Strong Winds in Extratropical Cyclones

David M. Schultz
University of Manchester

Thanks to
Joseph Sienkiewicz,
Tim Slater, and Geraint Vaughan
“The pressure gradient is especially tight to the west of the storm center and approaches 1 mb (5 km)$^{-1}$.”
“The pressure gradient is especially tight to the west of the storm center and approaches 1 mb (5 km)$^{-1}$.”
Evolution of an Extratropical Cyclone

Bosart (1981)
“Weather conditions are somewhat less than ideal for ocean cruising.”
evolution of surface airstreams and fronts

Clark et al. (2005)
cold conveyor belt jet

evolution of surface airstreams and fronts

Clark et al. (2005)
evolution of surface airstreams and fronts

Clark et al. (2005)
Clark et al. (2005)
cold conveyor belt jet
sting jet
Death From Above
~ 650 mb
evolution of surface airstreams and fronts
cold conveyor belt jet

sting jet

warm conveyor belt jet

evolution of surface airstreams and fronts

Clark et al. (2005)
Clark et al. (2005)  

- cold conveyor belt jet  
- sting jet  

(a) cold conveyor belt jet wraps around the cyclone  
(b) warm conveyor belt jet  

Coincidence between front and sting jet?  

Cause of descent?  

Cause of the accelerations?
What causes the descent?
75 knots (39 m/s)
925-mb theta
wind speed
frontogenesis (shaded)
cross section through frontogenesis maximum
cross section through frontolysis maximum and sting jet
What causes the acceleration?
The momentum equation tells us how high winds develop.

\[
\frac{\partial u_h}{\partial t} = -(u_h \cdot \nabla_h) u_h - \omega \frac{\partial u_h}{\partial z} - f k \times u_h - \frac{1}{\rho} \nabla_h p + F_{PBL}
\]
The momentum equation tells us how high winds develop.

\[
\frac{\partial u_h}{\partial t} = - \left( u_h \cdot \nabla_h \right) u_h - \frac{\partial u_h}{\partial z} - f k \times u_h - \frac{1}{\rho} \nabla_h p + F^{PBL}
\]

just moves momentum around:
can’t explain acceleration
The momentum equation tells us how high winds develop.

\[
\frac{\partial u_h}{\partial t} = -(u_h \cdot \nabla_h) u_h - \omega \frac{\partial u_h}{\partial z} - f k \times u_h - \frac{1}{\rho} \nabla_h p + F_{PBL}
\]

acts perpendicular to winds:
can’t explain acceleration
The momentum equation tells us how high winds develop.

\[
\frac{\partial u_h}{\partial t} = -(u_h \cdot \nabla_h) u_h - w \frac{\partial u_h}{\partial z} - \frac{f k \times u_h}{\rho} - \frac{1}{\rho} \nabla_h p + F_{PBL}
\]

slows wind down: can’t explain acceleration
The momentum equation tells us how high winds develop.

\[
\frac{\partial u_h}{\partial t} = - (u_h \cdot \nabla_h) u_h - w \frac{\partial u_h}{\partial z} - f k \times u - \frac{1}{\rho} \nabla_h p + F_{\text{PBL}}
\]
Slater et al. (2014) idealized baroclinic wave
Slater et al. (2014)
Acceleration by PGF

Deceleration

Acceleration
Acceleration by vertical advection

Acceleration

Deceleration

(c) 1800 UTC 7 DEC 2005 850 mb Wind Speed, Theta, VADV
generation of kinetic energy by cross-contour flow

(also shown by Whitaker et al. 1988)

Bosart and Lin (1984)
generation of kinetic energy by cross-contour flow

(also shown by Whitaker et al. 1988)

Petterssen frontogenesis (observed wind)

° C (100 km 3 h)^{-1}

Bosart and Lin (1984)
Frontolysis causes descent of the sting jet.

- End of bent-back front
- Lasts for a finite time just before maturity of cyclone
Strong winds in cyclones: Re-learning and Learning

Frontolysis causes descent of the sting jet.
- End of bent-back front
- Lasts for a finite time just before maturity of cyclone

Cold conveyor belt jet accelerated by strong pressure-gradient force in direction of motion.
Strong winds in cyclones: Re-learning and Learning

Frontolysis causes descent of the sting jet.
• End of bent-back front
• Lasts for a finite time just before maturity of cyclone

Cold conveyor belt jet accelerated by strong pressure-gradient force in direction of motion.

Southwest wind maximum accelerated by both:
• Pressure-gradient force
• Downward advection of momentum.
Strong winds in cyclones: Re-learning and Learning

Frontolysis causes descent of the sting jet.
• End of bent-back front
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Cold conveyor belt jet accelerated by strong pressure-gradient force in direction of motion.

Southwest wind maximum accelerated by both:
• Pressure-gradient force
• Downward advection of momentum.

Complicates the definition of “sting jet”
Revisiting strong winds in cyclones

Frontolysis causes descent of the sting jet.
• End of bent-back front
• Lasts for a finite time just before maturity of cyclone

Single wind-speed maximum could derive from two different mechanisms.
• Acceleration due to pressure-gradient force
• Downward advection of momentum


Neiman and Shapiro (1993)
18 UTC 4 January 1989
“The SLP gradient continued to increase west of the storm center, with the strongest gradient rotating cyclonically around into the cyclone’s southern quadrant. There, near-surface wind speeds approached 45 m s⁻¹.” – Neiman and Shapiro (1993)
Bosart and Lin (1984) 12 UTC 19 Feb

- $\nabla \cdot \nabla \Phi$

- $-\omega' \alpha'$

Generation of kinetic energy by cross-contour flow

Conversion of eddy available potential energy to eddy kinetic energy
Clark et al. (2005)

Dynamics of strong winds in cyclones

Relationship between front and sting jet?

Descending sting jet distinct from cold-conveyor belt?

evolution of surface airstreams and fronts

Clark et al. (2005)
Schultz and Sienkiewicz
Storm
Sea-level pressure
925-mb theta
wind speed (shaded)
700-mb relative humidity (shaded)
925-mb theta
925-mb wind speed
low stability

900

950

high stability

925-mb Theta, Wind Speed, Static Stability
strong heat flux
Top: sea-level pressure, 925-mb theta, wind speed (shaded)

12 UTC 7 Dec
18 UTC 7 Dec
00 UTC 8 Dec

Bottom: 925-mb theta, wind speed, frontogenesis (shaded)
COMPARISON
Mysteries remain…

Eastern US storm Nemo: 925-mb wind

12 UTC 7 Dec 2005 Sea-Level Pressure, 925 mb Theta and W

18 UTC 7 Dec 2005 Sea-Level Pressure, 925 mb Theta and W

1800 UTC 11 FEB 2008 Sea-Level Pressure, 925 mb Theta and W

0000 UTC 12 FEB 2008 Sea-Level Pressure, 925 mb Theta and W
Mysteries remain…

Eastern US storm Nemo: 925-mb wind 6 h later

1200 UTC 9 Feb 2013
NEMO STORM
925-mb Geostrophic Wind Speed (m s$^{-1}$)

UTC Times:
- 00 UTC
- 20 UTC
- 23 UTC
- 06 UTC
Frontogenesis (shaded), Theta, Wind Speed
trajectories

Init: 00 UTC Fri 08 Feb 13
Valid: 06 UTC Sat 09 Feb 13 (01 EST Sat 09 Feb 13)
Fct: 30 h

Sea Level Pressure (hPa)
925-hPa Trajectory
trajectories
Trajectories

Init: 00 UTC Fri 08 Feb 13
Valid: 06 UTC Sat 09 Feb 13 (01 EST Sat 09 Feb 13)

Sea Level Pressure (hPa)
600-hPa Trajectory

Model Info: V3.4.1 BMJ PBL Thompson Noah LSM 12 km, 39 levels, 24 sec
LW: RRTM SW: Dudhia DIFF: simple MM: 2D Smagor
Summary

**Strong Winds:**
- acceleration of winds into cold conveyor belt
- highest pressure gradient to rear of cyclone
- no sting jet at surface
GENERIC SLIDES
Evolution of an Extratropical Cyclone

Shapiro–Keyser (1990)

isobars

isotherms
Ingredients for a Sting Jet

1. Frontogenesis and ascent of warm air along bent-back front.

2. Frontolysis at end of back-bent front and descent of warm air.

3. Low static and symmetric stability favors descent.

4. Near-neutral static stability in boundary layer favors mixing downward of high momentum air.
Why have sting jets only been documented in Shapiro–Keyser cyclones?
Norwegian Cyclone

Shapiro–Keyser Cyclone

sea-level pressure
near-surface temperature
axes of dilatation
frontolysis (FL)

(Schultz et al. 1998)
Frontogenesis/frontolysis is the physical mechanism for sting jets.

Why sting jets occur at the end of bent-back front.

Why sting jets occur in Shapiro–Keyser cyclones, but not Norwegian cyclones.

Why trajectories ascend, then descend.

Why evaporation is unimportant.

Why CSI results are ambiguous.
Lessons from Today’s Talk

1. When introducing terminology and speculation in your own work, do so carefully.

2. Beware persistent, but potentially incorrect, conventional wisdom.

3. Be aware of the previous literature.
"I don't know that much about sting jets as they came to light since I retired."
Gray et al. (2011):

“CSI release has a role in the generation of the sting jet, that the sting jet may be driven by the release of instability to both ascending and descending parcels, and that DSCAPE could be used as a discriminating diagnostic for the sting jet based on these four case studies.”

“The presence of CSI release in the sting-jet storms and sting jets, and its absence in the non-sting-jet storm, strongly suggests that this mechanism is important in the generation of the sting jet in these cases.”

“CSI release is not a necessary criterion for the presence of weakly descending jets that satisfy the definition of sting jet used here.”
"I don't know that much about sting jets as they came to light since I retired."
Smart and Browning (2013):

“CSI did not play a major role in the evolution of these [sting jet] parcels. This does not necessarily rule out a role for CSI at other times and places in this storm but a thorough investigation of this is beyond the limited scope of this paper.

Three papers and nine years later, CSI in the Oct 1987 Great Storm is finally addressed.
surface airstreams and fronts

Clark et al. (2005)
Why is it called a *sting jet*?

“‘the poisonous tail’ of the back-bent occlusion”
(Grønås 1995, after F. Spinnangr, Western Norwegian Forecasting Office)

“The sting at the end of the tail”
(Browning 2004)
Only called a *sting jet* in the last sentence of the paper
Browning (2004) defined the research agenda.

Re-examination of observations from the Great Storm of 15–16 October 1987

Strongest winds south and east of the low center

Proposed causes:
1. Attributed evaporative cooling to descending air

2. Release of conditional symmetric instability (CSI) in comma cloud head
Browning (2004) defined the research approach. Peak surface wind gusts (m s\(^{-1}\)) 0130 UTC 16 October 1987
How has the argument for CSI and evaporation evolved?

1. Browning and Coauthors

2. Gray and Coauthors
Browning (2004):

“Evidence has been presented of the existence of multiple slantwise circulations.... It is tempting...to attribute these circulations to CSI.”

“A proper evaluation of the possible importance of CSI on this occasion awaits the application of a methodology for estimating 3-dimensional SCAPE.”
Clark et al. (2005):

“It is suspected that the multiple slantwise circulations may be a manifestation of CSI. This remains to be proved.”

“It is left to a third paper in this series to demonstrate the causal link between the evaporation and the intensification of the SJ.”
Smart and Browning (2013):

“CSI did not play a major role in the evolution of these [sting jet] parcels. This does not necessarily rule out a role for CSI at other times and places in this storm but a thorough investigation of this is beyond the limited scope of this paper.”
Gray et al. (2011):

“CSI release is not a necessary criterion for the presence of weakly descending jets that satisfy the definition of sting jet used here.”
Martinez-Alvarado et al. (2011):

“…it is assumed that the release of CSI is needed for sting jets to develop.

Evaporative cooling of rain and snow falling from upper levels into the sting jet is necessary for the release of CSI by descending air parcels and has also been proposed as a mechanism that enhances the development of sting jets.”
L. Baker et al. (2013):

“While evaporative cooling occurs along the sting-jet trajectories, a sensitivity experiment with evaporation effects turned off shows no significant change to the wind strength or descent rate of the sting jet....”
L. Baker et al. (2013):

“While evaporative cooling occurs along the sting-jet trajectories, a sensitivity experiment with evaporation effects turned off shows no significant change to the wind strength or descent rate of the sting jet…."

(This result also corroborated by Tim Baker and David Smart in different cases.)
“While evaporative cooling occurs along the sting-jet trajectories, a sensitivity experiment with evaporation effects turned off shows no significant change to the wind strength or descent rate of the sting jet implying that instability release is the dominant sting-jet driving mechanism.”
Gray et al. (2011):
CSI not necessary for sting jets

Martinez-Alvarado et al. (2011):
CSI assumed necessary for sting jets, evaporation is necessary to release CSI

L. Baker et al. (2013):
release of CSI “dominant”, evaporation not important
What do we make of the previous literature?

Evaporative cooling is not important in sting jets.

CSI may or may not be important in sting jets.

CSI release depends upon some vertical motion. The mechanism for that vertical motion is not identified.

No firm conclusion about what controls sting-jet formation.
Let’s try a different ingredients-based approach.

Our work is based on kinematics and dynamics, not thermodynamics.

What is the physical process that is responsible for the descent of the air eventually forming the sting jet?
Frontogenesis (Petterssen 1936)

\[
F = \frac{d}{dt} | \nabla_H \theta | ,
\]

\[
\frac{d}{dt} = \frac{\partial}{\partial t} + u \frac{\partial}{\partial x} + v \frac{\partial}{\partial y},
\]

\[
\mathbf{V}_H = u \mathbf{i} + v \mathbf{j},
\]

\[
\nabla_H = \mathbf{i} \frac{\partial}{\partial x} + \mathbf{j} \frac{\partial}{\partial y}.
\]

\[
F = \frac{1}{2} | \nabla_H \theta | (E \cos 2\beta - \nabla_H \cdot \nabla_H),
\]

deformation divergence
Frontogenesisis

horizontal

vertical

isentropes
Frontogenesis  

Frontolysis  

horizontal  

vertical  

isentropes
75 knots (39 m/s)

0731 UTC 8 December 2005
Sea-level pressure
925-mb theta
wind speed (shaded)
925-mb theta
wind speed
frontogenesis (shaded)
700-mb relative humidity (shaded)
925-mb theta
925-mb wind speed
cross section through frontogenesis maximum
cross section through frontolysis maximum and sting jet
low stability

high stability

925-mb Theta, Wind Speed, Static Stability
cold advection

warm advection

925-mb Theta, Wind Speed, Thermal Advection
strong heat flux
One case is intriguing...

Is frontolysis present in other cyclones with sting jets?
Grønås (1995, Figs. 3b and 4b)
Clark et al. (2005, Fig. 7)
Smart and Browning (2013):

Attribution of strong winds to a cold conveyor belt and sting jet, QJRMS, in press.

3 January 2012
Scottish storm
theta-e = 300K
Miller Frontogenesis (3D) (div+def)
Pressure
Horizontal wind vectors
(relative to $V = 17.9\ m/s$)
Horizontal wind speed
(at theta $e = 300\ K$)

theta-e = 300K

David Smart
Frontogenesis (3D) (div+grad)
Pressure
Horizontal wind vectors
(relative to V= 17.9 m/s)
Horizontal wind speed
at theta e = 300 K

$\theta_e = 300K$

David Smart
theta-e = 300K
Ingredients for a Sting Jet

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4. Near-neutral static stability in boundary layer favors mixing downward of high momentum air.
(b) After Occlusion

Schultz and Vaughan (2011)
Why have sting jets only been documented in Shapiro–Keyser cyclones?
Norwegian Cyclone

Shapiro–Keyser Cyclone

sea-level pressure
near-surface temperature
axes of dilatation
frontolysis (FL)

(Schultz et al. 1998)
Frontogenesis/frontolysis is the physical mechanism for sting jets.

Why sting jets occur at the end of bent-back front.

Why sting jets occur in Shapiro–Keyser cyclones, but not Norwegian cyclones.

Why trajectories ascend, then descend.

Why evaporation is unimportant.

Why CSI results are ambiguous.
Mysteries remain...

Eastern US storm Nemo: 925-mb wind

1200 UTC 9 Feb 2013

6 h later
Mysteries remain…

Eastern US storm Nemo: 925-mb wind 6 h later

1200 UTC 9 Feb 2013
Mysteries remain…

Eastern US storm Nemo: 925-mb wind

6 h later

1200 UTC 9 Feb 2013

Frontogenesis (shaded), Theta, Wind Speed

Frontogenesis (shaded), Theta, Wind Speed

Frontogenesis (shaded), Theta, Omega

Frontogenesis (shaded), Theta, Omega
Mysteries remain...

Eastern US storm Nemo: 925-mb geostrophic wind

1200 UTC 9 Feb 2013

6 h later
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Frontogenesis/frontolysis is the physical mechanism for sting jets.

Why sting jets occur at end of bent-back fronts.

Why trajectories ascend, then descend.

Why evaporation is relatively unimportant.

Why CSI results are ambiguous.

Mesoscale dimensions and descent.
"I don't know that much about sting jets as they came to light since I retired."
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“CSI release is not a necessary criterion for the presence of weakly descending jets that satisfy the definition of sting jet used here.”
Top: sea-level pressure, 925-mb theta, wind speed (shaded)

Bottom: 925-mb theta, wind speed, frontogenesis (shaded)
"I don't know that much about sting jets as they came to light since I retired."
“CSI did not play a major role in the evolution of these [sting jet] parcels. This does not necessarily rule out a role for CSI at other times and places in this storm but a thorough investigation of this is beyond the limited scope of this paper.
Whitaker et al. (1988)
Frontogenesis (Petterssen 1936)

\[ F = \frac{d}{dt} |\nabla_H \theta|, \]

\[ \frac{d}{dt} = \frac{\partial}{\partial t} + u \frac{\partial}{\partial x} + v \frac{\partial}{\partial y}, \]

\[ \nabla_H = ui + vj, \]

\[ \nabla_H = i \frac{\partial}{\partial x} + j \frac{\partial}{\partial y}. \]

\[ F = \frac{1}{2} |\nabla_H \theta| (E \cos2\beta - \nabla_H \cdot \nabla_H), \]

\begin{itemize}
  \item deformation
  \item divergence
\end{itemize}
Frontogenesis

- Horizontal: Cold air is above warm air.
- Vertical: Isentropes (lines of constant entropy) are depicted, showing the vertical movement of air masses.

isentropes
Frontogenesis

Horizontal:
- Cold
- Warm

Vertical:
isentropes
Frontogenesis

horizontal

Frontolysis

vertical

isentropes
evolution of surface airstreams and fronts

Clark et al. (2005)
Coincidence between front and sting jet?

Descending sting jet distinct from cold-conveyor belt?

evolution of surface airstreams and fronts

Clark et al. (2005)