Front Range Flash Flooding and El Niño

by

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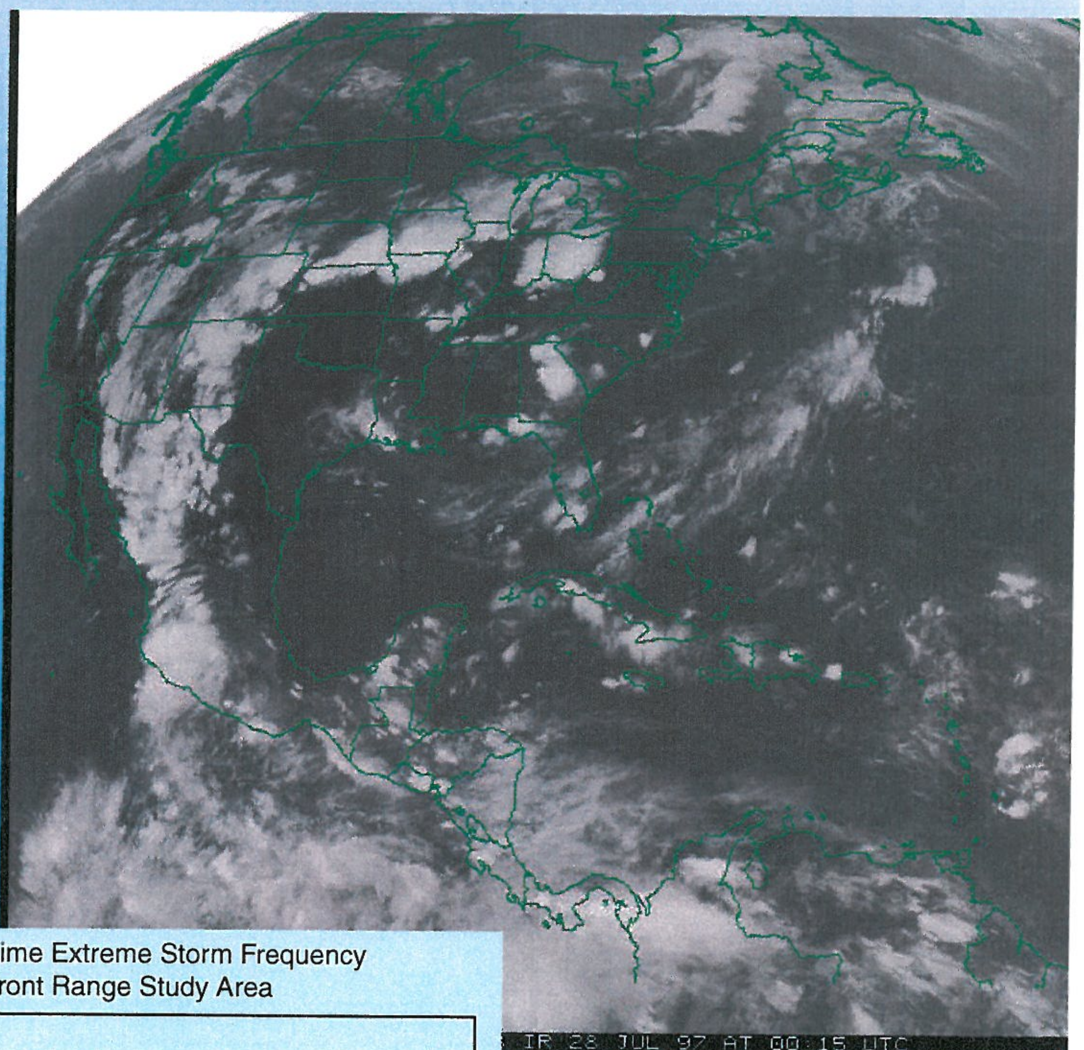

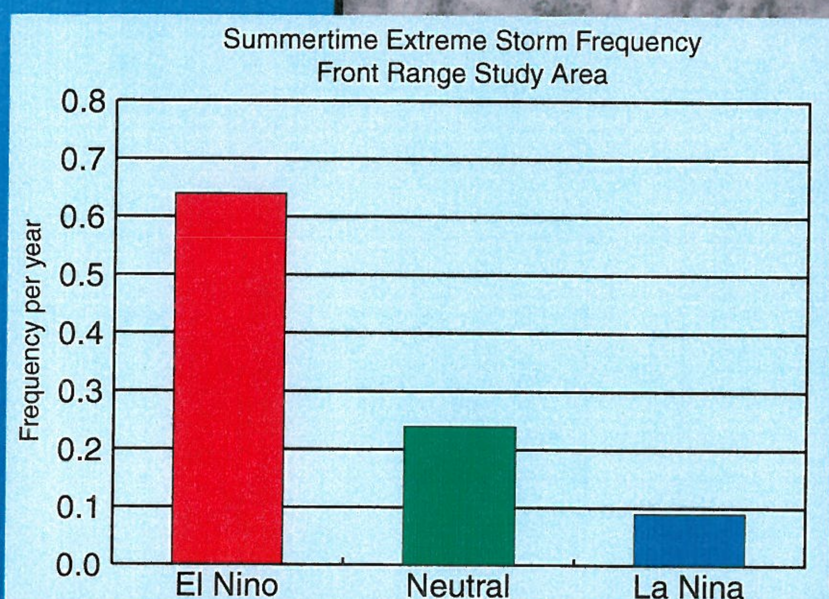

Technical Report: 2000-02
September 2000

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Front Range Severe Flash Flooding and El-Niño

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FOREWORD

In July 1997, I was in Aspen, CO, when Fort Collins got hit by its flood. I saw on the Weather Channel a river of upper troposphere moisture streaming from the Pacific Ocean south of Acapulco, Mexico. When I returned to FSU, I asked my staff to find out the relationship of ENSO with Front Range floods. I was delighted to discover that ALL of the Front Range floods occurred in El Niño pre-summer or the summer before the usual El Niño winter (such as 1982-83).

This is a Master's thesis of Mr. Kreitner. He discovered the work of Tom McKee which observes how heavy Colorado rain storms are more likely during El Niño periods, and much suppressed during La Niña periods.

The statistics in this report are very important. Forecasters of severe rainstorms and Front Range floods should be more alert in pre-summer El Niño events.

Dr. Jim O'Brien
Director, COAPS
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ABSTRACT

We develop a major breakthrough in the ability to forecast flash floods in the Colorado Front Range. Three major flash flood events are compared by examining the similarities of the rain events that produced them and their link to the El-Niño/Southern Oscillation (ENSO). Two of these events occurred in Colorado's Front Range while the other occurred in the Black Hills of South Dakota. All three occurred during the onset summer of an ENSO warm phase. A comparison of the origin of their mid-tropospheric level moisture supply is done using NCEP reanalysis data and satellite imagery. This comparison reveals the major source of moisture to be the ENSO-warmed waters of the eastern Pacific. Climatological data show a significant increase in flash flood frequency during the onset summer of an ENSO warm phase over the past decade. Similarly, a study of extreme storms of the type that are capable of producing flash floods shows a much greater frequency of occurrence during ENSO warm phases. Since El-Niño can be forecast with accuracy, considerable advance warning of potential flash floods is possible if one combines knowledge of the ENSO phase with the synoptic signatures outlined in this study.

1. INTRODUCTION

Flash floods are defined as floods that occur quite rapidly and usually are the result of intense rainfall over a relatively small area (Huschke 1959). They are responsible for more deaths nationally than any other weather phenomena (Davis 1997). What separates a flash flood from a regular flood is the sudden onset and rapid water rise, turning a relatively harmless-looking stream into a raging torrent in a matter of minutes. The sudden, unexpected appearance of a flash flood usually occurs within 6 hours of a rain event and is characterized by a high peak discharge. This is the key to its destructive and often terrifying nature. Victims often speak of the flash flood's awesome power. They describe a seemingly unstoppable wall of water that sweeps away everything in its path: rocks, trees, cars, buildings, bridges and people. Any insight into the processes that produce flash floods would thus be of value to the Nation, especially if a forecast based on this insight leads to better preparedness for the protection of lives and property.

The authors note that other causes of flash floods exist that may not directly involve intense rainfall as defined above, such as ice jam breaks or dam failures. In addition, there are several factors which influence the production and severity of a flash flood. Certain types of terrain, such as narrow, steep canyons, are more prone to flash flooding due to their drainage characteristics. Deep snow cover, when subjected to heavy rain, may melt quickly and cause flash flooding which otherwise would not have occurred. The state of the ground's moisture content and preexisting water levels in rivers and streams will also have an important bearing on flash flood severity. High levels of soil moisture and high water levels in streams can be a precursor to severe flash flooding. Similarly, frozen ground, which cannot absorb water as fast as unfrozen soil, can increase the chances of flash flooding. However, the most important and influential factor is a period of intense, localized rainfall. This study will focus on these periods of intense rainfall and the conditions of their formation.

Three of the worst flash floods in the past 30 years in terms of lives lost and property damaged, the Fort Collins (FC) flood of 28 July 1997, the Big Thompson

Canyon (BTC) flood of 31 July 1976, and the Rapid City (RC) flood of 9 June 1972 share common features that have been well documented in various case studies (Bresch 1997; Caracena et al. 1979; Doesken and McKee 1998; Maddox et al. 1978, 1980; Petersen et al. 1999). What has not been investigated until now is the possible link between these floods and the El-Niño - Southern Oscillation (ENSO). These three floods all occurred during the summer prior to the peak of an ENSO warm phase (known as the onset summer of a warm phase), and this study investigates a potential relationship between these floods and the warm phase of ENSO. We identify the large-scale atmospheric phenomena common to these three events. We postulate that anomalously high levels of mid-level moisture, identified by Caracena et al. (1979) as key in increasing precipitation efficiencies in the BTC and RC floods, are more prevalent over the Front Range of the Colorado Rockies and the Black Hills of South Dakota, during the onset summer months of an ENSO warm phase and that this mid-level moisture is of tropical origin.

While this study focuses on the three cases noted above, a review of flash flood frequency over the study areas (Section 3.4, 3.5) reveals that flash flooding in general is much more common during onset summers of an ENSO event, with secondary peaks of occurrence during subsequent summers. Severe flash flooding is almost entirely absent during summertime cold phases of ENSO. Additional supporting evidence is found in the form of a recent climatological study conducted by Colorado State University's Department of Atmospheric Science (McKee and Doesken 1997). Inspection of data contained within the report supports the conclusion that severe precipitation events of the type most likely to produce flash flooding are much more common during the onset summers of ENSO warm phases. These findings are in line with our hypothesis and will be further explored. Data from the National Center for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) Reanalysis Project (hereafter NCEPR, Section 2) will be used to establish a link between ENSO and the increased supply of moisture.

The main goal of this study is to show that the ENSO warmed waters of the eastern Pacific work in tandem with the North American Monsoon (NAM) to provide a source of the mid-tropospheric moisture that increased the precipitation efficiency of the FC, BTC, and RC storms. The secondary goal is to show that extreme precipitation and flash flooding are more common during the onset summer of an ENSO warm phase. Data sources are described in Section 2. Section 3 presents essential background information, including data on flash flood and severe storm frequency and the relationship between ENSO and the NAM. The three flood events are examined and compared in Section 4. Analyses derived from NCEPR data and the findings of other synoptic studies are used to illustrate the link between ENSO, the NAM and the increased levels of mid-tropospheric moisture found over our study areas. Section 5 contains a discussion of auxiliary results including the discovery of reduced flash flood and severe storm frequency during cold phase ENSO events. Conclusions and guidelines for forecasters are presented in Section 6.

2. DATA SOURCES

The NCEPR (Kalnay et al. 1996) is primary data source used to deduce the wind fields and the origin of the mid-tropospheric moisture. The first run of the NCEPR resulted in global analyses of atmospheric fields from 1957 to 1997. A wide variety of data were used to construct the NCEPR: land and ship surface reports, rawinsonde, satellite, aircraft, pibal and other available data. These data were quality controlled and assimilated using a scheme was frozen over the reanalysis period so as to eliminate perceived climactic shifts that accompany changes in data assimilation systems.

Gridded fields from the NCEPR used for this study include the pressure level data for specific humidity and winds. These variables are instantaneous values output every 6 hours at the reference times of 00Z, 06Z, 12Z and 18Z. Spatial coverage is a global 2.5° latitude by 2.5° longitude grid with no missing data. Six pressure levels were initially used in this study, the 850, 700, 600, 500, 400 and 300 hPa levels; however, we focus on levels from 600 through 300 hPa. These mid-tropospheric levels proved most useful in illustrating the apparent middle level moisture link between the Front Range of the Colorado Rockies and the El-Niño warmed waters of the eastern Pacific.

Flash flood occurrence data are taken primarily from *Storm Data*, the monthly publication of the National Oceanic and Atmospheric Administration (NOAA) which contains the only comprehensive national summary of severe weather events. *Storm Data*, compiled by the National Weather Service, summarizes severe weather events in all 50 states. The data are listed alphabetically by state and county and show the character of the event, the date, time, estimated property and crop damage, and the number of people injured or killed (if any). The observations include thunderstorms, high winds, floods and flash floods, tornadoes, hail, hurricanes, heavy precipitation, and other extreme weather phenomena. Although not all inclusive, *Storm Data* is the most comprehensive source available for the United States. While the period of record covers from 1959 through the present, only data from 1989 to present (NOAA 1989-1998) are used to examine flash flood events. Prior to 1989, flash floods are not typically listed as a separate category, but may be mentioned or inferred within the descriptions of other listed events, such as "heavy precipitation" or "severe thunderstorms". Sorting these earlier flash floods out of the data is beyond the scope of this study.

Data regarding the most extreme storms to affect Colorado and the surrounding areas are extracted from the Colorado Extreme Storm Precipitation Data Study (McKee and Doesken 1997). This study identified over 300 of the heaviest storms in Colorado (and some similar storms in surrounding areas) since May of 1864 in terms of precipitation duration and intensity. The identified storms all produced very heavy precipitation either over localized or wide-ranging regions of Colorado and surrounding areas, and many of them produced flash floods. The purpose of the study was to better understand extreme precipitation as a function of location and elevation and focused on observational precipitation and streamflow data during the period of instrumental records. The heaviest storms that have occurred in or near the Rocky Mountains of Colorado are documented. The criterion used for a storm to be listed is that a storm must exceed the 100-year storm precipitation amounts for specified storm durations (Miller et al. 1973).

3. ENSO BACKGROUND AND RESULTS FROM PRIOR STUDIES

The focus of our analysis of flash floods is the Front Range of the Rockies and the Black Hills of South Dakota. Prior to the case study discussion of these events, we first define the geographic regions of interest for our flash flood studies. As the phase of ENSO is key to our discussion, we will follow with our ENSO definitions. An overview of the NAM and its variation with the phases of ENSO is then presented. The NAM is hypothesized to be the transport mechanism for mid-level moisture from the tropics into the intermountain west. The background concludes with results extracted from *Storm Data* (NOAA 1989-1998) and the Colorado Extreme Storm Precipitation study (McKee and Doesken 1997).

3.1 Selecting the study areas

The boundaries of the study areas are selected to encompass the locations of the FC, BTC, and RC flash flood events. We considered the role that elevated terrain played in triggering and maintaining the convection that produced these flash flood events. The Black Hills study area is defined as the area centered on and to the east of the Black Hills of South Dakota. This region is topographically and geologically distinct from the surrounding terrain. The Front Range, a region east of the continental divide, rising westward up from the Great Plains, is a region that historically experiences extreme storms of a magnitude beyond that which is found elsewhere in Colorado (McKee and Doesken 1997). As with the Black Hills, topographic effects also play a critical role in this regions floods. Our Front Range study area includes only the northern portion of the Colorado Front Range (fig. 1) because our focus is on the BTC and FC floods.

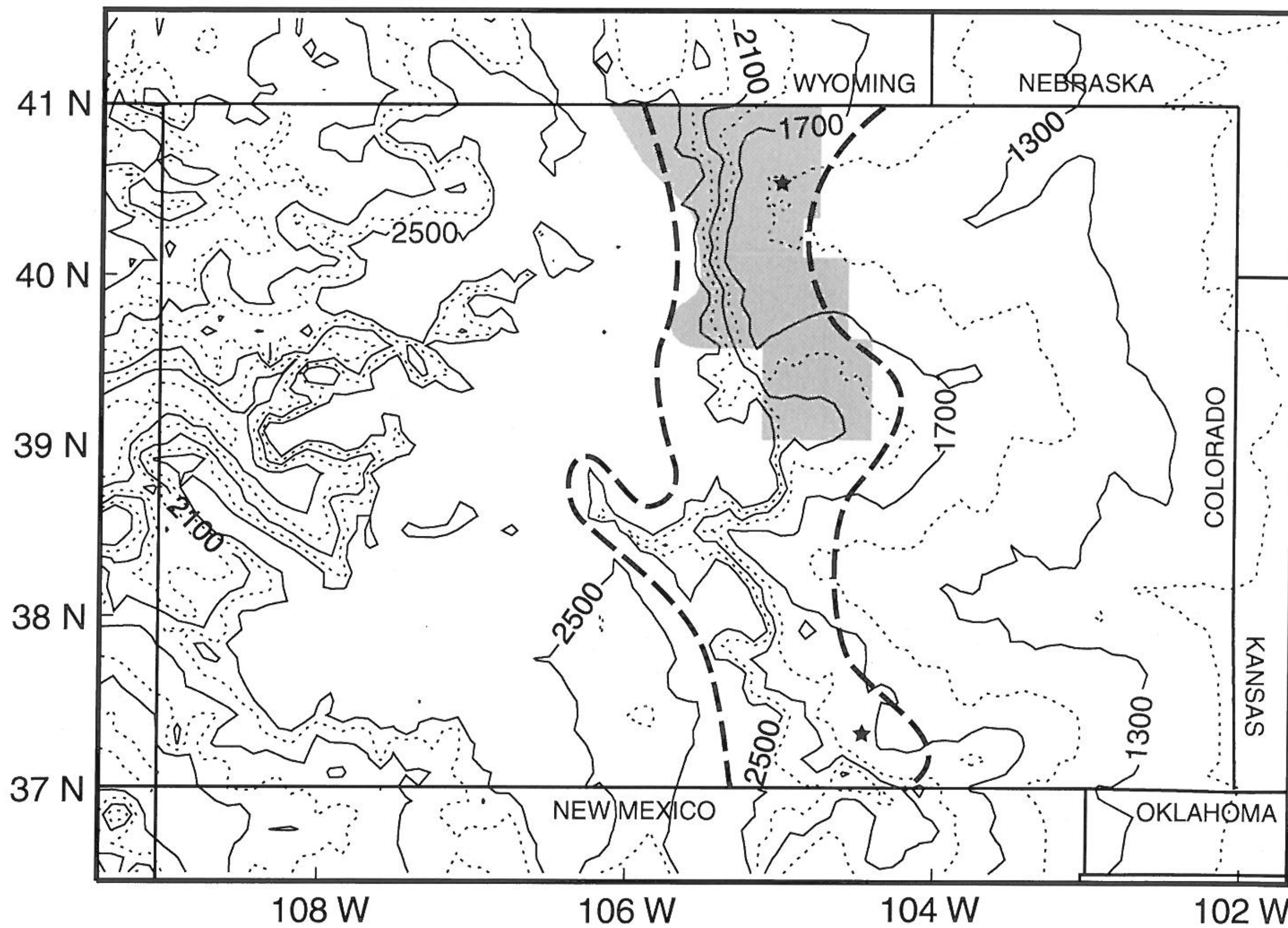

Figure 1: Topographic map of Colorado identifying the location of our Front Range study area (shaded). The region between the heavy dashed lines is defined by McKee and Doesken (1997) as Area2. The approximate locations of Fort Collins and Trinidad, CO are marked with the northern and southern stars, respectively. Topographic contours are spaced every 200 m with alternating solid and dotted lines.

3.2 The El-Niño/Southern Oscillation

ENSO is an interannual climate fluctuation, both anomalous in its meteorological and oceanographic characteristics, that affects the tropical Pacific Ocean. The warm phase of ENSO, also known as El Niño, is characterized by anomalous warming of the waters of the eastern Pacific, weakening of the trades and enhanced equatorial convection. The cold phase of ENSO, also known as La Niña or El Viejo, is characterized by anomalous cooling of the waters of the eastern equatorial Pacific. The lower sea surface temperatures (SST) reduce equatorial convection and strengthen the trades. The neutral phase of an ENSO event occurs when neither the warm or cold phases dominate. Of primary interest to this study is the enhanced equatorial convection that occurs over the ENSO warmed waters of the eastern Pacific during El Niño. Trenberth and Guillemot (1996) note that the reversed Pacific SST anomalies characteristic of an ENSO event are responsible for major shifts in convection in the Intertropical Convergence Zone. A recent study by S. Murillo (1998, personal communication) shows that the enhanced equatorial convection of a warm phase significantly increases the number of landfalling hurricanes north of 25°North for the eastern Pacific (fig. 2). These storms are a significant source of excess moisture available for northward transport by the NAM and can trigger widespread flooding over western Mexico and the American Southwest.

Several methods of defining an ENSO event exist (Trenberth 1997). These are usually based on mean pressure anomalies or sea surface temperature anomalies (SSTA) over the Pacific Ocean. This study uses an index based on SSTA as developed by the Japanese Meteorological Agency (JMA). The JMA SSTA is presented from 1970 through 1998 in Fig. 3. When the JMA SSTA are 0.5°C or greater for 6 consecutive months, that year (ENSO years are defined to run from October through September of the following year) is categorized as a warm phase or El-Niño. A cold phase is defined when the JMA SSTA are -0.5°C or less for 6 consecutive months. All other ENSO years are categorized as neutral. This study is focuses on the summers preceding an ENSO warm phase. The warm phase onset summer season is defined as the months of June, July and August prior to the start of a defined ENSO warm phase year. For the period 1970 through 1998, there have been 4 cold, 7 warm, and 16 neutral ENSO phases.

There is some debate in the community as to which index should be used to identify ENSO warm phases (the focus of this study). A comparison of warm phase years selected using the JMA SST to those selected by Kiladis and Diaz (1989) and Shabbar et al. (1997) reveal no differences for the period 1970 to present. Kiladis and Diaz (1989) defined warm phase years using a combination of a Southern Oscillation Index (SOI) and equatorial sea temperatures. Shabbar et al. (1997) used the SOI to define only moderate and strong warm phases. The authors wish to note that no single index of ENSO warm phases is definitive and that these indices are continually undergoing refinement (Trenberth 1997). The authors have successfully used the JMA index in other published ENSO studies and believe it is a reliable indicator of the phase of ENSO.

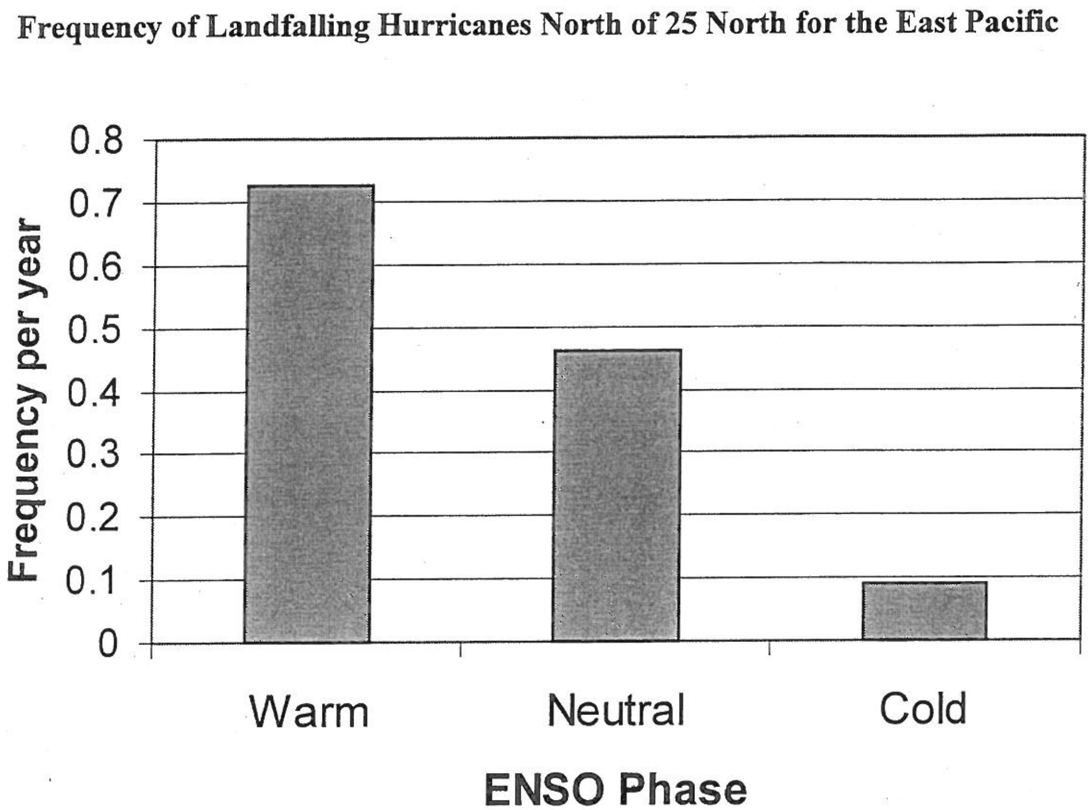

Figure 2: Mean number of landfalling tropical storms/hurricanes north of 25°North for the eastern Pacific. Only landfalling storms are used because they are not biased with time. Tropical systems are over seven times more likely to make landfall along the Mexican coastline during a warm phase ENSO event as during a cold phase. This reflects the greatly increased convective activity during a warm phase as compared to other phases.

JMA Sea Surface Temperature Anomalies (SSTA) Index

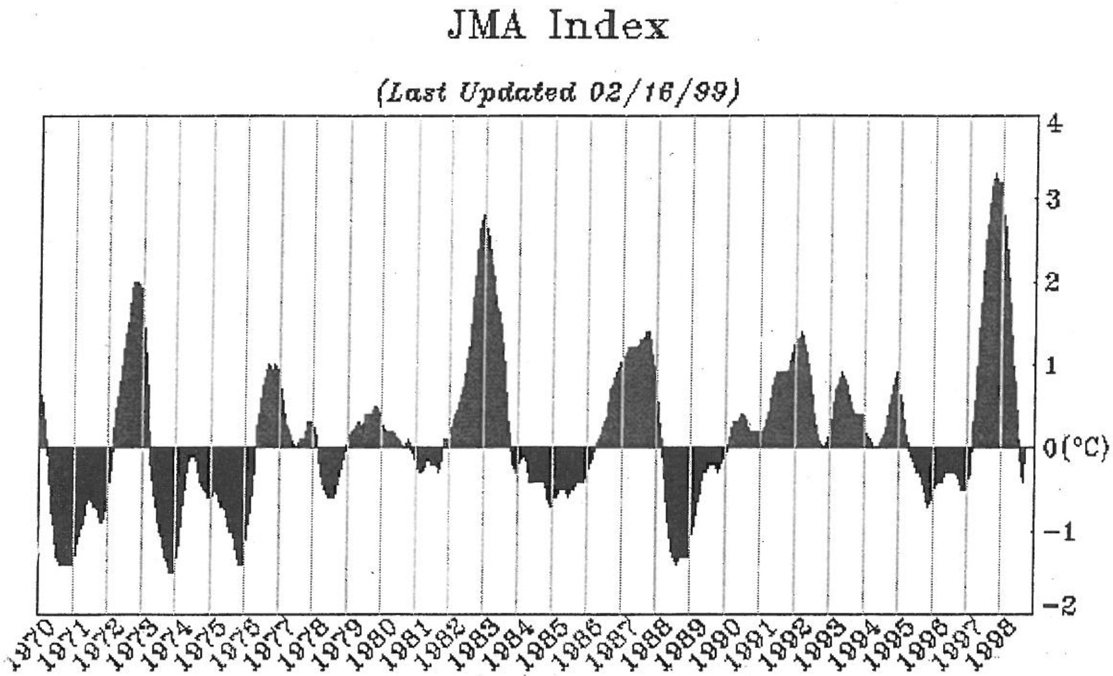

Figure 3: Japan Meteorological Agency (JMA) sea surface temperature anomaly index used to identify the three phases of ENSO for the period 1970-1998. The index is a 5 month running mean of spatially averaged SST anomalies for a section of the tropical Pacific with the following boundaries: 4°South to 4°North and 150°West to 90°West. Based upon the JMA criteria (see text), ENSO warm phases occurred in 1972, 1976, 1982, 1986, 1987, 1991, and 1997. ENSO cold phases for the same period occurred in 1971, 1973, 1975, and 1988.

3.3 ENSO and the North American Monsoon (NAM)

The relationship between ENSO warm phases and the enhancement of equatorial convection over the eastern Pacific has been known for many years (e.g., Philander 1990). In addition, Adams (1998) showed that the NAM regime extends northward into Arizona, New Mexico and Colorado. What is not conclusive from the literature is the existence of an ENSO-related change to the NAM flow regime, especially over our area of interest. For our hypotheses to be valid, the anomalously warm pool of water over the eastern Pacific must supply the NAM with additional mid-tropospheric moisture through increased convective activity. This extra moisture must then eventually be advected to the Colorado Front Range and Black Hills of South Dakota to increase the precipitation efficiencies of the storms that produced the studied flash floods.

Adams and Comrie (1997) conclude that while the interannual variability of the NAM is high, it is not strongly linked to warm phase ENSO events. They also conclude that the bulk of the monsoonal moisture is advected in at low levels from the eastern tropical Pacific, with the Gulf of Mexico possibly contributing upper level moisture which mixes over the Sierra Madre Occidental. Higgins et al. (1997) evaluated the influence of the NAM on the United States summer precipitation regime and were more positive on the Gulf of Mexico moisture link. This study found that most of the moisture below 850 hPa over the desert Southwest comes from the northern Gulf of California, while most of the moisture at and above 850 hPa comes from the Gulf of Mexico. Andrade and Sellers (1988) provide an ENSO/NAM relationship over Arizona and New Mexico by linking the presence of unusually warm water off the California coast and west coast of Mexico to enhanced precipitation over the Southwest. The warm water provides the necessary energy for the development of strong west coastal troughs, weakens the trade wind inversion, and allows monsoonal moisture to penetrate in larger quantities than normal into the Southwest. When prevailing flow aloft is from the southwest, moisture from these storms is advected into the Southwest, resulting in increased precipitation. Ropelewski and Halpert (1986) provide additional evidence for above normal precipitation in New Mexico from October of an ENSO year until March of the following year and also in the Great Basin of the western United

States from April to October of an ENSO year. Their results also suggest an ENSO/NAM link for these regions; however, Harrington et al. (1992) were contradictory, finding no ENSO/NAM link for Arizona and New Mexico. Clearly no consensus on an ENSO/NAM relationship has been reached in the scientific community.

A relationship between ENSO phases and general precipitation over our study areas has not been found to date. Looking much further back in time, a 5000 year paleoflood chronology (Ely et al. 1993) of Arizona and southern Utah revealed that the largest floods in the region coincide with periods of cool-moist climate and frequent El Niño events and that the major factors of our present global atmospheric circulation were in place by 5000 years ago. This hints that ENSO and the NAM have been working in tandem for thousands of years to produce flooding, at least in the American southwest.

There are a couple of broad-scale studies which include or border on the Front Range and Black Hills that concern ENSO-related precipitation anomalies. Bunkers et al. (1996) studied ENSO-related precipitation and temperature anomalies across the northern Plains (North and South Dakota and portions of adjacent states and provinces, which include the Black Hills study area) and found a mean increase in precipitation for warm events between April and October. In addition, Ropelewski and Halpert (1986) found above normal warm phase precipitation in the High Plains region (the Front Range and Black Hills study areas are on the fringes of the High Plains) while studying North American precipitation and temperature patterns associated with ENSO; however, they found this response to be inconsistent from event to event.

The contradictory nature of these NAM/ENSO studies may be, in part, due to the use of various definitions for ENSO events. What one author may consider a warm event ENSO year, another may define as a neutral period. There is only broad agreement amongst these studies when particularly strong warm or cold events are considered. It would be interesting to see if there would be more consistency in the results if a single definition of ENSO were used. Another problem could be with the evaluated parameters. Our study looks at mid-level moisture, while most past research considers precipitation changes locally in the Southwest. Hypothetically, tropical Pacific moisture from anomalous ENSO warm phase convection may simply be flowing overhead and not impacting precipitation until it reaches the Front Range.

3.4 Flash flood frequency over the past decade

While we focus on the FC, BTC, and RC floods, if ENSO phases do effect the prevalence of mid-level moisture over the study areas as our hypothesis suggests, then flash flooding in general should be more prevalent over our study areas during the onset summer of a warm phase ENSO event. To confirm an increase in flash floods associated with ENSO warm phases, a review of flash flood frequency data for the Front Range study area from 1989-1998 is completed using *Storm Data* (NOAA 1989-1998). The analysis (fig. 4) reveals that flash flooding is much more common during onset summers of an ENSO event (1991 and 1997), with secondary peaks during the following summers (1992 and 1998). The authors wish to note that two warm phases in too small a sample to establish any statistical confidence, but the results are striking. Flash flooding over the Black Hills study area is relatively uncommon in all years (no more than 2 occurred during any summer during the past decade), so a similar comparison is not possible.

Summertime (June/July/August) Flash Flood Occurrences

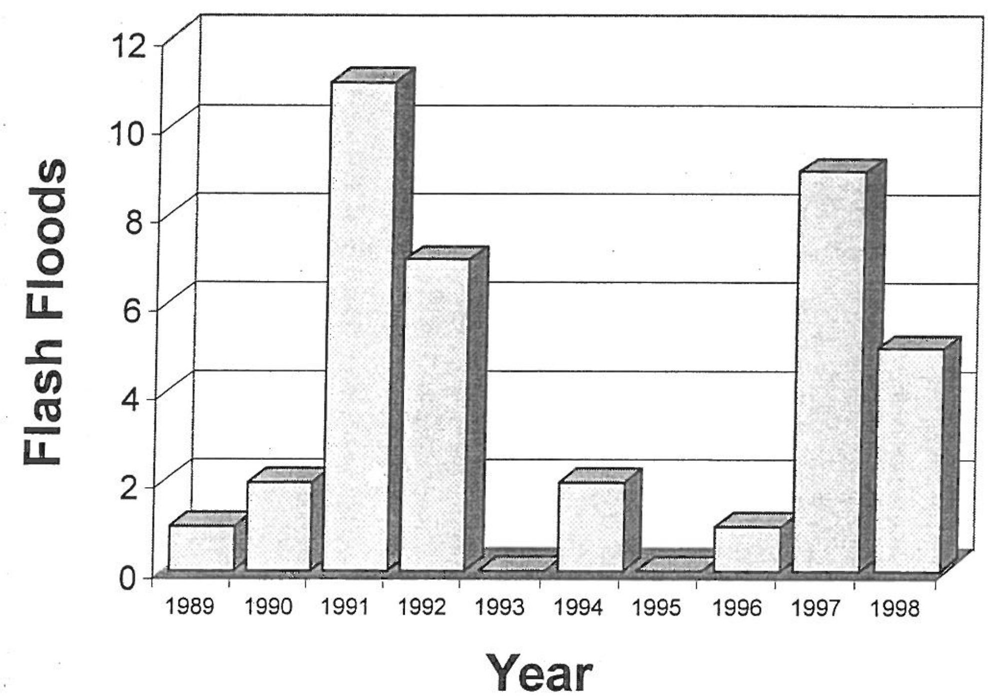

Figure 4: Comparison of summertime (June/July/August) flash flood occurrences for the Front Range study area from 1989 through 1998, as reported by the NOAA publication *Storm Data*. When multiple flash floods occurred at the same time in a localized area due to the same storm, these floods were judged to be part of one convective system and counted together as one flash flood. If these events were counted separately, the totals, especially for the summer of 1991, would be significantly higher. Onset summers of ENSO warm phases were in 1991 and 1997.

3.5 Extreme storm precipitation frequency

Additional evidence that flash flooding over the Front Range is more frequent during onset summers of an ENSO warm phase can be found in McKee and Doesken (1997). Inspection of their data reveals that severe precipitation events of the type that may to produce flash flooding are nearly three times more likely during the onset summers of ENSO warm phases than during neutral ENSO summers over our Front Range study area (fig. 5). Although not all of the storms listed in McKee and Doesken (1997) produced flash floods, they are all of the magnitude that reasonably could, given the proper location over the right watershed. The critical properties of all storms that determine their potential for flooding are precipitation intensity, storm duration and storm area. We will not connect the storms on McKee and Doesken's list directly to specific flash floods; however, the inherent flash flooding potential shared by these storms and the long period of record of the study make it instructive to look at the storms' statistical distribution in relation to ENSO phases.

A statistical analysis using a method outlined by Bove (2000) was done to determine the significance of the distribution of these extreme precipitation events. The analysis shows that the difference in frequency between the warm phase and neutral phase events are significant at above the 95% level. This indicates a high level of confidence that the Front Range study area will experience an increased frequency of extreme storms during onset summers of ENSO warm phases.

Additional findings from McKee and Doesken (1997) that are most germane to our study of flash flood events include:

- The heaviest precipitation amounts and the largest number of extreme storms observed in Colorado have occurred along the Front Range from northwest of Fort Collins southward to Trinidad (fig. 1).
- Of the subset of 11 storms that produced more than 10 inches of rainfall, no storms of this magnitude appear in the observed data in the high mountains or over western Colorado. The greatest propensity for such storms is along the eastern base of the Rocky Mountain foothills.
- Areas east of the continental divide at a given elevation are more likely to receive high-intensity rainfall than areas west of the divide due to a more

abundant and reliable source of moisture from the Gulf of Mexico and the humid Plains states.

McKee and Doesken (1997) broke up Colorado into six regions to describe and characterize extreme precipitation events. Of these, Area 2, which includes the Front Range and Eastern Foothills, encompasses virtually all of our Front Range study area (fig. 1). This region is also much more extensive than our study area, extending south to the New Mexico border and further eastward towards the Great Plains. This area is examined for storm frequency in addition to our Front Range study area in order to include a larger sample of storms for comparison to ENSO phases. Summertime extreme storm frequency for Area 2 (fig. 6) shows a similarly significant, although not as striking, pattern as the Front Range study area. Summertime extreme storms for Area 2 are shown to be about twice as likely during a warm ENSO phase as during a cold or neutral phase. A statistical analysis of these events was performed as above for the Front Range study area and reveals that Area 2 experiences a significant (95% level) increase in extreme storm activity during ENSO warm phases.

Evaluating only the seven storms that produced over 10 inches of rainfall (fig. 7) over Area 2, we again find the highest frequency during onset summers of ENSO warm phases. Based on their limited occurrences, there are not enough storms in this sample to perform the statistical analysis as above. Overall the data from McKee and Doesken (1997) suggests a strong relationship between the frequency of the type of storm that could produce a flash flood, the Colorado Front Range, and ENSO phases; however, these data do not directly reveal a synoptic mechanism responsible for the relationship.

Summertime Extreme Storm Frequency for the Colorado Front Range Study Area

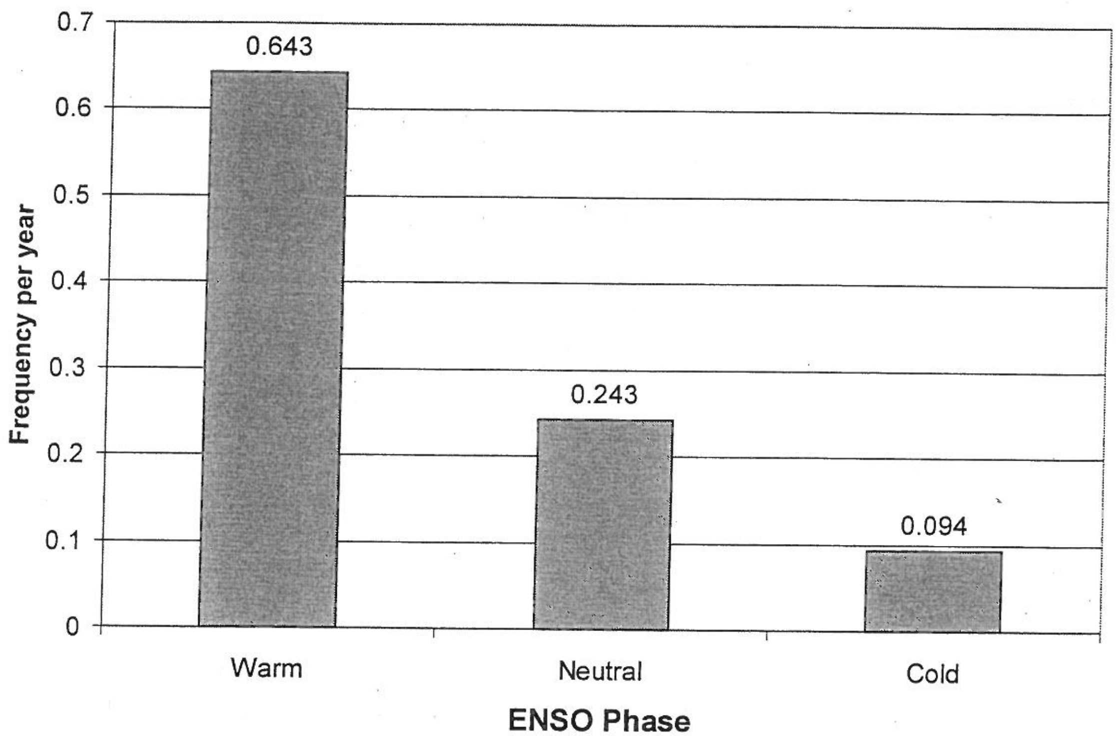

Figure 5: Summertime (June/July/August) extreme storm frequency for the Colorado Front Range study area from 1868-1997. Extreme storms of the type as defined by the Colorado Extreme Storm Study are almost seven times more likely to occur during the warm phase of an ENSO event as compared to a cold phase, and two and a half times as likely to happen when compared to a neutral phase. These storms form a subset of 38 of the study's 328 storms (the FC storm in 1997, not included in the Extreme Storm Study, is included in the tabulation above).

Summertime Extreme Storm Frequency for the Region Defined as "Area 2"

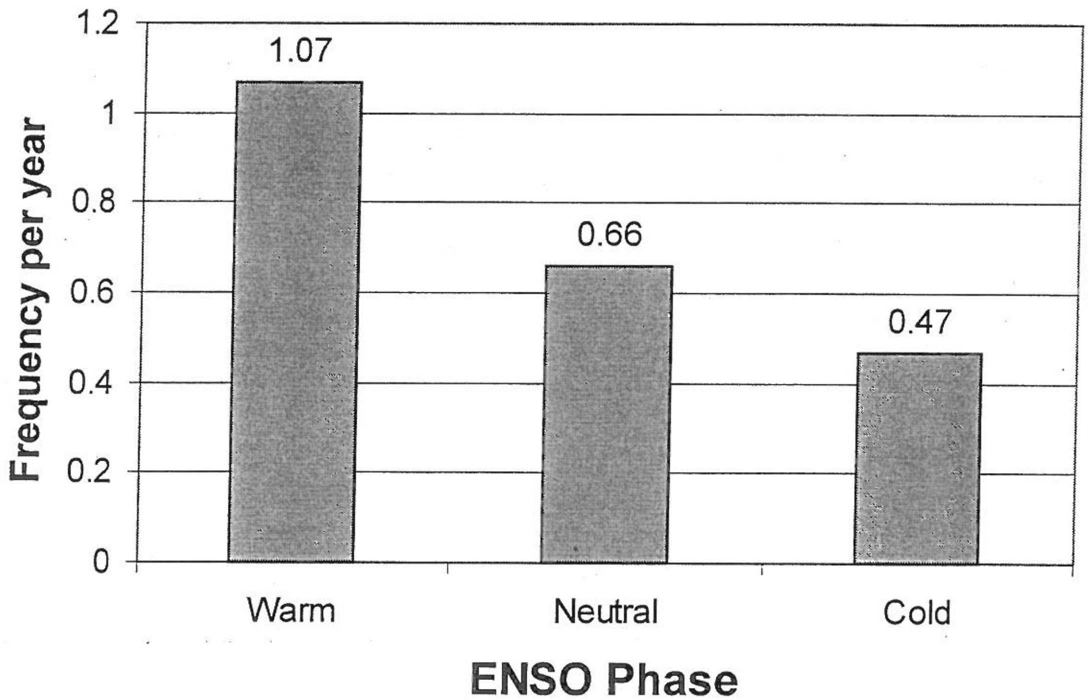

Figure 6: Summertime (June/July/August) extreme storm frequency for the region defined as "Area 2" in McKee and Doesken (1997) for 1868-1997. Extreme storms are about twice as likely to occur during a warm event as during a cold or neutral event. A total of 91 storms were included in this sample, including the FC storm.

Summertime Extreme Storm Frequency: Storms that Deposited at Least 10 inches

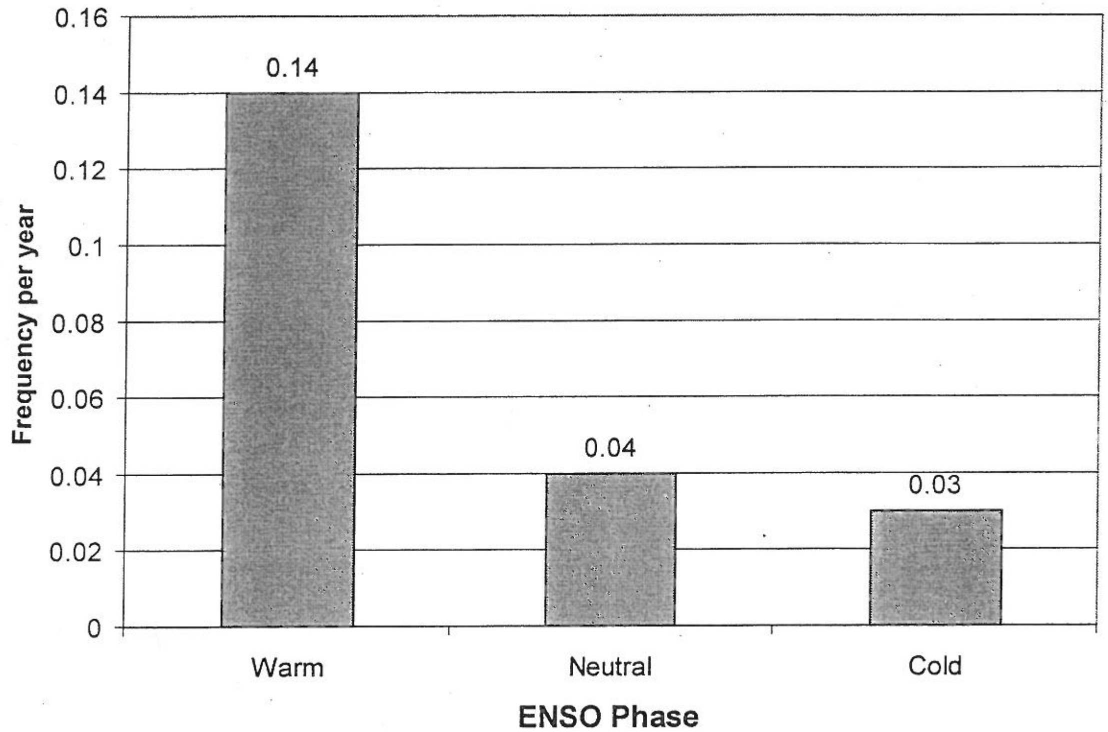

Figure 7: Summertime (June/July/August) extreme storm frequency for Area 2 covering the period from 1868-1997 for storms that deposited at least 10 inches of rain. Only 12 of these were recorded for Colorado during this period. Of these, 7 occurred over area 2. Four occurred during a warm phase, two during a neutral phase and only one during a cold phase. These most devastating of storms are over 4 times more likely to occur during a warm phase as during a cold or neutral phase.

4. CASE STUDIES

The three flash flood events are individually examined and compared. It is shown that the FC, BTC and RC floods share similar synoptic characteristics as well as timing in relation to ENSO phases. In summary, all are supplied with ample low-level moisture advected by easterly winds up sloping terrain, the Front Range of the Colorado Rockies for the FC and BTC floods and the Black Hills of South Dakota for the RC flood. All are characterized by a deep layer (up to 500 hPa) of very moist air. Tropospheric winds are light for all three cases, and they all share a similar large-scale synoptic environment with a westward tilting ridge centered near Mississippi and a long wave trough over the west coast. All are also strongly influenced, if not dependent upon, the surrounding topographic environment.

4.1 The Fort Collins flood

The FC flood, which occurred on the evening of 28 July 1997, is the best documented of the three floods. Petersen et al. (1999) provides a detailed study involving extensive mesoscale observations which include satellite, radar, rain gauge and lightning observations and detailed synoptic analysis. Five people died and over 200 million dollars worth of damage was caused by this flood, which destroyed a trailer park and extensively damaged the campus of Colorado State University. The FC flood is characterized by an extended period of heavy showers that lasted nearly 24 hours and culminated in a torrential rain event that resulted in the devastating flooding. Maximum precipitation values above 12 inches in 7 hours were recorded along the western edge of the city.

The upper level synoptic conditions of the FC flood are similar to that of the BTC and RC floods, with the key similarity, as we shall see, being the availability of mid-tropospheric moisture of tropical origin as transported by the NAM. A long wave trough at 500 hPa along the west coast and a negatively tilted ridge over the Great Plains permits a large amount of monsoonal moisture at mid-levels to advect northward over the Rockies. This moisture plume is clearly visible over Mexico and the western U. S. on infrared satellite imagery (fig. 8). Specific humidity and wind fields from the NCEPR (figs. 9-11) also show a plume of mid-level moisture with a source over the ENSO-warmed waters of the eastern Pacific. The moisture plume from Mexico northward to Colorado is clear at all levels from 300 hPa (fig. 9) down to 700 hPa (not shown), with southerly winds from the tropics occurring over northern Mexico into Colorado at the 300, 400, and 500 hPa levels. This large supply of moisture available through a deep layer combines with relatively weak wind shear to result in a deep layer of warm rain processes over FC. The resulting convective cells exhibited warm-rain characteristics (Caracena et al. 1979), including relatively little lightning, no hail, warm cloud top temperatures and, most importantly, efficient precipitation growth, which are atypical for the Front Range. The increased mid-level moisture reduces the entrainment of dry air and suppresses the convective downdrafts, thereby leading to the increased precipitation efficiencies, which are characteristic of tropical thunderstorms. The monsoonal flow prompts high precipitation efficiencies because entrainment of moist air is much less debilitating to convection than is entrainment of dry air. This is key to the development, severity and longevity of the FC storm. High boundary layer humidity also contributes to the high rain efficiency because evaporation was mitigated by the low cloud base and by air of high relative humidity through which the rain falls. Multi-parameter radar data presented by Petersen et al. (1997) also suggests that the FC storm exhibited tropical characteristics .

According to Maddox et al. (1978), surface features on 27 July included high dewpoints over eastern Colorado, relatively light winds, and indications of a convergence line to the south of Fort Collins. As with the other floods, a key triggering mechanism is the terrain, which induces orographic lifting as the low level moisture is advected up the easterly facing slopes of the Front Range. The terrain plays a very important role in the anchoring and maintaining of the storm, as noted by Doesken and McKee (1998). Surface easterly flow is the primary precondition for the FC storm; the only apparent surface trigger is the foothills. It has been noted (U.S. Geological Survey 1998) that flash flood events are often the result of convective precipitation that has been orographically enhanced and that terrain sometimes has an anchoring effect on a developing storm. Terrain can cause storms to remain relatively stationary, while one cell after another is generated in approximately the same location. Precipitation from this type of storm can be excessive. When terrain anchoring is further combined with warm rain processes, results can be catastrophic.

In an experiment (Bresch 1997) conducted to test numerical forecasts of the FC flood, backwards air-parcel trajectories were constructed based on MM5 model output in order to determine air mass source regions. These trajectories showed that at the higher levels, 500 hPa and above, air parcels originated to the south or south-southwest of Fort Collins in the light monsoon flow (see fig. 4 in Bresch 1997). Air parcels at lower levels originated to the east of Fort Collins in the moist upslope flow. An additional experiment to determine what role the monsoon played in the development of the FC storm and others like it concluded that monsoon moisture is a "necessary ingredient" by acting to reduce entrainment and increase efficiencies. We conclude that the ENSO warm pool of the eastern Pacific is the upper-air moisture source in the FC case.

GOES Infrared Image at Time of Fort Collins Flood
28 July 1997

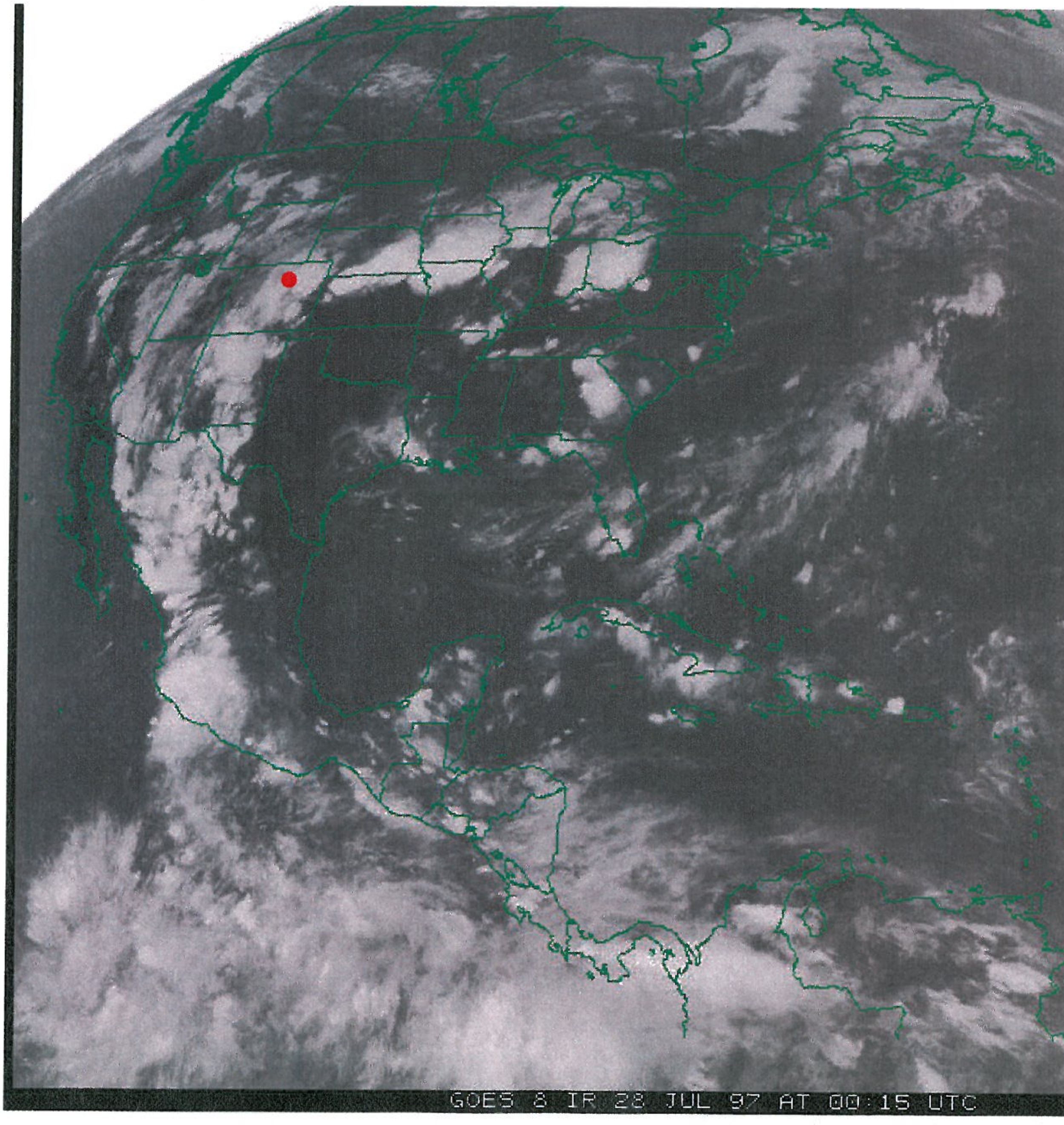

Figure 8: GOES 8 infrared image for 28 July 1997 at 00:15 UTC, at about the time of the Fort Collins flooding. Moisture is transported northward by the NAM from the El Niño warmed waters of the eastern Pacific, along the spine of the Rockies, to the flood area.

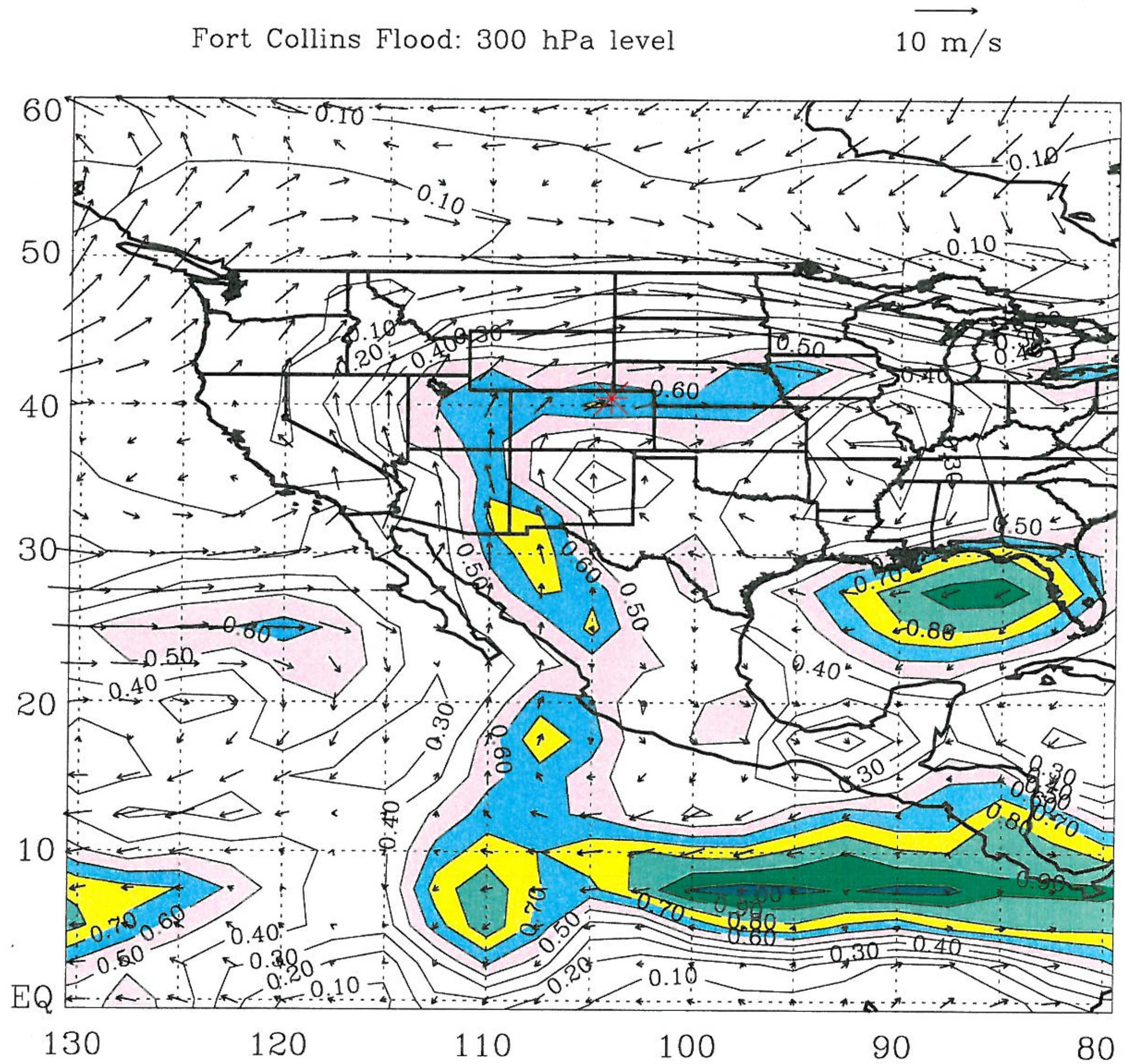

Figure 9: 300 hPa specific humidity (g kg-1) and vector winds (m s-1) at 12:00 UTC on 28 July 1997. The path of the moisture can be traced from its source region over the tropical eastern Pacific, north along the Rockies. Fort Collins is indicated by a red star. Specific humidity contours are spaced every 0.1 gkg-1 with values greater than 0.5 gkg-1 color shaded for clarity.

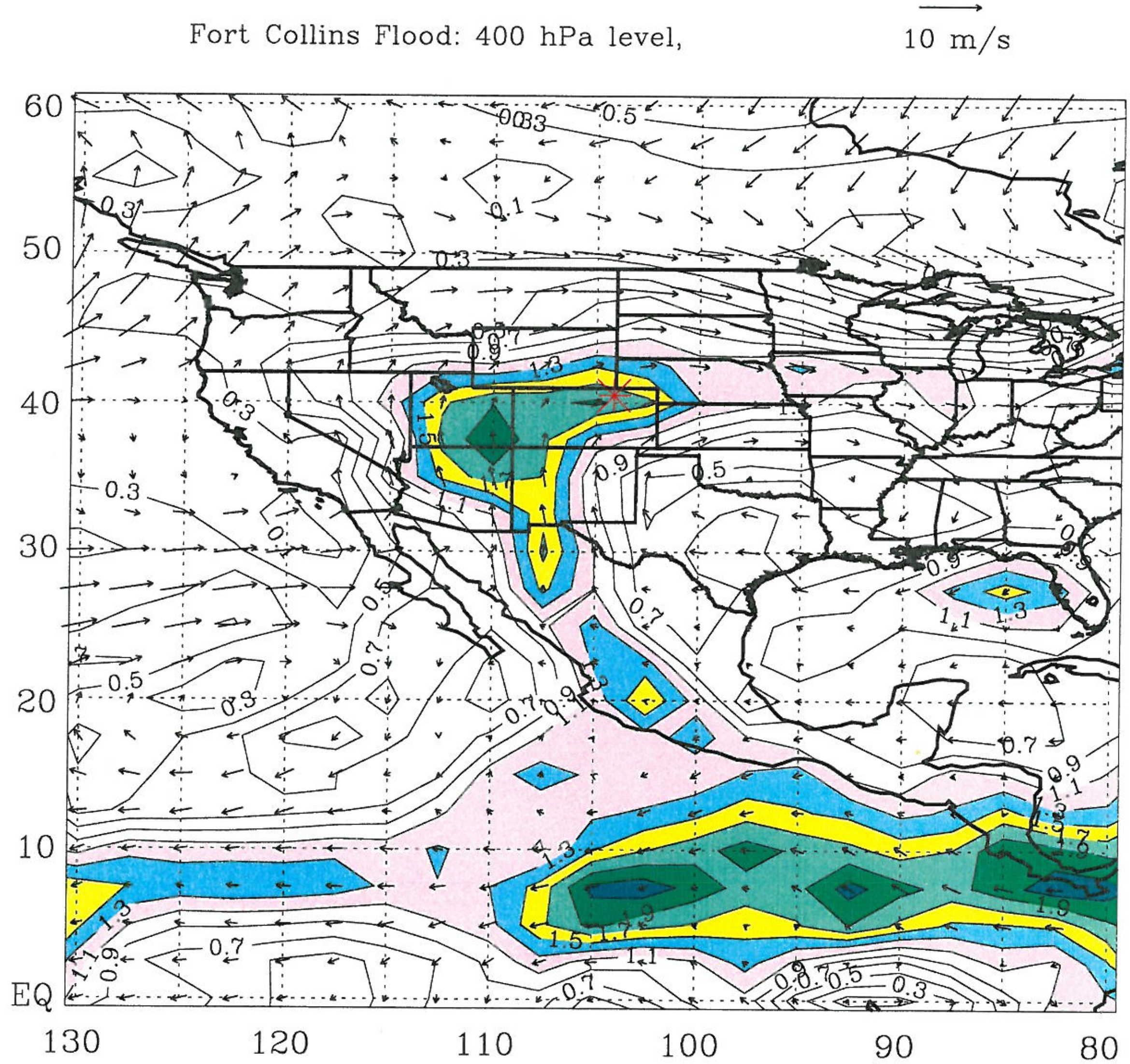

Figure 10: 400 hPa specific humidity (g kg-1) and vector winds (m s-1) at 12:00 UTC on 28 July 1997. The pattern is very distinct, with indications of the northward transport of moisture. Fort Collins is indicated by a red star. Specific humidity contours are spaced every 0.2 g kg-1 with values greater than 1.1 g kg-1 color shaded for clarity.

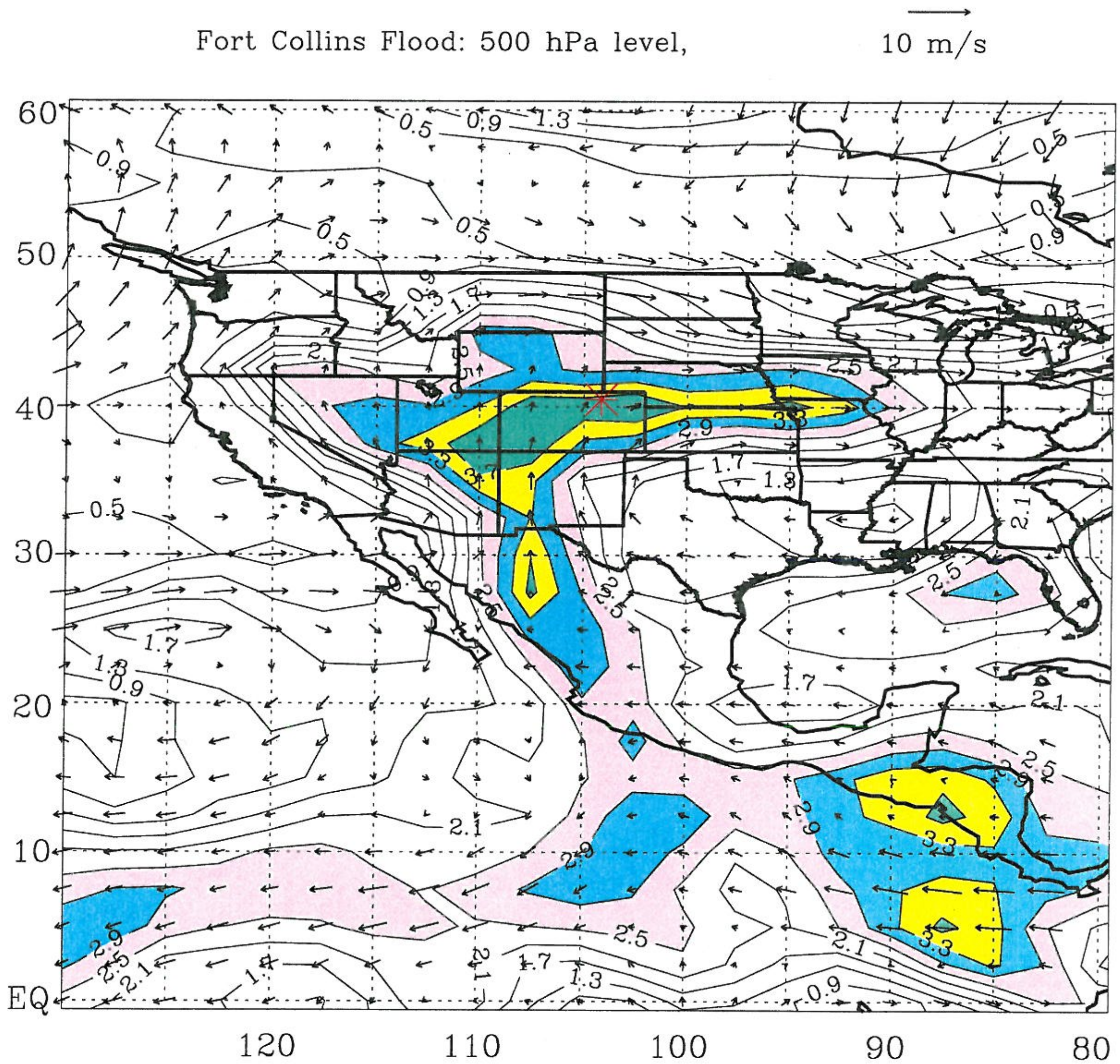

Figure 11: 500 hPa specific humidity (g kg-1) and vector winds (m s-1) at 12:00 UTC on 28 July 1997. Maximum specific humidity values are found near Fort Collins (red star). Specific humidity contours are spaced every 0.4 gkg-1 with values greater than 2.5 gkg-1 color shaded for clarity.

4.2 The Big Thompson Canyon flood

The BTC flood occurred on the evening of 31 July 1976, about 20 miles to the southwest of Fort Collins. As with the FC storm, the convection associated with the BTC flood was nearly stationary over the canyon's watershed, dumping torrential rainfall in accumulations of over 12 inches. This caused a devastating flash flood that killed at least 145 people and caused tens of millions of dollars of damage to businesses and residences that lined the canyon.

Caracena et al. (1979) conducted a detailed mesoanalysis of the BTC storm, including radar and upper air observations. From this study we find striking similarities to the FC storm. Once again, the combination of terrain and light southeasterly winds act to anchor the storm over the headwaters of a watershed. The airmass that is advected westward up the sloping terrain is conditionally unstable. The resulting orographic uplift serves to trigger the convective instability.

Surface conditions are nearly identical to the FC case with a nearly stationary front to the south of the flood area and high dewpoints to the north of this front (Caracena et al. 1979). Cloud bases are very low and there is a lack of appreciable hail fall. Atmospheric soundings show a very deep layer of moist air extending up to 300 hPa. Large scale upper air conditions are the same as with the FC flood, with a long wave trough at 500 hPa aligned across the western United States and a negatively tilted ridge to the east providing a path for monsoonal moisture of tropical origin to the south to advect north along the Rocky Mountains. The NCEPR specific humidity and wind fields reveal the path taken by this moisture to be at a slightly lower level in the troposphere than for the FC storm (figs. 12, 13). These figures illustrate the path taken by the anomalously high levels of moisture extending northward from the source region over the tropical eastern Pacific and along the Rockies. Maximum values are found near the flood region. The pattern shown is very similar to that of the FC floods, although the specific humidity magnitudes are lower overall for a given pressure level.

When comparing the FC flood to the BTC results of Caracena et al. (1979), we note another interesting similarity: the rainfall in both floods grows mainly through warm-cloud coalescence processes with characteristic high precipitation efficiencies. The combination of high precipitation efficiencies and the terrain-anchoring effect leads to the excessive precipitation that triggers the flood. The ultimate source of the excess upper level moisture that improved the precipitation efficiencies is the anomalously warm waters of the eastern pacific, as transported by the NAM.

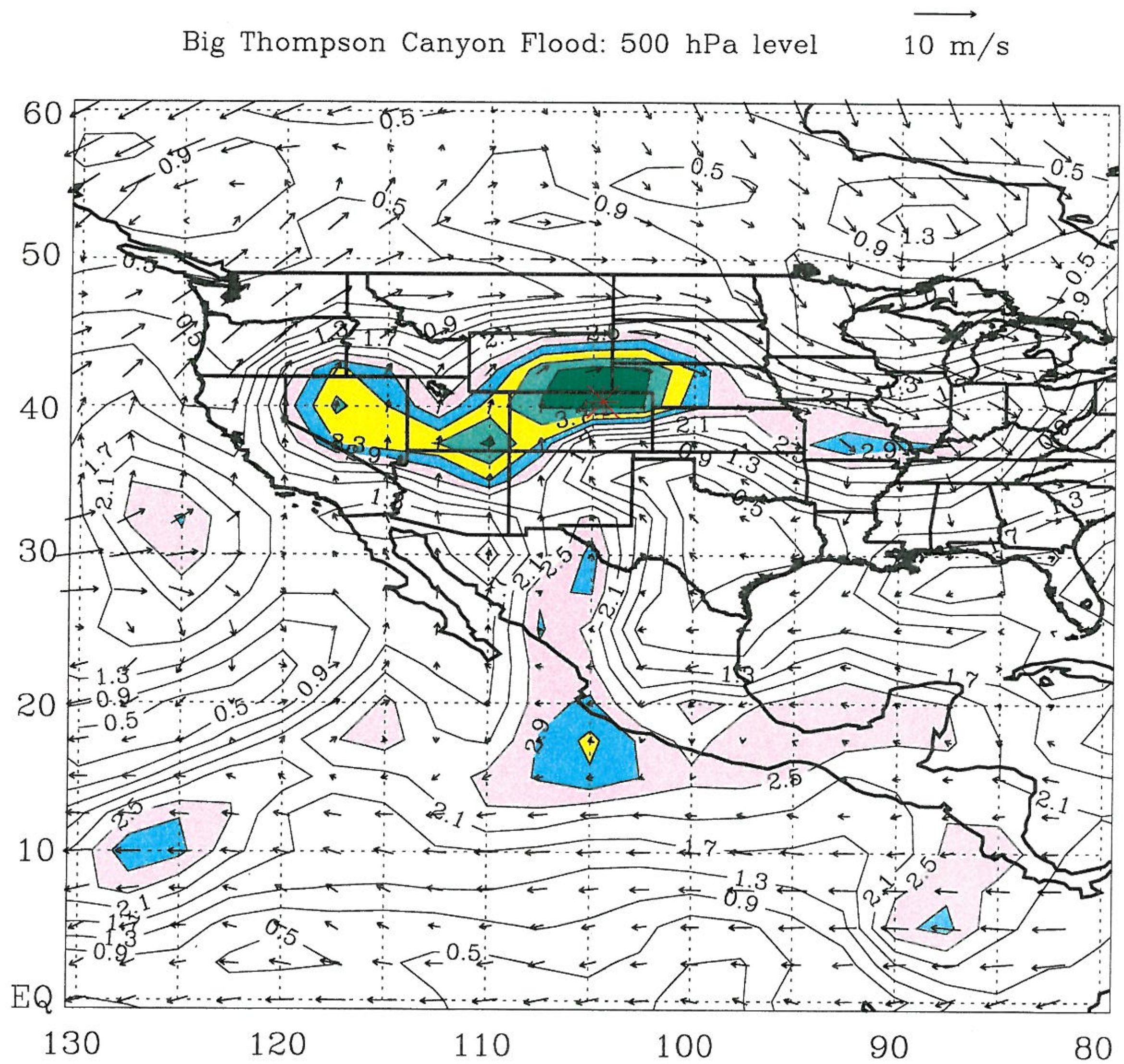

Figure 12: 500 hPa specific humidity (g kg-1) and vector winds (m s-1) at 12:00 UTC on 31 July 1976. As with the FC flood, maximum values of specific humidity are found near the flood location. Light winds advect the moisture north along the rocky mountains from the source region over the tropical eastern Pacific. The location of Big Thompson Canyon is indicated by a red star. Specific humidity contours are spaced every 0.4 g kg-1 with values greater than 2.5 g kg-1 color shaded for clarity.

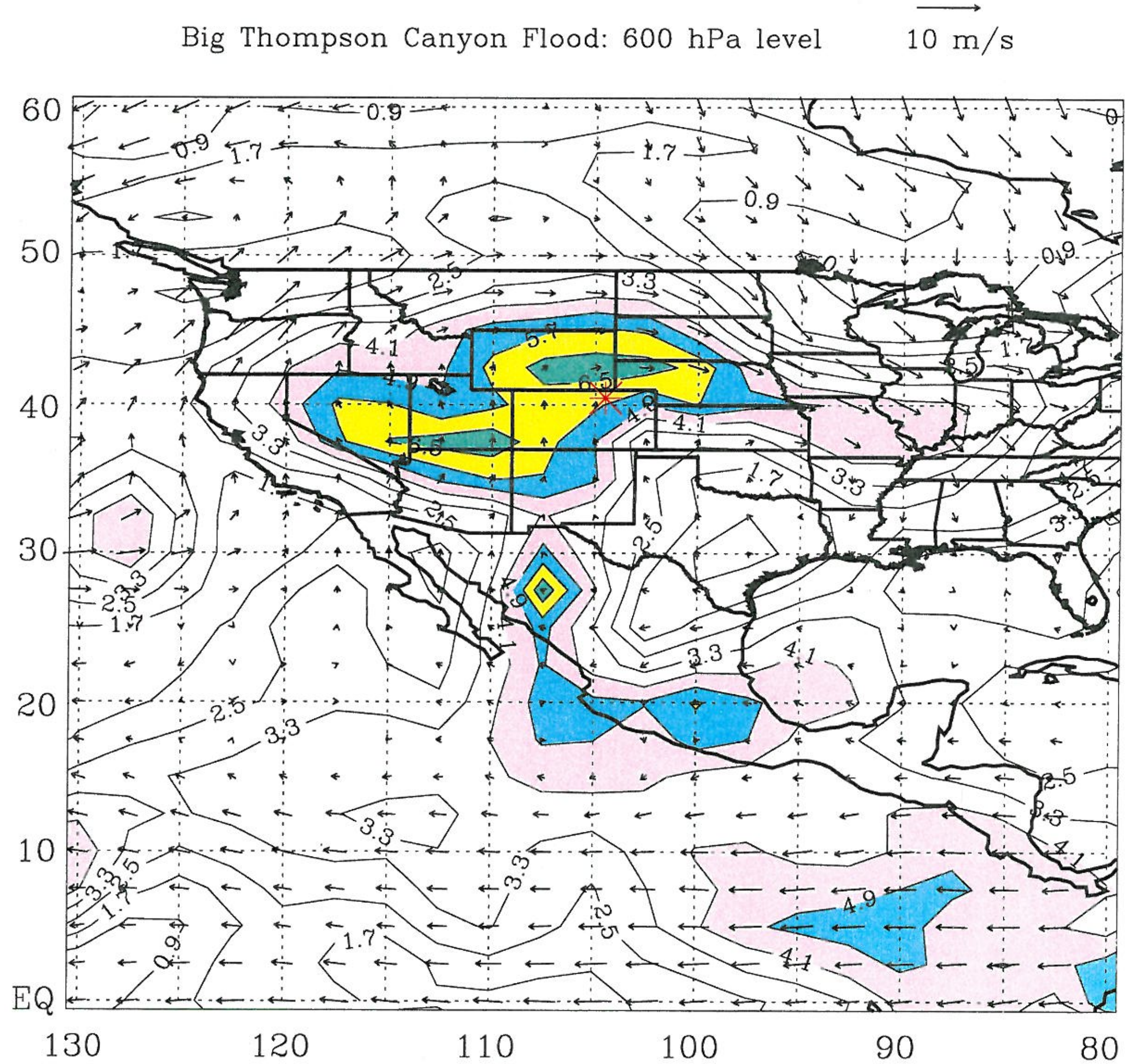

Figure 13: 600 hPa specific humidity (g kg-1) and vector winds (m s-1) at 12:00 UTC on 31 July 1976. As with the FC storm, winds are very light over the BTC (red star). Specific humidity contours are spaced every 0.8 g kg-1 with values greater than 4.1 g kg-1 color shaded for clarity.

4.3 The Rapid City flood

The RC flood, which occurred on 9, 10 June 1972, was one of the most deadly weather events in U.S. history, killing at least 236 people and causing over 100 million dollars worth of damage to Rapid City, South Dakota. Maximum rainfall amounts of over 15 inches were recorded. This storm shares the major characteristics of the FC and BTC storms. A detailed comparison (Maddox et al., 1978) of the meteorological aspects of the BTC and RC floods highlighted their similarities. To summarize, both events have light southeasterly winds advecting a moist, conditionally unstable airmass upslope into hilly terrain, which in RC case are the Black Hills. The orographic uplift experienced by the airmass triggers the convective instability that drives the storm, which also is anchored by the terrain to remain nearly stationary. Upper tropospheric winds are light, less than 15 knots.

Maddox et al. (1978) identified a slow moving polar front just to the south of the Rapid City area at the surface. Atmospheric soundings indicated a very deep, moist airmass to the north of this front. Precipitable water contents from the surface to 500 hPa were found to be nearly twice that of normal values for that time of year.

Large scale conditions aloft are very similar to the RC and BTC floods, with a long-wave trough at 500 hPa over the western U.S. and a large-amplitude, negatively-tilted ridge extending northwest from Texas. A weak short wave trough travels northward up the backside of the ridge. This configuration, as with the BTC and FC events, provides a pathway for abundant mid-level moisture of tropical origin to move north over the flood area. The NCEPR specific humidity and wind fields at 500 (fig. 14) and 600 hPa (fig. 15) partially reveal a transport pathway for moisture from the tropics, although the moisture path is shifted further east and is not as clear as the FC and BTC cases. In this case it appears that some of the mid-level moisture source may be the Gulf of Mexico.

Finally, a key similarity of the RC case to the FC and BTC floods is the presence of warm rain processes indicative of high precipitation efficiencies. They help maintain the storm and drive it to produce extreme precipitation values. Caracena et al. (1979) noted the similarity of the structure of this storm to that of the BTC storm. He found that they are both of the type of storm that are typical of tropical orographic storms and shared the mechanisms of warm rain processes that are rarely found in this part of the world. Though not as clear, the source of the mid-tropospheric moisture is, in part, the El-Niño warmed waters of the eastern Pacific.

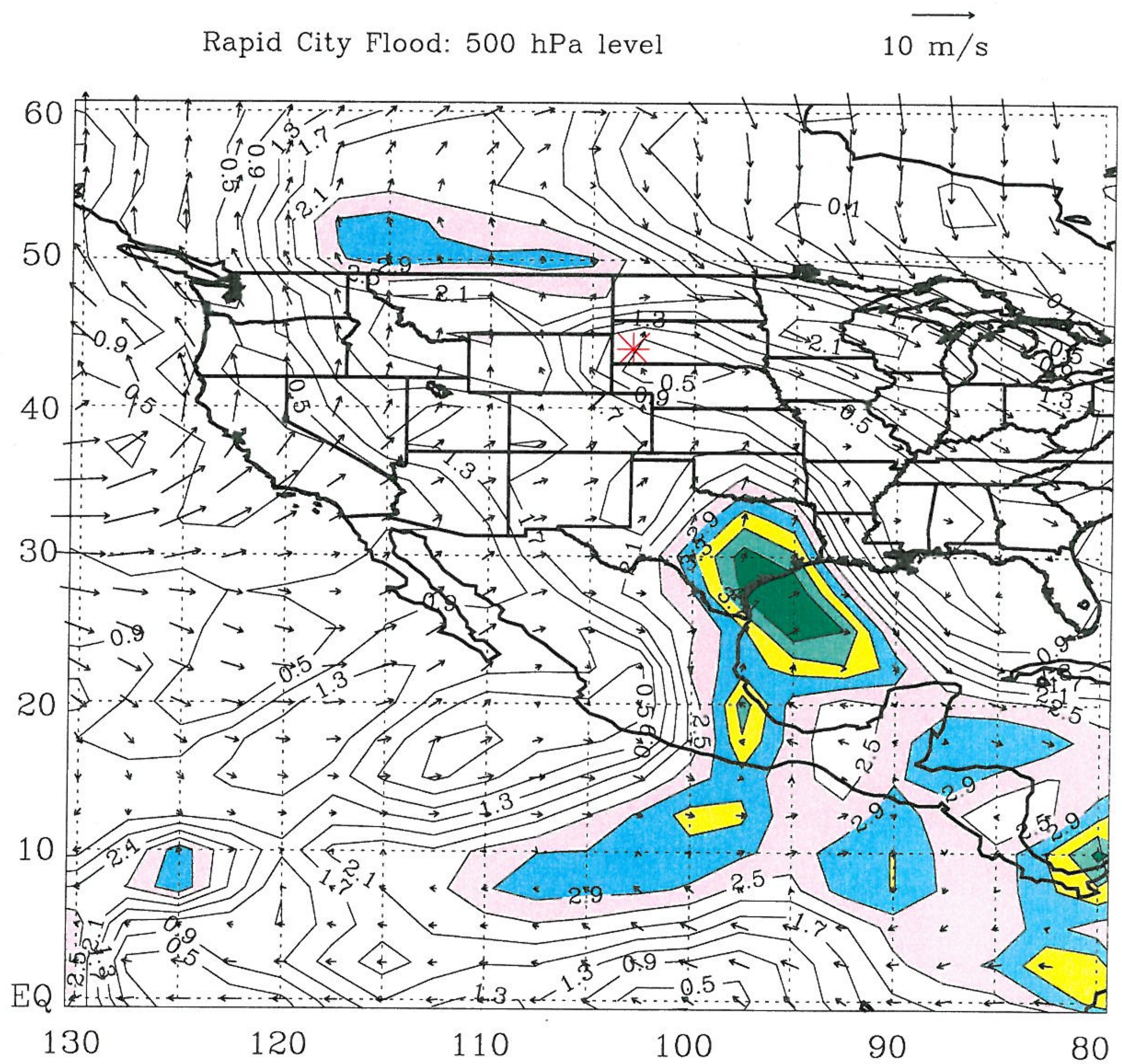

Figure 14: Same as fig. 12, except for Rapid City (red star) at 12:00 UTC on 09 June 1972. The path of the moisture is displaced further east as it leaves its source region as compared to the BTC and FC floods. It possibly mixes with moisture originating from the Gulf of Mexico.

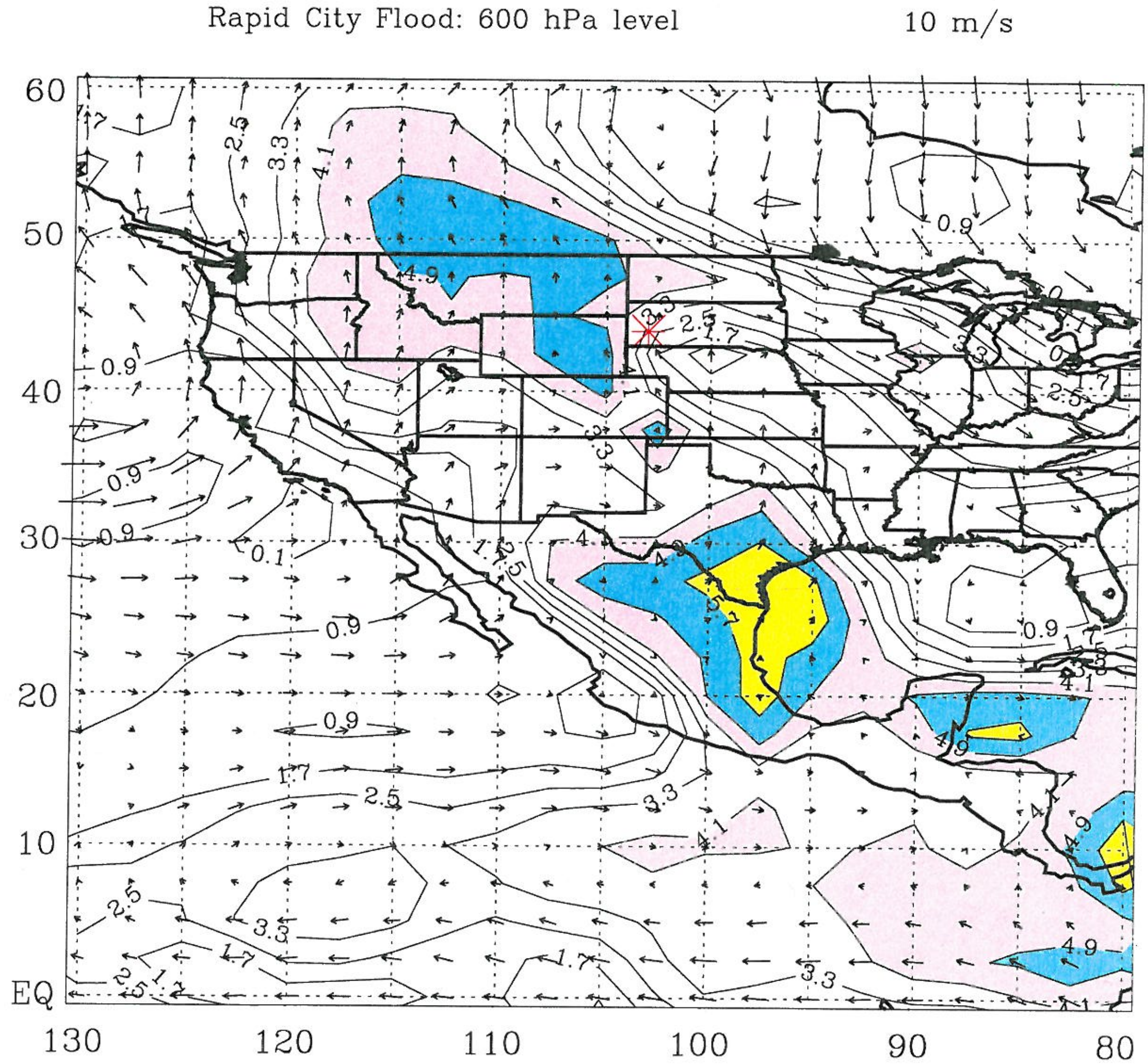

Figure 15: Same as fig. 13, except for Rapid City (red star) at 12:00 UTC on 09 June 1972. Here the moisture follows a path northwest across Texas, Colorado and Wyoming towards the flood region. The path is displaced further east as compared to the FC and BTC floods.

5. AUXILIARY RESULTS

When categorizing storms by ENSO phase from the Colorado extreme storm precipitation data study (McKee and Doesken 1997), our initial focus was on warm phase events (Section 3.5). However, it was also noted that extreme storms of the type that are likely to produce flash flooding are least likely to occur during cold phase ENSO events. This is true for both the Front Range (fig. 5) and Area 2 (fig. 6). Statistical analysis (as performed in Section 3.2 for warm phase versus neutral events) show that the reduced frequency of extreme storms during ENSO cold phases is significant at the 95% confidence level for both the Front Range study area and for Area 2.

Our evaluation of flash flood frequency over the Front Range (Fig. 4) did not include any cold phase years (1988 was the last ENSO cold phase before 1999); however, it would be reasonable to assume that flash flood frequency is greatly reduced during cold phase events. During cold phase events (defined in Section 3.2) there is reduced equatorial convection over the eastern Pacific, which is a source region of moisture for the NAM. It is therefore postulated that during ENSO cold phases, decreased amounts of moisture are available for transport into the mid-levels of the troposphere, which in turn diminishes the amount of moisture advected at these levels into the western United States by the NAM. This in turn minimizes the ability of warm rain processes to occur over our study regions, thus reducing the odds of a major flash flood of the type studied, or flash floods in general, to occur. Note that ENSO cold phases would not eliminate the possibility of a severe flash flood occurring, just significantly reduce the risk. Other factors that influence the formation and severity of flash floods (Section 1), as well as the terrain anchoring effect, may still come into play even if warm rain processes are not available. A study of flash flood frequency going back before 1989 using NOAA's Storm Data publication for the study areas and a climatology of mid and mid-level tropospheric moisture for cold phase ENSO events using NCEPR data would help resolve this question.

6. CONCLUSIONS

Three major flash flood events, two in the Front Range of the Colorado Rockies and one near the Black Hills of South Dakota, all occurred during the onset summer of an ENSO warm phase. These events are compared to identify a synoptic mechanism that may link the flood to the enhanced equatorial Pacific convection during El Niño. A quick look at flash flood frequency in general over the Front Range reveals that flash flooding is much more frequent during the onset summers of an ENSO warm phase (1991 and 1997) than during cold or neutral phases (there are not enough documented flash floods over the Black Hills to make a meaningful comparison.) A review of extreme storms of the type that may typically be expected produce a flash flood shows that these heavy rains are nearly seven times more likely to occur over the Colorado Front Range during the onset summer of an ENSO warm phase than during an ENSO cold phase.

Case studies of the FC, BTC, and RC flood events show the major meteorological aspects of these convective events to be nearly identical. All are supplied with ample low-level moisture advected by easterly winds up sloping terrain. All three are characterized by a deep layer of very moist air and all share a similar synoptic environment. Two key features that combined to produce the extreme amounts of rainfall common to these three storms are examined. One was the influence of the terrain, which, in combination with the low-level easterly flow, allows the three storms to remain nearly stationary. This allows anomalous amounts of precipitation to accumulate over the headwaters of a drainage basin, leading to the catastrophic flooding. The second feature is anomalously high levels of mid-tropospheric moisture of tropical origin. The presence of this moisture leads to efficient precipitation growth typical of warm rain processes that are common to tropical convection, but rare to storms of the Great Plains or Rocky Mountains. Using NCEP data and other sources (satellite imagery, the monsoonal moisture experiment), this moisture is found to be of tropical origin and transported northward by the NAM.

Historically ENSO warm events are associated with increased convective activity over the equatorial eastern Pacific. This increased convective activity feeds excess moisture into the NAM, which transports it at mid-tropospheric levels along the spine of the Rocky Mountains to the Front Range and, at times, northward to the Black Hills. This moisture enables warm rain processes to develop within the flood producing storms by reducing entrainment of mid-tropospheric dry air. It is therefore concluded that extreme flash floods and their associated storms are much more common during the onset summer of a warm phase ENSO event than during other ENSO phases.

6.1 Applications

The consequences of this research can have a unprecedented impact on the ability to forecast flash floods in the Colorado Front Range. We have identified that a large scale ocean-atmosphere oscillation (ENSO) can play a key role in enhancing precipitation in Front Range convective systems. This new knowledge will allow forecasters to be more vigilant depending on the phase of ENSO. When combined with the work of other authors, we can provide a list of warning signs for forecasters on both the seasonal and synoptic time scales. The ability to forecast the likelihood of disastrous floods using a technique based on the presence or absence of these warning signs will have a significant impact on the material readiness and safety of a population in a danger area. In much the same way as a tornado or severe thunderstorm warning area, a flash flood warning area based on this technique will help localize the danger area and target the people most in need of an official warning. Based on our research, the warning signs to look for are:

- The onset summer of an ENSO warm phase (or an El-Niño). This can be forecast with skill months in advance (Trenberth 1997), and is key to the flood scenario, as the anomalously warm waters of the eastern Pacific will provide the NAM the excess mid-tropospheric moisture necessary to increase the precipitation efficiencies typical of warm-rain processes. Knowledge of a warm phase onset will alert the forecaster to look for the following synoptic signatures that indicate the potential for flash flooding.
- From satellite imagery (IR or water vapor), a "river of moisture" being

advected by monsoonal flow from its source region over the eastern Pacific northward along the spine of the Rocky Mountains (fig. 8).

- A negatively-tilted ridge at 500 hPa over the Great Plains in concert with a long-wave trough along the US west coast. This pattern provides the path for the monsoonal moisture of tropical origin to advect north along the Rocky Mountains.
- Light mid-tropospheric winds and easterly flow at the surface. These act in concert to help produce the orographic uplift needed to trigger convective instability and to help keep the storm topographically anchored. This helps maximize accumulations over a single area.
- Location: eastward facing slopes. The northern portion of the Front Range of the Colorado Rockies and the Black Hills are the focus of this study, although these techniques can also be used over the rest of the Front Range. As shown in Section 3.5, the greatest danger of intense storms and flash flooding tends to be at eastern base of the Rocky Mountains.

When the above have been identified, the following should be looked for to develop a short-term forecast:

- At 500 hPa, a short wave trough traveling northward along the backside of the long-wave trough. This short wave can help serve as a triggering mechanism for the storm, enhancing the orographic uplift.
- Atmospheric soundings indicating a deep layer of very moist air. Anomalous mid-tropospheric moisture is necessary to evolve a warm-rain process characteristic of the storms that produce catastrophic floods
- A line of convergence or a nearly stationary front just to the south of the target area, with high dewpoints at the surface to the north.

Using these signals, forecasters should be able to improve flash flood forecast in the regions covered by this research.

6.2 Future research

Further work can be done on the applicability of this research to other geographic regions, especially along the eastern-facing slopes of the Rocky Mountains.

Since nature knows no political boundaries, we expect that these findings will apply to regions outside the Colorado study area (such as northward into Wyoming and southward into New Mexico) that share common topographic features. Expanding our region of study would greatly increase the utility of the methods outlined herein.

Further case studies of extreme storms that occurred over the Colorado Front Range would also add to our knowledge. At least 5 other storms that occurred along the eastern base of the Rocky Mountains, besides the BTC and FC events, produced greater than 10 inches of rainfall. These are not as well documented but could provide further useful findings. Trajectory studies, mid-level moisture climatologies, GCM simulations, and moisture budget or transport studies would also better determine the typical moisture sources and transport mechanisms during all the phases of ENSO.

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