Potential effects of climate change on the temperate zones of North and South America

Potenciales efectos del cambio climático en zonas templadas de América del Norte y del Sur

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ABSTRACT

Under current conditions, large areas of temperate western North America and temperate southern South America have arid to subhumid climates that make them vulnerable to changes as a result of human-induced climate change. Predictions of climate change from global circulation models with a doubling of present atmospheric levels of CO_2 suggest large changes in mean annual temperature and small to no changes in mean annual precipitation and the proportion of precipitation received during the summer. Our objective here was to evaluate how predictions of climate change from global circulation models will influence climatic patterns and by inference the distribution of temperate zone ecosystems in North and South America. Calculations of annual water deficits suggest that the area affected by very dry conditions will double as a result of climate change. This expansion will take place in the vicinity of the currently dry areas. Monthly water deficit calculations suggest that approximately half of the temperate zone on each continent is affected by at least one month of deficit. Under a doubled CO_2 climate, these areas would expand to cover up to 77 % of the temperate zone of North America and up to 80 % of South America. The resulting changes to the current distribution of ecosystems will likely be an expansion of deserts at the expense of grasslands in North and South America and an expansion of grasslands at the expense of deciduous and boreal forest in North America. Our analyses assumed that future climatic changes will be encompassed by the predictions of our three doubled CO_2 scenarios. The most likely situation is that actual changes, if they occur, will be different from our scenarios. Therefore, our analyses should be interpreted as indications of the sensitivity of portions of the North and South American temperate zones to increases in temperature. The key conclusion from our analyses is that any increase in temperature caused by climate change will result in expansion of the driest portions of both continents.

Key words: climate change, temperate ecosystems, global circulation model, CO_2.

RESUMEN

Bajo condiciones actuales, extensas áreas de las zonas templadas del oeste de América del Norte y del sur de América del Sur tienen regímenes climáticos áridos a subhúmedos, que son vulnerables a cambios climáticos inducidos por actividades humanas. Predicciones obtenidas a partir de modelos de circulación global bajo una duplicación del CO_2 atmosférico sugieren grandes cambios en temperatura media anual, y cambios pequeños o nulos en la precipitación media anual y la proporción de precipitación estival. Nuestro objetivo fue evaluar cómo las predicciones de cambio climático obtenidas de modelos de circulación global influirán sobre los patrones climáticos, e inferir a partir de ello la distribución de los ecosistemas de las zonas templadas de América del Norte y del Sur. Cálculos de déficit hídrico anual sugieren que, debido al cambio climático, se duplicará el área afectada por condiciones muy secas. Esta expansión ocurrirá en las cercanías de las zonas áridas actuales. Cálculos mensuales de déficit hídrico sugieren que aproximadamente la mitad de la zona templada de cada continente se ve afectada por al menos un mes de déficit. Bajo un clima con doble CO_2, estas áreas se expandirían y cubrirían hasta 77 % de las áreas templadas de América del Norte y hasta 80 % de América del Sur. Los cambios en la distribución de ecosistemas resultantes probablemente serán debidos a la expansión de los desiertos a expensas de los pastizales en América del Norte y del Sur, y la expansión de los pastizales a expensas de los bosques deciduos y boreales en América del Norte. Nuestros análisis asumen que

los cambios climáticos futuros estarán abarcados por las predicciones de los tres escenarios de duplicación de CO_2 que utilizamos. La situación más probable es que los cambios reales, si es que ocurren, serán distintos a nuestros escenarios. Por lo tanto, nuestros análisis deberán interpretarse como indicaciones de la sensibilidad de partes de las zonas templadas de América del Norte y del Sur a aumentos de temperatura. La principal conclusión de nuestros análisis es que cualquier aumento de temperatura debido a cambios climáticos resultará en una expansión de las porciones más áridas de ambos continentes.

Palabras clave: cambio climático, ecosistemas templados, modelos de circulación global, incremento en CO_2.

INTRODUCTION

Understanding ecosystem responses to climate change is one of the most urgent problems facing ecologists at the beginning of the 21st century. A key first step to understanding ecosystem responses is to evaluate the relative change in climatic constraints for ecosystem processes at regional scales. For instance, how will predicted climate change alter the patterns of water availability in the water limited regions of the temperate zone? Will the temperate regions of different continents respond similarly to these changes? As with many other regional problems, a comparative approach is a very powerful way to understand these patterns and to investigate how ecosystems will respond to global change.

There are important similarities in the structure of temperate ecosystems between North and South America (Bailey 1984, 1989, Schultz 1995). These similarities in ecosystems are based upon similarities in temperate zone climatic patterns between the two regions (Paruelo et al. 1996).

A comparative approach using sites in North and South America is a powerful tool for exploring the potential or actual consequences of global change. The flora and fauna of North and South America have had different evolutionary histories over the past 10,000 years. Additionally, post settlement (past 200 years) and current land use are different. Both the post-settlement extent of conversion of native ecosystems to agricultural ecosystems and the intensity of the use of those converted systems have been greater in North America than in South America. Furthermore, the predicted rates of climate change are different in the grassland and shrubland regions of North and South America (Hall et al. 1992, Smika 1992). To what extent have the differences in land use or evolutionary histories overridden climatic similarities in determining the structure and function of temperate ecosystems on the two continents? A good representation of the climatic similarities between the two continents is a critical step in the process of answering this question. Furthermore, using a comparative approach, we can begin to test the generality of our understanding of particular ecosystems.

Our objective is to evaluate how predictions of climate change from global circulation models will influence climatic patterns and by inference the distribution of temperate zone ecosystems in North and South America. While we used specific results from global circulation models, we are less interested in any of the specific changes predicted by the models than in assessment of the sensitivity of ecologically significant climatic characteristics to those changes.

MATERIALS AND METHODS

Our comparisons were based upon the current climates of the temperate zones of North and South America using the Leemans & Cramer (1991) database and predicted changes from three global circulation model scenarios for equilibrium temperatures under conditions of an effective doubling of CO_2. The Leemans & Cramer (1991) database was constructed from climatic data for 2,583 stations worldwide. Weather records were interpolated to a 5º x 5º (Latitudinal, Longitudinal) grid. The database includes monthly average temperature, precipitation, and cloudiness for each grid cell. This database has been previously used in a number of biogeographical and ecological studies (Solomon & Leemans 1990, Prentice et al. 1992, Cramer & Solomon 1993, Leemans & Solomon 1993, Paruelo et al. 1996).

The three global circulation models from which climate change scenarios were used included geophysical fluid dynamics laboratory (GFDL, Manabe & Weatherald 1987), Goddard institute for space studies (GISS, Hansen et al. 1983) and United Kingdom meteorological office (UKMO, Wilson & Mitchell 1987). The models produce a range of estimates of warming under double CO_2 for both the earth and for the temperate zones of North and South America. We produced the climate change

scenarios by modifying the current monthly temperature and precipitation data from the Leemans & Cramer (1991) database using the estimated change values from the outputs of the global circulation models. The climate scenarios, then, are hybrids between the historical climatic data and the model outputs (Smith & Tirpak 1988).

Our approximation of the temperate zone includes the areas between 30º and 55º of latitude in North and South America. Because we are most interested in characterizing the grassland and shrubland areas we further limited our analysis to the areas between west longitudes 85º and 125º for North America, and west longitudes 48º and 76º for South America (Fig. 1). This resulted in a total of 3,816 5º x 5º terrestrial grid cells for North America and 1,232 for South America. In North America, we excluded the area east of 85º W longitude where there are no substantial areas of grassland or shrubland. Monthly temperature and precipitation data for current conditions and for the climate change scenarios were imported into a geographical information system (ARC/INFO 7.0 - ESRI, Redlands, California).

Fig. 1: Map of the Americas showing the study areas between 30º and 55º latitude. For the North American region, we discarded the area east of the 85º W longitude because there are no comparable areas in South America.

Mapa de América mostrando las áreas de estudio entre las latitudes 30° y 55°. Para la región de América del Norte, se eliminó el área al este de la longitud 85° W debido a que no existen áreas comparables en América del Sur.

Our analysis focuses on four variables. Three of these were identified by Paruelo et al. (1996) as important for explaining a large fraction of the variability in the spatial patterns of current climates on both continents: mean annual precipitation (MAP), mean annual temperature (MAT), and the seasonality of precipitation (SEAS). SEAS was defined as the proportion of the precipitation falling during the summer months (June, July and August in North America and December, January and February in South America). The fourth variable, water deficit, was included to account for the anticipated general decrease in water availability to ecosystems as a result of climate change. We adopted Heinrich Walter's formulation of water deficit from climate diagrams (Walter 1973). Because the potential natural vegetation of much of the area of our analysis is grassland or shrubland, we used Walter's recommendation of a ratio of 1 °C = 3 mm precipitation on a monthly time step to calculate water deficit (Walter 1973). Therefore, a month of water deficit was identified when the mean monthly temperature exceeded the mean monthly precipitation when

plotted at a ratio of 1 °C = 3 mm (Fig. 2). The equations for calculating the water deficit are

$$wd = \Sigma \; wd_i \; (i = 1,2,3,\dots 12)$$
$$wd_i = mmp_i - mmt_i \times 3$$

(equation 1) where wd is annual water deficit in mm, wd_i the deficit for month i, mmp_i is mean monthly precipitation for month i in mm, and mmt_i is mean monthly temperature for month i in °C. The constant three has units of mm °C^{-1}. At the Central Plains Experimental Range in northeastern Colorado, according to Walter's calculations, water deficits occur in July, August, September and October (Fig. 2). Water deficits are represented by negative numbers and water surpluses by positive numbers. For example in Fig. 2, the water deficit at the central plains experimental range in August is 18 mm.

RESULTS AND DISCUSSION

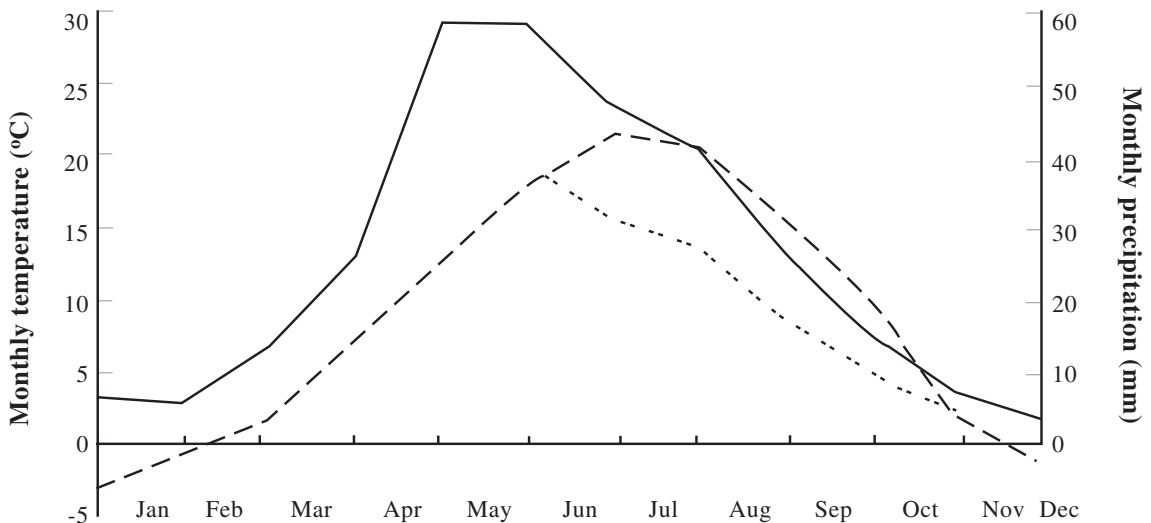The patterns generated from our analyses highlight the large-scale similarities between

Fig. 2: Climate diagram for the central plains experimental range (40.8° N, 104.8° W) illustrating the periods of water deficit and surplus. The solid line is mean annual precipitation plotted at a ratio of 1 °C = 2 mm, the dotted line is mean annual temperature and the dashed line is mean annual precipitation plotted at a ratio of 1 °C = 3 mm. See text for more explanation.

Diagrama climático para el rango experimental de los "central plains" (40,8° N, 104,8° W) ilustrando los períodos de déficit y sobreabundancia de agua. La línea sólida es la precipitación media anual graficada a una razón de 1°C = 2 mm, la línea punteada es la temperatura media anual y la línea en trazos corresponde a la precipitación graficada a una razón de 1 °C = 3 mm. Véase el texto para mayores explicaciones.
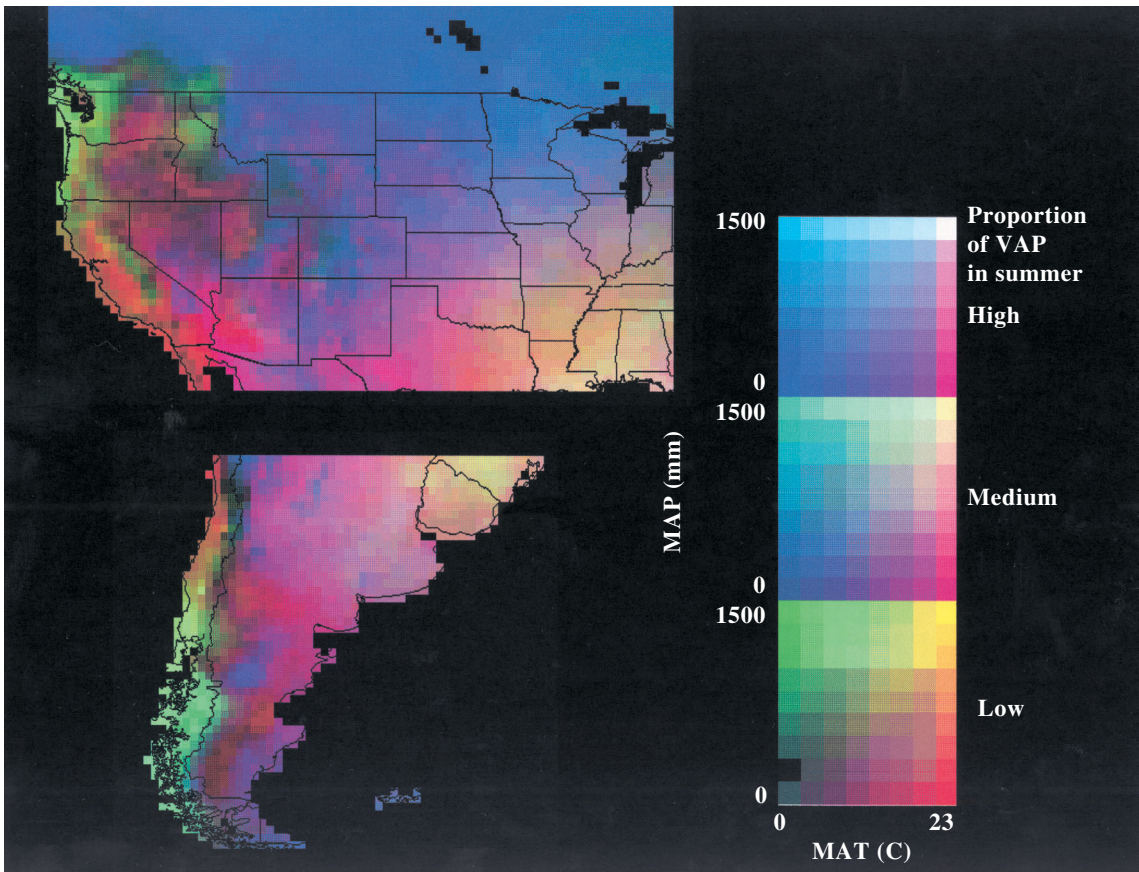
Fig. 3: The geographic distribution of mean annual temperature (MAT), mean annual precipitation (MAP), and seasonality (proportion of summer precipitation) (SEAS) and the climates resulting from combining these three variables in both North and South America. Each variable (MAT, MAP, SEAS) was assigned to a band (Red, Green, and Blue) and displayed as composite color raster image (large maps). For the single variable maps (small maps), the value of each variable increases with the intensity of the color.

Distribución geográfica de la temperatura media anual (MAT), precipitación media anual (MAP), y estacionalidad (proporción de precipitación de verano) (SEAS) y los climas resultantes de combinar estas tres variables en América del Norte y del Sur. Cada variable (MAT, MAP, SEAS) fue asignada a una banda (Rojo, Verde y Azul) y representada como una imagen "raster" compuesta en colores (mapa grande). Para los mapas de una variable (mapas pequeños), el valor de cada variable incrementa con la intensidad del color.

North and South America and reinforce our current knowledge of climatic patterns (Fig. 3). The grassland and shrubland areas on both continents are located between wetter, forested areas. In North America, this occurs on a west-east axis, and in South America it occurs on a southwest to northeast axis. An area of high precipitation (> 1,500 mm MAP), moderate temperature (~ 10 ºC MAT) and domination of winter precipitation occurs along the west coasts of both continents (represented by green in Fig. 3). Coniferous forests dominate these areas in North America (Barbour & Billings 1988) and deciduous and evergreen forests (*Nothofagus* sp.) are dominant in South America (Cabrera 1976). The eastern boundary between the grasslands and temperate deciduous forests in North America (represented by a complex of tan, orange, and yellow in Fig. 3) is characterized by high precipitation (>1,200 mm MAP), high temperature (15-20 ºC MAT) and a lack of seasonality in precipitation (Lauenroth et al. 2000). Similar climatic conditions are suggested by similar colors in the northeast portion of the study area in South America

(Fig. 3) but there is no concomitant vegetation transition (Soriano 1992). The potential vegetation on both sides of the climatic transition in South America is dominated by grasslands which has puzzled plant geographers and ecologists for at least the past century (Schmieder 1927, Parodi 1942, Ellenberg 1962, Walter 1967, 1973).

The grasslands of central North America are found in areas of low to moderate amounts of precipitation (300-800 mm MAP) concentrated during the warmest months (Coupland 1992, Lauenroth et al. 2000). While these areas (pinkish- purple changing to purple areas in the northcentral United States and southern Canada, Fig. 3) span a range of MAT from less than 5 ºC to greater than 20 ºC, the majority have MAT < 10 °C. These classically continental climates are substantially more widespread in North America than in South America.

The intermountain zone in the western United States and Patagonia in southern Argentina have similar climatic characteristics (mottled rust colors in Fig. 3) and similar vegetation (Soriano 1983, West 1983). These are areas of relatively low precipitation (150-500 mm of MAP) and MAT ranging from 0 to 12 °C. Shrublands and shrubland-grassland mixtures are the dominant vegetation types and most receive a large proportion of their annual precipitation in the winter. Northwestern Argentina and southwestern United States and northern Mexico (magenta colors in Fig. 3) are characterized by hot, arid shrublands with strong summer seasonality in precipitation. The structure of the vegetation in these areas is similar between the two continents with a predominance of creosote bush (*Larrea* sp.) and xerophilous trees (Fabaceae) (MacMahon & Wagner 1985, Mares et al. 1985).

Mediterranean climates, characterized by wet winters and dry summers occur on the west coasts of both continents (rusty red colors in Fig. 3). In North America, they occur along the southwestern coast of the United States and the northwestern coast of Mexico and in South America they occur along the northwestern coast of Chile. The area in North America is larger, but both support a mixture of annual grassland and sclerophilous shrubland and woodland (Mooney 1977). These areas grade into subtropical arid shrublands toward the equator.

The distributions of the three climatic variables have some important similarities and differences between the two continents (Fig. 4). Our study region in North America has a large

percentage its area with a high proportion of summer precipitation (> 30 %) and the corresponding region in South America has large percentage its area with a low proportion of precipitation in the summer (< 30 %) (Fig. 4A). The proportion of very dry areas (< 200 mm yr^{-1}) and very wet areas (>1,000 mm yr^{-1}) is lower in North America than in South America (Fig. 4B). Most of the grassland and shrubland areas of North America fall within the range of 200-800 mm yr^{-1}. A higher proportion of land at high latitudes and greater continentality are the reasons for the higher relative frequency of areas with low temperatures in North America (Fig. 4C).

Water deficit provides an integrated assessment of the effects of changes in MAT, MAP, and SEAS by combining this information into an annual ecological index of water availability (Walter 1973). According to our calculations, the majority of the temperate zones on both continents are currently in a state of water surplus on an annual basis (Fig. 5). Approximately 11 % of North America and 28 % of South America currently experience an annual water deficit. A much larger fraction of each continent experiences one to several months of deficit during the year. While a larger fraction of the South American temperate zone experiences water deficit than the North American temperate zone, maximum deficits in South America are 400 mm yr^{-1}. By contrast, in North America maximum deficits are > 700 mm yr^{-1}. In South America, the largest area of maximum deficit is in northwestern Argentina and in North America it is in the southwestern United States and northwestern Mexico. On both continents these areas are dominated by creosote bush (*Larrea* sp.). Maximum surpluses (4,000 mm) in South America occur along the southern coast of Chile. In North America, maximum surpluses (2,500 mm) occur in the Pacific Northwest.

The geographic distribution of water deficits does a good job of identifying arid and semiarid regions on both continents (Fig. 6). In North America, the driest areas are in the southwestern United States and northwestern Mexico. The central valley of California and much of the intermountain west have substantial deficits. The central grassland region has moderate deficits in the semiarid western portion grading into no deficits in the subhumid east where grasslands interface with deciduous forest. The forested areas of the Rocky mountains, the eastern United States and the portion of Canada included in our study area have no water deficits. The driest
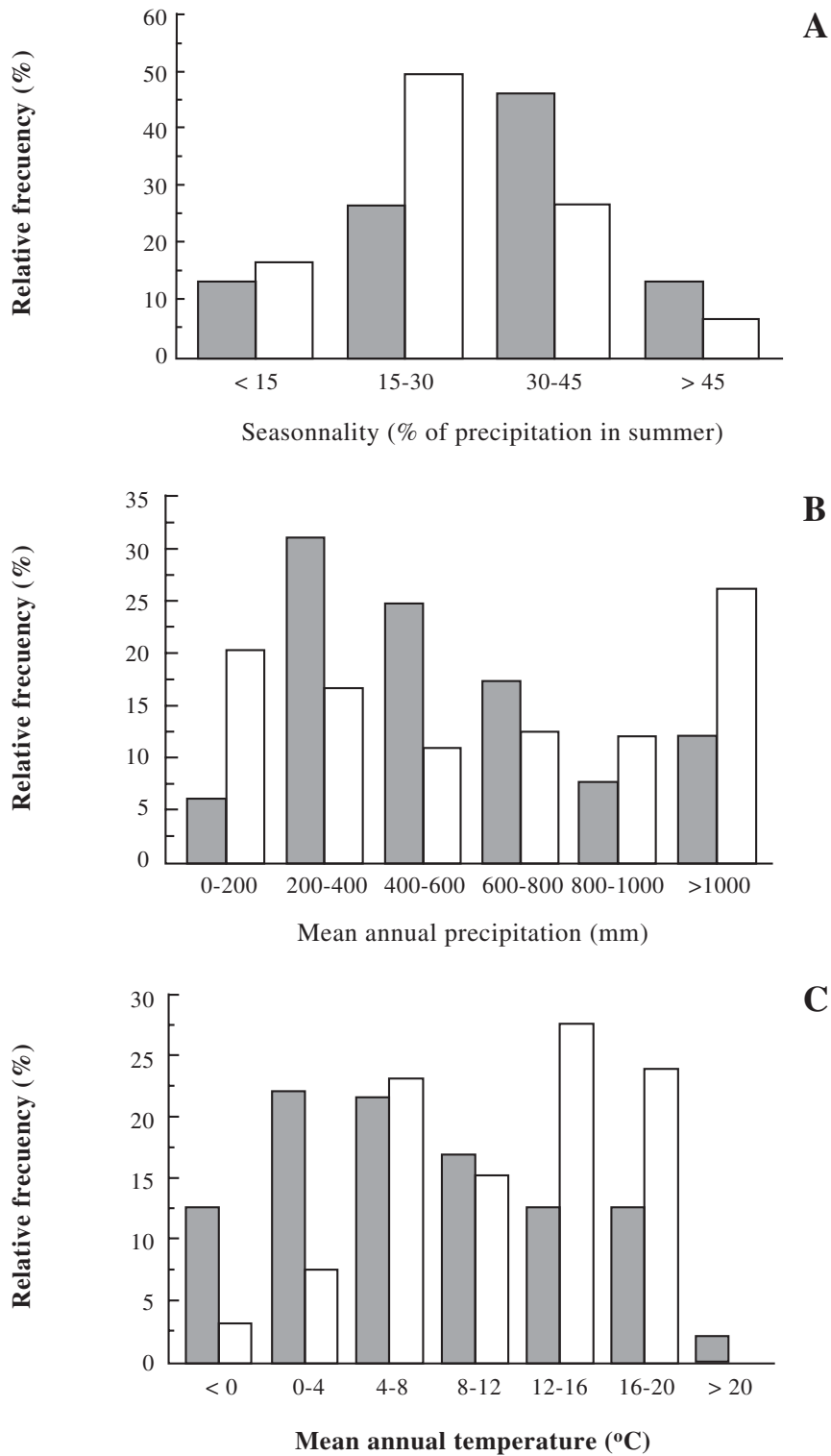
Fig. 4: Frequency distribution of seasonality of precipitation, mean annual precipitation, and mean annual temperature. Shaded bars: North America (n = 3816 grid cells), open bars: South America (n = 1232 grid cells).

Distribución de frecuencia de estacionalidad de la precipitación anual, precipitación media anual, y temperatura media anual. Barras oscuras: América del Norte (n = 3816 celdas), barras claras: América del Sur (n = 1232 celdas).
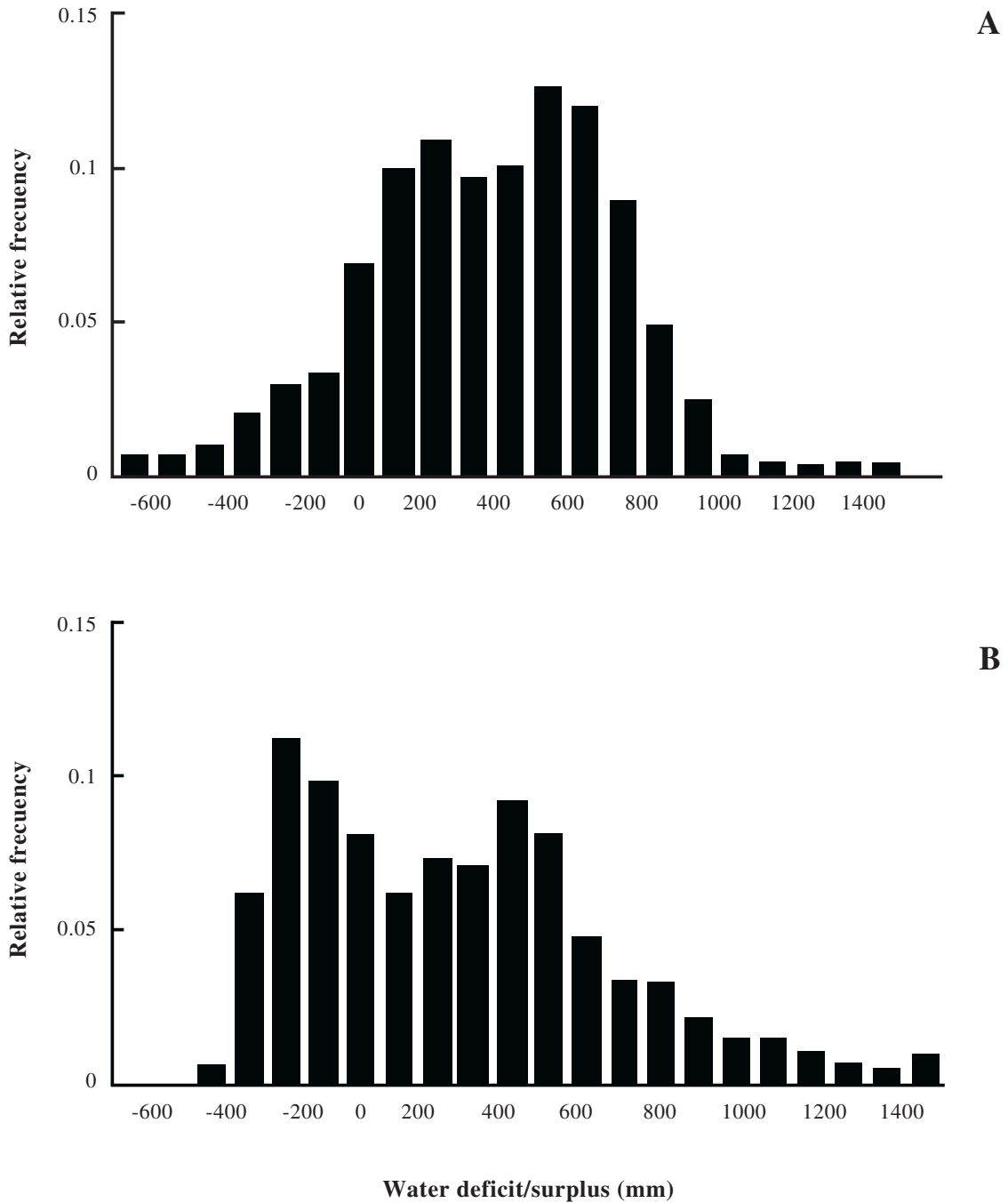
Fig. 5: Frequency distribution of annual water deficits and surpluses for the temperate zones of North and South America.

Distribución de frecuencia de los déficit y sobreabundancia anual de agua para las zonas templadas de América del Norte y Sur.
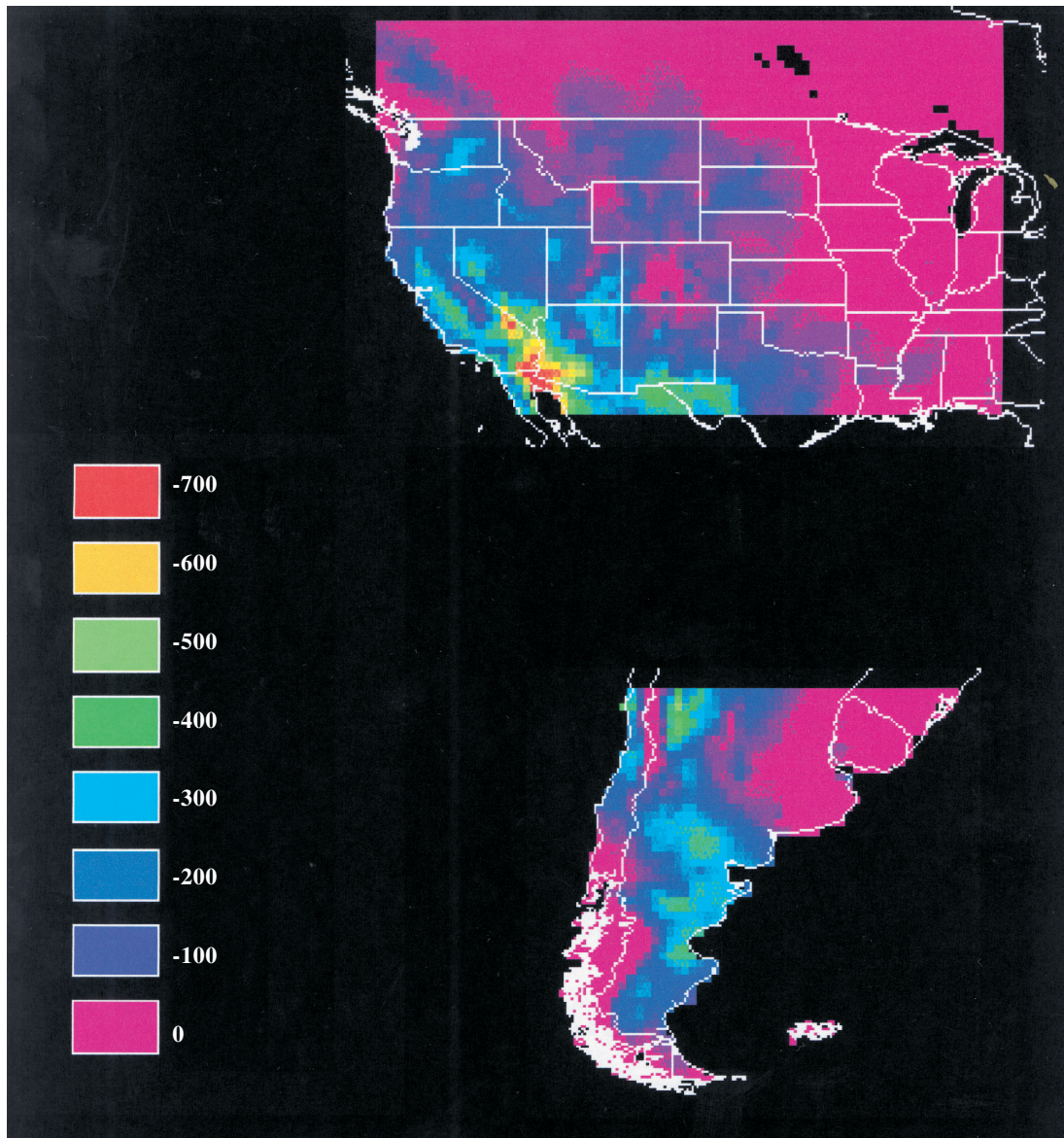
Fig. 6: Geographic distribution of current monthly water deficits in North and South America.

Distribución geográfica de los déficit actuales de agua en América del Norte y Sur.

areas of South America are in the northwestern portion of Argentina and the north coast of Chile. Other dry areas occur in central and southeastern Argentina. The Rio de la Plata grassland region has moderate deficits in the west grading into no deficits in the subhumid east and northeast. In contrast to North America, the grasslands do not grade into forest. The entire area is natural grassland (Soriano 1992). Areas with no monthly water deficit include the eastern and northeastern Rio de la Plata grasslands, high elevation areas in the Andes mountains, and the

southwestern coast of Chile all the way to Tierra del Fuego.

All three global circulation models predicted increases in MAT and no change or increases in MAP for the temperate zones of North and South America (Table 1). Changes in seasonality were predicted to be none or very small. Increases in MAT ranged from 4.40 ºC for the GFDL model in South America to 7.17 ºC for the UKMO model in North America. All three models predicted greater increases in temperature in North America than in South America. Regressions of changes against

latitude resulted in relatively good relationships for MAT but no similar relationships were found for either MAP or SEAS (Table 2).

Predicted changes in MAT increased with latitude for both GFDL and UKMO on both continents while GISS predicted a very small decrease in change with latitude (Fig. 7). Despite the differences in the slopes of the relationships, the predictions from the GFDL and GISS models were similar and differed by < 1 ºC at all latitudes on both continents. The average predicted change in MAT for both models of approximately 4.5 ºC is a good approximation at any latitude on both continents. By contrast, the predictions from the UKMO model were strongly related to latitude (Fig. 7). In North America, predicted changes for 30º N were 6 ºC while those for 55º N were > 8 ºC. Temperature changes were

predicted to be smaller for South America and ranged from 5.2 ºC at 30º S to 6.5 ºC at 55º S.

Climatic change increased the proportion of areas on both continents that experience an annual water deficit. In North America, the proportion doubled from 11 to 22 % and in South America the increase was from 28 to 41 %. The three models were quite similar in their predictions of the increase in annual water deficit despite the differences in their predictions of changes in MAT and MAP (Table 1). The locations of increases encompassed and were adjacent to the existing areas of deficit. The main effect of climate change was to expand the present dry areas.

Since many plants are sensitive to the existence of any period of water deficit, we conducted an additional analysis to identify the magnitudes of deficit periods. We did this by

TABLE 1

Latitudinally averaged means for predicted changes in mean annual temperature (MAT; ºC) mean annual precipitation (MAP; proportion of current MAP), and proportion of precipitation falling in summer (SEAS) for North and South America under a 2 x CO_2 scenario for three global circulation models

Promedios de medias latitudinales para los cambios predichos en la temperatura media anual (MAT, °C) precipitación media anual (MAP; proporción del MAP actual), y proporción de precipitación que cae en verano (SEAS) para América del Norte y Sur bajo un escenario de 2 x CO_2 en base a tres modelos de circulación global

	North America			South America		
	GFDL	GISS	UKMO	GFDL	GISS	UKMO
MAT	4.50	4.69	7.17	4.40	4.47	5.76
MAP	0.12	0.12	0.21	0.00	0.17	0.22
SEAS	-0.02	0.00	0.00	-0.03	0.01	-0.02

TABLE 2

Regression parameters for relationships between predicted changes in mean annual temperature (MAT) and latitude for North and South American. Predicted changes were for 2 x CO_2 scenarios from three global circulation models

Parámetros de regresión para la relación entre los cambios predichos en la temperatura media anual (MAT) y latitud para América del Norte y Sur. Los cambios predichos fueron para escenarios de 2 x CO_2 en base a tres modelos de circulación global

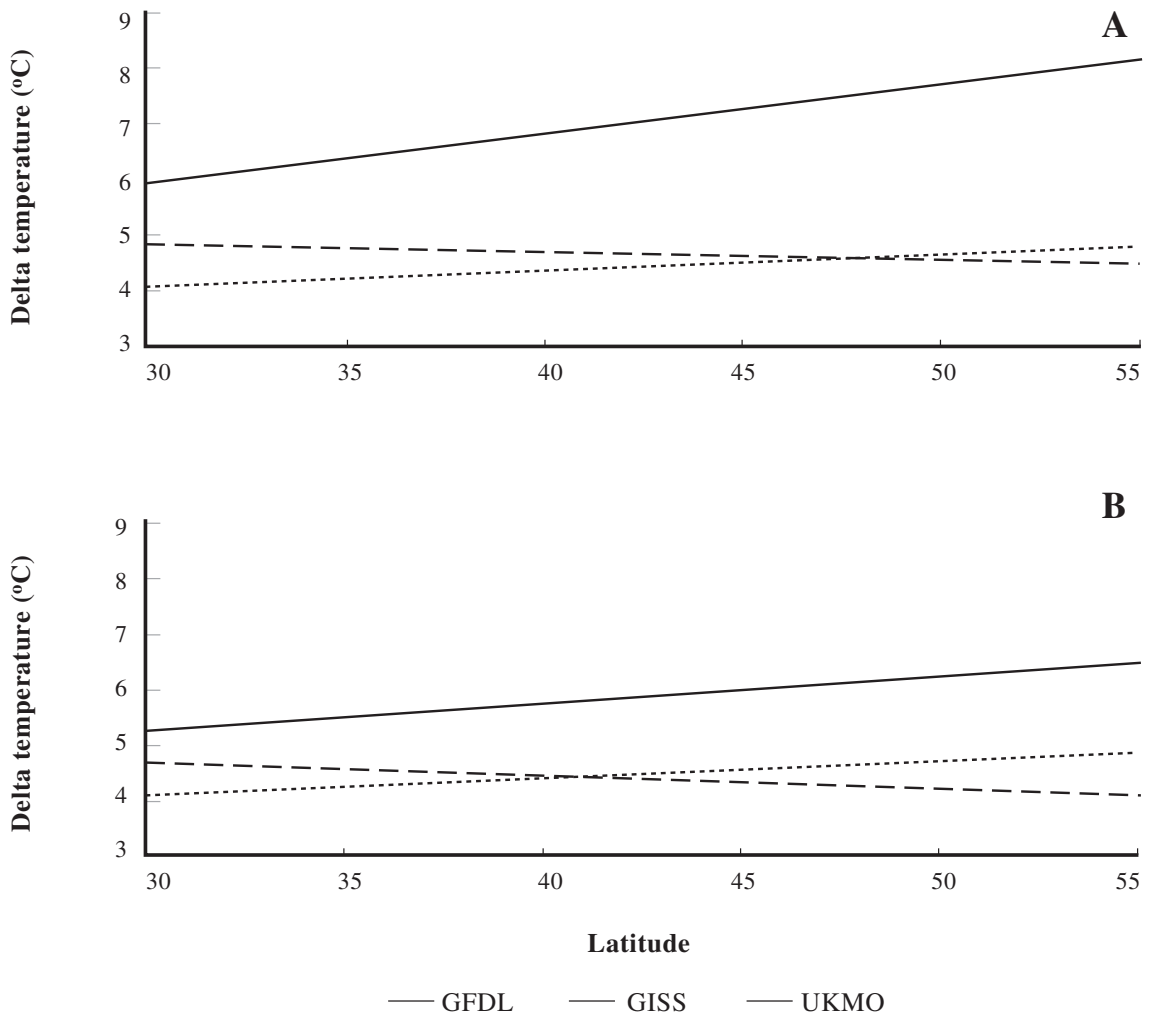|		Intercept	Slope	r^2
North America				
	GFDL	3.187	0.0299	0.26
	GISS	5.237	-0.0133	0.06
	UKMO	3.278	0.0895	0.33
South America				
	GFDL	3.155	0.0314	0.33
	GISS	5.318	-0.0214	0.18
	UKMO	3.791	0.0497	0.45

Fig. 7: Regression relationships between predicted changes in mean annual temperature and latitude for North American (a) and South American (b). Parameters for regression equations are in Table 2.

Relaciones de regresión entre los cambios predichos en la temperatura media anual y latitud para América del Norte (a) y América del Sur (b). Los parámetros de las ecuaciones de regresión están en la Tabla 2.

summing the deficits for all months in which there was a deficit ($wd_i < 0$, Equation1). We will refer to this as the monthly deficit to distinguish it from the annual deficit discussed above. Calculation of monthly deficits identifies the same dry areas as were identified with annual deficits but does a better job of identifying areas of semiarid grasslands and shrublands. Approximately 48 % of the study area in North America experiences at least one month of water deficit at some time during the year (Table 3, Fig. 8A). These deficits range from 25 mm up to > 500 mm. Fifty-three percent of the study area in South America has

at least one month of deficit ranging up to 500 mm.

Climatic change increased the proportions of the areas experiencing monthly water deficit on both continents (Table 3). The largest increases were associated with the results from the GFDL model. In North America, using GFDL results the area with monthly water deficit increased from 48 to 71 %, and in South America the increase was from 53 to 80 %. All three models resulted in an intensifying of dry conditions in the areas that are currently the driest (Fig. 9). The very dry areas (water deficit 500 mm) in the southwestern United States and

TABLE 3

The percentages of the temperate portion of western North America and South America with monthly water deficits or surpluses under current climatic conditions and a 2 x CO_2 climate predicted by three global circulation models

Porcentajes de la porción templada del oeste de América del Norte y Sur con déficit o sobreabundancia anual de agua bajo las actuales condiciones climáticas y en un escenario de 2 x CO_2 predicho por tres modelos de circulación global

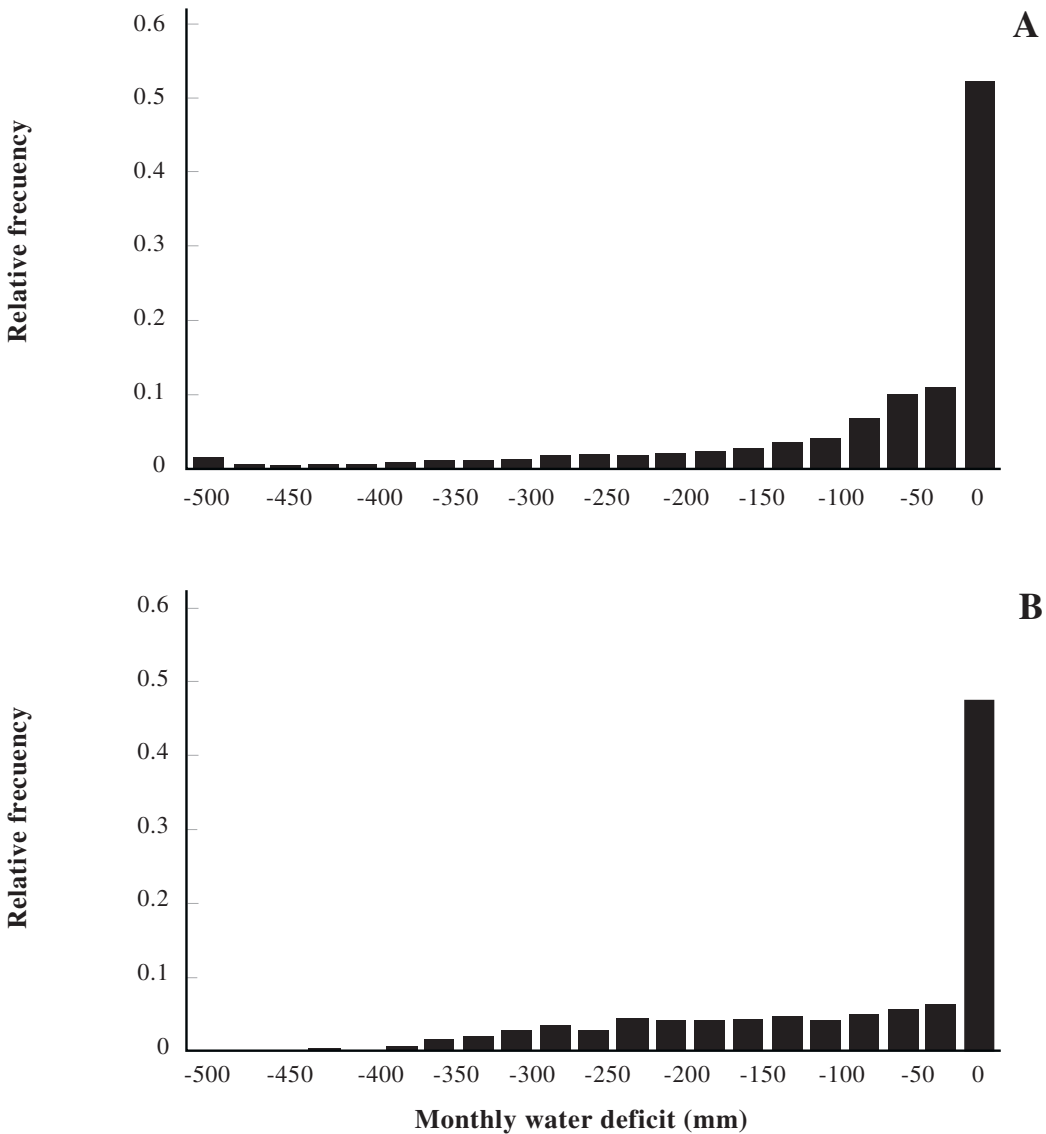|		Current	GFDL	GISS	UKMO
North America	Surplus	52	29	32	23
	Déficit	48	71	68	77
South America	Surplus	47	20	37	37
	Déficit	53	80	63	63

Fig. 8: Frequency distribution of monthly water deficits for the temperate zones of North and South America.

Distribución de frecuencia de los déficit y sobreabundancia mensual de agua para las zonas templadas de América del Norte y Sur.

northwestern Mexico intensified and expanded to the north and east. Additional very dry areas were identified for southern New Mexico and western Texas as well as small outlying areas in the Great Basin and the central valley of California (Fig. 9). Northwestern Argentina became drier and the extent of the very dry conditions expanded north and east. New very dry areas became evident in central and southern Argentina. The size of these areas varied depending upon the model. The very wet areas of the Pacific northwest in North America and the southern coast of Chile in South America remained at zero monthly water deficits. The wettest areas of the central grassland region of North America and the Rio de la Plata grasslands of South America were encroached upon by deficit conditions based upon results from all three models. Additionally, monthly water deficits spread into eastern North America to areas currently occupied by deciduous forest, suggesting this area could be vulnerable to vegetation change.

These patterns of change in monthly water deficit suggest that some changes in the current distribution of ecosystem types may occur under climatic change. While we recognize that these changes will occur at different rates depending upon the exact conditions and the inertia in the vegetation to be displaced, our objective here is to match the new climatic conditions to the most likely potential ecosystem type. This assumes that ecosystem types track climatic zones. In North America, there will be an expansion of both subtropical and temperate deserts to the north and east of their current positions. Lower tree line will move upwards in western mountain ranges. Areas of mixtures of shrubs/low trees and grasses may shift towards increased importance of woody plants. The subtropical desert conditions now characteristic of southern New
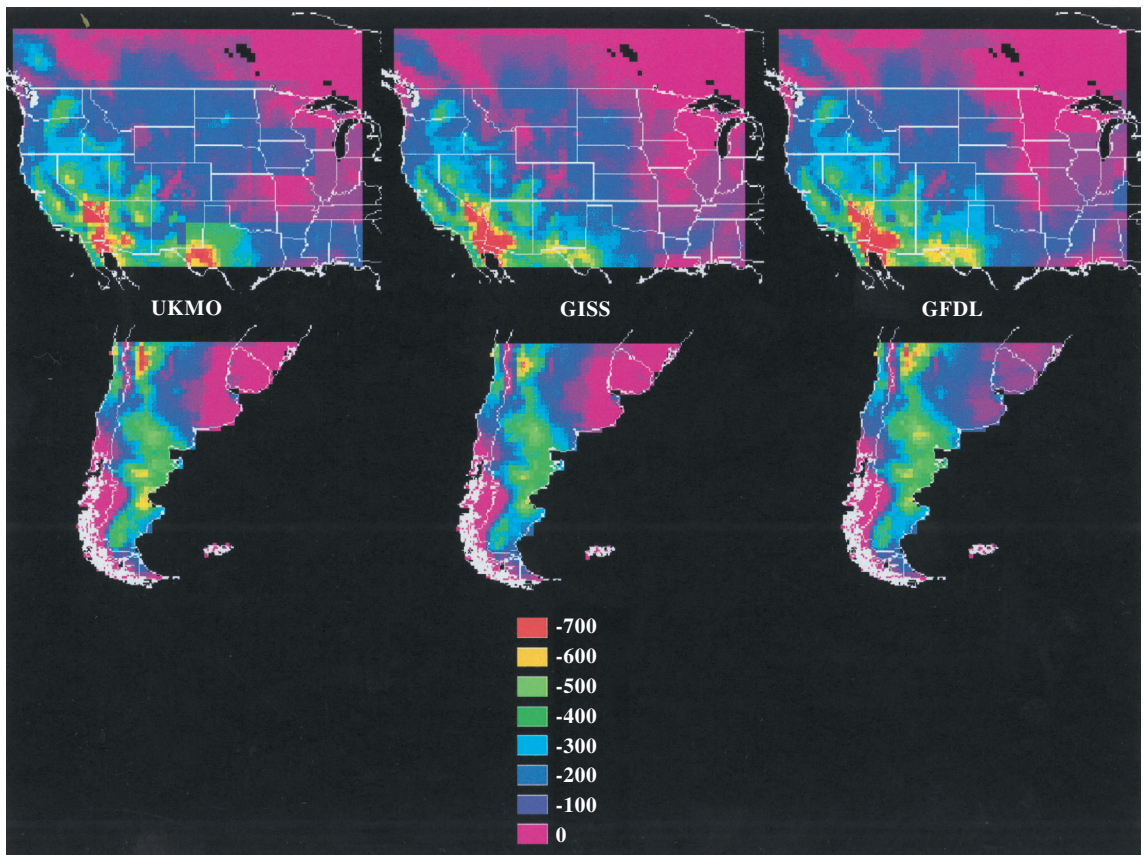
Fig. 9: Geographic distribution of monthly water deficits in North and South America for a double CO_2 climate predicted from three global circulation models. (A) GFDL, (B) GISS, and (C) UKMO.

Distribución geográfica de los déficit mensuales de agua en América del Norte y Sur para un clima con el doble de CO_2 en base a predicciones de tres modelos de circulación global. (A) GFDL, (B) GISS, y (C) UKMO.

Mexico and western Texas will spread into the great plains to areas currently occupied by dry grassland. Dry grasslands currently characteristic of the western portion of the central grassland region will spread to the east. The wet grasslands of the eastern portion of the grassland region will spread to the east displacing deciduous forest. In the north, grasslands will spread into areas currently occupied by boreal forest. The wettest areas in the Pacific northwest will be affected very little by changes in water deficit.

Climatically induced changes in ecosystems in South America will have a similar character to those in North America with some notable differences as a result of the size and shape of the area. Deserts will expand into areas now occupied by grasslands. Subtropical deserts will expand much more than temperate deserts and the result will likely be a net loss of temperate desert. Lower tree line in Argentina and northern Chile will move upward. The area currently occupied by Rio de la Plata grassland will decrease as a result of desert expansion from the west and the lack of area to expand eastward because of the Atlantic ocean.

LITERATURE CITED

BAILEY RG (1984) Delineation of ecosystem regions. Environmental Management 7: 365-373.

BAILEY RG (1989) Explanatory supplement to ecoregions map of the continents. Environmental Conservation 16: 307-309.

BARBOUR MG & WD BILLINGS (1988) North American terrestrial vegetation. Cambridge University Press, Cambridge, United Kingdom. 434 pp.

CABRERA AL (1976) Regiones Fitogeográficas Argentinas. In: Kugler WF (ed) Enciclopedia Argentina de Agricultura y Jardinería: 1-85. Segunda edición. Editorial Acme S.A.C.I, Buenos Aires, Argentina.

CRAMER WP & AM SOLOMON (1993) Climatic classification and future global redistribution of agricultural land. Climate Research 3: 97-110.

COUPLAND RT (1992) Overview of the grasslands of North America. In: Coupland RT (ed) Ecosystems of the world: natural grasslands: 147-150. First edition. Elsevier, Amsterdam, The Netherlands.

ELLENBERG H (1962) Wald in der Pampa Argentiniens? Veroff Geobotanical Institute ETH (Switzerland) 37: 39-56.

HALL AJ, CM REBELLA, CM GHERSA & JP CULOT (1992) Field-Crop Systems of the Pampas. In: Pearson CJ (ed) Ecosystems of the world: field crop ecosystems: 413-440. First edition. Elsevier, Amsterdam, The Netherlands.

HANSEN J, G RUSSELL, D RIND, P STONE, A LACIS, S LEBEDEFF, R RUEDY & L TRAVIS (1983) Efficient three-dimensional global models for climate studies: models I and II. Monthly Weather Review 111: 609-662.

LAUENROTH WK, IC BURKE & MP GUTMANN (2000) The structure and function of ecosystems in the central North American grassland region. Great Plains Research (United States) 9: 223-259.

LEEMANS R & W CRAMER (1991) The IIASA database for mean monthly values of temperature, precipitation and cloudiness on a global terrestrial grid. International Institute of Applied Systems Analyses, Luxemburg, Research Report RR-91-18.

LEEMANS R & AM SOLOMON (1993) Modeling the potential change in yield and distribution of the earth's crops under a warmed climate. Climate Research 3: 79-96.

MACMAHON JA & FH WAGNER (1985) The Mojave, Sonoran and Chihuahuan deserts of North America. In: Evenari M, I Noy-Meir & DW Goodall (eds) Ecosystems of the world: hot deserts and arid shrublands: 105-202. First edition. Elsevier, Amsterdam, The Netherlands.

MANABE S & RT WEATHERALD (1987) Large scale changes in soil wetness induced by an increase in carbon dioxide. Journal of Atmospheric Science 44: 1,211-1,235.

MARES MA, J MORELLO, & G GOLDSTEIN (1985) The Monte desert and other subtropical semi-arid biomes of Argentina, with comments on their relation to North American arid areas. In: Evenari M, I Noy Meir & DW Goodall (eds) Ecosystems of the world: hot deserts and arid shrublands: 203-238. First edition. Elsevier, Amsterdam, The Netherlands.

MOONEY, HA (ed) (1977) Convergent evolution in Chile and California: Mediterranean climate ecosystems. Dowden, Hutchinson & Ross, Stroudsburg, Pennsylvania, USA.

ORIANS GH & OT SOLBRIG (eds) (1977) Convergent evolution in warm deserts. Dowden, Hutchinson and Ross, Stroudsburg, Pennsylvania, USA.

PARODI LR (1942) ¿Por qué no existen bosques naturales en la llanura bonaerense si los árboles crecen en ella cuándo se los cultiva? Revista del Centro de Estudios Agronomía (Argentina) 30: 387-397.

PARUELO JM, WK LAUENROTH, HE EPSTEIN, IC BURKE, MR AGUIAR & OE SALA (1995) Regional climatic similarities in the temperate zones of North and South America. Journal of Biogeography 22: 2,689-2,699.

PRENTICE IC, W CRAMER, SP HARRISON, R LEEMANS, RA MONSERUD & AM SOLOMON (1992) A global biome model based on plant physiology and dominance, soil properties and climate. Journal of Biogeography 19: 117-134.

SCHMEIDER O (1927) The pampa, a natural or culturally induced grassland? University of California Publications in Geography (United States) 2: 255-276.

SCHULTZ J (1995) The ecozones of the world. Springer-Verlag, Berlin, Germany. 449 p.

SMIKA DE (1992) Cereal systems of the North American central Great Plains. In: Pearson CJ (ed) Ecosystems of the world: field crop ecosystems: 401-412. First edition. Elsevier, Amsterdam, The Netherlands.

SMITH JB & DA TIRPAK (1988) The potential effects of global change on the United States. EPA, Washington, District of Columbia, USA.

SOLOMON AM & R LEEMANS (1990) Climatic change and landscape-ecological response: issues and analysis. In: Boer MM & RS de Groot (eds) Landscape-ecological impact of climatic change: 293-316. IOS-Press, Amsterdam, The Netherlands.

SORIANO A (1992) Rio de Plata grasslands. In: Coupland RT (ed) Ecosystems of the world: natural grasslands: 367-408. First edition. Elsevier, Amsterdam, The Netherlands.

SORIANO A (1983) Deserts and semi-deserts of Patagonia. In: West NE (ed) Ecosystems of the world: temperate deserts and semi-deserts: 423-460. First edition. Elsevier, Amsterdam, The Netherlands.

WALTER H (1967) The pampa problem and its solution. Publications ITC, UNESCO, Centre for Integrated Surveys. Delft, The Netherlands. 15 pp.

WALTER H (1973) Vegetation of the earth and ecological systems of the geo-biosphere. Springer-Verlag, New York, New York, USA. 274 pp.

WEST NE (1983) Overview of North American temperate deserts and semi-deserts. In: West NE (ed) Ecosystems of the world: temperate deserts and semi-deserts: 321-330. First edition. Elsevier, Amsterdam, The Netherlands.

WILSON CA & JFB MITCHELL (1987) A double CO_2 climate sensitivity experiment with a global climate model including a simple ocean. Journal of Geophysical Research 92: 13,315-13,343.

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