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Subtropical coral reveals abrupt early-twentieth-century freshening in the western North Pacific Ocean

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ABSTRACT

Instrumental climate observations provide robust records of global land and ocean temperatures during the twentieth century. Unlike for temperature, continuous salinity observations in the surface ocean are scarce prior to 1970, and the magnitude of salinity changes during the twentieth century is largely unknown. Surface ocean salinity is a major component in climate dynamics, as it influences ocean circulation and water mass formation. Here we present an annually resolved reconstruction of salinity variations in the surface waters of the western subtropical North Pacific Ocean since 1873, based on bimonthly records of $\delta^{18}O$, Sr/Ca, and U/Ca in a coral from the Ogasawara Islands. The reconstruction indicates that an abrupt regime shift toward fresher surface ocean conditions occurred between 1905 and 1910. Observational atmospheric data suggest that the abrupt freshening was associated with a weakening of the winds that drive the Kuroshio Current system and the associated subtropical gyre circulation. We note that the abrupt early-twentieth-century freshening in the western subtropical North Pacific precedes abrupt climate change in the northern North Atlantic by a few years. The potential for abrupt regime shifts in surface ocean salinity should be considered in climate predictions for the coming decades.

INTRODUCTION

Changes in surface ocean salinity and their role in influencing ocean circulation, water mass formation, and global climate are currently being widely discussed. However, assessing the range of salinity changes in the past is crucial for improved estimates on future climate based on model simulations. In the North Pacific Ocean, little is known about the range of surface ocean salinity variations throughout the twentieth century, due to a lack of continuous instrumental observations and appropriate proxy records.

The Kuroshio Current system is an important component of Earth's climate system. The northward-flowing Kuroshio, the western boundary current of the wind-driven North Pacific subtropical gyre, transports warm and saline tropical waters to higher latitudes (Fig. 1A). After leaving the Japanese coast it flows eastward as the Kuroshio Extension. A recirculation gyre exists to the south of the Kuroshio and its extension. In this region of the Pacific, where cold dry air masses from continental Asia encounter the warm Kuroshio waters, the ocean to atmosphere heat flux is among the highest in the world (KESS, 2008; Qiu, 2002; Yasuda, 2003). Here we present a reconstruction of sea-surface salinity (SSS) since 1873 from an annually banded coral growing in the western subtropical North Pacific, within the Kuroshio Current system.

MATERIAL AND METHODS

A core was drilled in 2002 through a living *Porites* coral at Chichijima, Ogasawara Islands (Japan), located in the southwestward return flow

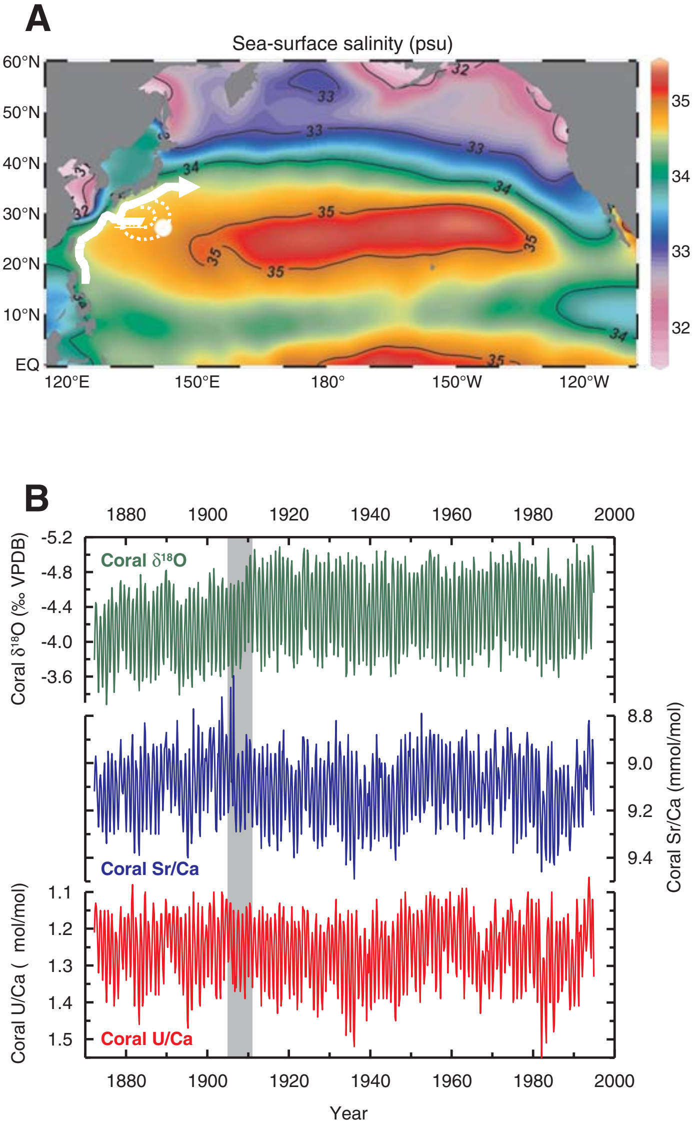

Figure 1. Map of the North Pacific Ocean and bimonthly $\delta^{18}O$, Sr/Ca, and U/Ca records from a western subtropical North Pacific coral. A: Sea-surface salinity map (Conkright et al., 2002). The coral site in the Ogasawara Islands and schematic flow patterns of Kuroshio, Kuroshio Extension, and Kuroshio recirculation are shown (Imawaki et al., 2001; Taneda et al., 2000). B: Coral $\delta^{18}O$, Sr/Ca, and U/Ca records. Gray bar—time interval 1905–1910.

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of the Kuroshio recirculation system (Taneda et al., 2000). The massive colony, growing at 5.6 m water depth on the island's northern side (27° 6.355′ N, 142° 11.645′ E), is directly exposed to open-ocean conditions. The bimonthly resolved records of $\delta^{18}O$, Sr/Ca, and U/Ca generated from the aragonitic coral skeleton show clear annual cycles that can be counted back to the year 1873 (Fig. 1B) (for detailed methods see GSA Data Repository[1]). This age model is corroborated by the skeletal pattern of annual density-band pairs as revealed by X-radiographs (Fig. DR1 in the GSA Data Repository). The annual cycles in coral $\delta^{18}O$, Sr/Ca, and U/Ca reflect the sea-surface temperature (SST) seasonality, which has an amplitude of 7 °C at Chichijima.

RESULTS

The most striking feature of the coral $\delta^{18}O$ record is a prominent shift toward more negative values in the early twentieth century (Fig. 1B). Because coral $\delta^{18}O$ reflects both temperature and $\delta^{18}O$ of seawater, this shift could indicate a change toward warmer and/or fresher conditions. The corresponding coral Sr/Ca and U/Ca paleothermometer records, however, do not reveal simultaneous warming. The annual average coral Sr/Ca and U/Ca records are in excellent agreement with each other and are highly correlated with a 20-year instrumental SST record from Chichijima (Fig. 2). We reconstructed SST from coral Sr/Ca and U/Ca, which allowed us to subtract the temperature component from coral $\delta^{18}O$. We generated two annually resolved salinity reconstructions by combining the annual average coral $\delta^{18}O$ record with the Sr/Ca and U/Ca records, respectively. The residual coral $\delta^{18}O$ ($\Delta\delta^{18}O$) reflects variations in $\delta^{18}O_{seawater}$, which are closely related to salinity changes. The two annually resolved coral $\Delta\delta^{18}O$ records are in excellent agreement with each other and are highly correlated with regional SSS based on reanalysis data (SODA 1.4.2) (Carton and Giese, 2008), giving confidence in their application as SSS proxy. Furthermore, our results suggest that U/Ca in this coral is a robust paleothermometer and not influenced by salinity variations.

Coral physiology, calcification rate, and diagenesis can be excluded as causes of the early-twentieth-century shift toward more negative coral $\delta^{18}O$. The Ogasawara coral $\Delta\delta^{18}O_{Sr/Ca}$ and $\Delta\delta^{18}O_{U/Ca}$ records are therefore interpreted to indicate an abrupt freshening of the surface waters in the western subtropical North Pacific between 1905 and 1910, which has the character of a regime shift. The average of the two paleosalinity records indicates that this freshening was associated with a 0.345 ± 0.005‰ decrease in seawater $\delta^{18}O_{VPDB}$. Using the relationship of 0.433‰ $\delta^{18}O_{VSMOW}$ per 1 psu (0.420‰ $\delta^{18}O_{VPDB}$ per 1 psu) for this region of the Pacific (24.5°–35° N, 140°–171° E; 0–50 m water depth) (Schmidt et al., 1999), this would translate into a 0.82 ± 0.01 psu decrease in SSS. The analytical uncertainty for annual average coral $\Delta\delta^{18}O$ is ±0.038‰ or ±0.09 psu. The magnitude of the freshening is high but on the same order as interdecadal variations in South Pacific coral $\delta^{18}O_{seawater}$ reconstructions (Calvo et al., 2007; Hendy et al., 2002; Linsley et al., 2006; Quinn et al., 2006) when translated into salinity. We note that the quantification of the freshening is dependent on the applied $\delta^{18}O_{seawater}$-salinity relationship. For instance, a 0.345 ± 0.005‰ decrease in $\delta^{18}O_{seawater}$ would translate into a 0.14 ± 0.02 psu decrease in SSS, based on the regression of coral $\Delta\delta^{18}O$ with regional SSS. However, the amplitude of regional SSS is dependent on the reanalysis procedure and data set version. A higher interannual variability in coral-based compared to SODA 1.4.2 salinity has also been observed at other locations (Cahyarini et al., 2008).

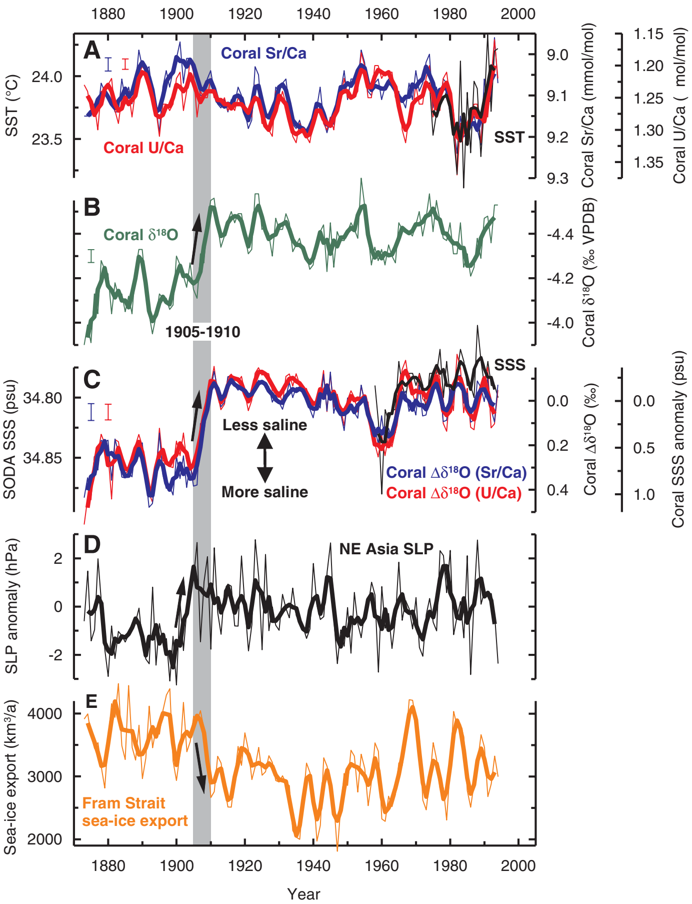

Figure 2. Interannual records of Sr/Ca, U/Ca, $\delta^{18}O$, and paleosalinity from a western subtropical North Pacific coral. Instrumental SST and SSS axes are visually scaled. Thin lines—annual records and corresponding error bars; bold lines—three-year running averages; gray bar—time interval 1905–1910. A: Coral Sr/Ca and U/Ca records, and local sea-surface temperature (SST) (Tokyo Metropolitan Ogasawara Fisheries Center). B: Coral $\delta^{18}O$ record. C: Residual coral $\delta^{18}O$ records ($\Delta\delta^{18}O$) based on $\delta^{18}O$ and Sr/Ca, and $\delta^{18}O$ and U/Ca; coral-based sea surface salinity (SSS) anomaly calculated from regional $\delta^{18}O_{seawater}$-salinity relationship (0.42‰ per 1 psu) (Schmidt et al., 1999); and regional SSS from Simple Ocean Data Assimilation (SODA) reanalysis (Carton and Giese, 2008) (27.0°–27.5° N, 142.0°–142.5° E). D: Northeast Asia winter (December, January, February) sea-level pressure (SLP) (45°–60° N, 110°–130° E) (Basnett and Parker, 1997). E: Fram Strait sea-ice export reconstruction (Schmith and Hansen, 2003).

DISCUSSION

Potential causes of the abrupt 1905–1910 surface ocean freshening include changes in precipitation and atmospheric and oceanic circulation. Instrumental observations of Ogasawara precipitation started in 1907 (Vose et al., 1992). At the western margin of the Pacific, however, precipitation records from Okinawa (26.2° N) and Tokyo (35.8° N) extend back into the nineteenth century and show no evidence for an early-twentieth-century regime shift. We therefore exclude precipitation changes as a cause of the freshening.

The difference in average Northern Hemisphere sea-level pressure (SLP) fields (Basnett and Parker, 1997) between the periods after (1910–1942) and before the freshening (1873–1905) reveals maximum gradients over southern Japan, close to the Ogasawara Islands (Fig. 3). This spatial and temporal coincidence provides evidence that the reconstructed freshening is associated with a shift in the large-scale atmospheric circulation. The SLP anomalies indicate an anomalous anticyclonic circulation over

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[1] GSA Data Repository item 2009123, Figures DR1–DR10 (X-radiographs, spectral analysis results, thin-section photomicrographs, scanning electron microscope images, and results from the 1995–2002 interval of coral record), material and methods, and supporting text, is available online at www.geosociety.org/pubs/ft2009.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

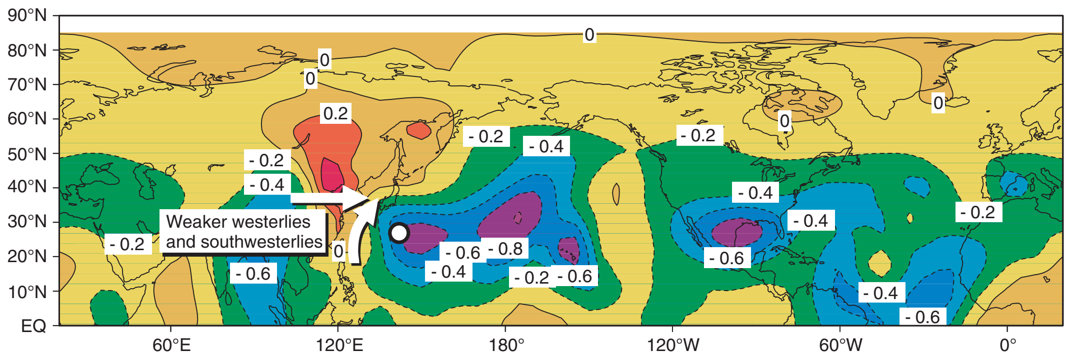

Figure 3. Sea-level pressure (SLP) difference between the periods after and before the 1905–1910 freshening. Average SLP (Basnett and Parker, 1997) for 1910–1942 minus that for 1873–1905 for annual average conditions. Climatological surface winds, which are weakened by the anomalous atmospheric circulation resulting from the SLP anomaly pattern that is characterized by maximum gradients over southern Japan, are schematically represented as white arrows. Units are hPa. White dot—Ogasawara Islands.

northeast Asia most pronounced in winter, and an anomalous cyclonic circulation over the western subtropical North Pacific most prominent in summer (Fig. DR2). An anomalous easterly/northeasterly surface circulation over southern Japan is associated with this atmospheric pattern, which is physically consistent with a weakening of the prevailing westerlies/southwesterlies over the western subtropical to midlatitude North Pacific.

Since precipitation changes are not likely the cause of the freshening, this suggests changes in evaporation and/or water masses. Our findings are consistent with a weakening of the winds that drive the Kuroshio Current system and the associated subtropical gyre circulation. In this region of the North Pacific, wind stress forcing, Kuroshio transport, subtropical gyre intensity, and westward expansion of high-salinity waters are strongly coupled (Deser et al., 1999; Miller et al., 1998; Nakano et al., 2005; Qiu and Chen, 2005; Shuto, 1996; Suga et al., 2000; Yasuda and Hanawa, 1997). A weakened Kuroshio would result in decreased northward transport of warm saline water to subtropical latitudes. Weakened westerlies would, in addition to reducing Kuroshio transport, result in decreased advection of cold dry air from Asia, reducing evaporation over the ocean. The two mechanisms would affect regional SSS in the same sense, resulting in an amplified freshening signal, but would affect SST in the opposite sense. This is consistent with the only minor cooling accompanying the abrupt freshening (Fig. 2), probably reflecting the dominance of Kuroshio transport relative to continental air advection in controlling regional SST. High-salinity surface waters (>35 psu) are restricted today to the central subtropical North Pacific (Fig. 1A). Because a wind-driven weakening of the Kuroshio Current system is associated with an eastward contraction of these waters (Shuto, 1996; Suga et al., 2000), this mechanism could have further amplified the freshening in the western subtropical North Pacific. We conclude that the Ogasawara Islands represent a very sensitive location with respect to SSS changes, because the combination of atmospheric and oceanic advection processes results in a large-amplitude salinity signal.

Observational studies indicate a four- to five-year lag of the strength of the Kuroshio Extension and associated gyre-scale circulation relative to wind stress forcing (Deser et al., 1999). Consistent with these observations, the winter SLP record from the northeast Asian atmospheric anomaly center reveals that the 1905–1910 freshening lags an abrupt shift toward higher SLP (1901–1905) by approximately four years (Fig. 2). This suggests an important role for the northeast Asian atmospheric center in initiating the weakening of the winds that drive the Kuroshio Current system. In the subtropical atmospheric center, a corresponding shift toward lower summer SLP is more gradual (Fig. DR3). We note that the early-twentieth-century freshening shift is different from the overall interannual to decadal variability of our salinity reconstruction. This variability with significant variance at periods of two to six years (Fig. DR4) does not show strong similarity to northeast Asian SLP throughout most of the twentieth century, and is very likely controlled by other processes.

Pacific $\delta^{18}O_{seawater}$ reconstructions resolving interannual to decadal variability are restricted to coral records (Calvo et al., 2007; Hendy et al., 2002; Linsley et al., 2006; Quinn et al., 2006). These Southern Hemisphere records reveal no early-twentieth-century freshening but a mid-nineteenth-century freshening of the tropical southwestern Pacific (Hendy et al., 2002). However, a causal link between the latter and our subtropical northwestern Pacific freshening is speculative. The coral $\delta^{18}O$ record closest to the Ogasawara Islands, from tropical Guam (13° N, 145° E) (Asami et al., 2005), apparently indicates no early-twentieth-century freshening. We conclude that the latter reflects a phenomenon restricted to the subtropical North Pacific.

Evidence for early-twentieth-century abrupt climate change is rare in the North Pacific. A 1905 regime shift is observed in a Pacific Decadal Oscillation (PDO) reconstruction (Gedalof et al., 2002) that combines tropical and extratropical archives (Fig. DR5). The relevance of this finding has been neglected so far, mostly because the instrumental PDO index (Mantua et al., 1997), solely based on extratropical North Pacific SST, does not reveal a corresponding shift. The occurrence of a regime shift ca. 1905 in reconstructions of the PDO (Gedalof et al., 2002) and SSS in the Kuroshio recirculation is consistent with the hypothesis that the PDO arises from superposition of phenomena of tropical and North Pacific origin, including oceanic advection in the Kuroshio Extension (Schneider and Cornuelle, 2005). In the western United States, a region strongly influenced by North Pacific climate (Mantua et al., 1997), a period of persistent wet conditions started in 1905 (Woodhouse et al., 2005). This pluvial period lasted until 1917. The reconstructions of western subtropical North Pacific salinity, PDO, and western U.S. rainfall do not correlate otherwise, but a 1905 regime shift is common to all of them. This demonstrates the large-scale nature of this shift, which is superimposed on regional climate variability.

More evidence for early-twentieth-century abrupt climate change comes from the northern North Atlantic. A regime shift toward lower Fram Strait sea-ice export from the Arctic Ocean occurred between ca. 1909 and 1914 (Schmith and Hansen, 2003), lagging our western subtropical North Pacific freshening by a few years (Fig. 2). The freshwater export through Fram Strait is thought to influence the Atlantic thermohaline circulation (Dima and Lohmann, 2007; Schmith and Hansen, 2003). A physical mechanism linking the two abrupt early-twentieth-century regime shifts could involve (1) North Pacific atmosphere-ocean interactions affecting Fram Strait sea-ice export via atmospheric teleconnections (Dima and Lohmann, 2007), and/or (2) changes in transport of North Pacific water to the North Atlantic through Bering Strait (Keigwin and Cook, 2007).

The 1995–2002 interval of the coral record was not interpreted. Although all proxies show clear annual cycles during this interval, the annual average Sr/Ca and U/Ca indicate anomalously low SST, which is in conflict with anomalously high observed SST (Figs. DR6 and DR7). We speculate that this paleothermometer breakdown is due to thermal stress

(Marshall and McCulloch, 2002), which is supported by local evidence for coral bleaching during this period.

CONCLUSIONS

Our results indicate an abrupt regime shift toward fresher surface ocean conditions between 1905 and 1910 in the western subtropical North Pacific, resulting from a combination of atmospheric and oceanic advection processes. Further investigations should address the potential triggers for this shift. We note that the early twentieth century is characterized by a rise in global temperatures (Brohan et al., 2006) and a minimum in the Gleissberg cycle of solar activity (Peristykh and Damon, 2003). Whether our regime shift is a consequence of anthropogenic or natural climate change or a combination of both remains to be shown.

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