Possible solar forcing of century-scale drought frequency in the northern Great Plains

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ABSTRACT

A 2100-yr decadal-resolution salinity and aridity proxy record of lacustrine ostracode-shell Mg/Ca ratios from a closed-basin lake in the northern Great Plains shows statistically significant periodicities of ~400, 200, 130, and 100 yr. These periodicities are similar to the three principal solar-oscillation periods (420, 218, 143 yr) as inferred from the atmospheric radiocarbon record, suggesting strong solar forcing of century-scale drought frequency with a fundamental 400-yr period and its 2nd, 3rd, and 4th harmonics. Our proxy record correlates visually and statistically (cross-spectral analysis) with the atmospheric $\Delta^{14}C$ record (solar proxy) and the GISP2 (Greenland Ice Sheet Project Two) $\delta^{18}O$ record (climate proxy), showing that solar minima are in phase with drought periods in the northern Great Plains and cold periods in Greenland. This spectral similarity together with phase correlation indicates a possible teleconnection of century-scale global climate fluctuations through common solar forcing.

INTRODUCTION

The cyclic nature of solar and climate changes has long been documented at short time scales, such as the 11-yr Schwabe, 22-yr Hale, and 90-yr Gleissberg cycles (Eddy, 1976; Siscoe, 1978; Mitchell et al., 1979; Friis-Christensen and Lassen, 1991; Crowley and Kim, 1996; Cook et al., 1997), on the basis of instrumental, historical, and proxy records. Recently, the cosmogenic isotopes ^{14}C (from tree rings; Stuiver and Braziunas, 1989, 1993; Damon and Sonett, 1991) and ^{10}Be (from ice cores; Beer et al., 1994) have been used as proxies of solar variability for the past several millennia. There are, however, a limited number of high-resolution climate records of sufficient duration (Sonett and Suess, 1984; Scuderi, 1993) to test the possible Sun and climate connections at longer time scales.

We use a 2100-yr decadal-resolution record of ostracode-shell Mg/Ca ratios, a proxy of lake salinity (Chivas et al., 1986; Engstrom and Nelson, 1991), from a closed-basin lake in the northern Great Plains of North America to investigate the Sun and climate connection on a century scale. Rice Lake (lat 48°00′29″N, long 101°31′49″W; 620 m above sea level) is situated on the Missouri Coteau near the edge of the Missouri Escarpment in north-central North Dakota, United States (Fig. 1). The lake is on outwash gravel and sand surrounded by extensive glacial till. The present-day lake is topographically closed; it has a relatively low salinity of 1.8‰ but a high Mg/Ca molar ratio of 50, due possibly to its through-flow hydrological setting. Because of its mid-continental location and limnological and hydrological characteristics, Rice Lake's salinity, which is recorded in ostracode-shell geochemistry, fluctuates readily in response to climate change.

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GEOCHEMICAL ANALYSIS

The sediment core from Rice Lake was taken in December 1985 from the deepest part of the lake basin (water depth of 8.63 m; E. C. Grimm, 1998, personal commun.). The sediment, mostly homogeneous carbonates, has ~70% aragonite. Three AMS (accelerator mass spectrometry) radiocarbon dates fit a straight age vs. depth line and were used to derive the chronology based on linear interpolation between the calibrated ages (Table 1; also see Appendix[1]). The lake has a rapid sediment-accumulation rate of 2.5 mm/yr. The top 5.5 m of sediment—representing the past 2100 yr—was contiguously sampled at decadal time intervals (average 2.5-cm-thick sediment slice per sample). Juvenile shells (instars A-1, A-2) of *Candona rawsoni* (a benthic ostracode species with broad salinity tolerance) were used for analysis because juveniles molt predominantly during mid-summer, thus minimizing the effect of intra-annual variation in hydrochemistry (Xia et al., 1997). The trace-element analysis was carried out with ICP-MS (inductively coupled plasma mass spectrometer) methods on the acid residue remaining after the stable isotope analysis (Chivas et al., 1993)

The measured or raw Mg concentrations in the diluted solution range from 4.7 ppb (parts per billion in the solution) to 118.1 ppb; the Ca con-

[1]GSA Data Repository item 9926, appendix, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301. E-mail: editing@geosociety.org.

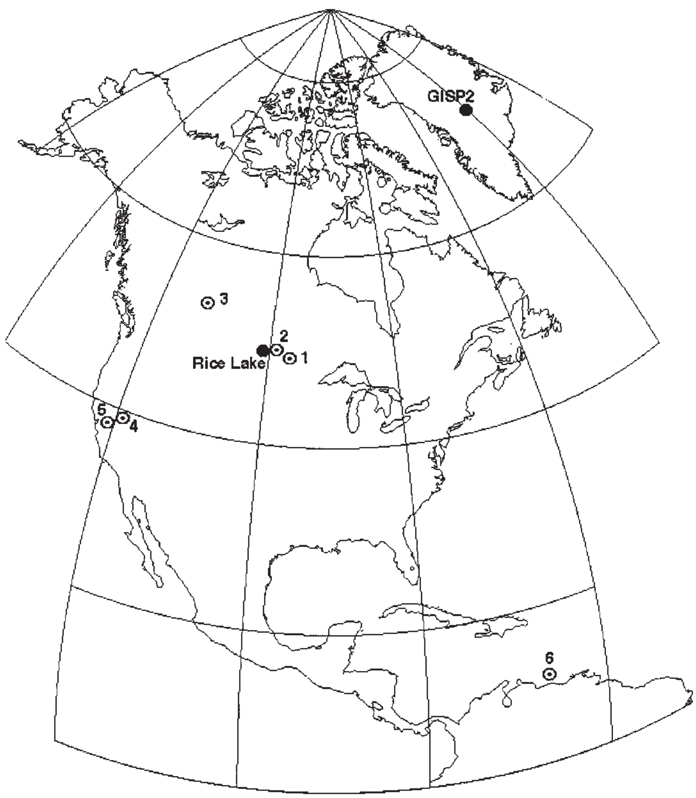

Figure 1. Locations of Rice Lake in northern Great Plains and GISP2 ice core in Greenland. Other paleoclimate sites discussed in text: 1—Elk Lake (Minnesota, USA; Dean, 1997; Anderson, 1992); 2—Moon Lake (North Dakota, USA; Laird et al., 1996); 3—Pine Lake (Alberta, Canada; Campbell et al., 1998); 4—Sierra Nevada (California, USA; Scuderi, 1993); 5—Campito Mountain (California, USA; Sonett and Suess, 1984); 6—Cariaco Basin (Caribbean Sea; Peterson et al., 1991); 7—Lake Johnston (Tasmania, Australia; not shown on map; Cook et al., 1996).

Data Repository item 9926 contains additional material related to this article.

TABLE 1. RADIOCARBON DATES AND THEIR CALIBRATED AGES FROM RICE LAKE, NORTH DAKOTA, UNITED STATES

Depth (cm below water surface)*	^{14}C date (yr B.P. ± SD)	Lab no. CAMS-	Calibrated age (1 σ range) (cal yr B.P.)[§]	Material dated
1047–1048	560 ± 60	9157	540 (520-560)	Plant stem (*Scirpus*?)
1254–1262	1360 ± 60	9158	1290 (1240-1310)	*Scirpus* seeds
1431–1432	2090 ± 60	9159	2020 (1990-2130)	Wood

*Water depth is 863 cm at the coring site.

[§]Calibrated ages (in calendar years before present [i.e., A.D. 1950]) were derived from the radiocarbon calibration program CALIB 3.0.3 by using decadal tree-ring dates (UWTEN93.14C) (Stuiver and Reimer, 1993). Age ranges were obtained as highest

centrations range from 355.7 ppb to 7099.1 ppb. Detection limits are 0.12 ppb for Mg and 30 ppb for Ca, which are 3 SDs (standard deviations) of the operational (procedural) blank analysis. The measured Mg and Ca concentrations are well above the detection limits. The analytical precision is well within ±5% on concentration measurements of individual elements. We estimate that the Mg/Ca ratios have an analytical precision better than 10% (i.e., maximum error of 10% as for a sample with Mg and Ca reaching maximum and minimum analytical errors, respectively). The variations of Mg/Ca ratios we discuss here are 0.01 to 0.03 (Fig. 2A), about 5–15 times greater than the uncertainty of 0.002 (10% of the average ratio of 0.02).

The Mg/Ca ratios in ostracode shells are directly correlated with Mg/Ca ratios in lake water and with water temperature at the time of low-Mg calcite shell formation (Chivas et al., 1986). Evaporative enrichment causes selective removal of Ca from lake water due to precipitation of calcium carbonates. Thus, the Mg/Ca ratios and salinity of lake water increase during drought periods in closed-basin lakes (Chivas et al., 1986; Engstrom and Nelson, 1991; Xia et al., 1997). Mg/Ca has been shown to be a reliable salinity indicator in the arid northern Great Plains (Engstrom and Nelson, 1991; Xia et al., 1997) because Mg behaves conservatively (i.e., precipitation of Mg-bearing carbonates occurs only in highly concentrated water) in lakes precipitating carbonates.

SPECTRAL ANALYSIS OF SALINITY TIME SERIES

The Mg/Ca molar ratios of ostracode shells from Rice Lake show a maximum range of 0.04 (Fig. 2A). Singular spectral analysis (SSA; Vautard and Ghil, 1989; Dettinger et al., 1995), a data-adaptive and objective band-pass filtering, was used to decompose the raw time series (Fig. 2, B–E). The first eight reconstructed components (RCs) represent 82% of the total variance, and each of these components represents from 17% to 7% of the variance. An oscillatory signal is represented by a pair of RCs, the associated variance being the sum of the variances of these paired RCs (Vautard and Ghil, 1989; Cook et al., 1997). The spectral analysis of the raw time series and its reconstructed components show several significant century-scale periodicities (Fig. 2, B–E). The high-resolution maximum entropy method (MEM; Haykin, 1983; Paillard et al., 1996) spectra on RCs 1–8 indicate that four robust periods of about 400, 200, 130, and 100 yr persist at various autoregressive (AR) orders (Fig. 3). The classical Blackman and Tuckey (1958) spectral method shows similar results. The four major periods have a harmonic relationship with a fundamental 400-yr period.

During each of five 400-yr periods covering the past 2100 yr (e.g., intervals between numbers 4, 10, 16, 20, and 22), the drier periods that have Mg/Ca ratios above the 2100-yr mean of 0.021 appear to occur in about two-thirds of the time interval (Fig. 4A). The Little Ice Age (600–150 yr before A.D. 1950 [yr B.P.]) and Medieval Warm Period (1050–600 yr B.P.) appear to be times of significant fluctuations in effective moisture, showing wet to dry cycles within their respective 400-yr periods (Figs. 2 and 4).

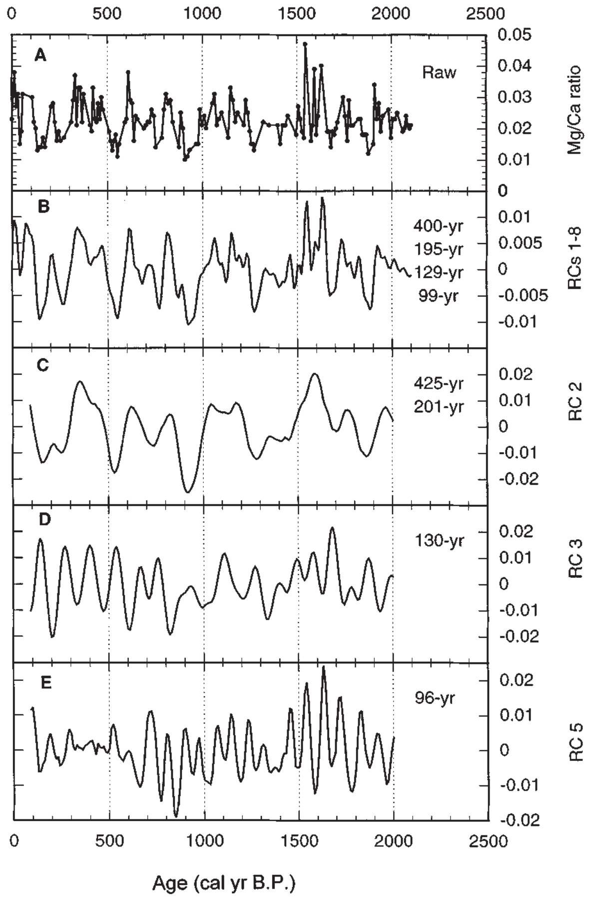

Figure 2. Time series from Rice Lake for past 2100 cal yr. A: Raw Mg/Ca molar ratios in juvenile ostracode (*Candona rawsoni*) shells. Uncertainty was estimated to be better than 10% (~0.002 in terms of ratios; see text for detail). B: First eight reconstructed components (RCs) derived from singular spectrum analysis (SSA) (Vautard and Ghil, 1989; Dettinger et al., 1995); these eight RCs together represent 82% of total variance and have significant periodicities of 400, 195, 129, and 99 yr. Vertical scale is in arbitrary units. C: Relative contribution of 425- and 201-yr RC based on SSA. D: Relative contribution of 130-yr RC based on SSA. E: Relative contribution of 96-yr RC based on SSA.

CENTURY-SCALE SOLAR OSCILLATIONS

The 9600-yr atmospheric ^{14}C record from tree rings shows three principal solar oscillations at 420, 218, and 143 yr (Stuiver and Braziunas, 1989), with a pronounced 126-yr peak in the past 4000 yr (Stuiver and Braziunas, 1989, 1993). Historical observations of aurora (an index of solar activity) show a 130-yr period (Attolini et al., 1988). Spectral analysis results of high-resolution climatic time series include the 208- and 114-yr periods from tree-ring widths of bristlecone pine (Sonett and Suess, 1984), the 125-yr period from tree-ring–reconstructed temperatures (Scuderi, 1993) in the western United States, and the 200-yr period from tree-ring–reconstructed temperatures in Tasmania (Cook et al., 1996). The 200 and 136-yr periods have been related to solar forcing of upwelling and trade-wind intensity in the Cariaco Basin in the southern Caribbean Sea (Peterson et al., 1991). Wigley and Kelly (1990) also found a statistically significant correlation between century-scale variations of the ^{14}C record and Röthlisberger's (1986) record of global glacial advances. Our Mg/Ca-based salinity and drought history matches these periodicities in surprising detail, so this spectral similarity forces us to consider solar variability as the major cause of century-scale drought frequency in the northern Great Plains.

The dry periods at Rice Lake (odd numbers in Fig. 4A) correspond to solar minima and $\Delta^{14}C$ maxima (Fig. 4C). Similar phase locking (drought =

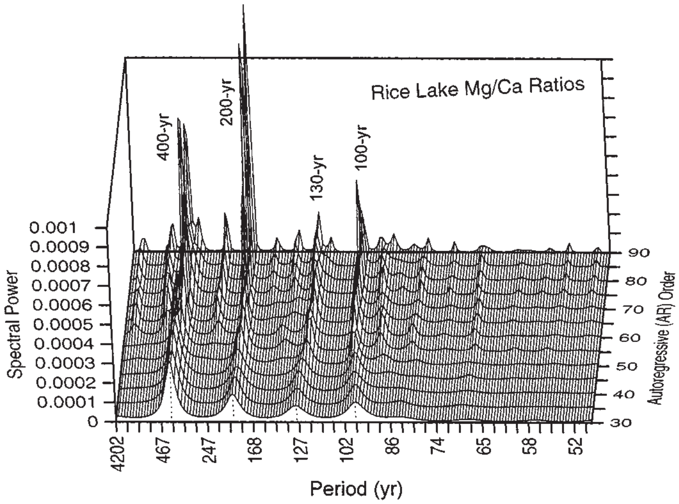

Figure 3. Spectral power of Mg/Ca time series from Rice Lake. Plot shows periods (in years; converted from frequency) and relative spectral power at different autoregressive (AR) orders derived from maximum entropy method (MEM; Haykin, 1983; Paillard et al., 1996). Dominant 400-, 200-, 130-, and 100-yr periods (as distinct set of harmonics) persist from AR order of 30 (high confidence and low resolution) to AR order of 90 (low confidence and high resolution) and are significant at 95% level on basis of Siegel's test (Siegel, 1980; Schulz and Stattegger, 1997). Four dominant periods fully represent basic features of our Mg/Ca record, but periodicities at higher AR orders may represent Mg/Ca record in finer detail.

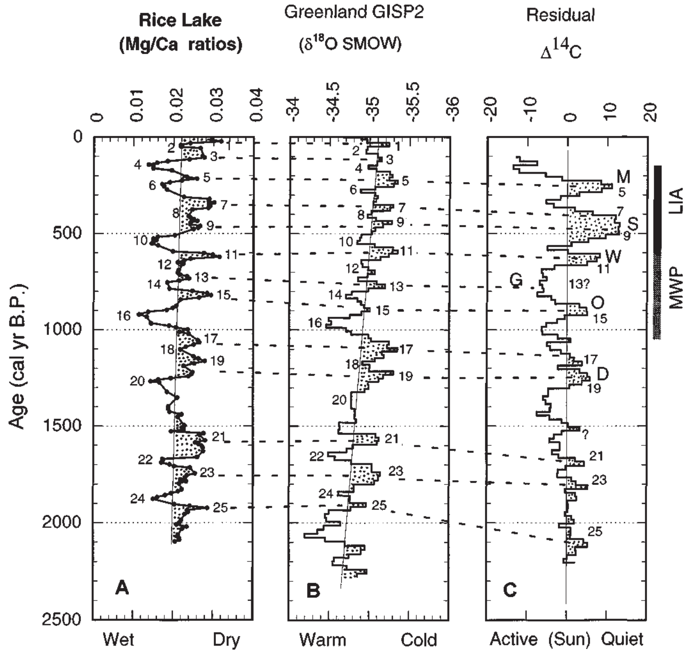

Figure 4. Correlation of paleoclimate and paleo-solar proxies. A: Mg/Ca molar ratio curve (three-point moving average) from Rice Lake. B: Bidecadal $\delta^{18}O$ curve from GISP2 ice core at Greenland Summit (Grootes et al., 1993). Numbers correspond to those in A. C: Bidecadal residual $\Delta^{14}C$ curve from tree rings (M. Stuiver and B. Becker [in Stuiver and Reimer, 1993]; slightly modified, P. J. Reimer, 1998, personal commun.). Classical historical $\Delta^{14}C$ maxima and solar (i.e., sunspot) minima include M—Maunder (A.D. 1645–1715), S—Spörer (A.D. 1420–1530), W—Wolf (A.D. 1280–1340), O—Oort (A.D. 1010–1050), and D—Dark Age (A.D. 660–740). G is Grand Solar Maximum (A.D. 1100–1250) (Eddy, 1976). LIA is Little Ice Age (600–150 yr B.P.); MWP is Medieval Warm Period (1050–600 yr B.P.). All curves are plotted on common age scale (calendar years before A.D. 1950 [i.e., cal yr B.P.]).

solar minimum) has been found in a 22-yr large-scale drought rhythm in the western and central United States (Mitchell et al., 1979; Cook et al., 1997). Sediment records from Elk Lake in northwestern Minnesota displayed the 400- and 88-yr periods in Al concentration over the past 1600 yr (Dean, 1997). Varve thickness during the mid-Holocene prairie time at the same lake showed a 200-yr period (Anderson, 1992). Both proxies are interpreted to represent eolian activity and drought. Significant ~400-yr periodicities have also been found in proxy paleoclimate records at Moon Lake in eastern North Dakota (our analysis of data in Laird et al., 1996) and at Pine Lake in southern Alberta, Canada (Campbell et al., 1998). The variations in effective moisture at these northern Great Plains sites during the late Holocene appear to be coherent, at least for the 400-yr periods, within their cumulative sampling and dating uncertainty of ±120 yr (Appendix; see footnote 1). Additional high-resolution data from other sites in the northern Great Plains are clearly needed to determine if there is a consistent regional drought pattern with 200-, 130-, and 100-yr periodicities and also showing phase correlation with solar proxy.

SOLAR FORCING AND CLIMATE TELECONNECTIONS

Stuiver et al. (1997) found a dominant solar influence on Greenland climate during the past 1000 yr; their interpretation was based on the similarity of GISP2 ice-core $\delta^{18}O$ and atmospheric $\Delta^{14}C$ records. Our Mg/Ca ratios (Fig. 4A) match GISP2 $\delta^{18}O$ variations (Fig. 4B) remarkably well, suggesting a common solar forcing as inferred from $\Delta^{14}C$ fluctuations (Fig. 4C). All the climate maxima and minima (numbers 1–25 in Fig. 4) can be identified from these two climatic series: dry periods at Rice Lake correspond to cold periods at GISP2 (odd numbers), as well as to $\Delta^{14}C$ maxima and solar minima in most cases. As noted by Stuiver et al. (1997), the $\delta^{18}O$ perturbation near 770 yr B.P. (our number 13) is not represented in the $\Delta^{14}C$ record, but our weak Mg/Ca peak 13 seems more comparable with $\Delta^{14}C$ record. From 2100 to 1000 yr B.P. (numbers 25–17), the poorer correlation of $\Delta^{14}C$ with either $\delta^{18}O$ or Mg/Ca is in contrast with much better correlation in timing, magnitude, and phase between Mg/Ca and $\delta^{18}O$ at that time. The climate events at both Rice Lake and Greenland lag behind the solar forcing (inferred from the $\Delta^{14}C$ record) (Fig. 4, A–C). In Greenland, the $\delta^{18}O$ lags $\Delta^{14}C$ by about 40 yr, probably because of the thermal inertia of the mixed layer of the oceans (Stuiver et al., 1997). Cross-spectral analysis of Rice Lake Mg/Ca and $\Delta^{14}C$ records shows statistically significant coherence in the 400- and 130-yr bands, though coherence is below 80% significance in the 200- and 95-yr bands. Their phase spectrum indicates that $\Delta^{14}C$ series lead the Mg/Ca by 45° to 127° (50–140 yr) in the 400-yr band and 140° (50 yr) in the 130-yr band (Appendix; see footnote 1).

General circulation models (GCMs) give a climate sensitivity of ~4 °C for a 2% change in the solar constant (Hansen et al., 1984); thus, a reconstructed 0.25% reduction during the Maunder solar minimum (Lean et al., 1992) would cause 0.5 °C global cooling. A GISS (Goddard Institute for Space Studies) GCM sensitivity experiment using a flat spectrum decrease of 0.25% in solar irradiance (Rind and Overpeck, 1993), however, shows a maximum cooling of about 1 °C and a decrease in effective moisture (precipitation minus evaporation) in interior North America accompanied by warming in the Pacific West and the Northeast due to regional changes in advection patterns (Rind and Overpeck, 1993). This modeling result, together with our Rice Lake record, suggests either a more sensitive response of the continental interior to small changes in the solar constant or the absence of significant internal climatic and oceanic influences in the midcontinent that otherwise would have obscured weak solar signals. It also implies the presence of an amplifying mechanism, possibly through influences of solar-modulated cosmic-ray flux on cloud coverage (Svensmark and Friis-Christensen, 1997) or through influences of solar insolation and continental heating on monsoon strength.

CONCLUSIONS AND IMPLICATION

1. The 2100-yr high-resolution Mg/Ca-ratio time series from Rice Lake in the northern Great Plains shows several strong century-scale periodicities,

which are similar to the principal solar oscillations (Stuiver and Braziunas, 1989). This similarity, together with some of these periodicities in other paleoclimate records in this region, suggests strong solar forcing of century-scale drought frequency in the interior North America.

2. Our climate-proxy record correlates statistically and visually with solar-proxy ($\Delta^{14}C$) and climate-proxy (GISP2 $\delta^{18}O$) records, showing that solar minima ($\Delta^{14}C$ maxima) are in phase with dry periods in the northern Great Plains and cold periods in Greenland. This spectral similarity and phase correlation indicate a possible teleconnection of century-scale global climate fluctuations through common solar forcing.

3. Our results, together with GCM simulation results (Rind and Overpeck, 1993), suggest either a sensitive response of the continental interior to small changes in the solar constant or an absence of significant internal climatic and oceanic influence in the midcontinent that otherwise would have obscured weak external solar forcing.

4. Understanding the regularity with which drought has occurred in the past 2000 yr will help greatly in predicting the timing of future droughts in interior North America. Our data indicate that we are in the middle of the 260-yr-long relatively dry period and suggest that this climate will persist for about another century before the next 130 yr of relatively wet climate. The human-induced global warming over the past century, however, may add its own effects on top of this 400-yr cycle and exacerbate the intensity of natural fluctuation and drought.

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