The Decadal Variability of the Global Monsoon Links to the North Atlantic Climate Since 1851

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Abstract To date, the decadal variability of the Global Monsoon (GM) has been mainly studied using instrumental data collected over the last 50 years, and further discussion has been hampered by the limited data length. Here, we present a coral δ18O record from the northern South China Sea, where the hydrology is related to the seasonal Intertropical Convergence Zone (ITCZ) migration, and we use this record to reconstruct the decadal migration of the ITCZ since 1851 A.D. Combining our record with a synthesis of monsoon records reveals an anti-phase inter-hemispheric variability of the GM over the last 150 years, indicating that the decadal-scale hydrologic variability in the tropics is modulated by the meridional migration of the ITCZ. The plausible relationship observed between the decadal variability of the GM and the Atlantic Multidecadal Oscillation suggests that the decadal variability of tropical hydrological changes is likely linked to the climate perturbations in the North Atlantic.

1. Introduction

The Global Monsoon (GM), defined as the global-scale seasonal reversal of tropical overturning circulation associated with the migration of the Intertropical Convergence Zone (ITCZ) (Trenberth et al., 2000; Wang & Ding, 2008), has recently been suggested as a dominant influence on the regional monsoons across different timescales (An et al., 2015; Cheng et al., 2012; Wang et al., 2014). On millennial and orbital timescales, the anti-phase inter-hemispheric variability of the GM is related to changes in the North Atlantic (NA) climate and asymmetric hemispheric solar insolation variations (An et al., 2015; Cheng et al., 2012; Wang et al., 2014). A weakened Northern Hemisphere Summer Monsoon (NHSM) and a strengthened Southern Hemisphere Summer Monsoon (SHSM) usually correspond to extended high-latitude ice cover, a slowdown of the Atlantic Meridional Overturning Circulation (AMOC) and reduced insolation in the Northern Hemisphere relative to the Southern Hemisphere, and vice versa. Several studies have investigated the variability of the present-day GM and its driving forces on interannual and decadal timescales (Ding et al., 2015; Wang & Ding, 2006; Wang et al., 2012, 2013). The decadal variability of the GM has been associated with the synchronous intensification of both the NHSM and SHSM over the past 30 years, and the mechanism was ascribed mainly to the enhanced zonal thermal gradient in the Pacific Ocean (Wang et al., 2012).
Observations during the 1960s revealed the significant decadal variations of monsoon precipitation over different monsoon domains (Baines & Folland, 2007; Chiang & Friedman, 2012; Hwang et al., 2013). During this period, reduced precipitation occurred over the Sahel, India and northern China, while enhanced monsoon rainfall occurred over the southern Amazon (Baines & Folland, 2007; Chiang & Friedman, 2012). Several studies have identified this phenomenon as a "climate shift" beyond the regional scale, and it is characterized by the global-scale southward shift of tropical rainfall, which is different from the rainfall pattern indicated in the studies of the present-day GM (Chiang & Friedman, 2012; Wang et al., 2012). The mechanism of the "climate shift" is controversial and has been attributed to increasing anthropogenic aerosol forcing (Hwang et al., 2013) or to changes in the NA temperature during that period (Green et al., 2017; Kang et al., 2009). However, previous studies of the present-day GM precipitation are based mainly on model simulations and instrumental data from the last 50 years (Ding et al., 2015; Wang & Ding, 2006; Wang et al., 2012, 2013). The limited length of instrumental data hampers further discussions of the decadal variability of the GM and its possible driving mechanisms.

In this study, we present a 157-year, monthly resolved coral δ^{18}O record from Yongxing Island (16.84°N, 112.33°E), Xisha Islands, in the northern South China Sea (NSCS; Figures 1, S1 and S2), which is close to the northern limit of the ITCZ. The results suggest that the coral δ^{18}O record captures the decadal hydrological changes related to the regional ITCZ migration. To discuss the decadal variability of the GM, we combine our record with a synthesis of the monsoon records. Our results suggest that the GM varied in an anti-phase inter-hemispheric mode on decadal timescales associated with the ITCZ migration over the past 150 years. We found a plausible linkage between the decadal variability of GM and the Atlantic Multidecadal Oscillation/Variability (AMO/AMV). This result, together with the knowledge that the NA SST change has the potential to induce the ITCZ migration (Green et al., 2017; Kang et al., 2009; Monerie et al., 2019), indicated that the NA has been driving the anti-phase inter-hemispheric variability of the GM on decadal timescales.

2. Local Setting and ITCZ Migration

As Yongxing Island is located near the northern limit of the ITCZ, the hydrology in the vicinity of the island is sensitive to the ITCZ migration (Kajikawa & Wang, 2012). Seasonally, when the ITCZ moves northward to the Xisha area in the boreal summer and autumn, decreased SSS occurs in the vicinity of Yongxing Island due to the increased precipitation (Supplementary Information) (Kajikawa & Wang, 2012). Particularly, the precipitation/SSS of the Yongxing Island (~16.84°N) peaks in October, when the ITCZ is almost overhead (~16.25°N) (Figure S9).

3. Materials and Methods

A 2-m-long core was drilled in late June 2008 from a living Porites lutea coral head at a water depth of 6m off Yongxing Island, Xisha Islands (16.84°N, 112.33°E). Monthly resolution sub-samples (~15 samples/yr) for stable isotope analysis were drilled along the maximum growth axes identified in the X-ray radiographs (Figure S2). Coral δ^{18}O was analyzed using a ThermoFisher MAT-253 Isotope Ratio Mass Spectrometer with an automatic Kiel IV carbonate reaction device at the Key Laboratory of Ocean and Marginal Sea Geology, South China Sea Institute of Oceanology, Chinese Academy of Sciences (Supplementary Information). The coral δ^{18}O data were interpolated to 12 points per year (Supplementary Information). The monthly coral δ^{18}O record shows clear annual cycles that can be counted back to 1851 A.D. (Figures S1 and S2).

4. Results and discussions

4.1. Contributions of salinity and temperature to coral δ^{18}O

The variability of coral δ^{18}O is controlled primarily by the sea surface temperature (SST) and sea surface salinity (SSS; linearly correlated with seawater δ^{18}O) (Yü, 2012); therefore, we first investigated the instrumental SST and SSS records. Seasonally, there is no doubt that the SST component is recorded in the coral δ^{18}O because of the pronounced seasonal SST cycle, which is much larger than the seasonal SSS cycle (Figure S3 and Table S1). On super-annual timescales, however, the contribution of SSS becomes non-negligible since the 1σ standard deviation (SD) of the annually averaged SST was 0.44°C (resulting in the 1σ SD of ~0.08‰ for coral δ^{18}O based on a slope of -0.18‰/°C) (Shen et al., 2005; Sun et al., 2005) and the
σ of the annually averaged SSS was 0.28 psu (resulting in the 1σ SD of ~0.06‰ for coral δ18O based on a slope of 0.23‰/psu) (Hong et al., 1997) for the period of 1961–2007. Moreover, the cross-spectral analysis (Howell et al., 2006) indicates that the amplitude of SST variability is large on interannual timescales, while the SSS variability is strong on decadal timescales (Figure S4). The non-significant (at 95% confidence level) coherence of the cross-spectral analysis indicates that little common variance existed between the instrumental records on superannual timescales, allowing us to separate the contributions of SST and SSS on different timescales (Figure S4). Therefore, an interannual SST signal and a decadal SSS component are expected to be observable in the coral δ18O record on superannual timescales.

Considering that the instrumental SST data show a significant warming trend while the instrumental SSS data do not show a significant trend (at 95% confidence level; Figure S5), we applied an 11-year moving average after linear trend removal to isolate the decadal SSS component in the coral δ18O. The smoothed coral δ18O is highly correlated with the smoothed instrumental SSS for the period of 1961–2007 (r = 0.92, p < 0.01; Supplementary Information; Figure 2b), suggesting that 85% of the δ18O variance on decadal timescales is attributable to the decadal changes in SSS.

Since the instrumental SSS was unavailable before 1961, we used the SODA SSS data produced by the ocean model (Carton & Giese, 2008) to extend the δ18O-SSS calibration back to the late 19th century, though its relationship with the instrumental SSS on decadal timescales (r = 0.77, p < 0.05; Figure 2b) is not as consistent as that between the coral δ18O and the instrumental SSS. A significant correlation was found between the smoothed coral δ18O and the smoothed SODA SSS data for the period of 1871–2007 (r = 0.73, p < 0.01), supporting the persistent δ18O-SSS correspondence on decadal timescales from the perspective of model simulations (Figure 2b). The comparison between the decadal variability of the coral δ18O and the Δδ18O (δ18O variability with temperature component removed)

**Figure 1.** Locations of the monsoon records. The colour shadings indicate the climatological mean of annual mean precipitation from 1981 to 2010 (Huffman et al., 1997). The star indicates the location of our record (YX–South China Sea). The dotted rectangles outline the area of instrumental records (O1-Core-Monsoon India Rainfall Index [CMIRI (Parthasarathy et al., 1994)], O2-Sahel Precipitation Index [SPI (Janowiak, 1988)], O3-North China Precipitation Index [NCP] (Ding et al., 2008)], O4-Northeast Brazil Rainfall Index [NEBRI (Moura & Shukla, 1981)], O5-Northern Australia Rainfall Index [NARI (Lavery et al., 1997)]. The locations of other proxy records are shown with circles [P1-northern India (Sinha et al., 2015), P2-Guinea Coast (Shanahan et al., 2009), P3-northern China (Li et al., 2015), P4-mid-west Brazil (Novello et al., 2016), P5-Indonesia (D’Arrigo et al., 2006)]. The brown lines outline the monsoon domains defined by the precipitation seasonality (Wang & Ding, 2008). The dashed lines indicate the modern positions of the ITCZ in July and January.

**Figure 2.** Comparison of proxy instrumental data for hydrological variability in the NSCS. (a) Annually averaged (grey) and 11-year moving averaged (black) coral δ18O records (detrended). (b) Comparison of the decadal variability of coral δ18O (black), instrumental SSS (dark blue) (provided by the Xisha Oceanographic Observatory) and gridded SSS data (light blue) (Carton & Giese, 2008). (c) Comparison between the decadal variability of coral δ18O (black) and the ITCZ position index (Freeman et al., 2016) derived from the ICOADS 2°×2° products (dark green) and the ICOADS 1°×1° products (light green), respectively (Supplementary Information). The grey lines in (b) and (c) indicate the 1σ uncertainties in the salinity (instrumental SSS) and the regional ITCZ (ICOADS 1°×1° products) reconstructions respectively. The series in (b) and (c) were linearly detrended and smoothed with an 11-year moving average to highlight the decadal variabilities.
also confirms the consistency between the coral $\delta^{18}O$ and the SSS on decadal timescales (Figure S6). To further quantify the relative contributions of SSS and SST to coral $\delta^{18}O$ on decadal timescales, we developed a “pseudocoral” forward model (Thompson et al., 2011) based on the instrumental and gridded series and determined the percent SST/SSS contribution of ~10/90% (Supplementary Information). These results indicate a robust relationship between the coral $\delta^{18}O$ and SSS on decadal timescales during the period spanning the entire coral $\delta^{18}O$ record. Considering that the SSS is linearly correlated with the precipitation in the NSCS (Figure S8), the decadal variability of the coral $\delta^{18}O$ could be used as a reliable proxy for the decadal hydrological changes in the NSCS.

4.2. ITCZ migration recorded in coral $\delta^{18}O$

To validate the relationship between the regional hydrology and the decadal ITCZ migration, we correlated the smoothed coral $\delta^{18}O$ (linearly detrended) with the smoothed regional ITCZ position index (ICOADS $2^\circ \times 2^\circ$ products: $r = -0.71$, $p_{adj} < 0.05$, for the period of 1904–2007; ICOADS $1^\circ \times 1^\circ$ products: $r = -0.74$, $p_{adj} = 0.10$, for the period of 1960–2007) (Freeman et al., 2016), which is an index of the zonal mean latitude of the regional ITCZ (Supplementary Information). The correlation between the coral $\delta^{18}O$ and the regional ITCZ position on decadal timescales indicates that the regional hydrology variability is predominantly controlled by the decadal migration of the ITCZ. Decadally, the coral $\delta^{18}O$ tends to become more negative when the ITCZ migrates northward, suggesting a wetter condition associated with the northward ITCZ migration, and vice versa (Figure 2c).

Large fluctuations in the decadal variability of the coral $\delta^{18}O$ record suggest substantial hydrological changes near Yongxing Island related to the ITCZ migration during the past 150 years (Figures 2a and S11). To investigate the ITCZ migration on a global scale, we compared the decadal variability of the coral $\delta^{18}O$ with other ITCZ records (Black et al., 1999; Green et al., 2017; Hetzinger et al., 2008; Oppo et al., 2009). The comparison among the records broadly shows that a wetter NSCS, wetter southern Caribbean and drier Indonesia occur when the global ITCZ migrates northward and that the opposite occurs when the global ITCZ migrates southward, although a discrepancy is observed from ~1970–1980s (Figure 3). From ~1970–1980s, the southward global ITCZ migration corresponded to a wetter NSCS and the drier Indonesia, indicating anomalous ITCZ migration over the Indo-Pacific during that period (Figure 3). The correlations between our coral $\delta^{18}O$ and other ITCZ records (Green et al., 2017; Hetzinger et al., 2008) further support a coherent global ITCZ migration on decadal timescales (coral $\delta^{18}O$-global ITCZ position: $r = -0.66$, $p_{adj} = 0.06$; coral $\delta^{18}O$-Caribbean coral: $r = 0.64$, $p_{adj} < 0.05$). Overall, although individual records may be influenced by additional factors, the common signal among the decadal variability of the ITCZ records reflects a northward ITCZ migration from ~1860–1900s, ~1920–1960s and ~1990–2007 and a southward ITCZ migration from ~1851–1860s, ~1900–1920s and ~1960–1990s (Figure 3).

4.3. Decadal variability of the Global Monsoon

On millennial and orbital timescales, the anti-phase inter-hemispheric variability of GM associated with the migration of the ITCZ is suggested to be the dominant mode of the GM (An et al., 2015; Cheng et al., 2012; Wang et al., 2014). However, the variability of the GM on decadal timescales remains unclear. To investigate the dominant mode of the GM on decadal timescales, we compared our ITCZ reconstruction with the regional monsoon records, including both instrumental and proxy records. For the period after 1900, when rain gauge networks were available, enhanced rainfall was observed in India (Parthasarathy et al., 1994), the Sahel (Janowiak, 1988), and northern China (Ding et al., 2008), whereas reduced rainfall occurred in northeast Brazil (Moura & Shukla, 1981) and northern Australia (Lavery et al., 1997), such as in ~1920–1960s, when the ITCZ migrated northward, and vice versa (Figure 4). Because most observations were unavailable before 1900, we selected proxy records with high resolution and accuracy to extend the monsoon records back to 1851 (Supplementary Information and Table S4). Similar patterns were also found in the records prior to 1900: When the ITCZ migrated northward from ~1860–1900s, a strengthened Indian Summer Monsoon (ISM) was indicated by increased rainfall in India (Parthasarathy et al., 1994) and by the decreased stalagmite $\delta^{18}O$ from northern India (Sinha et al., 2015), despite several differences associated with the local effects on stalagmite record. The more negative lake sediment $\delta^{18}O$ from West Africa has been interpreted as a strengthened West African Summer Monsoon (WASM) during that time (Shanahan et al., 2009). Both the multi-proxy tree ring chronologies (Li et al., 2015) and the observations (Ding et al., 2008) revealed an
enhanced monsoon precipitation over northern China during that period, indicating a strengthened East Asian Summer Monsoon (EASM). The observations in northeast Brazil (Moura & Shukla, 1981) and the stalagmite $\delta^{18}O$ from mid-west Brazil (Novello et al., 2016) showed a weakened South American Summer Monsoon (SASM) at that time. Meanwhile, the monsoon drought variability retrieved from tree ring widths and coral $\delta^{18}O$ is indicative of a weakened Indonesian–Australian Summer Monsoon (IASM) (D’Arrigo et al., 2006). Opposite conditions occurred when the ITCZ migrated southward in ~1851–1860s (Figure 4).

In general, the synthesis of the records from different monsoon domains outlines a scenario in which enhanced summer monsoon occurred over most Northern Hemisphere monsoon domains (Figures 4b–d) along with the northward ITCZ migration (Figure 4a), whereas monsoon precipitation decreased over the Southern Hemisphere (Figures 4e–f), and vice versa. This characteristic indicates that in addition to millennial and orbital timescales (An et al., 2015; Cheng et al., 2012; Wang et al., 2014), the anti-phase inter-hemispheric variability is also the dominant mode of the GM on decadal timescales, at least for the period from ~1851–1980. Previous studies have reported the simultaneous intensification of NHSM and SHSM since ~1980 (Wang & Ding, 2006; Wang et al., 2012); however, our results show that this phenomenon was unusual during the period from 1851 to 2007 and may have been associated with the anomalous variation in the IASM after ~1980s (Figure 4).
We generalized 6 phases of the GM over the past 150 years, including the strong NHSM/weak SHSM from ~1860–1900s, ~1920–1960s, and after ~1990s along with the weak NHSM/strong SHSM from ~1851–1860s, ~1900–1920s, and ~1960–1990s. Several exceptions, such as the weakened SASM from ~1900–1910s, the weakened ISM after ~1990s and strengthened IASM after ~1980s (Figure 4), may have been caused by regional factors related to the distinct land-ocean configurations. Furthermore, five “climate shift” events were identified based on the phase transitions of GM, including the well-known event that occurred during the 1960s (Figure 4) (Baines & Folland, 2007; Chiang & Friedman, 2012).

Figure 4. Linkage among the decadal variabilities of the ITCZ, regional monsoons and NA SST. (a) Coral $\delta^{18}$O record in this study. (b–g) The instrumental indices and the proxy records of the regional monsoon precipitation. Locations of the monsoon records are given in Figure 1. (g) The AMO index (Enfield et al., 2001) and the proxy-based AMV reconstruction (Wang et al., 2017). The coral record in (a) and the instrumental records in (b–g) were plotted in shaded colours; red indicates relatively wet/warm conditions, while blue indicates relatively dry/cold conditions. The black lines in (b–g) indicate the proxy records. The shaded grey areas denote the periods corresponding to “climate shift” events (the common phase transitions among the records). The records were interpolated to annual resolution, linearly detrended, smoothed with an 11-year moving average and standardized by a Z-score to highlight the decadal variabilities.
4.4. Possible driving mechanism underlying the Global Monsoon over the past 150 years

The mechanism of GM dynamics on millennial to orbital timescales has been well discussed (An et al., 2015; Cheng et al., 2012; Wang et al., 2014); however, the driving force of the GM variability on decadal timescales remains elusive. Previous studies based on instrumental data have attributed the decadal variability of the GM to the zonal thermal contrast in the Pacific Ocean, such as the El Niño–Southern Oscillation (ENSO) and the Interdecadal Pacific Oscillation (IPO) (Wang et al., 2012, 2013). Changes in the zonal thermal gradient in the Pacific tend to cause a simultaneous enhancement/attenuation of both the NHSM and SHSM by strengthening/weakening the Pacific subtropical highs in both hemispheres and, in turn, by influencing the intensity of the trade winds (Wang et al., 2012, 2013). If the zonal thermal gradient in the Pacific is the driving force, the decadal variability of GM should act as the in-phase inter-hemispheric mode, instead of the anti-phase inter-hemispheric mode revealed in our results. Therefore, the zonal thermal gradient in the Pacific is unlikely to be the driving force of GM variability on decadal timescales.

The AMO/AMV is a low-frequency oscillation of the NA SST (Enfield et al., 2001) and its potential to influence tropical hydrology has been reported (Green et al., 2017; Kang et al., 2009; Monerie et al., 2019). Here we also investigate the linkage between the GM and the AMO, for which a close teleconnection was observed on decadal timescales (Figures 4, S12 and Table S5). The strengthened NHSM/weakened SHSM and the northward ITCZ migration corresponded to the warming of NA, whereas the weakened NHSM/strengthened SHSM and the southward ITCZ migration were coeval with the cooling of NA (Figures 4 and S12). This pattern not only indicates the importance of the NA temperatures in modulating tropical climate but also emphasizes the existence of a global teleconnection between the NA climate and tropical rainfall on decadal timescales in addition to millennial timescales (An et al., 2015; Cheng et al., 2012; Wang et al., 2014). Studies have suggested the importance of the NA temperature in influencing the hemispheric temperature on decadal timescales (Chiang & Friedman, 2012; Thompson et al., 2010; Zhang et al., 2007). The cooling of the NA leads to cooling and pressure increases over the continents and a large part of the oceans in the Northern Hemisphere, and vice versa (Knight et al., 2005; Parker et al., 2007; Zhang et al., 2007). Change in the hemispheric temperature alters the inter-hemispheric energy exchange and therefore leads to the asymmetric response of the Hadley circulation (Chiang & Friedman, 2012; Green et al., 2017; Schneider et al., 2014), which results in the meridional migration of the ITCZ and the anti-phase inter-hemispheric variation of the GM (Chiang & Friedman, 2012; Schneider et al., 2014). In particular, all the “climate shift” events corresponded to the phase transitions of the AMO (Figure 4), suggesting a robust relationship between the “climate shift” and NA temperature. Many studies have attributed the origin of the AMO to the internal climate variability related to ocean circulation, particularly the AMOC (Knight et al., 2005; Parker et al., 2007; Wang et al., 2017). The strengthening of the AMOC could lead to a warm NA and even Northern Hemisphere by delivering heat northward across the equator and vice versa (Knight et al., 2005; Parker et al., 2007). Coincidentally, anomalous freshwater and sea ice were observed in the high-latitude NA in the 1960s and referred to as the “Great Salinity Anomaly” (Dickson et al., 1988), which is thought to be responsible for the cooling of the NA during that period by weakening the AMOC (Thompson et al., 2010; Zhang & Vallis, 2006). These results further indicate that “climate shift” events are a possible result of internal climate variability.

5. Conclusions

Our new coral record, together with other monsoon records from different regions, show that the GM varied in an anti-phase inter-hemispheric mode on decadal timescales over the past 150 years. Thus, this variation seems to be linked to the changes in the NA climate since 1851 A.D. Considering that the decadal-scale climate changes in the NA may be more cyclical and predictable than in other regions (Mann et al., 2016), our findings here have implications for the accurate prediction of monsoon variability in the coming decades. Nonetheless, further study is still needed to investigate the decadal variability of the GM in different climate mean states (such as the Little Ice Age) using the combination of proxy records and coupled models.

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