Chapter 9
The Connection Between the North and South American Monsoons

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Abstract We review evidence for a potential link between the North American Monsoon (NAM) and the South American Monsoon (SAM). Such a link is poorly documented in the literature, but if it were to exist, it could involve the influence of a monsoon onset on the cross-equatorial flow, atmospheric wave responses, and oceanic feedback to monsoon heating anomalies, which could in turn influence the decaying monsoon. With such a link, the variability of the NAM demise could be influenced by that of the SAM onset (or vice versa), in addition to its known dependence on regional land surface and adjacent oceans. The historical correlation between the NAM and the SAM appears to be mainly a consequence of both being dependent on tropical oceanic variability, such as El Niño-Southern Oscillation (ENSO), but an inter-monsoon link could be important for understanding the future climate variability of the American monsoons when the effects of anthropogenic forced change become more dominant—e.g., through reduction of evapotranspiration (ET) due to CO₂ fertilization of the rainforest and large-scale land use over the Amazon. These effects might perhaps not only delay the onset of the SAM, but also impact the demise of the NAM.

Keywords North American Monsoon · South American Monsoon · Inter-hemispheric connection · Monsoon variability

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9.1 Why Do We Care About Inter-monsoon Connections?

Monsoon systems influence the livelihoods of more than half the world’s population, and occur in areas of rapid population growth. Consequently, understanding their causes and variability has been an important focus of climate research, and substantial progress has been made in clarifying the dynamics of individual monsoon systems and of global monsoons in general. In contrast, relatively little attention has been paid to the potential inter-connections among various monsoon systems. Consequently, it is still unknown whether there are such connections among the different monsoon systems, and, if so, which mechanisms are responsible for them and how important they are in determining the variability of the monsoon systems, especially in a changing climate. The aim of this chapter is to explore these questions with a focus on the American monsoons, which serve as an example to illustrate the importance of investigating inter-monsoon connections.

Why do we focus on the American monsoons? First, the land masses over the American sector are more symmetric between the Northern and Southern Hemispheres than those of the Asia-Australian and African sectors, and so give rise to a relatively symmetric inter-hemispheric contrast of surface heating between land and oceans during the equinox seasons. Several processes could be involved in linking the inter-hemisphere monsoons: Firstly, the onset of a monsoon in one hemisphere could accelerate the reversal of the cross-equatorial flow, and the latter in turn would contribute to the decaying monsoon in the other hemisphere. Secondly, the tropical eastern Pacific-America-Atlantic sector is a region of weak upper westerly winds or the “westerly duct” (e.g., Dickinson 1971; Webster and Holton 1982). Thus, planetary waves triggered by monsoon diabatic heating anomalies, for example over the SAM region, could propagate across the Equator and influence atmospheric circulation over the NAM (e.g., Gedney and Valdes 2000). Finally, coupled ocean-atmospheric model simulations suggest that reduced monsoon diabatic heating, for example over the SAM region, could influence sea-surface temperature anomalies (SSTA) over the tropical eastern Pacific and Atlantic (e.g., Richter and Xie 2008; Nobre et al. 2009), which in turn could influence the NAM (e.g., Carleton et al. 1990; Higgins and Shi 2001; Liebmann and Marengo 2001; Marengo 2004; McCabe et al. 2004; Kushnir et al. 2010; Nigam et al. 2011).

Although the above processes may be favored by geographic and atmospheric dynamic configurations over the American continents and adjacent oceans, it is virtually unknown whether any of them provides a significant connection between the NAM and SAM, and, if so, what is the role of such a connection in determining climate variability of the American monsoons, especially in a changing climate. This chapter reviews the observed relationships between the NAM and SAM, the potential underlying physical mechanisms, and their importance in determining the variability of these American monsoons. It suggests challenges and a possible path forward to advance our understanding of this subject.
9.2 Is There Evidence Suggesting a Connection Between the American Monsoons?

Monsoons are commonly defined as the regions where the annual range of rainfall exceeds 2 mm/day and 70% of the annual mean (e.g., Wang and Ding 2011), although there are many other similar criteria used for regional monsoon studies. The NAM encompasses the intense rainfall emanating from the eastern Pacific Inter-Tropical Convergence Zone (ITCZ), extending northward over Mexico to the southwestern United States (SW US), northeastward over the Gulf of Mexico, and southward to the Central American isthmus and northernmost South America. As the NAM expands northward, the upper tropospheric monsoon anticyclonic center shifts from southwestern to northwestern Mexico along the Sierra Madre Occidental, and finally to the SW US. Moisture is transported to the NAM region by a broad-scale southeastern flow in the lower and middle troposphere from the Gulf of Mexico and low-level jets (LLJs) over the Gulf of California and east of the Rockies. The latter, along with synoptic disturbances from the north, control the active and break phases of the NAM.

The SAM includes the Amazon and adjacent Atlantic ITCZ to the north and northeast, the South Atlantic Convergence Zone (SACZ) to the southeast, and central Brazil and Bolivia to the southwest. Its anticyclonic circulation (the Bolivian High) is centered close to the Altiplano Plateau. Moisture is transported by the northeasterly trade winds from the Atlantic Ocean to the Amazon, where it rains out and is recycled, and then is transported to the SACZ and southern Brazil by the South American LLJs (SALLJs). Trenberth et al. (2000), Vera et al. (2006), Mechoso (2011), Liebmann and Mechoso (2011), and Wang and Ding (2011) have provided concise and excellent descriptions of the structure of the NAM, SAM, and global monsoons and the mechanisms that control them. Chapters 6 and 7 of this book provide a more comprehensive discussion of the NAM and SAM.

Once a monsoon is established, it tends to reinforce itself through moisture convergence in the atmospheric boundary layer (ABL) driven by the monsoon diabatic heating. This stabilization of the monsoon makes it less prone to external influences exerted by other monsoon systems. In contrast, the circulations during the transition periods of monsoon onset and demise are unstable and so likely more prone to external influences, including those from other monsoons. Thus, we focus on the inter-monsoon connections during the period of monsoon onset and demise.

9.2.1 Is There a Cross-Hemispheric Relationship Between the Onset and Ending of American Monsoons?

Could the onset of the NAM influence the demise of the SAM, or vice versa? Under the concept of a regional monsoon, the onset and demise of a monsoon system are determined by the surface heating contrast between the local land and adjacent
oceanic regions. Influence from other monsoon systems is generally not considered. However, under the concept of a global monsoon, the transition from the NAM to the SAM, or vice versa, is part of the seasonal transition of the large-scale tropical overturning circulation (e.g., Trenberth et al. 2000; Wang and Ding 2011), with its rising branch controlled by the monsoon onset in the hemisphere of spring and its compensational sinking branch located over the decaying monsoon in the hemisphere of fall (Trenberth et al. 2000). Thus, the onset of NAM could, in principle, influence the demise of the SAM or vice versa. However, whether such a hypothetical link exists in reality is unclear.

The seasonal evolution of the onset and demise of the NAM and SAM (Fig. 9.1) is summarized as follows: Beginning in early boreal spring (February and March), the Western Hemispheric Warm Pool of SST ($\geq 27.5$ °C; Wang and Enfield 2001) first begins expanding northward into the northeastern tropical Pacific (Fig. 9.1a), then over the Caribbean Sea and western Atlantic (Fig. 9.1b). Subsequently, the rainy area (rain rate $\geq 7$ mm/day) moves from the southern Amazon to the northernmost area of the South American continent and then to the Central American isthmus during April–June. By early- to mid-June, the rainy season expands to southwestern Mexico and then advances to northwestern Mexico, and

![Fig. 9.1](image_url) Seasonal-latitudinal evolution of rain rate (shown by shades) and sea surface temperature (shown by contours) over the NAM (80°–110°W) and the SAM (40°–80°W) sectors suggesting a close temporal relationship between the onset of the NAM and demise of the SAM and vice versa. The Tropical Rainfall Measurement Mission (TRMM) rain rate and NOAA interpolated SST data are used for the period of 1998–2013 in units of mm/day and °C, respectively.
the southwestern U.S. in July and August, when surface sensible heat flux over the Sierra Madre peaks (e.g., Douglas et al. 1993; Higgins et al. 1997; Barlow et al. 1998). At the same time, the dry season reaches its peak over the SAM region.

In August, the northern edge of the warm pool in the eastern Pacific and western Atlantic begins to retreat southward. However, rainfall in the NAM region continues to expand until reaching its northernmost location in September. From late September to early October, the dry-to-wet transition season, as indicated by increasing rainfall, begins over the Southern Amazon (5°–15°S, Fig. 9.1b). Rather than gradually moving southward across the Equator as a mirror image of the NAM onset, another rainy center forms in the southern Amazon in October. The northward and southward spread of the center is associated with the onset of the SAM (Kousky 1988; Horel et al. 1989; Liebmann and Marengo 2001). The NAM, remaining over southern Mexico, ends abruptly after the onset of SAM (Fig. 9.1a).

The temporal relationship shown in Fig. 9.1 provides some evidence that the onset of the NAM contributes to the demise of the SAM or vice versa. Alternatively, these correspondences could solely result from the seasonal migration of surface solar heating and SSTs. Wang and Fu (2002) show that during the monsoon transitions in the equinox seasons, rainfall change over South America leads that of the cross-equatorial flow, whereas during the peak of the monsoons in solstice seasons, variations in the cross-equatorial flow lead that of rainfall. These relationships suggest that the reversal of the cross-equatorial flow may be driven by rainfall change during the onset and demise of the SAM, and its variability contributes to rainfall variability once the monsoon is established; however, such analysis of the rainfall is limited to the South American continent. Consequently, the link between the dry-to-wet transition of the NAM, the southerly reversal of the trade wind over the Gulf of Mexico, and the cross-equatorial flow is not clear.

Does the reversal of the cross-equatorial flow influence the NAM onset during the boreal spring (March–May)? Apparently it does not. Higgins et al. (1997), Adams and Comrie (1997), and Higgins and Shi (2001) suggest that the moisture supply to western Mexico, i.e., the NAM core region, is dominated by the LLJs over the Gulf of California. Extra-tropical synoptic systems and intensification of the LLJs largely control the active and break phases of this monsoon rainfall.

Conversely, could the onset of NAM contribute to the reversal of the cross-equatorial flow over the American-Atlantic sector? To our knowledge, this question has not been addressed in the literature, but the following provides some evidence for such a connection. We look at the lead-lag regression between the anomalous near surface wind (925 hPa) over the eastern Pacific-American western Atlantic sector and the anomalous NAM V-index during April-June, the period of the NAM onset and SAM demise (Fig. 9.2a, b). Seasonal change has been removed in both fields. The SAM and NAM V-indices are defined, by the meridional wind at 925 hPa averaged over western Amazonia (5°S–5°N, 65°–75°W), and that over northern Mexico and the southwestern U.S. (17.5°–35°N, 120°W–100°W), respectively. These domains are chosen because the robust seasonal reversal of their meridional winds, including the cross-equatorial flow, meets the criterion of a global monsoon index (Lu and Chan 1999; Wang and Fu 2002; Li and Zeng 2002).
Fig. 9.2 The near surface wind anomalies (925 hPa) lagging the NAM and SAM V-indices anomalies, respectively, suggest an influence of the NAM onsets on the SAM demise during boreal spring and that of the SAM onset on the NAM demise in austral spring. a The 925 hPa wind anomalies lagging the NAM V-index anomalies by 2 pentads based on linear regression during the period of NAM onset and SAM demise (April–June) for 1979–2013. The lagged southerly meridional wind anomalies within the SAM region after the southerly NAM V-index suggest that the onset/intensification of the NAM could contribute to the demise/weakening of the SAM during boreal spring. b As in (a), but for the 925 hPa wind anomalies leading the NAM V-index anomalies by 2 pentads. The lack of southerly anomalies over the SAM region suggests that the southerly 925 hPa wind anomalies over the SAM region shown in (a) are not due to the correlation of the winds on seasonal scale. c As in (a), but for the 925 hPa wind anomalies lagging the SAM V-index anomalies by 2 pentads during the period of SAM onset and NAM demise (September–November). These northerly meridional wind anomalies over the NAM region lagging the northerly SAM V-index suggest that the onset/intensification of the SAM could contribute to the demise/weakening of the NAM during austral spring. d As (c), but for the 925 hPa wind anomalies leading the SAM V-index anomalies by 2 pentads. The lack of northerly anomalies over the NAM region suggests that the northerly 925 hPa wind anomalies over the SAM region shown in (c) are not due to the correlation of the winds on a seasonal scale. The regions of NAM and SAM V-indices are shown by black boxes in each panel. The scale of the wind vector and unit are indicated below the lower-right corner of each panel. NCEP-NCAR reanalysis is used.
As evidenced for an influence of NAM onset on SAM demise, Fig. 9.2a shows southeasterly and easterly wind anomalies over western Amazonia and anticyclonic anomalies over southeastern Brazil, lagging the southerly NAM V-index by 2 pentads. The former indicates a weakening of moisture transport to Amazonia and SACZ, and both would weaken the SAM rainfall, whereas the latter indicates a strengthening of the NAM. Similar wind patterns persist for phases lagging the southern NAM-V index anomalies by 1–4 pentads (not shown), and are accompanied by southerly meridional wind anomalies over the eastern Pacific and anomalous anticyclonic circulation over the Central American isthmus and adjacent eastern Pacific and Caribbean Sea.

To evaluate whether the regression pattern shown in Fig. 9.2a is a result of auto-correlation of the wind anomalies, we compare it to the anomalous wind pattern that leads the NAM V-index by two pentads (Fig. 9.2b). The anomalous southeasterly wind over western Amazonia and anticyclonic circulation over southeast Brazil shown in Fig. 9.2a are replaced by the anomalous westerly wind over the equatorial Amazonia, strong northerly over the northeastern Brazil and cyclonic anomalous over southeast Brazil in Fig. 9.2b. The anomalous wind over the southeast Pacific is dominated by northerly or northwesterly leading the NAM V-index (Fig. 9.2b) instead of the southerly winds that lag the NAM V-index. These distinctively different anomalous wind patterns before and after the anomalous southerly NAM V-index suggests that the intensification of the NAM could weaken the SAM during April–June.

How can the intensified NAM weaken the SAM? Rodwell and Hoskins (2001) have shown that the rising motion driven by monsoon diabatic heating can induce poleward flow into the monsoon region, as required by Sverdrup vorticity balance. This mechanism presumably explains the northerly flow over western Mexico, the southwestern and central U.S., and eastern Pacific shown in Fig. 9.2a. How these changes would physically influence southeasterly wind anomalies over the equatorial western Amazonia is not clear; however, their statistical relationship, as shown in Fig. 9.2a, b, highlights the need to investigate their underlying physical mechanisms.

During austral spring (September–November), the onset of SAM is primarily driven by an increase of surface solar radiation and the resultant increase of surface fluxes, and thus the humidity in the ABL increases over the Amazon (e.g., Fu et al. 1999; Li and Fu 2004). The latter increases the moisture transport to the SACZ, and thus its rainfall intensity during the cyclonic phase of the Pacific-to-South America (PSA) wave train over the SACZ region (e.g., Mechoso et al. 2005; Li and Fu 2006; Ma and Mechoso 2007). Liebmann et al. (1999) have shown an anomalous northerly cross-equatorial flow two days after the intensification of the SACZ, suggesting that the increase of convective diabatic heating associated with the intensified SACZ could further drive the northerly SAM V-index and intensify moisture transport to the SAM region. The positive feedback between the SAM rainfall and northerly cross-equatorial flow and moisture transport eventually lead to the SAM onset.
Could this SAM onset influence the NAM demise during austral spring? Fig. 9.2c, d appear to suggest so. Figure 9.2c shows anomalous northerly and northwesterly winds over the NAM region lagging the northerly SAM V-index by two pentads (Fig. 9.2c). The former is associated with the weakening of the NAM over northwest Mexico, whereas the latter is associated with the intensification of the SAM over Amazonia. In contrast, Fig. 9.2d shows nearly zero or southwesterly wind anomalies over the NAM region prior to the northerly SAM V-index, suggesting stronger moisture transport to eastern Mexico. Thus, the distinctive weakening of the NAM following the strengthening of the SAM (Fig. 9.2c) indicates the possibility of the latter impacting the former.

Over the equatorial and southeastern tropical Pacific, eastern equatorial South America, and tropical western Atlantic, northerly meridional wind anomalies are correlated both leading and lagging the SAM V-index with some change in magnitudes. This weak dependence on the SAM V-index suggests that these northerly wind anomalies are probably connected to large-scale seasonal changes of the SSTs and wind fields.

Although the observed relationships shown in Figs. 9.1 and 9.2 are only suggestive, and the supporting evidence available in the literature is indirect, together they point toward a possible influence of the onset monsoon on the demising monsoon over the American continents during the equinox seasons, as illustrated schematically in Fig. 9.3—namely, as discussed above, the onsets of the NAM and SAM are primarily driven by the seasonal change of SSTs over the adjacent oceans, regional land surface heating, and associated meso-scale and regional circulation change, rather than by any remote influence through inter-monsoon connection. However, such connections seem possible for the monsoon demise. Its variability appears to be related to the variability of the reversal of the large-scale cross-equatorial flow as primarily driven by the onset monsoon on the opposite side of the equator. The importance of such an influence relative to that of the seasonal migration of the SST in the eastern tropical Pacific and western tropical Atlantic for the reversal of the cross-equatorial flow over the American sector is not clear, and needs to be investigated.

9.2.2 Is the Monsoon Variability Connected on the Intra-seasonal to Multi-decadal Scales?

Significant correlation between the variability of the NAM and SAM has been found on intra-seasonal, inter-annual, and decadal scales (Wang and Fu 2002; Arias et al. 2015). However, the NAM and SAM systems share the same tropical sources of variability at different time scales, such as the Madden-Julian Oscillation (MJO), El Niño-Southern Oscillation (ENSO), Atlantic Multi-decadal Oscillation (AMO), and Pacific Decadal Variability (PDV—e.g., Carleton et al. 1990; Higgins and Shi 2001; Liebmann and Marengo 2001; Marengo 2004; Lorenz and Hartmann 2006;
(a) The onset of the NAM contributes to the southerly reversal of the V-index of SAM, (the cross-equatorial flow over South America) and so contributes to its demise during April–June.

(b) The onset of the SAM contributes to the northerly reversal of the V-index of NAM and so contributes to its demise during September–October.

Fig. 9.3 Schematic illustration of how a The NAM onset influences the seasonal reversal of the large-scale overturning circulation along the western edge of the NASH, contributing to the demise of the SAM during April–June. The sources of NAM onset variability are listed in the text box; b As in (a), but for the influence of the SAM onset on the demise of the NAM during September–November.

Casarin and Kousky 1986; Kiladis and Weickmann 1992; Nogues-Paegle and Mo 1997; Paegle et al. 2000; Carvalho et al. 2004; Grantz et al. 2007; Zhu et al. 2007; Hu and Feng 2008; Arias et al. 2012). This shared forcing can result in correlated rainfall variability between these two monsoon systems, posing a challenge for observational diagnosis of any direct physical linkage between them.
Whether or not there is such a linkage between intra-seasonal and multi-decadal climate variability of the NAM and SAM is virtually unknown. To illustrate the need for investigating this potential linkage, we show the co-variability between NAM and SAM in Figs. 9.4 and 9.5 for the austral spring season. The co-variations of NAM and SAM rainfall anomalies on the intra-seasonal time scale can be represented by the two leading modes of the singular value decomposition (SVD) of the 30–70 day band-pass filtered pentad precipitation anomalies (seasonality is removed) in the NAM and SAM regions for 1979–2010. The two modes are characterized by an in-phase relationship and an out-of-phase relationship, respectively, between the intra-seasonal precipitation anomalies in the two monsoon regions. The first mode shows in-phase correlations of rainfall between Central America and South America between 10°N and 20°S (Fig. 9.4a, b). Such simultaneous increase or decrease of rainfall over both regions is correlated with an anticyclonic low-level flow centered over Mexico and an enhanced easterly wind over the eastern Pacific ITCZ area. The second mode shows an out-of-phase correlation between rainfall over Central America and that over the western Amazon and the land part of the SACZ (Fig. 9.4c, d), suggesting an intra-seasonal increase of rainfall in Central America and an anomalous anticyclonic circulation over the Gulf of Mexico and western Caribbean Sea in association with a decrease of rainfall over the SAM. The associations of anomalous NAM and SAM precipitation with the anomalous V-indices on the intra-seasonal time scale can be seen from the lead and lag correlations between the corresponding SVD time series and the V-indices in Fig. 9.5.

The SAM V-index anomalies (Fig. 9.5a) are negatively correlated with the leading first SVD mode of SAM rainfall anomalies, suggesting that an increase of SAM rainfall may drive the northerly cross-equatorial flow over South America, i.e., the SAM V-index. The SAM V-index is also positively correlated with the leading second SVD mode of the SAM rainfall, suggesting that an intensification of SACZ and decrease of rainfall over the Amazon may give rise to an anomalous southerly cross-equatorial flow over South America. The SAM V-index is only marginally correlated with the in-phase and leading first SVD principal component of the NAM rainfall.

Surprisingly, the NAM V-index (Fig. 9.5b) anomalies are correlated with the in-phase and lagged first SVD of the NAM and SAM precipitation anomalies. The physical implication of such a relationship is unclear, but it may represent the influence of MJO on the eastern Pacific ITCZ and the resultant intra-seasonal variations of both the NAM and SAM rainfall variability, as has been suggested by many previous studies (Higgins and Shi 2001; Lorenz and Hartmann 2006; Casarin and Kousky 1986; Kiladis and Weickmann 1992; NoguesPaegle and Mo 1997; Paegle et al. 2000; Carvalho et al. 2004).

The inter-annual relationships between monthly anomalies of the NAM and SAM can be different from their counterparts on the intra-seasonal time scale. For example, during austral spring, the two leading SVD modes are both dominated by a seesaw relationship between the NAM and the SAM precipitation anomalies. The pattern of the first mode shows that an increase of rainfall over the SACZ is
correlated with a decrease of rainfall over the Central American isthmus (Fig. 9.6a, b), and an anomalous anticyclonic flow over the Gulf of Mexico and western Caribbean Sea. Both the anomalous rainfall and associated wind patterns resemble the second SVD mode of the intra-seasonal rainfall anomalies between NAM and SAM regions (Fig. 9.4c, d). The second SVD mode shows that an increase in

Fig. 9.4 The pentad rainfall anomalies (shades, mm/day) and near surface wind anomalies (925 hPa, vectors, unit m s$^{-1}$), respectively, projected onto (a), (b) the first and (c), (d) second SVD modes of intra-seasonal variation of the precipitation over the NAM and SAM regions, respectively, during austral spring. The intra-seasonal rainfall anomalies are obtained by a 30–70 day band-pass filtered for 1979–2010. The percentage of the total intra-seasonal precipitation variance explained by each mode is given at the top right of each panel. The precipitation data are the NOAA CMAP pentad data and the 925 hPa pentad winds are derived from the NCEP/NCAR reanalysis daily data
rainfall over the equatorial and northernmost South America is correlated with an increase in rainfall over southern Mexico and a decrease in rainfall over an area extending from southeastern Texas to eastern Georgia (Fig. 9.6c, d). The associated anomalous low-level wind pattern in Fig. 9.6c resembles that of the first SVD mode of intra-seasonal rainfall over the NAM region (Fig. 9.4a), but not over the SAM region (cf. Fig. 9.6d, b).

**Fig. 9.5** Lead and lag correlations between a The anomalous pentad SAM V-index (NCEP/NCAR reanalysis data) and the time series of the first (red) and second (blue) SVD modes of the 30–70 day band-pass filtered precipitation anomalies over the SAM region (closed square) and the NAM region (open circle) during austral spring for 1979–2010. and b Similar lead and lag correlations, but with the NAM V-index. Negative lag means the V-index leading precipitation. Gray dash lines denote the 99 % significance level; the number of effective samples is determined based on Chen (1981)
The differences of spatial correlation patterns between intra-seasonal and inter-annual rainfall variability are expected because the former is largely controlled by the atmospheric internal variability and wave response to diabatic heating anomalies, whereas the latter is dominated by the patterns of SSTA associated with major modes of the coupled ocean-atmospheric variability. These modes could easily overwhelm any signal of inter-hemispheric monsoon connection, where such a signal exists.

On a decadal scale, Lee et al. (2014) have shown the connection among the climate variability of the northern hemispheric monsoons (i.e., Asian, African, and

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**Fig. 9.6** As in Fig. 9.4, but for the monthly mean rainfall anomalies (shading, mm/day) and 925 hPa wind anomalies (vector, unit m s\(^{-1}\)) projected onto (a), (b) the first and (c), (d) the second SVD modes of monthly precipitation anomalies over the two monsoon regions for austral spring
North American) to be a result of changing El Niño types. In particular, from 1994 to 2009 these northern hemispheric monsoons intensified during the summer and weakened during the winter, and their inter-annual variability became weaker than during 1979–1993. By contrast, the variability of southern hemispheric monsoons has not changed. Consequently, no connection between the variations of NAM and the SAM intensity is found in their study. However, Arias et al. (2015) have observed a statistically significant correlation between an early demise of the NAM and a late onset of the SAM on inter-annual and decadal scales (Fig. 9.7). Such an early demise of the NAM and late onset of the SAM is also correlated with an increase of rainfall and moisture convergence over the tropical eastern Pacific and the Central American isthmus, leading to moisture divergence from the NAM and SAM regions. The early ending of the NAM is also influenced by a westward displacement of the NASH, which enhances moisture divergence from the NAM region (Arias et al. 2012). On an inter-annual scale, the increase of rainfall over the northeastern tropical Pacific and Central American isthmus appears to be connected to the warmer SST anomalies over the central and eastern Pacific, and the westward expansion of the NASH appears to be linked to the variability of the Asian monsoon (Chen et al. 2001; Kelly and Mapes 2011) and surface temperature changes over Africa (Miyasaka and Nakamura 2005; Li et al. 2012). On a decadal scale, the earlier demise of NAM and the late onset of SAM appear to be related to the global SST warming and positive AMO modes. The influence of one monsoon on the other cannot be isolated from the above oceanic variability modes.

In short, the observed relationships between the inter-annual and decadal variability of the NAM and SAM onset and demise appear to be primarily forced by the tropical Pacific and Atlantic SST variability, and possibly a global warming mode (Arias et al. 2012, 2015). Whether an inter-monsoon connection plays any significant role in determining these observed correlations cannot be established.

![Fig. 9.7](image-url) The time series of the NAM demise date (red) and SAM onset date (black) show an increasing time gap between the NAM demise and SAM onset between 1978 and 2009. The early NAM retreats and late SAM onset dates are also statistically correlated at $P < 0.05$. Correlation is computed for the de-trended time series.
Liu et al. (2009) have used climate model simulations to explore connections between the variability of monsoons globally, using a coupled ocean-atmospheric model. Their study suggests that without external forcing, the individual monsoons' variabilities are not interdependent. However, when they are forced by external factors, such as changes of atmospheric greenhouse gases, aerosols, and Earth’s orbit, connection appears, e.g., the global monsoons are intensified during the Medieval Warming Period and weakened during the Little Ice Age. Such correlated change is due to the greater land surface temperature changes than those of the ocean, leading to a greater land-ocean surface temperature contrast in a warmer climate and a weaker land-ocean surface temperature contrast in a cooler climate. A similar mechanism appears to be responsible for the projected intensification of Northern Hemispheric global monsoons by the climate models that participated in the Fifth Report of the Intergovernmental Panel on Climate Change (e.g., Lee and Wang 2014).

Could land surface processes and land use influence not only the SAM but also the NAM, or vice versa, through inter-monsoon connections? Both numerical model experiments and observations suggest that conversion of the rainforests to pasture and produce would reduce ET in the dry season and increase runoff in the wet season (Dickinson and Henderson-Sellers 1988; Gash and Nobre 1997; Davidson et al. 2012; Harper et al. 2014). The former would reduce the dry season rainfall and delay the SAM, since ET is the main source of rainfall during those seasons (Li and Fu 2004; Fu and Li 2004). Such an effect could be further exacerbated by fire-generated aerosols, produced as part of land use over the Amazon (e.g., Zhang et al. 2008; Bevan et al. 2009; Zhang et al. 2009). The latter would increase annual peak river flow over the SAM region. In addition, the improved vegetation water use efficiency in an elevated atmospheric CO₂ environment would also reduce ET and possibly rainfall in the dry season, and increase runoff in the wet season (Sellers et al. 1996; Gedney et al. 2006; Doutriaux-Boucher et al. 2009; Coe et al. 2011; Pu and Dickinson 2014). Whether such a vegetation response to the elevated atmospheric CO₂ with changing land use over the SAM will influence the NAM has not been directly addressed in the literature, yet such a possibility exists for several reasons:

Firstly, Nobre et al. (2009) showed that in a coupled ocean-atmospheric system, rainfall reduction due to large-scale removal of the rainforests over the Amazon could induce an El Niño-like SSTA pattern, which in turn would exacerbate rainfall reduction over the SAM region. We suggest that such an El Niño-like SSTA pattern could also potentially weaken the NAM due to an equatorward shift of the eastern Pacific ITCZ (e.g., Higgins and Shi 2001). Secondly, Gedney and Valdes (2000) have suggested that a Rossby wave train induced by rainfall reduction due to deforestation over the Amazon would increase rainfall over the southern U.S. and
Mexico during the boreal winter season. Such an atmospheric wave response to deforestation over the Amazon could in principle influence the NAM during the boreal spring and fall (e.g., Dickinson 1971), but has not been investigated. Finally, observations have shown a statistically significant intensification of hurricanes as they pass the Amazon and Orinoco river plumes (Field 2007). Thus, an increase of runoff and river flow due to large-scale deforestation could potentially increase the intensity of hurricanes in the Caribbean Sea. The hurricanes that make landfall over Mexico can significantly influence the NAM rainfall. Whether these mechanisms suggested by numerical model experiments and past observations will influence long-term and future climate variability of the NAM and SAM in a changing climate needs to be clarified.

9.3 Outstanding Questions, Challenges and a Path Forward

Few studies on the connection between the NAM and SAM are found in the literature, but the available evidence discussed in this chapter points toward a possible link between these two monsoon systems that deserves further investigation. Such a link could be provided by the influence of the monsoon onset on cross-equatorial flow, atmospheric wave responses, and oceanic feedback to the monsoon heating anomalies, and through these processes an influence on the decaying monsoon. With such inter-monsoon links, the climate variability of the NAM could be influenced by that of the SAM, or vice versa, in addition to the variability of the regional land surface and adjacent ocean climate conditions. Although the variability of both the NAM and SAM in today’s climate is mainly forced by tropical oceanic and atmospheric variability, such as ENSO, AMO, and MJO, an inter-monsoon link may be more important for understanding the variability of American monsoons in the future, when the anthropogenic forced change becomes dominant, especially over the SAM region. For example, were the above-discussed inter-monsoon links to exist, the reduced ET due to CO₂ fertilization of the rainforest and large-scale land use over the Amazon would not only delay the onset of the SAM, but also impact the demise of the NAM. Likewise, a future earlier onset of the NAM could influence the demise of the SAM. Thus, a clarification of inter-monsoon connections would provide a key to addressing this future variability of the American monsoons.

Without concrete evidence, the inter-monsoon links over the Americas, as well as globally, remains speculative. As a first step, it is critical for future investigations to address these outstanding questions:

a. What is the relative importance of inter-monsoon links versus the variability of the regional land surface and adjacent oceans in determining monsoon climate variability, especially in the future?
b. What are the key dynamic mechanisms that provide the inter-monsoon links over the Americas, and globally?

c. How would the response of the Amazonian rainforests, the world’s largest biome, to elevated CO2 and global climate change, influence the NAM? How would a change of NAM influence the demise of the SAM?

Because the NAM and SAM systems share mostly the same sources of tropical oceanic and atmospheric variability, one of the main challenges is to isolate the inter-monsoon links from the correlated variability forced by these common sources of the tropical variability. Understanding the atmospheric dynamic responses on synoptic to intra-seasonal scales through observational analysis, numerical model experiments of various levels of complexity, and clarification of the role of inter-monsoon connection in improving seasonal prediction and future climate projections, would be particularly useful.

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