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COLLEGE OF ARTS AND SCIENCES

FRONT RANGE SEVERE FLASH FLOODING AND EL-NIÑO

By

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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 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 uses the synoptic signatures developed in this study.

SECTION 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 [*AMS, 1995*]. 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 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.

There are other causes of flash floods that may not directly involve intense rainfall as defined above, such as ice jam breaks or dam failures, and 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

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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 pre-existing 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 of all is the period of intense, localized rainfall as described above. This can cause flash flooding even if other factors are unfavorable and is often the cause of some of the other exacerbating factors such as wet soil, high stream levels and overtaxed dams. 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 flood of 28 July 1997, the Big Thomson Canyon flood of 31 July 1976 and the Rapid City 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, Peterson et al., 1999*]. What has not been investigated until now is the possible link between these floods and the El-Niño - Southern Oscillation (ENSO). All three events occurred during the summer prior to a peak ENSO warm phase (as determined by the JMA index, Section 3). It is postulated that the anomalously high levels of mid-level moisture that drove these events are more prevalent over the regions where these events occurred, the Front range of the Colorado Rockies and the Black Hills of South Dakota, during the onset summer months of an

prevalent over the regions where these events occurred, the Front range of the Colorado Rockies and the Black Hills of South Dakota, during the onset summer months of an

ENSO warm phase. Considering the times and places of occurrences, this study will limit itself to the summer (June, July and August) time frame for the 2 regions as defined above.

While this study focuses on the three cases noted above, a review of flash flood frequency over the study areas (Section 3) 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 recently available NCEP/NCAR Reanalysis Project (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 an upper level conduit of moisture of tropical origin supplied by the ENSO warmed waters of the eastern Pacific, working in tandem with the North American Monsoon, is the source of the mid-tropospheric moisture that increased the precipitation efficiency of these storms. The secondary goal is to show that this type of event is much more likely to happen during the onset summer of an ENSO warm phase. Section 3 will present essential background information

to show that this type of event is much more likely to happen during the onset summer of an ENSO warm phase. Section 3 will present essential background information,

including data on flash flood and severe storm frequency and the relationship between ENSO and the North American Monsoon. In Section 4 the three flood events will be examined and compared. Images derived from NCEP data and the findings of other synoptic studies will be used to illustrate the link between ENSO, the North American Monsoon and the increased levels of mid-tropospheric moisture found over our study areas. In Section 5 auxiliary results will be discussed. This will consist of a discussion of the findings of reduced flash flood and severe storm frequency found during cold-phase ENSO events. The conclusions of this study will be presented in Section 6.

SECTION 2

DATA SOURCES

Data from several sources are used. The primary data source used to deduce the origin and trajectory of the mid-tropospheric moisture and the pattern of the wind fields is obtained from the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) Reanalysis Project, referred to hereafter as NCEP data. Flash flood occurrence data are taken primarily from the monthly NOAA "Storm Data" publication, which is the only comprehensive national summary of severe weather events. Data regarding the most extreme storms to affect Colorado and the surrounding areas was taken from the Colorado Extreme Storm Precipitation Data Study [*McKee and Doesken, 1997*]. The primary data sources used for this study are described in more detail below:

2.1 NCEP/NCAR Reanalysis Data

The NCEP/NCAR Reanalysis project [*Kalnay et al., 1996*] is an ongoing effort to produce a world-wide record of global analyses of atmospheric fields from 1957 to the present. A wide variety of data from different sources are used in this effort: land and ship surface reports, rawinsonde, satellite, aircraft, pibal and other available data. These data are quality-controlled and assimilated using a scheme that is kept unchanged over

ship surface reports, rawinsonde, satellite, aircraft, pibal and other available data. These data are quality-controlled and assimilated using a scheme that is kept unchanged over

the reanalysis period so as to eliminate perceived climactic shifts that accompany changes in data assimilation systems.

The general kinds of data available include pressure level and surface data, flux data and tropopause level data, among others. This study uses several variables from the pressure level data: specific humidity and U and V wind. These variables are instantaneous values output every 6 hours as gridded fields at the reference times of 00Z, 06Z, 12Z and 18Z, from 1957 through 1997. Spacial coverage is a global grid of 144 by 73 points, or grid points of 2.5° latitude by 2.5° longitude apart. There are no missing data. Six pressure levels were initially used in this study, the 850, 700, 600, 500, 400 and 300 hPa levels, although it was soon concluded that the study should focus on those levels from 600 hPa and above. These upper levels proved most useful in illustrating the apparent upper level moisture link between the Front Range of the Colorado Rockies and the El-Nino warmed waters of the eastern Pacific. The 500 and 600 hPa levels were especially revealing in this regard.

The pressure level variables are divided into four categories, “A” through “D”, depending upon how much these variables are influenced by the observational data. This is an indication of how reliable the various classes of data are. Class “A” data are most strongly, or directly, influenced by observational data and are thus the most reliable of the classes. U and V wind data and temperature data are examples of class “A” data. Class “B” data are also directly influenced by observational data, but are also influenced very significantly by the reanalysis model. That makes this class of data less reliable than class “A” data. Specific humidity is an example of class “B” data. Class “C” and class “D” data

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are not directly influenced by observations, but are reliant on the data assimilation scheme and climatology. This makes them the least reliable of the data classes. Only class “A” (U and V winds) and class “B” data (specific humidity) are used in this study. The model itself utilizes an interpolation scheme that can transport information into otherwise data-poor areas from other areas that are more well defined by observations. This works very well with class “A” data, giving the most accurate reanalysis. Class “B” data, while still influenced by observations, will thus be more heavily influenced by the climatology of the model in data poor regions.

2.2 NOAA Storm Data

Storm Data, a NOAA publication, is a monthly summary of severe weather events as compiled by the National Weather Service, that occur in all 50 states. The data are listed alphabetically by state and county and arranged in table format, showing 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, this source is the most comprehensive available for the United States. While the period of record covers from 1959 through the present, the data are only used to examine flash flood events from 1989 onwards. This is because before 1989, flash floods are not in general 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 and in any case unnecessary to its goal

precipitation” or “severe thunderstorms”. Sorting these earlier flash floods out of the data is beyond the scope of this study and in any case unnecessary to its goal.

2.3 Colorado Extreme Storm Precipitation Data Study

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. These storms all produced very heavy precipitation either over localized or wide-ranging areas 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 [*NOAA, 1973*].

SECTION 3

BACKGROUND

Three of the worst flash floods in the past 30 years in terms of lives lost and property damaged, the Fort Collins flood of 28 July 1997, the Big Thomson Canyon flood of 31 July 1976 and the Rapid City flood of 9 June 1972 (referred to hereafter as the FC, BTC and RC floods respectively) share common features that have been well documented in various case studies. These will be further analyzed in Section 4. Recently, it was noted that all three events occurred during the summer prior to a peak ENSO warm phase (as determined by the JMA index, Section 3.4). The natural question that emerges from this fact is, "Is there a link between these three events and ENSO phases?" This study investigates the possible link between these floods and the warm phase of ENSO. In other words, we identify the large-scale atmospheric phenomena common to these three events. It is postulated that the anomalously high levels of mid-level moisture that increased the precipitation efficiency of these events are more prevalent over the regions where these events occurred, 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.

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3.1 Selecting the Study Areas

The boundaries of the study area are selected to encompass the locations of the 3 flash flood events and to take into consideration the role that the elevated terrain played in the triggering, maintenance and character of the storms that produced these events. The Black Hills study area (figure 1) is topographically and geologically distinct from the surrounding terrain. Orographic lifting played a strong role in the RC flood. The Front Range (figure 2), 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. The study area only included the northern portion of the Front Range because of the focus on the BTC and FC floods.

3.2 Flash Flood Frequency Over the Past Decade

While this study focuses on the three cases noted above, it was concluded that if, as postulated, ENSO really did have an effect on the prevalence of mid-level moisture over the study areas, then flash flooding in general should be more prevalent for these areas during the onset summer of a warm phase ENSO event. In confirmation of this, a review of flash flood frequency data for the study areas over the past decade reveals that flash flooding in general is much more common during onset summers of an ENSO event, with secondary peaks of occurrence during the proceeding summers. This is most evident over the Front Range study area (figure 3); 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) and is not considered as statistically significant

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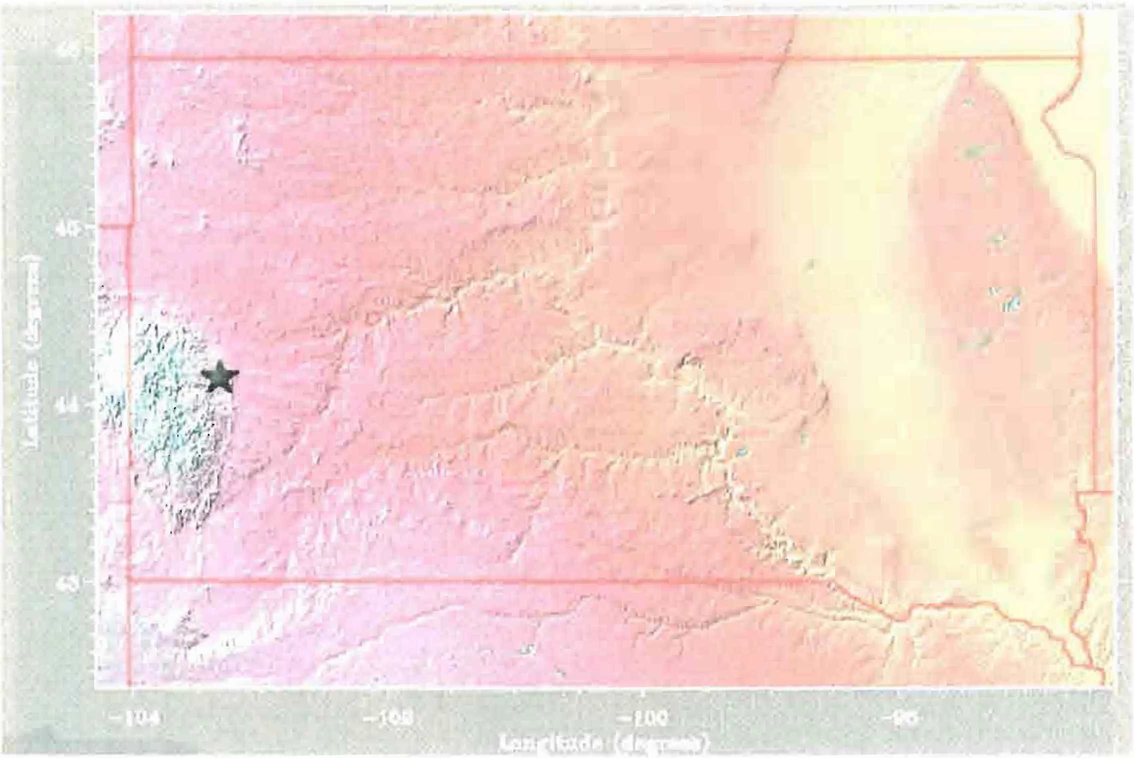

Figure 1. Relief map of South Dakota. The Black Hills, situated at the southwestern edge of the state, stand out topographically in contrast to the relatively low relief of the surrounding Great Plains. The study area includes Lawrence and Custer counties, western Pennington, northern Fall River and extreme southwestern Meade counties. The flood location is marked by the black star.

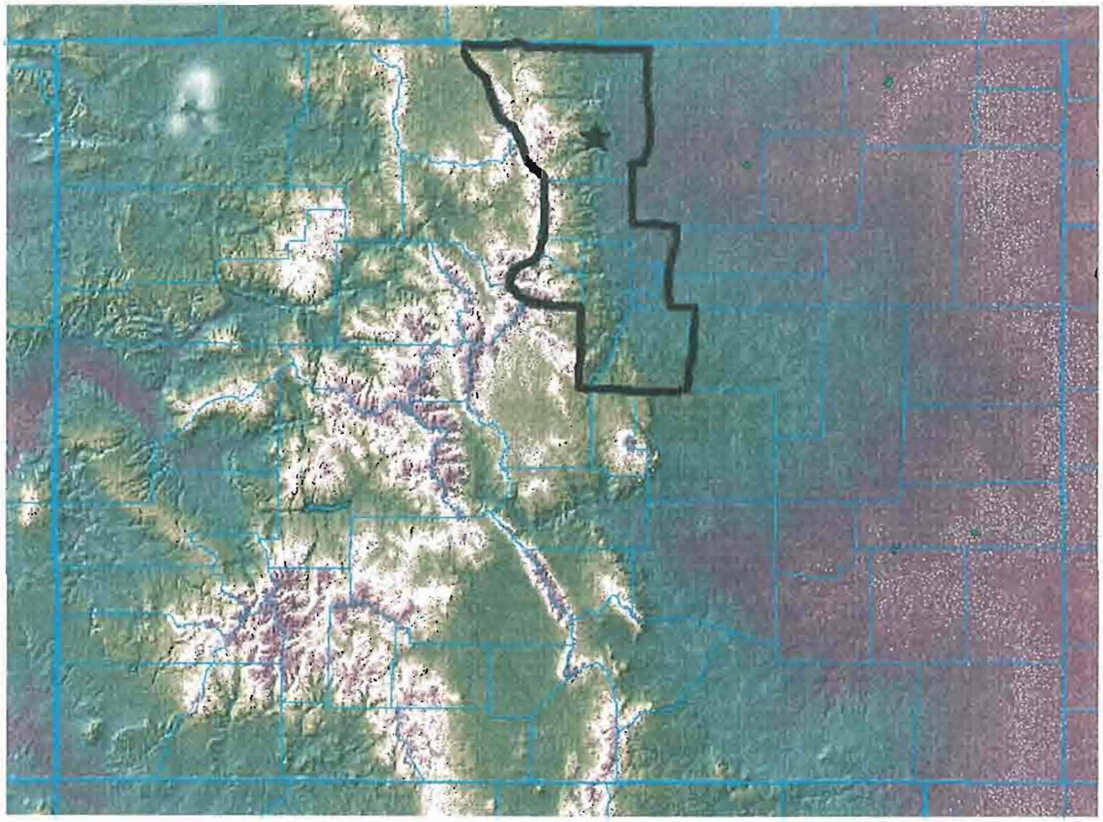

Figure 2. Relief map of Colorado, with the Front Range study area outlined. The study area encompasses the counties of Larimer, Boulder, Gilpin, Clear Creek, Jefferson, Douglas, Denver and the extreme western portions of Adams and Arapahoe counties. This region extends westward from the edge of the Great Plains across the foothills of the Rocky Mountains to the Continental Divide. The back star marks the approximate location of the BTC and FC flood.

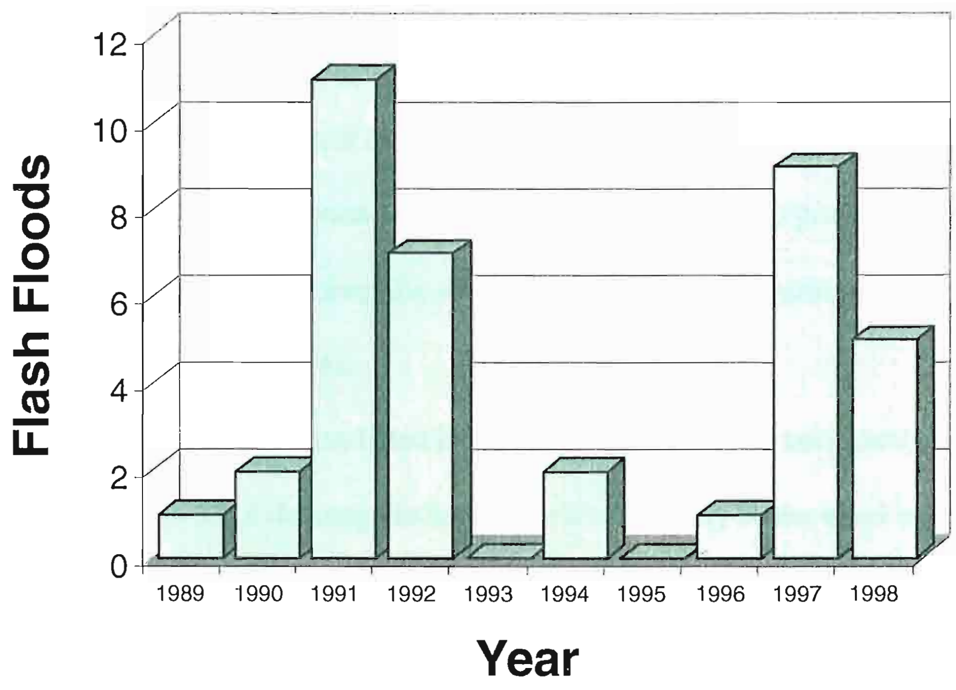

Figure 3. Comparison of summertime (June/July/August) flash flood occurrences for the Front Range study area from 1989 through 1998, as reported by the NOAA publication "Storm Data". When more than one flash flood occurred at the same time in a localized area due to the same storm, these floods were judged to be single events 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.

3.3 Extreme Storm Precipitation Frequency

Additional and much more convincing 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 their data supports the conclusion that severe precipitation events of the type most likely to produce flash flooding is much more likely during the onset summers of ENSO warm phases over the Front Range study area (figure 4).

Although not all of the storms listed in the extreme storm study necessarily produced flash floods, they are all of the magnitude that could reasonably be expected to, 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. Although we will not directly connect the storms on this list to specific flash floods, because of the inherent flash flooding potential shared by these storms and the long period of record of the study, it is instructive to take a statistical look at their distribution in relation to ENSO phases.

Among the findings produced by the extreme storm study, the following are most germane to our study of flash flood events:

✷ 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. This also had a bearing on our choice of the study areas boundaries.

✷ Of the subset of 11 storms that produced more than 10 inches of rainfall, no storms

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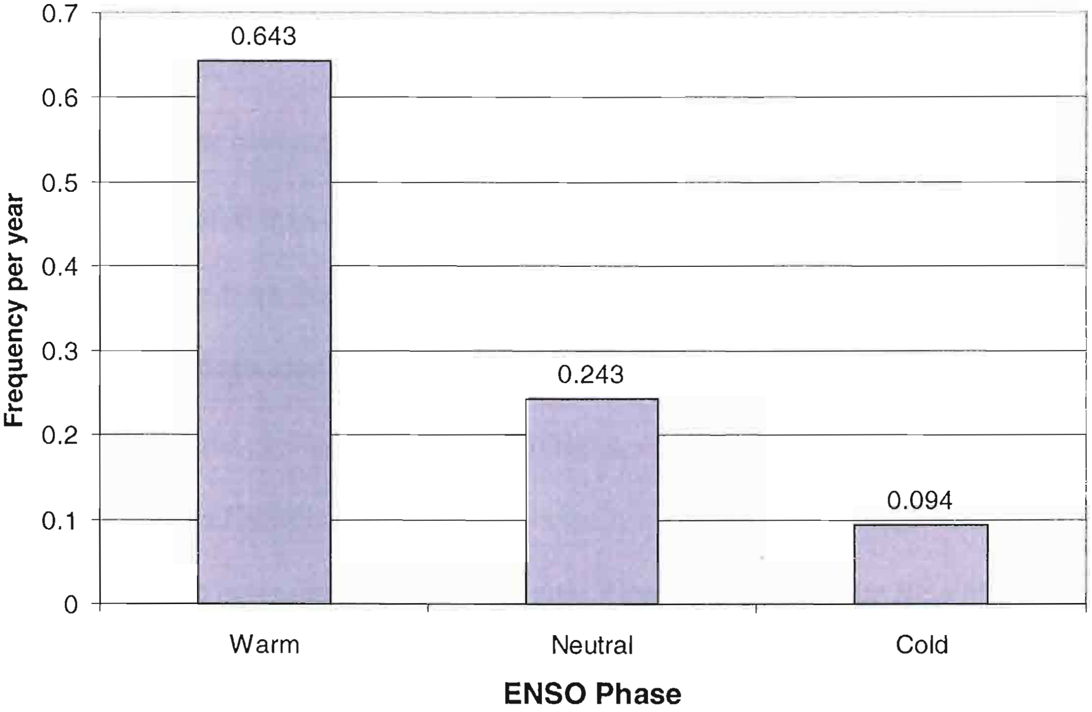

Figure 4. Summertime (June/July/August) extreme storm frequency for the Colorado Front Range study area from 1868-1997. Extreme storms of the type as defined by the Colorado Extreme Storm Study are almost seven times more likely to occur during the warm phase of an ENSO event as compared to a cold phase, 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).

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.

The Colorado State study 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. It 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 (figure 5) 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 to happen over this area during a warm ENSO phase as during a cold or neutral phase. For the seven storms that produced over 10 inches of rainfall (figure 6) over Area 2 in the summer, we see a similar pattern. Based on their limited occurrences, they are much more frequent during warm phase ENSO events.

While this data suggests a strong link between the frequency of the type of storm that could produce a flash flood, the geographic area, and ENSO phases, it does not yet directly reveal the synoptic mechanism of such a link.

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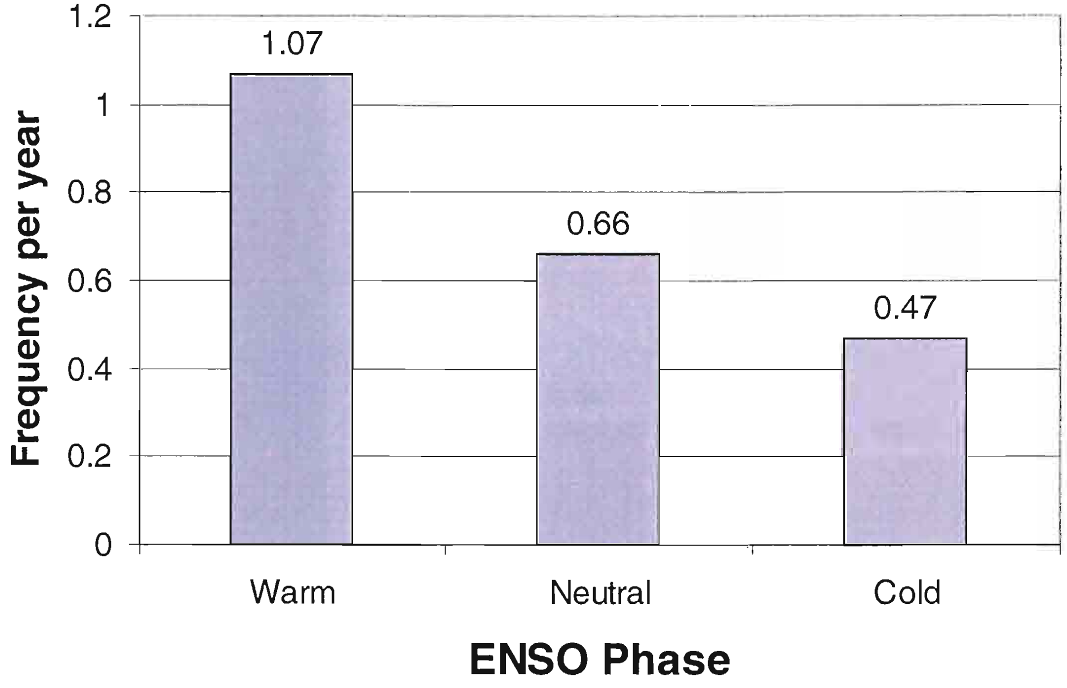

Figure 5. Summertime (June/July/August) extreme storm frequency for the region defined as "Area 2" in the Colorado Extreme Storm Precipitation Data Study for 1868-1997. Extreme storms are about twice as likely to occur during a warm event as during a cold or neutral event. A total of 91 storms were included in this sample, including the FC storm.

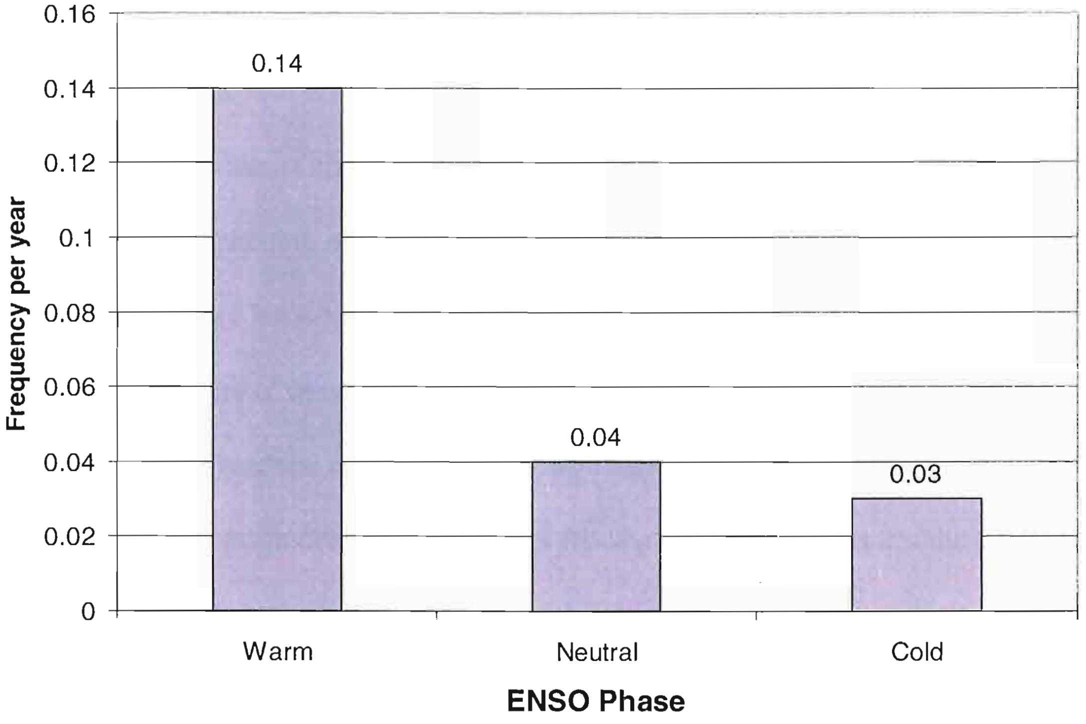

Figure 6. Summertime (June/July/August) extreme storm frequency for Area 2 covering the period from 1868-1997 for storms that deposited at least 10 inches of rain. Only 12 of these were recorded for Colorado during this period. Of these, 7 occurred over area 2. Four occurred during a warm phase, two 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 one.

3.4 The El-Niño/Southern Oscillation

ENSO is an interannual climate fluctuation, an anomalous meteorological and oceanographic event 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 most interest to this study is the enhanced equatorial convection that occurs over the ENSO warmed waters of the eastern Pacific. 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 Inter-tropical Convergence Zone (ITCZ). A recent study (personal communication with Shirley Murillo, COAPS, 1998) 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 (figure 7). These storms are a significant source of excess moisture available for transport by the North American Monsoon into 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 will use an index based on SST anomalies as developed by the Japanese Meteorological Agency (JMA). The JMA SSTA is a reliable

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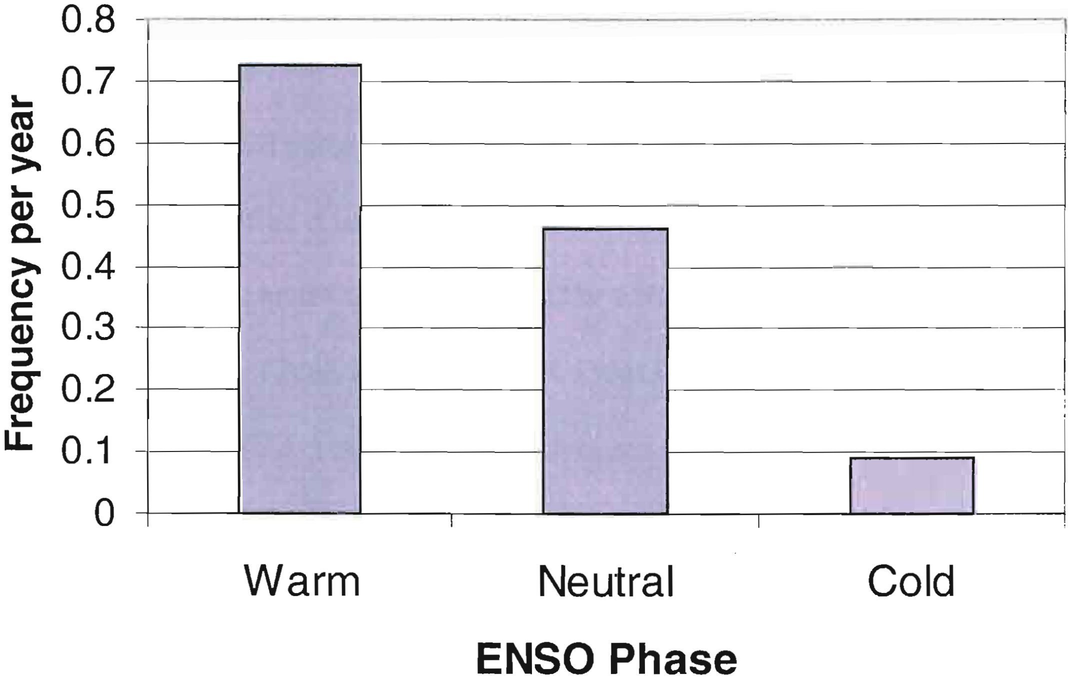

Figure 7. Mean number of landfalling tropical storms/hurricanes north of 25 North for the eastern Pacific. Only landfalling storms are used because they are not biased with time. Tropical systems are over seven times more likely to make landfall along the Mexican coastline during a warm phase ENSO event as during a cold phase. This reflects the greatly increased convective activity during a warm phase as compared to other phases. Landfalling storms of this type can be a tremendous source of moisture to the NAM, and can trigger widespread flooding over western Mexico and the American Southwest. Adapted from personal communication with Shirley Murillo, COAPS, 1998.

indicator of well-known ENSO events and is available from 1868 to the present (figure 8). If the index values are 0.5°C or greater for 6 consecutive months, that year (ENSO years are defined to run from October through September) is categorized as a warm phase or El-Niño. A cold phase has values of -0.5°C or less for 6 consecutive months. Otherwise, the ENSO year is categorized as neutral. This study is specifically looking at the summers preceding an ENSO warm phase. The ENSO onset summer season is defined as the months of June, July and August. From 1868 through 1997, there have been 32 cold phase ENSO events, 28 warm phases and 70 neutral phases.

3.5 ENSO and the North American Monsoon (NAM)

It is clear that warm phase events result in the enhancement of equatorial convection over the eastern Pacific. It is also known that the NAM regime extends northward into Arizona, New Mexico and Colorado [*Adams, 1998*]. What is not conclusive from the literature is whether there is an ENSO-related change to the summer monsoonal flow regime, especially over our area of interest, which would be necessary for the ENSO/flash flood link to prove valid. For our hypotheses to be correct, the anomalously warm pool of water over the eastern Pacific must supply the summer monsoon with additional mid-tropospheric moisture through increased convective activity. This extra moisture must then eventually be advected over the Colorado Front Range and Black Hills of South Dakota to increase the precipitation efficiencies of the storms that produced the flash floods.

A recent study [*Adams and Comrie, 1997*] concludes that while the interannual variability of the NAM is high, it is not strongly linked to warm-phase ENSO events.

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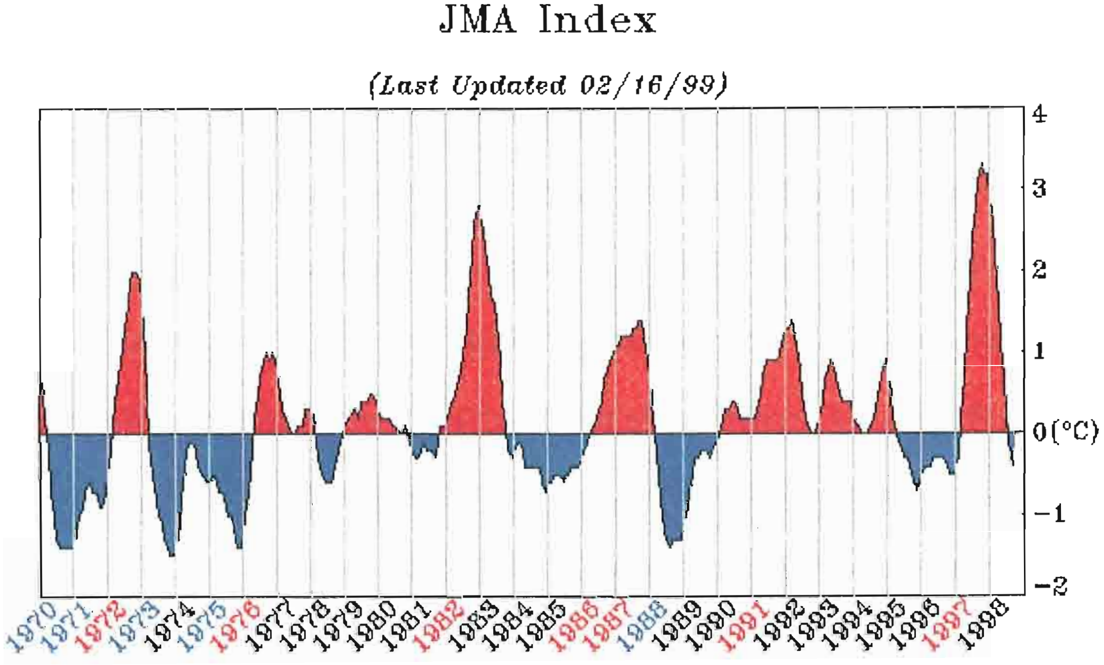

Figure 8. Japan Meteorological Agency (JMA) Sea Surface Temperature Anomalies (SSTA) index indicating the three phases of ENSO. The index is a 5 month running mean of spatially averaged SST anomalies for a section of the tropical Pacific with the following boundaries: 4° South to 4° North and 150° West to 90° West. The years in red are warm phase ENSO events (indicating warm SST anomalies), the blue years are cold phase ENSO events (indicating cold SST anomalies) and the black years are neutral phase ENSO events.

This paper also concludes 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. A study on the influence of the NAM on the United States summer precipitation regime [*Higgins et al., 1997*] was 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. A study [*Andrade and Sellers, 1988*] covering Arizona and New Mexico provides an ENSO/NAM link for that region. It showed that over the American southwest, precipitation is enhanced by the presence of unusually warm water off the California coast and west coast of Mexico. This warm water provides the necessary energy for the development of strong west coast troughs, weakens the trade wind inversion and allows monsoonal moisture to penetrate in larger quantities than normal into the southwest. This warmer water also spawns more numerous, stronger tropical systems than normal off the coast of Mexico. When prevailing flow aloft is from the southwest, moisture from these storms is advected into the southwest, resulting in increased precipitation. Additional evidence [*Ropelewski and Halpert, 1986*] 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 also points to an ENSO/NAM link for these regions. However, another study [*Harrington et al., 1992*] was contradictory, finding no ENSO/NAM link for Arizona and New Mexico.

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Until now, a solid correlation has not been found between ENSO phases and precipitation in general over our study areas like there has been for other areas of the country. In a look 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. In a study of ENSO-related precipitation and temperature anomalies [*Bunkers et al., 1996*] across the northern Plains (North and South Dakota and portions of adjacent states and provinces, which include the Black Hills study area), there was found a mean increase in precipitation for warm events between April and October. A 1986 study of North American precipitation and temperature patterns associated with ENSO [*Ropelewski and Halpert, 1986*] found that although there was some indication of an ENSO-related signal in the High Plains region (the Front Range and Black Hills study areas are on the fringes of the High Plains), this response was not consistent.

The contradictory nature of these studies could be due to the fact that various definitions of an ENSO event were used. There was no consistent definition used throughout these studies. What one author may consider a warm event ENSO year, another may define as a neutral period. There is only broad agreement amongst these

throughout these studies. 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. This study looks at upper-level moisture, while most of the other studies consider precipitation changes locally. It could be that ENSO moisture is simply flowing overhead and not impacting precipitation until it reaches the Front Range.

SECTION 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. Peterson 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 also destroyed a trailer park

observations and detailed synoptic analysis. Five people died and over 200 million

dollars worth of damage was caused by this flood, which also destroyed a trailer park

and extensively damaged the campus of Colorado State University. This 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 (figure 9) were recorded along the western edge of the city.

The upper level synoptic conditions of the FC flood are similar to that of the BT 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. Satellite imagery (figure 10) shows the transport mechanism to be the NAM. Output from the NCEP data set also clearly shows (figure 11 through 15) the source of the mid-level moisture to be the anomalously ENSO-warmed waters of the eastern Pacific. This is most clearly seen at the 500 and 600 hPa levels (figures 13 and 14), but can be detected up through the 300 hPa level (figure 11). Moisture levels are high at most pressure levels, dewpoint depressions are found to be about 1°C at sounding sites in New Mexico, Colorado and Wyoming. Dewpoint temperatures exceed 50°F at 700 hPa where winds were from the southeast. Total precipitable water below 500 hPa at Denver is 3.26 cm (the July average is 1.90 cm and values exceed 2.8 cm only 5% of the time). This large amount of moisture available through a deep layer combine with relatively weak wind shear to result in a deep layer of warm rain processes. This results in unusual (for the Front Range) storm cells that exhibit warm-

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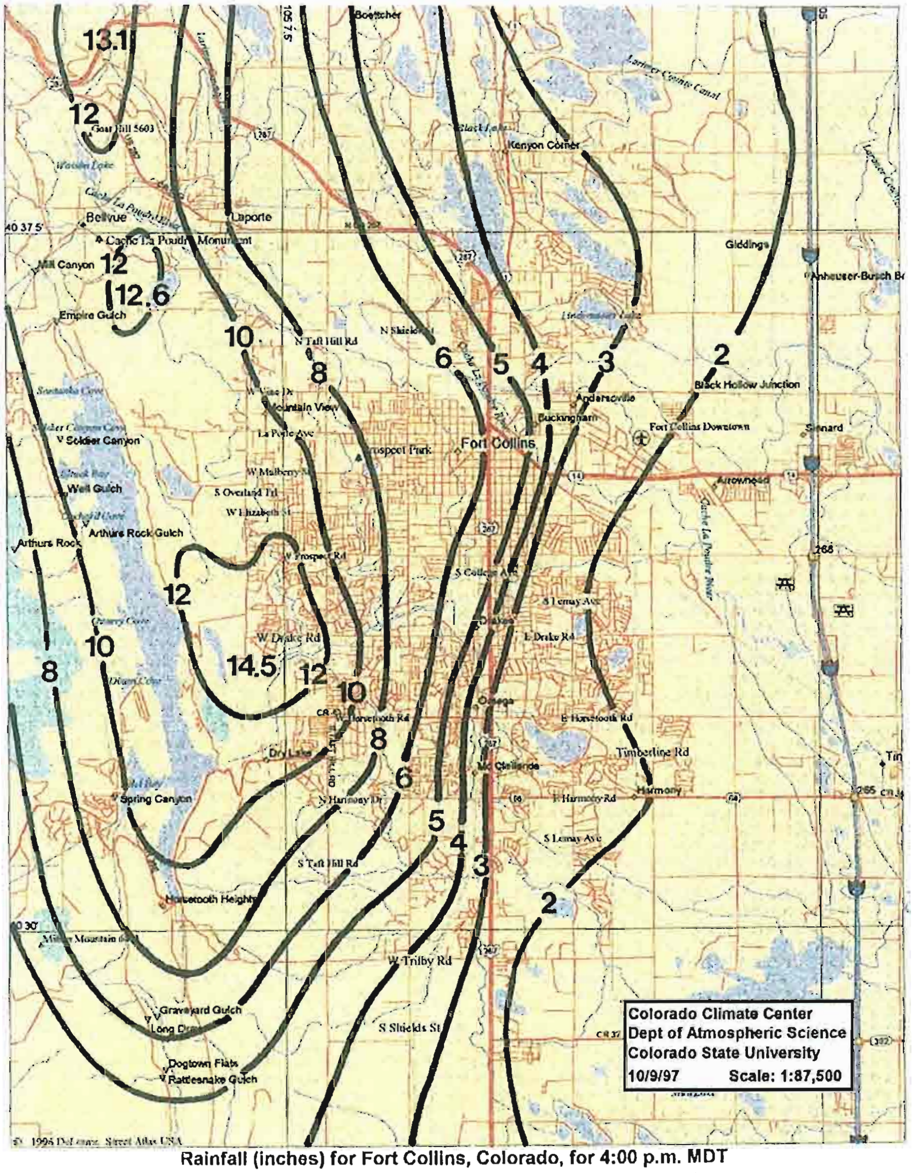

Rainfall (inches) for Fort Collins, Colorado, for 4:00 p.m. MDT
July 27, 1997 through 11:00 p.m. MDT for July 28, 1997

Figure 9. Rainfall totals for the Fort Collins flood. Greatest amounts fell in the foothills over the western portion of the city. Figure adapted from Doesken and McKee (1998).

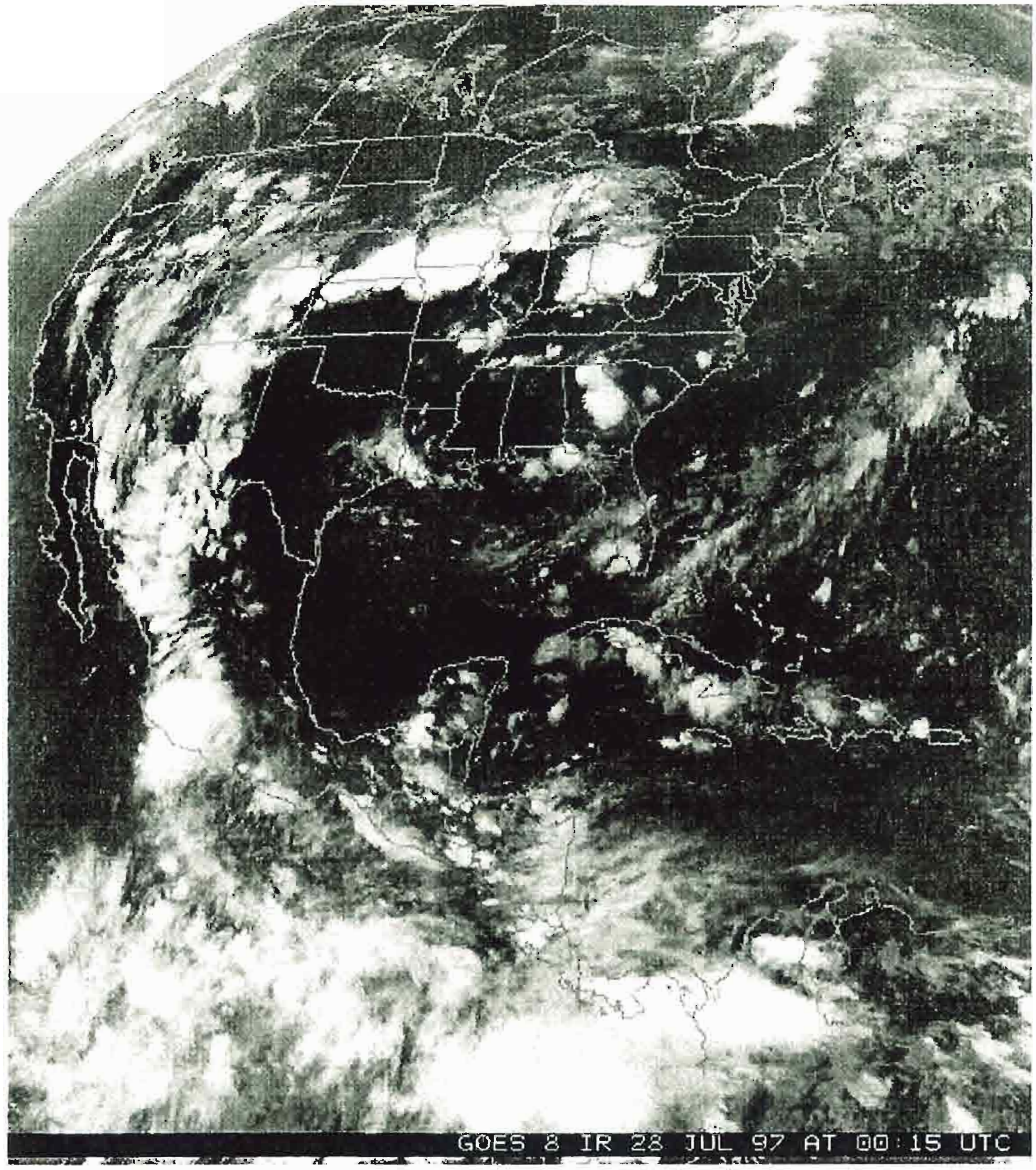

Figure 10. GOES 8 IR image for 28 July 1997 at 00:15 UTC, at about the time of the Fort Collins flooding. Moisture is transported northward by the NAM from the El Niño warmed waters of the eastern Pacific, along the spine of the Rockies, to the flood area.

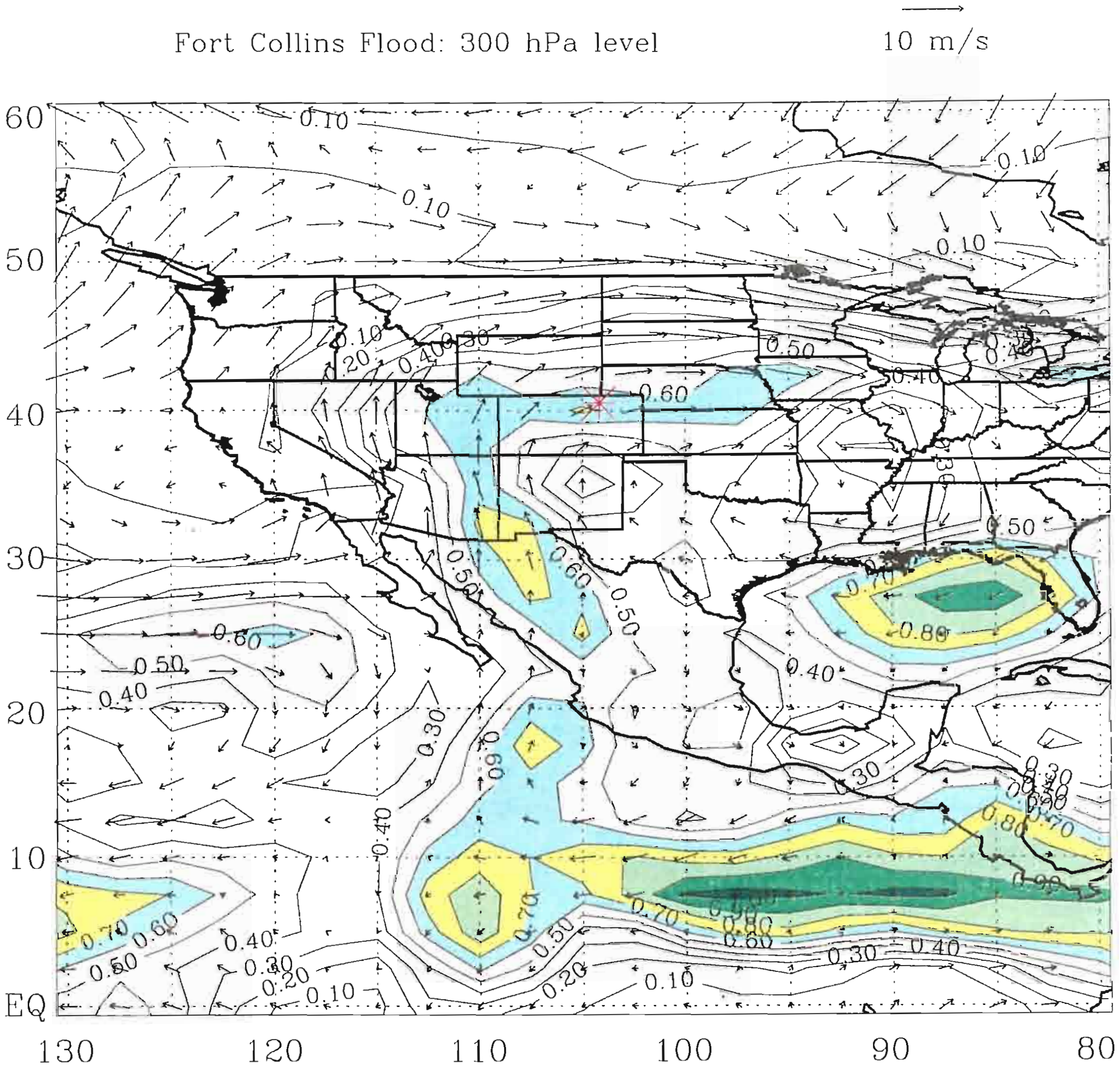

Figure 11. Specific humidity (g/kg) and vector winds (m/s) at the 300 hPa level at 12:00 UTC on 28 July 1997. The path of the moisture can be traced from its source region over the tropical eastern Pacific, north along the Rockies. Fort Collins is indicated by a red star.

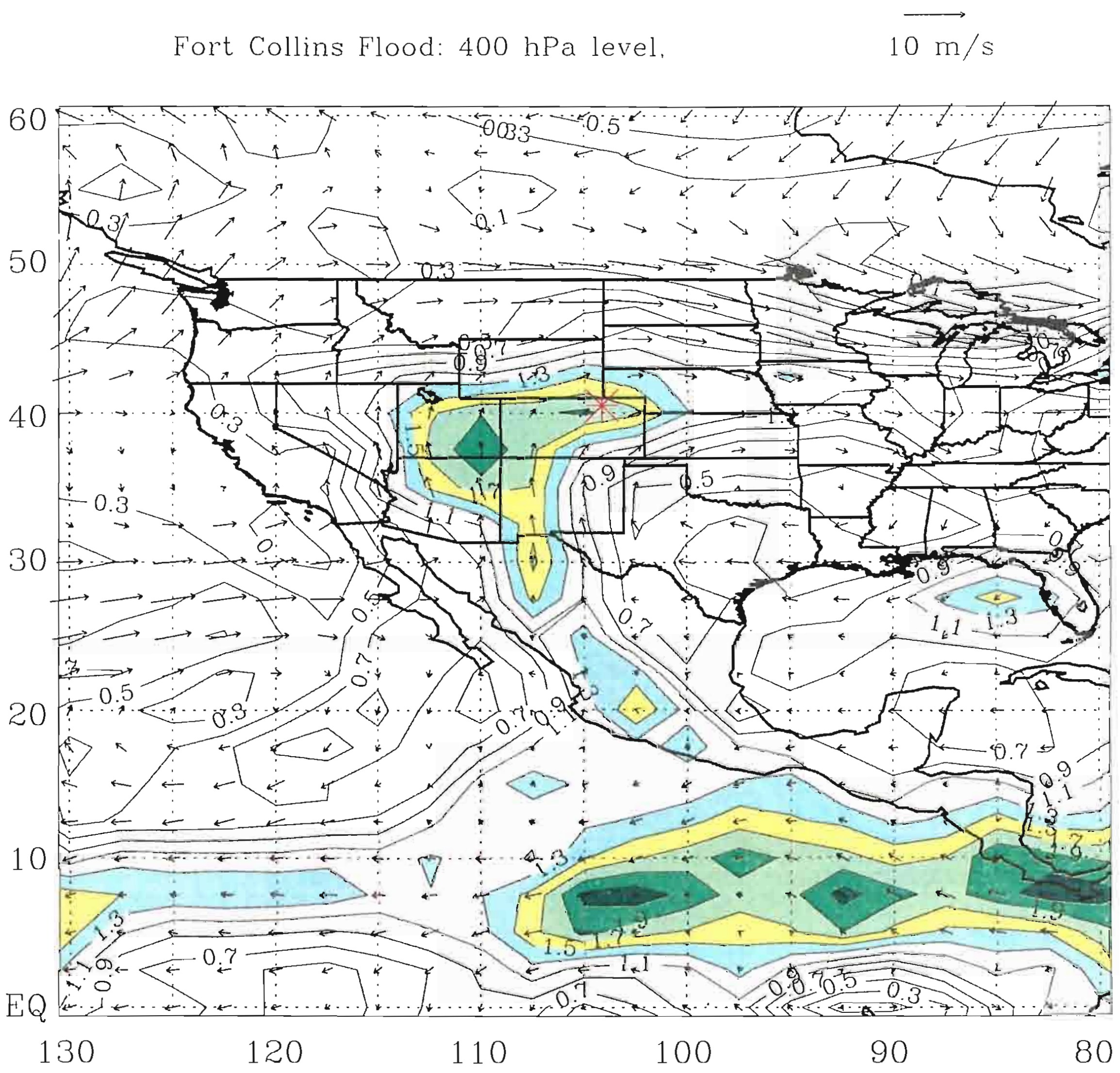

Figure 12. Specific humidity (g/kg) and vector winds (m/s) at the 400 hPa level at 12:00 UTC on 28 July 1997. The pattern is very distinct, with indications of the northward transport of moisture.

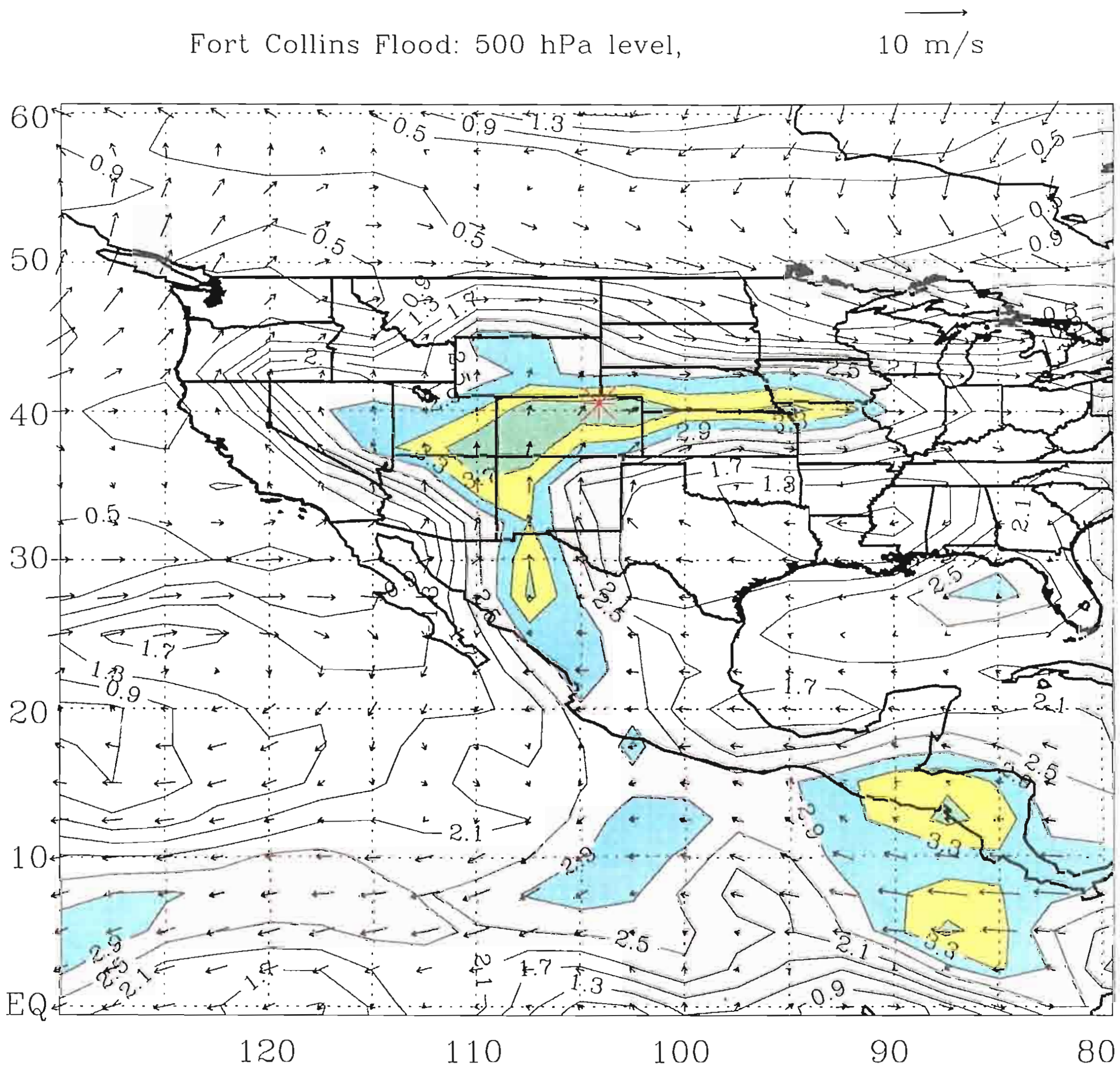

Figure 13. Specific humidity (g/kg) and vector winds (m/s) at the 500 hPa level at 12:00 UTC on 28 July 1997. Maximum specific humidity values are found near Fort Collins.

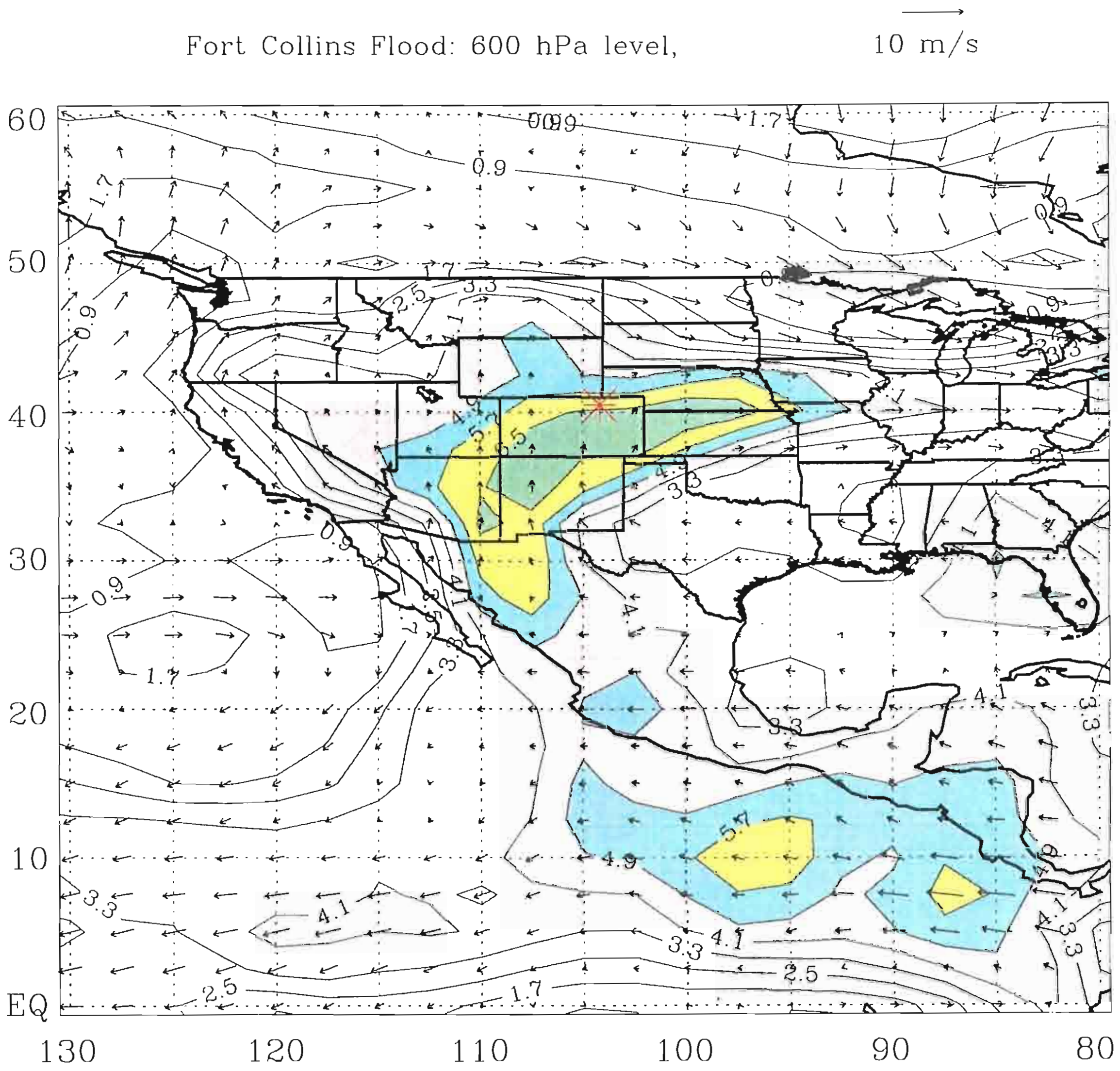

Figure 14. Specific humidity (g/kg) and vector winds (m/s) at the 600 hPa level at 12:00 UTC on 28 July 1997. Notice the light winds over the flood region.

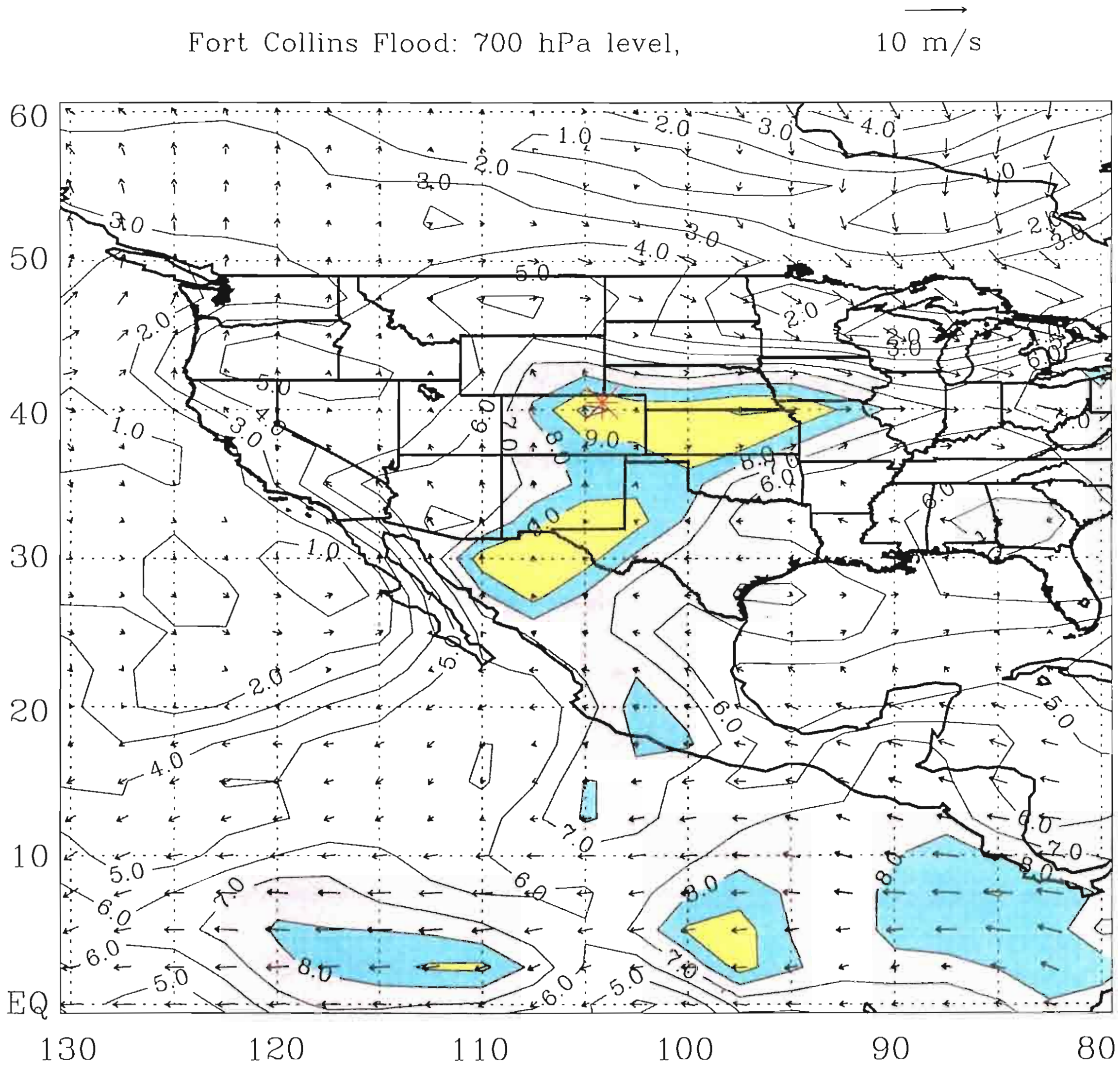

Figure 15. Specific humidity (g/kg) and vector winds (m/s) at the 700 hPa level at 12:00 UTC on 28 July 1997. Again, notice the very light winds over Colorado.

rain characteristics, including relatively little lightning, no hail, warm cloud top temperatures and, most importantly, efficient precipitation growth. 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. The high humidity also fosters weak downdrafts. Multi-parameter radar data also suggests that the FC storm exhibits tropical characteristics [*Peterson et al., 1999*].

At the surface, high dewpoints over eastern Colorado also indicate the presence of high levels of moisture. Surface winds are relatively light, and there are indications of a convergence line to the south of Fort Collins on the 27th of July. 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 preconditioner 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

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. 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. From this I conclude that the ENSO warm pool of the eastern Pacific is the upper-air moisture source in this case.

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 BTC was nearly stationary over its target 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

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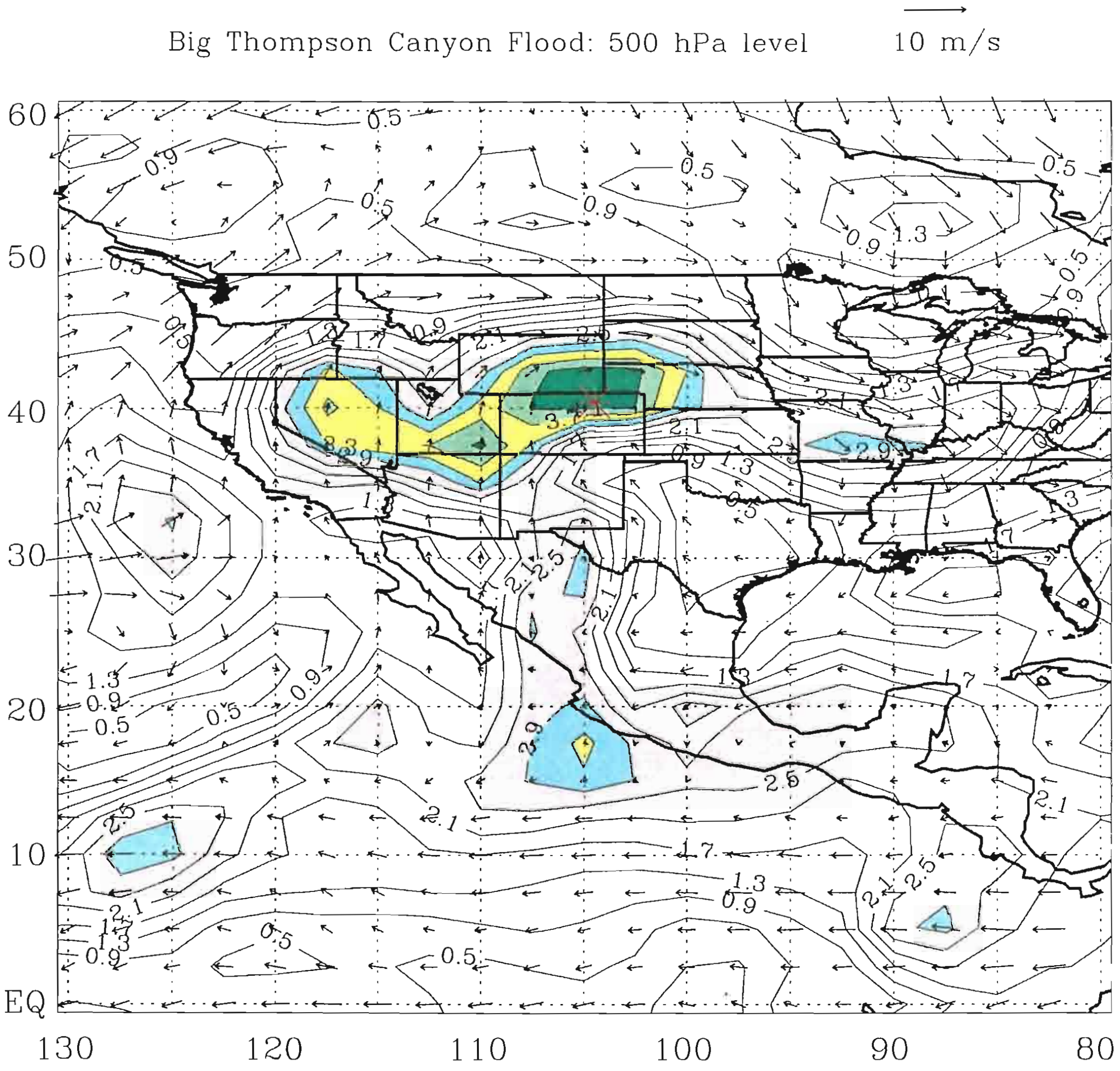

Figure 16. Specific humidity (g/kg) and vector winds (m/s) at the 500 hPa level at 12:00 UTC on 31 July 1976. The location of Big Thompson Canyon is indicated by a red star. As with the FC flood, maximum values of specific humidity are found near the flood location. Light winds advect the moisture north along the rocky mountains from the source region over the tropical eastern Pacific.

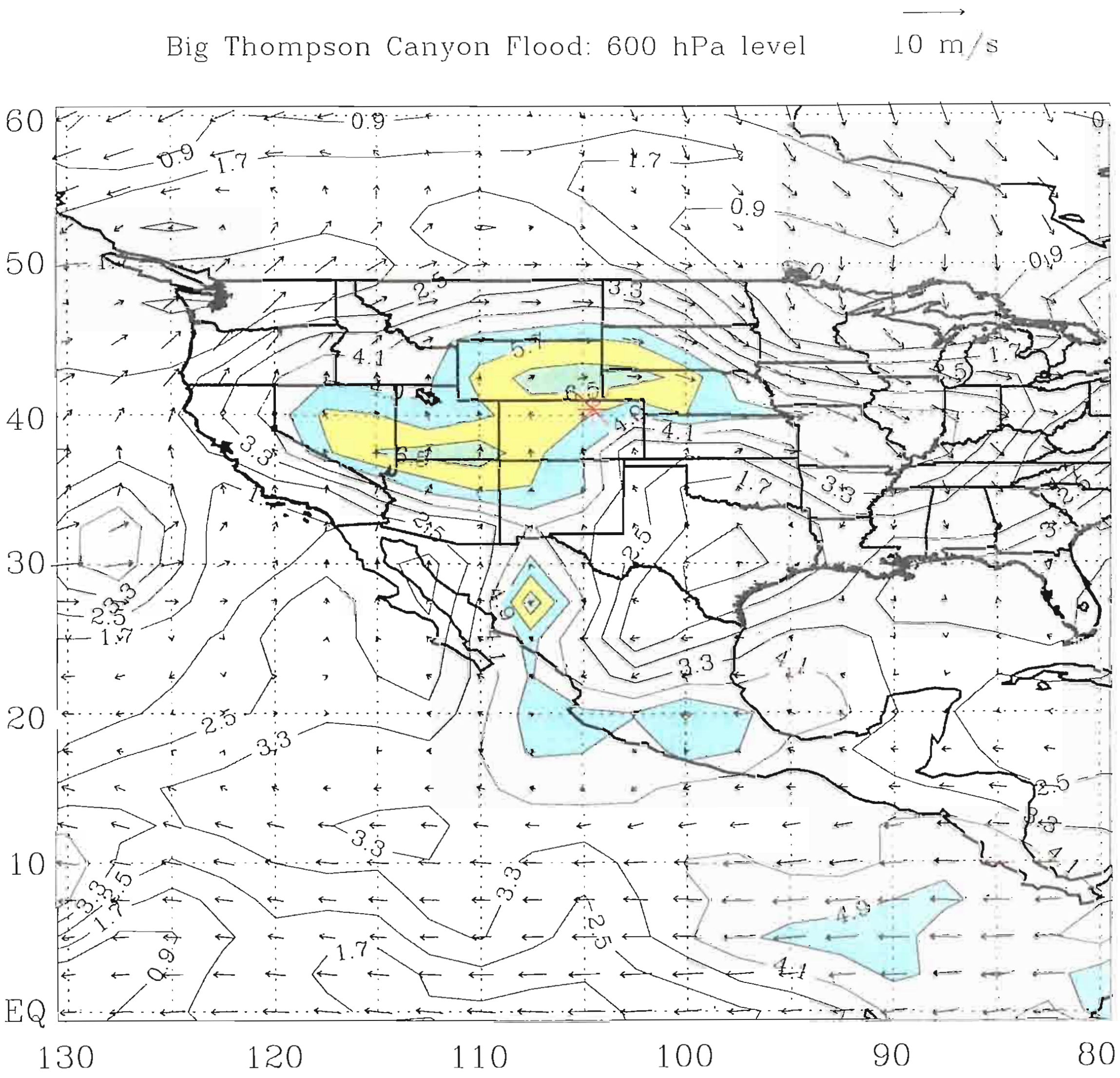

Figure 17. Specific humidity (g/kg) and vector winds (m/s) at the 600 hPa level at 12:00 UTC on 31 July 1976. Similar to figure 16. As with the FC storm, winds are very light over Colorado.

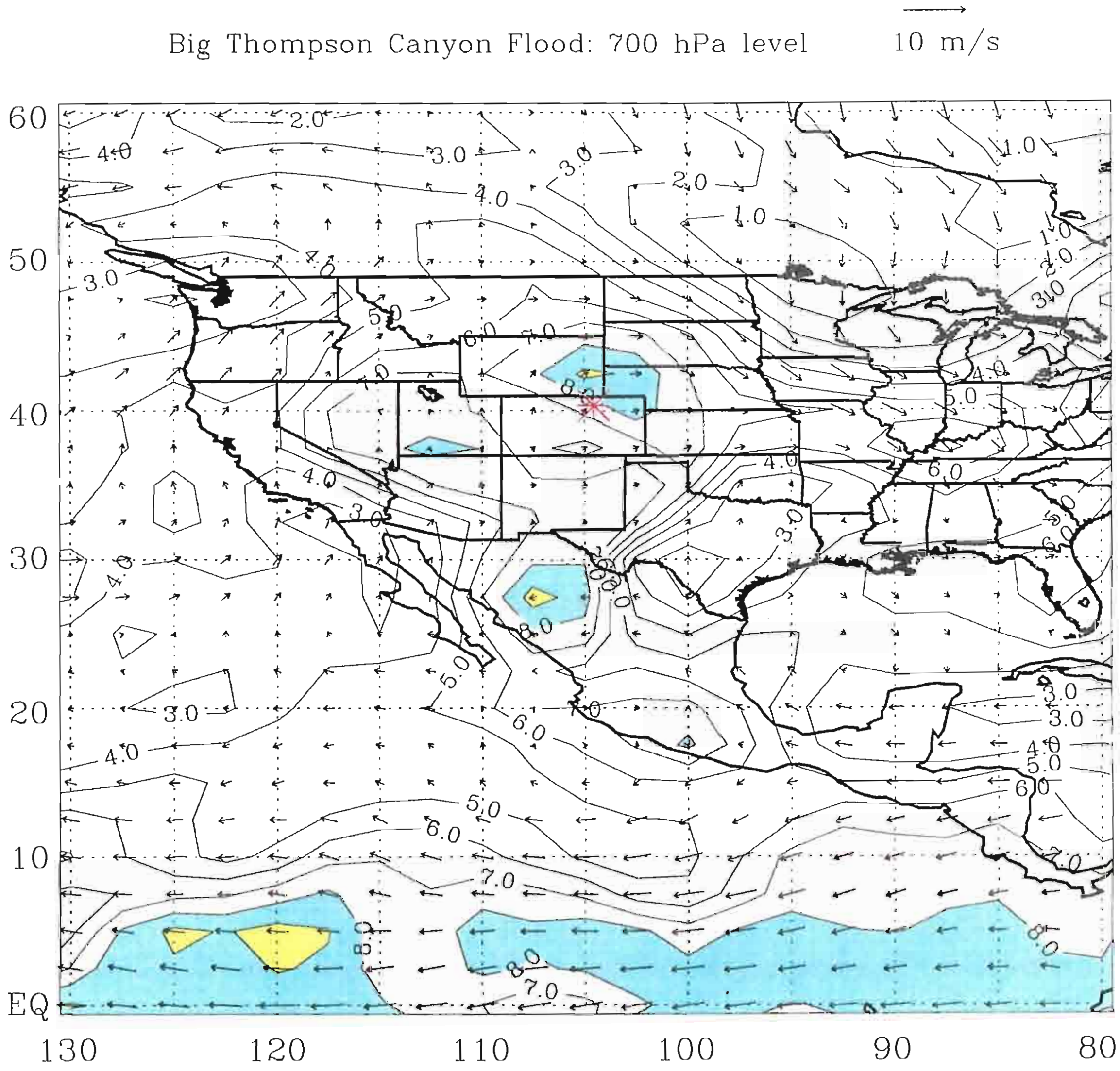

Figure 18. Specific humidity (g/kg) and vector winds (m/s) at the 700 hPa level at 12:00 UTC on 31 July 1976. Values of specific humidity over the Great Plains region are comparable to those values found over the tropical eastern Pacific.

storm. Once again, we find that 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.

At the surface, there is a nearly stationary front to the south of the flood area, with high dewpoint air to the north of this front. 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 path taken by this moisture is again clearly shown by NCEP data analyses of specific humidity values (figures 16 through 18). 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 values are lower overall for a given pressure level.

Another interesting finding is that as with the FC flood, the rain grows mainly through warm-cloud coalescence processes of the type most typical of tropical thunderstorms. It is found that the entrainment of moist air at the mid and upper levels again contributes to high precipitation efficiencies. Once again, the deep warm, moist layer of convective clouds fosters precipitation growth through warm-rain processes. The

again contributes to high precipitation efficiencies. Once again, the deep warm, moist layer of convective clouds fosters precipitation growth through warm-rain processes. 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.

4.3 The Rapid City Flood

The RC flood, which occurred on 9 through 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. Here again, we have light southeasterly winds advecting a moist, conditionally unstable airmass upslope into hilly terrain, in this case, the Black Hills of South Dakota. 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.

At the surface, a slow moving polar front lays to just to the south of the Rapid City area. Atmospheric soundings indicate a very deep, moist airmass to the north of this front. Precipitable water contents from the surface to 500 hPa are 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

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 monsoonal moisture of tropical origin to move north over the flood area. This is again illustrated by NCEP data analyses of specific humidity (figures 19 and 20), which shows a similar pattern to that of the BTC and RC events, although the moisture path seems shifted further east. Here again we have high moisture values over the equatorial Pacific feeding northward across southeastern Mexico, then across the Mexican and Texas Gulf coasts, across the Great Plains, to the flood region.

Importantly, the warm rain processes indicative of high precipitation efficiencies are present in this storm as well. 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. The source of this moisture is again the El-Niño warmed waters of the eastern Pacific.

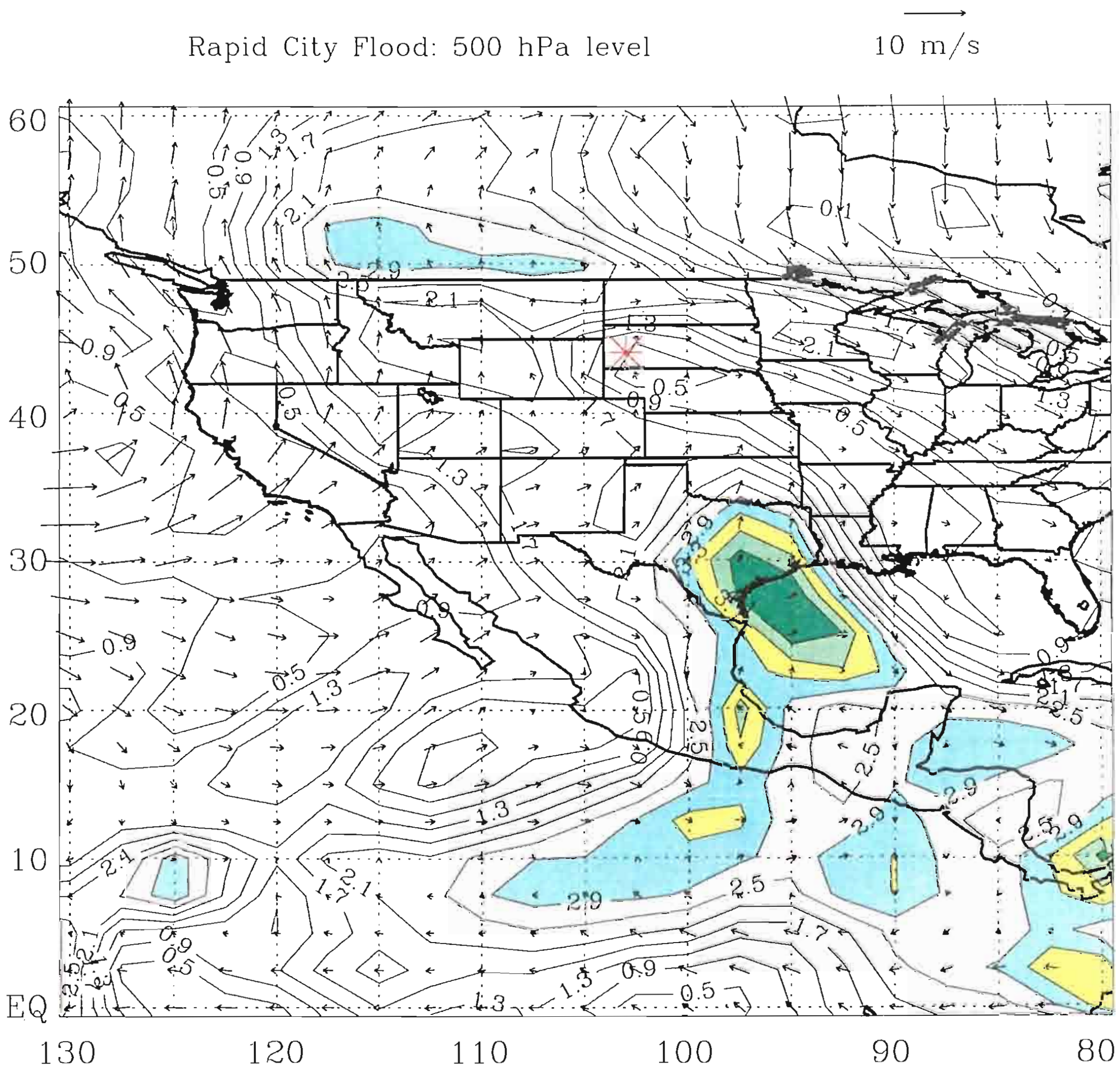

Figure 19. Specific humidity (g/kg) and vector winds (m/s) at the 500 hPa level at 12:00 UTC on 09 June 1972. The location of Rapid City is indicated by a red star. The path of the moisture is displaced further east as it leaves its source region as compared to the BTC and FC floods. It possibly mixes with moisture originating from the Gulf of Mexico.

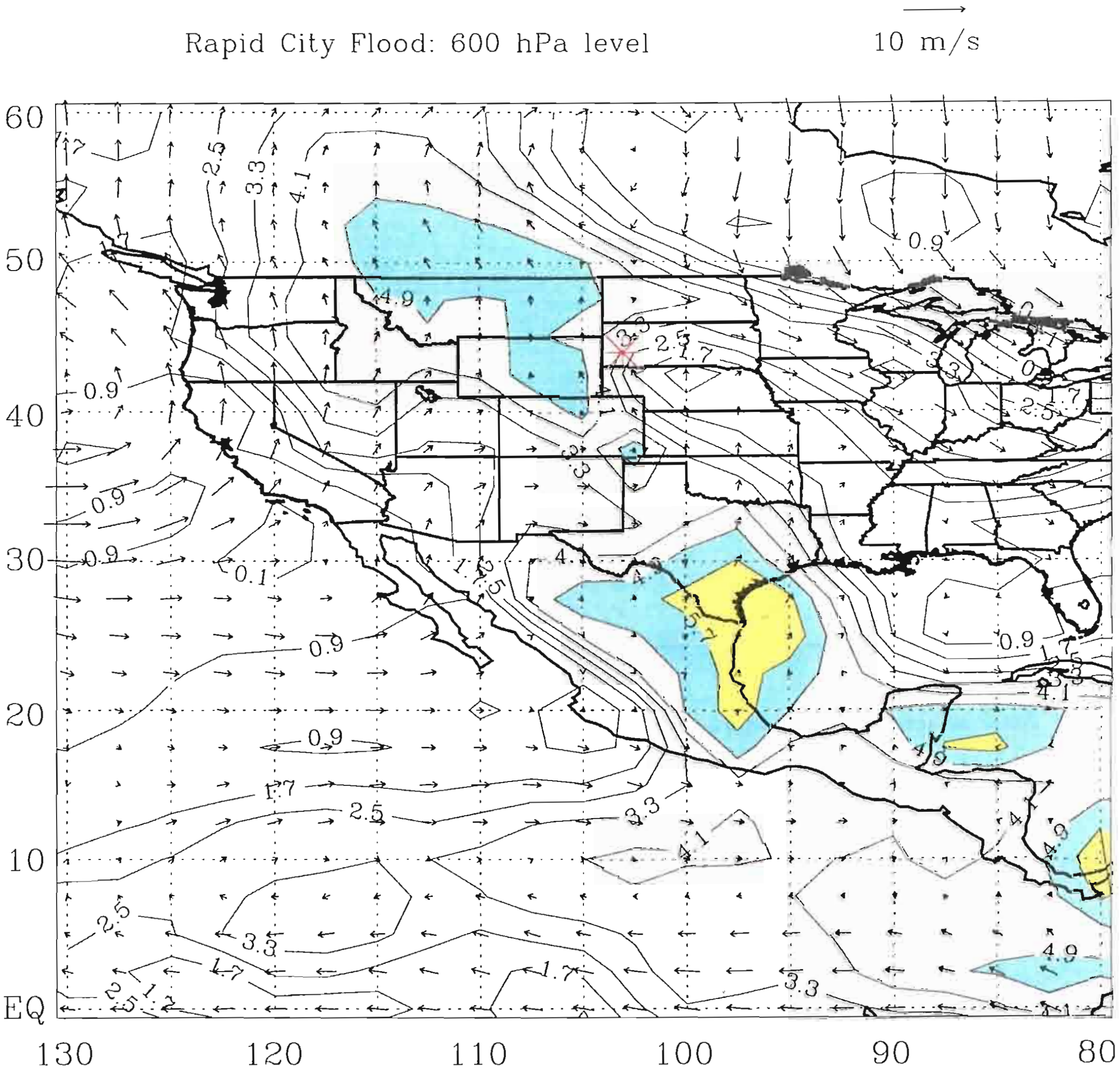

Figure 20. Specific humidity (g/kg) and vector winds (m/s) at the 600 hPa level at 12:00 UTC on 09 June 1972. Here the moisture follows a clearer path northwest across Texas, Colorado and Wyoming towards the flood region. Again, the path is displaced further east as compared to the other two floods. As with the other floods, winds are light over the flood region.

SECTION 5

AUXILIARY RESULTS

When categorizing storms by ENSO phase from the Colorado extreme storm precipitation data study [*McKee and Doesken, 1997*], the focus was on warm phase events (section 3.2). 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 and Area 2 regions. Although the look at flash flood frequency over the Front Range (section 3.1) did not include any cold phase years (1988 was the last ENSO cold phase before 1999), it would be reasonable to assume that flash flood frequency is greatly reduced during cold phase events. During cold phase events (section 3.4) 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 this phase of ENSO, decreased amounts of moisture are available for advection into the mid and upper levels of the troposphere, which in turn diminishes the amount of moisture advected at these levels into the western United States by the North American Monsoon. This in turn minimizes the ability of warm rain processes to occur over the study region, thus reducing the odds of a major flash flood of the type studied, or flash floods in general, to occur. It would not eliminate the possibility of a severe flash flood

study region, thus reducing the odds of a major flash flood of the type studied, or flash floods in general, to occur. It would not eliminate the possibility of a severe flash flood

occurring during a cold phase event. Other factors that influence the formation and severity of flash floods (Section 1), as well as the terrain anchoring effect, will still come into play even if the warm rain processes do not. 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 upper-level tropospheric moisture for cold phase ENSO events using NCEP data would help resolve this question.

SECTION 6

CONCLUSIONS

Three major flash flood events, two that occurred in the front range of the Colorado Rockies and one that occurred in the Black Hills of South Dakota, all happened during the onset summer of an ENSO warm phase. These events are compared to determine the synoptic mechanism. A quick look at flash flood frequency in general over the Front Range shows 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 could typically be expected produce a flash flood shows that these types of storms are much more frequent over the Front Range during a warm phase ENSO event. Extreme storms of this type are least common during cold phase ENSO events.

The three flood events were examined as case studies. The major meteorological aspects of their associated storms are found 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

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 easterly flow, allows the three storms to remain approximately stationary. This allows anomalous amounts of precipitation to accumulate over the headwaters of their respective drainage basins, leading to the catastrophic flooding. The second feature that acted to produce the extreme rainfall amounts is anomalously high levels of mid-tropospheric moisture of tropical origin. The presence of this moisture lead to efficient precipitation growth typical of warm rain processes that are common to tropical orographic storms, 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.

It is known that during a warm phase ENSO event that convective activity increases 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 study areas. When the other conditions are just right, this moisture enhances the warm rain processes that drive the storms to produce the flash flooding. 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 found the significant

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synoptic mechanisms for the production of severe flash flooding over this region. The ability to forecast the likelihood of disastrous floods using a technique based on the presence or absence of these mechanisms can 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*). This 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 its onset will alert the forecaster to look for the other signatures.
- From water vapor channel satellite imagery, 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 (figure 10).
- 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 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

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 (see figure 3). As shown in Section 3.2, the greatest danger of intense storms and flash flooding to be at eastern base of the Rocky Mountains.
- For the shorter term forecast, the following should be looked for:
  - At 500 hPa, short wave traveling northward along the backside of the long-wave trough. This short wave can help serve as a triggering mechanism for the storm in addition to the orographic effect.
  - 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.

6.2 Future Research

Further work can be done on the applicability of this research to other areas, especially along the rest of the eastern-facing slopes of the Rocky Mountains. Since nature knows no political boundaries, it would be logical to assume that these findings may also apply to regions outside of the Colorado study area (such as northward into Wyoming and southward into New Mexico) that share common topographic features. Findings of applicability to these regions would greatly increase the utility of the

Wyoming and southward into New Mexico) that share common topographic features. Findings of applicability to these regions would greatly increase the utility of the

methods outlined here.

Further case studies of extreme storms that occurred over the Colorado Front Range can also be done. 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, upper-level moisture climatologies, GCM simulations and moisture budget and transport studies can also be done to further determine the typical moisture sources and transport mechanisms during all the phases of ENSO.

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BIOGRAPHICAL SKETCH

Richard Emil Kreitner was born on 2 February 1960 in Oceanside, New York. He attended the State University of New York at Oneonta and Cornell University in Ithaca, New York, where he received a B.S. degree in Atmospheric Science in January of 1983. That year he attended the U.S. Navy's Officer Candidate School in Newport, Rhode Island and received his commission as a Geophysics Officer in June. He served on active duty for 12 years, serving 2 tours of duty aboard oceanographic research ships, the NOAA ship Discoverer and the USNS Chauvenet. While onboard the Chauvenet he planned and participated in shallow water bathymetric surveys around Indonesia and the Philippines. Onboard the Discoverer he served as the Executive Officer of a unit that conducted deep-ocean gravity, magnetic and bathymetric surveys in the Pacific Ocean. During Operation Desert Storm, while aboard the USS Guadalcanal, an amphibious helicopter carrier, he served as Staff Oceanographer and ship's Meteorologist. Here he provided meteorological and oceanographic support to the ship, the embarked air wing and surrounding battle group. Richard has also served at several shore commands. He was assigned to the Naval Environmental Prediction Research Facility (now part of the Naval Research Laboratory) in Monterey California as a Research and Security Officer. He also served at two major regional naval weather centers (the Naval Eastern Oceanography Center and the Naval Pacific Meteorology and Oceanography Center) as Command Duty Officer. At these centers he supervised divisions responsible for providing a wide range of environmental support to a number of shore activities and ships at sea. After leaving active duty in 1995, he joined the Naval Reserve. Now a Lieutenant Commander in the Reserves, he is presently assigned as the Staff Oceanographer to the Commander, U.S. Naval Central Command (COMUSNAVCENT). He has served several tours of active duty with COMUSNAVCENT in Bahrain where he provided environmental support for strike missions over Iraq. Richard also attended Florida State University (FSU) in Tallahassee, where he worked as a Research Assistant for Dr. James J. O'Brien at the Center for Ocean/Atmospheric Prediction Studies. He received a Master of Science degree in Meteorology from FSU in August of 1999.