12.103 The Science and Policy of Natural Hazards

Module 3: Tornadoes

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What is a Tornado?

**Glossary Definition:** A violently rotating column of air, in contact with the ground, either pendant from a *cumuliform* cloud or underneath a *cumuliform* cloud, and often (but not always) visible as a *funnel cloud*. 
Tornadoes need not have funnel clouds

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Please see a similar image on:
http://www.newtonarc.net/weather/tornado2.jpg
TORNADO

- WORD DERIVED FROM SPANISH WORD ‘TORNADA’ – THUNDERSTORM

- TORNADOS ARISE FROM SEVERE THUNDERSTORMS

- MOST TORNADOS OCCUR IN THE CENTRAL US

- ON AVERAGE ABOUT 770 TORNADOS ARE REPORTED ANNUALLY IN THE US

- OCCUR ALL YEAR ROUND, BUT MAINLY FROM APRIL TO JUNE
TORNADO

• LESS THAN 1.6 KM WIDE, AND SHORT LIVED – A FEW SECONDS TO MORE THAN AN HOUR...MOST ~10 MINUTES

• TRAVELS AT ABOUT 45 KM PER HOUR AND AVERAGE PATH IS ABOUT 8 KM LONG

• PRESSURE AT CENTER OF VORTEX AS MUCH AS 10% LOWER THAN SURROUNDINGS.

• WIND SPEEDS AS LARGE AS 140 M/S (300 MPH) HAVE BEEN MEASURED
TORNADO MORPHOLOGY
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Please see a similar image on:
http://www.image.ucar.edu/GSP/Projects/KhareTornado.jpg
Mature Stage

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Please see a similar image on:
http://texastailchaser.com/chases/2008/20080523/IMG_6429.JPG
Rope Stage

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Please see a similar image on:
http://www.jondavies.net/photos/tornadoes/061204mulvanetor_rope2(c)_sml.jpg
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Please see a similar image on:
http://image02.webshots.com/2/9/25/63/161792563QBbYRd_ph.jpg
Orienta, Oklahoma, 2 May 1979

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Please see the similar images on:
http://2.bp.blogspot.com/_EnpquhPP5Hw/SordHJRIfnI/AAAAAAAAEkk/rPvKWNg3UoE/s400/bulacan+tornado+august+16+2009.jpg
http://upload.wikimedia.org/wikipedia/commons/d/d1/Binger_Oklahoma_Tornado.jpg
http://weatherpictureoftheday.files.wordpress.com/2008/08/07-11-01tornado.jpg
Tornado Damage

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Please see a similar image on:
http://upload.wikimedia.org/wikipedia/commons/a/a6/F3_tornado_damage_example.jpg
Ranking Tornado Strength: The Fujita Scale
<table>
<thead>
<tr>
<th>Category</th>
<th>Damage</th>
<th>Wind speed range</th>
</tr>
</thead>
<tbody>
<tr>
<td>F0</td>
<td>Light</td>
<td>Tree branches broken; heavy damage to crops; chimneys damaged.</td>
</tr>
<tr>
<td>F1</td>
<td>Moderate</td>
<td>Trees uprooted, some snapped; mobile homes overturned; moving cars pushed off road.</td>
</tr>
<tr>
<td>F2</td>
<td>Considerable</td>
<td>Large trees uprooted and snapped; mobile homes destroyed; roofs torn off houses; railroad boxcars pushed off track.</td>
</tr>
<tr>
<td>F3</td>
<td>Severe</td>
<td>Most trees in a forest uprooted or snapped; walls torn off well-constructed farm houses; trains overturned; autos lifted off ground and moved.</td>
</tr>
<tr>
<td>F4</td>
<td>Devastating</td>
<td>Trees debarked by flying debris; well-constructed frame houses leveled; autos thrown some distance.</td>
</tr>
<tr>
<td>F5</td>
<td>Incredible</td>
<td>Trees completely debarked; strong frame houses lifted off foundations and demolished over some distance; steel-reinforced concrete structures badly damaged; autos becomes missiles and fly distances of 100 meters.</td>
</tr>
</tbody>
</table>

Figure by MIT OpenCourseWare.
## Enhanced Fujita Scale

<table>
<thead>
<tr>
<th>F Number</th>
<th>Fas 1/4-mile (mph)</th>
<th>3 Second Gust (mph)</th>
<th>EF Number</th>
<th>EF Number</th>
<th>3 Second Gust (mph)</th>
<th>EF Number</th>
<th>3 Second Gust (mph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>40-72</td>
<td>45-78</td>
<td>0</td>
<td>0</td>
<td>65-85</td>
<td>0</td>
<td>65-85</td>
</tr>
<tr>
<td>1</td>
<td>73-112</td>
<td>79-117</td>
<td>1</td>
<td>1</td>
<td>86-109</td>
<td>1</td>
<td>86-110</td>
</tr>
<tr>
<td>2</td>
<td>113-157</td>
<td>118-161</td>
<td>2</td>
<td>2</td>
<td>110-137</td>
<td>2</td>
<td>111-135</td>
</tr>
<tr>
<td>3</td>
<td>158-207</td>
<td>162-209</td>
<td>3</td>
<td>3</td>
<td>138-167</td>
<td>3</td>
<td>136-165</td>
</tr>
<tr>
<td>4</td>
<td>208-260</td>
<td>210-261</td>
<td>4</td>
<td>4</td>
<td>168-199</td>
<td>4</td>
<td>166-200</td>
</tr>
<tr>
<td>5</td>
<td>261-318</td>
<td>262-317</td>
<td>5</td>
<td>5</td>
<td>200-234</td>
<td>5</td>
<td>Over 200</td>
</tr>
</tbody>
</table>
Here are broken tree branches and only superficial house damage; so this scene was rated F0. Elsewhere in the tornado path through Columbus GA, on 13 March 1997, there was isolated F1 damage.

Photo courtesy NWS Birmingham

Image courtesy of NOAA.
F1

This wood-frame house was pushed bodily off its concrete block foundation by the Spencer SD tornado of 30 May 1998 (a tornado which later did marginal F4 damage in the town of Spencer). Here, the house had no bottom anchoring at all. It was simply resting on its foundation by gravity alone; so it was easy for relatively weak winds near the edge of the tornado to slide the house aside with minor structural damage. It experienced partial roof removal, only on the windward (near) side; therefore, this damage site was rated F1.

Image courtesy of NOAA.
On 3 January 2000, a tornado struck this wood-frame home near Paris, MS. The roof and one large outer wall segment came off; while the remaining inner and outer walls were left (barely) standing. Quality of construction must be considered when rating damage; since the F scale is best applied to well-built homes. Here, the wall-to-roof and wall-to-wall attachments were very weak or nonexistent; so this is only marginal F2 damage.
F3

All but a few parts of the outer and inner walls were toppled or removed from this house in Moore, OK, on 3 May 1999. For a well-built home, any removal of inner walls constitutes F3 damage; so this site was rated high-end F3. The same tornado caused F5 damage in several locations elsewhere in its path.

Image courtesy of NOAA.
A tornado in Moore, OK on 3 May 1999 demolished this house (foreground) down to a short pile of debris on and around the foundation, with no walls standing. In order for this scene to be rated F5, the debris must have been swept away, leaving behind evidence that the house was well-attached to its slab. [The brick house in the left background suffered F3 damage, with a mixture of inner and outer walls removed.] This tornado caused an immense amount of F4 damage on its path through the southern portion of the Oklahoma City metropolitan area, and several locales of F5 damage.
This is classic F5 damage. The Bridge Creek/Moore, Oklahoma, tornado of 3 May 1999 leveled this house, swept the foundation almost completely clean, shredded the house remains into small pieces and scattered the debris downwind to the northeast (rear). The house was relatively well-constructed with slab-to-wall anchor bolts evenly spaced around the bottom plate. Some of those bolts can be seen in this photo, protruding upward from just inside the edges of the concrete slab.

Image courtesy of NOAA.
Greensburg, Kansas, 2007

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Please see a similar image on:
http://www.drjudywood.com/articles/erin/spics/tornado-760291.jpg
Tornado Climatology
Global Distribution

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Please see the image on:
http://www.windows2universe.org/earth/images/tornado_agri_map.jpg
Number of days per year with tornadoes reported

Tornado Days Per Year (1980–1999)

Image courtesy of NOAA.
Number of Significant (>= F2) Tornadoes per Century

Significant (F2 or greater) Tornado Days Per Century (1921–1995)

Image courtesy of NOAA.
Number of Violent (>= F4) Tornadoes per Millenium

Violent (F4 or greater) Tornado Days Per Millenium (1921–1995)
U.S. Tornado Tracks

SPC Storm Reports for 08/18/05
Map updated at 1804Z on 08/19/05

Image courtesy of NOAA.
Seasonality

U.S. Tornadoes by Month 2003-2005

- May: Highest number of tornadoes
- April and June: Significant numbers of tornadoes
- Lowest numbers in January, February, and December
Diurnal Variation

# of Tornadoes (168 Total)
Trends in U.S. Tornadoes
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Please see the images on:
http://www.tornadoproject.com/graphics/pie1rb.gif
http://www.tornadoproject.com/graphics/pie2rb.gif
Tornado Physics
Fundamentals of Convection

- Buoyancy
- Moist thermodynamics
- Stability
- Meta-stability
- Effects of precipitation
- Non-equilibrium convection
When is a fluid unstable to convection?

- Pressure and hydrostatic equilibrium
- Buoyancy
- Stability
Buoyancy

\[ B = g \frac{\rho_e - \rho}{\rho_p} \]
Hydrostatic equilibrium:

Weight: \(-g \rho \delta x \delta y \delta z\)

Pressure: \(p \delta x \delta y - (p + \delta p) \delta x \delta y\)

\[ F = MA: \quad \rho \delta x \delta y \delta z \frac{dw}{dt} = -g \rho \delta x \delta y \delta z - \delta p \delta x \delta y \]

\[ \frac{dw}{dt} = -g - \alpha \frac{\partial p}{\partial z}, \quad \alpha = \frac{1}{\rho} = \text{specific volume} \]
Pressure distribution in atmosphere at rest:

Ideal gas: \[ \alpha = \frac{RT}{p}, \quad R \equiv \frac{R^*}{m} \]

Hydrostatic: \[ \frac{1}{p} \frac{\partial p}{\partial z} = -\frac{g}{RT} \]

Isothermal case: \[ p = p_0 e^{-z/H}, \quad H \equiv \frac{RT}{g} = \text{"scale height"} \]

Earth: \( H \sim 8 \text{ Km} \)
Buoyancy:

**Weight:** \(- g \rho_b \delta x \delta y \delta z\)

**Pressure:** \(p \delta x \delta y - (p + \delta p) \delta x \delta y\)

\[ F = MA : \quad \rho_b \delta x \delta y \delta z \frac{dw}{dt} = -g \rho_b \delta x \delta y \delta z - \delta p \delta x \delta y \]

\[ \frac{dw}{dt} = -g - \alpha_b \frac{\partial p}{\partial z} \quad \text{but} \quad \frac{\partial p}{\partial z} = - \frac{g}{\alpha_e} \]

\[ \rightarrow \quad \frac{dw}{dt} = g \frac{\alpha_b - \alpha_e}{\alpha_e} \equiv B \]
Buoyancy and Entropy

Specific Volume: $\alpha = \frac{1}{\rho}$

Specific Entropy: $s$

$$\alpha = \alpha(p, s)$$

$$\left(\delta\alpha\right)_p = \left(\frac{\partial \alpha}{\partial s}\right)_p \delta s = \left(\frac{\partial T}{\partial p}\right)_s \delta s$$

$$B = g \left(\frac{\delta\alpha}{\alpha}\right)_p = \frac{g}{\alpha} \left(\frac{\partial T}{\partial p}\right)_s \delta s = -\left(\frac{\partial T}{\partial z}\right)_s \delta s \equiv \Gamma \delta s$$
Note: For ideal gas:
\[ \Gamma = \frac{g}{c_p} \]

Earth’s atmosphere:
\[ \Gamma = \frac{1K}{100 m} \]
Model Aircraft Measurements
(Renno and Williams, 1995)