Science and Technology Infusion Climate Bulletin
NOAA's National Weather Service
36th NOAA Annual Climate Diagnostics and Prediction Workshop
Fort Worth, TX, 3-6 October 2011

Decadal Variation of Rainfall Seasonality in the North American Monsoon Region and Its Potential Causes

Paola A. Arias[1, 2], Kingtse C. Mo[3], and Rong Fu[1]

[1]*Department of Geological Sciences, The University of Texas at Austin*
[2]*Grupo de Ingeniería y Gestión Ambiental (GIGA), Universidad de Antioquia, Colombia*
[3]*Climate Prediction Center, NCEP/NWS/NOAA*

1. Introduction

The North American Monsoon System (NAMS) produces most of the annual rainfall over the southwestern (SW) United States (US) and Mexico (Douglas *et al.* 1993; Stensrud *et al.* 1995). Previous studies have suggested that the interannual variation of the NAMS is mainly controlled by the El Niño-Southern Oscillation (ENSO), whereas its decadal variability can be linked to the Pacific Decadal Oscillation (PDO) (Higgins and Shi 2000; Castro *et al.* 2001, 2007, Grantz *et al.* 2007), the Atlantic Multi-decadal Oscillation (AMO) and the Arctic Oscillation (AO, *e.g.*, Hu and Feng 2008, 2010). These studies have been focused on variability of its onset and rainfall amount, whereas variability of its retreat has received much less attention. This study aims to identify whether seasonality and strength of the NAMS have changed during the period 1948-2009. If so, what causes such a change? A recent study of Li *et al.* (2011) has shown a westward expansion of the North Atlantic Subtropical High (NASH) since late 1970s during the summer season (June-August). This change has increased rainfall variability over southeast US. We will investigate whether such a change could also influence climate variability of the NAMS.

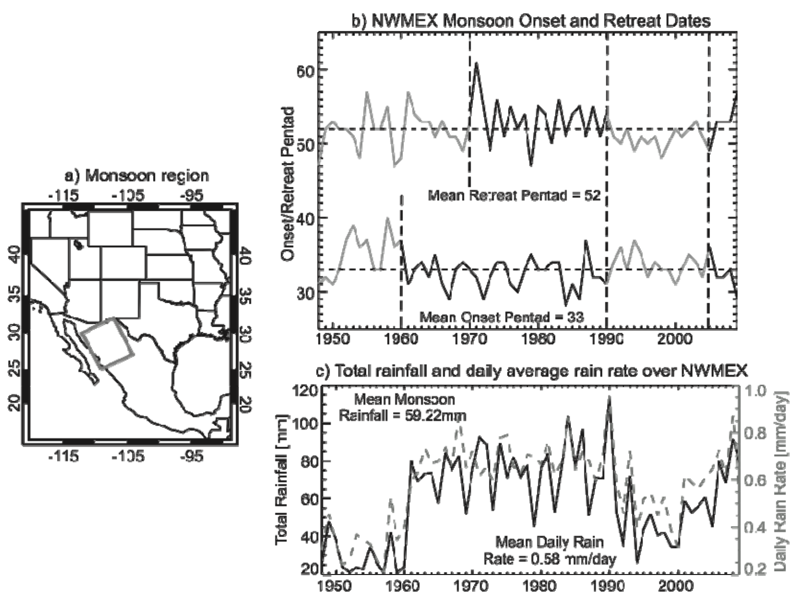

Fig. 1 a) Monsoon region (NWMEX) considered for onset and retreat computations. b) Monsoon onset (lower line) and retreat dates (upper line) over NWMEX during 1948-2009 obtained from the CPC rain rate data. Solid black lines represent periods with early onset and late retreat whereas solid grey lines represent periods with late onset and late retreat. c) Total rainfall (solid black line) and daily average rain rate (dashed grey line) during the entire monsoon season over NWMEX. In b), vertical dashed lines indicate the years when monsoon regime changed. Mean values during 1948-2009 are indicated in b) and c).

2. Data and Methodology

We used 1-degree gridded daily precipitation over the US and Mexico during 1948-2009 from the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center (CPC, Higgins *et al.* 1999). The daily rain rate was averaged over this analysis domain (Fig. 1a) and converted to mean pentad values (*i.e.*, 5-day averages) before obtaining the onset/retreat dates. We also use the National Center for Environmental Prediction (NCEP) reanalysis and extended reconstructed monthly mean sea surface temperature (SST) from the NOAA Climate Diagnostic Center (CDC) (Reynolds 1988) to determine

Correspondence to: Rong Fu, Department of Geological Sciences, The University of Texas at Austin, Austin, Texas 78712; E-mail: rongfu@jsg.utexas.edu.

atmospheric circulation and SST changes associated with changes of NAMS rainfall and seasonality.

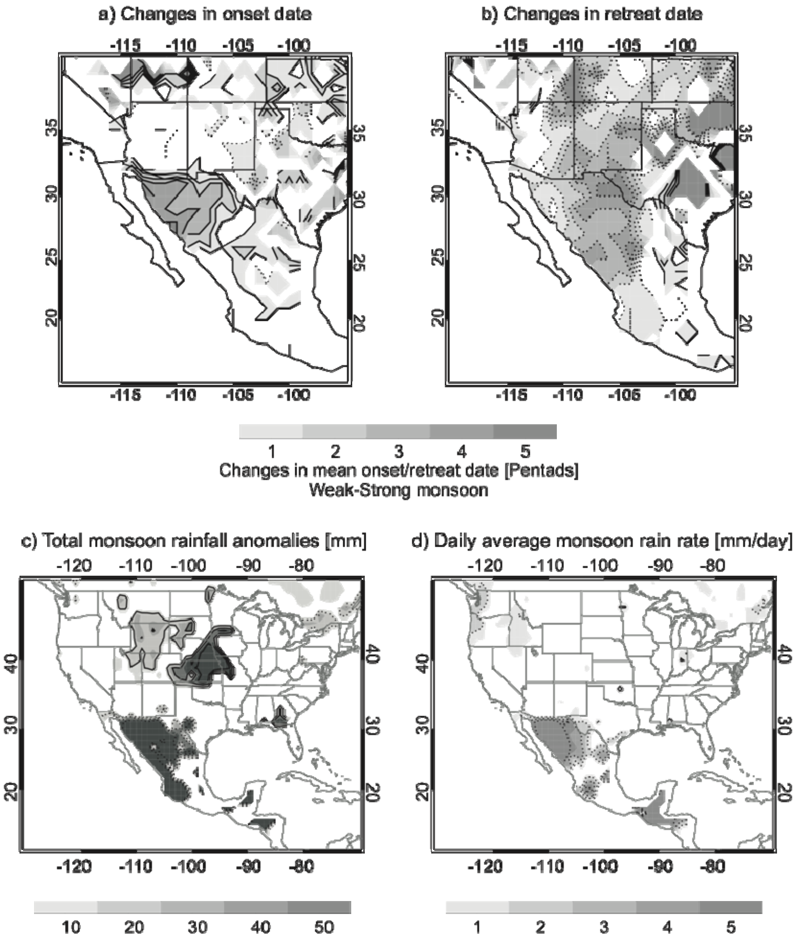

Fig. 2 Changes of a) onset and b) retreat dates over the SW US and Mexico between weak and strong monsoons. Composite difference between weak and strong monsoons for c) total monsoon precipitation anomalies and d) daily average monsoon rain rate. The differences are statistically significant according to a bootstrap test. Dotted (solid) contours indicate negative (positive) changes. The color scale indicates the magnitude of the change.

Different definitions for NAMS onset have been used in previous studies (*e.g.*, Higgins *et al.* 1999; Zeng and Lu 2004). The onsets and retreats of the NAMS were identified using the Li and Fu (2004) method to identify tbecause of its objectivity and potential for unifying definitions of the North and South American monsoon onsets and retreats. Because NAMS rainfall is more variable than that of South America, the duration threshold is relaxed from 6 consecutive pentads used in the South American region to 5 consecutive pentads in the North American monsoon region. Timing of the onsets of the NAMS obtained by this definition is generally consistent with those defined by Higgins *et al.* (1997). Early (late) retreat monsoon events are defined as those when the retreat occurred one pentad before (after) the climatological retreat pentad, namely, during the period August 21-September 5 (September 25-October 30), following Gutzler (2004). Weak (strong) monsoons were identified as those when the monsoon total rainfall (*i.e.*, total amount of rainfall during the monsoon season) was 0.5 standard deviation (σ) below (above) its the climatological mean. We also use a sequential t-test analysis of regime shifts (STARS; Rodionov 2004; Rodionov and Overland 2005) to test for changes in monsoon retreat and onset dates, and composites for early and late-retreat events to identify changes of the atmospheric fields. The statistical significance of the composite difference between weak and strong monsoons was tested using a bootstrap test (Efron 1979). We performed 1000 iterations using 95% as the statistical significance threshold and used the bias corrected and accelerated percentile method to estimate the confidence interval. Rotated Empirical Orthogonal Functions (REOFs) was applied to the September global SSTAs during 1948-2009 to identify the leading modes of SSTA, following Schubert *et al.* (2009).

3. Results

The decadal variations of onset/retreat dates are more clear over northwestern Mexico (NWMEX, Fig. 1a) than over southwestern Mexico. The sequential analysis STARS identified shifts in monsoon retreat during 1971, 1991, and 2006 whereas shifts in monsoon onset were identified during 1960, 1991, and 2006. A simple running-mean-based analysis (not shown) supports the shifts identified using STARS. This analysis suggests that both monsoon onset and retreat exhibit multi-decadal variations: more late-onset and early-retreat monsoons occurred during the periods 1948-1970 and 1991-2005 whereas more early-onset and late-retreat monsoons occurred during 1971-1990 and 2006-2009. Early-onset events are associated with late-retreat events while late-onset events are associated with early-retreat events. Fig. 1c shows periods of lower monsoon rainfall over NWMEX during 1948-1970 and 1991-2005, whereas periods of higher monsoon seasons occur during 1971-1990 and 2006-2009. The periods of lower and higher monsoon rainfall were generally overlap with those of late onset/early retreat and early onset/late retreat, respectively, except for the ending of the first early retreat and lower monsoon rainfall regime. Correlation coefficients between monsoon total rainfall and onset and retreat dates are -0.58 and 0.6, respectively, both significant at 1% level.

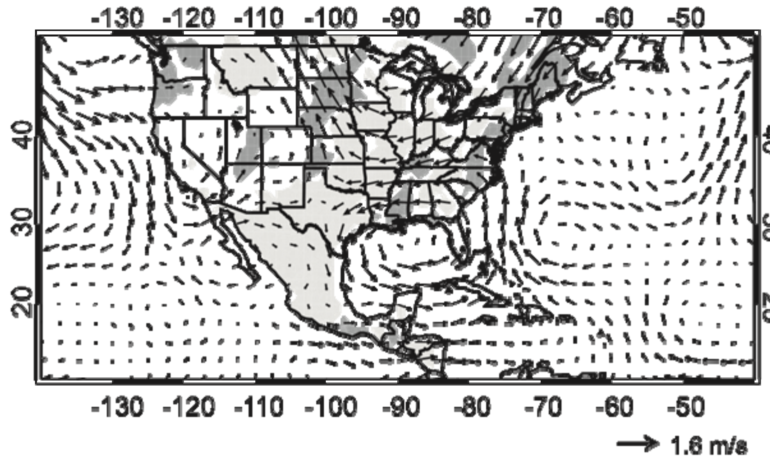

Fig. 3 September mean 850 hPa wind anomalies (arrows) and rain rate anomalies (shades) composites for early NAMS retreat events during 1948-2009. Dark (light) shades represent positive (negative) rain rate anomalies.

Figs. 2a and 2b show the spatial patterns of composite difference in onset/retreat dates between 21 weak and 25 strong monsoon events, passed the bootstrap test (Efron 1979). A weaker summer monsoon over NWMEX is associated with a later monsoon onset and an earlier retreat over the entire core area of the NAMS, namely, the western Mexico region. In addition, changes in the monsoon retreat associated with variations in the monsoon strength occur over the entire NAMS domain whereas changes in the monsoon onset are more confined to NWMEX. Monsoon total precipitation anomalies and daily average monsoon rain rate were also composited for 14 early and 17 NAMS late retreats. Early retreats are associated with reduced precipitation over the monsoon region and increased rainfall over the central United States (US), not only in terms of total monsoon rainfall (Fig. 2c) but also in terms of average daily rain rate (Fig. 2d). This out-of-phase relationship between rainfall over the central US and the monsoon region has been extensively documented (*e.g.* Douglas *et al.* 1993; Douglas and Englehart 1996; Mo *et al.* 1997; Higgins *et al.* 1997; Barlow *et al.* 1998).

To explore the causes of NAMS early retreats, we plot the anomalous circulation patterns at 850 hPa associated with early retreats in Fig. 3, and compare to those associated with positive anomalies of AMO mode, the warming SST mode and northwestern expansion of the NASH in September when NAMS retreats occurred (Figs. 4a-4c). The SST warming mode and AMO mode are represented by the first and third REOF of the global SSTA in September during 1948-2009 (Schubert *et al.* 2009). The composite anomalous circulation patterns for these two SSTA modes were based on the events with their principle component values greater than 0.5. The 2nd REOF mode represents variability of ENSO like SSTA in Pacific. This mode is not chosen because its associated anomalous circulation pattern does not resembles the pattern associate with variation of NAMS retreats.

Fig. 3 shows that the early retreats are characterized by a clearly defined lower tropospheric cyclonic center over the Gulf of Mexico and the SE US and an anticyclonic center over Baja California. These circulation anomalies are associated with the positive rainfall anomalies over the SE US and negative rain rate anomalies over the NAMS region (*i.e.*, most of Mexico and the SW US). The southwesterly lower tropospheric wind anomalies over the NAMS region associated with the positive AMO and SST warming modes (Figs. 4a and 4b) are similar to those associated with the early-retreat events (Fig. 3). However, these two modes cannot adequately explain the anomalous cyclonic circulation over the SE US and the Gulf of Mexico associated with the NAMS early retreats, which appears to be associated with northwestward expansion of the NASH (Fig. 4c). Thus, the composite anomalous lower tropospheric circulation pattern of the combined positive AMO, SST warming modes and northwestward expansion of the NASH appears to contribute to the anomalous circulation pattern associated with NAMS early retreats.

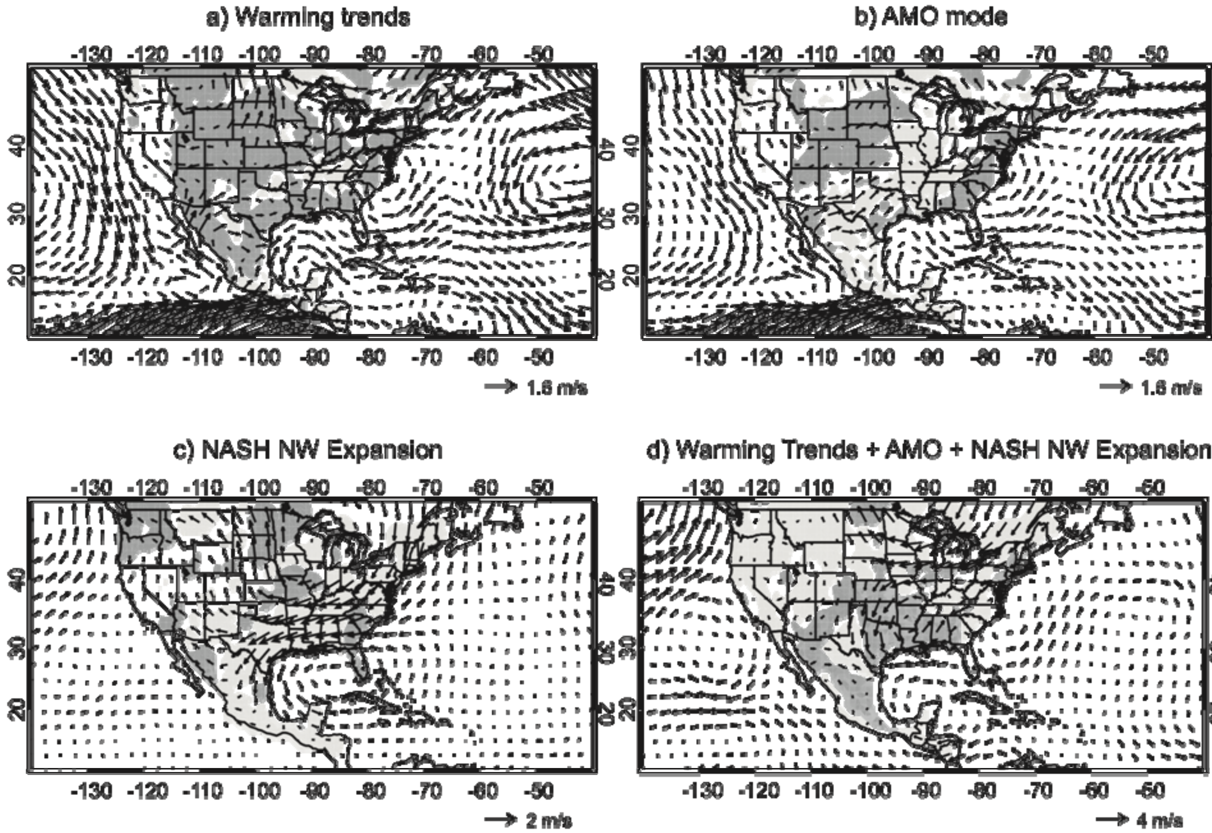

Fig. 4 September mean rain rate anomalies (shades) and 850 wind anomalies (vectors) composites for the events for (a) warming mode, b) AMO mode, c) NASH northwestern expansion, and d) warming + AMO + NASH northwestern expansion occurred during 1948-2009. The vector scale is shown in the right-bottom corner of each panel. Dark (light) shades represent positive (negative) rain rate anomalies.

Main features of the 200 hPa circulation changes associated with early-retreats are an anomalous anticyclonic circulation centered over Texas and northeastern Mexico (to the northwest of the lower tropospheric anomalous cyclonic circulation) and a northwestward shift of the subtropical jets over western US and North Mexico (not shown). These features also most closely resemble those obtained from the combined anomalous circulation patterns associated with positive AMO, SST warming modes and northwestern expansion of NASH.

4. Conclusion

This study shows a decadal scale NAMS regime change occurred during the period of 1948-2009. NAMS was weak due to its late onset, early retreats and weak rainrate during the periods of 1948-1970 and 1991-2005, and was strong due to early onset, late retreat and stronger rainrate during the period of 1971-1990. NAMS appears to have recovered its strength after 2006. This study focuses on causes of the decadal variability of the NAMS retreats because it is not as well understood as those of NAME onset and rainfall. The NAMS early-retreats are associated with an anomalous anticyclonic flow over Baja California and an anomalous cyclonic low-level flow and an increase of rainfall over the SE US and Gulf of Mexico. These changes appear to be more related to an increased atmospheric stability than to a decreased moisture transport to the monsoon region. In the upper troposphere, the early retreats are associated with anomalous divergence, increased (decreased) 200 hPa geopotential height over the SE US (the SW US and northern Mexico), and a northwestward displacement of the subtropical jets over western North America.

The comparison of the anomalous circulation patterns between the variations of NAMS, AMO and SST warming modes suggests that the early NAMS retreats are contributed by positive anomalies of the two SST modes, as represented by the first and third REOFs of SSTA during Septembers. In particular, they contribute to the westerly anomalous wind and anticyclonic circulation in the lower troposphere over the NAMS region. They also contribute to an increase of geopotential height in the upper troposphere over the SE and the south central US, and in part to an anomalous cyclonic circulation in the lower troposphere over the SE US and the Gulf of Mexico associated with early NAMS retreats. However, these two SST modes cannot explain the anomalous cyclonic circulation in the lower troposphere over SE US and the Gulf of Mexico and the northwestward shift of the subtropical jets in the upper troposphere associated with the early NAMS retreats. The northwestward shift of the NASH appears to be primarily responsible for these two changes. The former probably drives the upper tropospheric divergence over the SE US and compensational upper tropospheric convergence and subsidence over the NAMS region, whereas the latter has been found to cause weaker NAMS by previous studies (*e.g.*, Hu and Feng, 2010). Thus, decadal variation of the NAMS retreats, especially over the NWMEX, appear to be contributed by expansion/contraction of the NASH western edge, AMO and SST warming modes.

Acknowledgments. This work was supported by the NOAA Climate Program Office Climate Prediction Program for the Americas (CPPA) grant (NA10OAR4310157). We sincerely appreciate the insightful suggestions from Dave Gochis and Renguang Wu and Robert Dickinson.

References

Barlow, M., S. Nigam, and E.H. Berbery, 1998: Evolution of the North American Monsoon System. *J. Climate*, **11**, 2238-2257.

Castro, C.L., T.B. McKee, and R.A. Pielke, 2001: The relationship of the North American monsoon to tropical and North Pacific Sea surface temperatures as revealed by observational analyses. *J. Climate*, **14**, 4449–4473.

—, R.A. Pielke, J.O. Adegoke, S.D. Schubert, and P.J. Pegion, 2007: Investigation of the summer climate of the contiguous United States and Mexico using the Regional Atmospheric Modeling System (RAMS). Part II: Model climate variability. *J. Climate*, **20**, 3866–3887.

Douglas, A.V., and P.J. Englehart, 1996: An analysis of the starting date for the summer monsoon in Western Mexico and Southeast Arizona. *Proc. Twentieth Ann. Climate Diagnostics Workshop*, U.S. Department of Commerce, NOAA 207-211.

Douglas, M.W., R.A. Maddox, K. Howard, and S. Reyes, 1993: The Mexican monsoon. *J. Climate*, **6**, 1665-1677.

Efron B., 1979: Bootstrap methods: Another look at the jackknife. *Ann. Stat*., **7**, 1-26.

Grantz, K, B. Rajagopalan, M. Clark, and E. Zagona, 2007: Seasonal Shifts in the North American Monsoon. *J. Climate*, **20**, 1923–1935.

Gutzler, D.S., 2004: An index of interannual precipitation variability in the core of the North American monsoon region. *J. Climate*, **17**, 4473–4480.

Higgins, R.W., J.E. Janowiak, and X. Wang, 1997: Influence of the North American Monsoon System on the United States summer precipitation regime. *J. Climate*, **10**, 2600–2622.

—, Y. Chen, and A.V. Douglas, 1999: Interannual variability of the North American warm season precipitation regime. *J. Climate,* **12**, 653–680.

—, and W. Shi, 2000: Dominant factors responsible for interannual variability of the summer monsoon in the southwestern United States. *J. Climate*, **13**, 759–776.

Hu, Q., and S. Feng, 2008: Variation of the North American Summer Monsoon Regimes and the Atlantic Multidecadal Oscillation. *J. Climate*, **21**(11), 2371-2383.

—, and S. Feng, 2010: Influence of the Arctic oscillation on central United States summer rainfall. *J. Geophys. Res*., **115**, D01102, doi:10.1029/2009JD011805.

Li, W., and R. Fu, 2004: Transition of the large-scale atmospheric and land surface conditions from the dry to the wet season over Amazonia as diagnosed by the ECMWF Reanalysis. *J. Climate*, **17**, 2637-2651.

—, L. Li, R. Fu, Y. Deng, H. Wang, 2011: Changes of the North Atlantic Subtropical High and Its Role in the Intensification of Summer Rainfall Variability in the Southeastern United States. *J. Climate*, **24**, 1499–1506.

Mo, K.C., J.N. Paegle, and R.W. Higgins, 1997: Atmospheric processes associated with summer floods and droughts in the central United States. *J. Climate*, **10**, 3028–3046.

Reynolds, R.W., 1988: A real-time global sea surface temperature analysis. *J. Climate*, **1**, 75-86.

Rodionov, S.N., 2004: A sequential algorithm for testing climate regime shifts. *Geophys. Res. Lett*., **31**, L09204.

Rodionov, S.N., and J.E. Overland, 2005: Application of a sequential regime shift detection method to the Bering Sea ecosystem. *ICES J. Mar. Sci*., **62**, 328-332.

Schubert S.D., and coauthors, 2009: A USCLIVAR project to assess and compare the responses of global climate models to drought related SST forcing patterns: Overview and Results. *J. Climate*, **22**, 5251-5272.

Stensrud, D.J., R.L. Gall, S.L. Mullen, and K.W. Howard, 1995: Model climatology of the Mexican monsoon. *J. Climate*, **8**, 1775–1794.

Zeng, X., and E. Lu, 2004: Globally unified monsoon onset and retreat indexes. *J. Climate*, **17**, 2241–2248.