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Article

# Unreported Characteristics Of The North American Monsoon

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**Abstract:** The North American Monsoon (NAM) in southern Arizona continues to be a topic of interest to ecologists, climatologists, and citizens as well as the triggers and characteristics of plant growth and reproduction in relation to the onset of the monsoon. In researching the onset of the North American Monsoon (NAM) in south-central Arizona relative to the phenology of Saguaro cactus (*Carnegiea gigantea*) and other Sonoran Desert species we identified interesting and previously unreported features in the NAM rainfall data. We present preliminary descriptive analyses of (1) monsoon onset as measured by the first day after June 1 with precipitation  $\geq 10$  mm (1990-2022), (2) first day of year warming of Sea Surface temperatures (SST) in the Gulf of California to  $\geq 29^\circ$  C measured across five open-sea blocks (mean 9452 km<sup>2</sup>), and (3) El Niño Southern Oscillation (ENSO) anomaly with a threshold of  $\pm 0.5^\circ$  C for the Oceanic Niño Index (ONI) in the Niño 3.4 region (5°N-5°S, 120°-170°W). Three patterns emerge from our analyses: (1) The day of the year of monsoon onset occurs approximately 12 days earlier in the year from 1990-2022 in south-central Arizona. (2) There appears to be a signal in the rainfall onset data very roughly approximating cycles of ENSO Oceanic Niño Index (ONI) anomalies in Niño region 3.4. (3) Gulf of California sea surface temperature (SST) and monsoon onset data support an expected link between the timing of SST warming and monsoon rainfall onset.

**Keywords:** monsoon; North American Monsoon; precipitation; Sonoran Desert; Gulf of California; megadrought; phenology; climate change; climatology; El Niño; ENSO; temperature anomaly; sea surface temperature; SST; Sonora; Arizona

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## Introduction

As plant ecologists, we are interested in the influence of environmental signals on phenological triggers and how this might affect the viability of the Saguaro cactus (*Carnegiea gigantea*) and many other Sonoran Desert species. During investigations of the relationships between Saguaro phenology and climate, we found interesting patterns in the timing of monsoon rainfall onset. We also examined the possible relationship between the cycles of the El Niño Southern Oscillation (ENSO) anomaly and sea surface temperatures (SST) in the Gulf of California (GoC).

This is an analysis of phenological event timing in a keystone Sonoran Desert Species, rainfall, and SST data intended to identify possible patterns and relationships between previously unreported features of the North American Monsoon (NAM).

## Methods

### *Monsoon Onset*

Several criteria have been developed for detecting monsoon onset for a given year. Brenner (1973) noted several surface measurements to indicate that the northward surge of the seasonal maritime airmass from the Gulf of California to Arizona has begun:

- Drop in temperature
- Rise in dew point
- Wind shift to southerly

- Increase in wind speed
- Rise in sea-level pressure
- Lower visibility (due to haze and blowing dust)
- Increasing low to mid-level cloud cover

Brenner noted that one detects the onset of the monsoon moisture surge by comparing hourly observations of temperature, dew point, and pressure. Meteorologists, especially those associated with the U.S. National Weather Forecasting Offices in Phoenix and Tucson began to rely on dew point temperature criteria (Carleton 1985). Mitchell et al. (2003), in their analysis of Gulf of California (GoC) sea surface temperatures, noted the accepted onset definition: the first consecutive three-day period with daily average dew point of 12.78°C or greater at the Phoenix NWS Forecast Office and 12.2°C in Tucson. Zeng and Lu (2004) developed and tested an index with global application based on gridded, 1° x 1° daily precipitable water values.

Fonseca-Hernandez et al. (2021) recently suggested an onset indicator based on local daily precipitation records: the first daily sequence of five consecutive days with average precipitation  $\geq 2$  mm/day.

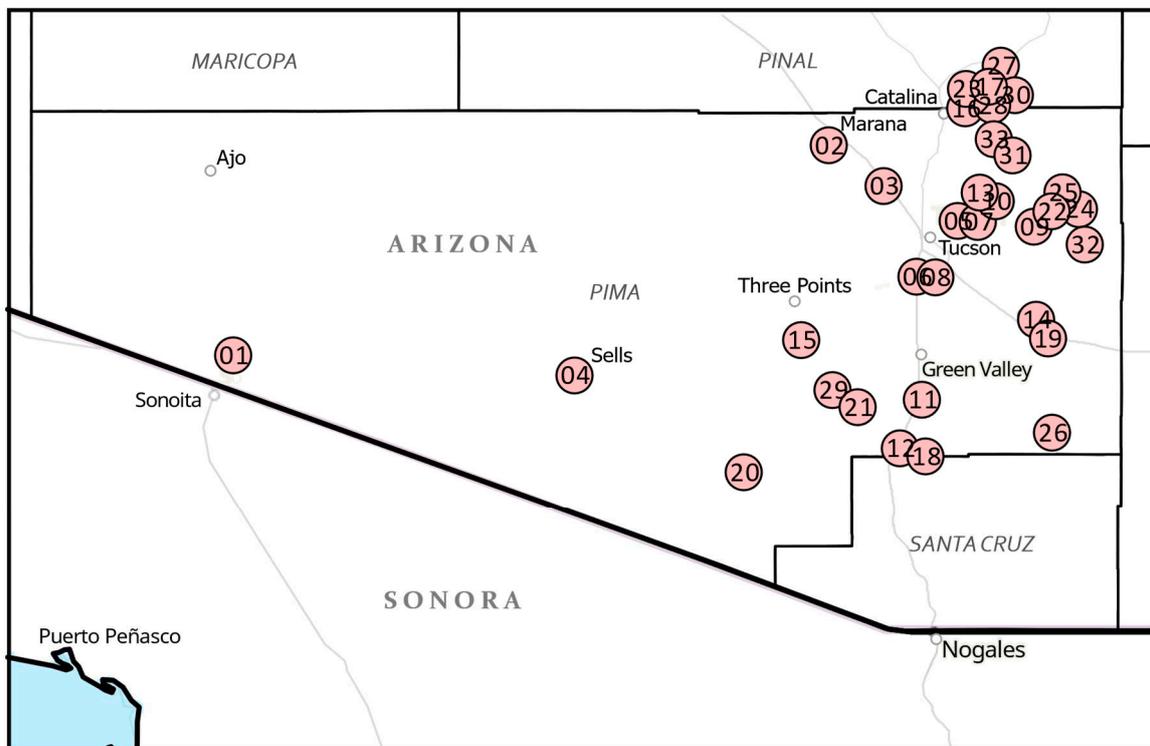
We gathered data from the Pima County, Arizona, ALERT network of remote reporting rain gauges, NWS (Tucson), and several NWS COOP and RAWS stations, most with records from 1990-2023 (Table 1, Figure 1). Of the 33 stations used in the analysis all but three were within a 65 km radius of downtown Tucson. They include representation across 2274 m of elevation from 512 m, at the Organ Pipe Cactus National Monument Headquarters to 2786 m at the summit of Mt. Lemmon, Santa Catalina Mts. We recorded the first annual one-day rainfall events of  $\geq 10$  mm after 31 May for each station. We used 10 mm precipitation because it represents the smallest amount that would be biologically relevant to plants of the Sonoran Desert (Bowers & Dimmitt 1994) and it is the smallest amount that the weather stations we used experienced on at least one day almost every summer. In the few occasions that no rainfall  $\geq 10$  mm was recorded we used the first highest one-day amount.

**Table 1.** List of 33 weather stations sorted by elevation. Stations were chosen for length of record (preferably 1990-2021) and elevational representation. Any year with >20 missing daily rainfall totals during the June 1-September 30 sample period was omitted. Station record period listed here is that used for this analysis.

	Network	Station ID	Station Name	Period of Record Used	Elev. (m)	Latitude	Longitude
1	US Park Service <sup>3</sup>	USC00026132	Organ Pipe Cactus NM	1990-2001, 2003-2022	512	31.9555	-112.8002
2	Pima Co. ALERT <sup>1</sup>	6110	Avra Valley Air Park/Santa Cruz R	1990-2000, 2002-2022	604	32.42902	-111.2251
3	Pima Co. ALERT <sup>1</sup>	6020	Santa Cruz R/Ina Rd	1990-2000, 2002-2022	662	32.33725	-111.0801
4	RAWS <sup>4</sup>	021209	Sells	2005-2006, 2008-2009, 2011-2022	721	31.91	-111.8975
5	Pima Co. ALERT <sup>1</sup>	2370	Alamo Wash/Glenn St	1990-2008, 2010-2021	744	32.25871	-110.8841
6	Pima Co. ALERT <sup>1</sup>	6040	Santa Cruz R/Valencia Rd	1990-1996, 1998-2021	750	32.13306	-110.9931
7	Pima Co. ALERT <sup>1</sup>	2120	Tanque Verde Sabino Bridge	1990-2000, 2001-2010, 2011-2022	755	32.26529	-110.8415
8	US Weather Service <sup>2</sup>	USW00023160	Tucson Int'l Airport	1990-2022	778	32.13153	-110.9564
9	Pima Co. ALERT <sup>1</sup>	2090	Tanque Verde Guest Ranch	1990-2008, 2010-2021	829	32.2458	-110.6828
10	Pima Co. ALERT <sup>1</sup>	2160	Sabino Dam	1990-2022	847	32.31464	-110.8109
11	Pima Co. ALERT <sup>1</sup>	6050	Santa Cruz R/Continental Rd	1990-2021	871	31.85512	-110.9788
12	Pima Co. ALERT <sup>1</sup>	6060	Santa Cruz R/Canoa Ranch	1990-2022	917	31.7451	-111.037
13	RAWS <sup>4</sup>	021202	Saguaro	2002-2022	945	32.31667	-110.8133
14	Pima Co. ALERT <sup>1</sup>	4250	Pantano Vail	1990, 1992-2019, 2022	981	32.03595	-110.6768
15	Pima Co. ALERT <sup>1</sup>	6410	Diamond Bell Ranch	1990-1999, 2001-2022	992	31.98991	-111.298
16	Pima Co. ALERT <sup>1</sup>	1040	Dodge Tank	1990-2020	1006	32.51192	-110.8642
17	Pima Co. ALERT <sup>1</sup>	1070	Catalina State Park	1991-2021	1009	32.52609	-110.7948
18	Pima Co. ALERT <sup>1</sup>	6350	Elephant Head	1990-2022	1058	31.72684	-110.9694
19	Pima Co. ALERT <sup>1</sup>	4310	Davidson Canyon	1990-2022	1061	31.99358	-110.6452
20	RAWS <sup>4</sup>	021206	Sasabe	1992-2022	1067	31.69083	-111.45

21	Pima Co. ALERT <sup>1</sup>	6320	Tinaja Ranch	1990, 1992, 1994-2022	1189	31.83826 -111.1487
22	Pima Co. ALERT <sup>1</sup>	2080	Alamo Tank	1990-2022	1204	32.28031 -110.6359
23	Pima Co. ALERT <sup>1</sup>	1050	Cherry Tank	1990-2021	1231	32.51808 -110.837
24	Pima Co. ALERT <sup>1</sup>	2030	Italian Trap	1990, 1992-2022	1244	32.28517 -110.5635
25	Pima Co. ALERT <sup>1</sup>	2050	Ranch Rd	1990-1993, 1995-2022	1311	32.30989 -110.6069
26	RAWS <sup>4</sup>	021205	Empire	1990-2011, 2013-2016, 2018-2022	1417	31.78056 -110.6347
27	Pima Co. ALERT <sup>1</sup>	1020	Oracle R.S. CDO	1990-2019, 2021	1420	32.58566 -110.7859
28	Pima Co. ALERT <sup>1</sup>	1060	Pig Springs	1990-2022	1465	32.52609 -110.7948
29	Pima Co. ALERT <sup>1</sup>	6310	Keystone Peak	1990-2021	1881	31.87694 -111.2152
30	Pima Co. ALERT <sup>1</sup>	1030	Oracle Ridge	1990-2021	1957	32.5328 -110.7563
31	Pima Co. ALERT <sup>1</sup>	2150	White Tail	1990-1992, 1994-202	2490	32.41311 -110.7319
32	RAWS <sup>4</sup>	021207	Rincon	1995-2022	2512	32.20556 -110.5481
33	Pima Co. ALERT <sup>1</sup>	1090	Mount Lemmon	1990-2022	2786	32.44264 -110.7885

1 <https://alertmap.rfcd.pima.gov/gmap/gmap.html> 2 <http://climod2.nrc.cornell.edu/> 3  
<https://www.ncei.noaa.gov/metadata/geoportal/rest/metadata/item/gov.noaa.ncdc:C00861/html> 4  
<https://raws.dri.edu/wraws/azF.html>



**Figure 1.** Map of the locations of the 33 weather stations used in this analysis, Pima and Pinal counties, Arizona.

We suspected that the monsoon onset, identified each year by our criteria (first day  $\geq 10$  mm rainfall), would track at least a few days earlier at higher elevations than at lower elevations. A correction derived for each weather station from a monsoon onset on elevation regression was applied to every DOY monsoon onset; this had little effect on the monsoon onset calculations and was not included in these results.

#### *El Niño Southern Oscillation*

An interesting pattern observed in the monsoon onset data seen in the analysis resembles decadal-scale patterns in El Niño Southern Oscillation (ENSO) SSTs (Di Lorenzo et al. 2023). A list of cold and warm SST episodes, calculated by 3-month season was retrieved from the US National Weather Service, Climate Prediction Center, 31 January 2023

[https://origin.cpc.ncep.noaa.gov/products/analysis\\_monitoring/ensostuff/ONI\\_v5.php](https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php). These data represent warm and cold periods based on a threshold of +/- 0.5°C for the Oceanic Niño Index (ONI, 3 month running mean of ERSST.v5 SST anomalies in the Niño 3.4 region, 5°N-5°S, 120°-170°W). We calculated the annual mean for the five sample blocks for the period 1990-2021.

#### *Gulf of California (GoC) Sea Surface Temperatures (SST)*

The timing of the seasonal surge of maritime air masses from the south into Arizona is believed to be enhanced or even triggered by the warming sea surface temperature (SST) in the Gulf of California (GoC). The mechanics of the GoC SST warming and monsoon onset relationship have been the subject of much research over the past three decades (Douglas et al. 1993, Mitchell et al. 2002, Erfani & Mitchell 2014, Fonseca-Hernandez et al. 2021). These models suggest that the thermal inversion overlying the GoC only breaks down once the SST has reached 29°C. The exact geographic extent of the thermal inversion within the Gulf and the geographic extent of warming needed to degrade the inversion are yet to be determined.

We retrieved the Daily Optimum Interpolation Sea Surface Temperature (OISST) from five rectangular sampling blocks of the GoC from the mouth of the Gulf north to the Colorado River delta outflow (Figure 2; Huang et al. 2020; SST, Daily Optimum Interpolation (OI), AVHRR Only, Version 2.1, 0.25°, [https://coastwatch.pfeg.noaa.gov/erddap/griddap/ncdcOisst21Agg\\_LonPM180.html](https://coastwatch.pfeg.noaa.gov/erddap/griddap/ncdcOisst21Agg_LonPM180.html)). We averaged daily SST (1990-2022) across five large blocks of open sea spaced from south to north (mean 9452 km<sup>2</sup>, total 47259 km<sup>2</sup>) and identified the first day of the first of the year 3-day period in which the temperature reached or exceeded 29°C.

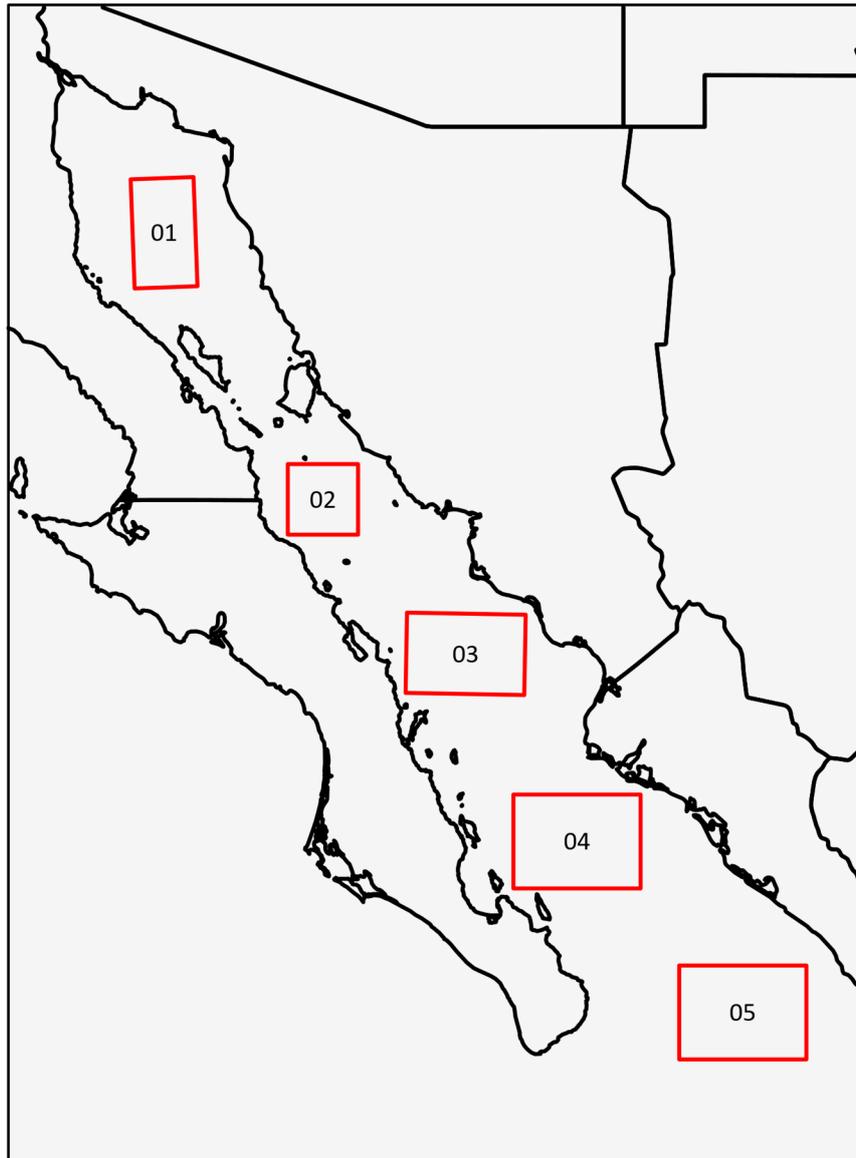


Figure 2. Distribution of Gulf of California SST sampling blocks.

## Results

Our investigations of the monsoon onset in south-central Arizona suggest two previously unreported features. First, the monsoon begins almost two weeks earlier in the year now than it did in 1990, and second, the monsoon onset data exhibited a sinusoidal waveform pattern with a period similar to that of ENSO warm/cool variations. A preliminary comparison of the monsoon onset pattern with ENSO and Gulf of California anomalies did not suggest a relationship. The dew point temperature, traditionally relied upon to signal monsoon onset, does not exhibit the same change in onset timing or sinusoidal pattern found in precipitation analysis. Unfortunately, dewpoint temperature data for our study area, over the same time period, are not available anywhere except at the Tucson National Weather Service, Tucson, with sensors located at Tucson International Airport.

### *Monsoon Onset Timing*

Table 2 lists the 33 weather stations and the mean day of year of monsoon onset day of year, monsoon precipitation total, and annual precipitation totals for each station. There is a significant relationship between monsoon precipitation and elevation, as is well-known, and monsoon onset is earlier in the year as elevation increases. Figures 3 & 4 illustrate this with regressions of mean station

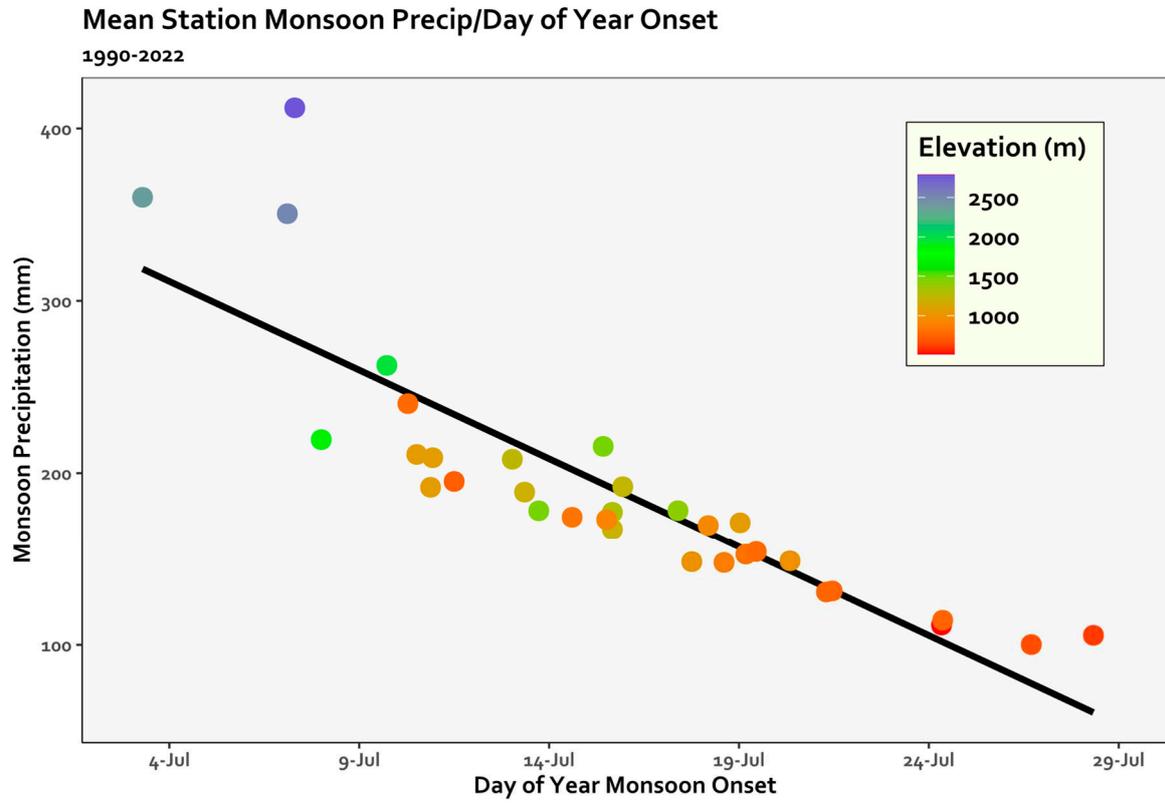
monsoon precipitation total on day of year of monsoon onset ( $R^2=0.71$ ,  $p\text{-value}<0.0001$ ) and monsoon precipitation on station elevation ( $R^2=0.8815$ ,  $p\text{-value}<0.0001$ ).

Figure 5 presents a plot of 1,051 monsoon onset day-of-year estimates, GAM (General Additive Model), and linear regression for the 33 weather stations listed in Table 2. The mean monsoon onset at all 33 stations from 1990-2022 was 13 July (std. dev.=19.16, min.=7 June, max.=7 Oct.). The first day, after 1 June, of monsoon rainfall  $\geq 10$  mm has recessed 12.032 days from 1990 to 2022 ( $R^2=0.0344$ ,  $F_{1,1068}=37.5$ ,  $p\text{-value}<0.0001$ ; 1990=22 July, 2022=10 July).

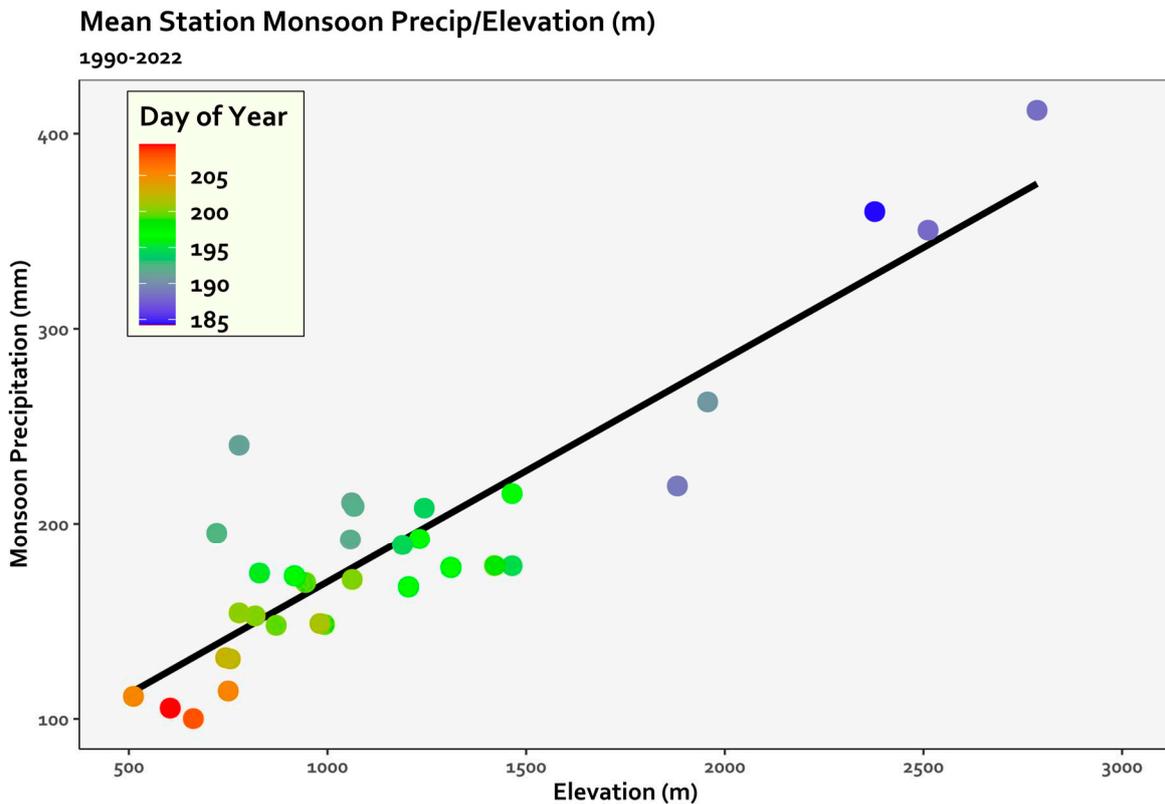
**Table 2.** Average day of monsoon onset, total average monsoon precipitation (1 June – 30 Sept) and total average annual precipitation for 33 weather stations sorted by elevation (as in Table 1) in Pima and Pinal Counties, Arizona, 1990-2022.

Station Name	Mean Onset (day of year)	Monsoon n Total (mm)	Annual Total (mm)	No. Years	Elev. (m)	Latitude	Longitude
Organ Pipe Cactus NM	205.33	111.49	234.81	33	512	31.956	-112.800
Avra Valley Air Park - Santa Cruz Basin	209.18	105.51	206.68	33	604	32.429	-111.225
Santa Cruz River at Ina Road	207.70	100.15	201.24	33	662	32.337	-111.080
Sells	192.50	195.23	322.60	22	721	31.910	-111.898
Alamo Wash below Glenn St	202.45	131.23	244.69	33	744	32.259	-110.884
Santa Cruz River at Valencia Road	205.36	114.23	208.66	33	750	32.133	-110.993
Tanque Verde Sabino Bridge	202.30	130.59	240.29	33	755	32.265	-110.842
Tucson Int'l Airport	200.45	154.09	273.47	33	778	32.132	-110.956
Tanque Verde Guest Ranch	195.61	174.43	328.58	33	829	32.246	-110.683
Sabino Dam	200.18	152.55	302.59	33	847	32.315	-110.811
Santa Cruz River at Continental Rd	199.61	147.73	243.46	33	871	31.855	-110.979
Santa Cruz River at Canoa Ranch	196.52	173.03	271.15	33	917	31.745	-111.037
Saguaro	199.19	169.61	309.14	21	945	32.317	-110.813
Pantano Vail	201.34	148.65	104.41	32	981	32.036	-110.677
Diamond Bell	198.76	148.17	249.32	33	992	31.990	-111.298
Dodge Tank	200.03	171.17	343.37	33	1006	32.512	-110.864
Catalina State Park	194.73	178.18	348.69	33	1009	32.526	-110.795
Elephant Head	191.88	191.82	306.42	33	1058	31.727	-110.969
Davidson Canyon	191.52	210.89	360.39	33	1061	31.994	-110.645
Sasabe	191.94	208.99	334.04	31	1067	31.691	-111.450
Tinaja Ranch	194.35	189.03	310.90	31	1189	31.838	-111.149
Alamo Tank	196.67	167.40	345.44	33	1204	32.280	-110.636
Cherry Spring	196.94	192.16	379.87	33	1231	32.518	-110.837
Italian Trap	194.03	208.11	393.66	32	1244	32.285	-110.564
Ranch Road	196.67	177.29	360.22	33	1311	32.310	-110.607
Empire	191.28	240.36	359.13	32	1417	31.781	-110.635
Oracle Ranger Stn at Canada del Oro	198.39	178.23	356.17	33	1420	32.586	-110.786
Pig Springs	196.42	215.57	451.81	33	1465	32.526	-110.795
Keystone Peak	189.00	219.48	328.04	33	1881	31.877	-111.215
Oracle Ridge	190.73	262.55	480.58	33	1957	32.533	-110.756
White Tail	188.78	402.34	772.65	32	2490	32.413	-110.732

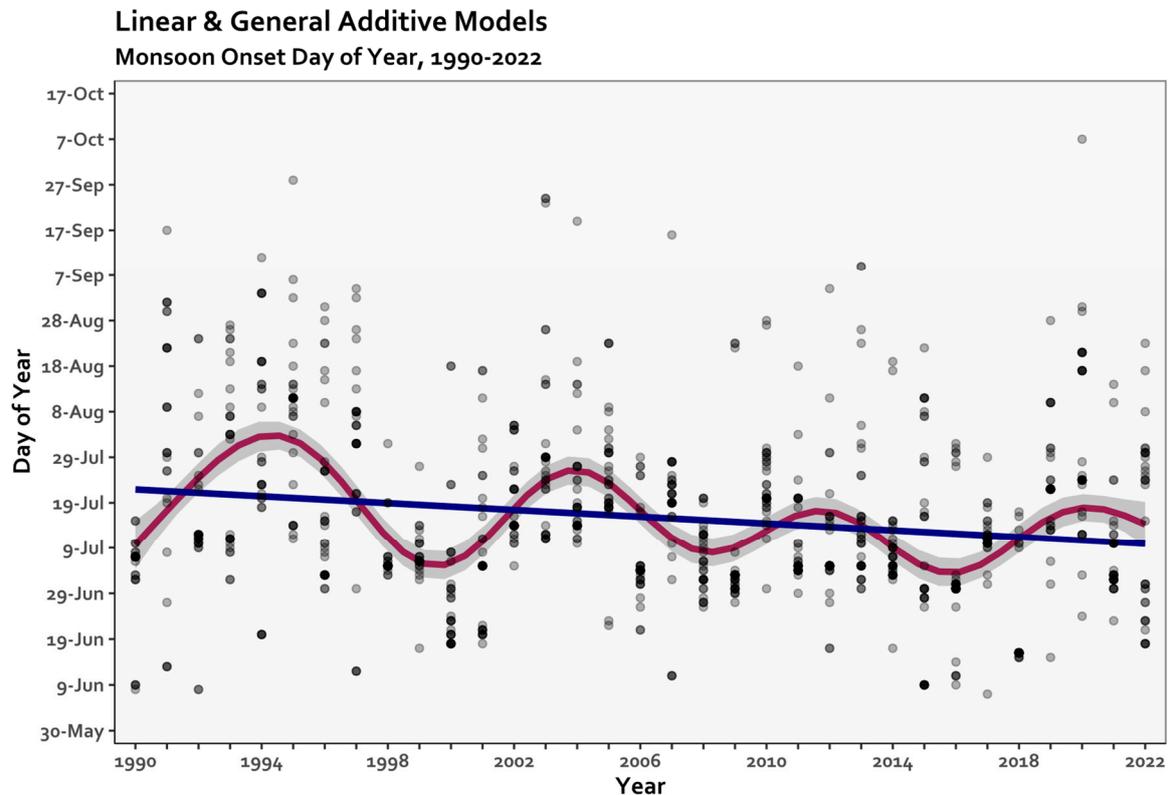
Rincon	188.11	350.55	574.48	28	2512	32.206	-110.548
Mountain Lemmon	188.30	411.99	809.18	33	2786	32.443	-110.789



**Figure 3.** Regression of Mean monsoon precipitation by station and station elevation (Table 1) on day of year of monsoon onset, 1990-2022.  $R^2=0.6793$ ,  $p\text{-value}<.0001$ .



**Figure 4.** Regression of Mean monsoon precipitation by station and station day of year of monsoon onset (Table 1) on elevation, 1990-2022.  $R^2=0.8815$ ,  $p\text{-value}<.0001$ .



**Figure 5.** General Additive Model (GAM) and Linear Model (LM) of monsoon onset time series, 1990-2022,  $n=1053$ . GAM:  $k=10$ ,  $R^2=.195$ ,  $F=28.97$ ,  $p\text{-value}<0.0001$ , deviance explained=20.2%. LM:  $R^2=0.0325$ ,  $F_{1,1051}=35.3$ ,  $p\text{-value}<0.0001$ . Wave period=8.8 years.

The GAM function displayed in Figure 5 was configured with default basis dimension  $k=10$  ( $\text{edf}=8.801$ ), explaining 20.2% of the deviance with an  $R^2$  of 0.195. The crest and trough dates of the wave patterns are presented in Table 3.

A sinusoidal wave pattern in the data is evident in the point visualization and even more obvious in the GAM fit plot (Figure 5). The wave exhibited four crests, three troughs, and a crest-to-crest period of 8.8 years.

It may be noteworthy that the first deep trough in Figure 5, with a nadir on 30 September 1999, is approximately coincident with the onset of the current 21<sup>st</sup> century western North American megadrought described in the literature (Williams et al. 2022). Fonseca-Hernandez et al. (2021) found that early monsoon onset results in, or is characteristic of, a drier monsoon rainfall season. They speculate that, "...the longer a monsoon onset is delayed the greater amount of convective energy is stored in the boundary layer, being kept there by the thermal inversion over the GoC. Once the surface temperature of the gulf is sufficient to break the inversion, the low-level gulf accumulated moisture is released and becomes available for monsoon precipitation". As noted previously, they used a monsoon onset definition similar to, but not identical to ours, and derived their rainfall data from gridded interpolation in a large rectangular polygon on the western slopes of the Sierra Madre Occidental several hundred kilometers south of our south-central weather stations.

**Table 3.** Crest-trough pattern in GAM fit ( $\text{mgcv}$ ,  $\text{predict}()$  function).

Year	Month-day	Phase
1994	28 Jun	Peak

1999	30 Sep	Valley
2004	9 Feb	Peak
2008	4 May	Valley
2011	30 Dec	Peak
2015	28 Nov	Valley
2020	10 Jul	Peak
<i>Period = 8.7 years</i>		

We obtained the daily average dew point temperatures for the Tucson National Weather Service (TUS, sensors located at Tucson International Airport) for 1973-2022. and applied the monsoon onset criteria discussed above: day of year of 1<sup>st</sup> day with dew point  $\geq 12.22^{\circ}\text{C}$  for 3 consecutive days, ( $R^2=0.0087$ ,  $p\text{-value}=0.6064$ ,  $n=33$ ). Linear regression was also applied to the number of days from 1 June-30 Sept with dew point  $\geq 12.22^{\circ}\text{C}$ , 1990-2022, time series ( $R^2=0.0006$ ,  $p\text{-value}=0.8962$ ,  $n=33$ ). In addition, we also applied our own monsoon onset criteria to TUS precipitation data from 1990-2022 (this is included in the datasets shown in Table 2 and Figure 5). This too failed to show a significant relationship ( $R^2=0.0066$ ,  $p\text{-value}=0.6536$ ,  $n=33$ ). Table 4 lists the results of linear regression of monsoon onset on year with all 33 weather stations and highlighting five stations with positive slope concentrated at the lower elevations and stations with a significant  $p\text{-value}$  concentrated at the higher elevations.

**Table 4.** Results of linear regression monsoon onset on year, for 33 weather stations in Pima and Pinal Cos., Arizona, sorted by elevation. Positive slopes and significant P-values ( $<0.05$ ) are highlighted.

Station Name	Elev. (m)	Intercept	Slope	P-value	R <sup>2</sup>
Organ Pipe Cactus NM	512	724.9356	-0.2590	0.5658	0.0108
Avra Valley Air Park - Santa Cruz Basin	604	1365.7159	-0.5765	0.1370	0.0699
Santa Cruz River at Ina Road	662	1260.9811	-0.5251	0.1757	0.0583
Sells	721	-1402.0401	0.7930	0.0890	0.1378
Alamo Wash below Glenn St	744	1206.7955	-0.5007	0.2027	0.0518
Santa Cruz River at Valencia Road	750	1581.5329	-0.6860	0.1000	0.0849
Tanque Verde Sabino Bridge	755	-486.2538	0.3432	0.3790	0.0251
Tucson Int'l Airport	778	553.7841	-0.1761	0.6536	0.0066
Tanque Verde Guest Ranch	829	341.0947	-0.0725	0.8162	0.0018
Sabino Dam	847	761.3523	-0.2797	0.3317	0.0304
Santa Cruz River at Continental Rd	871	-183.8939	0.1912	0.6811	0.0055
Santa Cruz River at Canoa Ranch	917	321.2197	-0.0622	0.8656	0.0009
Saguaro	945	0.6035	0.0987	0.8797	0.0012
Pantano Vail	981	1960.0453	-0.8765	0.0263	0.1540
Diamond Bell	992	81.4280	0.0585	0.8275	0.0016
Dodge Tank	1006	1707.8826	-0.7517	0.0439	0.1246
Catalina State Park	1009	881.9432	-0.3426	0.3283	0.0308
Elephant Head	1058	1589.1061	-0.6965	0.0038	0.2399
Davidson Canyon	1061	1356.0947	-0.5805	0.0811	0.0949
Sasabe	1067	1431.7435	-0.6177	0.0521	0.1239
Tinaja Ranch	1189	-72.4807	0.1330	0.6373	0.0078
Alamo Tank	1204	1731.3371	-0.7650	0.0441	0.1244
Cherry Spring	1231	582.4508	-0.1922	0.5592	0.0111
Italian Trap	1244	1590.9192	-0.6962	0.0446	0.1277
Ranch Road	1311	1615.3485	-0.7072	0.0346	0.1362
Empire	1417	496.2033	-0.1520	0.6082	0.0089
Oracle Ranger Stn at Canada del Oro	1420	626.8144	-0.2136	0.5863	0.0097
Pig Springs	1465	1050.5833	-0.4258	0.1835	0.0563

Keystone Peak	1881	591.2727	-0.2005	0.4065	0.0223
Oracle Ridge	1957	1396.8750	-0.6013	0.0437	0.1249
White Tail	2490	1264.1146	-0.5359	0.0524	0.1197
Rincon	2512	755.9179	-0.2827	0.3621	0.0320
Mountain Lemmon	2786	1634.4735	-0.7209	0.0322	0.1396

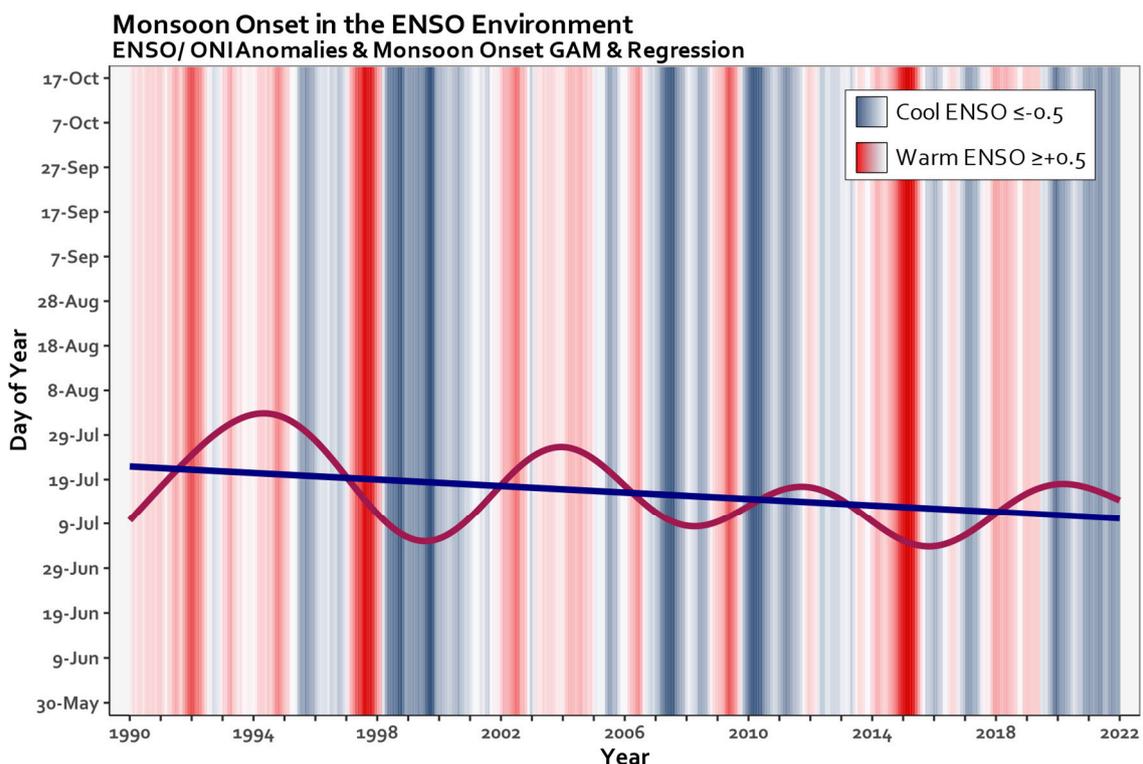
While Fonseca-Hernandez (2021) provide a possible explanation for the relationship between monsoon onset and total monsoon rainfall, it is not known whether or why the onset of the 21<sup>st</sup> century megadrought might be linked to the date of monsoon onset in any year nor is there an explanation for the sinusoidal wave pattern seen in the monsoon onset data presented here. We suspect that decadal-scale patterns in the Gulf of California and ENSO SST temperature data might provide insights into these questions.

#### *El Niño Southern Oscillation*

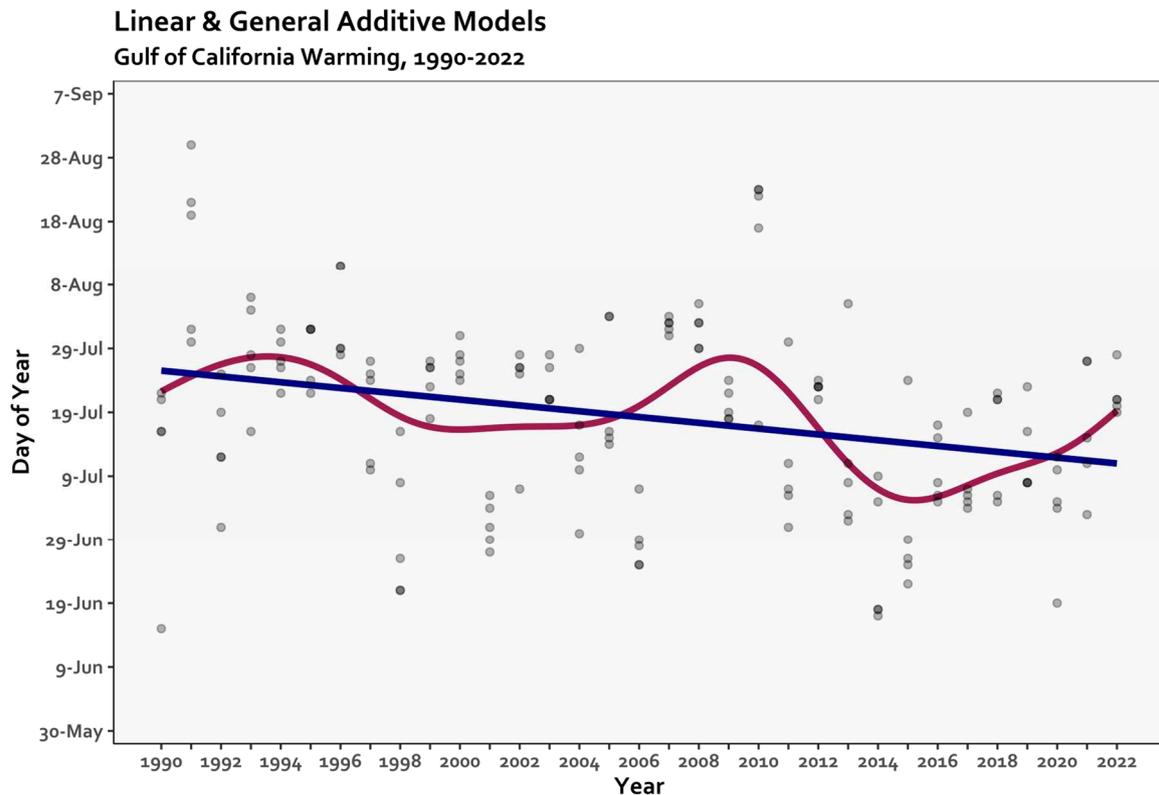
Figure 6 shows ENSO anomalies with threshold of  $\pm 0.5^{\circ}\text{C}$  for the Oceanic Niño Index (ONI) in the Niño 3.4 region ( $5^{\circ}\text{N}$ - $5^{\circ}\text{S}$ ,  $120^{\circ}$ - $170^{\circ}\text{W}$ ) and the GAM fit model from Figure 5. No pattern of relationship between the ENSO warm/cold episodes and the monsoon onset GAM sinusoidal wave was evident.

#### *Gulf of California SST Warming*

We averaged the daily sea-surface temperatures in each of the five sampling blocks in the Gulf of California (GoC; Figure 2 ) from 1990-2022 and then identified the first consecutive 3-day period with average temperatures  $\geq 29^{\circ}\text{C}$  after 1 June of each year in each box. The results are plotted in Figure 7 with points, the GAM, and a regression line. The GAM plot in Figure 7 shows crests and troughs but is hardly sinusoidal as the GAM plot of monsoon onset in Figure 5. Interestingly, the regression equation for this GoC plot (Y-intercept=1109, slope=-0.4537) was very similar to that of the monsoon onset plot (Y-intercept=934, slope=-0.7675). If there is a relationship, we speculate that it supports the idea noted above that it is GoC warming and the lifting of the boundary layer that allows monsoon moisture to stream northward into the south-central Arizona study area.



**Figure 6.** Monsoon onset GAM and regression from Figure 5 and visualization of ENSO warm periods. Threshold of +/- 0.5oC for the Oceanic Niño Index (ONI) in the Niño 3.4 region (5°N-5°S, 120°-170°W).



**Figure 7.** Gulf of California SST warming to  $\geq 29^{\circ}$  C after 1 June in each of the bounding boxes (Figure 2) GAM and regression, 1990-2022,  $n=165$ . GAM:  $k=10$ ,  $R^2=.218$ ,  $F=6.03$ ,  $p\text{-value}<0.0001$ , deviance explained=25%. LM:  $R^2=0.08857$ ,  $F_{1,163}=15.8$ ,  $p\text{-value}=0.0001$ .

## Discussion

Our research indicates a recession of approximately 12 days in the timing of monsoon onset, at least as we have defined it, in south-central Arizona from 1990-2022. Are biological entities living in our area affected? It is clearly too early to tell, but whether or not the onset recession is related to anthropogenic climate change, organisms are already under stress. Many species will find physiological and behavioral synchrony with phenological triggers increasingly challenging unless the monsoon onset recession returns to a normal state (the definition of which is currently unknown).

We presume that this change to earlier onset is recent and suspect that it may be short-lived. Creative analyses of interpolated rainfall data looking back to pre-drought times may be useful in this regard. It is tempting to connect the monsoon onset recession to the current 21<sup>st</sup> century megadrought, and we did suggest that the wave pattern of the monsoon onset coincides with the megadrought onset.

The sinusoidal wave pattern seen in our monsoon onset data does not seem to be related to ENSO anomalies or variations in the timing of warming SSTs in the Gulf of California. However, the GoC is warming to  $\geq 29^{\circ}$  C earlier in the year in much the same way that the monsoon onset in south-central Arizona is recessing. This may provide some support for the models reported in the literature that suggest a connection between GoC warming and monsoon onset.

We were, and still are, concerned about the geographic space sampled by the weather stations we chose to include in our primary dataset. We have already noted that monsoon onset is negatively correlated with elevation, whereas total monsoon precipitation is positively correlated with elevation. There are other confounding variables that we did not consider which may also reflect or influence monsoon onset such as slope and elevation, not to mention both latitude and longitude.

Fonseca-Hernandez et al. (2021) obtained an average monsoon onset date of 18 June which is within two days of the dates determined by Xu et al. (2004) and Higgins et al. (1999). Our mean combined monsoon onset date, including all 33 stations and all years from 1990 was 13 July, nearly a month later. Their study areas, far to the south of Arizona, are expected to experience an earlier monsoon onset, and, more subtly, none of the areas sampled in those three studies was north, that is, downwind, of the Gulf of California.

It is hoped that future work on the monsoon onset features found in our data will be explained and clarified with greater resolution than we have done here. We look forward to insights into the nature of the sinusoidal wave pattern in the monsoon onset data, clarification of the geospatial characteristics of monsoon onset timing, and we hope that some progress may be made in extending the analysis of monsoon onset substantially before 1990.

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