P97. A SYNOPTIC CLIMATOLOGY OF WINTER STORMS IN THE SOUTHERN PLAINS: 1993-2011

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1. INTRODUCTION

Winter weather can present significant hazards to transport and infrastructure. In the southern United States, winter weather is infrequent compared to many other regions of the U.S, however, socioeconomic impacts may be particularly salient given the relative lack of winter weather infrastructure (Changnon, 2003). In this study, we present an 18-year climatology of the average distribution and common synoptic characteristics associated with freezing (freezing rain or 'ice' and sleet) and frozen (snow) precipitation over a regional domain defined as the 'Southern Plains', centered over Oklahoma and extending between 92 and 102W and 32-38N. This region of the U.S is known for infrequent, yet potentially damaging accumulations of freezing rain, but there is a dearth of literature regarding the synoptic and mesoscale aspects of such events. Notable recent work includes Kovacik et al. (2011), who developed a regional climatology of Ice Storm frequency over the Southern Climate Impacts Planning Program (SCIPP) domain between 2000-2009. Note that 'Ice Storm', according to the National Weather Service, denotes accumulations of freezing rain at or above 0.25 inches. Grout et al. (2012) examine the relationship between various NWS winter weather categories (e.g. ice storm, snow storm, winter weather watch/advisory), and federal disaster declarations on a county-by-county basis within Oklahoma over the aforementioned time period. This analysis ascertained that counties experiencing ice storms received the bulk of federal aid, associated with the particular severity and disruption that such conditions create; especially to power and utility services. Prior to these studies, Changnon's (2003) Ice Storm climatology for the contiguous U.S had demonstrated sensitivity of the south central region to significant financial losses, ranking the region fourth in total damage losses between 1949-2000, but first in the ratio of freezing rain days to significant loss (3.5 days). This result was attributed to higher average ice accumulations for a given event, associated with longer single-duration icing and greater moisture availability.

Numerous climatologies of winter weather, including freezing precipitation and snow have been constructed for the contiguous U.S (Bennett, 1959, Baldwin 1973, Zerr, 1997, Bernstein, 2000, Rauber et al, 2000, 2001, Robbins and Cortinas, 2002, Changnon, 2006, Ressler et al, 2012). However, evaluation of synoptic features, especially for freezing precipitation, has often been examined with respect to single or small subsets of case studies. Notable work includes that of Rauber et al (2000, 2001), who used a large database of atmospheric soundings associated with freezing precipitation to construct a surface based synoptic climatology for events east of the Rocky Mountains. Robbins and Cortinas (2002) examine several point locations within the U.S and evaluate upper air thermodynamic profiles at each location. As a result of these, and other past and recent work, there is improved understanding of thermal profiles associated with freezing rain, and some of its major distinctions from sleet/pellets. In addition, it is known that thermal advection at low levels is important in maintaining a thermal profile suitable profile for freezing precipitation. Forecasters are also able to interpret synoptic conditions promoting freezing precipitation to a large extent. Nonetheless, the high spatial variability of freezing precipitation and microphysical phase transitions still make winter weather forecasting a challenge. It is hoped that this analysis can aid forecasters in the southern U.S interpret synoptic conditions favorable for winter weather, especially in distinguishing snow and mixed phase events from large scale indicators.

2. DATA AND METHODOLOGY

(a) Case Studies

Winter weather case studies were compiled primarily from the National Climatic Data Center's *Storm Event* database from January 1993-February 2011, with additional information supplied via NCDC daily summaries for stations

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within the domain. Information concerning winter storm type (e.g. ice storm, freezing rain, sleet, snow) are gathered initially by state and subsequently combined to form a database denoting the date, approximate duration, locations within domain and precipitation phase types of winter weather events. A total of 145 events were manually identified, however many of these were confined to a localized area. In order to remove any bias of the climatology to a specific sector, events of small spatial extent were not used in the *synoptic climatology*, which reduced the event sample size to 90. Events spread over multiple days are considered to be a single event unless there is a clear temporal gap of 2 days (48 hours). Unfortunately, unlike snowfall, no direct measures of freezing precipitation are available, and so distributions of freezing precipitation are interpreted through thermal profile and location of precipitation as derived from North American Regional Reanalysis (NARR). Ideally, the database should be extended in time in order to increase event sample size, however, this is beyond the scope of this study and remains a potential area for further work. The greatest limitation of this analysis is, as mentioned, a lack of consistent measurements for freezing precipitation, and (2) a low sample size. Given the relative infrequency of events, we did not reference a point location within the domain, instead, the analysis is intended to identify, in a broad sense, locations commonly impacted by a given synoptic type.

(b) Climatology

Using the dataset, a domain-wide climatology of winter weather is evaluated by considering the approximate number of calendar days where ice (freezing rain/drizzle and/or sleet) or snow was reported within a given climate division. Climate divisions are geopolitical boundaries wherein meteorological averages are assessed. The Storm Event database does provide county information, however, in some cases, county reports are sporadic and/or not easy to interpret, so a reasonable compromise is to assess over a broader area, whilst still capturing the gross nature of the winter weather distribution. Given the aforementioned problems with identifying freezing precipitation, we do not consider accumulation, but rather the presence of falling winter precipitation over a calendar day (e.g. event reported on a given day= 1 calendar day). Since each climate division differs in area, the number of events per climate division are weighted by the area of the division (in square miles), in order to provide a consistent measure of frequency.

(c) Synoptic Pattern Classification

In order to evaluate distinctions between the synoptic evolution of mixed phase winter weather, as compared with snowfall, case studies are identified as either ice or snow ‘dominant’. In this context, our definition of ‘dominant’ refers to the precipitation phase that best characterizes the event in terms of duration and impact. For example, a winter storm exhibiting a brief or absent window of freezing precipitation with little accumulation, followed by measureable accumulations of snowfall (as inferred from the storm event database, summaries and precipitation accumulation) would be considered as snow dominant. Where possible, short duration events with little accumulation (e.g. < 1/10in ice or < 1in snow) and events with no clear dominant phase are excluded from the analysis. Note also that while mixed phase/ice events may have snowfall associated with them, snow case studies should not be associated with a pronounced and/or long duration mixed phase region. Using these criteria, 41 snow, and 31 ice case studies remained in the analysis.

In order to identify common synoptic patterns, the rotated principal components of the 500hPa height field at the approximate initiation time of winter precipitation are evaluated for both datasets separately. Principal Component Analysis (PCA) is a statistical method used to reduce the complexity of a dataset to common elements and is a popular tool for resolving common flow fields. The 500hPa height fields have been extensively used in the literature to classify flow regimes, and are associated with determining the movement of surface features and predicting surface pressure evolution (Ahrens, 2000). The geopotential heights are derived from the North American Regional Reanalysis at 1^{o}x1^{o} horizontal resolution. Heights are standardized prior to applying the PCA. For this analysis, we apply the PCA is ‘T’ mode, or ‘temporal mode’, typically used when the data is in the form of discrete events (Richman, 1986). Ordinary PC loadings are calculated, and eigenvalues evaluated in order to determine the number of PCs to subsequently rotate. The benefits of rotated PCA are explained in Richman (1986). The final number of retained rotated PCs are determined through an analysis of congruence between each PC-vector and the correlation matrix of the original variable, shown in equation (1):

$$C_{ab} = \frac{\sum_{j=1}^{n} e_{ja} e_{jb}}{[(\sum_{j=1}^{n} e_{ja}^2)(\sum_{j=1}^{n} e_{jb}^2)]^{1/2}} \qquad (1)$$

e_a is the PC loading, and e_b the correlation matrix, with a summation over *j* observations (see also Harman, 1976). In order to extract the 'true' field, PC scores are converted to physical units via a simple conversion, shown in equation 2, where x is the variable field, X is the mean field, Z the RPC score, and σ the standard deviation.

$$x = X \pm \sigma Z \tag{2}$$

Therefore, for every RPC, there are *two* possible circulation fields. The relative importance of each pattern, in terms of frequency of occurrence within the original dataset, is assessed by the correlation of each 500hPa field over the domain 20-50N and 140-80W with the original PC loading (calculated over the same domain). The 5 most common patterns are kept for both snow and ice, which describe 62 and 70% of all case studies in the data set respectively. In order to examine the evolution of other key thermodynamic variables, the events conforming to each pattern are composited and extended back and forward in time by 24-hours. Given the low sample size, this work represents a pilot study that can be expanded/repeated once a longer temporal dataset has been constructed. Nonetheless, in order to check whether the derived patterns are representative, we briefly examine the 500hPa flow during winter weather events between 1970-1993 (case studies derived from NCDC monthly/daily weather summaries), finding that such patterns are observed, increasing confidence that the derived patterns are realistic and repeatable.

3. RESULTS

(a) Climatology

The spatial distribution of weighted ice days and snow days are shown in Fig. 1. Freezing precipitation appears to be more common in a southwest to northeast zone encompassing central Oklahoma through southwestern Missouri and northwestern Arkansas, in general agreement with the work of Kovacik et al (2011) and Grout et al (2012). Snowfall is typically more frequent in the west and north and regions of elevated terrain in the east (e.g. Ozarks). The domain slopes upward approximately 3,000 ft from east to west, therefore the far western sub-region is typically cooler, but also more remote with respect to warm low-level moist air, and thus less favorable for freezing precipitation. The distribution of snow-days agrees well with the spatial climatology (for Oklahoma) by Branick (2001). The lack of smooth transitions between climate divisions reflects the area weighting, and also possibly discrepancies in reporting (Branick, 1997, Kovacik et al, 2011), although localized effects by topography cannot be excluded.

The monthly average distribution of precipitation types is shown in Fig 2, averaged over four roughly equal quadrants over the domain. Freezing precipitation is primarily confined to December-February, the peak of boreal winter, with maxima during mid-winter. Snow events are more bi-modal, especially in the north and west, and have a broader seasonal distribution.

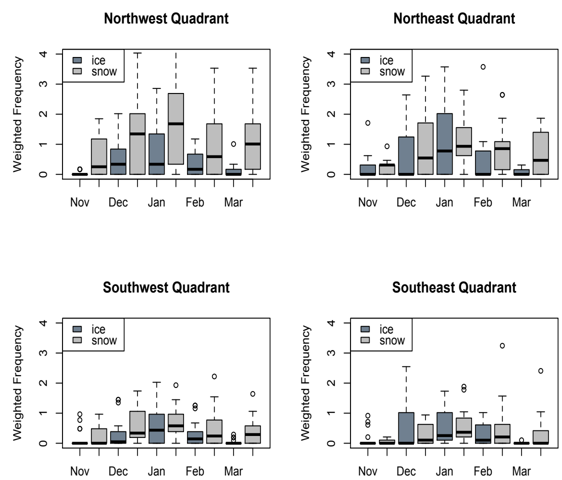


Figure 2 (above): Distribution of snow and freezing precipitation events between November and March from 1993-2011, weighted by the area of each climate division.

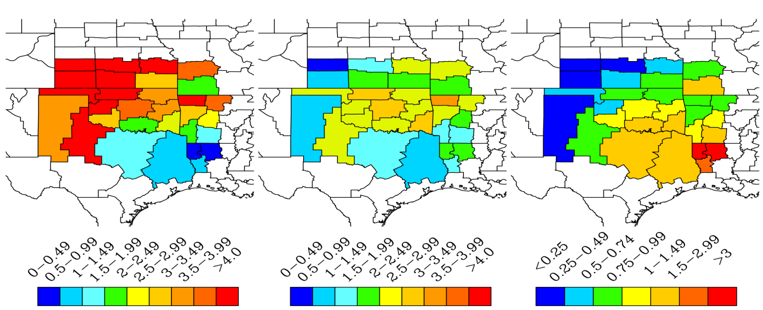


Figure 1 (left): Spatial distribution of snowfall (left), freezing precipitation (center) days per year, normalized by the area of each climate division. The right hand panel expresses the ratio of freezing precipitation days to snow days.

(b) *Synoptic Patterns: Freezing Precipitation (Ice)*

Figure 3 and 4 show the composite 500hPa (250hPa wind) circulation at T_{-24}, T_0 and T_{+24} hours, and the sea level pressure (SLP) and 975hPa winds for T_{-24} and T_0 respectively. Note that in all patterns considered, the composite represents a single plausible scenario. In reality there are numerous differences in thermodynamic evolution and trough movement that control the exact distribution of key variables. Fig. 5 examines the distribution of standardized anomalies in precipitable water and temperature over the composite average freezing precipitation zone, where the standardized anomaly is evaluated against the 1979-2012 daily mean and standard deviation from NARR data, Fig. 5 also displays the wind field (850hPa) at 35N (within domain) and 25N (south of domain), and a schematic evaluation of the areas impacted by freezing precipitation – a measure of the variability of location across events in each category. Finally, Figure 6 displays NARR derived values of composite pressure vertical velocity (pas^{-1}), and the location of the surface and 850hPa zero degree isotherms for each pattern at T_0.

Ice Pattern 1: Depicts a positively tilted shortwave trough west of the domain and south of a zone of northwesterly flow over the eastern conus. A broad area of high sea level pressure is present prior to winter precipitation. Warm air advection (WAA) and diffluent flow east of the trough provide forcing for ascent, while the high surface SLP and low level WAA promote a thermal profile supportive of mixed phase. Over the region, precipitable water vapor is in the region of 1.5σ above the NARR derived climatology, while temperature anomalies are less pronounced. The average composite melting layer temperature at 850hPa is in the range of 2-5^{o}C. Moisture is typically sourced from the Gulf region, evidenced by the preponderance of southerly flow at 850hPa. The distribution of winter precipitation associated with each event in this pattern is broad, indicative of a high degree of variability. This is related to (i) the southward extent of the sub-freezing surface air (ii) the evolution and track of any weak surface cyclone (iii) location of upper trough with respect to the domain and (iv) moisture availability.

Ice Pattern 2: This pattern is associated most typically with high icing events within the region, with a focus over the I-44 corridor, shown in Fig. 5 and 6. Unlike pattern 1, there is low variability in the location of impact. The major features of this pattern include a broad slow-moving trough over the far western U.S/Baja California, with very strong southwesterly flow aloft – associated with strong baroclinicty associated with a slow moving southwest-northeast frontal zone. Air south of the frontal zone is warm, with temperature anomalies at 850hPa between 2-3σ (maximum melting layer temperatures between 6-10^{o}C). Moisture is plentiful over the region, with airmass trajectories directly from the Gulf of Mexico, and strong low-level flow associated with a low-level jet. Four of the seven severe ice storms over the region since 2000 are associated with this synoptic type. Factors contributing to the potential severity include: (i) quasi-stationarity of the frontal zone promoting continued ascent, (ii) large positive PWV anomalies associated with direct Gulf moisture (iii) upper level steering flow parallel to the front, promoting training precipitation (iv) high melting layer temperature promoting freezing rain as the dominant phase type over a broad area. Fig. 6 also indicates moderately high vertical velocities, and possibly the potential for elevated convection, which has been observed for similar synoptic flow (e.g. Rauber et al, 1994), and was present during the severe ice storm of December 9th-11th 2007.

Ice Pattern 3: This pattern is infrequent within the study temporal period, but was associated with a high impact icing event during December 12th-13th 2000. The mid-level trough is considerably weaker in amplitude, but upper level jet dynamic favor ascent over the region, in addition, a surface stationary front is typically present. Surface temperatures are particularly cold over the northern and central plains, and the zero degree isotherm typically extends further south, such that the northern sections of the domain are more favorable for snowfall, while southern areas, including southern Oklahoma, Arkansas, and north Texas, lie in the composite freezing precipitation zone. 850hpa temperatures and moisture are unremarkable compared to climatology.

Ice Pattern 4: A broad trough in the western U.S amplifies considerably by T_0, with an axis just west of the domain. Cold air at the surface, and WAA aloft ahead of the trough create an environment favorable for freezing precipitation parallel and south of the I-44 corridor, whilst favoring the warmest 850hpa temperatures and highest moisture to the eastern sub-domain. This pattern may in some cases be associated with a weak surface cyclone.

Ice Pattern 5: Bears some visual similarities to pattern 2, including a western positively tilted trough, and strong upper level southwesterly jet. Moisture is adequate, however, WAA is typically weaker, and melting layer temperatures lower – associated with the lack of ridging over the Gulf of Mexico/eastern U.S that promotes low level flow directly from the Gulf region. Therefore, the magnitude and duration of freezing precipitation is typically lower.

(c) *Synoptic Patterns: Snow*

Figures 7-9 follow those of Fig. 3-5 but describe snowfall patterns 1-5.

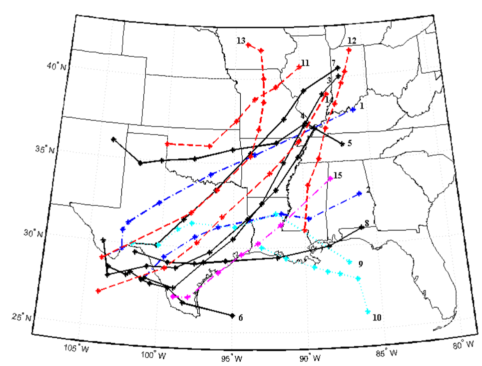
Snow Pattern 1: This flow pattern indicates a weak trough that amplifies at T_0 before accelerating eastward over the subsequent 24-hours. A strong jet streak is located over the southeastern U.S. Cold air is already present in the region. The composite evolution suggests cold air advection to the rear of an exiting low-pressure system over the Great Lakes. This deep layer of northwesterly flow precludes the formation of a melting layer. Forcing for ascent occurs via a frontal boundary, favorable upper jet and/or in some cases, the formation of a weak surface cyclone.

Snow Pattern 2 and 4: Both patterns are associated with an amplified trough, in some cases a closed upper low, and the development of a surface cyclone. At T_0 the trough axis/upper low is located over the domain, with a low-pressure system typically located along the Oklahoma/Arkansas border. Snow pattern 4 evidences a deeper trough with stronger upper level flow upwind, a stronger surface low, and often the development of a negative tilt to the trough axis as the surface cyclone continues to deepen. Both patterns are associated with higher moisture availability, however, the stronger dynamics of pattern 4 limit the westward extent of the snowfall due to stronger subsidence in the wake of the system (shown by the spread of higher negative PWV anomalies). Cold air is advected into the domain via the low-pressure system and is typically not in place in the 24-hours prior to winter precipitation, thus, there is little time to form a substantial melting layer, and one that does form is typically eroded fairly rapidly by stronger vertical motion and/or cold air advection associated with the cyclone.

Snow Pattern 3: Like snow pattern 1, the upper level flow remains generally zonal, with weak shortwave disturbances. The surface airmass is cold ahead of precipitation, evidenced by a broad region of high pressure. While this bears visual similarities to the shallow arctic airmasses associated with most composite ice patterns, the low level (850hPa) flow tends to originate from a cooler source over higher terrain in the west/southwest, and is not conducive to freezing rain, though perhaps sleet may occur. This pattern is not typically associated with surface cyclone development over the domain.

Snow Pattern 5: This pattern is the least common within the temporal period examined. Lift is primarily associated with the western trough and favorable jet dynamics (region located between left exit and right entrance region of two distinct jet streaks). Like snow pattern 1, cold air initially filters into the region on average behind a stronger system. In addition, surface cyclone development is indicated south of the domain at T_0.

60% of events within these categories were associated with a surface cyclone. Figure 10 shows the approximate tracks of the pressure center over the 48-hour study period. Most surface cyclones are associated with patterns 2 and 4, as the composite would suggest.



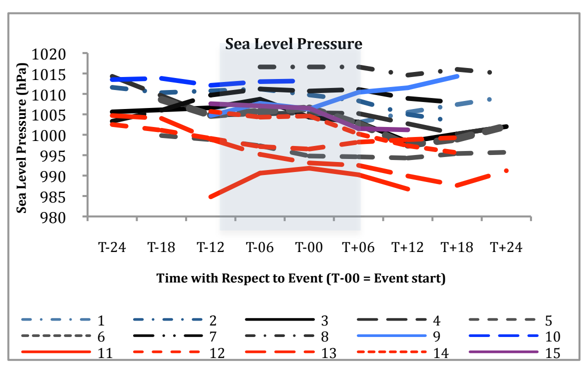


Figure 10: Top: Approximate trajectories of low-pressure systems producing snowfall within the southern plains domain. Tracks are based on local pressure minima at 6-hour intervals. Tracks are color-coded based on synoptic type: blue = 1, black = 2, cyan = 3, red = 4, magenta = 5. Bottom: Values of SLP associated with each trajectory.

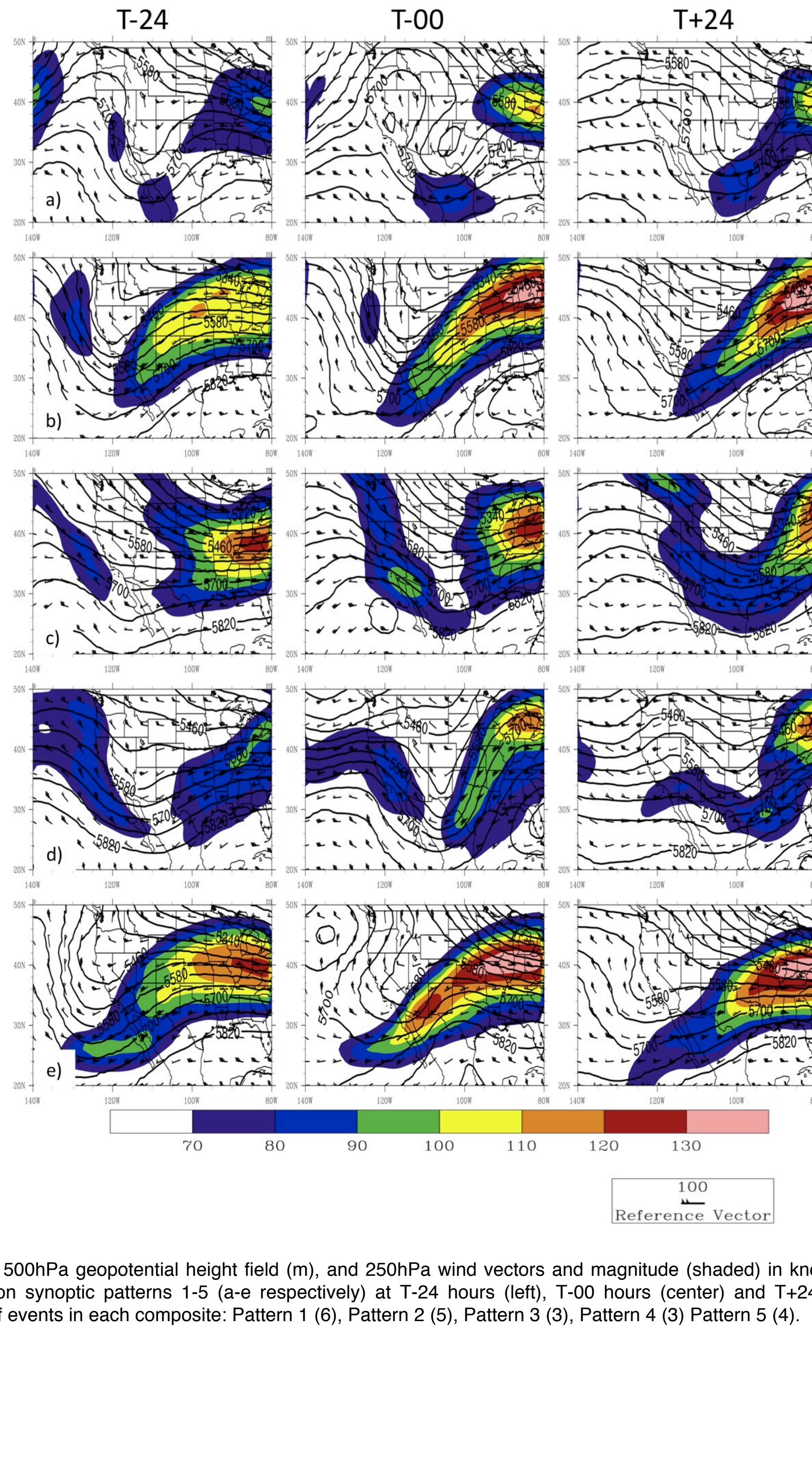


Figure 3: 500hPa geopotential height field (m), and 250hPa wind vectors and magnitude (shaded) in knots for freezing precipitation synoptic patterns 1-5 (a-e respectively) at T-24 hours (left), T-00 hours (center) and T+24 hours (right). Number of events in each composite: Pattern 1 (6), Pattern 2 (5), Pattern 3 (3), Pattern 4 (3) Pattern 5 (4).

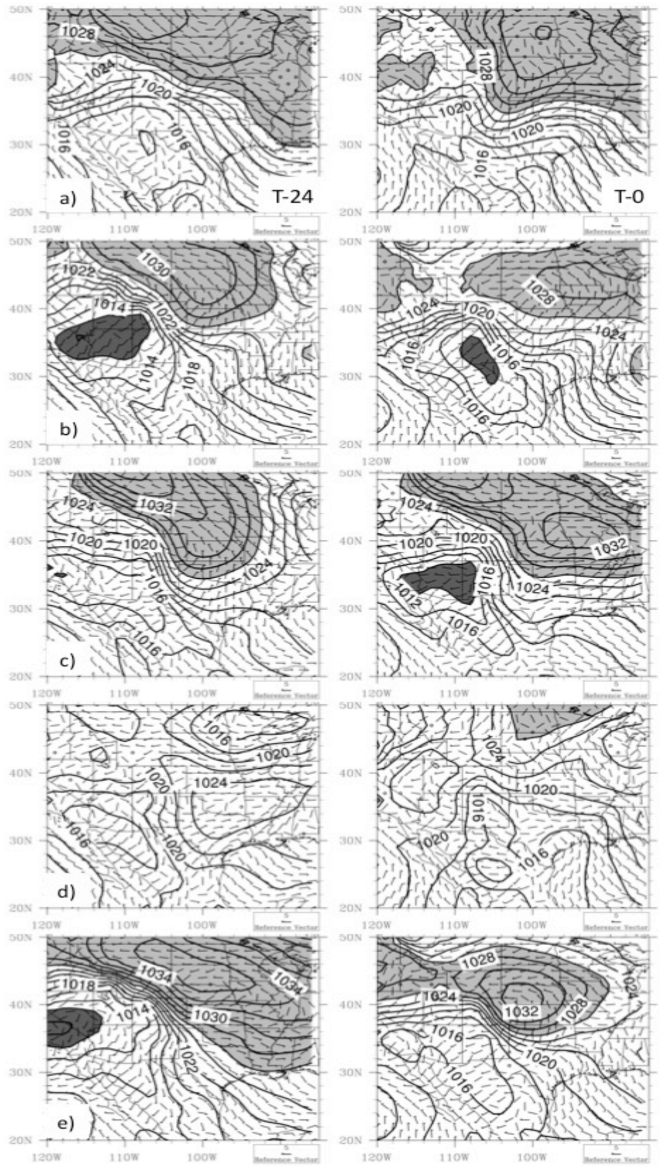


Figure 4: Sea Level pressure and 975 hPa winds for freezing precipitation patterns 1-5 for T-24 hours (left) and T0 (right). SLP > 1026 hPa is shaded in light grey, and SLP < 1012 hPa is shaded in dark grey. Given that the surface airmass characteristics are more pivotal for precipitation phase as the system develops, we did not plot T+24.

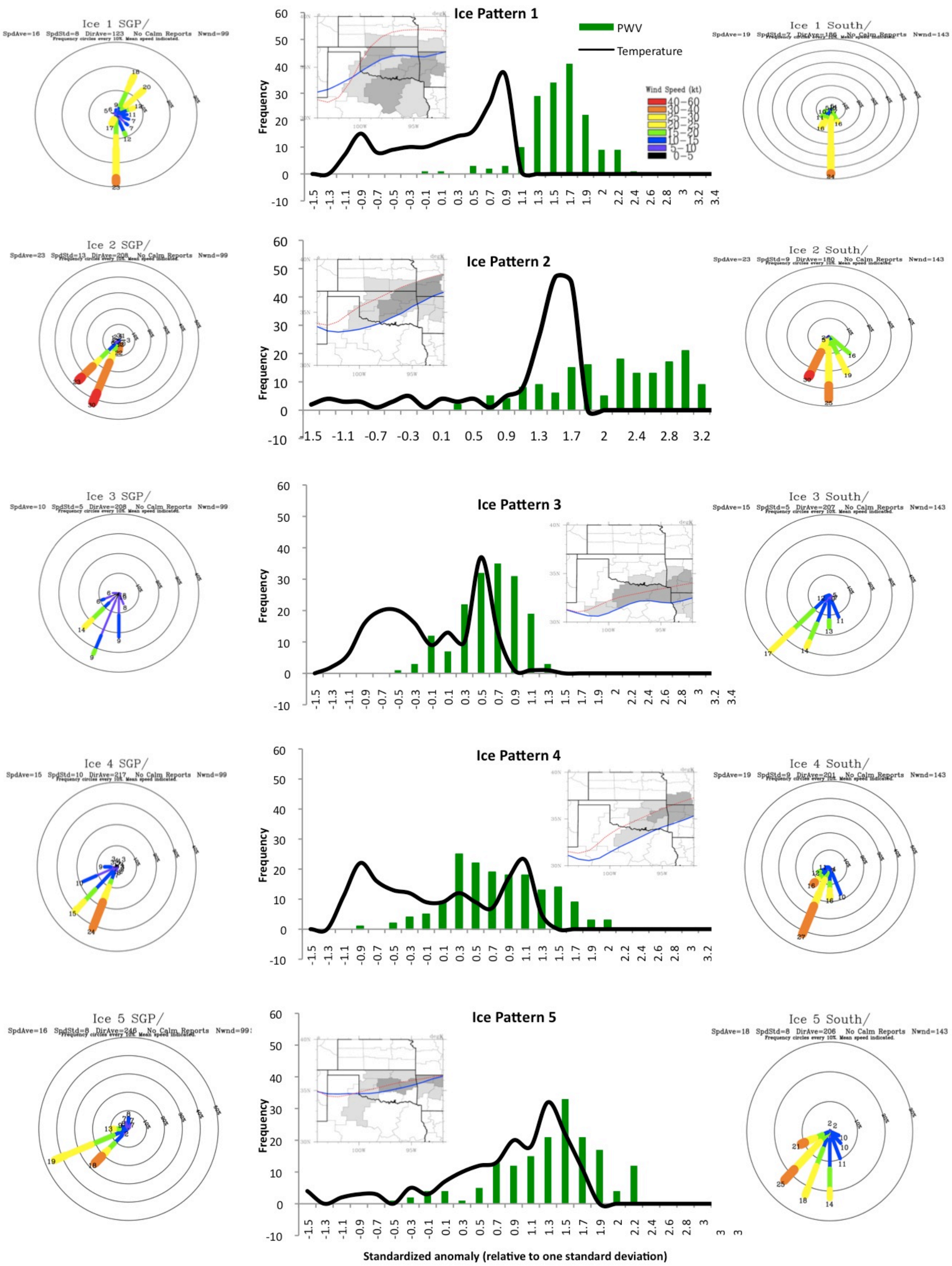


Figure 5: Multi-panel plot highlighting thermal and wind characteristics for ice patterns 1-5 respectively. Left: Wind rose averaged over the Southern Plains domain at 850hPa, center: frequency plots of standardized anomalies in temperature at 850hPa and column precipitable water for the aforementioned region. The inset figure shows the locations of the composite average surface (blue) and 850hPa (red) 0^{o}C isotherms, while the shaded areas depict locations experiencing freezing precipitation, with the darker shades indicate greater frequency. The right-hand panel is a wind rose at 850hPa for the domain south of the southern plains and over the central Gulf of Mexico. By comparing with roses within and south of the domain, one can infer the trajectory of 850hPa flow into the region.

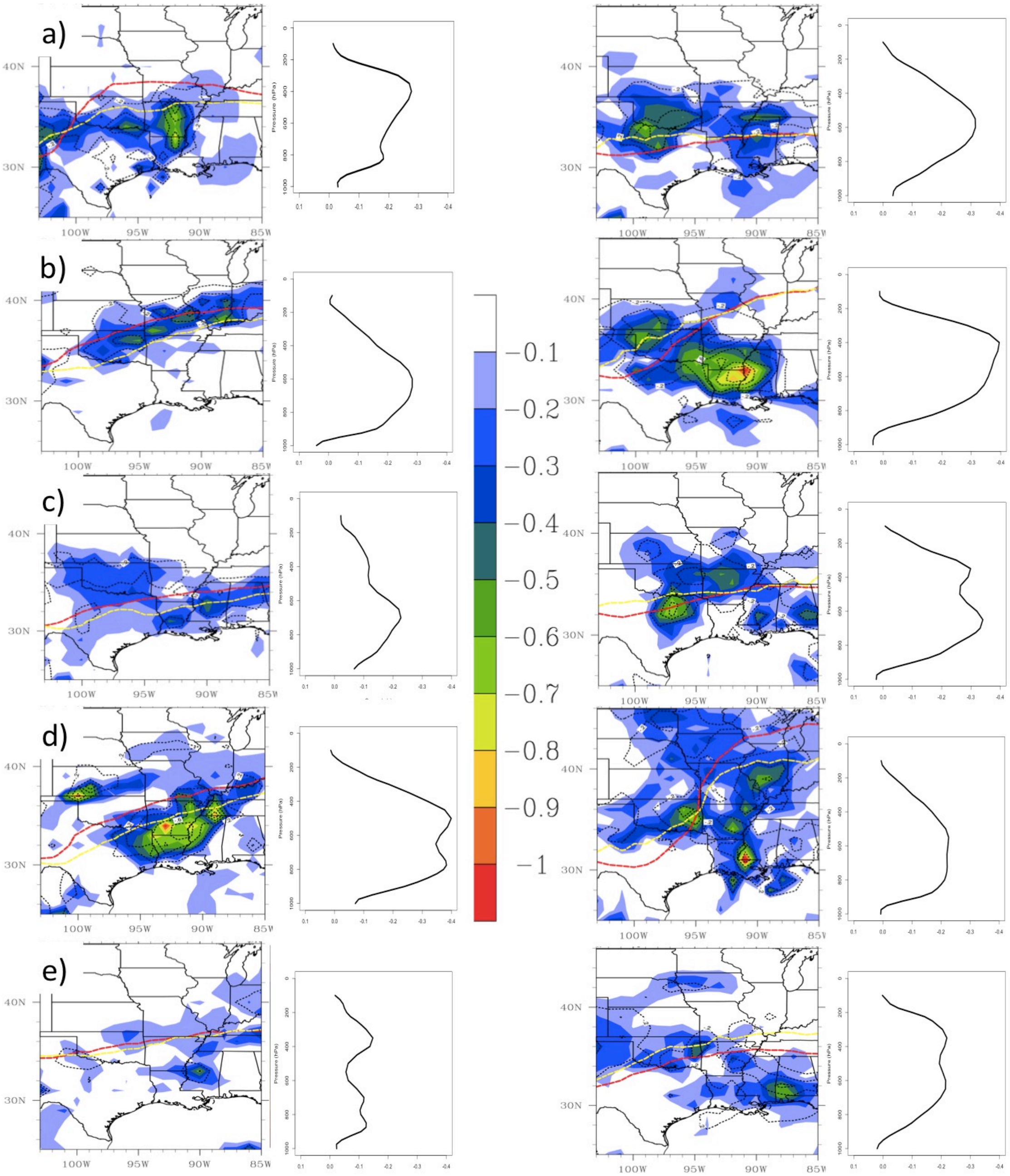


Figure 6: QG Omega (pas^{-1}) at 700 hPa at T0 for freezing precipitation patterns 1-5 (left) and snowfall patterns 1-5 (right), composite vertical motion (pas^{-1}) with height are also displayed for each pattern. Surface and zero degree isotherms (yellow and red respectively) are overlaid.

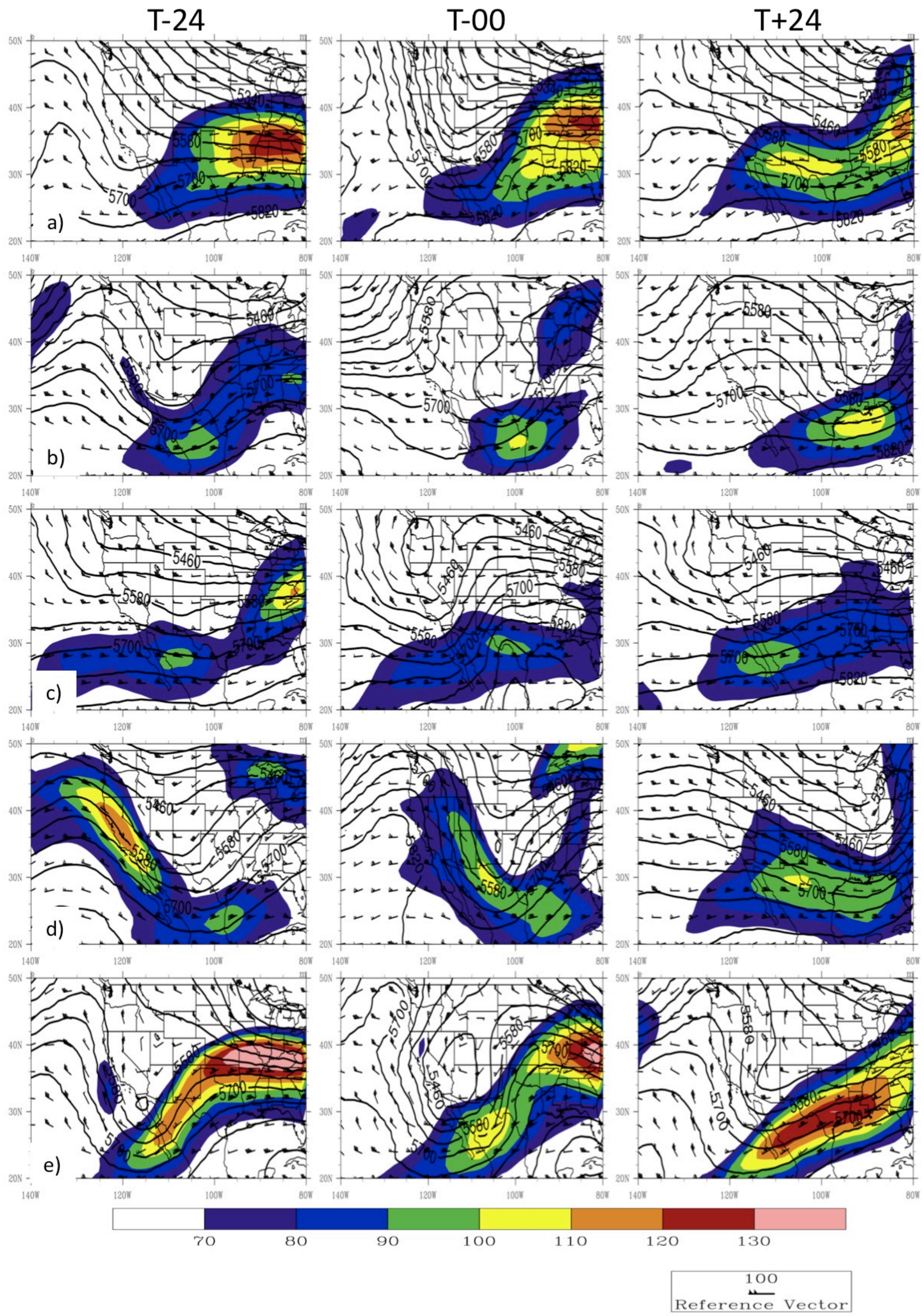


Figure 7: As Fig. 3 but for snow pattern 1-5 (a-e) respectively.

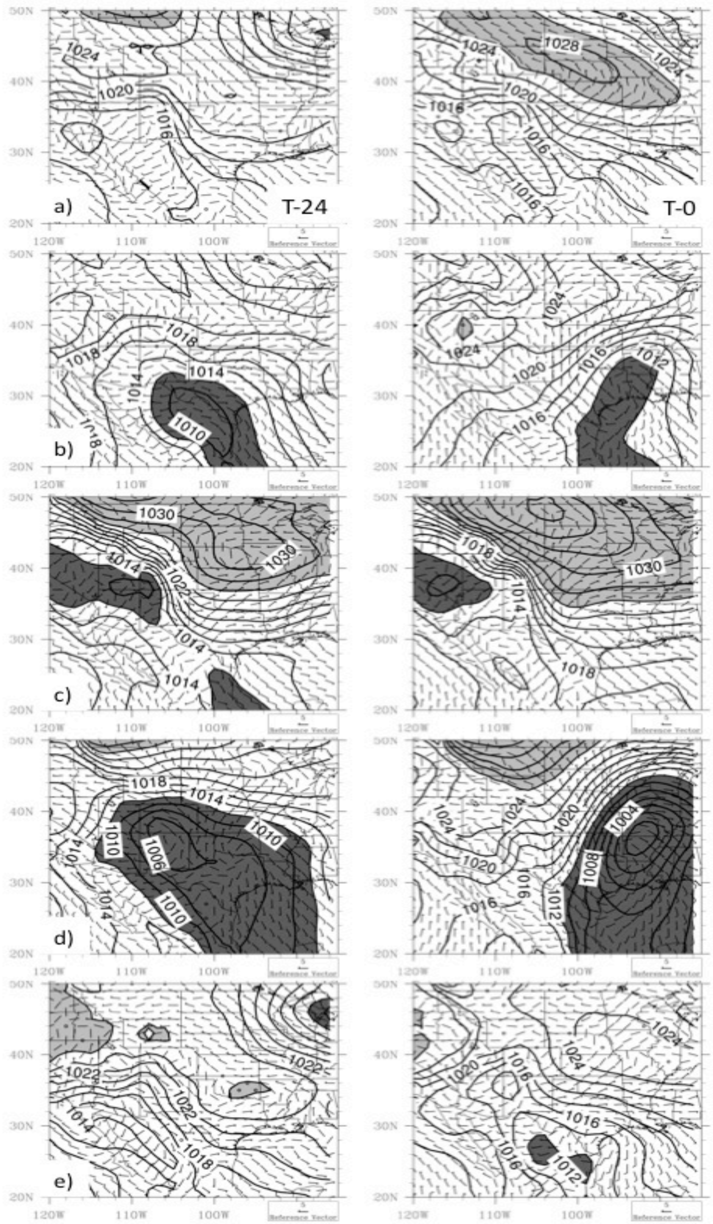


Figure 8: As Fig. 4, but for snow patterns 1-5 (a-e) respectively.

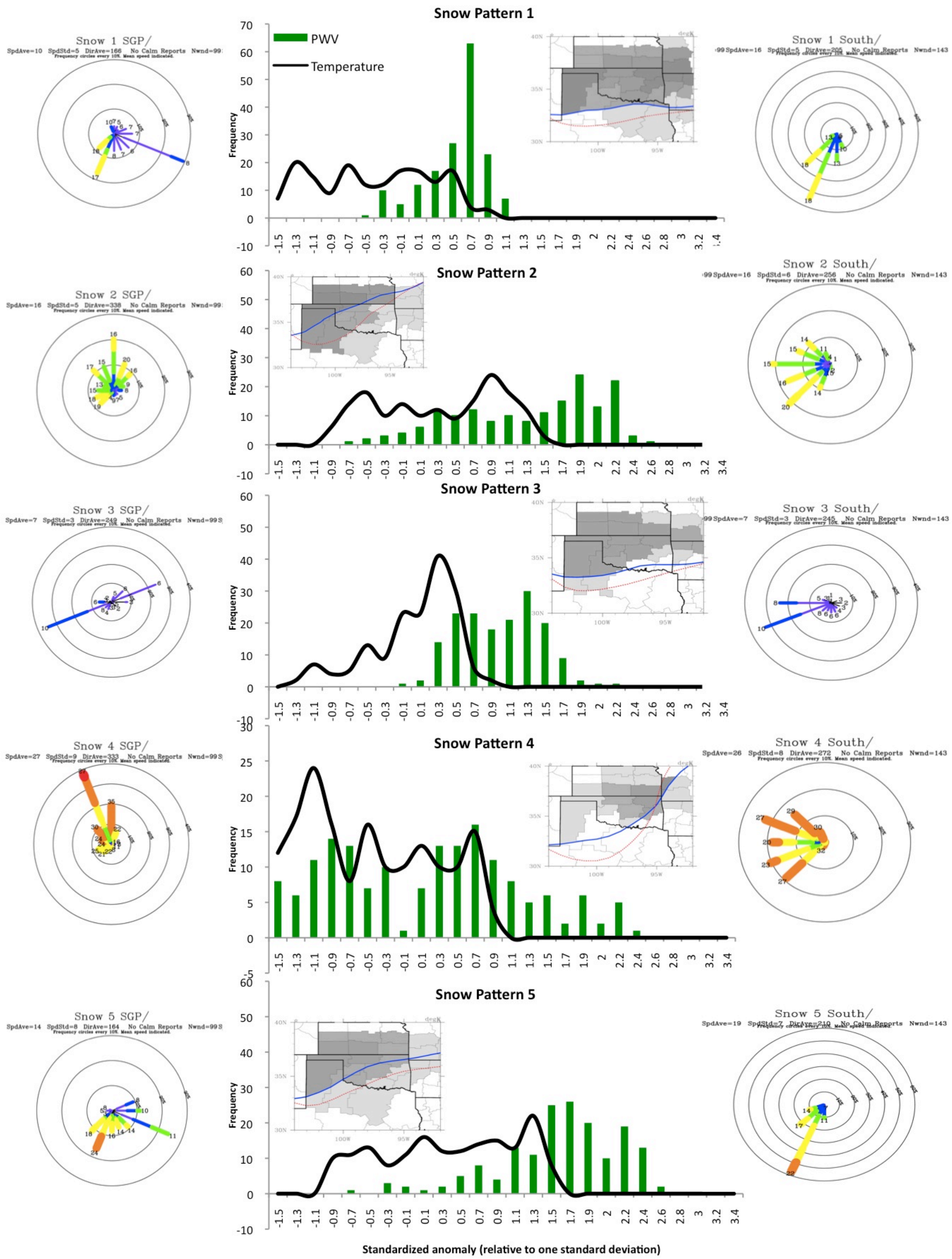


Figure 9: As Fig. 5 but for snow patterns 1-5 respectively.

(c) Synoptic Distinctions between Mixed Phase and Snow Producing Systems

Sea Level Pressure

A comparison between Fig. 4 and 8 suggests that freezing precipitation on average is associated with higher SLP, especially over the northern and central Great Plains. A two-tailed Students T-test of SLP at T_{-24} suggests that this difference is statistically significant to the 99% confidence interval over the U.S east of the Rocky Mountains, however the highest statistical significance is found over the northern plains. Freezing precipitation is commonly associated with shallow 'cold' anticyclones. As these cold stable airmasses advect southwards, they become increasingly shallow, and can undercut warmer air, creating conditions favorable for the formation of a melting layer, especially in circumstances where the low-level airmass to the south of the anticyclone is already warm. There appears to be a topographical influence of the nearby Rockies on the movement of the shallow airmass, which is too stable to ascend over the mountain chain. Thus, the airmass accelerates southwards down the gradient of pressure. Colle and Mass (1995) examined the nature of these so-called 'cold surges' east of the Rockies and suggested that the width of the surges are wider than the Rossby Radius of deformation (~500km), due to the sloping domain, which promotes small scale damming of air parcels with a westerly (upslope) component. Nonetheless, the cold air typically moves further south in the elevated terrain just east of the mountain barrier, and as a consequence over the southern plains the southern edge of the arctic airmass is typically orientated southwest to northeast.

Trough Axis and Speed

It is observed that mixed phase winter storms tend to be associated with weaker dynamics. As ascertained above, a strong surface cyclone in the southern plains generates snow, with brief or absent freezing precipitation, albeit longer periods of sleet may be possible. For mixed phase storms, the upper level trough axis on average is further west of the domain, which removes the strongest forcing for ascent. This can promote freezing precipitation as it reduces the magnitude of ascent over the whole column, which would tend to erode a melting layer due to adiabatic cooling. Fig 6 demonstrates that *on average*, the vertical velocities associated with freezing precipitation are lower than those associated with snowfall systems, and the level of maximum vertical velocity is also often located in the lower-mid atmosphere, associated with a surface front and in many cases, the region of maximum WAA. Mixed phase precipitation is typically associated with a surface front, either a stationary or warm front, and persistent warm air advection, which maintains the melting layer over cooling due to precipitation/ascent. Slower moving upper level flow promotes conditions that allow persistence of these features. This is especially clear in ice pattern 2, where the composite upper level flow pattern remains quasi-stationary over the 48-hour period of study.

Low-level Airmass Trajectories.

In snowfall cases where no well-defined cyclone is present and lift is primarily isentropic/frontal, with an arctic airmass to the north, the main distinction to mixed phase events is in the thermal characteristics of the low-level atmosphere. In this case, airmass trajectories into the 850hPa layer may be evaluated. Freezing precipitation events (excluding some freezing drizzle cases associated with dry mid-levels and subfreezing low-levels) commonly have a well-defined melting layer with airmass trajectories originating from the south or southwest. In most cases these trajectories can be considered as 'warm' trajectories. Trajectories that descend from high altitude and/or spend a considerable amount of time within a cool airmass may lead to a shallow or absent melting layer. Airmass trajectories may be assessed using model data, and may also be fed into the NOAA air resources lab HYSPLIT model which can compute meteorological parameters along back trajectories, which may be of benefit in short-medium range forecasting of winter weather.

4. SUMMARY AND FUTURE WORK

This study has presented a preliminary synoptic climatology of winter weather for the Southern Plains region of the United States. Principal component analysis is used to categorize common flow fields associated with freezing precipitation and snowfall, while composite analysis is used to evaluate synoptic and thermodynamic evolution. Tables 1 and 2 provide some summary information for the ice and snow patterns respectively. Key results from the analysis include:

i) Providing additional evidence on the distribution of freezing and frozen precipitation over the Southern U.S.

ii) Identifying common synoptic types conductive to freezing and frozen precipitation over the domain, and

Table 1: Summary table for Ice patterns 1-5. *indicates data obtained from station-based local weather summaries. Temperatures estimated from NARR data.

FZRA Pattern (# cases)	Location of Greatest Impact	Mean maximum 850hPa temperature (°C)	Mean Minimum near Surface Temperature (°C)	Median (mean)* Duration (hr)	Median (mean) liquid equivalent precipitation (in)*
1 (6)	Varies	4.1 ± 1.5	-3.5 ± 1.4	6 (14.5)	0.73 (0.64)
2 (5)	Axis through southwest, central and northeast domain	8.4 ± 1.9	-4.5 ± 1.6	24 (30)	1.26 (1.42)
3 (3)	Southern Oklahoma, north Texas, western Arkansas	5.4 ± 2.1	-4.9 ± 2.2	15 (17)	0.40 (0.38)
4 (3)	Central-southern Oklahoma, north Texas, and much of the eastern domain.	4.3 ± 2.1	-3.8 ± 1.8	9 (9)	0.29 (0.33)
5 (4)	Central OK through central Arkansas	5.0 ± 3.3	-6.5 ± 2.8	18 (18)	0.15 (0.24)

Table 2: Summary table for Snow pattern 1-5.

Snow Pattern (# cases)	Location of Greatest Impact	Median (mean)* Duration (hr)	Median (mean) liquid equivalent precipitation (in)*	Range of Maximum Snowfall (in)*
1 (6)	Northern and central domain	15 (20)	0.18 (0.35)	2.6-11.2
2 (6)	Northern and western domain	18 (18)	0.60 (0.71)	1.0-13.0
3 (4)	Similar to pattern 1	27 (25.5)	0.43 (0.46)	3.1-12.0
4 (5)	Northeastern and eastern domain	12 (12.6)	0.95 (0.92)	1.1-13.5
5 (3)	Northwestern and northeastern domain	24 (23)	0.40 (0.48)	2.7-7.5

forming a conceptual model regarding their evolution and average region of impact.

(iii) Finding distinct differences in the evolution of storms containing a substantial freezing precipitation component, including evidence for shallow stable arctic air in place over the northern plains well prior to precipitation onset, and topographical cold-air damming. These signatures are not as prevalent for most snowfall patterns, with snow more commonly associated with either a deep cold airmass already in place, or a more intense surface cyclone, but a lack of subfreezing air prior to the passage of the cyclone.

These, along with the additional results displayed above, represent a preliminary effort to improve understanding of the large-scale features differentiating mixed phase winter storms from snow events on a regional scale. The results can be used to assist local Forecasters in the interpretation of winter weather, however, the study cannot account for local and mesoscale variations within individual events.

Future work intends to eventually extend this work by increasing the temporal range of the dataset and reevaluating the synoptic pattern analysis. In addition, in order to better understand the evolution of high impact freezing precipitation on a variety of scales, a series of diagnostic and sensitivity studies have been designed using the

WRF-ARW. A case study of a severe winter storm during December 2007 will be examined in detail, with emphasis on synoptic, mesoscale and microscale processes that contributed to its longevity. Given the proximity of the region to the Gulf of Mexico, some observational analysis has suggested a positive association between the depth and magnitude of the melting layer, and sea surface temperature anomalies in the basin. Using two case studies, both of differing synoptic evolution, we intend to investigate this association by perturbing the model SSTs in the region and examining the response. The implications of this study may be applicable to current and future trends in the freezing precipitation distribution with climate change.

5. ACKNOWLEDGEMENTS

This research was supported by the Atmospheric System Research (ASR) Program of the Department of Energy, for which it is a contribution from the Southern Great Plains Site Scientist Team. Additional Funding provided by NOAA's office of Oceanic and Atmospheric Research under NOAA-University of Oklahoma Cooperative agreement NA080AR4320904, U.S Department of Commerce.

Thanks to Dr Michael Richman for his assistance in formulating the PCA component for this work.

6. REFERENCES

Ahrens, D. 2003: *Meteorology Today: An Introduction to Weather, Climate and the Environment.* Thompson/Brooks/Cole. 230pp.

Baldwin, J., 1973: The climates of the United States. NOAA, 113 pp. [NTIS COM-74-11708/6.].

Bennett, I., 1959: Glaze: Its meteorology and climatology, geographical distribution, and economic effects. Environmental Protection Research Division Tech. Rep. EP-105, Headquarters, U.S. Army Quartermaster, Research and Engineering Command, Natick, MA, 217 pp. [NTIS AD-216668.].

Bernstein, B.C, 2000: Regional and Local Influences on Freezing Drizzle, Freezing Rain, and Ice Pellets (*Wea. Forecasting*, 15, 485-508)

Branick, M.L., 1997: A climatology of significant winter-type weather events in the contiguous United States, 1982-94. *Wea. Forecasting,* **12**, 193-207.

Branick, M. 2001: Monthly and Geographic Distribution of Heavy Snow events in Oklahoma, 1951-2001. *http://www.srh.noaa.gov/oun/?n=climate-heavysnow-study.*

Changnon, S. A., 2003: Characteristics of ice storms in the United Sates. *J. Appl. Meteor.*, **42,** 630–639.

Changnon, Stanley A., David Changnon, Thomas R. Karl, 2006: Temporal and Spatial Characteristics of Snowstorms in the Contiguous United States. *J. Appl. Meteor. Climatol.*, **45**, 1141–1155.

Colle, Brian A., Clifford F. Mass, 1995: The Structure and Evolution of Cold Surges East of the Rocky Mountains. *Mon. Wea. Rev.*, **123**, 2577–2610.

Grout, T, Yang H, J Basara, B Balasundaram, Z Kong, Satish T. S. Bukkapatnam, 2012: Significant Winter Weather Events and Associated Socioeconomic Impacts (Federal Aid Expenditures) across Oklahoma: 2000–10. *Wea. Climate Soc.*, **4**, 48–58.

Harman, H.H. 1976: *Modern Factor Analysis*. University of Chicago Press, Chicago, IL.

Kovacik, C., Hocker, J., Shafer, M. 2011: An Analysis of Southern U.S Ice Storm Frequency from 2000-2009. *AMS Extended Abstract. http://www.caps.ou.edu/reu/reu10/papers/Kovacik.pdf*

Rauber, R. M., M. K. Ramamurthy, and A. Tokay, 1994: Synoptic and mesoscale structure of a severe freezing rain event: The St. Valentine's Day ice storm. *Wea. Forecasting*, **9,** 183–208.

Rauber, R. M., L. Olthoff, M. Ramamurthy, and K. Kunkel, 2000: The relative importance of warm rain and melting processes in freezing precipitation events. *J. Appl. Meteor.*, **39,** 1185–1195.

Rauber, R. M., L. Olthoff, M. Ramamurthy, D. Miller, and K. Kunkel, 2001: A synoptic weather pattern and sounding based climatology of freezing precipitation in the United States east of the Rocky Mountains. *J. Appl. Meteor.,* **40**, 1724-1747.

Ressler, G M., S.M. Milrad, E.H. Atallah, J.R. Gyakum, 2012: Synoptic-Scale Analysis of Freezing Rain Events in Montreal, Quebec, Canada. *Wea. Forecasting*, **27**, 362–378.

Richman, M.B. 1986: Rotation of Principal Components. *J. Climatology*. **6,** 293-335.

Robbins, C., and J. V. Cortinas Jr., 2002: Local and synoptic environments associated with freezing rain in the contiguous United States. *Wea. Forecasting*, **17,** 47–65.

Zerr, R. J., 1997: Freezing rain: An observational and theoretical study. *J. Appl. Meteor., 36,* 1647–1661