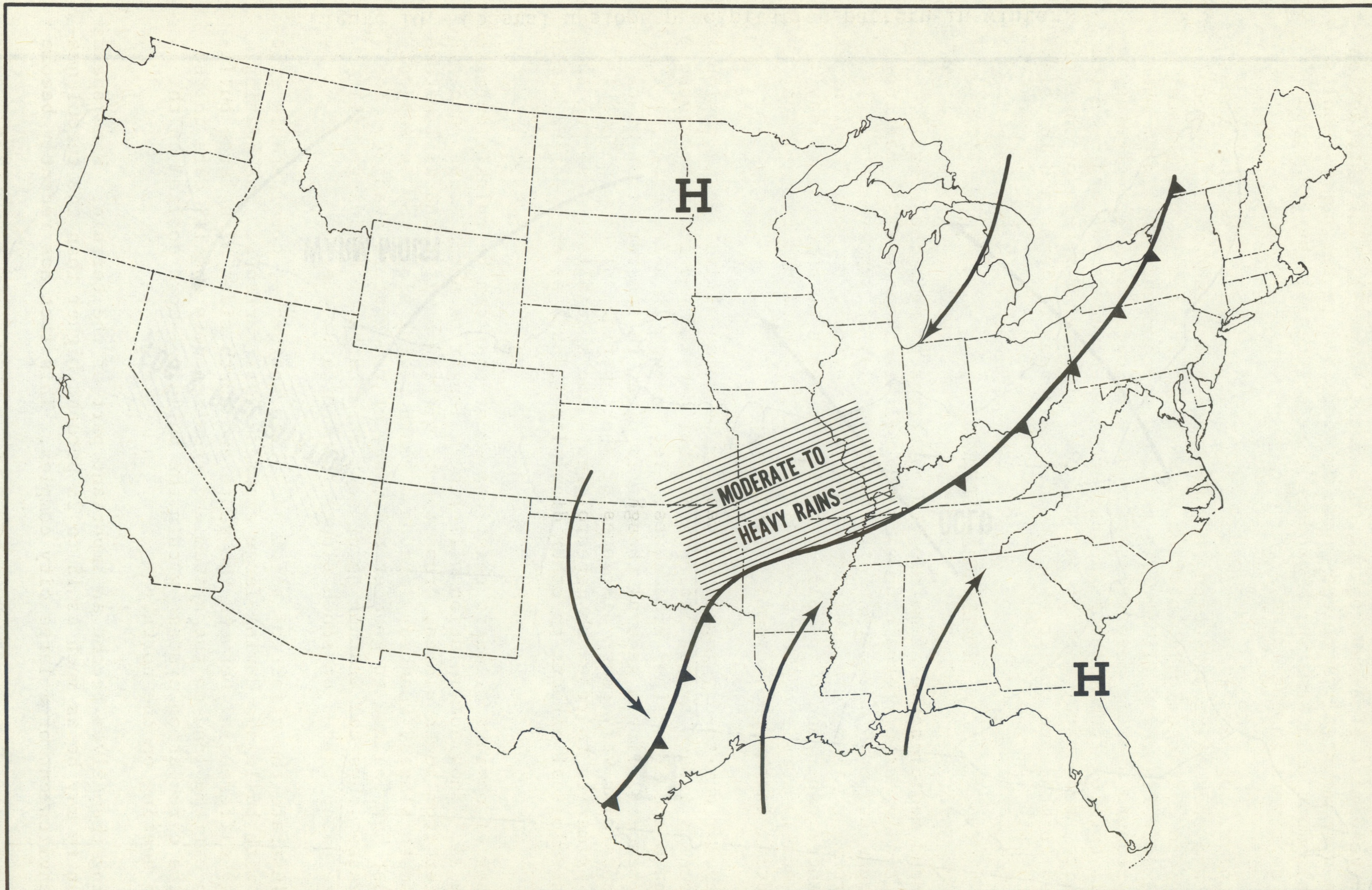

Figure 9.--Influence of Ozarks on storm redevelopment along cold fronts.

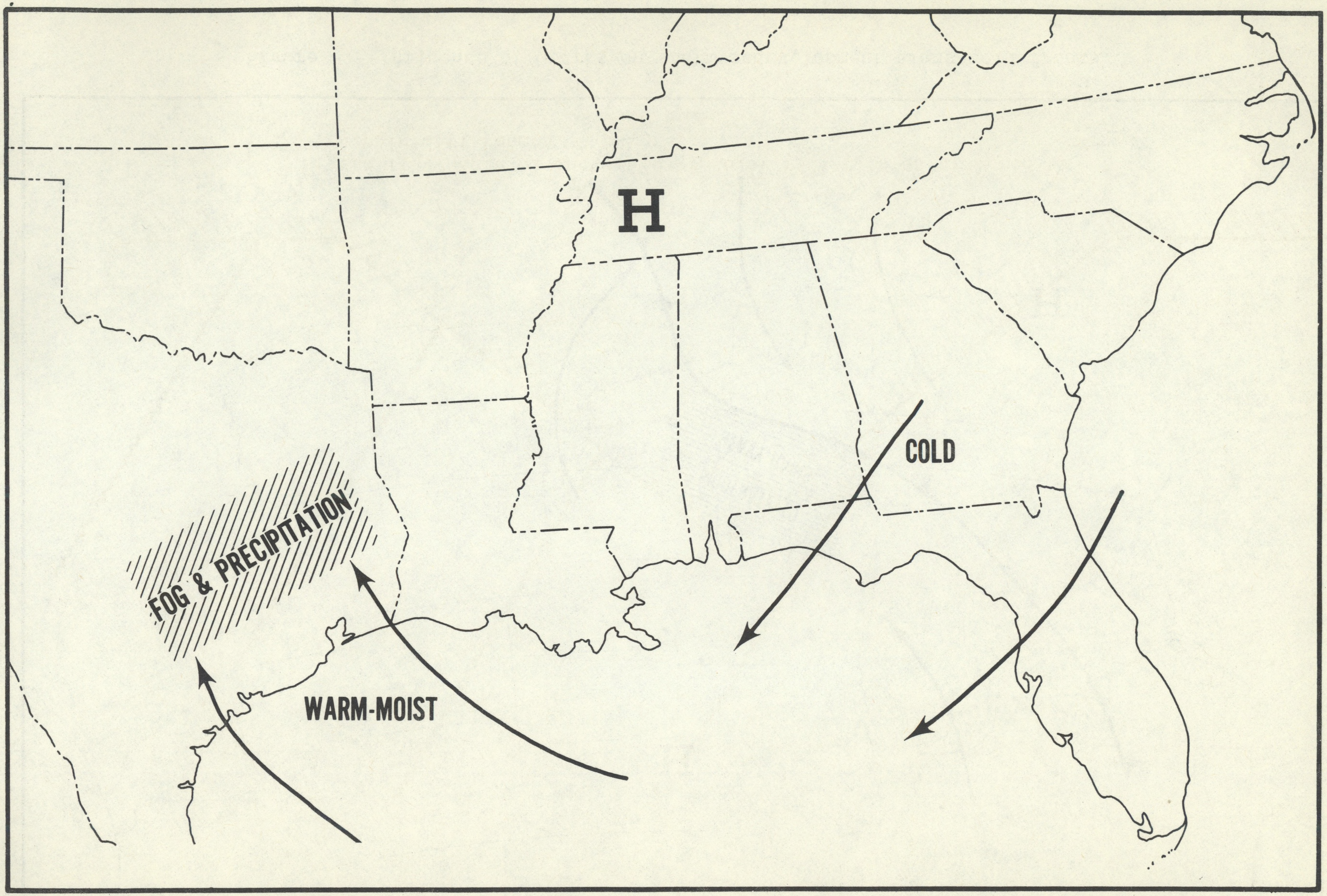

Figure 10.--Coastal upslope precipitation pattern in winter.

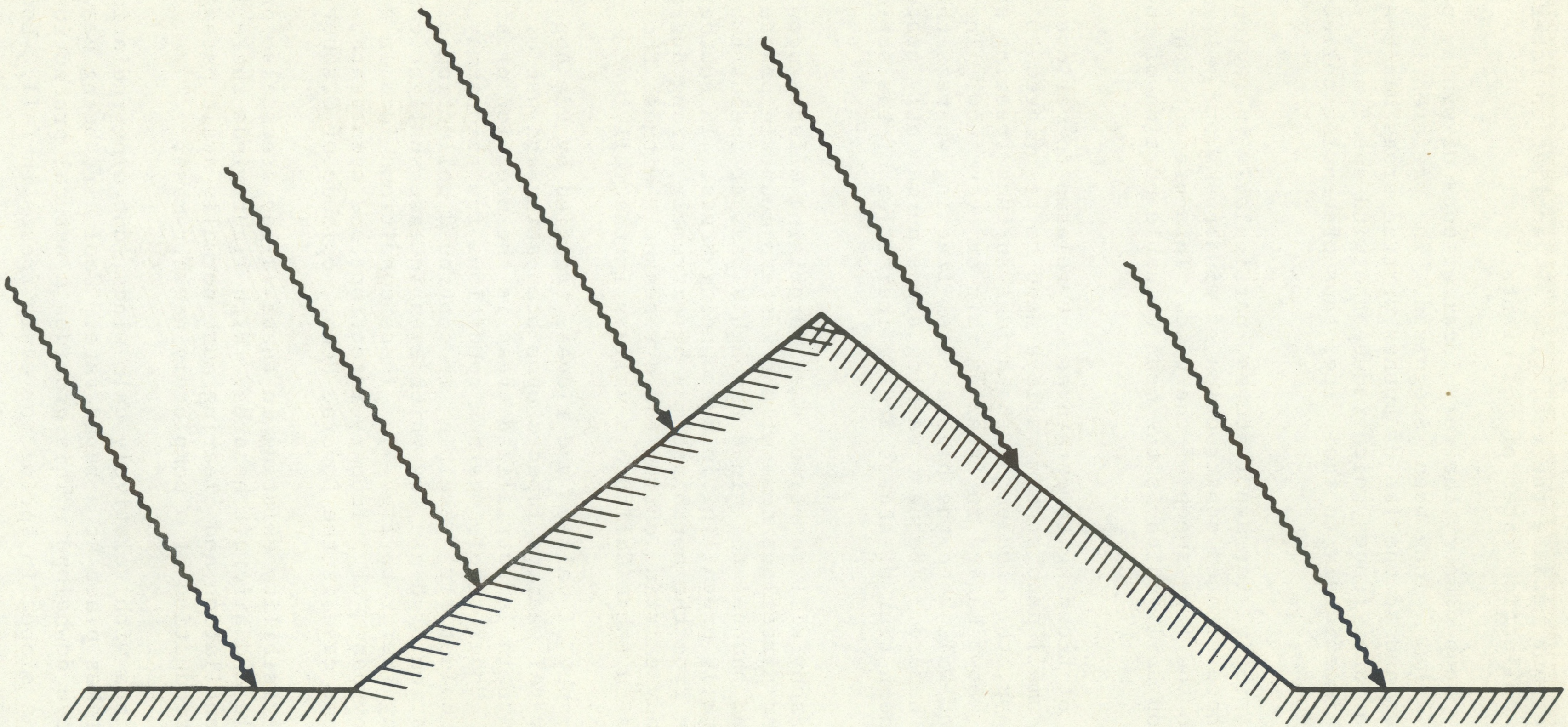

Figure 11.--Angle of incidence of solar radiation as affected by terrain differences.

increasingly important because the reduction of ventilation rates within cities increases collection rates of pollutants.

In generally open country the very local effects of winds, particularly in snowy regions, have long been recognized. The preferential collection of snow in gullies and to the lee of bushes or tree areas has been simulated by the erection of snow fences,which reduce the wind speed and result in dropping of snow immediately to their lee, thus preventing collection on highways or railroads.

Lack of restrictive terrain features, particularly in regions of a light loose soil, has necessitated construction of windbreaks or hedgerows to provide a barrier to the free sweep of the wind. This prevents the excessive blowing of the top soil, which is the most valuable portion of the land surface.

The effects of freezing temperatures are related to various topographic features. Where small deep stream valleys need to be bridged to level out our modern highways, the problem of the bridge surface freezing earlier than the roadway is a known hazard in freezing rain or even snow. The heat reservoir in the ground will keep the highway from freezing whereas the bridge will become a traffic hazard. Frequent warning signs permanently posted on thruways in the northern tier of states are an indication of the seriousness of this phenomenon.

Local topography will sometimes have surprising effects upon winds. Under certain wind directions some of the western mountain passes literally act as funnels and channel the winds through a pass at speeds two and three times those generally prevailing in surrounding areas. In southern California such winds from the northeast may be extremely strong and add to the fire hazard already existing during the dry season. Witness the frequent devastating fires in these California valleys in the fall.

Local topography of valleys and ridges, typified by the Appalachian area, leads to several weather impacts upon occupation and use of the area. Of greatest concern in industrialized areas is the creation of air pollution and fog hazards. Under stable weather conditions inversions may develop (warmer air over colder air) resulting in continued collection of air pollutants, or the creation of dense fog which even intense sunlight cannot burn off during the day (refer to fig. 4). These conditions lead in serious situations to many cases of pulmonary infections and even death. The most recent such extreme case is the Donora, Penn., episode of October 1948.

Fog and low visibility existing in these valley areas also present increased automobile and aircraft hazards. With light winds there is very little natural ventilation and clearing must normally await passage of a cold front and the introduction of a completely new air mass.

On clear nights with relatively calm winds, outgoing radiation from ground surfaces takes place at a rapid rate. Cool air, being heavier than warm air, will move downslope. This provides a natural protection against late frosts on the slopes in spring, or early frosts in fall. Local terminology in the Appalachian area refers to these areas as "thermal belts" which are a natural protection for orchards, particularly apple and peach.

Hilly country has other beneficial effects on climate. The presence of hills provide a certain degree of immunity from severe storm incursions. As can be noted from the map of tornado occurrences (fig. 12), the Appalachian area and the Rocky Mountains have notably fewer such storms. Because of local frictional effects, damage from high winds due to hurricanes and other wind storm situations is not as likely (fig. 13). However, under certain conditions--such as an increased moisture input into a storm system from another moisture source plus increased uplift causing an enhancement of instability--severe rains may occur in highly localized areas. Such was the case in the rejuvenation of hurricane Camille in August 1969. Figure 14 shows the highly localized precipitation resulting from just the right combinations of moisture, upslope motion, and a decadent hurricane system.

Very early in the development of the aviation industry, climatological studies of the winds were used to determine the orientation of runways. Many localities were able to greatly economize by situating the airport in a valley. This was particularly true in the west where, except under the most unusual conditions, winds would either blow up the valley or down the valley depending upon the general pressure gradients. Thus, a single runway was able to provide adequate landing facilities a very high percentage of the time.

Certain terrain-associated climatological conditions have an impact on photogrammetry. Quite often the upwind sides of hills or mountains will have cloud development while the downwind sides are clear. Sun angles on the variously orientated slopes and ridges must be given due consideration in aerial photography.

Sun angle effects also exert a great influence on the character of the natural vegetation as well as on possible agricultural use. North slopes characteristically exhibit vegetation typical of level regions much further north, whereas southward facing slopes, receiving more nearly vertical radiation, exhibit vegetative growth typical of areas much further south.

CAUSES OF TERRAIN CHANGE

So far we have discussed only the interaction between existing terrain and weather patterns. There are two geophysical processes that determine terrain-earth movement and erosive actions including winds and precipitation with resulting runoff. In the time scale of thousands of years of climate, characteristic land forms and features have developed through joint actions of earth movement and climate.

The rounded slopes of the Appalachian area in contrast to the rugged topography of the west are a result of their much greater age and of persistently heavier rainfalls. The arroyos of the west are the physical evidence of infrequent but intense short bursts of rainfall. The relatively uniform sedimentation of loess soils in the Plains States is the result of many years of persistent winds picking up soil particles in dry areas and

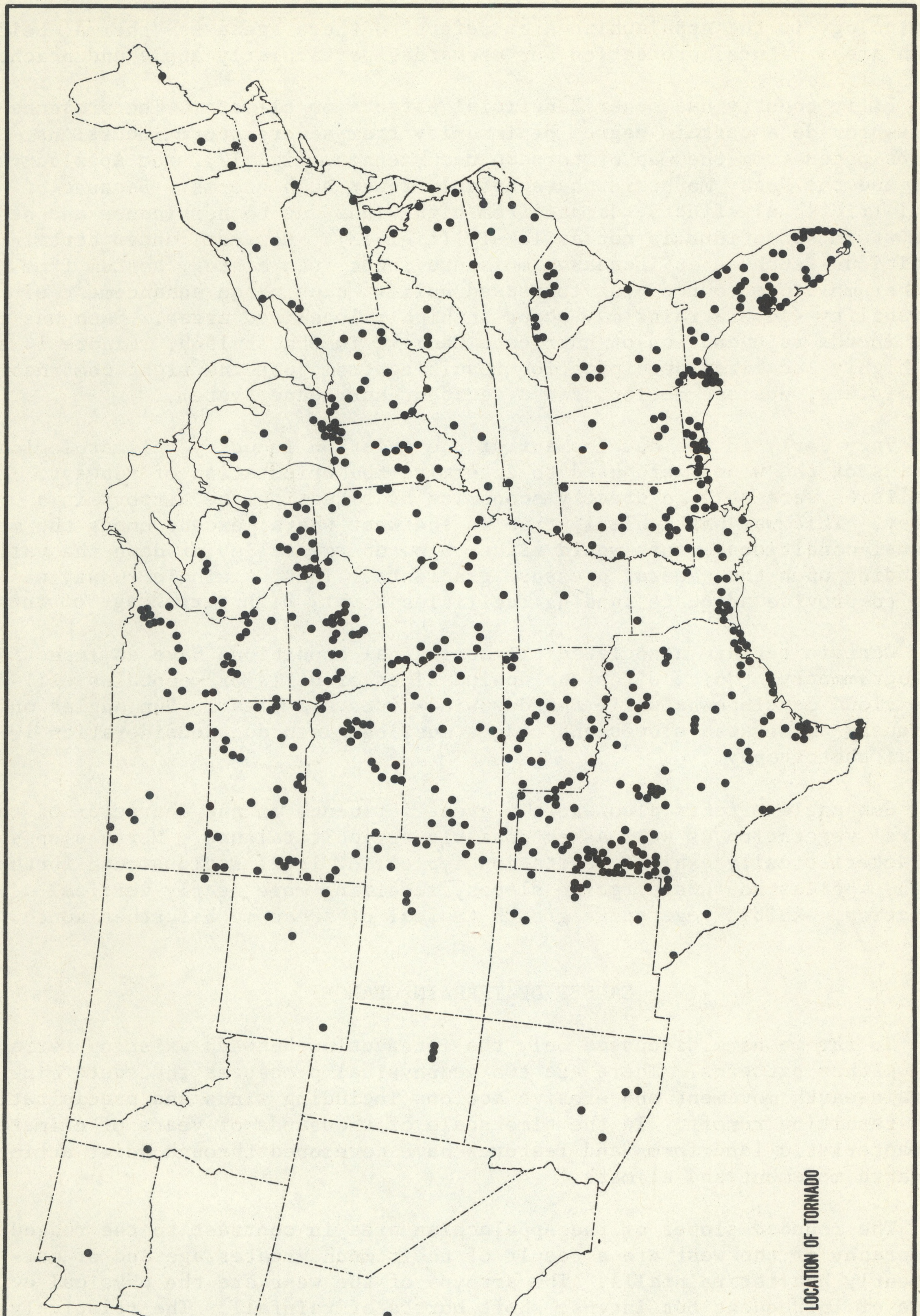

Figure 12.--Tornado occurrence in the United States, 1969.

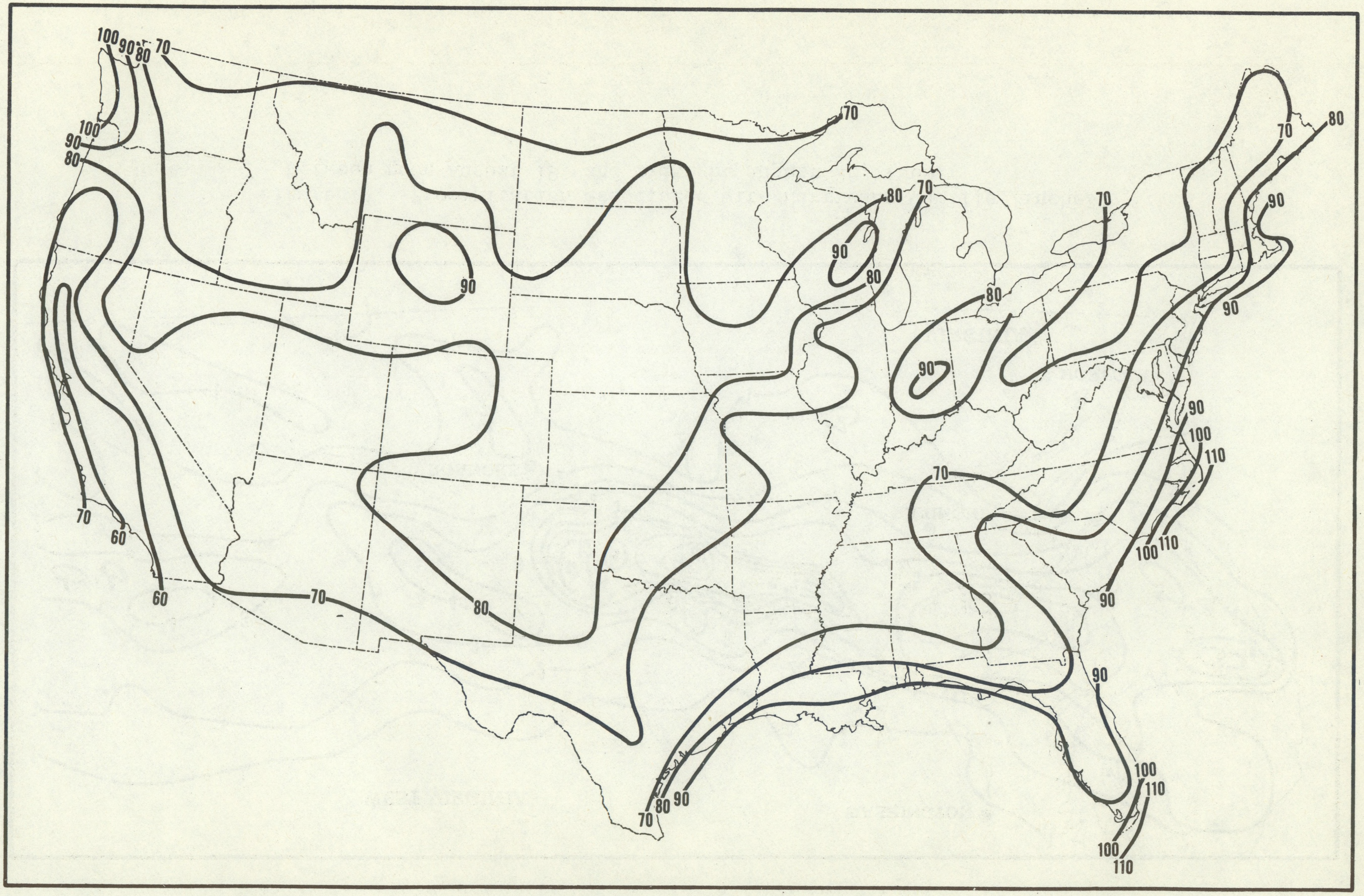

Figure 13.--Contours of 0.02 probability quantiles of annual maximum wind (miles per hour) 50-year mean interval or recurrence. (H. C. S. Thom)

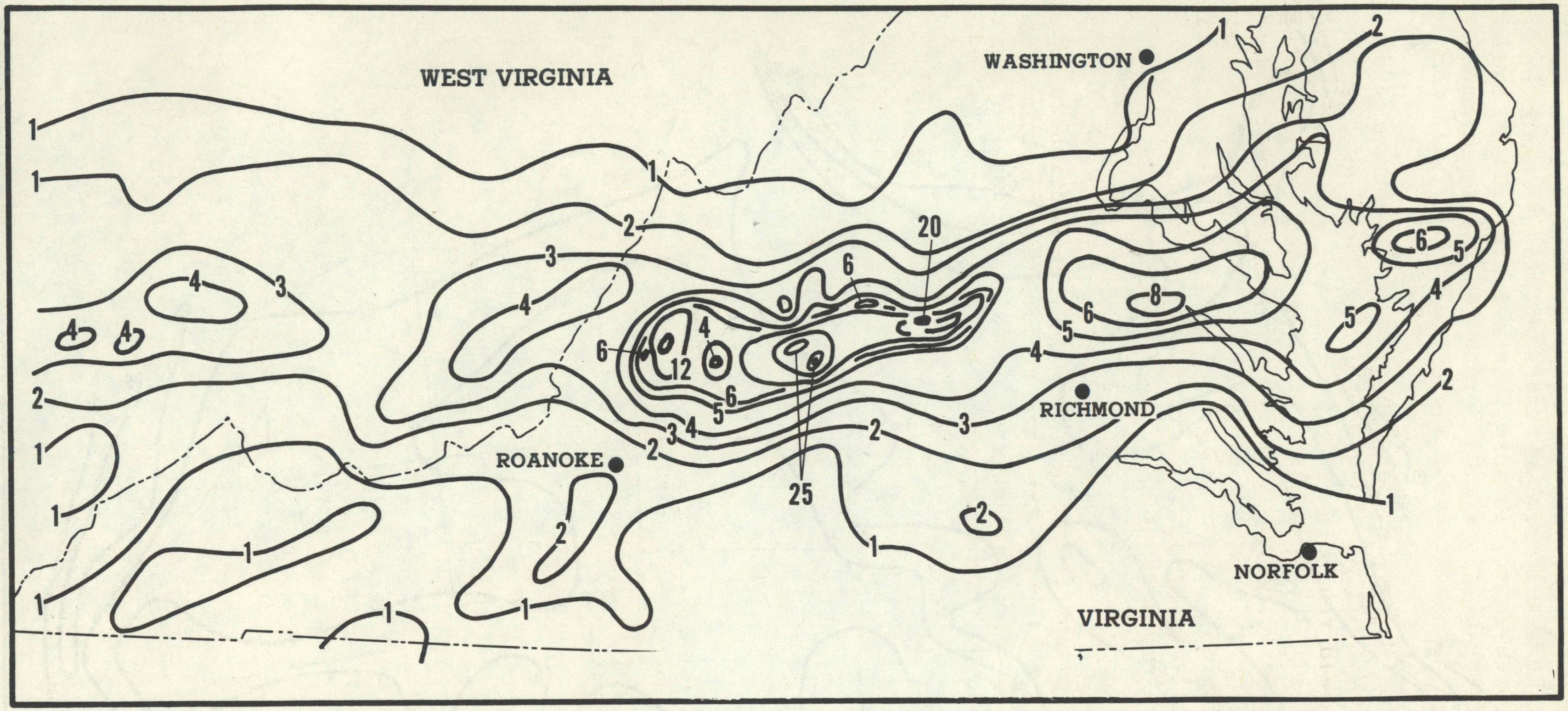

Figure 14.--Precipitation associated with Hurricane Camille (inches) between noon August 19, and midnight August 20, 1969.

depositing them downwind. The stark profiles of tall columns in such areas as Bryce Canyon are the result of many years of wind abrasion on exposed surfaces, interspersed with short, intense bursts of rainfall. Sand dunes, deltas, spits, and rocky cliffs are all products of persistence in weather patterns of wind and water movements, acting in concert with rock formation.

Over thousands of years the changing climate has produced distinctive terrain features by glaciation. Most notable of these are the scarred lands of the Laurentian shield resulting in the lakes and swamps of Canada and Northern United States, the terminal moraines and outwash plains extending across the United States from the East Coast to the Rockies, and the smaller landscape features such as drumlins and eskers. The outwash plains and eskers provide a readily available source of gravel for the construction industry. Blocked river valleys resulting in wonderful resort areas such as the Finger Lakes of New York are products of the impact of climate on the existing terrain.

One person's life span is too short to see the continuous impact of climate on terrain, but by reconstruction of the past through geomorphology we can integrate the span of thousands of years and recognize the slow but persistent tooling of the terrain by climate.

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