

Using Sounding Data to Detect Gulf Surges during the North American Monsoon

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ABSTRACT

Periodic surges of moisture from the Gulf of California are considered to be partly responsible for widespread showers and thunderstorms across the deserts of Arizona during the summer monsoon season. Presently, the primary method for detecting these surges is to look for changes in the surface observations at Yuma, Arizona. Unfortunately, these surface data are easily influenced by gust fronts, marine layers, and the dramatic diurnal patterns of the desert environment. Therefore, a new method for Assessing Low-level Atmospheric Moisture using Soundings (ALARMS) is proposed. Gulf surge-induced moisture increases identified by this new set of criteria are compared to other methods in order to determine the usefulness of each. This study demonstrates that the proposed method performs much better than the others that were tested, with the additional advantage of being relatively easy to apply.

1. Introduction

The annual arrival of moisture to the southwest deserts of the United States is known as the North American monsoon, the Mexican monsoon (due to its greatest strength over northwest Mexico), and the Arizona monsoon (Adams and Comrie 1997). While the onset of the actual monsoon is roughly consistent each year due to a seasonal shift in synoptic circulation (Bryson and Lowry 1955), much debate has focused on the intraseasonal variations in monsoon intensity and the amount of moisture and precipitation in the deserts, especially the low-lying parts of southern Arizona (Rowson and Colucci 1992; Schmitz and Mullen 1996; Stensrud et al. 1997; Mullen et al. 1998; Anderson et al. 2000). One of the most common mechanisms by which moisture and precipitation are thought to increase in the Sonoran Desert is periodic surges of the low-level transport of water vapor from the eastern Pacific Ocean via the Gulf of California (Hales 1972). These “gulf surges” are difficult to detect and nearly impossible to forecast (McCollum et al. 1995; Maddox et al. 1995), and their impacts on desert precipitation are still not fully understood (Adams and Comrie 1997; Douglas et

al. 1998; Fuller and Stensrud 2000). Many researchers have made assumptions about this relationship (e.g., Hales 1972; Brenner 1974; Adang and Gall 1989; Dunn and Horel 1994; Maddox et al. 1995; McCollum et al. 1995; Stensrud et al. 1997), but no formal studies have provided a clear connection. Given the difficulty of forecasting precipitation and severe weather in central Arizona during the monsoon season (Dunn and Horel 1994; McCollum et al. 1995; Maddox et al. 1995), further insight into the role of low-level moisture is crucial. Perhaps part of this research void is due to the inconsistency of gulf surge definitions. Without a strict, widely accepted method for identifying gulf surge events, it is difficult for researchers to correlate them with precipitation and climatological variables. Therefore, before a relationship between gulf surges and precipitation can be tested, a simple, objective method for identifying the associated increases in moisture must be introduced and applied. Unfortunately, it becomes problematic to test the accuracy of any new method that detects gulf surges, or the associated moisture increases, because there are no widely accepted methods to use as standards.

2. Background

The North American monsoon was first described as the result of a thermal low over the Colorado River

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valley pulling moisture inland from the Gulf of California (Ward 1917; Blake 1923; Willett 1940). However, Gulf of California moisture was rarely mentioned again in monsoon research for over three decades (Hales 1972), as the Gulf of Mexico was thought to be the primary source of monsoon moisture (Jurwitz 1953; Bryson and Lowry 1955; Reitan 1960; Green and Sellers 1964; Hastings and Turner 1965). Eventually, Reitan (1960) identified the greatest amount of moisture in Phoenix to be at low levels (50% below 800 hPa; 86% below 600 hPa), and Hales (1972) argued that monsoon moisture originated over the tropical eastern Pacific Ocean and was channeled up the Gulf of California in the form of surges induced by a pressure gradient up the Gulf of California. Likewise, Schmitz and Mullen (1996), using the European Centre for Medium-Range Weather Forecasts reanalysis data, determined that most water vapor enters the Sonoran Desert region at low levels (below 700 hPa) from the northern Gulf of California, and that most of the upper-level moisture (above 700 hPa) comes from the Gulf of Mexico.

Brenner (1974) supported Hales (1972), and both agreed that the pressure gradient was induced by development of a cloudy, showery air mass at the mouth of the Gulf of California, and that such an air mass was due to tropical cyclones or easterly waves crossing the mouth. Since that time, the gulf surge theory has been widely accepted as a primary source of monsoon moisture in the deserts of Arizona (Hales 1974; Carleton 1985, 1986; Carleton et al. 1990; Rowson and Colucci 1992; Douglas et al. 1993), and many recent studies have focused directly on gulf surges (Douglas 1995; Maddox et al. 1995; McCollum et al. 1995; Stensrud et al. 1997; Fuller and Stensrud 2000; Douglas and Leal 2003; Zehnder 2004).

Gulf surge identification methods

When Hales (1972) initially proposed the idea of gulf surges, he listed seven criteria on which to base detection of these events. Essentially, a surge was identifiable by a strong shift to south-southeast winds, higher moisture, and lower temperatures. Hales (1972) stated that these changes would take place primarily below 700 hPa, and that the effects could be best observed in Arizona at Yuma. Brenner (1974) and Stensrud et al. (1997) agreed that Yuma is the key station for surge identification since it is usually the first regularly reporting station in Arizona where the arid, continental air mass is suddenly replaced by a tropical, maritime air mass. Fuller and Stensrud (2000) defined a surge as a rapid increase in surface dewpoints (at Yuma) in which the maximum daily dewpoint remains elevated above 15.6°C (60°F) throughout the following several days. In

addition, Fuller and Stensrud's (2000) definition of a surge requires that surface winds (10 m) must be southerly and exceed 4 ms⁻¹ for at least one reporting time.

Unfortunately, most surge identification methods rely solely on surface data due to the shallow depth of the events (Douglas 1995) as well as the lack of upper-air data near the northern end of the Gulf of California (Fuller and Stensrud 2000). Reliance solely on surface data to identify surge events can be complicated due to the similar characteristics of surge passage and the outflow from thunderstorms. Furthermore, diurnal wind shifts (especially near the coast or mountains) can mask or exaggerate the surge signal (Douglas and Leal 2003). Forecasters use surges in the determination of maximum and minimum temperatures and in the evaluation of whether convective formation or structure will be altered (e.g., dry microburst events on nonsurge days; flash flooding, hail, and wet microbursts on surge days). According to K. Runk, Meteorologist in Charge, National Weather Service Forecast Office (NWS) in Las Vegas, Nevada, there are many days in which the Yuma dewpoint rises significantly, but no surge occurs. Further, some events that might be classified as a genuine surge at Yuma are too shallow to extend more than a few tens of kilometers northward before mixing out (K. Runk 2003, personal communication). While Douglas and Leal (2003) incorporated a surge-detection method that uses radiosonde data at Empalme, Mexico, that study defines surge characteristics and effects only for northwest Mexico rather than the southwest United States. Also, the method used by Douglas and Leal (2003) is rather complicated (e.g., requiring moisture flux calculations from multiple sounding levels) and subjective (moisture changes over a period of 24 h or longer are needed), and it is not easily applied in real time.

An experimental method for defining gulf surges is presently being tested in operational forecasting by the NWS Forecast Office in Las Vegas (K. Runk 2003, personal communication). This method uses threshold values of dewpoint temperature (separated by 5°C) at corresponding levels (Table 1) for each location (K. Runk 2003, personal communication). This definition is designed so that the threshold values at each location represent approximately the same change in mixing ratio. Therefore, this method identifies events with a specific magnitude of moisture while excluding many events with significant increases in moisture), and many surge events are likely missed since the initial moisture value is already relatively high.

3. ALARMS

Currently, no published methods for identifying increases in low-level moisture associated with gulf surges

TABLE 1. Sounding criteria for defining gulf surges used by the Las Vegas National Weather Service Forecast Office (K. Runk 2003, personal communication). At each site's mandatory pressure level, a gulf surge occurs when the dewpoint temperature remains below the low threshold for at least 2 days and then immediately increases to a value above the high threshold for at least 2 days. This moisture change must also be accompanied by cooling, a wind shift, and a rise in surface pressure.

Site	Mandatory pressure level (hPa)	High dewpoint threshold ($^{\circ}\text{C}$)	Low dewpoint threshold ($^{\circ}\text{C}$)
Empalme	925	12.5	17.5
Phoenix	850	8.0	13.0
Tucson	850	7.5	12.5
Yuma	925	9.0	14.0

are accurate enough to allow forecasters to rely on their results due to the uncertainty associated with surface-based methods. Similarly, climatologists cannot rely on the current, inaccurate methods when studying archived data in attempts to further understand these events. Therefore, the method proposed in this study for Assessing Low-level Atmospheric Moisture using Soundings (ALARMS) is designed to be accurate, objective, and easy to apply. This method was initially modeled after the Las Vegas NWS method. However, the ALARMS method is based on a sliding scale rather than a set of static thresholds. To be considered a surge event, two consecutive days of relatively low dewpoints must be immediately followed by two consecutive days of dewpoints at least 4°C greater than the first two days. The Las Vegas NWS method requires an increase of 5°C , but during the development and testing of the ALARMS method, no increases in false alarms occurred if 4°C were used instead. Rather, a couple of events that exhibited surgelike properties and would have been missed with the 5°C scale were included using the 4°C scale. The mandatory level for each location should be approximately 1 kilometer above the surface in order to represent the low-levels without being heavily influenced by surface processes. Therefore, the Phoenix and Tucson, Arizona, soundings are analyzed at the 850-hPa level while the Yuma, Arizona, and Empalme, Mexico, soundings are analyzed at the 925-hPa level (Fig. 1).

It is important to note that soundings from different times of the day are kept separate when applying the ALARMS method due to the dramatic diurnal temperature ranges experienced in this region. The soundings at 0000 and 1200 UTC may display drastically different values of absolute humidity due to varying, temperature-induced boundary layer heights, even though the total moisture content is largely unchanged. There-

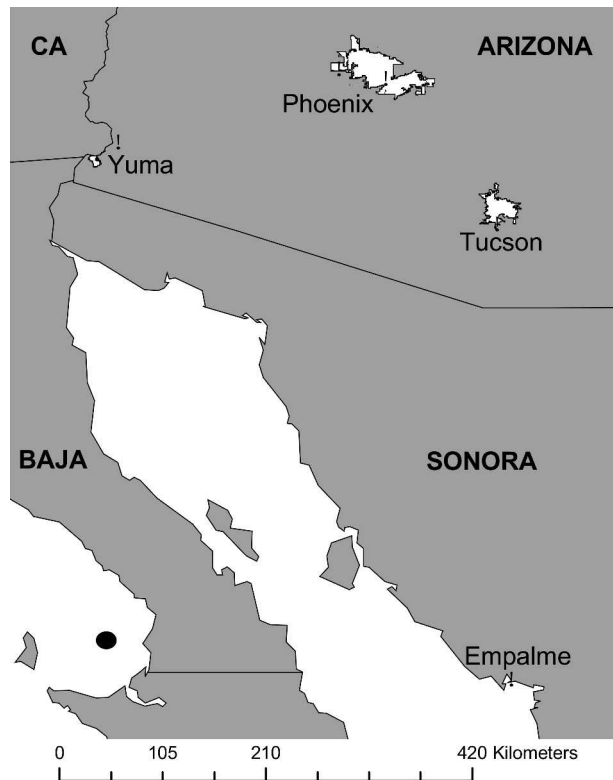


FIG. 1. Upper-air stations used in this study; soundings in Phoenix were taken at two locations.

fore, this method requires four consecutive days of sounding data recorded around the same time of day.

Wind speed values are not incorporated into the ALARMS method for a few reasons. First, it is quite unlikely that sounding data, which are recorded once or twice per day, will allow observation of wind gusts and shifts associated with gulf surges. Second, wind data from PHX are less reliable for many soundings throughout the period than are temperature and dewpoint.

Due to the possible influence of thunderstorm outflow, diurnal circulations (mountain-valley breeze, sea breeze, etc.), and localized cloud cover, air temperature values are not a part of the analysis in the ALARMS method. Past research has shown that gulf surges tend to produce decreased temperatures (Hales 1972); however, this effect is mostly due to the increased moisture content associated with surges. Therefore, low-level moisture is the essential variable used in these analyses.

4. Data

This project utilizes observational sounding data collected within the Sonoran Desert region of the United

States and Mexico (Fig. 1). Data from upper-air sounding sites in Arizona, including Phoenix, Tucson, and Yuma, as well as a fourth sounding site at Empalme, Mexico, are used to develop and test the ALARMS method for detecting significant increases in low-level moisture associated with gulf surges. Sounding data from Phoenix are available from the Salt River Project, in Phoenix, while data from the other three sites are available jointly from the National Climatic Data Center, in Asheville, North Carolina, and the Forecast Systems Laboratory, in Boulder, Colorado.

To compare the results of the ALARMS method to the Fuller and Stensrud (2000) criteria, hourly surface dewpoint and wind data are required for Yuma. Hourly data were obtained from the Arizona Meteorological Network (AZMET). AZMET stations are maintained by the University of Arizona, College of Agriculture, and data are averaged each hour. There are three AZMET stations in Yuma, but the Yuma Mesa station (32.62°N, 114.63°W) is the southernmost of these stations, and it is also the closest to the Yuma airport. This study uses only the Yuma Mesa station.

Most gulf surge research results do not list specific dates and locations of each surge. Further, there is no accepted standard of accuracy with respect to gulf surge detection. Therefore, the results of this study are compared to two detailed, post-monsoon season summaries compiled by R. A. Maddox (2004, personal communication). These summaries cover the monsoon seasons of 2001 and 2003, and each summary details individual gulf surge events during the respective seasons (Table 2). These analyses, although subjective, are very thorough and based on all available data (sounding, satellite, surface, radar, etc.). More information on the methods used by Maddox is given by Gochis et al. (2004).

5. ALARMS method testing and comparison

Three gulf surge identification methods (Fuller and Stensrud 2000; Las Vegas NWS; and ALARMS) were applied to the monsoon months of July and August during the years 2001 and 2003. If the Las Vegas NWS method or the ALARMS method identified a surge event at even one of the sounding locations, then a surge was counted for that method. Table 3 shows the results of these comparisons. The surges identified by each method were compared to each other as well as to the list of events outlined by R. A. Maddox (2004, personal communication). Since there is no widely-accepted method for identifying surges, Maddox's summaries will be used to test the accuracy of the other methods.

TABLE 2. Summary of 2001 and 2003 gulf surge events compiled by Maddox for the months of Jul and Aug.

Day(s)	Month	Yr
3–4	Jul	2001
19–21	Jul	2001
24–25	Jul	2001
1–2	Aug	2001
27–29	Aug	2001
9–11	Jul	2003
18–19	Jul	2003
25–27	Jul	2003
6–8	Aug	2003
13–14	Aug	2003
18–20	Aug	2003
23–24	Aug	2003

Based on the raw results, it is evident that the ALARMS method performs better than the other two methods. However, even though the ALARMS method detects eight events correctly, it also misses three events and produces three false alarms. Therefore, each event was individually analyzed in order to gain insight as to how the method could be improved. This analysis revealed that one of the events missed by the ALARMS method was a “near miss,” or an event that spanned a day or two of missing data in the middle of the surge. Based on the available presurge and postsurge data, a near miss is classified as a surge event; however, it cannot be confidently verified without consecutive days of data. A subjective analysis would most likely include these days as surges. Additionally, another event was missed because no sounding data were available during the surge. Consequently, there is no way to determine whether this event would have met the necessary qualifications to be deemed a surge, so this event (23–24 August 2003) was removed from the analysis. After these considerations, the results become even more convincing with 9 of the 10 surges detected, 1 undetected surge, and 3 false alarms.

TABLE 3. Number of surge events identified by each method, and comparison to events identified by R. A. Maddox (2004, personal communication); numbers in parentheses reflect results after adjustments were made for missing data and one event that was questioned by Maddox.

Method	Total	Correct	Missed	False alarms
Fuller and Stensrud (2000)	3	1	10 (9)	2
Las Vegas NWS	1	1	10 (9)	0
Sliding scale	11 (12)	8 (9)	3 (1)	3 (3)
Maddox	11 (10)	11 (10)	0	0

6. Conclusions

A new method is proposed for detecting significant increases in low-level moisture in the low-lying deserts of Arizona during the annual summer monsoon season. These increases in moisture are typically associated with gulf surges and are thought to dramatically affect regional temperatures and precipitation patterns. The ALARMS method is based on dewpoint data at specific mandatory levels over a 4-day period. There are four sounding sites in the region to which this method can be applied.

It is important to note that none of the methods used in this comparison study should be considered sufficient for identifying gulf surges. This is because these methods are based primarily on low-level increases in moisture, and gulf surges are not the only means by which these increases occur. While a gulf surge will most likely result in a significant increase in low-level moisture, such an increase does not automatically signal a surge. Further, the mechanisms responsible for the initiation of gulf surges are not clear even though numerous possibilities have been suggested and evaluated (Zehnder 2004). Therefore, a dynamically based detection method is not feasible at this point. Nevertheless, the ALARMS method should be operational as an easy-to-use method for detecting significant increases in low-level moisture that commonly occur with gulf surges, and this technique proves more reliable than other approaches for accurately identifying these surges. The ALARMS method, when accompanied by other available tools, should prove valuable for forecasters and researchers in the southwest United States as they attempt to gain a better understanding of gulf surges and their effects. In addition, climatologists can easily apply this new method to archived sounding data in order to gain insight into the spatial and temporal patterns of surge events.

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