Extratropical Control of Monsoonal Surges in the Northern Great Basin

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Atmospheric Science

by

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December 2011
We recommend that the thesis prepared under our supervision by

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entitled

Extratropic Control Of Monsoonal Surges In The Northern Great Basin

be accepted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

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December, 2011
The northwestern fringe of the North American Monsoon (NAM) circulation covering the Great Basin of the United States is characterized by highly variable intraseasonal convective precipitation activity. Although typically dry during the summer months, sporadic moisture pulses associated with transient monsoonal surges interacting with mid-latitude disturbances yield low-frequency high-impact events including lightning-ignited wildfires and flash floods. Mountainous terrain in the Northern Great Basin (NGB) is extremely vulnerable to the dangers of monsoonal convection as the initial development of convective showers typically occurs over high-altitude terrain due to differential heating between the terrain and surrounding atmosphere. We have incorporated expert knowledge from four National Weather Service Offices in the NGB along with 30 years (1980-2009) of data from the North American Regional Reanalysis (NARR) to answer the following question: What mechanisms fuel monsoonal moisture surges into the NGB?

In order to better understand the nature of these surges, an objective means of identifying surge events was done using precipitable water and vertically-integrated moisture flux during the months of July-September. Preliminary results indicate that moisture surges are associated with either a progressive mid-latitude trough that infiltrates the West Coast, or a strong four-corners ridge. Trough event signals reveal statistically significant moisture flux extending from the northern Gulf of California northward into southeast Idaho with positive flux anomalies on the order of 70-100 kg/m²/s. With ridge events, we see a similar trend but with a greater northward extension.
of moisture flux into northern Idaho with similar anomaly values as that of trough events. Additionally, 330K isentropic potential vorticity (IPV) was plotted for various case studies in order to better understand if there exists a Rossby Wave Break signal (e.g., Postel and Hitchman 1999; Abatzoglou and Magnusdottir 2006) prior to the monsoonal outbreaks in the NGB. There is a strong possibility that these extratropical wave breaks play a significant role in adjusting the subtropical dynamics which lead to enhanced moisture surges northward. Our results also suggest large interannual variability with a significant number of these events occurring during 82/83 and 97/98 coincident with strong El Nino events. Ultimately, we would like the results of our work to be readily translatable to forecasters in order to improve the predictability of these events.
I would like to thank my “official” committee members, Michael Kaplan, Darko Koracin, and Fred Harris, for their support, advice, and time. I would also like to send a huge special thanks to my non-committee member John Abatzoglou who has taught me the majority of what I know about meteorology and for being a mentor and friend all throughout my academic career from undergrad through grad school. I’d like to thank the National Science Foundation (NSF) for their funding of this project. A heartfelt thank you to everyone at the Desert Research Institute who assisted in this project and who provided friendship, advice, and support. I would like to thank Michael Kaplan for all of his assistance and guidance in this project and for always being incredibly supportive and understanding. Finally, I would like to thank my friends and family for always being there for me and for helping me with the steps that it took to get back into and through a Master’s degree. Also I’d like to give a heartfelt thanks to my mom, dad, and sister for their continued and endless support!
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1. INTRODUCTION

The northwestern fringe of the North American Monsoon (NAM) circulation which covers the Great Basin of the United States is characterized by highly variable intraseasonal activity. The infrequent nature of summertime precipitation events over the NGB results in low-frequency high-impact events that are a noted concern for flash flooding. In addition, on the leading edge of surge events, dry-lightning ignitions provide a threat for land managers due to the high wildfire potential. While there is a strong influence from the subtropics on the NAM (Carleton 1986, 1987; Watson et al. 1994), the question of how mid-latitude dynamics provide and direct monsoonal moisture northward into the Great Basin remains unanswered.

Previous work has attempted to understand the mechanism of moisture transport into the Southwest United States. Past research has concluded that the moisture is transported from the tropics into the desert Southwest (Douglas et al. 1993; Douglas 1995) via tropical easterly waves (Stensrud et al. 1995; 1997; Fuller and Stensrud 2000). At its research infancy, monsoonal precipitation in the NGB was linked to seasonal mid-tropospheric variations of large scale pressure systems (Bryson and Lowry 1955). Years later, the presence of a significant low-level jet providing moisture from the Gulf of California into the Great Basin was discussed by Hales (1972), Brenner (1974), and Carleton (1986). The influence of tropical cyclones on southern Great Basin precipitation has been discussed in Corbosiero et al. (2009) concluding that a significant portion of summer rainfall occurs when tropical cyclones propagate northward into the Southwest US.
As stated in the NSF monsoon project proposal, “The upper-tropospheric monsoonal anticyclone is hypothesized to play a dominant role in such coupling processes as it provides an interface between extratropical and tropical circulations. The upper-tropospheric ridge over North America is a quasi-stationary feature embedded within the summertime mid-latitude Rossby wave pattern that arises in response to large-scale diabatic heating and topographic forcing (Ting 1994). Higgins et al. (2004) suggest that the relative location of the upper-tropospheric monsoonal ridge is more important than the occurrence of easterly waves in discriminating significant moist surges from weaker surges of relatively dry air. A northeast shift in the monsoonal ridge is shown to promote convective outbreaks over the poleward fringes of monsoon region through both enhanced poleward moisture transport and enhanced large-scale convective instability. Prior work has failed to show the dynamical mechanisms that lead to the northeast shift in the monsoonal ridge.

Large-scale Rossby waves that circumnavigate the extratropics are primarily responsible for defining much of the weather and climate experienced outside of the tropics. The upper-tropospheric monsoonal ridge over North America during June-August exemplifies a quasi-stationary wave pattern that governs meteorological conditions over much of the continent. The jet stream provides the restoring mechanism for quasi-geostrophic (QG) wave propagation. However, wave propagation is not possible when the jet is unable to provide a sufficient restoring mechanism (e.g., jet exit region). Large amplitude RWB follows as the wave undulates irreversibly, and mixes potential vorticity (PV) between the tropical and extratropics (McIntyre and Palmer 1983).”
Prior to the start of performing this research, communication with multiple NGB National Weather Service Weather Forecasting Office (NWS-WFO) Science Operation Officers (SOO) was established and feedback was acquired in response to the question, “how do these convective surges impact your region of the northern Great Basin and what needs to be done to better forecast/predict them?” The responses to this question can be seen in Appendix 1 for the four NWS-WFO stations surveyed.

The current scientific gap in understanding the northward extension of the monsoon which exists requires answering the question of how the extratropical circulation control the northward progression of moisture surges as they interact with complex terrain features. There is currently limited knowledge and literature on the relative influence of tropical and extratropical processes in providing an environment conducive to monsoonal surges as well as their triggering processes. A better understanding of these events is needed to increase the accuracy of short term-to-medium range monsoonal forecasts. To do this, previous theories will be applied in conjunction with a novel set of analyses linking the extratropics, tropics, and mesoscale dynamics which ultimately drive moisture surges poleward.

Moisture surges that affect the Great Basin are hypothesized to occur through three mechanisms. Testing the relative importance of these three mechanisms is the central focus of our research study. These three mechanisms are: (1) The location and intensity of the four-corners ridge established over the mid-US which acts as the initiating mechanism for moisture transport from the subtropics to the extratropics. (2) Shortwave troughs and cut-off lows which migrate through the interior Western U.S. or are positioned off the West Coast of the U.S., respectively, are hypothesized to provide
increased instability aloft plus an enhancement to the mid-upper level steering current responsible for the northward moisture transport from the monsoonal core. (3) RWB is hypothesized to destabilize the atmosphere in the Great Basin by initiating cool air advection and/or ascent aloft (if the break occurs near the NGB) and also modify the subtropical jet near Northern Mexico/Gulf of Mexico (if the wave break occurs in the Eastern U.S. extending southward near the Gulf of Mexico). The focus of this research is a better understanding of these three mechanisms. Practically, this better understanding of processes leading to significant moisture flux into the Great Basin is the end goal of this research in order to improve monsoonal forecast accuracy in the often ignored NGB.
2. DATA AND METHODOLOGY

30 years of North American Regional Reanalysis (NARR) and National Centers for Environmental Prediction (NCEP) Reanalysis data for the months of July, August, and September (JAS) were acquired (Meisner et al. 2006; Kalnay et al. 1996). The NARR data consists of a fully cycled 3-hr ETA data assimilation system with lateral boundary conditions supplied by the Global Reanalysis 2. Horizontal grid resolution is 32km with 45 vertical layers included as can be seen in Figure 1.

![NARR Grid](image1.png)

Figure 1: Grid spacing for the North American Regional Reanalysis (NARR) dataset. Each dot represents a datapoint within the NARR dataset.

Data for this study consists of a temporal resolution of daily averaged data from 1979-2003. The NARR data analyzed consists of precipitable water (PWATER), integrated water vapor flux (IWVF), precipitation (PPT), and both zonal (UWND) and meridional winds (VWND). PWATER is the depth of the amount of water in a column of the atmosphere if all the water in that column were precipitated as rain. As a depth, the
PWATER is measured in millimeters or inches. For this study we will use inches as is commonly used by operational NWS meteorologists. The IWVF NARR data is a derived field calculated directly from the NARR pressure field of winds and specific humidity using finite differencing between the surface and 500mb. The NCEP data consisted of temperature, as well as zonal, and meridional winds at 500, 400, 300, 250, 200, and 150 mb which was then used to compute isentropic potential vorticity (IPV). To acquire the event dates in which the most significant moisture propagated into the Great Basin, the intersection of the 90\(^{th}\) percentile of precipitatable water (PW) and integrated water vapor flux (IWVF) were taken. A total of 26 events (16 trough and 10 ridge events) resulted and were analyzed further in depth.

30 years of precipitation data for the same temporal period as the NARR data were acquired from the NASA Land Data Assimilation Systems (NLDAS). These data were acquired for higher resolution precipitation visualization purposes for both individual events and composit ed events. NARR data has been known to have some flaws at lower levels (sub-925mb) and thus obtaining another precipitation data source was necessary. The main source of NLDAS-1 forcing is NCEP's Eta model-based Data Assimilation System (EDAS) (Rogers et al., 1995) which represents a continuously-cycled North American 4DDA system. It uses 3-hourly analysis-forecast cycles to derive atmospheric states by assimilating many types of observations, including station observations of surface pressure and screen-level atmospheric temperature, humidity, and U and V wind components. EDAS 3-hourly fields of the latter five variables plus surface downward shortwave and longwave radiation and total/convective precipitation are provided on a 40-km grid, and then interpolated spatially to the NLDAS grid and
temporally to one hour. NLDAS-1 precipitation forcing over CONUS is anchored to NCEP’s 1/4th degree gauge-only daily precipitation analyses of Higgins et al. (2000). In NLDAS-1, this daily analysis is interpolated to 1/8th-degree, then temporally disaggregated to hourly values by applying hourly weights derived from hourly 4-km, radar-based (WSR-88D) precipitation fields. The latter radar-based fields are used only to derive disaggregation weights and do not change the daily total precipitation. Finally, convective precipitation is estimated by multiplying NLDAS-1 total precipitation by the ratio of EDAS convective to EDAS total precipitation. The Convective Available Potential Energy (CAPE) is the final variable in the forcing dataset, also interpolated from EDAS.

NCEP/NCAR 40-yr reanalysis data was primarily used to derive isentropic potential vorticity (IPV) values at 330K through 360K. The NCEP/NCAR 40-yr reanalysis uses a frozen state-of-the-art global data assimilation system and a database as complete as possible. The data assimilation and the model used are identical to the global system implemented operationally at the NCEP on 11 January 1995, except that the horizontal resolution is T62 (about 210 km). This includes land surface, ship, rawinsonde, pibal, aircraft, and satellite data which is quality controlled and assimilated with a data assimilation system that is kept unchanged over the reanalysis period 1957–2010. For this study only data from 1980-2009 were used for the months July-September. This period was used because of the required temporal consistency with the NARR datsets which were only available during that period.
3. ANALYSIS

Analysis of IWVF, PW, and precipitation at the following NWS-WFO offices: Salt Lake City, UT (SLC), Elko, NV (EKO), Pocatello, ID (PIH) and Reno, NV (REV) were done and can be seen in Figures 2–4. SLC revealed an increase in daily climatological precipitation after the end of August with a dominant zonal IWVF (U-IWVF) component. On the other hand IWVF was primarily dominated by the meridional component (V-IWVF) in the Nevada NWS-WFO locations. EKO had greater overall daily climatological precipitation and V-IWVF than REV with the greatest average precipitation after the end of August. This finding is expected as the synoptic pattern becomes more transitional and extratropical troughs progress southeastward. Before the end of August, U-IWVF and V-IWVF components trade off as dominant IWVF influence during the warm season months. The PIH NWS-WFO office experiences a dominant moisture flux from the U-IWVF component and overall experienced the greatest precipitation and total IWVF of all NGB states. In general, the average PW hovered around 0.5 inches for all NWS-WFO locations. All offices in the NGB revealed a decrease in V-IWVF influence after late August which, again, is reflective of an increasingly synoptic scale baroclinic environment contributing to the influx of moisture from the SSW.
Figure 2: Salt Lake City, UT National Weather Service – Weather Forecast Office time series for warm season months (July-September) of daily climatological means for precipitation (inches) (top row), integrated water vapor flux (kg/m/s) (middle row), precipitable water (kg/m²) (bottom row).

Figure 3: Elko, NV National Weather Service – Weather Forecast Office time series for warm season months (July-September) of daily climatological means for precipitation (inches) (top row), integrated water vapor flux (kg/m/s) (middle row), precipitable water (kg/m²) (bottom row).
Figure 4: Reno, NV National Weather Service – Weather Forecast Office time series for warm season months (July-September) of daily climatological means for precipitation (inches) (top row), integrated water vapor flux (kg/m/s) (middle row), precipitable water (kg/m²) (bottom row)

Figure 5: Pocatello, ID National Weather Service – Weather Forecast Office time series for warm season months (July-September) of daily climatological means for precipitation (inches) (top row), integrated water vapor flux (kg/m/s) (middle row), precipitable water (kg/m²) (bottom row)
In order to visually understand the relationship between the IWVF, PW, and precipitation, a three-dimensional plot, seen in Figure 6, was created to illustrate how IWVF and PW affect accumulated daily precipitation in the NGB. The domain for the NGB contains latitudinal bounds between 38.5°N and 43°N and longitudinal bounds between -120°W and -112°W. There are a total of 2760 points on the plot representing 92 July-August-September (JAS) days over a 30 year span from 1980-2009. The more enhanced the shape size, the more precipitation accumulated in the NGB for that given day. What can be partially concluded, subjectively, is that larger precipitation events are a result of IWVF being at the 90th percentile threshold value of ~130 kg/m/s more so than the 90th percentile value of PW at 0.7 inches. This is an important statistic because one of the primary metrics by the National Weather Service (NWS) of whether the Great Basin will have a chance at significant summer-time precipitation is PW. Past area forecast discussions have mentioned PW values of ~0.6 inches and associated this with sufficient atmospheric column moisture for convective cells to form. Although this may be true, the influence of enhanced IWVF also adds to formation of convection in the Great Basin which can contribute to significant precipitation or on the other hand dry lightning scenarios. This IWVF metric may be more useful than PW because of its explicit dependence on kinematics, i.e., on moisture advection.
3.1 CASE STUDIES

Two case studies were analyzed and will be discussed. The analysis of the 9 September 1998 case study is an example of a trough-influenced surge event resulting in significant accumulated precipitation in the NGB (Figure 7) while the other case study is an example of significant IWVF and PW resulting in insignificant accumulated precipitation.
Figure 7: Precipitation (inches) for the 9 September 1998 case study with the event day being (e) with four days before (a-d) and one day after (f).

As seen in Figure 8, geopotential heights for the 5 September 1998 subplot (a) reveals a cut-off low positioned over southern California and as a response the cut-off, with a strong high pressure system just east of the four-corners region, acts as a mechanism to transport moisture from the south-southeast as can be seen in both the IWVF daily time series (Figure 9) and in the 700mb winds (Figure 10). While typically with these events the moisture plume progresses from the Gulf of California into the Great Basin, this case study has two episodes of moisture channeling into the Great Basin. The initial cut-off low present a few days before the event day in subplot (e) acts to moisten the NGB region but is then followed by a combination of enhanced moisture flux from Tropical Storm Javier in extreme southern Baja Mexico and an upper-level progressive trough moving into the NGB. This acts to further extend subtropical moisture into the NGB region while destabilizing the atmosphere. While Javier may not
necessarily be solely responsible for the moisture extension into the Great Basin, its strong southerly winds located on the east side of the cyclonic system adds a channel of significant southerly IWVF from the tropics into the subtropics. As seen on the event day once the trough from the eastern Pacific progresses over California, the southerly flow in the exit region of the low enhances the IWVF. This preconditioning is a result of Javier. Impressively, the northward extension of IWVF can be seen over parts of southern Canada with values exceeding ~200 kg/m/s. While the lower levels are being provided moisture early on from the Gulf of Mexico (GOM) and the Gulf of California (GOC) during the event day, the mid-to-upper levels are being modified by the onset of the upper-level trough over the NGB.

Figure 8. 500mb geopotential heights for the 9 September 1998 case study with the event day being (e) with four days before (a-d) and one day after (f).
Figure 9: Integrated Water Vapor Flux (kg/m/s) (NARR) for the 9 September 1998 case study with the event day being (e) with four days before (a-d) and one day after (f).

Figure 10: 700mb winds (m/s) (NARR) for the 9 September 1998 case study with the event day being (e) with four days before (a-d) and one day after (f).

Figures 11 and 12 show the 500mb and 250mb winds, respectively, for the event day sequence revealing strong upper-level winds contributing to the enhancement of upper-level divergence. This divergence is needed for convective cells over the NGB to develop and maintain their intensity as it forces upward vertical motion and adiabatic
cooling/lapse rate destabilization. 850-500mb lapse rates in the region of interest on and one day before the events day are ~7 – 7.5 C/km signifying destabilization of the atmosphere conducive to a convective environment (Figure 13). In regards to RWB, it can be seen that one day prior to the event day RWB occurs and is positioned over the northern California Sierras and western Nevada (Figure 14). 330K isentropic potential vorticity (IPV) was plotted here to graphically represent the nature of this wavebreak. RWB may be regarded as the rapid and irreversible deformation of PV contours (McIntyre and Palmer 1984). The velocity field connected with RWB drives a cascade of momentum to fine scales of motion where an intensification of gradients and the enhancement of mixing processes occur simultaneously. Impacts of RWB on subtropical dynamics have been shown by Kiladis (1998), who discussed how the influx of PV-rich air into the subtropics can produce convective outbreaks. This can be applied similarly to the monsoonal outbreak we see in the NGB as subtropical moisture propagates northward intersecting the higher IPV region. Once this occurs there exists a stratosphere-troposphere exchange along the horizontal isentropes between the extratropical lower stratosphere (higher PV) and the upper troposphere (lower PV). This synoptic scale interaction can modify temperatures and increase lapse rates significantly while modifying the static stability in the mid-to-upper tropospheric layers. The origin of the wavebreak occurs 2-3 days prior to the event day. This brings up the question, why was there not a significant convective outbreak in the NGB a couple days before 9 September 1998? While there are those who argue that these significant precipitation events are mainly a result of dynamical forcing from the monsoon core, the reality is that in order for the NGB to see such intense convection, the timing of extratropical and subtropical
dynamics needs to be conterminous. This case in 1998 is a perfect example of that type of phased timing. Specifically, while the RWB amplified the poleward meridional structure of the ridge, the arrival of a propagating trough from the Pacific further enhanced the northward transport of monsoonal moisture.

Figure 11: 500mb winds (m/s) (NARR) for the 9 September 1998 case study with the event day being (e) with four days before (a-d) and one day after (f).

Figure 12: 250mb winds (m/s) (NARR) for the 9 September 1998 case study with the event day being (e) with four days before (a-d) and one day after (f).
A time series of the vertical NARR winds seen in Figure 15 for the 9 September 1998 case reveals a significant upper-level enhancement of winds at pressure levels above 600mb. This is consistent with an upper-level divergent wind pattern during an increasingly convective atmosphere over the NGB. The onset of the increasingly divergent wind pattern occurred at the upper levels (~200mb) initially on 9 September 1998 and 12 hours later extends down to the 400-500mb level. The flow during this case study is southwesterly after transitioning from a westerly pattern 2 days before the event day. It is important to note as well that there is a sudden southerly surge in the winds at 00z on 9 September 1998 which 6-9 hours later significantly enhances the southerly flow at 500mb and higher. This sudden enhancement of flow aloft is a synergistic sequential response to the favorable convective environment at levels greater than 500mb. As the synoptic scale adjustments transport PW and IWVF values large enough at these levels to support convection, the convective heating (below) and mass outflow (aloft) causes divergence aloft and this diverging flow represents a finer scale surge of mid-upper tropospheric wind. The surge at 00z at 750mb and lower is due to the surface low established because of the anomalously strong surface heating, i.e., air accelerating into the elevated low pressure center above the heated terrain. This produces enhanced convergence at the lower levels while the incoming and progressive trough provides the instability and divergent flow aloft and when combined with the enhanced moisture from the SSW provides a perfect scenario for convective storms in the NGB. Convection produces outflow which triggers sequential synergistic convection downstream as the outflow jet from upstream convection enhances downstream moisture transport and downstream diffluent flow. Convection acts to feedback to enhance secondary and
tertiary convective outbreaks

Figure 13: 850-500mb lapse rates and line contoured 500mb geopotential heights (geopotential meters) using NCEP-NCAR reanalysis for the 9 September 1998 case study with the event day being (e) with four days before (a-d) and one day after (f).

Figure 14: 330K isentropic potential vorticity (important 2-IPVU threshold indicated in red) derived using NCEP-NCAR reanalysis for the 9 September 1998 case study with the event day being (e) with four days before (a-d) and one day after (f).
Figure 15: Time series of vertical NARR winds (m/s) domain averaged in the Northern Great Basin for the 9 September 1998 case study.

In contrast to the previous case study, 2 September 1997 is a perfect example of a very strong high pressure system situated over the inter-mountain West as witnessed in the 500mb heights in Figure 16. The extension of the ridge stretches northward into parts of southern Canada. IWVF plots in Figure 17 reveal the high pressure system containing wrap-around moisture from the Gulf of Mexico and Gulf of California and limited precipitation on the event day in the NGB (Figure 18). Four days before the event day, the low-level jet strengthens and becomes increasingly amplified as the ridge intensifies over the intermountain West.
Figure 16: 500mb heights (geopotential meters) using NCEP-NCAR reanalysis for the 2 September 1997 case study with the event day being (e) with four days before (a-d) and one day after (f).

Figure 17: Integrated Water Vapor Flux (kg/m/s) (NARR) for the 2 September 1997 case study with the event day being (e) with four days before (a-d) and one day after (f).
Figure 18: Precipitation (inches) for the 2 September 1997 case study with the event day being (e) with four days before (a-d) and one day after (f).

This event, unlike many of the 26 events, has moisture propagating from not only the Gulf of California but the Gulf of Mexico as well. An increase in IWVF translates into enhanced PW in the NGB of ~0.8 inches which can be observed in Figure 19. While the lower levels may provide enough moisture to support a convective environment, mid-to-upper level support in the form of a translating synoptic scale trough or jet is lacking which diminishes the potential of any long-lasting thunderstorm activity in the region. 500mb wind plots (Figure 20) illustrate this lack of mid-level support over the NGB on the event day although there is a mid-level shear max on the event day +1 just south of the NGB domain, which is reflected by the precipitation plots in Figure 18 on 3 September 1997 (subplot (f)). The lack of contribution from RWB over the region of interest seen in Figure 21 also may reduce the chance for any measurable precipitation to occur as upper-level adjustments to the wave breaking is missing. While the necessary moisture may be present in the NGB, the mid-tropospheric dynamics are not favorable
for precipitation.

Figure 19: Precipitable water (inches) (NARR) for the 2 September 1997 case study with the event day being (e) with four days before (a-d) and one day after (f).

Figure 20: 500mb winds (m/s) for the 2 September 1997 case study with the event day being (e) with four days before (a-d) and one day after (f).
Figure 21: 350K isentropic potential vorticity (2-IPVU threshold) derived using NCEP-NCAR reanalysis for the 2 September 1997 case study with the event day being (e) with four days before (a-d) and one day after (f).

With the majority of these cases, the combination of a large trough or cut-off low is seen to propagate towards the large ridge. Upstream convection in the western GOM, GOC, and/or northern Mexico generates a convectively-forced outflow jet due to the convective heating and increasing local pressure from the mid to upper troposphere along the periphery of the ridge (e.g. Kaplan et al. 1998). (Figures 22 and 23) The jet at these levels tends to be narrow and wraps around the base of the western side of the ridge and is funneled northward and then northeastward into the NGB. This causes the anticyclonic vorticity plume to be stretched southwest to northeast over the NGB downstream from the low as a result of upstream convective outflow. Additionally, in some cases there exists a secondary jet streak in between the polar jet/trough and monsoonal high. Convective outflow from deep latent heating is responsible for the existence of this secondary jet. Successive mesoscale convective systems (MCS) produce deep heating and outflow accelerations. Outflow triggers lift and new MCS develop sequentially as the chain reaction continues downstream until subtropical moisture is condensed out. By this point the moisture can be extended northward into the most northern regions of the NGB.
The narrow striation of vorticity between the cyclonic maximum and anticyclonic maximum is a signal of a conduit for moisture and mesoscale lift particularly where upslope flow and mountain plains solenoidal circulations (MPS), i.e., differential mountain versus valley heating, e.g., Tripoli and Cotton (1988), enhance the lift of moist air. Many of the cases have a double vorticity maximum moving north and east from the Pacific Coast to the Great Basin indicative of the double jet, i.e., background quasi-geostrophic (Q-G) jet to the west and mesoscale convective jet to the east. The double jet is impressive as the diabatic heating processes are important for the monsoon for numerous reasons: 1) a convective outflow jet that is nonlinearly reinforced by successive days of orographic convection and 2) the sensible heating above the elevated plateaus (MPS) enhance the south - north frontal structure south of the polar jet between 850 and 500 mb. Mesoscale diabatic effects enhance the modification of the orographic convective environment due to both integrated latent heating and integrated deep surface sensible heat fluxes. The Q-G adective and circulation patterns are substantially altered by these two forms of diabatic heating.
These vorticity plots could lead one to conclude that there are four temporal and spatial scales of forcing: 1) Rossby Wave scale juxtaposing large Pacific cut-offs against Great Basin/four corners ridge (≈1000-5000 km), 2) meso-alpha scale convective jets (100-1000 km), 3) differential upslope heating at the meso-beta scale/MPS (10-100 km) and 4) meso-gamma scale clusters of orographic cells (1-10 km). Sequentially the
convective outflow jet then triggers more lift and moisture advection from the southwest up into Idaho, Wyoming, Utah and Montana. Additionally, the diurnal cycle focuses the heaviest rainfall where the convectively-forced anticyclonic jet (meso-alpha-meso-beta scales of motion) moves over the strongest orographic upslope flow and differential heating.

The juxtaposition of the large ridge and cut-offs create enough momentum that convective complexes can concentrate the plumes into narrow jet streaks even more effectively. Convection acting to create striations of a stronger PGF between the cut-offs and the big ridge focuses the moisture transport and lifts it into northward extended plumes. This is similar to low-level jets but much deeper and higher because the convective heating is well above the planetary boundary layer and thus the background jets in between the cutoff and ridge are focused through convective heating to upper levels above 600 mb.

3.2 COMPOSITE

While the case studies previously analyzed provide a deeper understanding for individual events, the following composite plots provide a more general understanding of the dynamics involved and remove any extra high frequency noise that may exist. Initially, composite plots of geopotential heights for 300mb, 500mb and 700mb (Figures 24, 25, and 26 respectively) were plotted in order to better understand the positioning and intensity of the heights averaged over the 26 events. The positioning of the continental high and eastern Pacific trough during these events is important as it provides the necessary moisture plume conduit into the NGB.
Figure 24: 300mb geopotential height (geopotential meters) composite for 26 event days.

Figure 25: 500mb geopotential height (geopotential meters) composite for 26 event days.
Analysis of the Boise, ID (BOI) radiosonde sounding composite (Figure 27) reveals a high jet stream maximum consistent with a very thick troposphere. Such a warm air column is consistent with quasi-geostrophic warm air advection and a preponderance of veering flow. There exists a very deep warm air advection pattern consistent with the 700-500mb warm boundary/front. The strong and high upper-level jet reflects high thicknesses over the Great Basin and increased heights also consistent with a deep and elevated warm air advection pattern causing veering winds higher in the troposphere than usual. The heating due to surface sensible heat and latent heat are deep befitting ridging in summer above an elevated heat source like the NGB.
Figure 27: Boise composite sounding anomalies with respect to 30-year daily climatology for all 26 event dates revealing (a) temperature anomaly (°C), (b) dewpoint depression anomaly (°C), (c) dewpoint anomaly (°C), and (d) wind speed anomaly (m/s) all with respect to pressure (mb).

Temperature composite plots for all events for the NGB are consistent with the previous sounding plots revealing an impressive baroclinic zone for the warm season to 500 mb. The presence of an elevated mixed layer with the 700 mb (Figure 28) warm air extending farther northward than at 850 and 500 mb is evident (Figure 29 and 30, respectively). The lifted indices are low on the anticyclonic side of the jet over the northwestern Great Basin. Comparison to lapse rates at 700-500mb (Figure 31) and 850-700mb (Figure 32) reveal two very unstable air masses over the NGB. Again, what is surprising during these events is the well-defined warm frontal boundary from Oregon/Nevada-Wyoming/Montana along with differential temperature values between 700-500mb of ~20+ °C and ~13+ °C at the 850-700mb level. Significant vertical decreases in temperature at both these levels are indicative of a low-to-mid-level vertical shear and a frontal boundary conducive to significant convection.
Figure 28: 700mb composite temperatures (degrees C) for all event days with the event day being (e) with four days before (a-d) and one day after (f). Statistically significant (p<0.05) regions compared to daily 30-year climatology are shaded.

Figure 29: 850mb composite temperatures (degrees C) for all event days with the event day being (e) with four days before (a-d) and one day after (f). Statistically significant (p<0.05) regions compared to daily 30-year climatology are shaded.
Figure 30: 500mb composite temperatures (degrees C) for all event days with the event day being (e) with four days before (a-d) and one day after (f). Statistically significant (p<0.05) regions compared to daily 30-year climatology are shaded.

Figure 31: 700-500mb composite lapse rate temperature differentials (degrees C) for all event days with the event day being (e) with four days before (a-d) and one day after (f). Statistically significant (p<0.05) regions compared to daily 30-year climatology are shaded.

Figure 32: 850-700mb composite lapse rate temperature differentials (degrees C) for all event days with the event day being (e) with four days before (a-d) and one day after (f). Statistically significant (p<0.05) regions compared to daily 30-year climatology are shaded.
The importance of the IWVF analysis in these case studies raises the question of how statistically significant these events were overall. To answer that question a series of statistically significant IWVF magnitude anomalies with IWVF vectors juxtaposed were plotted for all events (Figure 33), i.e., 14 subjectively chosen trough events (Figure 34), and 12 subjectively chosen ridge events (Figure 35). Only the grid points that met the 90th percentile using a t-test were plotted. The results show that for all events, there were statistically significant moisture flux anomalies extending from the southern Gulf of California up through central Idaho one day before the event day. On the event day however, there exists statistically significant moisture flux anomaly values up through parts of northern Idaho and the statistical significance is also much more widespread throughout the western U.S. While this holds true for trough and ridge scenarios, the difference between the two is that trough event scenarios contribute to the much more widespread statistically significant moisture flux anomalies over the entire NGB as opposed to ridge event scenarios. This indicates that the extratropical influence from eastern Pacific troughs on moisture flux into such an arid and dry region such as the Great Basin is more important than typically believed.
Figure 33: NARR Integrated Water Vapor Flux (kg/m/s) anomaly composite for all 26 event days with only t-test statistically significant (p<0.05) regions contour filled. Event days are compared to their respective average daily climatological anomaly values. Arrows indicate composite direction and magnitude of all 26 event days.

Figure 34: NARR Integrated Water Vapor Flux (kg/m/s) anomaly composite for 14 trough event days with only t-test statistically significant (p<0.05) regions contour filled. Event days are compared to their respective average daily climatological anomaly values. Arrows indicate composite direction and magnitude of 14 trough event days.
Figure 35: NARR Integrated Water Vapor Flux (kg/m/s) anomaly composite for 12 ridge event days with only t-test statistically significant (p<0.05) regions contour filled. Event days are compared to their respective average daily climatological anomaly values. Arrows indicate composite direction and magnitude of 12 ridge event days.

Analysis of convective available potential energy (CAPE) (Figure 36) reveals how difficult it is for really high CAPE values to propagate northwest of Las Vegas and how much better a forecast tool the lifted index (LI) (Figure 37) is compared to CAPE. CAPE calculations seem to be strongly controlled by elevation as if CAPE magnitudes are suppressed above ~1500m surface elevation. CAPE typically increases when dry air overlays moist air and in these cases when the surface is well above sea level high CAPE values do not occur. This occurs in other smaller scale models such as RUC as well. It could be that westerly wind flow aloft is far too moist over the NGB. This in turn means LI is most likely a better prognostic index because it is less directly dependent on dry air aloft but more due to cold air aloft.

Average CAPE values during the 26 events in the NGB begin at fairly low levels of ~100 J/kg and less two to three days prior to the event day (e) with peak values during the event day at range of 100-300 J/kg. While these values are not as impressive as those
in the continental Midwest, it does provide just enough instability in the dry NGB for a convective scenario to occur. Since there is not a massive differentiation in the CAPE values four days before the event day relative to one day after the event day, another variable such as the LI could be used as a better proxy by operational meteorologists. It is evident that on the event day (e) there is a north-northwest extension of LI with values averaging ~2-3 K° in the NGB. Another signal which is present during the 26 event composite is the breakdown of LI in the Midwest US. Three to four days prior to the event day there is an impressive region of LI that is initially present in the Midwest and appears to wrap around the base of the anticyclonic four-corners high in plots (c) and (d) and propagates northwestward into regions such as the southern part of Idaho. A day after the event day (f), the structure of the LI breaks down and loses its cohesion as it wraps around the NNW side of the ridge. It then forms again east of the Rockies and into greater portions of the Midwest.
Figure 36: NARR convective available potential energy (J/kg) for the 26 objectively identified events. Letters represent the event day (e) with four days before (a-d) and one day after (f).

Figure 37: NARR lifted index (K°) for the 26 objectively identified events. Letters represent the event day (e) with four days before (a-d) and one day after (f).
Composite mesoscale analysis of ground heat flux and horizontal moisture divergence reveals mixed results (Figures 38 and 39). The strongest heat flux in the NGB occurs over the elevated plateaus and the highest moisture convergence surrounds the surface heating maxima in the lower terrain adjacent to those elevated plateaus (see NGB terrain map in Figure 40). On the other hand, moisture divergence is evident over the elevated plateaus and mountainous regions of the NGB. The presence of moisture convergence at low levels and divergence at higher levels in this region is a proxy signal for mountain-plains solenoidal circulation forcing or mountain-valley circulation where the upslope flow on the sides of the elevated terrain is most favorable for convection. Ground heat flux maximizes over the elevated terrain thus facilitating lower pressure at the higher elevations. This also promotes higher pressure in the valleys which sustains the mountain-plains solenoidal circulations with convergence in the valleys and divergence above the heat sources as air accelerates up the mountain during the day and down the mountain at night.

Both ground heat flux and horizontal moisture convergence/divergence synergistically describe a mountain-plains or mountain-valley thermally direct upslope circulation with convection favored in the upslope regions between the valleys and elevated plateaus which dies out night. The composite effect on the larger synoptic scale is for the internal energy provided by ground heat flux and moist convective diabatic heating to be organized into a warm front situated south of the polar jet which in turn strengthens the polar jet at scales of motion greater than the Rossby radius of deformation, i.e. $\sim$1000 km. Convective eddies can work upscale to produce warm plumes which the diabatic heating term in Miller’s (1948) frontogenesis equation
explicitly describes. The warm front caused by the upscale heating resulting in quasi-geostrophic warm air advection strengthens veering in the polar jet which in turn enhances the jet aloft through the thermal wind.

Figure 38: Composite for event days of NARR Ground Heat Flux (W/m$^2$) starting at 18Z on the event day through 15Z of the following day (event day +1) (top-left to bottom-right)

Figure 39: Composite for event days of NARR Horizontal Moisture Divergence (kg/m/s) starting at 18Z on the event day through 15Z of the following day (event day +1) (top-left to bottom-right)
Figure 40: Northern Great Basin elevation and bathymetry on 2x2 minute (~4km) grid from the National Geophysical Data Center (NGDC).

The composite 700mb omega plot in Figure 41 reveals an anticyclonic arc of ascent above the high plateau stretching from southwest Utah to central Nevada and from western Nevada to eastern Idaho through western Wyoming. There also exists a band of ascent that splits into western Idaho. The omega signal follows the highest and thickest convection in the boundary layer most likely due to upslope ascending air flowing from the valleys to the highest regions of surface heat flux. There exists solenoids forming between the elevated plateaus and neighboring valleys with the arc of ascent enhancing the path of convective storms accompanying the inland convective outflow jet which in turn strengthens the jet itself synergistically.
Figure 41: Composite of NARR 700mb Omega (Pa/s) during the event day (e) with four days before (a-d) and one day after (f).

3.3 HOVMOLLER ANALYSIS

In order to further understand the response of extratropical planetary wave breaking (RWB), we examine the 330K isentropic potential vorticity level in relation to its effect on precipitation and its enhancement of and contribution to increased values of northward meridional IWVF. The 330K isentropic surface was selected for analysis because it is very close to the tropopause in these warm season events. Hovmoller plots of all three variables were generated for each year during the warm season months (July-Sept). These plots are used to highlight the role of waves during the summer months. A total of 30 Hovmoller plots, one for each of the 30 years, were analyzed however for this study only the top six most impressive years will be analyzed. Figures 42–47 represent years 1985, 1986, 1997, 2002, 2004, and 2007, respectively with the top row being meridional IWVF in kg/m/s, middle row representing precipitation in inches, and the bottom row representing IPV at the 330K level in IPVU. Each variable is longitudinally
averaged over the range -120W to -112W within the latitudinal bounds of 35N to 45N for the 92 day period of every year from July through September.

The most obvious commonality between the six years is September which experiences the highest amount of IPV wave breaks as is evident by the yellow-reddish contrast. In the majority of these cases where we see an influx of IPV, meridional IWVF almost always surges indicating that the incoming troughs into the NGB not only provide divergent upper level flow and the accompanying instability but enhances the surge of moisture from the south (darker red shaded areas of IWVF values of ~200 units). Now while many of these late warm season month events are reflected in high precipitation amounts, there are also times like 30 Aug 2002 and 18 September 2007 where the precipitation totals are not impressive. While rain may be limited in these two cases there is the definite possibility of dry lightning busts occurring (e.g., Nauslar 2009). This makes the use of meridional IWVF and 330K IPV a beneficial tool for operational meteorologists around the NGB in determining when and where outbreaks will occur.

While the majority of these events show an influx of higher 330K IPV in the NGB during the latter part of August through September, the opposite exists during known El Nino years such as what we see in Figure 44 during 1997. While there is a fairly strong meridional IWVF signature throughout the majority of the summer months, 330K IPV is limited throughout the warm season other than during an insignificant wave break around the dates 18-20 September. One could speculate that during El Nino years the precipitation distribution within these three months is more evenly spread with a more consistent meridional IWVF signature compared to a neutral El Nino-Southern Oscillation (ENSO) season. While more research in linking ENSO with synoptic patterns
during the monsoonal months in the NGB will have to be conducted, it can be said that a likely connection between monsoonal precipitation and ENSO exists as evident in Figure 48 which shows above average precipitation amounts during the El Nino years of 1983-84 and 1997.

Figure 42: Hovmoller plot using three variables: Meridional Integrated Water Vapor Flux (kg/m/s) (top row), (b) 330K Isentropic Potential Vorticity (IPVU), and (c) Precipitation (inches). Data is longitudinally averaged over the range -120W to -112W within the latitudinally bounds of 35N to 45N for the 92 day period of 1985 from July through September. Dashed lines indicate significant wet events.
Figure 43: Hovmoller plot using three variables: Meridional Integrated Water Vapor Flux (kg/m/s) (top row), (b) 330K Isentropic Potential Vorticity (IPVU), and (c) Precipitation (inches). Data is longitudinally averaged over the range -120W to -112W within the latitudinally bounds of 35N to 45N for the 92 day period of 1986 from July through September. Dashed lines indicate significant wet events.

Figure 44: Hovmoller plot using three variables: Meridional Integrated Water Vapor Flux (kg/m/s) (top row), (b) 330K Isentropic Potential Vorticity (IPVU), and (c) Precipitation (inches). Data is longitudinally averaged over the range -120W to -112W within the latitudinally bounds of 35N to 45N for the 92 day period of 1997 from July through September. Dashed lines indicate significant wet events.
Figure 45: Hovmoller plot using three variables: Meridional Integrated Water Vapor Flux (kg/m/s) (top row), (b) 330K Isentropic Potential Vorticity (IPVU), and (c) Precipitation (inches). Data is longitudinally averaged over the range -120W to -112W within the latitudinally bounds of 35N to 45N for the 92 day period of 2002 from July through September. Dashed lines indicate significant wet events.

Figure 46: Hovmoller plot using three variables: Meridional Integrated Water Vapor Flux (kg/m/s) (top row), (b) 330K Isentropic Potential Vorticity (IPVU), and (c) Precipitation (inches). Data is longitudinally averaged over the range -120W to -112W within the latitudinally bounds of 35N to 45N for the 92 day period of 2004 from July through September. Dashed lines indicate significant wet events.
Figure 47: Hovmoller plot using three variables: Meridional Integrated Water Vapor Flux (kg/m/s) (top row), (b) 330K Isentropic Potential Vorticity (IPVU), and (c) Precipitation (inches). Data is longitudinally averaged over the range -120W to -112W within the latitudinally bounds of 35N to 45N for the 92 day period of 2007 from July through September. Dashed lines indicate significant wet events.

Figure 48: Three-day running mean of NARR Precipitation (inches) averaged over the Northern Great Basin domain for the years 1980-2009 during the months of July-September.
4. DISCUSSION, SUMMARY AND CONCLUSIONS

The onset of the NAM circulation in the NGB brings on highly variable intraseasonal activity with the NGB experiencing low-frequency high-impact events that produce either flash flood or dry-lightning bust events. These make land managers’ decisions increasingly difficult and operational meteorologists’ forecasts equally challenging. The demand for an increased knowledge and understanding regarding the NAM in the NGB is needed as seen in Appendix 1. In the NGB, while the monsoonal anticyclone is known to play a large role in the monsoonal circulation, the influence of mid-latitude Rossby waves provide additional upper-level support in conjunction with the diabatic heating and topographic forcing present during the summer months. A shift in the monsoonal ridge has been shown in previous literature to promote convective outbreaks over the poleward fringes of the monsoon region but this previous literature (e.g., Higgins 2004) has failed to show the dynamical mechanisms that lead to this shift in the ridge as well as the structure of finer scale circulations around the periphery of the ridge.

The current void in understanding the northward extension of the NAM requires answering the question of how the extratropics control the northward progression of these monsoonal surges as they interact with complex NGB terrain. The current limited knowledge on this influence poses a problem for operational meteorologists and an improved understanding of this is needed to increase accuracy of short-to-medium range warm-season forecasts. The analyses presented in this thesis applied previous theories within a novel set of analyses that incorporated a broader multi-scale set of dynamics linking the extratropics, tropics, and mesoscale dynamics which are collectively and
interactively responsible for the northward push of moisture into the NGB.

Moisture surges which affect the NGB have been hypothesized to occur through a trio of mechanisms. These mechanisms include: (1) the positioning and intensity of the four-corners high located over the mid-US which provides the initiating mechanism for moisture transport from the subtropics northward into the NGB. (2) Trough and cut-off lows which propagated through the interior western U.S. or are located just off the West Coast of the U.S., respectively, and are hypothesized to enhance instability aloft and to provide an additional alteration to the mid-upper level steering current which aids in the northward transport of moisture from the monsoonal core. (3) RWB is hypothesized to destabilize the atmosphere in the NGB by providing the intrusion of troughs southwestward which contain cold air advection and/or ascent aloft (if the RWB occurs in the proximity of the NGB) and also modify the subtropical jet near Northern Mexico/GoM (in the case that RWB occurs in the Eastern U.S. extending southward near the GoM). An overall better understanding of these mechanisms is the focus of this research as well as a multi-scale synthesis of their interactions. Practically, the improvement of monsoonal forecast accuracy in the NGB is the ultimate goal.

The results of the analysis reveal three primary things with regards to the previously stated hypothesis: (1) the intensity and positioning of the four-corners upper-level high must be strong enough to support and reinforce the moisture flux circulation from the GoC and GoM. Early on in the warm-season, the presence of the progressive trough is not as evident as later on in the season and thus the most important factor in regards to moisture flux becomes the ridge strength. As the season progresses, however we find that the trough intrusion into the NGB strongly modifies what the ridge alone can
do in terms of IWVF. (2) As observed in the Hovmoller analyses, case study, and composite plots, the propagation of a trough or cut-off low does in fact influence the enhancement of moisture surges into the NGB as it increases the mid-upper level steering current of the moist air from the south-southeast. Although these lows have been proven to influence moisture influx into the NGB, it is important to note that this is true for primarily case studies in mid-August through late September. Our research details this strong seasonal signal in the role of trough intrusion into the NGB. (3) Lastly, RWB does in fact destabilize the atmosphere in the NGB, primarily in the latter half of the warm-season, and provides enhanced ascent aloft with an influx of cold air advection which increases the convective instability due to upper-level lift atmosphere. This RWB is often occurring, as we show, when the trough forcing upstream is more dominant. As seen in the Hovmoller diagrams, during a 330K IPV intrusion into the NGB, the majority of late warm-season events produce significant precipitation while during the early-to-mid warm-season (1 July – 15 Aug), the majority of IPV influx events don’t produce significant or measurable rainfall. Although the events may not be “wet”, the potential for dry lightning and the hazards that come with it in the NGB are a definite land management risk.

After in-depth analysis of 30 years of data, the overall extratropical large scale pattern during a monsoonal event in the NGB can be seen in Figure 49. The formation of an upper level ridge occurs in the four corners region of the western US and acts as a quasi-stationary blocking pattern until a shortwave/cut-off trough from the eastern Pacific intrudes. As the trough moves east and over of the NGB, 500mb heights fall consistent with ascent and cold air advection aloft which take place along with an increase of 330K
IPV. The largely positive anomalous ambient temperatures at the surface in the NGB allows for the surface thermal low to form and in combination with the influx of moisture from the GoC (and partially from the GoM), allows for moisture to intrude into the mid-levels where convection initiates, particularly above the multitude of elevated plateaus. Without a significant ridging event over the four-corners’ region, this moisture flux into the NGB is weak or non-existent and without the upstream trough it is less significant than otherwise would be. Therefore the existence of the progressive troughs from the Pacific amplify what the ridge alone can do in terms of IWVF.

Figure 49: Schematic of the synoptic/large-scale pattern ongoing during progressive trough approaching western US during the onset of a significant upper-level ridge with a surface low forming in the NGB.

While the large scale pattern is important in the evolution and sequence of moisture influx into the NGB, the mesoscale components of the circulation, which are coupled to elevated terrain forcing, adds to and amplifies the magnitude, frequency and areal coverage of local mesoscale convective systems present in the multiple valleys of
the NGB. These higher frequency processes are evident as seen in the previous analysis plots and do not alter the original hypothesis but instead enhance it considerably by adding an extra element to the nature of the monsoonal season in the NGB. Figure 50 represents a schematic of the overall synthesis from the earlier analyses of mountain-forced circulations presented in this paper. There exist two different dynamical scales of circulations that are depicted in this diagram. The first focuses on the low-to-mid-level circulations represented here which show the mountain-plains solenoid (MPS) at its mature stage (e.g., Koch et al, 2000) as it slowly migrates eastward. The MPS is formed by the differential solar heating in the morning and early afternoon between elevated slopes and the free atmosphere. Tripoli and Cotton (1989) suggest that gravity waves triggered by this MPS circulation can produce and modify strong convection both over and downstream from the heated slopes. They state that convection forming above the leeside convergence zone (LCZ) strengthened as it progressed eastward into a stationary wave updraft region approximately 60km downwind of the mountain peak. Numerical model simulations performed by Banta (1990) show that MPS can be the trigger for the generation of “secondary convection” east of the original MPS forcing which can in fact develop into a mesoscale convective system or complex with substantial longevity of many hours. Although the NGB is generally drier than the Great Plains, Maddox et al. (1981) stated that MCCs can bring a large percentage of the warm-season rainfall to the Great Plains and that almost half of all MCCs occurred on the leeside slopes of the Rocky Mountain Range. This low-level mesoscale process as described by Maddox which is observed on the east side of the Rockies can potentially be applied to what we experience in the NGB on the leeside of the Sierra Nevada’s and the mountain ranges spread
eastward through the mountainous NGB such as the Wasatch, Absaroka, Tetons, Windriver, Galletin and many others in Utah, Idaho, Oregon and Wyoming.
Figure 50: Mesoscale schematic of the NGB during the warm-season revealing mountain-plains solenoid cycle occurring at the low levels coupled with mid-to-upper level synoptic-mesoscale dynamics for a typical convective afternoon with upper level influence.
As the MPS circulations progress through the afternoon they contribute collectively moisture (provided by south-southwesterly flow from the GoC and south-southeasterly flow from the GoM) from the lower levels into the mid-to-upper levels as the ensemble effects of multiple mesoscale convective systems lift the moisture and advect it downstream. The LCZ transferring heat and momentum upward increases the pressure at ~600mb which in turn modifies the height and pressure gradient surrounding each mountain-plains solenoid (MPS) circulation thus, as a result, creating a wind maximum or convective outflow jet. Each MCS convective outflow jet triggers more secondary and tertiary convection and upward as well as outward moisture forcing in time. As a response to the LCZ and increased pressure in the mid-levels, ageostrophic momentum produces a circulation which supports additional divergence aloft and sequential convection downstream that grow into new MCS. In this cycle we see negative omega (positive omega) on the west side (east side) of the solenoidal center. Moisture present in this ongoing cycle allow for thunderstorms (wet and dry) to form over the valley floors in the NGB. The collective outflow often organizes a secondary jet aloft and vorticity plume ahead of the trough and upstream from the ridge. This synergy of synoptic and mesoscale processes often provides the preferred conduit for the preferred patterns of IWVF analyzed in this thesis.

The contribution of the upper-levels comes in the form of a more synoptically-forced dynamical pattern which focuses on the intrusion of a trough, whether it be a shortwave or cut-off low, and which provides positive vorticity advection at ~500mb along with enhanced mid-to-upper level shear and increasingly steep lapse rates. At the
highest levels (~200mb) of the convective circulation is the influence from the IPV RWB at ~330K or greater which destabilizes the atmosphere in the NGB by providing a region of cold air advection with ascent aloft. The presence of the enhanced upper-level flow due to the enhanced winds aloft provides convective cells with highly divergent flow aloft on top of the divergent flow already produced by the MPS. While this model represented in Figure 50 is the ideal scenario for convection to form during the warm-season in the NGB, not all convective complexes form in this nature. Likewise, not all thunderstorms over the NGB are in fact “wet” storms. The form of “dry” thunderstorms is a very like and becomes a serious threat to the public in the NGB due to fire concerns and hazards. The collective effects of these processes are to produce outflow jets, enhanced moisture transport and warm frontogenesis downstream from the elevated plateaus.

Future research that delves into the monsoonal flow and its effect on the NGB should focus more closely on how ENSO signals and other global circulation teleconnections influence the influx of moisture into the NGB. In regards to operational meteorologists in the Western US, the use of PW is currently the standard as to whether or not there exists sufficient moisture to produce an environment conducive to a monsoonal outbreak. Preliminary results in this thesis have shown that IWVF may be an equally useful, if not more important, moisture variable to use as it more accurately describes the moisture perturbation into a specific region at a three-dimensional scale as opposed to the strictly vertical scale used by PW. More in depth research with the aid of modeling IWVF surge cases should be attempted in the future. It would also be beneficial for operational meteorologists to understand whether or not a monsoonal surge into the NGB will produce dry lightning or not. Thus, developing an objective operational index
for the warm-season that would provide a distinction on whether convection in the NGB will produce dry lightning or not would help land managers and emergency personnel prepare for either scenario accordingly. Additionally, testing the scenarios of this research in a high resolution (4km or less) modeling atmosphere would be beneficial in confirming whether or not the mesoscale processes explained previously can be replicated in a similar environment over various synoptic pattern scenarios. The highly variant nature of the monsoon makes it difficult for researchers to derive an objective formula to identify and forecast moisture surges into the NGB accurately. The hope is that the analysis and results of this thesis will bring the monsoon research community some insight into the synoptic and mesoscale processes that occur during the height of the NAM in the western US.
5. REFERENCES


APPENDIX 1: NWS FORECAST OFFICE COMMENTARIES ON EXISTING MONSOONAL FORECASTING PROBLEMS AND DEFICIENCIES

The SLC NWS-WFO responding with the following. “At NWS-WFO Salt Lake City we are particularly interested in two aspects of the northern expansion of the monsoon into Utah. When the northern expansion results in high-based convection and "dry" lightning outbreaks where little or no rain reaches the ground over central and northern Utah. These events often occur at the onset of a northward surge when a dry air mass is replaced. These can be very high impact events for the fire weather community when the northern expansion reaches as far north as the Wasatch Front. This is the most heavily populated portion of Utah and any summer convection in this area has the potential to be a high impact event. The impacts can be heavy rain, strong downdraft winds, lightning, or even severe hail in some situations.

We have no baseline climatology on this phenomena. It would be great if this research could identify a criteria that identifies a northern expansion event (e.g. dewpoints, precipitable water, radar coverage, etc.) and provide a quantitative climatology. Right now, we don't really know how often these events occur. It is our perception that we average several a year, but there is no defined criteria by which to measure or test the assumption.

Generally, the models do a pretty good job of forecasting these events, but if there is a characteristic error, it is that the models can be too slow for the date of onset by about 24 hours. This is just a subjective impression, but if this research could validate or disprove this impression, that would be valuable. In other words, we typically feel that
the models do a decent job picking up on the monsoon surges and as forecasters they are usually well anticipated. However, our experience is that the onset is a little quicker than expected.

The large scale pattern that drives the expansion of the monsoonal surge into northern Utah seems to be well recognized. However, the significance of variations in the large scale pattern, and some of the subtleties which lie therein, have not been investigated. If your work can provide better understanding of the preconditions to the events or provide more insight into the relationship between the sub-tropics and extra-tropics that could be very useful. This is particularly significant if it would enable an extension in the time frame in which forecasters could be more confident of a monsoonal surge extending well to the north.”

Feedback from the PIH NWS-WFO included the following, “Subjectively, we experience somewhere between 4 to 10 monsoon surges through the summer depending on the overall pattern in place (i.e. some summers are more active than others). The timing of these surges is frequently handled poorly by operational models (usually too slow) with time of arrival in Southern Idaho off by up to 12 to 24 hours at times. The impact of these events varies somewhat, but the most notable is the occurrence of dry thunderstorms which can be efficient producers of wildfire starts if fuel conditions are conducive. In addition, public safety is also a concern since the timing of monsoon surges can be difficult and therefore thunderstorms may not be mentioned in the forecast with sufficient lead-time. Most of our events correspond with the climatological norm for SW monsoon event...so mainly a couple of weeks in July. My caveat is that they do happen in other months throughout the summer as well.”
The EKO NWS-WFO responded by saying “Surges vary from 3 or 4 per summer...sometimes more/less and usually in July/Aug. 1” PWAT is considered significant enough for good rains (flash flooding potential very high). When the surge begins, we usually have a dry lightning event as the moisture is enough for convection, but not quite enough for wetting rain (PWAT perhaps around or just under 0.75”). These dry lightning events can be a challenge to forecast and have high impacts on our fire weather community. When the flow is just right with the 4-corners high in place, the surge begins, but then the moisture eventually gets pushed eastward by a passing shortwave trough or a change to a more westerly flow.”

Lastly, the REV NWS-WFO SOO stated that, “These events are generally rare in our forecast area...occurring 1-2x per year, sometimes never. The last big one we had was 21 July 2008, associated with a supercell outbreak in western Nevada. We typically use satellite data (e.g. GOES sounder PW, LI) to help assess the northward extent of the monsoonal plume, as surface observations are somewhat sparse in much of the state. A good long term climatology of these events and a pattern composite would be helpful to us, especially in understanding what makes these events different than typical monsoon situations. We definitely could use some help in predicting thunderstorm coverage and storm modes during these events. Just about any time the dewpoint in Reno gets above 50-55F during the summer, that's pretty unusual and likely indicates a monsoonal surge. Large hail is rare in this part of Nevada, but it does happen. More frequent are high winds from microbursts due to evaporative cooling in downdrafts.”