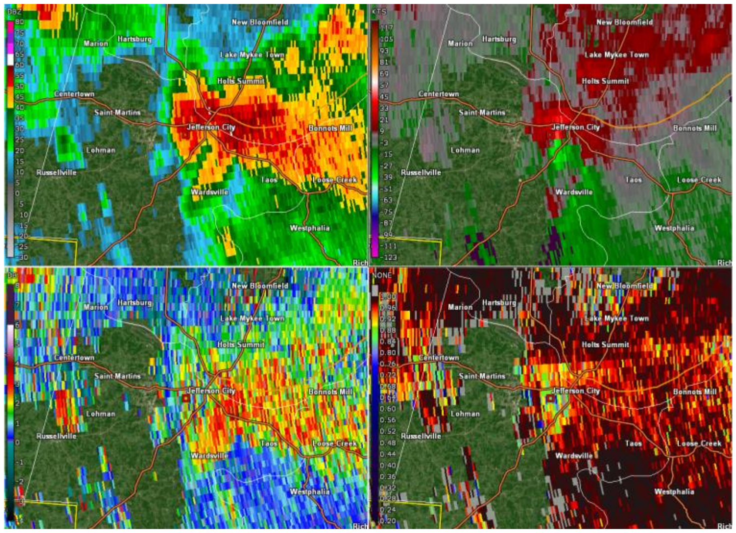

MAY 20 PARTICULARLY DANGEROUS SITUATION TORNADO WATCH AND MAY 22 JEFFERSON CITY TORNADO CASE STUDY

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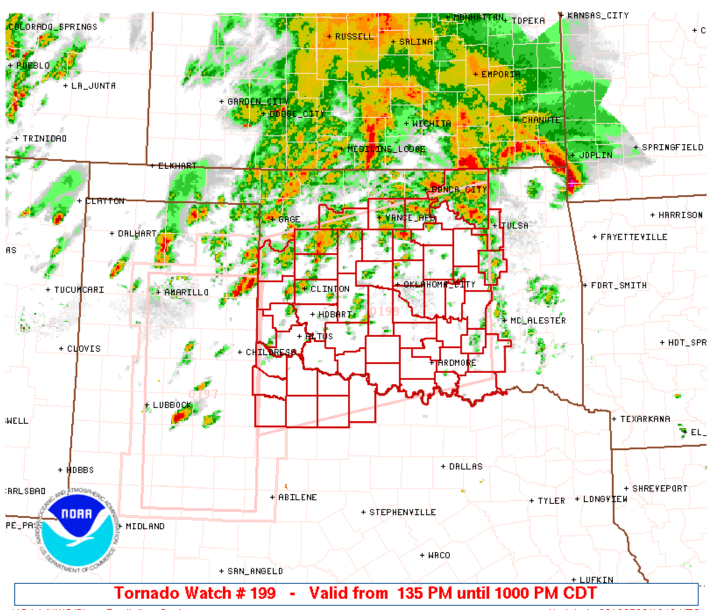


INTRODUCTION

From May 20 through May 22, 2019 an intense low-pressure system moved across the country, bringing severe weather to many parts of the Central United States. As the low was developing, the tornado sirens sounded in parts of Oklahoma and Texas on May 20 as a particularly dangerous situation (PDS) tornado watch was issued for these areas on this day. However, the storm did not bring any intense and violent tornadoes to the area as many meteorologists had expected. This case study will take a look at the synoptic scale details about how the low-pressure system evolved to form some severe weather on May 20, but also why several factors combined to limit the severe weather threat and why no long-track, violent tornadoes formed on that day that many meteorologists had warned the public about. Later in this paper, the way that this severe weather situation was communicated will be talked about, as well as how the public responded to the watches and warnings that were issued for the severe weather on May 20 across the Southern Plains.

The same low-pressure system continued to move across the country over the next couple of days, and by the overnight hours of May 22, a cold front, associated with the low-pressure system, was passing through Missouri's capital city, Jefferson City. This caused severe weather to develop in the area and produce a destructive, EF-3 tornado that tore through downtown Jefferson City during the middle of the night. This case study will take a look at all the synoptic scale features that contributed to the low-pressure system producing severe weather over central Missouri late at night on May 22. Additionally, later in the paper, the way that this severe weather threat was communicated will be talked about, as well as how well the public received this information and acted upon it so that no lives were spared in this very dangerous, nocturnal tornado.

Synoptic Meteorology Analysis

A strong mid-latitude low-pressure system traveled through the heart of the United States from May 20 through May 23, 2019, causing widespread severe storms from Texas to Oklahoma to Missouri. This mid-latitude cyclone was responsible for creating an environment that was very favorable for severe weather in northern Texas and southwest Oklahoma on May 20, causing meteorologists at the Storm Prediction Center to issue a rare PDS (particularly dangerous situation) tornado watch. This same cyclone continued to evolve over the coming days and produce a destructive, large, EF-3 tornado in Jefferson City, Missouri late at night on May 22. In this section, I will analyze this cyclone at all levels of the atmosphere to determine the factors that contributed to severe weather and factors that limited severe weather from occurring during this time frame.

Case 1: PDS Tornado Watch Over Southwest Oklahoma and Northern Texas
Monday, 5/20/19

Even though the severe weather outbreak across Oklahoma and Texas on May 20 did not pan out the way that many meteorologists expected, there were many meteorological parameters that indicated significant severe weather was a strong possibility on this day. Staring at the 250mb level, there was a strong trough that was digging southward on the morning of May 20 over the western United States (Figure 1). This trough moved towards the east throughout the day on May 20, so that by 00Z on May 21 there was a sharp curve in the jet stream over Arizona and New Mexico (Figure 1). Just ahead of this distinct trough at the 250mb level, we might expect to see some severe weather in this area, which was located over Western Oklahoma and Northern Texas, especially as the trough became negatively tilted by 12Z on May 21 (Figure 1). The left exit region of the jet streak that is present over California and Nevada throughout the day on May 20, would also be an area that is favorable for surface low development and strengthening, as this is an area that has upper-level divergence which leads to lower-level convergence (Figure 1). This favorable area for surface low development and strengthening due to the jet streak at the 250mb level moved eastward, and by 12Z on May 21 it was situated over the Southern Plains (Figure 1).

Moving down to the 500mb level, this trough continues to be a distinct feature over the Western and Central United States, and it strengthens throughout the day on May 20 (Figure 2). By 00Z, and especially by 12Z, on May 21, the trough axis is located over New Mexico and Western Texas, and it creates a very tight gradient of height lines over Northern Texas and Western Oklahoma, leading to strong winds over these areas at 500mb (Figure 2). Surface low development is likely and severe weather is possible just ahead of this trough, over Northern Texas and Western Oklahoma, because positive vorticity advection is present over this area at the 500mb level. The vorticity maximum, which is located along the trough axis, is shifting eastwards, and, therefore, higher values of vorticity are moving into this area creating positive vorticity advection. This positive vorticity advection on the eastern side of the trough promotes upper-level divergence and, therefore, lower-level convergence, leading to rising air. Rising air encourages the deepening of low-pressure systems and assists in convective storm development. Therefore, this area along the eastern side of the 500mb trough, over parts of Texas and Oklahoma, is an area that's favorable for severe weather development.

For optimal conditions for severe weather, strong winds at the 700mb level should be out of the southwest. This is the case at 00Z on May 21, as some areas were seeing 50 knot winds out of the southwest at 700mb over Northern Texas and Southwestern Oklahoma (Figure 3). The 700mb map also shows areas of high dew points, which would indicate the areas where moisture, clouds, and precipitation are present at this time. High dew points are present at the 700mb level at 00Z on May 21 over parts of Texas and Oklahoma, allowing for clouds to develop at this level of the atmosphere. This layer of moisture continues down to the 850mb level, with higher dew points over Eastern Texas and Oklahoma at 00Z on May 21 (Figure 4). The low-level jet, LLJ, helped to advect some of this moisture into this area from the Gulf of Mexico, which is located to the south. This low-level jet is characterized by faster moving winds blowing from the south, and the 850mb chart indicates that winds were out of the south at up to 50 knots over parts of Texas and Oklahoma at 00Z on May 21 (Figure 4). High levels of moisture at lower-levels of the atmosphere can help to lower the lifted condensation level, LCL, and the level of free convection, LFC, increasing the risk for severe weather development. This moist air that is being advected from the southwest at the 700mb level and down towards the surface is in contrast to the much drier air that is being advected above the 700mb level, which can be seen on the sounding launched at 00Z on May 21 from Norman, Oklahoma (Figure 7). The temperature and dew point lines on this sounding are very close together until 700mb when they become separated, indicating that dry air was in place in the mid- to upper-levels of the atmosphere at this time (Figure 7). Additionally, haze and smoke from wildfires in Southern Mexico was being advected into the region due to the strong southwesterly winds in the mid-layers of the atmosphere [20]. It is still unknown if smoke can have a negative, positive, or no effect on supercells in the area where these aerosols are present, but it is another variable that was in the region on this day due to strong winds out of the southwest from 800mb to 400mb [20] (Figure 7).

The surface weather maps from May 20 show that a stationary front was already in place across Central Texas from 00Z through 03Z (Figure 5). Throughout the day on May 20, a surface low-pressure system moved along the boundary from the northwest and towards eastern New Mexico and northern Texas (Figure 5). As the low-pressure system continued to strengthen during the day, a warm front extended from the low across Oklahoma and a dry line extended southward through parts of Texas by the afternoon on May 20 (Figure 5). The cold front at this time was situated farther back, over parts of New Mexico (Figure 5). The warm front over Oklahoma helped to lift some of the moist air that was being advected from the south on this day, and create precipitation due to overrunning. Most of the severe weather that did occur on this day was associated with the dry line over Texas and the warm front over Oklahoma, as these surface boundaries provided lift (Figure 12). The 12Z, 15Z, and 18Z surface maps indicate that there was an outflow boundary just to the north of the warm front over Oklahoma, and additional severe storms could have formed along this outflow boundary on May 20 (Figure 5).

Finally, looking at the soundings from this event on May 20 is very intriguing, as it gives us some insight as to why the severe weather event was not as widespread and devastating as it had originally been predicted to be. The morning sounding that was launched from Norman, Oklahoma at 12Z shows that the environment had very little to no CAPE (convective available potential energy) at that time, which did not allow for any thunderstorm development during the morning on May 20 over this area. However, the atmosphere turns rather unstable by the evening of May 20. The evening sounding, launched in Norman, Oklahoma at 00Z on May 21, shows a moist layer from the surface until about 700mb, with the temperature and dew point of the parcel rather close to one another (Figure 7). Lapse rates were also fairly steep between the surface and 700 mb, allowing for air parcels to rise rapidly and water vapor to condense into clouds (Figure 7). The hodograph was also rather impressive on the 00Z May 21 sounding, with the shape of the hodograph taking a sharp turn to the right, indicating that there was some strong wind shear present in the lower-levels of the atmosphere (Figure 7). We can see this by examining the wind barbs that were recorded with this sounding, as the winds were out of the southeast at 10-15 knots at the surface, but at the 800mb level the winds were out of the south-southwest at 50-55 knots (Figure 7).

At 00Z on May 21, the energy was available in the atmosphere for dangerous severe thunderstorm development, but several factors contributed to limiting the extent of this severe weather outbreak. The CAPE value on the 00Z May 21 sounding was 2805 J/Kg and the Lifted Index value was -6.7, both of which indicate very strong instability was present in the area (Figure 7). But the inversion, or “cap,” that was still present over the area during the evening on May 20, was what helped to limit severe thunderstorm development and prevent any large and violent tornadoes from occurring on this day. At 00Z on May 21, this inversion was still fairly strong as temperatures increase from about six degrees Celsius to about ten degrees Celsius almost instantaneously at around 700mb (Figure 7). A significant severe weather outbreak would have been a very distinct possibility if this cap had been able to be broken and overcome. There are a few factors that could have contributed to this inversion, or cap, remaining in the atmosphere throughout the evening on May 20 over Oklahoma. One of them is that immediately after the inversion at around 700mb, as you moved higher up in the atmosphere, temperatures began to decline very quickly, at almost the same rate as the dry adiabatic lapse rate up until about 500mb (Figure 7). This indicates the presence of an elevated mixed layer, or EML, over the area at 00Z on May 21. An EML can contribute to some convective inhibition, or CIN, which can be a good thing because some CIN is necessary for severe storms to develop. Some CIN should be present in the atmosphere so that low-level heat and moisture can build up throughout the day without convection forming everywhere before severe storms can get fired off. However, in this case, the capping inversion and CIN were enough to limit widespread severe storms from developing. An EML can also help to keep severe storms fairly isolated across an area. This is what happened across Oklahoma and Texas on May 20, as the cap and CIN were only able to be overcome along parts of the dry line and parts of the warm front, as these features provided a lifting mechanism for parcels to overcome that cap. However, for the most part, the capping inversion limited the severe storm potential for May 20 over Oklahoma and northern Texas, which caused the tornadoes that did occur on this day to not be as widespread and violent as meteorologists had predicted earlier that day.

Case 2: Low Development on May 21 and Jefferson City Tornado
Wednesday, 5/22/19

After producing severe weather across parts of Texas and Oklahoma on May 20, this low-pressure system continued to develop across the Southern and Central Plains on May 21. The system is shown on the archived surface maps as becoming occluded at 12Z on May 21, however the storm continued to strengthen throughout the rest of the day (Figure 5). The low-pressure system deepened to a minimum central pressure of 989 mb at 00Z on May 22, which is a fairly low central pressure for a system to achieve in this part of the country, as the center of circulation was situated over northern Kansas and southern Nebraska (Figure 5). The deepening of the center of the low can be attributed to the self-development feedback cycle. Even though an archived vorticity map was not available for this storm, we know that positive vorticity advection will be present just ahead, or upstream, of the vorticity maximum which will be located in the closed contour of lowest 500mb heights. This positive vorticity advection leads to increased upper-level divergence, which causes the low’s surface pressure to continue to decrease due to lower-level convergence. With a more intense low-pressure system, stronger cyclonic surface circulation will be present which helps to increase low-level temperature advections. Cold air advection west of the surface low will cause 500mb heights to fall west of the surface low, and warm air advection east of the surface low will cause 500mb heights to rise east of the surface low. Unfortunately, isotherms are not plotted on the surface maps, but we can infer that there's a wide swath of warm air advection occurring to the east of the surface low and to the north of the warm front. Specifically, at 18Z on May 21 as the low is still strengthening, warm air advection would be present north of the occluded front and north of the warm front across areas like Kansas, Missouri, Nebraska, and Iowa (Figure 5). This warm air advection causes 500mb heights to rise east of the surface low and it helps to amplify the 500mb trough even further. Cold air advection will be present west of and behind the cold front that's associated with the surface low at this time as well. Specifically, at 18Z on May 21 as the low is still strengthening, cold air advection would be present west of the cold front across areas like Eastern Texas and Oklahoma (Figure 5). This cold air advection causes 500mb heights to fall west of the surface low and it helps to amplify the 500 mb trough even further. We can see this happening on the 500mb maps, with the 500mb surface at a height of 5,680 meters in Central Oklahoma at 12Z on May 21, which then drops to 5,610 meters at the same location at 00Z on May 22 as the 500mb wave became more amplified and the surface low strengthened during this 12-hour period (Figure 2).

By 00Z on May 22, the low had reached its mature phase of development and it had become vertically stacked, as the center of the low can be traced up through the different levels of the atmosphere. Both the 850mb and 700mb maps show the lowest pressure contour situated along the border between Kansas and Nebraska at 00Z on May 22, which correlates nicely to where the center of the low was on the surface map at this time (Figures 3, 4, 5). The 500mb map also shows the lowest heights along the border between Kansas and Nebraska at 00Z on May 22, which matches up to where the center of circulation is at the surface (Figure 2). Even the 250mb map shows some tight circulation over this region at 00Z on May 22 due to the streamlines that are plotted on the map at this level (Figure 3). All of these maps and factors demonstrate that the low-pressure system had become vertically stacked by 00Z on May 22 and the system began to weaken over the next couple of days. By 12Z on May 22, the center of the low had risen a central pressure of 994mb (Figure 5).

Despite the low-pressure system weakening and reaching the end of its life cycle by May 22, it was still capable of producing severe weather across parts of the central United States. At 11:45pm CDT on May 22, a strong EF-3 tornado tore through downtown Jefferson City, Missouri, and we will see that many severe weather ingredients came together to cause this severe weather event in the capital city of Missouri. At the 250mb level, the trough that we saw over the western and south-central United States that brought the severe weather to parts of Oklahoma and Texas on May 20 has since moved off towards the north and it much less defined on the overall jet stream pattern by May 22 at 12Z (Figure 1). However, we can still see some of the remnants from this once well-defined trough as the isotachs and streamlines indicate an area of circulation over Nebraska and South Dakota at 12Z on May 22, which is now what's left of the once stronger 250mb trough (Figure 1). At the 500mb level, the flow is more zonal by May 22, with a less amplified trough compared to the severe weather case in Oklahoma and Texas on May 20 (Figure 2). At the 700mb level, we can see a well-defined area of lower heights over Minnesota at 00Z on May 23 and a very tight gradient of height lines over Iowa, Illinois, and Missouri, with a ribbon of fairly fast-moving winds over these areas as well (Figure 3). The higher dew point contours on this map, which correlate to areas that are favorable for clouds and precipitation, are located over parts of western Missouri at 00Z on May 23, and this moisture would move eastward over the next several hours to produce the severe weather in Jefferson City, which is located in central Missouri (Figure 3). At the 850mb level, we can see plenty of moisture being advected to the north from the Gulf of Mexico at 00Z on May 23, with high levels of moisture being shown all the way from Texas to Alabama to Missouri (Figure 4). Additionally, strong winds out of the south at this level of the atmosphere, associated with the low-level jet, helped to advect this moisture to the north (Figure 4). This lower-level moisture in Missouri at 00Z on May 23 is one of the ingredients that helped to fuel severe storms and a destructive tornado later that night in Jefferson City.

The surface maps from May 22 show that Jefferson City was in the warm sector of this occluded low-pressure system throughout the entire day, allowing for warm and moist air to build up in the region during the day before a cold front swept through the area overnight (Figure 5). A surface observation in St. Louis, Missouri from the archived surface weather map at 03Z on May 23, which would have been after the sun went down, shows that the atmosphere was still very warm and moist ahead of the cold front with a temperature of 78 degrees Fahrenheit and a dew point of 73 degrees Fahrenheit (Figure 5). The cold front associated with this low-pressure system moved through central Missouri and Jefferson City at around 06Z on May 23, and the surface weather map even indicates an outflow boundary was present due to the severe weather that occurred across this area at this time (Figure 5). The satellite shows widespread convection developing across Missouri and Illinois out ahead of this cold front between 21Z on May 22 and 00Z on May 23 and especially between 00Z and 03Z on May 23 (Figure 6). By 06Z on May 23, around the time that the tornado touched down in Jefferson City, widespread convection can be seen throughout central and southern Missouri and the entirety of Illinois, as indicated by very high cloud tops on the satellite image (Figure 6).

The morning sounding at 12Z on May 22, launched from Springfield, Missouri, shows that the atmosphere was fairly stable at this time across Missouri, with a very low-level inversion in place -- below 900mb (Figure 8). However, a decent amount of wind shear was already being observed at 12Z, with winds out of the south at 10 knots at the surface and winds out of the west-southwest at 45 knots at around 900mb (Figure 8). This generated a hodograph that had a sharp curve plotted on it, indicating that the environment had a decent amount of wind shear which is favorable severe weather development, especially since it was still early in the day at 12Z (Figure 8). The veering, or curving, of the line on the hodograph means that winds are changing speed and direction with height, creating an environment that's more conducive for severe weather. It's also interesting that this 12Z sounding shows a layer from 900mb to about 700mb with very steep lapse rates, as the temperature of the parcel through this layer runs almost parallel to the dry adiabats (Figure 8). As the surface is heated throughout the day and the temperature rises, the low-level inversion that was in place earlier in the day is erased. By the 00Z sounding on May 23, the layer of the atmosphere with very steep lapse rates that was present higher up in the atmosphere at 12Z on May 22, had shifted down to now be between the surface and about 750mb (Figure 8). Now parcels could immediately begin to rapidly accelerate upwards throughout this layer of the atmosphere with very steep lapse rates, helping to form convection and severe thunderstorms in the area throughout the night of May 22. On the 00Z sounding from May 23, there is a very small cap that is present at around 725mb, and a small area of CIN associated with this cap, however there are a couple of other factors that help parcels overcome this capping inversion (Figure 8). Primarily, there is a strong cold front that is moving across Missouri on the night of May 22, which will provide a lifting mechanism as it sweeps across the state (Figure 5). Additionally, the 850mb map shows some low-level advection of warm, moist air from the south into Missouri at 00Z on May 23, which can help to reduce the cap (Figure 4). Overall, the synoptic scale setup was very favorable for severe weather to develop over Missouri on the night of May 22, which led to a violent tornado touching down in Jefferson City that night.

Communications and Public Response

Case 1: PDS Tornado Watch Over Southwest Oklahoma and Northern Texas
Monday, 5/20/19

The Particularly Dangerous Situation (PDS) Tornado Watch that the Storm Prediction Center (SPC) issued on the afternoon of Monday, May 20, 2019 was very well communicated and supported meteorologists forecasts several days out that widespread severe weather could occur over this area on this date. However, the scale and severity of the severe weather did not come to fruition. It is important to mention that there *were* some tornadoes that did develop over this area on this day, but, at the end of the day, the reality of what happened did not meet most meteorologists' high expectations of the forecast. Some people have called the forecast a “bust” because the most intense and widespread tornadoes that were predicted did not come to fruition, but others think the SPC did a good job with the atmospheric setup that was in place.

The potential for a severe weather outbreak was very well predicted by the SPC as far out as seven days before the event on Monday, 5/20/19. On May 14, the SPC circled the area extending from Northern Texas to Eastern Kansas as having a 15% chance of experiencing severe weather on May 20 (Figure 9). The probability grew to 30% when the day 5 forecast was issued on May 16, and the 30% area was focused on Northern Texas and Western Oklahoma (Figure 9). The day 3 categorical outlook forecast from the SPC showed a moderate risk, level four out of five, outlook for severe weather on May 20 accompanied by a 45% total severe probability area over Northern Texas and Western Oklahoma (Figure 10). The day before the predicted severe weather outbreak on May 20, the SPC was consistent with its forecasts from the day before and between the morning, 06Z, and afternoon, 18Z, outlooks (Figure 10). A moderate risk of severe weather was still in place across the area and the total severe probability was still at 45% (Figure 10). However, on the morning of Monday, May 20, the SPC upgraded the area in Northern Texas and Western Oklahoma to a high risk, level five out of five, outlook for severe weather on that afternoon and evening (Figure 11). For the morning outlook, the tornado probability was at 30% and both the damaging wind and the hail probabilities were at 45% (Figure 11). By the afternoon outlook from the SPC, the tornado probability over parts of Oklahoma and Texas had grown to a 45% chance of tornadoes within 25 miles of a given point in this highlighted region (Figure 11). The last time a 45% tornado probability outlook was issued by the SPC was during the tornado outbreak in Oklahoma and Kansas on April 14, 2012

[3]. Therefore, the SPC reserves using the 45% tornado probability outlook for cases that they are very confident will produce strong severe storms that are very dangerous.

Since the forecast had been fairly consistent over the past week that there was going to be some kind of severe weather in the area on Monday, May 20, and the fact that probability that the severe weather was going to be very strong kept growing and growing by the day, there was a heightened sense of alert about the storms in the communities that were under the greatest risk. In fact, many businesses, schools, and government agencies in Oklahoma closed due to the risk of severe weather on May 20 [4].

At 1:35pm CDT, the SPC issued a rare PDS (particularly dangerous situation) tornado watch for the area that was under the high-risk category for severe weather, but it also extended into some areas that were under the moderate risk for severe weather on that day in Texas and Oklahoma [1]. The SPC highlighted that the primary threats of this PDS tornado watch included "numerous tornadoes and several intense tornadoes expected, widespread damaging winds and scattered significant gusts to 80mph expected, and widespread large hail and scattered very large hail events to 4 inches in diameter expected" [1]. The PDS tornado watch was issued because conditions were favorable for tornadoes and severe weather within the watch area and that "an outbreak of tornadoes, including the risk of intense and long-track tornadoes, is expected to develop this afternoon across the watch area" [1]. The probability of two or more tornadoes, one or more of them being strong (EF2-EF5), and the probability of ten or more severe hail and ten or more severe wind events both exceeded a 95% chance of occurring that afternoon and evening [1]. In fact, these are the requirements that need to be met for the SPC to issue a PDS tornado watch. All severe weather categories, including tornadoes, wind, and hail, must have greater than a 95% chance of occurring for the PDS watch to be issued. This is only the second known PDS tornado watch that has been issued by the SPC since they began doing so, the only other one being issued on April 27, 2011 [2].

After all of these watches and outlooks were issued and advanced notice of a large severe weather outbreak was communicated, this is what happened. There were 38 tornadoes that were reported in parts of Texas, Oklahoma, and Missouri on Monday, May 20, many of which were EF-0 or EF-1, however, there were a few of EF-2 intensity and one of EF-3 strength [5]. One of the EF-2 tornadoes struck Mangum, Oklahoma, in the far southwestern part of the state, and damaged some homes, including ripping the roof off of one apartment building [6]. The EF-3 tornado touched down near the town of Odessa, Texas, destroying oil pump jacks and leaving behind a swath of ground scouring as it moved through open oil fields [5]. Luckily, only one person was injured by these tornadoes when an EF-2 wedge tornado struck the town of Peggs, Oklahoma on this day, damaging many homes and businesses [5]. Verification maps from the SPC show that the tornadoes that did develop, for the most part, fell within their 30% to 45% tornado probability outlook area (Figure 12). There were also many reports of damaging winds and hail within those outlook areas that the SPC had outlined the day before and refined earlier that day (Figures 13 and 14). Therefore, the forecast did verify because several tornadoes, and even some strong ones, did develop on this day within the forecasted area. People's lives and property were impacted by the severe weather that actually did develop on May 20. These people would not say that the forecast from the SPC was a bust. However, some other people have made the claim that it was a bust, mostly because the forecast did not meet their expectations for a widespread severe weather outbreak with long-track, violent tornadoes. These people are correct in some sense because looking at the hard data, the severe weather that did occur does not meet the threshold of 45% coverage of tornadoes or long-track violent tornadoes in the forecasted area [4]. However, the messaging from the SPC did force people to act and prepare for the severe weather that was forecasted, even if it did not impact them directly.

Additionally, there was an added threat of flooding rain from this storm that resulted in many water rescues having to be made in Oklahoma [7]. In Payne County, for example, emergency responders had to conduct more than 30 water rescues because six to eight inches of rain fell on Monday, May 20 across the region in a short period of time [7]. The floodwater also caused parts of I-40 to be closed in Canadian County, Oklahoma, and an additional 40 water rescues had to be performed on Monday night in Canadian County due to the flash flooding [7]. The focus on the severity and rarity of the severe weather outlooks might have detracted from the threat of life-threatening flash flooding across the area. Many media outlets and forecasting services directed their focus on communicating the specifics of the possibly historic tornado and severe weather potential for May 20, while very few talked about how bad the flooding could be from the amount of rainfall that was forecasted to happen. Looking back at the event, it could be argued that more people were impacted by the flooding rains than by the tornadoes and severe weather that occurred on May 20. Therefore, I think it is important for meteorologists to realize that all impacts need to be focused on when communicating a complicated and impactful weather event, because putting all your attention on one aspect of the event can be detrimental to the people that will be impacted by the other aspects of the event.

From a messaging standpoint of communicating weather information, meteorologists need to be careful not to "hype" the weather events before they occur. Once meteorologists start using words like "extreme" and "violent" with regularity to talk about a predicted weather event, there's no other level for meteorologists to go to if something actually happens that is worse [8]. For instance, before this severe weather event, Mike Smith, a meteorologist with decades of experience monitoring Midwest storms, tweeted the he would “label this ‘the nightmare scenario’” [10]. Many other meteorologists communicated the message before the event using language similar to this, which can be misleading, especially if the forecast does not completely verify [11]. Dr. Marshall Shepherd brings up a good point in his article for Forbes that we have become a culture that frowns upon preparing for the worst and then nothing happens [4]. People had to adjust their Monday plans and not go to school or work on May 20 in order to prepare for the severe weather outbreak that was forecasted. If they weren’t directly impacted, there were many other people that were directly impacted by the severe weather on that day so they should not be mad that they prepared “for nothing” [4]. If people keep this mindset, then the next time there is a severe weather outbreak in their area and they don’t do anything to prepare for it because they don’t think it will impact them directly, they could be caught off-guard and unprepared. This is called the “cry wolf effect” and it’s something that false alarms can create in the public’s opinion [4]. If a person prepares over and over again for false alarms and they don’t directly feel the impacts from each weather event, they might become complacent and not feel like they need to prepare for or take shelter from the next event. In reality, there are many factors that likely influence an individual’s decision to act on a watch or warning. These include optimism bias, where people believe that it won’t be as bad as meteorologists say it will be; the person’s weighting of the risks versus costs of their decision; and the lack of trust in the watches or warnings themselves, just to name a few [9]. This is one of the many reasons why social science research is imperative within the weather enterprise so that we can understand some of the factors that drive people's decisions. We also need to realize that a forecast for a very complicated and impactful severe weather setup is tricky for severe storm forecasters at the SPC. If these forecasters miss a critical forecast for widespread severe storms, many lives could be unnecessarily lost. But if they over-forecast for an event, they will usually have to face criticism and potentially lose some of their credibility for the next severe weather event.

Case 2: Jefferson City Tornado
Wednesday, 5/22/19

On the evening of May 22, 2019, the severe weather ingredients came together at the right time to produce a large EF-3 tornado with winds estimated at 160 mph as it tore through the center of the capital city of Missouri [12] [15]. Thirty-three people were injured from this tornado, but thankfully zero people were killed [12]. This severe weather outbreak on May 22, including the Jefferson City tornado, did not appear on the SPC’s forecast maps until three days before the event, when a marginal risk of severe weather was highlighted on the SPC’s categorical outlook map over a portion of the Great Plains, but this highlighted area did not include Jefferson City (Figure 16). For the SPC's forecast maps four to as many as seven days before the event, the predictability for severe weather was too low for the SPC to highlight any areas to watch on their map (Figure 16). On the afternoon of May 21, the day before the event, the SPC now had a slight risk for severe weather highlighted for parts of eastern Kansas and northwestern Missouri, with the Jefferson City area now under a marginal risk for severe weather (Figure 16). The confidence in the forecast began to increase by the morning of May 22, as an enhanced risk was issued for parts of northeast Oklahoma, southeast Kansas, and western Missouri, and a tornado probability percentage of 10% was issued for most of this region as well (Figure 18). By 16Z on May 22, a moderate risk, level 4 out of 5, of seeing severe weather was issued by the SPC, and this area included parts of extreme northeastern Oklahoma, southeastern Kansas, and western Missouri, extending very close to Jefferson City (Figure 18). The probabilistic tornado guidance now showed a 15% chance of seeing a tornado within 25 miles of any given point in this highlighted area, which mimicked the moderate risk area on the 16Z convective outlook (Figure 18). Nothing much had changed to the forecast by the time the afternoon, 20Z, update was issued by the SPC, but there was high agreement that there would be severe weather across parts of northeastern Oklahoma, southeastern Kansas, and western Missouri with tornadoes, large hail, and damaging winds all possible, especially in the high-risk areas (Figure 18). The forecast verified fairly well, with most of the tornadoes that did develop forming in the highest tornado probability area, however some did form within the 10% or even 5% tornado probability areas of the forecast (Figure 17).

Despite the SPC not picking up on the severe weather potential until two days before the event, the tornado warning issued by the National Weather Service office in St. Louis, Missouri provided residents of Jefferson City with plenty of lead time to seek shelter before the tornado hit the city. The first emergency sirens were activated in Jefferson City at 11:10pm, shortly after the tornado warning was issued by the National Weather Service, and then the sirens were reactivated at 11:40pm [14]. The first reports of damage in Jefferson City occurred at 11:47pm, which gave residents at least 35 minutes to seek shelter and prepare for a tornado to come towards their house [14].

One of the scariest parts of this tornado in Jefferson City was that it tore through the city around the midnight hour on the night of May 22. This can be seen as a bad thing because some people may have been sleeping by this time, especially since it was on a weeknight, and not able to get to a safe place, such as the basement of their home if they were asleep in their bedroom. However, this can also be seen as a good thing because it meant that most people were at home and not outside driving around or doing other things outside of their homes. Strangely enough, this tornado occurred on the eight-year anniversary of the Joplin, Missouri tornado that killed 161 people and injured more than 1,100 others [15]. The two key differences between the Joplin tornado and the Jefferson City tornado were their intensity (the Joplin tornado was rated EF-5), but also their timing [15]. The Joplin tornado struck the city on a Sunday afternoon, when people were doing things away from their homes in vulnerable locations, such as high school graduation ceremonies [15]. Brian Houston, a communications professor and director of the University of Missouri's Disaster and Community Crisis Center, agrees that it was a good thing that the Jefferson City tornado arrived during the middle of the night because people were at home, inside structures that most likely have a safe place to go to, instead of out and about away from their homes [15]. Additionally, more homes in Jefferson City are built with basements, the ideal place to go when a tornado is headed for your house, rather than in Joplin where many people had to seek shelter in interior rooms or in their bathroom [15].

Overall, I think the Jefferson City tornado was a success in terms of messaging its impacts, especially after the major severe weather outbreak that the SPC had forecasted two days beforehand in northern Texas and western Oklahoma did not play out exactly as they had forecasted. Residents of Jefferson City received alerts about the tornado warning on their phones or by hearing the tornado sirens outside, and they responded appropriately by seeking shelter in time so that no one was seriously injured or killed. This goes to show people that even if a large, EF-3 tornado tears directly through the downtown of a city, no fatalities need to occur as long as the proper messaging is delivered and residents of the city respond to the warnings.

Conclusion

The May 20, 2019 particularly dangerous situation (PDS) tornado watch and the May 22, 2019 Jefferson City tornado had many differences in terms of the synoptic scale setup, as well as in terms of the communication of the event and how the public responded. Primarily, each event occurred at a different time in the low-pressure system's life-cycle, and therefore each event had its own set of reasons for why severe weather was able to develop on that day.

The PDS tornado watch on May 20 happened towards the beginning of the low's life-cycle as the system was still strengthening just east of the Rocky Mountains. High levels of moisture and instability were present across the area on that day, prompting many meteorologists to be very concerned about the potential for widespread severe storms and tornadoes during the afternoon and evening. The Storm Prediction Center would issue a PDS tornado watch, something that is very rare, during the early afternoon hours of May 20, with the forecast of numerous tornadoes, several of them being intense, and widespread damaging winds and large hail. Although 38 tornadoes did develop on this day across the Southern Plains, and there were widespread areas of wind and hail reports, many members of the public and other meteorologists were quick to say that the SPC's PDS tornado watch "busted." Despite the fact that no tornadoes were extremely violent or long-track, many people across the forecasted area were impacted by severe weather on this date. Severe weather events like this one are extremely hard to predict due to the fact that a capping inversion was in place across the region, helping to limit convection earlier in the day, but breaking the cap and setting off the domino effect for widespread severe weather to occur is very finicky and even a very subtle change in the atmosphere can cause the cap to remain just strong enough to limit the severe weather potential. Therefore, I believe that the SPC did a good job of communicating this tricky event as a whole to the population of Northern Texas and Oklahoma, as many people were preparing for a widespread severe weather outbreak.

The Jefferson City tornado occurred much later in the low's life cycle, after it had become occluded and after it had begun to weaken a little bit. However, the system still had plenty of moisture and instability available to produce severe weather along its cold front on the night of May 22. A strong and violent EF-3 tornado tore directly through downtown Jefferson City during the overnight hours causing a wide swath of damage, but, miraculously, no deaths. The potential for severe weather on this date did not enter the SPC's forecast until two days beforehand, which is much closer to the event than for the severe weather outbreak on May 20. The National Weather Service office in St. Louis, Missouri did an excellent job of giving the residents of Jefferson City plenty of lead time, around 35 minutes, from when they issued the tornado warning to when the first reports of damage were seen from the tornado.

This was critical so that people could wake up, if they were already sleeping, and seek shelter within the homes.

Both cases offered a very favorable setup for severe weather, and each offered its own unique challenges for forecasting the severe weather and communicating the possible impacts to the public. Therefore, it was very interesting to investigate the meteorological reasons why severe weather occurred on both of these days and why a large-scale severe weather outbreak was limited on May 20. It was also fascinating to take a social science approach to the communication side of each event, looking at how the public responded to these messages and warnings and what can be improved with messaging for severe weather events in the future.

Figures

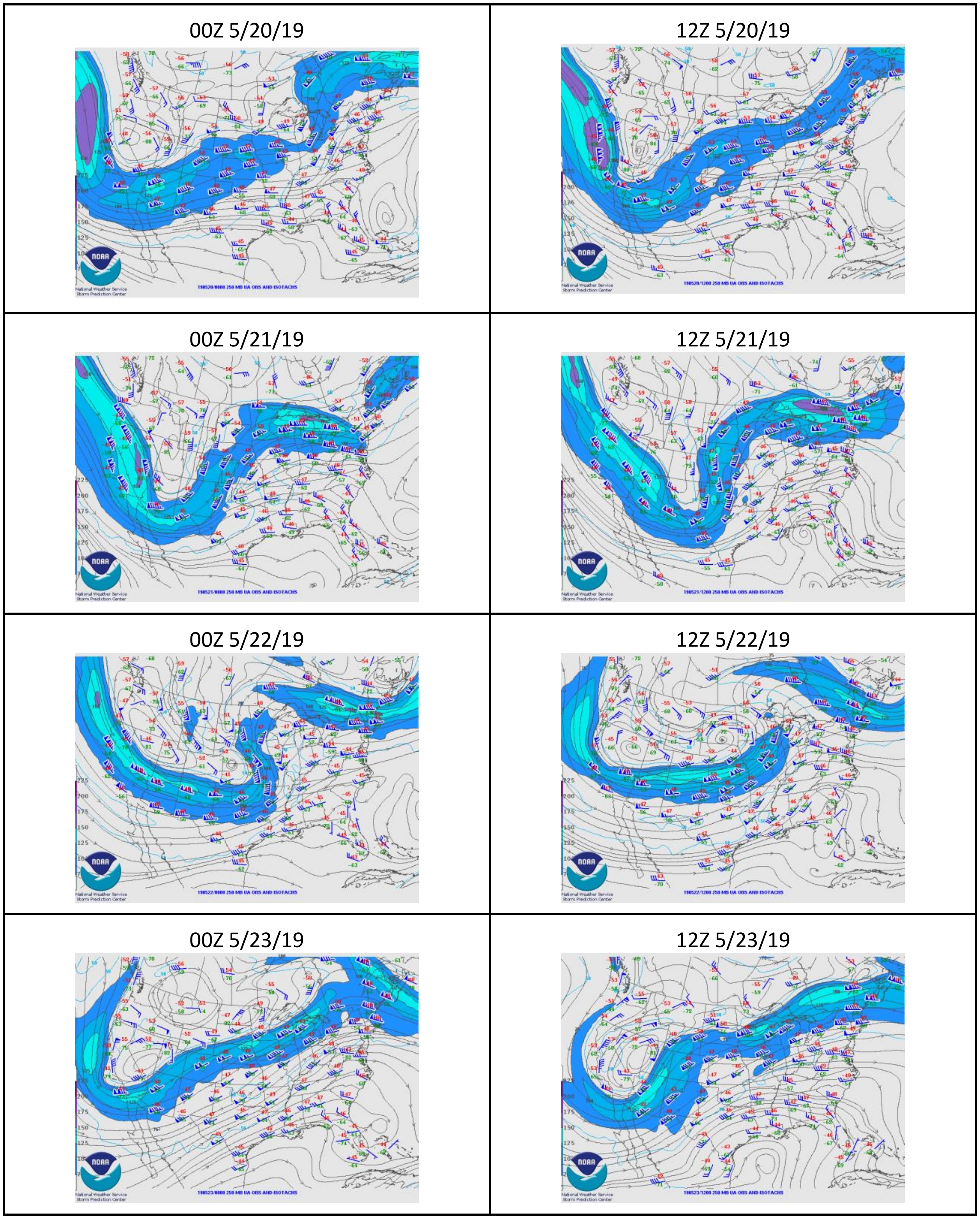


Figure 1: 250mb observations, streamlines and isotachs from 00Z 5/20/19 through 12Z 5/23/19. Maps courtesy of the Storm Prediction Center [16].

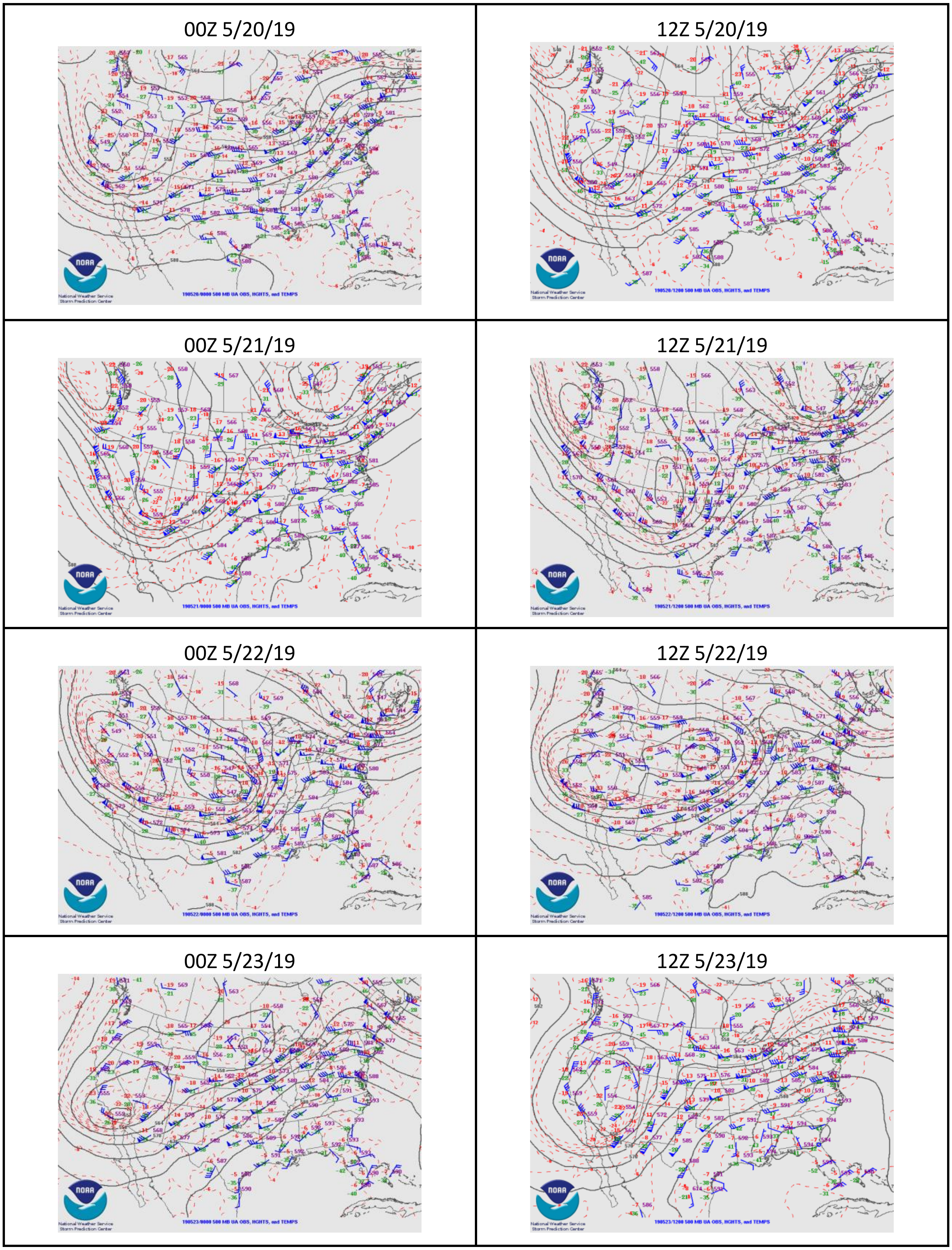


Figure 2: 500mb observations, heights, and temps from 00Z 5/20/19 through 12Z 5/23/19. Maps courtesy of the Storm Prediction Center [16].

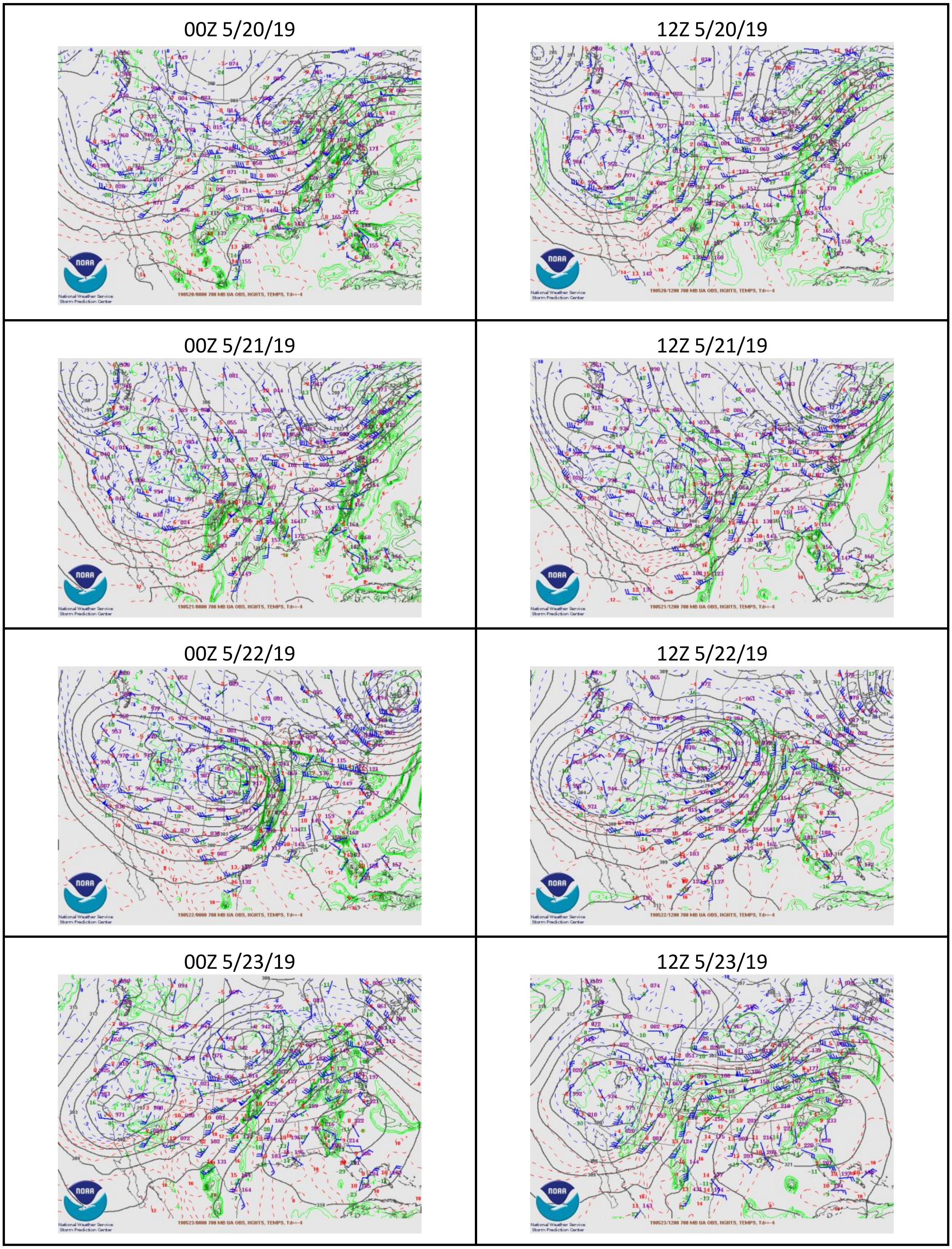


Figure 3: 700mb pressure, observations, heights, temps, dew point contours from 00Z 5/20/19 through 12Z 5/23/19. Maps courtesy of the Storm Prediction Center [16].

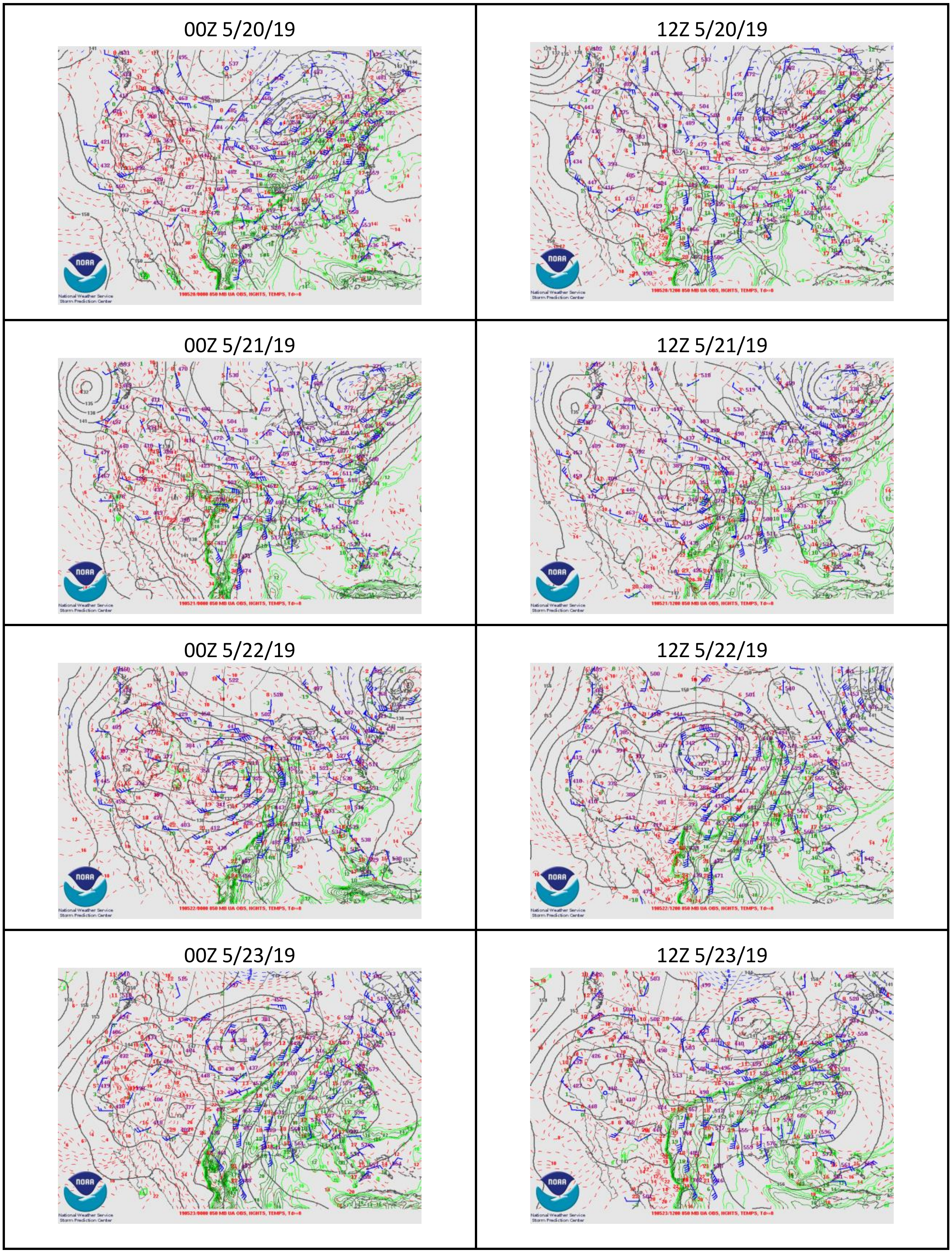
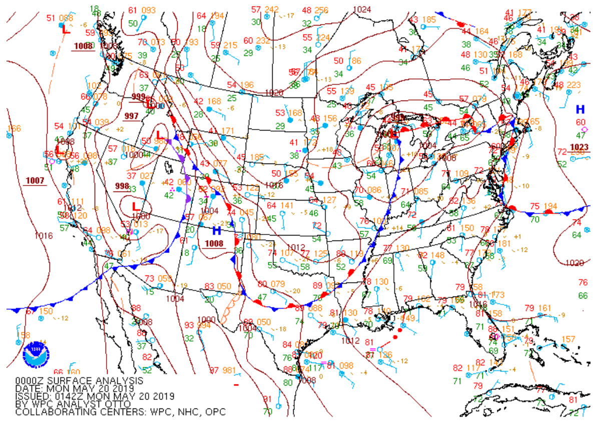
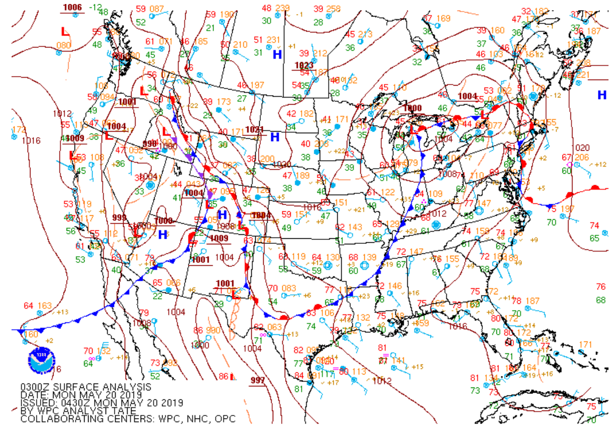


Figure 4: 850 mb pressure, observations, heights, temps, dew point contours from 00Z 5/20/19 through 12Z 5/23/19. Maps courtesy of the Storm Prediction Center [16].

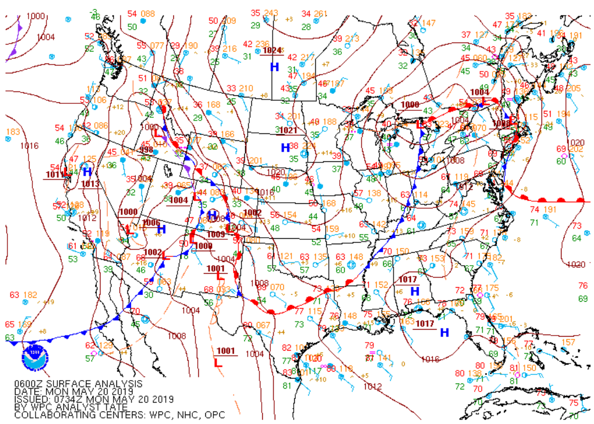
00Z 5/20/19



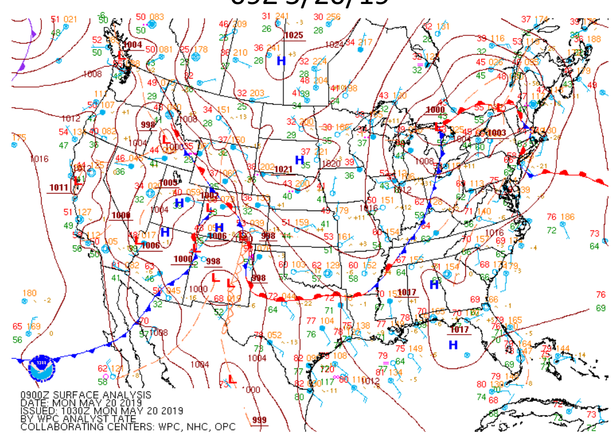
03Z 5/20/19



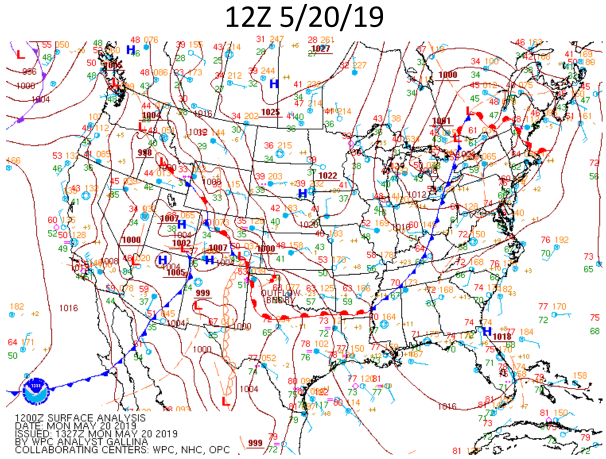
06Z 5/20/19



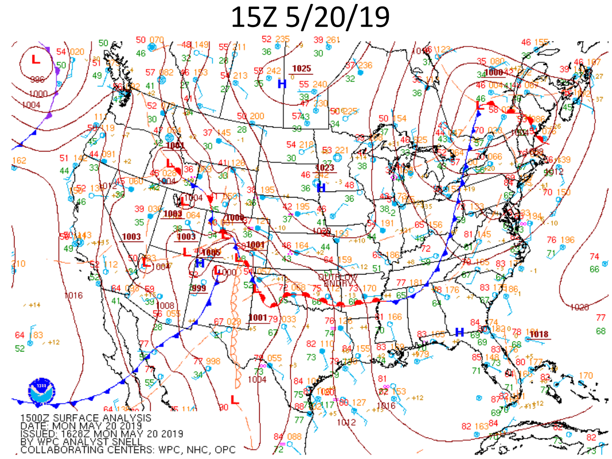
09Z 5/20/19



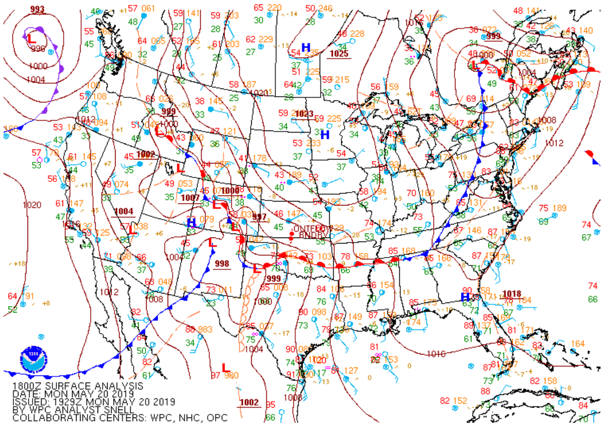
12Z 5/20/19



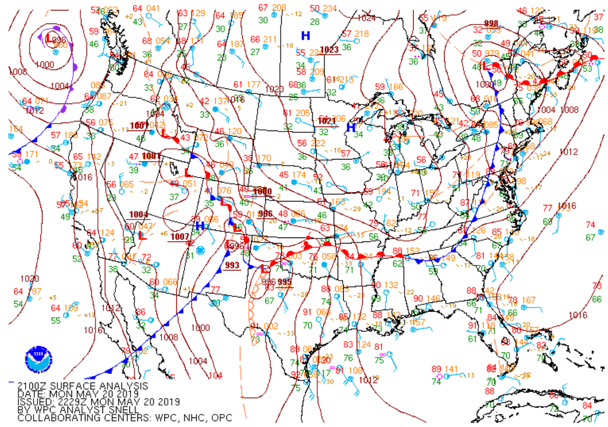
15Z 5/20/19



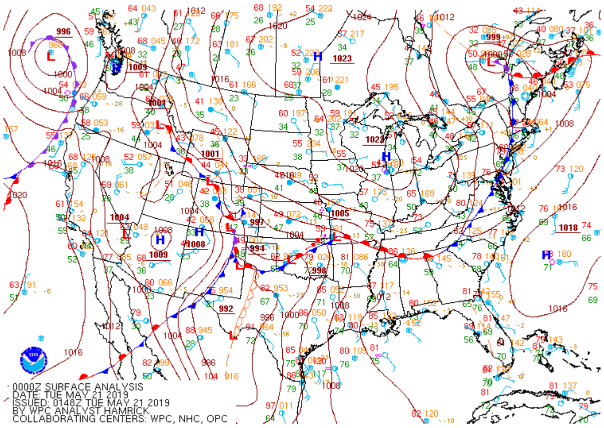
18Z 5/20/19



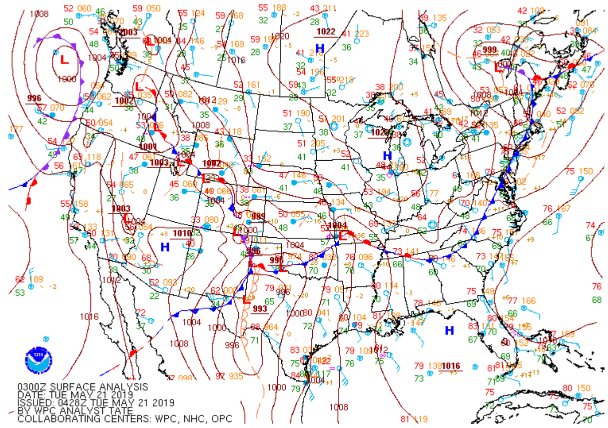
21Z 5/20/19



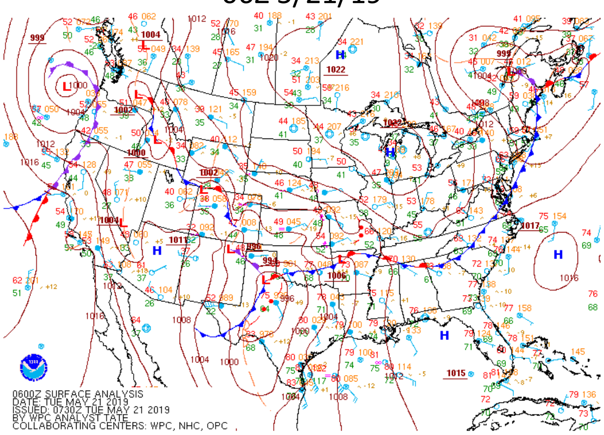
00Z 5/21/19



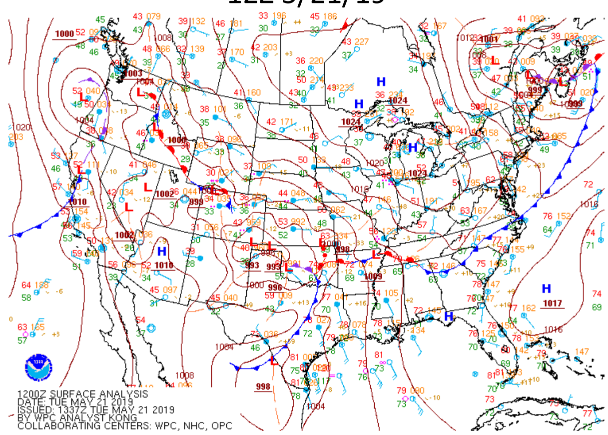
03Z 5/21/19



06Z 5/21/19

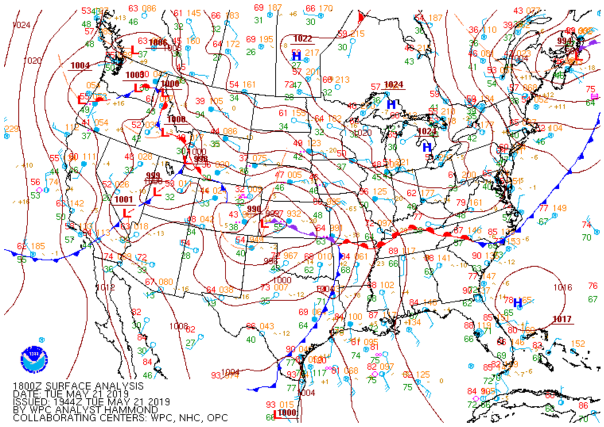


12Z 5/21/19

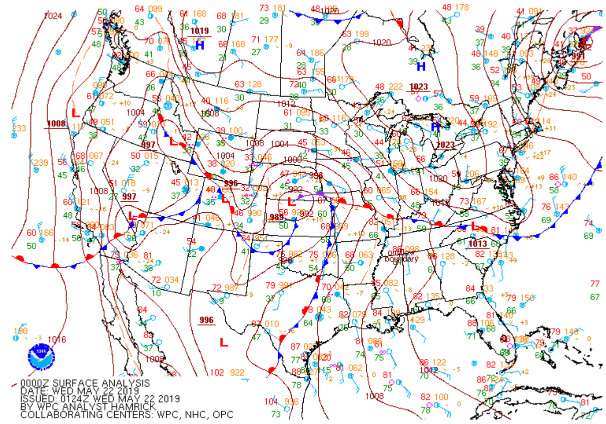


18Z 5/21/19	00Z 5/22/19

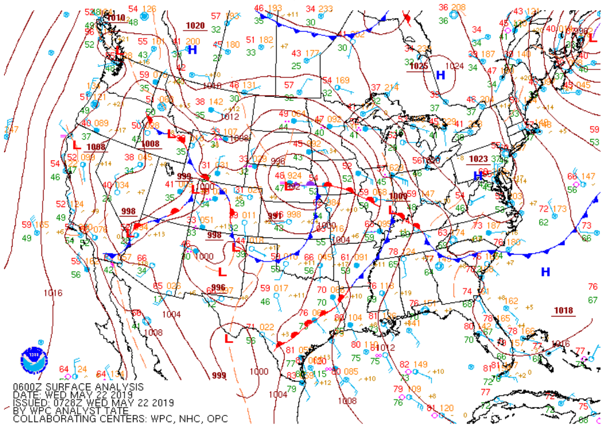
18Z 5/21/19



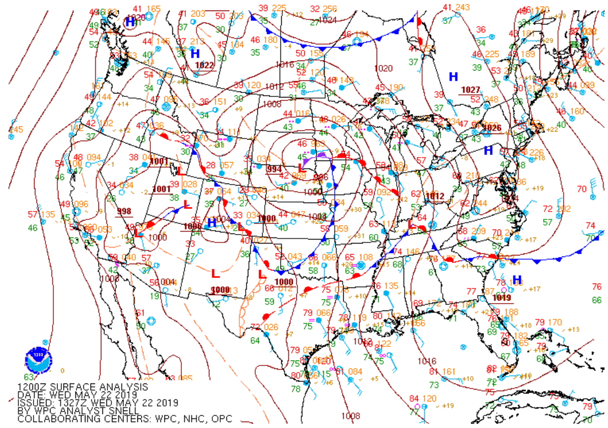
00Z 5/22/19



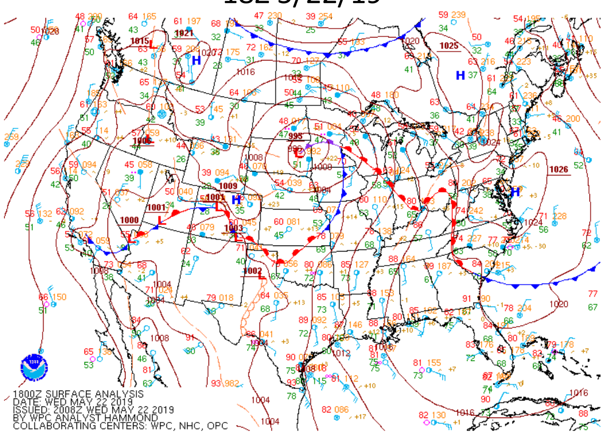
06Z 5/22/19



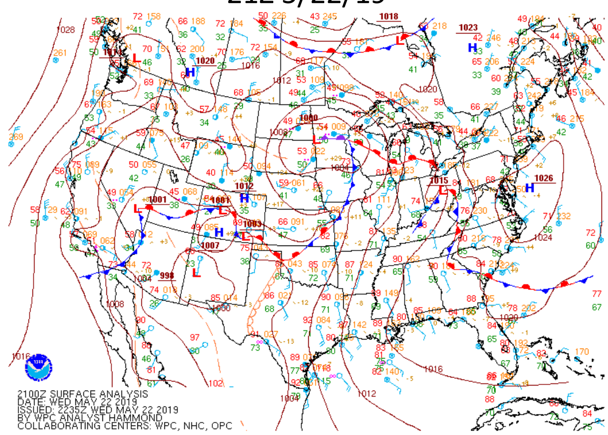
12Z 5/22/19



18Z 5/22/19



21Z 5/22/19



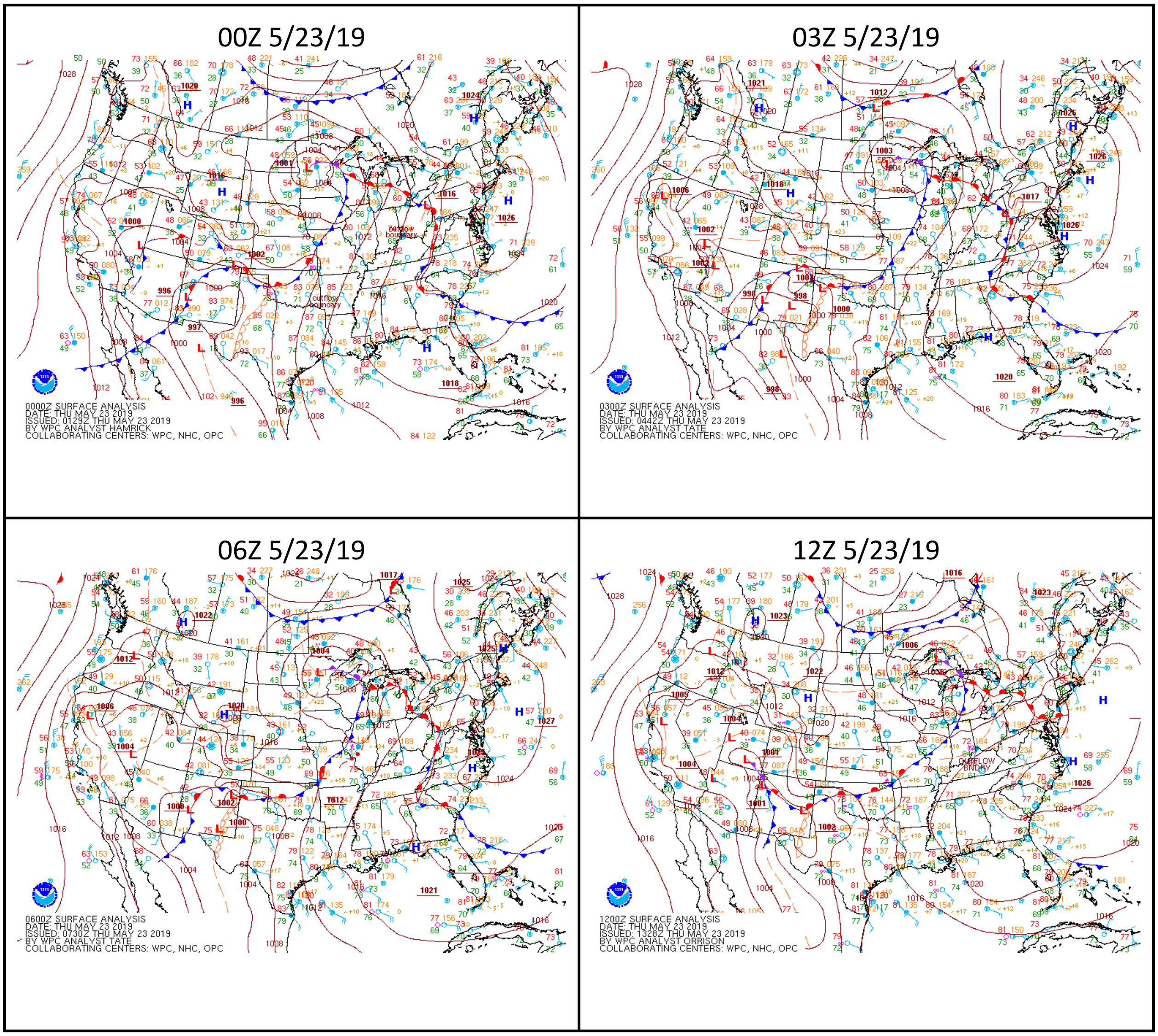


Figure 5: Surface Maps - Pressure and Observations from 00Z 5/20/19 through 12Z 5/23/19. Maps courtesy of the Weather Prediction Center [17].

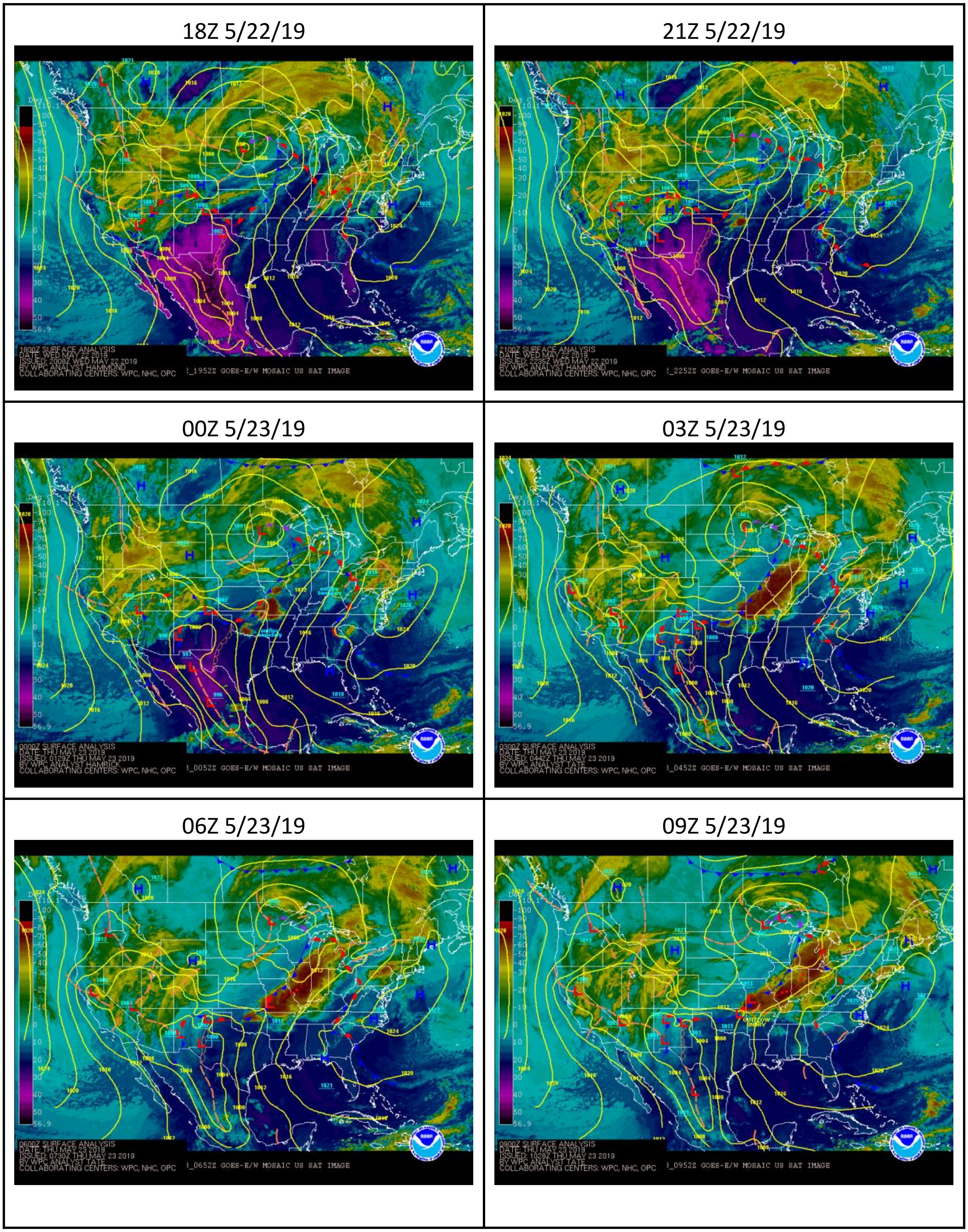
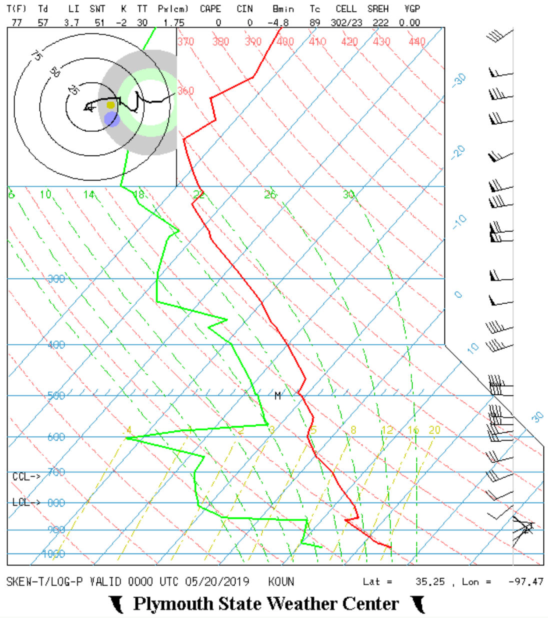
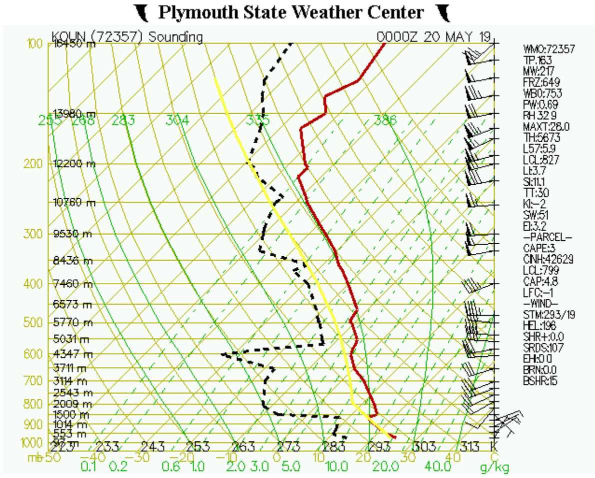


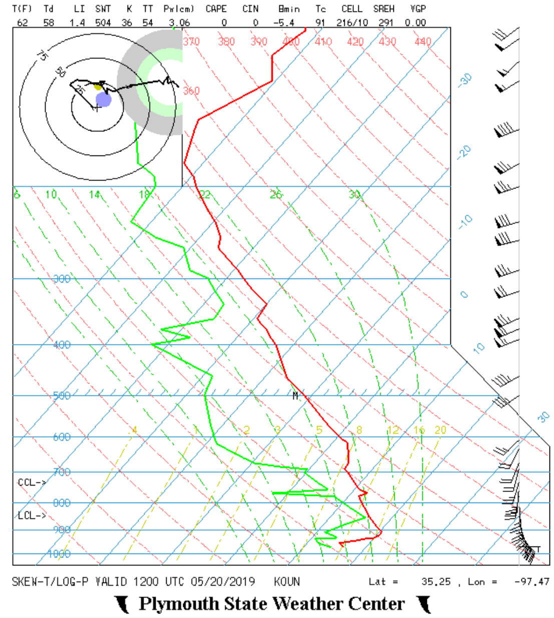
Figure 6: Infrared Satellite and Surface Analysis from 18Z 5/22/19 through 09Z 5/23/19. Maps courtesy of the Weather Prediction Center [17].

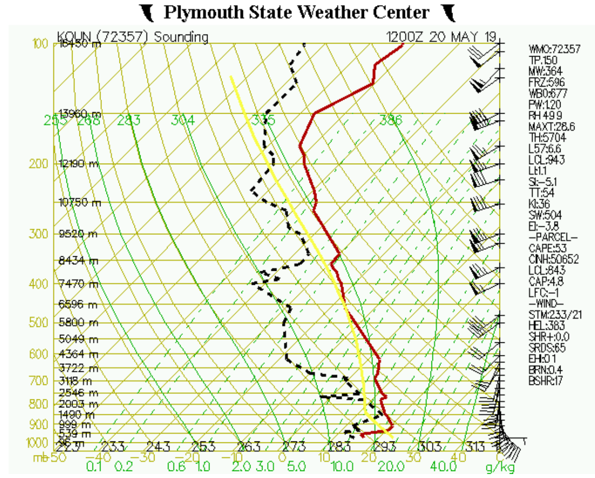
00Z 5/20/19





12Z 5/20/19





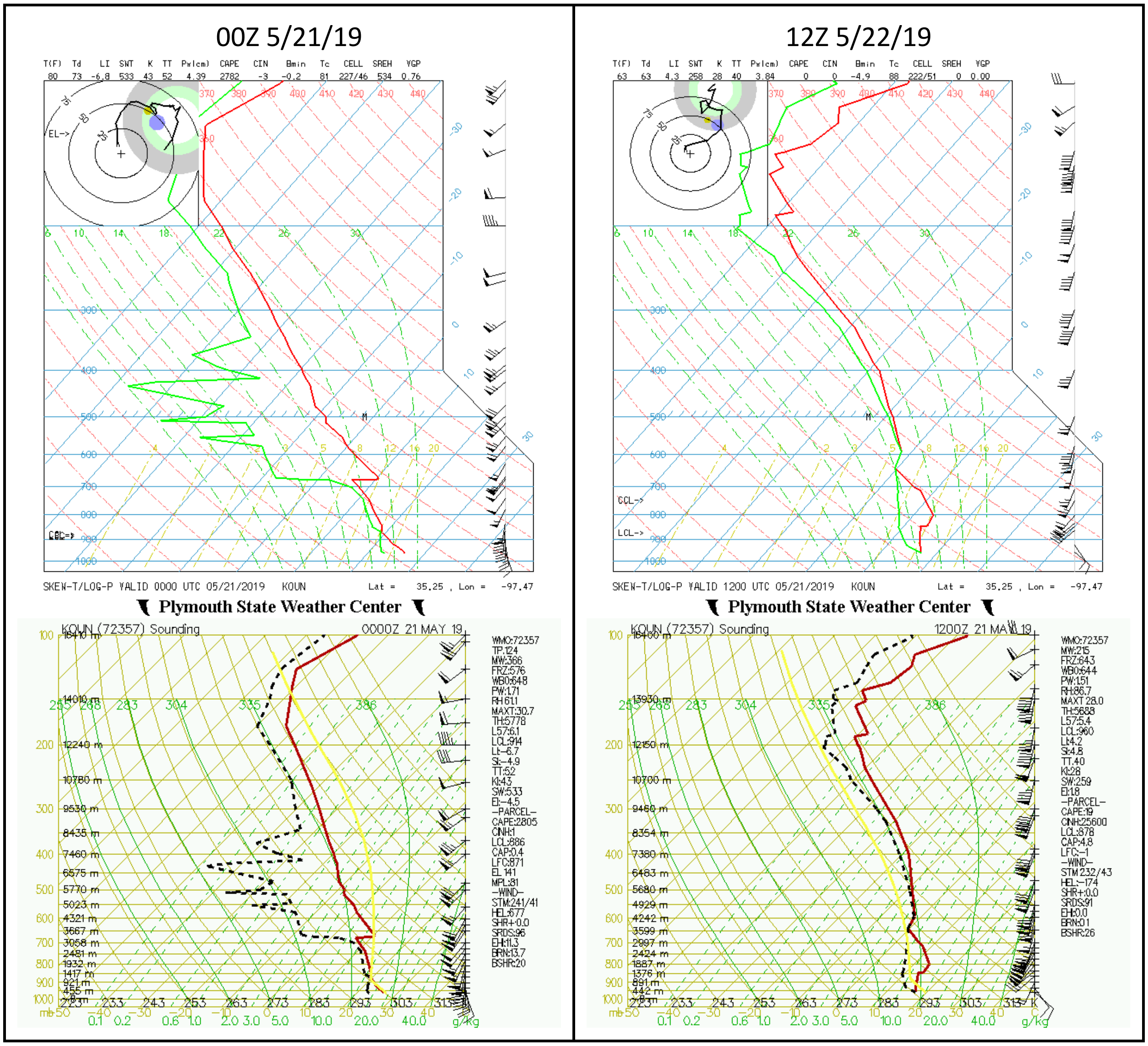


Figure 7: Soundings from 00Z 5/20/19 through 12Z 5/22/19 - launched from Norman, OK. Soundings courtesy of University Corporation for Atmospheric Research (UCAR) and Plymouth State Weather Center [18] [19].

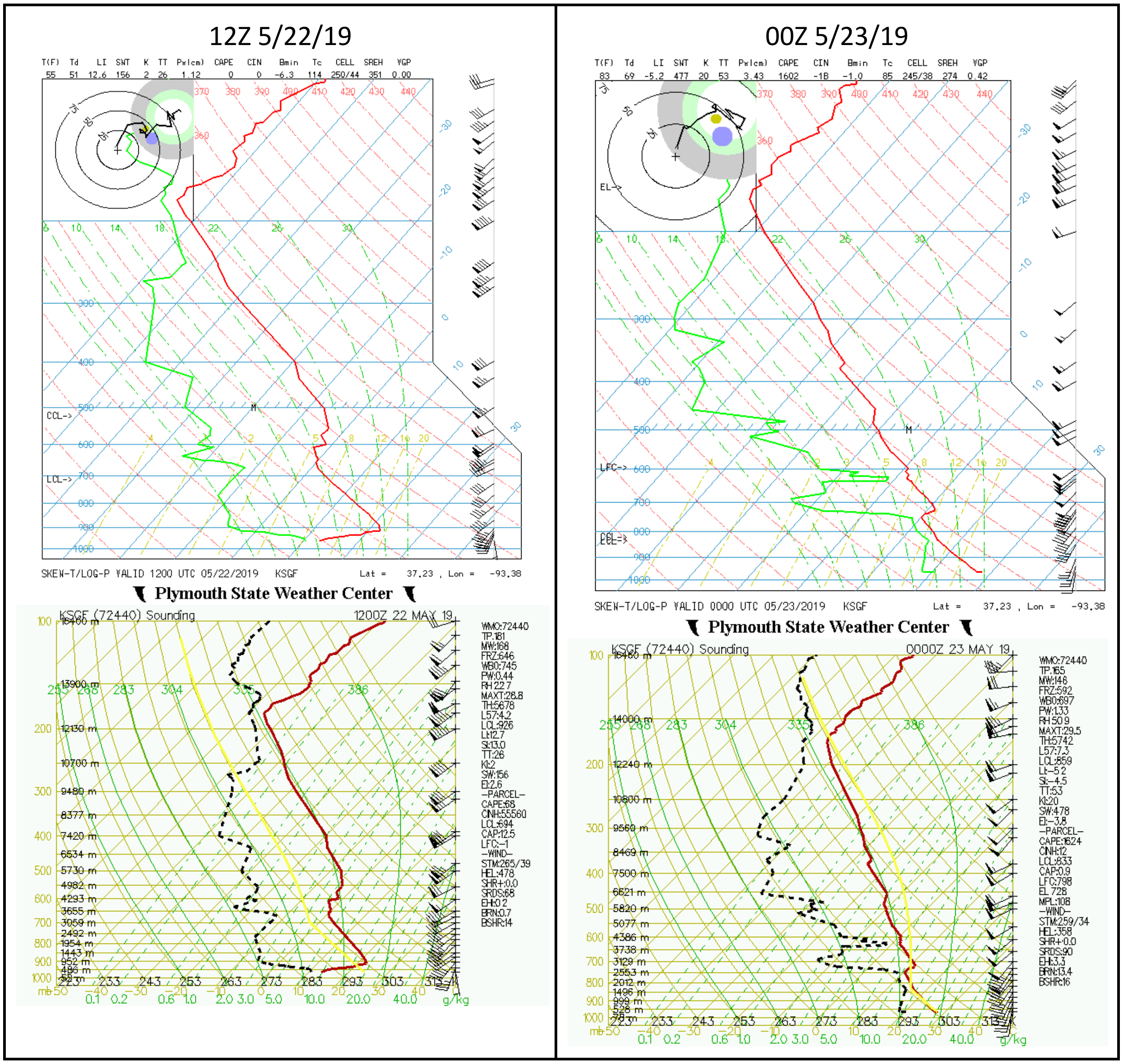


Figure 8: Soundings launched from Springfield, MO at 12Z 5/22/19 and 00Z 5/23/19. Soundings courtesy of University Corporation for Atmospheric Research (UCAR) and Plymouth State Weather Center [18] [19].

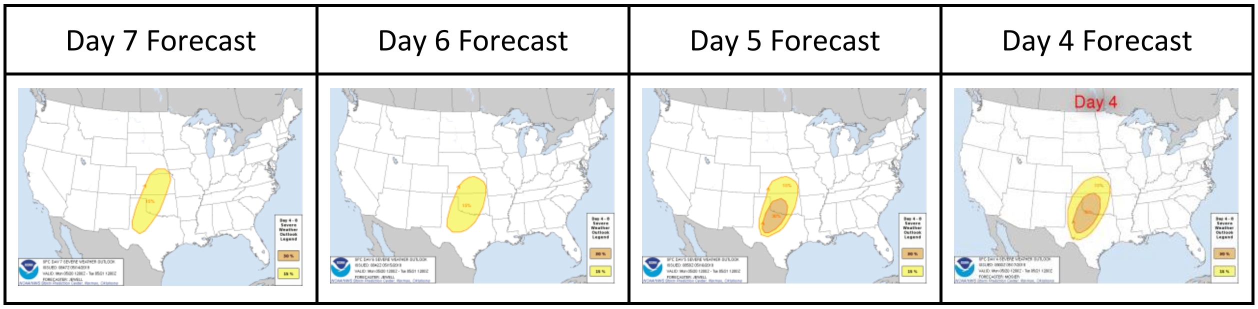


Figure 9: Storm Prediction Center (SPC) days four through seven convective outlook forecasts, showing areas of 15% and 30% chances of severe weather on May 20, 2019. Images courtesy of the Storm Prediction Center [13].

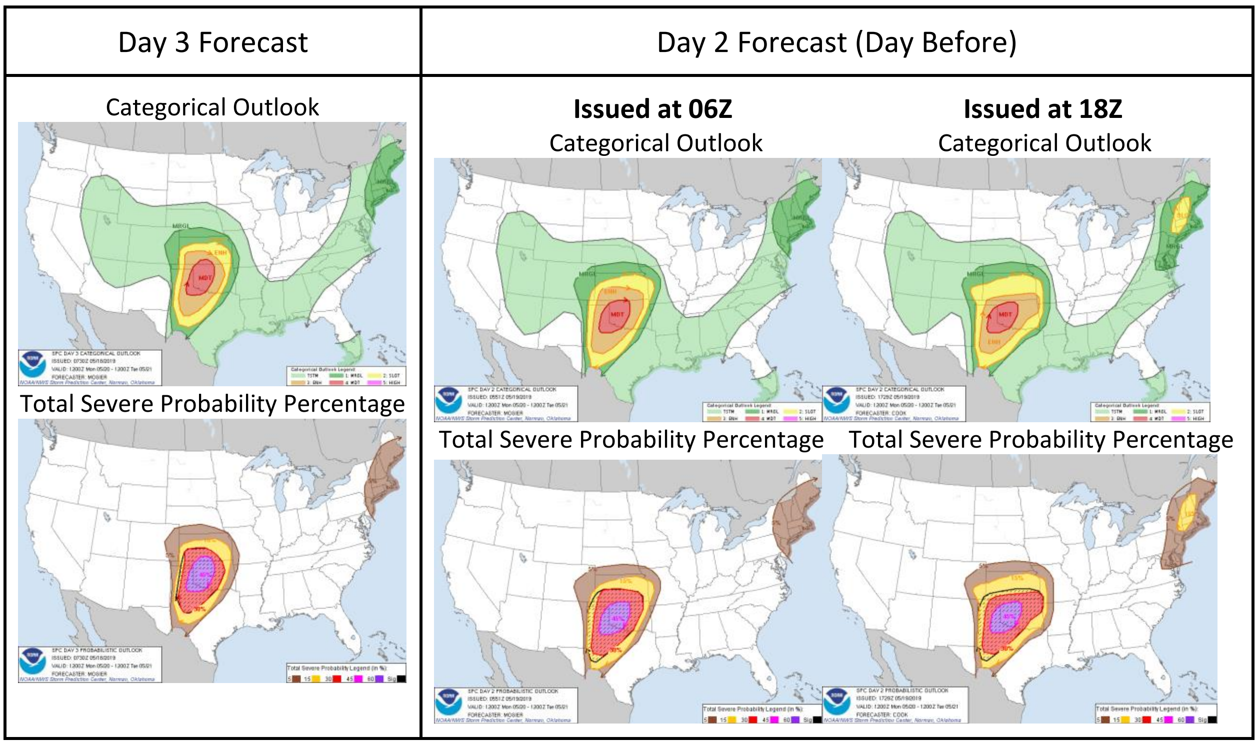


Figure 10: Storm Prediction Center (SPC) categorical outlook forecasts and total severe probability percentage forecasts issued three days and two days before May 20, 2019. The categorical outlooks show areas of marginal, slight, enhanced, and moderate risks for severe weather. The total severe probability percentage maps show areas of 5%, 15%, 30%, and 45% chances of severe weather on May 20. Images courtesy of the Storm Prediction Center [13].

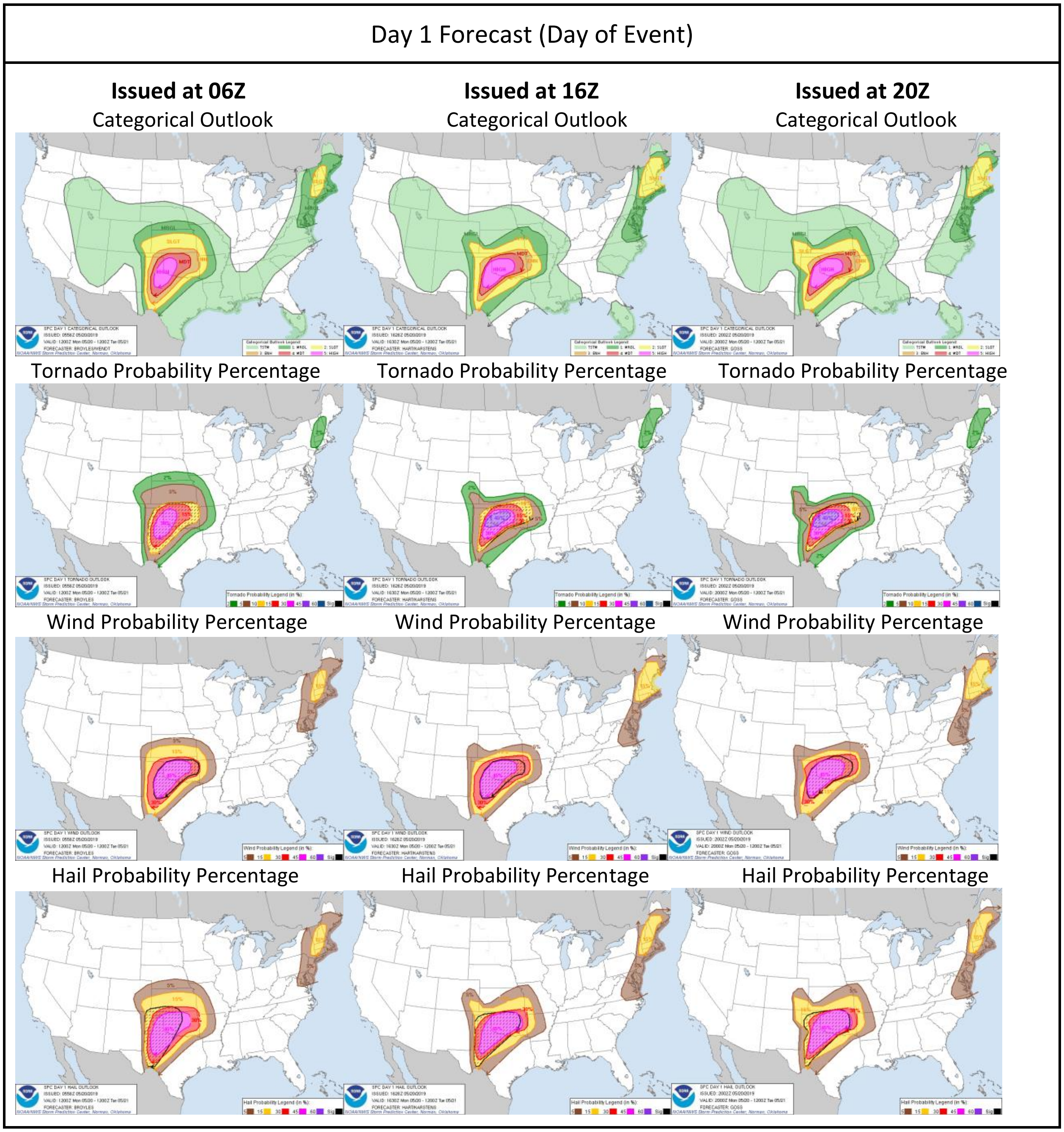


Figure 11: Storm Prediction Center (SPC) categorical outlook forecasts and tornado, wind, and hail probability percentage forecasts issued on May 20, 2019. The categorical outlooks show areas of marginal, slight, enhanced, moderate, and high risks for severe weather. The tornado, wind, and hail probability percentage maps show areas of 5%, 15%, 30%, and 45% chances of tornadoes, damaging winds, or large hail on May 20. Images courtesy of the Storm Prediction Center [13].

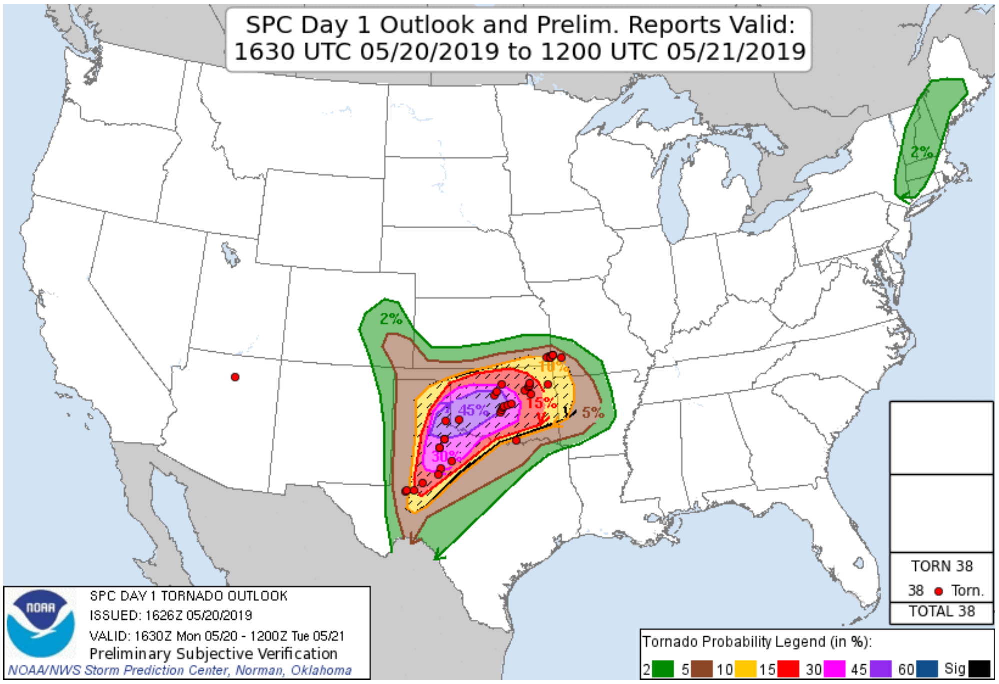


Figure 12: Storm Prediction Center (SPC) tornado probability percentage forecast issued at 1630 UTC on May 20, 2019, overlaid with preliminary tornado reports (in the red dots) from May 20 at 1630 UTC until May 21 at 1200 UTC. Image courtesy of the Storm Prediction Center [13].

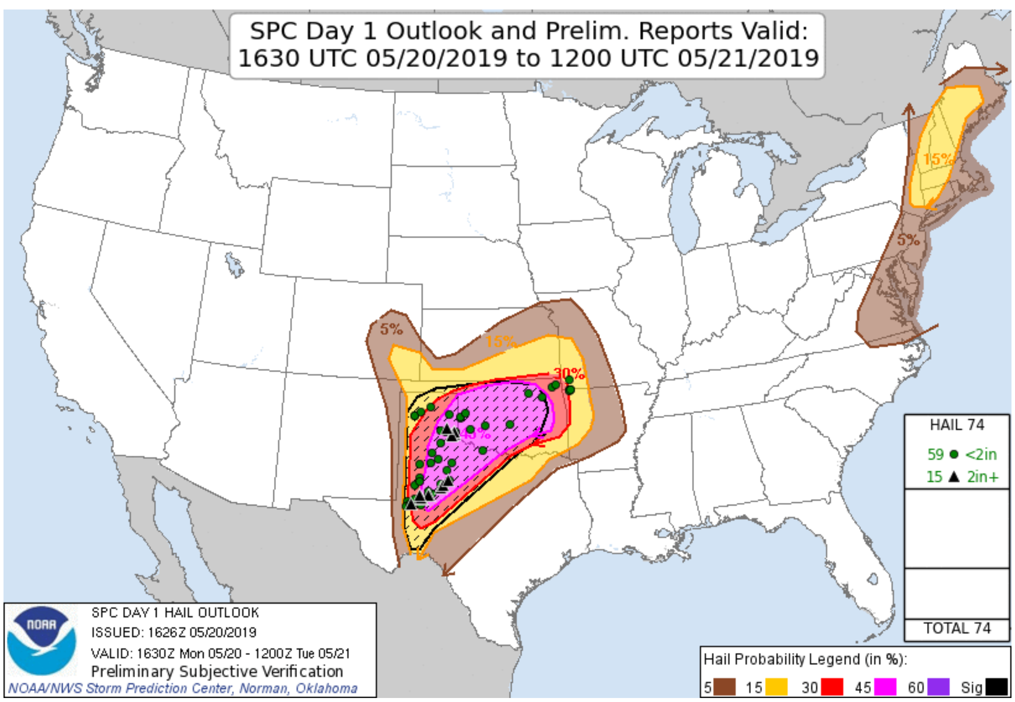


Figure 13: Storm Prediction Center (SPC) hail probability percentage forecast issued at 1630 UTC on May 20, 2019, overlaid with preliminary hail reports (in the green dots for hail reports under 2 inches and in black triangles for hail reports greater than 2 inches) from May 20 at 1630 UTC until May 21 at 1200 UTC. Image courtesy of the Storm Prediction Center [13].

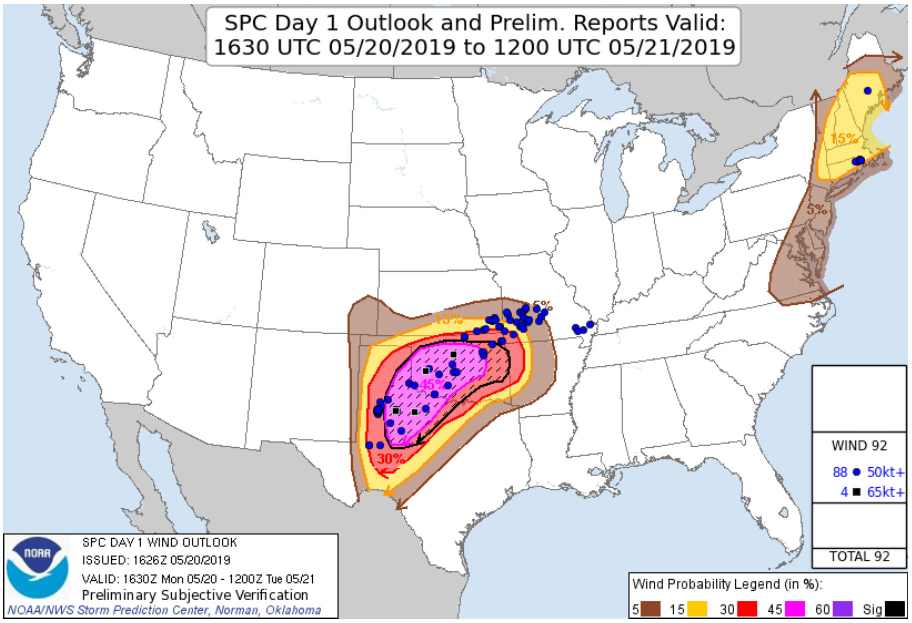


Figure 14: Storm Prediction Center (SPC) wind probability percentage forecast issued at 1630 UTC on May 20, 2019, overlaid with preliminary wind damage reports (in the blue dots for wind reports greater than 50 knots and in black squares for wind reports greater than 65 knots) from May 20 at 1630 UTC until May 21 at 1200 UTC. Image courtesy of the Storm Prediction Center [13].

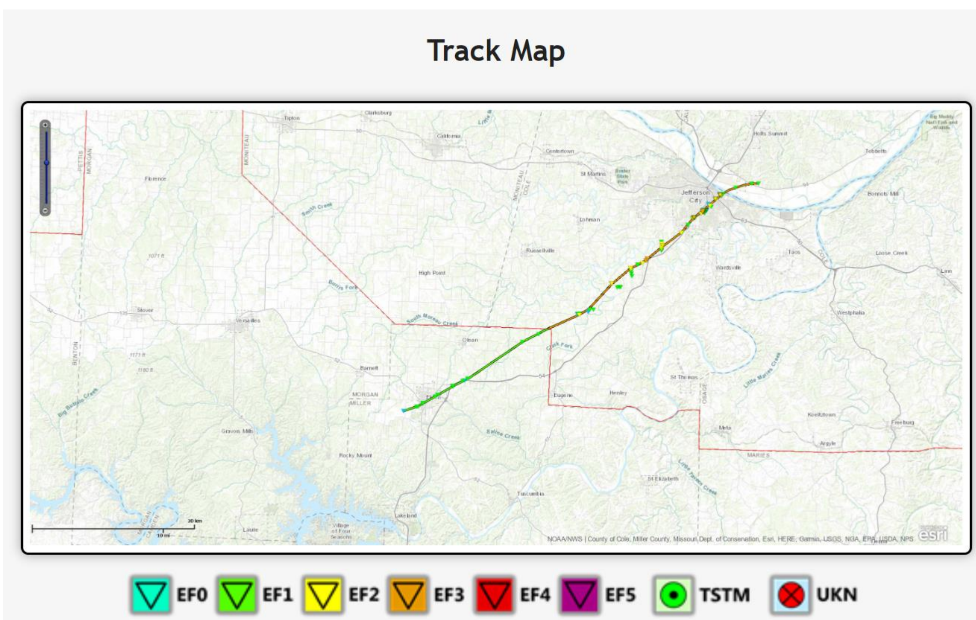


Figure 15: Tornado track from the Jefferson City, Missouri tornado on the night of May 22, 2019. The green line and the green triangles indicate where the tornado was rated EF1, the yellow triangles indicate where the tornado was rated EF2, and the orange line and triangles indicate where the tornado was rated EF3. Image courtesy of the National Weather Service St. Louis, Missouri [12].

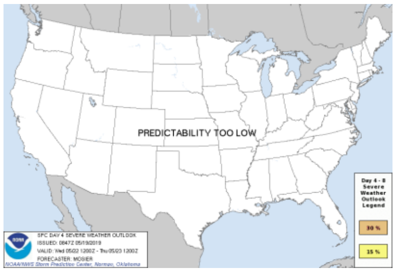
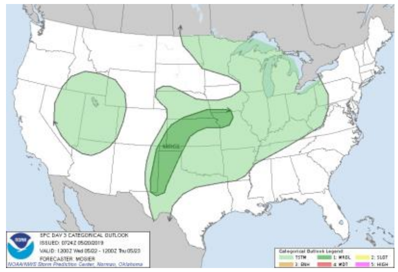
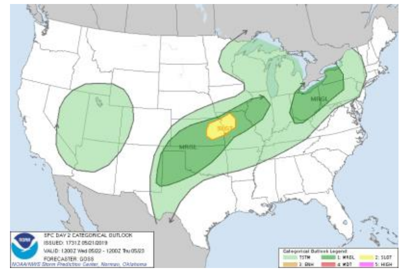
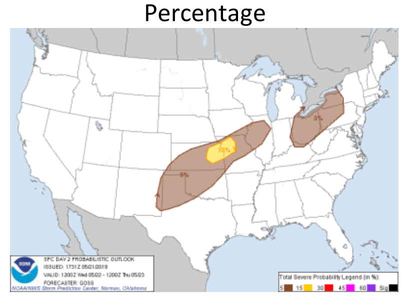
Day 4 Forecast	Day 3 Forecast	Day 2 Forecast
		Convective Outlook  Total Severe Probability Percentage 

Figure 16: Storm Prediction Center (SPC) categorical outlook forecasts issued four days, three days, and two days before May 22, 2019. The categorical outlooks show areas of marginal and slight risks for severe weather. The total severe probability percentage map issued two days before May 22, 2019 shows areas of 5% and 15% chances of severe weather on May 22. Images courtesy of the Storm Prediction Center [13].

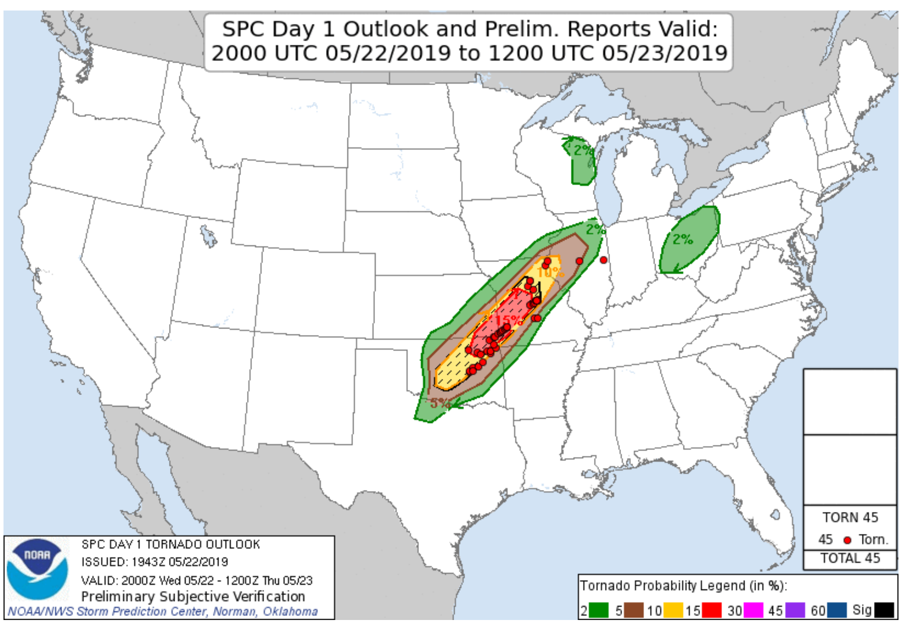


Figure 17: Storm Prediction Center (SPC) tornado probability percentage forecast issued at 2000 UTC on May 22, 2019, overlaid with preliminary tornado reports (in the red dots) from May 22 at 2000 UTC until May 23 at 1200 UTC. Image courtesy of the Storm Prediction Center [13].

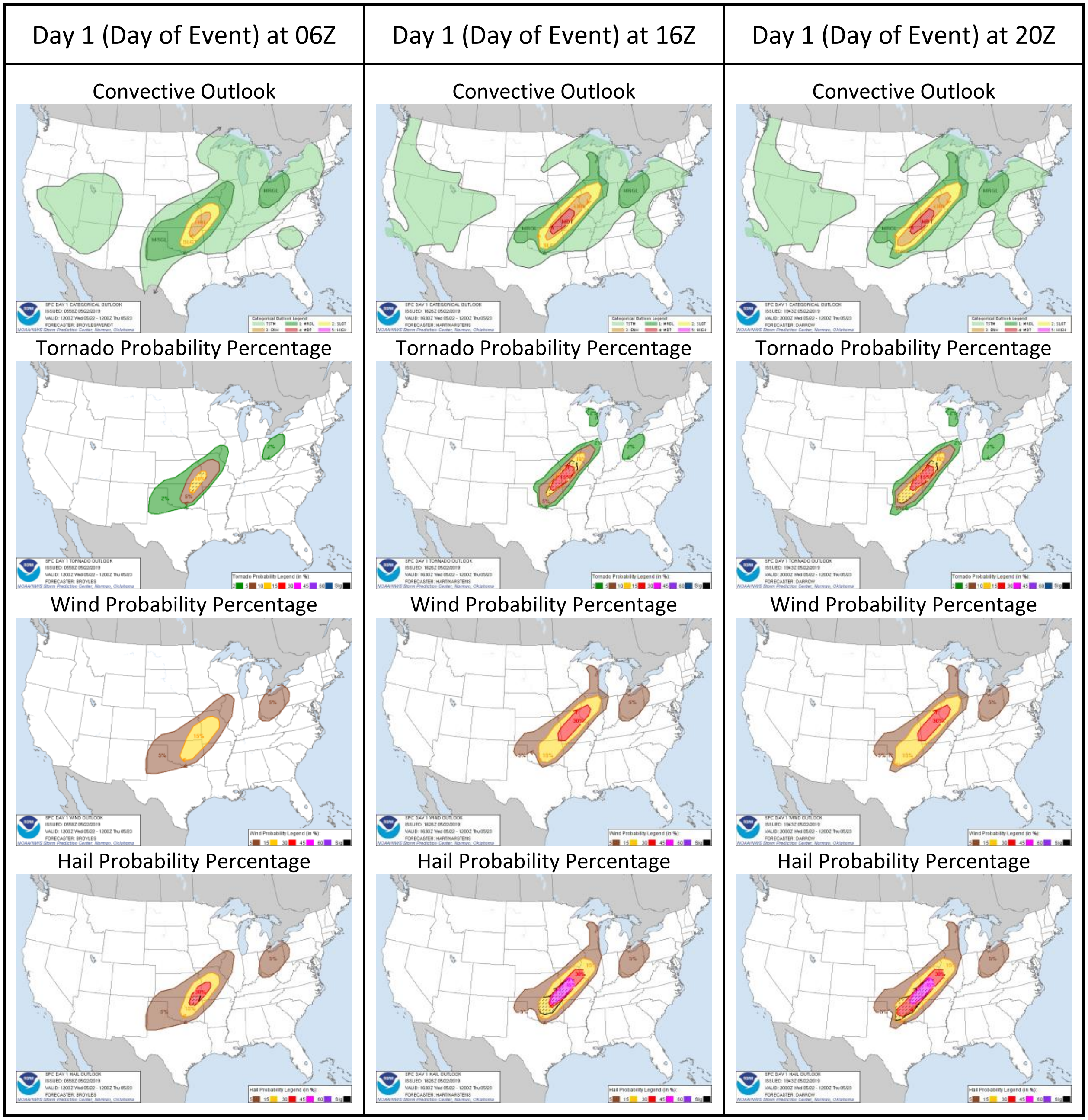


Figure 18: Storm Prediction Center (SPC) categorical outlook forecasts and tornado, wind, and hail probability percentage forecasts issued on May 22, 2019. The categorical outlooks show areas of marginal, slight, enhanced, and moderate risks for severe weather. The tornado, wind, and hail probability percentage maps show areas of 5%, 15%, 30%, and 45% chances of tornadoes, damaging winds, or large hail on May 22. Images courtesy of the Storm Prediction Center [13].

Sources

[1]: https://www.spc.noaa.gov/products/watch/ww0199.html
[2]: https://www.spc.noaa.gov/products/watch/2011/ww0235.html
[3]: https://twitter.com/NWSSPC/status/1130511960519237632
[4]: https://www.forbes.com/sites/marshallshepherd/2019/05/21/three-problems-with-the-word-bust-during-real-time-weather-threats/#dc31cf553386
[5]: https://www.spc.noaa.gov/climo/reports/190520_rpts.html
[6]: https://twitter.com/brianemfinger/status/1130618654649925632?ref_src=twsrc%5Etfw%7Ctwcamp%5Etweetembed%7Ctwterm%5E1130618654649925632&ref_url=https%3A%2F%2Fwww.cnn.com%2F2019%2F05%2F21%2Fus%2Fsevere-weather-tuesday-wxc%2Findex.html
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