Some heavy precipitation issues

AOS C115/C228
Fall 2014
Heavy precipitation at a location
= intensity x longevity
Common sources of heavy precipitation in U.S.

- Mesoscale convective systems and vortices
- Orographically induced, trapped or influenced storms
- Landfalling tropical cyclones
Mesoscale Convective Systems (MCSs)
MCSs & precipitation facts

- MCSs = squall-lines and supercells
- Large % of warm season rainfall and flash floods (Maddox et al. 1979; Doswell et al. 1996; Schumacher and Johnson 2005)
- Often not well forecasted by models (Davis et al. 2003; Bukovsky et al. 2006; Anderson et al. 2007)
- Supercells often produce *intense* but not *heavy* rainfall
  - Form in highly sheared environments
  - Tend to move quickly, not stay in one place
U.S. flash flood seasonality

Contribution of warm season MCSs clearly seen

Precipitable water higher in warm season

Maddox et al. (1979)
A common MCS: trailing stratiform squall-line

- Cellular leading convective line: unsteady, multicellular (e.g., Browning et al. 1976; Fovell and Tan 1998)
- Trailing region of lighter stratiform precipitation (e.g., Houze 1977; Smull and Houze 1985)
- Accounts for nearly 60% of line-oriented MCSs (Parker and Johnson 2000)

Parker and Johnson (2000)
Squall-lines usually multicellular
Storm motion matters

How a storm moves over a specific location determines rainfall received

Doswell et al. (1996)
Forecasting MCS motion

(or lack of motion…)

19980714 - North Plains
“Rules of thumb”

“Why?”

“Right for the right reason?”
Some common ingredients

- CAPE (Convective Available Potential Energy)
- CIN (Convective Inhibition)
- Precipitable water
- Vertical shear - magnitude and direction
- Low-level jet (LLJ)
- Midlevel cyclonic circulations (potential vorticity anomalies)
Some common “rules of thumb”

- MCSs tend to move towards the most unstable air
- MCSs “back-build” towards higher CIN
- 1000-500 mb layer mean RH ≥ 70%
- Convective cells “go with the flow”
- Convective systems follow 1000-500 mb thickness contours
- MCSs favored where thickness contours diverge
- Development favored downshear of midlevel cyclonic circulations
Back-building towards higher CIN

Lifting takes longer where there is more resistance
70% RH rule of thumb

Implication: Relative humidity more skillful than absolute humidity and necessary but not sufficient

# = precip. category

Junker et al. (1999)
Cells “go with the flow”

- Agrees with previous observations (e.g., Fankhauser 1964) and theory (classic studies of Kuo and Asai)

*Winds around MCS genesis used. Later some deviation to the right often appears.

Cells tend to move at speed and direction of 850-300 mb mass-weighted wind*

Corfidi et al. (1996)
MCSs tend to follow thickness contours

Implication: *vertical shear* determines MCS orientation and motion. Thickness divergence likely implies rising motion.
Composite severe MCS hodograph

Selective composite already excludes non-severe, non-TS squalls

Heights marked are km MSL

Bluestein and Jain (1985)
Composite severe MCS hodograph

Cells move at 850-300 mb wind direction at about 85% its speed

Consistent with Corfidi et al (1996) findings.
Composite severe MCS hodograph

System moves in direction of low-level shear vector
14 July 1998 - North Plains

Low-level shear vector shown
14 July 1998 - North Plains
The South Plains nocturnal low-level jet (LLJ)
Recall severe squall-line composite...

- Composite dominated by nocturnal cases
- LLJ appears as local wind max ~ 0.8 km above ground level (AGL)

Bluestein and Jain (1985)
South Plains LLJ

- Enhanced southerly flow over South Plains
- Most pronounced at night
- Responsible for moisture advection from Gulf & likely a major player in nocturnal thunderstorms and severe weather
LLJ occurrences meeting certain criteria
- most frequent in Oklahoma
- most frequent at night

Bonner (1968)
Explanations for LLJ

• Oscillation of boundary layer friction (mixing) responding to diurnal heating variation
  – Think Ekman spiral
• Vertical shear responding to diurnally varying west-east temperature gradients owing to sloped topography
• Cold air drainage down the Rockies at night
• Topographic blocking of some form
Observations of wind speed vs. height for days in which nocturnal LLJ appeared at Ft. Worth, TX

- Wind speed max about 800 m AGL at midnight and 6 AM local time

- Note increased low-level shear

Bonner (1968)
Observations of Ft. Worth wind at height of wind max.

- wind weaker, more southerly during afternoon

- nighttime wind stronger, more from southwest, elevation lower

- winds execute circular path over a day

Bonner (1968)
Mesoscale Convective Vortices (MCVs)
MCVs

• Can form behind MCSs like squall lines (Bartles and Maddox 1991)

• Can survive long after the squall line has decayed

• Can initiate new convection at another time & place

• Can cause very heavy precipitation (e.g., Bosart and Sanders 1981; Fritsch et al. 1994; Trier and Davis 2002)

Houze (2004)
8 May 2009
Episodes of MCSs & predictability

Hovmoller diagrams reveal westward-propagating MCSs

Note “envelope” of several systems with “connections”

Time increases downward

Carbone et al. (2002)
MCV role in predictability

Squall line #1
moves quickly
dies around 95°W

MCV
formed behind squall #1
drifts slowly w/ winds

Squall line #2
sparked by MCV
a day later!
moves quickly
MCV recipe

- Cyclonic circulations develop beneath diabatic heating
- Ascent and destabilization on windward side
- Ascent and destabilization on downshear side
- Windward and downshear sides can sometimes coincide
Vorticity

- **Vorticity** = circulation per area

\[ \zeta = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \]

- **Vertical vorticity** = curl of horizontal wind field

\[ \zeta_g = \frac{\partial v_g}{\partial x} - \frac{\partial u_g}{\partial y} \]

- **Geostrophic vertical vorticity** uses geostrophic winds

- **Absolute vorticity** = \( \zeta + f \)
One way to increase vorticity

... is to **squeeze** the circulation into a **smaller area**

\[
\frac{\partial \zeta_g}{\partial t} \propto -f \left( \nabla \cdot \vec{V} \right)
\]

...if convergence, 
\( \zeta_g \) increases with time
Potential vorticity

- Potential temperature (usually) increases with height
- Take a cylinder of air between two isentropes

- It has absolute vorticity = $\zeta + f$
- Stretch it vertically… what happens to its spin ($\zeta$)?

Fig. 4.7 A cylindrical column of air moving adiabatically, conserving potential vorticity.
Potential vorticity

• It’s relative vorticity (spin) increases but its potential vorticity (PV) does not.

• In this case, stretching causes $\partial \theta / \partial z$ decrease so $\zeta$ increases (f did not change)

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Fig. 4.7  A cylindrical column of air moving adiabatically, conserving potential vorticity.
PV tendency

\[ PV \propto (\zeta + f) \frac{\partial \theta}{\partial z} \]

\[ \frac{dPV}{dt} \propto (\zeta + f) \frac{\partial Q}{\partial z} \]

(least relevant term)

- \( Q = d\theta/dt = \) heating rate
- **We can change PV by heating or cooling**
- … *if the heating varies spatially* (here, with height)
Initial geopotential field
Midtropospheric diabatic heating

How does this affect thicknesses?

\[ Q = \frac{d\theta}{dt} \]
Effect on geopotential

Think hypsometric or QG geopotential height equations
Effect on geopotential

How does this affect low-level flow?
Effect on flow

Lowered heights beneath heating; convergence
Effect on vorticity

\[ \frac{\partial \zeta_g}{\partial t} \propto -f \left( \nabla \cdot \vec{V} \right) \]

Convergence => cyclonic spin-up
Effect on potential vorticity

Positive $Q$ gradient => cyclonic spin-up

$Q = \text{diabatic heating}$

$$\frac{\partial PV}{\partial t} \propto (\zeta + f) \frac{\partial Q}{\partial z}$$
Effect on potential vorticity

Cyclonic circulations spin up beneath heat sources... MCV

PV = potential vorticity

anticyclonic
cyclonic

Cyclonic circulations spin up beneath heat sources... MCV
Focus on +PV beneath diabatic heating…
We are looking North
MCV drifting with mean wind in westerly sheared flow

*Flow shown is relative to the MCV*
Adiabatic ascent induced beneath MCV lifts isentrope

Raymond and Jiang (1990)
Ascent occurs on windward (here, east) side beneath vortex… destabilization
Westerly vertical shear implies isentropes tilt upwards towards north (thermal wind equation)

Raymond and Jiang (1990)
Thus, cyclonic circulation *itself* results in ascent on east (downshear) side

Raymond and Jiang (1990)
MCV

Combination: uplift & destabilization on windward side AND downshear side

Raymond and Jiang (1990)
MCV and heavy precipitation

- Based on 6 cases poorly forecasted by models
- Composite at time of heaviest rain ($t = 0h$)
- Heaviest rain south of MCV in 600 mb trough in early morning

600 mb vorticity (color), heights and winds.  Map for scale only
S-J (2009) situation

Midlevel MCV

See also
Fritsch et al. (1994)

Schumacher and Johnson (2009)
S-J (2009) situation

Nocturnally-enhanced low-level jet transports high $\theta_e$ air; MCV’s windward side is to south

Schumacher and Johnson (2009)
“Hairpin” hodograph:
Downshear side (across vortex) is to south
S-J (2009) situation

South side of MCV is windward at low-levels and downshear relative to midlevel vortex

Schumacher and Johnson (2009)
S-J (2009) situation

Tends to result in very slow-moving, “back-building” convection south of MCV

Schumacher and Johnson (2009)
Back-building

Ground-relative system speed $\sim 0$

Schumacher and Johnson (2005)
Doswell et al. (1996)
2013 Colorado flooding

“the perfect deluge?”
82% of average annual precipitation in just 5 days
46% in just ONE day
Recipe for the deluge

- Slow moving upper air low over Southwest
- Strong northward moisture flux
- Record high precipitable water
- Frontal and orographic lifting
- 850 mb low-level jet
- Embedded mesoscale phenomena?
12Z 11 Sept 2013
500 mb

Rainfall maximum
Water vapor imagery

dry

moist
http://www.esrl.noaa.gov/psd/boulder/flood2013/dayplots/

Precipitable water anomaly

Columnar Precipitable Water kg/m^2 Composite Anomaly (1981–2010 Climatology)
9/12/13
NCEP/NCAR Reanalysis
1948–2012 DNR/DEN/LRY Surface–300-mb Precipitable Water

MAX

99th%

MEDIAN

00Z 11 Sept 2013
36.5 mm (1.44")
00Z 12 Sept 2013

surface
High Resolution Rapid Refresh model analysis

850 mb wind speed and vectors

00Z 12 Sept. 2013
700 mb moisture streamed northward from tropics
Precipitable water especially high just east of Colorado
850 mb winds directed generally upslope
1000+ year rain event for marked location
[end]

(extra material follows)
2-3 April 2006
2-3 April 2006
Why did new cells appear ahead of the mature line?

Effectively “speeds up” (earlier rain) & “slows down” (prolongs rain)
New cell initiation ahead of squall-lines

Unsteady multicellularity excites internal gravity waves

Fovell et al. (2006)
New cell initiation ahead of squall-lines

One possible trapping mechanism: the storm anvil

Fovell et al. (2006)
Trapping mechanism

• Trapping can occur when a layer of lower $l^2$ resides over a layer with higher values
• More general Scorer parameter ($c = \text{wave speed}$)

\[
l^2 = \left[ \frac{N^2}{(\bar{u} - c)^2} - \frac{\bar{u}_{zz}}{(\bar{u} - c)} \right]
\]

• Lowered $l^2$ can result from decreased stability or creation of a jet-like wind profile
  – Storm anvil does both
New cell initiation ahead of squall-lines

The waves themselves disturb the storm inflow

Fovell et al. (2006)
New cell initiation ahead of squall-lines

...and can create clouds

Fovell et al. (2006)
New cell initiation ahead of squall-lines

...some of which can develop into precipitating, even deep, convection

Fovell et al. (2006)
New cell initiation ahead of squall-lines

Other plausible mechanisms for new cell initiation exist

Fovell et al. (2006)
New cell initiation ahead of squall lines

Fovell et al. (2006)
New cell initiation ahead of squall-lines

Fovell et al. (2006)