Internship Report

"Severe Weather – Study of supercells and tornadoes"

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Acknowledgement

Before I explain my experience and my work here, I would like to thank the department of Applied Physics in Limoges who gave me the opportunity to work here and have the best experience ever. This internship in Norman permitted me to understand the mechanism of supercells, tornadoes and chase these phenomena.

It was really satisfying to work with professional people and share my passion with them. I would like to thank Jeff Basara and Brad Illston a lot for their patience, their help, and their welcome. Furthermore, I would like to thank Jeff so much for all of the miles on the road trying to chase the best supercell supporting a tornado. I would like to thank Brad so much for allowing me to partake in his weather courses and for trying to involve me with storm chasers of the Discovery Channel. Moreover, I would like to thank Françoise Nardou and Laurent Bourdier who helped me with my travel and my internship.

Finally, I want to thank everyone who helped me in the USA, in the airport, the waitresses in the National Weather Center's cafeteria, and the weather which permitted me to see amazing thunderstorms and a surprising tornado at night.

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INTRODUCTION

I have wanted to perform this internship for several years in the USA for 2 main reasons:

First, I wanted this internship because it is the only internship related to my passion, to study severe weather phenomena such as supercells and tornadoes. In fact, the National Weather Center, situated in the State of Oklahoma and in the Tornado Alley, is the best place to study these phenomena and chase them out in the field. I have a background in meteorology which I used for my weather forecasts in France, but it wasn't fully developed for thunderstorms forecast.

Second, this internship, is the best way to learn English since I am involved in the American life and I have to speak English all time. Furthermore, it permits me to discover another culture, a different way of life, and meet a lot of people. Finally, this internship is a good way to see a company structure and how its run. That is why this internship is a very good way to teach me about severe weather parameters, index or soundings. Moreover, I have a dream : to see and study a case of tornado.

During my internship, I will study in details how supercells and tornadoes form. That is why thermal science and thermodynamic are important to understand all of these mechanisms. I will study several cases of supercells which produced tornadoes. In addition, I will chase them out in the field to understand the relation between Maths/Physics and real life of thunderstorms.

In my following report, I will talk about my experience in Oklahoma in the first part with a description of the State, the University, the National Weather Center, and finally my personal experience. In the second part, I will explain a very important tool in weather forecasting : soundings. In the third part, I will study mechanism, structure and necessary ingredients for supercells. I will add further information about some cases and occurences in Oklahoma. Finally, I will explain as well as possible, structure, and mechanism of tornadoes and some theories behind them. This report will end with severe weather advisories and my experience in storm chasing.

I. EXPERIENCE IN OKLAHOMA

1. State of Oklahoma

Fig. 1 : The United States of America with Oklahoma shaded

Oklahoma, or the "Sooner State", is one of the 50 states in the United States of America. It is surrounded by six states : Texas, Missouri, Arkansas, Kansas, New Mexico, and Colorado. It is divided into 77counties, has an area of 1840000 km² and around 3 500 000 people are living in this state. The economic town is Tulsa but the capital is Oklahoma City situated in Oklahoma county in Central Oklahoma. This town has a civilian population close to one half million and is expanding with a lot of news buildings. Moreover, house prices are less expensive than others states such as New York.

Fig. 2 : State of Oklahoma

Since 1964, the State of Oklahoma has been politically republican and John McCain registered his highest score with 66% during the last election in the USA.

Fig. 3 : Oklahoma's seal

Fig. 4 : Oklahoma's flag

Finally, Oklahoma is an agricultural and industrial state and is the third and the sixth American producer of oil and natural gas. Indeed, we can find a lot of oil and chemistry.

2. University of Oklahoma

Fig. 5 : Seal and logo of University of Oklahoma

Fig. 6 : Bizzell Library

University of Oklahoma or "OU" is a coeducational research university located in Norman. The university consists of fifteen colleges, including 152 majors such meteorology, geology, petroleum engineering, architecture, law, medicine, Native American studies, history of science, and dance. While the two main campuses are located in Norman and Oklahoma City, affiliated programs in Tulsa expand access for students in eastern Oklahoma. Some of the programs in Tulsa include: medicine, pharmacy, nursing, public health, allied health, and liberal arts studies. Oklahoma is ranked in the top 10 for "Best Value Public Colleges" by the Princeton Review. Students come from all 50 U.S States and over 100 countries.

As of the Fall of 2007, the Norman campus had around 20 000 undergradute and 6 500 postgraduate students. Following the Sooner's 2000 football national championship season, the university experienced an

increase in college applicants and admissions. The falls of 1999 and 2000 both saw a 1.3% increase in the number of students
over the respective previous years while the fall of 2001 saw an increase of 4.8% over 2000 infrastructures.

Fig. 7: Athletics facilities grouped together at the Norman campus

The largest school, The College of Art&Sciences, enrolls 37% of the OU-Norman students. The next largest school, The Price College of Business enrolls 14% followed by the College of Engineering with 11% and the College of Education and the Gaylord College of Journalism and Mass Communication, each with approximately 6% of the student body. Smaller schools include the Colleges of Architecture and Atmospheric and Geographic Sciences, Earth and Energy, the Weitzenhoffer Family College of Fine Arts, and the Law School.

Then, the city of Norman is organized around a giant campus divided into three Sections : North Campus, Main Campus, and South Campus. These campuses are connected thanks to a free bus service for the owners of a student or faculty staff card. A free shuttle allows students to park at Lloyd Noble Center and provides 5-10 minutes service to the main and south campuses. Sports represent an important part of the main campus since we find a lot of sports places like the Oklahoma Memorial Stadium. This one can welcome 82,112 people, and represents the 15th largest college stadium in the United States, and welcomes the Sooners team (local team). Next to the stadium is the Barry Switzer Center : a museum dedicated the historical success of Oklahoma athletics, as well as a comprehensive training facility for Oklahoma athletes.

On the far north side of Norman is the OU Research Park, which includes University of Oklahoma Max Westheimer Airport, the Radar Operations Center, the old National Severe Storms Laboratory facility, the OU OKDHS Training and Research Center, the OU ITS Lab, and Merrick Computer and Technology Center. This part of campus is frequented by students studying aviation.

South of student housing is Timberdell Road, the approximate southern boundary of the university. South of this road are University-owned apartments and athletic complexes. On the south side of Timberdell Road is the law school building which has a recently added law library that opened in 2002. This area also includes many athletic complexes. Some of which include L. Dale Mitchell Baseball Park, OU Softball Field, and the Lloyd Noble Center (the basketball arena).

Fig. 8 : Lloyd Noble Center

3. National Weather Center

Fig. 9 : National Weather Center by night and Weather Sphere

The National Weather Center is the logical place to study severe weather since it is situated in Oklahoma and the Tornado Alley.

It is situated on the south side of the campus next to the Stephenson Research Center. It's an impressive building which opened its doors in 2006 and where a lot of organizations work together in partnership to understand and improve knowledge in Earth's atmosphere. Moreover, people improve analysis, observation and prediction systems and expertise in local/regional climate, numerical modeling, hydrology, or radar meteorology.

Information learned here helps reduce loss of life and property to hazardous weather. Over 650 employees, faculty, researchers and students work in this building.

It is home to OU's College of Atmospheric and Geographic Sciences, comprised of the Geography department and the School of Meteorology, which is the largest in the nation and ranked N° 1 in severe storm research.

In addition, it is the location of the Storm Prediction Center who issue weather advisories such as convective outlooks or severe thunderstorm watches. The Storm Prediction Center is part of the National Weather Service.

We can find on the first floor weather technicians who fix and calibrate weather sensors like anemometers. Finally, we can add Oklahoma Climatological Survey that I am going to explain in the next part.

4. OCS and Softwares

The Oklahoma Climatological Survey or "OCS" was established in 1980 to provide climatological services to the people of Oklahoma, conduct research on the impact of climate on human activities, and serve as a support facility for the State Climatologist. The OCS maintains a lot of climatological information, operates the Oklahoma Mesonet, and recently a micronet in Oklahoma City. Moreover OCS hosts a wide variety of educational outreach and scientific research projects. Indeed, a big project will take place in Croatia where technicians from the NWC will set up a large weather network such as Oklahoma Mesonet. The Oklahoma Climatological Survey is a research unit of the College of Atmospheric & Geographic Sciences at the University of Oklahoma with several categories of people. Indeed, we find people in relation with Oklahoma Mesonet, Climate Information, Technology, Outreach, Administration and Research. Director of OCS is Dr. Ken C. Crawford, my advisors are Jeffrey Basara who is the director of research and Brad Illston his research associate.

Now, I am going to present you two softwares I have used during my internship.

WeatherScope

Fig. 10 : Logo of WeatherScope

This software was developed by the Oklahoma Climatological Survey and displays a lot of weather data, especially in Oklahoma every 5 minutes, thanks to Oklahoma Mesonet (a huge weather network in Oklahoma). Indeed, since 1st January 1994, this system has collected around 4 billions observations of data. Moreover, Oklahoma Micronet was developed last year for Oklahoma City with 40 stations (36 traffic signal sites and 4 Oklahoma Mesonet sites). We can see other weather data in the USA, but these data are updated each hour.
Thanks to this software, we can see in real time all of weather parameters like air temperature, pressure, dew point, direction of the wind, gust wind, and precipitations radar as well as Doppler.
Additionally, this software displays a lot of past data. We can observe severe weather in the past year like the 1999's tornado outbreak in Oklahoma or during the 13th of May 2009 (underneath). Indeed, this software is a good way to know how and why we get supercells and tornadoes thanks to weather data.

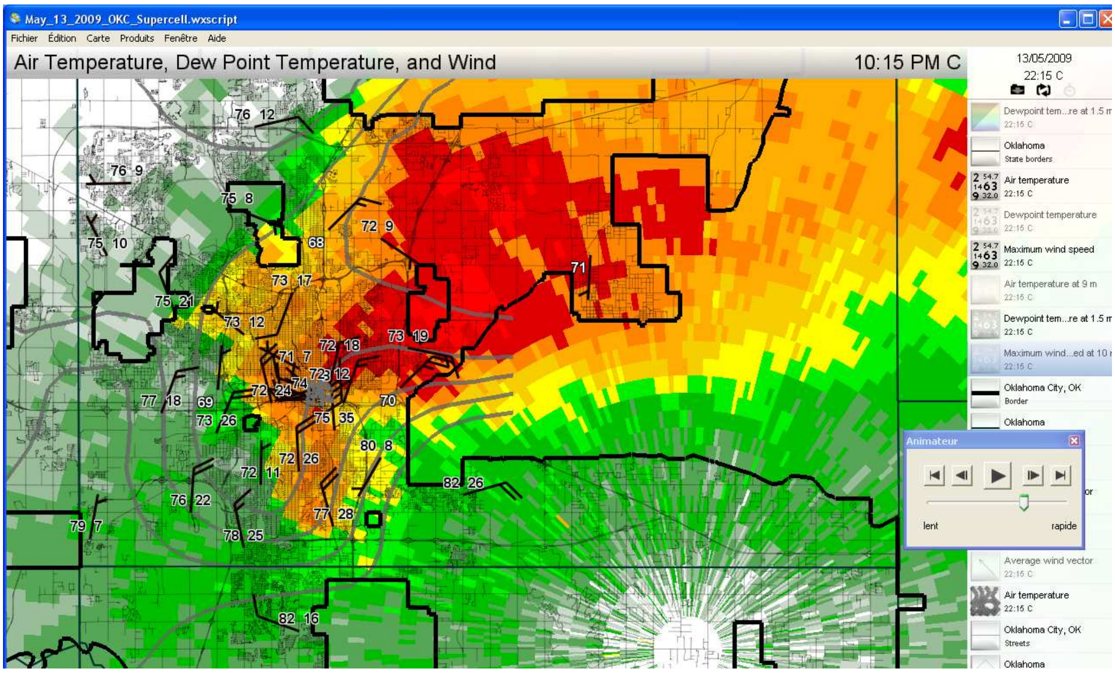


Fig. 11 : WeatherScope running

Radar First

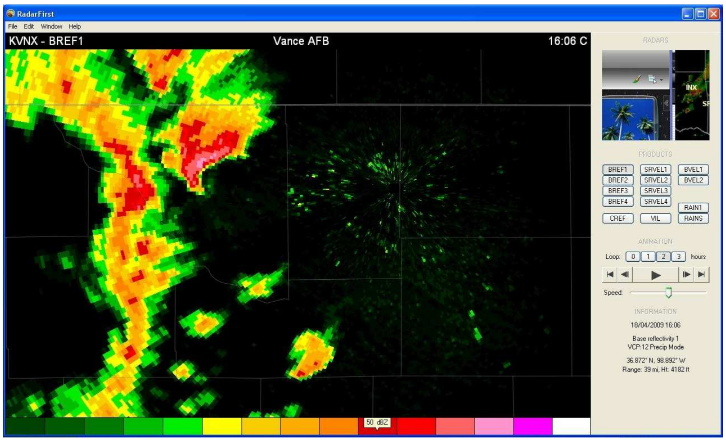


Fig. 12 : Radar First running show us a supercell front of a squall line

This software enables us to see precipitation's strength (light rain, heavy rain) in dBZ thanks to reflectivity radar. Indeed, the radar, transmitter, sends waves in several direction. When these waves (sinus) meet receivers which is precipitation here, they come back to the radar. The higher the echo, the stronger the precipitation. Indeed, the strength of the echo determines precipitation. CREF' s function is very interesting since we can see cells trajectory, percentage of hail and size of hail in the clouds. Moreover, we can see type of echo such as TVS (Tornado Vortex Signature) or MESO (Mesocyclone) to distinguish a possible potential tornadic supercell . Indeed, we can see another type of product, called "Storm Relative Velocity" and enable us to see wind shear. This radar detects two wind directions : one away from the radar, one toward the radar. We can distinguish these directions thanks to colors (for example orange for one direction, green for an other). Then, we get scales to measure wind speed and detects mesocyclones. ***(Appendix A).*** Finally, we are able to do loops for 3 hours.

5. Personal Experience and Works

The first day was really tiring with a lot of problems. Ironically, my flight from Atlanta to Oklahoma City was cancelled because of severe weather (high gust winds and tornadoes). I was in stand by for another flight, but this one was full, so I had to wait a couple hours. Finally, after 8 hours of waiting, I took one flight and met a woman who helped me. She brought me to Norman with her car and found me a hotel. In fact, I didn't sleep for 28 hours. This was the longest day in my life... After that, I found the campus, filled a lot of papers, got my OU ID card, and settled myself into my apartment with 3 other men (one Korean and two Americans). They left after one month, then I welcome a new roommate who was very friendly.

The first month was hard since everything was new for me. During the week-end, I visited the campus and met a lot of people, but just American people and never French people. That's why, I had the opportunity to enhance my English thanks to these people. During the first week-end, I went to the "Medieval Fair" which is a major event with many demonstrations connected to the Middle Ages.
Moreover, when thunderstorms were coming in Norman, I took some goods pictures of lightning and American people living in the campus wanted to know how my device ran . Indeed, I explained and shared my passion about weather with these people. Sometimes, when the weather cooperated, we chased with Jeff in Oklahoma, Texas and Kansas. The first chase will stay in my mind all time : a part of my dream was done this day since I saw an amazing supercell and funnels but no tornadoes ! On the campus, boys and especially girls were very welcoming and friendly with me.

The Science Fest in the Zoo of Oklahoma City was really good but the weather was too hot for me (85°F in the end of April). During this day, Jeff, Brad, and I set up a stand to present Oklahoma Mesonet and Micronet thanks to maps. I tried to explain this network to people when Jeff was busy. In addition, I made some weather stamps on kid's hands with a large children crowd this day. Unfortunately, we lost our tent because of a strong gust of wind.

During one week-end, Brad introduced me to his friend Danny, who is a storm chaser working for The Discovery Channel. This was a really good time since I saw an example of a cheap device, which Danny built, to study tornadoes like "Dorothy" in the movie Twister. I remember all of my life the last week-end of April with this Sunday (April 26th) where tornadoes were on the ground in West Oklahoma, so in the same place where we chased the day before. I was really frustrated since we got just strong thunderstorms in Norman with heavy rain and strong winds, but no tornadoes !

Thanks to Brad, I had the opportunity to attend his meteorology courses. It was really interesting since courses talked about supercells, advisories, tornadoes thus connected to my topic. One day, Danny and his storm chaser friend Aaron presented a topic on storm chases : organization and hazards. All of these courses and storm chases increased my passion for weather especially severe weather such as severe thunderstorms, supercells and tornadoes.

After that, I left Norman twice for Northeast of Oklahoma, more precisely Tar Creek, to fix weather stations with Jeff while Brad monitored our operation at the National Weather Center. We tested weather stations with a laptop to collect data and tried to understand why certain weather stations didn't work. Indeed, most of the weather stations worked but two had some problems. One was really damaged with a lot of ants and hornets inside and the data logger was out. That's why, we had to disassemble the weather station and put it into the truck in order to bring it to Norman. One problem was resolved on a weather station since he just had to change the battery. During these days in North-East of Oklahoma, I had the opportunity to see damages of the F4 tornado which devastated a town near Miami,OK.

The beginning of the biggest tornado research project Vortex 2 was a up beat. Indeed, the Media-Day was really impressive at the National Weather Center where a lot of people involved in Vortex 2 and journalists were present. All of storm chase cars, radars of Vortex 2 and specialists were on the NWC's parking in order to explain devices functioning. Indeed, this project allowed people to better understand the structure and mechanism of a tornado.

Moreover, one day was really awesome : awards ceremony for graduate students at the OU Stadium. It's looks like in American movies with the national anthem and all of graduate students were wearing this famous black hat. The show took over with a beautiful fire works in a warm and happy atmosphere. Moreover, I had the opportunity to meet the president of the University, very friendly, and took a picture with him.

Most of the time and after work, I spend my time in the recreation room which is a huge room where we can play any sports such as basket ball, volley ball or ping pong. In addition, we can use an impressive complex where we can develop our muscles. Moreover, when we got a sunny weather, I enjoyed my time at the pool and in the hot tub in Traditions Square West.

But I have learnt two things : American people are not fond of mayonnaise and we can compared water in France as coke here !

II. SOUNDINGS

1. Introduction

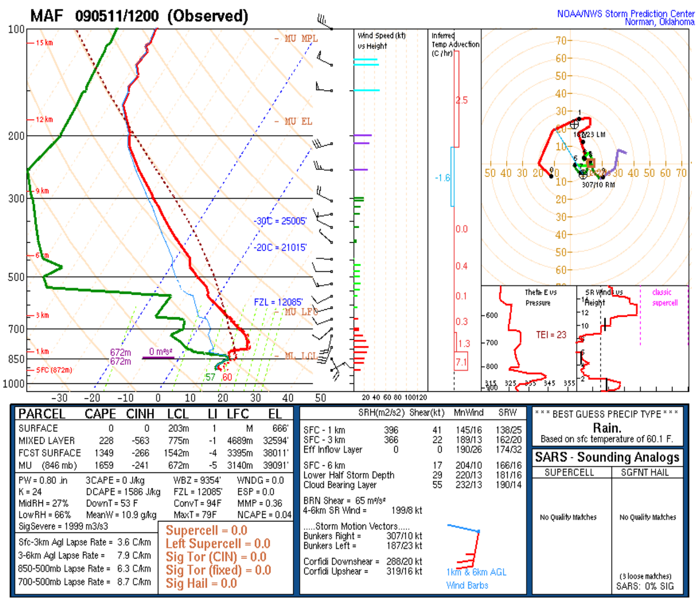


Fig. 13 : Example of a sounding

Fig. 14 : sounding balloon

Weather technicians and forecasters send sounding balloons into the troposphere. Thanks to this experience, we get soundings which are a very complete forecast tool and we have access to a lot of information into the troposphere and just above the tropopause which is the limit between the troposphere and the stratosphere. Indeed, I will explain all of parameters which can find into a sounding : the hodograph ,winds, state curves, CAPE, CIN etc...

2. Hodograph and Winds

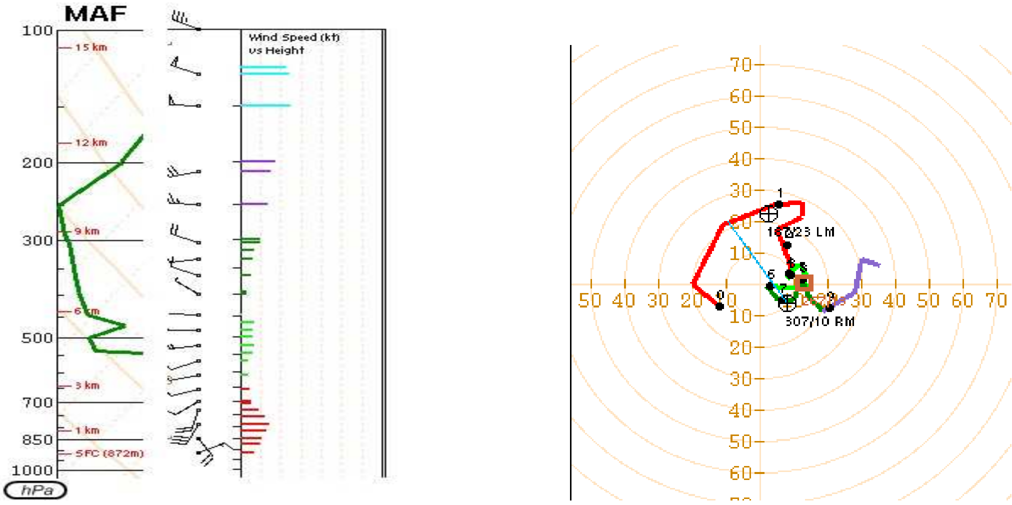


Fig. 15 : Wind and directional speed vs Height with the corresponding hodograph on the right

The picture on the left allows us to see the direction and speed of wind, according to altitude in hPa and correspondence in meters.
Barbs permits us to measure speed of wind in knots. Indeed, we have to add each bars and flags to calculate the speed such as the example below :

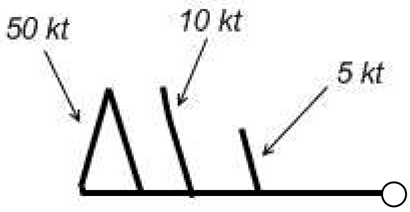


Fig. 16 : Example of a barb

Flag = 50 knots or 93 km/h
Large bar =10 knots or 18,5 km/h
Small bar = 5 knots or 9,3 km/h

In this example, we have a west wind of 50+10+5 = 65kt or around 120km/h

Thanks to this part of the sounding, we can see quickly if we have directional and speed shear.
Moreover, the picture on the right is a hodograph. It's a very good tool and an other way to see directional and speed wind every 0,5km altitudes. The scale (0-70) permits us to measure speed of wind in knots. For example, the first point (0 –red) shows a speed of 10 knots.

The color coded lines show each 3 km deep layer beginning at the surface, as shown to the left in the wind speed versus height plot.

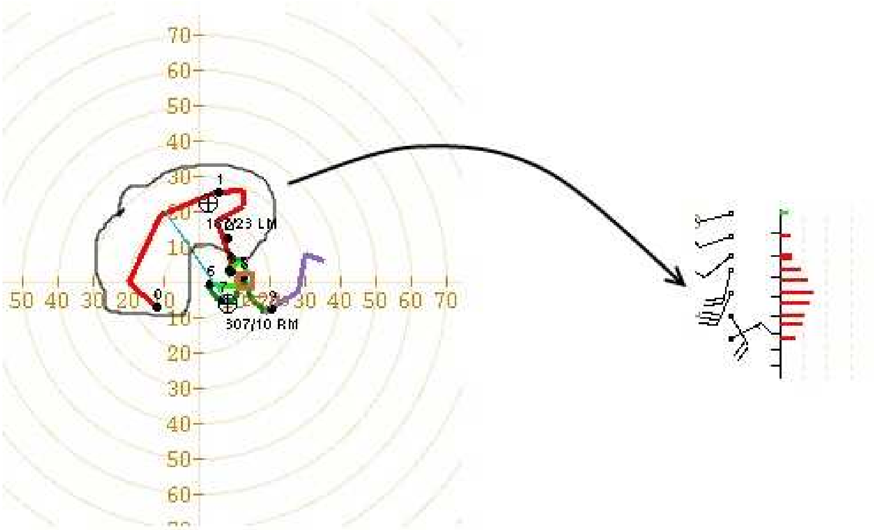


Fig. 17 : A color-coded example of a hodograph with corresponding winds (direction and speed)

Furthermore, the hodograph is the best tool to see a directional and speed shear. Figure 18 shows you how to measure direction and speed of the wind. Start to the middle of the hodograph and go to the chosen point. Then, we have a vector corresponding to the direction of our wind. The end of the vector corresponds to the speed of this wind in knots : we have to read this value thanks to the scales . In the example below, the vector at the top of the picture is oriented southwest to northeast so a southwest wind. End of the vector reaches the 50 knots line so we have finally a 50 knots southwest wind.

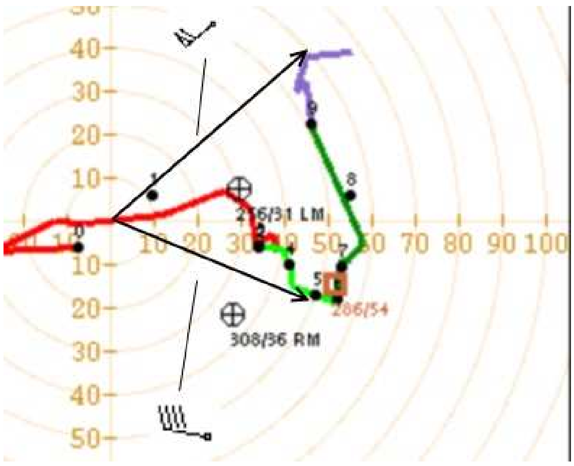


Fig. 18 : How measure speed and direction of wind with an hodograph

Finally, a curving hodograph is good sign to have supercells since it represents strong wind shear.

3. Basic Weather Parameters

- **PW :** The total amount of (condensed) water available within the lowest 400 hPa of the sounding in inches (1 in = 25,4mm)

- **Tropopause's level :** This is the level of the atmosphere which separates troposphere and stratosphere. We can easily recognize this level since it is shown by a right deviation of the air temperature's curve such as in the next example underneath.

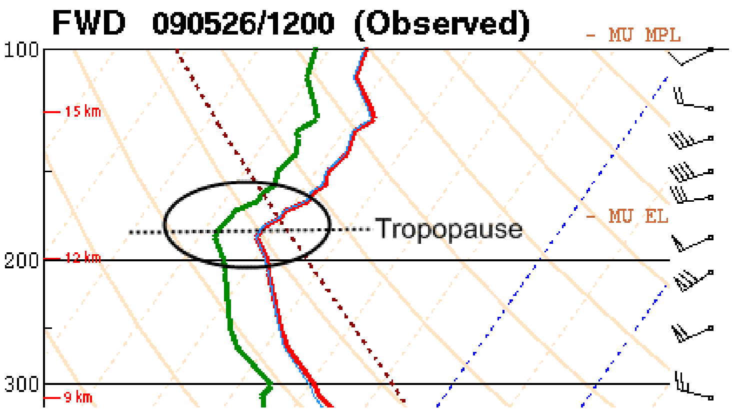


Fig. 19 : Tropopause's level in a sounding example

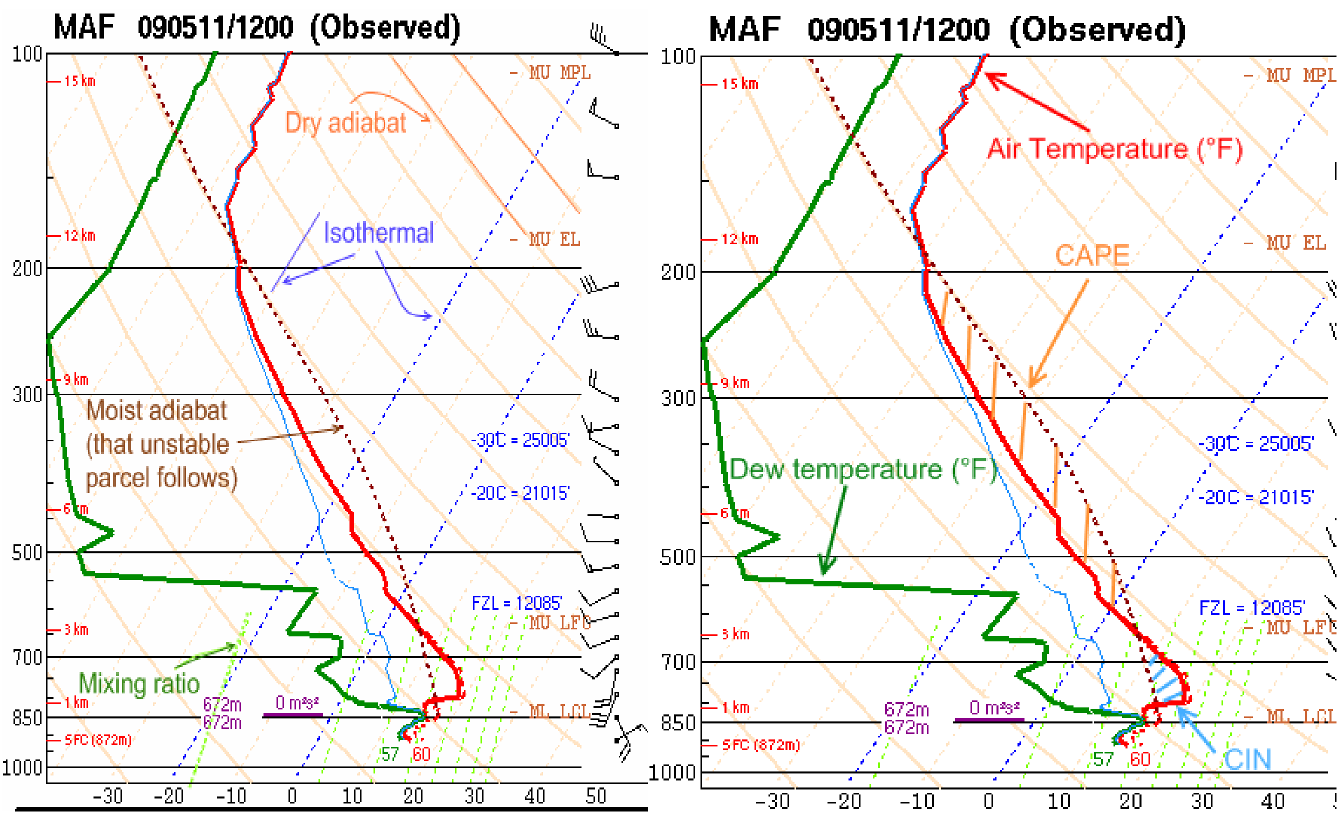


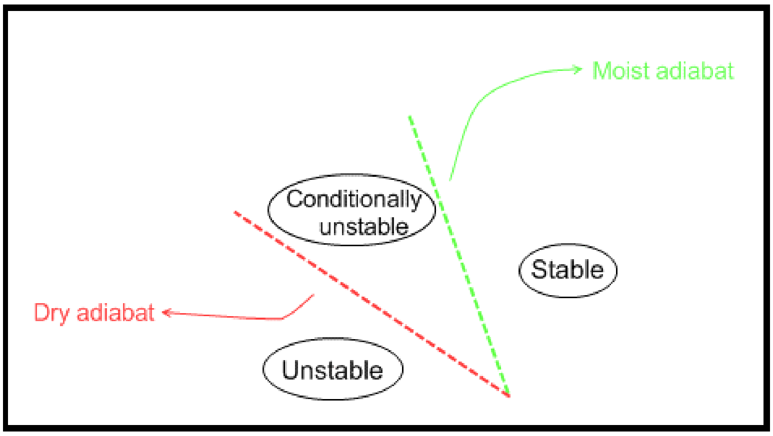
Fig. 20 : Soundings description

Sounding represent two mains temperature curves : the air temperature curve (red) and the dew temperature curve (green) in Celsius degrees. When these 2 curves are juxtaposed, that's means that air is saturated so humidity is equal to 100%. That's why, this is in that troposphere layer where we will find clouds. In the example above (figure 20), clouds are present between surface (SFC – 872m) and around 1km. On the contrary, when theses 2 curves are distant, we meet dry air so humidity inferior to 100%.

4. Severe Weather Parameters

We can see other parameters like LCL, EL, LFC, CAPE and CIN which permit us to understand how and where clouds are forming. Moreover these one inform us about instability and probability of severe weather.

Curves below permit us to see the stability of the environment : stable, unstable, or conditionally unstable. We need to know the temperature curve (red in the example right below) and compare it to the adiabats. For example, if our temperature curve is between the dry and the moist adiabat (such as example on the right below), we are in conditionally unstable environment. Moreover, if our temperature curve is situated left to the dry adiabat, we are in unstable environment.



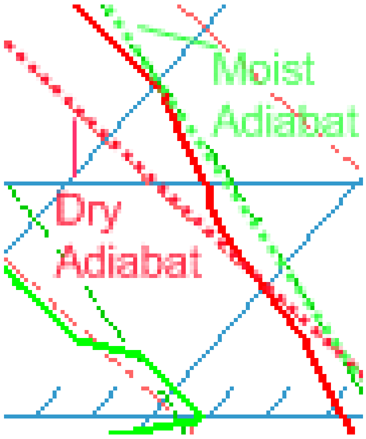


Fig. 21 : Explanation of a type of environment and an example at the right

- **LCL**, means **"Lifted Condensation Layer",** shows us cloud base height. Indeed, it's the level where a lifted parcel becomes saturated so an RH of 100% (RH means "Relative Humidity").

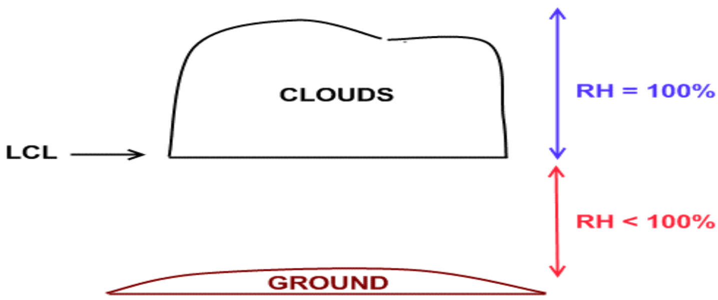


Fig. 22 : Diagram showing "Level Condensation Layer"

Moreover, to calculate RH, we need to know how much water we have in one kg of air (mixing ratio) in a precise layer of the troposphere. That's why we need to calculate mixing ratio of air temperature curve (written "Ws") and mixing ratio of dew point curve ("W").

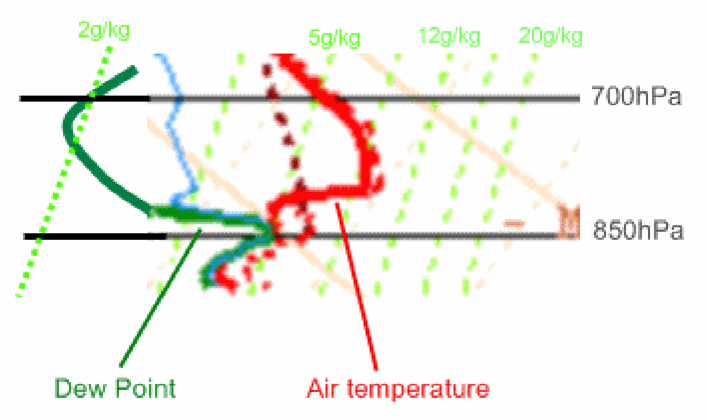


Fig. 23 : Picture showing the way to calculate RH

For example, in the layer 700hPa, we have Ws = 5 g/kg and W = 2 g/kg so :

RH = W/Ws = 0,4 or 40%

The 850hPa's layer is saturated (W=Ws) which means an RH equal to 100%. So we will find clouds in this troposphere's layer.

- **LFC**, meaning **"Level of Free Convection",** is the last level where a parcel becomes buoyant, or "warmer" than the environmental temperature at the same level. The LFC represents the bottom of the layer containing CAPE.

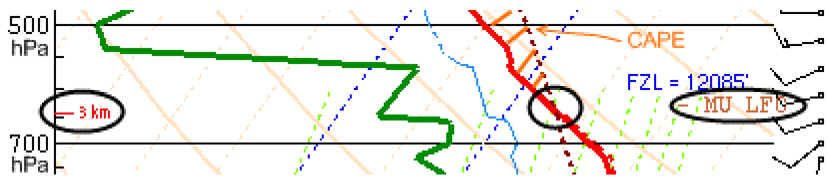


Fig. 24 : In the example above, LFC is around 3km.

- **EL** , meaning **"Equilibrium Level",** is the level where the lifted parcel again equals the environmental temperature. It represent the top of the layer containing CAPE. Moreover, it's a good element to calculate top of the cloud. We can check and compare this element with satellite pictures.

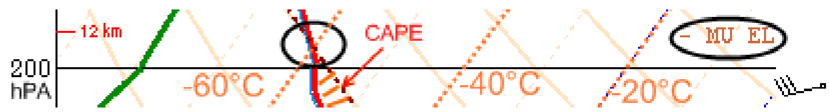


Fig. 25 : In the example above, we can make a link between the EL, thanks to the sounding, which show us a -60°C temperature EL and the satellite picture which confirms top clouds temperature (-60°C too). ***(Appendix B).***

- ***CAPE***, meaning **"Convective Available Potential Energy",** is the area between the air temperature curve and the curve (parallel to moist adiabatic) followed by an unstable parcel from the LFC to EL. CAPE is given in J/kg and is a very good element showing us the rising motion of a thunderstorm.

MUCAPE refers to the lifting of the most unstable parcel in the lowest 300hPa of the troposphere.
DCAPE is the downdraft CAPE. Values greater than 1000 J/kg are associated with increasing potential for strong downdrafts and damaging outflow winds.

CAPE (J/KG)	Hazards
500 - 1500	Light thunderstorms
1500 - 2500	Moderate/Strong thunderstorms. Slight risk of tornadoes.
> 2500	Very strong thunderstorms supporting tornadoes

However we need some other parameters to forecast thunderstorms !. One parameter like CAPE is not enough.

- **LI or "Lifted Index"** is the difference between the lifted parcel temperature and air temperature in the 500hPa layer (LI = B-A in the diagram below). LI and CAPE are closely related since strong CAPE is always with a negative LI. Negative values denote parcels that are warmer than the background 500 hPa temperatures, and are thus buoyant or "unstable".

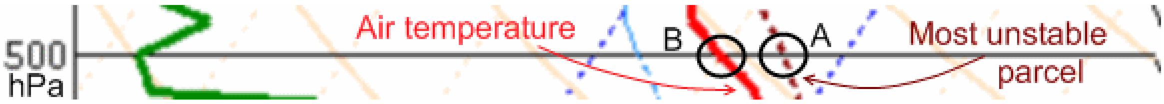


Fig. 26 : Calculation of Lifted Index

The more LI is negative, the better chance of strong thunderstorms. But we need some others parameters to have some thunderstorms too.

- **CINH or "Convective Inhibition"** is the integrated "negative area" in J/kg (from the original parcel level to the LFC) for the lifted parcel (blue on figure 20). The negative area represents the amount of energy needed for a parcel to reach its LFC. CINH's area is under a form of a cap on the sounding. "Breaking cap" is the moment where the parcel reach its LFC.
  We can compare with buoyant water in a saucepan and observe 2 cases :
  - without a cover, heat pulls out so CINH is not high. In weather situation, some clouds are developing (cumulus humilis or towering cumulus) but it's not enough for strong storms with powerful updraft.
  - with a cover, heat and humidity are locked up into the saucepan (high CINH). When we remove the cover (so when the parcel's breaking cap), we assist to a warm puff which can be compared to a strong vertical development of clouds. In this case, we can see quick and strong developments of thunderstorms with strong updrafts. That's a potential supercells' situation, especially if high CINH values are associated with high values of CAPE.

CINH (J/KG)	Hazards
< 15	Cumulus
15-50	Showers/ Scattered Thunderstorms
50 -150	Strong thunderstorms
> 150	Severe thunderstorms with possible tornadoes

*We can see on **Appendix C** an example of CAPE/CINH forecast.*

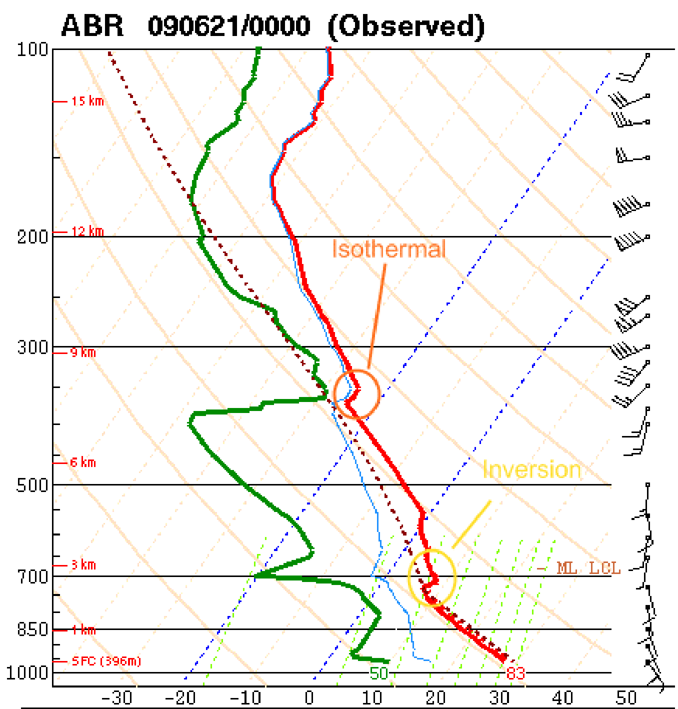


Fig. 27 : Example of sounding showing inversion and isothermal

The orange circle shows an isothermal. It's a layer where air temperature is the same. Indeed, this part of curve is parallel to another isothermal like -20°C or 0°C (blue).
The yellow circle show inversion of the air temperature. Indeed, in that case, temperature is increasing with altitude. That means a stable layer of the troposphere.

- **Tc** : called **"Convective Temperature"**, is the temperature which we can reach to break the cap. We will see in the next part some ways to break the cap (lift our unstable parcel up to pass the inversion layer) like a cold front or a dry line, but if these previous elements are not present, the only way to break the cap is Tc. So, if our air temperature reaches Tc and is greater, we will be breaking cap and thus have thunderstorms development

- Some other parameters are important for thunderstorm's forecast and more precisely, thunderstorms which can support tornadoes. I will introduce 2 of them, which are more important than the others :

➢ **<u>SRH or SREH, meaning "Storm Relativity Environmental Helicity"</u>** is a measure of the streamwise vorticity within the inflow environment of the convective storm. Streamwise vorticity is the component of vorticity that is parallel to the ambient velocity vector. Geometrically, the storm-relative environmental helicity is represented by the area on a hodograph (in blue on the diagram below) swept out by the storm-relative wind vectors between specified levels (typically the surface and 3 km to represent the primary storm inflow). It is thought to be a measure of the tendency of a supercell to rotate.

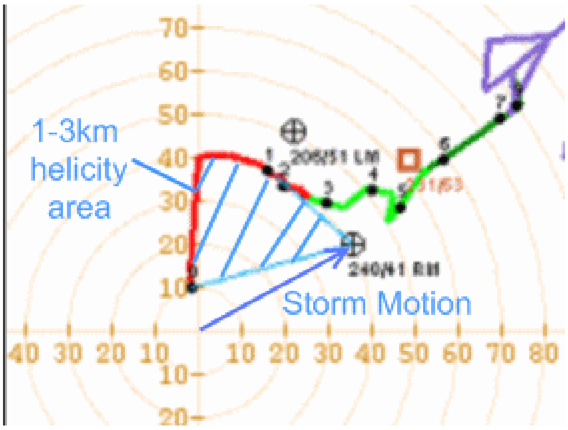


Fig. 28 : Picture representing an hodograph with storm motion and SRH

Moreover, SRH 0-1km's layer is a good way to make distinction between nontornadic and tornadic supercells. Indeed, this parameter is good to see the air mass low level that powers the thunderstorm's updraft.

<u>SRH (m^2/s^2)</u>	**<u>Potential tornado strength</u>**
150 - 300	Weak
300 - 450	Strong
> 450	Violent

*We can see an example of SRH forecast with **Appendix D***

- **VGP or "Vorticity Generation Potential"**

VGP = [*S*(CAPE)^1/2], where *S* is mean shear (or hodograph length divided by depth).
VGP is another experimental field for tornadoes supercells forecasting.
The units are m/s^2 (an acceleration). It is possible to have high values of VGP when helicity (and the EHI) is low. It's also possible that the larger the VGP the stronger the tornado. The VGP was developed by Erik Rasmussen for use over the central plains and may or may not be valid over other regions (Unknown problems).

VGP (m/s^2)	**Supercells tornadoes**
< 0,3	Rare
0,3 - 0,5	Unlikely
0,5 - 0,6	Likely
> 0,6	Likely to High Likely

5. Severe Weather Index

Soundings introduces a lot of index to forecast thunderstorms, supercells, and tornadoes. I will show us some one :

- **KI or "K Index"** :

K = (850hPa T - 500 hPa T) + 850hPa Td - (700hPa T- 700 hPa Td)

Where "Td" is dew point temperature and "T" air temperature in precise layer of the troposphere (500hPa, 850hPa or 700hPa). It's a good index to forecast thunderstorms risks.

Values greater than 30-40 tend to be associated with thunderstorms whereas little values are not common for thunderstorms.

- **Enhanced Stretching Potential (ESP) :**

This composite parameter identifies areas where low-level buoyancy and steep low-level lapse rates are co-located, which may favor low-level vortex stretching and tornado potential. ESP is formulated as follows:

ESP = (0-3 km MLCAPE / 50 J kg^{-1}) * ((0-3 km lapse rate - 7.0) / 1.0 C km^{-1})

where ESP is set to zero when the 0-3 km lapse rate is < 7 C km^{-1}, or when the total MLCAPE < 250 J kg^{-1}.

➢ **EHI or "Energy Helicity Index"**

EHI = (CAPE x SRH) / 160 000

EHI	Hazards
1,0 - 2,0	Potential for supercells
> 2,0	Large probability of supercells

This parameter is generally used for supercell and tornado forecasting. The EHI is a simple equation that combines helicity and instability into one number for estimating the potential for supercells. However, it is one of several parameters used for tornado forecasts, but we need some other tools to predict more precisely these phenomena.

Example of a supercell case sounding

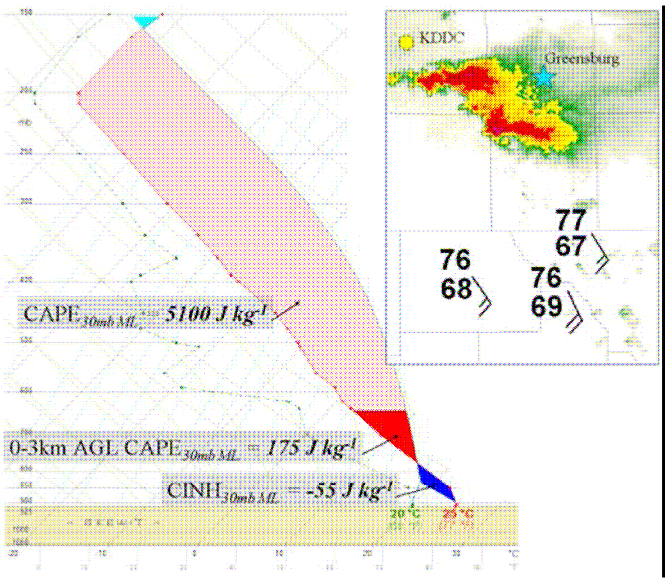


Fig. 29: Sounding of Greenburg (Kansas)

This example above concerns the Greensburg's case which products a strong tornado (F5) with a giant supercell across border Kansas-Oklahoma. We can see some interesting parameters such as high dew point (68°F or 20°C), very high values of CAPE (5100 J/kg), and a not impressive area of CINH (55 J/kg) but enough to have supercells. Moreover, we can see on the right picture moderate winds on the ground, coming from southeast, with high dew point meaning a strong moisture inflow in low level of troposphere. Of course, we need some others important parameters such as wind shear, curving of the hodograph, or SRH's rate to have a perfect description of this case.

III. SUPERCELLS

1. Introduction

Every day, a lot of thunderstorms take part in the world, but are more or less important. Supercells are the most powerful thunderstorms which we can found on the Earth. But to understand the mechanism of a supercell, we need to know how a thunderstorm forms.
First, a cumulus is formed in the low troposphere (0,5- 1 km). These clouds grow up in the troposphere thanks to convection and convergence on the ground. They grow up to towering cumulus stage as far as 6-7km is reaching the cumulonimbus stage. Cumulonimbus spread as far as tropopause, which is the troposphere-stratosphere's limit, in our atmosphere with an average altitude of 10 km in our regions. We recognize cumulonimbus thanks to its form. As it is under the form of an anvil. Why does this form?
At the end of its ascent, cumulonimbus can't spread more because of very dry and very stable air in the stratosphere. Updraft of the storm can't increase furthermore and there is to divergence at the updraft summit. In fact, cumulonimbus has no choice to spread out, hence anvil form. But we can see a little part of the cumulonimbus, under the form of dome, over the tropopause which is called "overshooting top".

Fig. 30 : Cumulus humilis > Cumulus congestus > Cumulonimbus

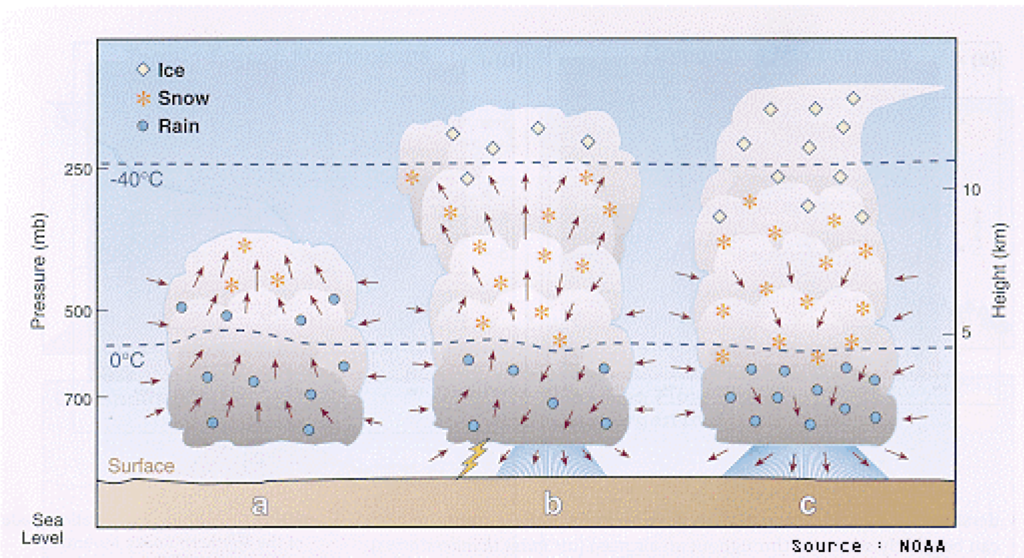


Fig. 31 : The 3 stages of a thunderstorm

2. Main Characteristics

Supercells are different from other thunderstorms since they rotate. They consist of a persistent powerful updraft and the presence of a mesocyclone. Sometimes they have the appearance of an atomic mushroom. A supercell thunderstorm's circulations so dominates its immediate area that the entire storm behaves as a single entity, rather than as a group of cells. Sometimes, supercells are produced in the front of thunderstorms line like squall line or from a storm splitting. Supercells contain a unique kinematic structure and that's why, we can identify and classify them into 3 main categories. These categories are classic (Browning 1964), "LP" for Low Precipitation (Bluestein and Parks 1983) and "HP" for High Precipitation (Mollet et al. 1990).
The main characteristics of supercells are that their life time is 4-6h average with 40-60km in width but a great supercell can reach 200km. Furthermore, they have a powerful updraft and strong wind shear (speed and direction), and produce severe weather like large hail, gust winds and tornadoes. Updraft wind speeds are usually between 45 and 90mph or 72 and 145 km/h, sometimes more (100mph).

We can give the characteristics of supercells based on reflectivity and velocity data. To classify as storm as a supercell, we must have several parameters. The first one is that the storm must contain a mesocyclone with an azimuthal velocity differential > 15kt or 27,8km/h at base level. We can see that from the radar's "Storm Relative Velocity" ***(Appendix A).*** The second is that the storm must persist 30min or more. Moreover, the cell initiation must produce a 40 dBZ echo. The third parameter is based on the end life of the mesocyclone. Finally, the last parameter shows a 20-30° deviation contrary to the main flow.

There are 3 types of supercells :

- "LP ", as its name indicates, presents little or sometimes no precipitation. However, this type of supercell is not a good producer of tornado. ***(Appendix E)***

- "HP" presents high precipitation with a powerful downdraft and large or very large hail (often golf/base ball or tennis ball size). However, this one is very dangerous since the tornado is hidden in heavy precipitations. This one is recognized thanks to a bean shape echo. HP supercells are the more dangerous than to the two others. ***(Appendix F)***

- "Classic": this one is the best supercell to chase since it's the best producer of tornado. Further information concerning structure/mechanism are given in the next part. However, types of precipitation, gust winds varied with parameters values like CAPE, CINH. ***(Appendix G)***

3. Supercell Structure

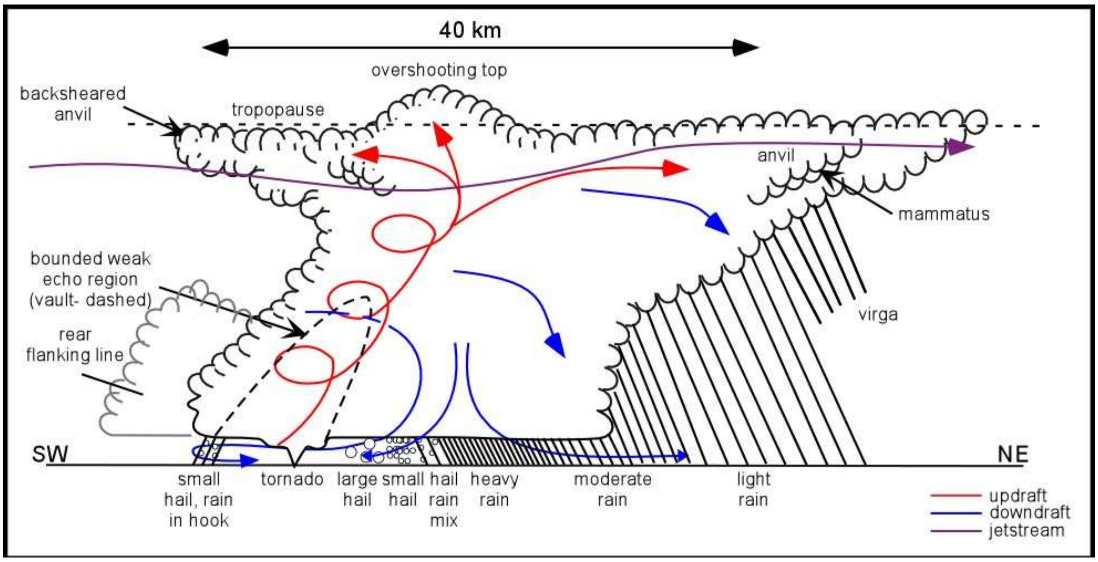


Fig. 32 : a supercell's view from the South-East

This picture is the main representation of a supercell in Central Plains of the USA.
It has again the structure of a cumulonimbus, but a supercell is more powerful and more developed...

- The red arrow represents a strong and rotative updraft. This is the main force of supercell since it's a kind of power supply. This updraft is more powerful in a supercell than in a basic cumulonimbus. Supercells grow up with overshooting top above the tropopause. Sometimes, this reaches very high altitudes. For example, the supercell of Greensburg (Kansas) which produced a huge tornado, had a powerful updraft which pushed this cumulonimbus to almost 22km above the ground ! Typically, as I said previously, the cumulonimbus climbs up around 10-12km. Very small cloud particles are carried aloft by the strong updraft resulting in a rain-free base. These particles are small and are detected by radar which result in a BWER echo.

  BWER means "Bounded Weak Echo Region". It appears "bounded" by the elevated precipitation core hanging nearby. We can see this echo on the diagram (vault dashed) and in this next picture. It is represented by a hole in the low level reflectivity on the southern side of the supercell, associated with a strong updraft and weak reflectivity.

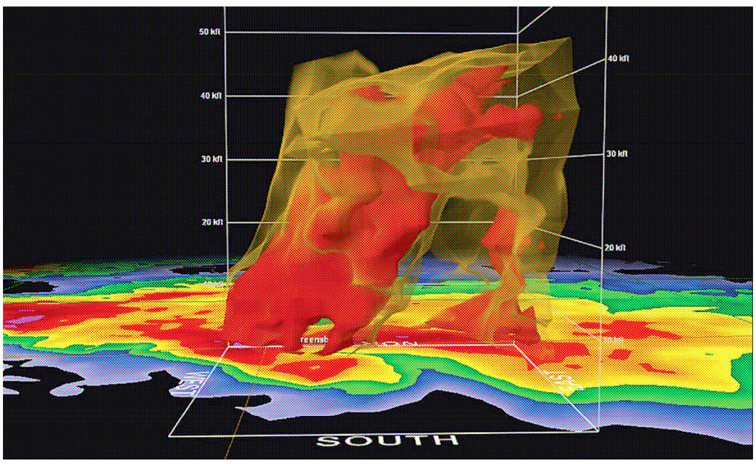


Fig. 33 : Vertical profile of a supercell with his BWER

- We often see a region of lowered clouds from the rain-free base, under the updraft. It's the wall cloud and this one rotates most of the time. Under the wall cloud, tornadoes often occur. The next picture shows that :

Fig.34 : Tornado under a wall cloud

- In another part of the diagram (figure 32), we can see the rear flanking line. It's a line of developing storms along the rear gust front. It's a kind of like Russian dolls since when the main storm dies, it can be replaced by them.

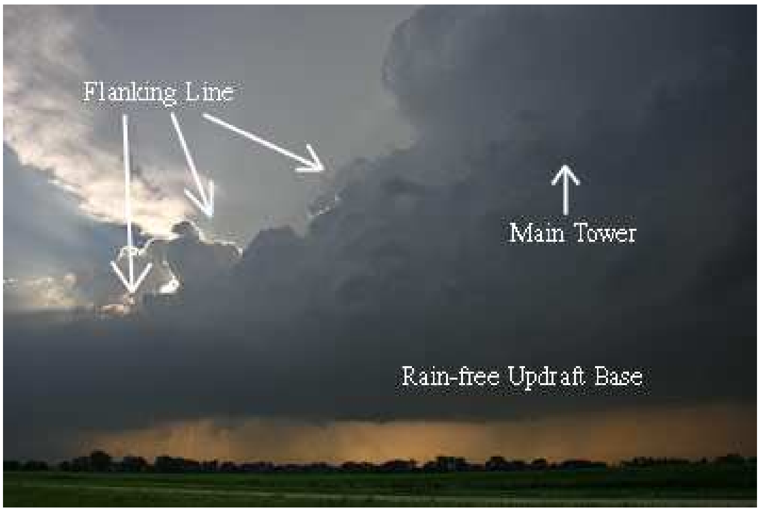


Fig.35 : a flanking line

- We can see the downdraft represented by blue arrows (figure 32). This one produces rain and hail, more and less heavy. Furthermore, these hydro meteors are heavier next to the tornado with often large hail (>2inches or 5cm and sometimes more).

4. Supercell Mechanism

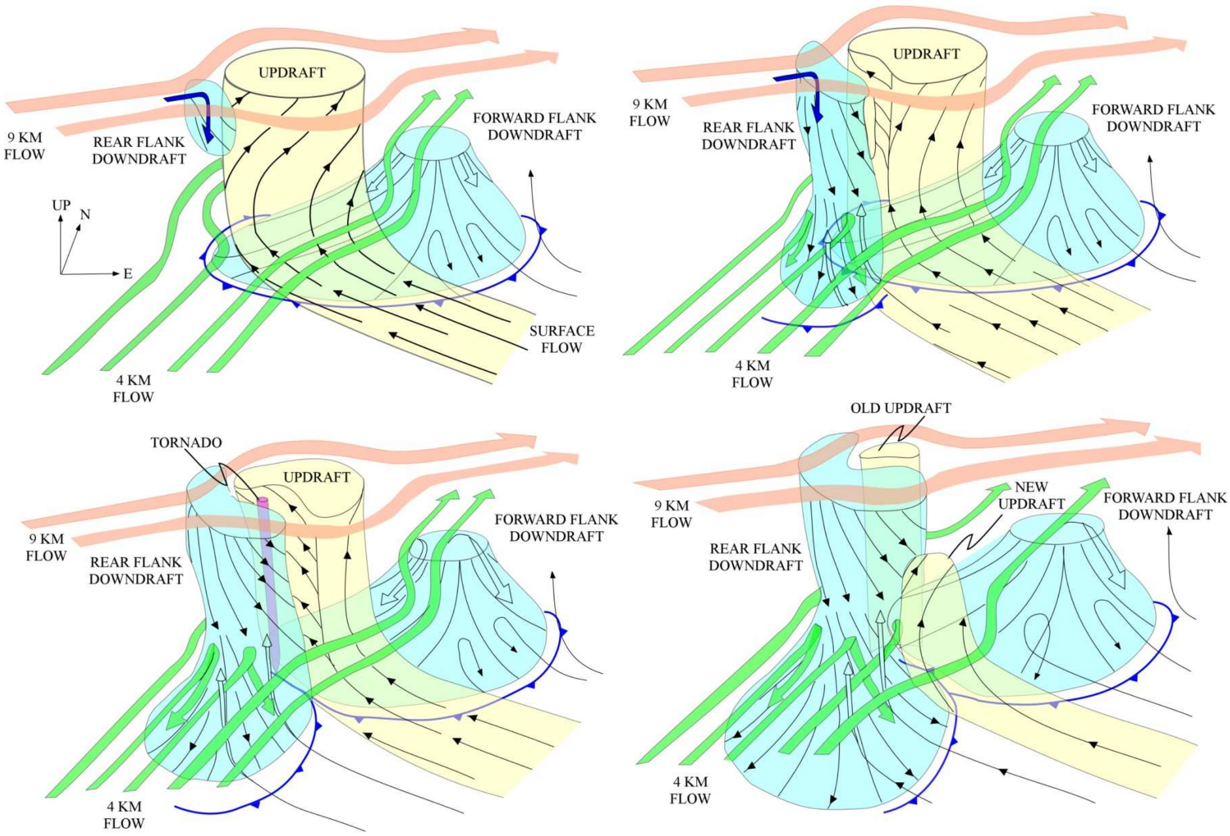


Fig. 36 : Diagram showing mechanism life of a supercell

Mechanism's supercell is composed of 3 main stages.

- During the first stage, a cell on the right rear flanking line develops 2 types of radar echo : a mid-level echo overhang and a weak echo region. A strong and persistent updraft is developing and is reaching top of troposphere. Then, this updraft meets very stable environment (stratosphere) and there is a strong divergence at the updraft summit hence the echo overhang.

- The second stage is defined when a special echo is detected. This is a Bounded Weak Echo Region. This one indicates where the updraft is located and is a good indication of increasing water and ice content. The mesocyclone forms at this moment which can be observed by a doppler radar. Moreover, during this stage, the largest surface hailfall generally occurs and we can often observe some funnel clouds or sometimes tornadoes (purple in schema) in the occluded area of the storm. This is, as we have previously seen, the meeting between updraft and rear flank downdraft.

- The final stage is the collapse phase. During this phase, there is the dissipation of the BWER with overhang decreasing. Furthermore, the storm's downdrafts increase in both magnitude and extend whereas the updraft is decreasing and becoming the "old updraft". Then, a new updraft can take place...

5. Necessary Ingredients

Four main ingredients are necessary to obtain a supercell. We need a very unstable environment with high CAPE (2000J/kg) and large lapse rates (>7°C/km) where lapse rates are the difference of temperature between 2 points in 2 different altitude (usually 2-4km or 0-500m).
In addition, strong moisture from Gulf of Mexico is preferable with high dew point (>60°F or 15,5°C) and low Dew Depression at 850hPa (= 1500m). A Low Level Jet (LLJ) is necessary, since it brings moisture from Gulf of Mexico. Moreover, moderate or strong vertical wind shear is necessary, primarily under the LCL (0-1km layer), which can be seen in a sounding.

When these parameters are present, we need something to trigger the convection such as cold front (C), dry line (A), or outflow boundary produced by old thunderstorms (B). We need something to lift our parcel up and break the cap. The speed of a cold front can be an important element. A sagging cold front will be worse than a fast cold front. In the second case, our parcel lift up better than the first case. If any of these 3 cases are not present, we need enough heat to break the cap ; a temperature higher than "Tc". I have explained more precisely this last element in the "Soundings" section.

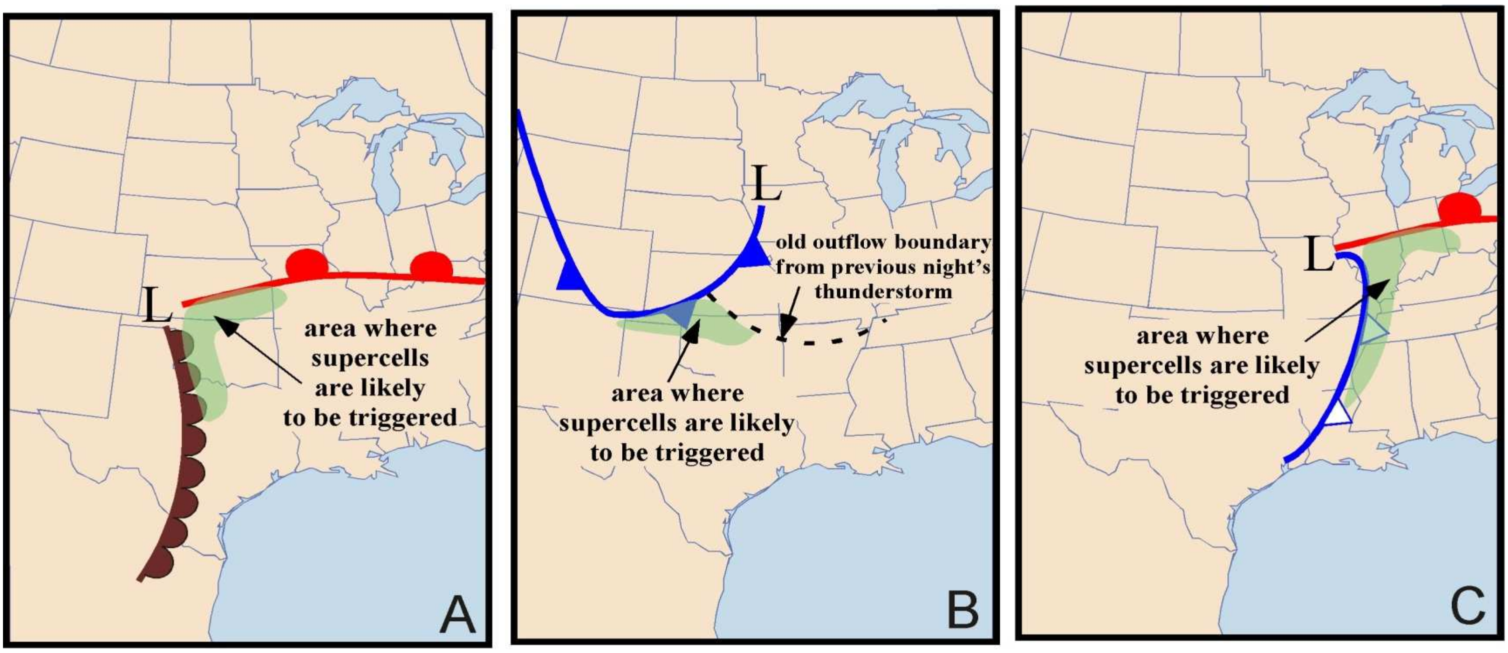


Fig. 37 : Trigger mechanisms

Moreover, we typically need one more element which is the jet streak and permits to see a trigger area for thunderstorms since we can identify clearly divergence/convergence areas. A convergence area in high altitudes (depicted by the jet streak) corresponds to a divergence area on the ground : this is really bad for convection. That's why we need a reverse situation with divergence in high altitudes and convergence on the ground which permits a strong rising motion also development of thunderstorms.

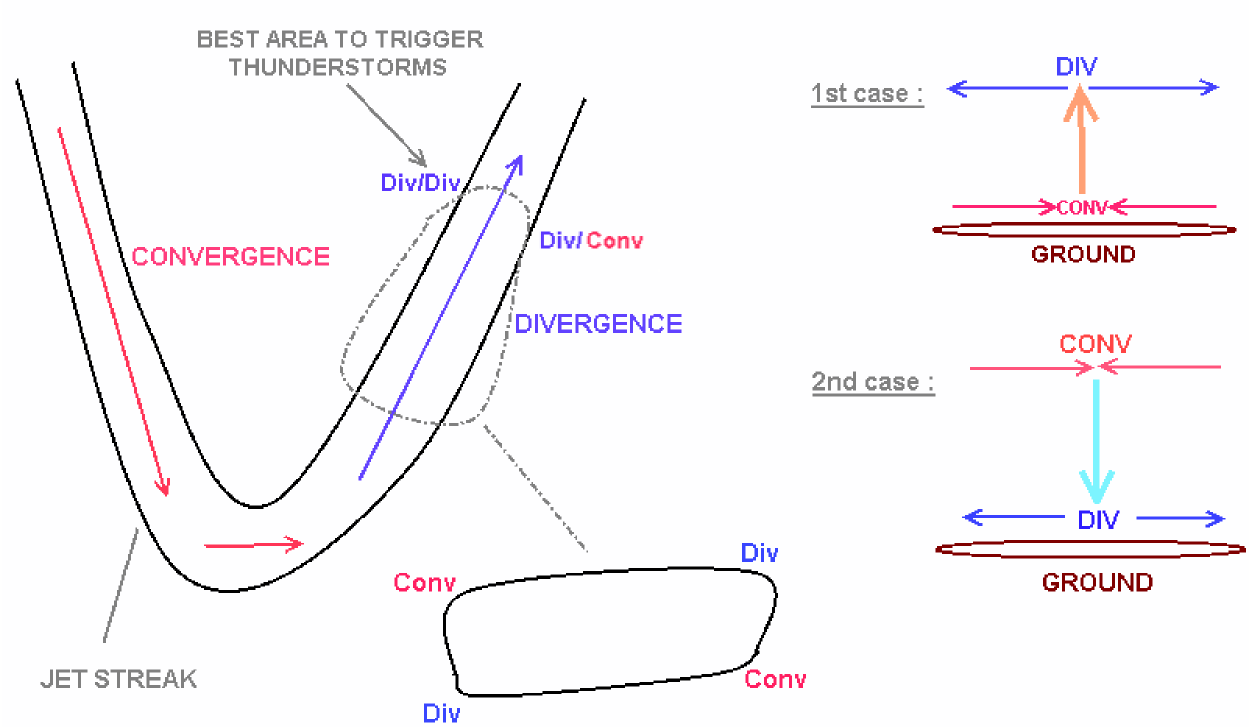


Fig. 38 : Jet streak with convergence/divergence areas and best area for thunderstorms

6. Radar Echoes

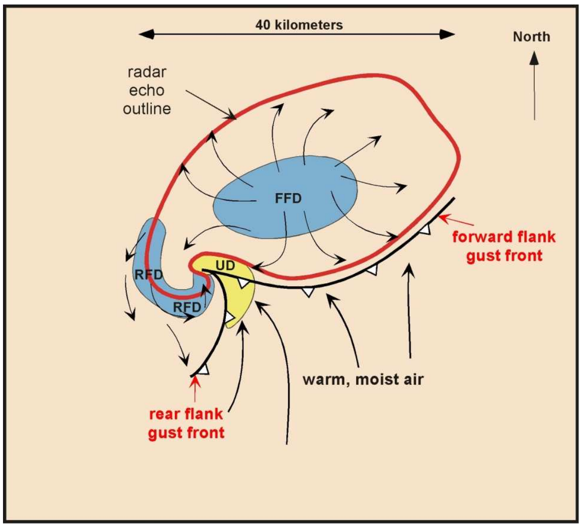


Fig. 39 : Typical radar echo of a supercell

Supercells have a specific radar pattern echo which can be distinguished thanks to the large NEXRAD network ***(Appendix H)*** :

- the updraft called "UD" on the diagram. This one was previously described. A rotative strong updraft is necessary to develop a mesocyclone then a tornado.
- the rear flank downdraft "RFD". As his name indicates, it's a downdraft at the rear of the supercell which produces a gust front (high wind). It is identifiable by a clear slot above the wall cloud like in ***Appendix I.***
- the forward flank downdraft "FFD". This one produces a gust front too covers the largest area in the supercell such as the diagram above.

- "Hook echo" is in the same area as the RFD/UD. This is in this part of the supercell where we find tornadoes. The rear flank gust front and forward flank gust front collide to form an occlusion. This interaction between the strong rotative updraft and the rear flank downdraft produce the mesocyclone.

Precipitations is strongest next to the hook echo with hail or large hail ; whereas, we find rain more or less heavy precipitation between forward flank core and anvil.

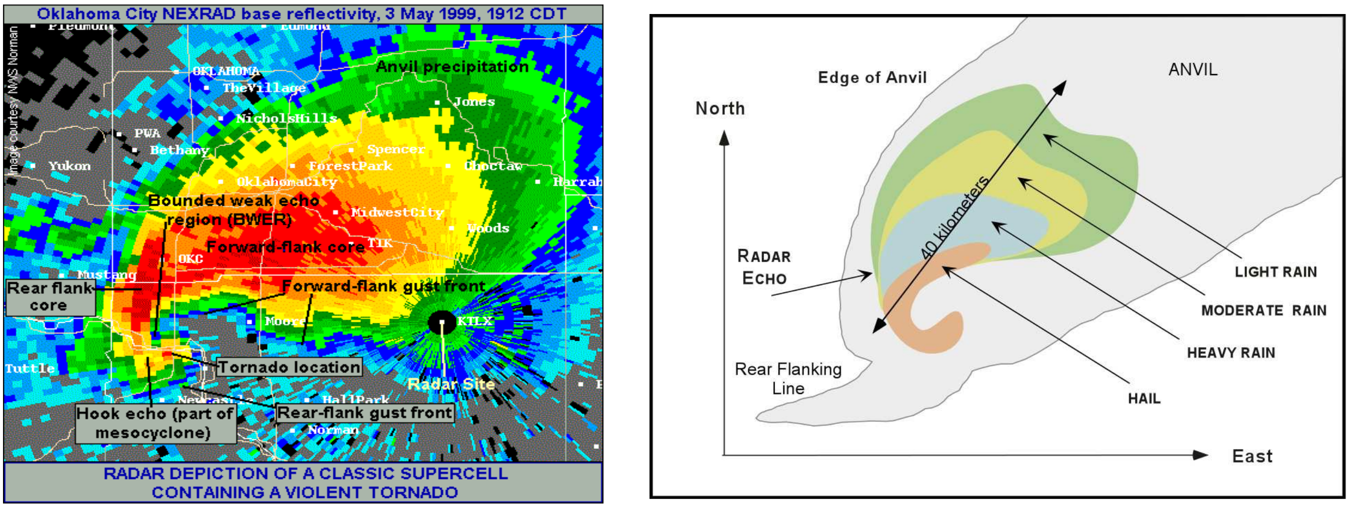


Fig. 40 : Others radar echoes showing us a supercell structure

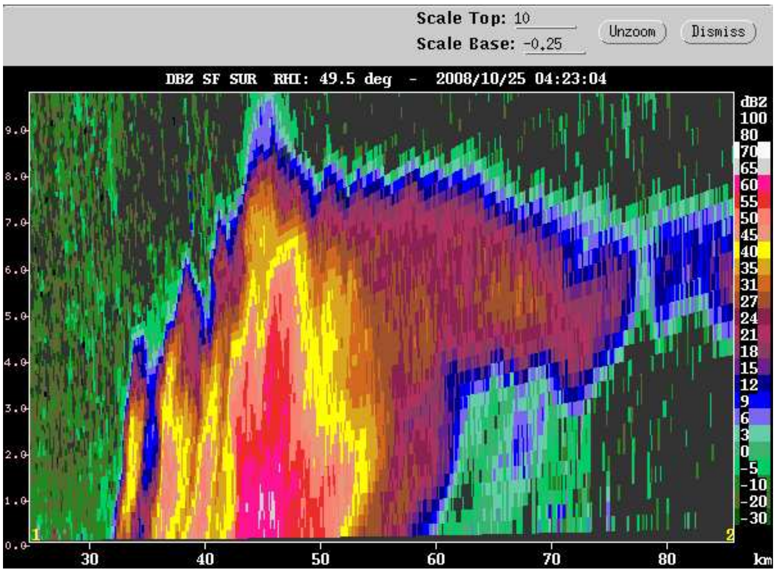


Fig. 41 : Vertical view of a supercell thanks to reflectivity

This picture shows a vertical view of a supercell. We can see 3 scales :

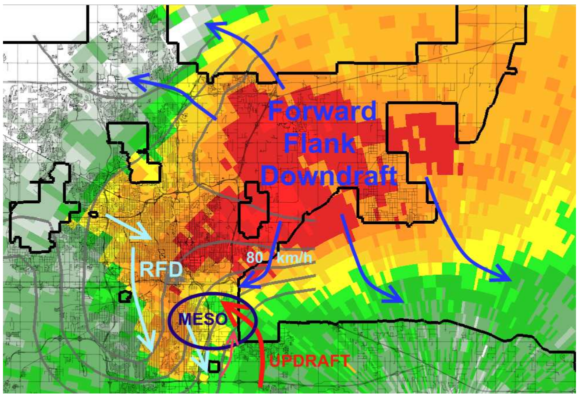
- Left's scale : this one presents altitude in km (0,0 - 9,0km here)
- Right's scale : this one allows to measure intensity of rain/hail in dBZ thanks to the NEXRAD radar network ***(Appendix H).*** Precipitations have different reflectivities. For example, light rain send back a low reflective echo (10 – 20 dBZ) whereas hail or heavy rain send back a high echo (50 dBZ and more).
- Bottom's scale : this one show us width of cell in km. In this example, the supercell is about 40 km wide.

We can see, as we saw on supercell's structure, large hail, heavy rain from 43km to 60km (bottom scale) and light rain under back sheared anvil between 60 and 75km. Moreover, the overshooting top is identifiable around 46km and reached a little bit more than 9km. Finally, we can see the flancking line (3 cells) rear to the supercell between 32 and 40km.

7. Supercells Cases

- ***May 13th 2009 – Oklahoma Center :***

We can observe a school case with hook echo, FFD, RFD, UD and mesocyclone shown by the Doppler radar. High dew point existed with 68°F average (66 to 70°F). Moreover, we can notice a strong rotation with rolling winds from Northeast for FFD, Northwest for RFD and southwest for UD.
Close to the mesocyclone, we can observe the strongest winds with a wind of north/northeast 25knots and a 80km/h gust. Furthermore, we can observe east winds in front of the supercell and west winds at the rear.
Thunderstorms formed along the convergence line (South Southeast before thunderstorms – Northeast after storms) and the edge of the cold front coming from the North.



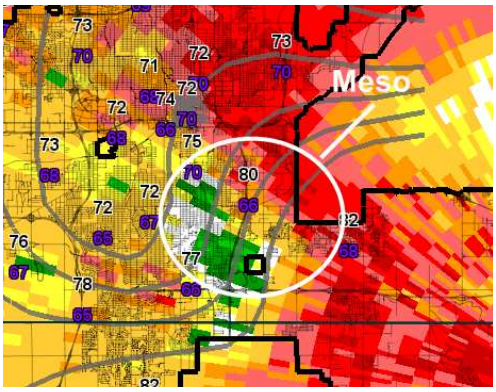
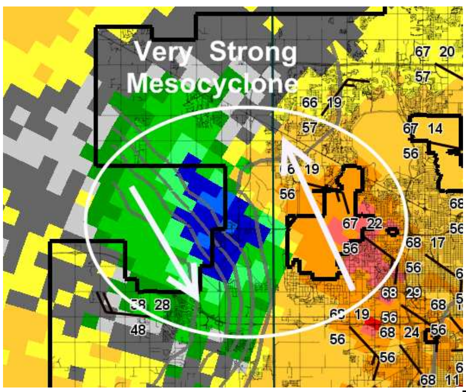


Fig. 42 : Diagrams showing different parts of structure supercell and the mesocyclone on the right picture

- ***February 10th 2009 :***

On this case, the supercell is much stronger than the previous case. Indeed, the hook echo is very strong such as the mesocyclone. We can see the main characteristics thanks to reflectivity of radar, such as FFD, RFD and UD. However, dew point is very low (only 56°F). We can observe a high temperature gradient toward the RFD with 8°F difference over a couple of miles. The same day, a strong tornado rated EF-4 was produced in southern Oklahoma (Lone Grove).



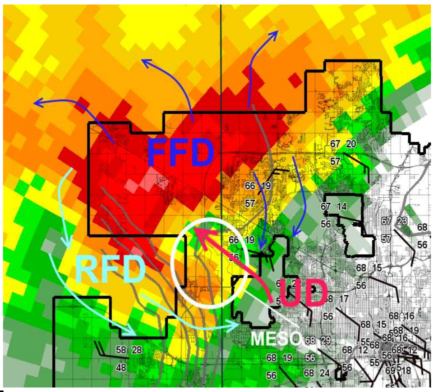


Fig. 43 : Same diagrams like above but for an other situation (10 February 2009)

8. Supercells in Oklahoma

The state of Oklahoma is the logical place to study severe weather and more precisely supercells. This state of the USA is situated between several huge air mass with very warm and moist air coming from Gulf of Mexico and very cold and very dry air coming from the Rocky Mountains. I will now show a different study realized by the OCS (Oklahoma Climatological Survey) during the period 1994-2003 which deals with trajectory, density, initiation, and termination of supercells.

- The trajectory of supercell changes during the year. We can observe 2 main supercell tracks. The first one is oriented from southwest to northeast occurs from January through June and the end of the year. After that, second supercell tracks are oriented from northwest to southeast from June to September.

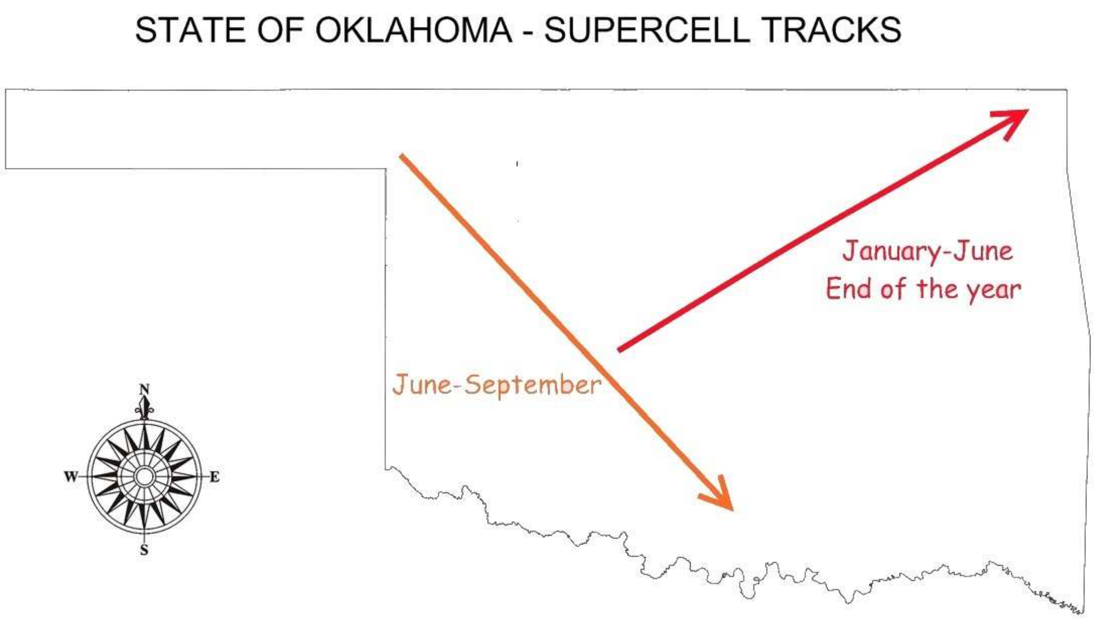


Fig. 44 : Supercell tracks in the State of Oklahoma during 2 main periods of the year

- Moreover, 75% of supercells take place from April to June and 25% during the year. May is the best month to observe these phenomena since it has the most of cases of supercells. During the period 1994-2003, about 366 supercells or 85 days of supercells were observed during this month, followed by April and June which had 190 and 145 supercells or 50 and 55 days of supercells. Finally, the mean total of supercells observed across Oklahoma during this period was 94. In addition, this study shows an average of 28 supercells days per year.

- Several region in Oklahoma have the highest number of supercell occurences : East Central, Southwest, and West Central into Northeast.

- Initiation of supercells occurs mainly between 20h and 00h UTC or 15h and 19h in local time (Oklahoma) whereas termination is most common between 23h and 3h UTC or 18h and 22h in local time.

IV. TORNADOES

1. Introduction and Occurences

A tornado is a violently rotating column of air that extends from a thunderstorm cloud (especially the wall cloud) to the ground. Tornadoes produce the fastest winds on our Earth and are thus more violent than hurricanes. However, they are often confused with dust devils, gustnadoes, waterspouts or landspouts, which are not produced by supercells but by cumuliform clouds such as towering cumulus or cumulonimbus. Tornadoes are often under the form of funnels of varying widths.
Moreover, 75% of the tornadoes in the world occur in the USA, primarily in the Tornado Alley (Texas, Oklahoma, Kansas, Nebraska). Each year, an average of 1000 tornadoes occur in the United States of America. This is the area where strong air mass meet warm moist air from Gulf of Mexico such as, warm dry air from Mexico's Lands and cold dry air from Rocky Mountains.

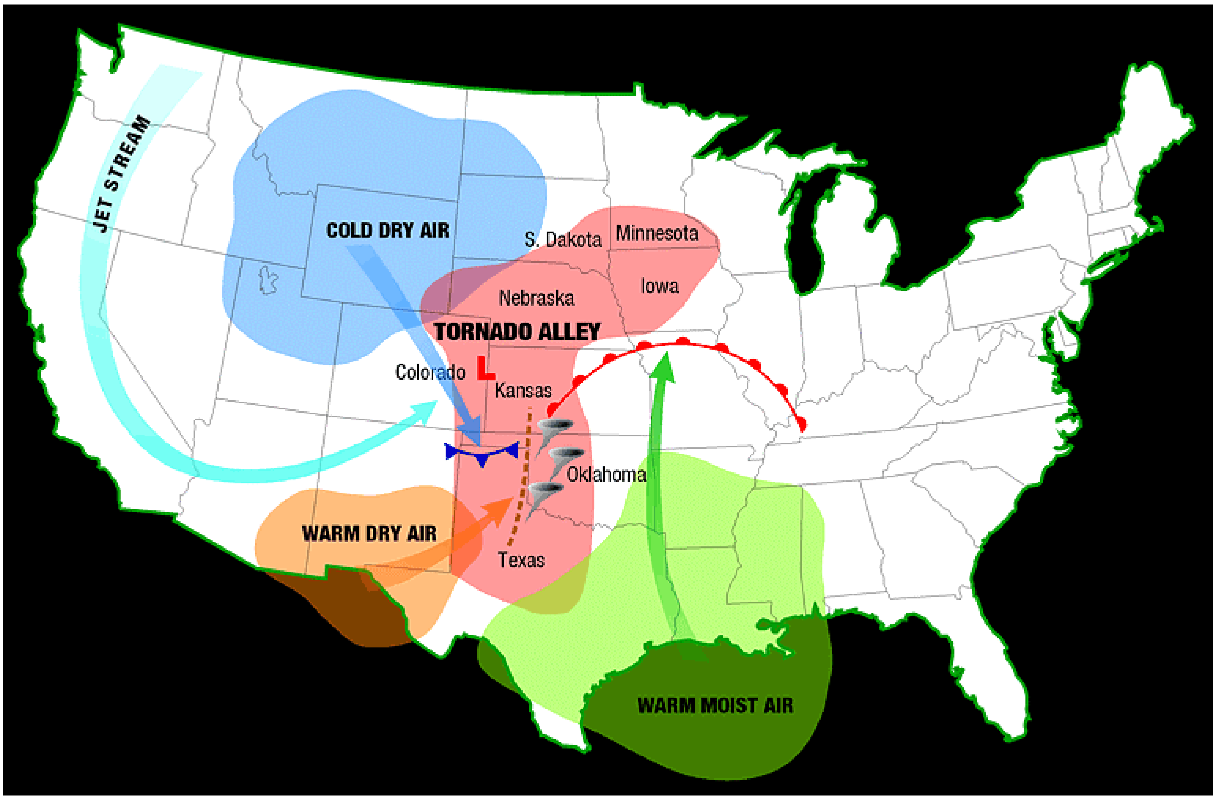


Fig. 45 : The Tornado Alley in the USA with typical synoptic situation giving severe weather and tornadoes

Tornadoes are still unknown for meteorology's professional. Weather forecasters can't predict precisely where tornadoes will occur, but they can issue weather advisories like tornado watch or tornado warnings before tornadoes occur. Thus, people can be well-informed by weather hazards in real time thanks to TV, radio or internet. However, the scientific community wants to know more about these phenomena. That's why, thunderstorm specialists have had to projects like "Thunderstorm project" ,"Vortex 1", and "Vortex 2" (this year and 2010 during springtime and tornadoes' season) to study thunderstorms, more precisely supercells, which produce tornadoes. Infact, some powerful computers give some data about supercells' structure thanks to 3D simulation, but we need other data to predict as well these phenomena. Unfortunately, weather didn't collaborate most of the time this springtime with Vortex 2 with only one tornado and few good supercells.

Tornadoes generally occur during springtime with the tornado peak during May followed by April and June. However, tornadoes can occur at any time of the year. The 10th of February 2009, which doesn't belong to the best period, is a good and recent example since a strong tornado touched down (EF4) in Southern Oklahoma. We can see in ***Appendix J*** the average number of tornadoes per year per 10 000 square miles (or 16 0000 km²) in the USA. The most concentration is situated in the Tornado Alley with an average of 9 tornadoes in Central Oklahoma, Northeast and Northwest Texas ; between 5 and 7 tornadoes from Southeast Texas to Iowa-South Dakota.

To conclude, this part, tornadoes mainly occur between 4 and 8 pm (16h and 20h), but tornadoes occur during the night too (Greensburg's case for example).

2. Structure and Mechanism

A tornado is a vortex where strong winds turn around in a cyclonic way in the North Hemisphere (so counterlockwise), rarely anticyclonicy way (only 2% of tornadoes). Pressure in the vortex is very low as opposed to environment pressure.
A lot of hypothesis are possible to explain a tornado's formation. That's why, lot of specialists develop projects such as Vortex 2 to understand how and why tornadoes form.
I will explain some theories of tornadogenesis and begin with tilting :

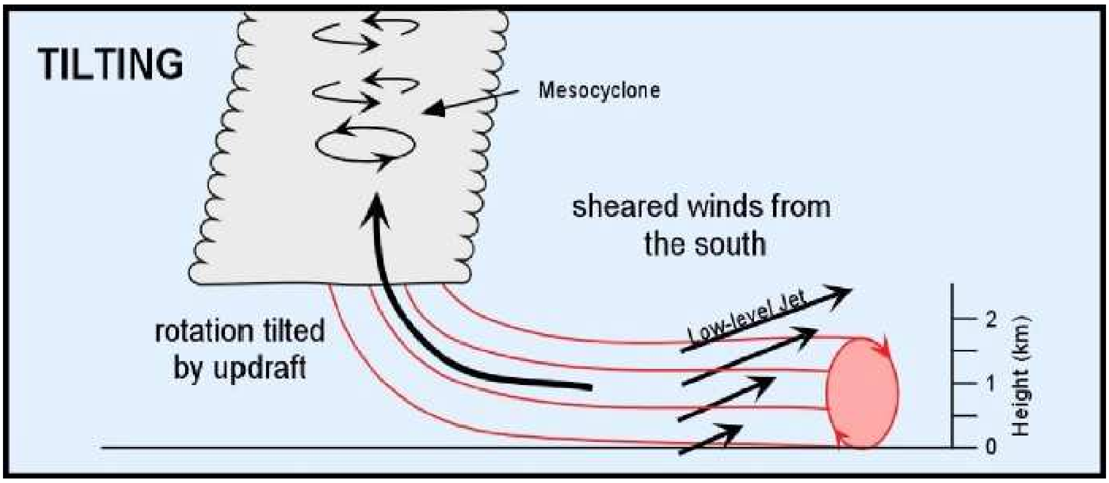


Fig. 46 : Tilting theory

We can see on the diagram above the mesocyclone produces by a supercell. Moreover, it shows the low-level jet that brings moisture in low level layer, as we have seen previously in the supercells' part. Infact, the first theory explains that we must have a vertical wind shear, which is horizontal with rotating winds from southeast to west (such as in the part talking about the hodograph). These winds meet the strong updraft, which tilts the mid-level rotation vertically. The circulation is tilted upward, that the diagram shows above, and we see to the creation of a low level mesocyclone with a vertically rotating flow which can produce a tornado.

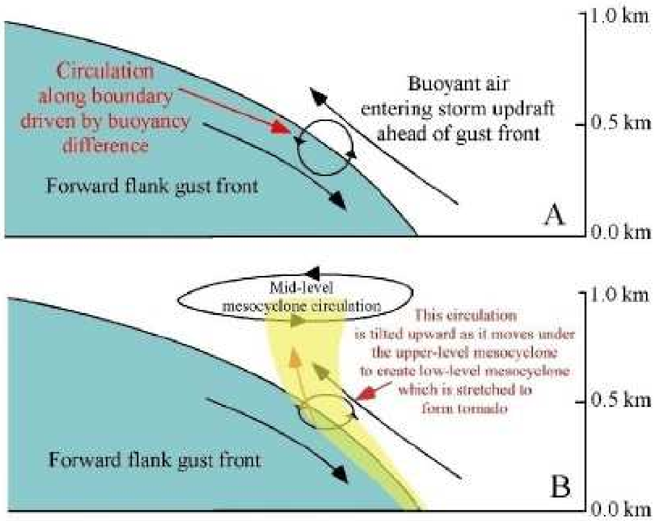


Fig. 47 : An other tornadogenesis theory

This diagram above shows us a second theory of tornadogenesis called "bottom-up process". A good element for producing rotation in a thunderstorm occurs along a gust front (identifiable by a shelf cloud that we can see on ***Appendix K***). We assist to buoyant air entering storm updraft ahead of the gust front (inflow of the storm) whereas air comes down to the ground forward the gust front. That creates a circulation along this boundary driven by buoyancy difference. This circulation is tilted vertically and is enable to create a low-level mesocyclone supporting a tornado.

After that, we have to talk about stretching which is a main element in the comprehension of the development of tornadoes. Indeed, thanks to the following law : R1*V1 = R2*V2, where R is a radius and V a velocity, we can see that angular momentum is conserved such as the diagram below :

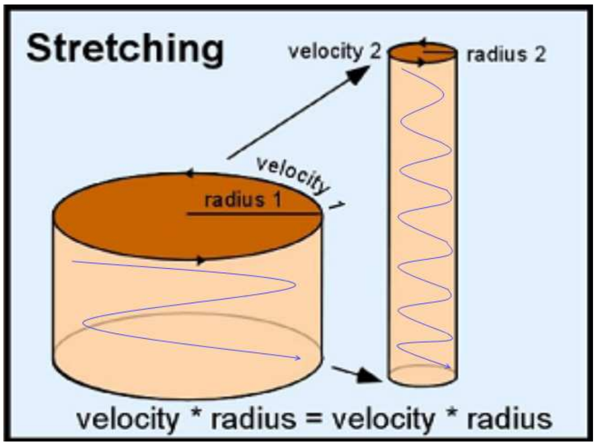


Fig. 48 : Stretching mechanism

That is how, downdrafts concentrate rotation into a smaller space at the ground. Thus, rotation is stronger since speed of winds is increasing whereas diameter of the column is decreasing. That is why, a tornado can be formed.

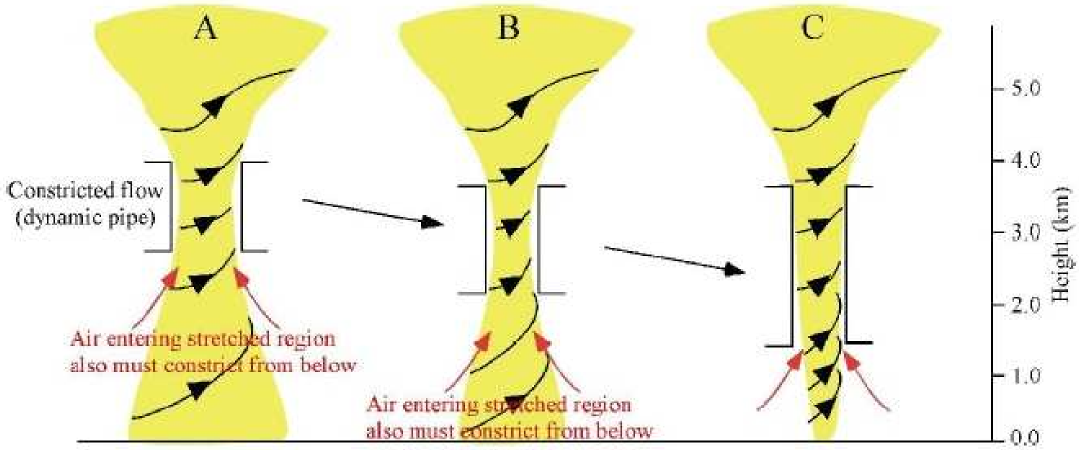


Fig. 49 : Dynamic pipe effect

We are going to talk now about the dynamic pipe effect called "top down process" represented by the diagram above. Black arrows in the diagram above show us constricted flow due to the dynamic pipe. Air entering stretched region also must constrict from below. Constricted flow in mid-levels from the mesocyclone being stretched works down to the ground. That's why, we can observe a cylinder cone and then a funnel, which can correspond to the tornado's strength.
We can see a good example in ***Appendix L.***

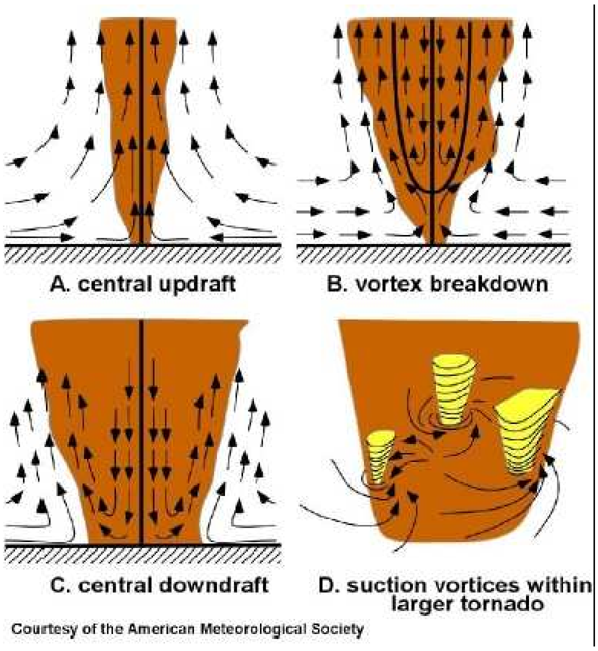


Fig. 50 : Theory of multiple vortex

The picture above represents the vortex with winds motion . Picture A shows us a small vortex with strong rotative updraft. Then, as vortex becomes larger, we see a vortex breakdown with strong downdraft in the middle of the vortex. It descends all the way to the ground and interacts with the outside rotating air. It results with one or several small vortex in the large vortex, so a multiple vortex tornado. Sometimes, we see a small tornado moving around a large tornado, such as a satellite around the Earth. But all of these diagrams are just theories and specialists need to learn more knowledge about tornadoes.

3. Ingredients

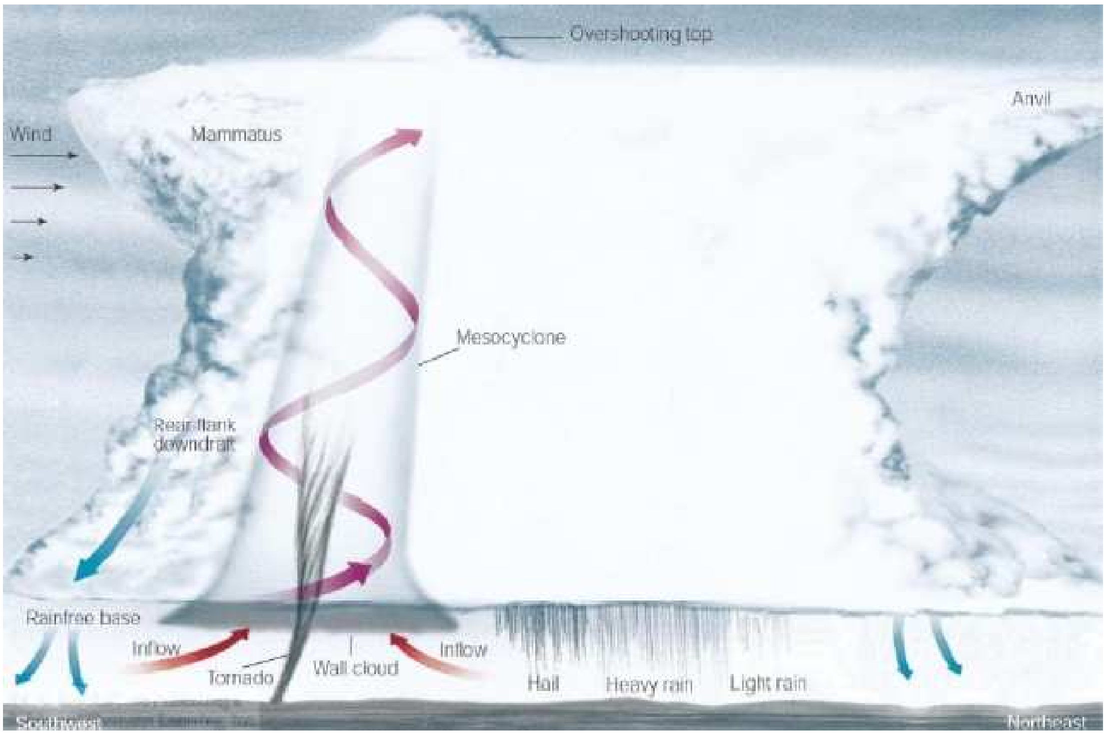


Fig. 51 : Typical structure of a supercell

Tornadoes occur in supercells since these thunderstorms rotate. Indeed, we need some ingredients that I have talked about in the supercell's part. Infact we need :

- high CAPE values (> 2000J/kg)
- high dew point values (> 60°F or more) with strong moisture coming from Gulf of Mexico
- low level jet to bring moisture
- strong upper levels winds (jet streaks in 200-300hPa) greater than 25 m/s and especially oriented South-North in the Tornado Alley
- moderate or high CINH (>150 J/kg) around 900-850hPa until later in the day
- a strong lifting mechanism (cold front, dry line) to break the cap (CINH's area)
- strong directional and speed wind shear, especially in low level (0 – 1km)
- large lapse rate > 7°C/km (2-4km layer)

Unfortunately for stormchasers or fortunately for local people, tornadoes don't occur all the time when we have all of these parameters above. Mother Nature doesn't always do what we think she is going to do, despite all of the equipment and technology in the world. That's why we have to stay humble in front of Nature and try to understand why tornadoes don't occur or occur thanks to project such as Vortex 2 this Springtime.

Then, to classify a supercell as a tornadic supercell, many elements must be in place such as a hook echo, a rotating updraft, a RFD (Rear Flank Downdraft), a mesocyclone, and/or a tornado.

4. Radar Echoes

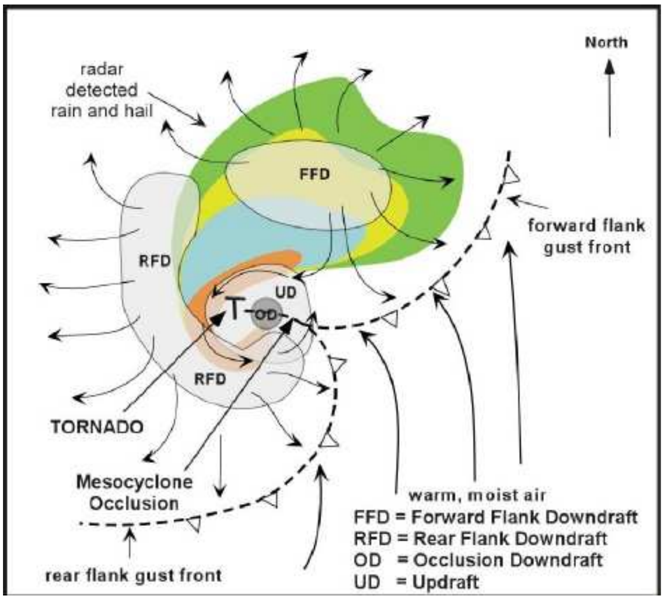


Fig. 52 : Radar echo of a tornadic supercell with tornado location

A tornado, more precisely strong tornadoes, can be only produced by supercells. Indeed, we need a storm which rotates and supercells are the only thunderstorms to do it. Moreover, classic supercells are the best producer of tornadoes since they present a good RFD correlated with a strong rotative updraft, as we have seen in the supercells part. We find the mesocyclone in this part of a supercell.
The diagram above shows us typical tornadic supercell radar echo with RFD, FFD, UD and particularly the TVS or "Tornado Vortex Signature". It is situated at the mesocyclone center and within the strong vertical velocity gradient. TVS precedes 10min before tornado touch down.
This diagram is almost the same I have used in the supercells part but we can see on this one the tornado location. The location of the tornado is situated in the occluded front (OD) with the meeting of RFD and UD. Moreover, the tornado location is surrounded by strong precipitations such as large/very large hail or very heavy rain.

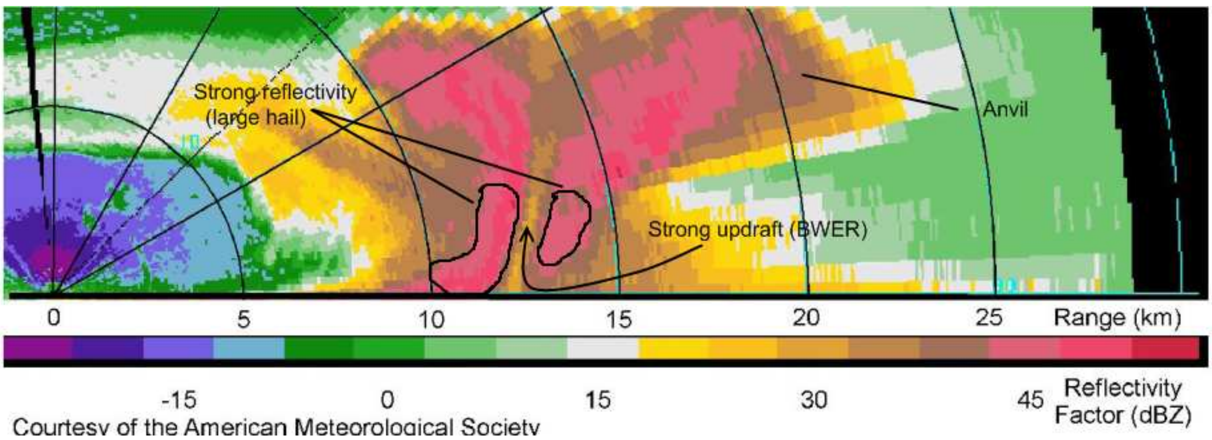


Fig. 53 : a verticall cross section of a tornadic supercell

This diagram above show us a vertical cross section of a tornadic supercell. Indeed, we can see reflectivity of the storm with anvil and strong reflectivity near the tornado such as large hail. The tornado location is shown by a weak reflectivity because of the strong rotative updraft (BWER).

5. Storm Chases

After many hours trying to understand mechanism of a supercell and typical radar echo, I have gone chasing supercells and tornadoes with Jeff and one time with 3 people working at the National Weather Center (NOAA, one graduate student and a meteorologist teacher).

During the first chase, we drove across West and Northwest Oklahoma where a moderate risk was issued by the SPC (Storm Prediction Center). This first chase was one of the best, since we got a beautiful classic supercell then HP (High Precipitation) with a very strong downdraft and since all of storm chasers were here. This downdraft produced large hail with base ball size hail. We saw a very low level base clouds with an impressive wall cloud very close to the ground. We could see a strong rotation under this one which produced a thin funnel, but unfortunately no tornadoes.

Fig. 54 : Pictures of the 25th supercell with a very low wall cloud and an impressive mesocyclone

The day after was really frustrating since we decided to stay in Norman (still moderate risk). A high risk was issued for West Oklahoma in the same place we chased the day before. Unfortunately, tornadoes occured in West Oklahoma exactly where we were the day before whereas we got nothing really interesting here in Norman !! The night was interesting with a gust front followed by heavy rain and strong lightning bolts.

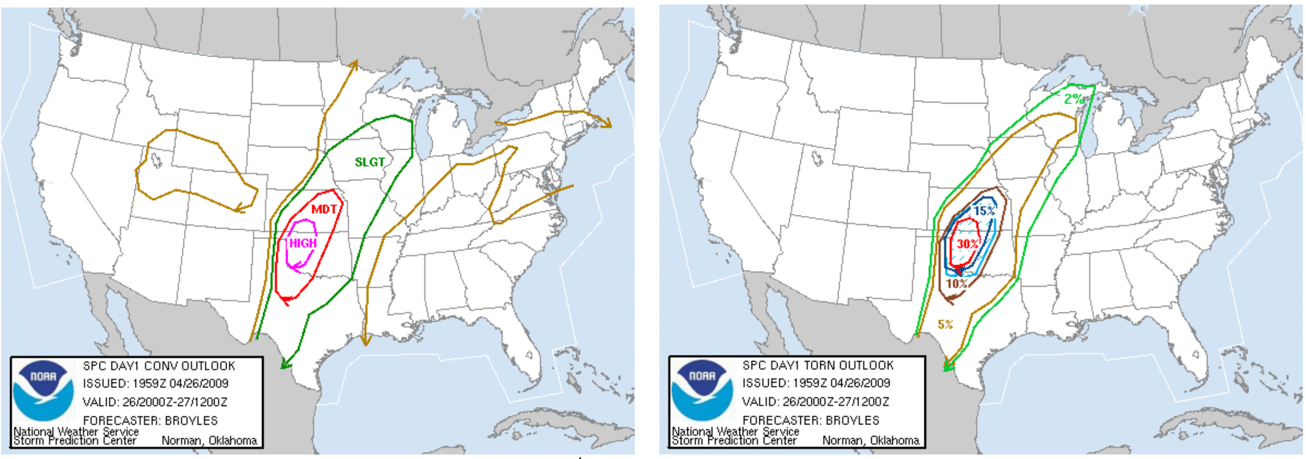


Fig. 55 : Convective outlook for April 26th (left) and chance of tornadoes (right) issued by the SPC

The second chase was in North Texas next to Seymour and Wichita Falls. We got a good supercell but this one died quickly. That's why, we came back early to Norman. I was really frustrated one more time since this cell regenerated after we left and produced a tornado just before dark.

The third chase was really interesting since we got a beautiful LP supercell evolving quickly in an amazing HP supercell in Southeast Kansas. We saw very strong rotation under the mesocyclone, but still no tornadoes. However, we got a tornado warning on this storm. The shelf cloud produced by the Rear Flank Downdraft was really gorgeous and the downdraft of this supercell produced very large hails (base ball and tennis ball size). I thought that we would see to a tornado thanks to the bottom-up process explained before. This supercell produced powerful lightning (CG) and regenerated itself several times. Lot of supercells moved south in Oklahoma with some tornado warnings issued such as in Norman where sirens where turned on.

Fig. 56 : Mesocyclone and view of the HP supercell with the shelf cloud and the RFD

We drove to South Kansas for the fourth chase with Kenny (a meteorologist), Kevin (graduate student) and Kim (NOAA) in the moderate risk. Lots of storm chasers where here next to Wichita. We got a nice supercell (classic in my opinion) with a little bit of rotation but really not enough for tornadoes. We drove in the downdraft and got some very heavy rain mixed with hail and strong gusty winds with some debris on the road. This supercell died while we left this place but regenerated itself with a new powerful updraft as seen in the next picture (on the right). Just a few brief tornadoes were reported during this day.

Fig. 57 : View of the thunderstorm and picture of a powerful updraft in our supercell

The fifth chase was not really a chase since we stayed in Norman. After watching a hockey-game with Brad and his friend Danny, we went out the house to take some pictures of lightning. Bases of clouds were very low because the dew point was very high (73°F). Moreover, we saw an impressive rising motion. We decided to see the storm in another point of view. At this moment, we saw an impressive wall cloud, but we were not sure by night. After that, I went back inside the house and I was really surprised since I saw on TV a tornado warning issued for our county. A mesocyclone was identified with a good circulation on the Doppler radar ! I didn't believe that... a tornado by night in Norman !? After that, thanks to my camera, I could take some good pictures and saw the wall cloud with the tornado on the ground. It was really impressive and really exciting.

Fig. 58 : Pictures of the tornado rated EF1 in Norman the 12th June 2009 (22h33)

We decided to take the car and go chase this tornado but it dissipated. However, this supercell produced some pretty lightning as seen as the next pictures (5 bolts in one picture) :

Fig 59 : Pictures of lightning

After this epic night, we decided to drive to see the damage from the tornado. In fact, we saw trees damage and discovered on different pictures other damages such as a fence blown down or roofs carried by the tornado.

Fig. 60 : Damages produced by the tornado and picture of a video for this tornado

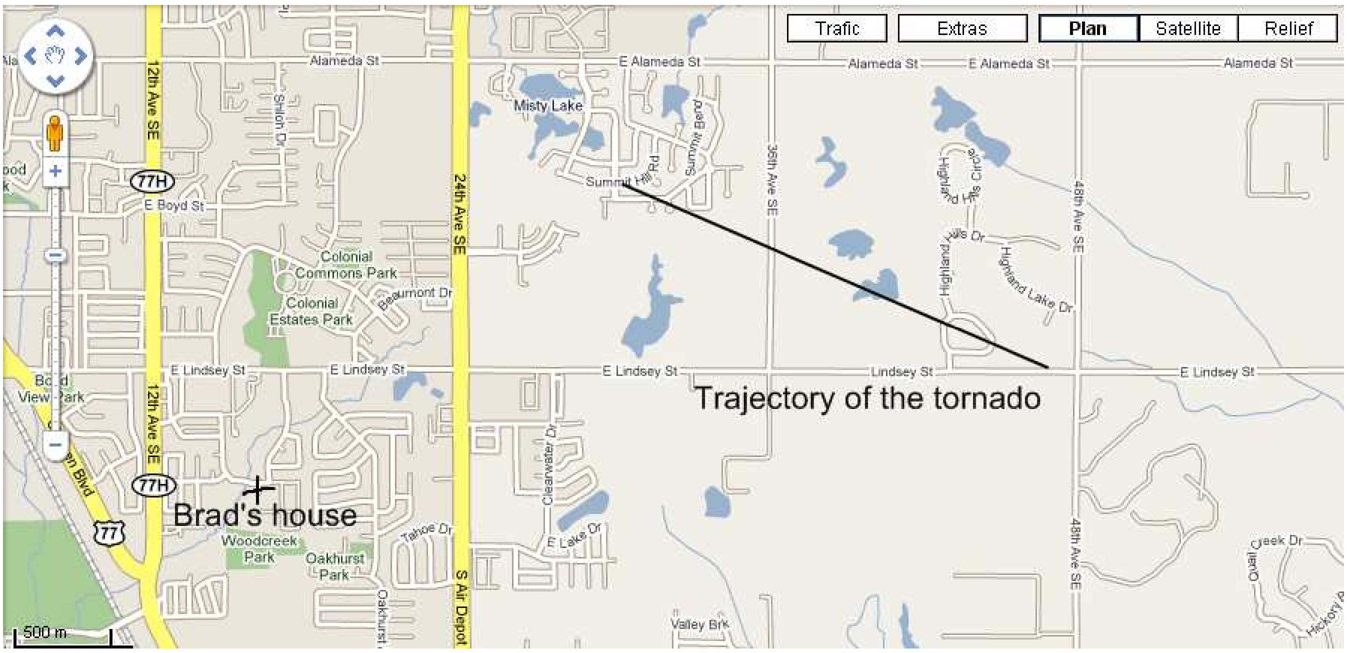


Fig 61. : Our location (Brad's house) and probable trajectory of the tornado

6. Advisories and Classification

First, Convective Outlooks are issued by the Storm Prediction Center (SPC) and cover only the USA. These maps allow to see risk of severe thunderstorms until 8 days. Moreover, we get 4 updates for day one and just one update for others days. SPS issue categorical chances of severe thunderstorm : general, slight, moderate, and high risk ***(Appendix M).*** Furthermore, they issue probabilities in percents for a kind of severe weather such as tornadoes***(Appendix N),*** large hail ***(Appendix O),*** and high winds ***(Appendix P).***

Now, I will talk about 2 main advisories connected to tornadoes : tornado watch and tornado warning.
A tornado watch is issued covering many counties, well before thunderstorms formation when conditions are favorable. This watch has a duration of a couple hours (4-8h) and is concerned with counties in and close to the area. Moreover, area size or duration of the watch will vary with the weather situation. ***(Appendix Q).***

On the other hand, tornado warnings are issued when a supercell is formed and has a hook echo and an evident mesocyclone. This is an sufficient criteria to alarm people since it's a main ingredient we can see before a tornado forms. TVS or "Tornado Vortex Signature" is still a very good element since it preceds (about 10min) the tornado touch down. A tornado warning can also be issued when storm chasers or local people are in the field and see a tornado. They are usually issued for a duration of around 30 minutes and sometimes can be issued without a tornado watch. ***(Appendix R)***

Finally, severe thunderstorm watch and warning are issued too, such as I explained previously. Moreover, another warning can be issued concerning flash flooding.

Tornadoes have been classified the first time by Ted Fujita. He created his own scale called " Fujita Scale" in 1971 to rate tornado intensity based on damages caused by tornadoes on infrastructures. This scale begins from F0 and ends at F5. We can see on ***Appendix S*** wind speed, relative frequency and potential according to a tornado such as F1, F2 or F5. Most of the time, F0 occur followed by F1, F2 and F3. F4 and F5 are very rare (only 0-1%) but produce the highest winds on the Earth (330-500 km/h) and the most severe damages.

ORIGINAL FUJITA SCALE		ENHANCED FUJITA SCALE	
F5	261-318 mph	EF5	+200 mph
F4	207-260 mph	EF4	166-200 mph
F3	158-206 mph	EF3	136-165 mph
F2	113-157 mph	EF2	111-135 mph
F1	73-112 mph	EF1	86-110 mph
F0	<73 mph	EF0	65-85 mph

Fig. 62 : Wind speed comparison between Fujita and Enhanced Fujita's scale (1mph = 1,6km/h)

Recently, the Fujita Scale was enhanced and was operational on February 2007. It takes into account building types and structure to give a more accurate depiction of tornadic strength. That's why this new scale is now used in the USA. We rated a tornado EF4 for example. ***(Appendix T)***

CONCLUSION

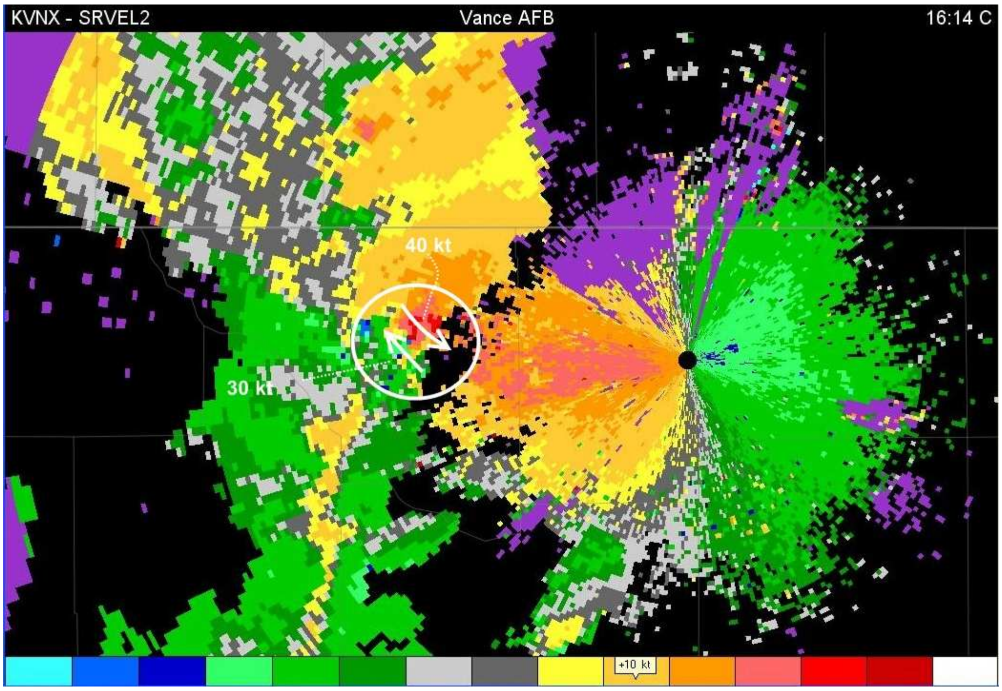
I think I had the best time ever in Oklahoma, more precisely at the National Weather Center. My goal was to understand the mechanism of supercells thus tornadoes and a lot of elements present in soundings. Moreover, my goal was to see and study a case of tornado with a description in real time. This goal was realized since I saw a tornado at night. Moreover, I learnt a lot of weather knowledge, especially concerning supercells and tornadoes. Furthermore, storm chases were really awesome and I had the opportunity to understand in real time structure of a supercell and take some great pictures of supercells, shelf cloud, or lightning.

My passion for meteorology has increased tremendously as a result of this internship. I wish pursue a career in this field once I am done with my studies. I would like to understand more about these phenomena and would like to be involved in a big project such as Vortex 2 to study cases of tornadic supercells and non-tornadic supercells.

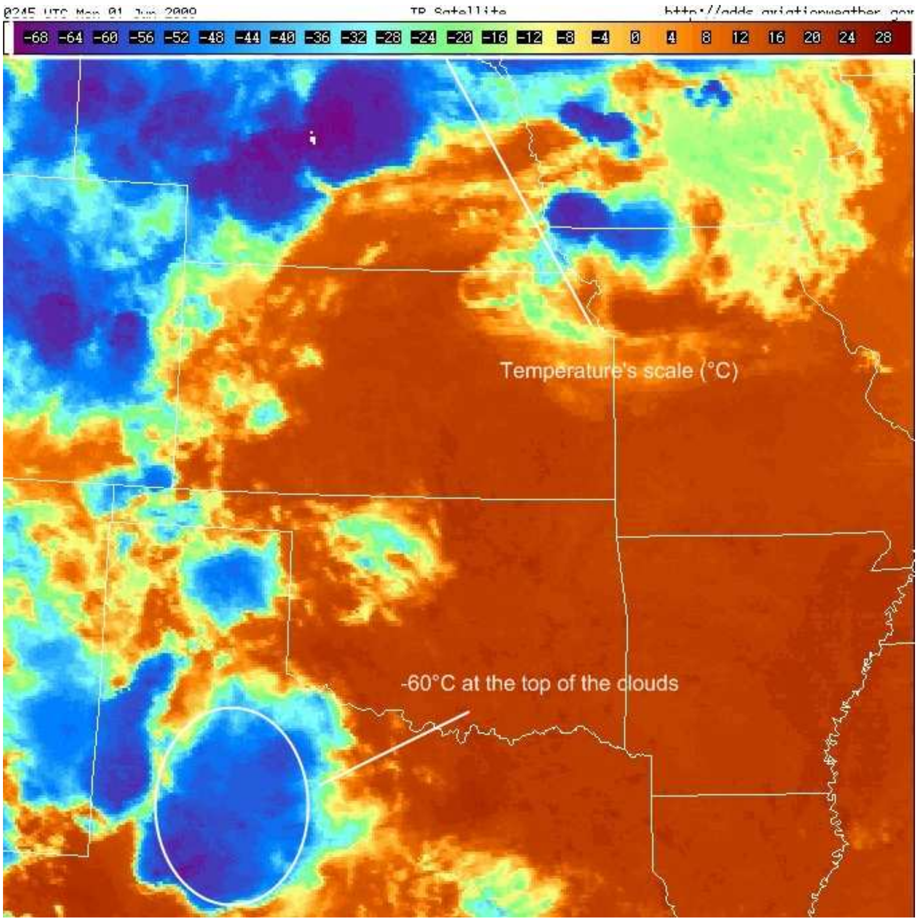
Finally, I loved the American life and my lodging at Traditions Square West. Indeed, the campus and its architecture are beautiful and people were very welcoming with me. I met a lot of people thanks to my roommate and discovered an other cultural and life mode.

APPENDIX

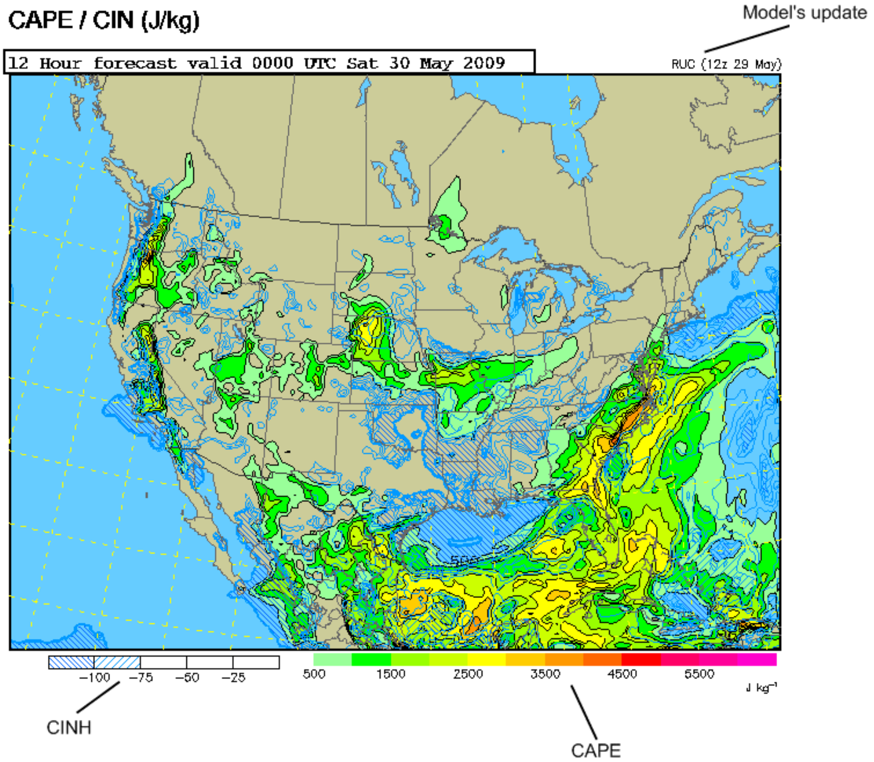
Appendix A : Mesocyclone viewed by Storm Relative Velocity Radar



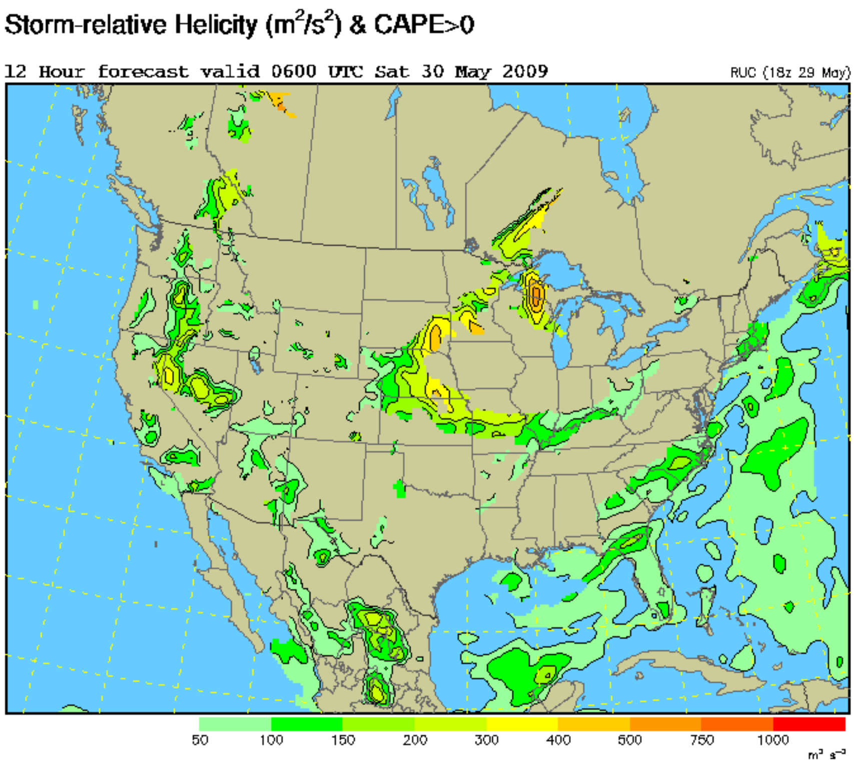
Appendix B : IR satellite picture



Appendix C : Example of CAPE and CINH forecast for the USA (RUC model)



Appendix D : Example of SRH forecast with the RUC model

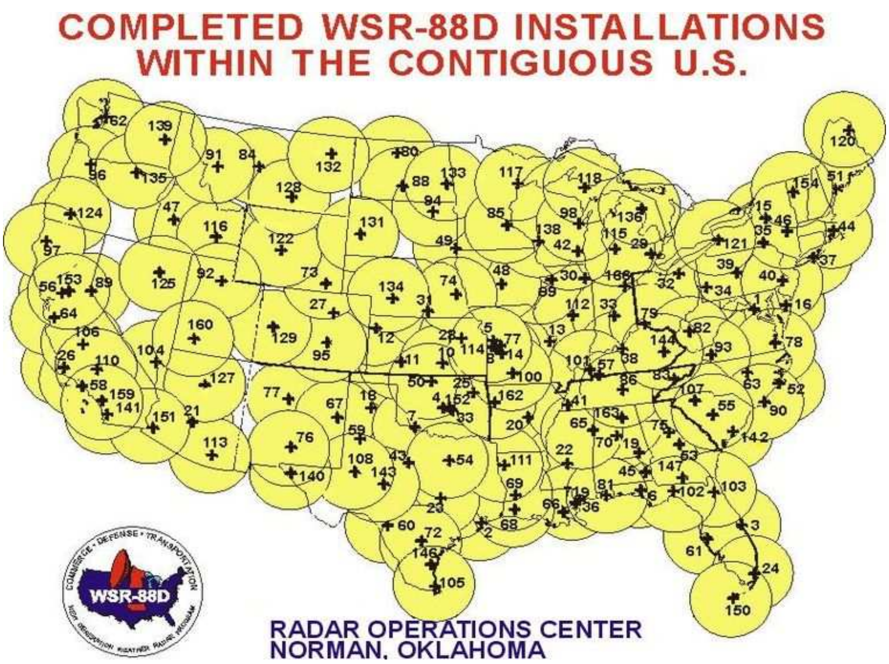


Appendix E : LP supercell with the strong rotating updraft shown by spiraled of clouds

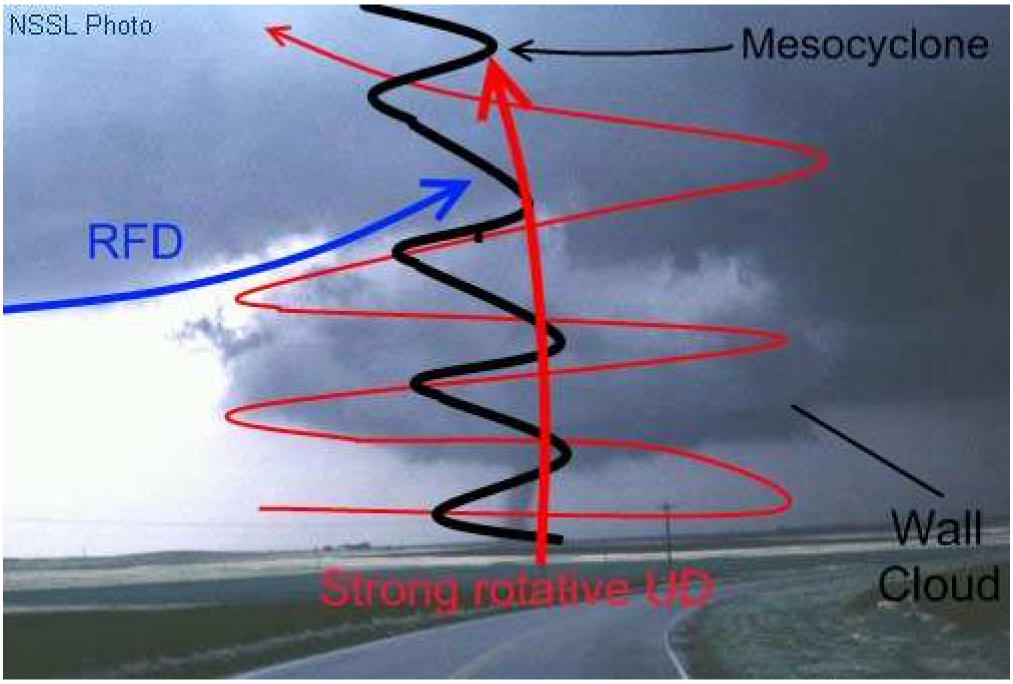
Appendix F : HP supercell with the shelf cloud gust front produced by the RFD

<u>Appendix G</u> : Classic supercell with a tornado on the ground

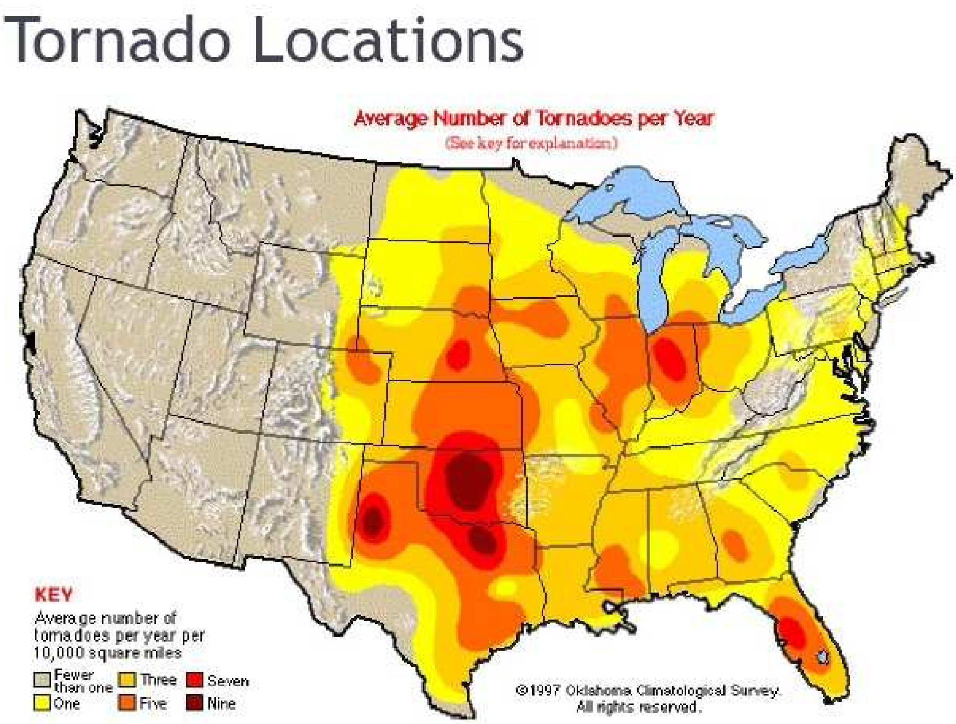
<u>Appendix H</u> : Nexrad network which consists of 160 WSR (Weather Surveillance radar)



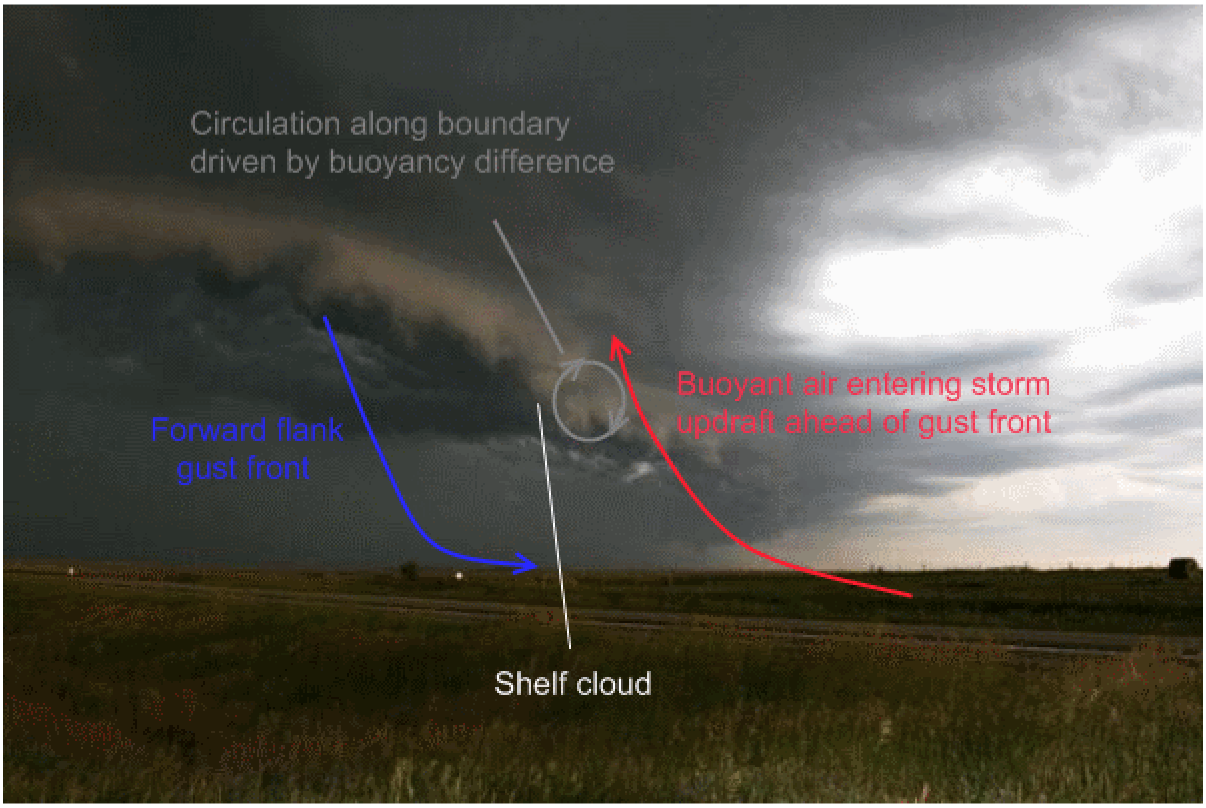
Appendix I : RFD or "Rear Flank Downdraft" (blue) with the wall cloud. We can identify location of the UD or "Updraft" (red) and the mesocyclone (black)



Appendix J : Average number of Tornadoes per year in the USA

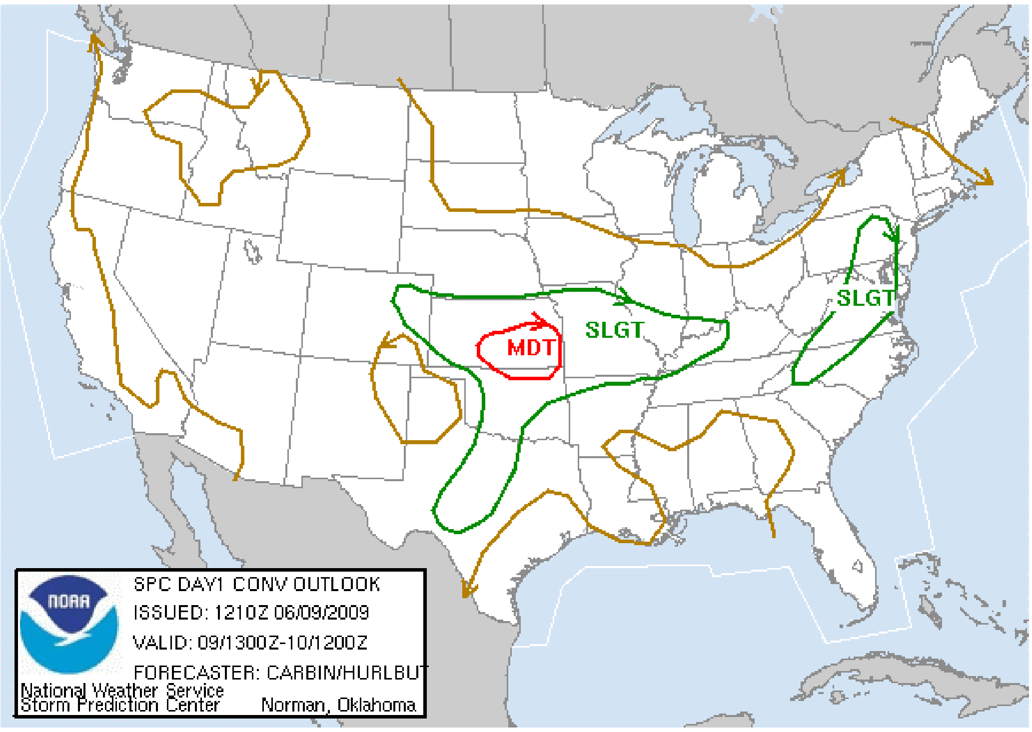


Appendix K : Explaination and mechanism of a shelf cloud which can produce a tornado (theory n°2)

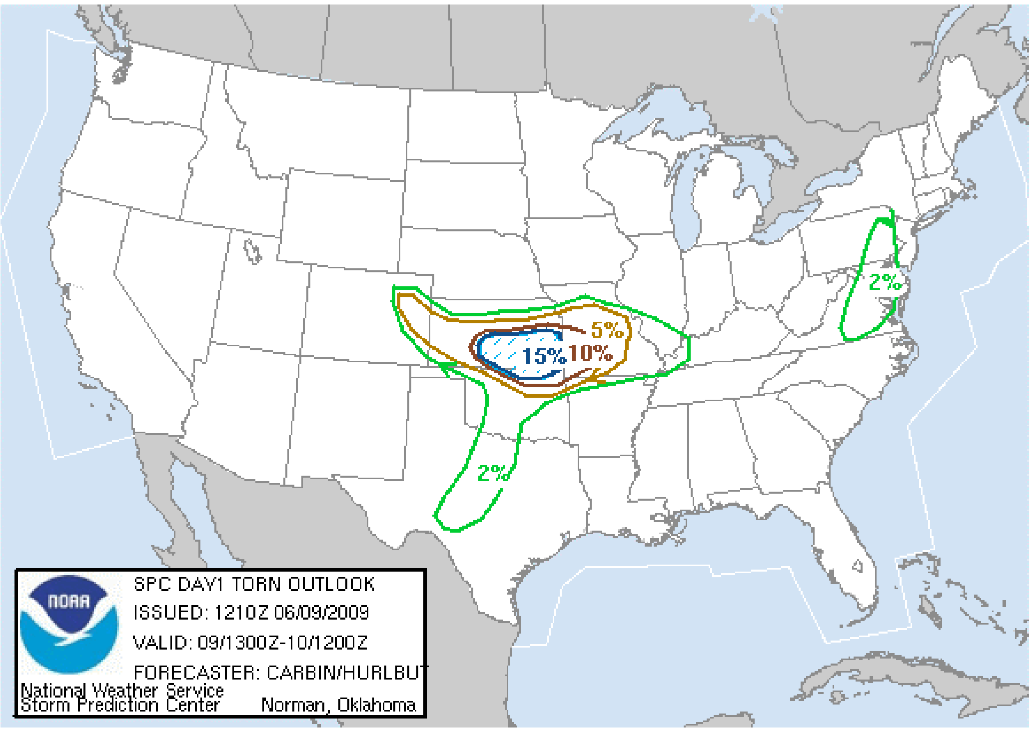


Appendix L : Wichita tornado in 2004 showing us a good example of a dynamic pipe effect

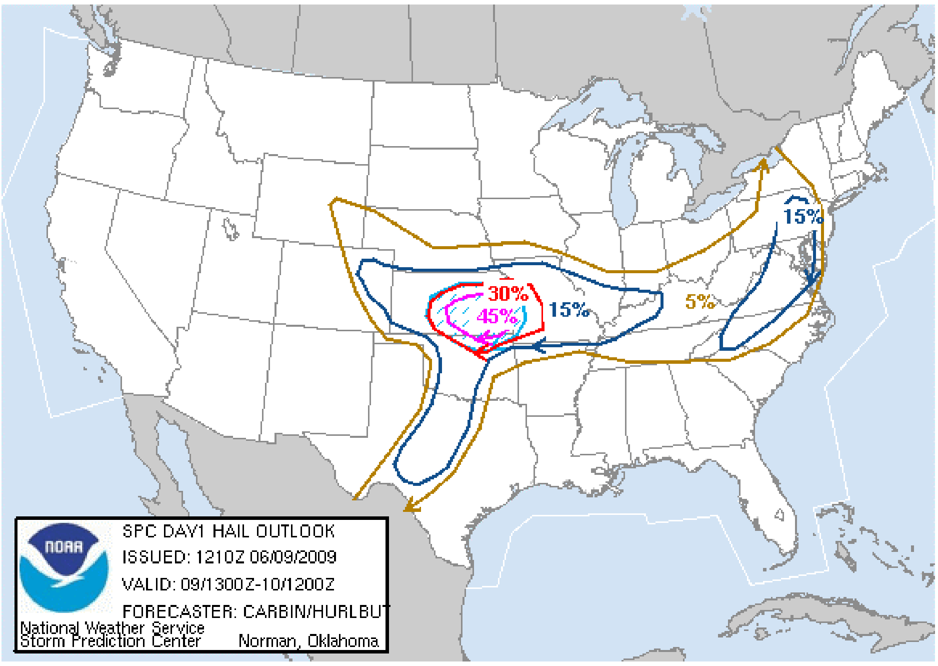
Appendix M : Example of Convective Outlook with a moderate risk bordering Kansas-Oklahoma



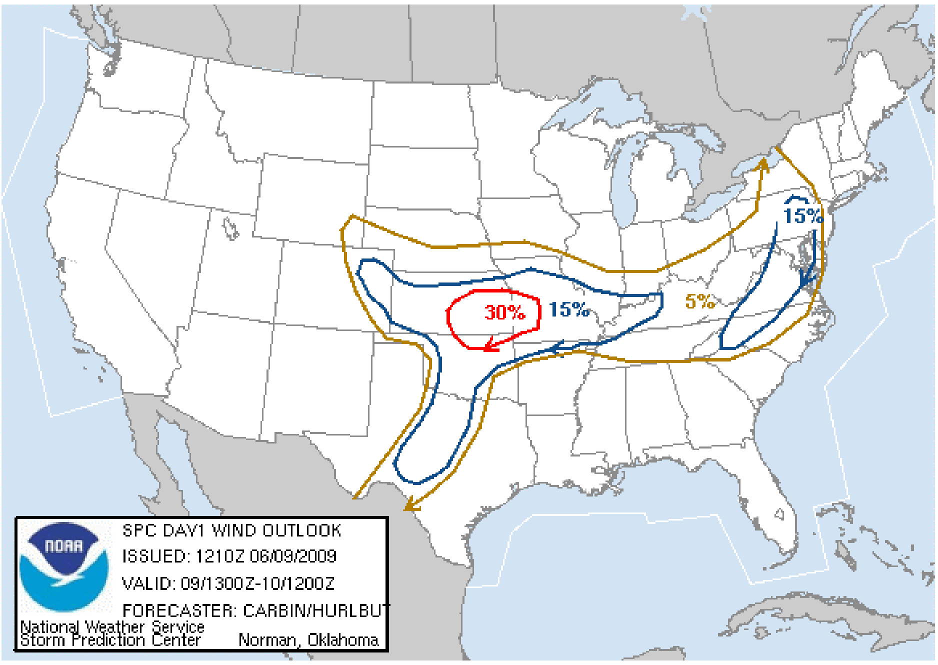
Appendix N : Probability of a tornado within 25miles of a point.
Hatched area means 10% or greater probability of EF2-EF5 tornadoes within 25 miles of a point.



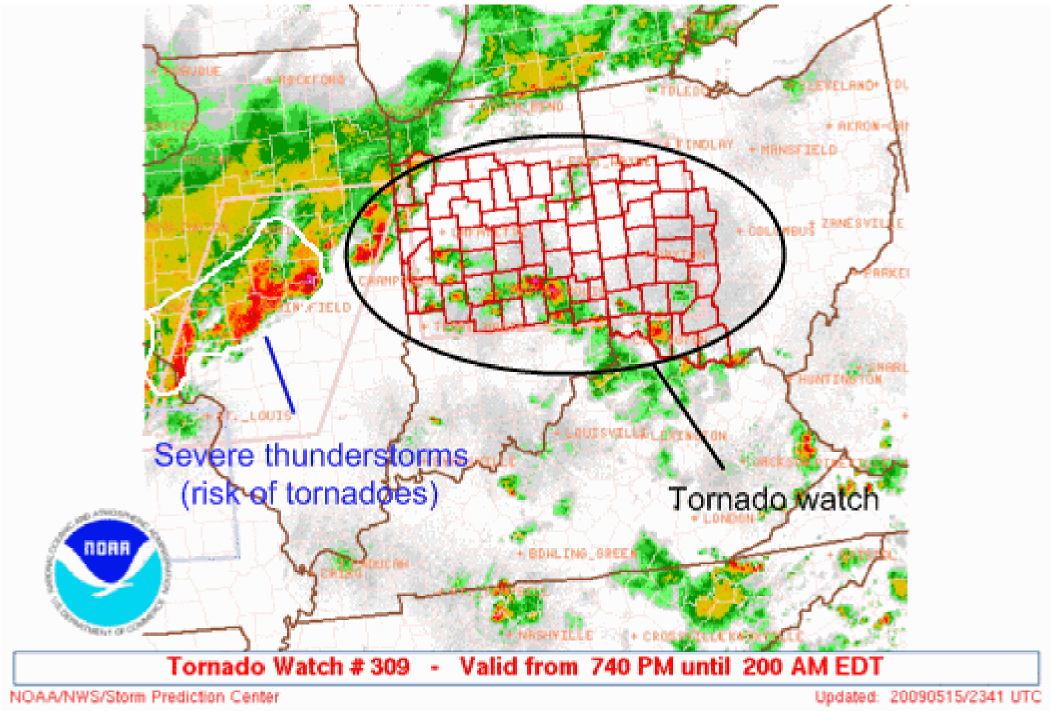
Appendix O : Probability of hail ¾" (= 2cm) or larger within 25miles of a point.
Hatched area means 10% or greater probability of hail 2" (= 5cm) or larger within 25 miles of a point.



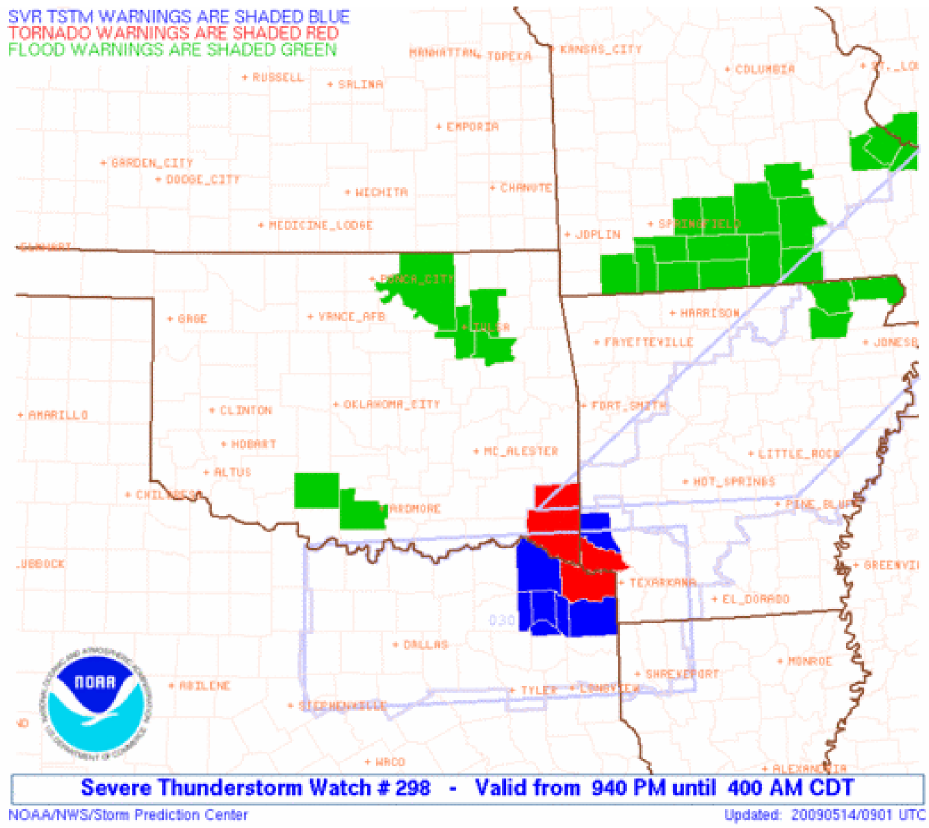
Appendix P : Probability of damaging winds or wind gusts of 50 knots or higher within 25 miles of a point. Hatched area means 10% or greater probability of wind gusts 65 knots or greater within 25 miles of a point.



Appendix Q : Tornado Watch surround counties (red) in prediction of severe thunderstorms which can support tornadoes.



Appendix R: Tornado warnings are shaded red in the the picture underneath. We can see others warnings such as flood warnings (green) and severe thunderstorms warnings (blue).



Appendix S : Fujita Scale in detail (wind speed, frequency, damages)

Scale	Estimated wind speed*		Relative frequency	Average Damage Path Width (meters)	Potential damage[3]	
	mph	km/h				
F0	40–72	64–116	38.9%	10 - 50	Light damage. Some damage to chimneys; branches broken off trees; shallow-rooted trees pushed over; sign boards damaged.	
F1	73–112	117–180	35.6%	30 - 150	Moderate damage. The lower limit is the beginning of hurricane wind speed; peels surface off roofs; mobile homes pushed off foundations or overturned; moving autos pushed off the roads; attached garages may be destroyed.	
F2	113–157	181–253	19.4%	110 - 250	Considerable damage. Roofs torn off frame houses; mobile homes demolished; boxcars overturned; large trees snapped or uprooted; light-object missiles generated.	
F3	158–206	254–332	4.9%	200 - 500	Severe damage. Roofs and some walls torn off well-constructed houses; trains overturned; most trees in forest uprooted; heavy cars lifted off the ground and thrown.	
F4	207–260	333–418	1.1%	400 - 900	Devastating damage. Well-constructed houses leveled; structures with weak foundations blown away some distance; cars thrown and large missiles generated.	
F5	261–318	419–512	Less than 0.1%	1100 ~	Total damage. Strong frame houses lifted off foundations and carried considerable distances to disintegrate; automobile sized missiles fly through the air in excess of 100 m (109 yd); trees debarked; steel reinforced concrete structures badly damaged; incredible phenomena will occur.	

<u>Appendix T</u> : Enhanced Fujita Scale in detail (wind speed, frequency, damages)

Scale	Wind speed		Relative frequency	Potential damage	
	mph	km/h			
EF0	65–85	105–137	53.5%	Light damage. Peels surface off some roofs; some damage to gutters or siding; branches broken off trees; shallow-rooted trees pushed over. Confirmed tornadoes with no reported damage (i.e. those that remain in open fields) are always rated EF0.	
EF1	86–110	138–178	31.6%	Moderate damage. Roofs severely stripped; mobile homes overturned or badly damaged; loss of exterior doors; windows and other glass broken.	
EF2	111–135	179–218	10.7%	Considerable damage. Roofs torn off well-constructed houses; foundations of frame homes shifted; mobile homes completely destroyed; large trees snapped or uprooted; light-object missiles generated; cars lifted off ground.	
EF3	136–165	219–266	3.4%	Severe damage. Entire stories of well-constructed houses destroyed; severe damage to large buildings such as shopping malls; trains overturned; trees debarked; heavy cars lifted off the ground and thrown; structures with weak foundations blown away some distance.	
EF4	166–200	267–322	0.7%	Devastating damage. Well-constructed houses and whole frame houses completely leveled; cars thrown and small missiles generated.	
EF5	>200	>322	<0.1%	Exploding damage. Strong frame houses leveled off foundations and swept away; automobile-sized missiles fly through the air in excess of 100 m (300 ft); steel reinforced concrete structure badly damaged; high-rise buildings have significant structural deformation; incredible phenomena will occur. So far there have been two EF5 tornadoes recorded since the Enhanced Fujita Scale was introduced on February 1, 2007. The most recent one occurred in Parkersburg, Iowa on May 25, 2008 and leveled half the city. *See Greensburg, Kansas tornado, Northeast Iowa supercell*