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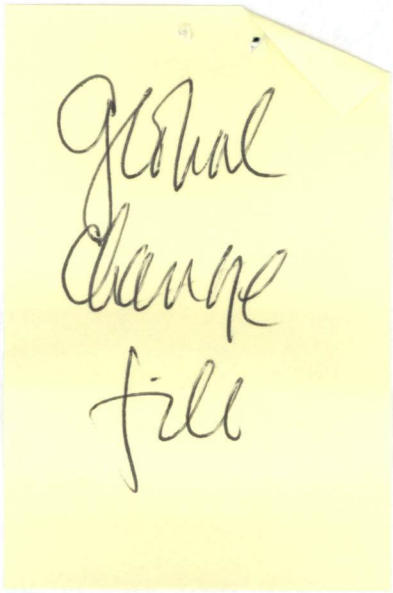
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SCIENTIFIC PERSPECTIVES ON THE GREENHOUSE PROBLEM

George C. Marshall Institute
Washington, D.C.

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PREFACE

This report is based on the technical literature relating to the climatic impact of increased greenhouse emissions and on discussions with several scientists actively involved in the technical problems of long-range climate forecasting. We are indebted to James Hansen of the NASA Goddard Institute for Space Studies for a highly informative briefing, and also to Albert Arking and Kenneth Schatten of the NASA Goddard Space Flight Center, T.M.L. Wigley of the Climate Research Unit of the University of East Anglia, Syukuro Manabe of the NOAA Geophysical Fluid Dynamics Laboratory, Robert D. Cess of the State University of New York at Stony Brook, Sabatino Sofia of Yale University and Michael Rampino of New York University.

We are particularly grateful to Drs. Manabe, Wigley, Arking and Rampino for extensive and enlightening discussions subsequent to the formal briefings.

We are also profited greatly from very interesting discussions with Robert Malone of Los Alamos Laboratory, Stephan Schneider, John Eddy and Gerald A. Meehl of the National Center for Atmospheric Research, Richard Lindzen of MIT, Michael McElroy of Harvard University and Wilmot Hess of the Department of Energy.

Finally, we wish to thank Sally Baliunas of Harvard University and Simon Worden of the U.S. Air Force for alerting us to the fact that stars with properties nearly identical to the sun have been observed to undergo variations of several tenths of a percent in luminousity, large enough to be climatically significant, and to Wes Lockwood of Lowell Observatory for transmitting to us data on variations of up to 0.4% in the luminosity of sun-like stars, which have not yet appeared in the scientific literature.

Frederick Seitz, *Chairman*
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I. THE GREENHOUSE PROBLEM

This study considers the technical issues involved in forecasting the intensity of the greenhouse effect — a warming of the earth produced by the presence of carbon dioxide and certain other gases in the atmosphere. These gases absorb heat that would otherwise escape into space, returning some of it to the earth's surface and raising the temperature on the planet. The gases that have this heat-absorbing property are called greenhouse gases, and their warming influence on the earth is called the greenhouse effect.

The focus of the study is the evidence for a significant rise in the temperature of the earth in the last 100 years, coincident with a substantial increase in the amount of carbon dioxide and other greenhouse gases in the atmosphere. The increased atmospheric concentration of these gases is apparently the result of human activities, such as the burning of coal and oil.

Several scientific groups have concluded that man-made emissions of carbon dioxide and other greenhouse gases are the cause of much or all of the rise in global temperatures that has been observed since the turn of the century. They predict that if the atmospheric concentration of greenhouse gases continues to increase as a result of the burning of fossil fuels and other human activities, the average temperature of the earth may rise in the 21st century by as much as 5° C, or 9° F. Such an increase might cause widespread drought in many agricultural areas and have a destructive impact on human life in many parts of the world.

Not all experts in the field of climate studies agree with these conclusions. However, a substantial body of scientific opinion considers the man-made greenhouse effect to be a serious concern that must be addressed.

IS THE GREENHOUSE EFFECT A NEW PHENOMENON?

The potentially harmful greenhouse effect resulting from human activities is a relatively small addition to a large, natural greenhouse effect that has warmed the earth for billions of years. This natural greenhouse effect — which is, of course, unrelated to human activity — comes largely from water vapor in the earth's atmosphere. Water vapor, like carbon dioxide, is a greenhouse gas; it partly blocks the return flow of heat coming up from the surface and atmosphere to space thereby warming the earth. Naturally occurring carbon dioxide in the atmosphere adds to the greenhouse warming produced by the water vapor, but its effect is much less than that of water vapor.

The greenhouse effect produced by water vapor and other gases occurring naturally in the earth's atmosphere has been highly beneficial to life on our planet. If it were not for this natural greenhouse effect, the average temperature on earth would be a chilly 0° F — well below freezing. The warming effect of the earth's greenhouse gases has raised the average global temperature by 60° F — from 0° F to 60° F. Sixty degrees Fahrenheit is a comfortable temperature as an average over the planet. In fact, it may be close to the optimum average temperature the earth could have, from the viewpoint of supporting life over the largest possible area of the globe.

REASONS FOR ADVOCATING PROMPT GOVERNMENT ACTION

The enhanced greenhouse warming produced by human activity will be no more than a few degrees, and quite small compared to the 60-degree natural greenhouse effect, but its consequences could be devastating in the short term. A temperature increase of

up to 5° C could lead to recurrent and severe summer drought in the midwestern states of the U.S. and other productive agricultural regions. Although opinion is divided on the matter, in the worst-case scenario a warming of 5° C might also break up the West Antarctic ice sheet, eventually, after several centuries, raising sea levels by as much as 15 feet. Large areas of New York City, Miami and other coastal cities and densely populated river deltas would be submerged, and the lives of hundreds of millions of individuals living in coastal areas all over the world would be disrupted.

Government officials in the U.S. and other countries have begun to address the need for major policy decisions dictated by these grim projections. Their concern is heightened by the fact that the warming caused by the greenhouse effect takes a long time to build up and may not be noticeable for several decades, but once it has developed, it may take centuries to eliminate. As a consequence, if corrective actions, such as cutting down on the burning of fossil fuels, are delayed until the full measure of the greenhouse warming is upon us, it may not be possible to ameliorate its destructive effects for centuries.

II. RELIABILITY OF THE PREDICTIONS

How accurate are the greenhouse forecasts? The basic statement that carbon dioxide and other greenhouse gases warm a planet is not in doubt. Venus, for example, has an enormous amount of carbon dioxide in its atmosphere — 60,000 times more than the earth — and the surface of Venus is also oven-hot, with an average temperature greater than 800 degrees Fahrenheit. A calculation of the greenhouse effect produced by the dense concentration of carbon dioxide on Venus indicates that this effect can explain the searing Venus temperatures. No other explanation known to planetary science is adequate to account for these high temperatures.

Mars also has carbon dioxide in its atmosphere; in fact, the Martian atmosphere, although relatively thin, is composed almost entirely of this greenhouse gas. As in the case of Venus, calculations of the greenhouse effect on Mars show that it is warmer by just about the amount that would be expected as a consequence of the carbon dioxide in its atmosphere.

Applying these results to the earth, we can be confident that an increase in the amount of carbon dioxide in the earth's atmosphere must raise the planet's temperature. But by how much? Scientists trying to forecast the amount of greenhouse warming resulting from the increase in man-made carbon dioxide face the problem that the man-made warming effect they are calculating is quite small compared to many natural warming and cooling effects that influence the earth's climate. To treat this small man-made effect accurately, they must be able to compute the natural changes in the earth's climate with great precision. When they attempt to do a precise calculation, they run into two difficulties — oceans and clouds.

INFLUENCE OF OCEANS ON FORECAST ACCURACY

Scientists forecasting the magnitude of the man-made greenhouse effect have found that their results are affected by the ocean currents which carry large volumes of water from one part of the globe to another. When the effect of these large-scale ocean currents is included in the calculations, the size of the greenhouse warming may be decreased.

In one representative case, in which the emission of greenhouse gases was assumed to increase at the equivalent rate of one percent a year (usually regarded as a realistic projection), the calculations showed that if the effect of ocean currents is not included, the entire globe warms up by roughly 2° C to 3° C over the course of the next 50 years. But when ocean currents are included, the northern hemisphere warms up by the same amount as before, but the southern hemisphere warms up by only 1° C.* The Antarctic Ocean hardly warms at all, and may cool slightly.**

The improvement in forecast accuracy resulting from the inclusion of ocean currents thus has an important practical consequence. It diminishes the probability of an eventual breakup of the West Antarctic ice sheet, accompanied by a rise of sea levels and flooding of coastal cities all over the world.

A possible breakup of the West Antarctic ice sheet with a consequent substantial rise of sea levels, although not expected for centuries and indeed a matter of dispute among the experts, is nonetheless among the most menacing potential consequences of the man-made greenhouse warming. Full allowance for the effect of ocean currents in the forecasts may remove this threat from the list of greenhouse dangers.

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* Eventually, the southern oceans must also heat up in response to the increased greenhouse effect, but this will probably take hundreds of years.

** S. Manabe, private communication.

INFLUENCE OF CLOUDS ON FORECASTS

Clouds are the second major problem area for the greenhouse forecaster. Clouds cover roughly half the area of the earth at any given time, shielding this large area from the sun's rays. As a consequence they have a cooling effect on the climate. Clouds also have a heating effect because, like greenhouse gases, they block the flow of heat to space from the earth's surface. However, recent satellite measurements have shown that this heating effect is outweighed by the cooling effect of the clouds.

Clouds create a problem for the greenhouse forecaster because the natural cooling effect they produce is ten times as large as the entire man-made greenhouse warming projected for the middle of the next century. Their heating effect — which is a natural greenhouse effect — is also considerably larger than the predicted size of the man-made greenhouse effect.

This means that a very small change in the earth's cloud cover and cloud heights can greatly change the actual greenhouse warming. Suppose, for example, that because of the greenhouse warming, more water evaporates into the atmosphere from the warmer oceans. That could mean that more clouds would form. But the increased cloud cover would cool the earth, partly offsetting the greenhouse warming. This would be an example of "negative feedback": the greenhouse warming produces more cloud cover; the increased cloud cover feeds back into the climate, and decreases the amount of the greenhouse warming.

On the other hand, suppose that fewer clouds form because, although the atmosphere has more water vapor, the warm air has a lower relative humidity. Consequently, the vapor is less likely to condense into cloud droplets. That would mean a decrease in cloud cover and, therefore, more sunlight reaching the earth's surface and warming the planet. In other words, a change in cloud cover produced by the greenhouse effect would itself enhance or magnify the effect. This would be a case of "positive feedback."

Because the effect of the clouds is roughly 10 times as large as the greenhouse effect predicted for the mid-21st century, a very small change in the cloud cover could either diminish the greenhouse warming by a large amount, or magnify it by a large amount, depending on whether the cloud feedback was negative or positive. But small changes in cloud cover are very hard to predict. Consequently, the cloud feedback is also very hard to predict with any accuracy.

Types of clouds and cloud heights are also very important for estimating cloud feedback, and again very difficult to predict with accuracy. The relatively low-altitude stratus clouds block incoming sunlight more effectively than they trap the outgoing heat from below, and hence tend to have a cooling effect. Higher-altitude, tenuous cirrus clouds, on the other hand, let more light through, but block the flow of heat from below, and tend to have a warming effect.

Most greenhouse forecasts show that the cloud feedback is positive. That is, the combined effect of changes in cloud cover and cloud height or cloud type, in response to a greenhouse warming, is to increase the amount of the warming.* But again, by how much? The scientific groups working on the problem differ by 300 percent in their estimates of the amount of extra greenhouse warming produced directly or indirectly by clouds. Some groups say the extra warming is small, while others say it is several degrees.

The practical consequences of these disagreements are very great. They constitute a large part of the difference between forecasts of up to 5°C of temperature increase in the mid-to-late 21st

* The studies show that fewer clouds are formed as a result of the warming because warm air has a lower relative humidity; thus, more sunlight penetrates, the earth is warmed, and the greenhouse effect is magnified. In addition, the clouds that do form tend to do so at higher altitudes. Since at the higher altitudes the cloud tops are colder, they radiate less heat to space, further increasing the greenhouse warming

[redacted]

Erratum: Page 8, 3rd paragraph, lines 5-7

Western Europe are easterlies, coming from the Eurasian land mass. Actually, these winds are known to be westerlies coming mainly from the Atlantic Ocean.

[redacted]

[redacted]

century, and forecasts of a temperature increase of only 1°C.

The disagreement arises because the formation of clouds is a complex phenomenon. The different types of clouds — cirrus, cumulus, and so on — absorb heat from below differently, and reflect sunlight differently. Each scientific group working on the greenhouse problem has its own way of handling these complications, and arrives at a different answer.

POOR QUALITY OF REGIONAL FORECASTS

It is important for greenhouse forecasts to be able to predict not only the worldwide temperature trends, but also the climate changes in a region, such as western Europe or the U.S. midwest. Regional climate changes can be very different from the global climate trends. For example, an analysis of temperature records reveals that in the 1970s and 1980s, when the world as a whole became warmer, England and Europe became somewhat colder.

Unfortunately, the greenhouse forecast models do very poorly in attempts to calculate regional climates, even when the region is as large as a continent. One climate forecast used in greenhouse studies predicts, for example, that the July prevailing winds over Eastern Europe are westerlies, coming mainly from the Atlantic Ocean. Actually, these winds are known to be easterlies coming from the Eurasian land mass. This remarkable mis-prediction has major consequences for the climate of Europe, since, inter alia, winds from the ocean carry more moisture, and cause more rainfall, than winds blowing off the continent.

EFFECT OF AVERAGING OVER LARGE AREAS

When the computations leading to the greenhouse forecasts are carried out, it is assumed at the outset that the surface of the earth

can be divided into a number of small areas. Within each area, the temperature of the surface is represented by a single number, which is supposed to be the average temperature for that area. The humidity, cloud cover, height above sea level, and all other quantities affecting the climate also are represented each by one number for the area, which is supposed to be their average value for that area. This is done to diminish the amount of computing required for the forecast.

The trouble with this process of averaging over areas is that the "small" areas assumed in the greenhouse forecasts are not so small. In most forecasts used for the greenhouse problem, the areas used to describe conditions at mid-latitudes — in the U.S., and Europe, for example — are about 500 miles in extent.*

In the U.S., an area 500 miles across nearly spans the distance between Los Angeles and Albuquerque. Two such adjacent areas encompass the territory running from the Mexican border to Canada.

When areas used for averaging are as large as this, two completely different climate zones — for example desert and fertile farmland — can exist within a single area. But an "average" over desert and fertile terrain would yield a forecast useless to the inhabitants of either region.

Averages over large areas also reduce the climate impact of mountain ranges, which can be very great. A mountain range deflects the flow of air and often causes moisture to precipitate as rain. As a result, the windward side of the range is generally wetter than the leeward side. But when the average height above sea level is computed for an area, the mountains are spread out and flattened, often to the point of insignificance.

A forecast based on such mountain-flattening averages would predict little difference in climate between heavily forested Ore-

* They are chosen to be that large because the computers available to climate forecasting groups do not have the speed and power needed to generate a more detailed forecast in a reasonable amount of time.

gon and the Nevada desert, because it would miss the effect of the Sierra and Cascade mountain ranges in dumping moisture from the Pacific on the west coast.

Most experts on climate forecasting agree that the computations used for current greenhouse forecasts have little or no capability for regional prediction. One demonstration of that fact can be seen in the fact that two independent greenhouse forecasts, yielding the same global temperature increase in response to greenhouse gas increases, can give contradictory regional forecasts.

COMPUTING DIFFICULTIES IN GENERATING ACCURATE FORECASTS

If the inclusion of ocean currents changes the greenhouse forecasts so markedly, why do most scientific studies of the greenhouse effect continue to ignore the effect of these currents? If averaging over large distances leads to inaccurate regional forecasts, why do greenhouse forecasters not average over smaller distances?

The reason is that averaging over smaller distances costs the forecaster very heavily in computing time. The amount of computing time required for a greenhouse forecast goes up sharply when the forecaster attempts to describe the earth and its atmosphere and oceans in more detail by breaking the globe up into small areas.

For example, if the forecasts are averaged over 250-mile areas instead of 500-mile areas, the computation takes eight times as long. A single 100-year forecast takes approximately 4 months when the areas are 500 miles across. If they were reduced to 250-mile areas, the forecast would take nearly three years.

These computing difficulties are exacerbated by the problem of the oceans. Exceedingly high resolution is required for an adequate treatment of ocean currents. The Gulf Stream, for example,

which has such an important effect on the climate of northern Europe, is less than 100 miles wide at its narrowest point. Describing such currents means dividing the ocean's surface into many areas, each no more than 100 miles across.

The oceans make up three-quarters of the area of the globe. An enormous amount of computing time would be required to generate a forecast with a description of the oceans as detailed as this. For example, if the size of the areas over which the currents are averaged is merely cut in half, the calculations become 16 times longer.*

If all the important questions about the greenhouse warming could be answered by two or three 100-year forecasts, the answers everyone is waiting for might be obtained in a reasonably short time — even though each forecast takes years — by dividing the workload among several computing groups.

But if the greenhouse forecasts are to make a useful input to policy decisions they must be repeated a large number of times, to determine how the greenhouse warming depends on different assumptions regarding such factors as the rate of consumption of coal and oil, increase in electrical power use and third-world economic growth. A great many computing runs are needed to answer these basic questions. With the limited computing power currently available to climate forecasters, decades would be needed to provide policy makers with the information they require.

Yet greater accuracy and reliability in the forecasts are essential, in spite of the heavy computing burden and lengthy computations that will entail. The forecasts do not appear to be good enough in their present form to provide a sound basis for decisions affecting the economies of the U.S. and other nations.

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* Normally, doubling the detail (and halving the area of averaging) leads to an eight-fold increase in computing time. The additional factor of two in this case comes from the fact that as the area over which the Gulf Stream is averaged diminishes, the velocity of the Gulf Stream increases proportionally.

IMPORTANCE OF ADDITIONAL COMPUTING POWER

Inadequate allowance for the effective changes in ocean circulation is a major source of uncertainty in the greenhouse forecasts. The inability to generate meaningful regional forecasts is another reason why these forecasts are not of much practical value at present, even for the limited purpose of sounding an alarm over the coming greenhouse warming.

Both problems would be ameliorated if the surface of the earth were broken up into considerably smaller areas — at the expense of a substantial increase in computing time.

As noted above, increased computing power will be helpful in meeting the need for more accurate forecasts. Computing power alone will not solve the problem of the regional forecasts, but it will enable the greenhouse forecast groups to represent mountains more accurately, and they will also be able to start experimenting with other changes needed to tune up the regional forecast capability of their climate models. At present, the greenhouse forecasters — forced to resort to averaging over areas that may span a quarter of a continent — cannot even make a start on that problem.

The bottom line is that greenhouse forecasts could be made both more accurate and more timely — and, therefore more useful to policy makers — if the leading climate forecasting groups had more powerful computing facilities for their work.

Supercomputers now on the market offer a 15-fold speed increase over the best computers now used by scientists working on the greenhouse problem. Even faster computers are under development. These supercomputers can diminish errors and uncertainties in the forecasts resulting from inadequate allowance for the effect of ocean currents. They will also allow greenhouse forecasters to make a serious attempt at accurate regional forecasts — an achievement not within their grasp at present.

Critically important policy decisions affecting the five-trillion-dollar U.S. economy depend on the reliability of the predictions

generated by the greenhouse forecasting groups. Their computing facilities are underpowered for the importance of the work being done. One hundred million dollars would purchase top-line supercomputer complexes for the four major scientific groups working intensively on the greenhouse problem. The expenditure would be a solid investment in the future of the economy.

NEED FOR MORE OBSERVATIONS AND BETTER PHYSICS

Computing power is one major requirement for better climate predictions. The other need, equally important, is for more observations of the actual conditions prevailing on the earth and in its oceans and atmosphere, and for monitoring of factors causing climate change, such as greenhouse gas concentrations, values of the "solar constant" and changes in the transparency of the atmosphere caused by volcanic eruptions.

Observations of the oceans are particularly important because the state of observational knowledge of the oceans is much poorer than that of the atmosphere. More complete data on the variation with depth of ocean temperature, salinity and currents are badly needed.

Moist Convection. These expanded programs for observing clouds, ocean currents and temperatures, and other climate-related properties are vital to the success of the climate forecasting effort. For example, how is heat carried from the ground up to space? Any calculation of global temperature increases due to carbon dioxide emissions must have a fairly accurate answer to that question. Yet the answer is not known very well.

What happens in a general way is that water evaporates from the earth's surface — mainly from the oceans — to form warm, moist air. The warm air expands and rises, carrying its warmth and moisture to higher altitudes.

As the air rises, it cools and condenses into water droplets, and

cumulus clouds form. The condensation of the water vapor into droplets of liquid water releases additional heat to the atmosphere. Eventually, the droplets collect into rain drops which fall to the surface, cycling the moisture back to the surface of the earth. However, the heat that was carried up stays in the atmosphere.

This process by which heat and moisture are transported to higher levels in the atmosphere is called "moist convection." Moist convection has an indirect but critically important consequence for the greenhouse effect. By carrying moisture to higher altitudes in the atmosphere, it leads to the formation of clouds. These clouds change the surface temperature because, as noted on page 7, they screen the earth from incoming sunlight, cooling the surface; but they also block the upward flow of heat to space, warming the surface. No one is certain what the net balance of heating and cooling is for the clouds created by moist convection.

Furthermore, when the earth begins to get warmer in the first stages of the greenhouse effect, both the process of moist convection and the clouds it generates are affected, and the balance of the heating and warming is shifted. Is the shift in the direction of more warming, which means the long-term greenhouse warming is increased; or is it in the direction of cooling, which means the long-term greenhouse warming is cut down?

These uncertainties in the size of the 21st-century greenhouse warming, which are associated with the complexities of moist convection, are only a part of the cloud problem. Clouds are formed in other ways than by moist convection, and each mechanism of cloud formation introduces its own uncertainties into the greenhouse forecasts. As noted earlier, attempts by several groups to deal with the effect of clouds on the greenhouse forecasts yield results that differ by as much as 300 percent.

There is some grounds for optimism that these cloud-generated uncertainties would be reduced if more information could be acquired on the types of clouds, and cloud heights, that arise under different conditions. Collecting this information should be a top-priority objective in greenhouse research in the next few years.

III. CURRENT STATUS OF THE GREENHOUSE FORECASTS

Several greenhouse forecasting groups have estimated the amount of warming that would result if the equivalent concentration* of carbon dioxide in the atmosphere were to double as a result of human activity — a condition that may be encountered in 30 to 50 years. As noted previously, their results for the long-term or "equilibrium" increase in the average temperature of the earth range from a lower limit of 1° C to an upper limit of 5° C, or roughly 2° F to 9° F.** This wide spread in the forecasts made by the different groups is mainly the result of differences in their treatment of clouds.

A greenhouse warming of 1° C — at the lower end of the predictions — could be partly or largely offset by natural climate changes unrelated to human activity. The natural cooling that occurred during the Little Ice Age of the 16th and 17th centuries represented a temperature drop of roughly 1° C relative to today's temperatures. If a natural cooling comparable to the Little Ice Age were to return in the next century, a greenhouse warming of 1° C would have the beneficial effect of ameliorating its destructive impact, leaving global temperatures within a degree or so of their present levels.

On the other hand, an eventual greenhouse warming of 5° C — at the upper end of the range of predictions — would lead to cat-

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* In addition to carbon dioxide, the greenhouse gases include methane, nitrous oxide, and chlorofluorocarbons. For simplicity, all are lumped with carbon dioxide and stated as an equivalent carbon dioxide concentration — i.e., equivalent in their impact on the climate.

** S.H. Schneider, *Science* 243, 771 (1989).

astrophic changes over large areas of the globe in the next century. These changes would be too large to be offset by any likely change in climate due to natural causes. Policy makers surely would undertake early action to forestall this development, if they were confident in the accuracy of the forecasts predicting the large effects.

It may be possible to achieve an accuracy that would warrant this confidence by the application of a heavier concentration of computing power, combined with global observations on the earth's clouds and oceans. At the present time, the greenhouse forecasts tell us only that a serious problem may exist — or it may not.

COMPARISON BETWEEN GREENHOUSE FORECASTS AND OBSERVED TEMPERATURE INCREASES

As noted, while the greenhouse forecasts point to the likelihood of a global warming, they cannot predict its size with confidence. However, the fact that the earth has already become appreciably warmer in the last 100 years apparently indicates that the greenhouse effect is already here, and that its size is substantial.

Carbon dioxide in the atmosphere has increased by about 25 percent since the Industrial Revolution, as the result of the burning of coal and oil, deforestation and other human activities. If the middle range of greenhouse forecasts is correct, this increase in carbon dioxide should have produced a temperature increase of roughly 0.5° C between 1880 and 1985. The temperature measurements show an increase in average global temperature by just the predicted amount of 0.5° C.

Figure 1 shows the comparison between the calculated greenhouse temperature rise and observed temperatures. The solid line in Figure 1 shows the global temperature change observed on land between 1880 and 1985, averaged over 5-year intervals, as compiled by Hansen and Lebedeff. The observed temperature increas-

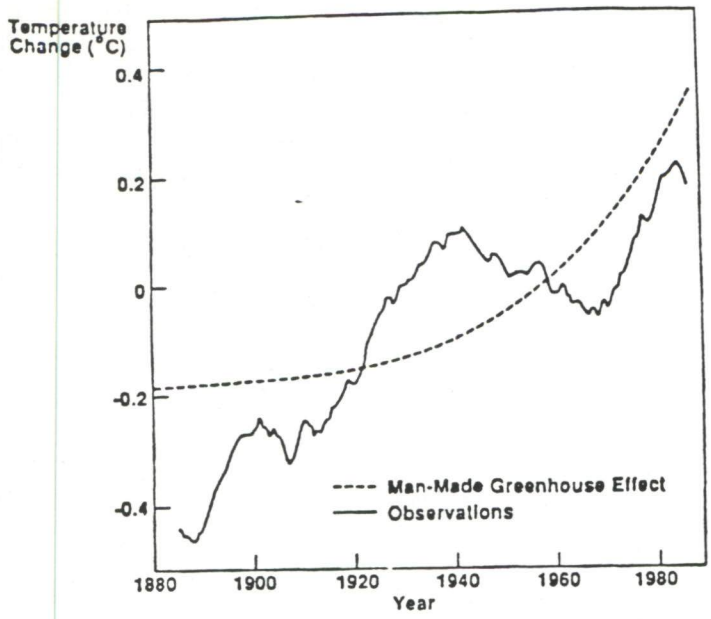


Figure 1. Comparison between observed global average temperature and calculations based on the greenhouse effect. The dashed line indicates the calculated temperature increase caused by the greenhouse effect since 1880. The solid line indicates the observed temperatures for the same period.

es by about 0.5° C between 1880 and 1985, as mentioned in the previous paragraph.

Similar results have been obtained by Jones and Wigley for land and ocean surface measurements combined, and by Folland and Parker from ocean surface measurements.*

The dashed line in Figure 1 shows the predicted greenhouse

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* Some experts have expressed skepticism regarding the reality of the 0.5° C rise in global temperature. Independent confirmation of the rise comes from recently reported findings that the sea level has risen by roughly one foot in the last 100 years. (W.R. Peltier and A.M. Tushingham, *Science*, 244, 806, 1989.) Calculations indicate that a sea level rise of just about this magnitude should accompany a temperature increase of 0.5° C. However, the authors of the report on the rise of sea level are careful to caution that their findings, while consistent with a 0.5° C global temperature increase, tell nothing about the cause of the increase.

warming during the same period. This curve is obtained from a calculation lying in the middle range of greenhouse forecasts, yielding a mid-to-late 21st century greenhouse warming of roughly 3° C. The dashed line also indicates a greenhouse temperature increase of about 0.5°C between 1880 and 1985.

EVIDENCE FOR A SUBSTANTIAL GREENHOUSE EFFECT

Several scientists interested in the greenhouse problem have remarked that the agreement between observations and the greenhouse predictions up to 1985 yields valuable information about the size of the long-time greenhouse warming expected for the 21st century. They point out that if the long-term greenhouse warming in the next century were very much larger than the current estimates suggest, we would have seen a temperature increase of substantially more than 0.5° C between 1880 and 1985.

On the other hand, if the long-term greenhouse effect were substantially less than the low end of the range of greenhouse estimates, it would not have produced the 0.5° C warming that has actually been observed in that period.

Some climate experts have concluded that the observed warming of 0.5° C tells us the middle range of greenhouse forecasts — a temperature rise of roughly 3° C in the mid-to-late 21st century — is roughly correct and should be a trustworthy guide to the full greenhouse warming that will occur in the 21st century.

IV. OTHER FACTORS INFLUENCING CLIMATE IN THE LAST 100 YEARS

A closer look at Figure 1, however, raises doubts about the accuracy of the greenhouse forecasts as a predictor of conditions in the 21st century. While the overall temperature increase in the greenhouse forecast agrees with the observed temperature increase of 0.5° C, the shape of the calculated greenhouse curve differs from the observations in important respects.

The greenhouse forecast (Figure 1, dashed line) shows a smooth increase in temperature with time, rising slowly at first and then more rapidly in recent decades. On the other hand, the observed temperatures (Figure 1, solid line) rose from the 1880s to around 1940. Then, although the concentration of man-made greenhouse gases in the atmosphere was now growing rapidly, the observed values dropped substantially between the 1940s and the 1970s.

Two aspects of this comparison seem significant. First, most of the rise of 0.5° C occurred in the first 50 years from 1880 to 1930, although less than a third of the total carbon dioxide increase occurred in that period. Second, no sign of the post-1940 drop in temperature appears in the greenhouse forecast for the period from 1940 to 1970, although this decrease was large enough to have a significant agricultural impact on Northern Europe.

The fall in temperature between 1940 and 1970 is particularly difficult to explain as a greenhouse phenomenon, because this entire period was one of strong economic growth and increasing emission of greenhouse gases. Even if allowance is made for a delayed response to the increased concentration of these gases, the

1940-1970 period should have been one of increasing temperatures — provided the greenhouse effect was the main driver of climate change in that period.

These departures from the calculated greenhouse temperature increase suggest that other forces besides the greenhouse effect have been influencing the earth's climate in recent decades.

VOLCANIC ERUPTIONS

What kinds of non-greenhouse forces could have been working on the earth's climate in the last 100 years? Volcanic eruptions are one possibility. Erupting volcanoes sometimes emit copious amounts of the gas sulfur dioxide, which become droplets of sulfuric acid in the atmosphere. The sulfuric acid droplets create a global haze that shields the earth's surface from the sun and cools the planet.

The global cooling produced by large eruptions can be substantial, of the order of several tenths of a degree. However, the particles that cause the cooling disappear from the atmosphere in a year or two, so that the climatic impact of even the largest eruptions is relatively brief.

Some experts say that many small volcanoes, erupting in succession in the 1940s and 1950s, could have caused a sustained temperature drop that would explain the post-1940s cooling. However, measurements of changes in the transparency of the atmosphere, shown in Figure 2 (p. 21), do not reveal any effect of this kind from 1914 to 1962. The atmosphere over that entire period was quite clear.*

Several volcanic eruptions did occur in the 1950s, but did not produce a global or hemispheric reduction in transparency and a consequent cooling effect. In some cases this was so because the eruptions were at high latitudes and their product did not enter

* M. Rampino and S. Self, private communication.

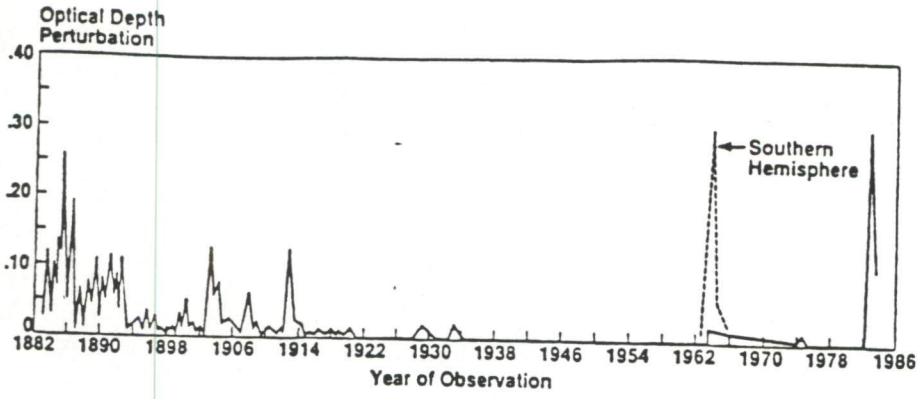


Figure 2. Observed changes in the transparency of the atmosphere, based on changes in the apparent brightness of non-varying stars. Two major volcanic eruptions of recent years — Mt. Agung in 1963 and El Chichon in 1982 — show up clearly as strong peaks. Very little volcanic obscuration of the atmosphere was observed in the 1940s and 1950s, contradicting the view that volcanoes caused the dip in temperatures commencing in the 1940s.

the mid-latitude circulation of the atmosphere. In two other cases — the large eruptions in Iceland in 1947 and Kamchatka in 1956 – – the eruptions not only were at high latitudes, but also produced relatively little sulphur dioxide, and so for two reasons did not add appreciably to the global haze of sulphuric acid droplets.

NATURAL VARIABILITY OF CLIMATE

The natural variability of the earth's climate is another possible explanation for the 0.5° C rise in temperature since 1880. Climate computations suggest that the earth's climate can undergo large swings in temperature that may last for several decades, and have no apparent cause. That is, the computed global temperature may vary by large amounts over decades, even if the computations hold constant the level of volcanic eruptions, concentration of greenhouse gases, changes in the sun's brightness and all other factors that would normally lead to a change in global cli-

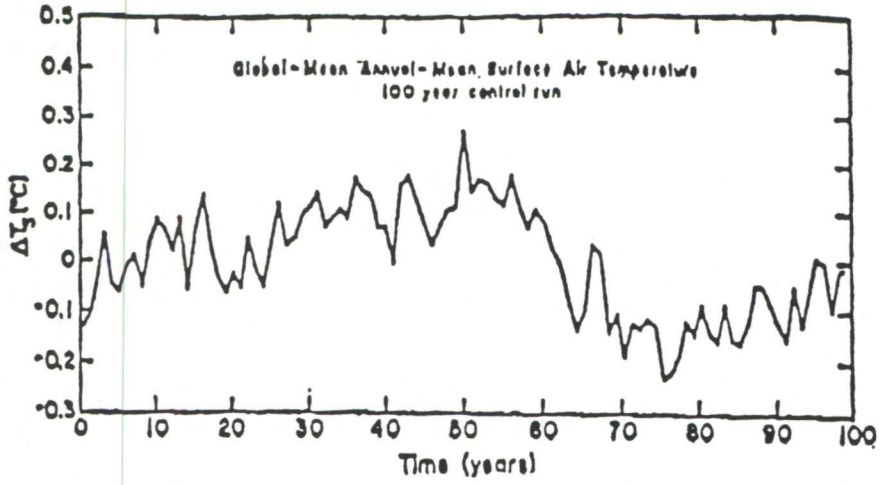


Figure 3. A 100-year computer run of global mean temperature. In addition to year-to-year fluctuations of about 0.1° C, the calculations show a 0.4° C drop over 25 years without known or obvious cause. This trend appears to be the product of a natural climate variability.

mate. This phenomenon of large and seemingly spontaneous changes in climate is known as the "natural variability" of the earth's climate.

Figure 3 shows the result of a 100-year computing run by Hansen et al., in which natural climate variability produced a significant change of roughly 0.4° C in temperature over 25 years, without any change in the so-called "forcing" terms, i.e., no changes in carbon dioxide concentration, solar energy output, volcanic activity or any other external agent.

Although the natural variation in this case happened to be a temperature drop rather than a rise, the implication in these results is that at other times the natural variability of climate might also produce a rise of 0.4° C, or even 0.5° C, over a comparable period.

It is important to note again that such variations in climate apparently can occur naturally, without any change in carbon dioxide concentration or other external "forcing" factors. Figure 3 is ev-

idence that much or all of the 0.5° C rise in temperature observed between 1880 and 1930 may be the product of natural variability rather than the greenhouse effect.

CHANGES IN THE SUN'S ENERGY OUTPUT

An increase in the sun's energy output is still another possible cause of the 0.5° C increase in temperature observed over the last 100-odd years. Climate calculations indicate that a temperature increase of 0.5° C could be produced by an increase of 0.3 to 0.5 percent in the total energy radiated by the sun to space.* Is it possible that the sun has grown brighter by 0.3 to 0.5 percent since 1880?

This idea that the sun's power could vary over intervals as short as years or decades has not been fashionable among astronomers and climate experts. However, recent findings in space science and astronomy have confirmed that such variations do occur. The possibility of solar energy changes on relatively short time scales, which was viewed until recently as an ad hoc conjecture without observational support, is now, because of these findings, an established astrophysical fact.

OBSERVATIONAL CONFIRMATION OF SOLAR CHANGES

The first of the new findings comes from satellite measurements of the sun's energy output, which can be made much more accurately than is possible from the ground. These measurements of the so-called "solar constant" — the amount of solar power per unit area reaching the earth — have revealed a decrease of about

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* T.M.L. Wigley, *Secular Solar And Geomagnetic Variations In The Last 10,000 years*, (Stephenson and Wolfendale, eds.), 209 (1988)

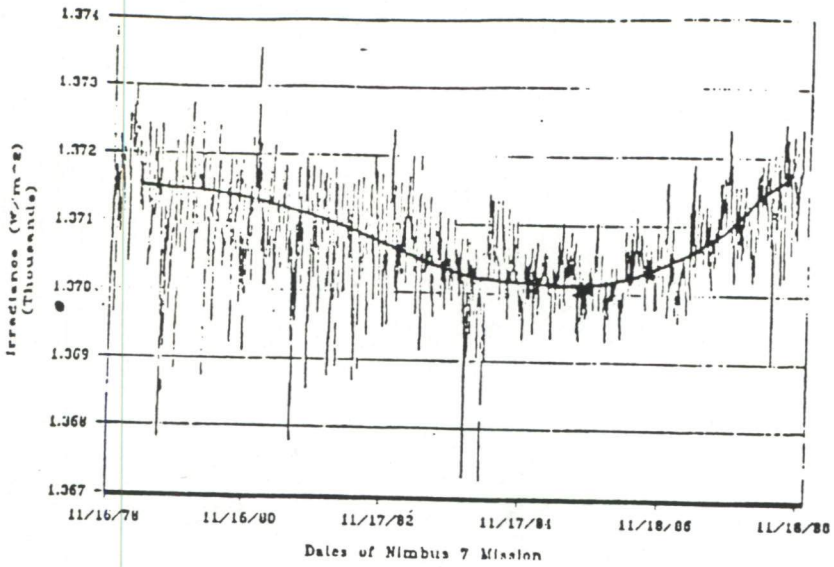


Figure 4. Changes in the solar constant between 1978 and 1988.

0.1 percent between 1978 and 1985, followed by an increase from 1985 to 1988.

Figure 4 shows the measured values of the changes in the solar constant between 1978 and 1988.

The satellite measurements prove that the sun's power does, in fact, change from year to year. It is now established that even on time scales as short as years or decades, the solar "constant" is not constant.

The measurements also show that the changes in the solar constant seem to follow changes in the number of sunspots observed during the sunspot cycle. When sunspots are most numerous on the face of the sun, the sun's energy output is greatest; when the sunspots decrease in number, the output of solar energy also decreases.

The measured change of 0.1 percent in the sun's energy output is not large enough to explain such changes of climate as the 0.5° C warming that occurred after 1880. As noted, that would require an increase of 0.3 to 0.5 percent in the solar constant. However, if a 0.1

percent change in solar energy output occurred in this one period of observation, it is possible that changes in the sun's output as large as 0.5 percent or more may occur at other times, or over longer periods of time.

Recent astronomical observations of stars have confirmed that such substantial changes in energy output do, in fact, occur in many stars similar to the sun. In a study of 36 such stars, Lockwood and Skiff found that nearly half varied by more than 0.5 percent in brightness over an interval of a little less than four years.*

Four among the varying stars were solar twins, almost identical to the sun in age, mass and other properties. Two of the four solar twins remained roughly constant over the four-year period, and the other two varied in brightness by 0.23 percent and 0.42 percent, respectively.

Figure 5 shows the variation in brightness from year to year observed in the latter two stars. Baliunas and Vaughan have found that one of the two variable stars also displays an eight-year cycle of surface activity similar to the sun's 11-year sunspot cycle (Fig-

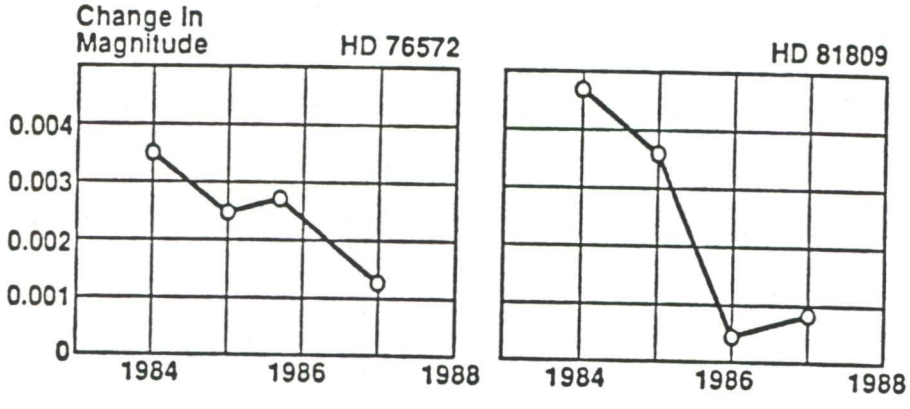


Figure 5. Changes of 0.23 percent (left) and 0.42 percent (right) in the brightness of two stars with nearly identical properties to those of the sun, over a four-year period.

* G.W. Lockwood and B.A. Skiff (Lowell Observatory), Air Force Geophysics Laboratory, Report AFGL-TR-88-0221 (1988)

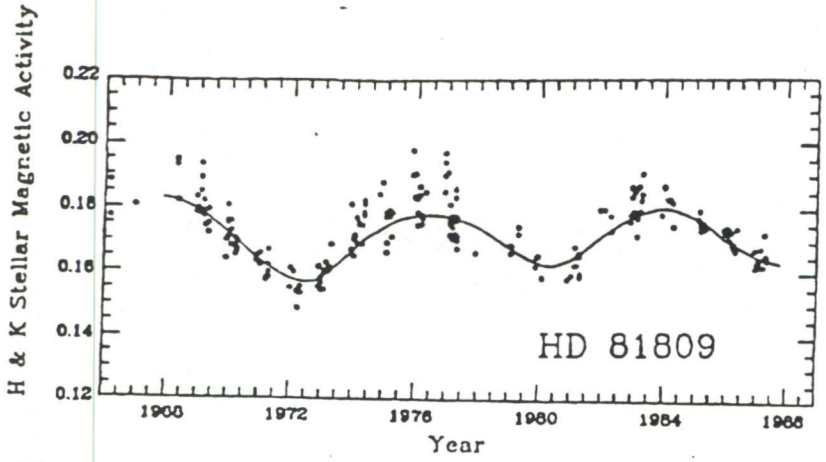


Figure 6. An 8-year cycle of changes in surface activity in HD 81809.

ure 6).* Comparison with Figure 5 reveals that, as in the case of the sun, when this star's surface activity declines, its brightness also decreases.

CHANGES IN SOLAR ENERGY OUTPUT AS A FACTOR IN CLIMATE CHANGE

Is the 0.5° C warming in the last 100 years the consequence of a man-made greenhouse effect?

As noted on page 19, the temperatures observed since 1880 have a pattern of change that does not resemble the temperature curve calcualted from the man-made greenhouse effect. However, they do resemble the changes in solar activity for the same period.

Figure 7 compares the changes in solar activity — represented by average sunspot numbers — to the changes in global temperature from 1885 to 1985. When solar activity increased between the 1880s and the 1940s, global temperatures also increased. When solar activity declined between roughly 1940 and the 1960s, temperatures also declined. When solar activity and sunspot numbers re-

* S. Baliunas and A. Vaughan, *Ann. Rev. Astron. Astrophys.* 23, 379 (1985)

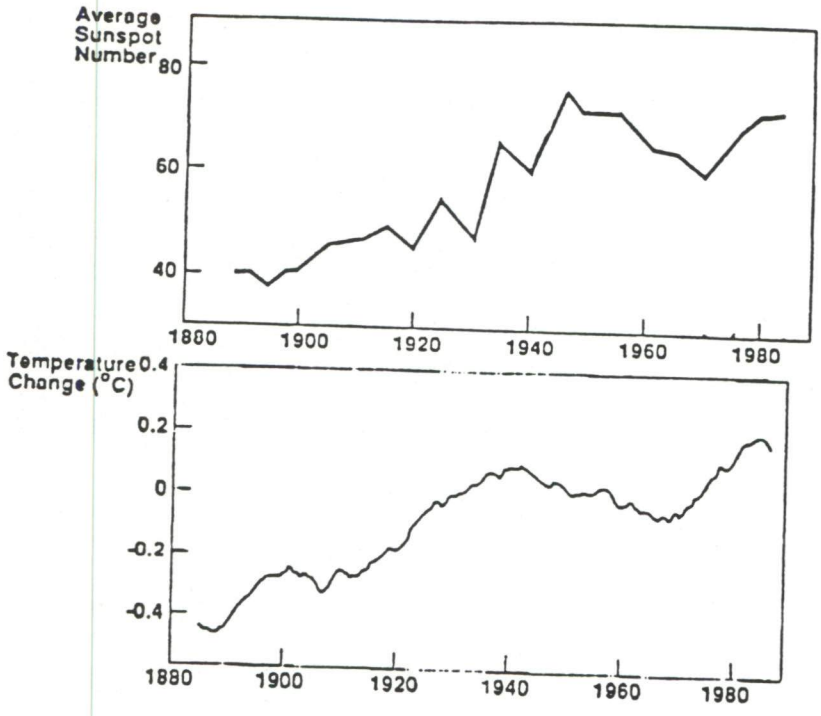


Figure 7. Comparison of (a) 33-year running average of sunspot numbers and (b) average global temperatures from 1885 to 1985.

versed and started to move up again, temperatures did the same.

These parallel patterns of change could be a coincidence, but they suggest a solar explanation for at least a part of the post-1880 temperature rise.

IMPLICATIONS FOR THE MAGNITUDE OF THE GREENHOUSE EFFECT

These findings on the climate impact of natural and solar variability have significant implications for policy makers considering today how to cope with the catastrophic greenhouse temperature

increase predicted for the mid-21st century.

Because of the wide spread in the amount of greenhouse warming predicted, and the difficulty in deciding which prediction is most accurate, scientists concerned with offering sound advice on the greenhouse problem have tended to rely on the observed temperature increase of 0.5° C since 1880 as their best evidence that the greenhouse effect is already here, and that steps should be taken now to cope with its full development in the next century.*

As noted on page 18, a greenhouse effect big enough to explain the post-1880 temperature rise of 0.5° C will probably produce a temperature increase of about 3° C in the mid-to-late 21st century. A temperature increase of this magnitude would be sufficiently serious to warrant consideration of early action by policy makers.

On the other hand, if some cause other than the greenhouse effect has produced much of the 0.5° C rise, and the greenhouse effect is responsible for only a small part of that rise, that means that we can expect a temperature increase of less than 3° C in the next century.

Suppose, for example, that some combination of natural variability and solar variability were responsible for 0.3° C of the 0.5° C increase observed since 1880. This would mean the greenhouse contribution is only 0.2° C. If that is the case, the mid-to-late 21st century warming will be only around 1° C.

This is considerably less than the warming of 3° C indicated by current mid-range greenhouse forecasts, which assume that the entire post-1880 rise of 0.5° C is due to the greenhouse effect.

In fact, it is possible that a combination of natural and solar variability is the cause of the entire temperature increase observed since 1880, with the greenhouse effect relegated to a negligible role.

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* "Since global climate models indicate the increase in greenhouse gases [in the past century] should have increased the temperature by 0.5° C, the modeling and observational evidence are consistent in indicating that the greenhouse effect is changing our climate." James Hansen, NASA Goddard Institute for Space Studies (*Washington Post*, February 11, 1989)

The effect of the wild cards introduced into the greenhouse studies by natural and solar variability is that no conclusion about the magnitude of the greenhouse effect in the next century can be drawn from the 0.5° C warming that has occurred in the last 100 years.

V. EVIDENCE FOR NATURAL CYCLES OF WARMING AND COOLING

Is other evidence available that might be pertinent to a prediction of global temperatures in the 21st century? An analysis of climate records for England by Lamb indicates that during the last millenium, protracted periods of cold weather occurred roughly every 200 years — in the 13th, 15th, 17th, and 19th centuries. The best known of these cold periods was the Little Ice Age — a time of very low temperatures marked by failed harvests, famine and social upheaval in northern Europe. Temperatures in the Little Ice Age were roughly 1°C lower than they are today. The 1690s were perhaps the coldest decade on record in the history of Europe.

Wigley and Kelly have compiled additional evidence for the natural occurrence of cold periods every few centuries. Their climate history is drawn from global records compiled by Röthlisberger on the advance and retreat of glaciers.

The pattern of recurring cold periods reported by Wigley and Kelly on the basis of the glacial records is not as regular as Lamb's records. However, it has greater validity because the glacial data are global, while the Lamb climate record is regional and may be valid only for northern Europe.

Wigley and Kelly also discovered a correlation between the climate record and the record of solar activity going back over many centuries. The levels of solar activity were determined from measurements of the carbon-14 content of trees, compiled by Stuiver and Braziunas.* (See the appendix for an explanation of the

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* *Secular Solar And Geomagnetic Variations In The Last 10,000 years*, (Stephenson and Wolfendale, eds.), 245-266 (1988)

relation between carbon-14 and solar activity.) Comparing the carbon-14 record to their climate history, Wigley and Kelly found that six out of the seven most severe decreases in solar activity correspond closely to cold spells in the climate record. One of these is the famous period of about 50 years of very low solar activity in the 17th century, which coincided with the coldest period of the Little Ice Age.

Figure 8 shows the carbon-14 record during the last thousand years. The figure indicates surprisingly regular cycles of solar activity, with periods of low activity every 200 years or so during the last thousand years — midway between the 10th and 11th

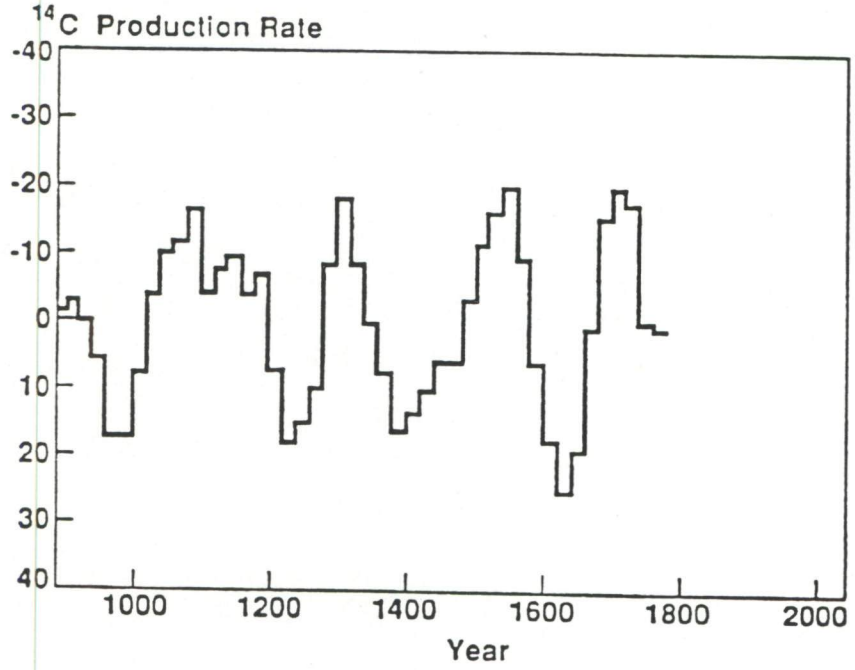


Figure 8. Anomalies in carbon-14 production rates associated with changes in solar activity. The negative of the production rate is plotted so that periods of low solar activity appear as low points on the chart. Dates are moved back 50 years to correct for the residence time of carbon-14 in the atmosphere.

centuries, and in the 13th, 15th, 17th and 19th centuries.

The carbon-14 record shows only the beginning of the period of low activity in the 19th century, because the interpretation of the carbon-14 production rates become less reliable after ca. 1800. However, sunspot records confirm that a minimum of solar activity also occurred in the 19th century, followed by a rise in the 20th century to the current high level of activity.

On the basis of this record, another period of low solar activity can be expected in the 21st century. If the correlation between low solar activity and low temperature continues, we can also anticipate a period of protracted cold in the 21st century as a result of the natural forces of climate change. If the 21st-century cooling is comparable to the Little Ice Age, the earth will be about 1° C colder as a result of natural factors alone than it has been in the 1980s.

VI. CONCLUSIONS

The fact that in the last 100 years, temperature and solar activity have followed a parallel course suggests that solar variability may be a significant part of the explanation for the post-1880 temperature rise of 0.5° C, and the greenhouse effect may be a relatively small contributor to the 0.5° C increase. In that case, the greenhouse effect that develops in the 21st century will also be relatively small — in the neighborhood of 1° C, rather than 3° C or more. A greenhouse warming of this magnitude could be partly or largely offset by the natural cooling expected in the 21st century. The balance of these man-made and natural forces of climate change would leave the world's climate within a degree or so of its present temperature.

RECOMMENDATIONS

Current forecasts of the man-made greenhouse effect do not appear to be sufficiently accurate to be used as a basis for sound national policy decisions. Policy makers would be wise to invest in the additional resources needed to improve the reliability of greenhouse forecasts before undertaking corrective programs that could turn out to be unnecessary — or even harmful if a substantial natural cooling occurs in the 21st century.

Procurement of top-line supercomputers for the major greenhouse forecasting groups could significantly diminish the level of uncertainty in the greenhouse forecasts by improving the treatment of clouds and oceans — the major unknowns in the present

forecasts.

The increased detail achievable with more powerful computers would also lead to information on regional climate changes — in particular, the occurence of regional droughts — which cannot be predicted with any useful degree of accuracy by the crude models currently in use.

The total cost of supercomputing facilities would be no more than $100 million. The investment would be cost-effective when viewed in the perspective of the large and potentially negative impact on the five-trillion-dollar U.S. economy, that could result from a premature decision based on inaccurate and possibly misleading forecasts.

The reliability of the greenhouse forecasts also suffers from gaps in observational coverage of clouds and oceans, and a poor understanding of certain processes vital to the determination of climate, such as moist convection. A stronger effort in global observations, and augmentation of the pitifully small force of scientists attempting to make progress on this important problem, are as important as the provision of computing power.

However, observations and personnel alone will not suffice to resolve the difficult public policy issues posed by the poor reliability of current forecasts. Number-crunching power is also essential.

Certainty will never be achieved in a matter as complex as the forecasting of climate for the coming century. However, it is our judgment that if a prudent investment is made in computing power, observing programs and added manpower, answers that have a usable degree of reliability can be provided for policy makers within 3 to 5 years. Through such an investment, the government can accelerate the pace of climate research to yield the necessary information in years rather than decades, so that timely action can be taken if needed.

APPENDIX:
CARBON-14 AND SOLAR ACTIVITY (Page 31)

Carbon-14 is made by cosmic rays striking the earth's atmosphere. During periods of peak sunspot activity, when the surface of the sun is very disturbed, solar particles and magnetic fields spread through the inner part of the solar system, deflecting cosmic rays and tending to keep them from the earth. As a result, during these times of vigorous solar activity the amount of carbon-14 made in the earth's atmosphere decreases.

During quiet periods in the sun, when sunspots decrease in number or disappear (e.g., the Maunder Minimum of the 17th century), the intensity of the sun's magnetic field decreases in the inner region of the solar system .

Some carbon-14 atoms made by cosmic rays reach the ground and are incorporated into the bodies of trees in the normal process of tree growth. Analysis of the carbon-14 content in a cross section of a tree trunk yields a picture of carbon-14 changes during the tree's lifetime. The resultant curve of carbon-14 abundance versus time is a measure of variations in sunspot numbers and solar activity over time.

The chart plots the negative of the variations in carbon-14, so that a minimum in the carbon-14 chart as plotted here also means a minimum in solar activity and sunspot numbers. Since carbon-14 atoms typically take many decades to reach the ground, for the purpose of comparison with times of occurrence of climate changes the carbon-14 record shown in the chart has been shifted back 50 years.

P. Langer

Greenhouse Warming: Science v. Consensus

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October 10, 1989

The assessment of the proper response to the possible danger of global warming depends critically on the determination of how likely the danger really is. There are certainly other potential problems that could be far more devastating for life on this planet (an asteroid collision for example), but which we regard as too unlikely to worry about.

Judging from much of what one sees in the media, there is little doubt about the coming global warming. The question is simply whether it will be unprecedentedly bad (1.5°C warming) or worse (5°C warming). To quote from Stephen Schneider at a recent conference hosted by Robert Redford at Sundance, Utah, 'there will be no winners.' The Democratic National Committee has made dealing with the warming an issue on a par with dealing with the drug problem[1]. Still, if one visits the Center for Meteorology and Physical Meteorology at M.I.T. (where I happen to teach) one encounters a general attitude of skepticism. There is a common feeling at M.I.T. and elsewhere, that this question has become enmeshed in hysteria. Such environmental scares are not unheard of. In recent years we have confronted the destruction of the ozone layer by supersonic transports, the coming ice age (popular in the early 70's, and the subject of Stephen Schneider's book, *The Genesis Strategy*), and nuclear winter. All these scares have withered for good reason. It is only fair to add that none of these earlier scares has been put forth with the vehemence associated with 'global warming.' In this talk, I propose to go over the scientific bases for our present concerns. I hope to show that both the data and our scientific understanding do not support the present level of concern. If time permits, I

[1] *Democrats*, Fall 1989, p. 5

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would also like to go over some aspects of the public treatment of this problem that bode ill for science itself.

Let me begin by putting forth some of the major contentions that are commonly treated as facts:

1. CO_2 has increased from 315ppm to 350ppm since 1958.
2. Preindustrial levels of CO_2 were on the order of 270ppm.
3. CO_2 is likely to double over the next century or so.
4. An increase of global mean temperature of $1.5 - 5°C$ is expected to accompany a doubling of CO_2.
5. Over the last century, a warming of $0.5°C \pm 0.2°C$ has occurred.
6. Greenhouse gases absorb infrared radiation; therefore, increasing the concentration of such gases must cause the earth to cool less effectively, and hence heat up.

The first item is based on measurements taken at Mauna Loa Observatory since 1958. The record of these measurements is shown in Figure 1. The increase is unambiguous, and because CO_2 is relatively well mixed in the course of a year, the increase is likely to be representative. Thus, the first contention appears to be solid. It would be difficult to look at Figure 1 without concluding that CO_2 concentrations were less than in 1958 in the 19th Century, and that they will be greater than they are at present a hundred years from now. The quantitative evaluation of these changes is, however, by no means trivial. The increase since 1958 corresponds to about half the CO_2 created by fossil fuel combustion alone. In addition there are additional sources associated with deforestation and 'slash and burn' agriculture. The bulk of the CO_2 introduced into the atmosphere seems to be taken up in the oceans which contain many times the CO_2 in the atmosphere. However, the nature of the mechanisms whereby the ocean is presumed to take up CO_2 are extremely unclear at present. This uncertainty as well as uncertainties concerning future and past production make extrapolation of the results in Figure 1 difficult. Nevertheless, items 2 and 3, above are at least plausible[2]. It is entirely legitimate to ask whether we should be worried. Certainly, we are dealing with significant changes in CO_2 itself, but this alone need not be serious. CO_2 is a minor constituent (about 0.03% of the

[2]These matters are reviewed in a manner adequate for our purposes in *Changing Climate - Report of the Carbon Dioxide Assessment Panel*, a report of the Board on Atmospheric Sciences and Climate of the National Research Council published by the National Academy Press in 1983. We shall refer to this report as NRC 83.

atmosphere), and as such its variations might not be too important. One can imagine some gas which is not normally present in the atmosphere. Releasing a molecule or two of such a gas would represent an enormous percentage increase without being of much concern. As it turns out, there are quite a few things that increasing CO_2 *might* do. For example, the atmosphere at altitudes between 25 km and 90 km is cooled primarily by thermal radiation emitted to space by CO_2. Increasing CO_2 should cool these regions, and this, in turn, should lead to *increasing* concentrations of ozone at these levels[3]. Increasing CO_2 might also stimulate the growth of vegetation. These possibilities are being studied, and are, on the whole, benign or even beneficial. As far as we know, there is no direct adverse effect on human beings arising from increases in CO_2 on the order of those anticipated (however uncertainly) over the next few centuries (certainly much higher concentrations are found in normal indoor environments). Our main concerns have focussed on the possibility that increasing CO_2 might significantly warm our climate. Although we do not know exactly what determines the concentration of CO_2, it is eminently plausible to ask what a doubling of present concentrations of CO_2 would do. For reasons that I will discuss later, there is pretty general agreement that increasing CO_2 will produce warming. Such a conclusion, by itself, is pretty useless. As has often been noted, science without numbers is not quite science. What we need to know is how much warming can be expected. If the expected warming is significantly less than the natural fluctuations in climate then there is little basis for useful concern. Item 4, above, suggests the expectation that very significant warming will indeed take place. These estimates arise from model calculations[4] To be sure the models are notoriously inadequate (including those models running on large computers); this is a matter we will discuss in greater detail later in this talk. For the moment, we wish to note that such large predictions suggest that the changes in CO_2 that have occurred over the last 150 years should already have produced warmings of about $0.75° - 2°C$. According to item 5, only the lowest of these estimates is even marginally consistent with past observations. This is a matter of some importance since this is the only observational evidence for anomalous greenhouse warming available now. As we shall see, the data, although quite uncertain, do not suggest that even this degree of warming has, in fact, occurred.

The determination of the globally averaged temperature of the earth's surface is a difficult task – at least at the level of accuracy we require for the present purpose. As everyone knows from personal experience, temperature can

[3]The radiative and photochemical processes of the middle atmosphere *Middle Atmosphere Dynamics*, Academic Press, New York, 489 pp (1987). The coupling of temperature and ozone is formulated in Lindzen, R.S. and R.M. Goody, *J. Atmos. Sci.*, 22, 341 (1965).

[4]NRC 83 *ibid*,

Hansen, J., E. Johnson, A. Lacis, S. Lebedeff, P. Lee, D. Rind, and G. Russell, *Science*, 313, 957 (1981).

vary markedly over short distances; urban areas are frequently warmer than the countryside; water surfaces differ in temperature from adjacent land surfaces: temperatures vary in the course of a day; seasonal changes are large. Moreover, there is what is referred to as natural climate variability from year to year. This variability is referred to as 'natural' because it is expected to occur even in the absence of external causes[5]. It is not clear that our network of surface temperature measurements is adequate to completely eliminate these sources of uncertainty. However, such averages as we are able to form show remarkable constancy from year to year. Estimated changes over the last 150 years are less than $1°C$[6]. We cannot be at all sure that these small changes are not in significant measure due to inadequate and/or improper sampling. For starters, most of the earth's surface is covered by oceans over which we have no fixed station records. The most commonly cited time series for globally averaged temperature is based solely on such fixed station records. Temperatures measured at St. Helena Island are assumed, for example, to be characteristic of almost a third of the Atlantic Ocean; this is unlikely to be a sufficiently good assumption for the purpose of determining the small changes in global temperature. There are, as it turns out, many records of temperature at sea taken from ships[7]. These data also present problems. Among other things, differences arise depending on whether water was sampled by bucket or through intake. For certain regions of the globe (namely the contiguous 48 states), there has been consistent and relatively dense measurement of temperature since the 1890's. Since this region is only a small portion of the earths surface, it is *a priori* expected to be more variable than the globe as a whole. In addition there is a substantial difficulty in correcting this record for the effects of urbanization. The National Climatic Data Center of NOAA (National Oceanic and Atmospheric Administration) has approached this correction with considerable care; but, again, the issue remains a matter of some debate[8]. Since the above data is about all we have, it is what

[5]The issue of 'natural' variability is far more serious than is commonly stated. In a review of the recent Workshop on Greenhouse-Gas-Induced Climatic Change (R.A. Kerr, *Science*, 244, 1041 (1989)), there was almost no mention of one of the most interesting findings: namely, that almost all models, when run for long periods of about 100 years, exhibited variability unrelated to greenhouse warming that was as large or larger than the greenhouse induced warming itself. The variability found in nature seems to be smaller than that found in the models, but still swamps anticipated greenhouse effects. The precise origin of natural variability is still uncertain, but it is not all that surprising. Although the solar energy received by the earth-ocean-atmosphere system is relatively constant, the degree to which this energy is stored and released by the oceans is not. As a result, the energy available to the atmosphere alone is also not constant.

[6]An excellent review of global climate data is given in Ellsaesser, H.W., M.C. MacCracken, J.J. Walton, and S.L. Grotch, *Rev. Geophys.*, 24, 745 (1986).

[7]Newell, N.E., R.E. Newell, J. Hsiung, and Wu Zhongxiang, *Geophys. Res. Letters*, 16, 311 (1989).

[8]Karl, T.R., R.G. Baldwin, M.G. Burgin, *Time series of regional season averages of maximum, minimum, and average temperature, and diurnal temperature range across the United States: 1901-1984*, 107 pp (1988) (Available from National Climatic Data Center, Federal Building, Asheville, NC 28801)

we will have to use. However, it is important to stress that all the above records have required uncertain corrections whose magnitude is as large as the climatic effects being sought. Under these circumstances, any scientist would intuitively regard any conclusions regarding such effects as suggestive at best. Only if the observed changes were substantially larger than the corrections would they be regarded as convincing. As we shall now see, this is not at all the case.

In Figure 2, we show three time series for annually averaged surface temperature. The top record is an area weighted average (that is to say records are weighted in proportion to the area they represent) of fixed surface measurements from all over the globe; it dates back to 1855. The middle record is derived from millions of ship records, and also dates from about 1855. The bottom curve is for the contiguous 48 states, and dates back to 1900[9]. All these records begin before the bulk of industrial CO_2 deposition into the atmosphere. Although all three series differ in detail, none indicate variability significantly in excess of $1°C$. None indicate *any* significant temperature change between the start of the record and the present. Finally, the best record (that for the 48 contiguous states), and the record expected to show the greatest variability because of the small area covered, shows almost no significant trend at all. On the basis of the available records, our best estimate for the global temperature change that has occurred over the industrial period does not significantly vary from *zero*, and this certainly suggests that current models are greatly exaggerating expected warming. The contention in item 5, above, comes from considering the top curve in Figure 2 to begin around 1880[10]. There is, in fact, a good reason to begin with 1880. Before this date there was little attempt to systematically organize and collect global climate data. However, earlier – albeit sparcer – data does exist which suggests that earlier temperatures were warmer. Even beginning at the 1880 minimum, the record is hardly one of uniform increase. The major sharp

Hanson, K., G.A. Maul, and T.R. Karl, *Geophys. Res. Letters*, 16, 49 (1989)
Karl, T.R., H.F. Diaz and G. Kukla, *J. Clim.*, 1, 1099 (1988b)
Bolling, R.C. and S.B. Idso, *J. Geophys. Res.*, 94, 3359 (1989)

[9]The references for these figures are
Ellsaesser, H.W., *et al, ibid*
Jones, P.D., S.C.B. Raper, R.S. Bradley, H.F. Diaz, P.M. Kelly, and T.M.L. Wigley, *J. Clim. Appl. Meteorol.*, 25, 161 (1986a)
Jones, P.D., S.C.B. Raper, B.S. Sauer, B.S.G. Cherry, C. Goodess, R.S. Bradley, H.F. Diaz, P.M. Kelly, and T.M.L. Wigley, *A grid point surface air temperature data set for the northern hemisphere, 1851-1984, Tech. rept.* 22, Carbon Dioxide Division, U.S. Dep. of Energy, Washington, D.C. (1986b)
Slutz, R.J., S.L. Lubker, J.D. Hiscox, S.D. Woodruff, R.L. Jenne, D.H. Joseph, P.M. Seurer, and J.D. Elms, *COADS comprehensive ocean/atmosphere data set; Release 1*, US DOC Climate Research Program, Environ. Res. Lab., Boulder, CO (1985)
Ramage, C.S., *J. Clim. Appl. Meteorol.*, 23, 187 (1984)
Folland, C.K., D.E. Parker, and F.E. Kates, *Nature*, 310, 670 (1984)
Karl, T.R., *et al*, (1988a) *ibid*

[10]Hansen, J. and S. Lebedeff, *J. Geophys. Res.*, 92, 13,345 (1987)

increase occurred by 1940. This increase antedated the much greater increase in CO_2 deposition after this date, and might reasonably be interpreted as a return of the global temperature to its value before the anomalous minimum around 1880. From 1940 until the 1960's the record suggested global cooling (leading to the suggestions in the 1960's that an ice age was coming). Beginning in the 1960's there is evidence of a reversal of the earlier cooling trend (leading to the current suggestions of global warming). It should be emphasized that the record is merely suggestive. The absence of a trend in the record for the contiguous 48 states leads to the suspicion that all the trends in the global record may, in fact, be spurious. We certainly cannot assert that no warming occurred; however, the data does not show it.

The above difficulty with detecting trends was clearly recognized in NRC 83. They suggested that this difficulty might be circumvented by a technique they referred to as 'fingerprinting.' The idea behind this approach was simply that models predict a detailed distribution of temperature and not simply a globally averaged temperature. Perhaps the data might confirm patterns of regional change more clearly than it could detect trends in globally averaged temperature. The trouble with this approach arises from the fact that existing models differ pronouncedly (sometimes even in sign) in their predictions of regional variations. The models do not even do a good job in simulating present day regional variations. About the only thing existing climate models agree on is that warming will be greatly exaggerated in polar regions – especially during winter. These predictions are shown in Figure 3. Unfortunately, observations show that exactly the opposite has occurred in the arctic; as we see in Figure 4, the arctic is not warming, but rather appears to be in a cooling trend which is particularly pronounced in winter[11].

Given the data alone, we would have little basis for alarm. The alarm arises instead from theoretical considerations – namely the so-called 'greenhouse effect.' The idea here is quite simple. Averaged over several years, the surface of the earth is in a state of approximate thermal balance. In particular, cooling balances heating. If the earth had no atmosphere at all, this balance would be achieved by radiation alone. The heating would be due to the absorption of sunlight, and the cooling would be due to thermal (infrared) radiation which increases with increasing temperature. The temperature would rise (or sink) until heating and cooling balanced. It can be shown that such a balance would

[11] Rogers, J.C. in *Proceedings of the thirteenth annual climate diagnostics workshop*, 170 (1989). (Prepared by the National Oceanic and Atmospheric Administration, and available from National Technical Information Service, Department of Commerce, Sills Building, 5285 Port Royal Road, Springfield, VA 22161) According to Kerr's review ibid, a model being run by Washington and Meehl is displaying arctic cooling. The observed cooling amounts to about 0.5°C between 1960 and the present. In terms of climate, this is a fairly significant cooling – especially in comparison with the expected warming.

lead to an average surface temperature of about -18°C – a value much lower than what is actually found which is close to +15°C. The difference arises because the earth does have an atmosphere, and that atmosphere contains infrared absorbers. These absorbers are known as greenhouse gases. What happens is that these absorbers absorb some of the infrared radiation cooling the earth and reemit the radiation both upward and downward. The downward component supplements the radiation from the sun. Thus the earth must warm up so that the total radiation incident on the earth can be balanced by cooling. This is known as the 'greenhouse effect[12].' The process is schematically illustrated in Figure 5. Far and away the most important infrared absorbers are water vapor and liquid water in the form of cloud droplets arrayed in stratiform (i.e., layer) clouds. (The latter also acts to reflect sunlight, which is a cooling effect; the heating and cooling effects almost balance. It is currently believed, however, that the cooling effect slightly exceeds the warming effect[13].) Additional minor absorbers like CO_2, ozone, nitrous oxide, and methane contribute a little to this effect, and all other things being equal, we may expect increasing absorber amounts will lead to increased surface temperature. However, it should be pointed out that *the contributions of the minor greenhouse gases to warming are small even compared to the estimated slight difference between the warming and cooling properties of stratiform clouds.* The above picture is hardly new; it was reasonably understood by the early part of this century. It was also known that the above picture as applied to the earths surface was too simple. The point is that the surface of the earth does *not* cool primarily by infrared radiation.

The surface of the earth cools mostly by evaporation[14]. Most of the evaporated moisture ends up in convective clouds (clouds with strong vertical currents which bodily carry the air and its contents upward, as opposed to layered clouds which form and stay at a particular level) where the moisture condenses into rain. Just as evaporation cools, the condensation of water vapor heats, and the atmosphere realizes most of this heat at altitudes greater than 5 km. It is at these heights that the atmosphere must balance the heat deposited by con-

[12] A relatively simple treatment of traditional greenhouse notions is given in J.T. Houghton, *The physics of atmospheres*, 203 pp, Cambridge Univ. Press, Cambridge (1977)

[13] Ramanathan, V., B.R. Barkstrom, and E.F. Harrison, *Phys. Today*, 42, 22 (1989)

[14] This fact is not always clear in schematic depictions of the earths surface energy budget. Figure 6 (from MacCracken and Luther, editors, *Detecting the climatic effects of increasing carbon dioxide*, *Rep. DOE/ER-0235*, U.S. Dept. of Energy, Washington, DC (1985)) would suggest that the surface cools primarily by infrared emission. The diagram shows an outward infrared flux from the surface that greatly exceeds the latent heat flux (i.e., the cooling due to evaporation). However, the same figure shows the atmosphere reemitting a large infrared flux back to the surface. It is the difference between these fluxes that represents the actual surface cooling due to infrared emission. In the limiting case where the atmosphere is totally opaque to infrared radiation this difference goes to zero. This is almost the situation in the tropics.

vection from the surface with cooling by thermal radiation. It is worth noting that in the absence of convection, pure greenhouse warming would lead to a globally averaged surface temperature of +72°C for current conditions[15]. Our current average temperature, +15°C, is actually closer to the black body temperature (temperature without any greenhouse warming), -18°C, than to the pure greenhouse result. It follows that it is primarily the distribution of infrared absorbers above 5 km (rather than below 5 km) that is important for the earths temperature[16]. On the face of it, this is only a minor gloss on the simple model of the purely radiative greenhouse. However, as we shall soon see, it has major implications for current predictions. In the mean time we see that item 6. above, is not nearly as straightforward as is commonly stated.

The physics described in the above few paragraphs is characteristic of all current models used to estimate the effect of doubling CO_2. These models include simple models that are readily evaluated on a small PC and gigantic codes that require supercomputers. Not surprisingly, results differ relatively little among these various models. Such differences as exist do not stem from differences in the size of the models, but rather from identifiable differences in physical assumptions. Moreover, at present there is little reason to trust the larger models more. All such models (at least in the current literature) predict that a doubling of CO_2 will lead to a global warming of between 1.5°C and 5°C[17]. This is the basis for item 4, above. As we have already noted such predictions are incompatible with the small value of the past increase in temperature claimed in item 5, above. We have further seen that the data hardly supports even this claim. Finally, the model result that such warming as was predicted to have occurred over the last hundred years should be strongest in the arctic is directly contradicted by the observed cooling trend in this region.

At this point, there would normally be a strong impetus toward discovering what was wrong with our models. Efforts along these lines are, indeed, in progress. The notion that there are likely to be serious problems in existing computer simulations of the climate is not at all surprising within the meteorological and oceanographic communities. Models commonly have difficulty reproducing well observed major features of the current climate (mean global temperature, the pole to equator temperature difference, the intensity and position of the jet stream, seasonally averaged regional variations of climate, etc.) without what is euphemistically referred to as 'tuning.' In 'tuning,' processes that are not resolved by the model are parameterized in such a manner as to

[15] Möller, F. and S. Manabe, *Z. für Met.*, 15, 3 (1961)

[16] Lindzen, R.S., A.Y. Hou, B.F. Farrell, *J. Atmos. Sci.*, 39, 2416 (1982)

[17] Reasonably current reviews of climate modelling may be found in papers by M.E. Schlesinger and by M.E. Schlesinger and J.F.B. Mitchell in M.C. MacCracken and F.M. Luther, *ibid.*

bring the model into agreement with what are believed to be the observations. Models used for climate predictions are usually somewhat primitive versions of the models used for weather prediction. Problems have also been observed with weather prediction models, though the situation has certainly been improving. The most likely area to search for severe problems is in the interaction of climate with water (in all its phases). The remarkable thermodynamic properties of water almost certainly lead to its acting as nature's thermostat. Yet in the major numerical models, all feedbacks between warming and water are *positive*. In the absence of these positive feedbacks, these same models would yield warmings (due to doubling of CO_2) only 1/4 to 1/7 of those in item 4, above. When it is recognized that at least some of these feedbacks are likely to be *negative* rather than positive, it is easy to see that the actual response to a doubling of CO_2 may readily be 1/8 to 1/14 – or even less – of what is suggested in item 4. These are by no means idle or eccentric suggestions. For example, we have already noted that the net observed effect of layer clouds is to cool the atmosphere. In models, while warming leads to increased cloud cover, the net effect is to amplify the warming. The modeling of cloud cover is a delicate and uncertain effort; modellers admit to doing a poor job of it. Still modest improvements can lead to dramatic results. The British Meteorological Office climate model had predicted a 5°C warming accompanying a doubling of CO_2. A few weeks ago, they reported that the simple matter of correcting the liquid water content of layer clouds had reduced this value to 2°C – a reduction of 60%! Another problem of comparably large magnitude may prove easier to correct. In all the large numerical models, about two thirds of the warming associated with the doubling of CO_2 is actually due to the fact that in the models, warming is associated with increasing water vapor at all levels[18]. Recall that water vapor is a far more important greenhouse gas than is CO_2. Recall, as well, that convection significantly short circuits the greenhouse absorption below about 5 km. Greenhouse absorption is primarily important above 5 km. Now, the existing climate models are notoriously bad at predicting upper level water vapor. While warming does increase water vapor near the ground in nature, warming is also associated with more and deeper cumulus convection. This is known to lead to drying of the upper troposphere[19] (above 5 km). The nature of this drying effect, which is omitted in current climate models, is illustrated in Figure 7. This cumulus convection occurs in deep towers of rapidly rising air. The air cools as it rises, and the water vapor in the air condenses and falls out as rain. By the time these clouds top out (at altitudes as great as 16 km), they are relatively drained of water vapor. Of course, one can't have these rapidly rising towers of air without compensating air subsidence almost everywhere else, and this subsidence acts to fill the atmosphere above about 3-5 km with dry air.

[18] Manabe, S. and R.T. Wetherald, *J. Atmos. Sci.*, 37, 99 (1980)

[19] The drying effect of cumulonimbus convection is well known to specialists in cumulus convection; *viz* Arakawa, A. and W.H. Schubert, *J. Atmos. Sci.*,31, 674 (1974), Geleyn, J.-F., C. Girard, and J.-F. Louis, *Beitr. Phys. Atmosph.*, 55, 325, (1982).

Figure 8 illustrates the effects of warming on this process. We see that warming leads to drying of the atmosphere above 5 km (as opposed to the moistening which occurs in current models); it also leads to the elevation of the altitude at which convected heat is deposited. The latter effect increases the extent to which convection short circuits greenhouse absorption. Both effects are negative and not positive feedbacks to CO_2 heating. These, will act to diminish the effect of CO_2 warming rather than magnifying it by a factor of three as occurs in present models. My guess is that this correction alone will diminish estimates of CO_2 warming by a factor of about six, but careful studies of this matter will probably not be completed for another year or so.

The above hardly exhaust the possible sources of error in present models. However, it suffices to show that the possibility of large overestimates is very real. Consistent with past data, one may reasonably expect that corrected models may very well end up predicting greenhouse warmings of only a few tenths of a degree Centigrade.

These, then, are my reasons (and those of others) for believing that greenhouse warming will be much smaller than current publicized estimates. I personally think it very unlikely that we will see more than a few tenths of a degree Centigrade *from this cause over the* next century – a magnitude that will continue to be masked by natural variability. No one can absolutely guarantee that the effect won't be larger, but I think the likelihood to be very small that a greater warming will arise from man's intervention. It should be added that I am in no position (nor is anyone else) to guarantee that the earth won't get significantly warmer or cooler; it certainly has done so in the past. Indeed, our climate has been both warmer and colder than at present solely due to the natural variability of the system. External influences are hardly required for such variability to occur.

Where then does the scientific concensus that people in public life are so enthusiastic about arise? This is an interesting question, and says much about the interaction between scientists and the public. Clearly, it is even hard for scientists to evaluate such problems as potential global warming – especially if their expertise is not in climate, oceanography and atmospheric physics. Within these fields, one is dealing with only a small number of active research scientists. Even amongst these, how is the public to distinguish between conflicting claims? Among scientists, there is, in principle, a commitment to objective assessment. One tests theories by trying to design measurements that will distinguish amongst them. One tests data by checking it against such fundamental constraints as may exist. (This, unfortunately, is highly dependent on the availability of both funds *and* scientists to conduct such tests; the amount of the former and the number of the latter are both becoming uncomfortably limited.)

One does not, as a rule, depend on votes. This is not a procedure with much attraction to most public figures. The public, therefore, seeks out spokesmen for science who will report back to the public on what are presumed to be legitimate scientific inquiries .

The selection of such spokesmen has a certain arbitrariness, since scientists rarely select or endorse such spokesmen. What happens more commonly is that scientists elect officers of scientific societies (such societies need officers for obvious non-scientific reasons), and the public conveniently assumes these officers to be spokesmen. University presidents and department chairmen occasionally serve a similar role. Many other spokesmen are self appointed. Though I do not pretend to speak for my colleagues, there is some self-evident danger that in writing this article, I am falling into this last category. In this country, the premier organization that is asked to represent science is the National Academy of Sciences (which together with the National Academy of Engineering and the Institute of Medicine sponsor the National Research Council). The National Academy consists in about 1500 members who are elected on the basis of their scientific accomplishments. Election to the Academy is considered a high honor. When, however, the Academy responds to an inquiry, it does so through committees of the National Research Council. Oddly enough, there is only minuscule representation of Academy members on these committees (approximately 6%). Thus the connection of so called National Academy reports to the Academy itself is tenuous and uncertain. In principle, these reports are reviewed by academicians, but the selection of these reviewers is fairly arbitrarily handled by the NRC staff and the Presidents of the Academies of Science and Engineering and the Institute of Medicine. As a member of the Academy, I have never felt that there is any malicious intent in these procedures; they simply represent a rather casual accession to bureaucratic convenience. Still there is a gnawing feeling that there is an issue of 'truth in labelling' here.

As concerns the problem of global warming, NRC 83 asserts that there is general agreement that increases in infrared absorbing gases will contribute to warming. It is acknowledged that there is substantial uncertainty in the magnitude of the expected warming, but it is also noted that existing models have, for the last ten years or so, all predicted warmings in a similar range (1.5°C - 5°C). As we saw earlier in this paper, these predictions are disturbingly inconsistent with past records; moreover, all the models (including one that I published[20]) shared common errors. This tendency for scientists to reproduce each others errors is not at all uncommon – especially when one recognizes that models are subject to 'tuning;' scientists are hardly resistant to human failing. Nevertheless, Frank Press (President of the National Academy of Sciences) and Robert White (President of the National Academy of Engineering) did informally poll

[20]Lindzen, R.S., A.Y. Hou, and B.F. Farrell, *ibid*

many of us on this issue. The question asked was did we agree that increased CO_2 would lead to warming. Most of us, including myself, did agree. Hence, perhaps the claimed concensus. Still science, to be science, must be quantitative, and there is a world of difference between a warming of .2°C and a warming of 4°C. The former has virtually no policy implications since it is undetectable; the latter would be very important indeed. Why then do scientific spokesmen obscure this fact? Certainly, the great enthusiasm of journalists and politicians for scientific unanimity is a not so subtle influence.

There is, however, another reason for the easy acquiescence of so many scientists. Namely, most of the policy implications resulting from assuming that the warming is significant seem benign. Many of us feel that a more thoughtful energy policy would be a good thing quite apart from the potential warming. More caution in our approach to deforestation is hard to criticize. Freeman Dyson commenting on 'nuclear winter,' suggested that it was bad science but good politics. But, is it really benign to invoke bad science on behalf of causes that certainly can stand on their own? I think not. Science is a crucial and advantageous tool for society only as long as it preserves its integrity. It seems pointless to sacrifice this for causes that hardly require such a sacrifice. Moreover, there is no assurance that the policy implications of ill-based environmental warnings are inevitably benign. The banning of freons, and their replacement by generally inferior, more expensive, and potentially as harmful products is a case in point. The ozone issue is, however, a separate and comparably complex issue that deserves a separate discussion.

Finally, one must ask why politicians have become so insistent on scientific unanimity on environmental issues – especially when the policy implications are independently virtuous? Here, I am venturing well beyond any expertise that I may pretend to. Nevertheless, as a scientist and as a citizen, the issue is important to me, and I will attempt a guess. Central to contemporary politics seems to be the matter of building constituencies. Energy conservation seems to have proven rather small and ineffective in this regard. On the other hand, saving 'mother earth' seems both high minded and effective. It is interesting to note in this regard the almost universal preference of the verb 'save' to more accurate verbs like 'protect,' 'improve,' 'preserve,' etc. Presumably, 'save' suggests a more ominous – though invisible – crisis, and presumably, crises are politically more effective. Both the temptations and dangers of such an approach are obvious. Initially, the politicians need the scientists' assent that 'mother earth' needs saving, but as passions mount and the issue assumes the role of a religion, dissent will become tantamount to heresy[21].

[21] Clearly, I am greatly understating the complexity of the political and social situation. Energy issues are not alone in molding the current response to the long term awareness of the possibility of global warming. Gro Harlem Bruntland, Norway's prime minister, in an

To be sure, things have not yet come to this point. However, either through ignorance or intent, conditions are arising which impede the needed scientific exploration of this problem. In popular, but serious articles[22], lip service is paid to 'scientific uncertainty,' but the nature of the uncertainty is so profoundly distorted as to virtually eliminate the role of scientific inquiry. What is done is to claim scientific concensus for the notion that increases in minor greenhouse gases will lead to a large and intolerable warming; the uncertainty as to physical processes is held to be mostly taken care of by the oft repeated range of prediction of 1.5°C-5°C. The main 'uncertainty' is held to be largely restricted to the ability to detect this warming in the record of observed temperature. It is then argued that thiry years or more of observations will be needed before the observations will unambiguously display the trend. It is finally argued that by the time thirty or more years have passed, it will be too late to save our planet. Thus, we must act now to severely curb the introduction of any minor greenhouse gases into the atmosphere. In support of this view, Jonathan Schell quotes Stephen Schneider, who describes what he refers to as the 'scientists' dilemma.' He points out that scientists as scientists are committed to the truth, but that as 'human beings' desirous of a 'better world,' they must "offer up scary scenarios, make simplified, dramatic statements, and make little mention of any doubts we might have" in order to get 'loads of media attention,' and thereby 'capture the public's imagination.' Schneider describes this as a 'double ethical bind,' and meakly concludes with the hope that scientists can manage to be both 'effective' and 'honest.' Still, the overall tenor of his remarks is that the humane and ethical position is to ignore the science and act now. Indeed, it sometimes appears that the litmus test of public morality has become the willingness to act out of ignorance. 'Scientific uncertainty' is relegated to the role of excessive fussiness. I personally believe that scientists can only be effective by being honest. The so-called 'double ethical bind' is not only an unconscionable attack on the role of science, but also an attack on the seemingly lost ideal of the practice of democracy by an educated citizenry. As we have seen, the real uncertainty is far greater than has been stated – and extends to the question of whether significant warming is to be expected at all. Although science can never be totally free of uncertainty, there is research that

interview with the *San Francisco Chronicle* (April 9, 1989), expressed the hope that environmental affairs will replace the Cold War as the main framework for international affairs. Similar remarks have been made by other major world leaders. The move of the Union of Concerned Scientists away from nuclear disarmament to prevention of global warming as their focus mirrors the replacement of disarmament by the environment as an issue for conveniently expressing a high degree of public morality. Environmental organizations (including profit making environmental information services) have not been slow to recognize that fear of global warming is an effective aid to fund raising. Political scientists, international affairs experts, lawyers, and others have found the possibilities of international environmental politics irresistable – especially as concerns global warming.

[22]McKibben, B., 'Reflections (The End of Nature)', *The New Yorker*, p. 47, September 11, 1989

Schell, J., 'Our Fragile Earth,' *Discover*, 10, 44 (1989)

can and must be done in order to improve our basic physical understanding of how the global climate actually functions. It is maliciously specious to suggest that thirty years or more would be needed to substantially reduce uncertainty. Within less than a decade we could sufficiently improve our understanding of convection, cloud cover, ocean chemistry, ocean dynamics, etc. so as to make our predictions vastly more meaningful. None of this is facilitated by assuming the answer to begin with and committing ourselves to ill thought out actions. While uncertainty can never be completely eliminated, and prudent care is usually worthwhile, prudent care cannot be permitted to give way to an intolerance of any risk whatever. Real mischief will be unavoidable. Given a week or so, I would have no difficulty generating a long list of environmental problems which although objectively exceedingly unlikely cannot be rigorously proven impossible. If each called forth a statutory response, our society would be quickly paralyzed – tied into excruciating knots by its well meaning but misplaced enthusiasm. Any power base that is built on such an enthusiasm would hardly serve the nation in a way that any of us would wish.

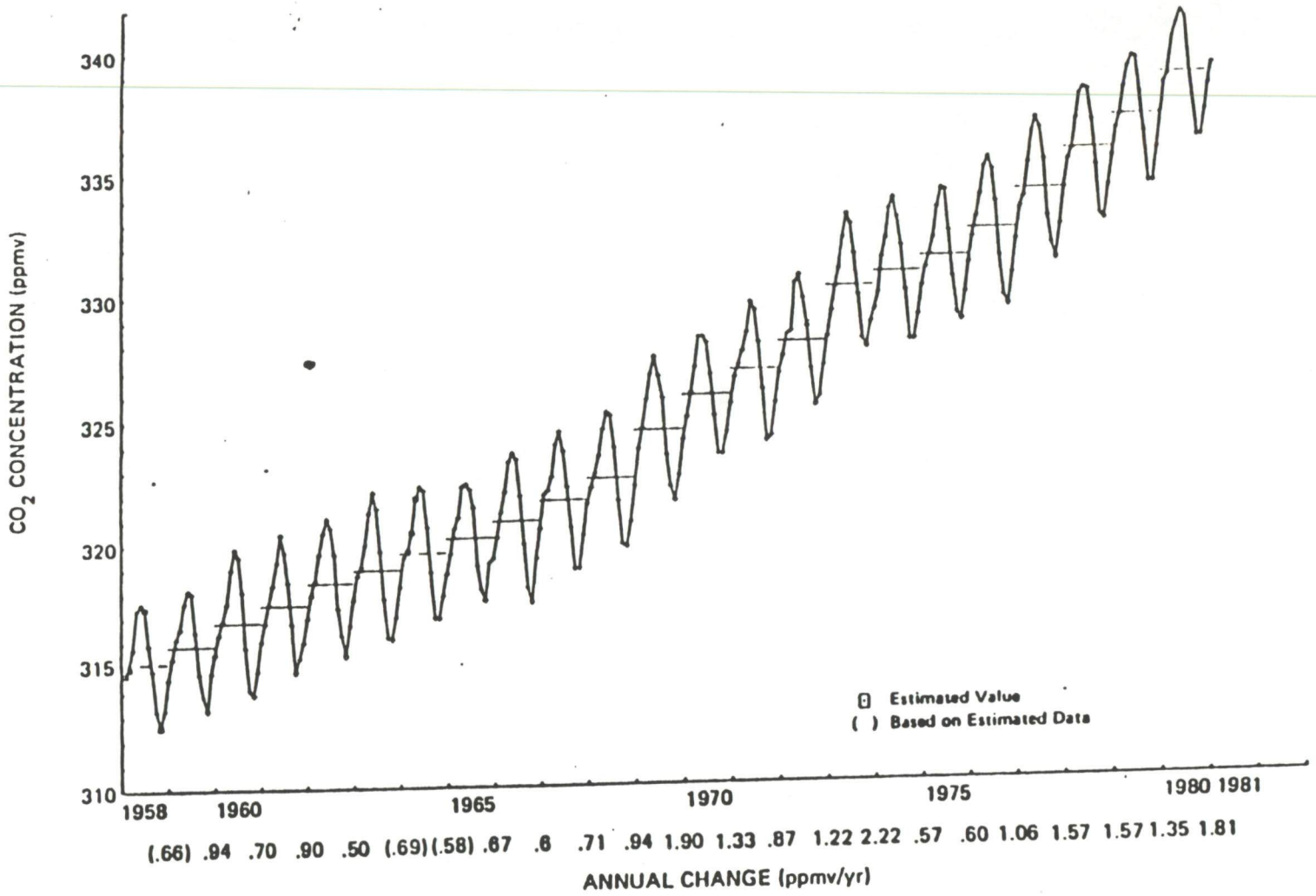


FIGURE 1 Mean monthly concentrations of atmospheric CO_2 at Mauna Loa. The yearly oscillation is explained mainly by the annual cycle of photosynthesis and respiration of plants in the northern hemisphere. See Section 1.2.2 for discussion of annual cycle. (Source: Geophysical Monitoring for Climate Change, National Oceanic and Atmospheric Administration.)

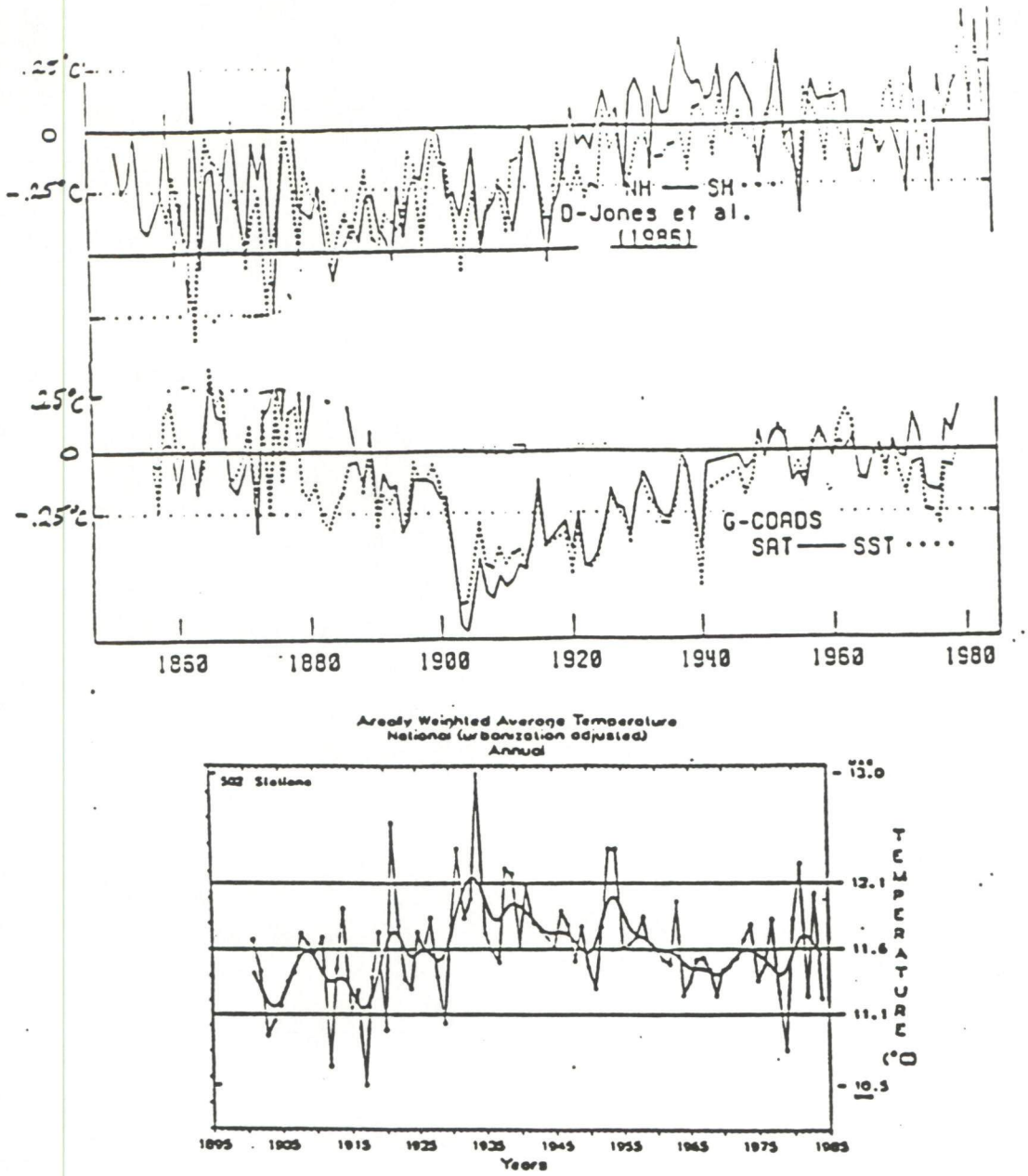


Figure 2

Top curves: Annual mean temperature departures from 1951-1970 normals derived from station data. The solid curve represents northern hemisphere data; the dotted curve represents southern hemisphere. The average between the two tends to be somewhat smoother than either curve. Reproduced from *Ellsaesser, et al, 1986* who used analyses from *Jones, et al, 1986a,b*[19].

Middle curves: Annual mean temperature departures from 1951-1970 normals derived from ship data for air temperature (solid line) and sea surface temperature (dotted line). Reproduced from *Ellsaesser, et al, 1986* based on analyses of *Slutz, et al, 1985*, *Ramage, 1984*, and *Folland, et al, 1984*[20].

Bottom curves: Annual mean temperature areally weighted over the contiguous 48 states. The solid curve represents a 9-year running smoother. Reproduced from *Karl, et al, 1988*[21].

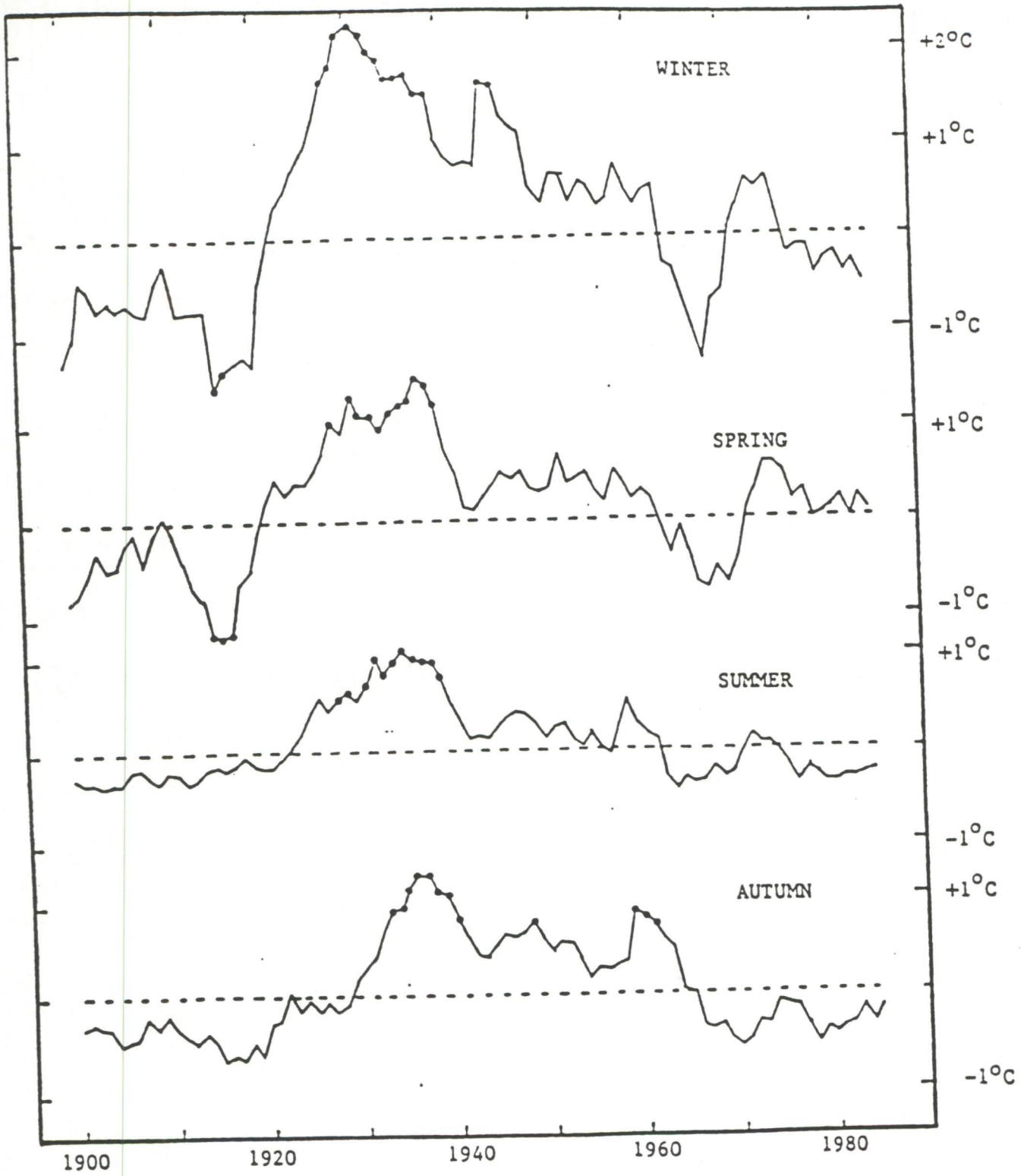


Fig. 4 Five-year averages of seasonal temperature anomalies over the Atlantic Arctic since 1900. Dots indicate five-year means temperature anomalies which are signifcantly above or below the 1881-1987 mean using the Cramer t-test. Temperatures are plotted on the middle year of the five-year means.

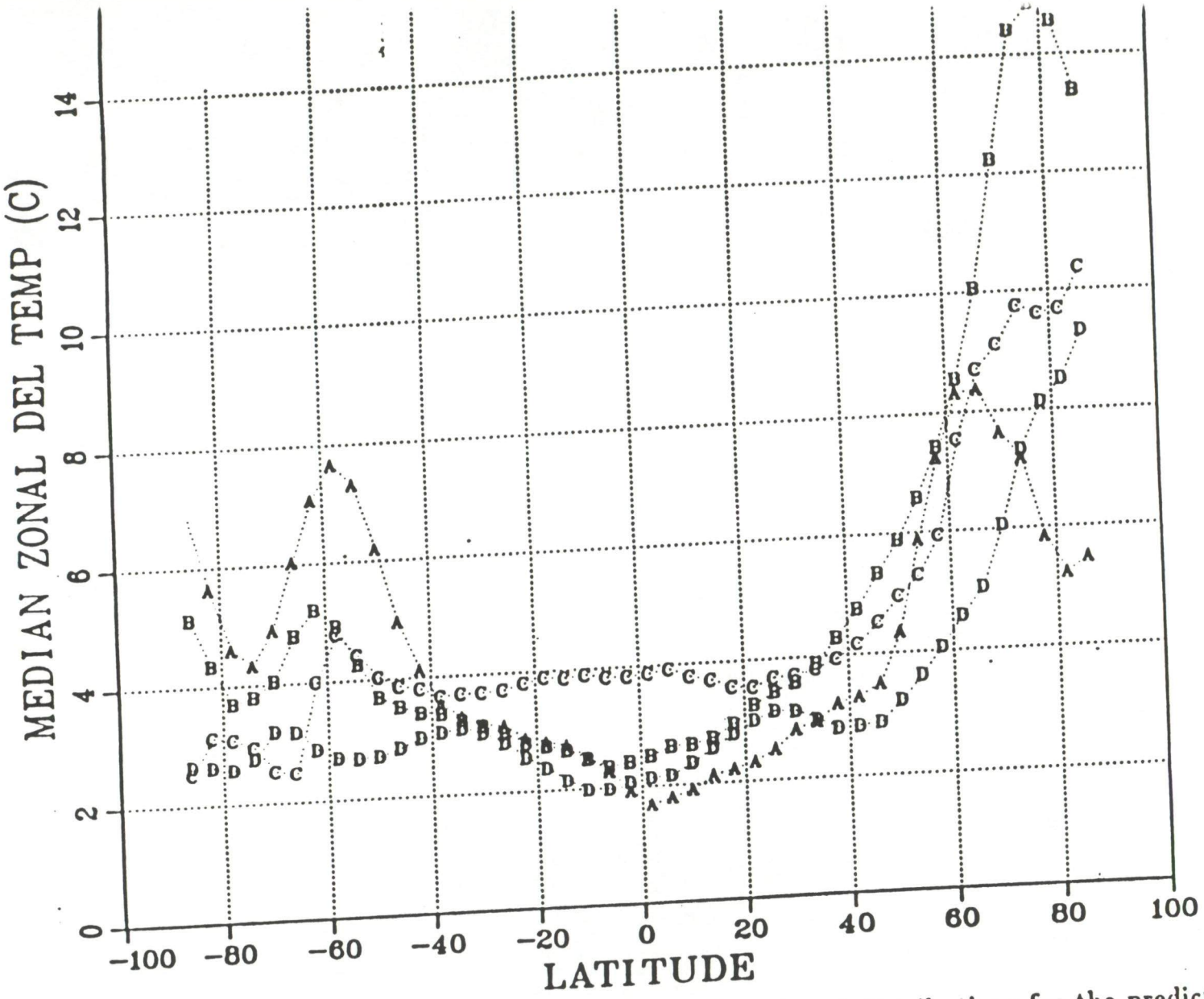


Figure 3 . Superposed medians for the four GCMs of the zonal distributions for the predicted change in surface air temperature due to a doubling of CO_2 for DJF (A = CCM, B = GFDL, C = GISS, D = OSU).

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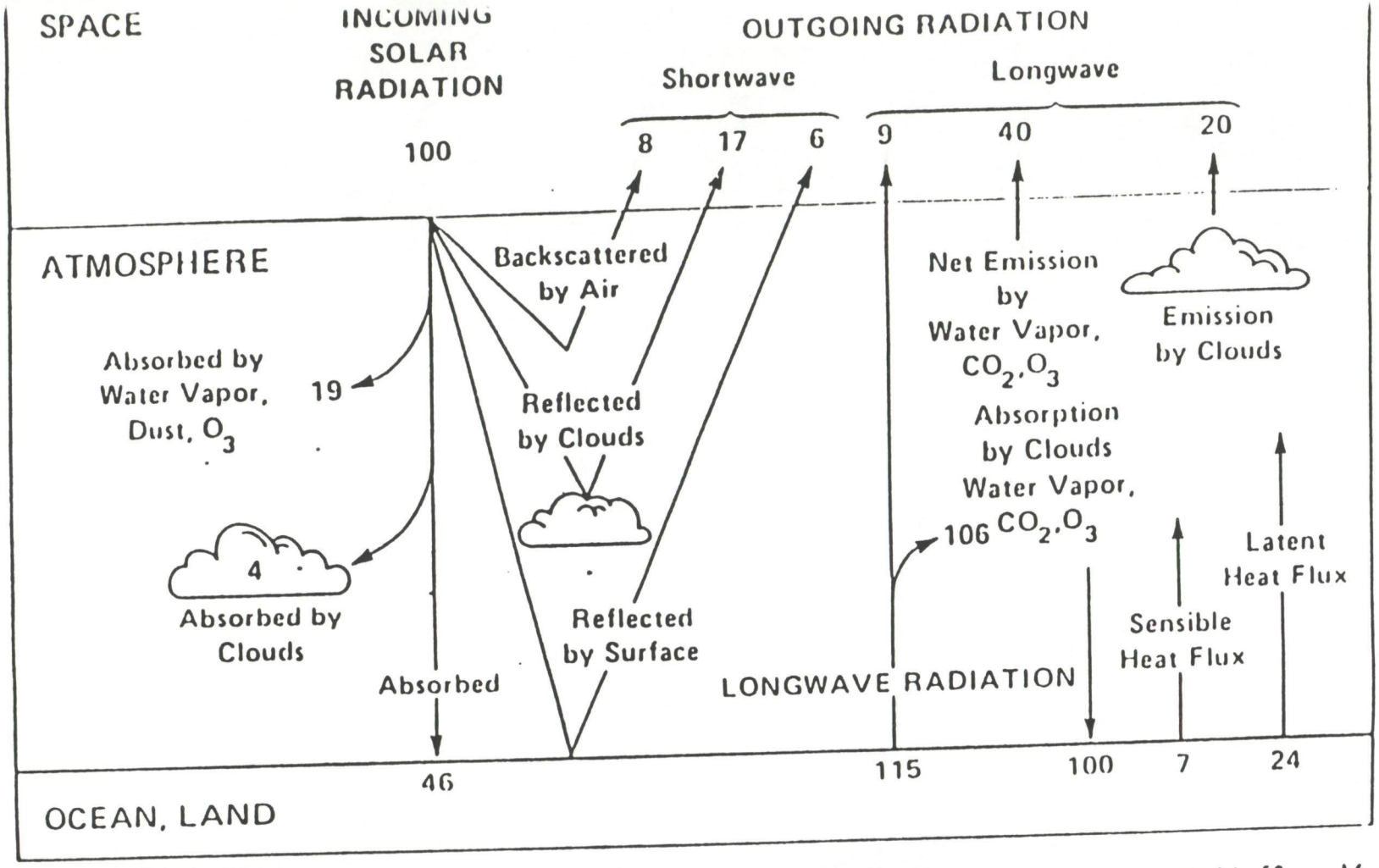


Figure 6 Schematic representation of the atmospheric heat balance. The units are percent of incoming solar radiation. The solar fluxes are shown on the left-hand side, and the longwave (thermal IR) fluxes are on the right-hand side [from *MacCracken and Luther*, 1985].

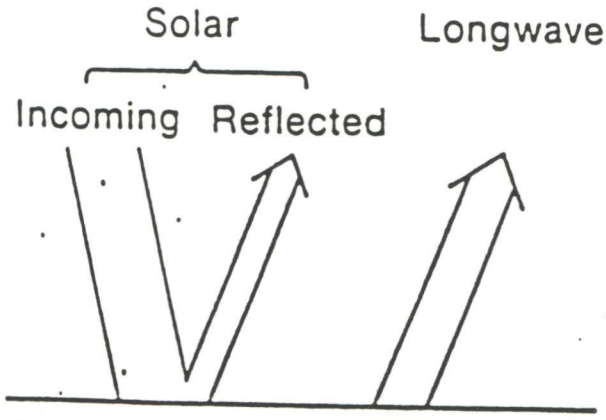
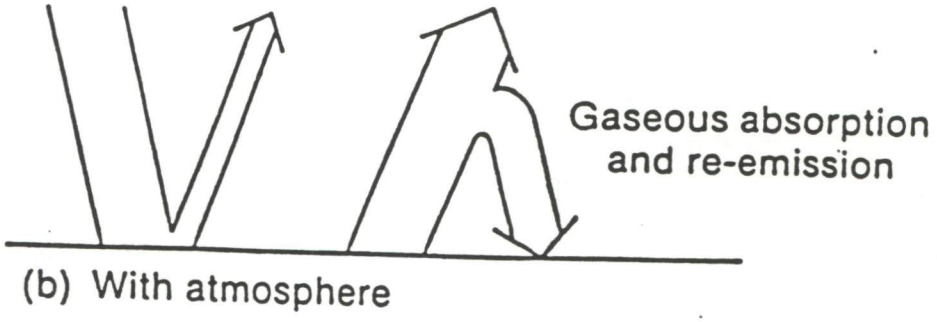
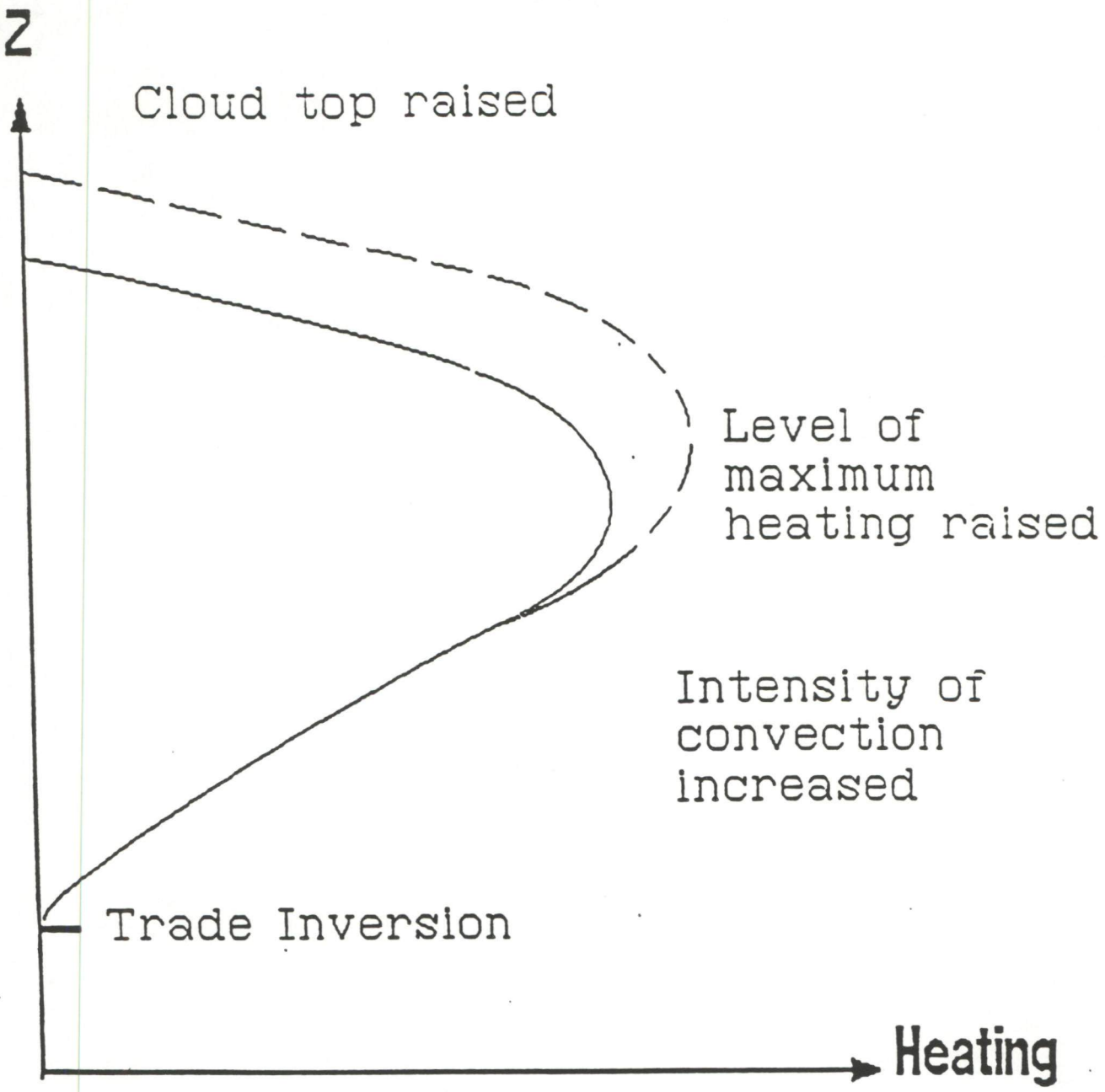


Figure 5 Schematic illustration of the greenhouse effect showing (*a*) no atmosphere, where long-wave radiation escapes directly to space, and (*b*) an absorbing atmosphere, where long-wave radiation from the surface is absorbed and reemitted both downward, warming the surface and lower atmosphere, and upward, maintaining radiative balance at the top of the atmosphere.





. Raising cloud top means that detrained air
s dryer.

2. Increased intensity means that dryer air
s pushed down more effectively.

3. Increased level of maximum heating means
hat heat is radiated through less absorber.

Figure 8

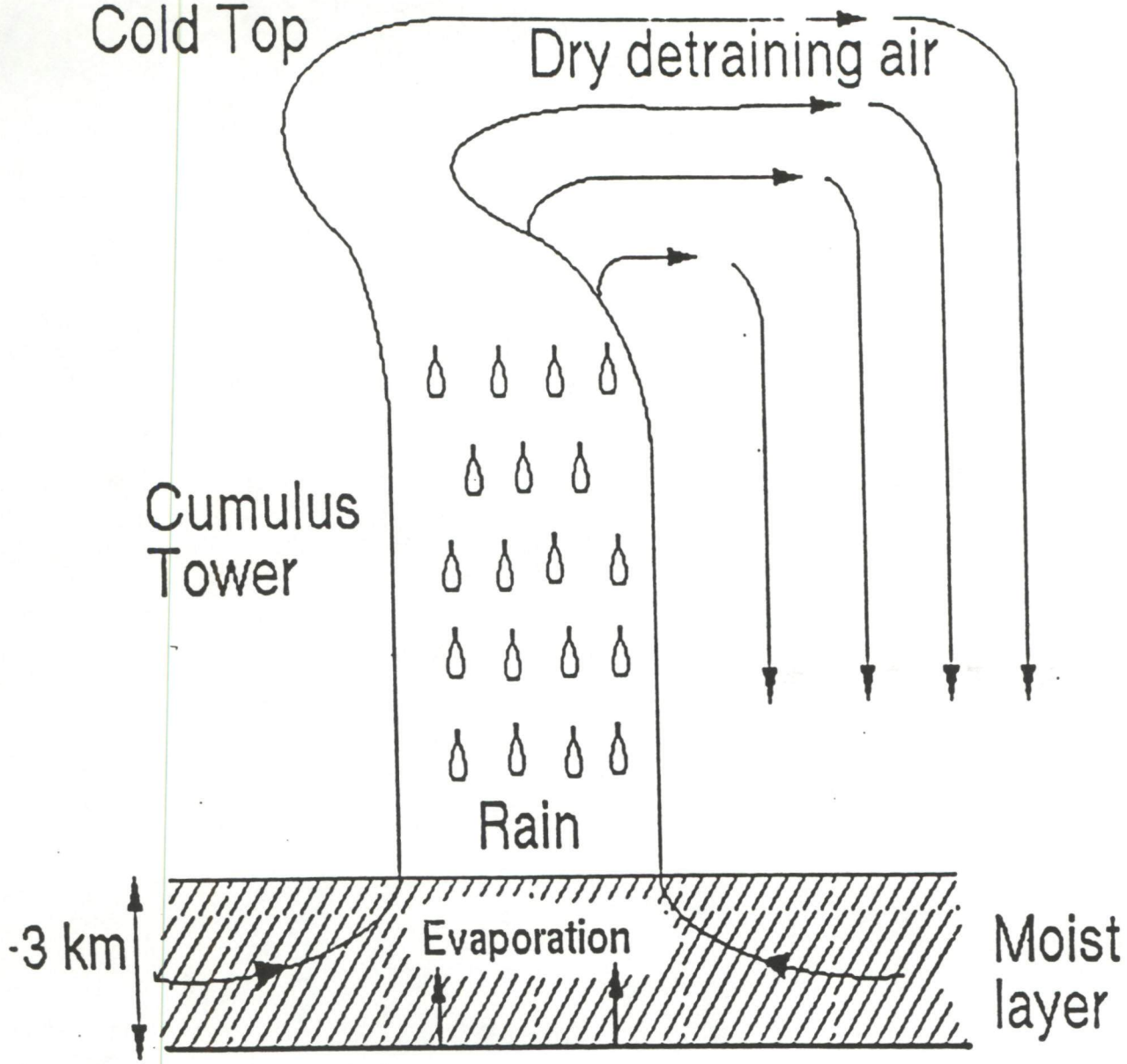

Cold Top
Dry detraining air
Cumulus
Tower
Rain
~3 km
Evaporation
Moist
layer

Figure 7

(Ken and Nancy)

Where is our next action - Do I take the paper to Simms?

Document Originally
Attached to
Following Page

COUNCIL OF ECONOMIC ADVISERS
EXECUTIVE OFFICE OF THE PRESIDENT
WASHINGTON

MEMBER OF THE COUNCIL

January 14, 1991

MEMORANDUM FOR D. ALLAN BROMLEY
ASSISTANT TO THE PRESIDENT FOR SCIENCE AND TECHNOLOGY

FROM: RICHARD L. SCHMALENSEE RS/HC

SUBJECT: Revisions to DPC Background Paper on Greenhouse Issues

Per the discussion at Friday's meeting, I have provided a revised version of the economics section that highlights uncertainty and other suggested language changes.

Revised Discussion of Economics:

Economics: Economic research on issues related to global change is in its infancy. Policy analysis is consequently plagued by considerable uncertainty regarding baseline emissions, abatement costs, and adaptation costs.

In order to predict future climate changes, scientific models require baseline forecasts of worldwide emissions of greenhouse gases over the next several decades. Emissions depend on population and GNP growth in both developed and developing nations, the rate and direction of technological advance, and developments in energy and other relevant markets. Long-range emissions forecasts, particularly for greenhouse gasses other than CO2, are considerably more uncertain than long-range economic forecasts. It does seem likely that emissions of CO2 will rise over time in the absence of controls and that the share of the U.S. and other developing nations in those emissions will continue to decline.

Very little work has been done on the costs of reducing emissions of greenhouse gases other than CFCs and carbon dioxide (CO2). CFC phaseout costs are generally agreed to be modest, while the costs of stabilizing or reducing world CO2 emissions are highly controversial. CO2 abatement costs have only been studied for the industrialized nations. Studies based on historical data suggest that stabilization or small reductions in CO2 emissions would impose costs on the order of 1 percent of GNP at the turn of the century and that those costs would rise over time. These studies also point to sharp adverse impacts on coal mining and other sectors, and to significant impacts on trade and competitiveness. Other studies based on analysis of particular technologies suggest that, in principle at least, costs could be more modest. Advances in technology could lower baseline

emissions, costs of reduction, and the tendency of costs to rise over time.

Policy analysis requires comparison of the costs of abating emissions with the consequences of the resulting changes in the timing and magnitude of possible climate changes. The sectors most directly affected by possible future climate change--agriculture, forestry, and fisheries--contribute only 3 percent of US GNP, but they are more important in developing nations. The impacts of variations in climate change on these sectors, which depend on regional level climate changes and adaptive responses that are not well understood at present, remain controversial. While the impacts of changes in the rate of sea level rise may be significant in some settings, little quantitative analysis of the corresponding costs has yet been done. Finally, the distinction between the total impact of climate change and the possible benefits of emissions reduction must be recognized. Climate processes (and therefore possible climate change impacts) depend on net world emissions of greenhouse gases, which would be affected only to a very small extent by emissions limitations efforts in the industrialized countries that are now being contemplated.

Other Suggested Revisions:

1. Page 2, lines 7-9: While estimates of impacts of potential climate changes may depend on regional predictions, the economic viability of response measures depends on: 1) their cost; 2) the extent to which they alter the magnitude and timing of potential climate changes and; 3) the responsiveness of impacts to the change in the climate change trajectory. For this reason, the sentence beginning on line 7 should be either deleted or replaced with the following:

> It is these smaller scale predictions that are of greatest use in determining the likely impacts of potential global climate change.

2. Page 6: In terms of substituting another term for "no regrets," I would caution against using the term "insurance" to characterize our approach. I think we would be hard pressed to explain how our approach (or that of the EC for that matter) insures anybody against anything.

Admittedly, it is difficult to come up with a good substitute for "no regrets." How about fail-safe, can't lose, sure win, win-win, or all weather (only kidding).

3. Pages 5 and 6: I would reiterate the concern raised at Friday's meeting that we characterize the positions of other countries accurately. Many of the commitments of other countries are highly conditional.

cc: Nancy Maynard
Ken Yale

EXECUTIVE OFFICE OF THE PRESIDENT
OFFICE OF SCIENCE AND TECHNOLOGY POLICY
WASHINGTON, D.C. 20506

January 10, 1991

Allan:

Here is the latest draft version. It has been sent out to all strategy task force members in preparation for the meeting on Friday, January 11, 1991 at 3:00 PM. Initial reactions to the paper have been very favorable.

Ken

Ken: What's the status of the program and the DSE paper? And what re input to Senate re Pres. speech (or not) on Feb 4?

DOS B

THE WHITE HOUSE

WASHINGTON

January 10, 1991

MEMORANDUM FOR THE GLOBAL CHANGE STRATEGY TASK FORCE

FROM: D. ALLAN BROMLEY

SUBJECT: Global Change Strategy Task Force Meeting

The Global Change Strategy Task Force will meet Friday, January 11, 1991, at 3 p.m. in Room 476 of the Old Executive Office Building.

As we discussed at our meeting last week, we will review a draft paper on key issues related to the preparations for the first negotiating session of the Framework Convention for possible submission to the Domestic Policy Council. Enclosed is a copy of that paper for your comment, but note that the document should be treated as "Close Hold". Please be prepared to discuss the issues presented in the paper at the meeting. Additional comments should be forwarded to Nancy Maynard at 456-6202 by COB Friday January 11, 1991.

Thank you

Enclosures

DRAFT

January 10, 1991

MEMORANDUM

FROM: D. ALLAN BROMLEY

SUBJECT: Global Change Framework Convention Negotiations

Issue: Negotiations on a global response to possible climate change will take place over the next 18 months under UN General Assembly auspices, with the aim of agreeing on the text of a framework convention in time for signing at the June 1992 UN Conference on Environment and Development (UNCED) to take place in Rio de Janeiro, Brazil. The United States will host the first session of the negotiations in Washington from February 4 to 14. The first session is expected to focus on organizational matters and the preparation of an initial negotiating text, without any attempt to resolve differences until subsequent sessions. The text will be based largely on the work of the Intergovernmental Panel on Climate Change (IPCC), which completed its first interim report last Fall.

BACKGROUND

Science: Scientific research has attempted to determine whether global warming is a potential threat and, if so, what would be the appropriate policy responses. Although atmospheric monitoring has shown an increase in concentrations of greenhouse gases, the mechanism of this increase, its natural and human components, and its potential effect on the earth's temperature regulation process and on climate change are unclear. What is known is that some human activities (such as the burning of fossil fuels, cattle raising, rice paddies, and garbage dumps) contribute to atmospheric concentrations of greenhouse gases (e.g., carbon dioxide - (CO_2), methane, nitrous oxide, and chloroflurocarbons). An increase in greenhouse gases increases the atmosphere's retention of heat. A complex natural system of temperature regulation can adjust to changes in temperature and greenhouse gas concentrations. It bears emphasis that the greenhouse gases entering and exiting the atmosphere through natural processes are more than twenty times larger than those resulting from human activities. This system involves complex cycles of emissions from "sources" of gases and sequester by "sinks". These cycles also include the absorption and radiation of energy.

Much effort has been undertaken to create computer models of this complex system in order to predict the effects on climate change of different levels of greenhouse gas concentrations. However, due to its complexity, the natural system of temperature

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regulation has never been accurately reflected in models, leading to uncertainties in the science and limited ability to predict climate change. Thus, there are great differences of opinion regarding the magnitude, spatial distribution, and timing of any climate changes caused by increased concentrations of greenhouse gases and the effect of natural mitigating factors. Moreover, the models are reasonably successful in representing global average phenomena, and incapable presently of giving reliable predictions on a regional basis. It is these smaller scale predictions that are of the greatest interest in developing economically viable measures to respond to potential global climate change.

International Action: The United States has participated in and endorsed the activities of the Intergovernmental Panel on Climate Change (IPCC). The IPCC was set up in 1987 by the World Meteorological Organization and the United Nations Environment Programme to assess the scientific information pertaining to the climate change issue, to assess impacts and to assess the factual basis for possible strategies to assist in controlling and responding to climate change. The IPCC adopted an interim report at the Second World Climate Conference in November 1990. The report addresses four major areas of climate change: 1) research, 2) the impacts of potential change, 3) response strategies, and 4) legal measures to implement response strategies, including possible elements of a framework convention on climate change. The report gives the current international perspective on global climate change and will form the basis for these international negotiations on a framework convention on climate change.

Congressional Action: There has been growing interest in global climate change issues among members and committees of the Congress. Over 50 bills, concurrent resolutions, and amendments were introduced in the 101st Congress dealing with various aspects of this issue. In addition, Congress has increased its attention to activities both of the Executive branch and the international community in global change research and international discussions. Congressional interest and activity will certainly increase in the 102nd Congress, with likely impacts on the framework convention negotiations.

Economics: Policy in this area must weigh the economic costs and human consequences of proposed response measures against the benefits associated with any resulting change in the timing and magnitude of any possible warming. Current analyses of the costs of a commitment to permanently hold carbon dioxide emissions at 80 or 100 percent of present levels show widely varying assessments of impacts on output and economic growth. Most studies using aggregate methods show an impact in the range od .05 percent to 1 percent of GNP (about $35 to $70 billion) at the turn of the century. Particular sectors, such as coal mining, would be particularly hard hit. Also, because the share of fossil fuels in the total primary energy supply varies widely across industrialized countries, there are likely to be significant trade and competitiveness effects.

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Some "bottoms up" analyses show that the substitution of more energy-efficient technologies (better lightbulbs, more insulation) can contribute to emissions reduction on the near term without raising the lifecycle cost of energy-using activities. Such evaluations do not account for the differences in taste and usage across consumers or the need to weigh energy-efficiency investments against alternative uses of capital. Obtainable energy savings and emissions reductions are almost certainly lower than estimates of technological potential.

Maintenance of any constant emissions level implies an ever increasing percentage reduction from an emissions baseline that is expected to grow as the economy expands. Since the marginal cost of emissions reduction increases after the cheapest opportunities are exploited, both aggregate and "bottoms up" modelling suggests that the costs of a constant emissions target are likely to rise over time. Finally, in considering the possible benefits of emissions reductions, it must be recognized that climate processes depend on world emissions, which are dominated by expected emissions increases outside of the industrialized countries.

Energy Issues: In spite of the relatively small contribution made by human activities, concerns about climate change and the build up of greenhouse gas concentrations have led to discussions of ways to reduce manmade emissions. Fossil fuel use is one source of these emissions. U.S. fossil fuel use produced almost 6 billion tons of CO_2, one major greenhouse gas, in 1988. This represents about 25% of total human induced emissions world-wide.

Since 1973 various strategies have been used to reduce our dependency on foreign oil imports. Additional steps to address energy issues could have an impact on the level of greenhouse gas emissions if they involve incentives to reduce fossil fuel use or increase the use of alternative energy sources, such as energy efficiency, conservation, or substitution.

CLIMATE CONVENTION NEGOTIATIONS

Process: The climate change negotiations will be carried out through a single process and forum provided by the Intergovernmental Negotiating Committee (INC). Following the first session here in Washington, most of the negotiating sessions will be held at UN facilities in Geneva, with one or possibly more sessions in Nairobi. Sessions will be one to two weeks in length, at intervals of three to four months in 1991, that is, in May or June, in August or September and in November or December. One to two sessions will be scheduled as needed in 1992. Jean Ripert of France will likely chair the negotiations. At the first session the United States will press for all substantive decisions to be taken by consensus and will seek appropriate participation by NGOs (non-governmental organizations, including both environmental and industry groups).

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U.S. Delegation: The U.S. delegation for the first session will be headed by Curtis "Buff" Bohlen, Assistant Secretary of State for Oceans and International Environmental and Scientific Affairs. The alternate head of delegation will be Robert A. Reinstein, Deputy Assistant Secretary of State for Environment, Health and Natural Resources. Reinstein will function as negotiator for this and subsequent sessions. The negotiating team is expected to include 12-15 representatives of the agencies with relevant environmental, scientific and economic expertise.

Scenario for First Session: Although a draft agenda has not yet been circulated by the UN Secretariat the following work-plan is anticipated for the nine-day session:

- o Organizational matters -- 1 day;
- o initial country statements (more than 100 countries are expected to attend) -- 2 days;
- o establishment of subgroups and preparation of the legal negotiating -- text 5 days;
- o and other matters (including establishment of relationship with IPCC and setting date and place of next session) -- 1 day.

Countries will propose text they wish to see included in the convention. All of the proposals will be bracketed in those instances where the text has not been agreed to by all participants. Although there will be some discussion of the reasons why specific text is being proposed, an attempt to resolve brackets will not be made during the first session. The U.S. delegation will propose the inclusion of language for elements we wish to see included in the convention. U.S. proposals will concern trade particularly on scientific research and cooperation. U.S. proposals will seek to address greenhouse gases in a comprehensive manner, that will include consideration of all sources and sinks. U.S. negotiators will make it clear that the U.S. considers such a comprehensive approach, with its potential for sharing any obligations across sources and sinks, gases, and countries to be of fundamental importance.

Elements for Possible Inclusion:

A number of non-controversial elements that may be included in the framework convention have been identified by the IPCC. We expect additional elements to be proposed as well, including controversial elements that more properly should belong in future protocols to the convention dealing with specific commitments following-on general commitments made in the convention itself. Both types of proposals are discussed briefly below:

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Noncontroversial:

-- Preamble: This generally consists of hortatory language and declarative findings and is often negotiated after the body of the agreement has been completed. It may include statements on issues where the countries cannot agree and accordingly may be used for compromises.

-- General obligations: A framework convention would usually contain a set of general obligations that may or may not be followed by specific commitments. One possibly potentially controversial general obligation may be raised by the inclusion of a formulation of the "Precautionary Principle" (discussed below).

-- Institutions: Such agreements generally establish a permanent secretariat to carry out administrative functions (presumably institutionalizing the ad-hoc secretariat that will support the negotiations) and a Conference of the Parties, which is simply the mechanism through which the countries become Parties to implement the agreement.

-- Research, systematic observations and analysis: This is a section of the agreement on which we will want to concentrate.

-- Information exchange and reporting: The U.S., consistent with our preference for a comprehensive approach, will want to emphasize comprehensive monitoring and reporting of data on all sources and sinks of all greenhouse gases in these sections.

-- Settlement of disputes: This is not controversial as long as there are no specific obligations.

-- Final clauses: These include miscellaneous legal provisions, and requirements for, entry into force, amendments, withdrawal, etc.

Controversial:

-- Annexes and protocols: The major issue to be debated over the next 18 months is the question of targets and timetables for reductions of greenhouse gas emissions, particularly CO2 emissions from the burning of fossil fuels. We are committed to addressing all greenhouse gases in a comprehensive manner, and that we will not be part of any agreement that does not include a comprehensive approach. Any specific obligations of this kind would be included in annexes or protocols to the convention. We have taken the position that such commitments are not appropriate at this time and should be negotiated subsequent to signing of the convention in 1992, and then only if analysis demonstrates that they are necessary. All other OECD countries, except Turkey, have made political statements arguing that such obligations should be undertaken now, either as part of the convention itself or in protocols negotiated simultaneously with the convention.

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-- General obligations: the Precautionary Principle: Many countries are on record as wanting to include in the framework convention an article on the so-called "Precautionary Principle." To date, there is no internationally agreed definition of the principle. Some have described it as merely expressing the general notion that it is desirable to prevent pollution. Others have taken a more extreme position, describing it as meaning that, before an activity may be undertaken, it must be affirmatively proven that the activity will not cause harm to the environment. If unable to avoid it, we should seek a climate-specific definition of the precautionary principle or "precautionary approach" based on the [no-regrets] policy, that is a policy that will take into account the degree of scientific certainty and economic considerations.

-- Financial assistance: Consistent with the Houston Economic Declaration, a general commitment to promote financial assistance for developing countries will be raised in the framework convention. Developing countries will undoubtedly propose that this include a commitment to provide "new and additional" funding, a commitment that we oppose. The United States, and other donor nations, believe that financial assistance should be to meet incremental costs incurred, based on the extent to which global benefits of a project are expected to exceed benefits to the recipient country. The United States also believes that the newly established Global Environmental Facility (GEF) in the World Bank is the appropriate mechanism through which any multilateral assistance should be processed.

-- Development and transfer of technology: The developing countries have often called for technology transfer on a "preferential and noncommercial basis." Although this language raises the problem of protection of intellectual property rights (IPR), there is in fact, a wide range of technologies where IPR issues do not arise and where there may indeed be significant opportunities for providing technical assistance to developing countries through existing bilateral cooperation programs. As a counter to unreasonable demands in this area, we will need to explore some of these options as the negotiations proceed. We will also stress that failure to address the technology transfer question on a commercial basis, with full account taken of market forces and the protection of IPR, will act as a disincentive to the development of needed technology. A proactive approach to assisting in the application of technology that is readily available and does not involve IPR issues will benefit the environment, increase market share, give an opportunity for a positive political action, and enhance the development of new technologies.

Strategy: In addition to our substantive positions, we need to develop a realistic strategy to carry us through the course of the negotiations. Our strategy will need primarily to address two arenas: (1) the negotiations themselves, and (2) Congress and the U.S. public. The United States is entering these negotiations from a relatively isolated position, seeing it is the only major developed country not committed to some target and timetable for greenhouse gas reductions.

Within the negotiations themselves, we can bolster our basic position on the targets and timetables by demonstrating the economic costs of such commitments and their administrative complexities, possible trade problems arising from the imposition of

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large taxes on the carbon content of fossil fuels (the principal means of achieving major reductions), and other problems that are far from being solved. This will require solid economic and scientific analysis in order to back up our positions. But such analysis is already well underway and partially completed.

Many other countries have expressed some doubt about our sincerity about addressing the climate issue. In this regard, any signal we might give that we are willing to take actions, even though fully justified for other reasons (such as energy security, longer-term industrial competitiveness, other proven environmental concerns, etc.), which would result in some significant reduction in greenhouse gas emissions would have a major beneficial strategic impact. Such a signal from the United States would also help to ensure that the climate negotiations do not affect other international environmental issues. It is important to emphasize that both in terms of the U.S. investment in a deeper understanding of the phenomena involved in global change, and in specific policy actions, that we are already acting to reduce U.S. greenhouse gas emissions. These U.S. activities are unmatched by any other country. For various reasons, the U.S. has found itself in a reactive mode in national and international media coverage. It will be essential for us to focus on changing the situation so that our achievements are widely recognized and credited to the President's initiatives and programs.

We expect the negotiations to receive considerable press attention. Foreign governments and U.S. environmental groups will use the media to further their positions, particularly during the first negotiating session. We will have a list of Administration achievements for distribution during the first session to the press and other governments. Congress to continue will also play a vocal role throughout the negotiations.

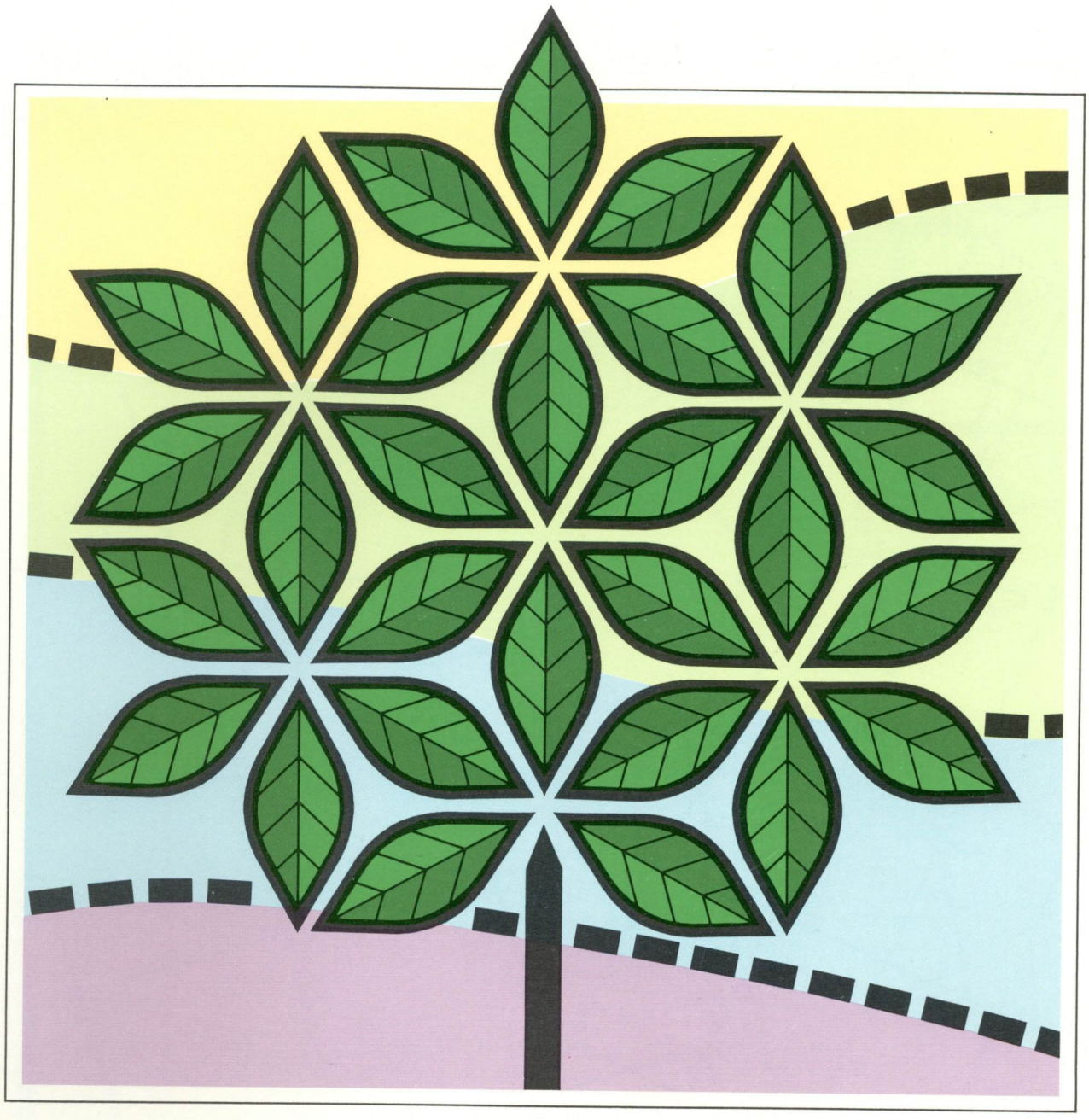
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United States
Department of
Agriculture

Agricultural
Research
Service

Miscellaneous
Publication
Number 1475

USDA Plant Hardiness Zone Map



USDA Plant Hardiness Zone Map

Henry M. Cathey

THIS map supersedes U.S. Department of Agriculture Miscellaneous Publication 814, "Plant Hardiness Zone Map," which was revised in 1965. It shows in detail the lowest temperatures that can be expected each year in the United States, Canada, and Mexico. These temperatures are referred to as "average annual minimum temperatures" and are based on the lowest temperatures recorded for each of the years 1974 to 1986 in the United States and Canada and 1971 to 1984 in Mexico. The map shows 10 different zones, each of which represents an area of winter hardiness for the plants of agriculture and our natural landscape. It also introduces zone 11 to represent areas that have average annual minimum temperatures above 40°F (4.4°C) and that are therefore essentially frost free.

Basic Plant Requirements

All agriculturists, environmentalists, horticulturists, and home gardeners have one all-abiding question about any plant they wish to introduce into their growing spaces. Will it flourish?

The ability to predict whether a newly collected species or cultivar can be successfully grown in a location is fundamental to the continued productivity of America's agriculture and to the survival of our landscapes. The plants in our urban spaces, farms, fields, and forests consist of native vegetation and exotic plants introduced into our land from all over the world. All plants must be placed in an environment that meets their basic requirements:

Day length. Day length is usually the most critical factor in regulating vegetative growth, flower initiation and development, and the induction of dormancy. Plants survive only when the day length promotes their growth and prepares them for the seasonal changes.

Radiation. Most plants respond to radiation in the 270- to 3000-nm region. Cloudy, rainy days coupled with the shade provided by nearby plants and structures can significantly reduce the amount of radiation available. Plants survive only where the amount is within a specified range.

Temperature. Plants grow best within an optimum range of temperatures; and the range may be wide for some species, narrow for others. Plants survive only where temperatures allow them to metabolize.

Frost. Plants differ in ability to survive frost, their responses varying from immediate death to sustained performance. The previous environmental and cultural conditions of plants can often shift, but not permanently alter, their tolerance to freezing. Plants survive only when they are adapted to subfreezing weather.

Director, U.S. National Arboretum, Agricultural Research Service, U.S. Department of Agriculture, Washington, DC 20002. Temperature data were compiled and maps prepared under contract with the Meteorological Evaluation Services Co., Inc., 165 Broadway, Amityville, New York 11701.

Heat. The thermal cutoff temperature varies widely from species to species. By tradition we group plants into sun, partial sun, and shade types and plant them according to their light and heat tolerances.

Rainfall. Gardeners need to know how much water a landscape plant requires in determining its usability in low maintenance landscapes. Rainfall gardening often greatly limits which species can be used successfully. Gardeners also need to know how much and how often to water plants in high maintenance landscapes.

pH. The ability of plant roots to take up water and nutrients depends on the pH (measure of acidity or alkalinity), presence of soluble and insoluble salts, and aeration of the growing medium. The successful culture of all plant species requires that they be grown in a medium within a definite pH range and with from 10 to 14 essential nutrients in appropriate balance. Although plants may tolerate some extraneous elements and compounds, every plant species and cultivar has well-prescribed limits.

How the Map Was Started

Every plant can adapt to a range of environments. Gardeners have learned through experience where the great variety of landscape plants can be grown. Over the years many schemes have been proposed to help gardeners locate those environments when they introduce new species, forms, and cultivars. The pooling of many of these schemes culminated in the development of the widely used "Plant Hardiness Zone Map," under the supervision of Henry T. Skinner, the second director of the U.S. National Arboretum. In cooperation with the American Horticultural Society, he worked with horticultural scientists throughout the United States to incorporate pertinent horticultural and meteorological information into the map.

The elements of that map were—

Zones. The contiguous United States and southern Canada were divided into 10 zones based on a 10°F (5.6°C) difference in average annual minimum temperature.

Winter Hardiness. Survival of landscape plants over winter was selected as the most critical criterion in their adaptation to the environment.

Classification. The zone ratings were intended to indicate *excellent adaptability* of the plants. Many plants may survive in warmer or colder zones. Usually, mere survival does not represent satisfactory performance.

Interactions With Other Environmental Factors. Many other factors may come into play in determining satisfactory growth. Wind, soil type, soil moisture, humidity, snow, and winter sunshine may greatly affect the adaptability of plants.

Interactions With Cultural Factors. The way plants are placed in the landscape, how they are planted, and their size and health can greatly influence satisfactory adaptability.

Why the New Map Was Created

The "Plant Hardiness Zone Map" was published in 1960 and revised in 1965. Since then, many changes, new interests, and new responsibilities have emerged in North American landscaping:

Changes in Weather. We have been losing from our landscapes plants that apparently survived the 1940's to the 1960's. Many of the hardiness zone classifications of plants are no longer considered valid. In North America, the ranges of temperature and moisture for the past decade were wider than those recorded for the 1940's through the 1960's.

Introduction of New Elite Forms. Our landscape industry has worked with plant explorers and breeders to introduce many new forms of traditional plants that are adapted to a wider range of environments than the older forms.

Scope. The continental United States is contiguous with Canada to the north and Mexico to the south. We share more than a common border—we share indigenous plants and many introduced plants that can be grown successfully. We needed to expand the scope to include the whole of North America.

How To Use the New Map

Zones 2-10 in the map have been subdivided into light- and dark-colored sections (a and b) that represent 5°F (2.8°C) differences within the 10°F (5.6°C) zone. The light color of each zone represents the colder section; the dark color, the warmer section. Zone 11 represents any area where the average annual minimum temperature is above 40°F (4.4°C). The map shows 2° latitude and longitude lines. Areas above an arbitrary elevation are traditionally considered unsuitable for plant cropping and do not bear appropriate zone designations. There are also island zones that, because of elevation differences, are warmer or cooler than the surrounding areas and are given a different zone designation. Note that many large urban areas carry a warmer zone designation than the surrounding countryside. The map contains as much detail as possible, considering the vast amount of data on which it is based and its size.

In using the map to select a suitable environment for a landscape plant, today's gardeners should keep in mind the following:

Stress Factors. We became aware of additional stresses to plants during the 1970's. Acid rain, gaseous and particulate pollution, security lighting, and toxic wastes, among many other stress factors, have significantly increased the potential for unsatisfactory performance of landscape plants. We need to document the tolerances of plants to these factors.

New Plant Management Systems. New techniques of planting, transplanting, watering, fertilizing, and providing pest control measures have done much to increase the vigor of landscape plants. But used unwisely, these same measures can reduce plant hardiness.

Artificial Environments. We have pushed the use of plants into totally artificial environments such as expressways, malls, elevated decks, and buildings where plant roots are totally removed from the ground and its warming influence. The assortment of plants that can adapt to such environments is proving to be very restricted. Hardiness ratings alone are inadequate to guide landscapers in selecting the most successful plants.

How the Map Was Created

The average annual minimum temperature data were analyzed for Mexico, the United States, and Canada. Of 14,500 stations that measured temperature during the period of interest, almost 8,000 could be identified by latitude and longitude and by a valid average annual minimum temperature (i.e., an average based on at least 10 years of data). Data from only the latter stations were used in the map. The data were archived by Servicio Meteorologico Nacional (Tucubaya, D.F., Mexico), the National Climatic Data Center (Asheville, NC), and Environment Canada - Canadian Climate Centre (Downsville, Ontario). The map is an Albers Equal Area Projection. Standard parallels of 29.5° and 45.5° were used to generate the map of the three countries. The map was computer generated by latitude and longitude. Because of the large area involved, it is not possible to draw one map that is accurate for all of North America. The part representing the United States has the least distortion. The Agricultural Research Service proposes to periodically evaluate weather data and issue updated maps as necessary and appropriate.

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Issued January 1990

Indicator Plant Examples

Following are names of representative persistent plants listed under the coldest zones in which they normally succeed. Such plants may serve as useful indicators of the cultural possibilities of each zone.

Zone	Botanical Name	Common Name
1 **°F** Below -50 **°C** Below -45.6	*Betula glandulosa*	Dwarf birch
	Empetrum nigrum	Crowberry
	Populus tremuloides	Quaking aspen
	Potentilla pensylvanica	Pennsylvania cinquefoil
	Rhododendron lapponicum	Lapland rhododendron
	Salix reticulata	Netleaf willow
2 **°F** -50 to -40 **°C** -45.6 to -40	*Betula papyrifera*	Paper birch
	Cornus canadensis	Bunchberry dogwood
	Elaeagnus commutata	Silverberry
	Larix laricina	Eastern larch
	Potentilla fruticosa	Bush cinquefoil
	Viburnum trilobum	American cranberry bush
3 **°F** -40 to -30 **°C** -40 to -34.5	*Berberis thunbergii*	Japanese bayberry
	Elaeagnus angustifolia	Russian olive
	Juniperus communis	Common juniper
	Lonicera tatarica	Tatarian honeysuckle
	Malus baccata	Siberian crabapple
	Thuja occidentalis	American arborvitae
4 **°F** -30 to -20 **°C** -34.5 to -28.9	*Acer saccharum*	Sugar maple
	Hydrangea paniculata	Panicle hydrangea
	Juniperus chinensis	Chinese juniper
	Ligustrum amurense	Amur River privet
	Parthenocissus quinquefolia	Virginia creeper
	Spiraea x vanhouttei	Vanhoutte spirea
5 **°F** -20 to -10 **°C** -28.9 to -23.3	*Cornus florida*	Flowering dogwood
	Deutzia gracilis	Slender deutzia
	Ligustrum vulgare	Common privet
	Parthenocissus tricuspidata	Boston ivy
	Rosa multiflora	Japanese rose
	Taxus cuspidata	Japanese yew

Zone	Botanical Name	Common Name
6 **°F** -10 to 0 **°C** -23.3 to -17.8	*Acer palmatum*	Japanese maple
	Buxus sempervirens	Common box
	Euonymus fortunei	Winter creeper
	Hedera helix	English ivy
	Ilex opaca	American holly
	Ligustrum ovalifolium	California privet
7 **°F** 0 to 10 **°C** -17.8 to -12.3	*Acer macrophyllum*	Bigleaf maple
	Rhododendron Kurume hybrids	Kurume azalea
	Cedrus atlantica	Atlas cedar
	Cotoneaster microphylla	Small-leaf cotoneaster
	Ilex aquifolium	English holly
	Taxus baccata	English yew
8 **°F** 10 to 20 **°C** -12.3 to -6.6	*Arbutus unedo*	Strawberry tree
	Choisya ternata	Mexican orange
	Olearia haastii	New Zealand daisy-bush
	Pittosporum tobira	Japanese pittosporum
	Prunus laurocerasus	Cherry-laurel
	Viburnum tinus	Laurestinus
9 **°F** 20 to 30 **°C** -6.6 to -1.1	*Asparagus setaceus*	Asparagus fern
	Eucalyptus globulus	Tasmanian blue gum
	Syzygium paniculatum	Australian bush cherry
	Fuchsia hybrids	Fuchsia
	Grevillea robusta	Silk-oak
	Schinus molle	California pepper tree
10 **°F** 30 to 40 **°C** -1.1 to 4.4	*Bougainvillea spectabilis*	Bougainvillea
	Cassia fistula	Golden shower
	Eucalyptus citriodora	Lemon eucalyptus
	Ficus elastica	Rubber plant
	Ensete ventricosum	Ensete
	Roystonea regia	Royal palm

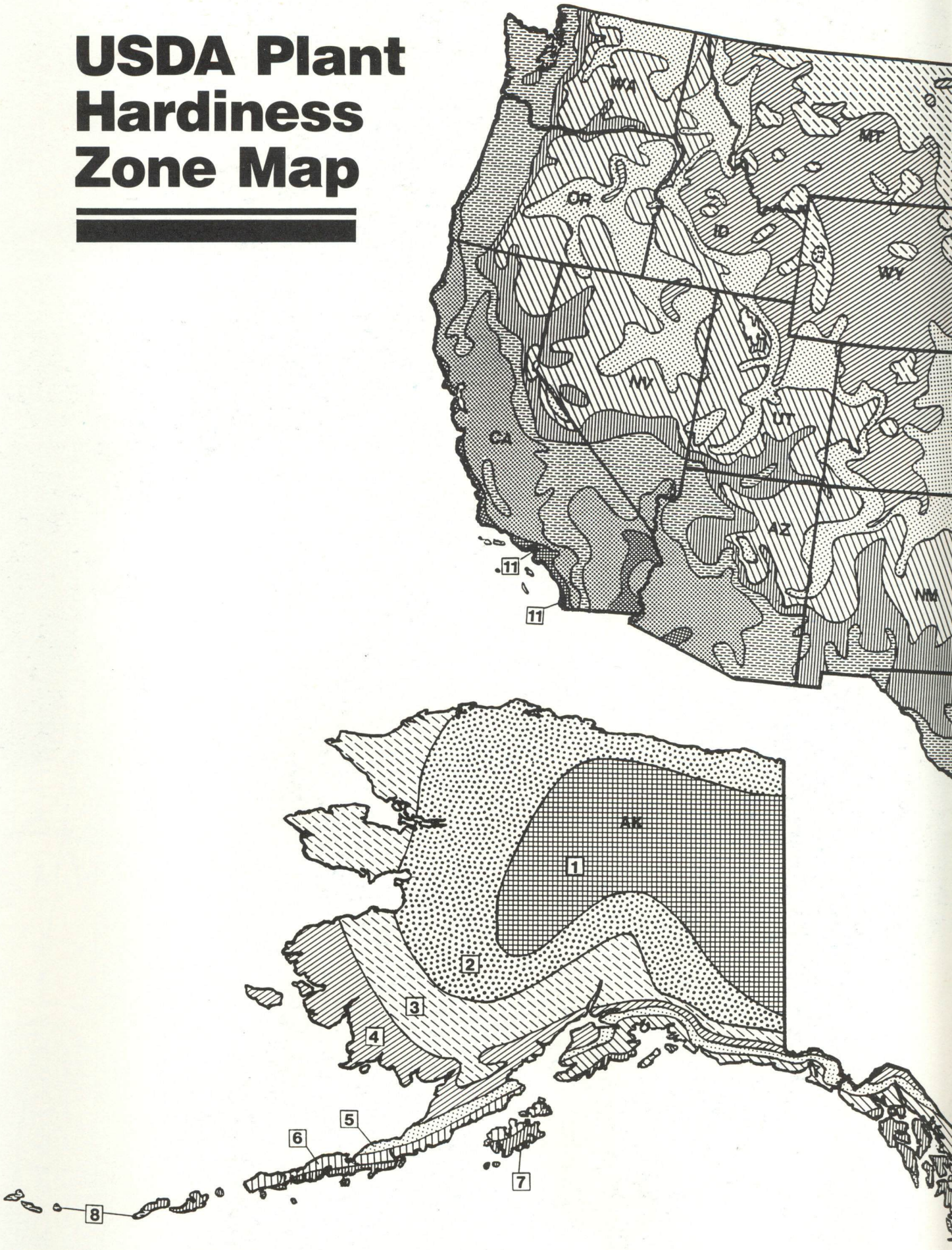
Cold Hardiness Ratings for Some Additional Woody Plants

Botanical and Common Names	Zone
Abeliophyllum distichum (white forsythia)	**5b**
Acer platanoides (Norway maple)	**4**
Aesculus x *carnea* (red horsechestnut)	**4**
Araucaria araucana (monkeypuzzle)	**7b**
Arctostaphylos uva-ursi (bearberry)	**2b**
Aristolochia durior (Dutchman's-pipe)	**4b**
Aucuba japonica (Japanese aucuba)	**7b**
Bauhinia variegata (purple orchid tree)	**9b**
Berberis darwinii (Darwin barberry)	**8**
Betula pendula (European white birch)	**3**
Bouvardia 'Coral' (Coral bouvardia)	**9**
Butia capitata (Pindo palm)	**8b**
Camellia reticulata (*reticulata camellia*)	**9**
Camellia sasanqua (*sasanqua camellia*)	**7b**
Carya illinoinensis 'Major' (pecan)	**5 (grows)** **6 (fruits)**
Casuarina equisetifolia (Australian pine)	**9b**
Ceanothus impressus (Santa Barbara ceanothus)	**8**
Cedrus deodara (deodar cedar)	**7b**
Cercis chinensis (Chinese redbud)	**6b**
Chamaecyparis lawsoniana (Lawson cypress)	**6b**
Chamaecyparis pisifera (Sawara cypress)	**5**
Cinnamomum camphora (camphor tree)	**9**
Cistus laurifolius (laurel rockrose)	**7**
Cistus x *purpureus* (purple rockrose)	**8**
Cornus alba (Tatarian dogwood)	**3**
Cornus kousa (Japanese dogwood)	**5b**
Cunninghamia lanceolata (cunninghamia)	**7**
Cytisus x *praecox* (Warminster broom)	**6**

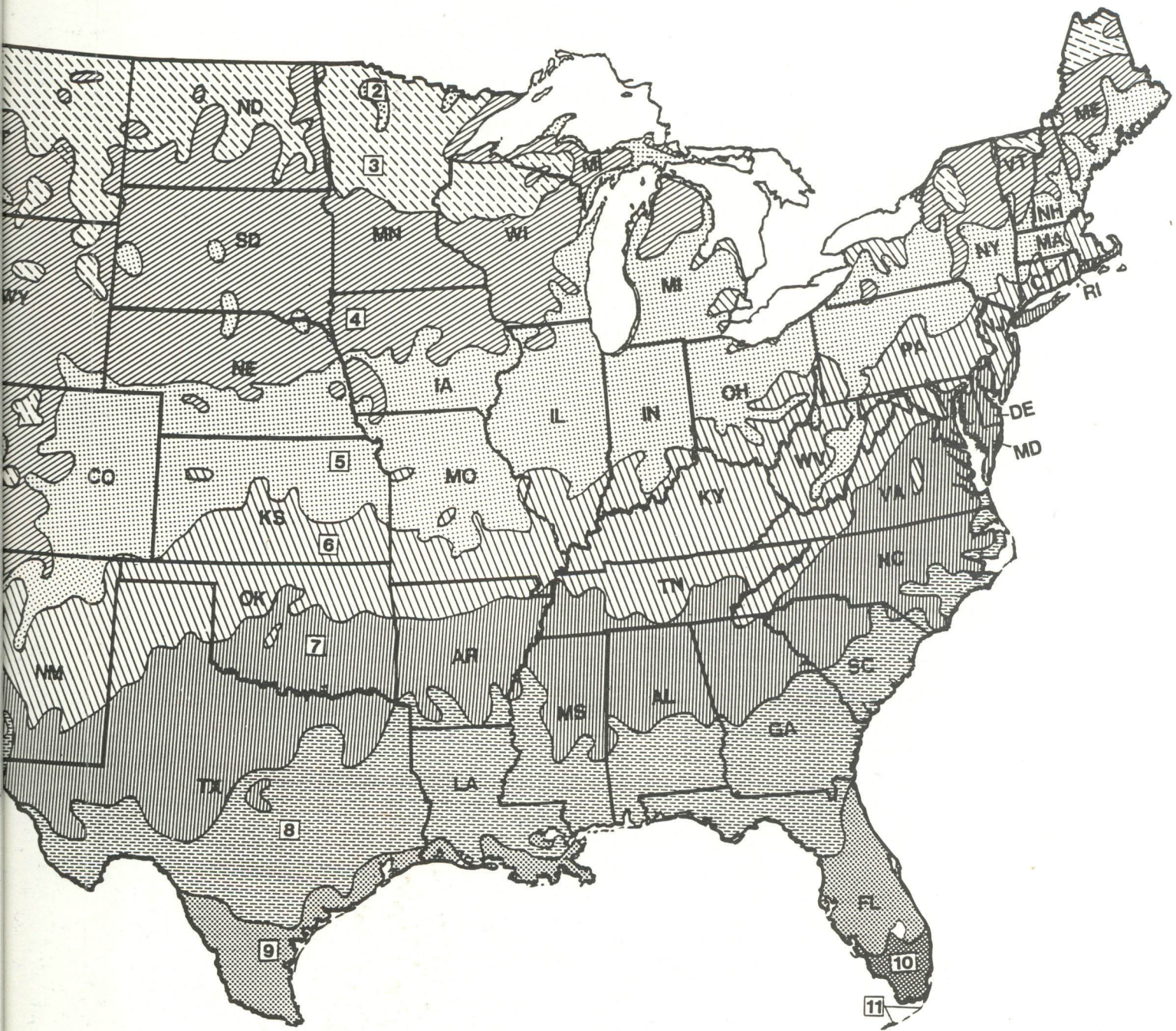
Botanical and Common Names	Zone
Elaeagnus multiflora (cherry elaeagnus)	5
Elaeagnus pungens (thorny elaeagnus)	7
Eriobotrya japonica (loquat)	8
Euonymus alatus (winged euonymus)	3b
Euphorbia pulcherrima (poinsettia)	10
x *Fatshedera lizei* (botanical-wonder)	8
Forsythia ovata (early forsythia)	4b
Forsythia suspensa (weeping forsythia)	5b
Fremontodendron mexicanum (flannel bush)	9
Ginkgo biloba (ginkgo, maidenhair-tree)	5
Hibiscus rosa-sinensis (Chinese hibiscus)	9b
Hibiscus syriacus (shrub althea)	5b
Hypericum 'Hidcote' (Hidcote St. Johnswort)	6
Iberis sempervirens (evergreen candytuft)	5
Ilex crenata 'Convexa' (convexleaf Japanese holly)	6b
Jacaranda acutifolia (green ebony)	10
Juglans regia (English or Persian walnut)	6b
Juniperus horizontalis (creeping juniper)	3
Koelreuteria paniculata (goldenrain-tree)	6
Laburnum x *watereri* (Waterer laburnum)	5b
Lagerstroemia indica (crapemyrtle)	7
Mahonia aquifolium (Oregon hollygrape)	5b
Malus x *arnoldiana* (Arnold crabapple)	4
Melia azedarach (chinaberry)	7b
Metasequoia glyptostroboides (dawn redwood)	5b
Myrtus communis (true myrtle)	8b
Nandina domestica (heavenly bamboo)	7
Nerium oleander (oleander)	8b

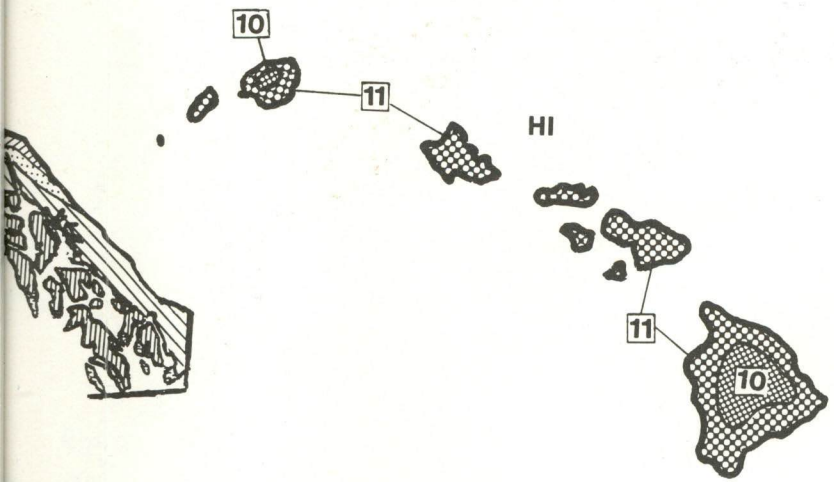
Botanical and Common Names	Zone
Olea europaea (common olive)	9
Osmanthus heterophyllus (holly osmanthus)	7
Picea abies (Norway spruce)	3
Pieris japonica (Japanese andromeda)	6
Pinus mugo var. *mughus* (Mugo pine)	3
Pinus radiata (Monterey pine)	7b
Pinus strobus (eastern white pine)	3b
Prunus yedoensis (Yoshino cherry)	6
Rhaphiolepis indica 'Rosea' (Indian hawthorn)	8
Rhododendron 'America' (hybrid rhododendron)	5
Rhododendron 'Loderi King George' (hybrid rhododendron)	8
Rhododendron mollis hybrids (mollis azalea)	5
Rhododendron prinophyllum (*roseum*) (roseshell azalea)	4
Rhododendron 'Purple Splendor' (hybrid rhododendron)	7
Rhododendron southern Indian hybrids (Indian azalea)	8b
Rosa rugosa (rugosa rose)	3
Schinus terebinthifolius (Brazilian pepper-tree)	9b
Sequoia sempervirens (redwood)	8
Sequoiadendron giganteum (giant sequoia)	7
Stewartia pseudocamellia (Japanese stewartia)	6
Syringa vulgaris (common lilac)	3b
Ulmus americana (American elm)	2
Viburnum burkwoodii (Burkwood viburnum)	5b
Zelkova serrata (Japanese zelkova)	5b

USDA Plant Hardiness Zone Map



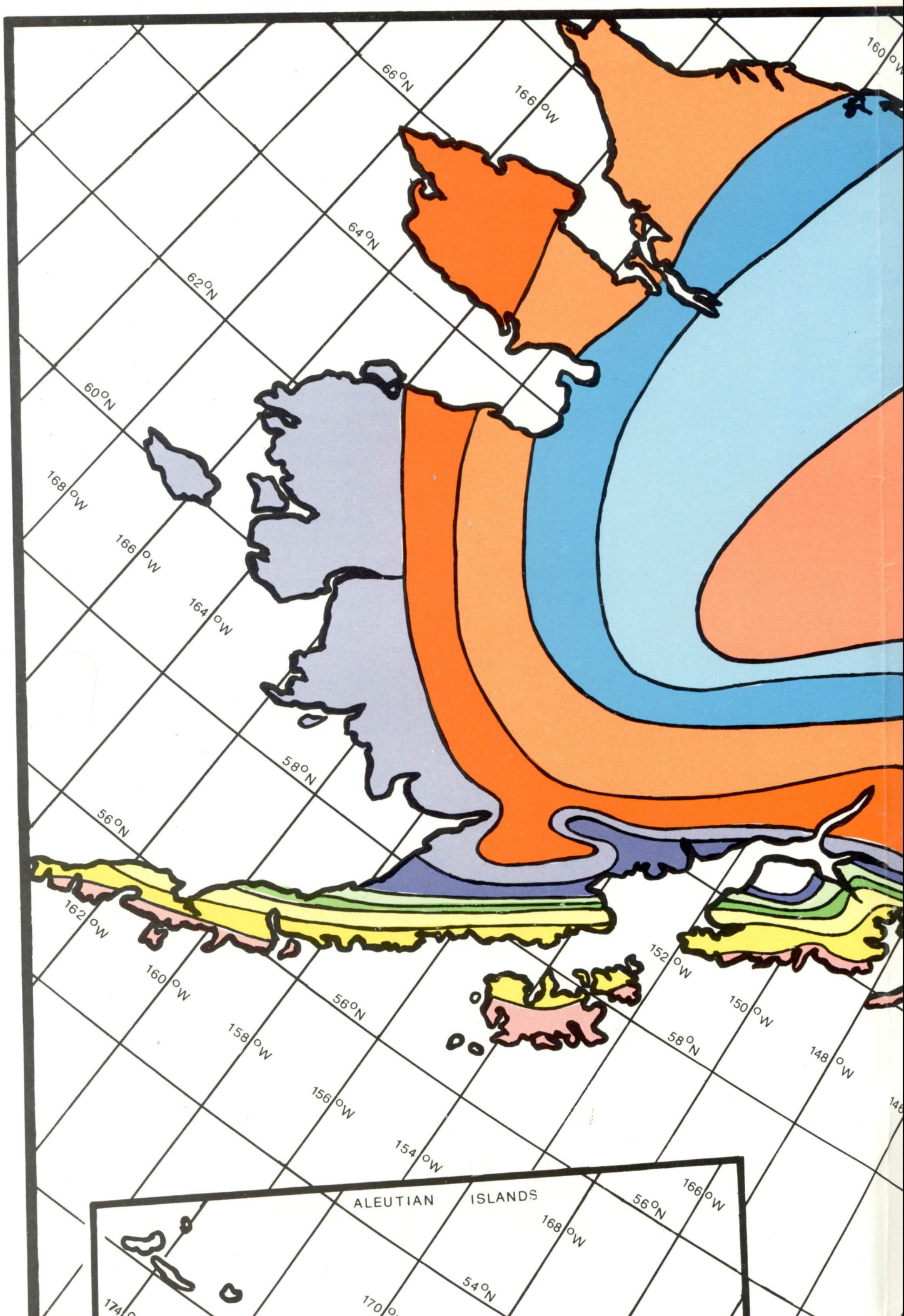
The zones of plant hardiness in the United States—This map is an adaptation of the color map on the reverse side. It lacks many fine details of the color map but may be useful for small-scale reproduction in books, magazines, and nursery catalogs.

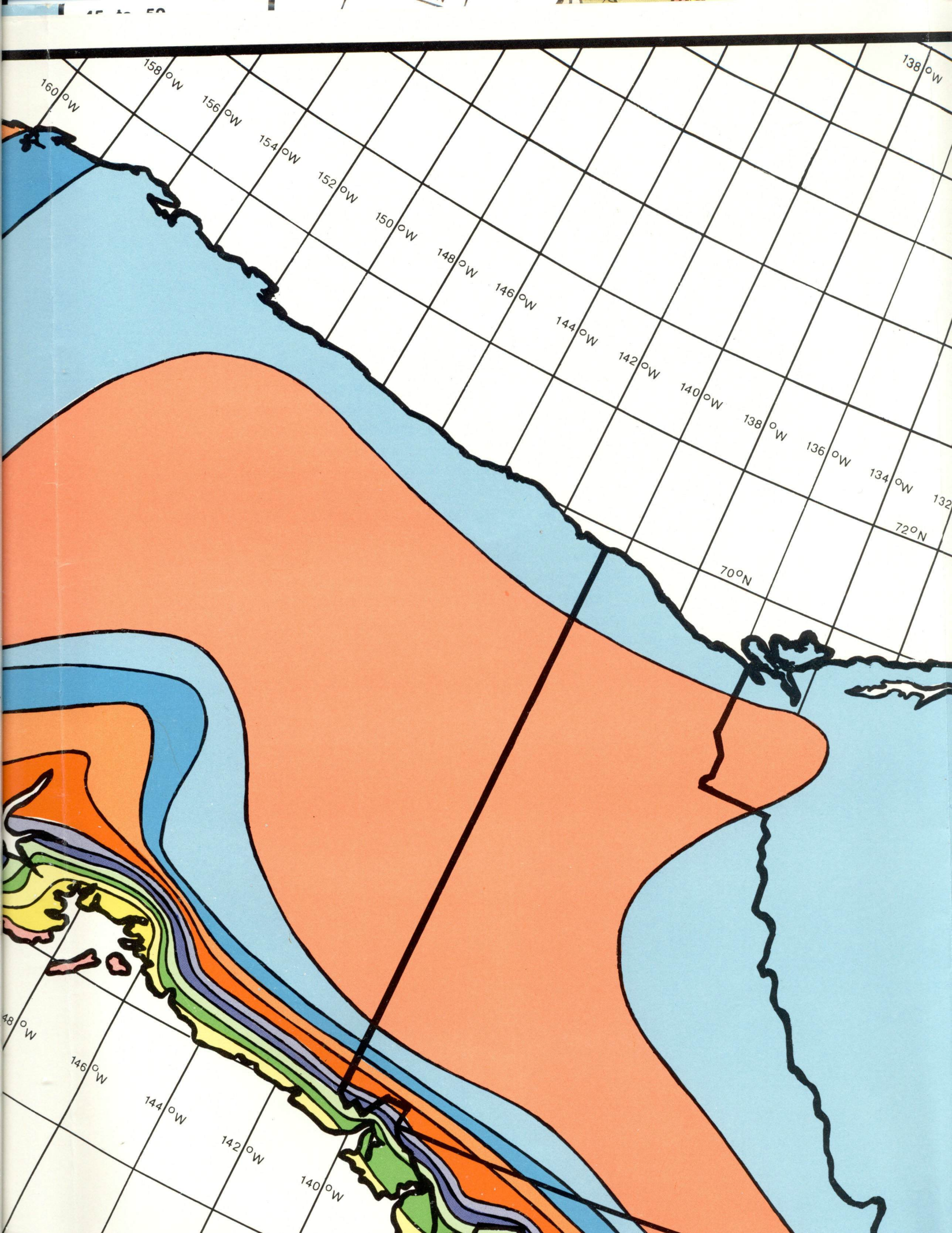


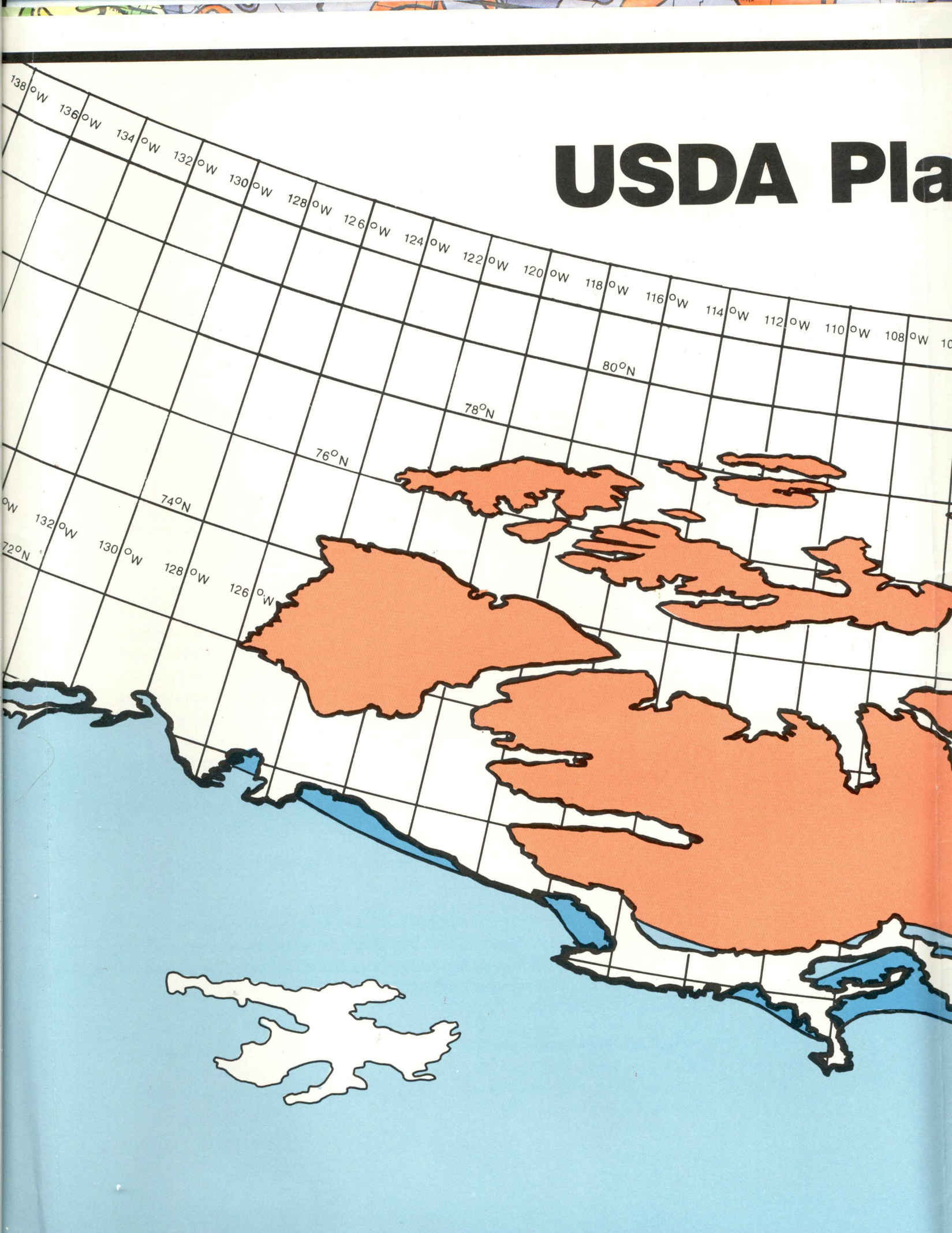


RANGE OF AVERAGE ANNUAL MINIMUM TEMPERATURES FOR EACH ZONE

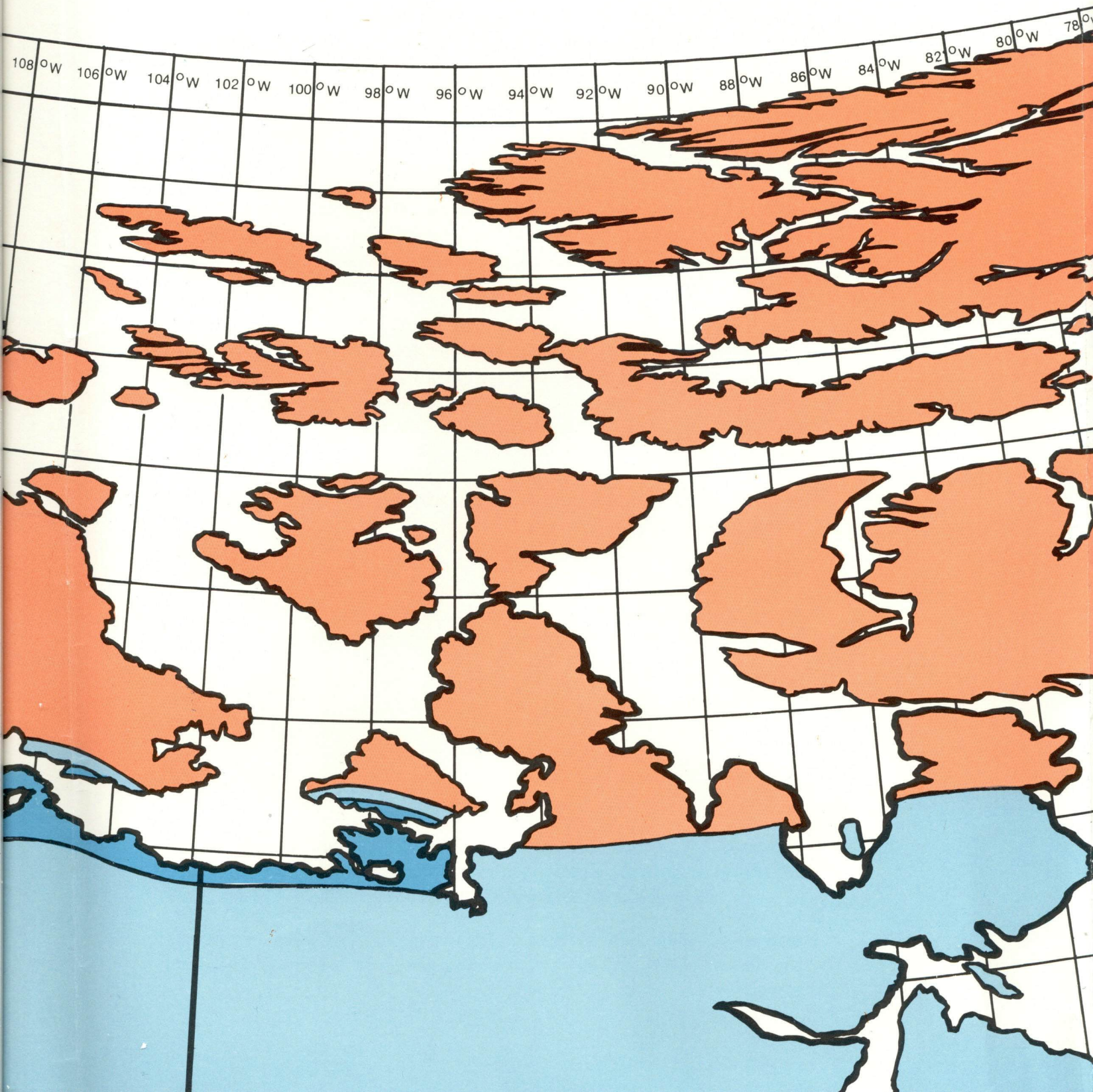
ZONE 1	BELOW -50° F	
ZONE 2	-50° TO -40°	
ZONE 3	-40° TO -30°	
ZONE 4	-30° TO -20°	
ZONE 5	-20° TO -10°	
ZONE 6	-10° TO 0°	
ZONE 7	0° TO 10°	
ZONE 8	10° TO 20°	
ZONE 9	20° TO 30°	
ZONE 10	30° TO 40°	
ZONE 11	ABOVE 40°	


66°N
166°W
64°N
62°N
60°N
168°W
166°W
164°W
58°N
56°N
162°W
160°W
56°N
158°W
156°W
154°W
152°W
150°W
58°N
148°W
ALEUTIAN ISLANDS
166°W
56°N
168°W
54°N

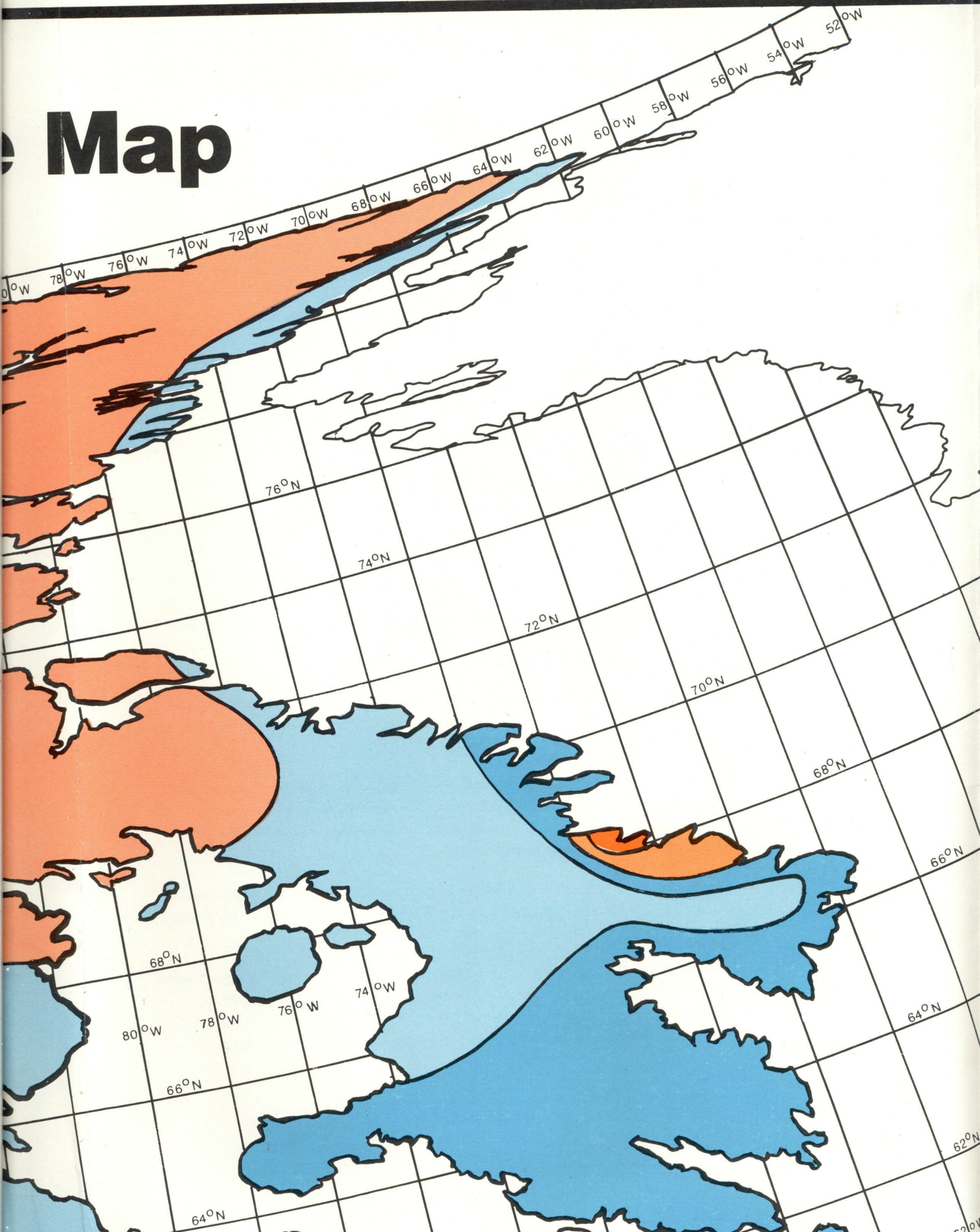

160°W
158°W
156°W
154°W
152°W
150°W
148°W
146°W
144°W
142°W
140°W
138°W
136°W
134°W
72°N
70°N
148°W
146°W
144°W
142°W
140°W

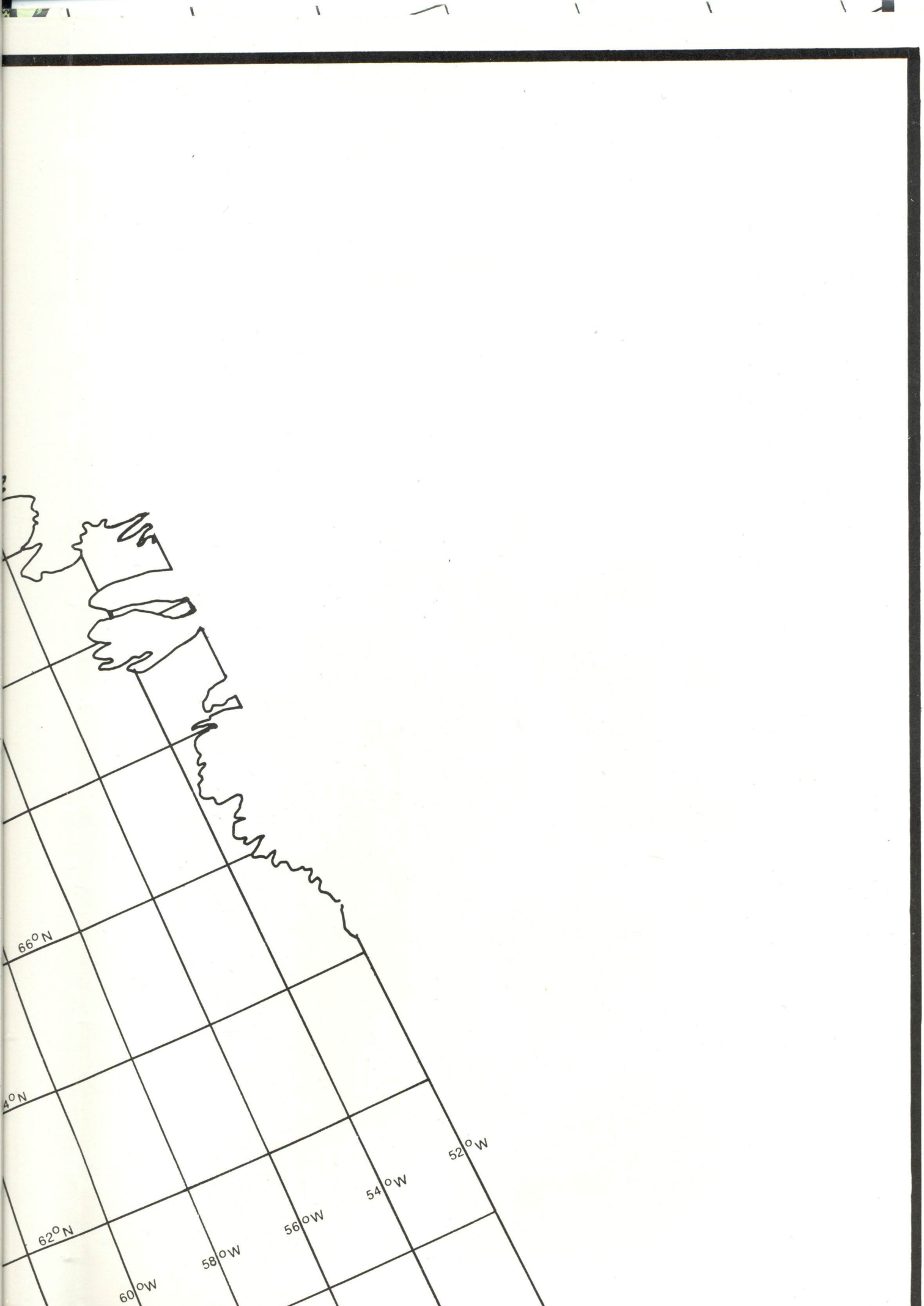

USDA Pla
138°W
136°W
134°W
132°W
130°W
128°W
126°W
124°W
122°W
120°W
118°W
116°W
114°W
112°W
110°W
108°W
80°N
78°N
76°N
74°N
72°N
132°W
130°W
128°W
126°W

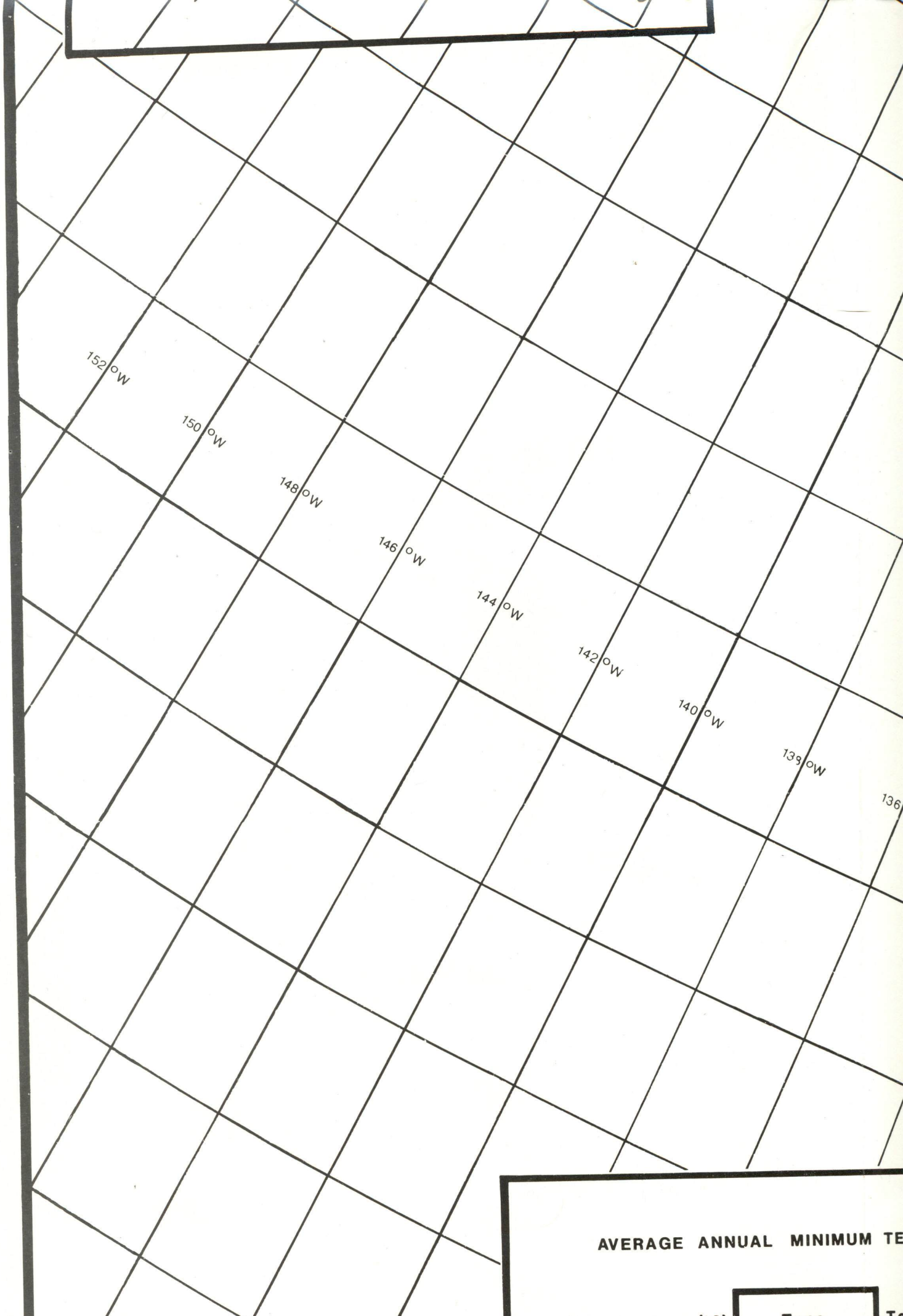
Plant Hardiness Zone M

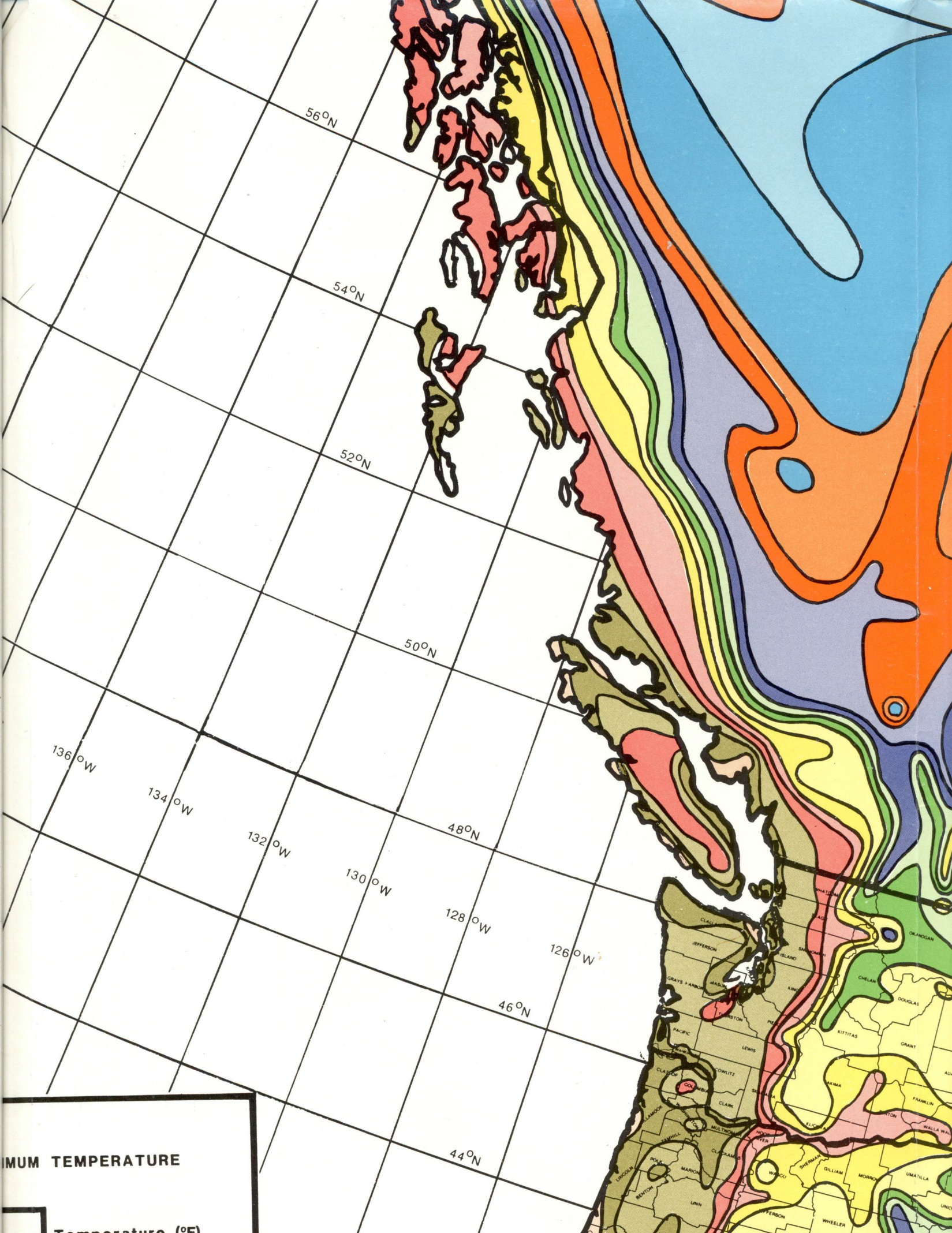


e Map


52°W
54°W
56°W
58°W
60°W
62°W
64°W
66°W
68°W
70°W
72°W
74°W
76°W
78°W
76°N
74°N
72°N
70°N
68°N
66°N
64°N
62°N
80°W
78°W
76°W
74°W
68°N
66°N
64°N

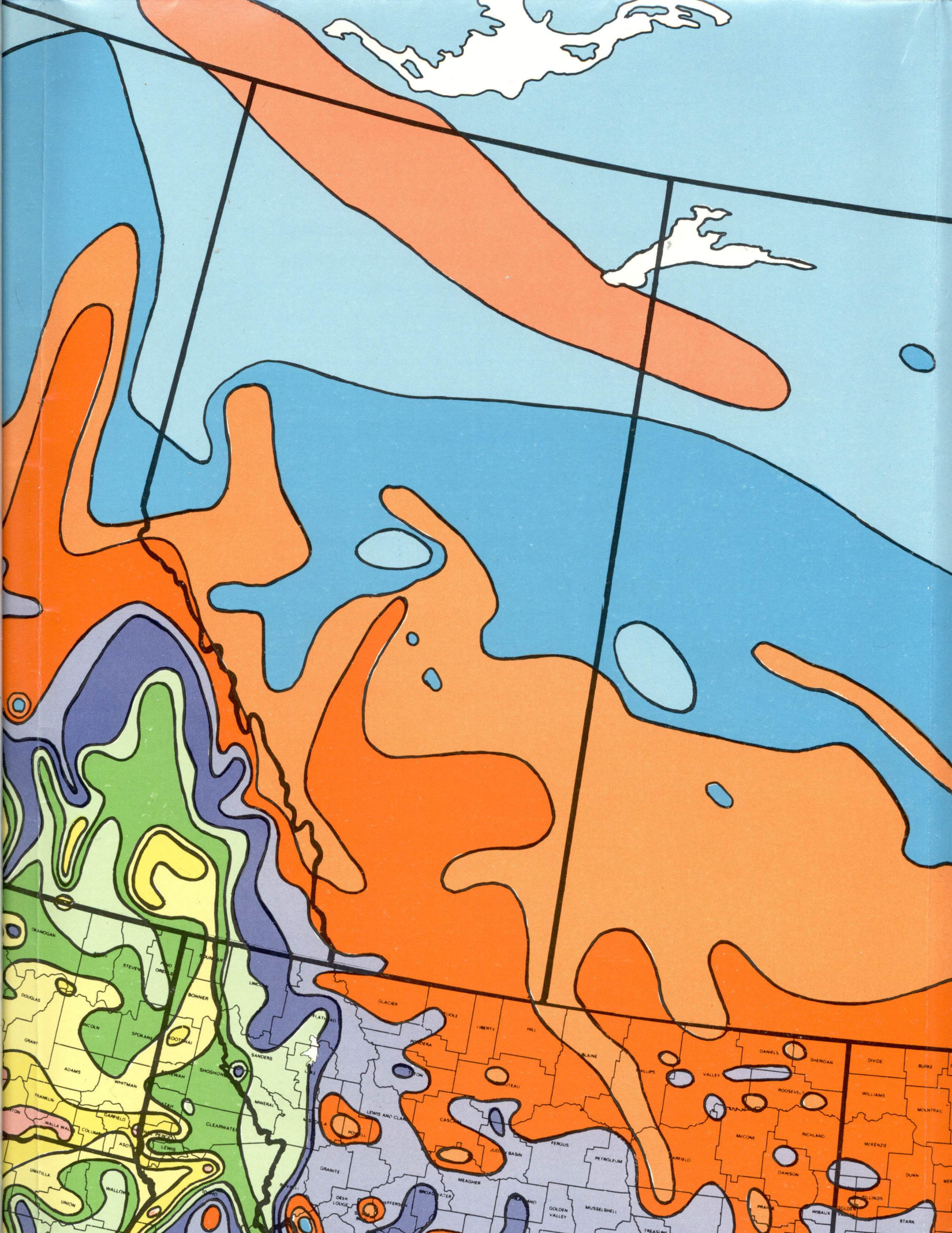

66°N
62°N
60°W
58°W
56°W
54°W
52°W

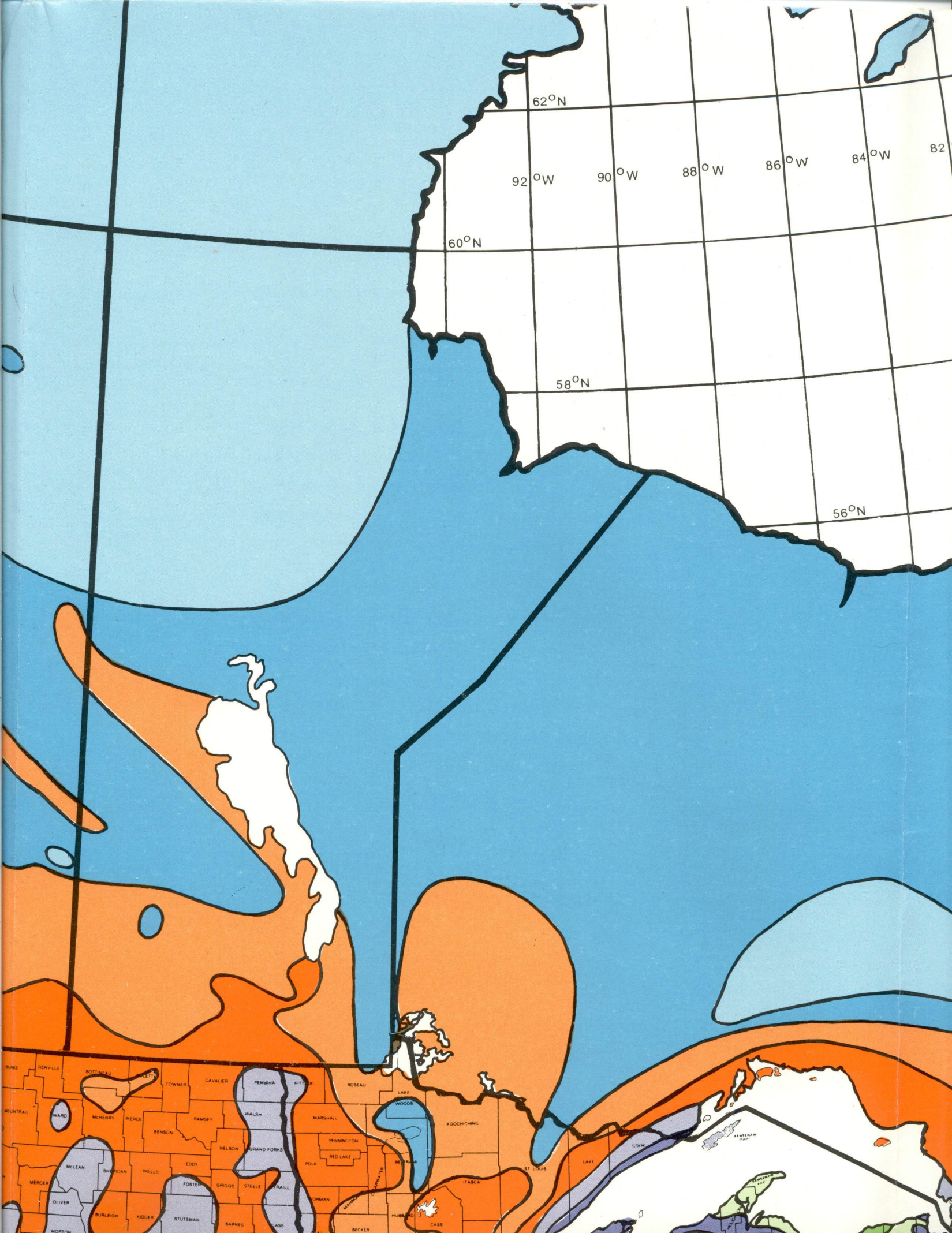

152°W
150°W
148°W
146°W
144°W
142°W
140°W
139°W
AVERAGE ANNUAL MINIMUM TE

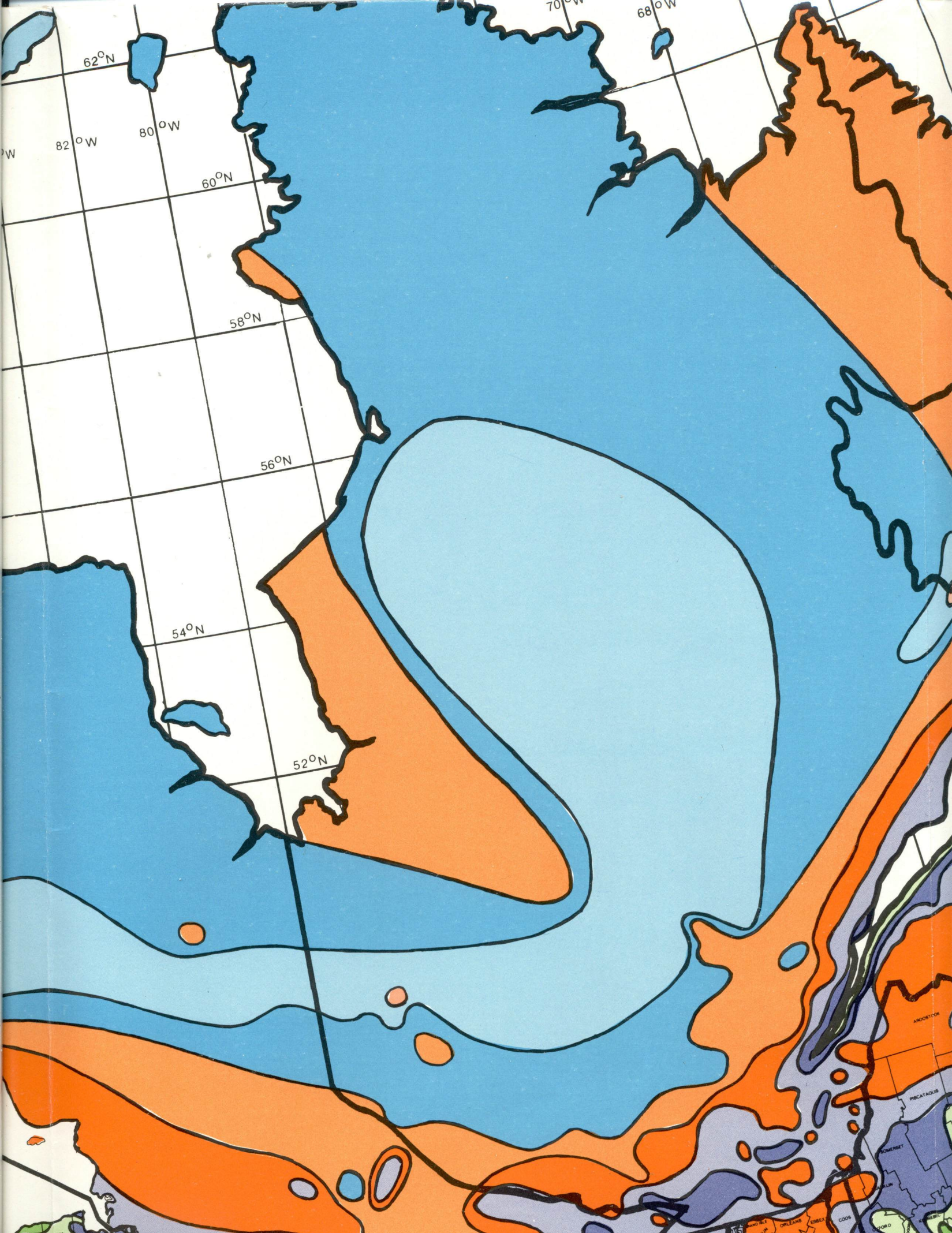


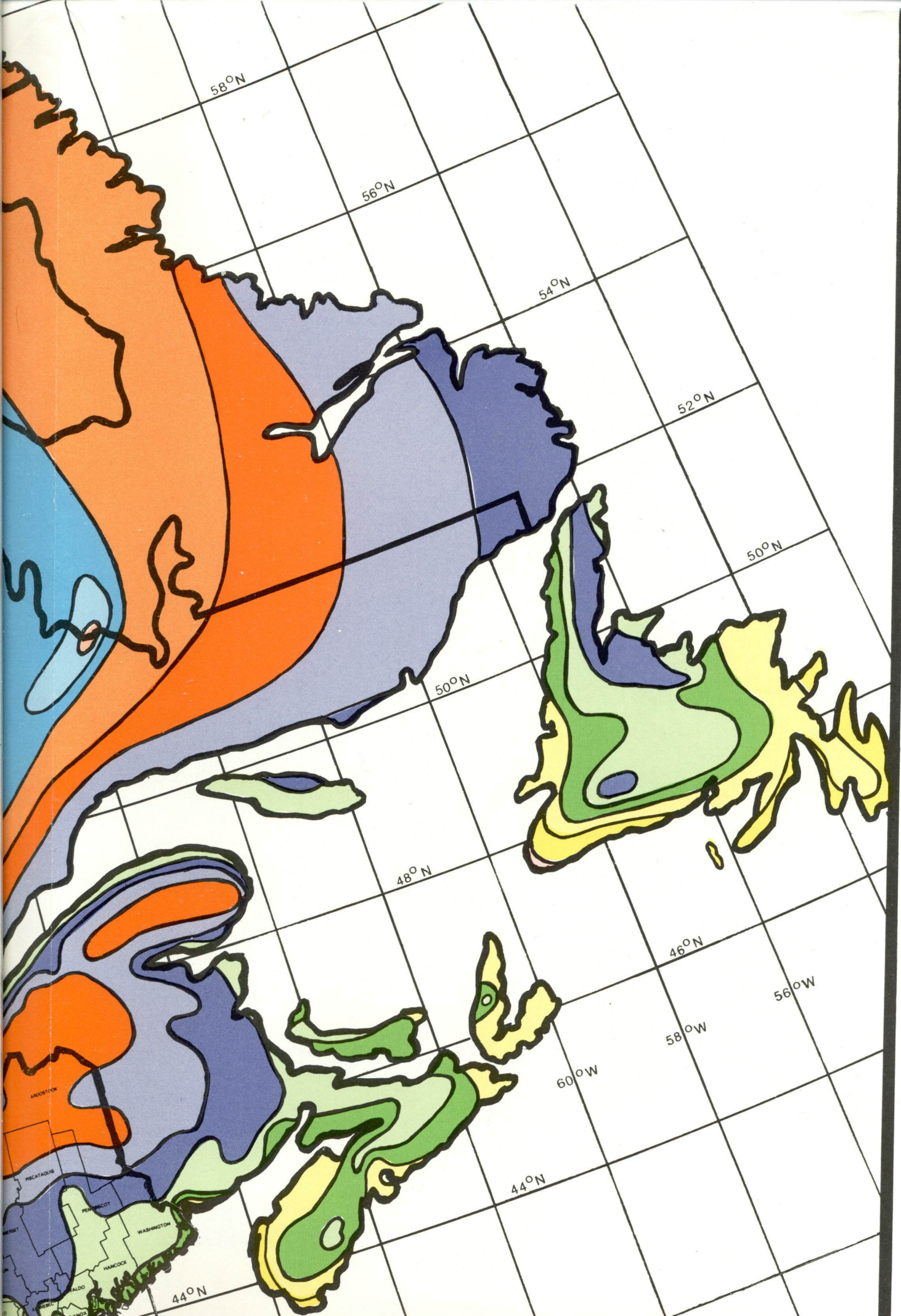
IMUM TEMPERATURE

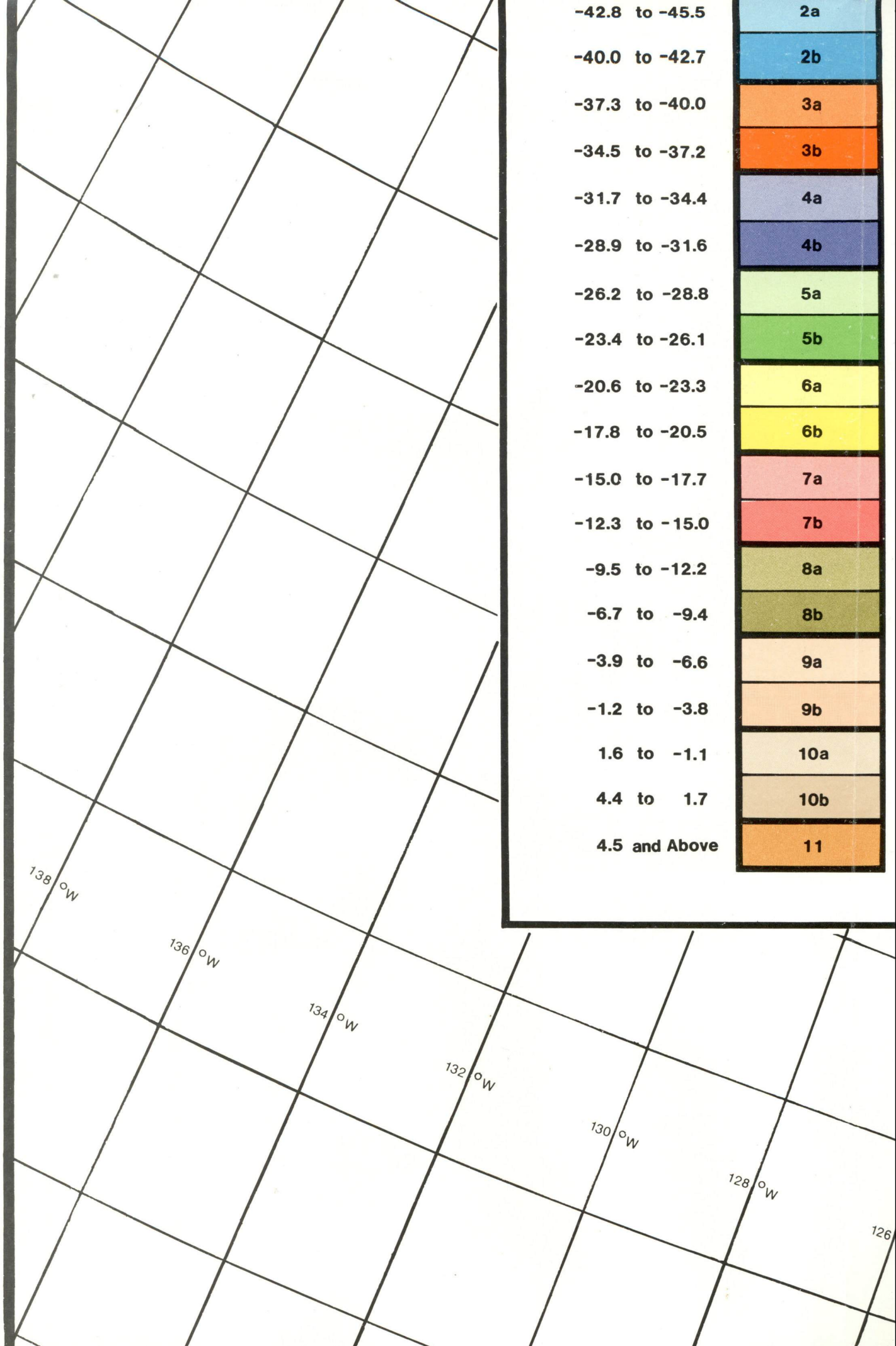
Temperature (°F)

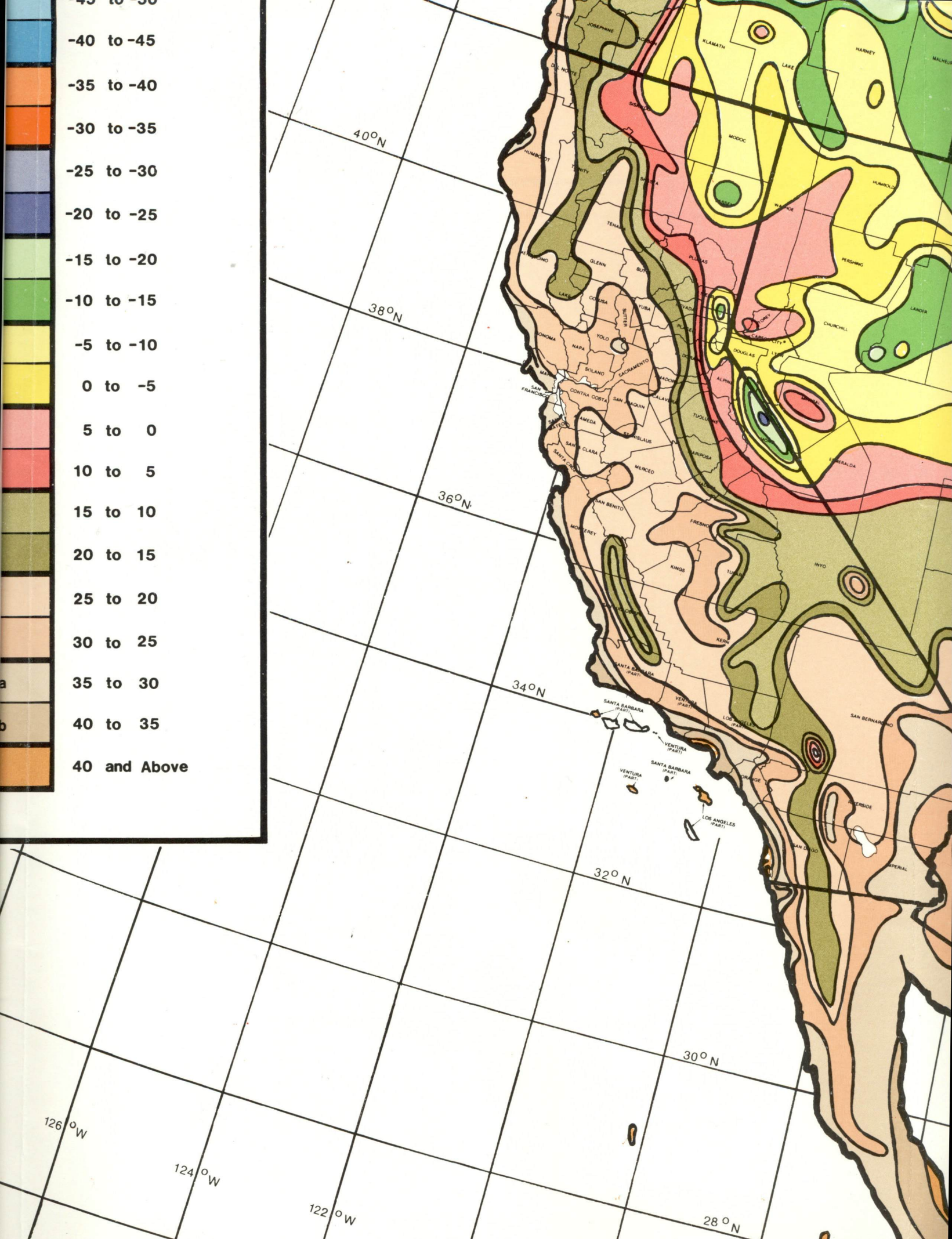

OKANOGAN
STEVENS
PEND OREILLE
DOUGLAS
BONNER
LINCOLN
SPOKANE
KOOTENAI
GRANT
ADAMS
LEWIS
SHOSHONE
WHITMAN
FRANKLIN
BENEWAH
LATAH
GARFIELD
WALLA WALLA
COLUMBIA
NEZ PERCE
ASOTIN
CLEARWATER
LEWIS
UMATILLA
WALLOWA
UNION
IDAHO
GLACIER
TOOLE
LIBERTY
HILL
BLAINE
PHILLIPS
VALLEY
DANIELS
SHERIDAN
DIVIDE
BURKE
ROOSEVELT
WILLIAMS
MCKENZIE
RICHLAND
DAWSON
DUNN
GARFIELD
FERGUS
PETROLEUM
GRANITE
MEAGHER
GOLDEN VALLEY
MUSSELSHELL
PRAIRIE
WIBAUX
STARK
TREASURE

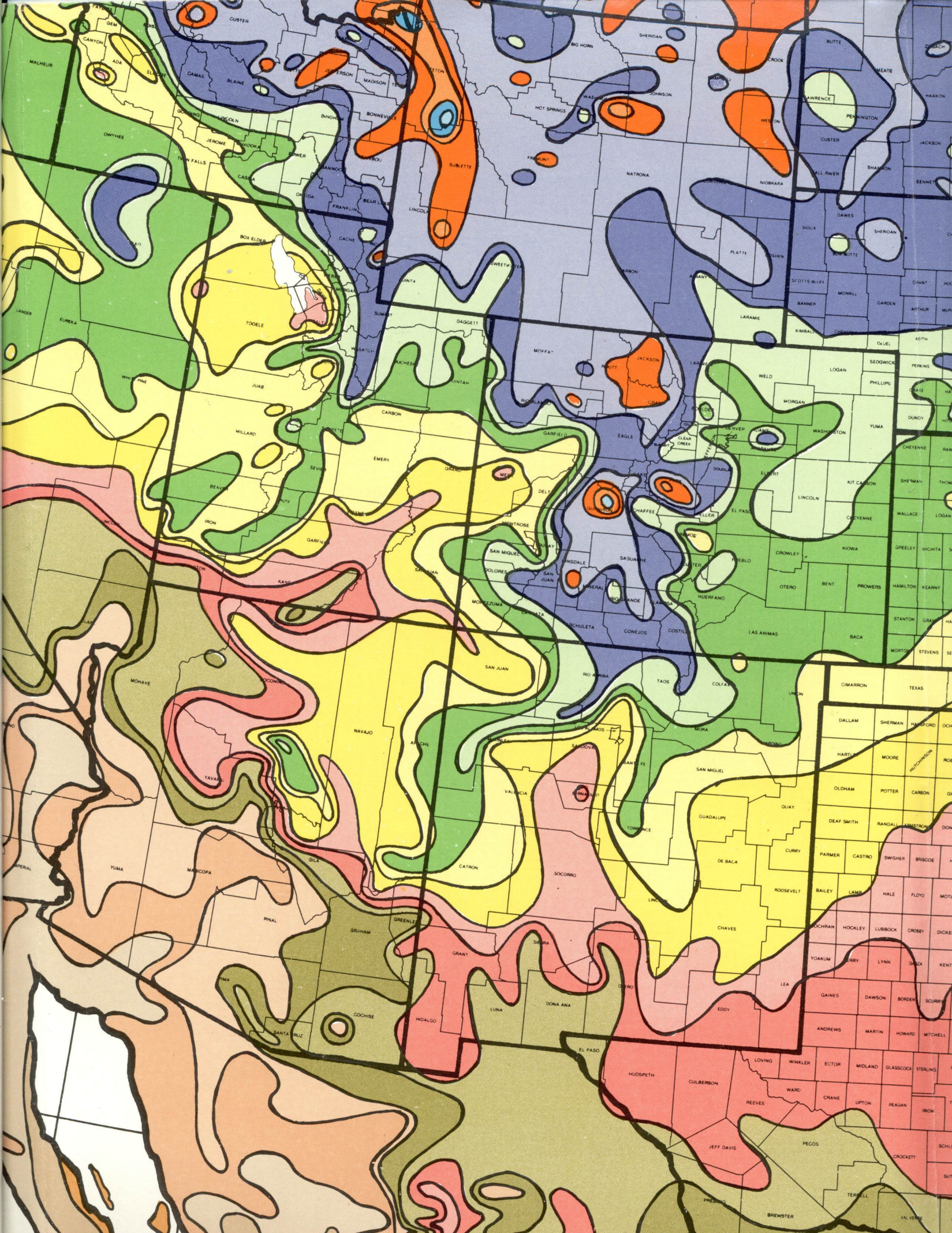

62°N
92°W
90°W
88°W
86°W
84°W
82
60°N
58°N
56°N
BURKE
RENVILLE
BOTTINEAU
TOWNER
CAVALIER
PEMBINA
ROSEAU
MOUNTRAIL
WARD
MCHENRY
PIERCE
RAMSEY
WALSH
LAKE OF THE WOODS
MARSHALL
KOOCHICHING
BENSON
NELSON
GRAND FORKS
PENNINGTON
RED LAKE
POLK
MCLEAN
SHERIDAN
WELLS
EDDY
FOSTER
GRIGGS
STEELE
TRAILL
NORMAN
MERCER
OLIVER
BURLEIGH
KIDDER
STUTSMAN
BARNES
CASS
HUBBARD
BECKER
ITASCA
ST. LOUIS
LAKE
COOK


62°N
60°N
58°N
56°N
54°N
52°N
82°W
80°W
70°W
68°W
ARCOSTOOK
PISCATAQUIS
SOMERSET
PENOBSCOT
HANCOCK
WASHINGTON

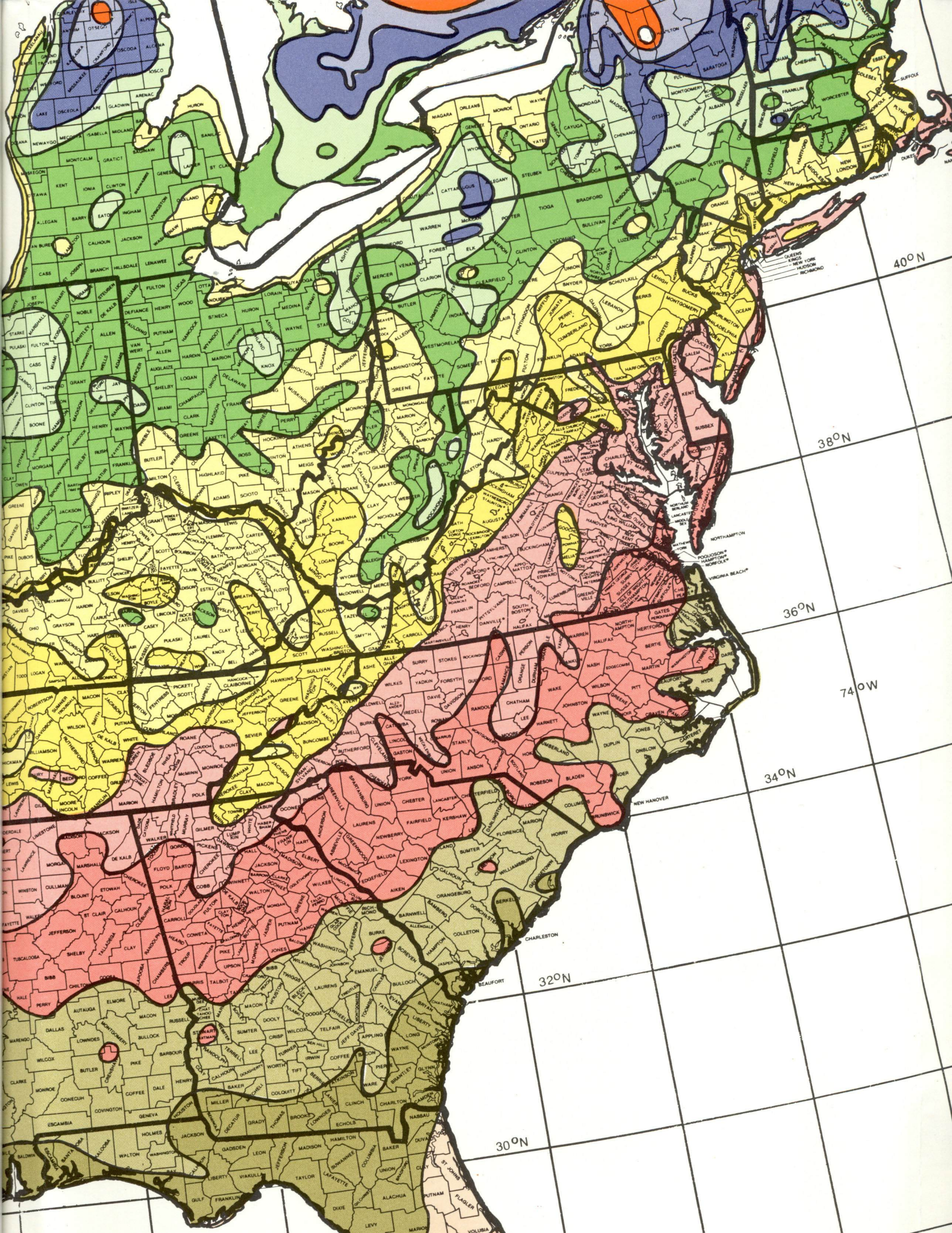

58°N
56°N
54°N
52°N
50°N
50°N
48°N
46°N
56°W
58°W
60°W
44°N
44°N
ARCOSTOOK
PISCATAQUIS
PENOBSCOT
WASHINGTON
HANCOCK
WALDO

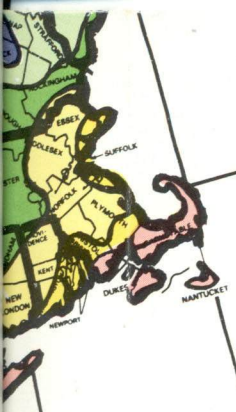

-42.8 to -45.5
2a
-40.0 to -42.7
2b
-37.3 to -40.0
3a
-34.5 to -37.2
3b
-31.7 to -34.4
4a
-28.9 to -31.6
4b
-26.2 to -28.8
5a
-23.4 to -26.1
5b
-20.6 to -23.3
6a
-17.8 to -20.5
6b
-15.0 to -17.7
7a
-12.3 to -15.0
7b
-9.5 to -12.2
8a
-6.7 to -9.4
8b
-3.9 to -6.6
9a
-1.2 to -3.8
9b
1.6 to -1.1
10a
4.4 to 1.7
10b
4.5 and Above
11
138 °W
136 °W
134 °W
132 °W
130 °W
128 °W
126


-40 to -45
-35 to -40
-30 to -35
-25 to -30
-20 to -25
-15 to -20
-10 to -15
-5 to -10
0 to -5
5 to 0
10 to 5
15 to 10
20 to 15
25 to 20
30 to 25
35 to 30
40 to 35
40 and Above
40°N
38°N
36°N
34°N
32°N
30°N
28°N
126°W
124°W
122°W
KLAMATH
HARNEY
MODOC
LAKE
PERSHING
LANDER
CHURCHILL
DOUGLAS
ESMERALDA
INYO
KERN
SAN BERNARDINO
RIVERSIDE
IMPERIAL
SAN DIEGO
ORANGE
SAN FRANCISCO
CONTRA COSTA
ALAMEDA
SAN JOAQUIN
SACRAMENTO
SOLANO
NAPA
SONOMA
YOLO
SUTTER
YUBA
GLENN
COLUSA
LAKE
MENDOCINO
HUMBOLDT
TRINITY
SHASTA
PLUMAS
TEHAMA
BUTTE
LASSEN
MODOC
SISKIYOU
MARIPOSA
MERCED
STANISLAUS
TUOLUMNE
CALAVERAS
AMADOR
EL DORADO
ALPINE
MONO
FRESNO
KINGS
TULARE
SAN BENITO
MONTEREY
SANTA CLARA
SANTA CRUZ
SAN MATEO
SANTA BARBARA (PART)
VENTURA (PART)
LOS ANGELES (PART)


MALHEUR
CANYON
ADA
ELMORE
CAMAS
BLAINE
CUSTER
LEMHI
JEFFERSON
MADISON
TETON
BIG HORN
SHERIDAN
BUTTE
MEADE
HARDING
OWYHEE
JEROME
LINCOLN
BINGHAM
BONNEVILLE
HOT SPRINGS
WASHAKIE
JOHNSON
CROOK
LAWRENCE
PENNINGTON
TWIN FALLS
CASSIA
POWER
ONEIDA
FRANKLIN
BEAR LAKE
FREMONT
SUBLETTE
NATRONA
WESTON
CUSTER
JACKSON
NIOBRARA
FALL RIVER
SHANNON
BENNETT
BOX ELDER
CACHE
LINCOLN
DAWES
SIOUX
SHERIDAN
BOX BUTTE
PLATTE
GOSHEN
SWEETWATER
CARBON
ALBANY
SCOTTS BLUFF
MORRILL
GRANT
BANNER
GARDEN
ARTHUR
LARAMIE
KIMBALL
CHEYENNE
DEUEL
KEITH
LANDER
EUREKA
TOOELE
SUMMIT
DAGGETT
WASATCH
DUCHESNE
UINTAH
MOFFAT
JACKSON
JUAB
WHITE PINE
CARBON
MILLARD
GARFIELD
EAGLE
GRAND
MESA
CLEAR CREEK
DENVER
ADAMS
ARAPAHOE
DOUGLAS
ELBERT
LOGAN
WELD
SEDGWICK
PHILLIPS
PERKINS
MORGAN
WASHINGTON
YUMA
DUNDY
CHEYENNE
KIT CARSON
LINCOLN
SHERMAN
THOMAS
BEAVER
IRON
EMERY
SEVIER
DELTA
CHAFFEE
EL PASO
TELLER
PUEBLO
CROWLEY
KIOWA
WALLACE
LOGAN
GREELEY
WICHITA
GARFIELD
KANE
MONTROSE
SAN MIGUEL
OURAY
DOLORES
SAN JUAN
HINSDALE
SAGUACHE
CUSTER
OTERO
BENT
PROWERS
HAMILTON
KEARNY
MONTEZUMA
LA PLATA
ARCHULETA
CONEJOS
COSTILLA
HUERFANO
LAS ANIMAS
BACA
STANTON
GRANT
MORTON
STEVENS
SAN JUAN
MOHAVE
COCONINO
RIO ARRIBA
TAOS
COLFAX
UNION
CIMARRON
TEXAS
DALLAM
SHERMAN
HANSFORD
NAVAJO
APACHE
MORA
SAN MIGUEL
HARTLEY
MOORE
HUTCHINSON
SANTA FE
SANDOVAL
OLDHAM
POTTER
CARSON
VALENCIA
TORRANCE
QUAY
GUADALUPE
DEAF SMITH
RANDALL
ARMSTRONG
YAVAPAI
CURRY
PARMER
CASTRO
SWISHER
BRISCOE
IMPERIAL
YUMA
MARICOPA
GILA
CATRON
SOCORRO
DE BACA
ROOSEVELT
BAILEY
LAMB
HALE
FLOYD
PINAL
GREENLEE
GRAHAM
SIERRA
GRANT
LINCOLN
CHAVES
COCHRAN
HOCKLEY
LUBBOCK
CROSBY
YOAKUM
TERRY
LYNN
GARZA
PIMA
COCHISE
HIDALGO
LUNA
DONA ANA
OTERO
LEA
EDDY
GAINES
DAWSON
BORDEN
SCURRY
ANDREWS
MARTIN
HOWARD
MITCHELL
SANTA CRUZ
EL PASO
LOVING
WINKLER
ECTOR
MIDLAND
GLASSCOCK
STERLING
HUDSPETH
CULBERSON
WARD
CRANE
UPTON
REAGAN
IRION
REEVES
JEFF DAVIS
PECOS
CROCKETT
TERRELL
PRESIDIO
BREWSTER
VAL VERDE




40°N
38°N
36°N
34°N
32°N
30°N
74°W
NEW HANOVER
CHARLESTON
BEAUFORT
VIRGINIA BEACH*
NORTHAMPTON
QUEENS
KINGS
NEW YORK
HUDSON
RICHMOND



42°N

40°N

N

74°W

72°W

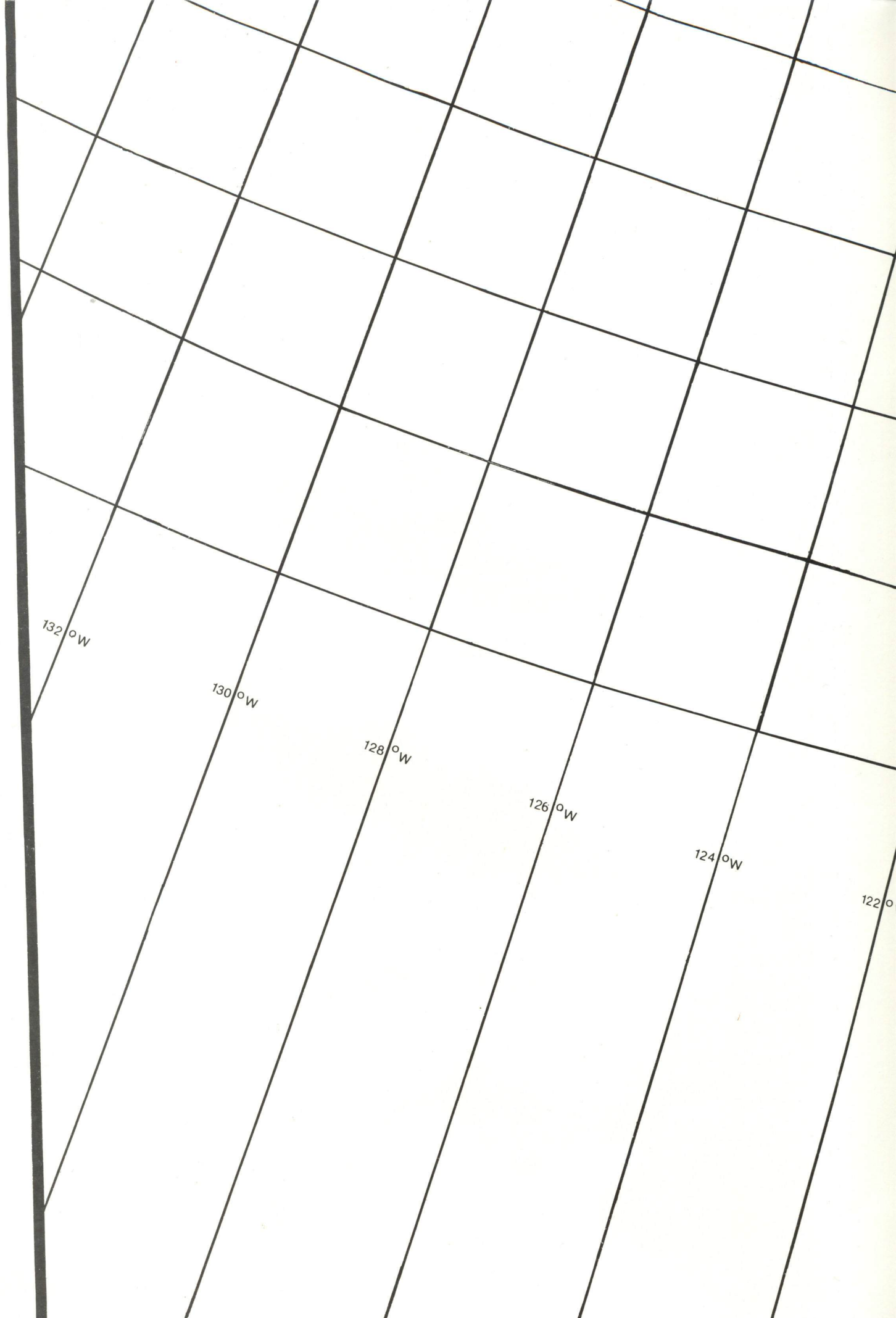
70°W

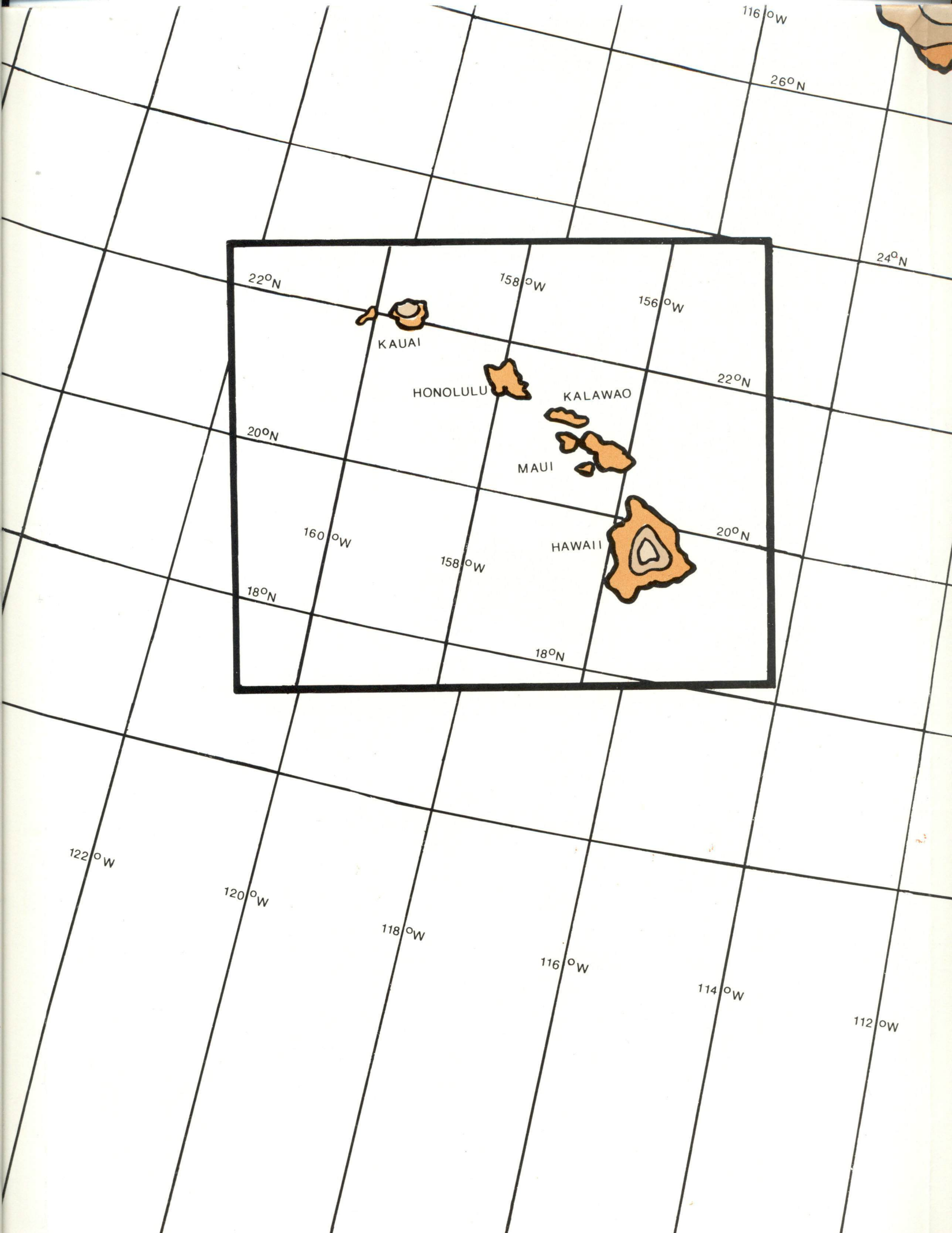
68°W

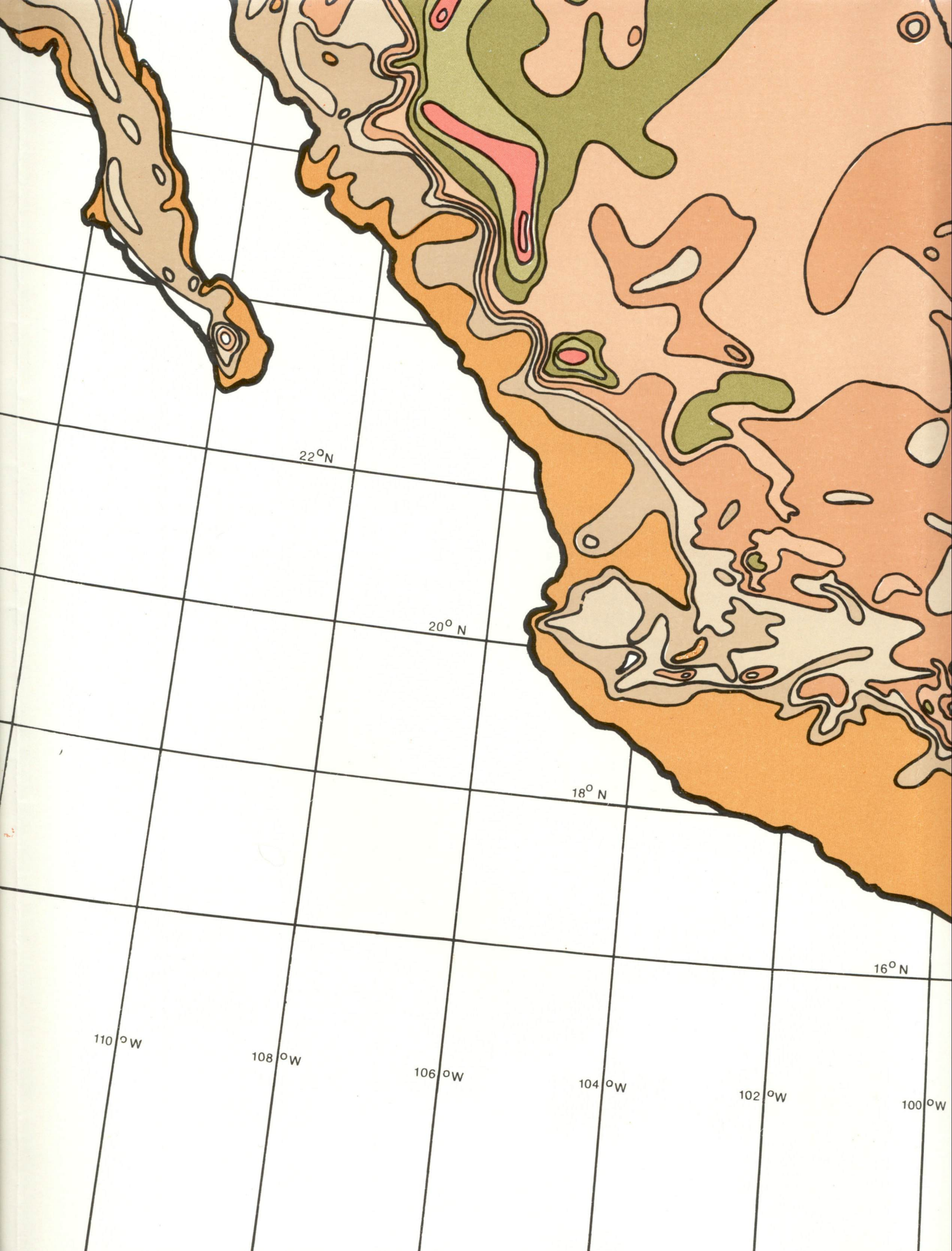
66°W

64°W

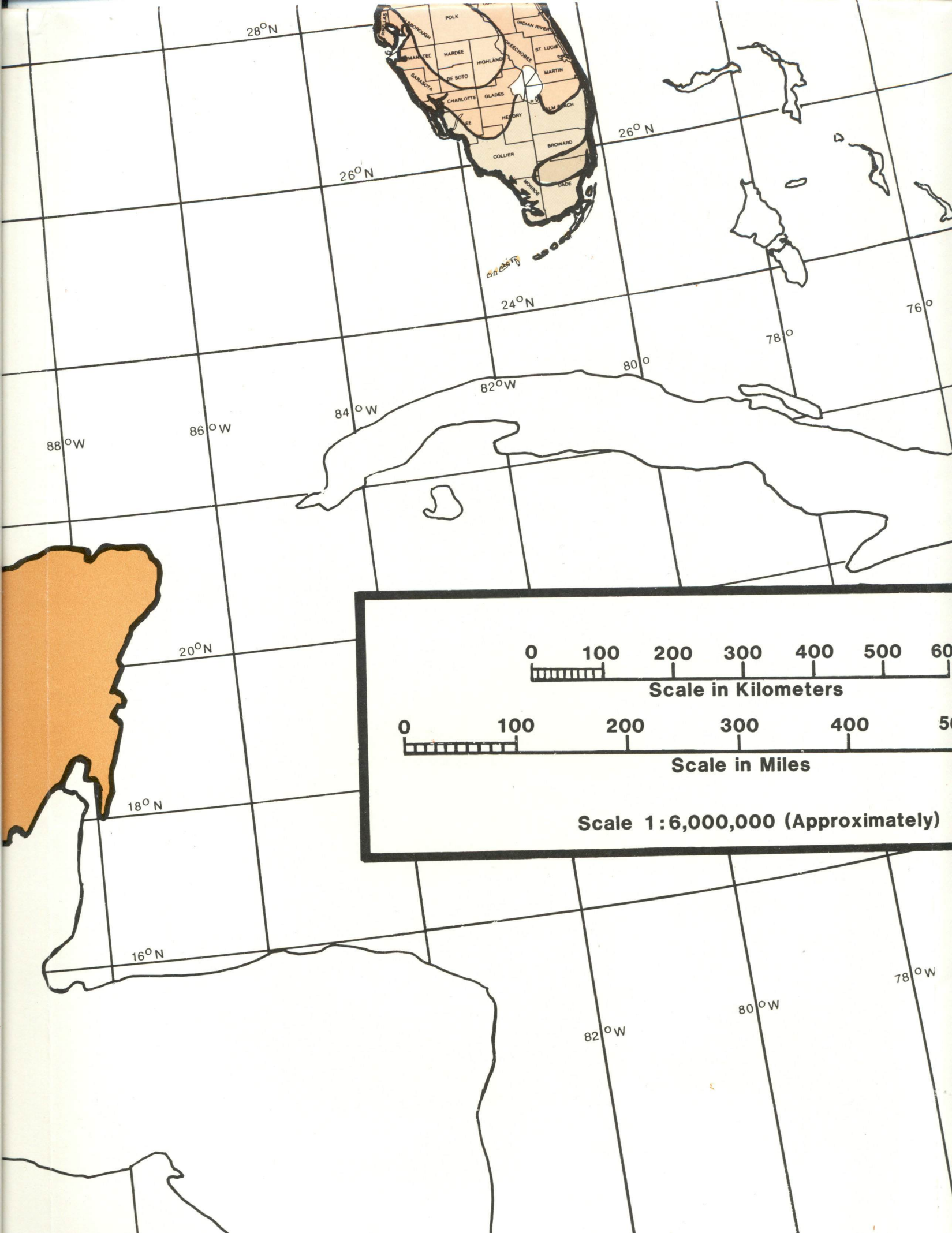
62°W

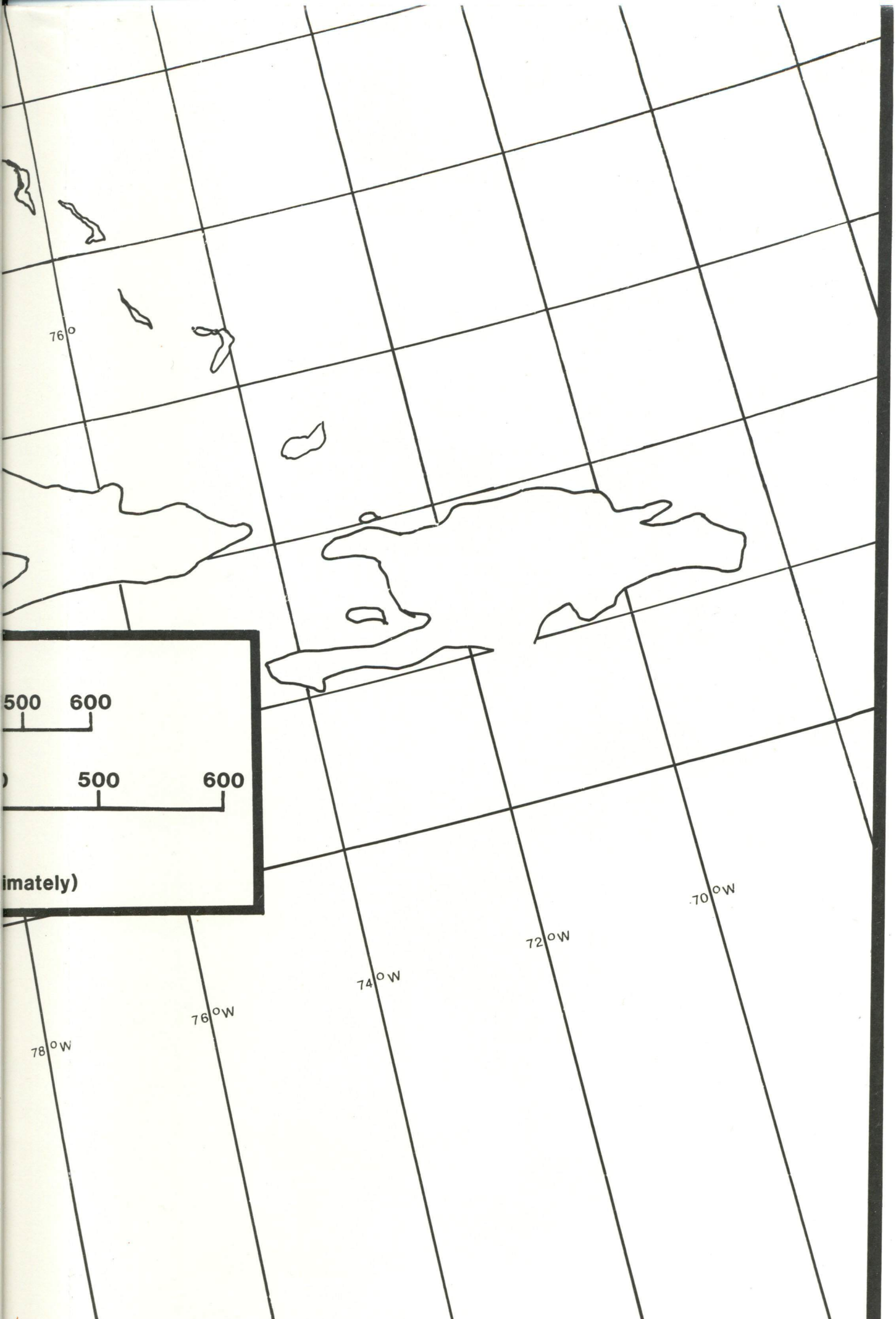

132°W
130°W
128°W
126°W
124°W
122°


116°W
26°N
24°N
22°N
158°W
156°W
KAUAI
HONOLULU
KALAWAO
22°N
20°N
MAUI
160°W
158°W
HAWAII
20°N
18°N
18°N
122°W
120°W
118°W
116°W
114°W
112°W


22°N
20° N
18° N
16° N
110 °W
108 °W
106 °W
104 °W
102 °W
100 °W


MAVERICK
ZAVALA
FRIO
ATASCOSA
KARNES
JACKSON
VICTORIA
MATAGORDA
GOLIAD
DIMMIT
LA SALLE
BEE
REFUGIO
CALHOUN
SAN PATRICIO
ARANSAS
WEBB
DUVAL
JIM WELLS
NUECES
KLEBERG
JIM HOGG
BROOKS
KENEDY
STARR
HIDALGO
WILLACY
CAMERON
28°N
26°N
24°N
22°N
20°N
20°N
6°N
100°W
98°W
96°W
94°W
96°W
94°W
92°W
90°W
88°


28°N
26°N
24°N
20°N
18°N
16°N
88°W
86°W
84°W
82°W
80°
78°
76°
POLK
INDIAN RIVER
HARDEE
HIGHLANDS
OKEECHOBEE
ST LUCIE
MANATEE
MARTIN
DE SOTO
SARASOTA
CHARLOTTE
GLADES
HENDRY
BROWARD
COLLIER
DADE
MONROE
0 100 200 300 400 500 60
Scale in Kilometers
0 100 200 300 400 5
Scale in Miles
Scale 1:6,000,000 (Approximately)
78°W
80°W
82°W


500 600
500 600
imately)
76°
78°W
76°W
74°W
72°W
70°W