The impact of Gulf Surges on the North American Monsoon and their modulation by tropical and extra-tropical waves

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The North American Monsoon

The North American Monsoon (NAM hereafter) is a large-scale circulation that develops during the summer months primarily over northwestern Mexico. Distinctive features are: surface wind reversal along the Gulf of California (Fig. 1), establishment of an upper-level anticyclone over the southwestern U.S. and a consistent increase in rainfall (with up to 80% of annual precipitation over the Sierra Madre Occidental falling during the NAM season).

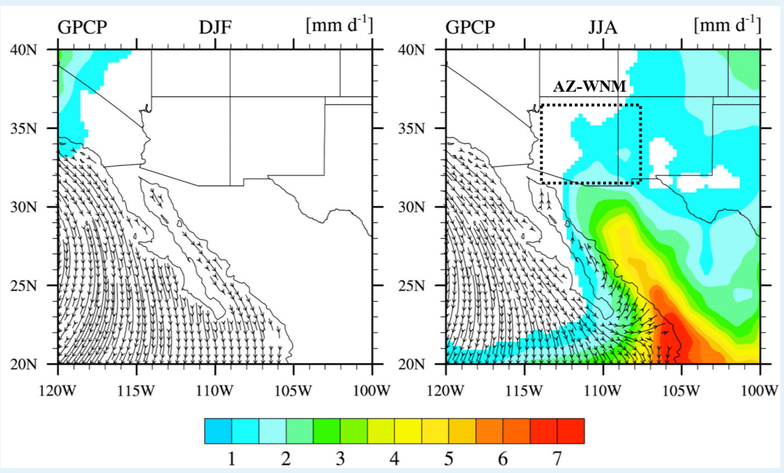

Figure 1: *Mean DJF (left) and JJA (right) 10-m QuickSCAT winds and GPCC precipitation (mm/day). Adapted from Bordoni et al. (2004).*

By the end of June the monsoonal precipitation extends northward to southwestern U.S. (mainly Arizona and western New Mexico, AZ-WNW hereafter), contributing to about 50% of the total annual precipitation in this region (Adams and Comrie, 1997). Occasionally, intrusions of southerly tropical moist air can reach the Great Basin and Colorado.

The role of the Gulf of California Surges

Precipitation in the AZ-WNM region is modulated by transient disturbances, known as Gulf Surges (Hales, 1972), which carry moisture northward along the GoC into the arid Southwest and causing enhanced convective activity there (Fig. 2).

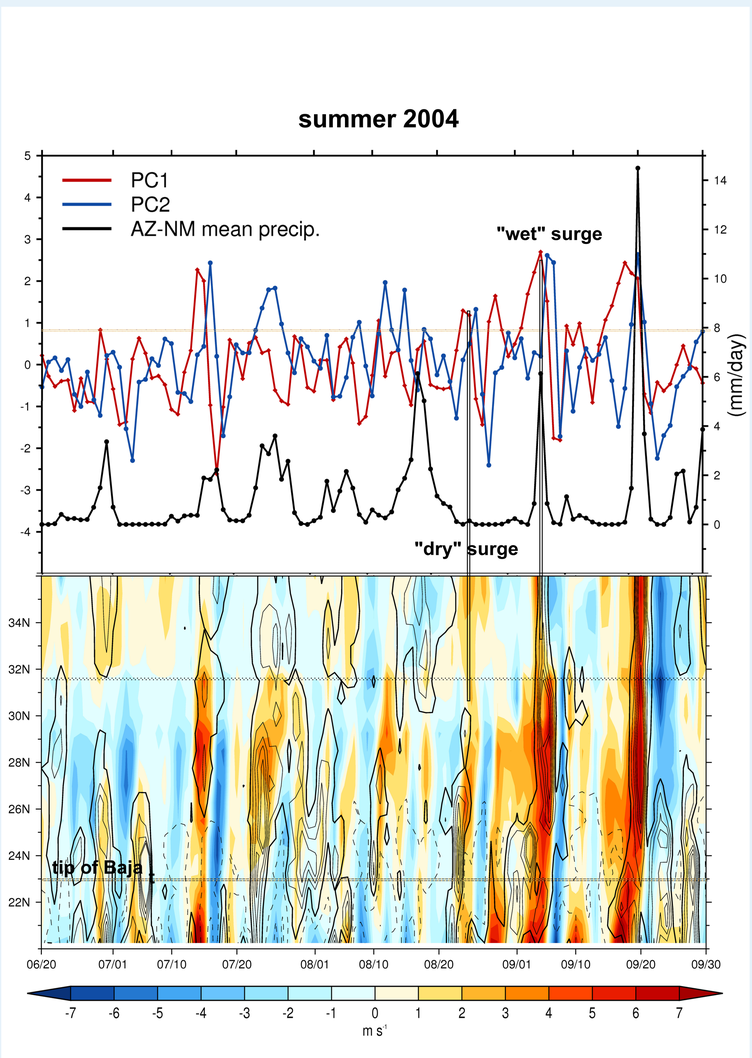

Figure 2: *Upper panel: Standardized PC1 (blue line) and PC2 (red line) of the GoC wind and mean precipitation (black line) over Arizona-West New Mexico area for summer 2004. We define values of PC1 or PC2 greater than 0.75 (indicated by dash) as surge events. Lower panel: Hovmöller diagram of the zonally averaged wind anomalies (shade) and precipitation anomalies (contours, unit: 1 mm) on a strip land along the GoC eastern side and in AZ-WNM.*

Most surges feature positive wind anomalies all along the GoC. Fewer ones, called "minor" surges (Adams and Comrie, 1997), extend only in the northern part of the GoC (e.g., on 07/25, Fig.2) and are thus characterized by large wind anomaly difference between the northern and the southern part of the gulf. GoC surges are of fundamental importance for AZ-WNM as 70-80% of total summer precipitation is associated with GoC surges. However, not all surges are associated with enhanced precipitation over AZ-WNM (Fig. 3), and some are "dry" (Higgins et al., 2004).

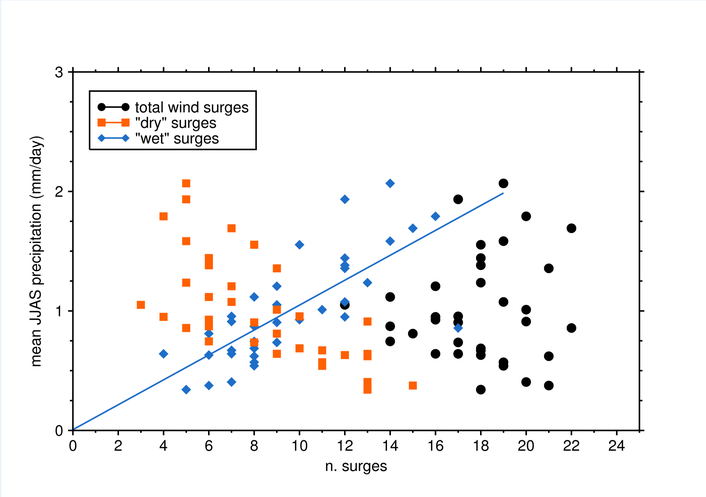

Figure 3: *Mean JJAS precipitation over AZ-WNM vs. number of dry, wet and total surges over the 1979-2014 ERA-Interim period.*

Identifying Surge events

Motivations Traditionally, surges have been identified using dew-point temperature at Yuma (e.g Higgins et al., 2004). Here, we introduce a dynamical index of synoptic scale activity of the GoC winds to investigate emerging larger-scale patterns associated with wind surges. Such index might allow to more robustly link regional-scale surges to larger scale circulation patterns, and might be more directly applicable to analyses of General Circulation Model (GCM) outputs than more local measures. Additionally, a wind-based approach may be better suited to GCM evaluations than precipitation-based approaches, given that precipitation is parameterized while the flow is explicitly resolved.

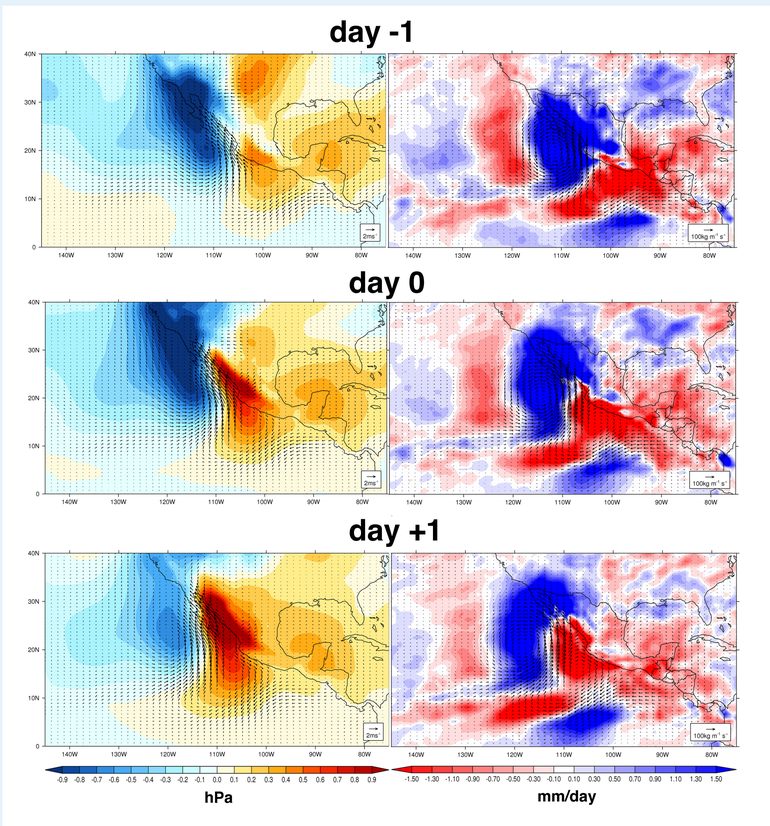

Figure 4: *Multiple lagged regressions of surface pressure and surface wind anomalies on PC1 and PC2 for lag $= -1, 0, +1$ days from a surge (left) and vertically integrated moisture flux and moisture flux convergence anomalies (right) on PC1 and PC2 for lag$= -1, 0, +1$ days from a surge event.*

Interpretation of PC1 and PC2 We perform an EOF analysis of the JJAS GoC daily alongshore wind anomaly u'_G using data from ERA-Interim (1979-2014). The first principal component (PC1) accounts for 60% of the total variance and is highly correlated (99%) to the mean u'_G. PC2 accounts for about 20% of the total variance and is proportional to the mean north-south u'_G difference (98%). While large PC1 values are indicative of strong u'_G all along the GoC, large positive PC2 values are associated with large north-south u'_G differences. In most cases, as the surge propagates northwards, a peak in PC2 follows by one day a peak in PC1. However in some cases, u'_G blows northward only in the north GoC section (e.g., on the 07/23, Fig. 2).

Surge dynamics: lagged regressions Extending the method of Bordoni and Stevens (2006) – who used only PC1 as a predictor– here we relate atmospheric fields (e.g., sea levels pressure, 10m wind, etc.) to two predictors, PC1 and PC2, which together explain more than 80% of the summertime u'_G variability. In Fig. 4 we show lagged regression anomalies of mean surface pressure, surface wind, vertically integrated moisture flux and vertically integrated moisture flux convergence. As the wind surge progresses northwards, a marked increase of moisture flux convergence spreads over AZ-WNM, which is a clear indication of a positive precipitation anomaly (not shown). The inclusion of PC2 leads to an improved, more realistic precipitation anomaly pattern.

Modulation by extra-tropical waves

Lagged regression patterns of 200-hPa and 700-hPa on PC1 and PC2 (Fig. 5) show a Rossby wave train (RWT) from the northwestern Pacific converging into North America. The RWT has a barotropic structure but at 700 hPa it seems to originate from the tropical western Pacific at 120 E. At day -4, as the RWT breaks over western U.S., an upper-troposphere easterly tropical wave (TEW) also converges over central America, re-emerging reinforced over eastern Pacific (day 0), when the wave perturbation associated with the surge is evident at 700 hPa.

A link between RWT dispersion into U.S. and summertime precipitation over AZ-WNM has been previously suggested by Kiladis and Hall-McKim (2004) and Jiang and Lau (2008). However it still unclear under which circumstances such RWTs precede a wet event or a dry surge event. A goal of our work is to clarify this crucial aspect and how its interactions with TEWs.

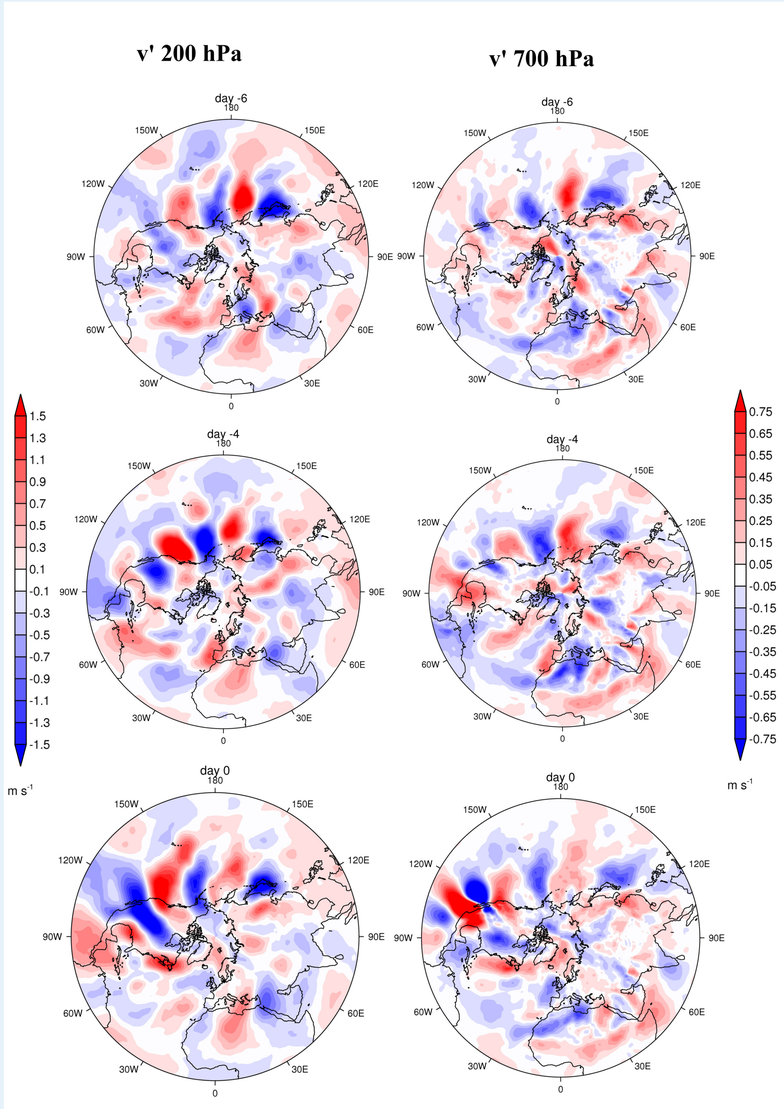

Figure 5: *Multiple lagged regressions of 200-hPa (left) and 700-hPa (right) meridional wind anomalies on PC1 and PC2 for lag$= -6, -4, 0$ days from a GoC surge event. Data from ERA-Interim.*

Conclusions and ongoing research directions

We have defined a new dynamical index based on the GoC wind variability to identify synoptic scale disturbances in the NAM and associated large-scale tropical and extra-tropical waves. More investigation is undergoing to understand what determines whether a surges is dry or wet and better understand the role played by RWTs and TWEs. the Geophysical Fluid Dynamics Laboratory (GFDL, Princeton), we are extending this methodology to evaluate simulations of NAM transient eddies in historical and forced runs with CM2.5-FLOR, a last generation, high resolution ($0.5° \times 0.5°$) coupled GCM.

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