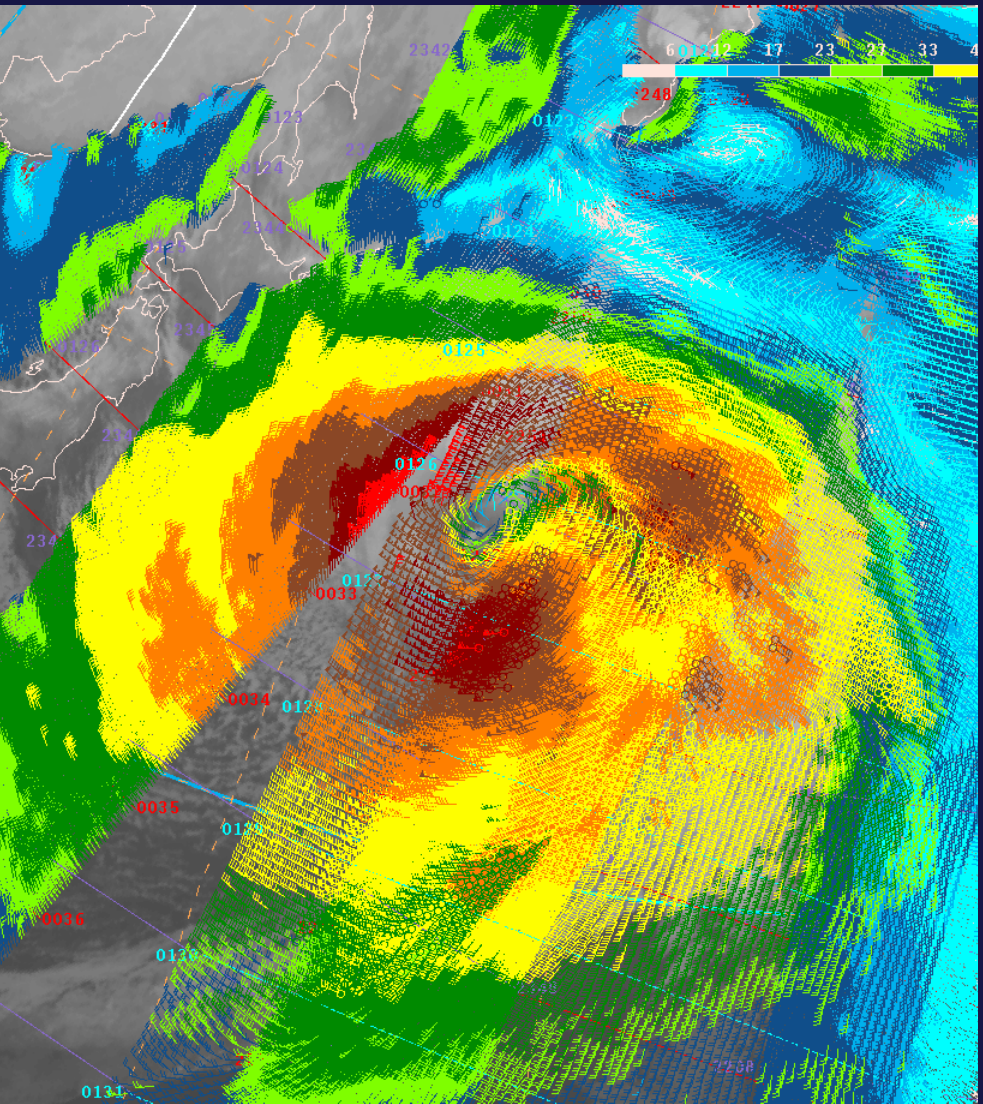
# Strong Winds in Extratropical Cyclones




David M. Schultz

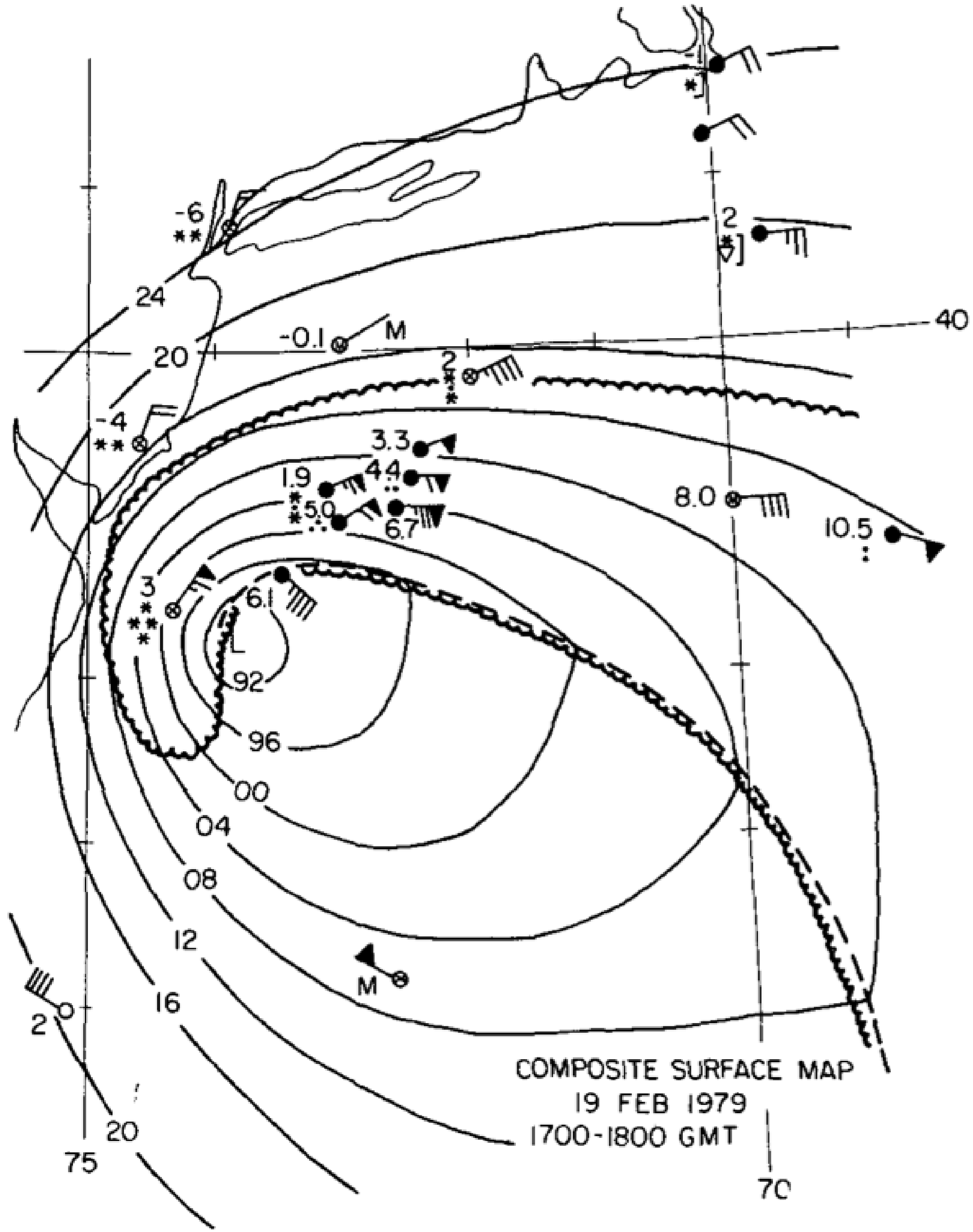
*University of Manchester*



Thanks to

Joseph Sienkiewicz,

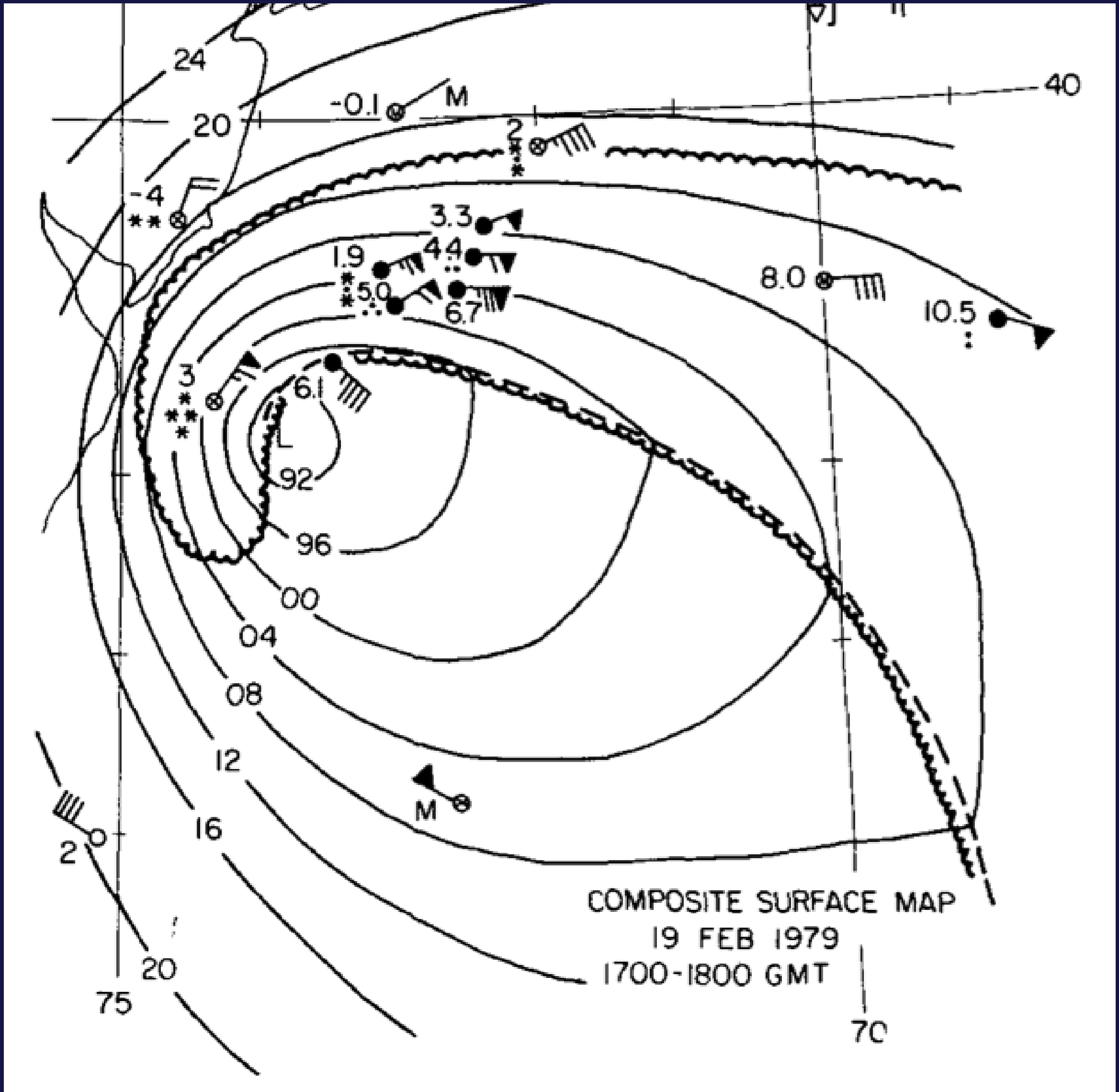
Tim Slater, and Geraint Vaughan



-6
24
20
-0.1
M
40
2
-4
3.3
1.9
4.4
5.0
6.7
8.0
10.5
3
6.1
L
92
96
00
04
08
12
16
20
2
M
75
70
COMPOSITE SURFACE MAP
19 FEB 1979
1700-1800 GMT

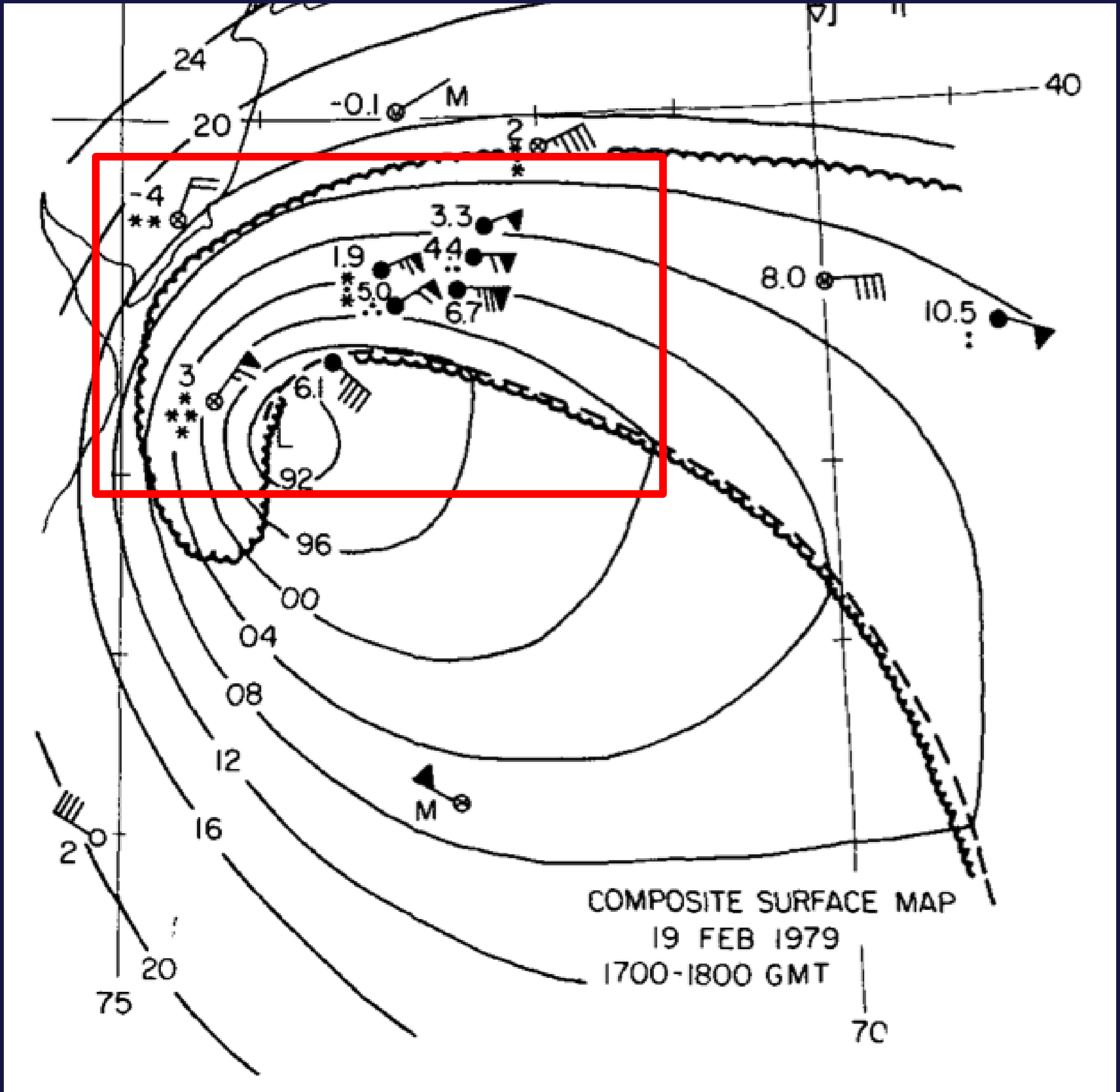

Bosart (1981)

“The pressure gradient is especially tight to the west of the storm center and approaches 1 mb (5 km)$^{-1}$.”

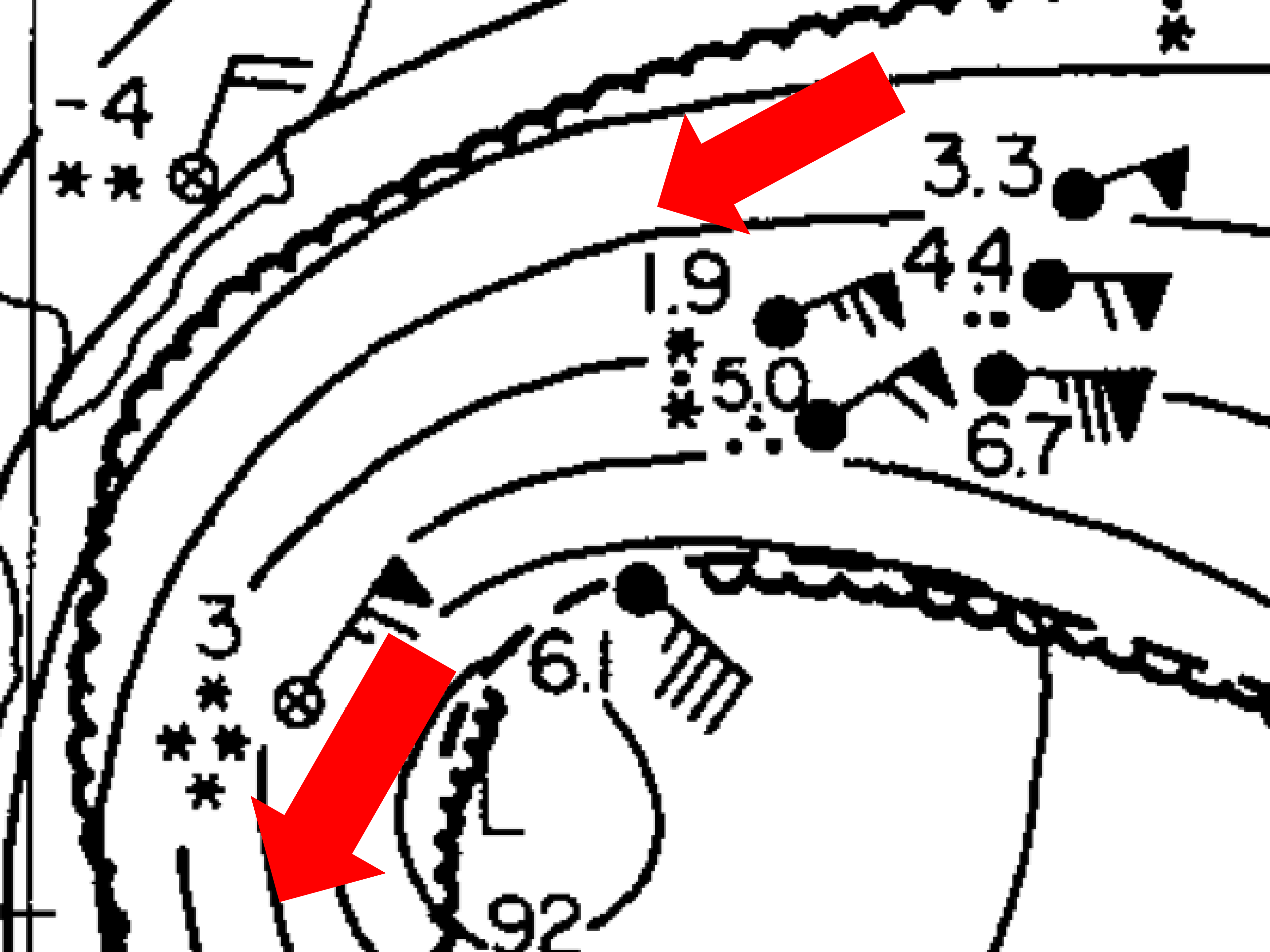



Bosart (1981)

“The pressure gradient is especially tight to the west of the storm center and approaches 1 mb (5 km)$^{-1}$.”

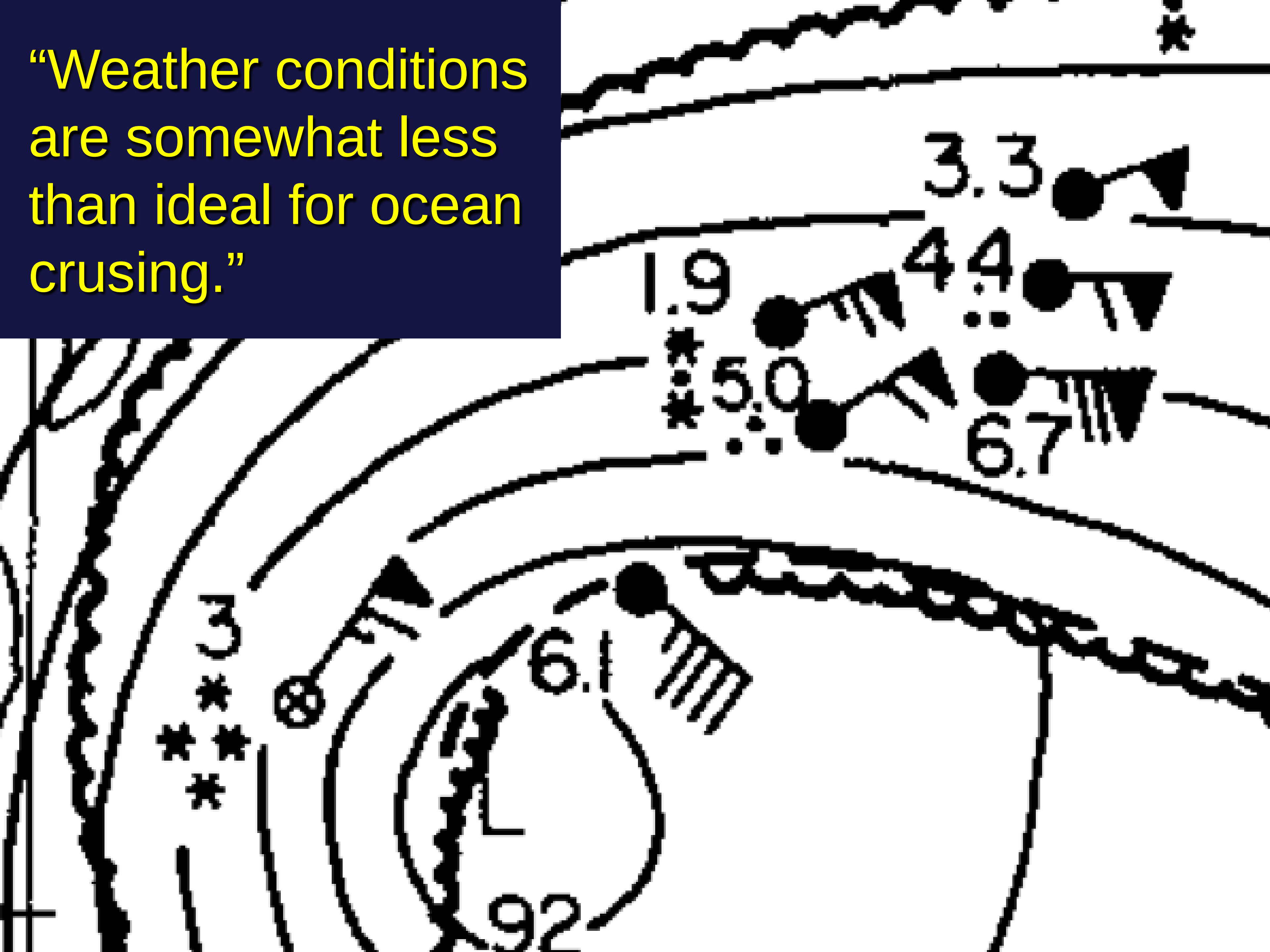



Bosart (1981)

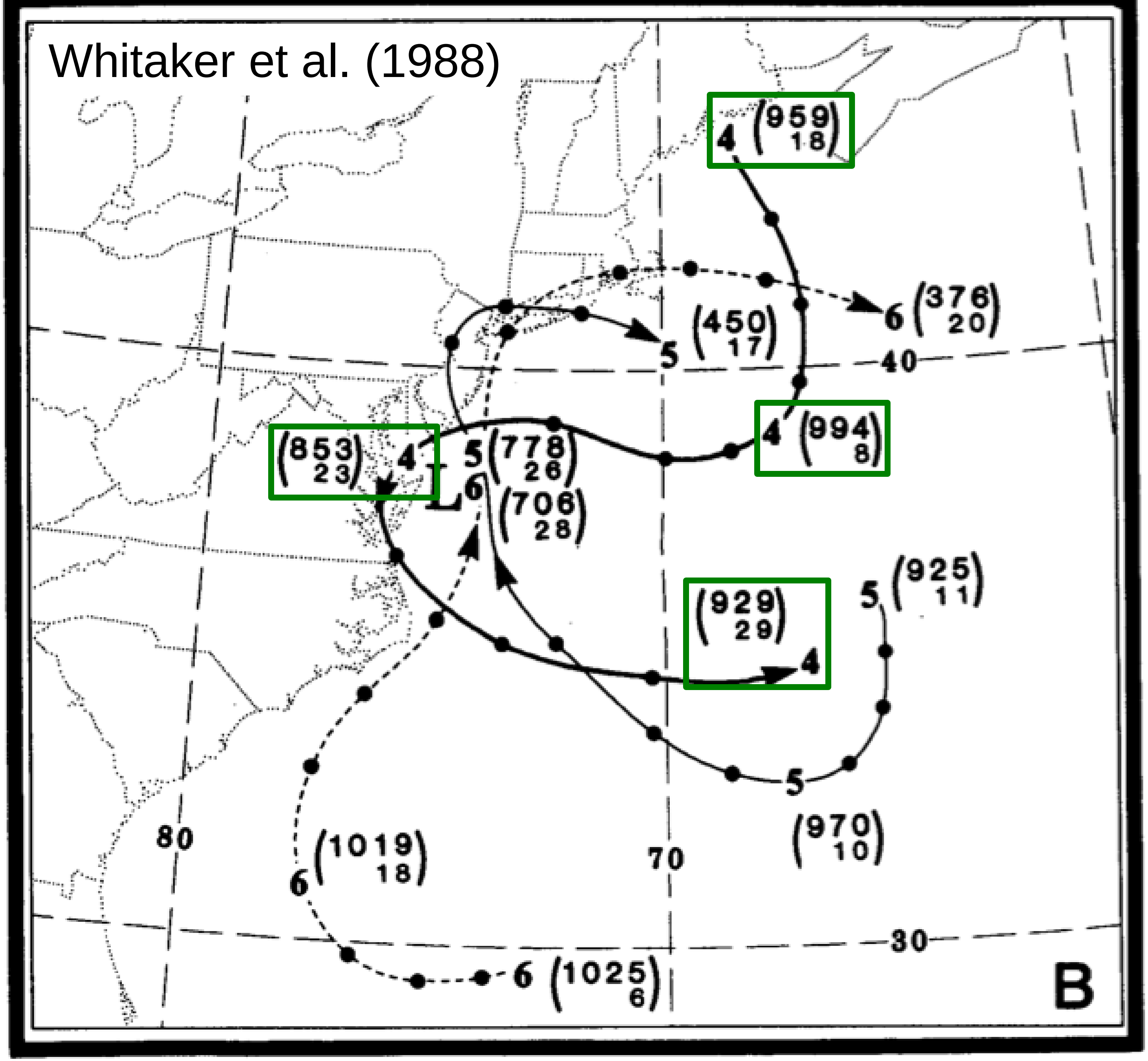


-4
3.3
4.4
1.9
5.0
6.7
3
6.1
L
92

“Weather conditions are somewhat less than ideal for ocean crusing.”

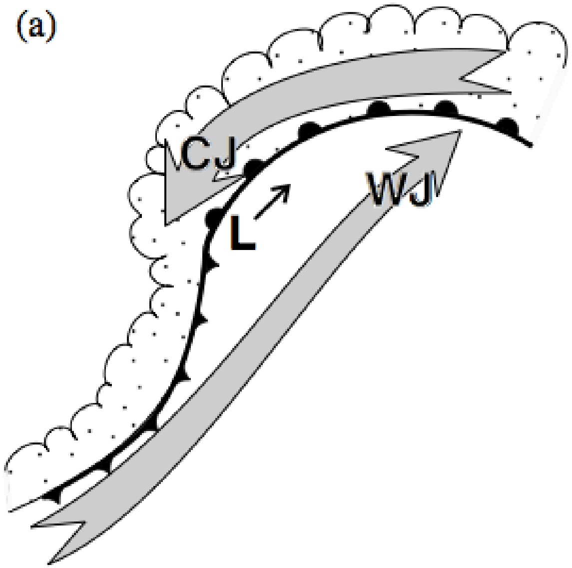


Whitaker et al. (1988)




pressure
mb

wind speed
m s$^{-1}$

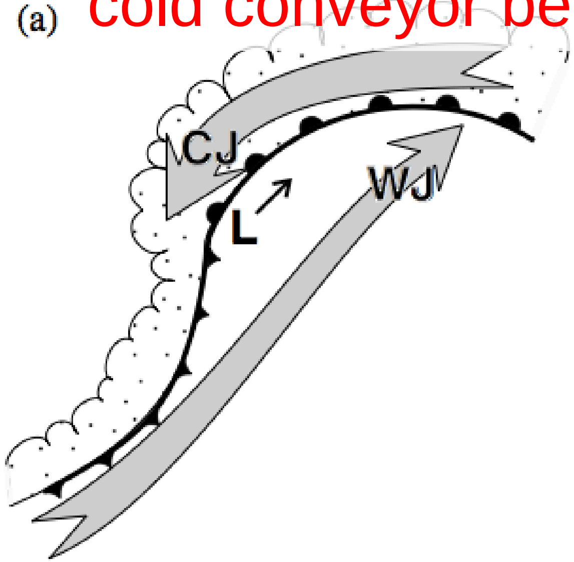



evolution of surface airstreams and fronts

Clark et al. (2005)

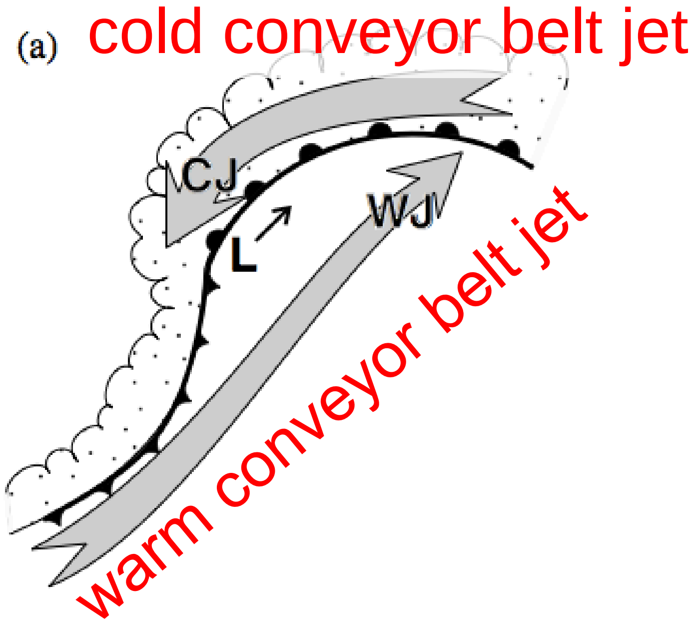
# cold conveyor belt jet

(a)



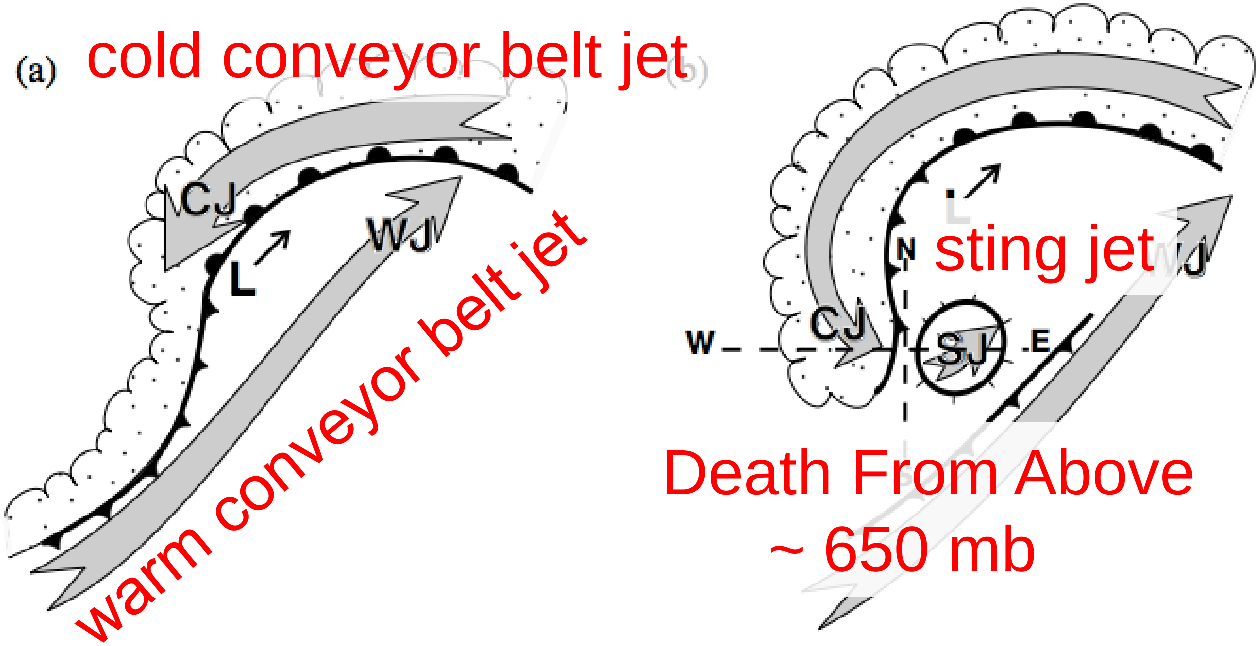

evolution of surface airstreams and fronts

Clark et al. (2005)



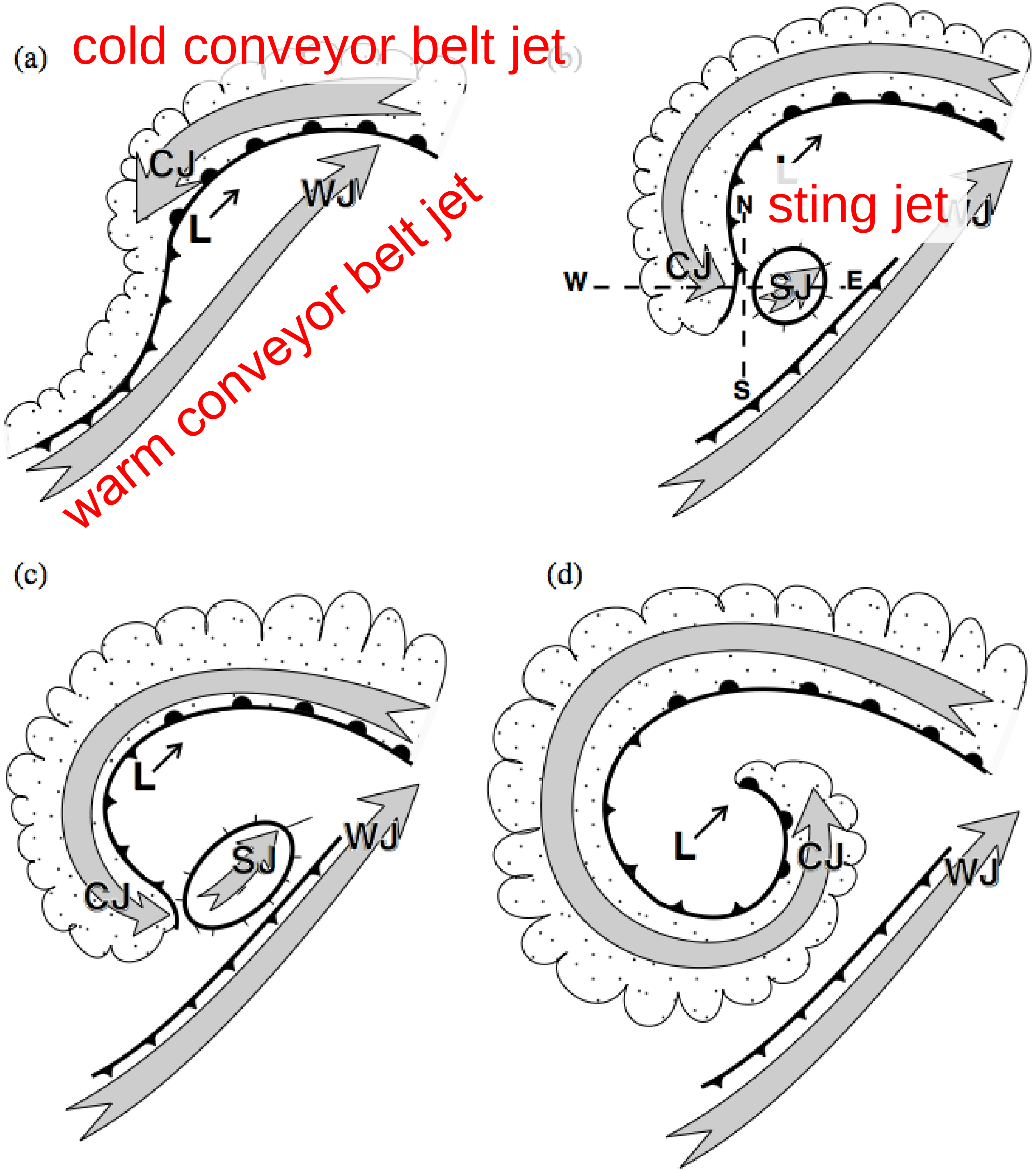

evolution of
surface airstreams
and fronts

Clark et al. (2005)



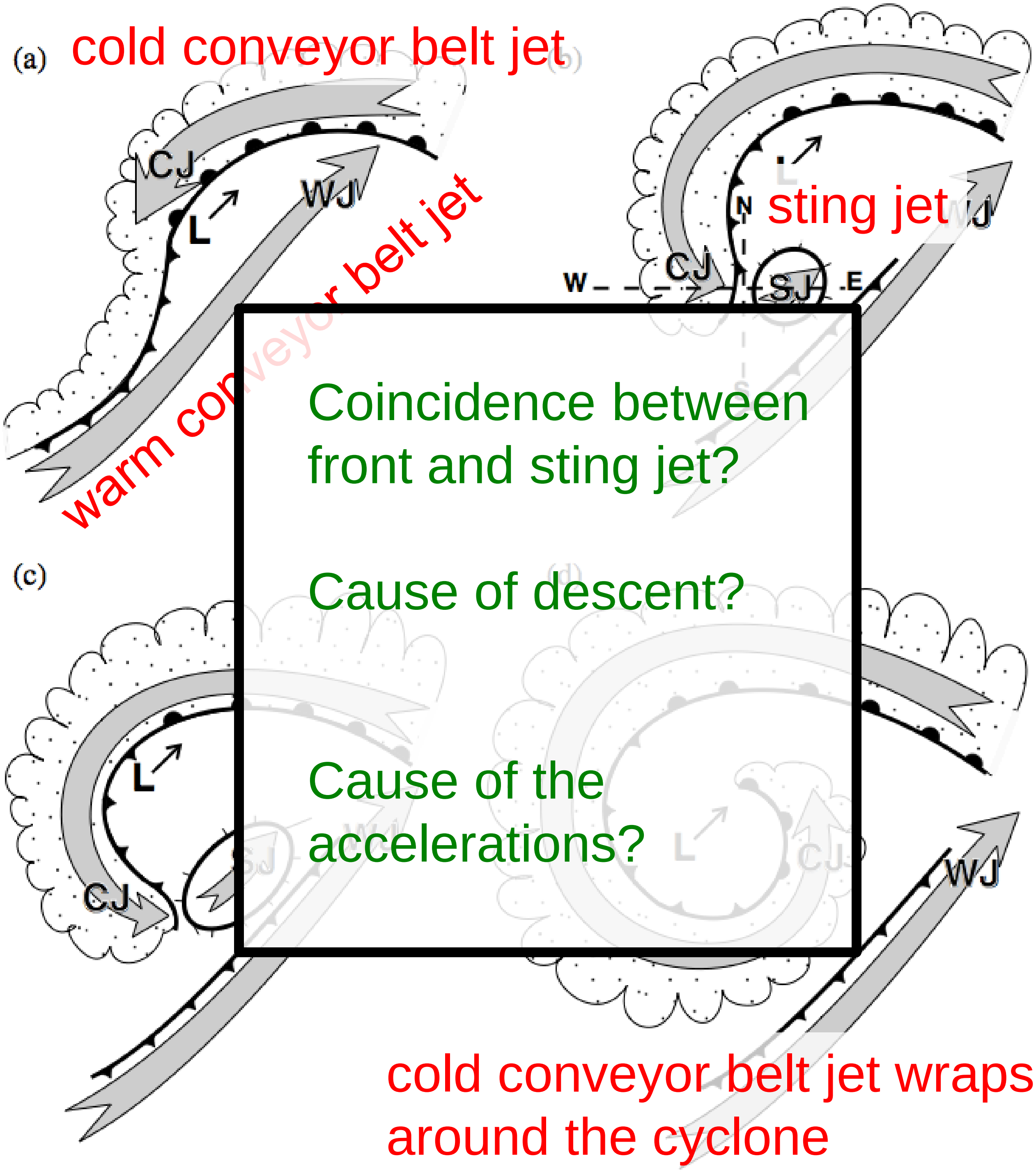

evolution of
surface airstreams
and fronts

Clark et al. (2005)




evolution of surface airstreams and fronts

Clark et al. (2005)




cold conveyor belt jet

warm conveyor belt jet

sting jet

cold conveyor belt jet wraps around the cyclone

Coincidence between front and sting jet?

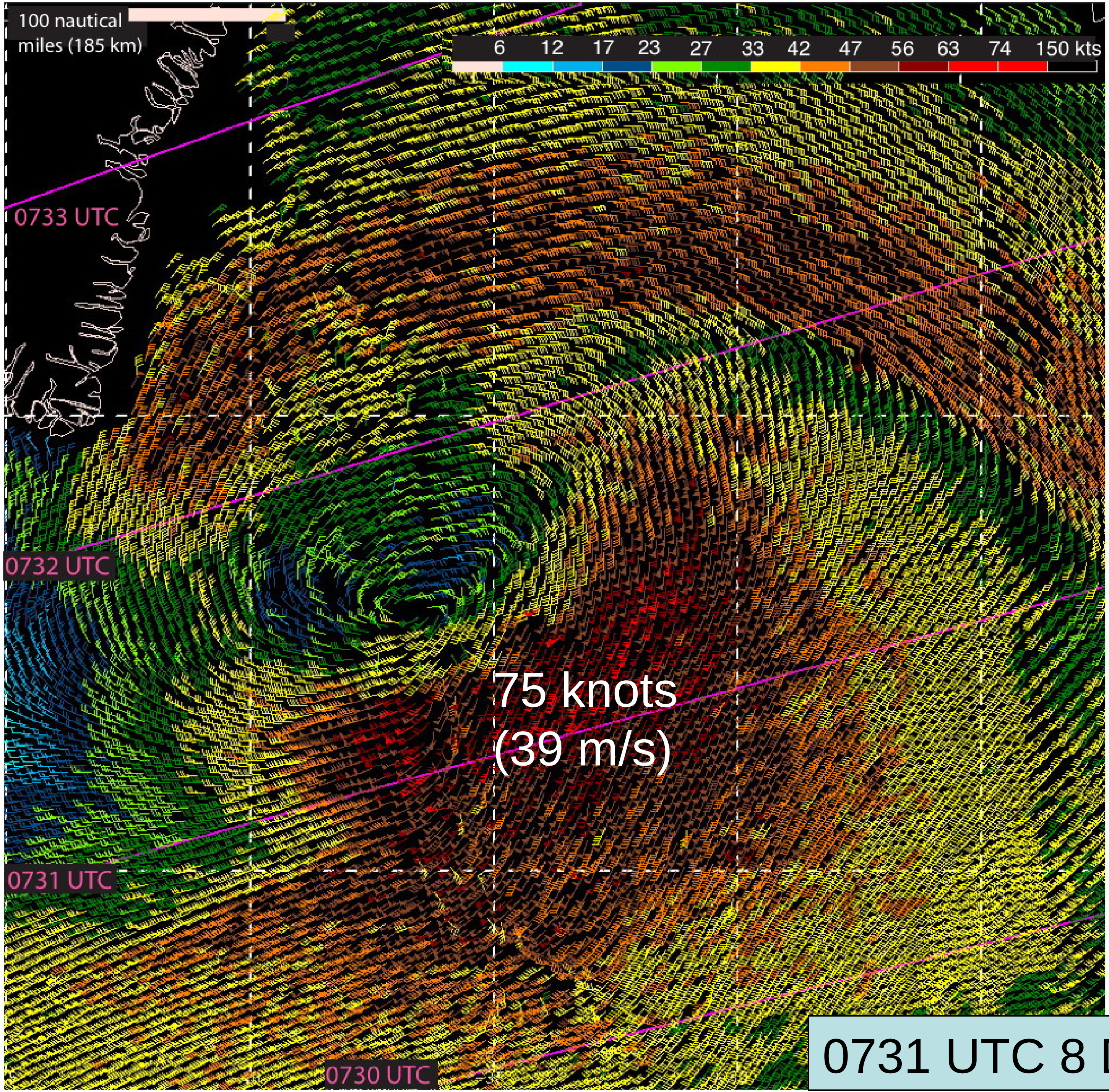
Cause of descent?

Cause of the accelerations?

evolution of surface airstreams and fronts

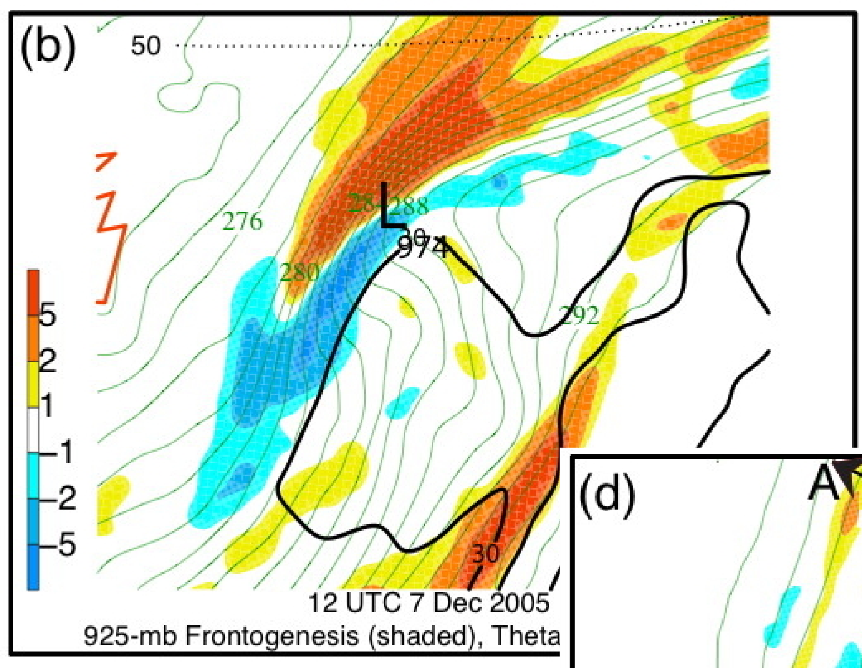
Clark et al. (2005)

# What causes the descent?

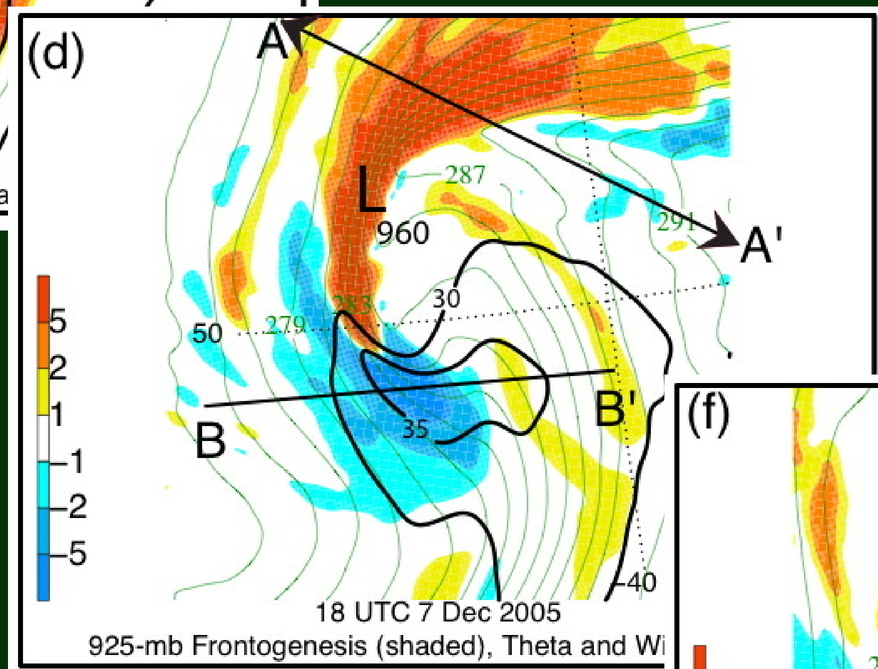



0731 UTC 8 December 2005

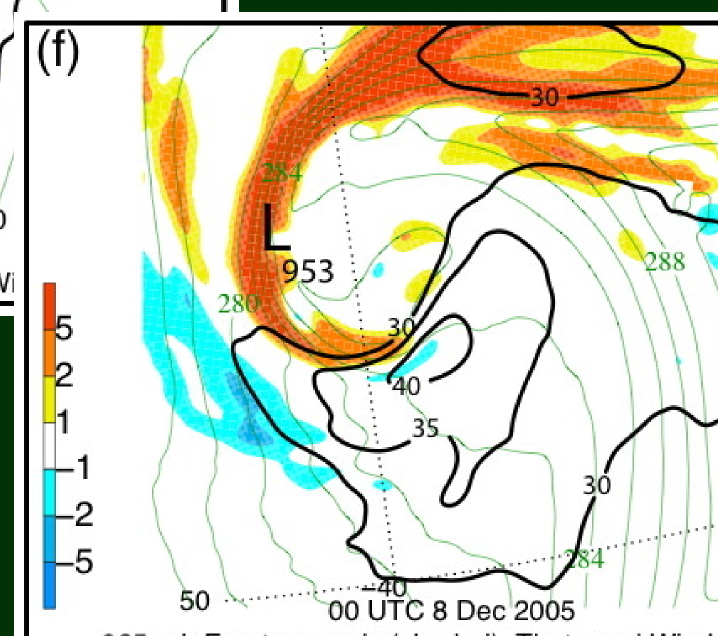
# 12 UTC 7 Dec



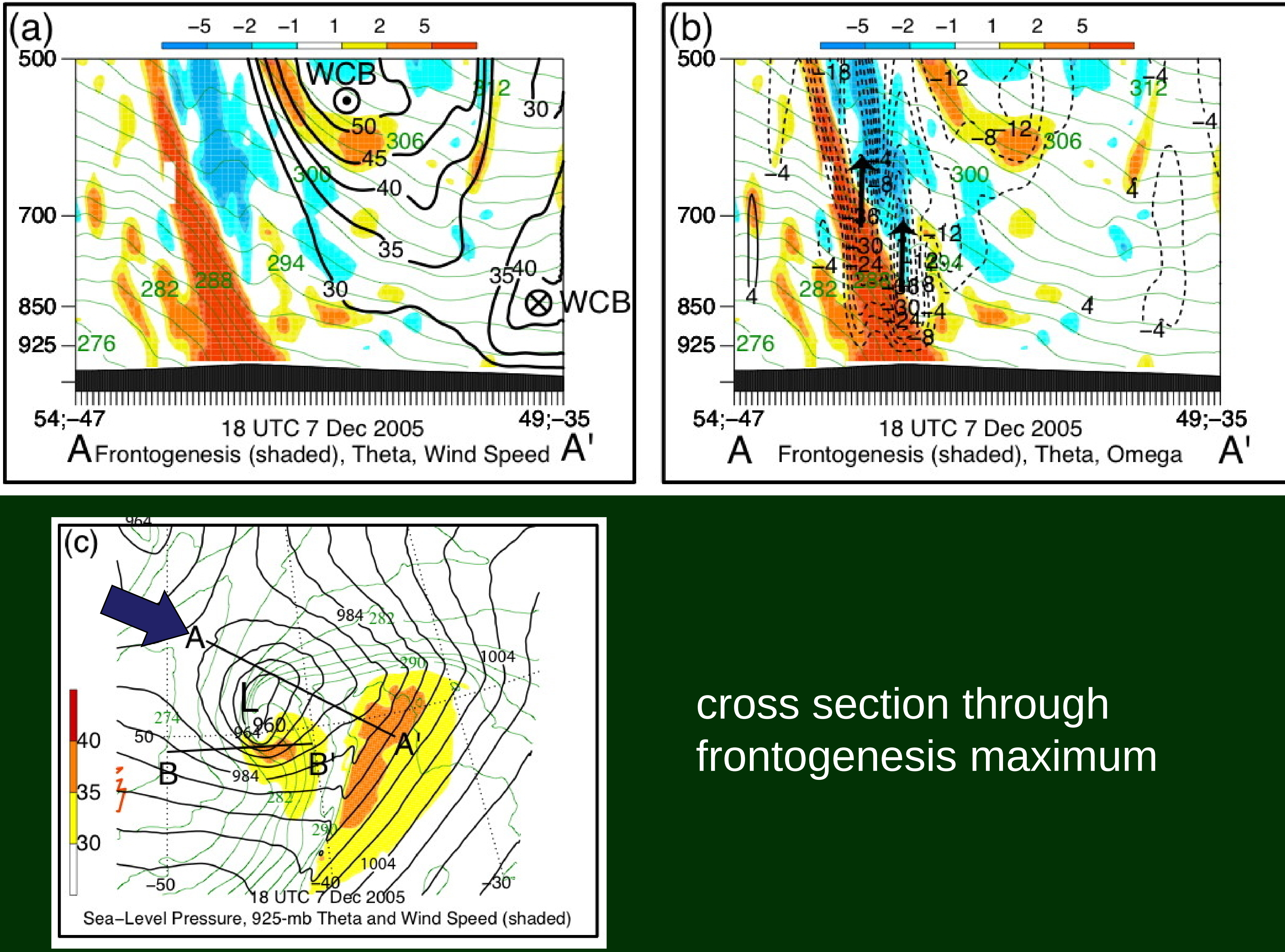

# 18 UTC 7 Dec



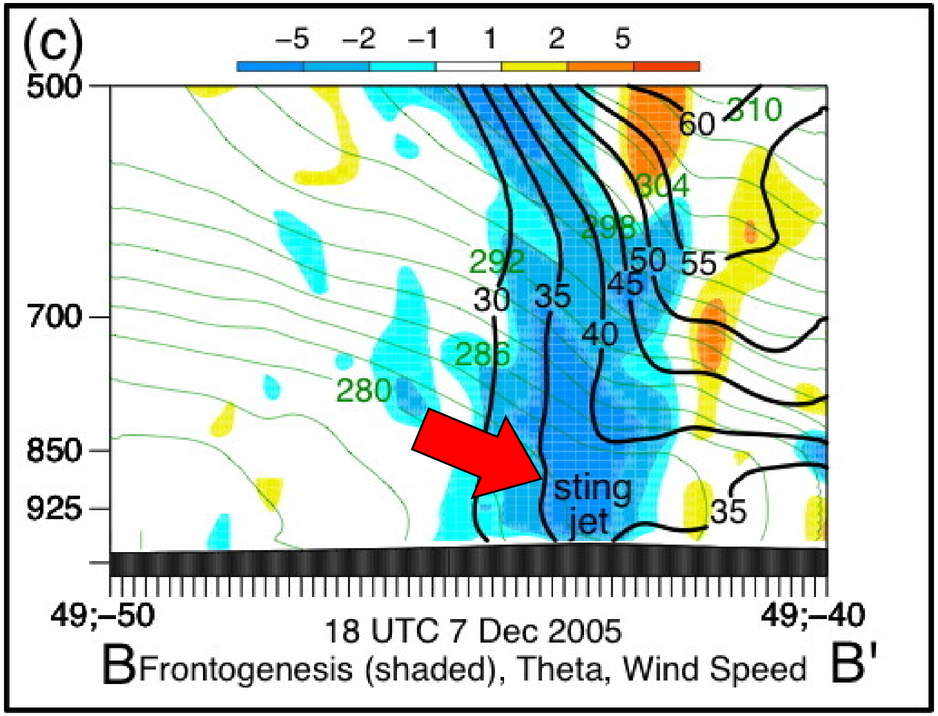

# 00 UTC 8 Dec

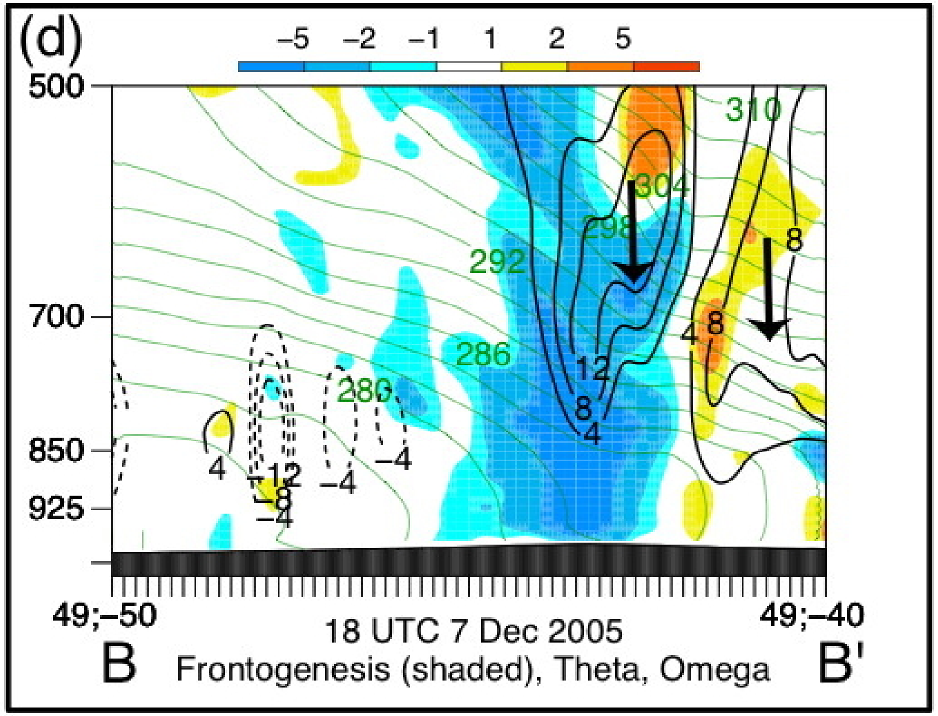


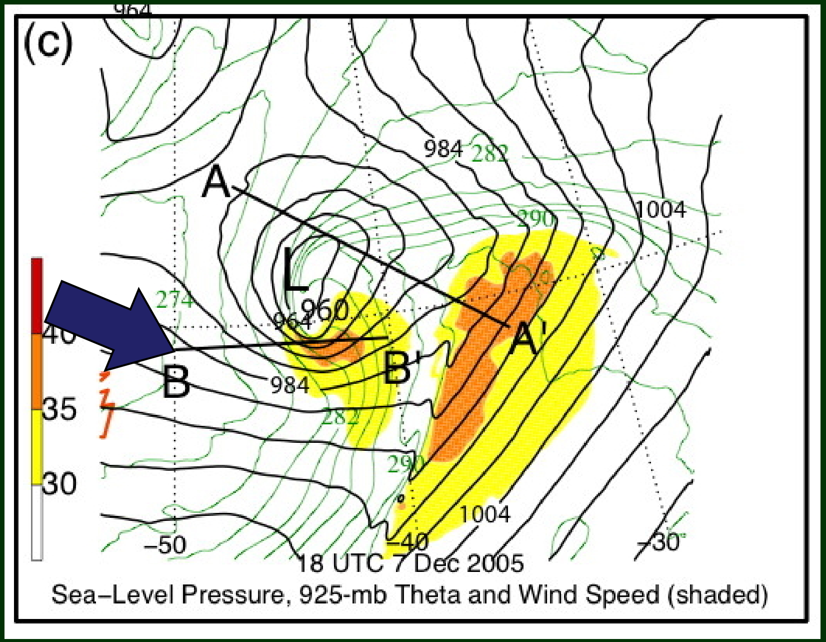

925-mb theta
wind speed
frontogenesis (shaded)




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.

$$\frac{\partial \boldsymbol{u}_h}{\partial t} = \underbrace{-(\boldsymbol{u}_h.\boldsymbol{\nabla}_h)\boldsymbol{u}_h}_{\boldsymbol{F}^{HADV}} \underbrace{-w.\frac{\partial \boldsymbol{u}_h}{\partial z}}_{\boldsymbol{F}^{VADV}} \underbrace{-f\boldsymbol{k} \times \boldsymbol{u}_h}_{\boldsymbol{F}^{COR}} \underbrace{-\frac{1}{\rho}\boldsymbol{\nabla}_h p}_{\boldsymbol{F}^{PGF}} + \boldsymbol{F}^{PBL}$$

Slater et al. (2014)

# The momentum equation tells us how high winds develop.

$$\frac{\partial \boldsymbol{u_h}}{\partial t} = \underbrace{-(\boldsymbol{u_h}.\boldsymbol{\nabla}_h)\boldsymbol{u_h}}_{\boldsymbol{F^{HADV}}} \underbrace{-w.\frac{\partial \boldsymbol{u_h}}{\partial z}}_{\boldsymbol{F^{VADV}}} \underbrace{-f\boldsymbol{k} \times \boldsymbol{u_h}}_{\boldsymbol{F^{COR}}} \underbrace{-\frac{1}{\rho}\boldsymbol{\nabla}_h p}_{\boldsymbol{F^{PGF}}} + \boldsymbol{F^{PBL}}$$

just moves momentum around:

can't explain acceleration

# The momentum equation tells us how high winds develop.

$$\frac{\partial \boldsymbol{u_h}}{\partial t} = \underbrace{-(\boldsymbol{u_h}.\boldsymbol{\nabla}_h)\boldsymbol{u_h}}_{\boldsymbol{F}^{HADV}} \underbrace{-w.\frac{\partial \boldsymbol{u_h}}{\partial z}}_{\boldsymbol{F}^{VADV}} \underbrace{-f\boldsymbol{k}\times\boldsymbol{u_h}}_{\boldsymbol{F}^{COR}} \underbrace{-\frac{1}{\rho}\boldsymbol{\nabla}_h p}_{\boldsymbol{F}^{PGF}} + \boldsymbol{F}^{PBL}$$

acts perpendicular to winds:
can't explain acceleration

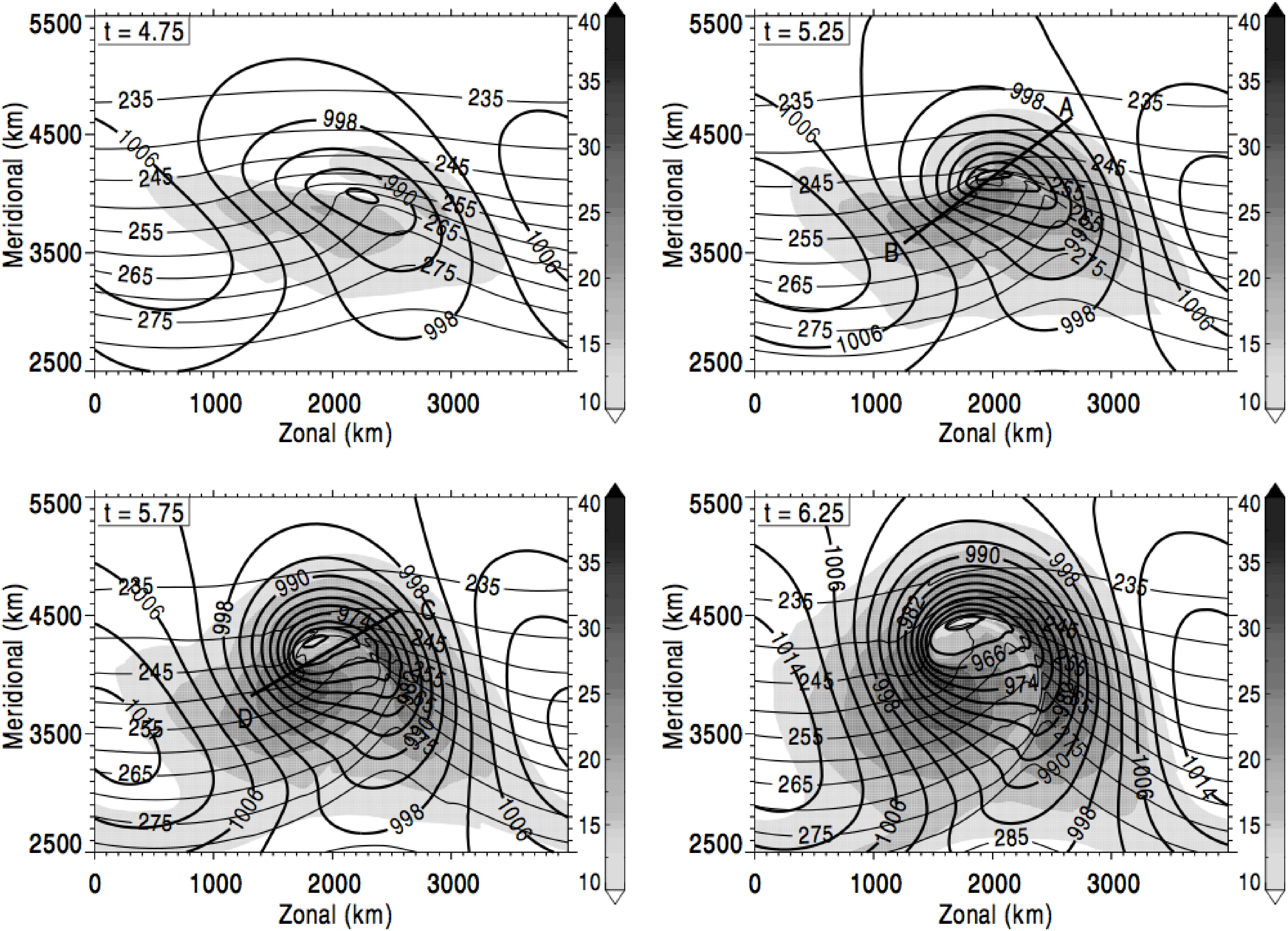
# The momentum equation tells us how high winds develop.

$$\frac{\partial \boldsymbol{u_h}}{\partial t} = \underbrace{-(\boldsymbol{u_h}.\boldsymbol{\nabla}_h)\boldsymbol{u_h}}_{\boldsymbol{F^{HADV}}} \underbrace{-w.\frac{\partial \boldsymbol{u_h}}{\partial z}}_{\boldsymbol{F^{VADV}}} \underbrace{-f\boldsymbol{k} \times \boldsymbol{u_h}}_{\boldsymbol{F^{COR}}} \underbrace{-\frac{1}{\rho}\boldsymbol{\nabla}_h p}_{\boldsymbol{F^{PGF}}} + \boldsymbol{F^{PBL}}$$

slows wind down:
can’t explain acceleration

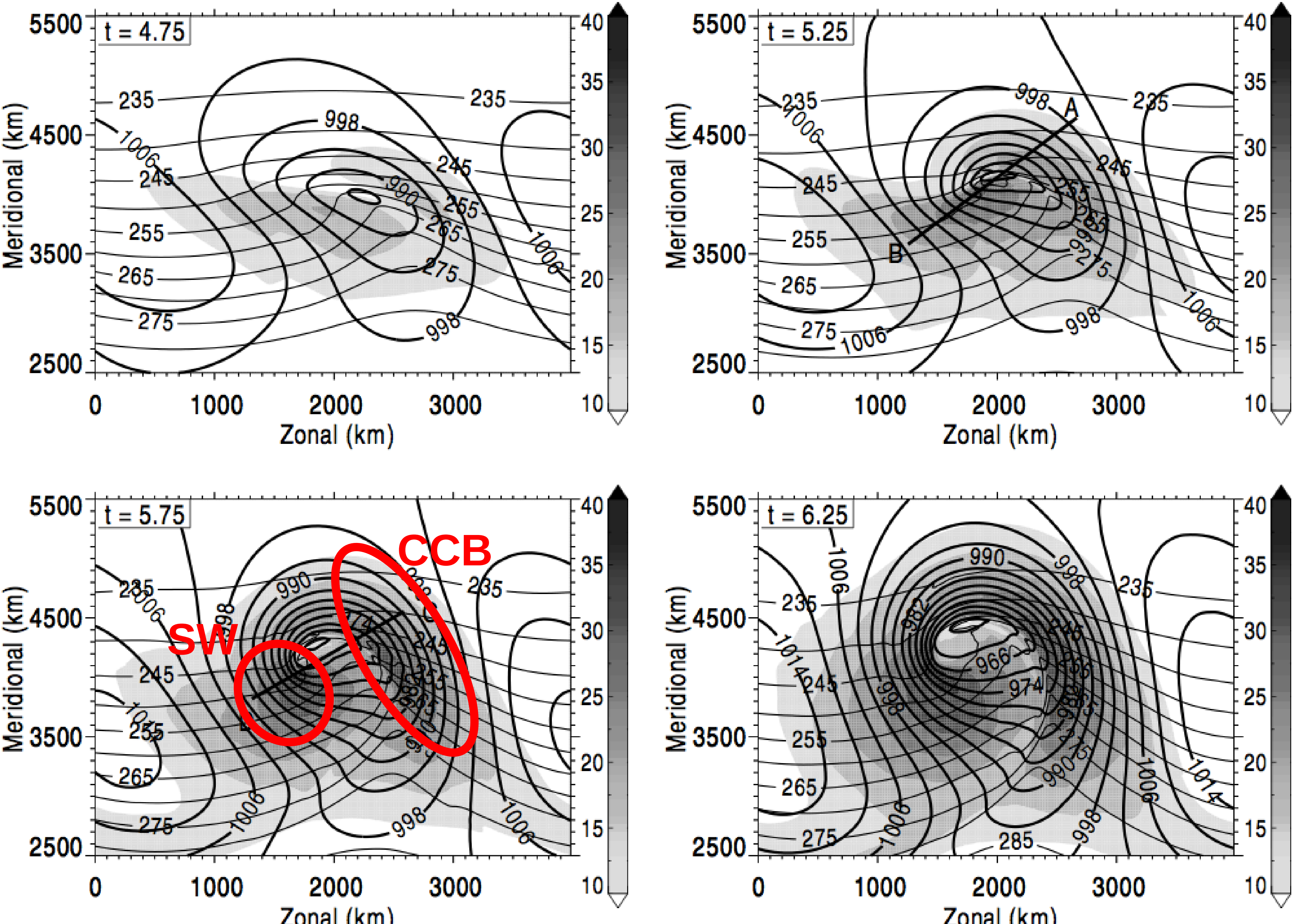
# The momentum equation tells us how high winds develop.

$$\frac{\partial \boldsymbol{u_h}}{\partial t} = \underbrace{-(\boldsymbol{u_h}.\boldsymbol{\nabla_h})\boldsymbol{u_h}}_{\boldsymbol{F^{HADV}}} \underbrace{-w.\frac{\partial \boldsymbol{u_h}}{\partial z}}_{\boldsymbol{F^{VADV}}} \underbrace{-f\boldsymbol{k} \times \boldsymbol{u_h}}_{\boldsymbol{F^{COR}}} \underbrace{-\frac{1}{\rho}\boldsymbol{\nabla_h} p}_{\boldsymbol{F^{PGF}}} + \boldsymbol{F^{PBL}}$$



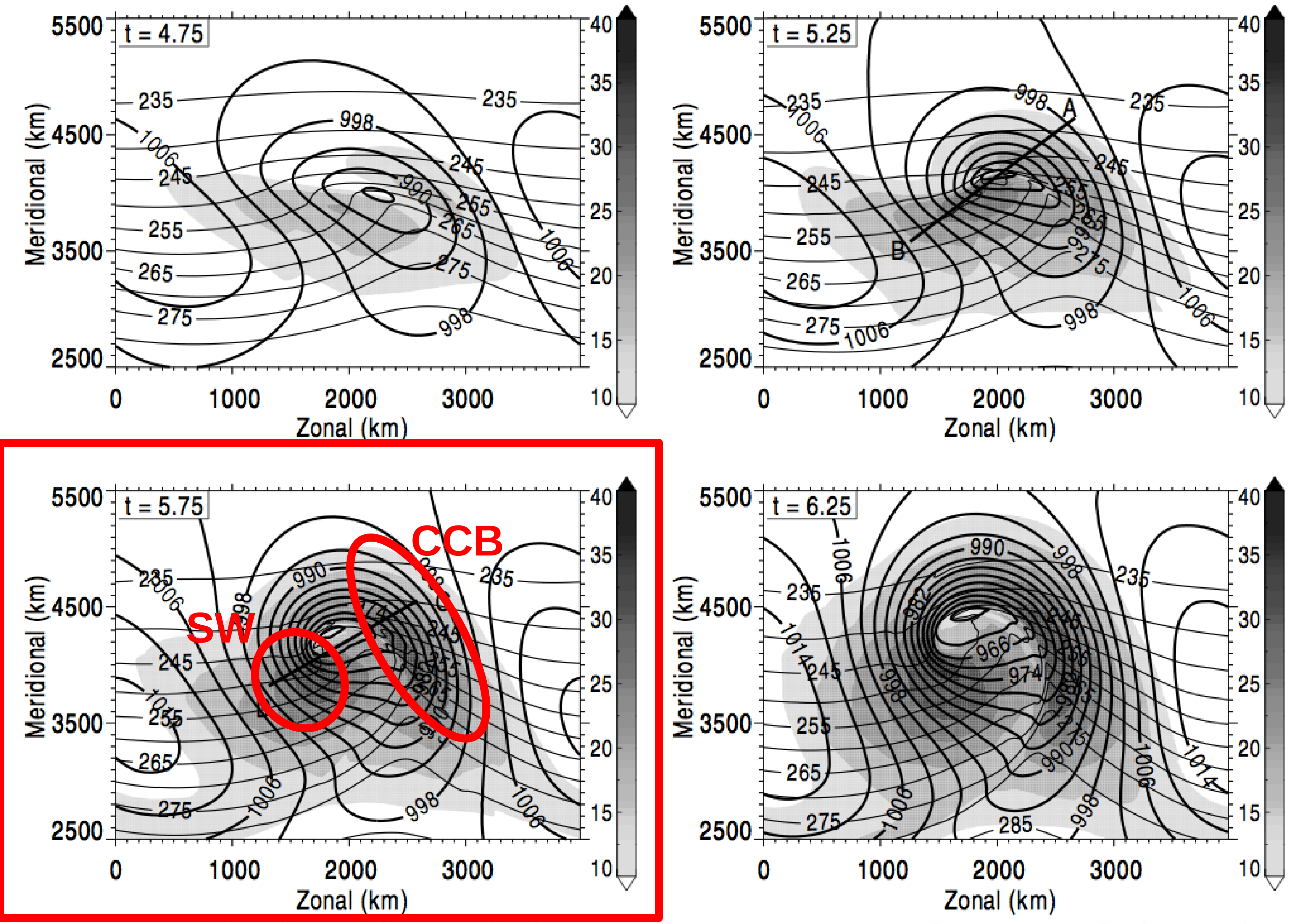

idealized baroclinic wave

Slater et al. (2014)



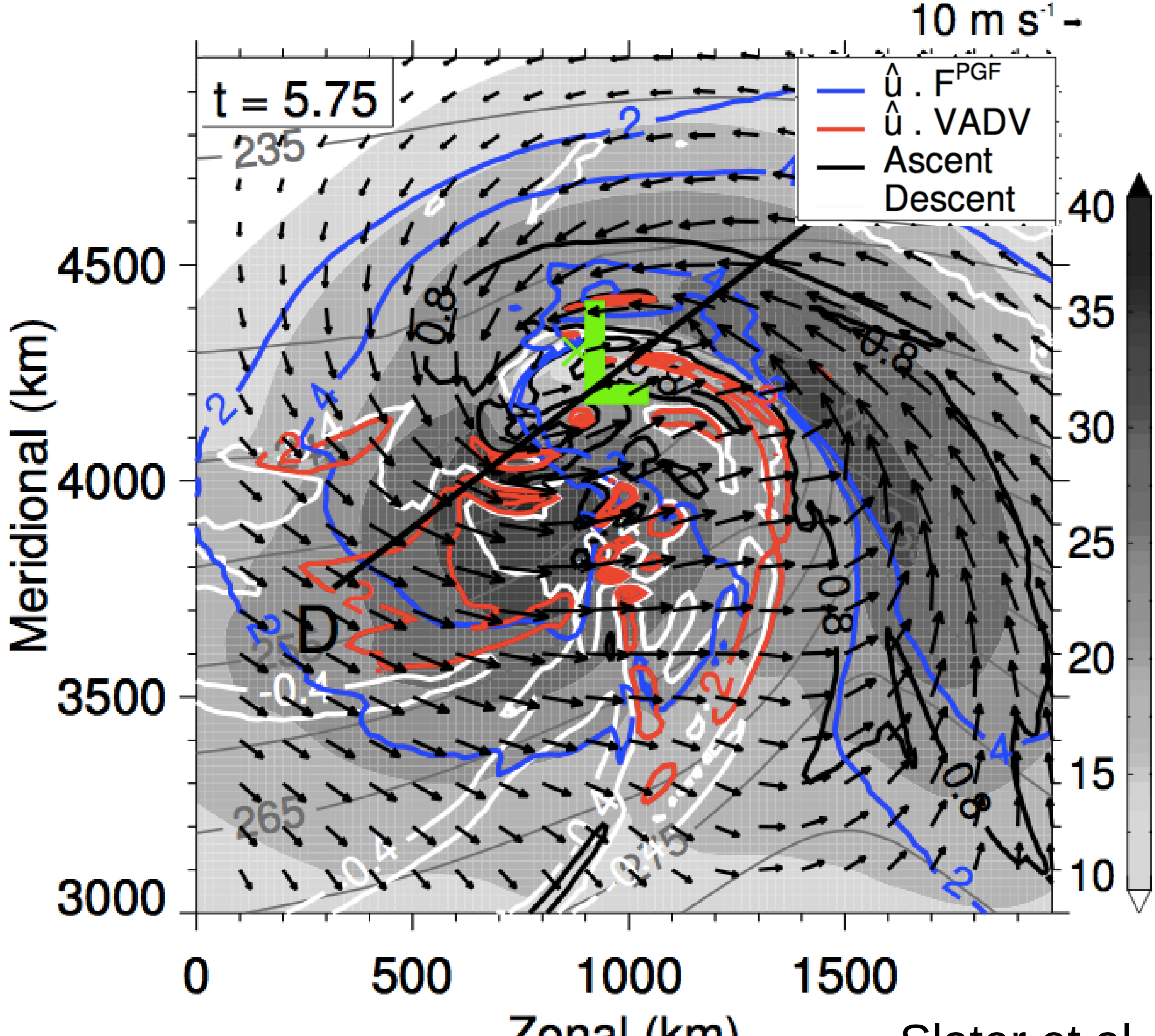

idealized baroclinic wave

Slater et al. (2014)

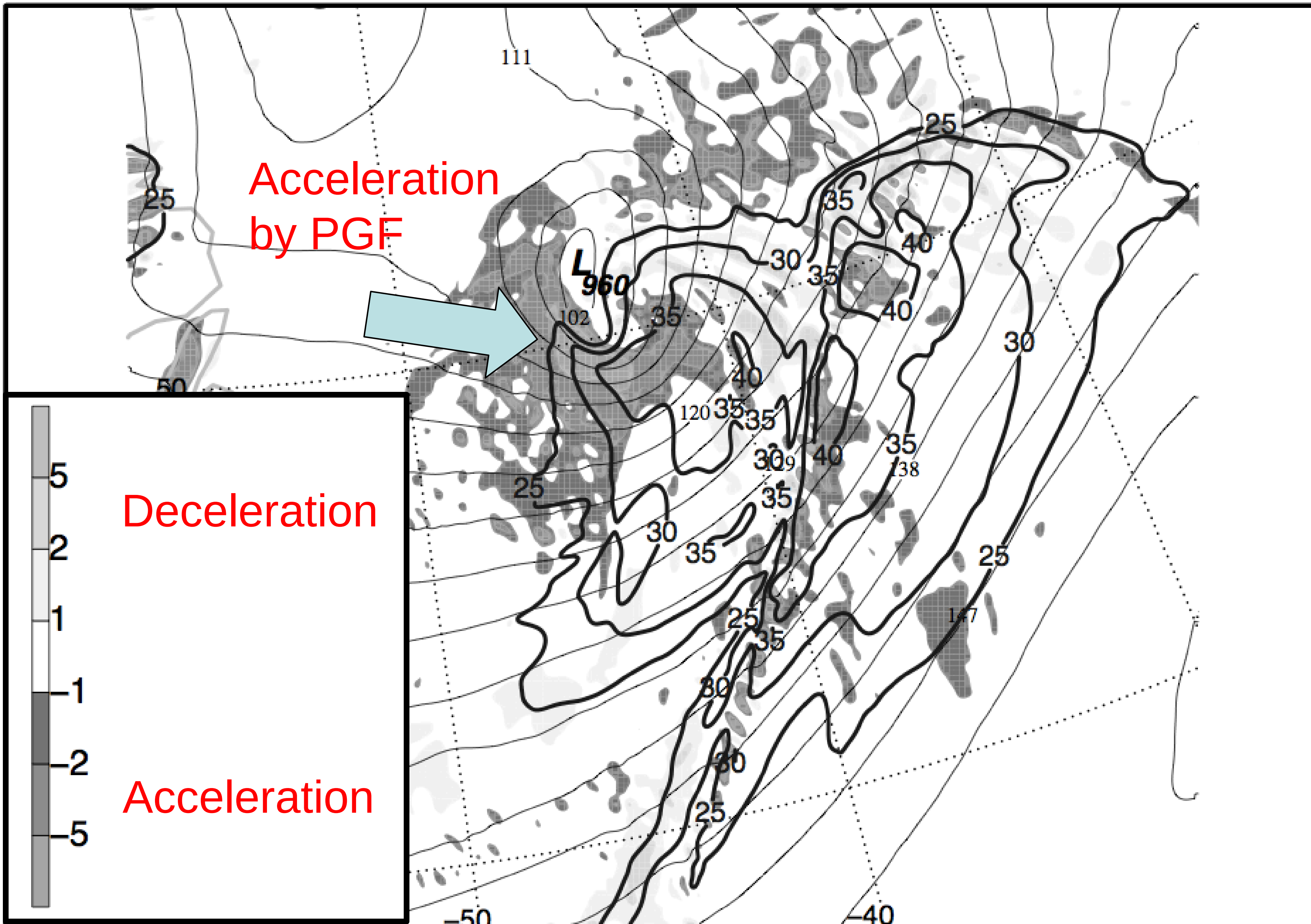



idealized baroclinic wave

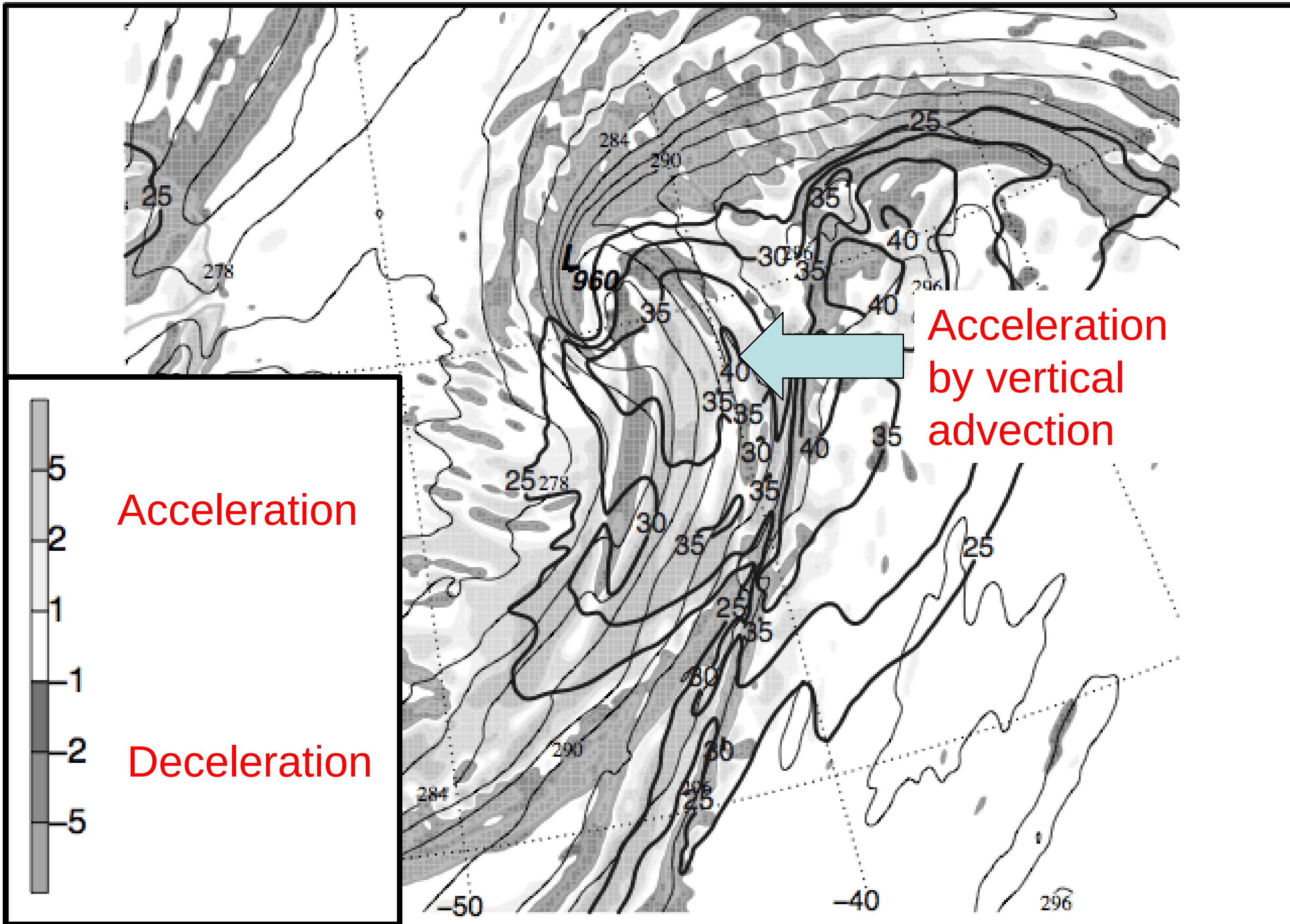
Slater et al. (2014)




Slater et al. (2014)

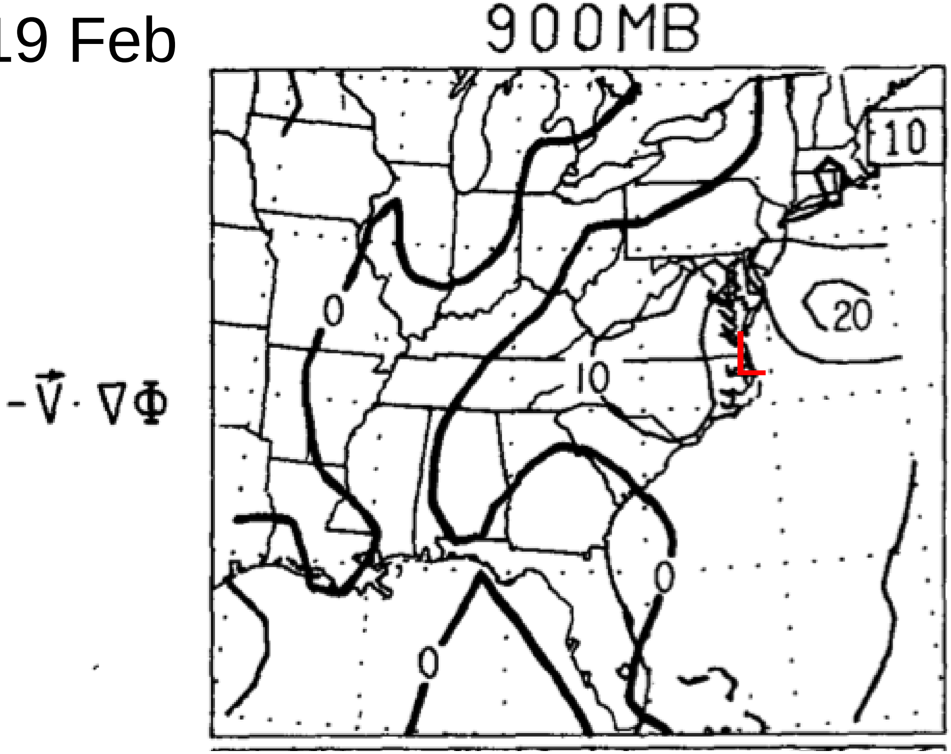



(c) 1800 UTC 7 DEC 2005 850 mb Wind Speed, Height, PGF



(c) 1800 UTC 7 DEC 2005 850 mb Wind Speed, Theta, VADV

12 UTC 19 Feb




generation of kinetic energy by cross-contour flow

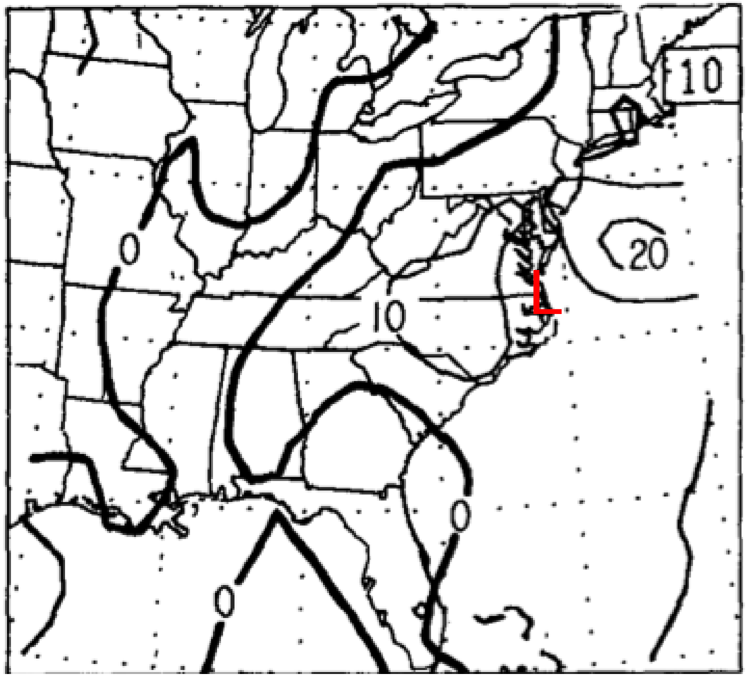
(also shown by Whitaker et al. 1988)

Bosart and Lin (1984)

12 UTC 19 Feb

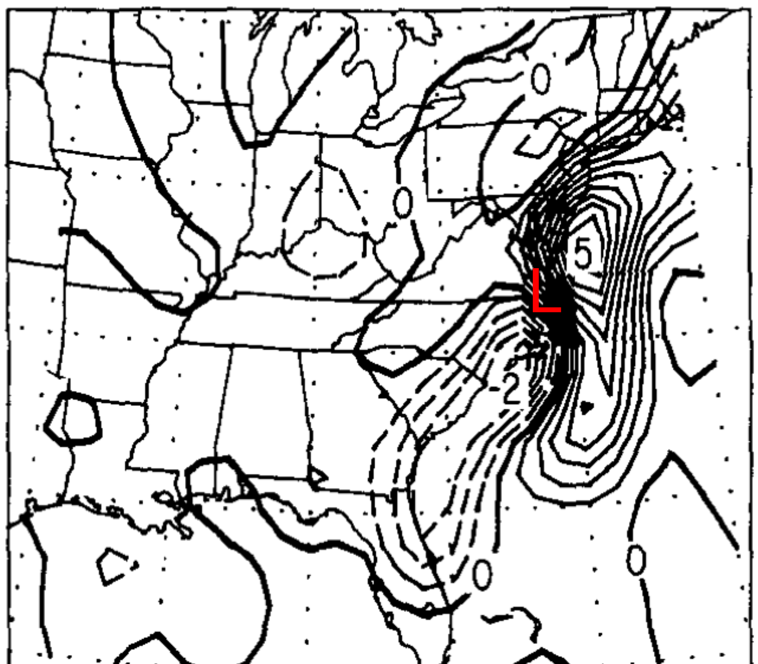
900MB

$-\vec{V} \cdot \nabla\Phi$




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)

# 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

# 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
- 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.

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

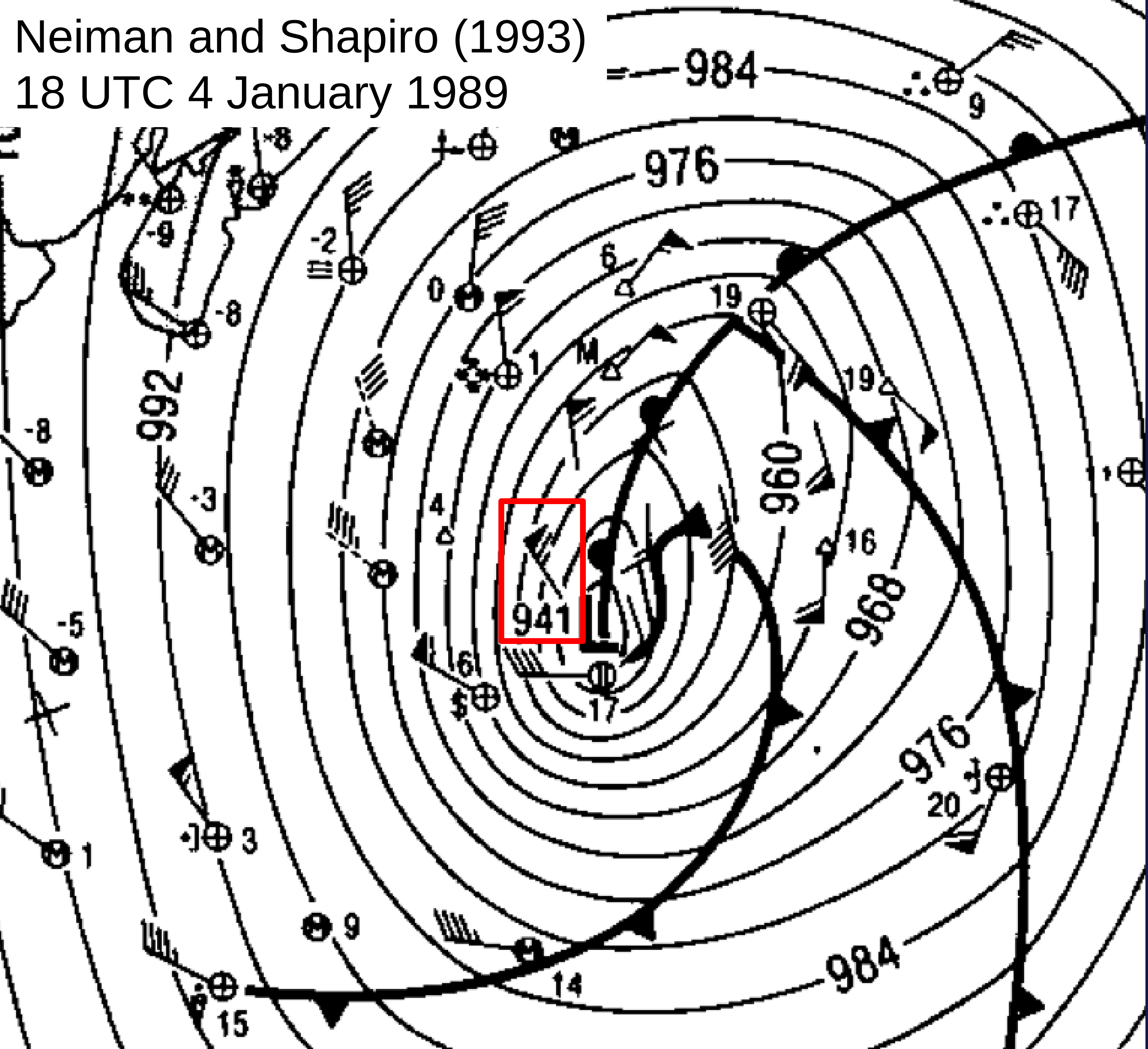
Single wind-speed maximum could derive from two different mechanisms.

- Acceleration due to pressure-gradient force
- Downward advection of momentum

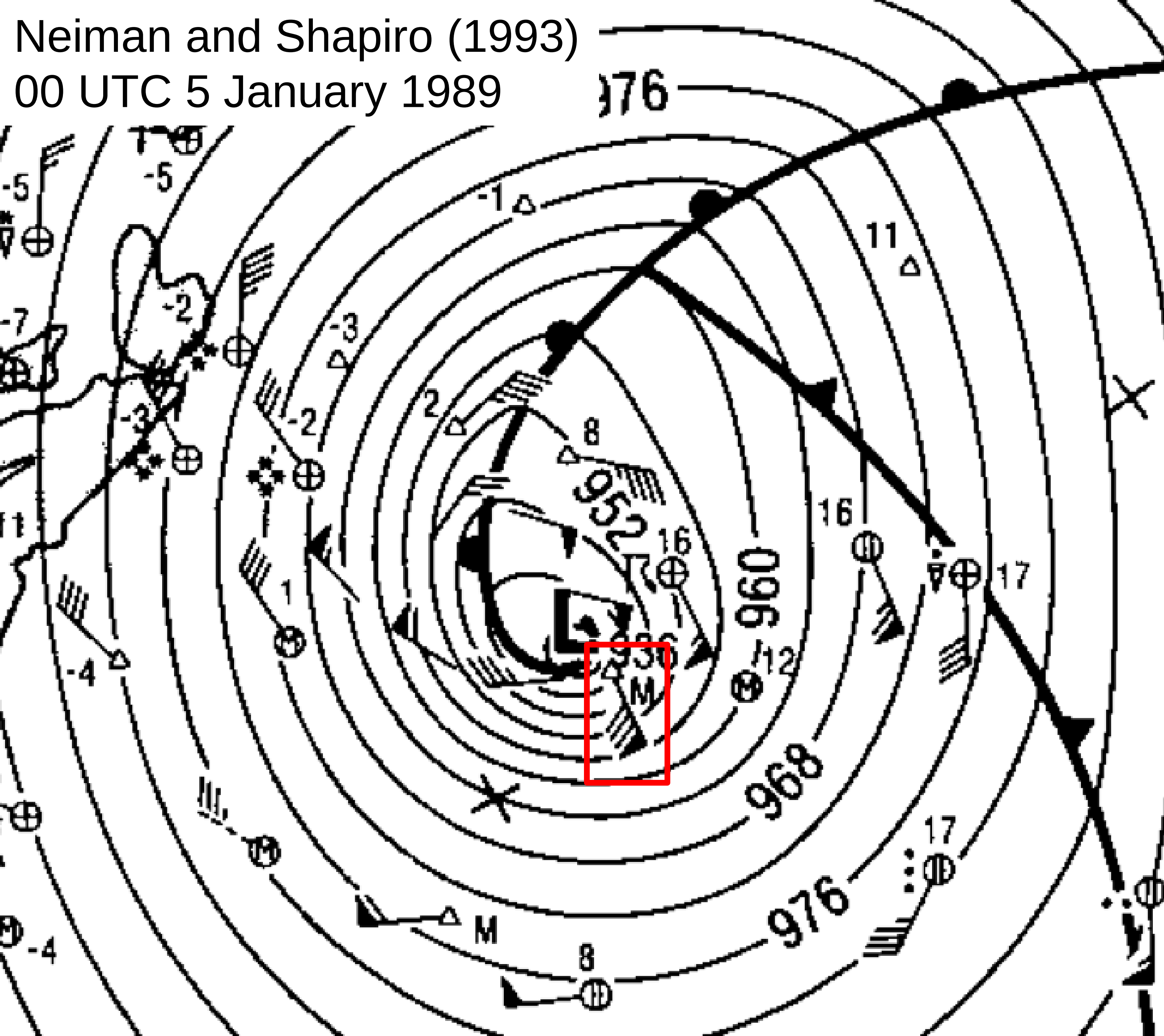
Schultz, D. M., and J. M. Sienkiewicz, 2013: Using frontogenesis to identify sting jets in extratropical cyclones. *Wea. Forecasting,* **28,** 603–613.

Slater, T., D. M. Schultz, and G. Vaughan, 2014: Acceleration of near-surface strong winds in a dry, idealised extratropical cyclone. *QJRMS,* submitted.

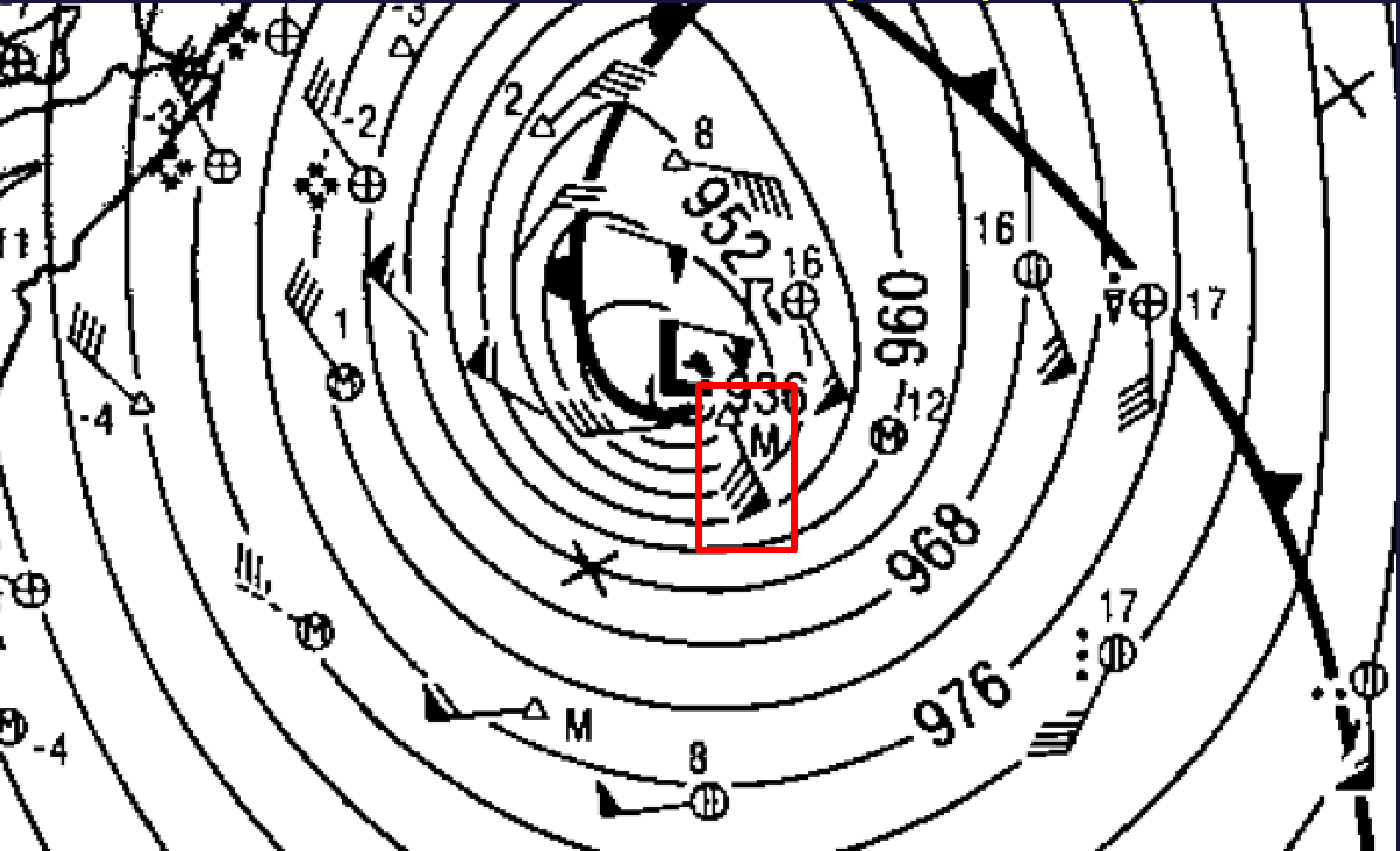
Neiman and Shapiro (1993)
18 UTC 4 January 1989



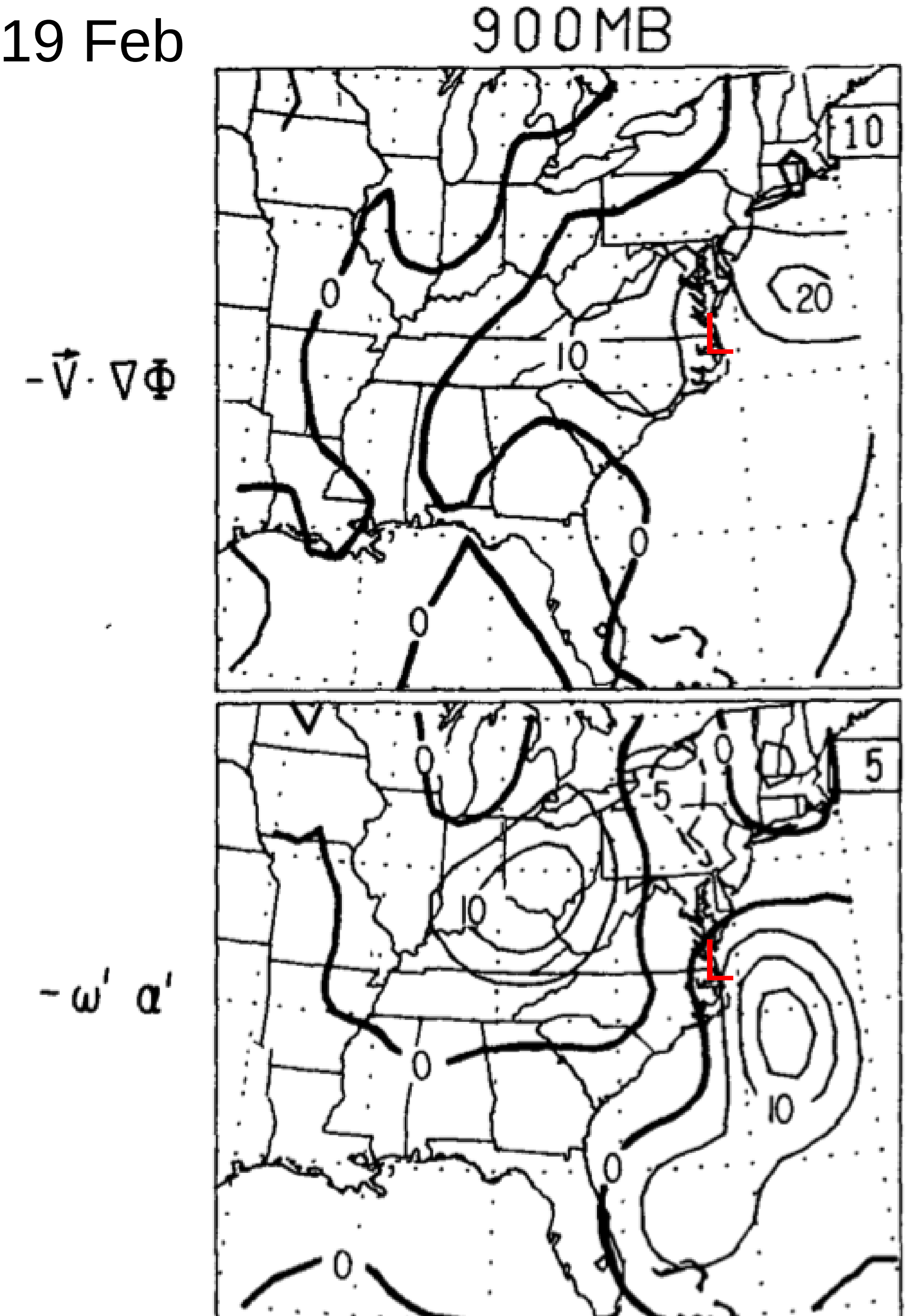
Neiman and Shapiro (1993)
00 UTC 5 January 1989



"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)



12 UTC 19 Feb



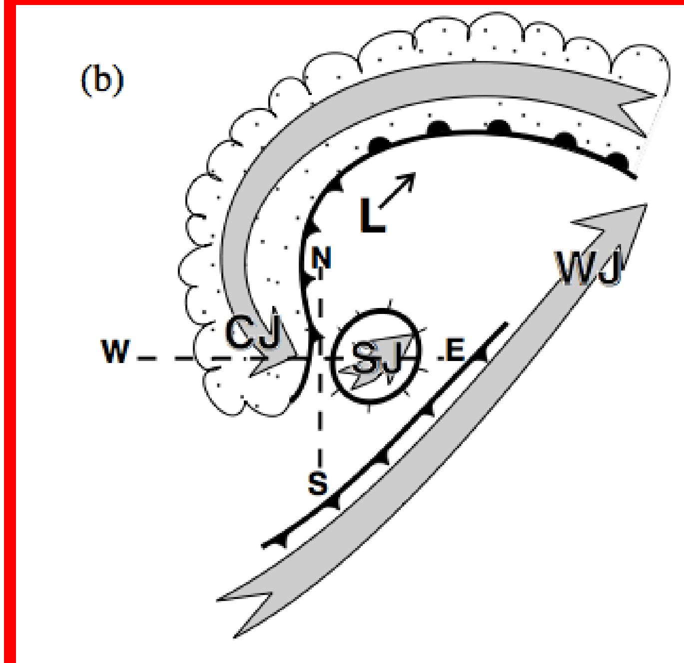

generation of kinetic energy by cross-contour flow

conversion of eddy available potential energy to eddy kinetic energy

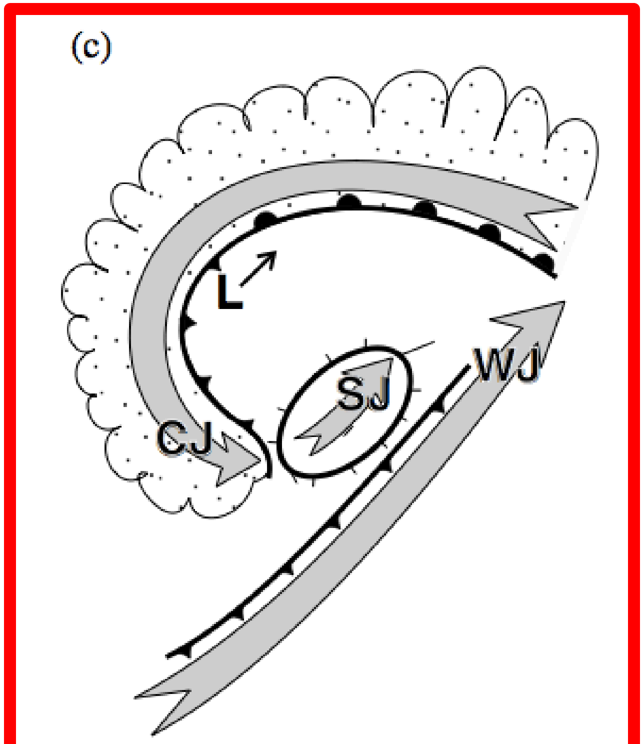
Bosart and Lin (1984)

Relationship between front and sting jet?

Descending sting jet distinct from cold-conveyor belt?




evolution of surface airstreams and fronts

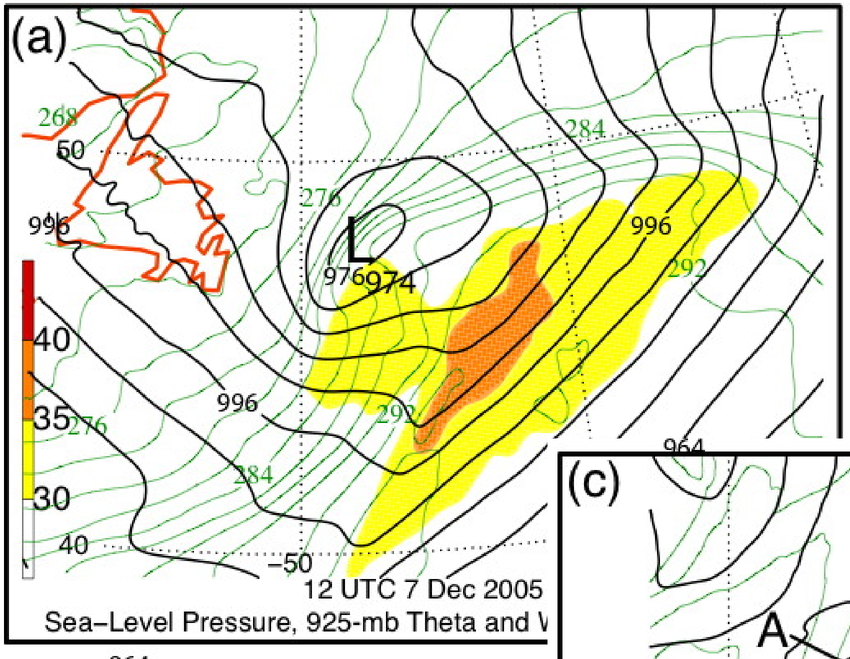



Dynamics of strong winds in cyclones

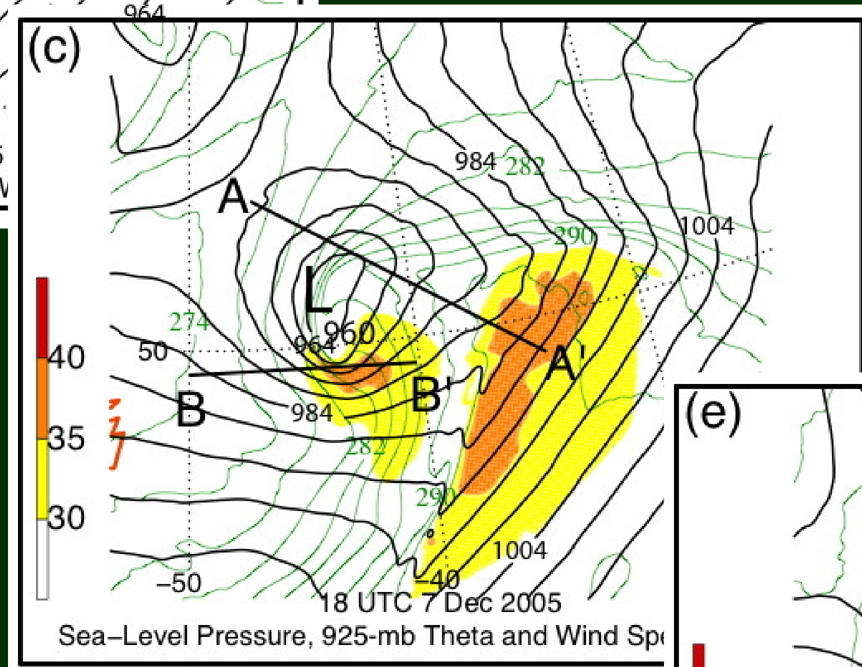
Clark et al. (2005)

# Schultz and Sienkiewicz
# Storm

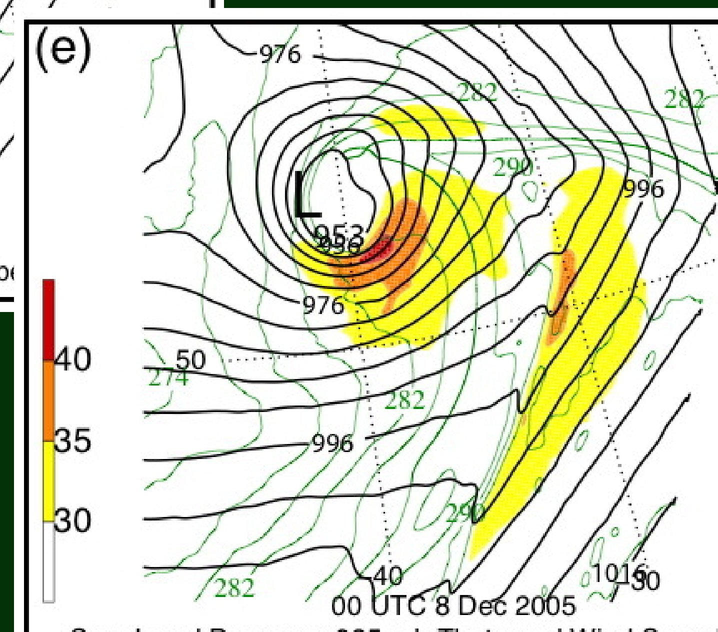
## 12 UTC 7 Dec



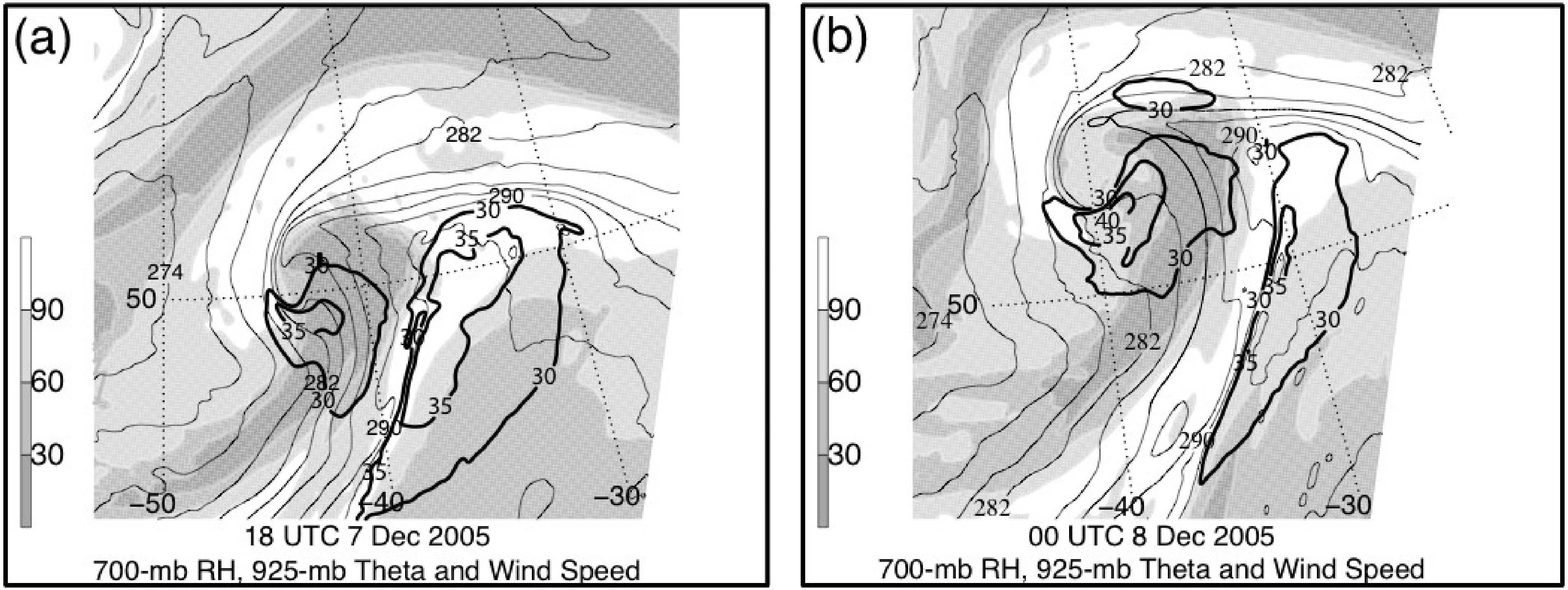

## 18 UTC 7 Dec



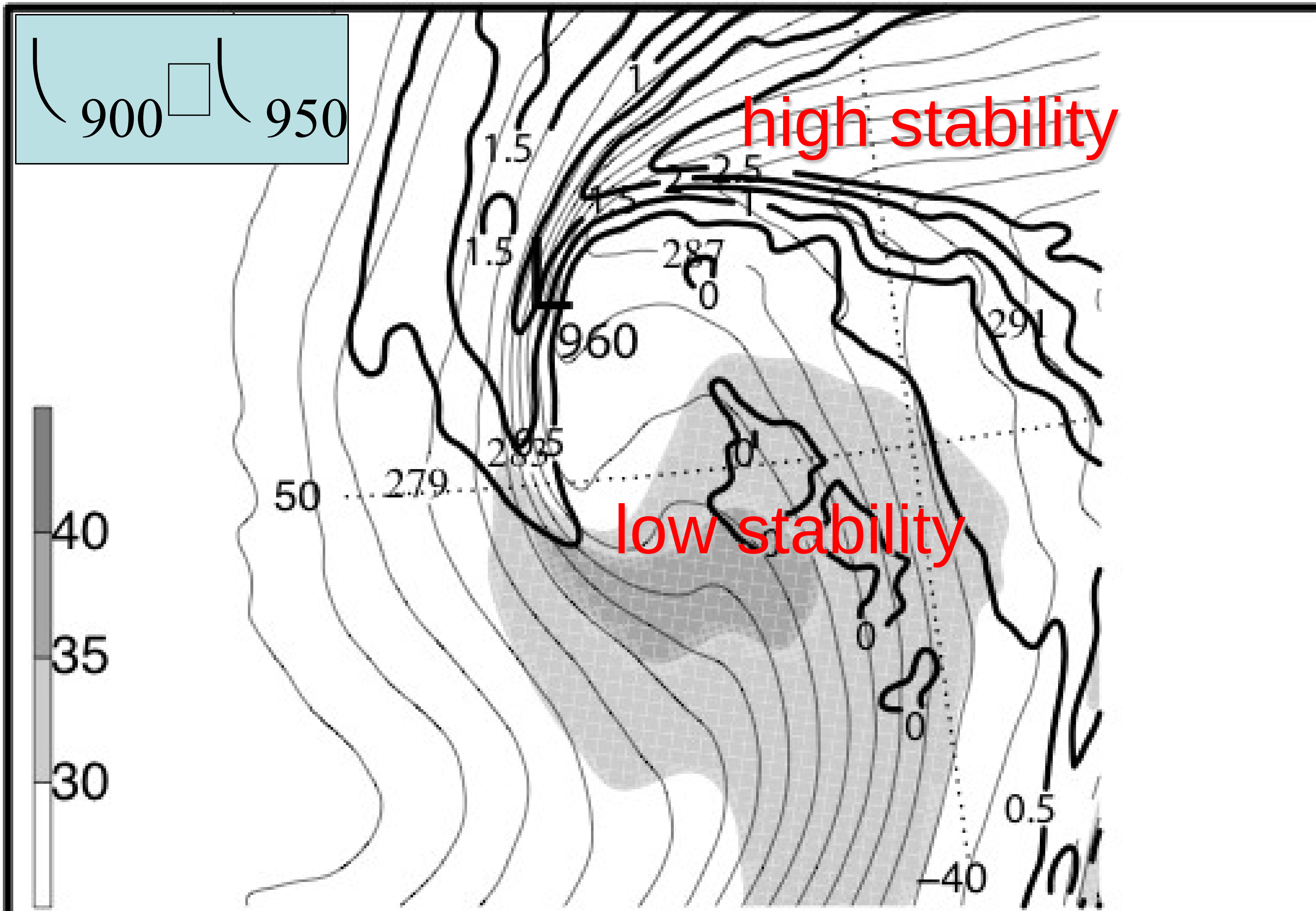

## 00 UTC 8 Dec



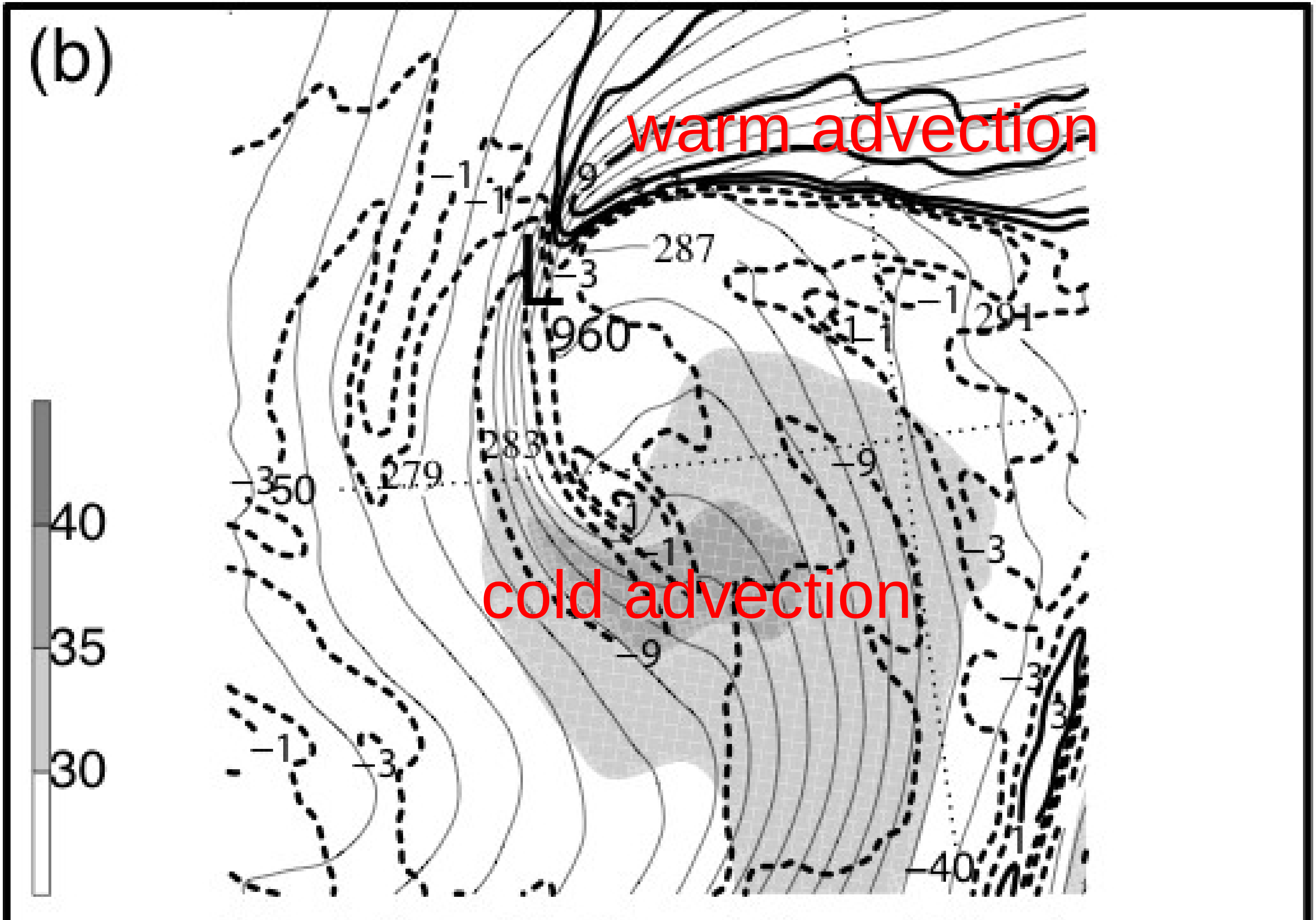

Sea-level pressure
925-mb theta
wind speed (shaded)



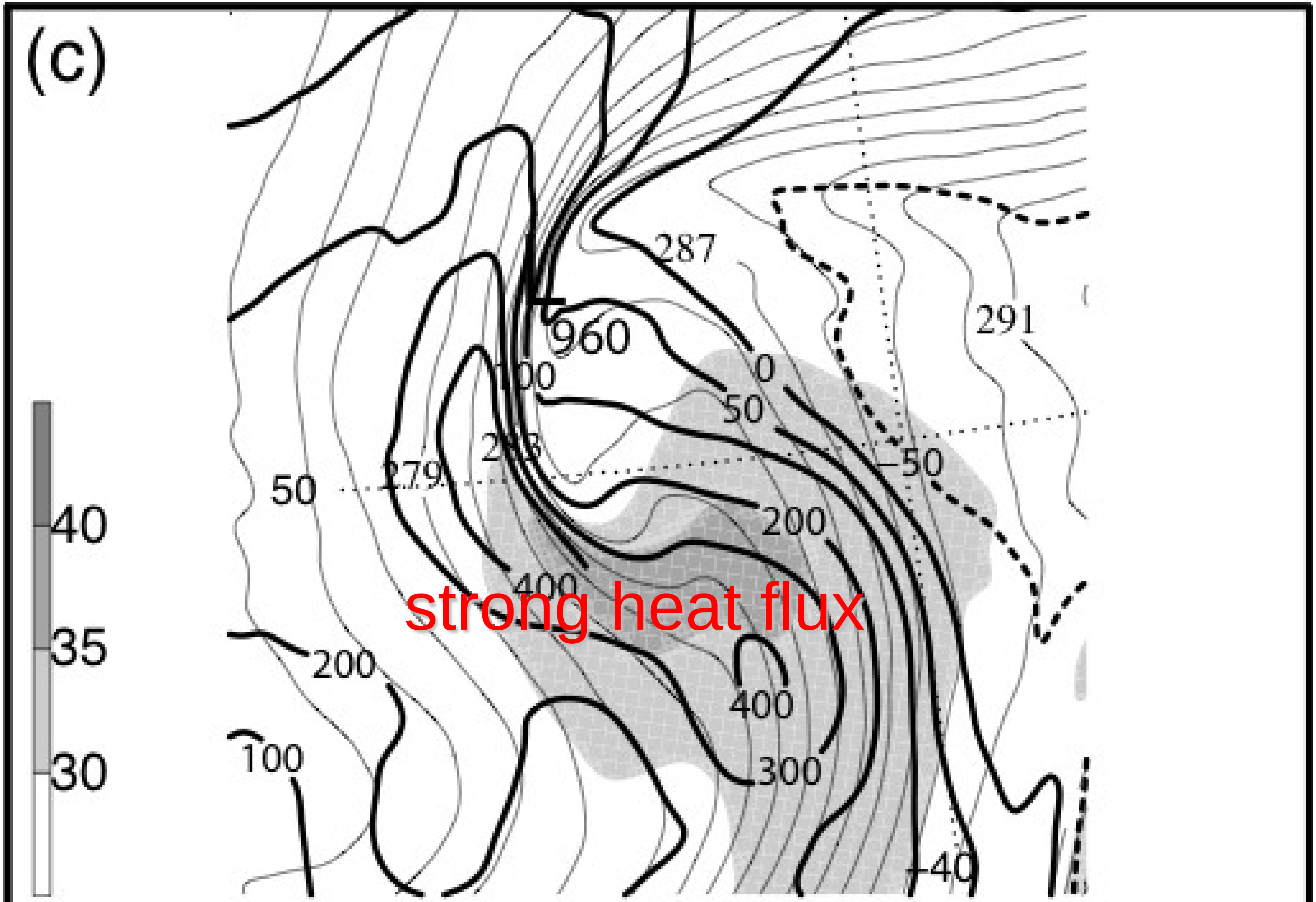

700-mb relative humidity (shaded)
925-mb theta
925-mb wind speed



925-mb Theta, Wind Speed, Static Stability

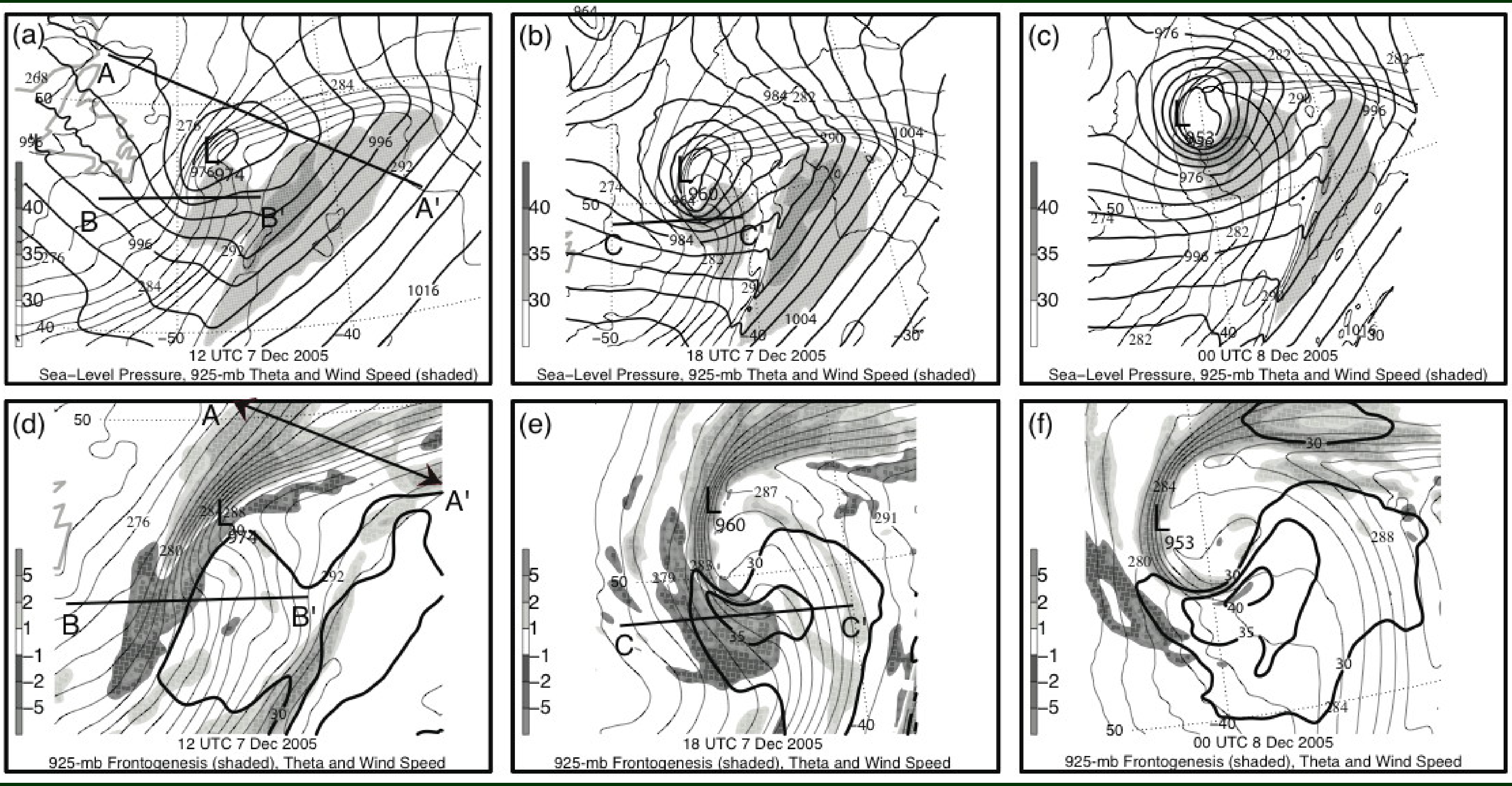



925-mb Theta, Wind Speed, Thermal Advection




925-mb Theta and Wind Speed, Surface Sensible Heat Flux

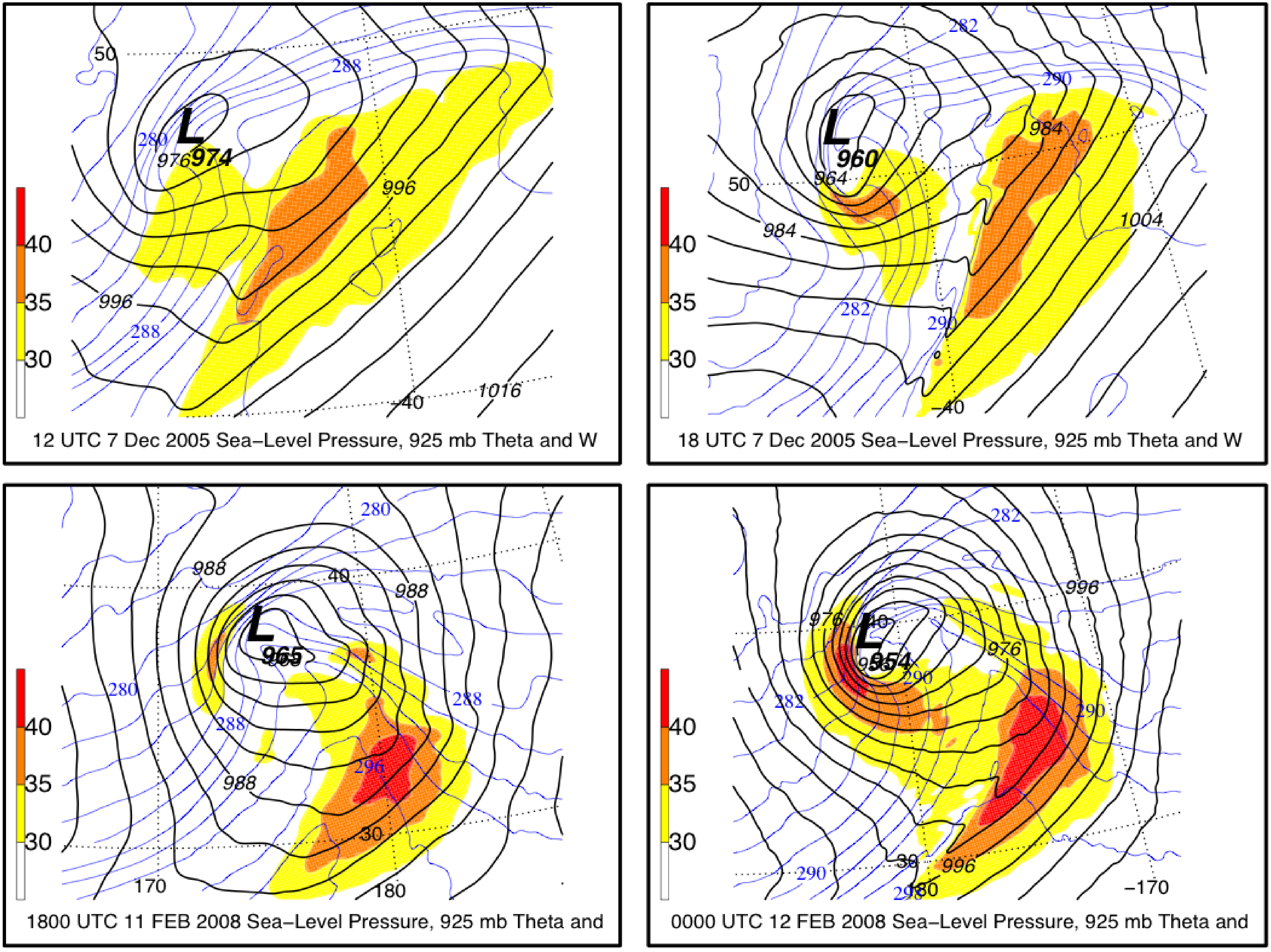
Top: sea-level pressure, 925-mb theta, wind speed (shaded)



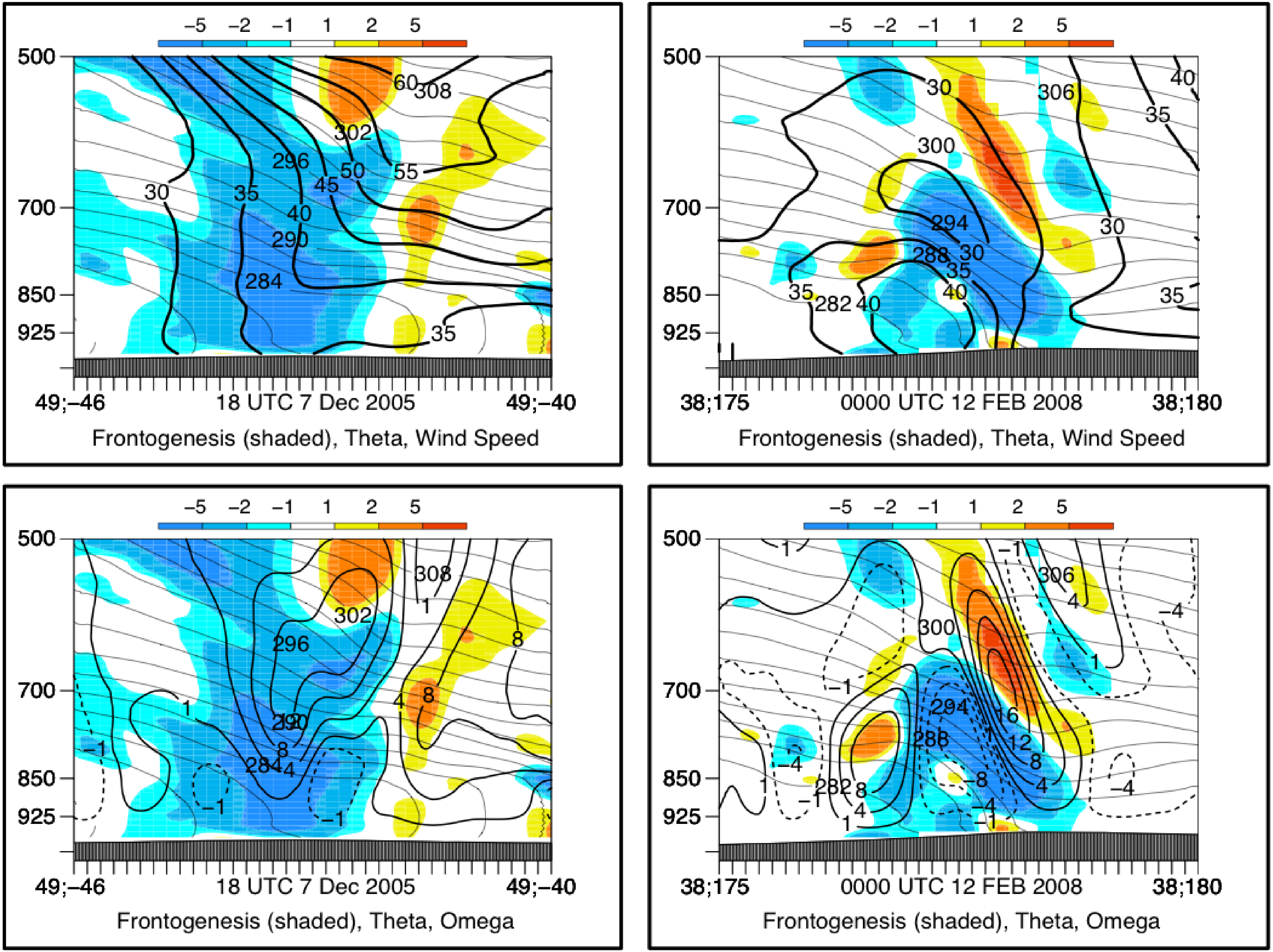

12 UTC 7 Dec 18 UTC 7 Dec 00 UTC 8 Dec

Bottom: 925-mb theta, wind speed, frontogenesis (shaded)

# COMPARISON



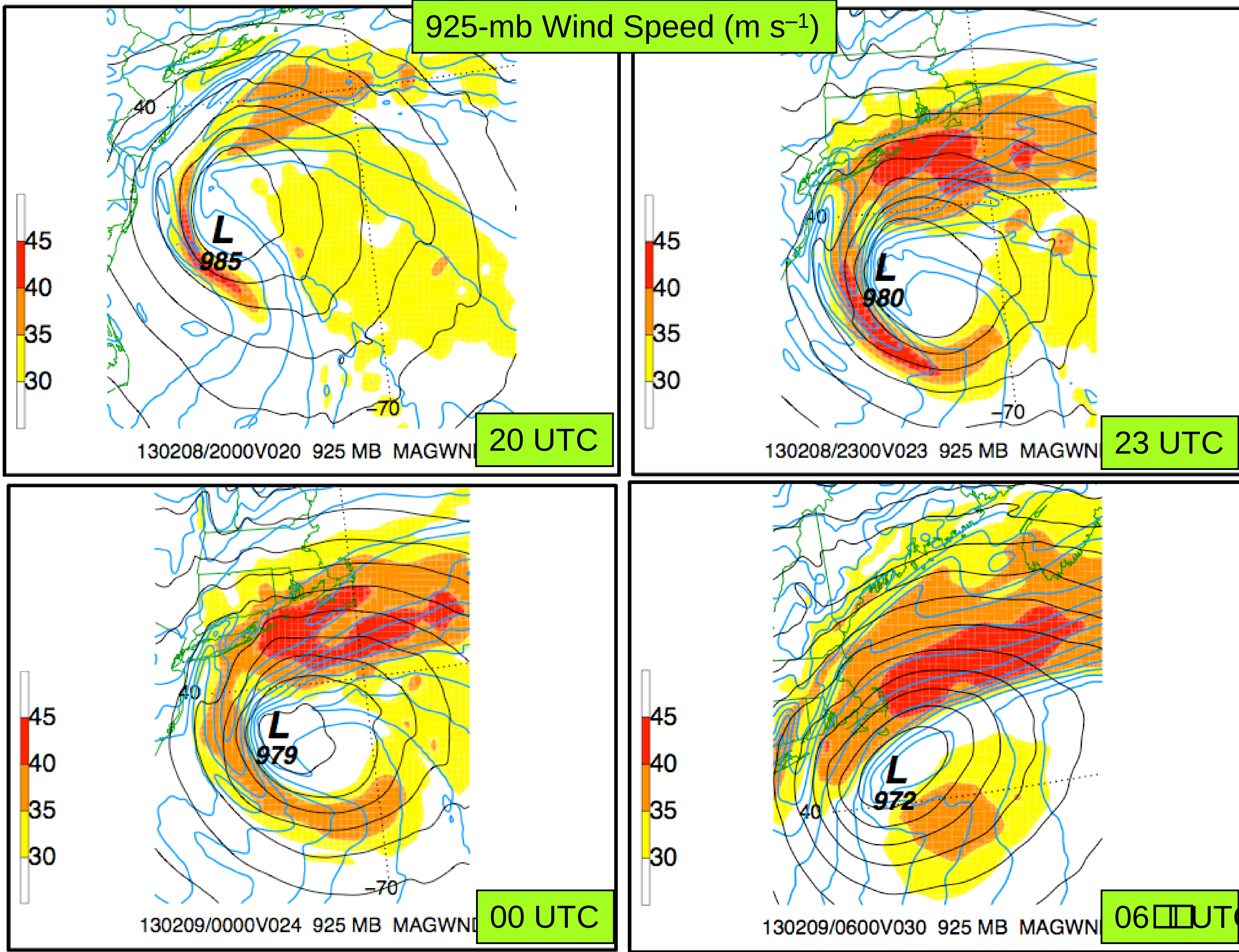
12 UTC 7 Dec 2005 Sea–Level Pressure, 925 mb Theta and W
18 UTC 7 Dec 2005 Sea–Level Pressure, 925 mb Theta and W
1800 UTC 11 FEB 2008 Sea–Level Pressure, 925 mb Theta and
0000 UTC 12 FEB 2008 Sea–Level Pressure, 925 mb Theta and
L
974
960
965
954
996
1016
984
1004
988
976
40
35
30
50
-40
170
180
-170
280
282
288
290
296

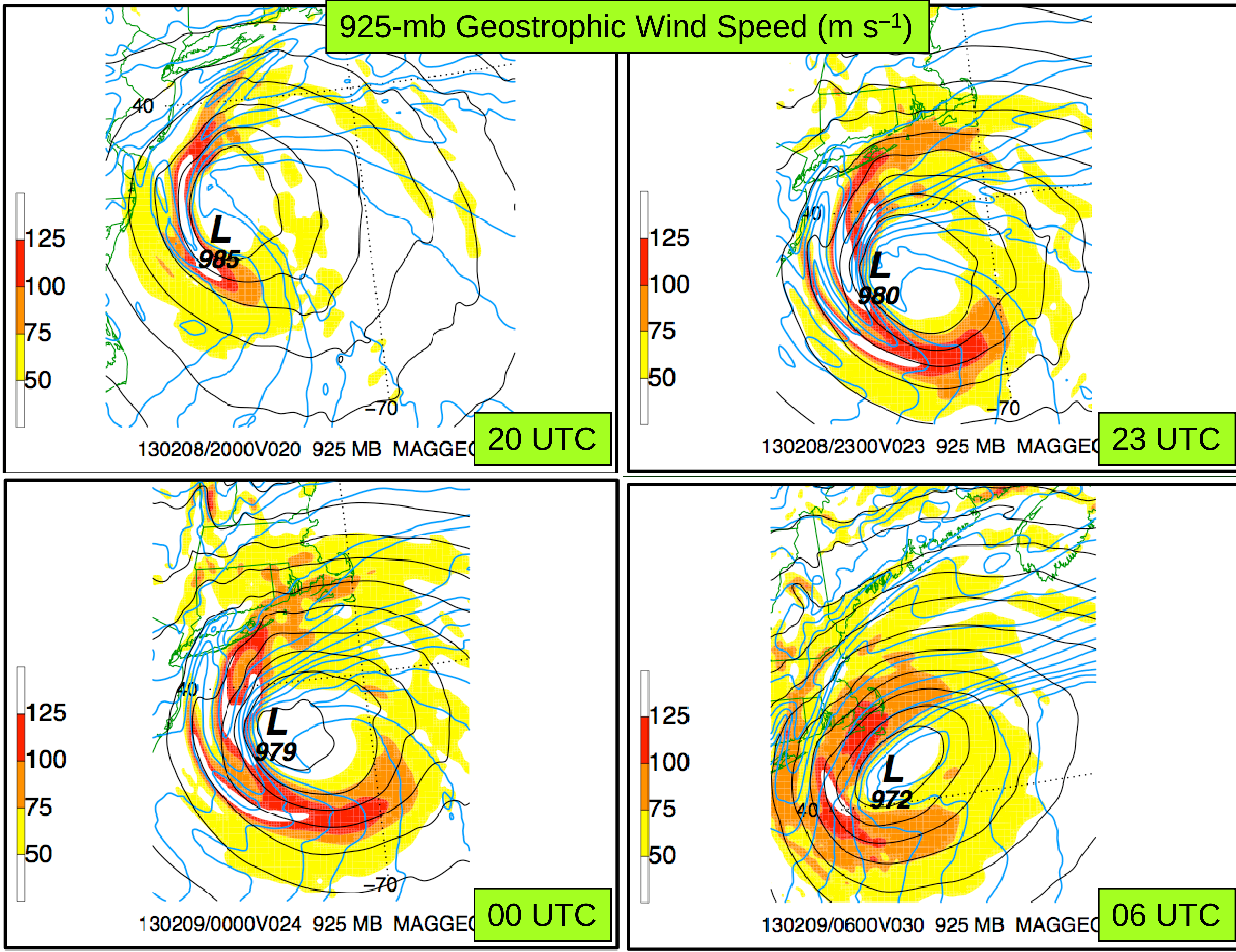


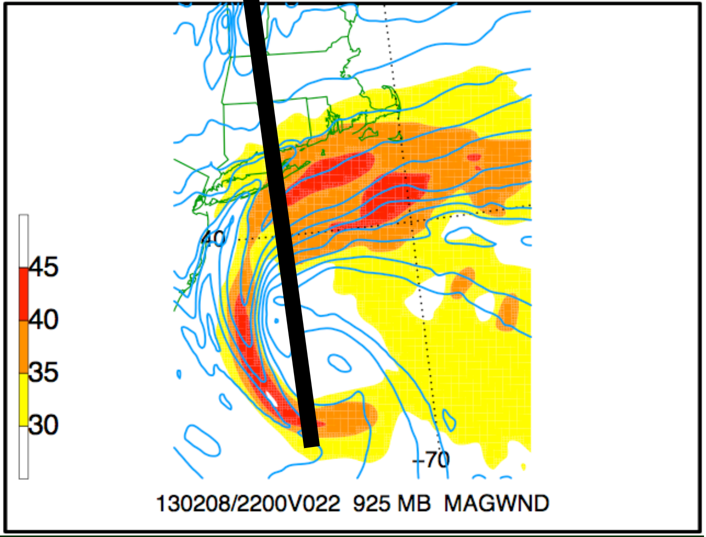
−5 −2 −1 1 2 5
500
700
850
925
49;−46
18 UTC 7 Dec 2005
49;−40
Frontogenesis (shaded), Theta, Wind Speed
38;175
0000 UTC 12 FEB 2008
38;180
Frontogenesis (shaded), Theta, Wind Speed
49;−46
18 UTC 7 Dec 2005
49;−40
Frontogenesis (shaded), Theta, Omega
38;175
0000 UTC 12 FEB 2008
38;180
Frontogenesis (shaded), Theta, Omega

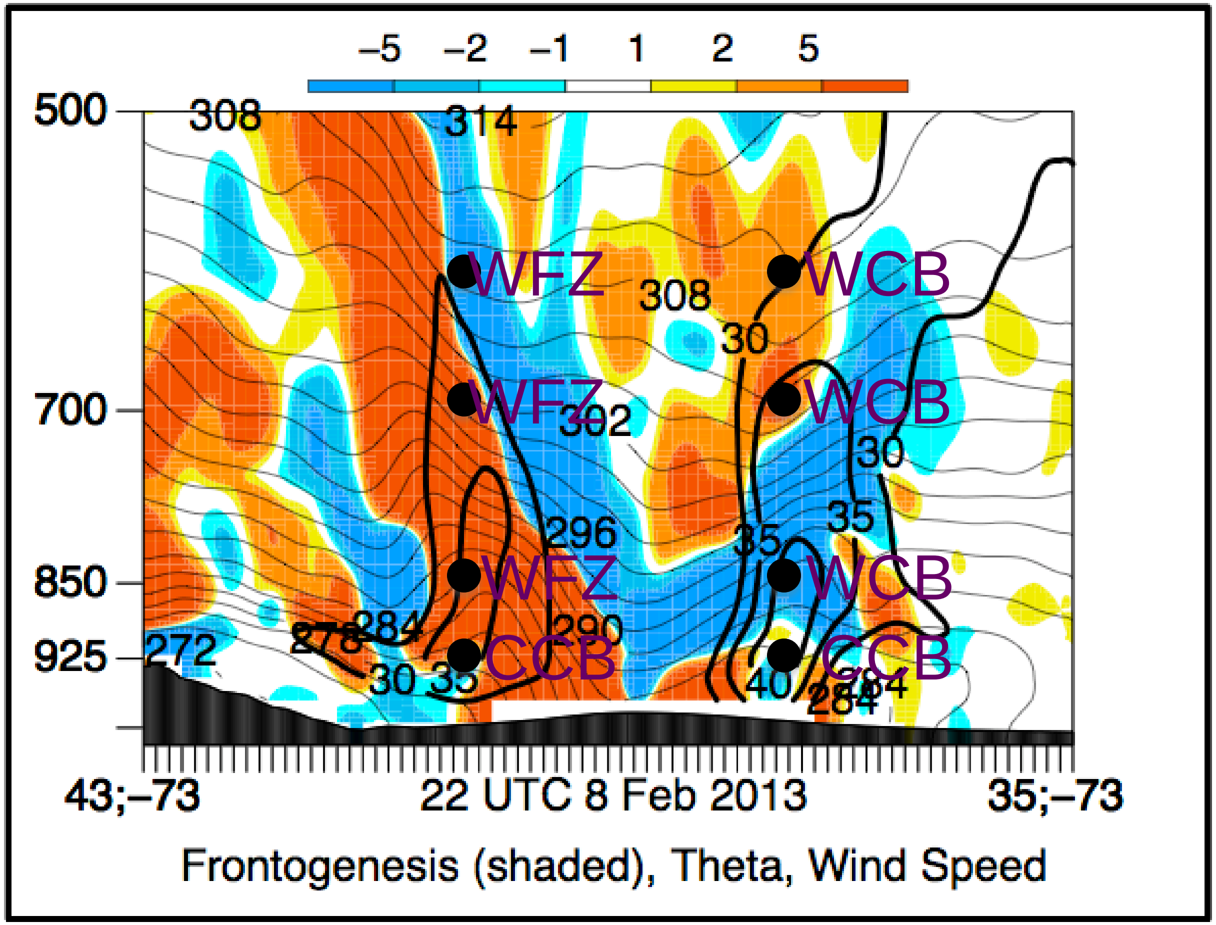
# NEMO STORM

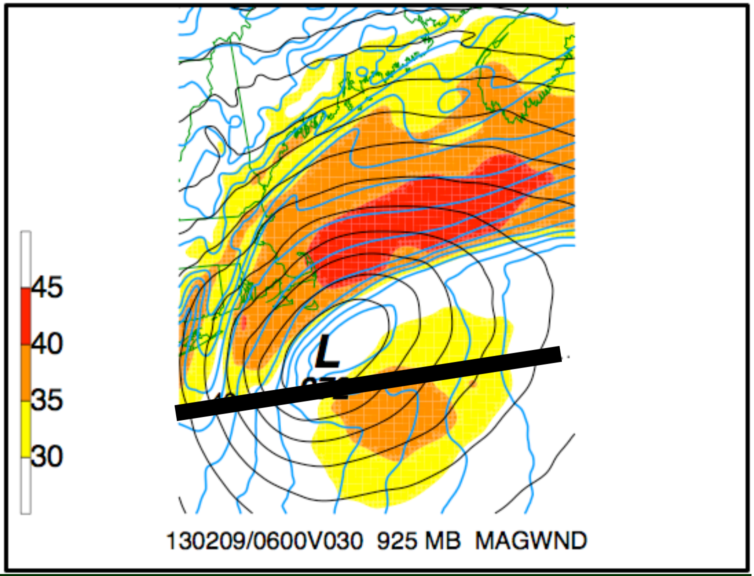
# 925-mb Wind Speed (m s$^{-1}$)

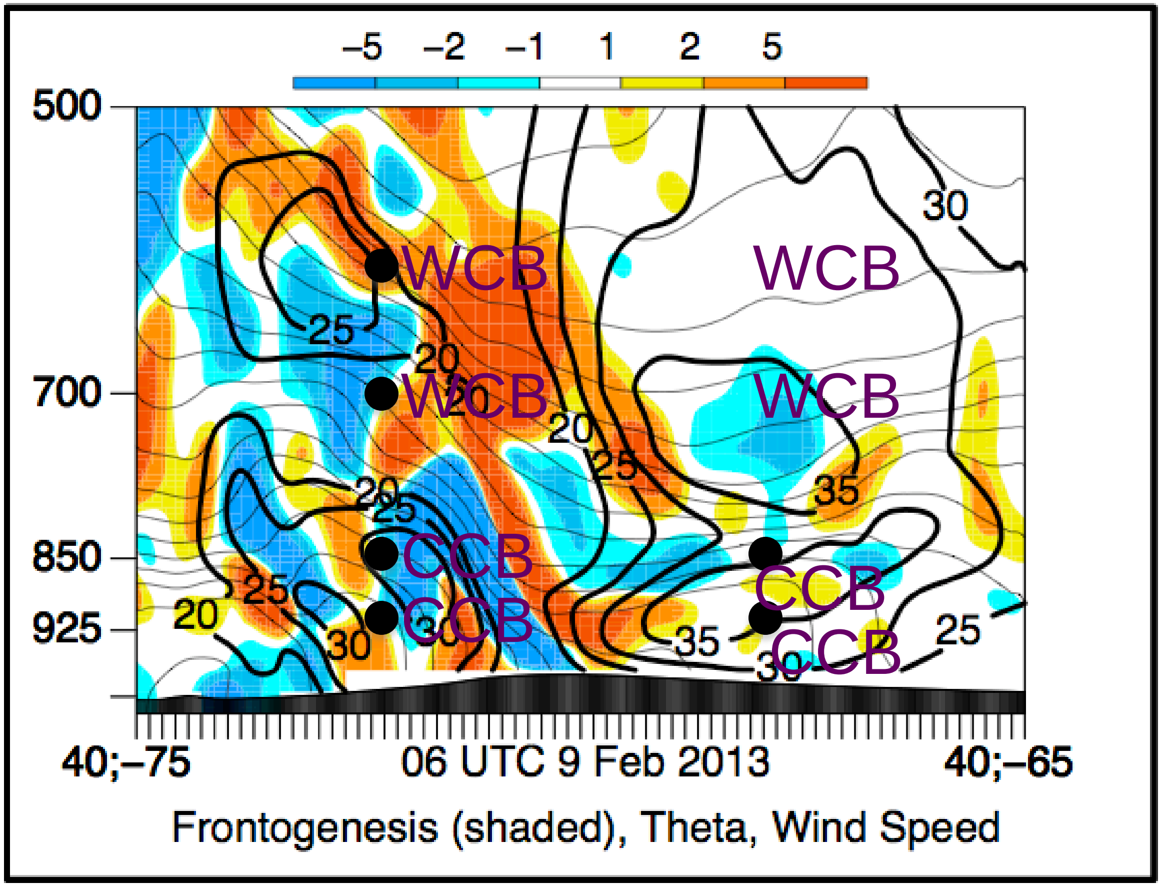



925-mb Geostrophic Wind Speed (m s−1)
20 UTC
130208/2000V020 925 MB MAGGEO
L
985
40
−70
125
100
75
50
23 UTC
130208/2300V023 925 MB MAGGEO
L
980
40
−70
125
100
75
50
00 UTC
130209/0000V024 925 MB MAGGEO
L
979
40
−70
125
100
75
50
06 UTC
130209/0600V030 925 MB MAGGEO
L
972
40
125
100
75
50

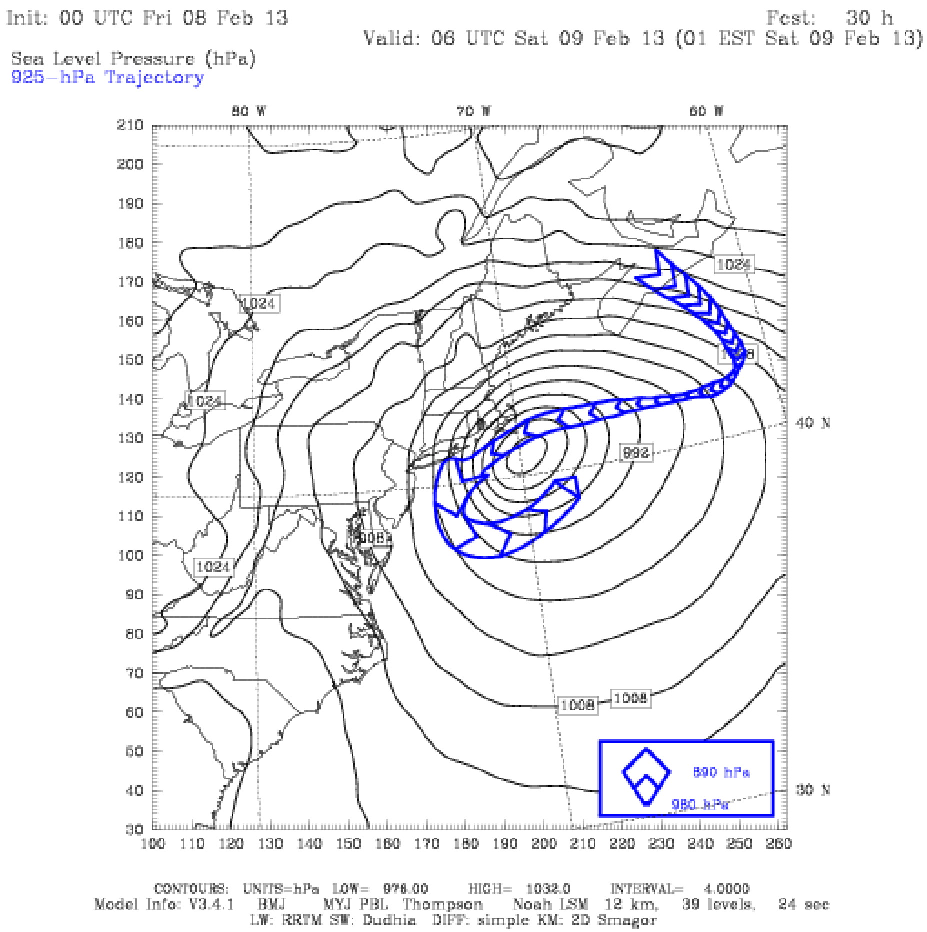

45
40
35
30
40
-70
130208/2200V022 925 MB MAGWND


-5 -2 -1 1 2 5
500
700
850
925
WFZ
WFZ
WFZ
CCB
WCB
WCB
WCB
CCB
43;-73
22 UTC 8 Feb 2013
35;-73
Frontogenesis (shaded), Theta, Wind Speed

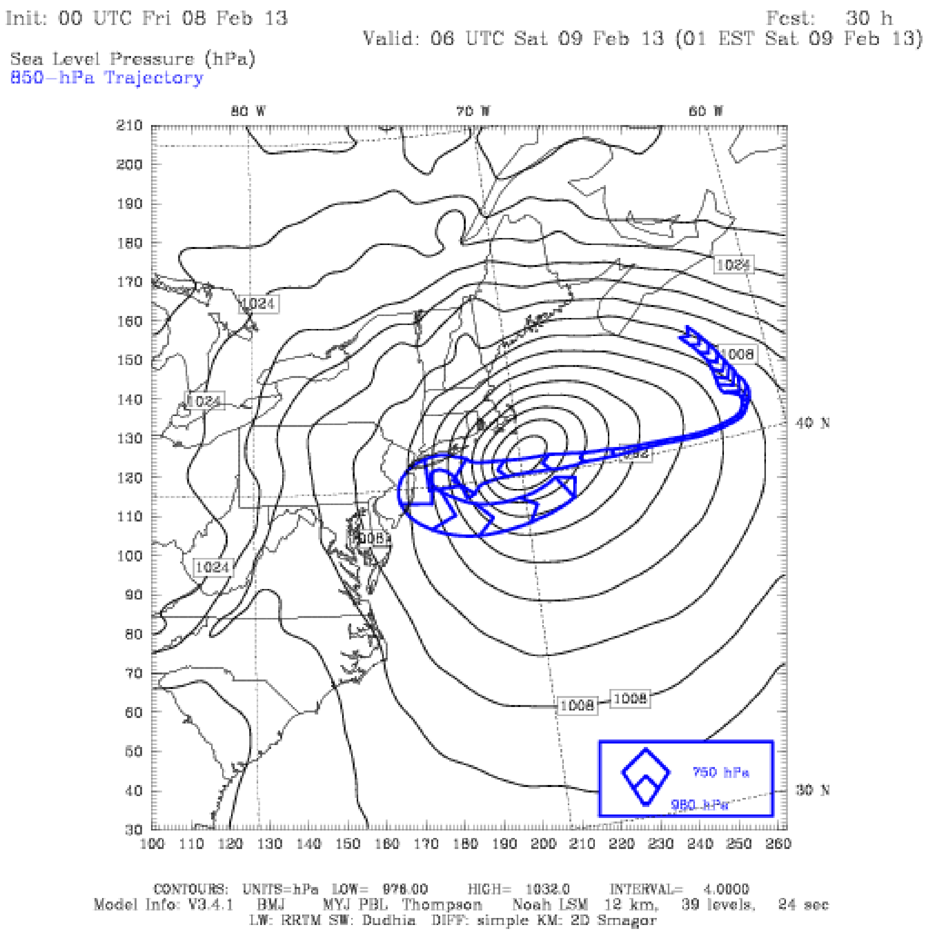

45
40
35
30
L
130209/0600V030 925 MB MAGWND


–5 –2 –1 1 2 5
500
700
850
925
WCB
WCB
WCB
WCB
CCB
CCB
CCB
CCB
40;–75
06 UTC 9 Feb 2013
40;–65
Frontogenesis (shaded), Theta, Wind Speed

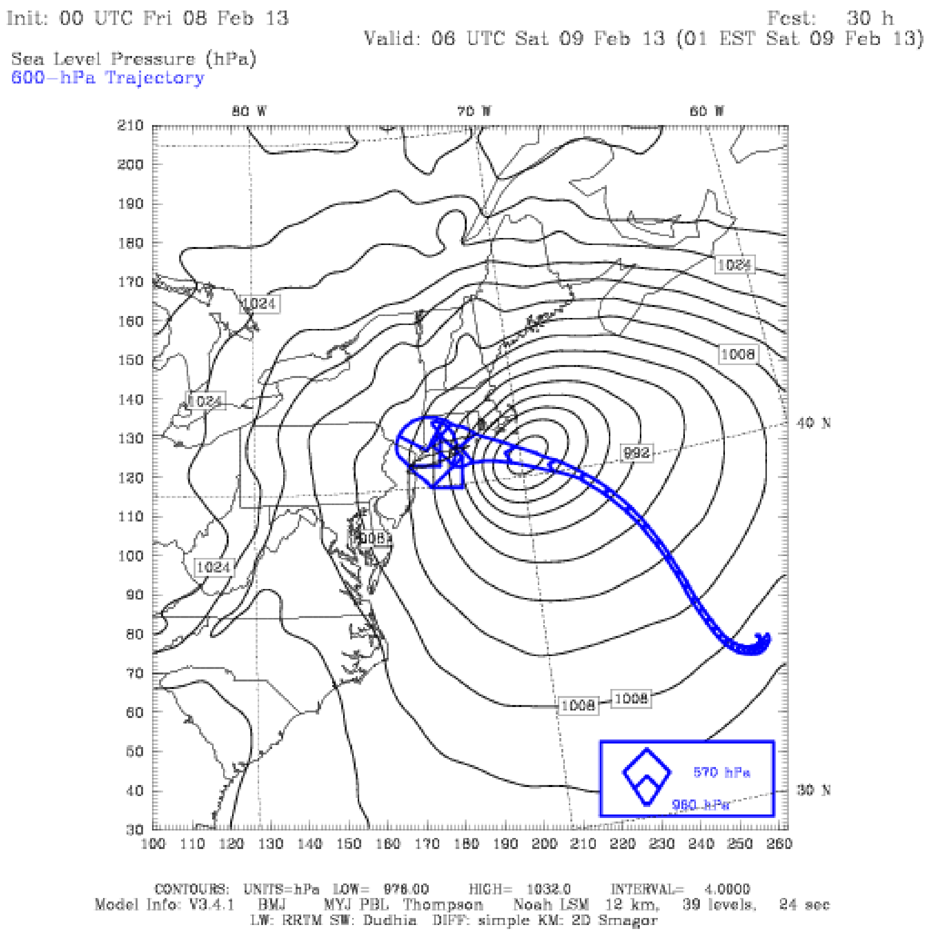
# trajectories



# trajectories



# trajectories



# Summary

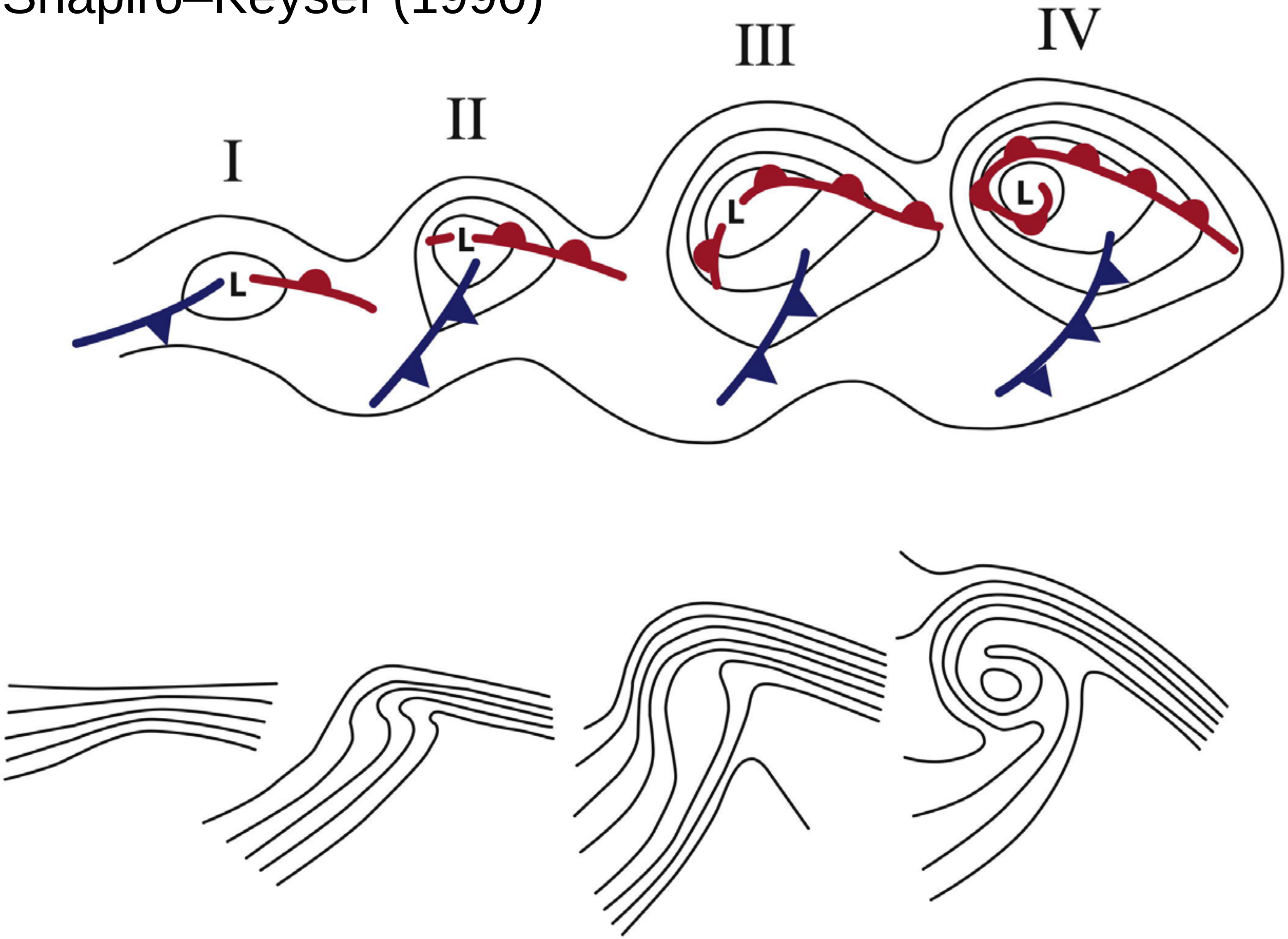
***Strong Winds***:

- 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

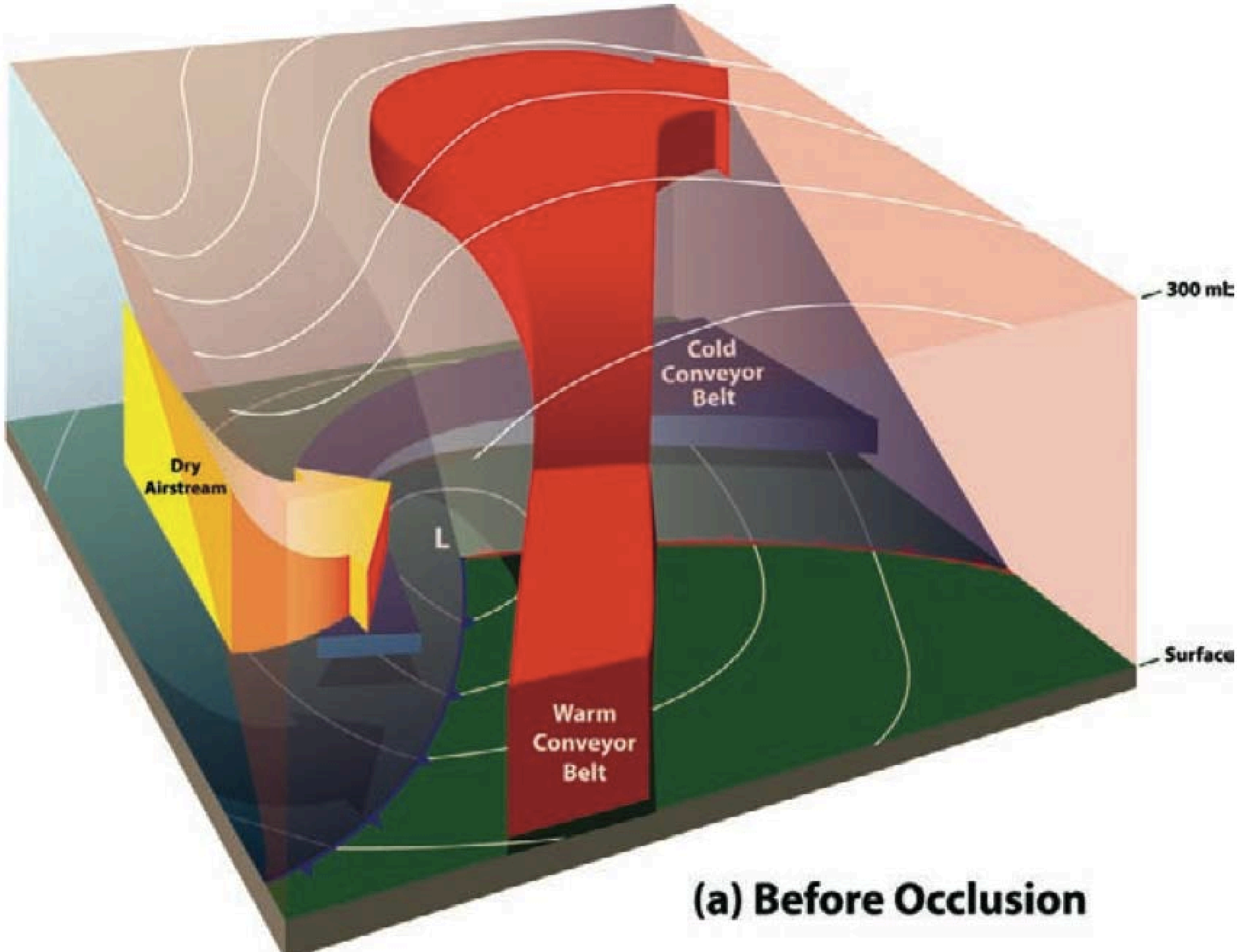
Shapiro–Keyser (1990)



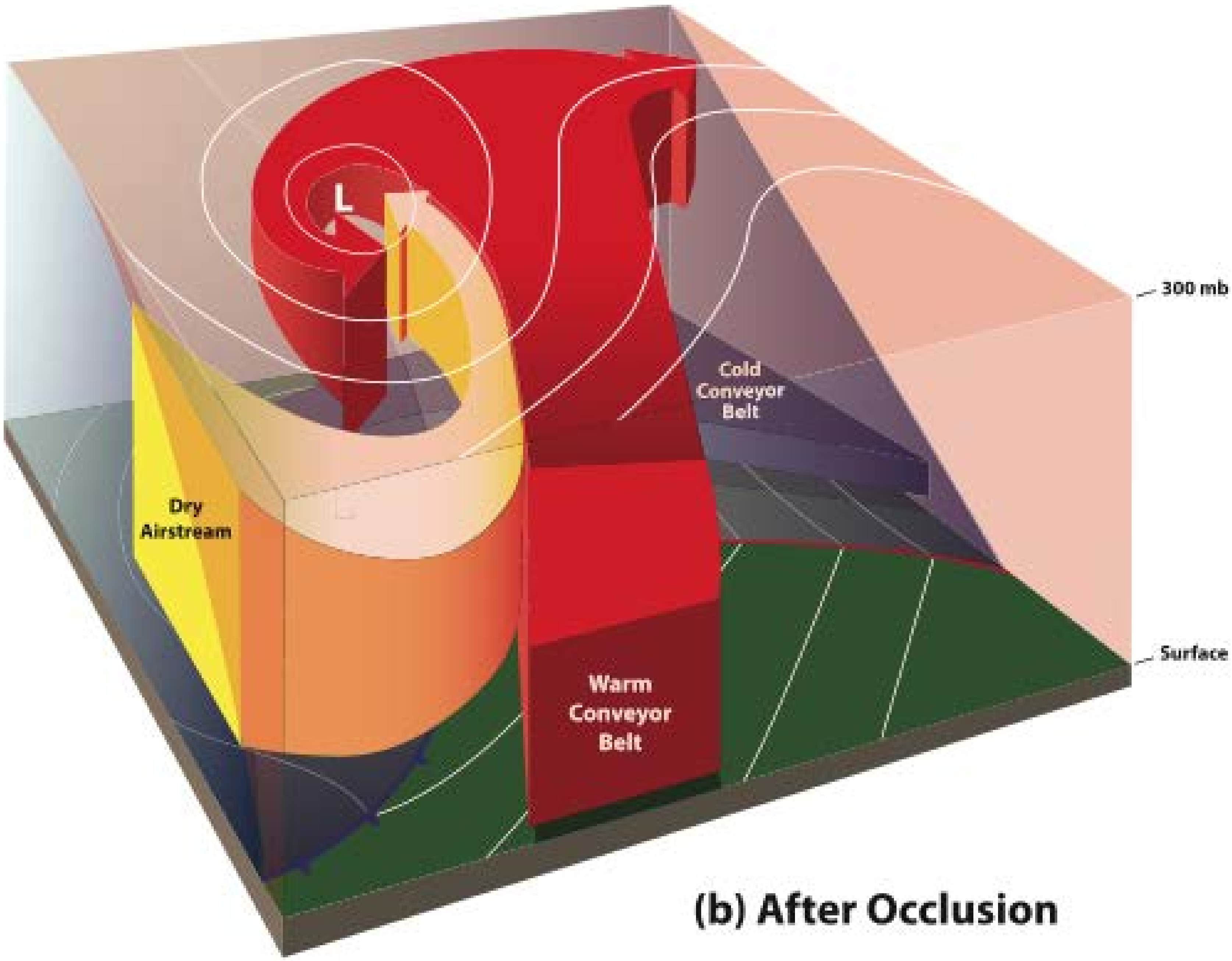

isobars

isotherms

Schultz and Vaughan (2011)



Schultz and Vaughan (2011)




(b) After Occlusion

# Ingredients for a Sting Jet

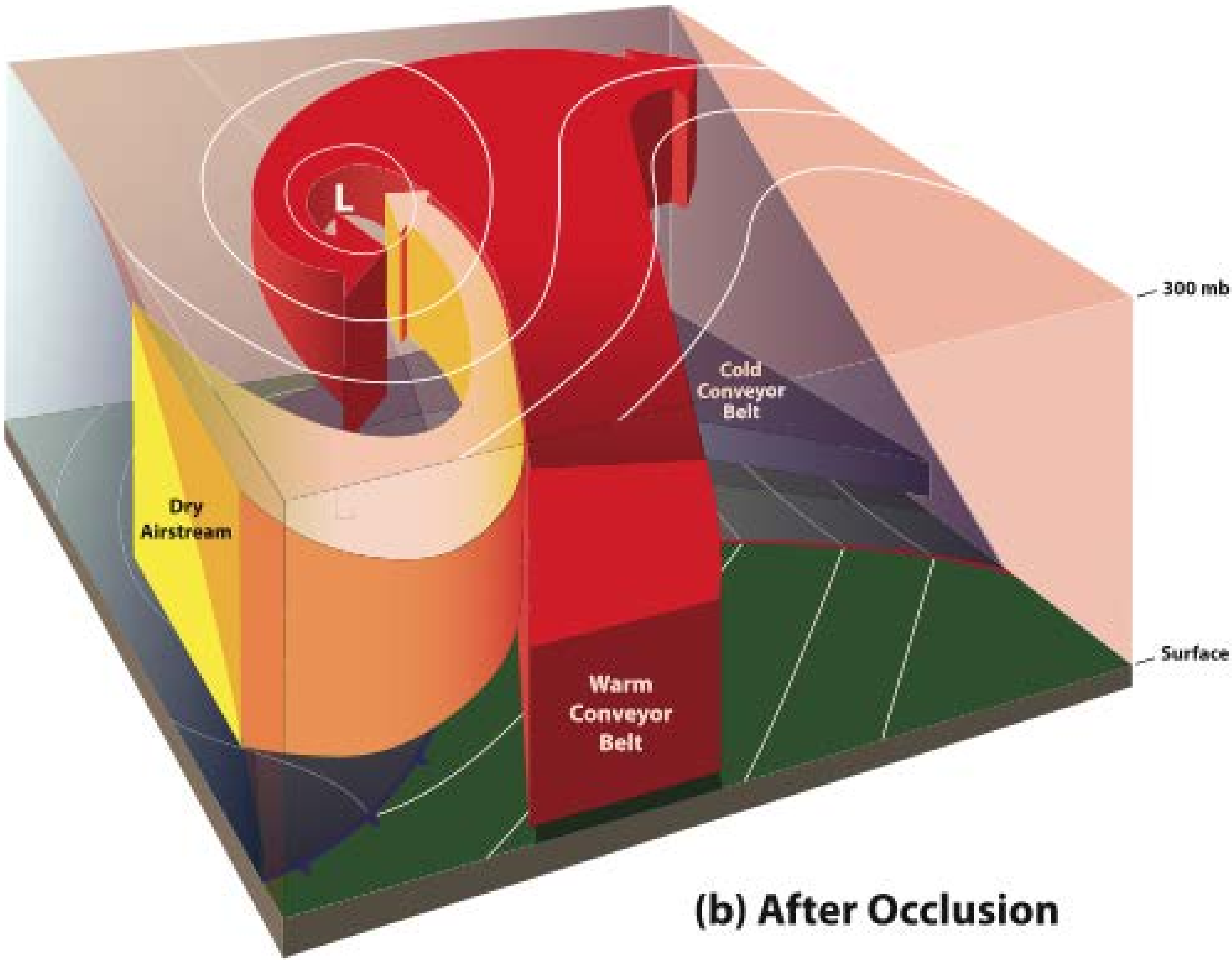
1. Frontogenesis and ascent of warm air along bent-back front.

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

3. Low static and symmetric stability favors descent.

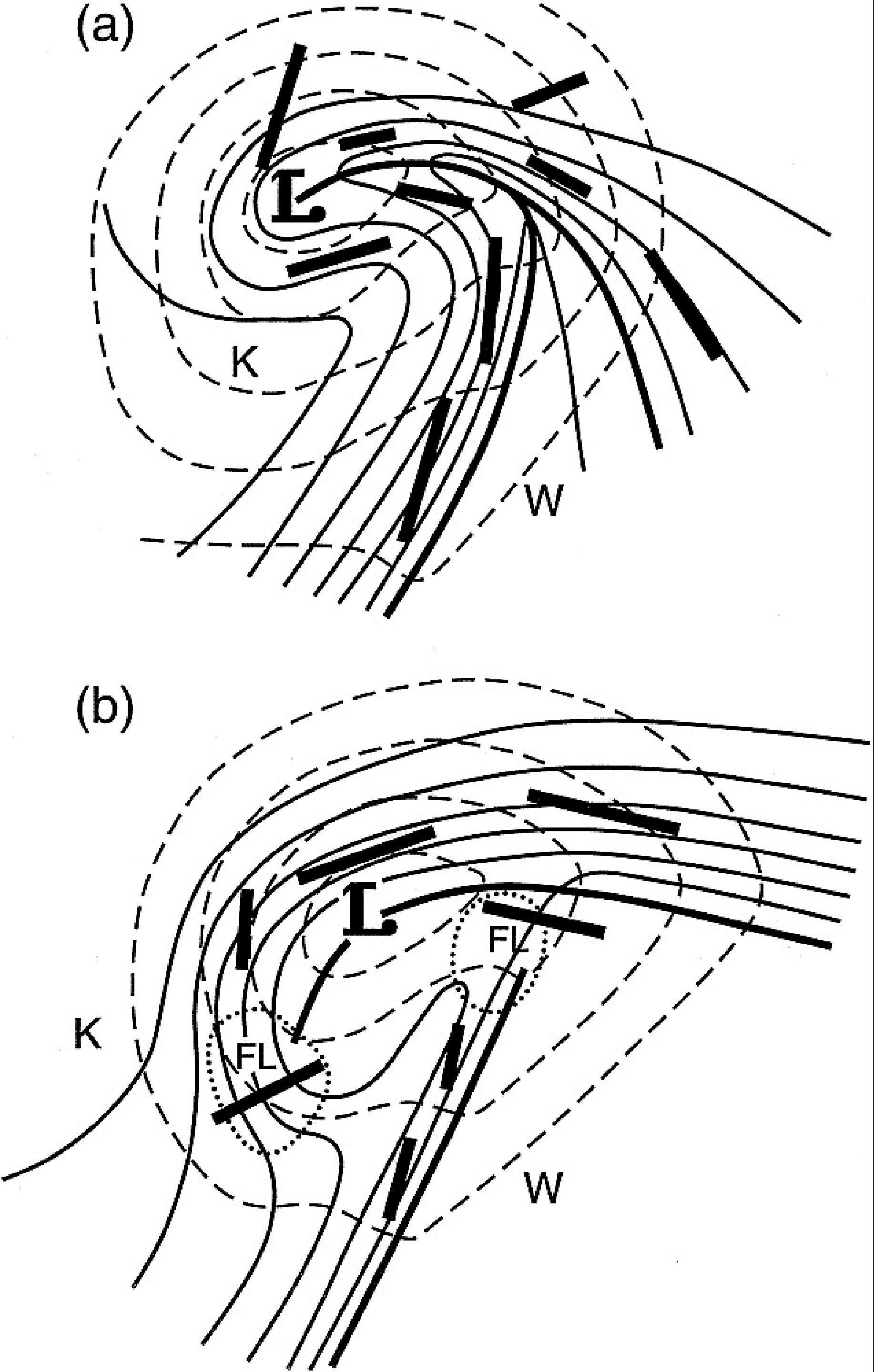
4. Near-neutral static stability in boundary layer favors mixing downward of high momentum air.

Schultz and Vaughan (2011)




(b) After Occlusion

*Why have sting jets only been documented in Shapiro–Keyser cyclones?*




# Norwegian Cyclone

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

# Shapiro–Keyser Cyclone

(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.

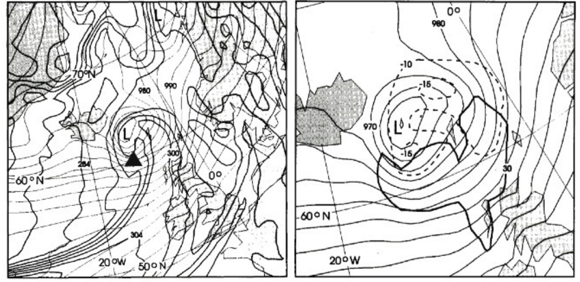
Why CSI results are ambiguous.

# Lessons from Today’s Talk

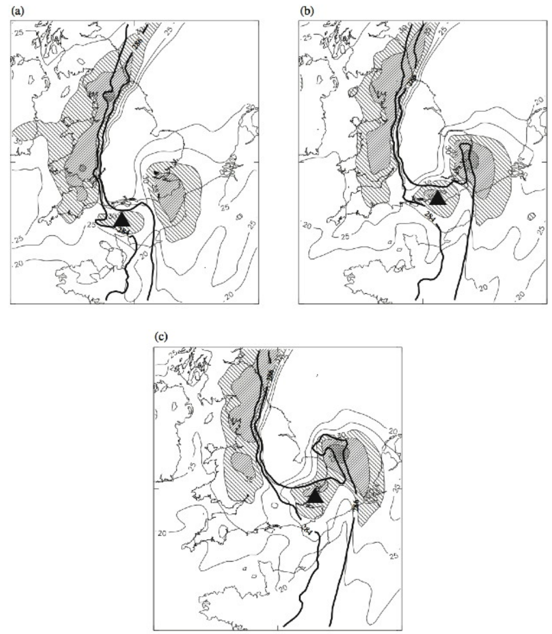
1. When introducing terminology and speculation in your own work, do so carefully.

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

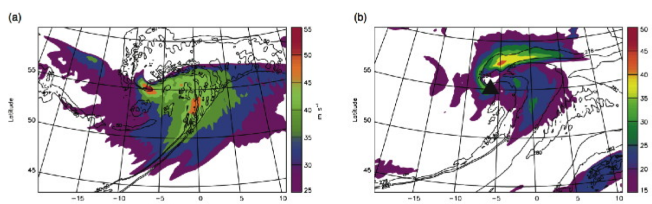
3. Be aware of the previous literature.



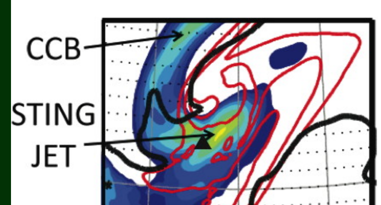

Gronas (1995, Figs. 3b and 4b)



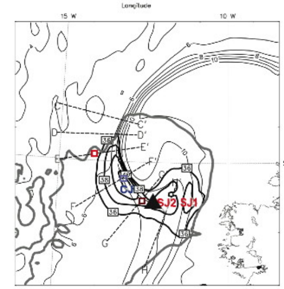

Clark et al. (2005, Fig. 7)



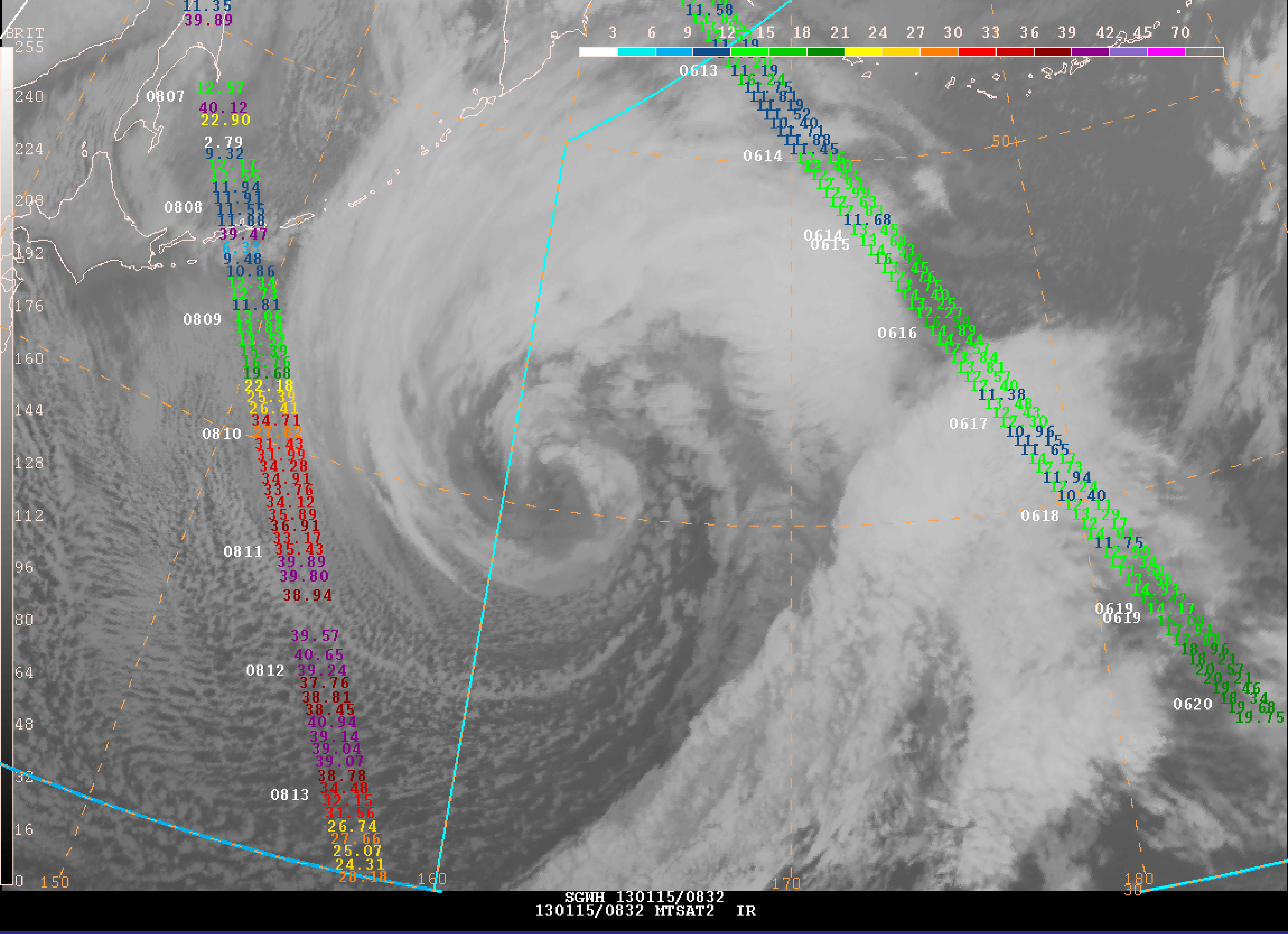

Baker (2009, Fig. 5)

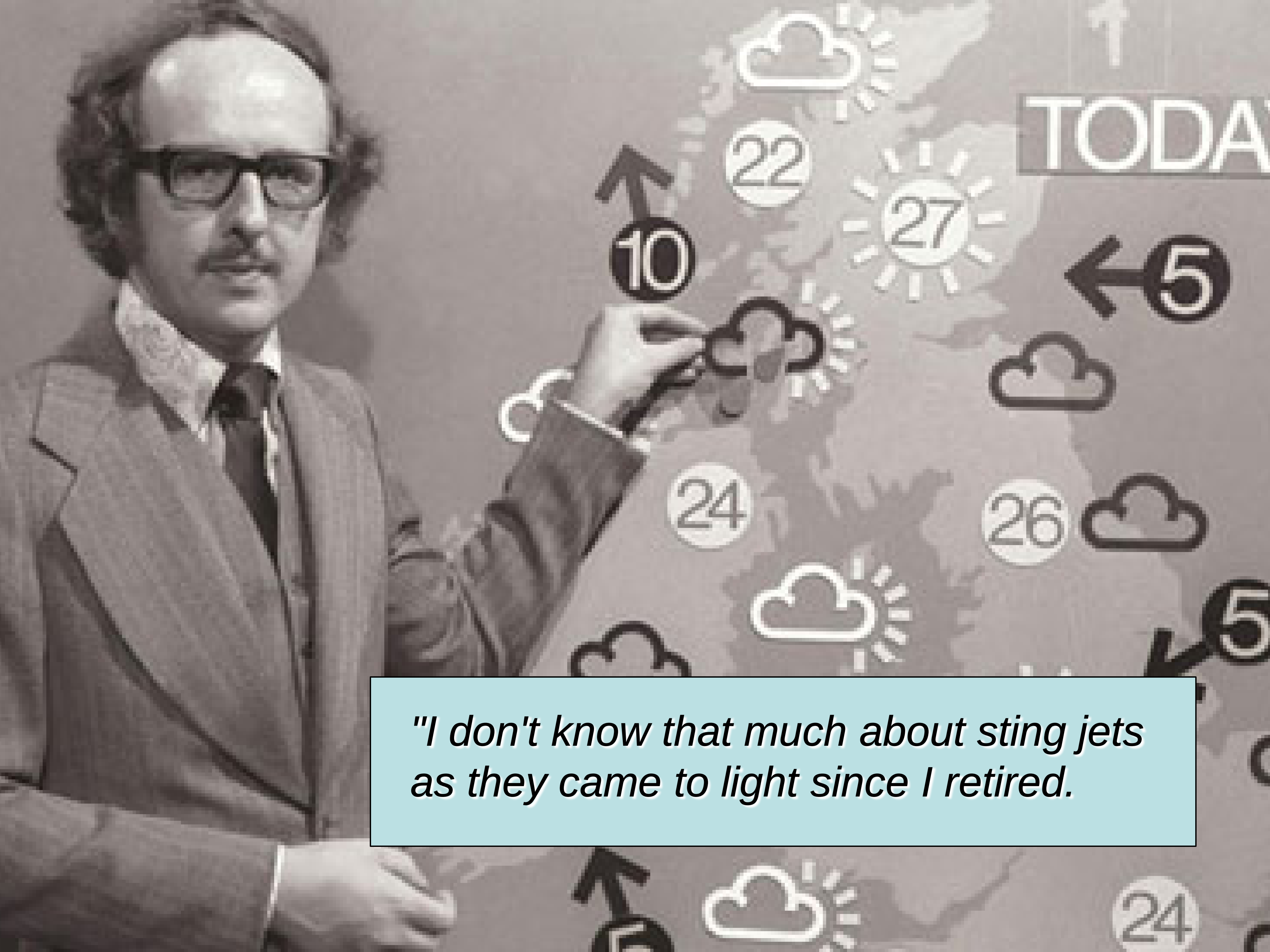



Baker et al. (2012, Fig. 5)




Smart and Browning (2012, Fig. 11)


BRIT
255
240
224
208
192
176
160
144
128
112
96
80
64
48
32
16
0
3 6 9 12 15 18 21 24 27 30 33 36 39 42 45 70
0807
0808
0809
0810
0811
0812
0813
0613
0614
0615
0616
0617
0618
0619
0620
12.57
40.12
22.90
2.79
9.32
11.94
11.91
11.88
39.47
9.48
10.86
11.81
19.68
22.18
25.39
26.41
34.71
27.82
31.43
31.99
34.28
34.91
33.76
34.12
35.89
36.91
35.43
39.89
39.80
38.94
39.57
40.65
39.24
37.76
38.81
38.45
40.94
39.14
39.04
39.07
38.78
34.48
32.15
31.56
26.74
27.66
25.07
24.31
28.18
11.35
39.89
11.58
11.19
11.45
11.68
11.38
11.94
10.40
11.75
19.75
150
160
170
180
50
30
SGWH 130115/0832
130115/0832 MTSAT2 IR



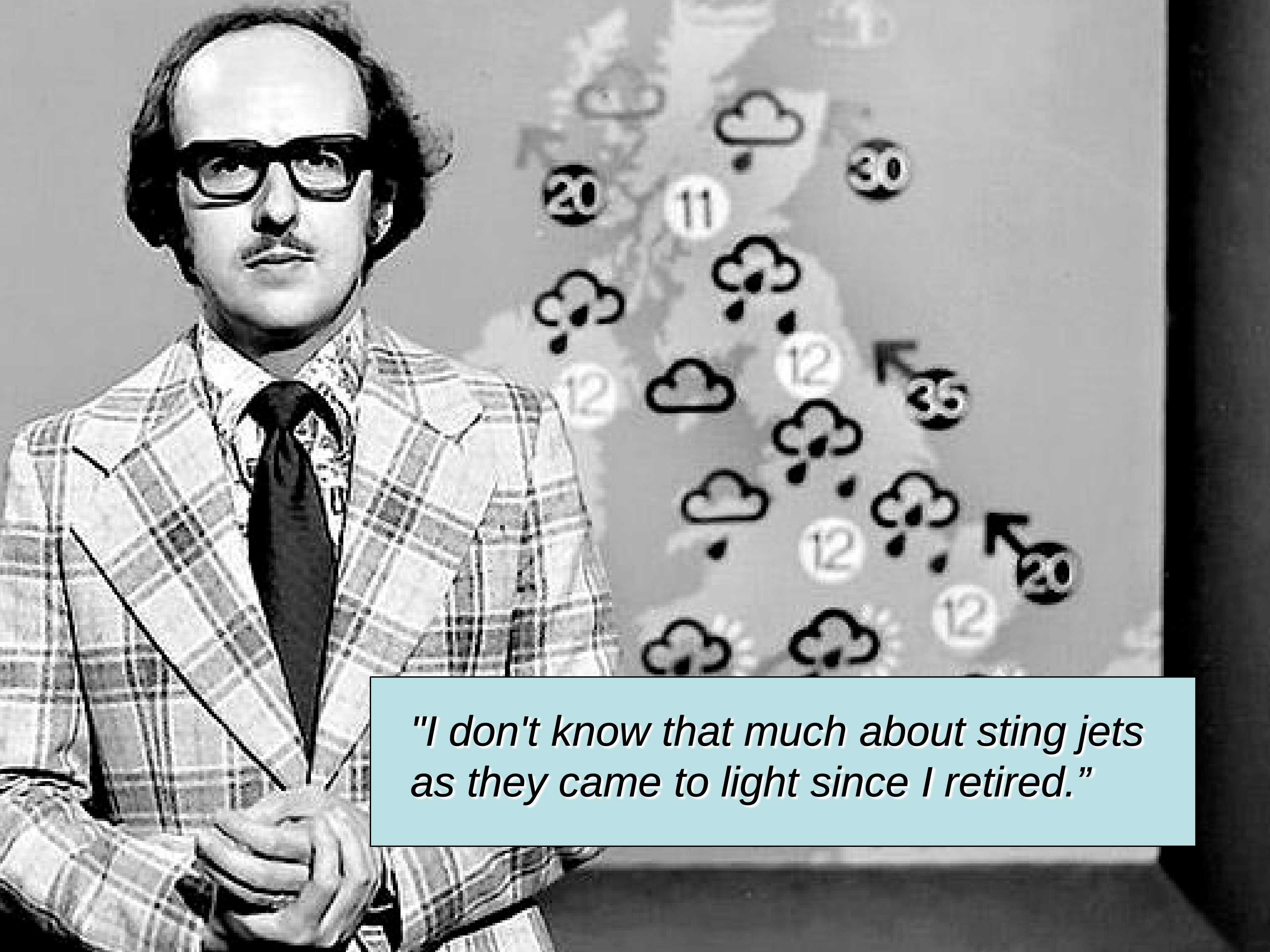

*"I don't know that much about sting jets as they came to light since I retired.*

## 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.”

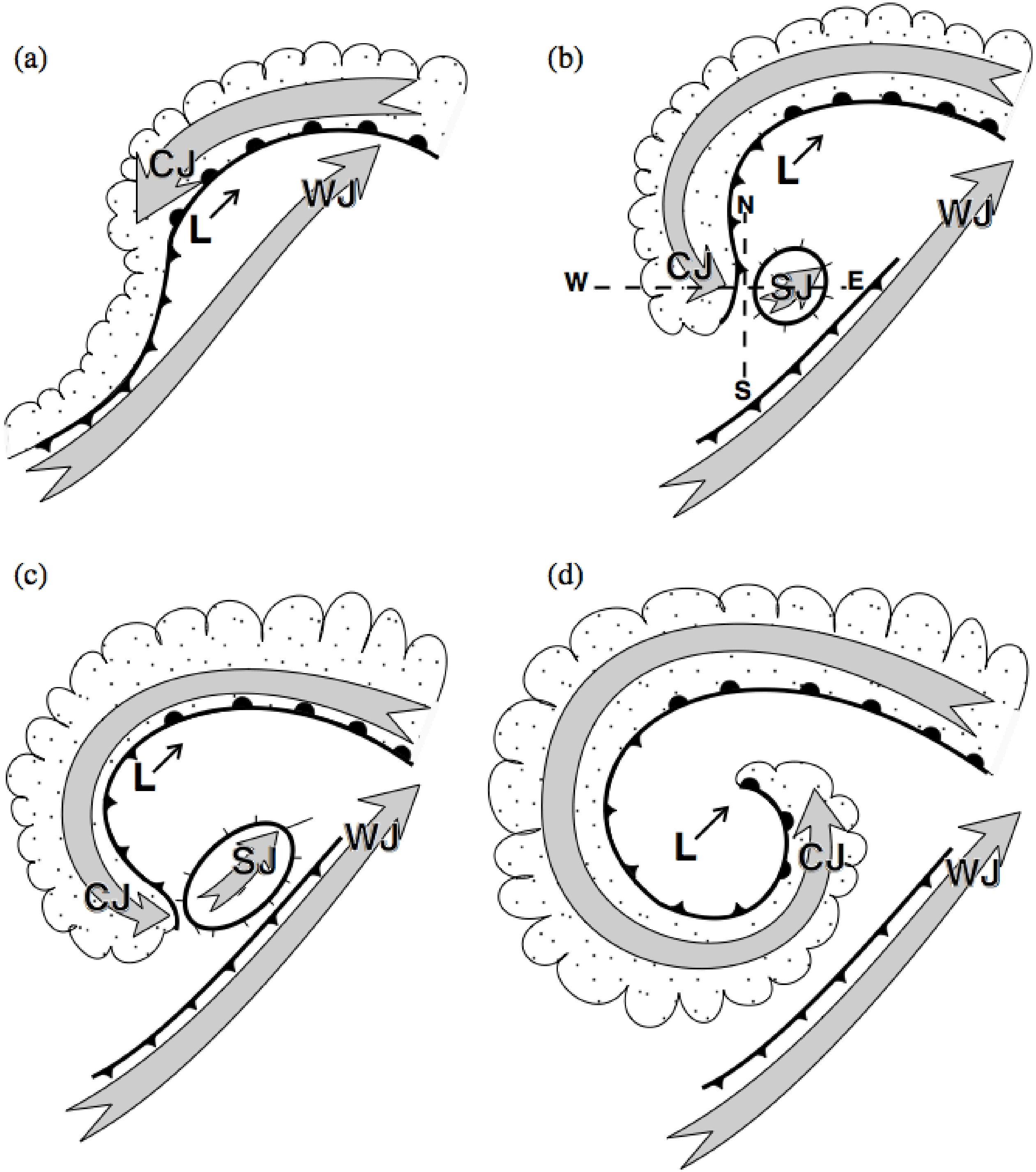



*"I don't know that much about sting jets as they came to light since I retired."*

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 p

**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.

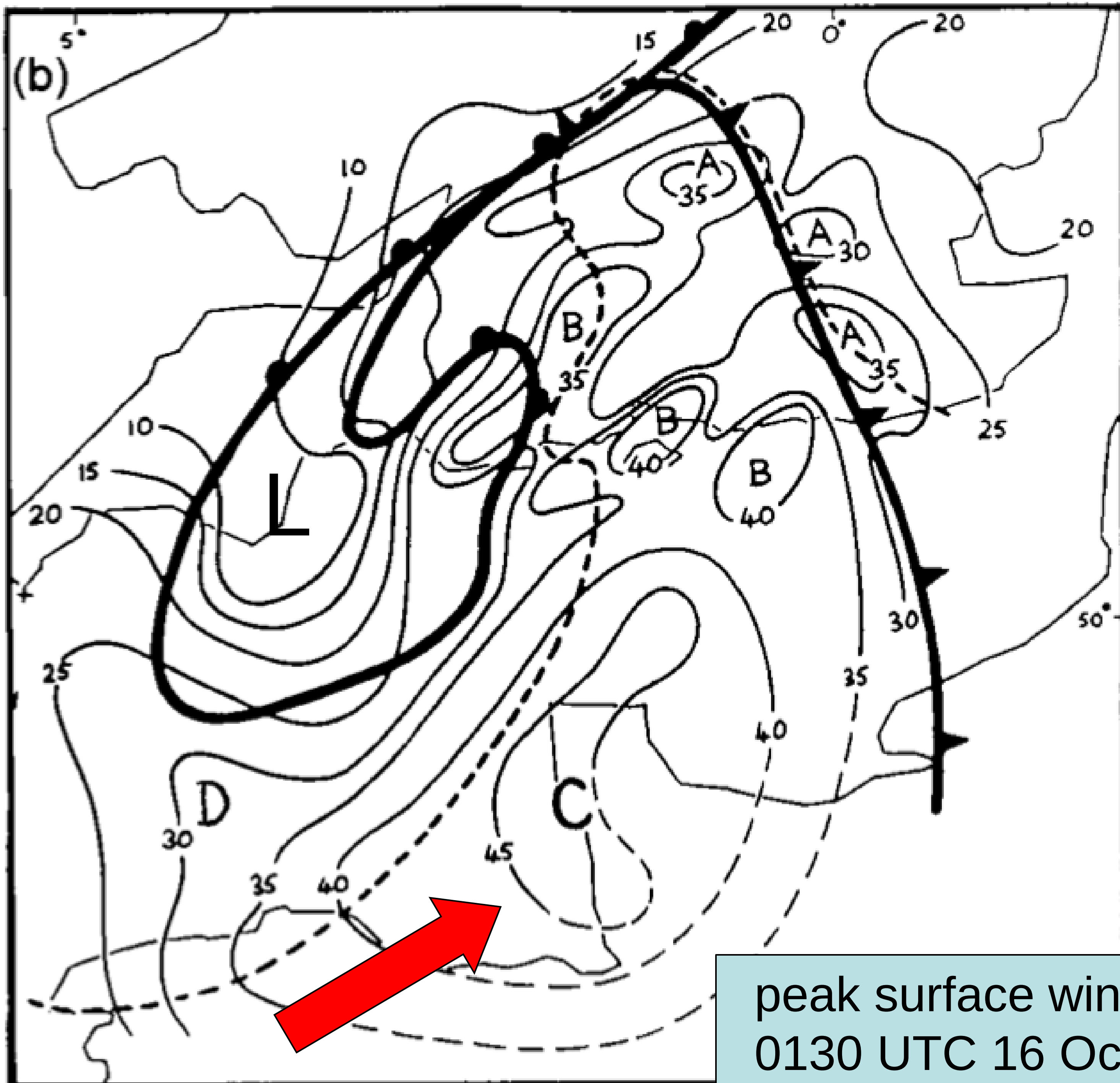
Re-examination of observations from the Great Storm of 15–16 October 1987

Strongest winds south and east of the low center

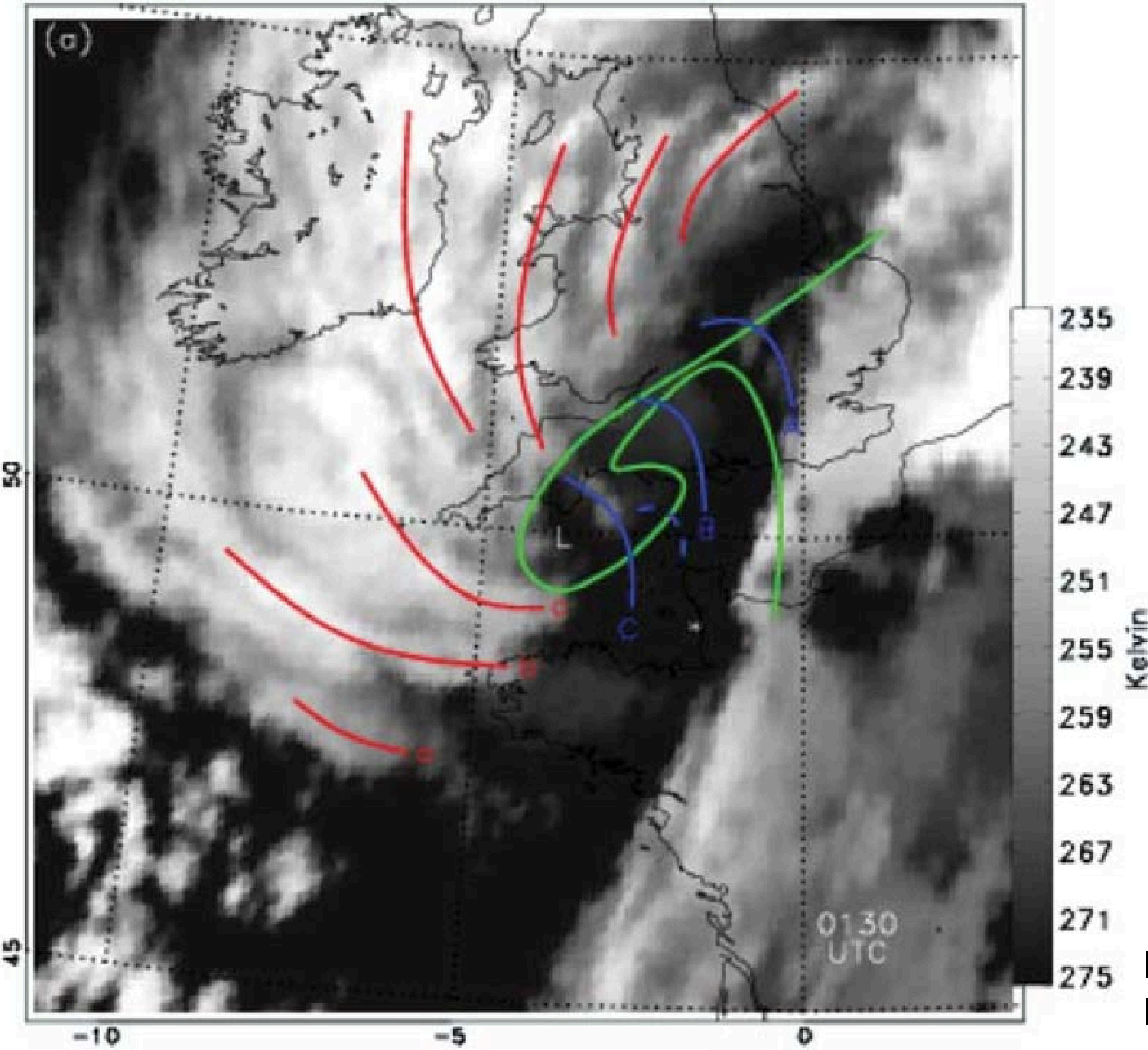
Proposed causes:

1. Attributed evaporative cooling to descending air

2. Release of conditional symmetric instability (CSI) in comma cloud head




peak surface wind gusts (m s$^{-1}$)
0130 UTC 16 October 1987




Browning and Field (2004)

# 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.)

## 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 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)

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

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

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

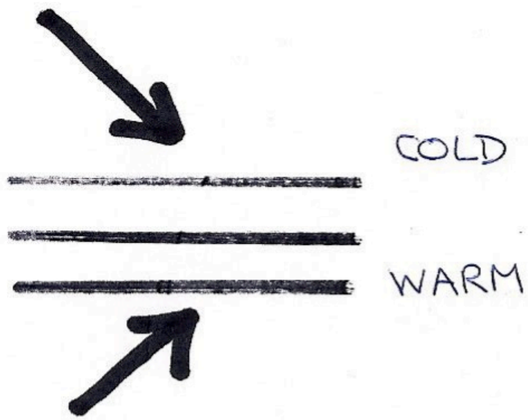
$$\nabla_H = \mathbf{i}\frac{\partial}{\partial x} + \mathbf{j}\frac{\partial}{\partial y}.$$

$$F = \frac{1}{2}|\nabla_H \theta|(E\cos 2\beta - \nabla_H \cdot \mathbf{V}_H),$$

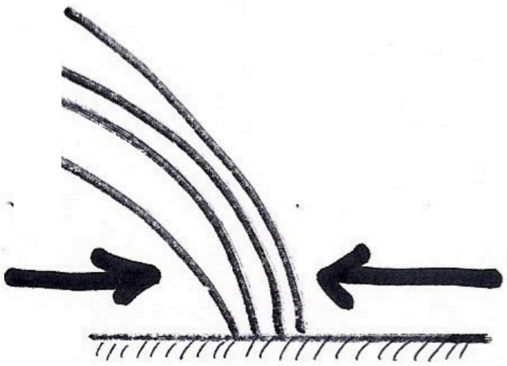
deformation divergence

# Frontogenesis

horizontal



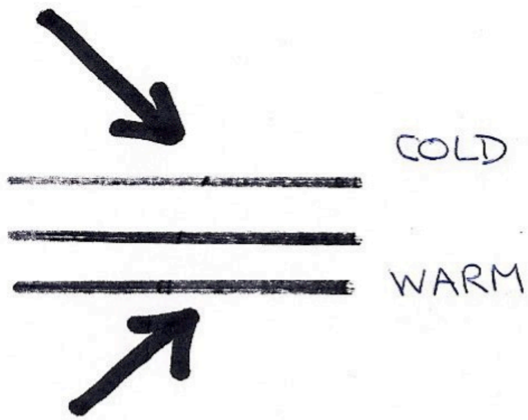

vertical



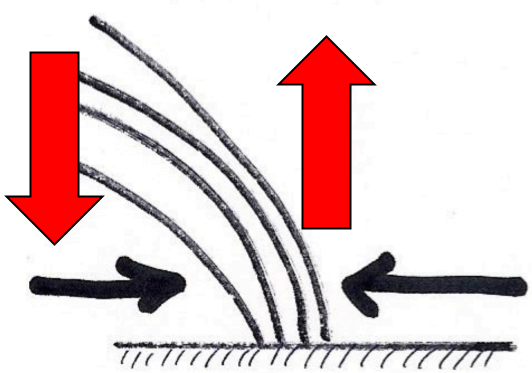
isentropes

# Frontogenesis

horizontal

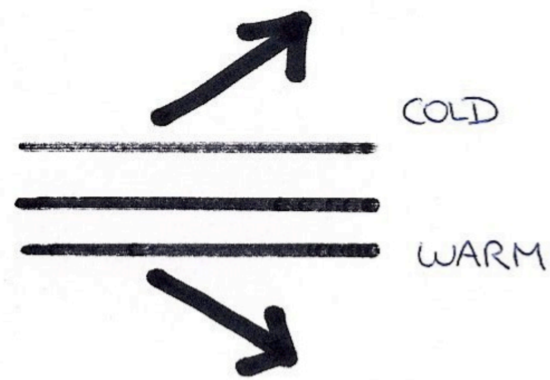


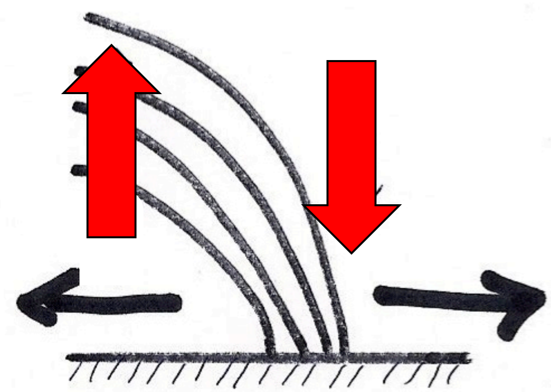

vertical

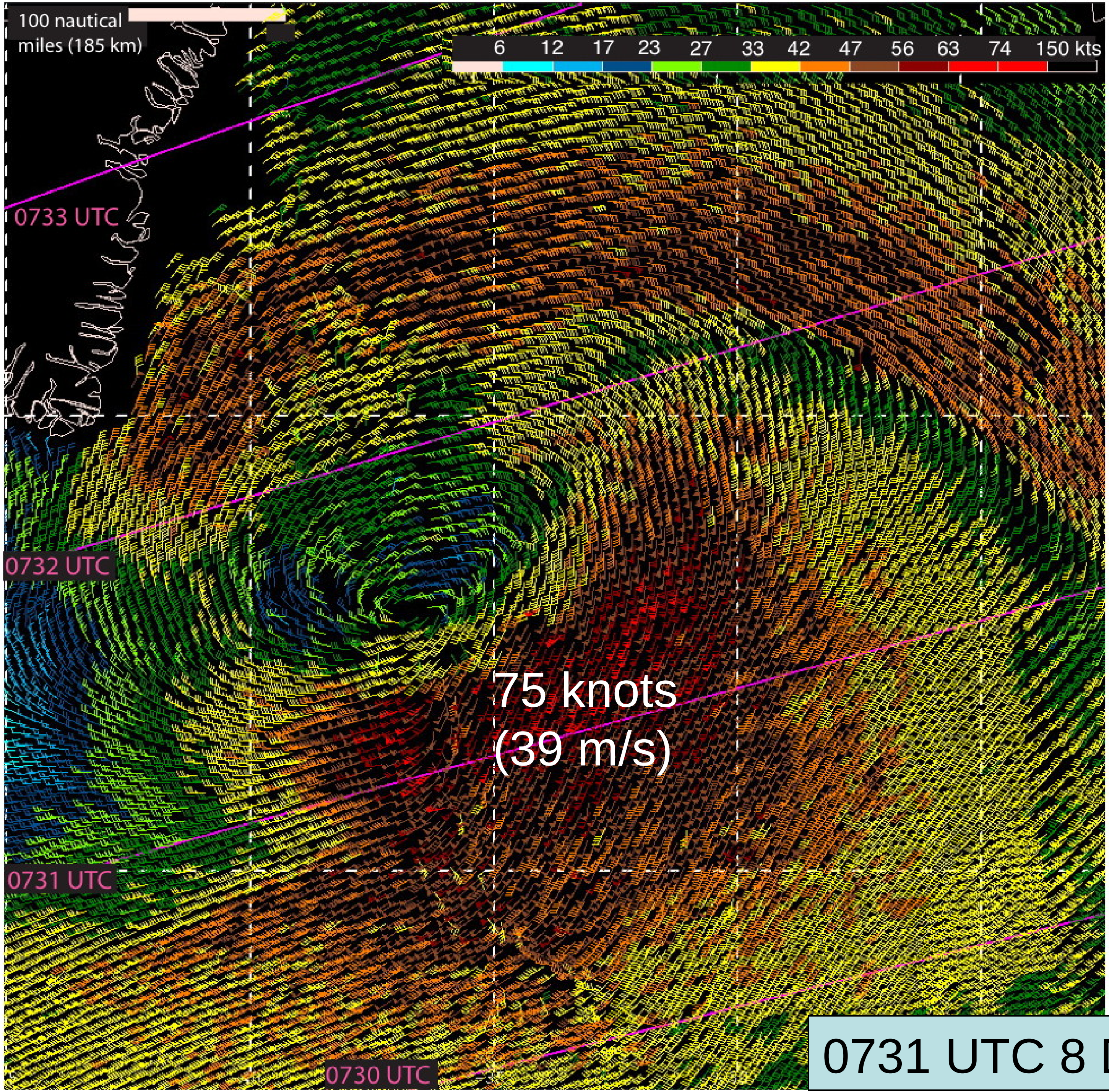


isentropes

# Frontolysis

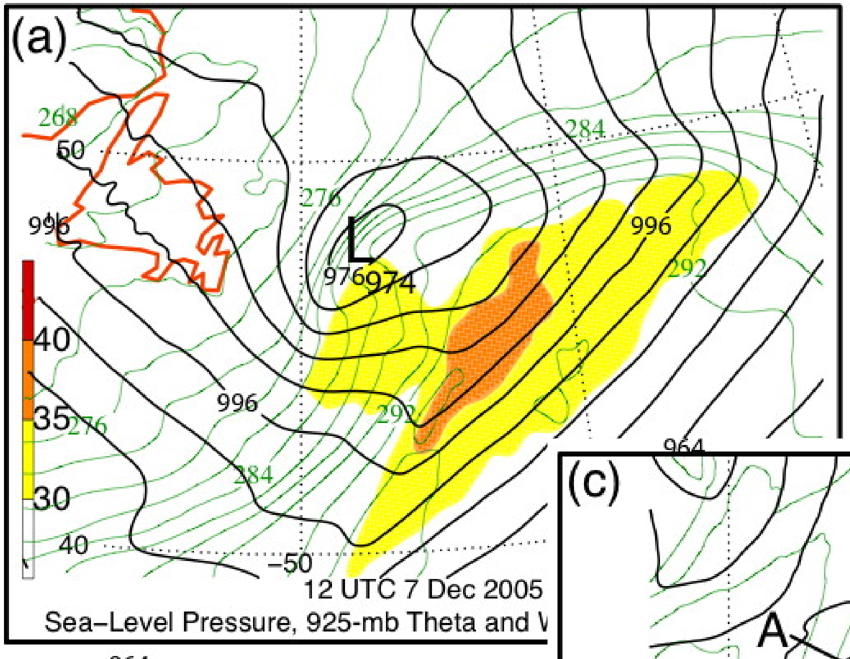


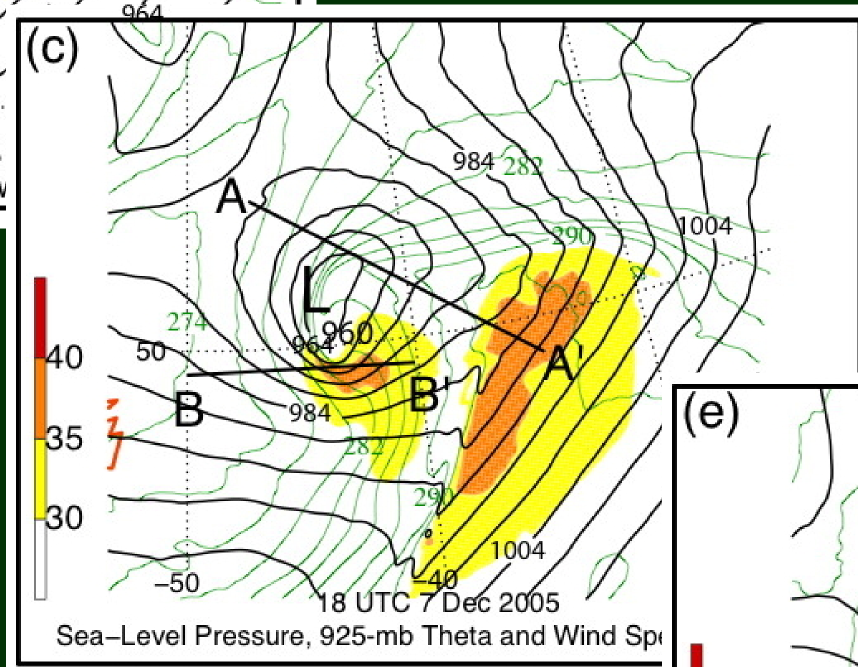



0731 UTC 8 December 2005

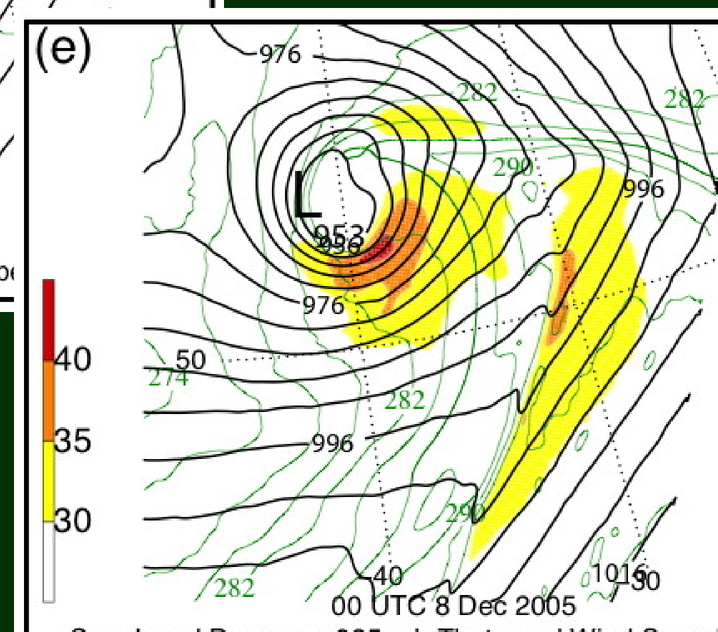
# 12 UTC 7 Dec




# 18 UTC 7 Dec

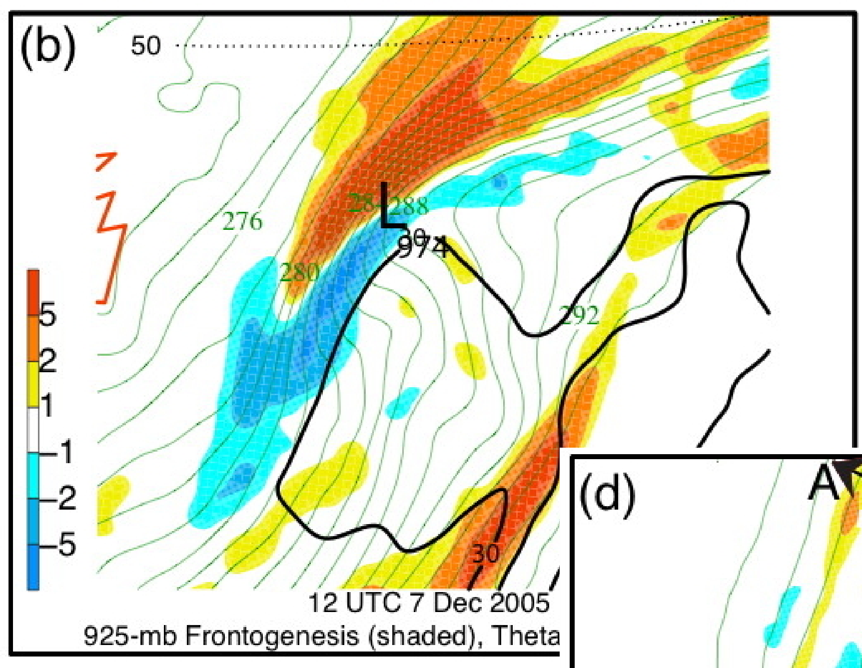



# 00 UTC 8 Dec

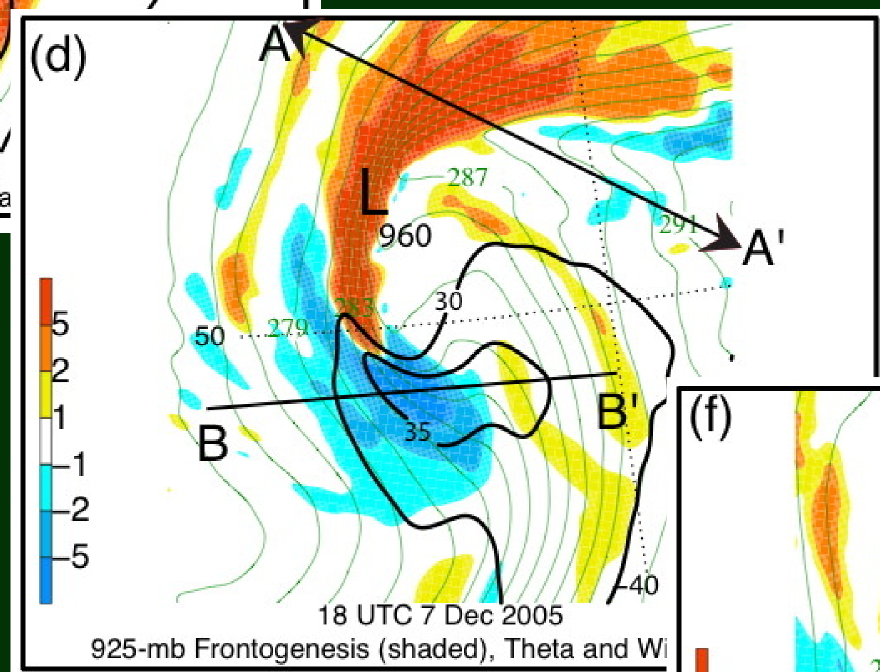



Sea-level pressure
925-mb theta
wind speed (shaded)

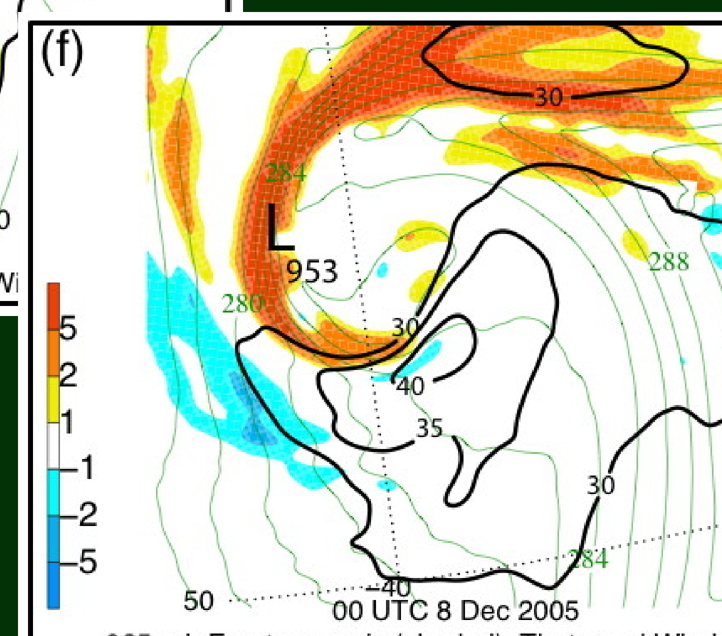
## 12 UTC 7 Dec



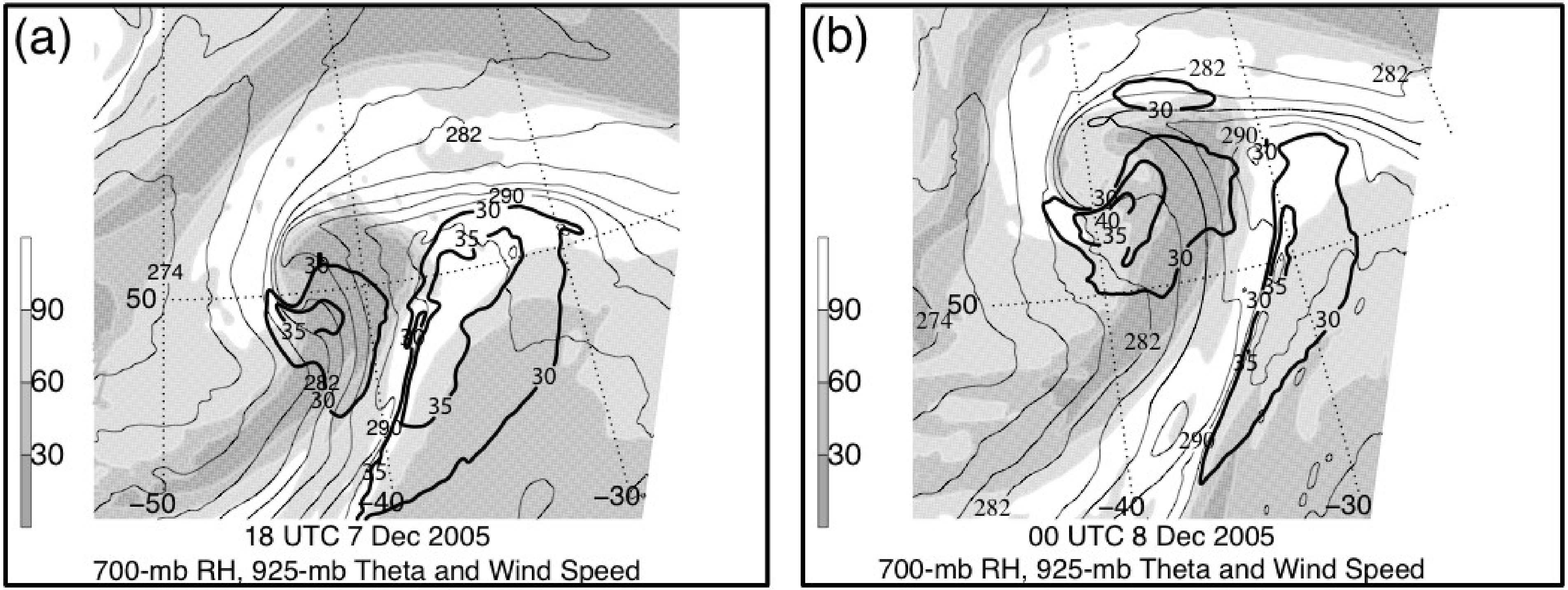

## 18 UTC 7 Dec



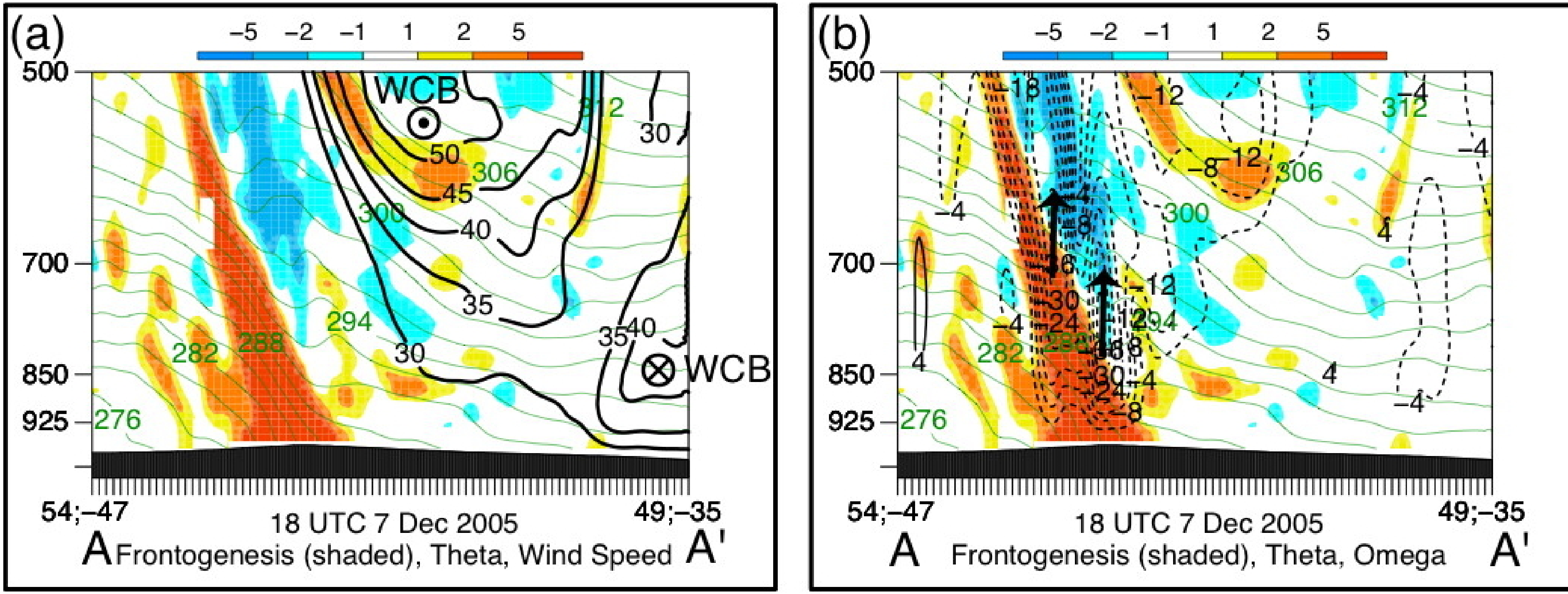

## 00 UTC 8 Dec

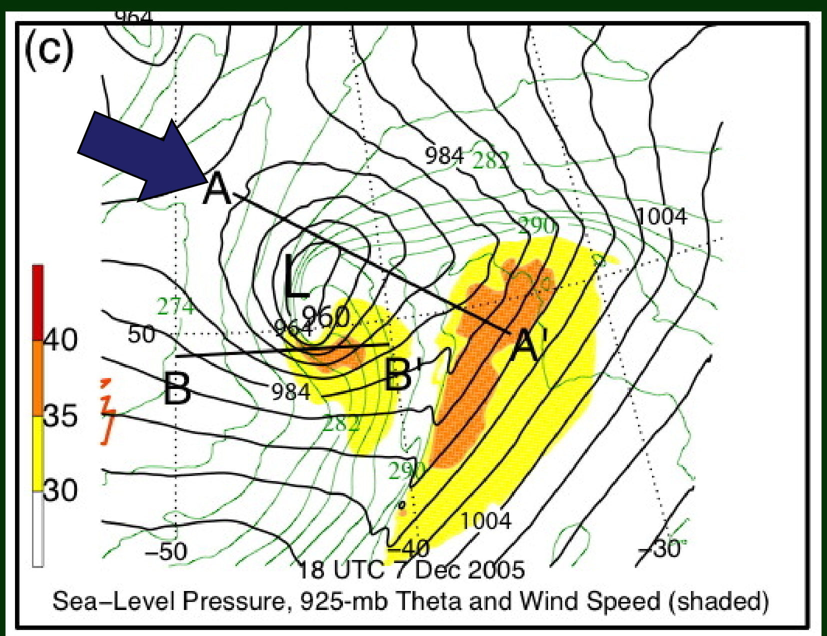



925-mb theta
wind speed
frontogenesis (shaded)

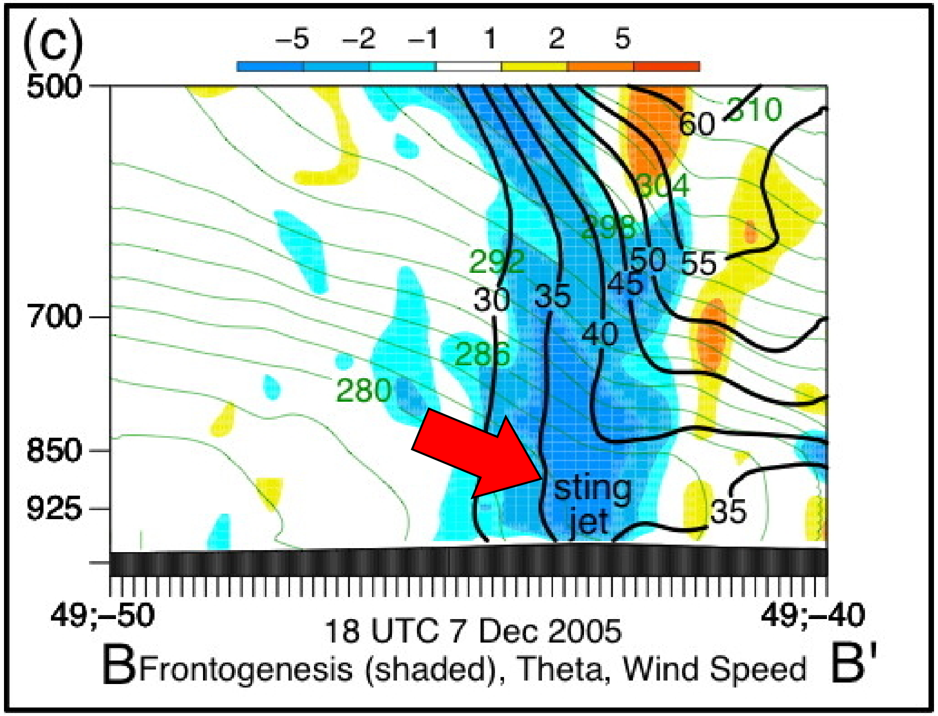


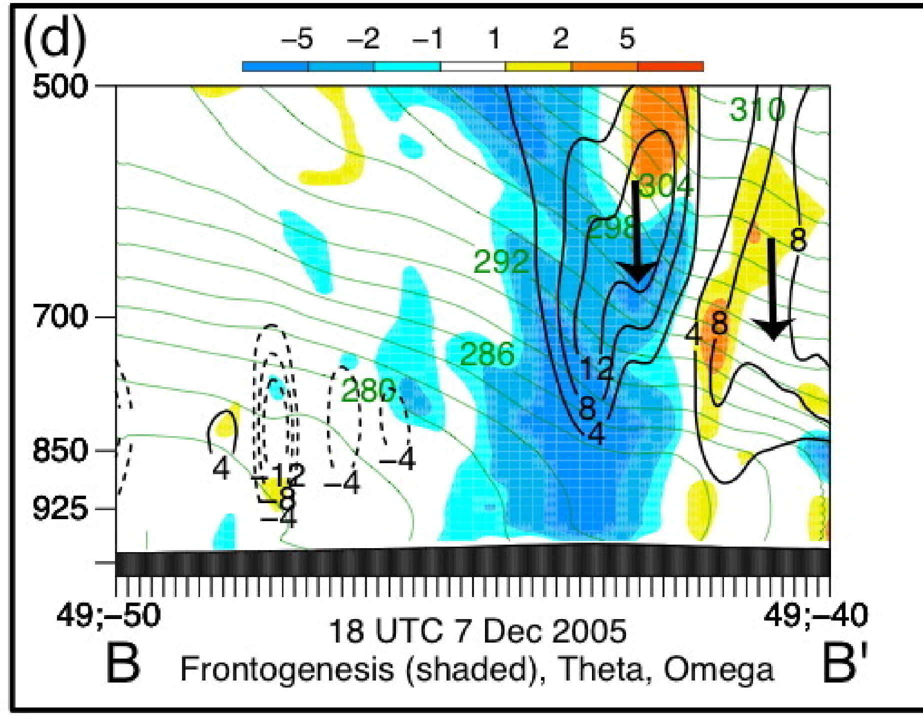

700-mb relative humidity (shaded)
925-mb theta
925-mb wind speed

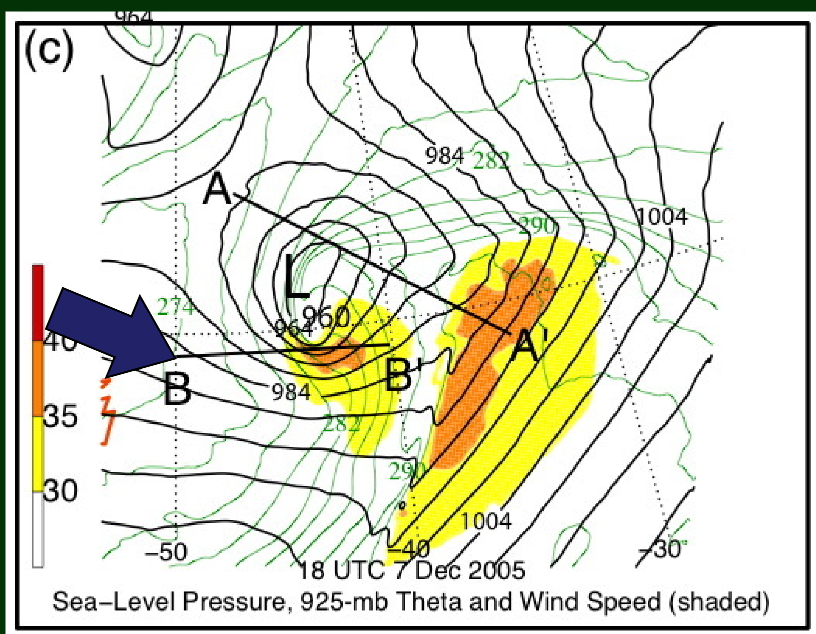


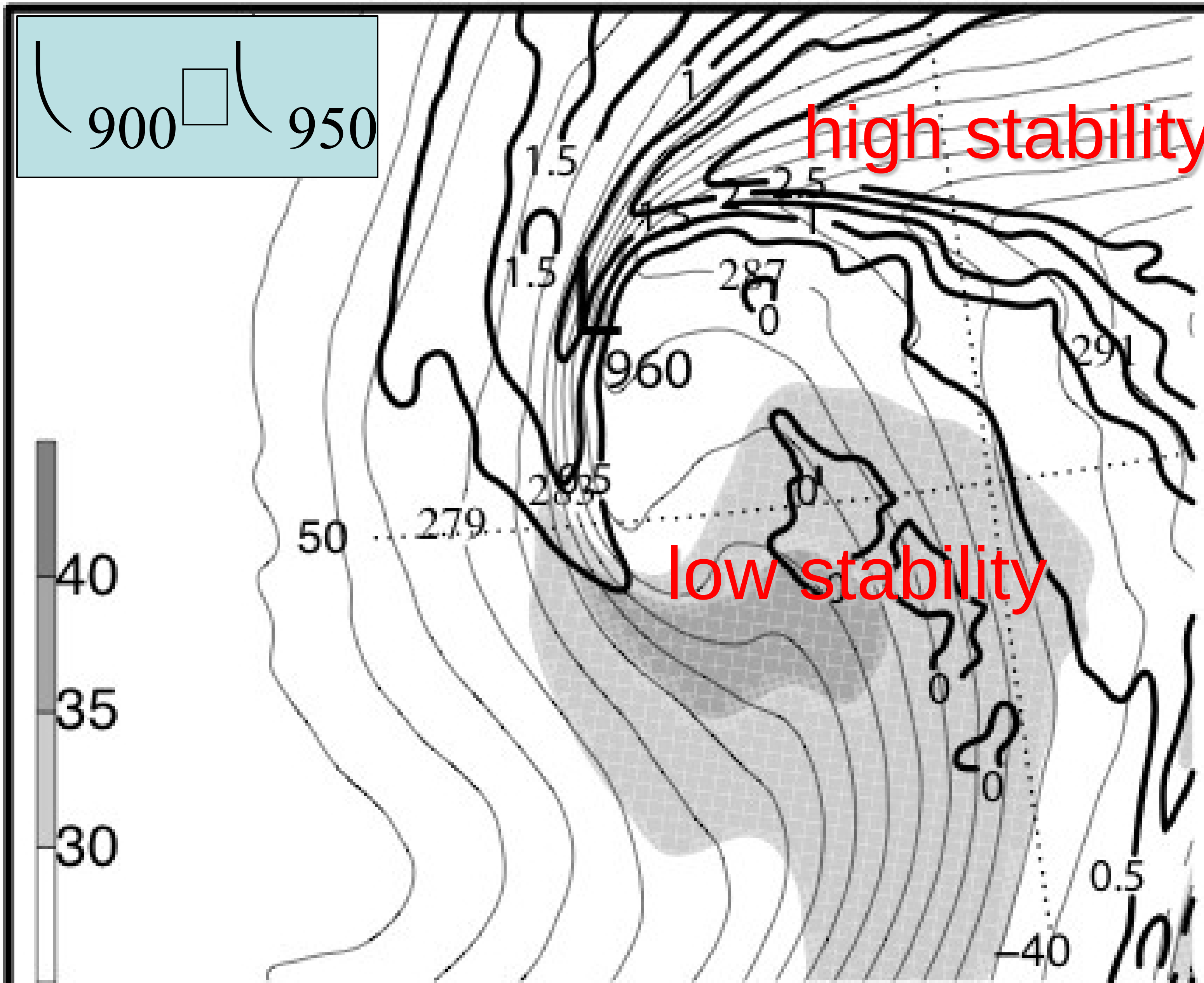

cross section through frontogenesis maximum



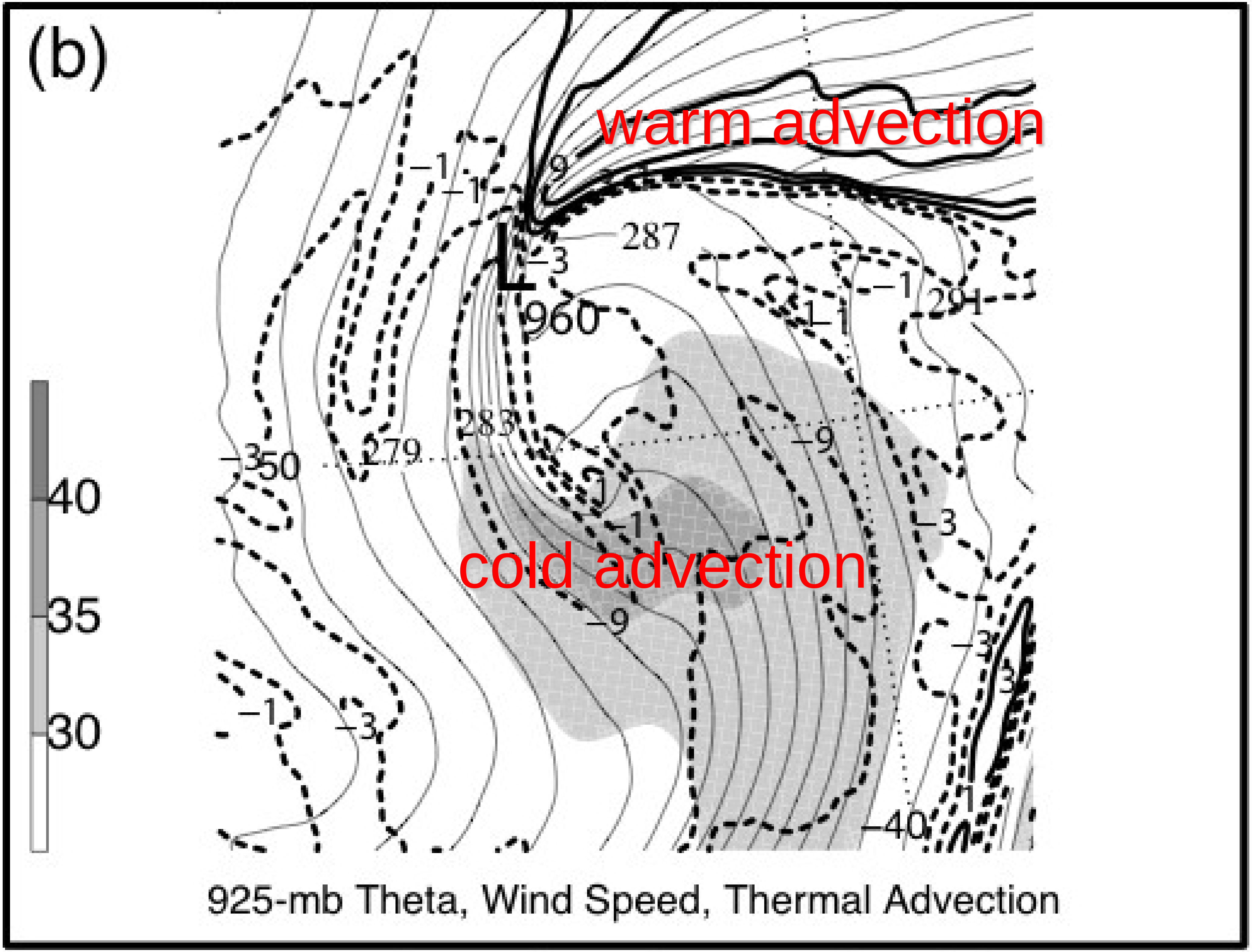



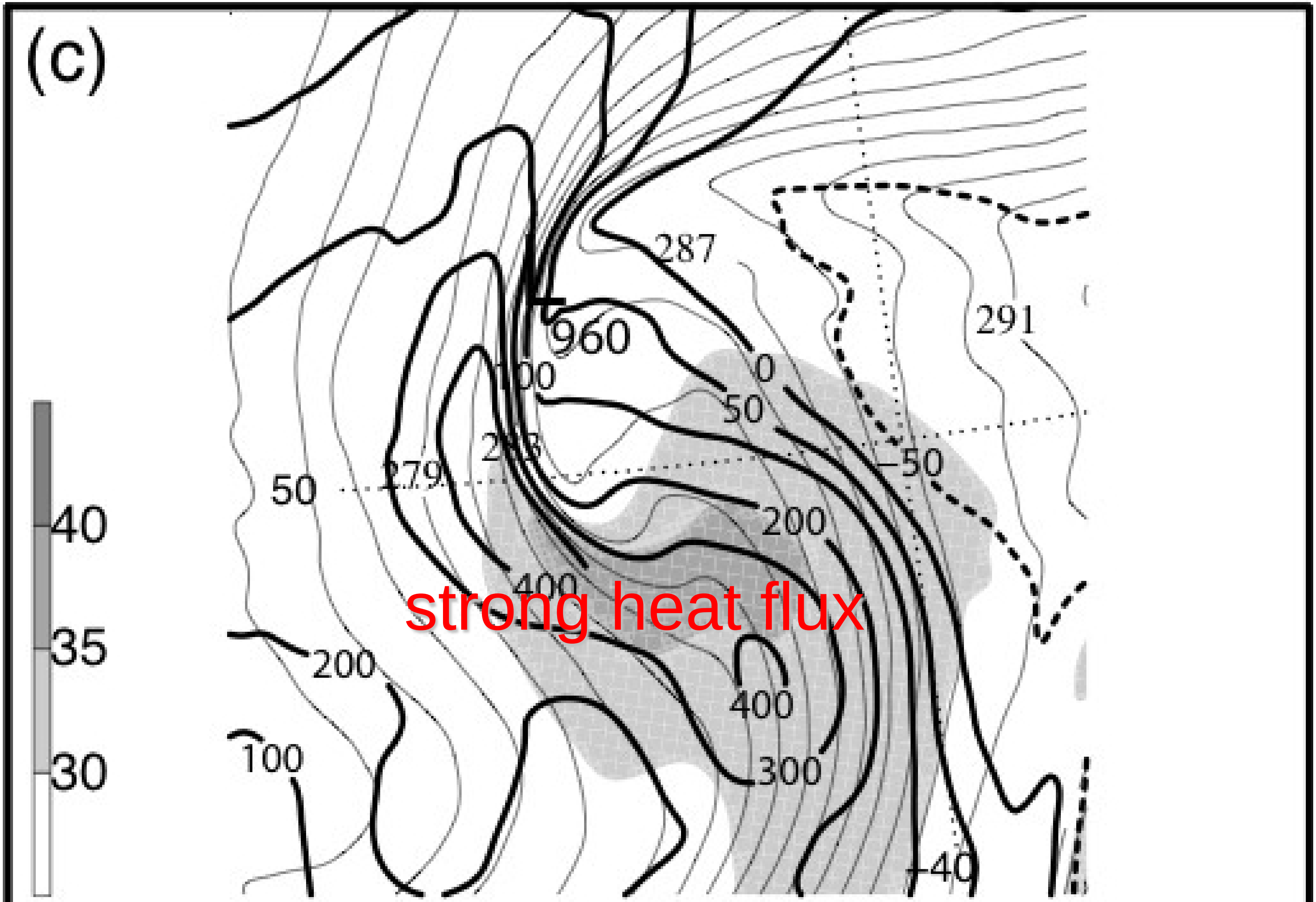




cross section through frontolysis maximum and sting jet




925-mb Theta, Wind Speed, Static Stability

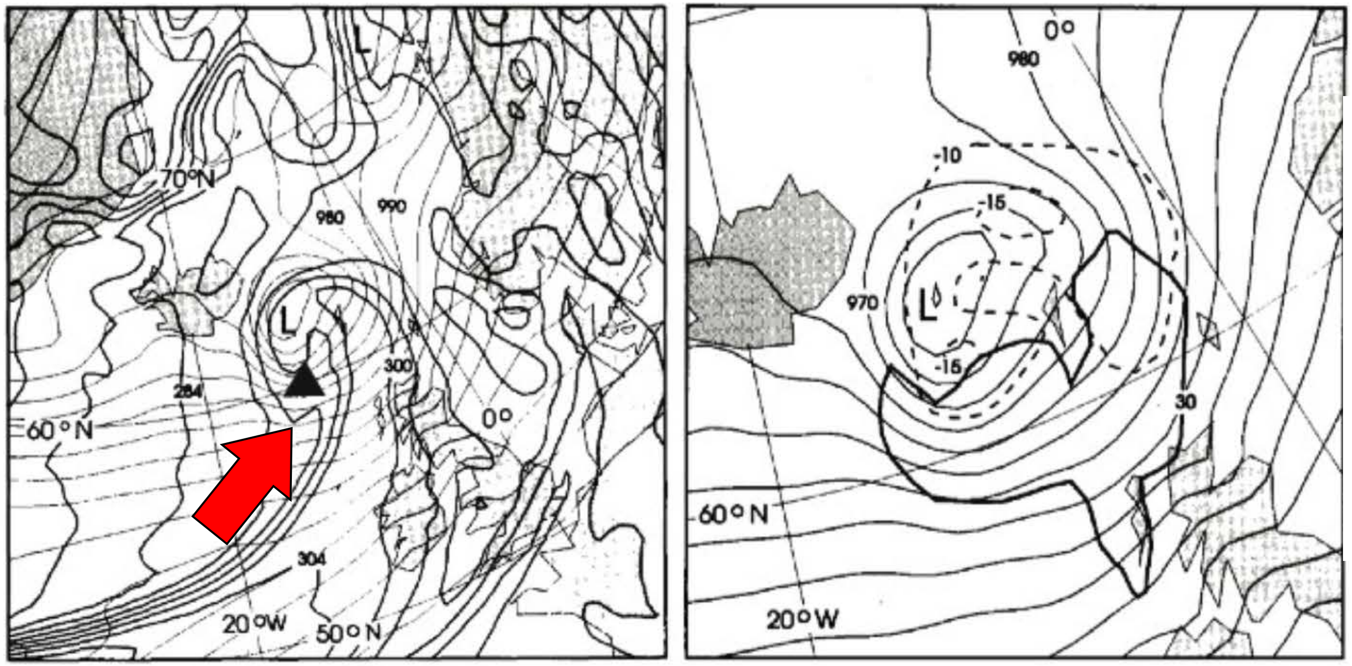

(b)
warm advection
cold advection
L
960
287
283
279
291
−3
−1
−9
50
40
35
30
−40
925-mb Theta, Wind Speed, Thermal Advection



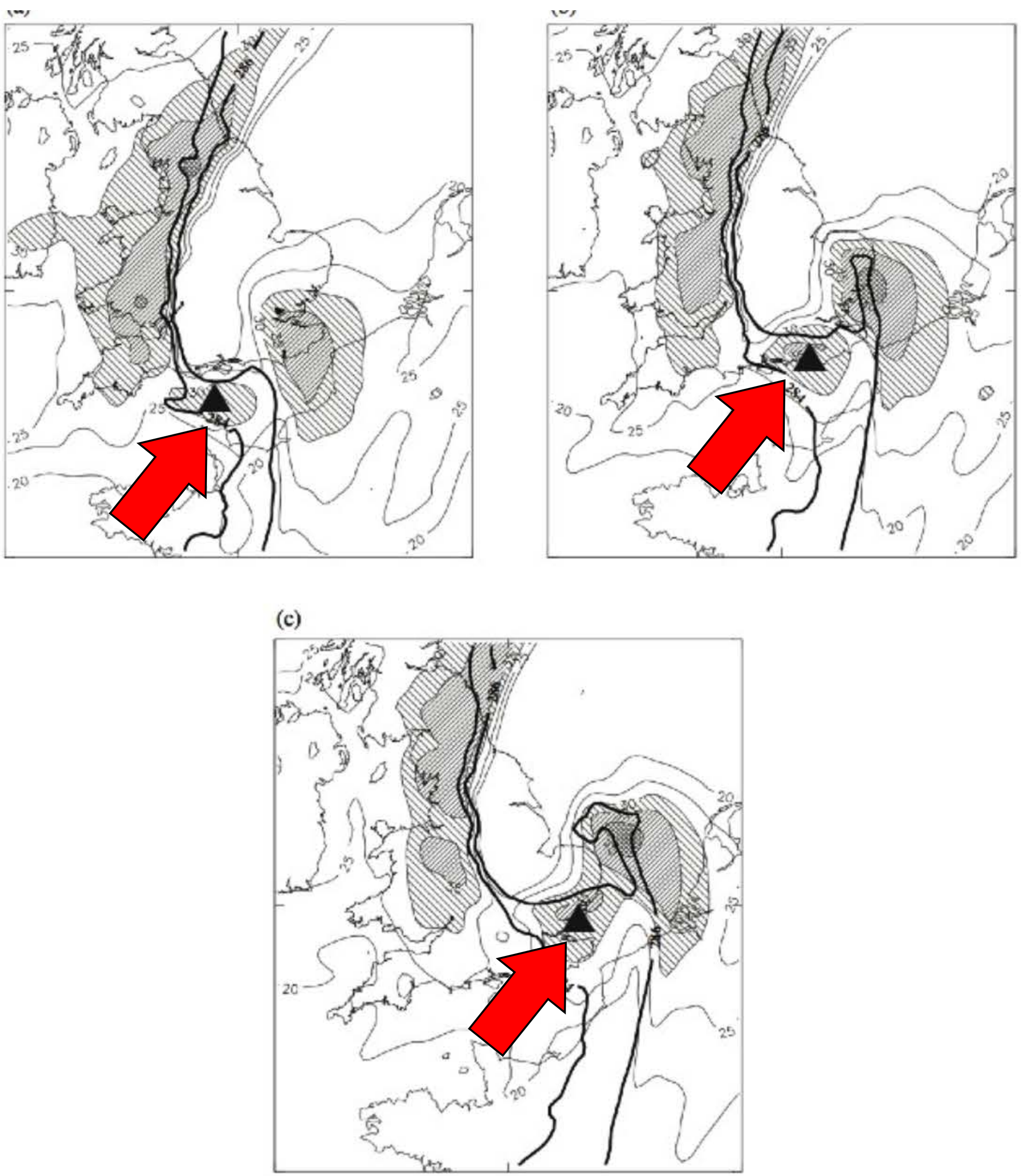

925-mb Theta and Wind Speed, Surface Sensible Heat Flux

*One case is intriguing....*

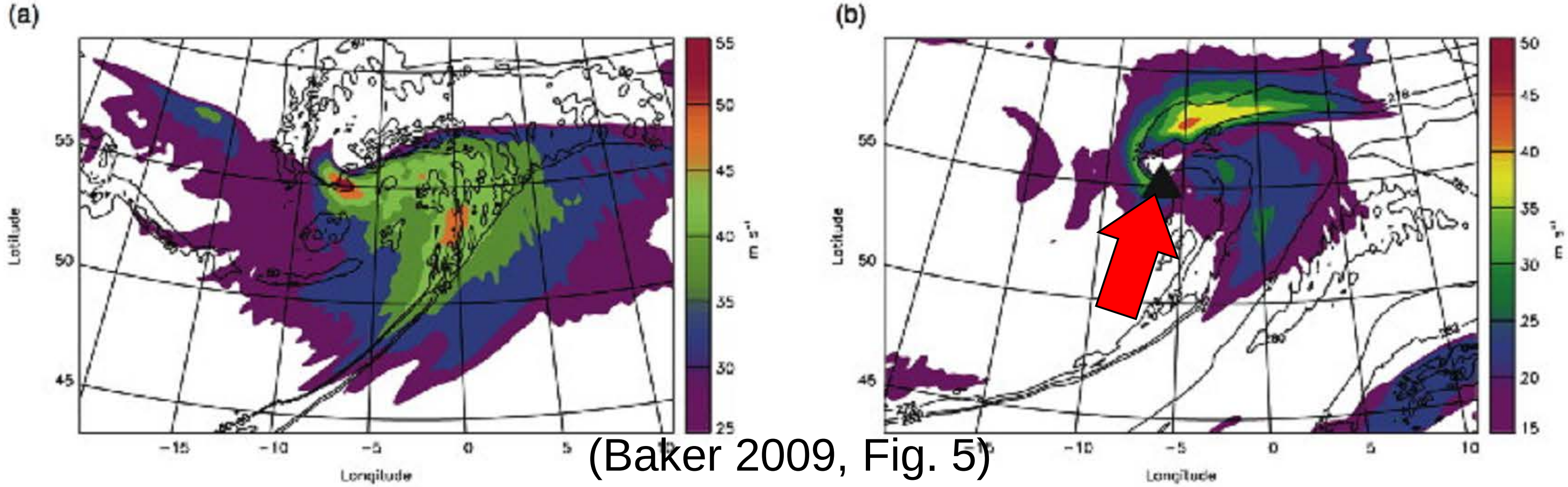
*Is frontolysis present in other cyclones with sting jets?*



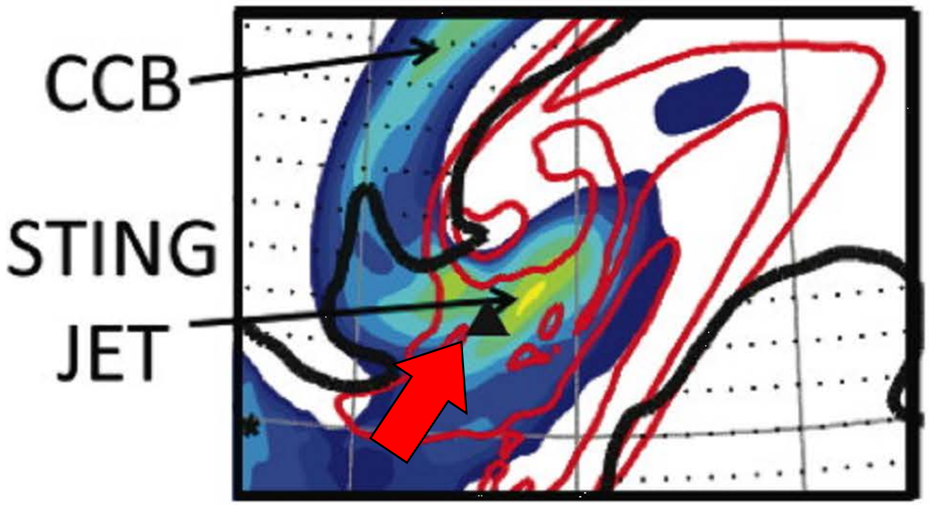

Grønås (1995, Figs. 3b and 4b)



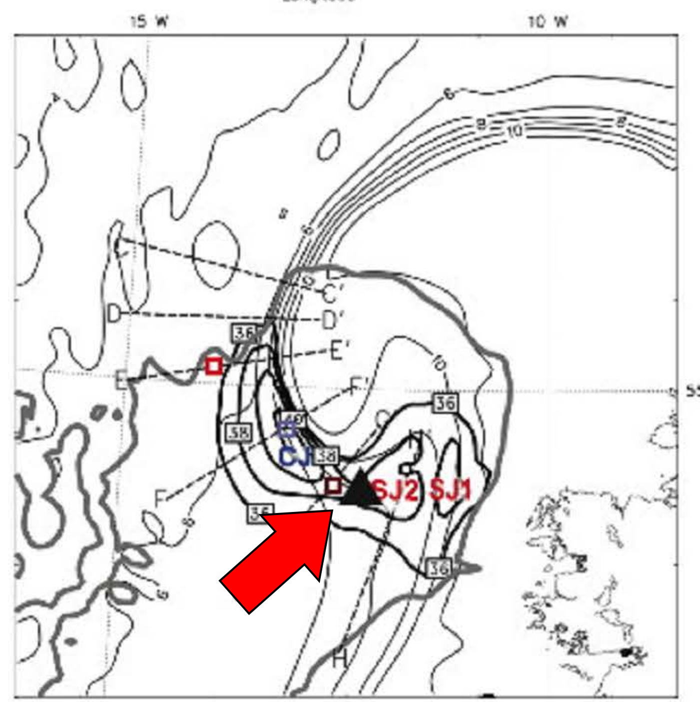

Clark et al. (2005, Fig. 7)



(Baker 2009, Fig. 5)



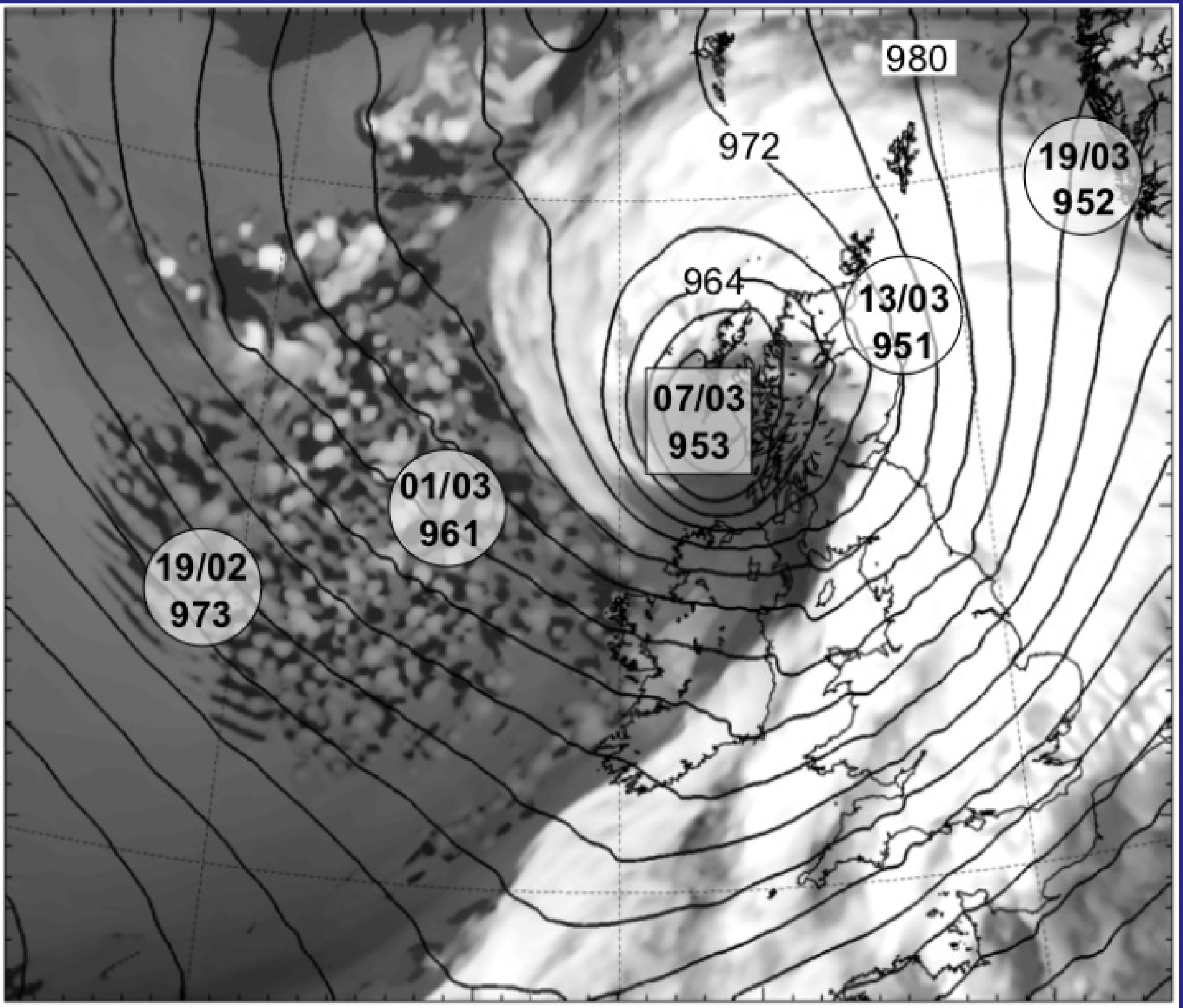
Baker et al. (2012, Fig. 5)



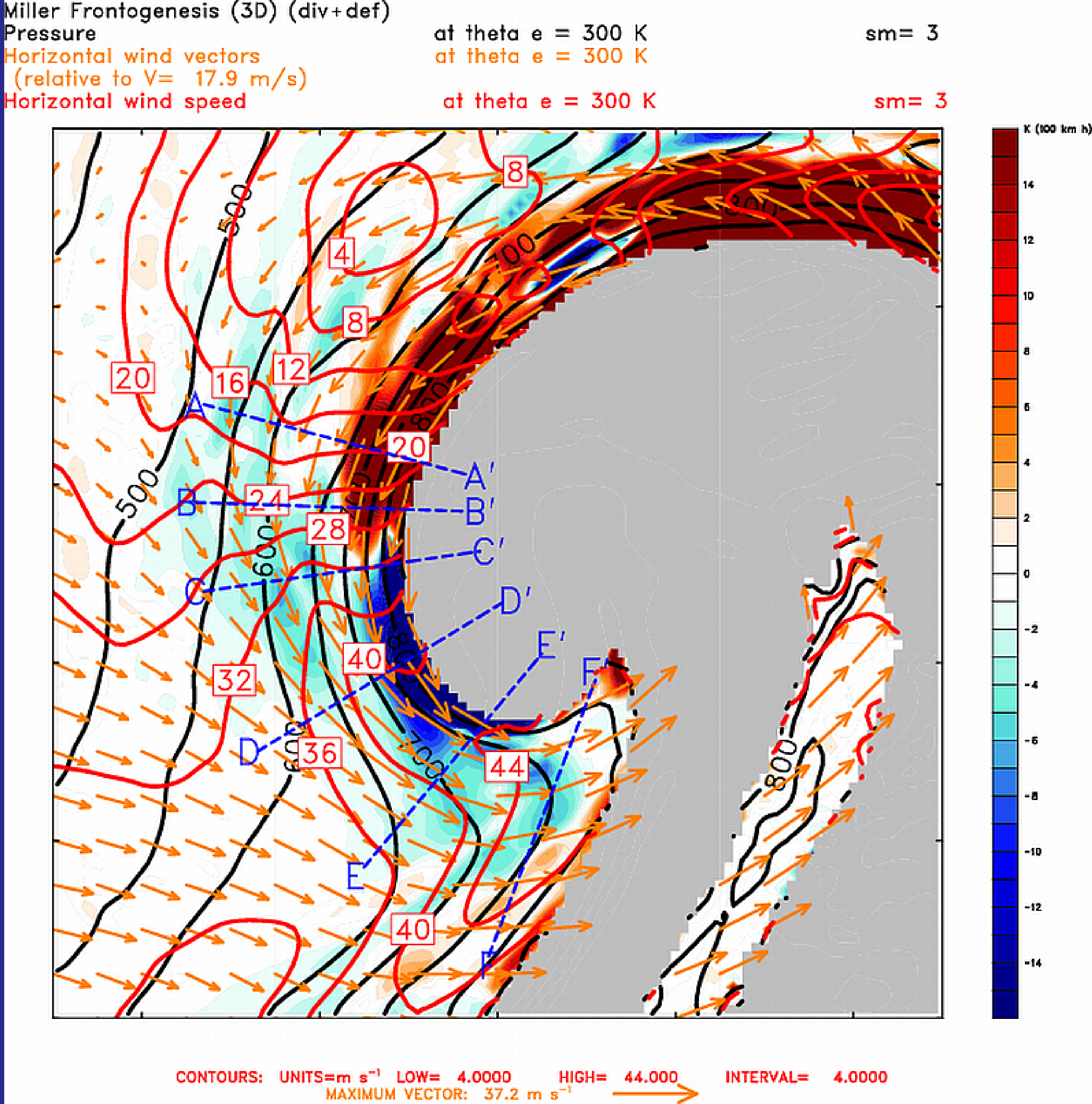
Smart and Browning (2012, Fig. 11)

# Smart and Browning (2013):

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

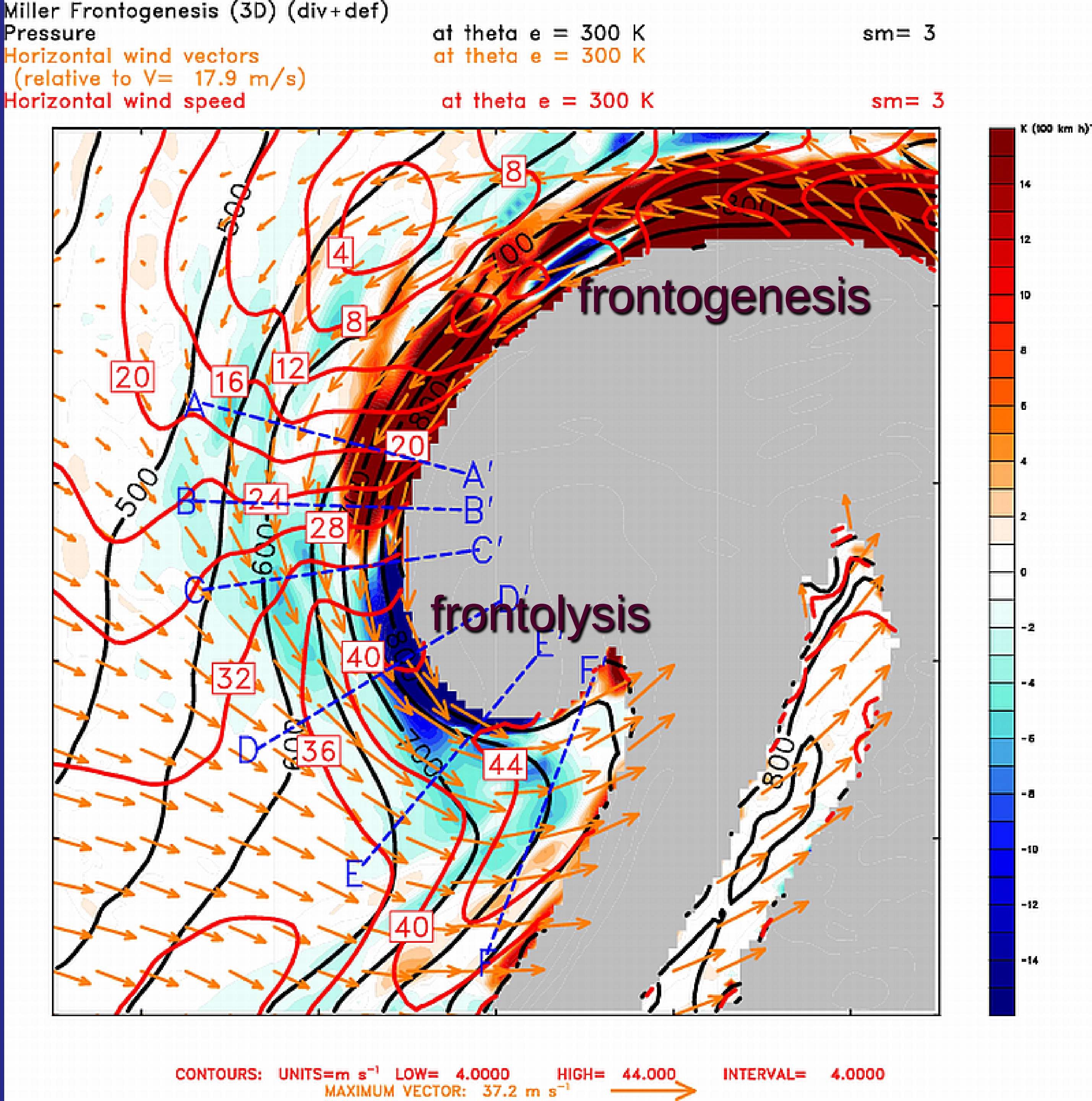



3 January 2012
Scottish storm



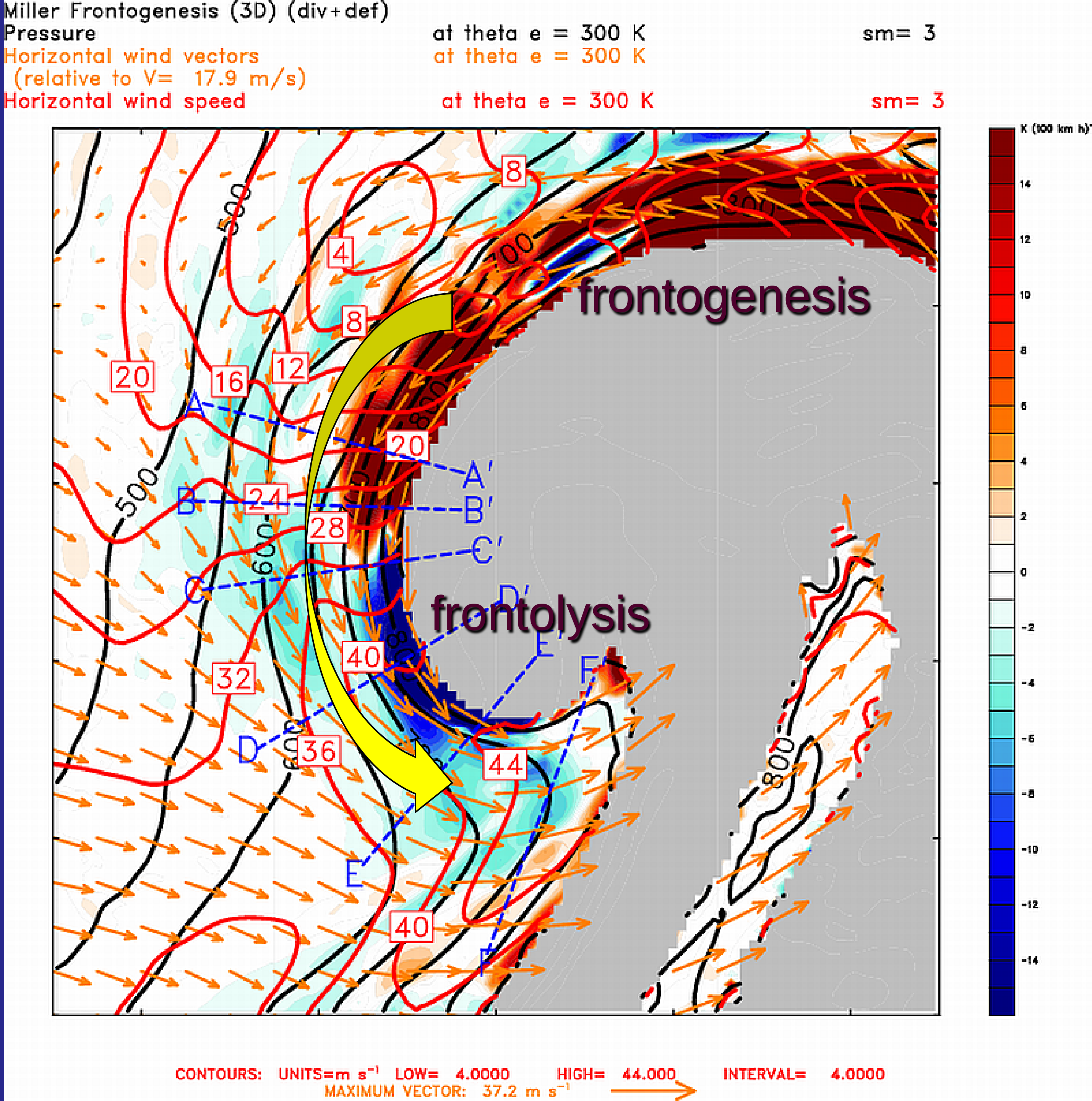

theta-e
= 300K

David Smart



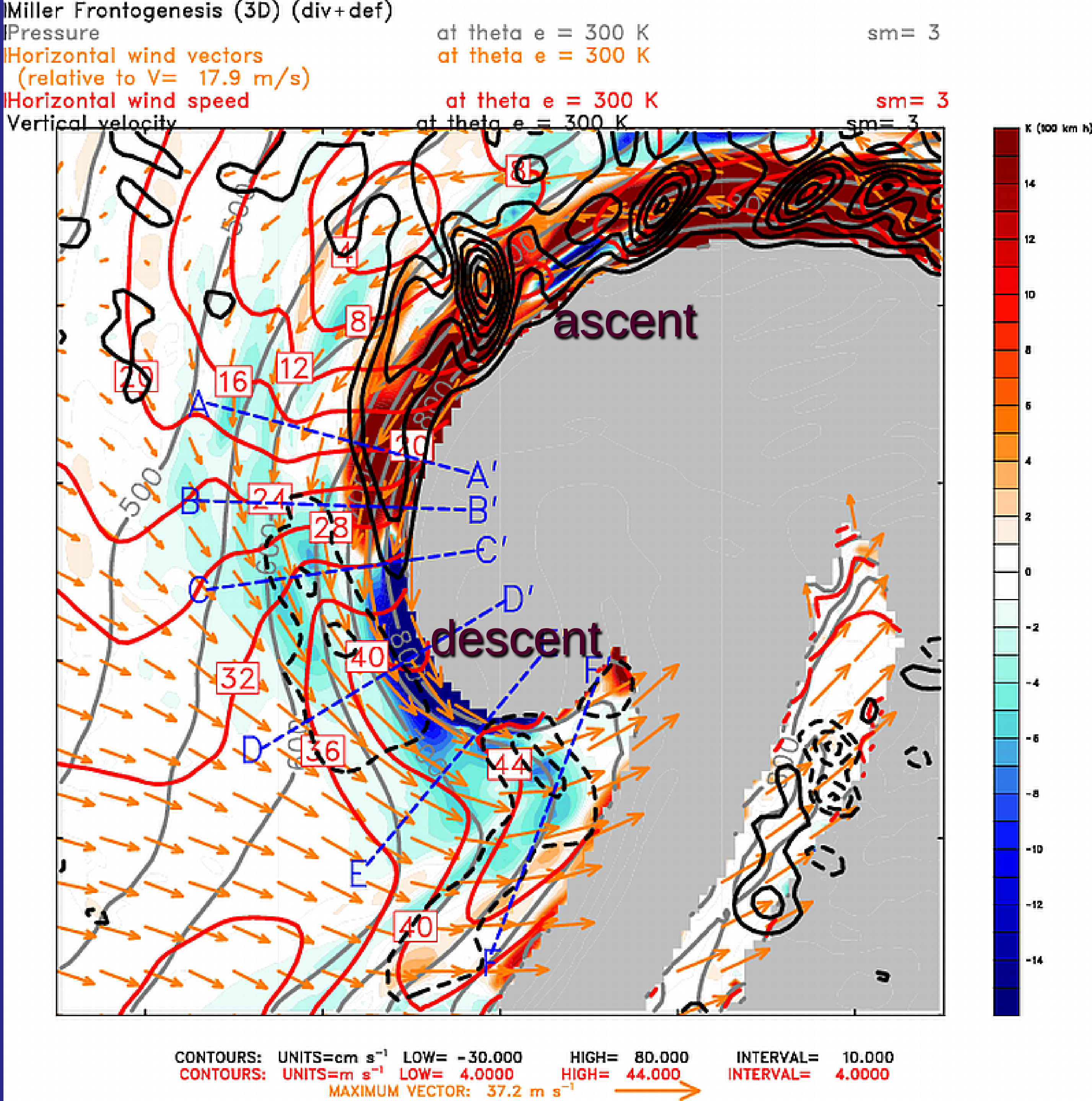

theta-e = 300K

David Smart




theta-e = 300K

David Smart

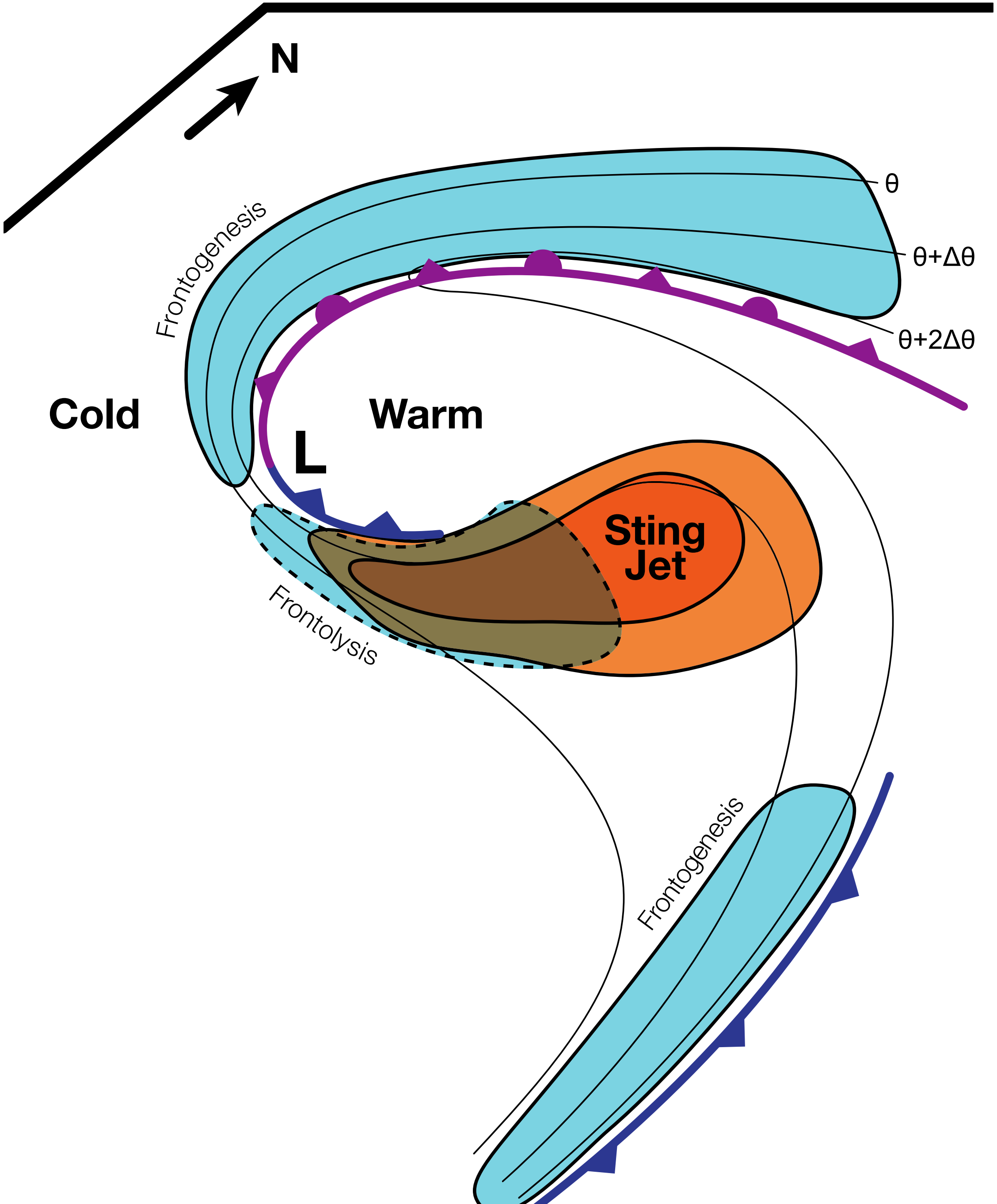



theta-e = 300K

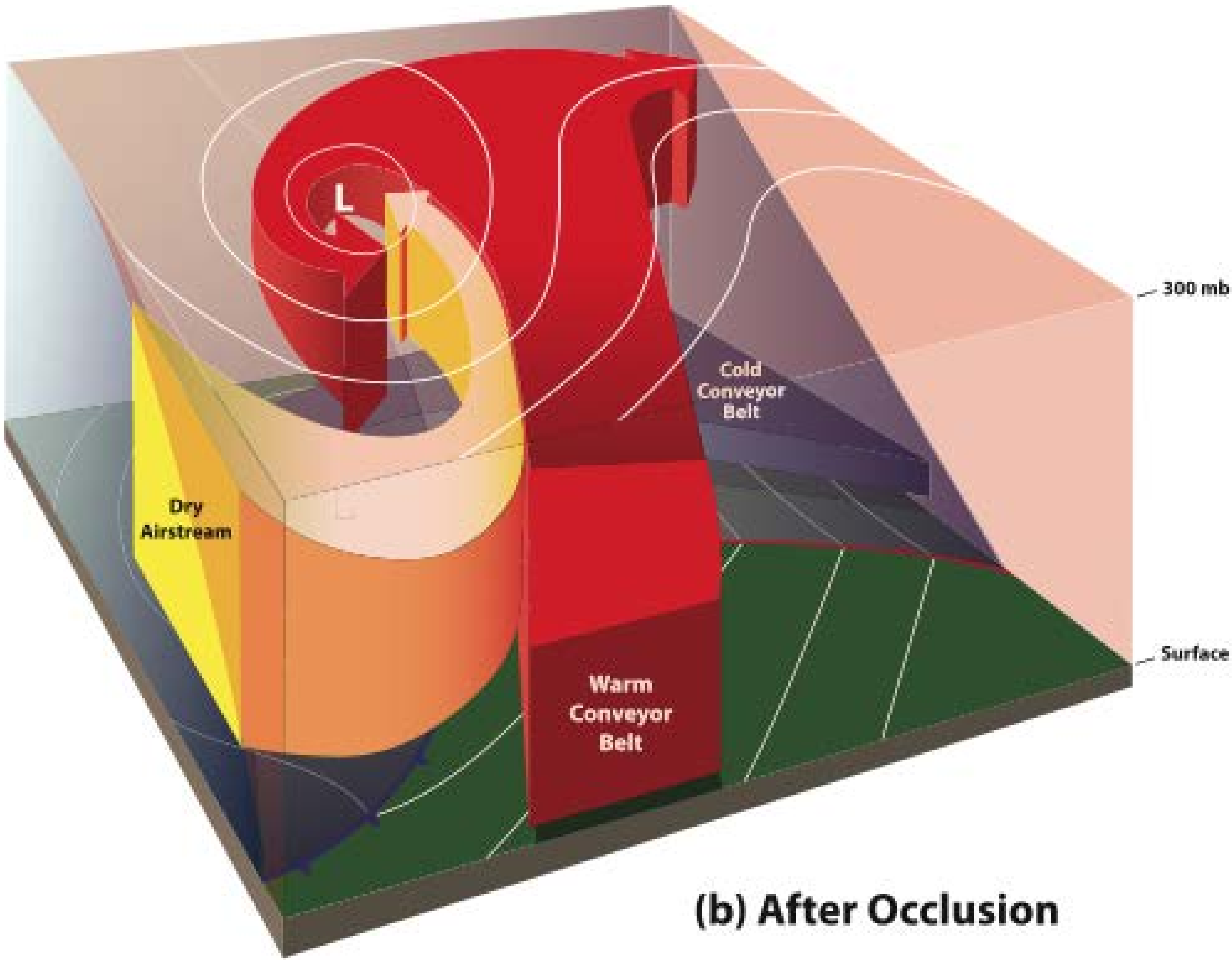
David Smart

# Ingredients for a Sting Jet

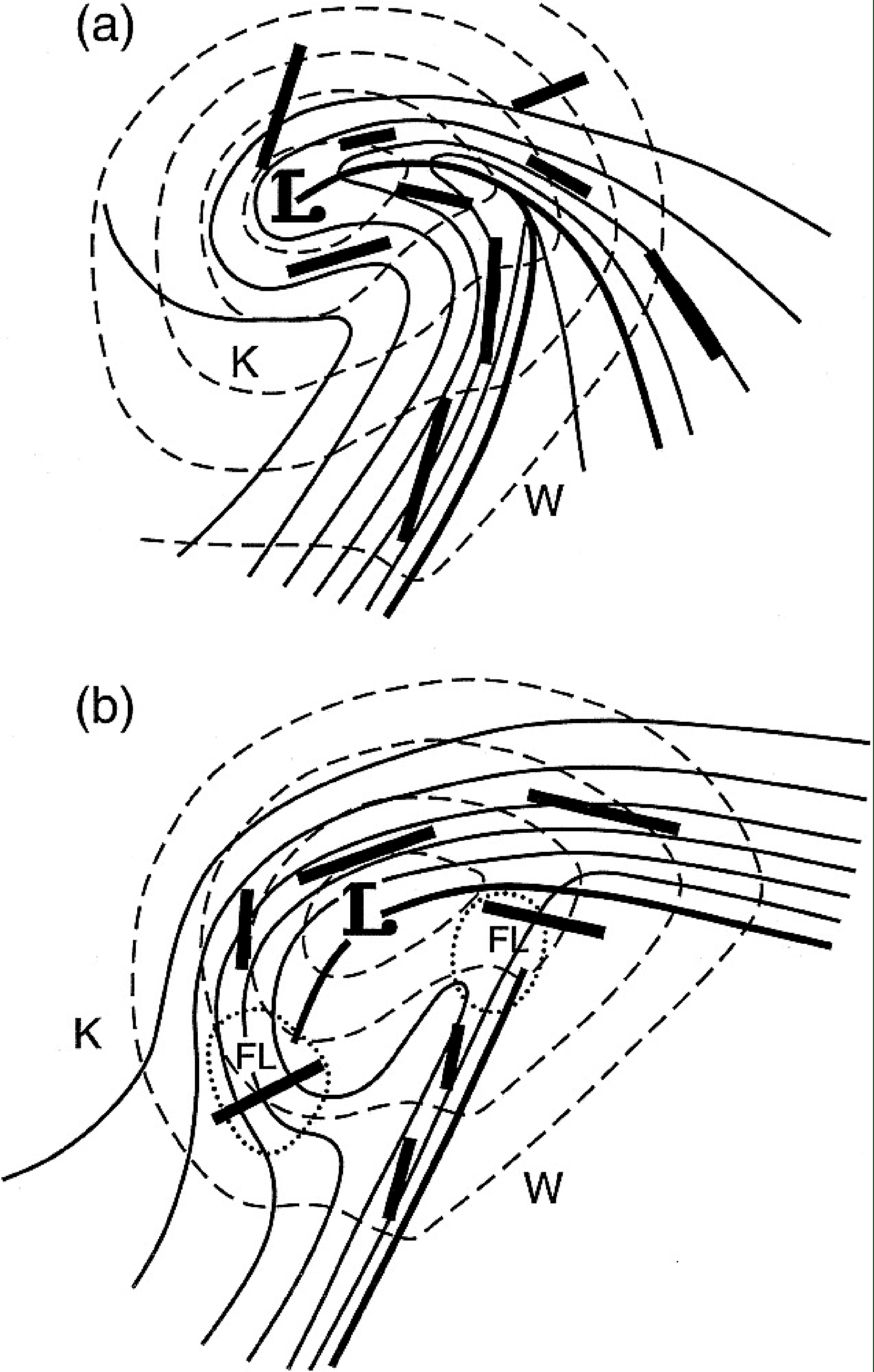
1. Frontogenesis and ascent of warm air along bent-back front.
2. Frontolysis at end of back-bent front and descent of warm air.
3. Low static and symmetric stability favors descent.
4. Near-neutral static stability in boundary layer favors mixing downward of high momentum air.


N
θ
θ+Δθ
θ+2Δθ
Frontogenesis
Cold
Warm
L
Sting Jet
Frontolysis
Frontogenesis

Schultz and Vaughan (2011)



*Why have sting jets only been documented in Shapiro–Keyser cyclones?*




# Norwegian Cyclone

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

# Shapiro–Keyser Cyclone

(Schultz et al. 1998)

# Frontogenesis/frontolysis is the physical mechanism for sting jets.

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

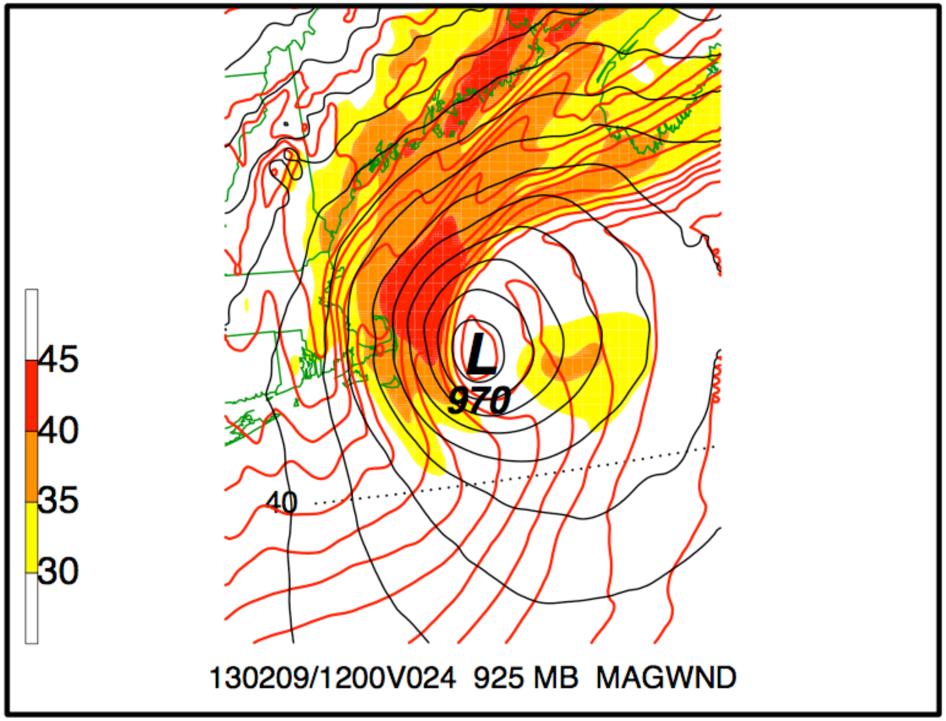
Why sting jets occur in Shapiro–Keyser cyclones, but not Norwegian cyclones.

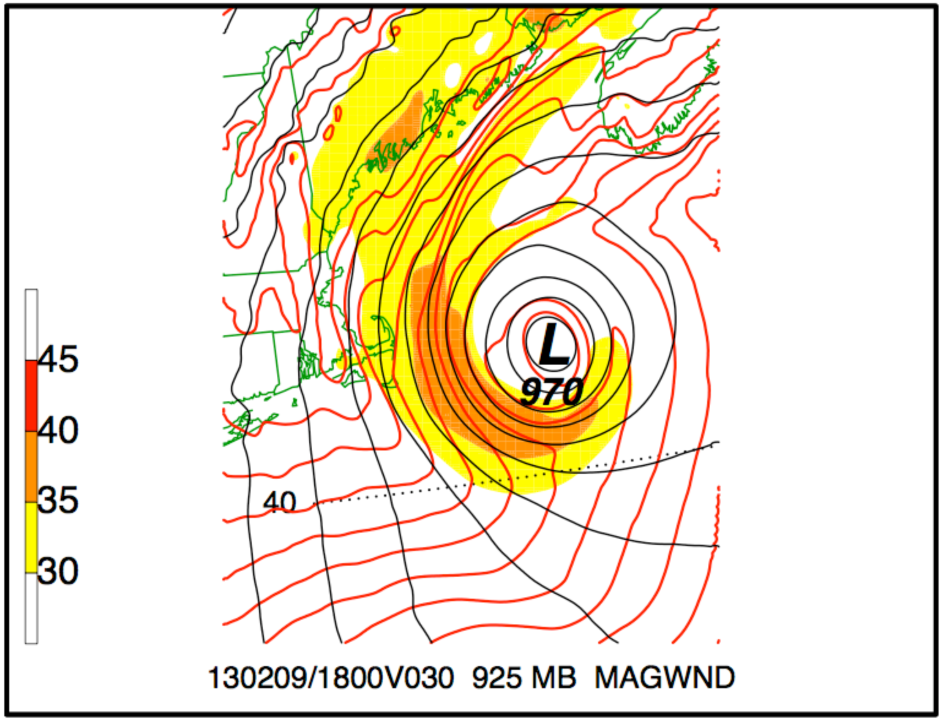
Why trajectories ascend, then descend.

Why evaporation is unimportant.

Why CSI results are ambiguous.

# Mysteries remain…

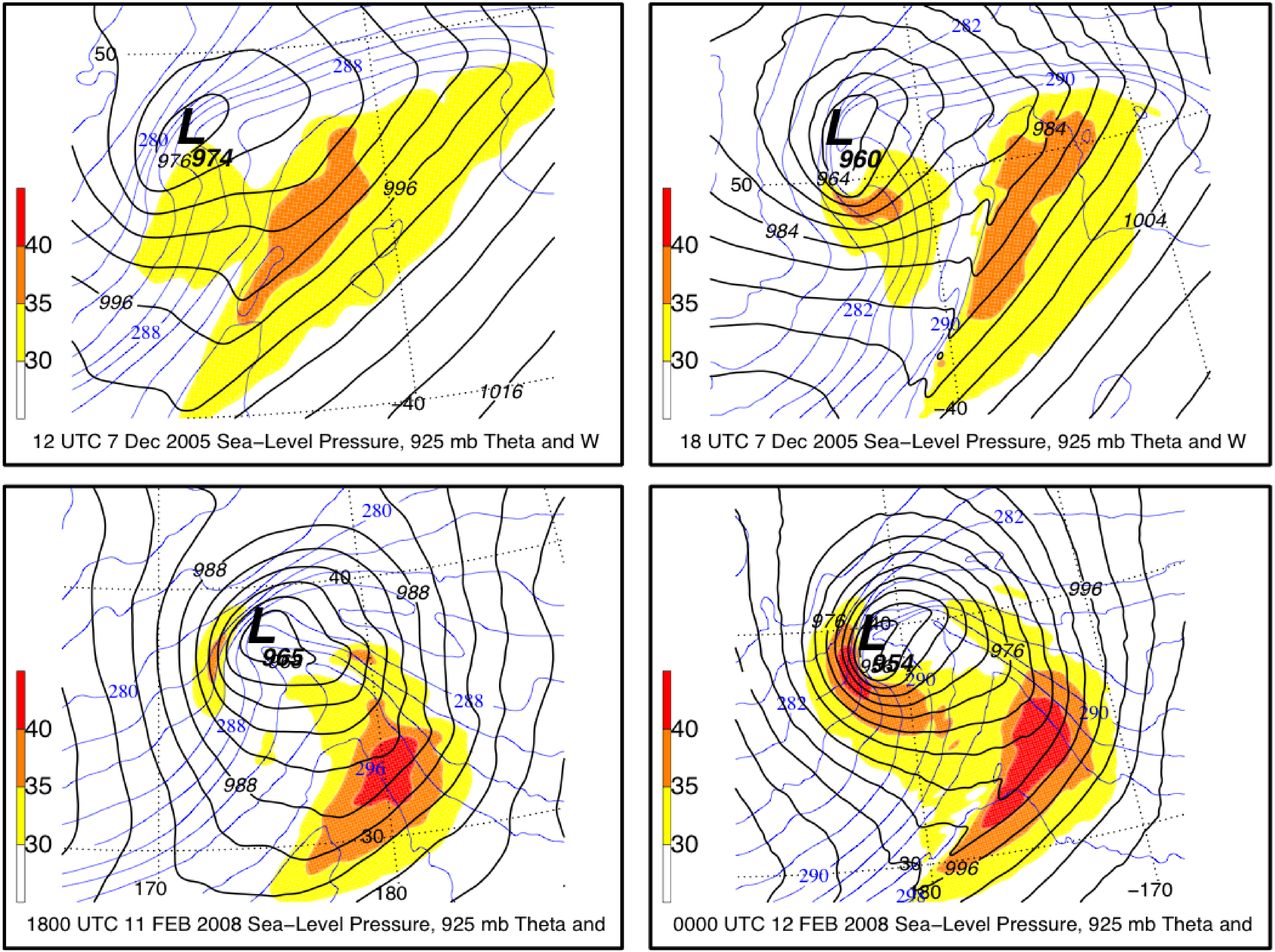


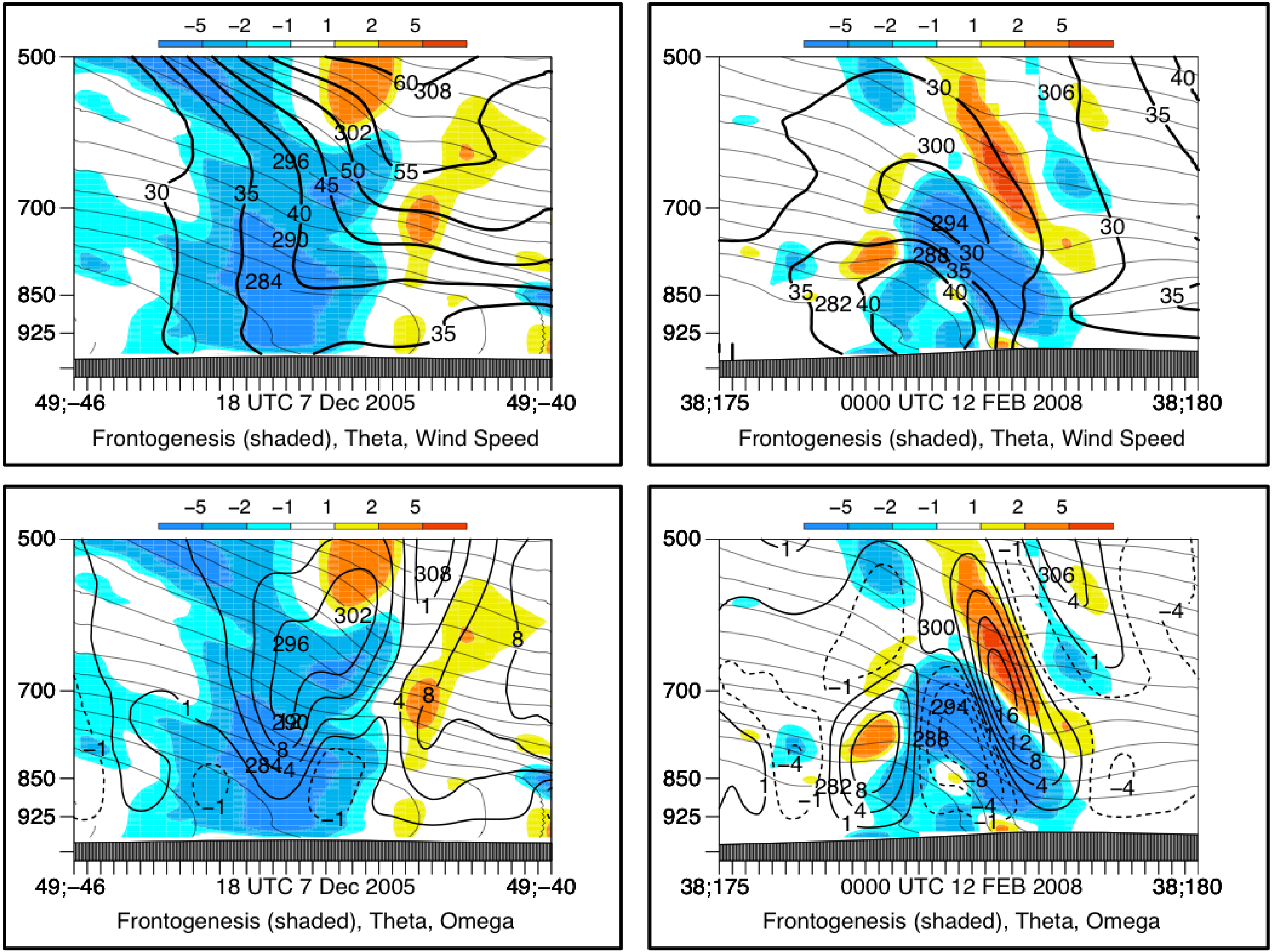

1200 UTC 9 Feb 2013

6 h later

Eastern US storm Nemo: 925-mb wind

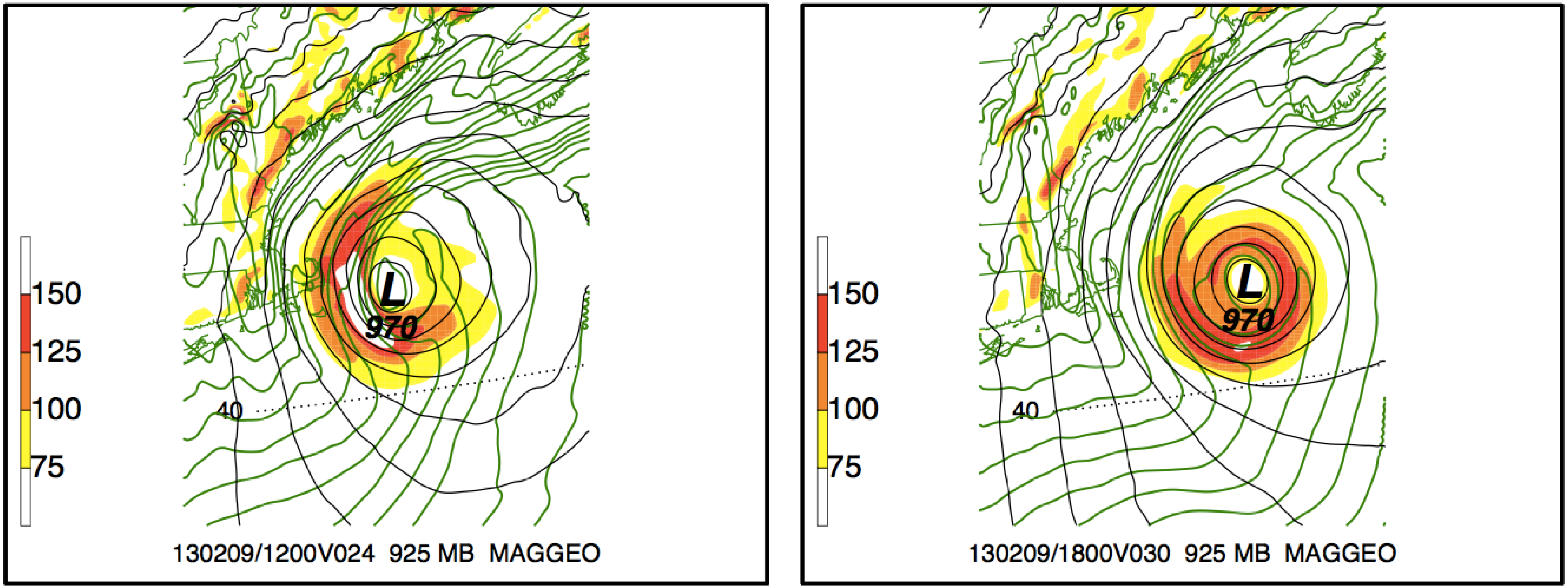


12 UTC 7 Dec 2005 Sea−Level Pressure, 925 mb Theta and W
18 UTC 7 Dec 2005 Sea−Level Pressure, 925 mb Theta and W
1800 UTC 11 FEB 2008 Sea−Level Pressure, 925 mb Theta and
0000 UTC 12 FEB 2008 Sea−Level Pressure, 925 mb Theta and
L
974
960
965
954
40
35
30



−5 −2 −1 1 2 5
500
700
850
925
49;−46
18 UTC 7 Dec 2005
49;−40
Frontogenesis (shaded), Theta, Wind Speed
−5 −2 −1 1 2 5
500
700
850
925
38;175
0000 UTC 12 FEB 2008
38;180
Frontogenesis (shaded), Theta, Wind Speed
−5 −2 −1 1 2 5
500
700
850
925
49;−46
18 UTC 7 Dec 2005
49;−40
Frontogenesis (shaded), Theta, Omega
−5 −2 −1 1 2 5
500
700
850
925
38;175
0000 UTC 12 FEB 2008
38;180
Frontogenesis (shaded), Theta, Omega

# Mysteries remain…




1200 UTC 9 Feb 2013 | 6 h later

Eastern US storm Nemo: 925-mb geostrophic wind

# 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.

# Frontogenesis/frontolysis is the physical mechanism for sting jets.

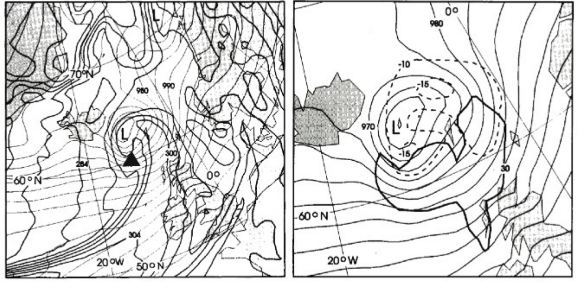
Why sting jets occur at end of bent-back fronts.

Why trajectories ascend, then descend.

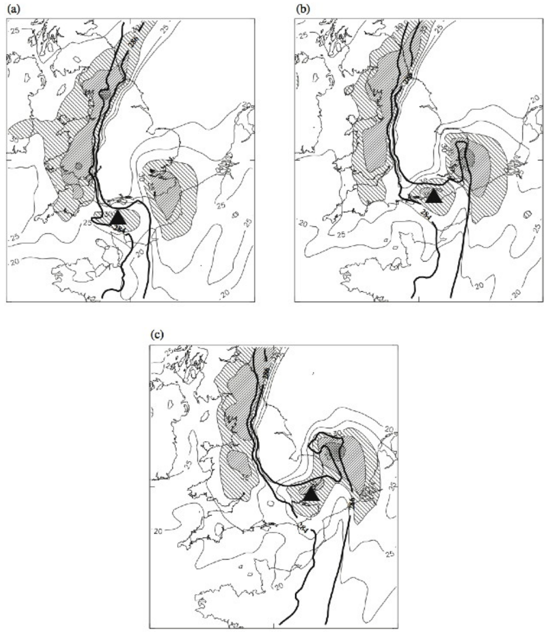
Why evaporation is relatively unimportant.

Why CSI results are ambiguous.

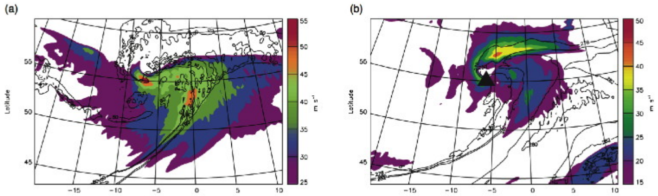
Mesoscale dimensions and descent.



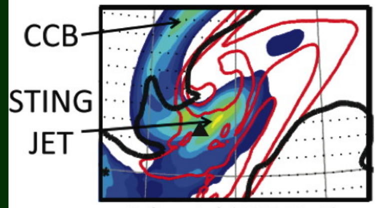

Gronas (1995, Figs. 3b and 4b)



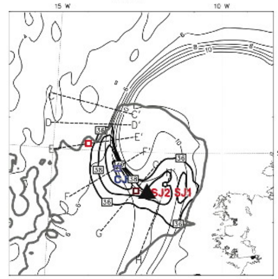

Clark et al. (2005, Fig. 7)




Baker (2009, Fig. 5)



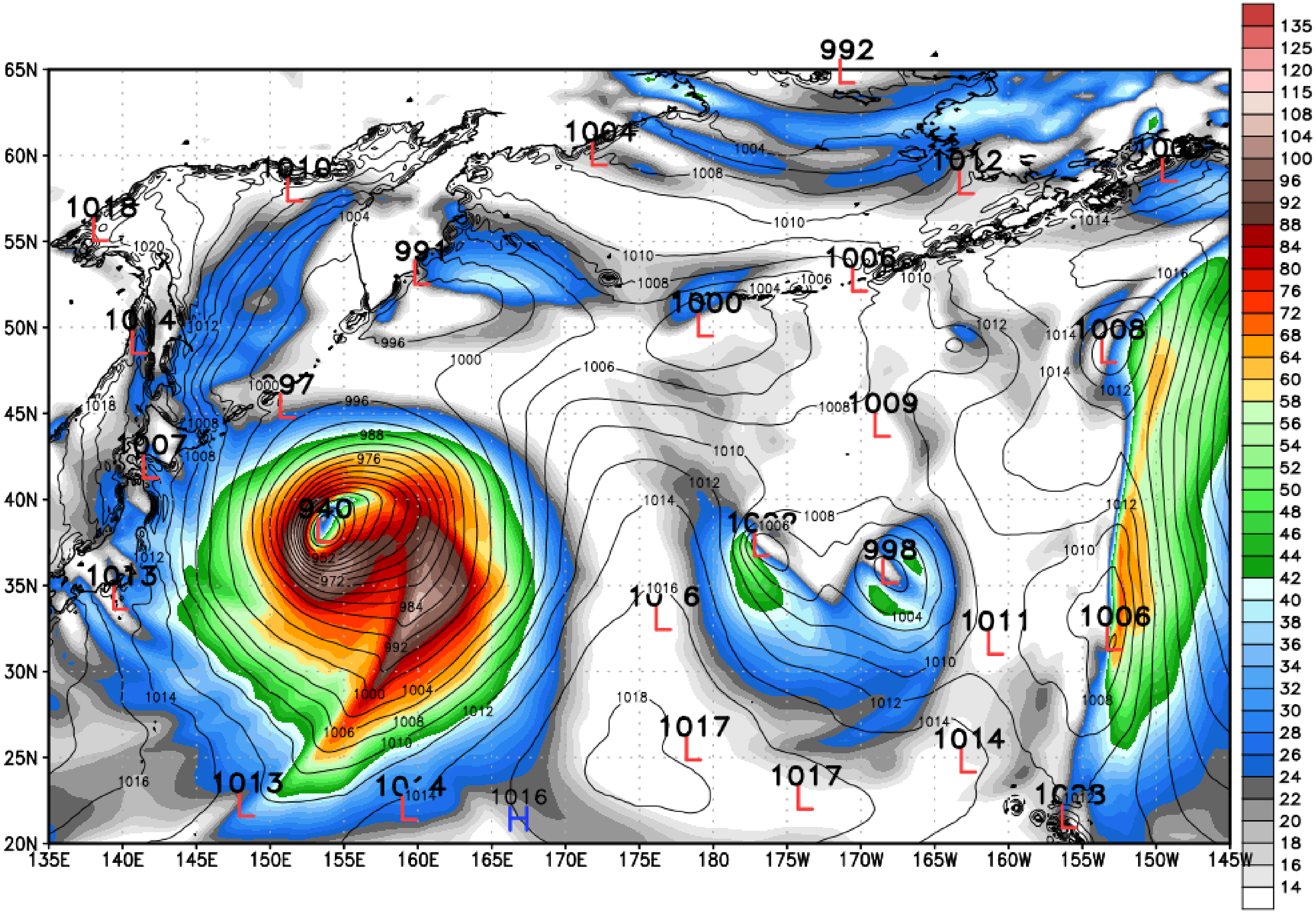

Baker et al. (2012, Fig. 5)



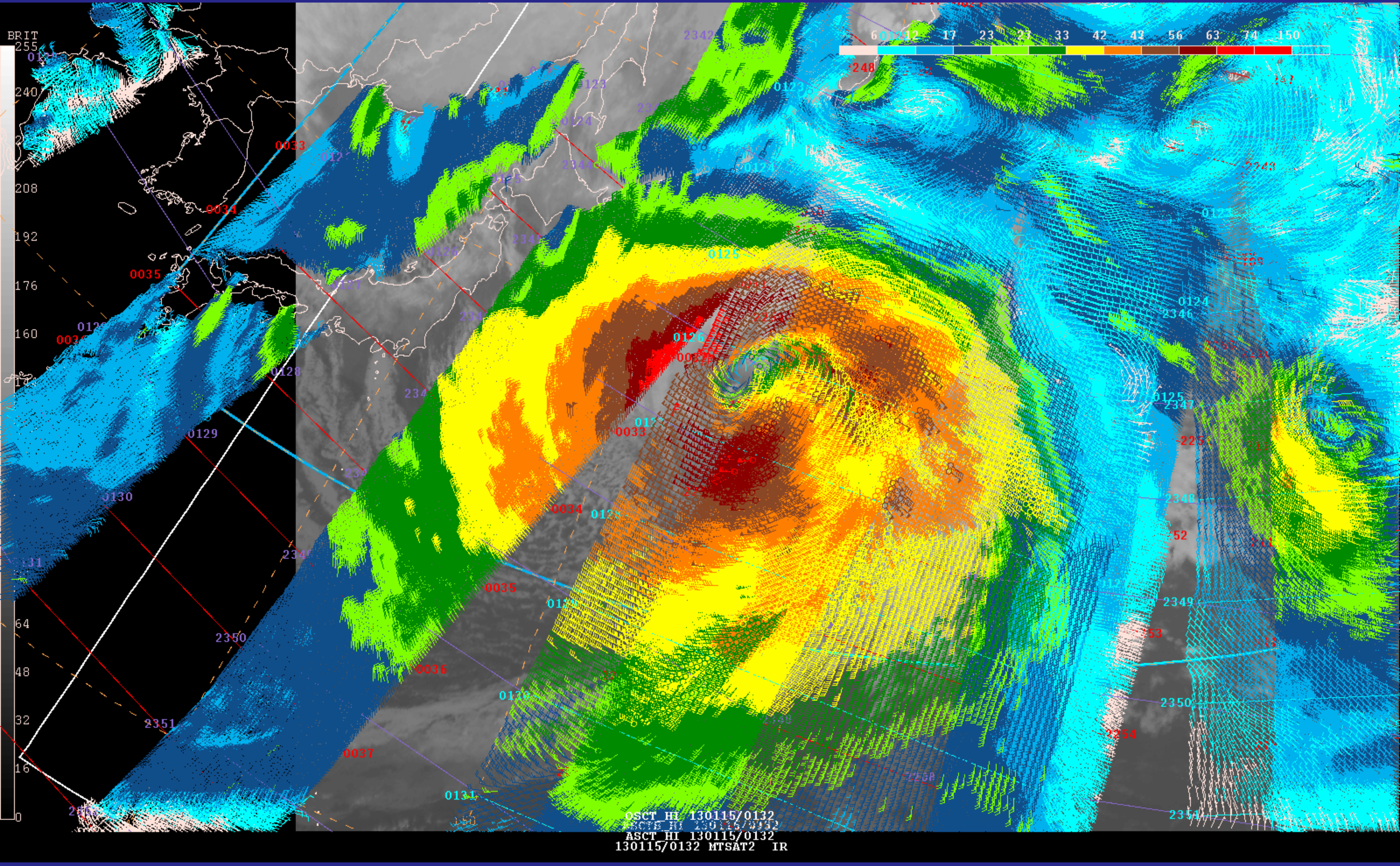

Smart and Browning (2012, Fig. 11)

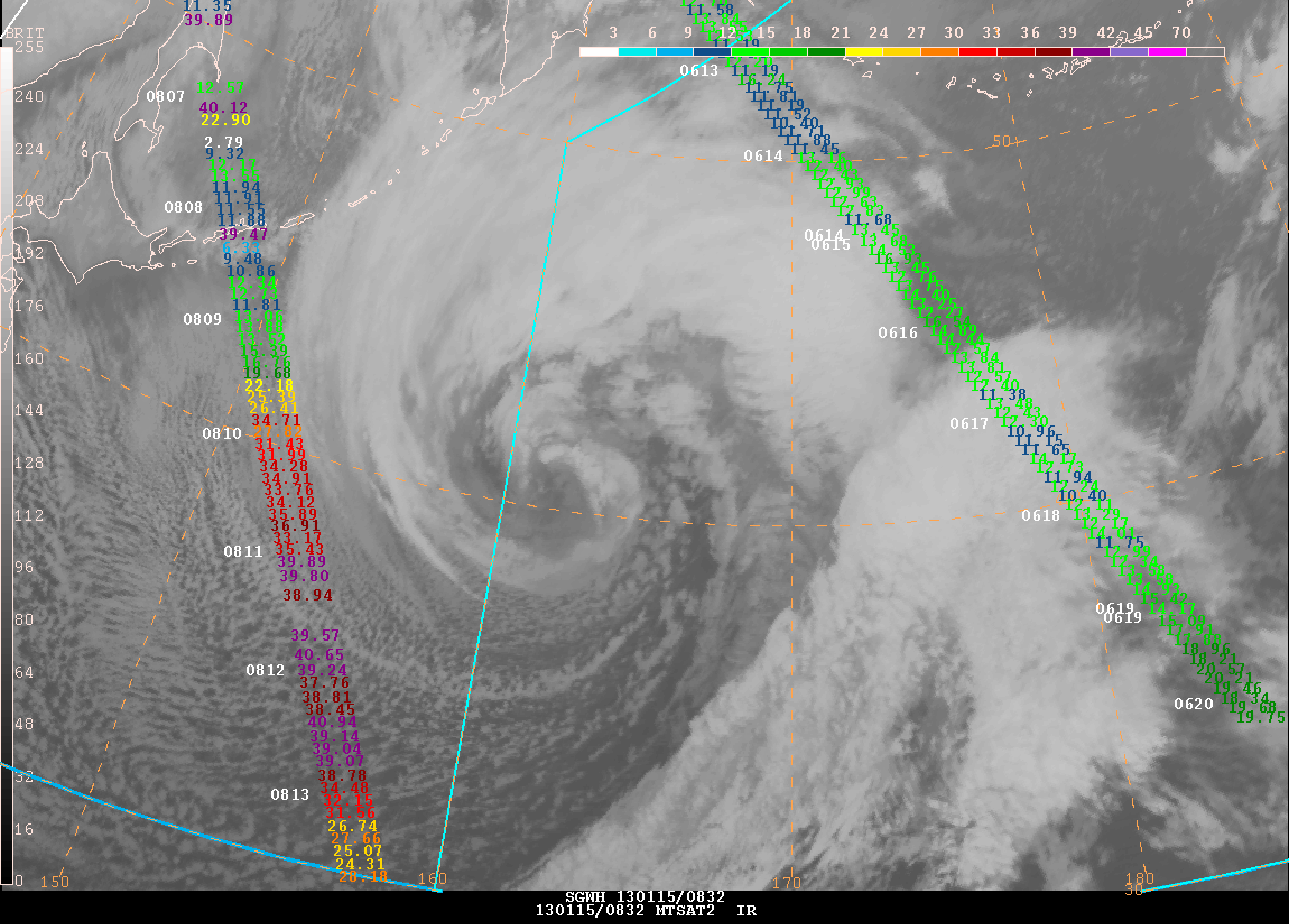
900 mb Wind Speed (kts) & MSLP (hPa) 00Z15JAN2013 fx: [0] hr --> Tue 00Z15JAN2013

GFS Global Deterministic Forecast Model T574    Domain Max: 108.2 kt

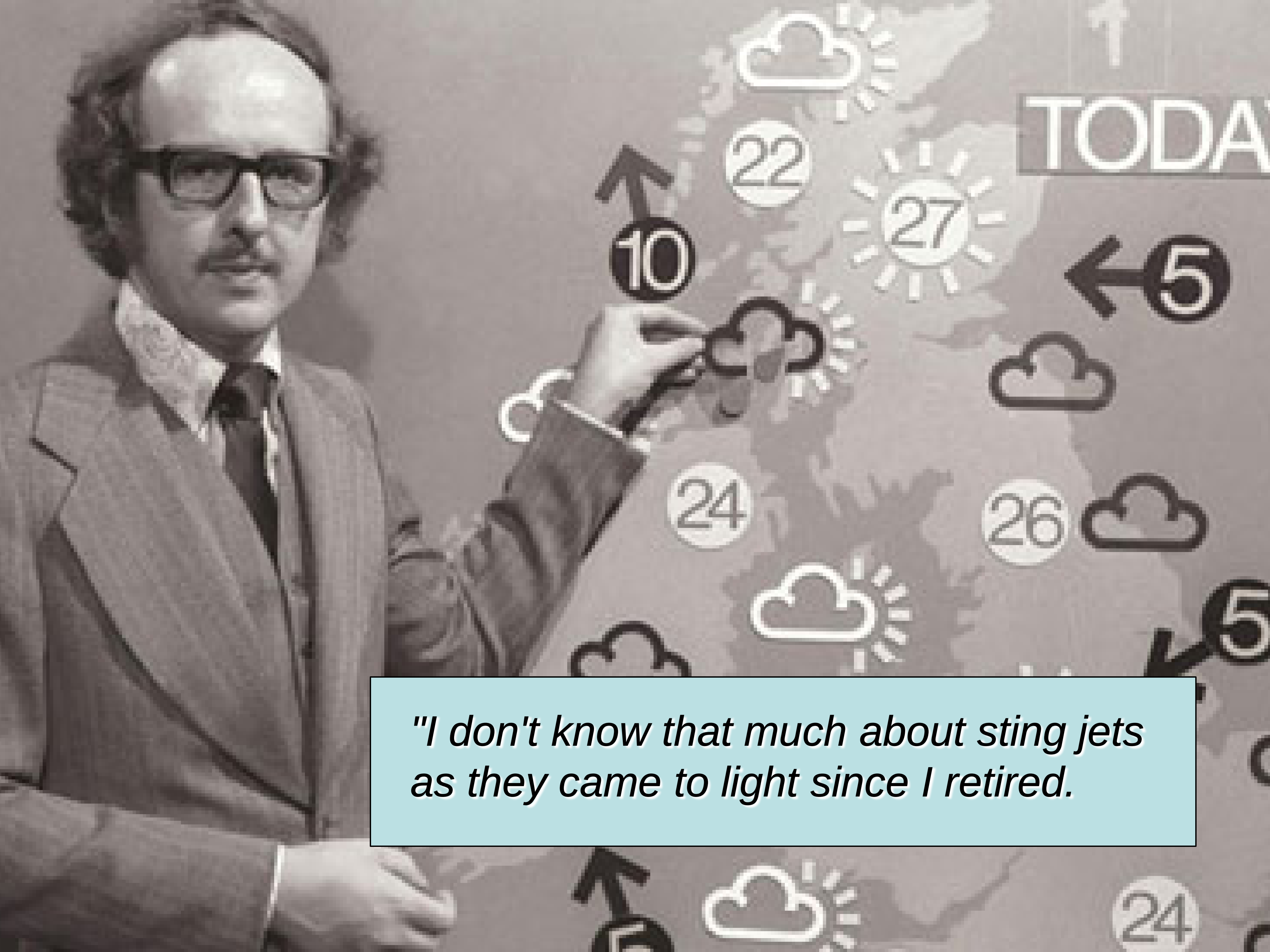



Full sflux 1760x880 Surface Pressure (only over the Sea-surface)


BRIT
QSCT_HI 130115/0132
ASCT_HI 130115/0132
130115/0132 MTSAT2 IR



BRIT
3 6 9 12 15 18 21 24 27 30 33 36 39 42 45 70
0613
0614
0615
0616
0617
0618
0619
0620
0807
0808
0809
0810
0811
0812
0813
150
160
170
180
50
30
SGWH 130115/0832
130115/0832 MTSAT2 IR



*"I don't know that much about sting jets as they came to light since I retired.*

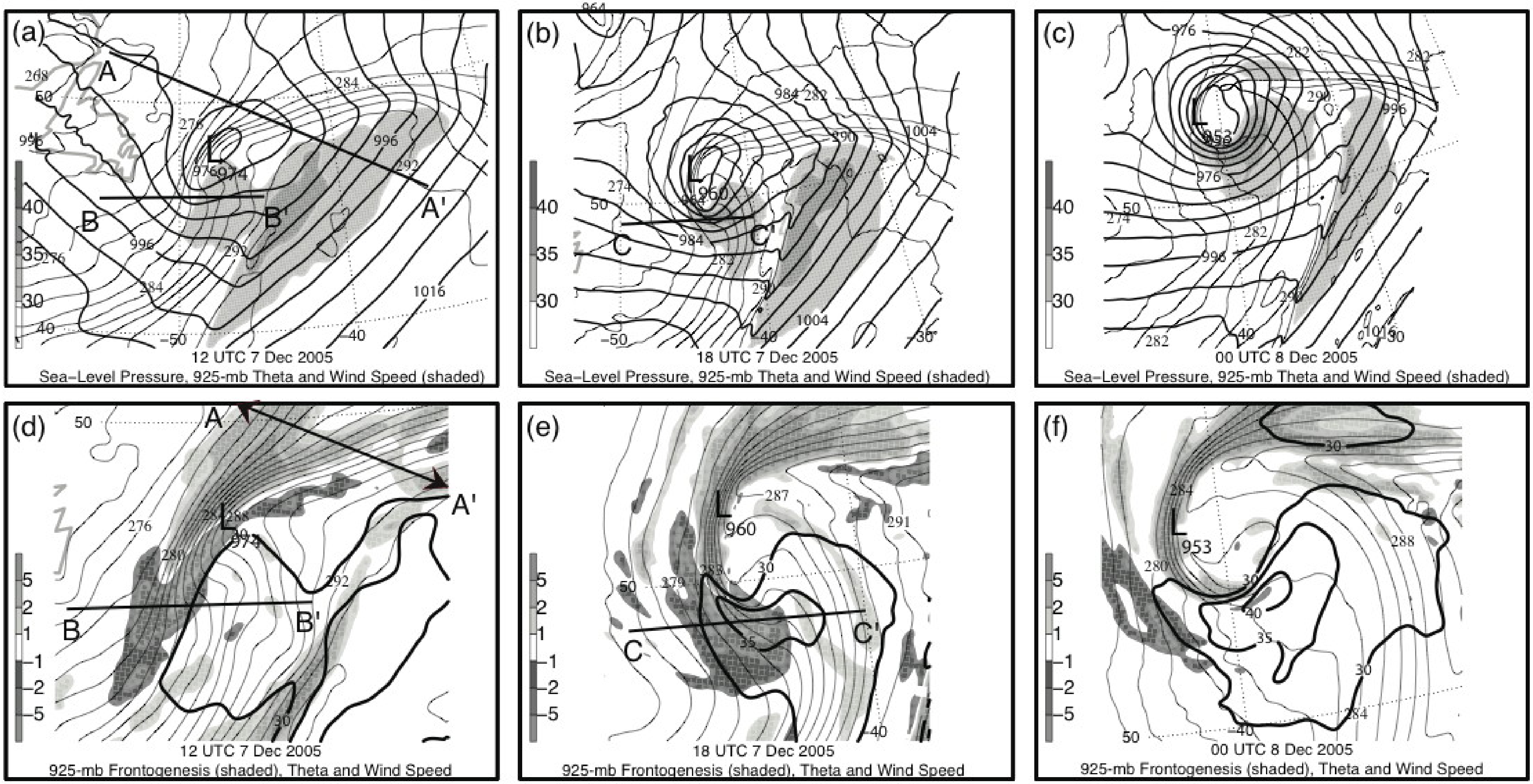
## Gray et al. (2011):

"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."

Top: sea-level pressure, 925-mb theta, wind speed (shaded)

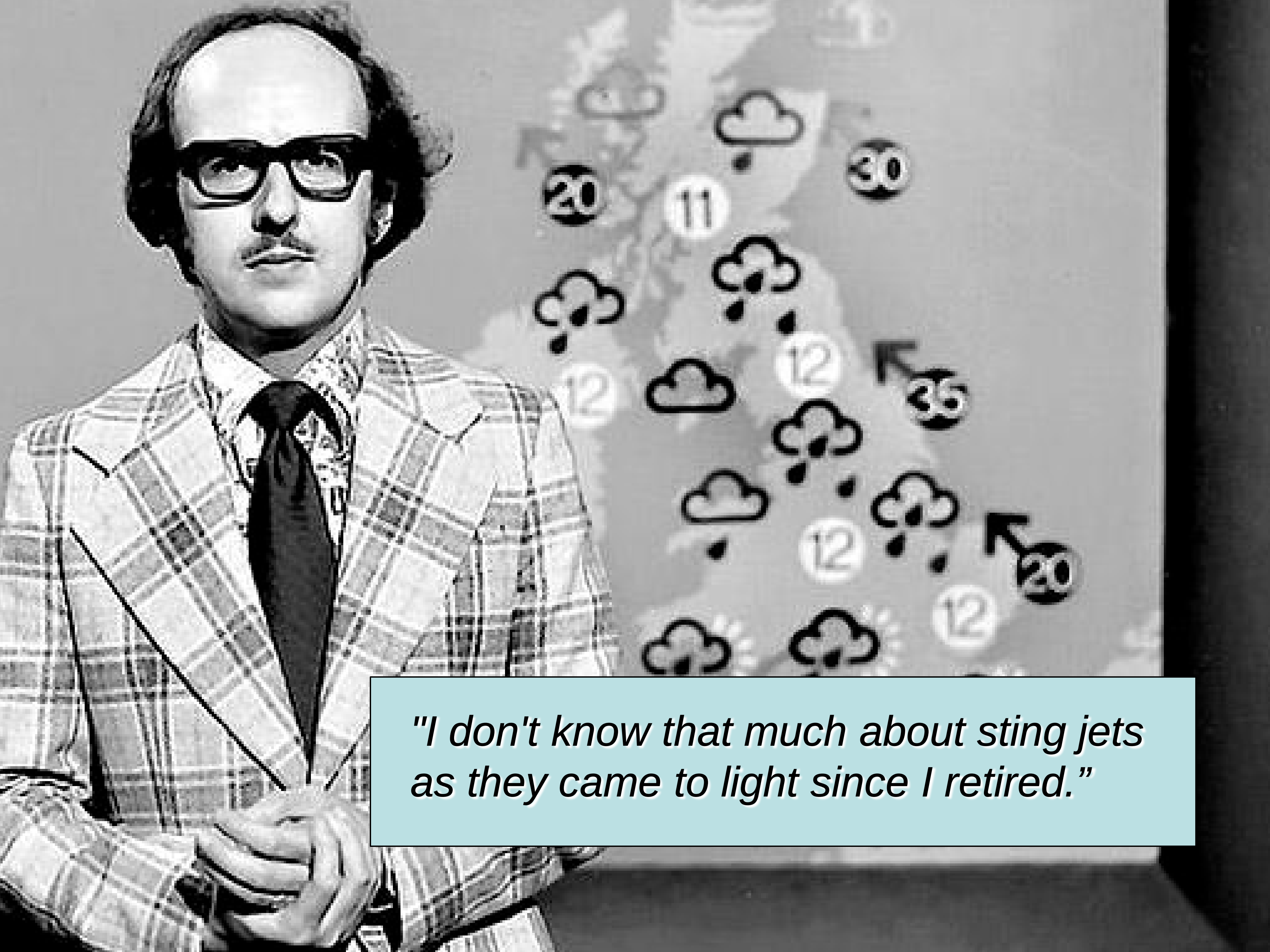



12 UTC 7 Dec

18 UTC 7 Dec

00 UTC 8 Dec

Bottom: 925-mb theta, wind speed, frontogenesis (shaded)



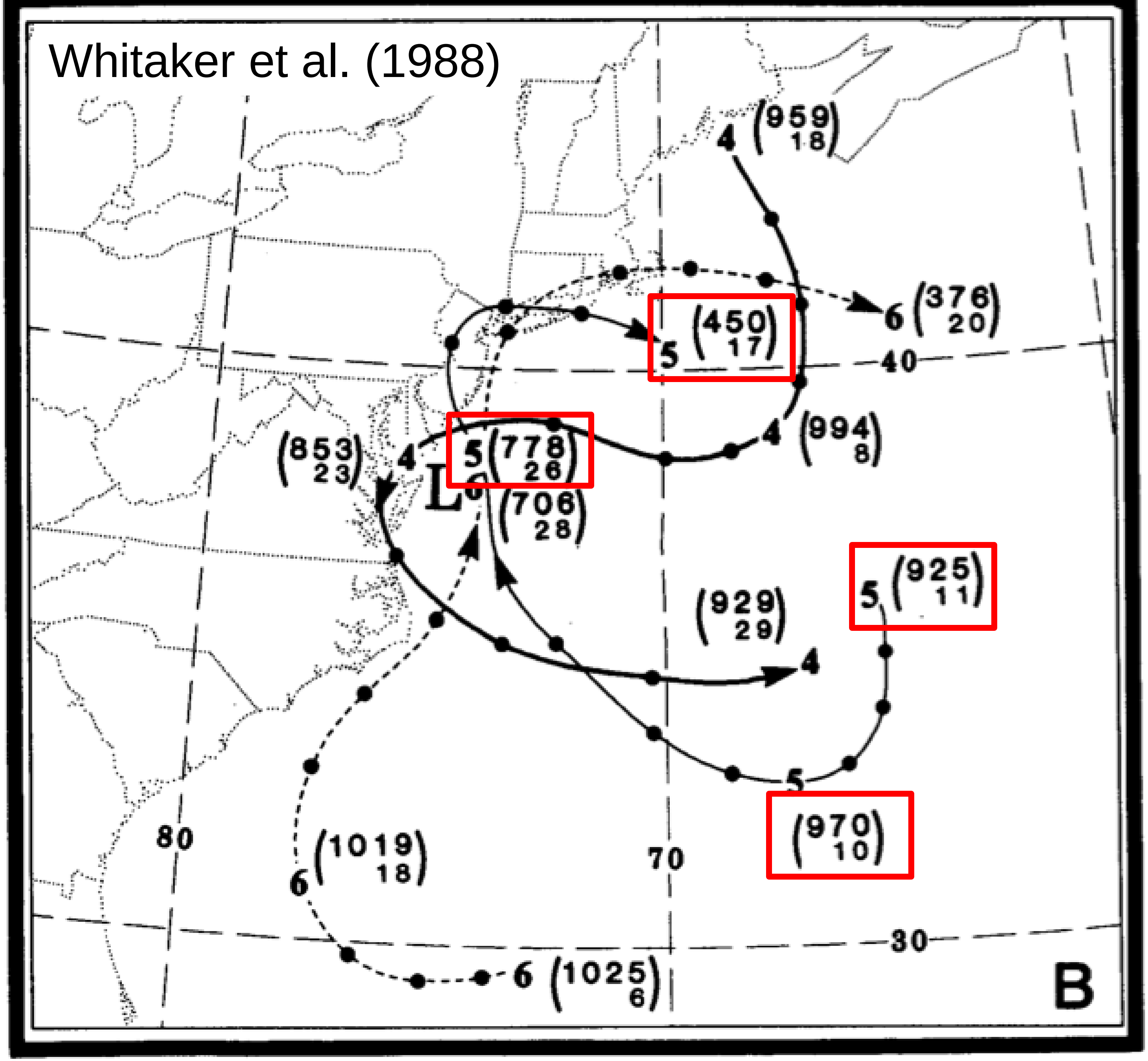

*"I don't know that much about sting jets as they came to light since I retired."*

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 p

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

Whitaker et al. (1988)



# Frontogenesis (Petterssen 1936)

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

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

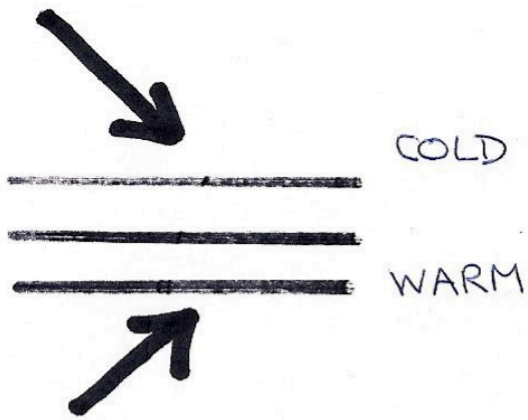
$$\mathbf{V}_H = u\mathbf{i} + v\mathbf{j},$$

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

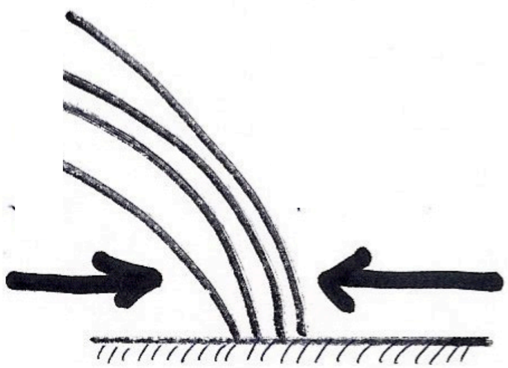
$$F = \frac{1}{2}|\nabla_H \theta|\,(\underbrace{E\cos 2\beta}_{\text{deformation}} - \underbrace{\nabla_H \cdot \mathbf{V}_H}_{\text{divergence}}),$$

# Frontogenesis

horizontal



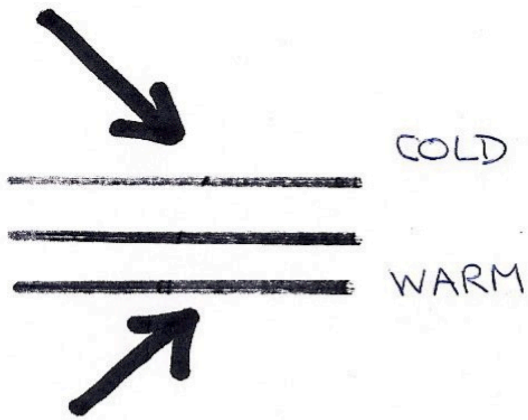

vertical



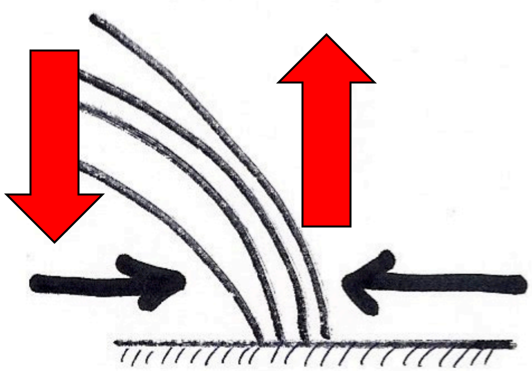
isentropes

# Frontogenesis

horizontal




vertical

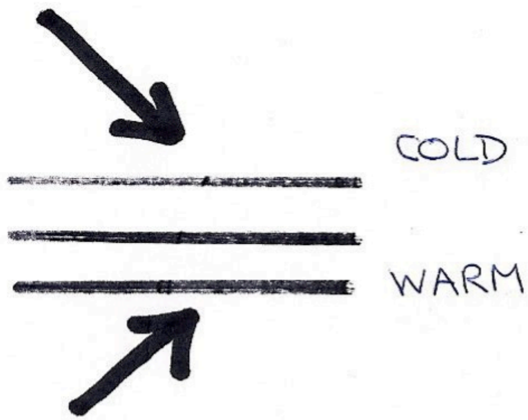


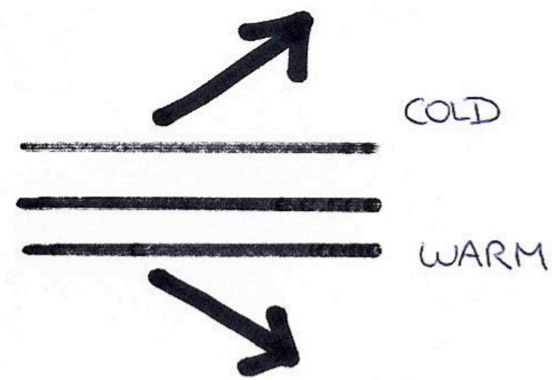
isentropes

## Frontogenesis

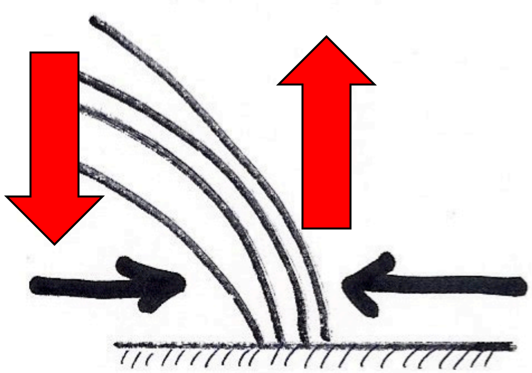
## Frontolysis

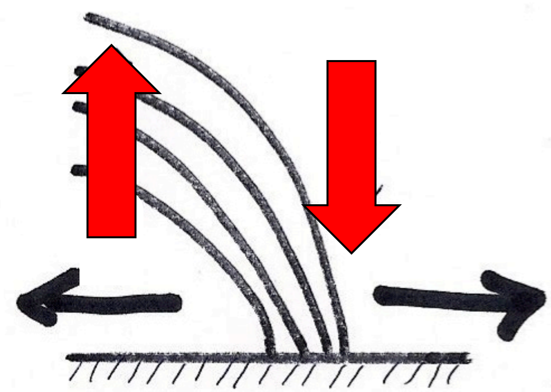
horizontal



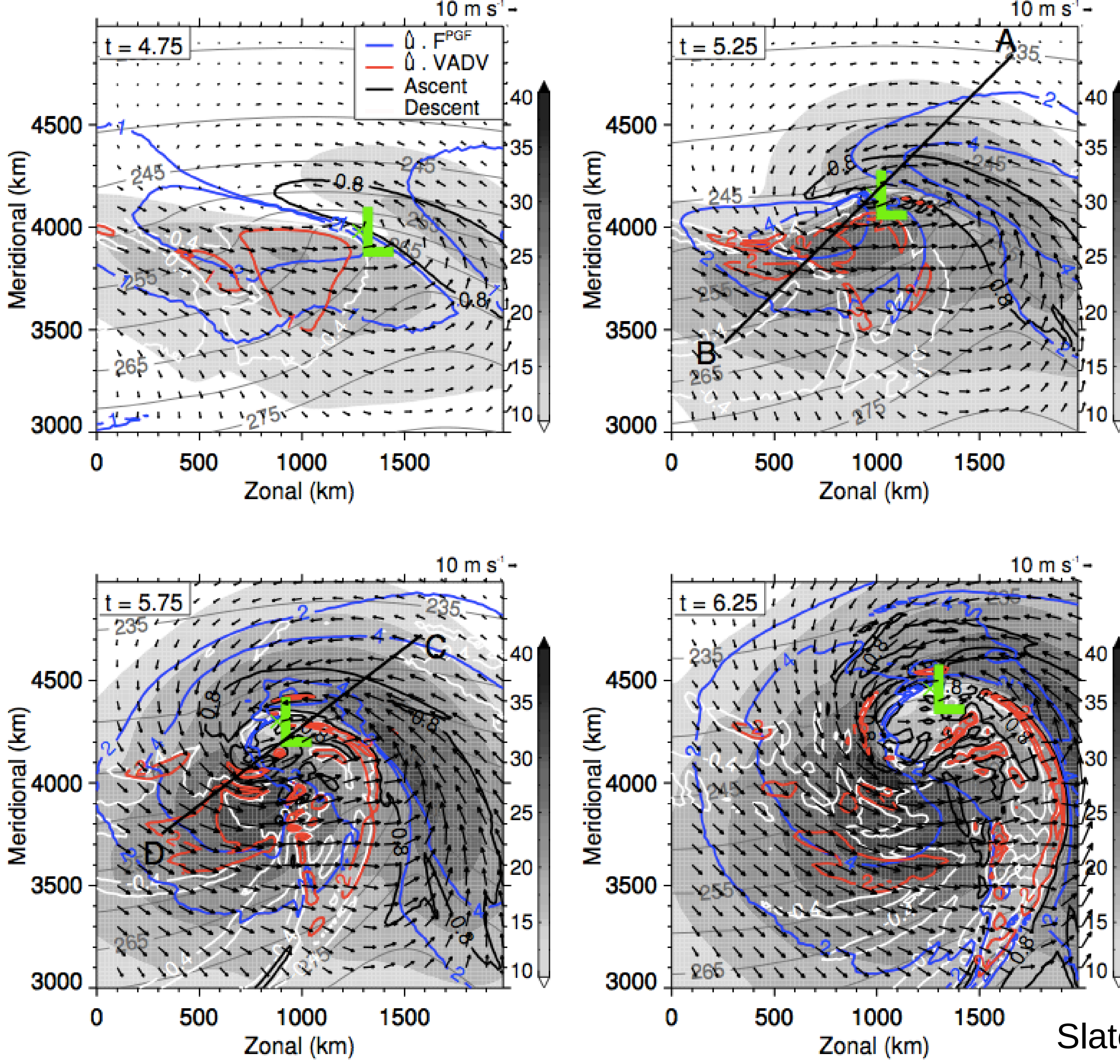




vertical

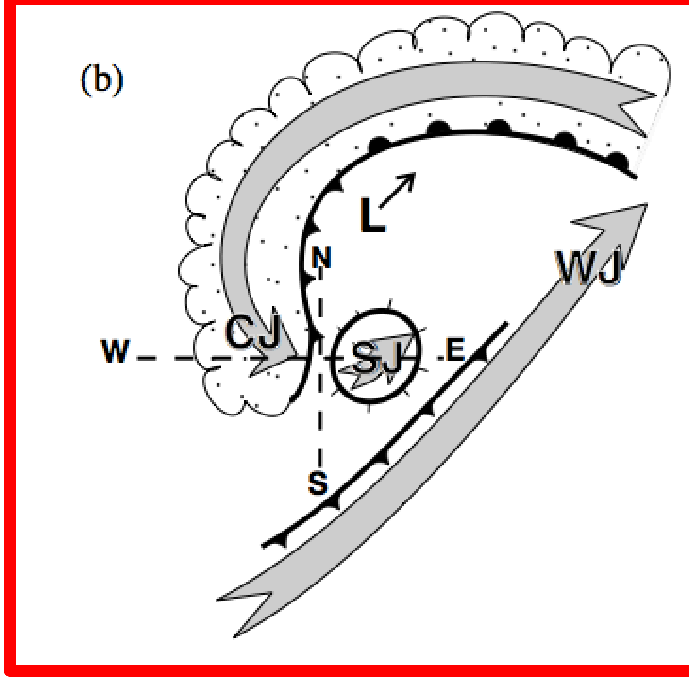


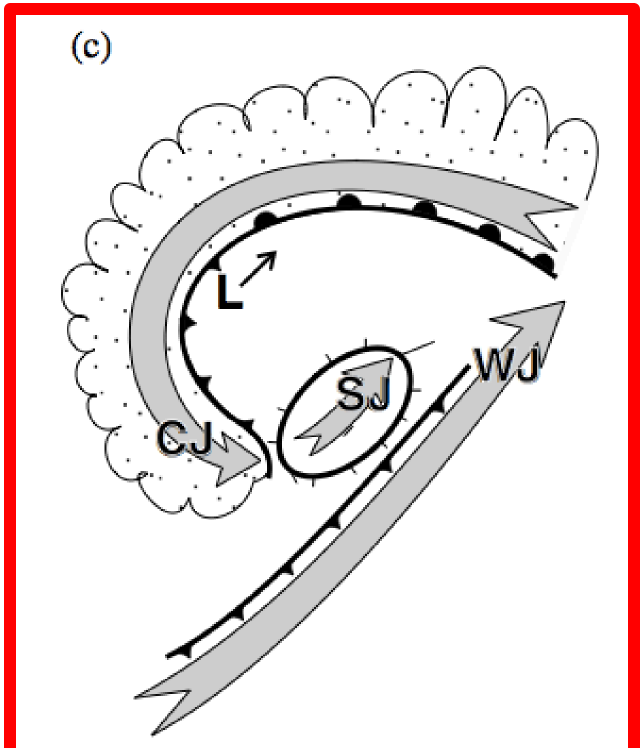


isentropes




Slater et al. (2014)



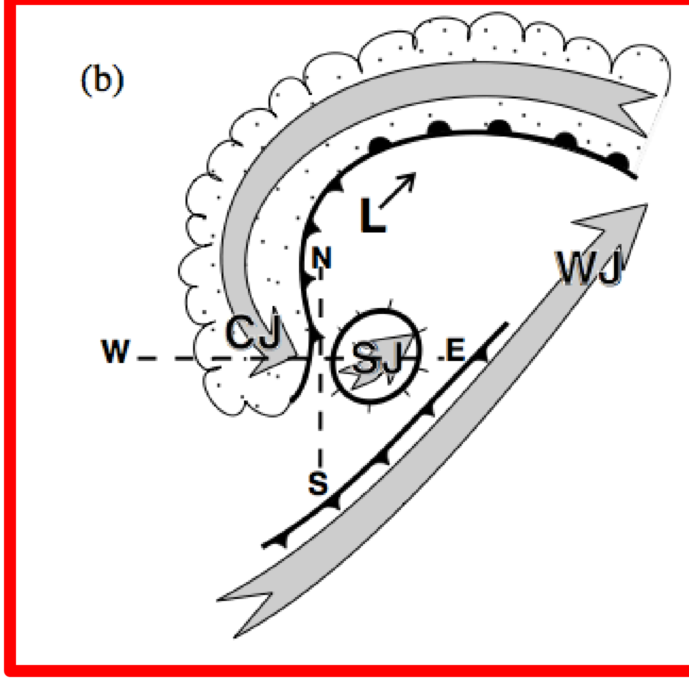




evolution of surface airstreams and fronts

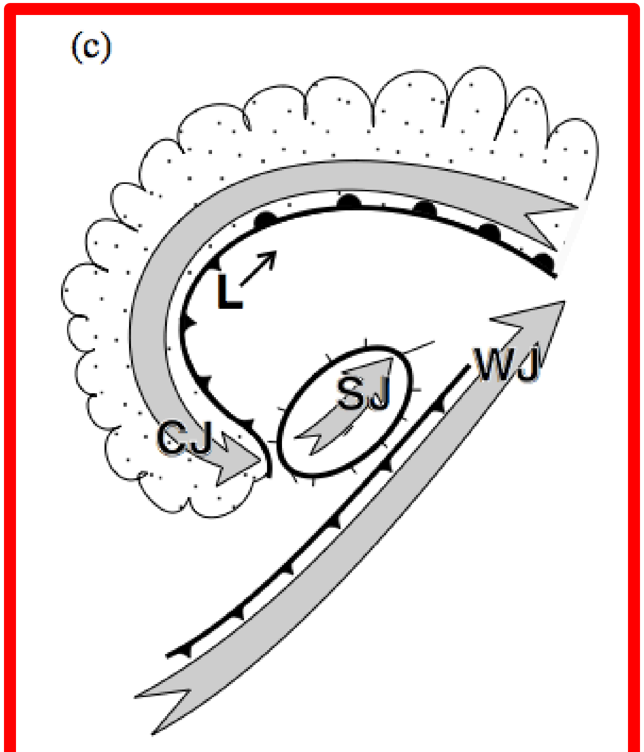
Clark et al. (2005)

Coincidence between front and sting jet?

Descending sting jet distinct from cold-conveyor belt?




evolution of surface airstreams and fronts




Clark et al. (2005)