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General Circulation Model Output for Forest Climate Change Research and Applications

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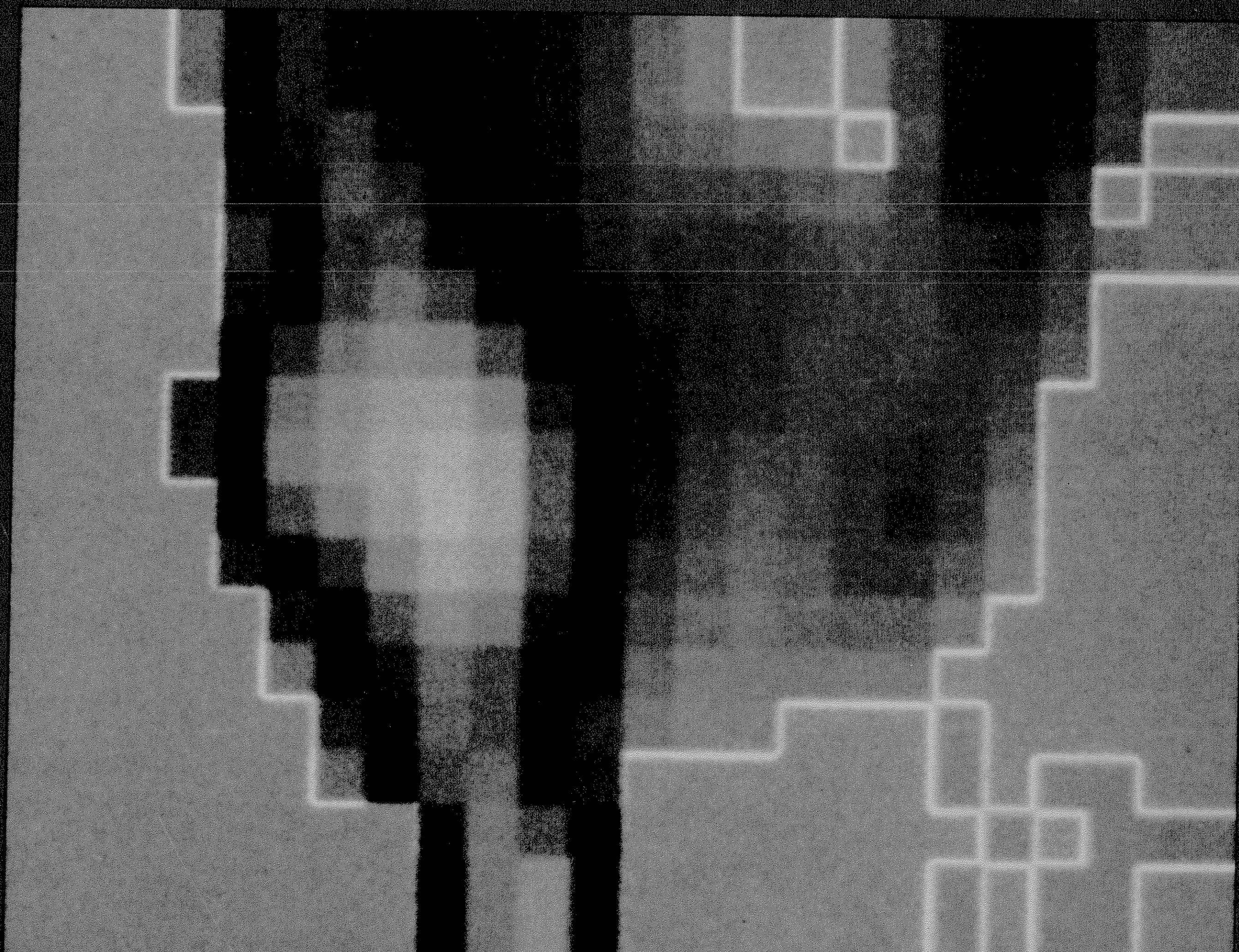

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Contents

Special Abbreviations
used in this publication

GCM	General Circulation Model
GFDL	Geophysical Fluid Dynamics Laboratory
GISS	Goddard Institute for Space Studies
NCAR	National Center for Atmospheric Research
OSU	Oregon State University
SGCP	Southern Global Change Program
UKMO	United Kingdom Meteorological Office

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ABSTRACT

General Circulation Models (GCMs) have projected a global warming between 3 and 8 °F over the next 50 to 100 years. The Forest Service's Southern Global Change Program (SGCP) has proposed to use GCM output as input to forest assessment models to estimate the potential impacts of climate changes on forests of the Southern and Southeastern United States. This report reviews technical aspects and summarizes output from four climate model projections. Recommendations concerning the use of these projections in forest impact assessments are made. Some primary sources of intermodel variability include model version (age), numerical solution technique, time and space resolution, and parameterization schemes. Model version generally impacts the time and space resolution and choice of parameterization schemes. Numerical solution technique impacts spatial variability, computational efficiency, and amount of model tuning required. Time and space resolution impacts the choice and detail of parameterization of the land surface and processes associated with the movement of energy and moisture. Parameterization schemes and associated feedbacks impact nearly every aspect of the climate projection. Magnitude of change varies widely, but the four GCMs examined here all project warmer air temperatures and higher humidities throughout the year; decreasing cloud cover during autumn, winter, and spring; and increasing summertime precipitation for the Southern and Southeastern United States. Although some consensus among models over large geographic regions can be identified, there is, as yet, no established means of determining the confidence that can be placed in these outlooks. GCM output should be combined with historical case studies, empirical, and semiempirically constructed climate scenarios to provide a range of possible climatological futures.

Keywords: Southern Global Change Program, humidity, cloud cover, precipitation, temperature.

Introduction

Sophisticated climate models have projected a global warming of between 3 and 8 °F over a period of 50 to 100 years. Changes in the global water cycle are predicted as well. Some regions could become wetter, while others could become drier. Even seasonal patterns of precipitation could change. Although historical and paleoclimatic records provide valid examples of a warmer earth for some geographic locations, other regions could experience conditions unlike those of any period in the Earth's history (COHMAP 1988; Smith 1990). General Circulation Models (GCMs) currently represent one of the best tools available for the estimation of alternative climate conditions.

This report was developed in support of the USDA Forest Service's Southern Global Change Program (SGCP). Under the SGCP, forest scientists have been directed to develop a range of forest and forest industry models for the Southern United States that are responsive to climate conditions. Although outputs from several GCMs are available, pertinent information needed for their use by such models was found to be scattered throughout the climatological, meteorological, forestry, and ecological literature. Without this information, it is difficult to draw meaningful management directives from the applications output. For instance, forest production changes modeled along the perimeter of the Gulf of Mexico could be interpreted to suggest the need for major economic or management adjustments. The confidence placed in such projections, however, might be tempered given an understanding of the ability of the climate models to represent coastal surface features and land–ocean interactions. This discussion reviews technical aspects and summarizes climate model output. Recommendations are made concerning the use of these outputs to assess the potential impacts of global warming on forests and forest industry in the Southern United States.

Definitions and Caveats

GCMs are systems of numerical equations solved over finite time steps for a regular three-dimensional grid.

The numerical solution technique may vary, but all models attempt to solve a set of fundamental physical equations representing the conservation of mass, momentum, and energy as well as equations of motion, state, and radiative transfer. Prognostic equations for water vapor and heat energy balances at the surface of the Earth are also included. The source terms in these equations incorporate numerical representations of the physical processes of radiation, turbulent transfers at the ground-atmosphere boundary, cloud formation, condensation or rain, and transport of heat by ocean boundary currents.

A recurrent question from the applications community is, "Which GCM is the best? which one should I use?" Cess and others (1990) and Randall and others (1992) summarize selected characteristics of no less than 19 models or model versions. One common approach is to compare the results produced by a suite of GCMs, but even this must be done carefully. Such studies should not be construed as a "beauty contest" in which one model is in some sense better than any other (Grotch 1988). Comparative performance in the simulation of current and past climate varies from region to region and season to season. If one were to require that a model do well in all comparisons, none would qualify.

Four widely known and well-documented models have been selected for discussion here: the Geophysical Fluid Dynamics Laboratory (GFDL) model (Manabe and Wetherald 1987); the NASA Goddard Institute for Space Studies (GISS) model (Hansen and others 1983); the Oregon State University (OSU) model (Schlesinger and Zhao 1989); and the United Kingdom Meteorological Office (UKMO) model (Wilson and Mitchell 1987). These models do not represent the most advanced versions but have been used to generate the most recent global climate change outputs available to the general applications community. The data used in this summary are housed at the National Center for Atmospheric Research (NCAR) in Boulder, CO. Output of more recent GCM versions may, on occasion, be obtained by contacting each model development organization directly.

Research suggests that differences among GCM projections stem from only a few "problem areas" such as cloud parameterization. Although such elements may dominate comparisons of model output, there are in fact many sources of intermodel variability. The approach taken here is to discuss some of the factors that introduce differences among GCM projections and their implications for applications research. Common GCM characteristics include model version, numerical solution technique, time and space resolution, parameterization scheme, and treatment of the greenhouse gases themselves (table 1).

Model Version

There are a variety of modeling philosophies among the scientists and organizations involved in GCM research and development, but two factors dominate. First, all are extremely concerned about the appropriate interpretation and use of their model results. Consequently, there is hesitancy on the part of these individuals and organizations to release what they consider to be preliminary analyses. Second, the whole science of atmospheric modeling is changing rapidly. As will be discussed throughout this report, new technology and knowledge of environmental processes is constantly being employed to improve GCM performance. The question then arises of not only "which model do I use? but "which version?"

One philosophy is that as knowledge advances, these new theories should be incorporated and released to the scientific community. Thus, a situation arises, illustrated in Cess and others (1990), in which three versions (CCM0, CCM1 and CCM/LLNL) of the same basic model are being used. Although confusing to the applications scientist, this is not model duplication. No two model versions are precisely the same and none can be easily dismissed since there is no agreement within the modeling community as to the form of the "best" GCM.

A second school of thought is illustrated by the GISS modeling group. Table 1 indicates this is a relatively old model run. In the interim, research has continued concerning the implementation of a wide range of modifications. GISS anticipates the release of output from a single, new, and significantly different GCM sometime during 1993.[1] Under this approach, applications research is given an opportunity to develop without constantly trying to keep up with new model releases. The result should be a generation of relatively comparable applications. This modeling dichotomy is not likely to change in the near future, and so it is

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[1]Personal communication. 1992. Cynthia Rosenzweig, Associate Research Scientist, Center for the Study of Habitability, Columbia University, NASA/Goddard Institute for Space Studies, 2880 Broadway, New York 10025.

Table 1—Attributes of four General Circulation Models

Model	GFDL	GISS	OSU	UKMO
Date of output generation	1988 (Q-Flux)	1982 (Q-Flux)	1984-1985	1986
Numerical solution technique	Spectral (R15)	Finite difference	Finite difference	Finite difference
Horizontal resolution (latitude x longitude)	4.5° x 7.5°	7.8° x 10.0°	4.0° x 5.0°	5.0° x 7.5°
Vertical resolution	9	9	2	11
Computation time (minutes per year)	240	1800	249	NA
Computer platform	CDC-205	Amdahl-V6	Cray 1A	NA
Time step (minutes)	NA	15 (dynamics) 60 (physics)	6	20
Surface characterization	Uniform	Fractional grid	Uniform	Uniform
Convective parameterization	Moist adiabatic	Penetrating convection	Penetrating convection	Penetrating convection
Ocean parameterization	60-meter slab, prescribed	65-meter slab, prescribed	60-meter slab, prescribed	50-meter slab, prescribed
Initial CO_2 concentration (parts per million)	300	315	326	320

critical that applications scientists always have access to the details of the particular model and model version they are using.

Numerical Solution Technique

There are two primary methods of solving the basic set of physical equations common to all the GCMs—finite differencing and spectral solutions. Comparisons of finite and spectral solution techniques in GCMs are presented in Gutowski and others (1990), Henderson-Sellers and McGuffie (1987), and Washington and Parkinson (1986). Some advantages and disadvantages of each approach are summarized in table 2.

Finite differences. Finite differences are simple, straightforward approximations to derivatives. They provide physically realistic results and resolve small-scale features well. This advantage, though, can produce greater variability from one grid cell to the next than similar spectral models, and may allow meteorologically unstable conditions leading to more frequent convection, particularly in regions of front formation. Finite difference solutions are most accurate when predicting the movement of weather systems that span eight or more grid cells.

Spectral solutions. Spectral solutions describe fields that are a function of both space and time using sine and cosine waves. Spectral models are named by the kind of numerical truncation scheme and the wave numbers they permit. For example, R15 (table 1) indicates a

Table 2—A comparison of two commonly used numerical solution techniques

Solution technique	Advantages	Disadvantages
Finite difference	Physically realistic results	Increased cell-to-cell variability
	Can resolve small-scale features well	
Spectral	Better conservation of energy and angular momentum	Dependent on artificial constraints to provide physically realistic forecasts
	Superior results for smoothly varying variables	
	Computational efficiency	

rhomboidal truncation of 15 waves. This resolution approximates large-scale motions of the atmosphere well, but misses some smaller scale features. Increasing the number of waves refines the resolution. Advantages of the spectral method over finite differencing procedures include better conservation of energy and angular momentum, superior results for smoothly varying variables, and computational efficiency over current finite differencing techniques. A major disadvantage is that spectral solutions must be artificially constrained to provide physically realistic forecasts. For instance, steep gradients can result in local predictions of negative masses of chemical species or humidities.

Gutowski and others (1990) conclude that there is an interplay between characteristics of the dynamics simulation and the tuning of parameterizations used in a model. The more model tuning and adjustment required to achieve results comparable to the historical climate record, the less confidence should be placed in nonverifiable forecasts of future conditions.

As computational power increases and costs decrease, finite difference techniques will be favored over spectral solutions (Gutowski and others 1990; Henderson-Sellers and McGuffie 1987). The next generation of grid-point models will be based on locally correct regional, rectangular grids. Of the four GCMs presented, only the GFDL model uses a spectral solution method.

Time and Space Resolution

Horizontal resolution. Horizontal resolution refers to spacing between grid points. Figure 1 illustrates the present grid spacing of the four GCMs over the South. The range is from 8 to 28 grid cells. Too many grid points result in excessive computation time, whereas too few points result in the generation of model errors. Present GCM horizontal grid spacing is on the order of 10^5 square miles (10^5 square kilometers). It will be about 5 years before the UKMO grid resolution will be increased to 2.5° latitude x 3.5° longitude. At present, there is a 4° latitude x 5° longitude grid prototype version of the GISS model in the testing mode. No date has been estimated concerning grid increases to a 2.5° latitude x 3.5° longitude grid. R30 and R60 versions of the GFDL model have been completed and data are in the analysis phase.

Model resolution. Model resolution refers to the amount of data required to accurately represent observations. Pielke (1991) emphasizes the important distinction between model resolution and what is referred to in this report as "horizontal or grid-mesh resolution." It has been suggested that a "four-times" rule should be used when simulating meteorological processes. For instance, a GCM with 400- by 400-kilometer horizontal grid increments (10^5 square kilometer horizontal resolution) would have a model resolution of no less than 1600 kilometers on a side (10^6 km^2, about 25 million acres).

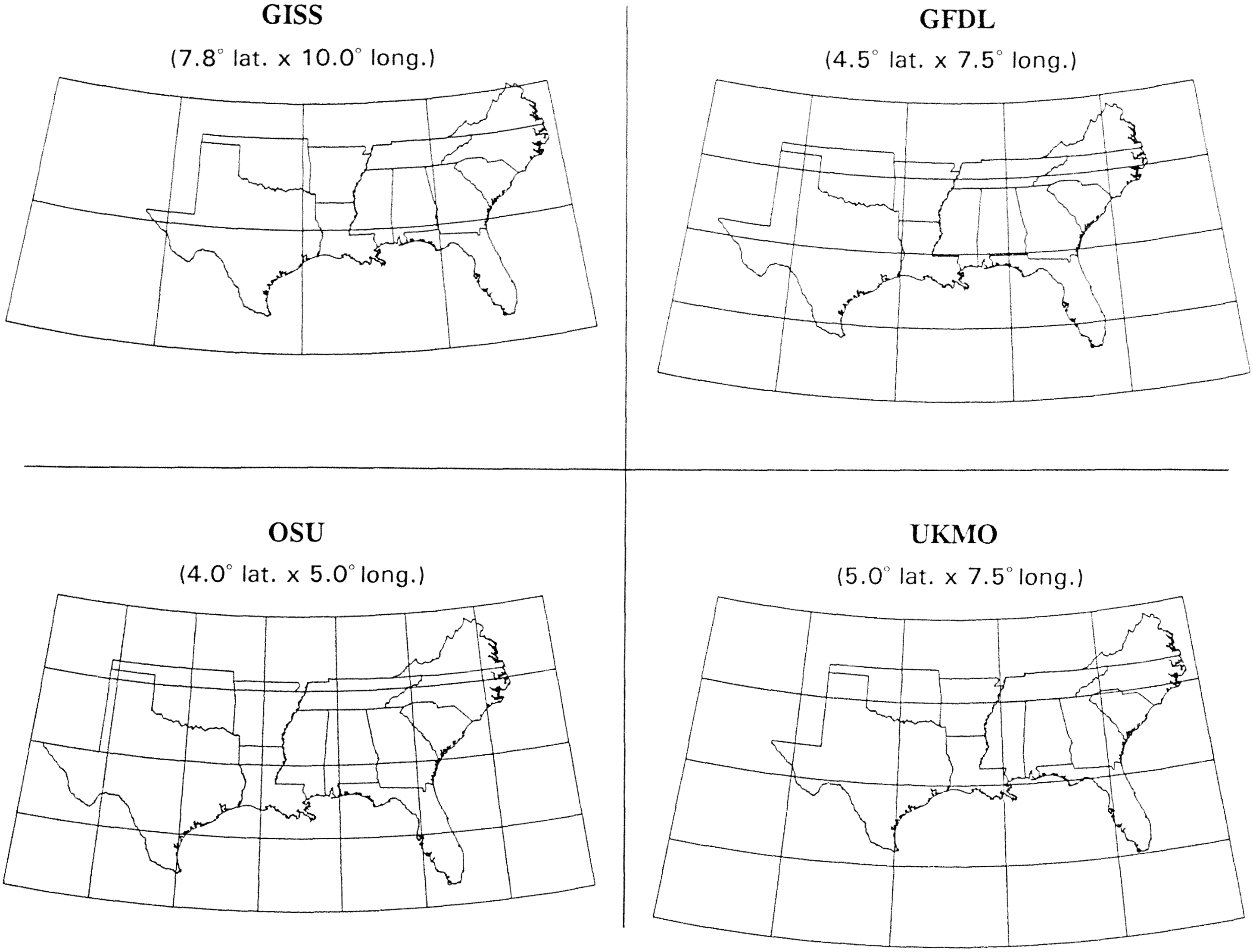

Figure 1—Horizontal resolution of four General Circulation Models (GCMs) across the South.

Vertical resolution. Vertical resolution refers to the number of grid layers in the vertical from the Earth's surface to the "top" of the atmosphere. For the four selected models, this ranges from 2 to 11 layers. In general, the number of layers influences boundary layer thermodynamics and the frequency of convection (Gutowski and others 1990).

Time step. A time-step approach is used to model most processes. The processes are allowed to act for a certain length of time, and new conditions are calculated. Using these new values, the process is then repeated and is continued until the desired conditions at the required time have been established.

It cannot be emphasized too strongly that GCMs are diagnostic, not predictive models. One definition of a diagnostic equation or model is that a system is being described which contains no time derivative and therefore specifies a balance in space at a moment in time. A GCM presents a "snapshot" of future conditions. Conversely, a prognostic model is one that contains time derivatives to determine the value of a quantity at a later time. Mesoscale meteorological models are examples of prognostic models. Although research is ongoing in nesting such prognostic models within GCMs (example, Giorgi 1990), GCMs will likely remain primarily diagnostic tools.

Because of their diagnostic nature, many GCM integrations must be performed and their results averaged before a climate projection can be made. The four scenarios examined here include monthly average values only. Although time steps of the four selected GCMs range from 6 minutes (OSU) to 20 minutes (UKMO), these raw values were never intended for direct use in application or assessment models. The values listed in table 1 represent the time step reported in the literature for each model. In fact, a variety of computational steps are used concurrently; they are specific to the physical process being modeled, and they range from minutes to hours (see GISS, table 1).

Time and space resolutions are the most serious GCM shortcomings identified by the applications community (Robinson and Finkelstein 1991). Practitioners commonly believe that computer capacity and processing speed are the fundamental stumbling blocks to higher resolution and more accurate global forecasts. Of far greater scientific importance is a lack of knowledge about a wide range of atmospheric processes, feedbacks, and system sensitivities. For example, Gutowski and others (1991) conclude that increasing horizontal resolution will not improve the consistency of regional-scale climate simulations unless discrepancies in the surface radiation budget are resolved. When technology outstrips the physical science, additional computational errors can also be introduced. Finally, experience has shown that employing the set of equations that is most complete and that incorporates the most detailed physical processes will not necessarily yield the most realistic results (Mitchell and others 1989; Washington and Parkinson 1986). One must use higher resolution model output in applications research with caution, making certain that knowledge of the processes being modeled is in step with the technology employed.

Topography and Land Surface Characteristics

GCM cell results are generated as a single variable value. Conceptually, these values represent the average of all the conditions within the cell. Although the applications community has employed a variety of interpolation techniques to estimate conditions within the cell (see Scenario Development), the GCM results in this report are presented as uniform throughout a grid cell.

Figure 2 illustrates topographic representation by GCMs. At current horizontal and vertical resolutions, steep mountain gradients cannot be represented without introducing errors into the estimates for wind. In the real world, large topographical complexes strongly affect the location of major semipermanent features in the sea level pressure field and the structure of the jet stream (Giorgi and Mearns 1991). On the mesoscale, topographically induced circulations include lee waves, downslope winds, and lee cyclogenetic processes. Temperature and precipitation are also strongly affected by topography. In GCMs, the Appalachian Mountains do not become clearly defined until grid resolution reaches 1.25° latitude–longitude (fig. 2C). Topographic representation possible under a 2.5° latitude x 3.75° longitude (R30) level of resolution is shown in figure 2B.

Figure 2A shows the lack of detailed coastline definition and the absence of a Florida peninsula. These missing features are natural obstacles to the windflow, and they generate land–water thermal contrasts. The poor coastline resolution is compounded by overly simplified ocean-atmosphere interaction models (see Parameterization Schemes, Ocean parameterizations). The result is a particularly poor GCM performance in regions dominated by land–ocean interactions (Kalkstein 1991).

The uniformly colored blocks of figure 2 also illustrate both GCM land surface characterization and output limitations. In the GFDL, OSU, and UKMO models, a single surface type and single albedo (the ratio of the amount of radiation reflected by a surface to the amount incident upon it) value are prescribed for each grid area (shown in fig. 2 as a solid block of color). The GISS model assigns each grid square a percentage land, a percentage water (lakes or ocean), and a percentage lake or ocean ice. If a square has both water and land parts, the surface air temperature will effectively be an area weighted mean of the temperatures for the land and water components.

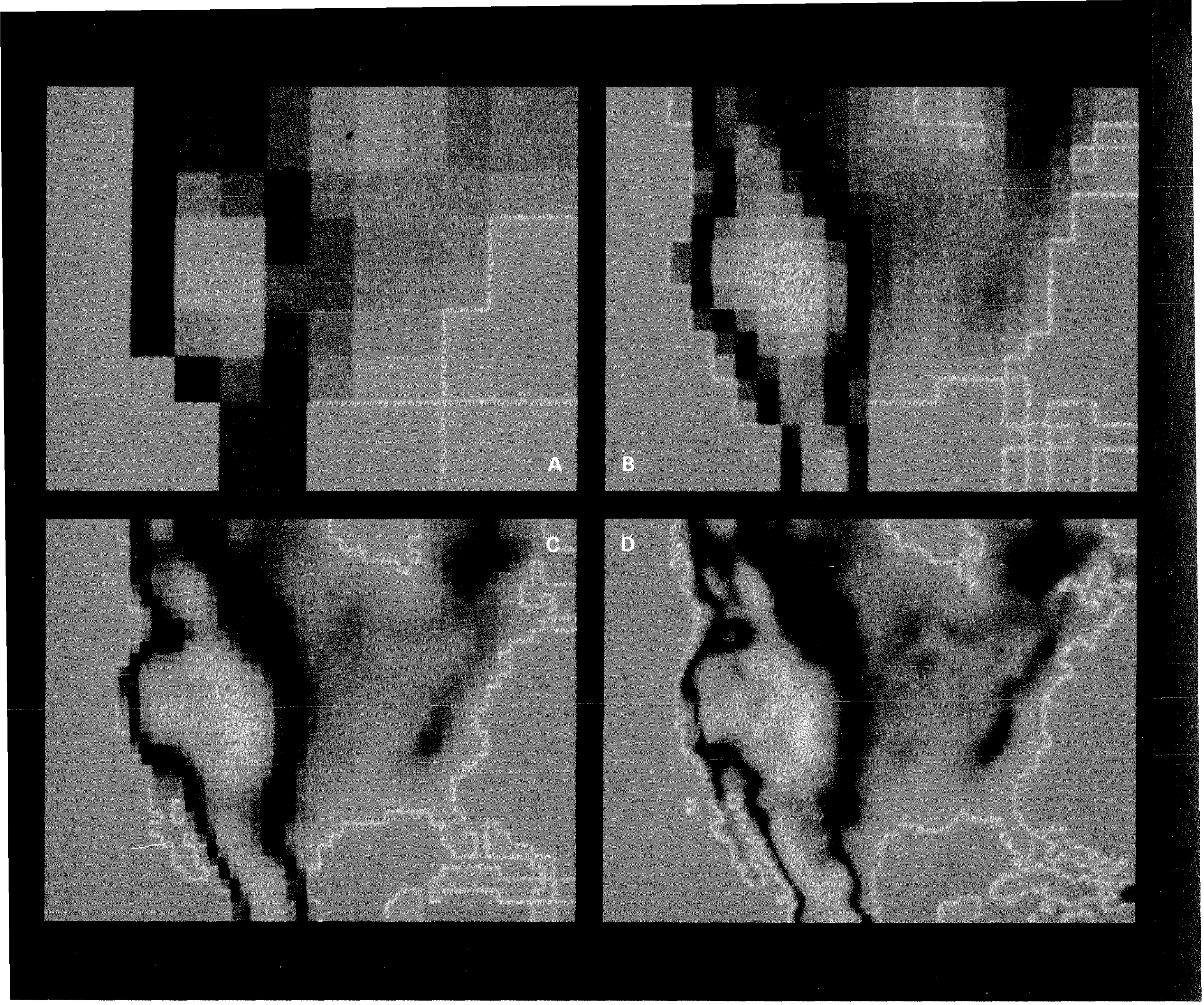

Figure 2—Terrain over North America at four increasing spatial (grid) resolutions: (**A**), 5° latitude-longitude; (**B**), 2.5° latitude-longitude; (**C**), 1.25° latitude-longitude; and (**D**), 0.625° latitude-longitude. (Source: National Center for Atmospheric Research, Boulder, CO.)

Parameterization Schemes

Parameterizations may take many forms. Climatological specification (such as sea surface temperature fixed at seasonal means) is a form of parameterization that is widely used in most models. Recently developed parameterizations have more theoretical underpinnings than such fixed value estimates. For example, theories of cloud and precipitation processes abound, but verified, accurate predictive models have yet to be developed. New parameterization schemes follow these theoretical descriptions to compensate for the absence of quantitative forecast models.

Great care is necessary when choosing the constants and empirical relationships for any parameterization scheme in any model. Values determined solely from empirical evidence may be appropriate only for the present day; the result is that the model may adequately predict the present-day situation but fail to respond realistically to future perturbations. The diversity of model formulations reflects both the continuing search for improved models and the fact that there can be no single set of "ideal" parameterizations for all purposes. The "best" combination of parameterizations will depend on the intended uses of the model. Garratt (1993) provides a detailed review of land surface parameterization schemes, both those used by the four models discussed here and others.

Vegetative cover. Vegetative cover strongly controls the amount of solar radiative heat that the land surface absorbs by varying the albedo. In addition to warming the soil, heat absorbed by the surface provides energy for evaporation and for warming the atmosphere directly. Changes in albedo can strongly affect evaporation and atmospheric heating, thereby affecting the hydrological cycle and atmospheric circulation. Other aspects of vegetative cover—such as roughness, stomatal resistance, canopy moisture capacity, and rooting depth—can alter the partitioning of solar radiation between evaporation and sensible heat. Although at least two vegetative parameterization schemes have been used extensively, GCM output that includes vegetative feedbacks are not widely available to the applications community (Garratt 1993).

Mountain wave drag. Mountain wave drag parameterizations are used to introduce the effect of mountains on the momentum budget of the atmosphere. Mountains are a key factor both in the maintenance of the observed large-scale atmospheric circulation and in the life cycle of many atmospheric phenomena. In the absence of sufficent spatial resolution and detailed knowledge to physically model mountains, mountain wave parameterizations are currently the only way to address this critical issue. Mountain (or gravity) wave drag is the drag of the mountains on atmospheric flow. It results in gravity waves that occur when buoyancy restores air parcels that have been displaced vertically (Holton 1972), much like the effect of a stone striking the surface of a pond. The importance of orographic forcing has been increasingly emphasized in GCM, and has resulted in marked improvements to model climates. Recent research suggests that effects of gravity wave drag significantly contribute to the process of forecasting the effects of topography on atmospheric flow down to grid scales on the order of 0.1° latitude (Clark and Miller 1991).

Convective adjustments. Convective adjustments are used in GCMs to simulate convective overturning in the atmosphere and to project the impacts of precipitation, clouds, and atmospheric moisture. Characteristics and impacts of two parameterization schemes—moist adiabatic and penetrating convection, or Kuo (1974)—are summarized in table 3. An adiabatic process is an ideal or theoretical process during which there is absolutely no heat exchange between a gas and its environment. A moist adiabatic process is one during which phase changes do occur, so that account must be taken of the exchange of latent heat. The Kuo scheme also assumes moist adiabatic processes, but only a fraction of the total water vapor is condensed and precipitated, while the remaining portion is stored in the atmosphere, increasing the humidity of the vertical column. All of the selected GCMs use this penetrating convective parameterization except for the GFDL model.

The effects of improved modeling technology (resolution) on convective or cloud parameterization schemes may or may not be positive for the applications community. Kristjánsson (1991) discusses the effects of changing spatial resolution on a cloud parameterization scheme while holding the model physics constant, as suggested by Sundqvist (1988). As resolution increases, precipitation increases (both stratiform and convective) and cloud cover systematically decreases (a result of enhanced vertical motions at high resolution, making frontal systems narrower with less cloudy surroundings). Simulations of orographic precipitation depended strongly on both grid resolution and resolution of the orography.

Although Kristjánsson's results are for a particular cloud parameterization routine, Kiehl and Williamson (1991) report that his cloud cover results are independent of the model or cloud parameterization scheme employed. This example reemphasizes the need for scientific knowledge to advance together with computing technology. As higher resolution GCM output becomes available, the applications community needs to verify that the model physics are appropriate. If they are not, the new scenario may be well tuned but no more capable of simulating reliable 2 x CO_2 conditions than the coarser model versions.

Ocean parameterizations. Ocean parameterizations usually assume that ocean depth is equal to the annual-average, global-average depth of the well-mixed water layer or slab. This depth, which actually varies with season and location, is not based directly on a time series of observations. It is chosen to bring the hemispheric averages of the phase and the amplitude of the annual temperature range in the model into rough agreement with average conditions (in other words, it is prescribed). The GISS and GFDL models also include estimates of ocean heat transport.

Table 3—Characteristics and impacts of the moist adiabatic and Kuo (1974) parameterization schemes

Convective parameterization scheme	Characteristics	Impact on GCM performance
Moist adiabatic	Assumes a moist adiabatic lapse rate to determine the presence of convection	Lower atmospheric humidity
	Temperatures are constrained so that they always decrease with height	Less frequent precipitation
	Moisture distribution is adjusted to prevent supersaturation	More latent heat added to the atmosphere
	Excess moisture is condensed and removed	
Kuo or penetrating convection	Uses low-level convergence of moisture and low-level lifting to determine the presence of cumulus convection	Higher atmospheric humidity
	Only a fraction of the available water vapor falls as precipitation, while the rest is stored in the atmosphere	More frequent precipitation
		Less latent heat added to the atmosphere

Carbon Dioxide (CO_2)

The concentration and spatial distribution of CO_2 can affect estimates of how forests respond to CO_2 enrichment and can alter the energy flux budgets of GCMs. To predict the impact on climate, GCMs model changes in radiation absorption in response to the distribution of vertical and horizontal gas concentrations. The distribution of CO_2 is assumed to be uniform horizontally and to possess a fixed vertical profile. The models examined here also tacitly assume no change in trace gas concentration. In reality, enhanced greenhouse warming can result from changes in a wide variety of trace gas concentrations. The concentrations of CO_2 and trace gases vary greatly horizontally as well as vertically. One way to compensate for trace gases is to calculate a CO_2 equivalent concentration, the concentration of CO_2 that absorbs radiation equivalent to that of a given trace gas. At present, initial CO_2 concentrations vary with model. Table 1 indicates that values range from 300 to 326 parts per million. Recent test cases have demonstrated, however, that GCM predictions of climate change are sensitive to the detailed characterization of specific greenhouse gas behavior and that improvements in the way these gases are treated by GCMs are needed (Wang and others 1991). Such changes should lead to increased confidence in 2 x CO_2 scenario projections.

As stated earlier, GCMs are essentially diagnostic models that provide "snapshots" of conditions at some future point in time. All output presented in this report are equilibrium model results. In equilibrium response experiments, both simulations (the control experiment with the present amount of atmospheric CO_2 and the perturbation experiment with 2 x CO_2) are run long enough to reach the respective equilibrium climate (Bretherton and others 1990). The equilibration time is the time taken for a component of the climate system to reach equilibrium with one or more of the other components (Henderson-Sellers and McGuffie 1987). It is a measure of the time it takes for the subsystem to reequilibrate after a small perturbation. These times are estimated to range from hours for the boundary layer of the atmosphere to decades for deep ocean components.

Equilibrium simulations have several advantages over time-dependent experiments. They use less computer time and are easier to compare because only one solution exists for each specification of forcing.

Other simulation techniques include transient simulations, which involve the abrupt doubling of CO_2. They are transient in that the time evolution of the whole climate system for a prescribed "switch on" instantaneous CO_2 doubling can be examined in a meaningful way. For instance, after the "switch on" point, the model is run for various simulation periods (examples: 6 years, 30 years, 50 years) and the results of each time period are analyzed.

An alternative approach—called a time-dependent simulation—imposes a gradual increase in CO_2 concentration over some extended period of time (Bretherton and others 1990). A rate of 1 percent per year for 100 years is used by Stouffer and others (1989). An increase of 0.8 percent per year over 200 years is used by Manabe and others (1990); although their zonal comparisons focus primarily on the poleward regions, Manabe and others (1990) conclude that pronounced interhemispheric response differences become apparent in the transient experiment. This is contrary to earlier results that indicate no difference or only modest differences.

Tsonis (1991) provides a word of caution when using such time-dependent scenarios. Analyses of statistically modeled GCM temperature time series indicate distinct sensitivity to initial conditions. Tsonis concludes that for transient time series generated by the GISS model, on the average, two runs starting very near each other will lose any resemblance after about 50 years. Thus, the advantage gained by temporal detail could be lost through the introduction of additional uncertainty. These results are still under active debate (Gray and Woodward 1992).

Selected Output Variables

Climate variables that were identified as important for forest growth and productivity applications were selected from Peer (1990) and Joyce and Kickert (1987). In general, these variables are associated with moisture or energy fluxes through photosynthetically active radiation (PAR) and evapotranspiration calculations (table 4).

Mean Surface Temperature

Air temperature is simulated similarly by all four GCMs. It is treated as a prognostic variable, using equations designed to simulate the balance of local energy fluxes between the atmosphere and the Earth's surface, while simultaneously satisfying the fundamental equations discussed above. Temperature is calculated in the lowest vertical layer of the model, which can extend from 32 to 97 feet (10 to 30 meters) above the Earth's surface. Observations made at these elevations are not directly comparable to temperatures recorded at standard National Weather Service shelters at a height of 3 to 6 feet, making the direct use of GCM surface temperature projections inadvisable. A reasonable alternative would be to apply GCM 1 x CO_2 and 2 x CO_2 scenario differences to existing surface climatological records.

Feedbacks associated with changes in air temperature are not fully understood, but the current consensus is that a 1 °C rise in global surface temperatures would increase the concentration of water vapor by roughly 6 percent (Manowitz 1990). Atmospheric moisture is driven almost exclusively by temperature in these four GCMs. This relationship is illustrated in the South by the consensus between atmospheric moisture predictions and projected temperature increases. Grotch (1988) and Kalkstein (1991) have compared regional (2-20 grid cell) temperature scenarios with historical data.

Diurnal Range of Surface Temperatures

As discussed above, surface temperature calculations are driven by incoming solar radiation (heat energy flux). This incoming radiation is held constant throughout each 24 hours of model execution in the GFDL and OSU models (in other words, no diurnal cycle). Radiation is allowed to vary through a 24-hour day in the GISS and UKMO models; however, the time steps for computing new radiation values are model specific, and they range from once every 2 model hours to once every 5 model

Table 4—Availability, process interactions, historical comparisons, and application notes for selected GCM variables

Output variable	GCM availability	Interactions with other processes	Comparison of baseline GCM output with historical data	Comments
Surface temperature	GISS GFDL OSU UKMO	With water vapor, strong and positive (Manowitz 1990)	Grotch (1988) Kalkstein (1991)	The direct use of GCM output is discouraged. Temperature is estimated for the lowest vertical layer, which may lie 10 to 30 meters above the Earth's surface. Use semiempirical scenarios.
Diurnal temperature range	GFDL OSU	With radiation	No	No strong evidence for reduction in diurnal amplitude under double CO_2.
Soil temperature	GISS	With soil moisture, snow depth, surface vegetative condition, surface cover (desert, nondesert)	No	Limited availability and lack of comparison studies discourage the direct use of these output.
Atmospheric moisture	GISS GFDL OSU UKMO	With the Earth's surface through energy and moisture fluxes	No	Comparison studies are needed. Lack of vegetative feedback suggests that assessment results must be interpreted with care.
Cloud cover	GISS GFDL OSU	With radiation (Cess and others 1990)	No	Formation and type of cloud are restricted to certain vertical layers of the atmosphere and occur only when relative humidity exceeds a prescribed threshold amount.
Precipitation	GISS GFDL OSU UKMO	With moisture flux, energy flux, cloud	Finkelstein and Truppi (1991), Grotch (1988), Kalkstein (1991)	Problems in areas dominated by orographic or convective precipitation and land/sea interactions. Rapid developments in parameterization schemes may yield improved large-scale performance in near future.

hours. Regardless of the presence or absence of a diurnal cycle, researchers have been advised not to expect any major differences in base case model output, since each version has been tuned to "adequately" represent current conditions. In the absence of a diurnal cycle, such an approach would require additional baseline tuning to compensate for the lack of physical detail.

Soil Temperature

Diurnal variations of ground temperature are important for GCM projections because of the highly nonlinear dependence that latent and sensible heat fluxes have on temperature. Soil temperature effects are included only in the GISS model, Version 2 (Hansen and others 1983). This model computes the mean temperature of each of two soil layers. The first (upper) layer is fixed at a depth of 4 inches and the second (lower layer) is 13 feet thick. The upper layer is thin enough to simulate diurnal surface temperature changes but thick enough to allow for long time steps. The lower layer is needed for seasonal heat storage. It is assumed that the heat capacity and conductivity are uniform in each layer, that the temperature in each layer is a quadratic function of depth, and that no heat crosses the lower edge of the bottom layer.

Soil temperature is linked to surface conditions in several ways, as shown by the following examples. Snow depth is assumed to be 10 times the water-equivalent depth so as to simulate its insulating effect on the soil profile. Thermal conductivity through the soil profile is adjusted to simulate the effects of dead grass and leaves on the surface. Soil moisture feedbacks are also included since soil temperature is computed as a function of heat capacity which is, in turn, a function of soil moisture. The GISS soil moisture model is adjusted for time of year (growing or dormant season) and surface cover type (desert or nondesert). The upward moisture diffusion coefficient is defined as infinite within the growing season and zero at other times. Deserts are assumed to have no vegetative cover.

Atmospheric Moisture

Water vapor produces the largest known positive feedback on climate, and so its simulation is fundamental to GCM projections (Del Genio and others 1991). Like temperature, moisture flux is calculated using a prognostic equation. Although neither spectral nor finite differencing techniques provide completely satisfactory solutions, spectral techniques are particularly prone to generate negative moisture fields, which must then be adjusted or "fixed" (Rasch and Williamson 1990).

Del Genio and others (1991) propose that water vapor feedback in GCMs is controlled primarily by temperature and is not very sensitive to the fine-tuning of the cloud models. Recall, however, that cloud parameterization can significantly impact temperatures. In general, surface feedbacks to atmospheric moisture are represented by the effect of surface albedo on energy and subsequent moisture fluxes from the surface to the atmosphere. Although recent versions of some GCMs parameterize surface vegetation impacts on atmospheric moisture, they are not a part of the present set of scenarios.

Mean zonal estimates of humidity are used to tune the 1 x CO_2 model, but regional climatological comparisons similar to those available for temperature and precipitation have yet to be published. The accuracy of atmospheric moisture estimates is often implied from large-scale comparisons of modeled and observed water vapor/climate feedbacks. The assumption is that if the feedback effects are correct, then large-scale horizontal, vertical, and seasonal moisture distributions are correct as well. Raval and Ramanathan (1989) compared satellite observations of the water vapor–greenhouse feedback mechanism to GCM estimates. Their conclusion—that the magnitude of the feedback is consistent with that predicted by climate models—is not uniformly accepted. For instance, Lindzen (1990) suggests that negative temperature–water vapor feedback processes are not adequately represented by these models and that such interactions could reduce estimates of global warming by a factor of "one-half to one-fifth." The adequacy of simulating positive and negative feedback effects on atmospheric moisture is a major source of model uncertainty.

Cloud Cover Amount

Accurate simulation of cloud and precipitation processes is essential to the performance of the GCMs. As seen in table 5, the four models parameterize stratified and convective cloud types rather simply. In general, cloud formation and type are restricted to certain vertical layers. They occur only when the relative humidity exceeds a prescribed threshold amount.

Table 5—Summary of convective and stratiform cloud formation parameterizations for four GCMs

Model	Convective cloud	Stratiform cloud
GFDL	No clouds unless saturation occurs (RH = 99 percent), then 100 percent cloudiness.	No clouds unless saturation occurs (RH = 99 percent), then 100 percent cloudiness.
GISS	Cloud fraction proportional to pressure thickness of all layers up to cloud top. No clouds above 100 millibars.	No clouds unless saturation occurs (RH = 100 percent), then cloud fraction equals saturated grid fraction. No clouds above 100 millibars.
OSU	Penetrative convection, 0 or 100 percent cloudiness. Convective cloud only in 200-400 millibars and 800-1000 millibars layer.	No clouds unless saturation occurs (RH = 100 percent), then 100 percent cloudiness. Stratiform cloud formation only in 400-800 millibars layer.
UKMO	Cloud fraction proportional to maximum parcel size in moisture convection.	Cloud fraction function of relative humidity, no clouds in the top layer.

While the parameterization of cloud formation is straightforward (but oversimplified), the resulting feedbacks are not. Cloud feedback, which is responsible for many of the differences among calibrated GCMs, is complex and can produce both positive and negative effects (Cess and others 1990). For instance, if global cloud amount decreases with global warming, the contribution to greenhouse warming of infrared radiation emitted by a warmer Earth's surface could be reduced (a negative feedback). Alternatively, less cloud would be available to reflect incoming solar radiation, and more heat energy would be available for absorption by the earth–atmosphere system (a positive feedback).

The cloud feedback picture is complicated further by research on the role of sulphate aerosols, cloud optical depth, and surface temperatures (Twomey 1991). The basic argument is that cloud optical properties change with cloud droplet size. For instance, very small cloud droplets that form around sulphate aerosols reflect incoming (shortwave) radiation more efficiently and insulate emitted (longwave) radiation better than larger droplets. There are implications for precipitation as well, since clouds made up of small droplets follow different physical rules of precipitation formation than clouds made up of large droplets. This is a crucial cloud characteristic that should be addressed in future GCMs. Most models of the type reviewed here prescribe cloud radiative properties so that studies of changes in cloud distribution can be conducted (for example: Mitchell and Ingram 1992). However, such prescription precludes the study of cloud composition and subsequent temperature and precipitation feedbacks.

Precipitation

Modeling schemes for precipitation employed by the four GCMs are fairly similar, especially for large-scale, stratified precipitation that is simulated when saturation is indicated by the prognostic equations for water vapor. The amount of water vapor which condenses and is removed, however, varies with the convective parameterization scheme. For instance, under the moist adiabatic scheme (table 3), any excess moisture in a vertical column is condensed and removed. Under the penetrating convection (Kuo) scheme, only a fraction of the water vapor falls as precipitation, while the remaining portion is stored in the atmosphere. The result is more frequent saturation conditions and more frequent precipitation.

Feedbacks are modeled among moisture flux, energy flux, clouds, and precipitation. Surface feedbacks occur only through the impact of surface albedo on energy fluxes. No other vegetation feedbacks are included in any of the models. Although time aggregation of output would probably mask precipitation frequency differences in GCM output (table 3), the choice of a convective parameterization scheme could influence the estimation of humidity and air temperature under 2 x CO_2

conditions. These factors are particularly important to assessment models driven by potential evapotranspiration. Comparisons of regional (2-20 grid cell) precipitation scenarios with historical data have been performed by Finkelstein and Truppi (1991), Grotch (1988), and Kalkstein (1991).

Scenario Development

The detailed information presented above can be used to guide the selection and use of GCM output, but sometimes applications needs and GCM capabilities do not match. Table 6 presents such an example for the climate variables discussed. Forest assessment models typically use either statistical relationships (empirical models) or sets of equations representing fundamental plant processes (process models).

From table 6 it can be seen that the climate data needs of empirical assessment models (identified here as temperature and precipitation only) can be met as long as the geographic scale for the study is large. None of the climate data needs of process assessment models can be met directly by current GCM output.

While one alternative is to wait for scientific knowledge and computing technology to catch up with applications demands, carefully constructed "scenarios" represent another, more immediately available option. A scenario is one possible set of future climate conditions. It should be internally consistent, developed using sound scientific principles, but having no specific probability of occurrence attached (Robinson and Finkelstein 1991). Scenarios from sources other than direct GCM output are needed for applications work because GCMs do not provide sufficiently detailed information. Frequently, it is mesoscale phenomena (and their inherent variability) that have the greatest impact on biological and socioeconomic systems. In spite of these shortcomings, Gates (1985) suggests that the fundamental structure and execution of GCMs provide a wide variety of statistics in the form of scenarios that are important to the surface ecosystem (examples: moisture stress, duration of rainless periods, and length of growing season).

General approaches to the simulation of regional climate change have been developed and are discussed in Carter and others (1992), Giorgi and Mearns (1991), and Robinson and Finkelstein (1991). Empirical and semiempirical techniques are most frequently employed in climate change applications research. Empirical scenarios are either based on climatic data from the distant past (paleoclimatic analogs or proxy data) or constructed from measurements made during the 20th century using instruments or instrumental analogs (Lamb 1987). In both cases, considerable regional and/or seasonal detail has been obtained. The basic underlying assumption is that for similar lower boundary conditions, the general circulation internally adjusts itself to give similar responses to different forcings, independent of the nature of the forcing mechanism (Giorgi and Mearns 1991). Examples of the use of climate change analogs to address potential socioeconomic responses are presented in Glantz (1988). The use of an analog approach is limited for regional climate change projections because it is nondeterministic and because of nonlinearities in the climate system. Analogs cannot provide accurate quantitative estimates of regional climate statistics. However, empirical scenarios can provide qualitative estimates of direction and ranges of possible regional climate variations.

Semiempirical approaches attempt to translate large-scale, GCM information into local statistics by using empirically derived relationships between large-scale and local surface variables (Giorgi and Mearns 1991). Most commonly, differences between perturbed climate GCM runs and control runs are appended to observational data sets for the region (as in Smith and Tirpak 1989). The basic assumption underlying this approach is that the inaccuracy from the GCM resolution is reduced when GCM-produced differences are applied to high-resolution observed data.

Semiempirically derived scenarios often provide more informative simulations of regional climate detail than direct use of GCM data. This improvement is more pronounced for measurements, such as temperature, that show a relatively high degree of spatial correlation. The primary limitation of semiempirical approaches is that the predictive empirical relationships developed for present-day climate may not apply as well under different forcing conditions. The extent of this uncertainty depends on the physical process being considered.

Table 6—Typical forest production model climate inputs and availability of these data from four common GCMs

Climate variable	Model type	Model time	Model space	GCM availability	GCM space (square kilometers)	GCM time	Needs/ capabilities agree?
Surface temperature	Empirical	Daily to monthly	Multistate	GISS GFDL OSU UKMO	100,000	Mean monthly	Yes
Surface temperature	Process	Hourly to daily	Hectare	GISS GFDL OSU UKMO	100,000	Mean monthly	
Diurnal range	Process	Daily	Hectare	GFDL OSU	100,000	Mean monthly	
Soil temperature	Process	Daily	Hectare	GISS	100,000	Mean monthly	
Atmospheric moisture	Process	Hourly to daily	Hectare	GISS GFDL OSU UKMO	100,000	Mean monthly	
Cloud cover	Process	Hourly to daily	Hectare	GISS GFDL OSU	100,000	Mean monthly	
Precipitation	Empirical	Daily-monthly totals	Multistate	GISS GFDL OSU UKMO	100,000	Mean monthly	Yes
Precipitation	Process	Daily	Hectare	GISS GFDL OSU UKMO	100,000	Mean monthly	

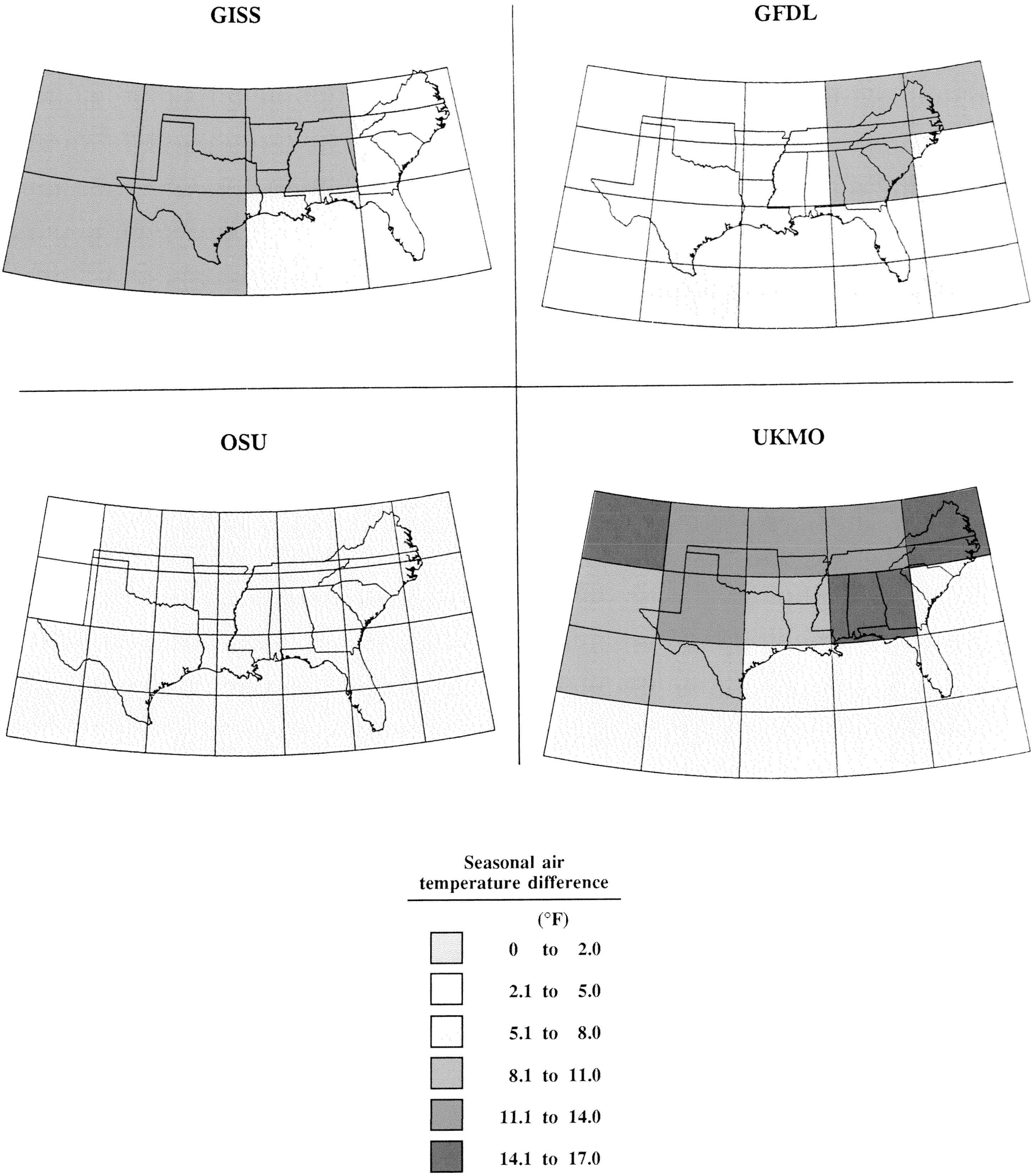

Figure 3—Winter season temperature differences (2 x CO_2 - 1 x CO_2) for the South.

Model Output for the South

Figure 3 illustrates changes in mean daily winter temperature under 2 x CO_2 conditions across four selected GCMs. Similar seasonal maps for diurnal air temperature, soil temperature, atmospheric moisture, cloudiness, and precipitation are presented in the appendix. The scenario values for each grid cell represent average conditions over the entire cell. No subgrid scale (within cell) spatial distributions can be inferred directly from these values. Higher resolution scenarios are needed for many forest applications, but current GCMs are unable to provide direct, reliable projections of sufficiently fine time and space resolution. Various means of developing such scenarios have been discussed previously, but even the GCM grid-scale scenarios described by Kristjánsson (1991) must be interpreted with care. For instance, climatologists frequently quote condition averages across time and space. Grotch (1988) reminds us that an infinite number of distributions will yield the same average. The agreement of two distributions, on average, is no guarantee that the distributions are spatially the same or even close.

One way to evaluate the strength of GCM projections is to compare scenarios and to determine consensus among GCM scenario output. Consensus is established if a simple majority of GCM scenarios (for instance, two of three or three of four) agree. Table 7 contains Southern and Southeastern consensus results, by season across variables and GCM models. Only direction of change is reported because consensus on specific values is rare. A blank table entry indicates no consensus among the GCMs about the direction of variable change.

Descriptions of the four seasonal scenarios of table 7 are presented below. See the appendix for individual model performance and the magnitude of projected change. Although there is some additional consensus if subregional comparisons are made, the current wisdom is to use such comparisons with extreme caution.

Autumn, Winter, and Spring

Air temperature and atmospheric moisture are projected to increase across the South. Cloudiness is predicted to decrease. There is no regionwide consensus about changes in precipitation.

Summer

Summertime air temperatures, atmospheric moisture, and precipitation are expected to increase across most of the South. There is no regionwide consensus about whether cloud cover will change.

Implications for Forest Applications

There is error within each model and variability among all four model scenarios examined. One means of assessing model adequacy is to compare GCM output with historical data. Although such comparisons are an important step towards model verification, they more accurately reflect the calibrating ability of the modelers than the accuracy of predictions. Generally, the more tuning and adjustment required to obtain historically comparable base-case output, the less confidence can be placed in model predictions of future conditions.

Table 7—Consensus results for GCMs across the Southern and Southeastern United States (consensus defined by a simple majority of available models)

Variable	Winter	Spring	Summer	Autumn
Precipitation[a]			↑	
Mean daily air temperature[a]	↑	↑	↑	↑
Atmospheric moisture[a]	↑	↑	↑	↑
Cloudiness[b]	↓	↓		↓

↑ = positive change is likely.
↓ = negative change is likely.
[a] = available from all models; [b] = available from GISS, OSU, and GFDL only.

Recent examples of such historical comparisons are Finkelstein and Truppi (1991), and Kalkstein (1991). Kalkstein compared the 1 x CO_2 GCM temperature and precipitation output to global average climate data developed by the RAND Corporation of Santa Monica, CA. Kalkstein concludes that the GCMs perform relatively well in the Eastern United States. The largest departures from RAND data occurred in coastal zones (especially transitions from oceans to mountains in short distances), to the lee of mountains, and in areas of strong convective precipitation.

Finkelstein and Truppi (1991) compared seasonality characteristics of the Climate Division, Historical Data Series (Cayan and others 1986) with GCM precipitation scenarios. They found that the GISS, GFDL, and OSU models adequately reproduced current precipitation seasonality patterns across the Southern United States. The UKMO results were reasonable along the Atlantic Coast, but the model produced too great a summer precipitation maximum along the Gulf Coast.

Given these observations and previous discussions of model caveats, the greatest source of error for southern climate change scenarios is inadequate modeling of land-ocean energy and moisture exchanges. This is reflected in poor historical comparisons for southern coastal areas, and in a lack of consensus in precipitation estimates. Topographic resolution and cloud parameterization represent a second source of uncertainty, which is most important to precipitation projections in western Texas and Oklahoma. A third source of uncertainty is the simulation of surface vegetation effects on moisture fluxes.

Diurnal temperature range and soil temperature scenarios should be used cautiously, if at all. They are not available from all models, nor have they been validated against regional historic records. Although a diurnal cycle is present in the UKMO model, the available output is reported as monthly extremes rather than as a diurnal range.

There is consensus among models about the direction and magnitude of changes in atmospheric moisture and cloudiness. Consensus in atmospheric moisture, whose simulation is driven primarily by energy fluxes, derives from model agreement of widespread temperature increases under 2 x CO_2 conditions. As modelers begin to select from among several viable surface vegetation parameterization schemes (see earlier discussion), intermodel variability should increase. Cloud formation is determined by very similar relative humidity constraints (table 3). At constant pressure, relative humidity is a function of temperature and water vapor. GCM projections of each of these variables under 1 x CO_2 and 2 x CO_2 conditions are in fundamental agreement. As more complex cloud parameterization schemes are included in GCMs, the level of consensus may diminish.

Grotch (1988) and Kalkstein (1991) agree that GCM air temperature scenarios, although far from perfect, compare more favorably with historical climatologies than any other output variable. This favorable comparison is the result of two factors. First, air temperature is coherent in space and time (especially when compared to precipitation results). Second, at the time these models were created, there was general agreement on the essential physical processes and feedbacks that must be included in a global climate simulation. This is no longer necessarily the case. Those who wish to apply GCM temperature scenarios should avoid direct use of the GCM scenario values, which do not necessarily represent normal surface temperatures.

In summary, although a set of alternative future climate conditions for the Southern United States has been presented, it is difficult to place quantitative confidence limits on the accuracy of any one projection. By definition, GCM scenarios cannot be assigned probabilities of occurrence. Error limits can be placed around retrospective scenarios, but the accuracy of their extension to future climate conditions is dubious. From a modeler's perspective, most intermodel variability comes from a few areas of GCM parameterization. This report has highlighted additional sources of model differences, many of which are masked by model calibration to current climate. These differences persist in 2 x CO_2 projections.

As model physics and parameterizations become more realistic, confidence in the ability of GCMs to simulate changed environmental conditions should increase. Unfortunately, given the complexity of the system being modeled, it is unlikely that the range of possible outcomes will narrow significantly in the near future. This **does not** mean that GCM scenarios should be avoided in applications research. It **does** emphasize the importance of understanding the sources of uncertainty in GCM projections. Such knowledge is critical to the efficient and scientifically appropriate application of these valuable diagnostic tools.

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Appendix

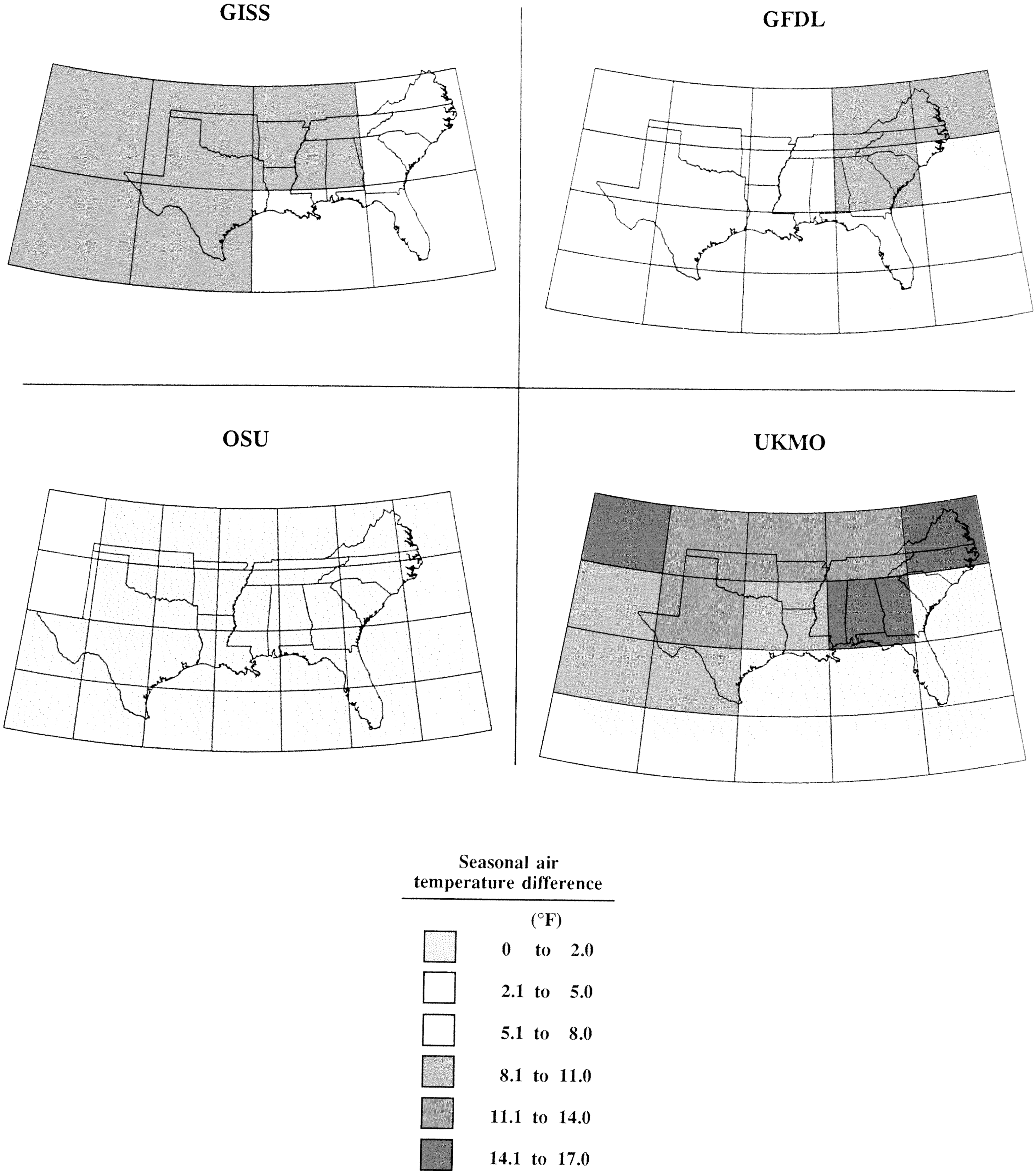


Figure 4—Winter season temperature differences (2 x CO_2 - 1 x CO_2) for the South.

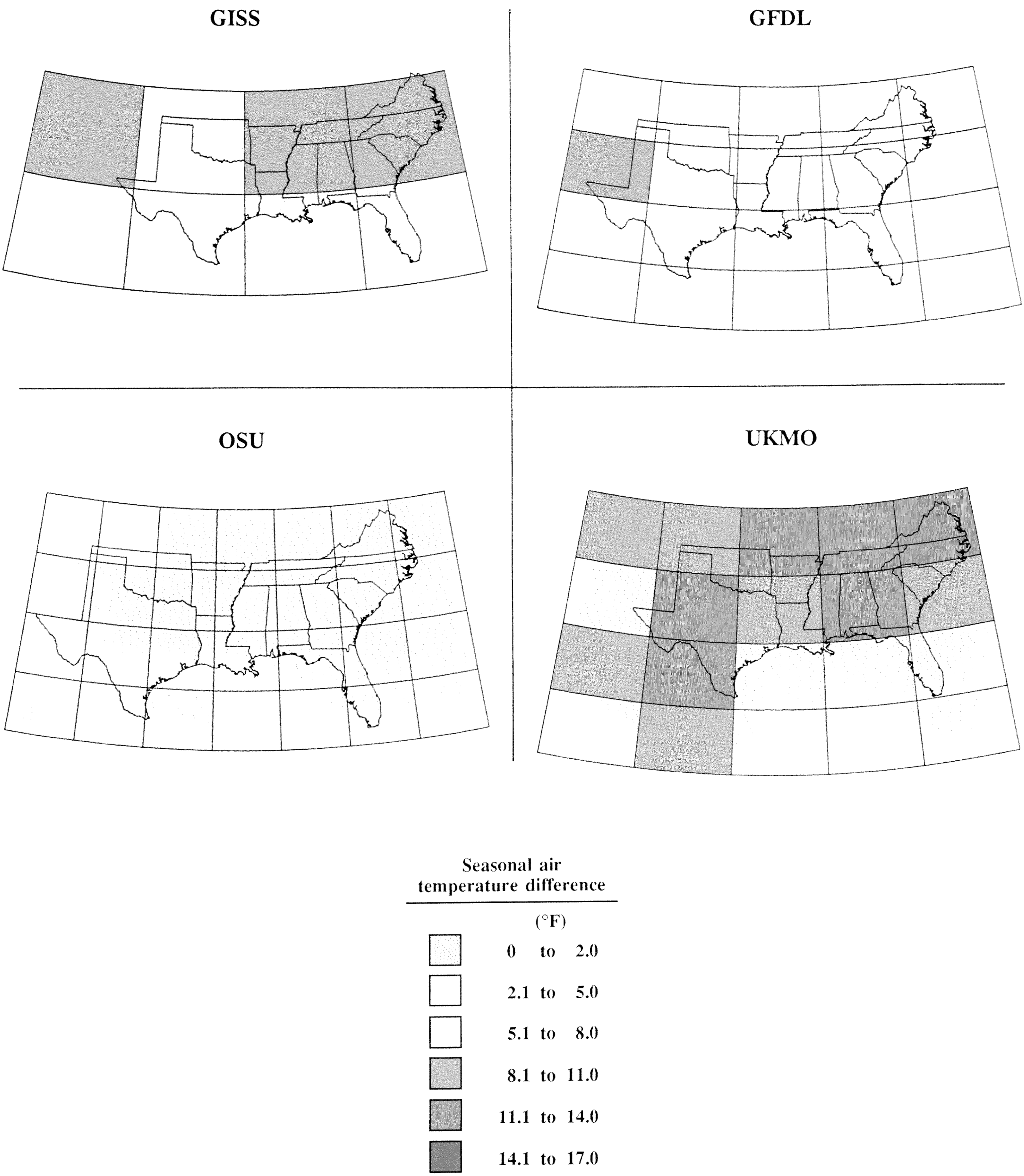


Figure 5—Spring season temperature differences (2 x CO_2 - 1 x CO_2) for the South.

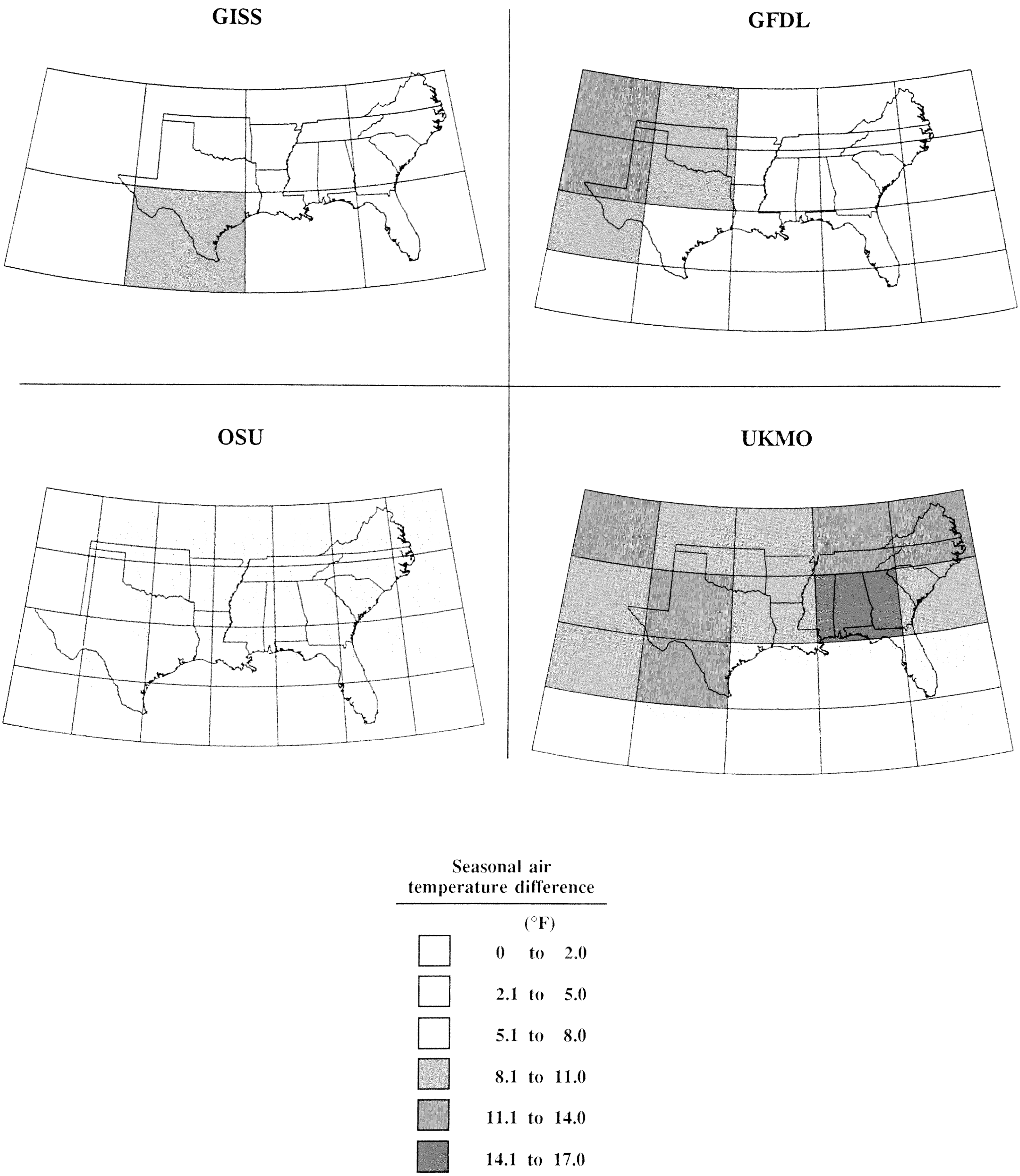


Figure 6—Summer season temperature differences (2 x CO_2 - 1 x CO_2) for the South.

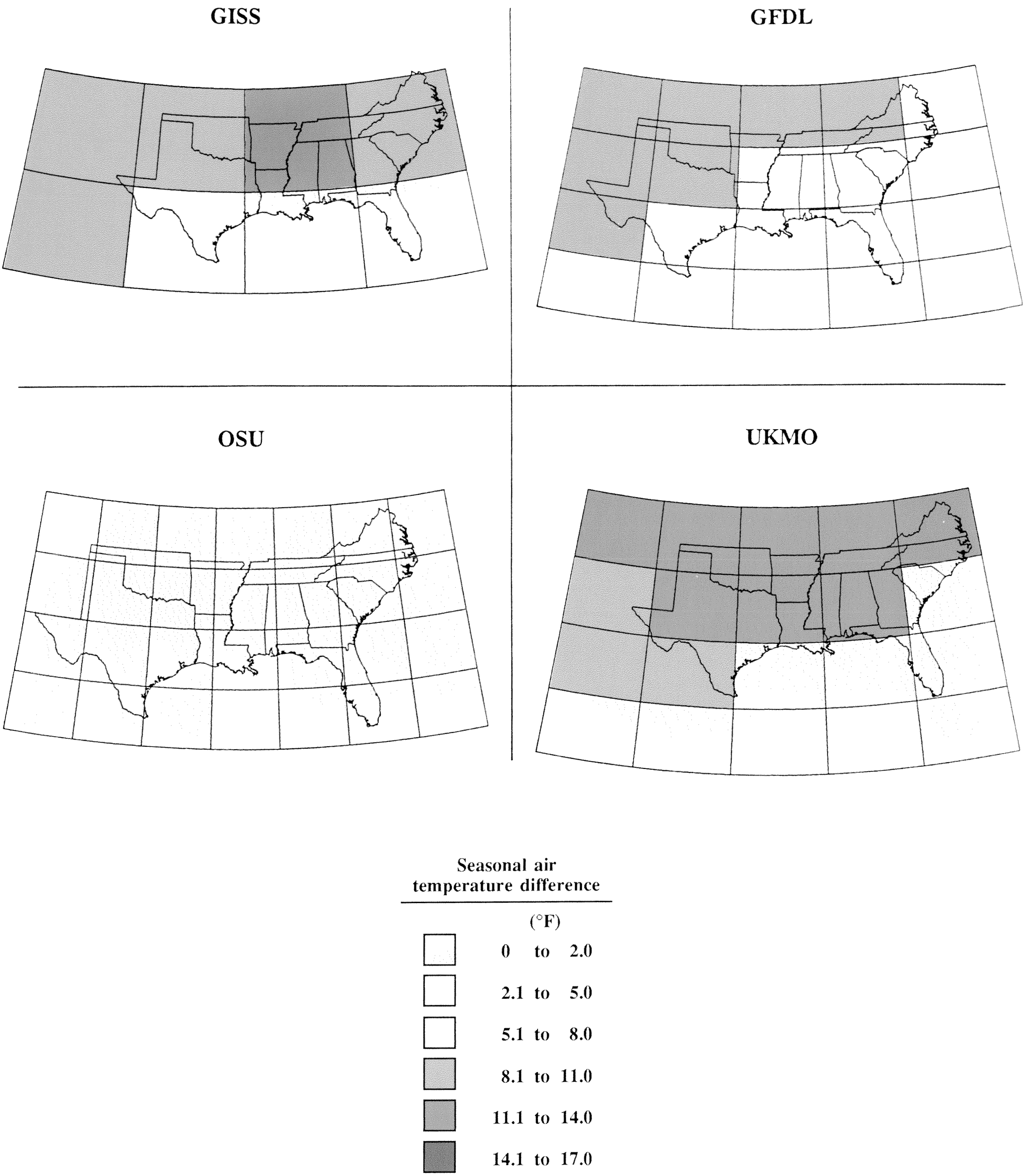
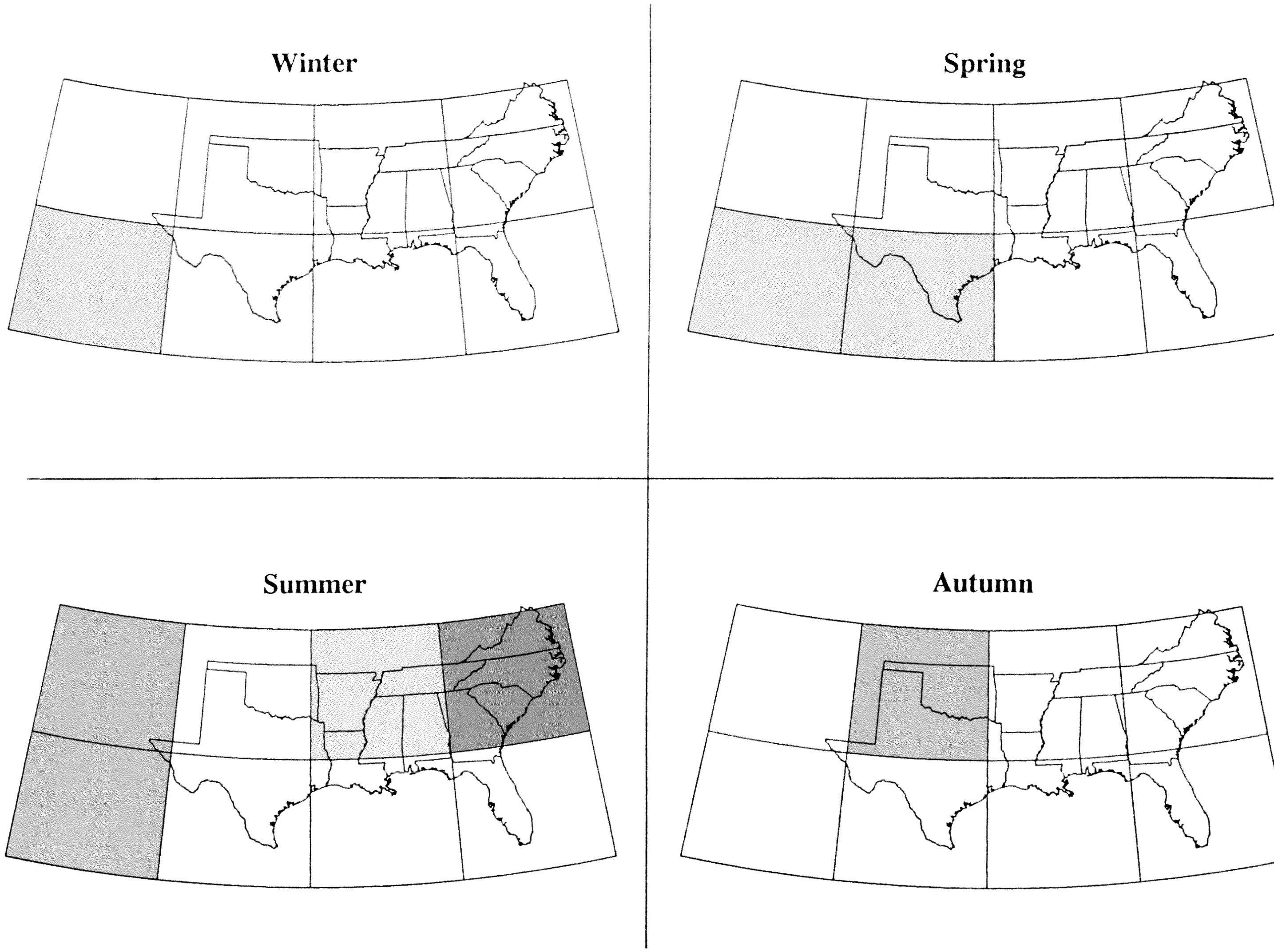


Figure 7—Autumn season temperature differences (2 x CO_2 - 1 x CO_2) for the South.



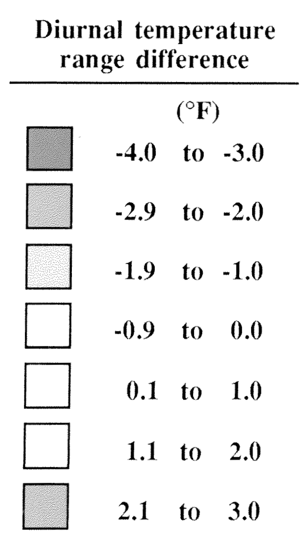


Figure 8—Diurnal temperature range differences (2 x CO_2 - 1 x CO_2) produced by the GISS model for the South.

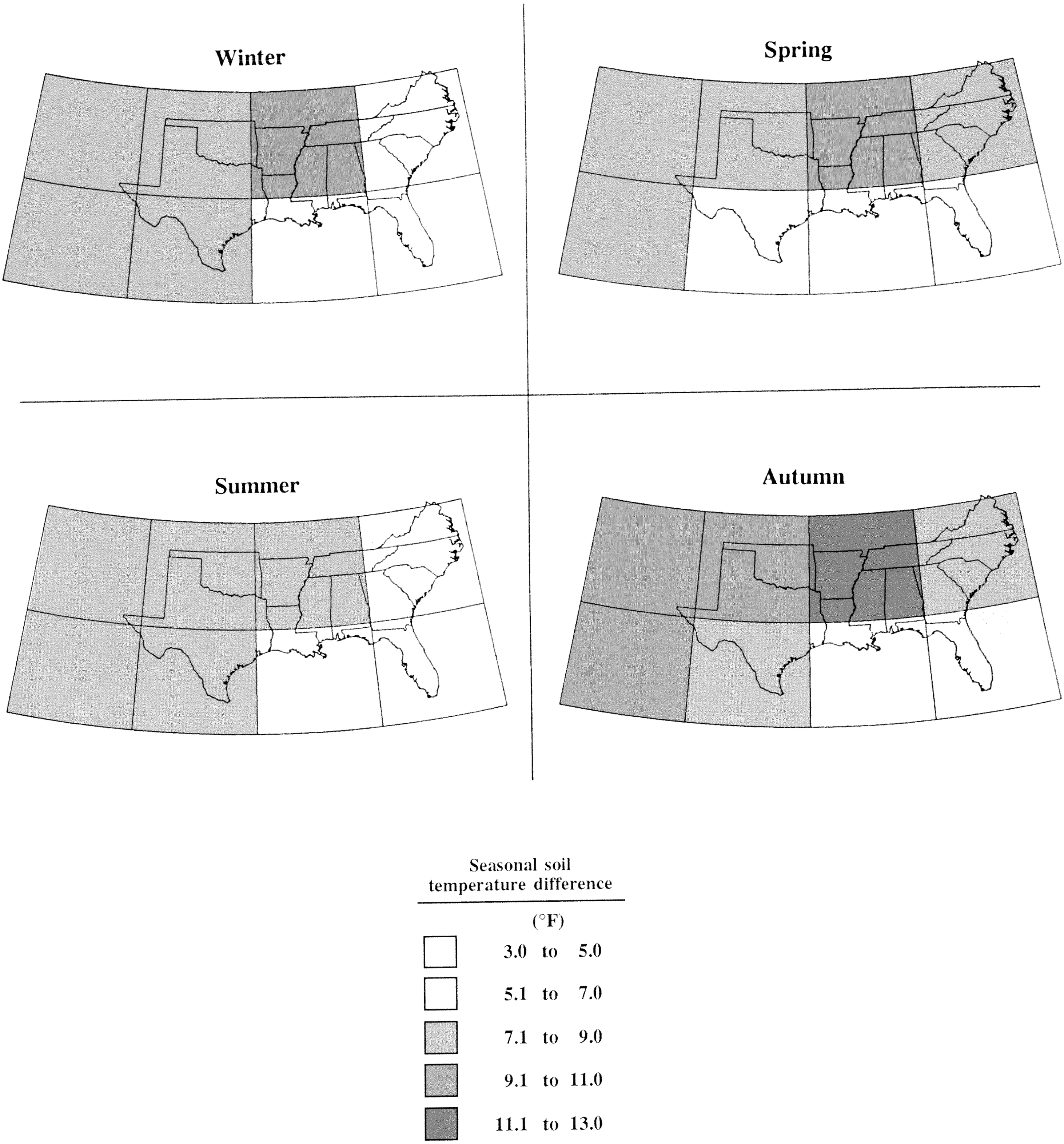


Figure 9—Soil temperature differences (2 x CO_2 - 1 x CO_2) produced by the GISS model for the South.

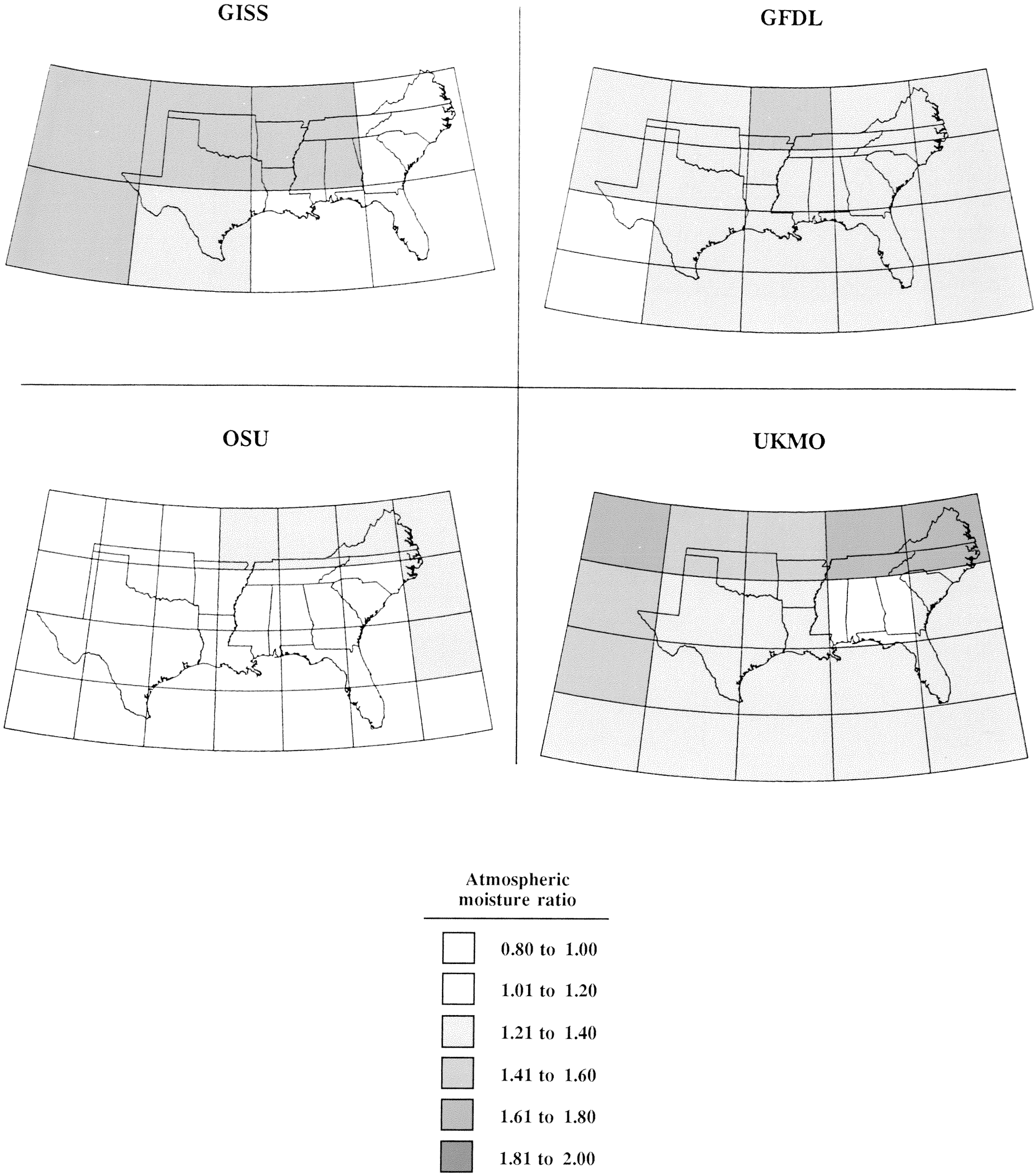


Figure 10—Winter season atmospheric moisture ratios (2 x CO_2 / 1 x CO_2) for the South.

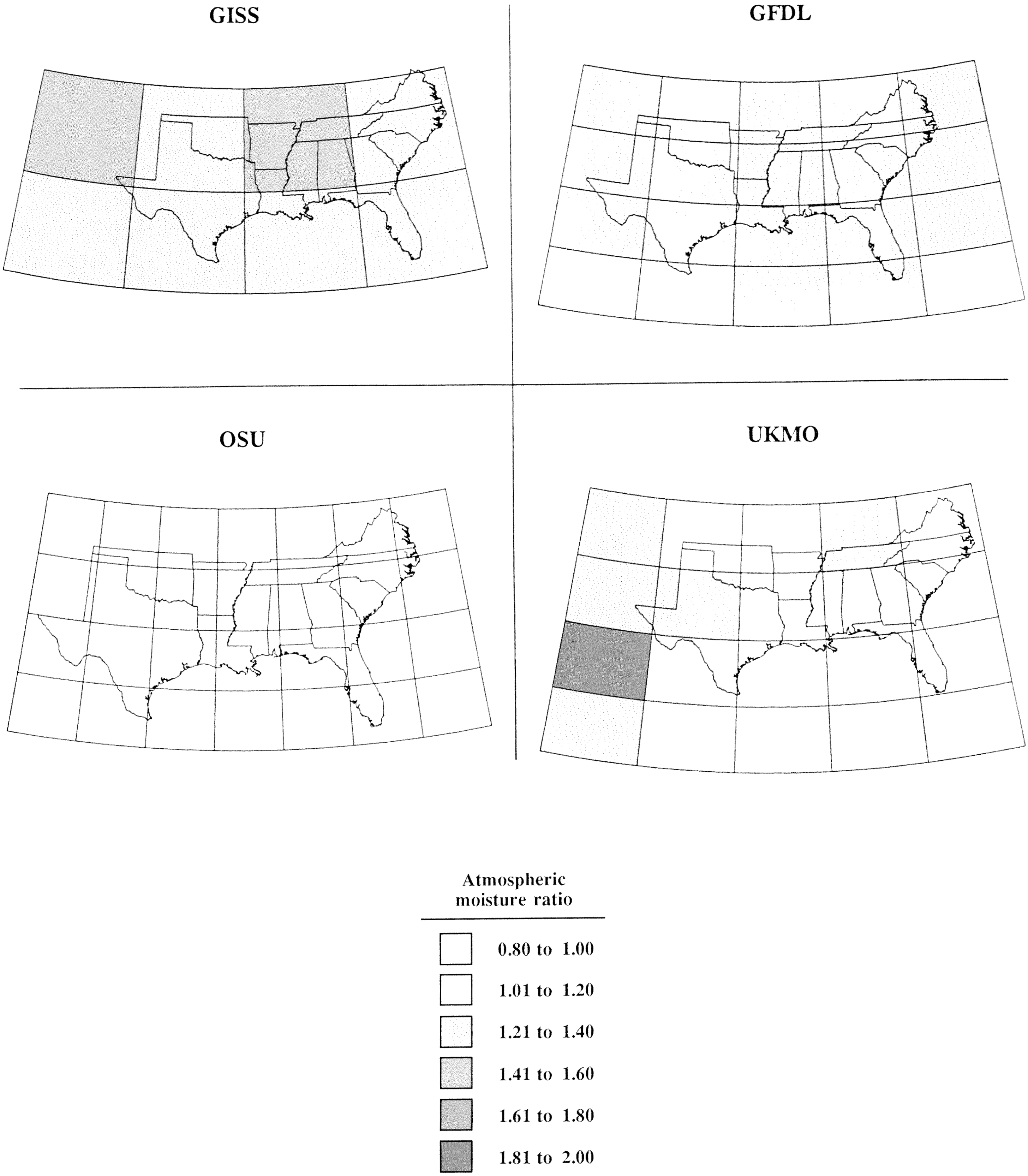


Figure 11—Spring season atmospheric moisture ratios (2 x CO_2 / 1 x CO_2) for the South.

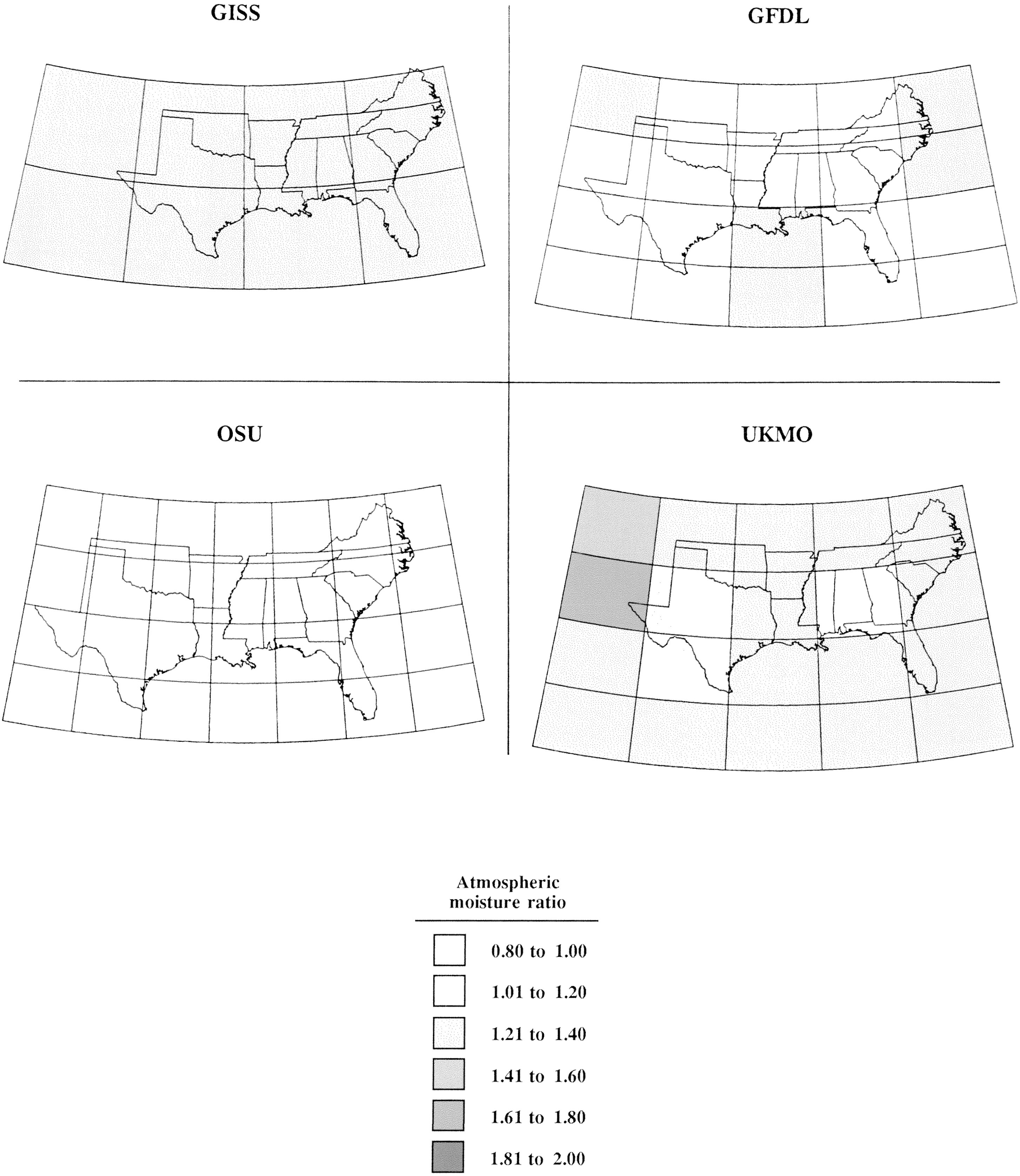


Figure 12—Summer season atmospheric moisture ratios (2 x CO_2 / 1 x CO_2) for the South.

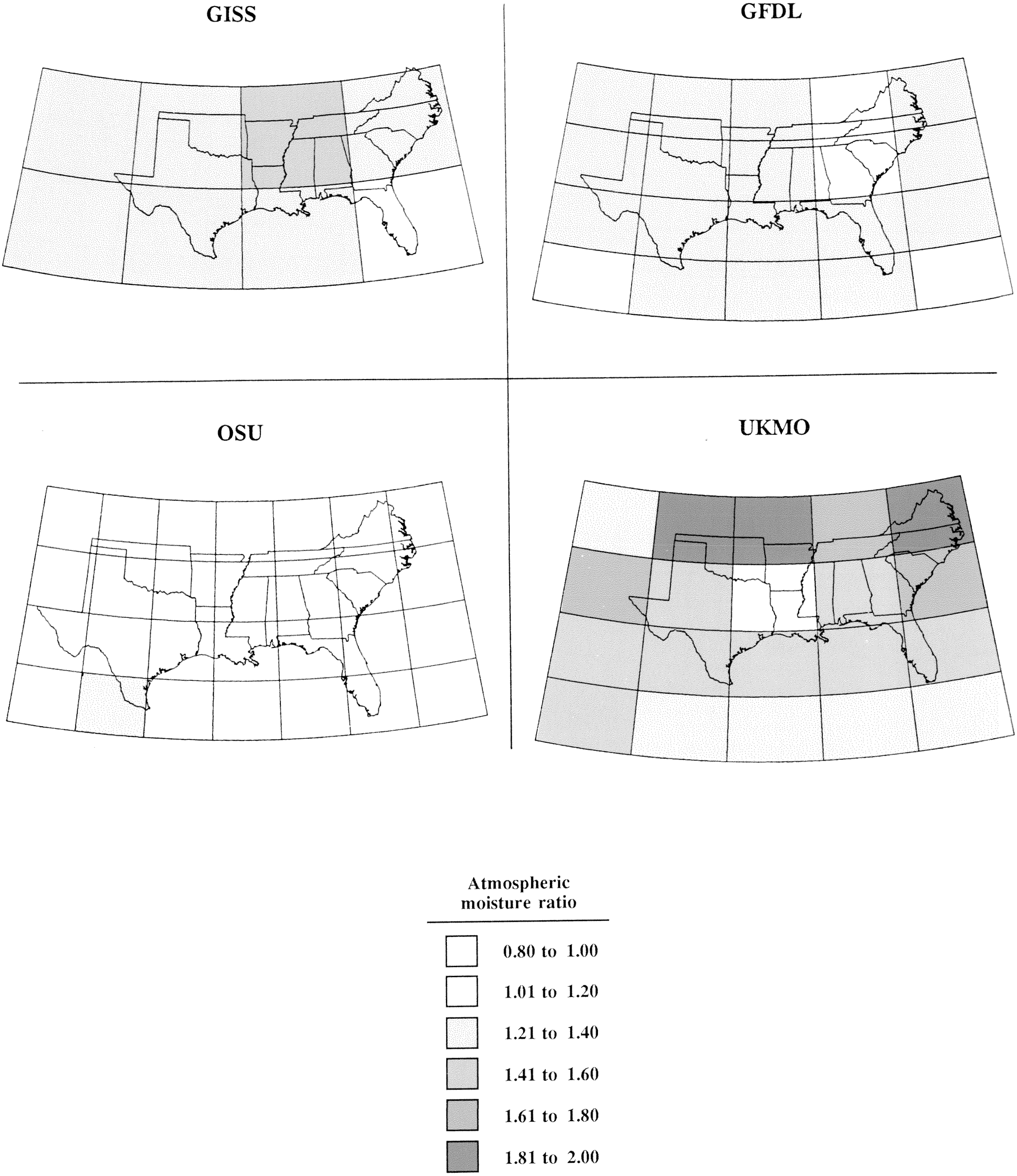


Figure 13—Fall season atmospheric moisture ratios ($2 \times CO_2$ / $1 \times CO_2$) for the South.

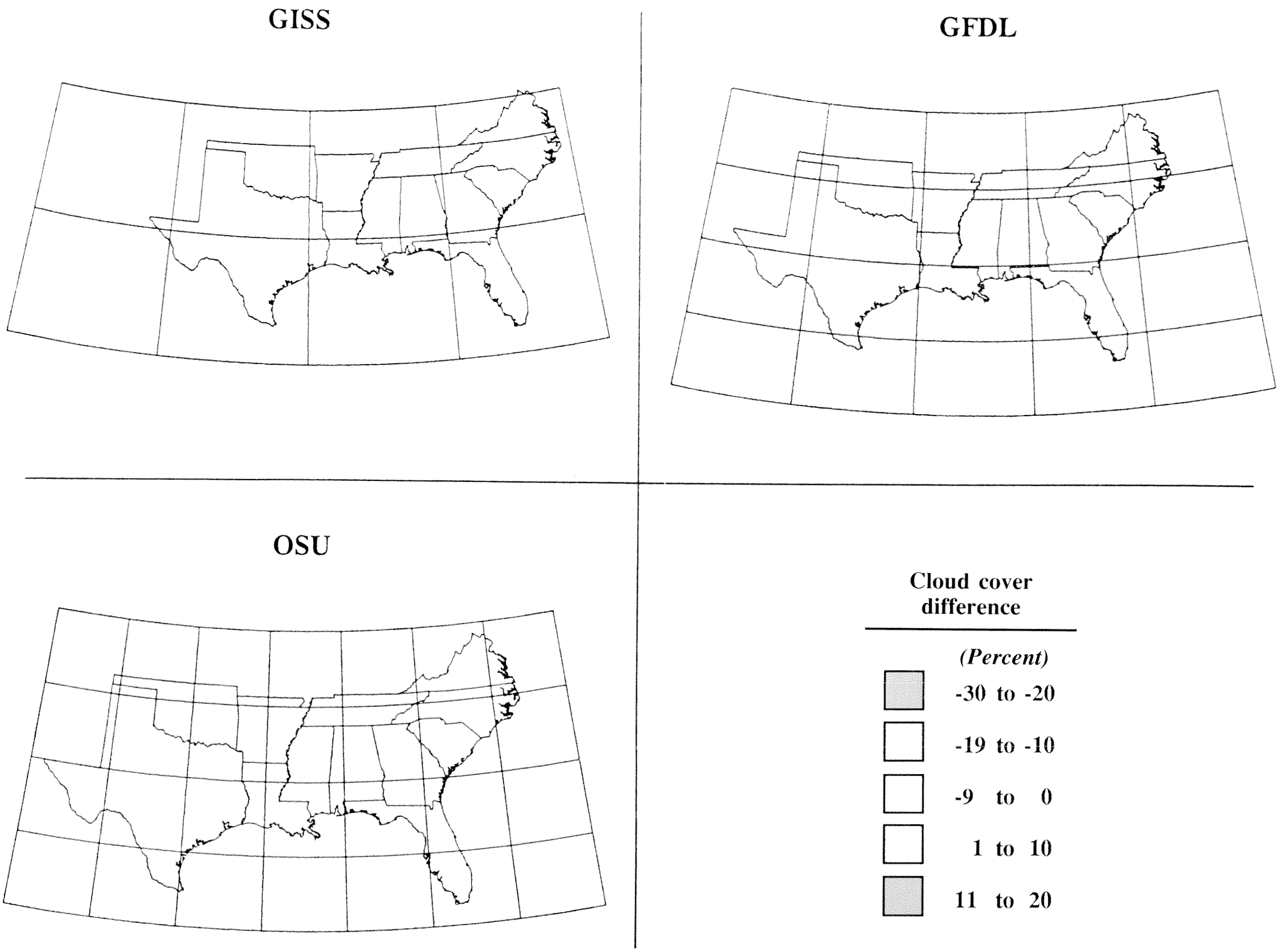


Figure 14—Winter season percent cloud cover differences ($2 \times CO_2$ - $1 \times CO_2$) for the South.

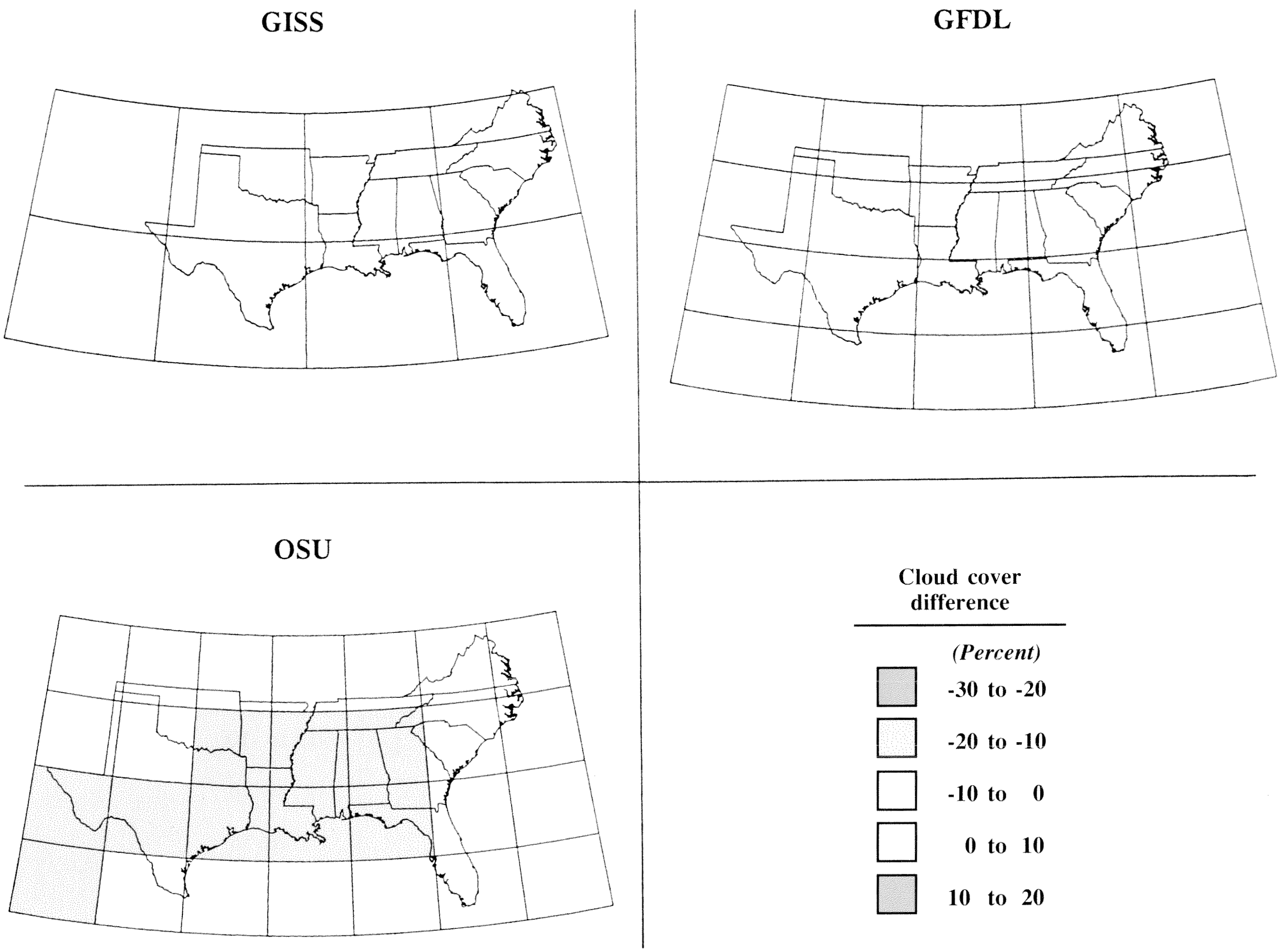


Figure 15—Spring season percent cloud cover differences (2 x CO_2 - 1 x CO_2) for the South.

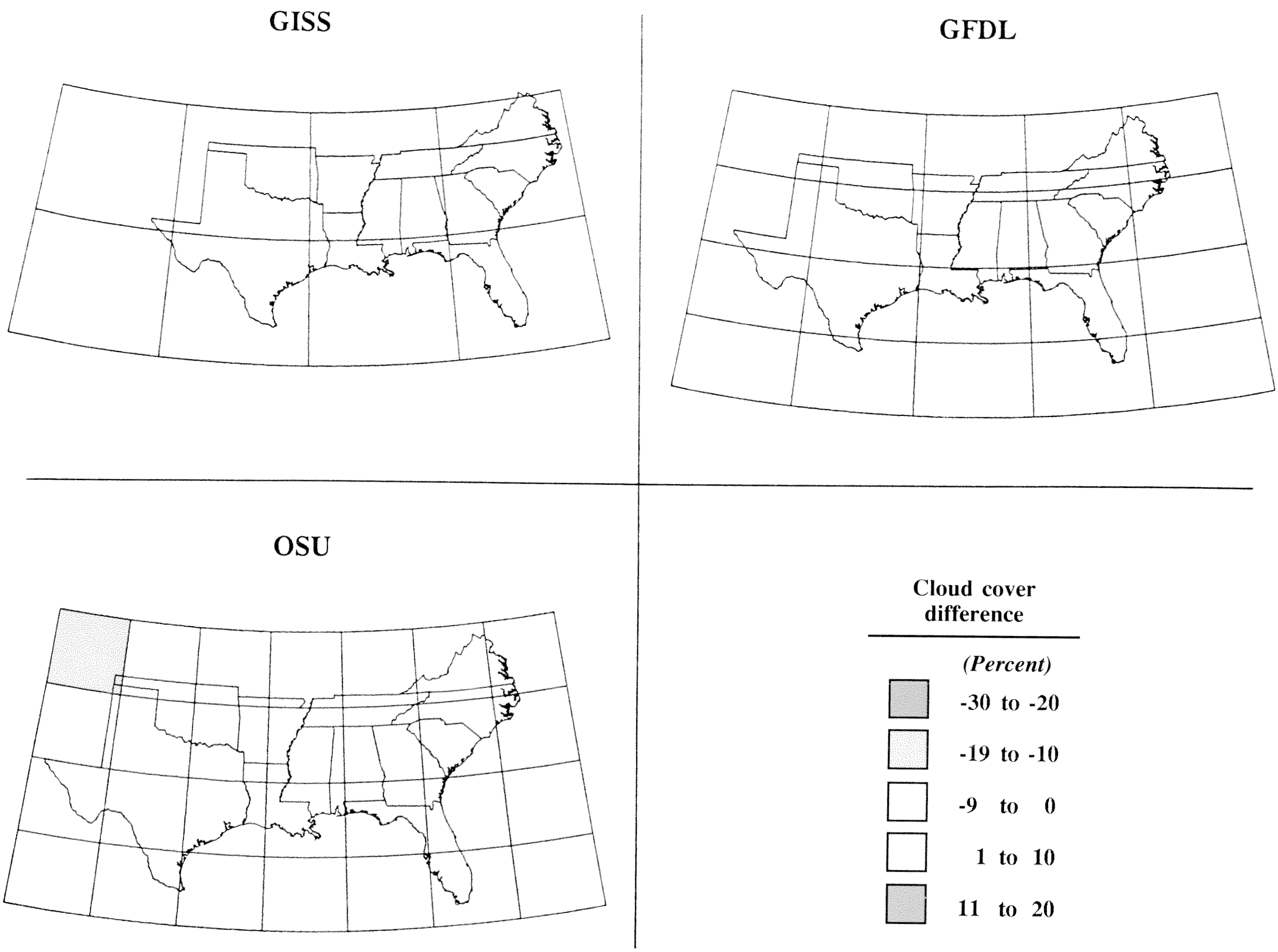


Figure 16—Summer season percent cloud cover differences (2 x CO_2 - 1 x CO_2) for the South.

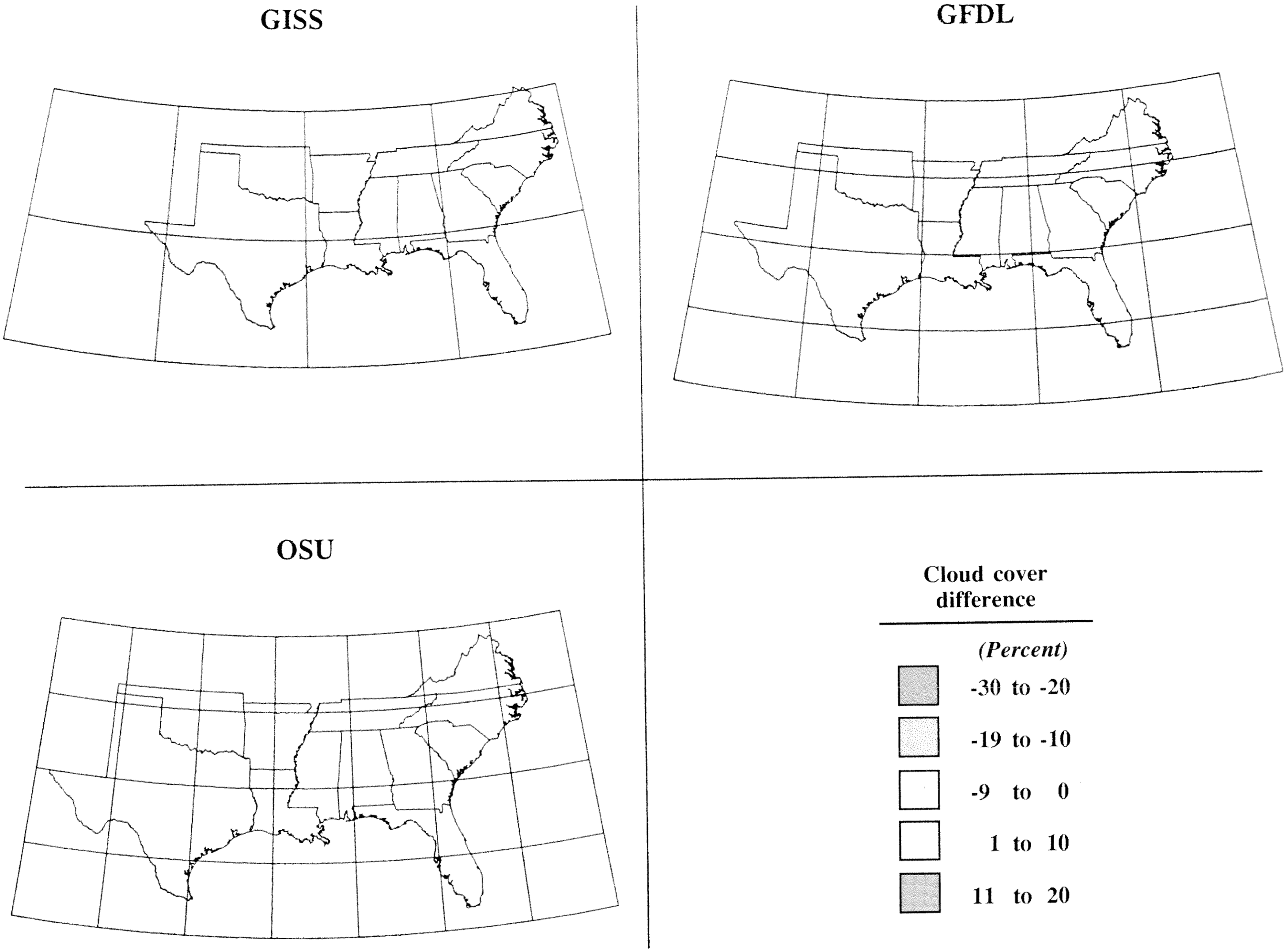


Figure 17—Fall season percent cloud cover differences ($2 \times CO_2$ - $1 \times CO_2$) for the South.

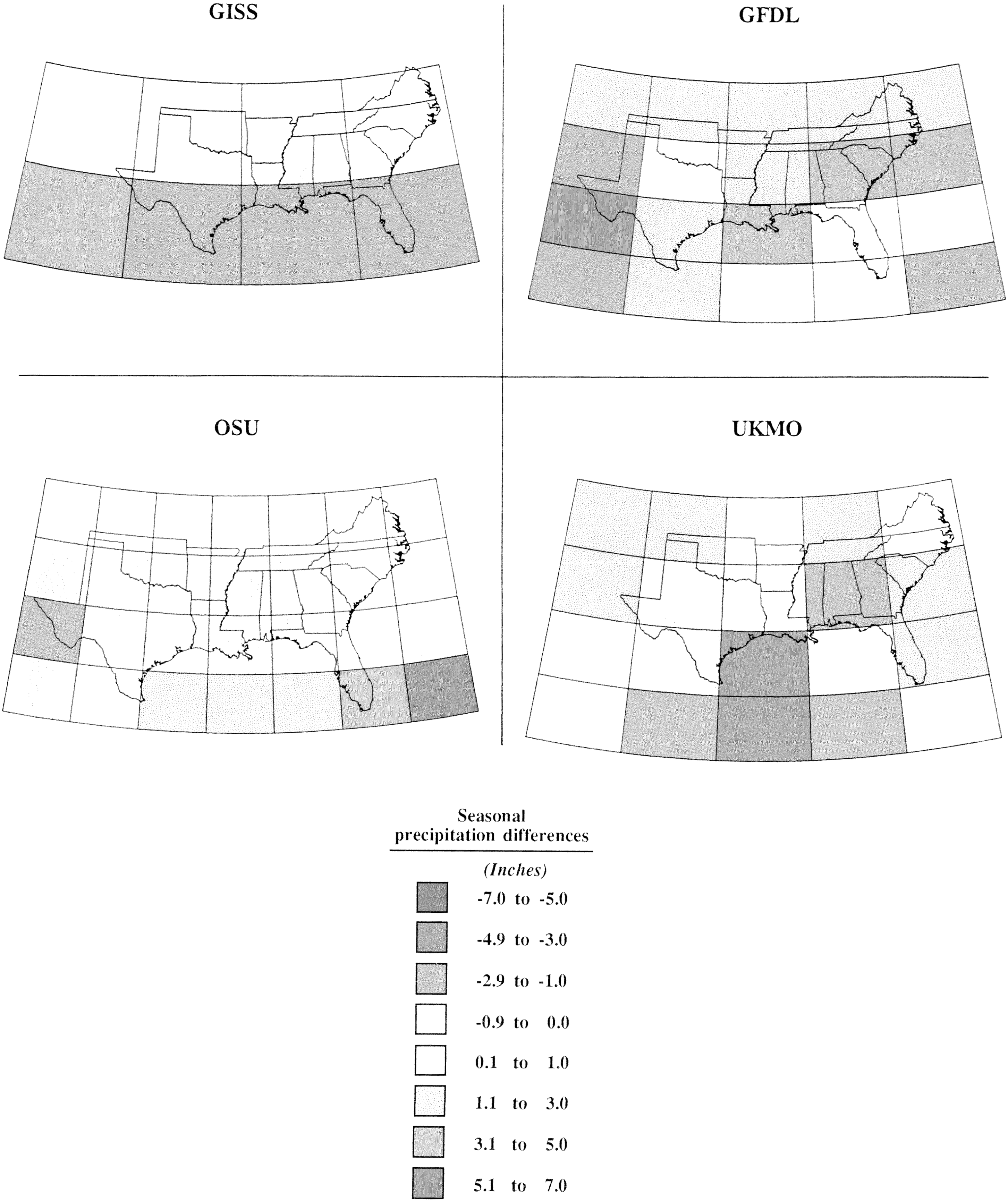


Figure 18—Winter season precipitation differences (2 x CO_2 - 1 x CO_2) for the South.

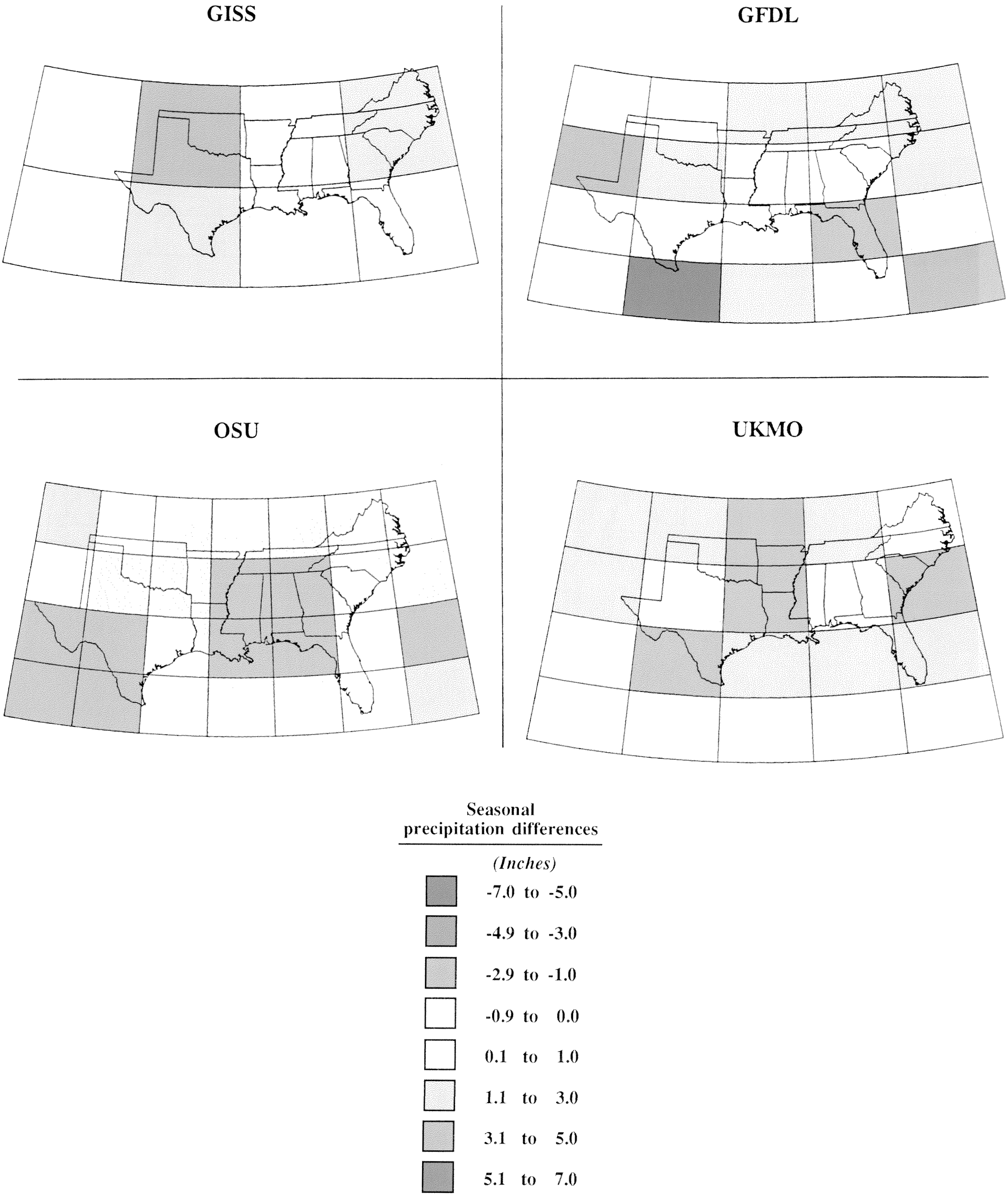


Figure 19—Spring season precipitation differences (2 x CO_2 - 1 x CO_2) for the South.

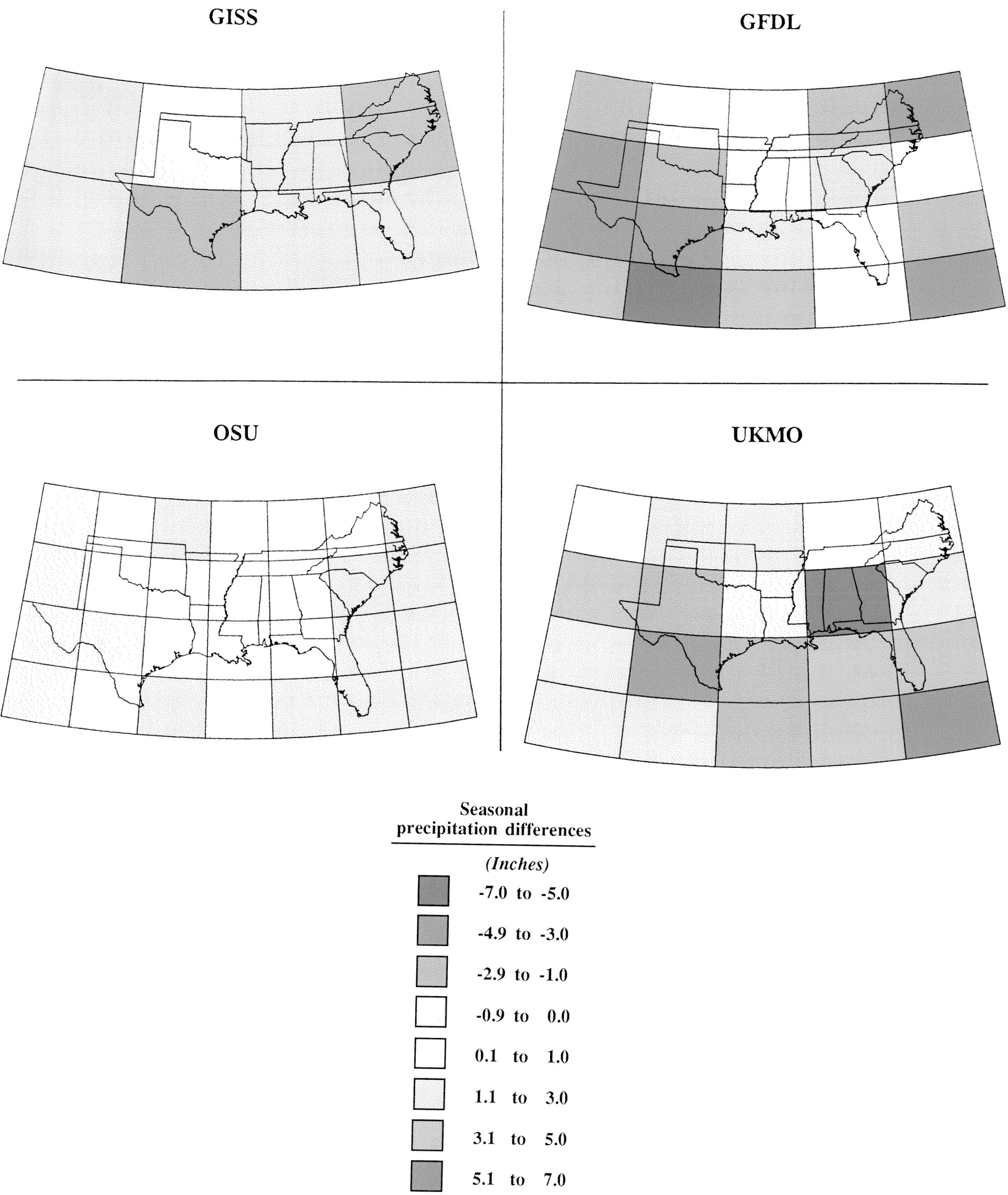


Figure 20—Summer season precipitation differences (2 x CO_2 - 1 x CO_2) for the South.

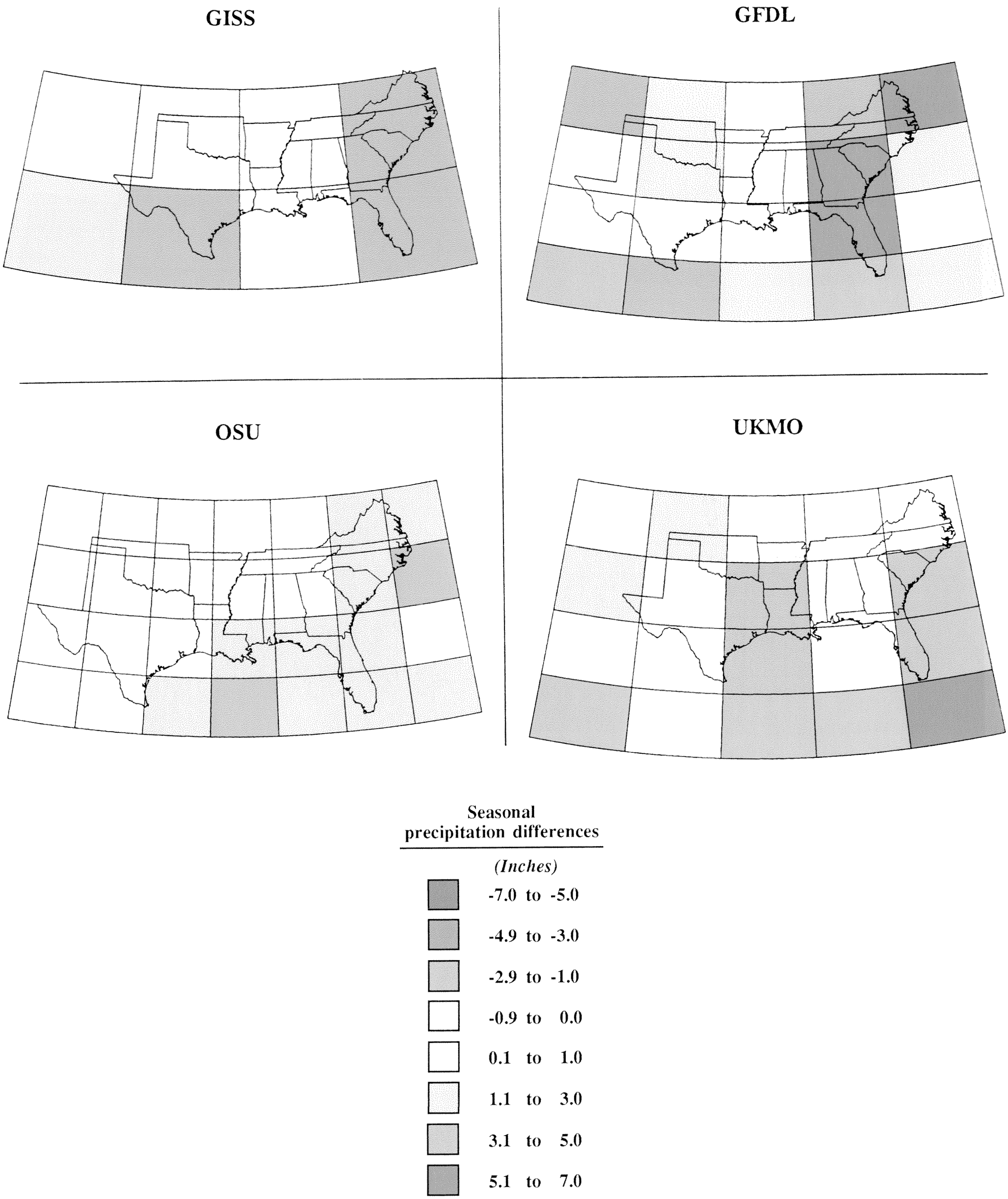


Figure 21—Fall season precipitation differences ($2 \times CO_2 - 1 \times CO_2$) for the South.

Cooter, Ellen J.; Eder, Brian K.; LeDuc, Sharon K.; Truppi, Lawrence E. 1993. General Circulation Model output for forest climate change research and application. Gen. Tech. Rep. SE-85. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station. 38 pp.

This report reviews technical aspects of and summarizes output from four climate models. Recommendations concerning the use of these outputs in forest impact assessments are made.

KEYWORDS: Southern Global Change Program, humidity, cloud cover, precipitation, temperature.

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