Record of the North American southwest monsoon from Gulf of Mexico sediment cores

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ABSTRACT

Summer monsoonal rains (the southwest monsoon) are an important source of moisture for parts of the southwestern United States and northern Mexico. Improved documentation of the variability in the southwest monsoon is needed because changes in the amount and seasonal distribution of precipitation in this semiarid region of North America influence overall water supply and fire severity. Comparison of abundance variations in the planktic foraminifer *Globigerinoides sacculifer* in marine cores from the western and northern Gulf of Mexico with terrestrial proxy records of precipitation (tree-ring width and packrat-midden occurrences) from the southwestern United States indicate that *G. sacculifer* abundance is a proxy for the southwest monsoon on millennial and submillennial time scales. The marine record confirms the presence of a severe multicentury drought centered ca. 1600 calendar (cal.) yr B.P. as well as several multidecadal droughts that have been identified in a long tree-ring record spanning the past 2000 cal. yr from west-central New Mexico. The marine record further suggests that monsoon circulation, and thus summer rainfall, was enhanced in the middle Holocene (ca. 6500–4500 ^{14}C yr B.P.; ca. 6980–4710 cal. yr B.P.). The marine proxy provides the potential for constructing a highly resolved, well-dated, and continuous history of the southwest monsoon for the entire Holocene.

Keywords: Holocene, paleoclimate, global change, tree rings, monsoon.

INTRODUCTION

Better documentation of change in the climate of the southwestern United States during the current interglacial interval is needed to understand the natural variability of the current climate system and to help anticipate future changes. In this study we demonstrate that the relative abundance of the planktic foraminifer *Globigerinoides sacculifer* in marine sediments of the Gulf of Mexico is a proxy for the summer monsoon, which is a critical component of the climate of the southwestern United States (Bryson and Lowry, 1955; Higgins et al., 1997).

Historical records demonstrate that precipitation in the southwestern United States is quite variable (e.g., Meko and Baisan, 2001). Several decades-long droughts have occurred in the recent past, and severity of fires has been linked to variability in amount and seasonal distribution of precipitation (e.g., Grissino-Mayer and Swetnam, 2000). Terrestrial paleoclimate records from the southwestern United States indicate that significant climate variability has occurred during the current interglacial interval or Holocene (past 10 k.y.) (e.g., Benson et al., 2002), but the preinstrumental record of the southwest monsoon is poorly known (Meko and Baisan, 2001). Studies based on tree rings can provide highly resolved records of past conditions, but separating temperature and precipitation signatures can be difficult, and determining seasonality of precipitation is challenging. In addition, tree-ring records usually represent short intervals of the Holocene, and they often reflect local conditions. Studies of pollen in lake sediments, lake-shoreline deposits, and vegetation in packrat middens are available, but these records are often discontinuous, many are difficult to date, and they are sometimes contradictory (e.g., see summaries in Betancourt et al., 1993; Metcalfe et al., 2000; Thompson et al., 1993).

MODERN CLIMATE SYSTEM

Summer monsoonal rains are an important source of moisture to the southwestern United States and northern Mexico (Higgins et al., 1997; Peterson, 1994). Large areas of New Mexico and Arizona receive more than half their annual rainfall from summer monsoonal circulation (Fig. 1; Higgins et al., 1997). In the modern climate system, seasonal changes in the position of the Intertropical Convergence Zone (ITCZ) influence the prevailing winds, and thus sources of moisture, for the southwestern United States and Caribbean–Gulf of Mexico regions (e.g., Metcalfe et al., 2000). During winter (Fig. 1) the ITCZ is near the equator, and westerly winds bring moisture in from the Pacific Ocean. During summer (Fig. 1) the ITCZ moves north due to warming of the Northern Hemisphere. The northward movement of the ITCZ results in southeasterly winds moving across the Caribbean and southerly winds moving across the Gulf of California (Fig. 1). The summer pattern is known as the southwest monsoon (Peterson, 1994) and results in significant summer rainfall that penetrates as far north as the Colorado Plateau. Flow of surface waters from the Caribbean through the Yucatan Channel into the Gulf of Mexico is also influenced by seasonal changes in the position of the ITCZ. The primary surface current in the gulf is the Loop Current, which brings warm tropical waters from the Caribbean Sea through the Yucatan Channel into the gulf before exiting into the North Atlantic Ocean through the Florida Straits. During winter, the Loop Current, and thus warm Caribbean tropical surface water, generally does not penetrate into the western or northern gulf. Tropical waters from the Caribbean are restricted in winter to a narrow band in the southeastern gulf, reflecting the flow of the Loop Current from the Yucatan Channel directly to the Florida Straits. During summer, surface-water flow through the Yucatan Channel is enhanced compared to winter (Sheinbaum et al., 2002), and warm tropical surface temperatures occur in the western and northern gulf (Brunner, 1982).

PREVIOUS WORK

Changes in solar insolation related to changes in orbital forcing caused the average position of the ITCZ to migrate during the Holocene (Hodell et al., 1991; Haug et al., 2001; Harrison et al., 2003). In the early Holocene, increased summer insolation in the Northern Hemisphere resulted in northward movement of the average position of the ITCZ. As the average position of the ITCZ moved northward, enhanced southeasterly winds resulted in increased precipitation, as monitored by lake-level records at Lake Miragoane in Haiti (Hodell et al., 1991). After ca. 6000 ^{14}C yr B.P. (ca. 6410 calendar [cal.] yr B.P.), decreasing summer insolation in the Northern Hemisphere and resulting southward movement of the average position of the ITCZ caused a decline in southeasterly winds in the Gulf of Mexico and Caribbean. Thus, precipitation in Haiti and in the area of the Cariaco Basin along the north coast of Venezuela declined (Hodell et al., 1991; Haug et al., 2001).

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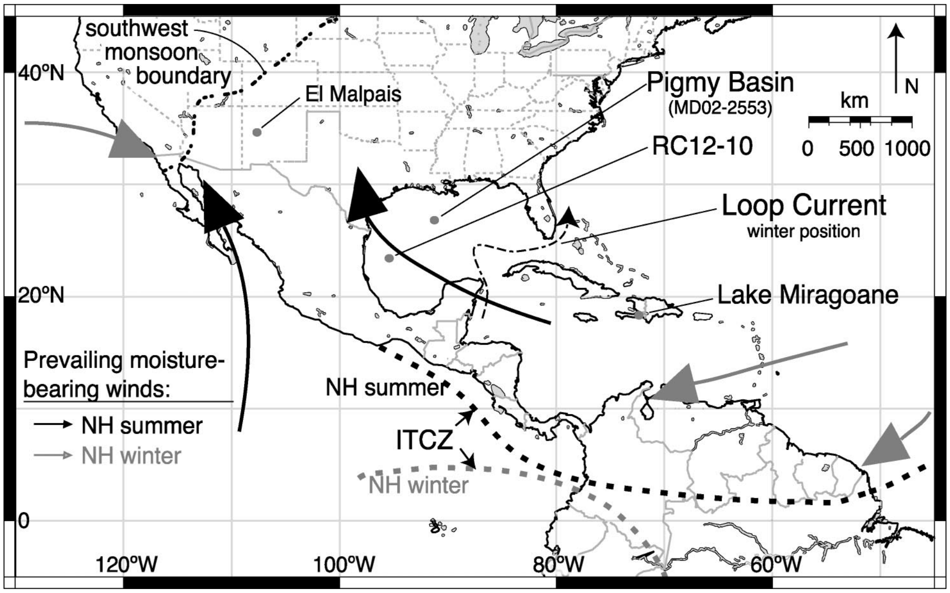

Figure 1. Location of Lake Miragoane, Haiti, core RC12-10 in western Gulf of Mexico, core MD02-2553 from Pigmy Basin on Louisiana slope, and El Malpais National Monument. Large arrows show prevailing wind direction during Northern Hemisphere (NH) winter and summer seasons. Small dash-dotted arrow shows generalized position of Loop Current during Northern Hemisphere winter. Dashed line shows position of Intertropical Convergence Zone (ITCZ) in Northern Hemisphere winter and summer seasons. Dotted line labeled "southwest monsoon boundary" marks northern limit of regions where more than half of their annual precipitation occurs during warm season. Modified from Metcalfe et al. (2000), Peterson (1994), and Poore et al. (2003).

Changes in surface-water circulation in the gulf paralleled the changes in atmospheric circulation inferred from the Lake Miragoane and Cariaco proxy records. The relative abundance of the planktic foraminifer *G. sacculifer* in faunal assemblages in gulf sediments is an indicator for influence of the Loop Current (Brunner, 1979; Poore et al., 2003). Increased penetration of the Loop Current into the gulf at the beginning of the Holocene in response to the northward migration of the ITCZ and the resulting enhancement of the summer circulation pattern are indicated by an increased abundance of *G. sacculifer* in faunal assemblages from northern and western gulf sediments (Poore et al., 2003). After reaching maximum values in the middle Holocene, the abundance of *G. sacculifer* in faunal assemblages from the northern and western gulf declined toward the present as the average position of the ITCZ migrated back toward the equator.

Poore et al. (2003, 2004) argued that century- to decadal-scale variability in *G. sacculifer* abundance was also related to changes in the average position of the ITCZ. Warmer intervals would result in a more northerly average position of the ITCZ and higher *G. sacculifer* abundances in gulf sediments, whereas cooler intervals would result in a more southerly average position of the ITCZ and lower *G. sacculifer* abundances in gulf sediments.

SOUTHWEST MONSOON

Submillennial-Scale Variability

Changes in the average position of the ITCZ should also influence the effect of the monsoon on the southwestern United States. Northward migration of the average position of the ITCZ should increase monsoonal precipitation, and equatorward migration of the ITCZ should decrease the monsoon precipitation in the southwestern United States. Poore et al. (2004) provided a highly resolved (30 yr sampling interval) record of *G. sacculifer* relative abundance variations for the past few thousand years of the Holocene in a sediment core (MD02-2553) from the Pigmy Basin on the Louisiana slope in the northern Gulf of Mexico. The MD02-2553 record shows distinct century-scale cycles, which suggests that similar variability should occur in the southwest monsoon. To test the validity of *G. sacculifer* abundance variations as a proxy for variations in the southwest monsoon, we compared the MD02-2553 *G. sacculifer* record with the long tree-ring record from El Malpais National Monument on the southern periphery of the Colorado Plateau in west-central New Mexico (Fig. 2). The El Malpais record is important because it is continuous from 136 B.C. to A.D. 1992, and variations in tree-ring width in the record are highly correlated with annual (water year) precipitation (Grissino-Mayer, 1996). Because precipitation in New Mexico occurs predominantly in mid-summer to fall (June to October) (Higgins et al., 1997, their Fig. 4), the El Malpais record is considered to be particularly sensitive to variations in the southwest monsoon. We first compared the MD02-2553 and El Malpais records by plotting each against its own independent age model. The tree-ring record is in calendar years, so we used the OxCal program to calibrate the AMS ^{14}C-controlled chronology for MD02-2553 to calendar years (=calibrated years). We removed low-frequency variations from the MD02-2553 record to match the tree-ring record, which had low-frequency trends removed during standard processing.

Initial comparison of the records revealed similar features, but the multicentury drought centered ca. 1600 yr B.P. in the El Malpais record was slightly offset (~60 yr) from the multicentury interval of low *G. sacculifer* abundance in the MD02-2553 record. We infer that these features correlate because previous work shows that a southward shift of the ITCZ and associated decrease in monsoon rainfall in the Caribbean region over the past 5 k.y. coincides with an overall decrease of *G. sacculifer* in gulf sediments (Hodell et al., 1991; Haug et al., 2001; Poore et al., 2004). Thus we uniformly shifted the MD02-2553 record 60 yr in Figure 2 so that the multicentury drought and multicentury *G. sacculifer* minimums coincided. The adjustment is well within the errors involved in ^{14}C dating and calibration from ^{14}C to cal. yr B.P. Inspection of Figure 2 reveals substantial overall similarity between the two records, but the details differ. Prominent decadal-scale precipitation maximums at 1400 yr and 900 yr B.P. and precipitation minimums at 2100, 2000, and 400 yr B.P. are evident in both records. Correlation over the entire record is low (r^2 = 0.25), but some intervals show a good correlation (r^2 = 0.66 between 1700 and 1400 yr B.P.) In contrast (e.g., between 900 and 500 yr B.P.), the MD02-2553 record appears slightly distorted with respect to the El Malpais record, as if the marine record had undergone minor stretching and compression. In some instances the records are exactly opposite. For example, a maximum in the El Malpais record at 1050 yr B.P. coincides with a minimum in the MD02-2553 record. The apparent distortion and phase changes between the records could be due to small changes in sediment-accumulation rates in the marine core. Alternatively, changes in the climate system could alter the seasonal distribution of precipitation in New Mexico. For example, sea-surface temperature structure of the equatorial Pacific can influence precipitation in the southwestern United States (Schubert et al., 2004). Thus a major El Niño–Southern Oscillation event could alter phasing between the El Malpais and MD02-2553 records. Although additional highly resolved records from the Gulf of Mexico are needed to verify the details of the MD02-2553 record, the overall similarity between the MD02-2553 and the El Malpais records indicates that variations in *G. sacculifer* in sediments of the northern gulf provide a reliable proxy for century-scale variations in the southwest monsoon over the past ~2000 yr.

Millennial-Scale Variability

Figure 3 shows the occurrence of packrat middens in New Mexico (Betancourt et al., 1993) along with smoothed records of *G. sacculifer* abundance variations from core MD02-2553 and core RC12-10 (Poore et al., 2003) from the western Gulf of Mexico. Because the midden and RC12-10 results are reported in radiocarbon years, the time scale and discussion of Figure 3 are in radiocarbon years. Each record in Figure 3 is plotted against its own ^{14}C-controlled independent chronology. Low-frequency variability in the MD02-2553 and RC12-10 records has not been removed.

The MD02-2553 and RC12-10 records show similar features since ca. 4500 ^{14}C yr B.P. The *G. sacculifer* abundance in both cores has declined from ca. 4500 ^{14}C yr B.P. toward the present. A brief rebound to higher values centered ca. 1250 ^{14}C yr B.P. is present in the MD02-2553 record. A similar rebound may be present in the RC12-10 record, but the rebound is not well developed. The similarity of the MD02-2553 and RC12-10 records over the past 4500 ^{14}C yr suggests that the RC12-10 record can be used as a proxy for monsoon changes in the earlier part of the Holocene. Relative abundances of *G. sacculifer* reached maximum values between ca. 6500 and 4500 ^{14}C yr B.P. in RC12-10, which indicates that maximum development of the monsoon occurred in the middle Holocene (Fig. 3).

The midden record in New Mexico shows that middens were consistently present between 11,000 and 9000 ^{14}C yr B.P., were sparse or absent between ca. 9000 and 4500 ^{14}C yr B.P., and then became fairly common after 4000 ^{14}C yr B.P. The data (Fig. 3) suggest an inverse relationship between *G. sacculifer* and midden occurrences over the past 7000 ^{14}C yr. In general, middens were sparse or absent during intervals of high *G. sacculifer* abundance and increased during intervals of lower *G. sacculifer* abundance.

Packrat middens are found in arid and semiarid regions. Most fossil middens are preserved by crystallized rat urine (amberat) that cements, preserves, and protects encased plant material (Spaulding et al., 1990). Amberat is hydroscopic and under humid conditions will rehydrate and flow. Middens that are depleted of amberat are susceptible to damage by insects (e.g., Spaulding et al., 1990).

Two likely explanations have been pro-

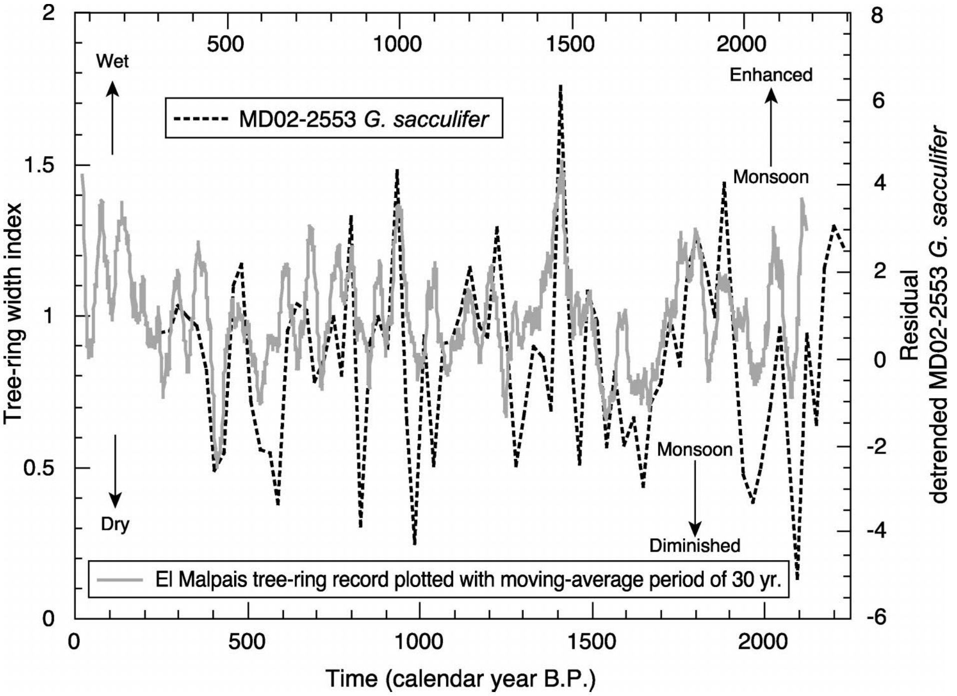

Figure 2. Comparison of (solid line) time series of standard tree-ring-width index developed from living trees and subfossil wood at El Malpais National Monument in west-central New Mexico and (dashed line) relative abundance of *Globigerinoides sacculifer* in core MD02-2553 from Pigmy Basin in northern Gulf of Mexico (see Fig. 1). MD02-2553 record has been detrended to remove low-frequency variability. Time scale is in calendar years before present (B.P., meaning before 2000). Development of El Malpais chronology was outlined in Grissino-Mayer (1996). Chronology for MD02-2553 *G. sacculifer* time series (Poore et al., 2004) is based on eight accelerator mass spectrometer ^{14}C dates that were calibrated to calendar years with OxCal Program (Ramsey, 2001). MD02-2553 record has been uniformly shifted 60 yr younger with respect to El Malpais chronology. Larger values of tree-ring width index represent increased annual precipitation. Increased *G. sacculifer* relative abundance values represent more northerly average position of Intertropical Convergence Zone, which results in enhanced monsoon circulation.

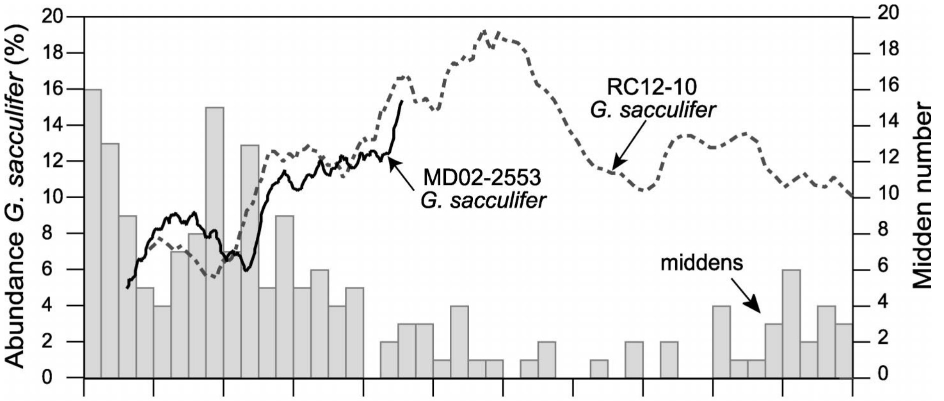

Figure 3. Time-series plot showing occurrence of packrat middens in New Mexico and *G. sacculifer* abundance variations in core MD02-2553 from Pigmy Basin and core RC12-10 from western Gulf of Mexico (Fig. 1). Each record is plotted against its own independent ^{14}C chronology. Packrat midden occurrences are grouped into 250 ^{14}C yr intervals based on accelerator mass spectrometer (AMS) ^{14}C dates on individual middens (Betancourt et al., 1993). Marine chronologies assume constant sediment-accumulation rates between individual AMS ^{14}C dates (see Poore et al., 2003, 2004, for discussion). *G. sacculifer* abundance plots are smoothed with 11 yr moving average for RC12-10 and 20 yr moving average for MD02-2553. Note that occurrences of middens are inversely related to *G. sacculifer* abundance for past 7 k.y., which is consistent with interpretation that increased monsoon rainfall results in decreased occurrences of middens.

posed for the middle Holocene ''gap'' in midden occurrence in Figure 3. One is that the lack of middens during the middle Holocene was due to lower productivity and less packrat activity during a period of dry winters and hot summers. Alternatively, the gap could have been due to wetter summers than today, leading to higher relative humidity, which would inhibit the crystallization of packrat urine that preserves middens (e.g., Betancourt et al., 1993).

The record of packrat middens in New Mexico can be explained by our interpretation that increased abundance of *G. sacculifer* in Gulf of Mexico sediments reflects northward movement of the ITCZ and enhancement of monsoonal precipitation in the southwestern United States. Packrat middens with ages between 9000 and 4000 ^{14}C yr B.P. are rare. The marine record indicates that the monsoon was most intense from 6500 to ca. 4500 ^{14}C yr B.P. Packrat-midden occurrences increased from 4000 ^{14}C yr B.P. to the present at the same time as the marine records indicate that the southwest monsoon was declining. The minimum in midden abundance ca. 1000 ^{14}C yr B.P. coincided fairly closely with the brief excursion to higher *G. sacculifer* abundances, implying a transitory increase in monsoon intensity.

The climate record from the southwestern United States during the middle Holocene is complicated and sometimes contradictory. For example, Thompson et al. (1993) noted that lake levels in western Texas, New Mexico, and Arizona were higher than today during parts of the middle Holocene. In contrast, Menking and Anderson (2003) found evidence of a severe middle Holocene two-stage drought from study of eolian deposits in the Estancia Basin in central New Mexico. Several regional summaries of available terrestrial records are consistent with our interpretation that the monsoon intensity was strongest in the middle Holocene. Thompson et al. (1993) reviewed vegetation records from the southwestern United States and concluded that maximum summer rainfall occurred ca. 6000 ^{14}C yr B.P. From a review of available data from northern Mexico and the southwestern United States, Metcalfe et al. (2000) concluded that a major increase in summer precipitation occurred after 9000 ^{14}C yr B.P. Modeling experiments coupled with a summary of lake level, vegetation, and eolian records from North America and Mexico suggest wetter conditions in the southwestern United States during the middle Holocene because of enhanced monsoon precipitation (Harrison et al., 2003). Records of the latest part of the Holocene (the past 4000 ^{14}C yr) are fairly consistent and suggest warmer and drier climates than during the middle Holocene (Thompson et al., 1993; Metcalfe et al., 2000), although several brief wetter intervals are found in some records (summary in Thompson et al., 1993). In general, the available data from the southwestern United States are consistent with our interpretation that the North American monsoon reached maximum intensity in the middle Holocene and then declined in intensity toward the present.

SUMMARY AND CONCLUSIONS

Comparison of abundance variations in the planktic foraminifer *G. sacculifer* in marine cores from the western and northern Gulf of Mexico with terrestrial proxy records of precipitation from New Mexico support the conclusion that *G. sacculifer* abundance variations are a reliable proxy for changes in the southwest monsoon on millennial and submillennial time scales. The development of a marine monsoon proxy provides the potential for constructing a highly resolved, well-dated, and continuous history of the southwest monsoon for the entire Holocene. More research is needed to understand the teleconnections between tropical climate variability in the Caribbean and the southwestern monsoon.

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