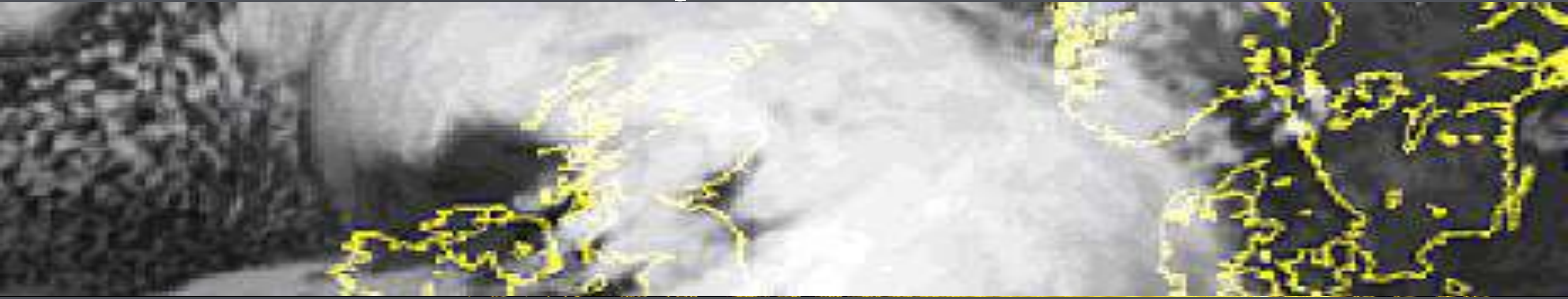
Department of Meteorology

University of Reading

Mesoscale features in extratropical cyclones

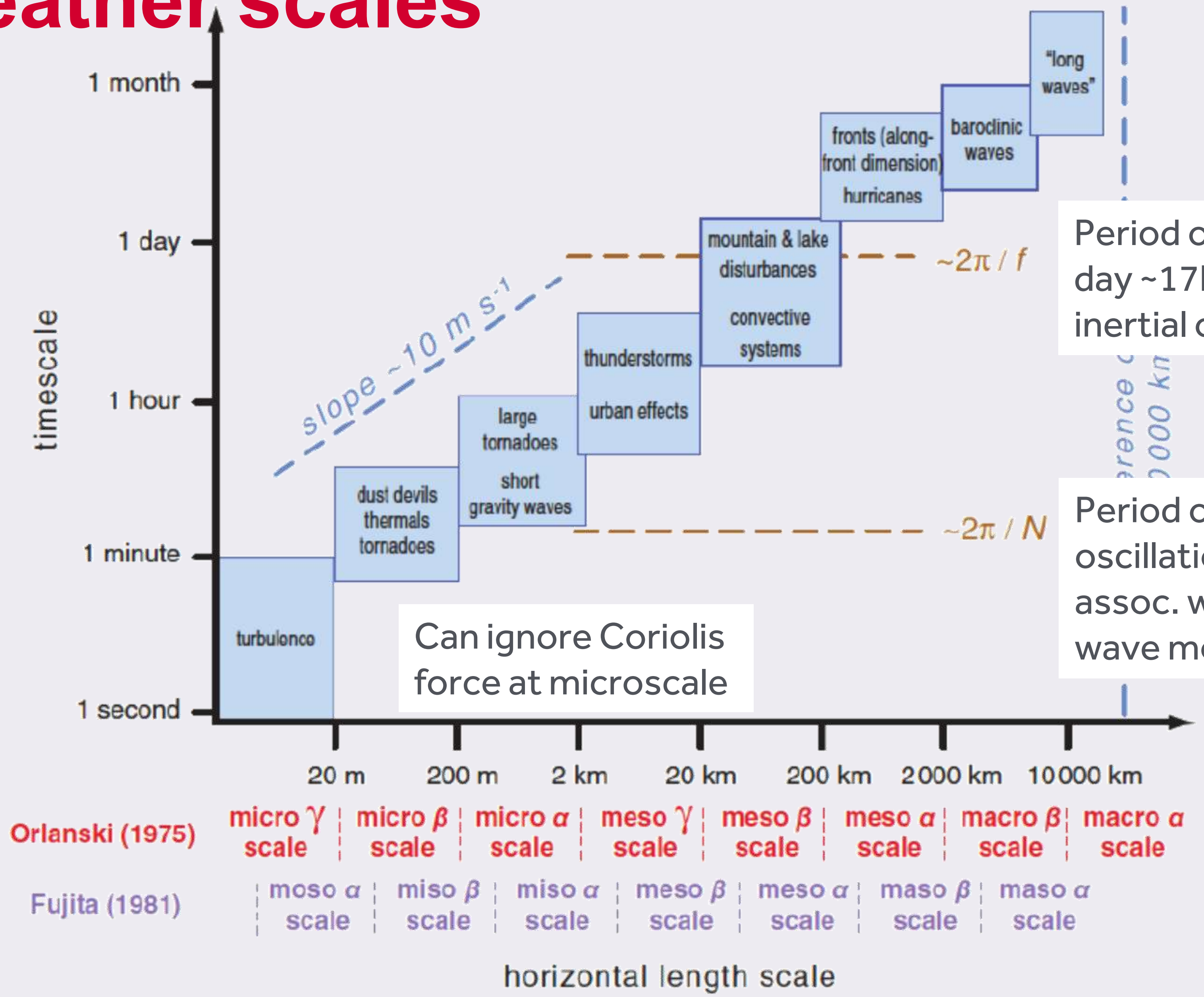


Suzanne Gray

Introduction

Weather scales

Can ignore vertical acceleration and advection by ageostropic wind at synoptic scale



Period of pendulum day ~17h assoc. with inertial oscillations

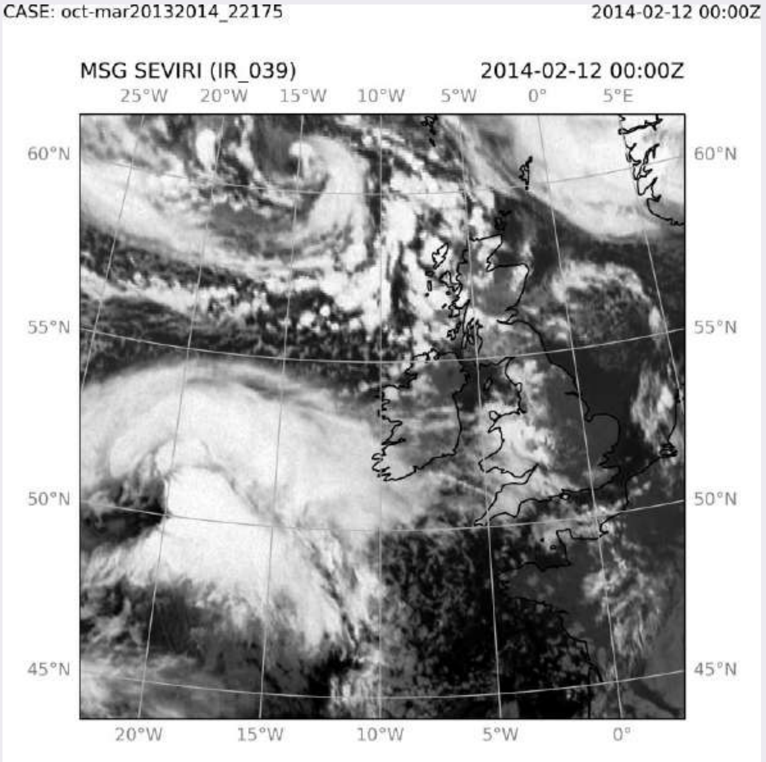
Period of buoyancy oscillation ~10 min assoc. with gravity wave motions.

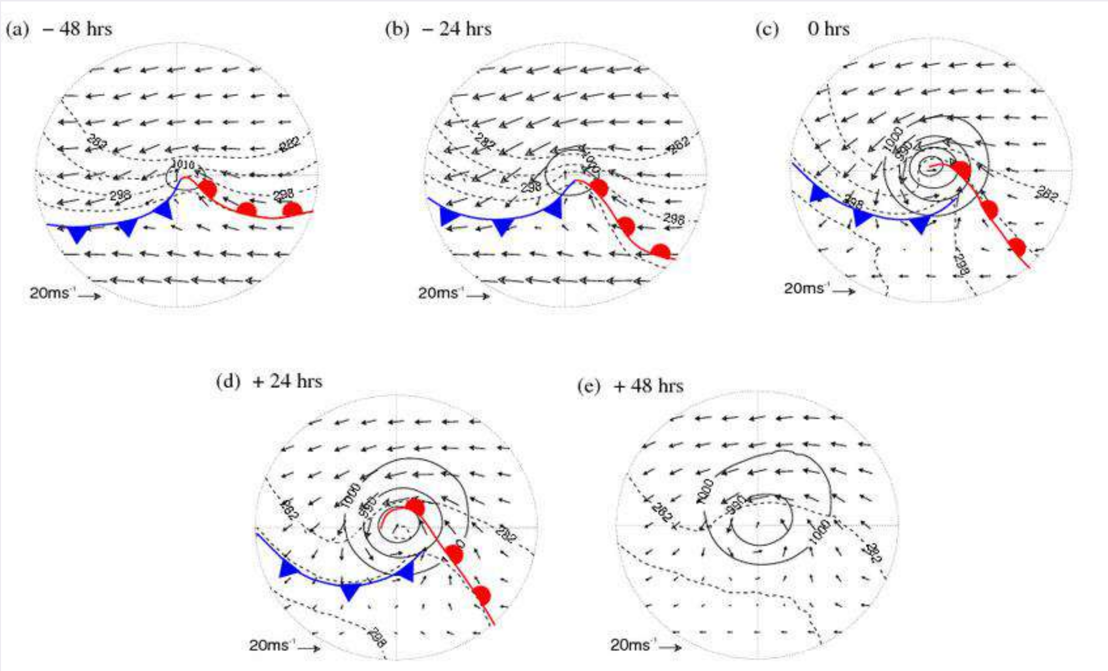
Can ignore Coriolis force at microscale

From "Mesoscale Meteorology in the Midlatitudes" by Markowski and Richardson

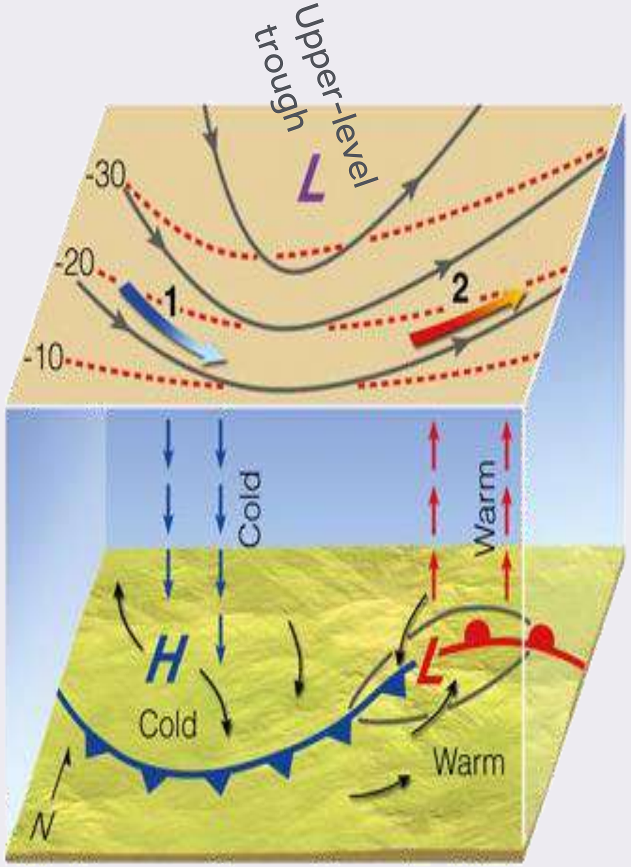
Extratropical cyclones

AMS glossary: (Sometimes called extratropical low, extratropical storm.) Any cyclonic-scale storm that is not a tropical cyclone, usually referring only to the migratory frontal cyclones of middle and high latitudes.





Dacre et al. (2012)



Ahrens 'Meteorology today'

Storm-tracks: northern hemisphere

"Cyclogenesis": developing or strengthening of a mid-latitude cyclone

"Cyclolysis": cyclone decay

Some regions are especially prone to cyclone formation:

Regions of strong temperature contrast

e.g., Continental coastlines (Atlantic, Pacific and Mediterranean – in winter)

Gulf stream/Kuroshio current

Ice shelf versus sea in Arctic/Antarctic

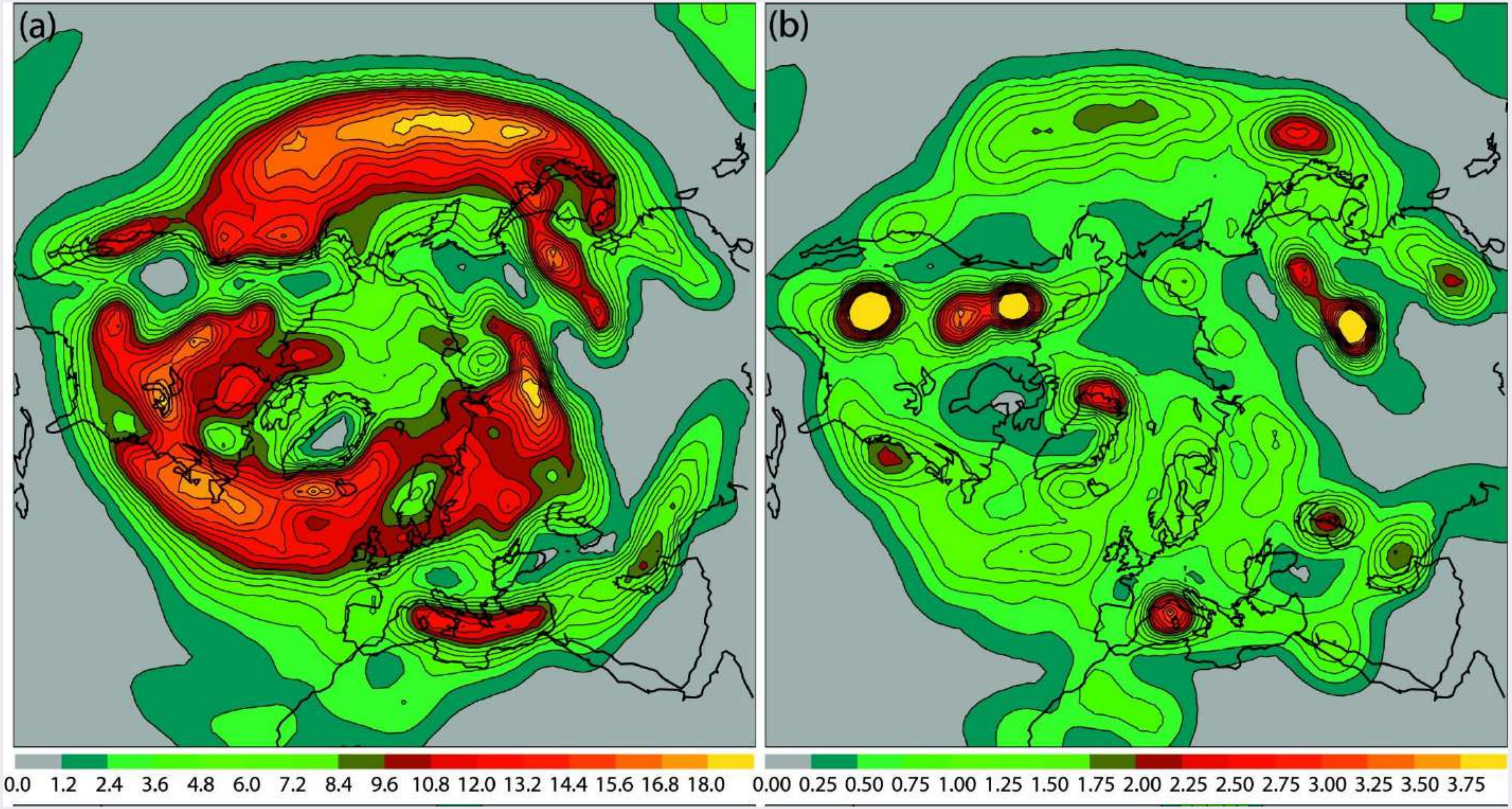
Eastern sides of high mountain ranges – lee cyclogenesis

Dacre et al. (2012): Extratropical Cyclone Atlas, see also https://www.met.rdg.ac.uk/~storms/

Storm-tracks: northern hemisphere

Track density

Genesis



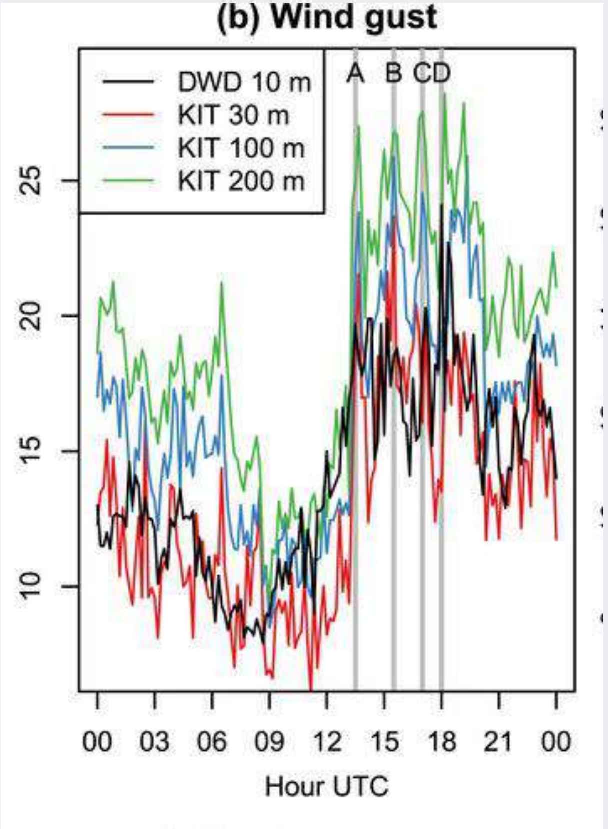
units of number density per month per unit area, where the unit area is equivalent to a 5° spherical cap (~10^6 km^2).

Hodges et al. (2011)

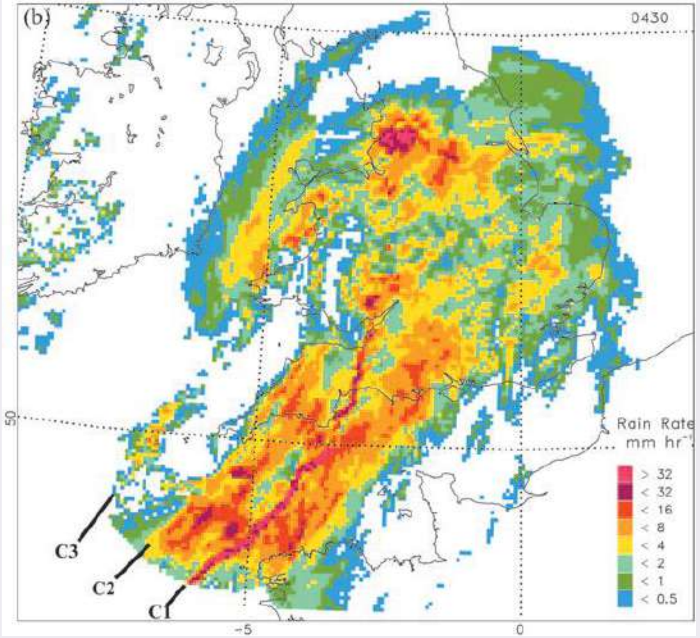
Embedded mesoscale features

Features can include....

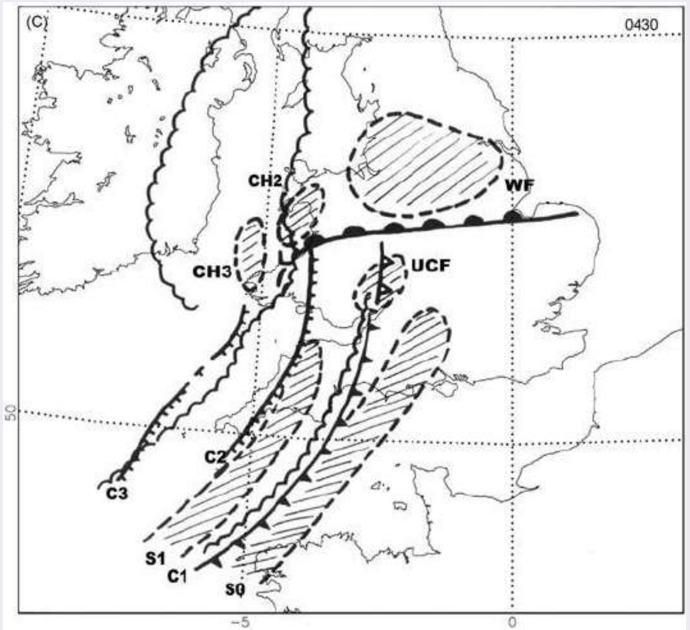
- Multiple rainbands
- Stacked slantwise circulations
- Cloud top striations
- Cloud heads with substructure
- Inertia-gravity waves in the region of tropopause folds
- Sting jets, tornadoes, and derechoes
- These features can all cause localised regions of extreme wind speeds/gusts and precipitation



Pantillon *et al.* (2020)



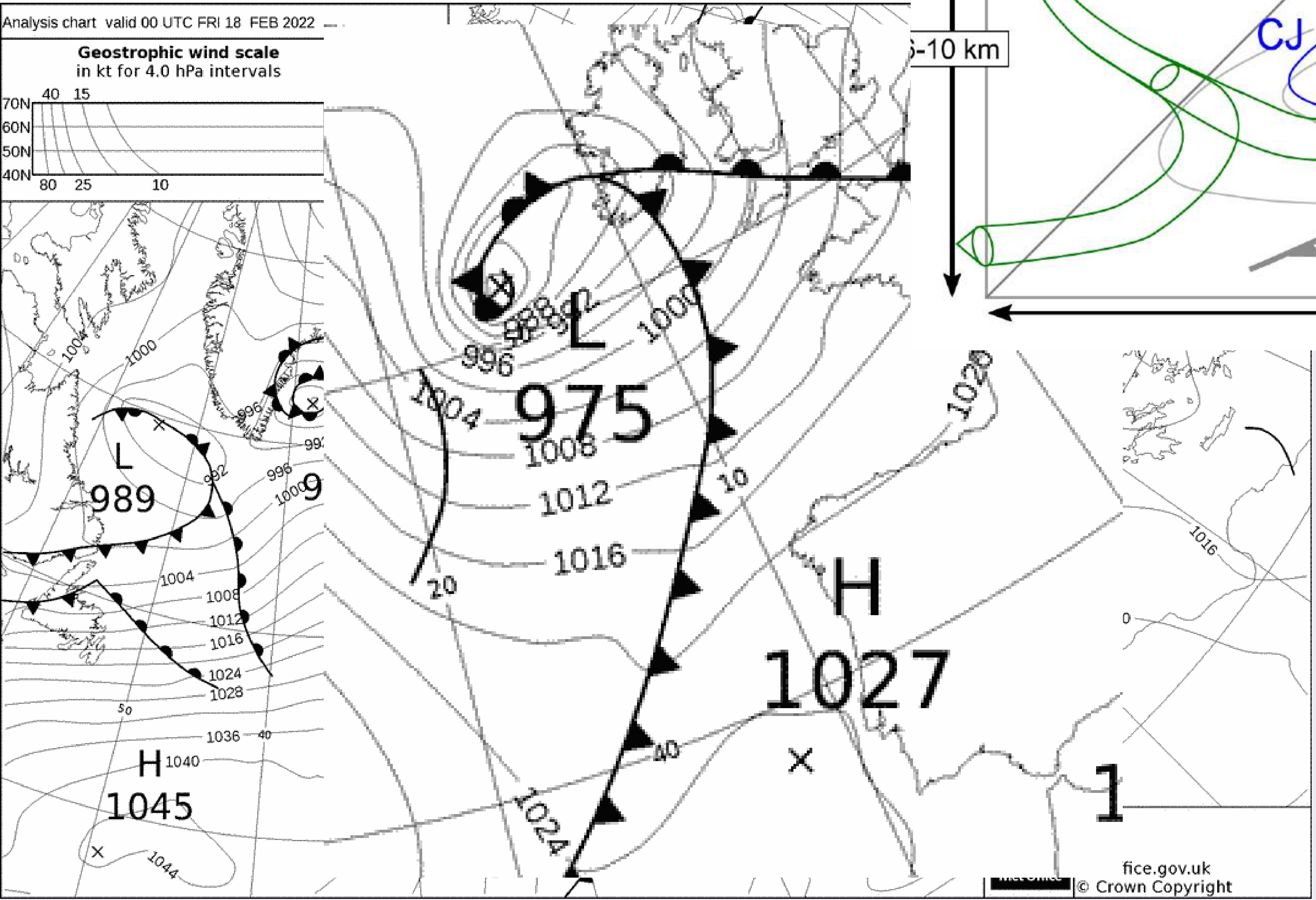
Embedded convection and precipitation bands (Browning 2005)

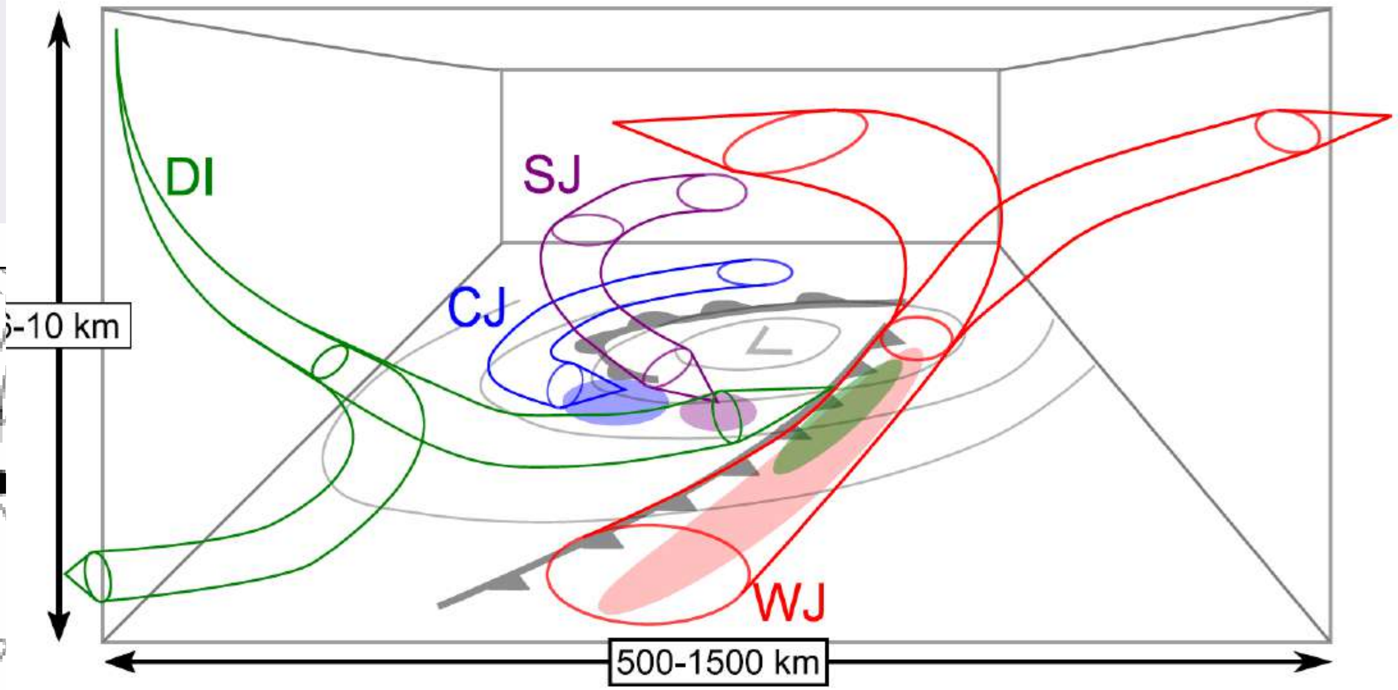


Prof. Keith Browning FRS. Made exceptional use of radar techniques, especially Doppler radar, to elucidate the structure and evolution of precipitating cloud systems. Performed first detailed study of a supercell thunderstorm – in Wokingham, UK!

Fronts

Fronts……..





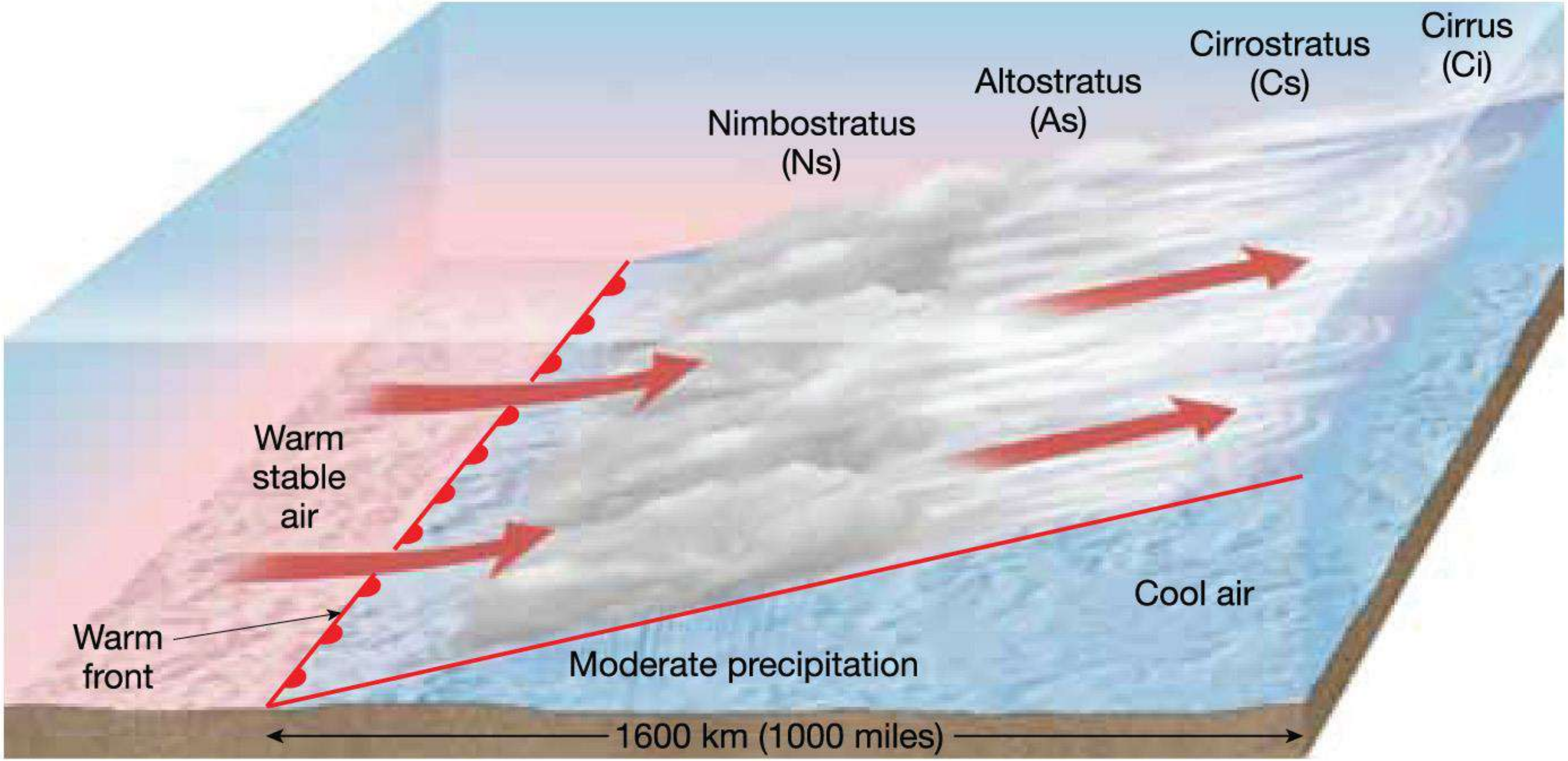
WCB – warm conveyor belt

CCB – cold conveyor belt

DI – dry instrusion

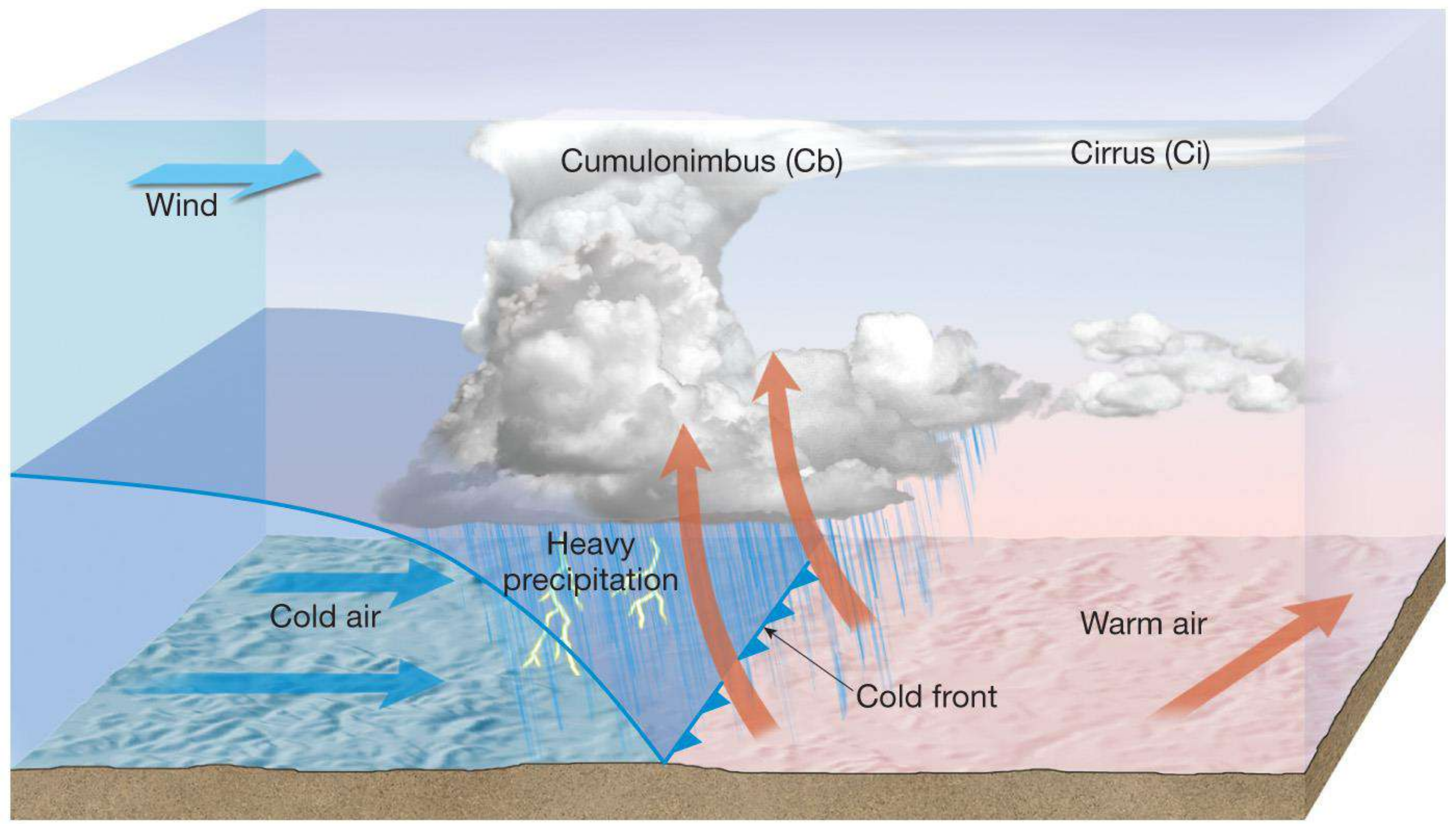
SJ – sting jet

Warm Front



(a) Warm front, stable air

Cold Front



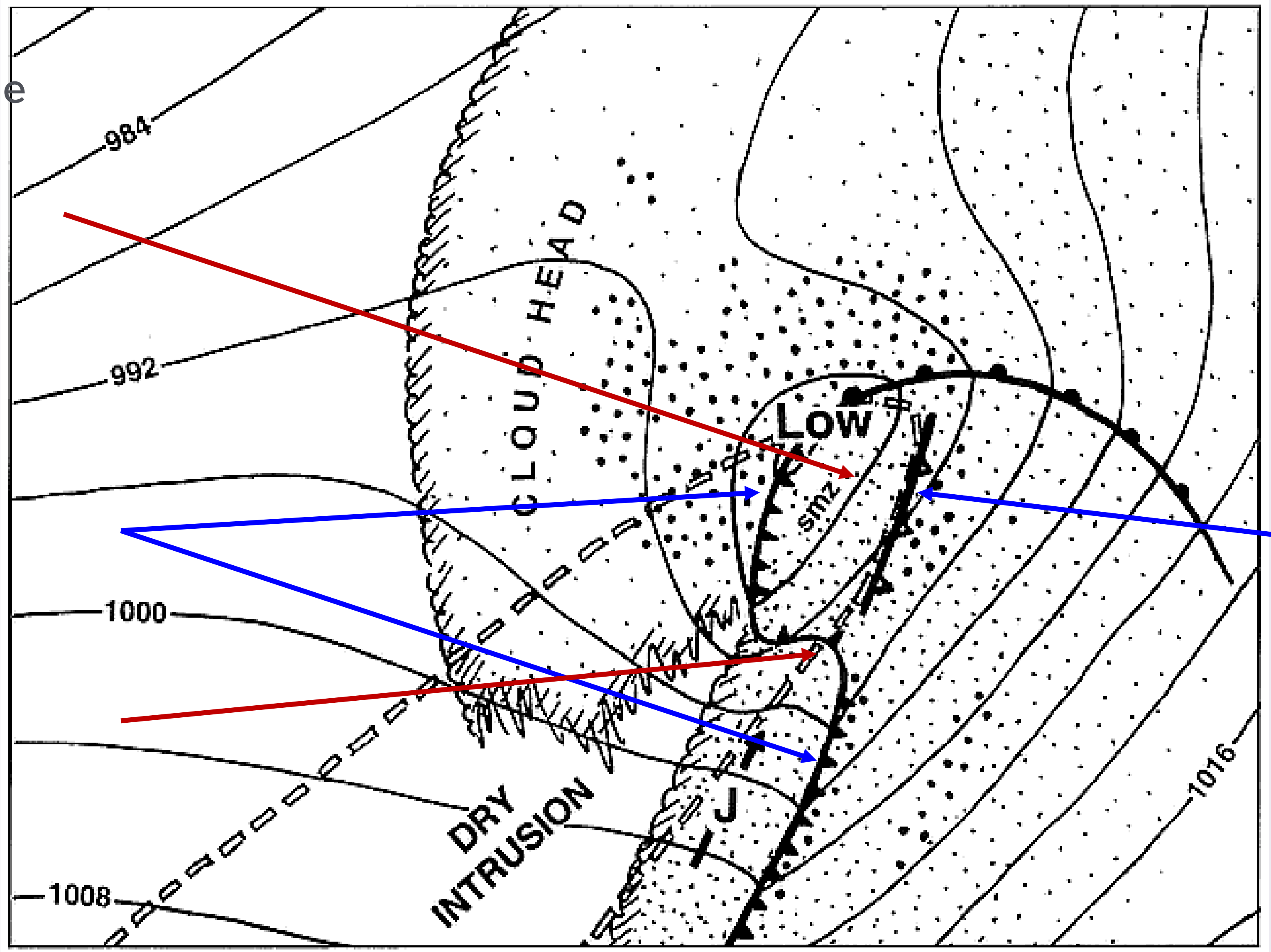
Cumulonimbus (Cb)
Cirrus (Ci)
Wind
Heavy
precipitation
Cold air
Warm air
Cold front

Frontal cyclone structure (during frontal fracture)

Shallow moist zone from dry intrusion air with low θ_w overrunning boundary layer air with high θ_w

Sharp surface cold front

Diffuse surface cold front



Upper cold front – marks leading edge of dry intrusion

Browning and Roberts (1994)

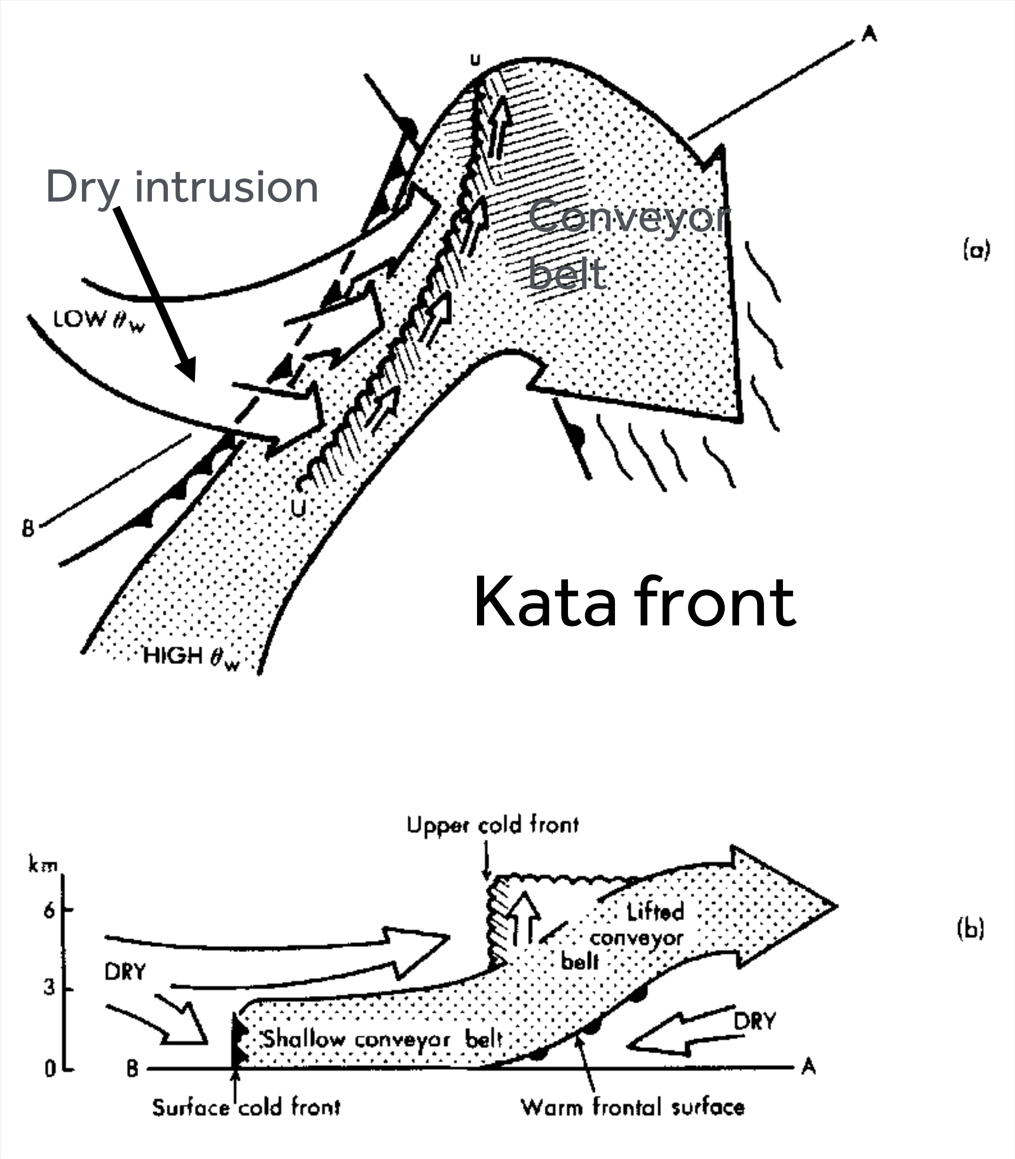
Ana and kata (cold) fronts

Bergeron (1937) suggested the introduction of the names ana front and kata front to distinguish between fronts at which there was general upsliding of the warm air and those for which descent occurred at all but the lowest layers.

Specifically, for vertical velocity, *w*, and along-front wind component, *v*,

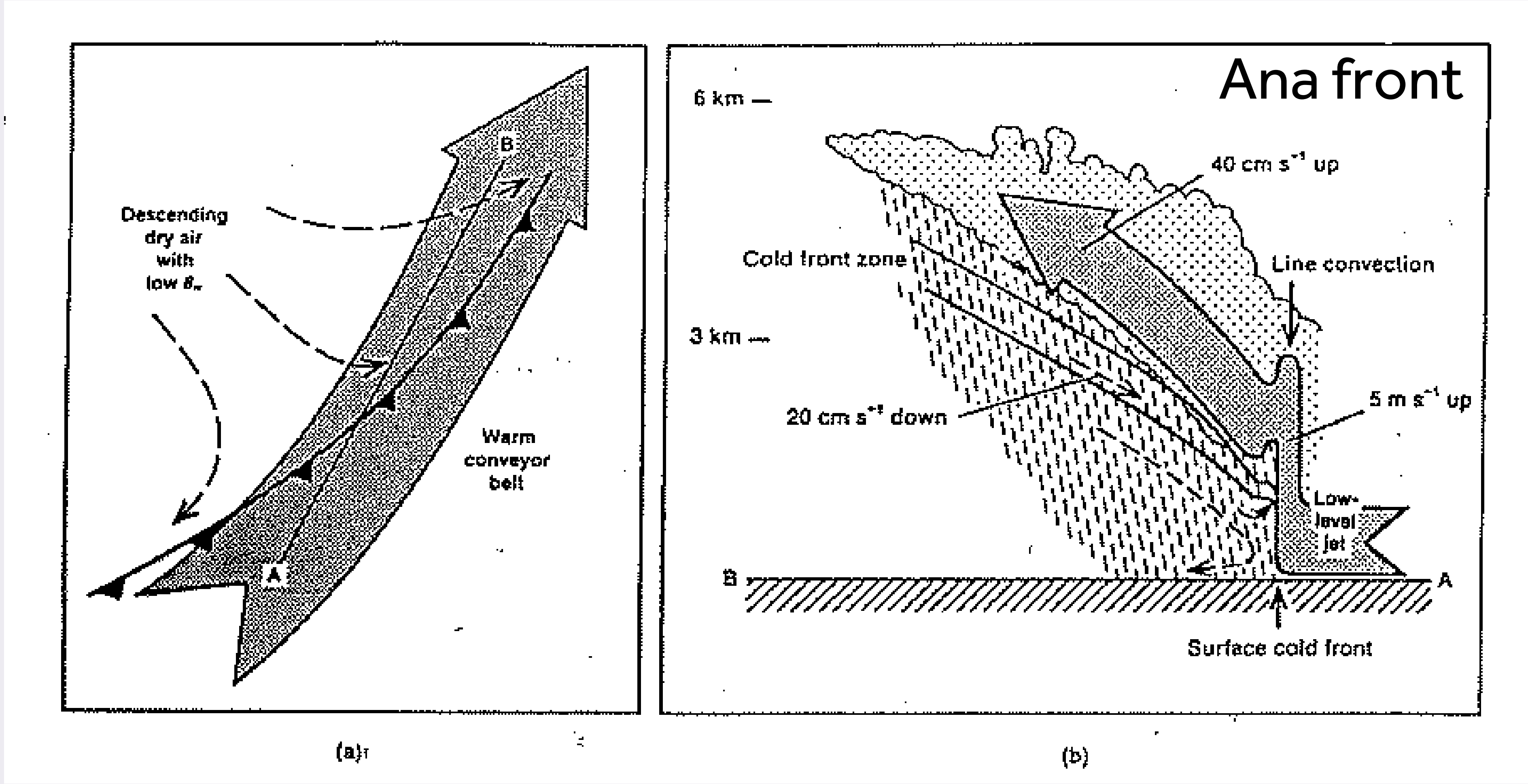
Ana: $w_{warm} > w_{cold} \, (v_{warm} > v_{cold})$

Kata: $w_{warm} < w_{cold} \, (v_{warm} < v_{cold})$



From Browning and Monk (1982)

Ana and kata (cold) fronts



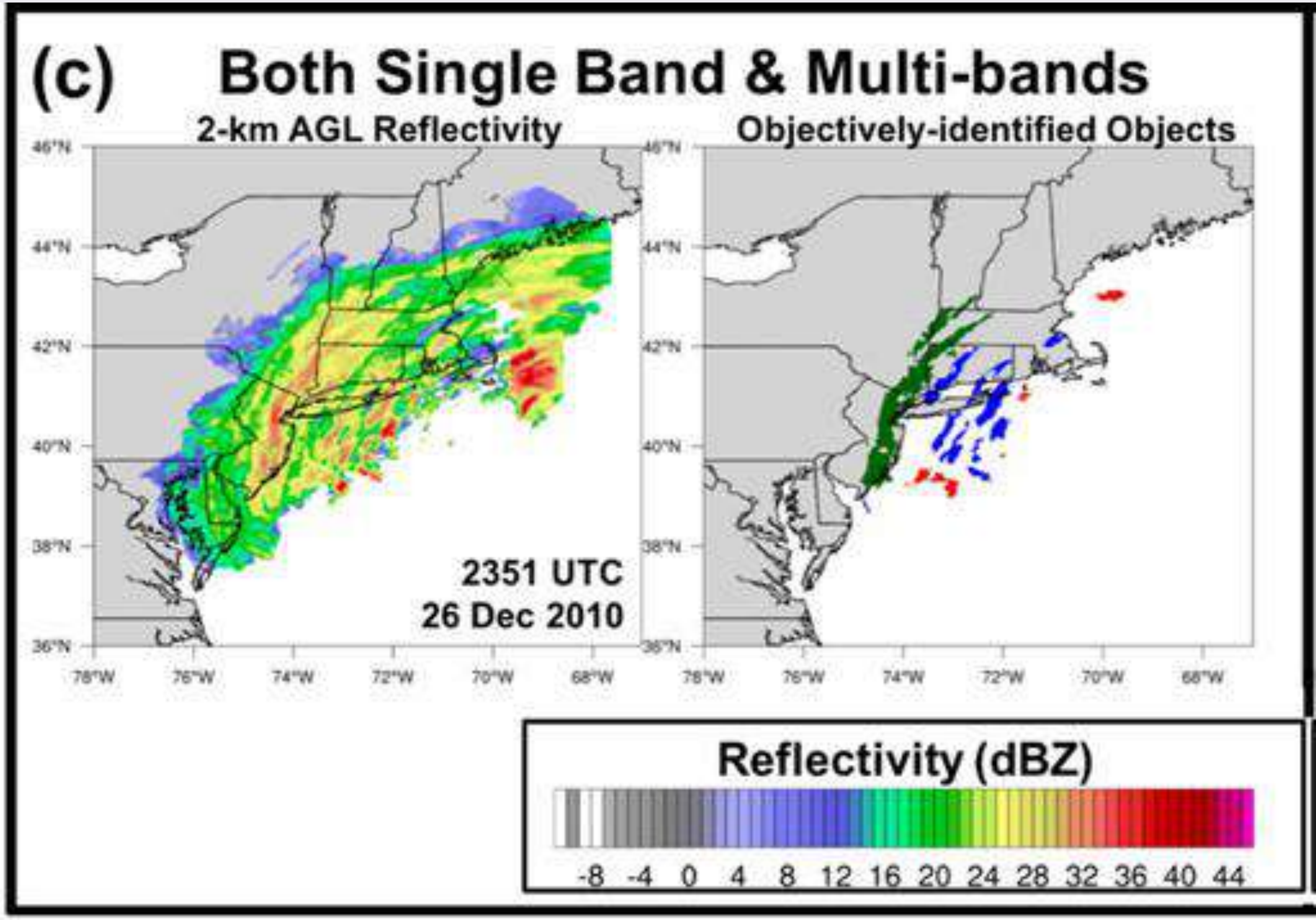
From Browning (1990)

Ana and kata fronts are usually associated with different stages in the development of a cold front; an ana front is usually the initial state but develops into a kata front later on, as the depression becomes more occluded.

Rainbands

Rainbands

- Mesoscale rainbands are a common feature of extratropical cyclones.
- In analysis of 11 cases Houze et al. (1976) found 6 types: warm frontal, warm sector, cold frontal-wide (50-km wide), cold frontal-narrow (5-km wide), wavelike (10-20-km wide) and post-frontal.
- Typically, 5-50km wide and 100s km long.
- Rainbands were contained small-scale areas of especially concentrated (10-500 km^2) rainfall that moved with the steering level wind (850-700 hPa).

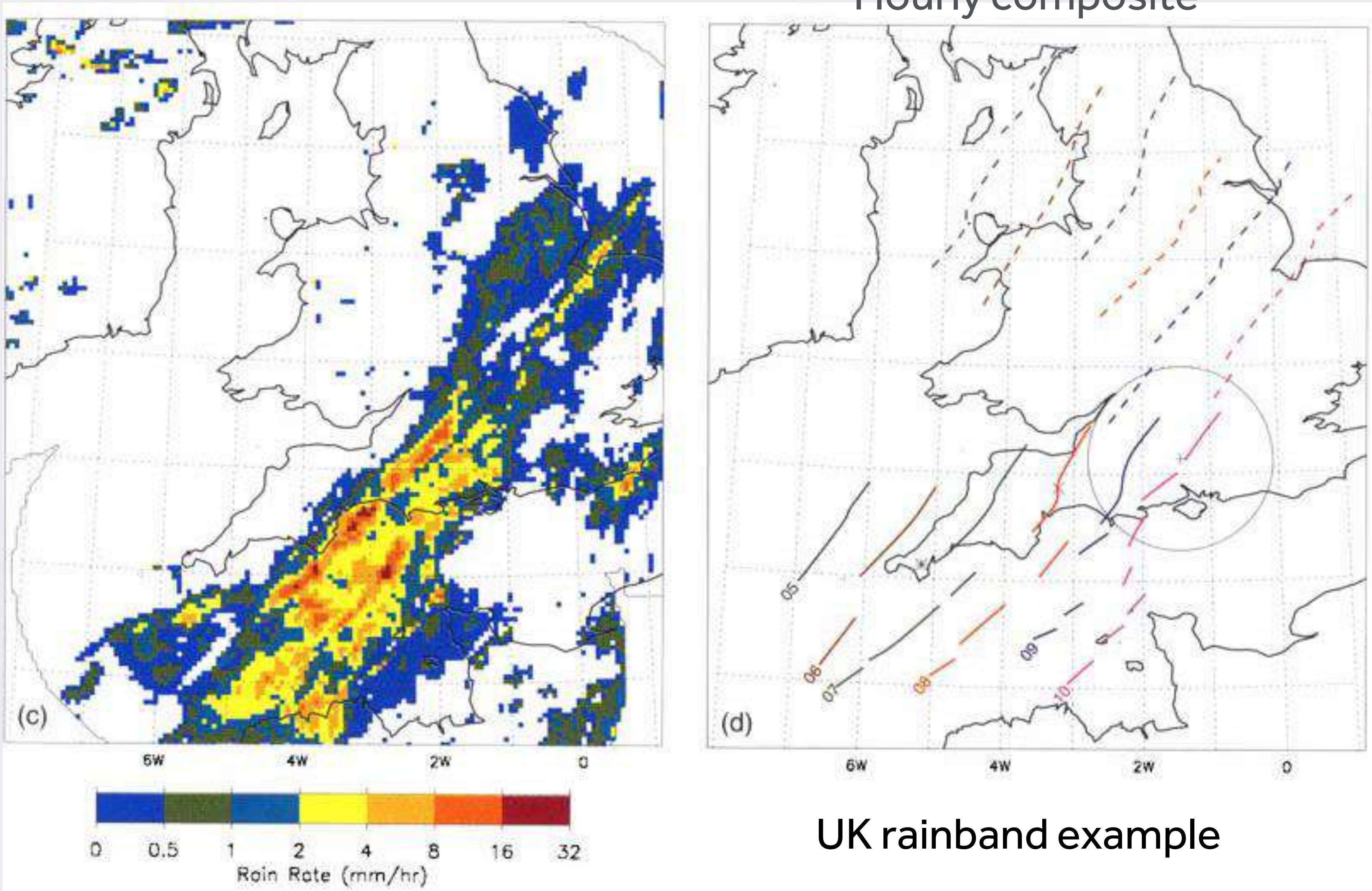


Snowbands (scale <200 km) in NE US winter storm (and objectively defined bands). Concurrent single and multiple bands were most common, present for 55% of storm times, and were usually in the NW quadrant of a mature cyclone.

From Ganetis et al. (2018)

Rainbands

Hourly composite



UK rainband example

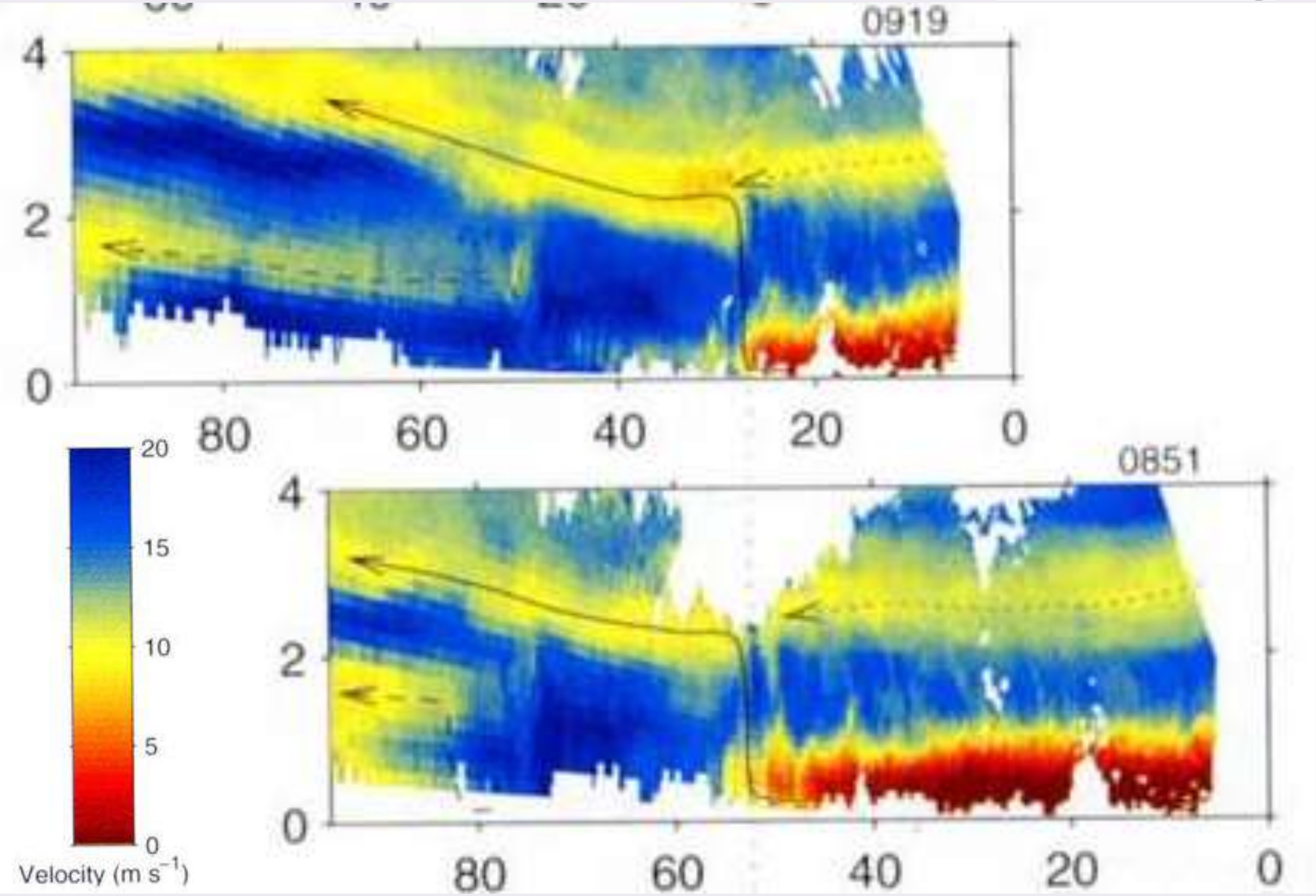
From Browning et al. (2001)

Note: Multiple rainbands are also a common feature of tropical cyclones

Rainband substructure I

Stacked slantwise circulations in ana cold front.

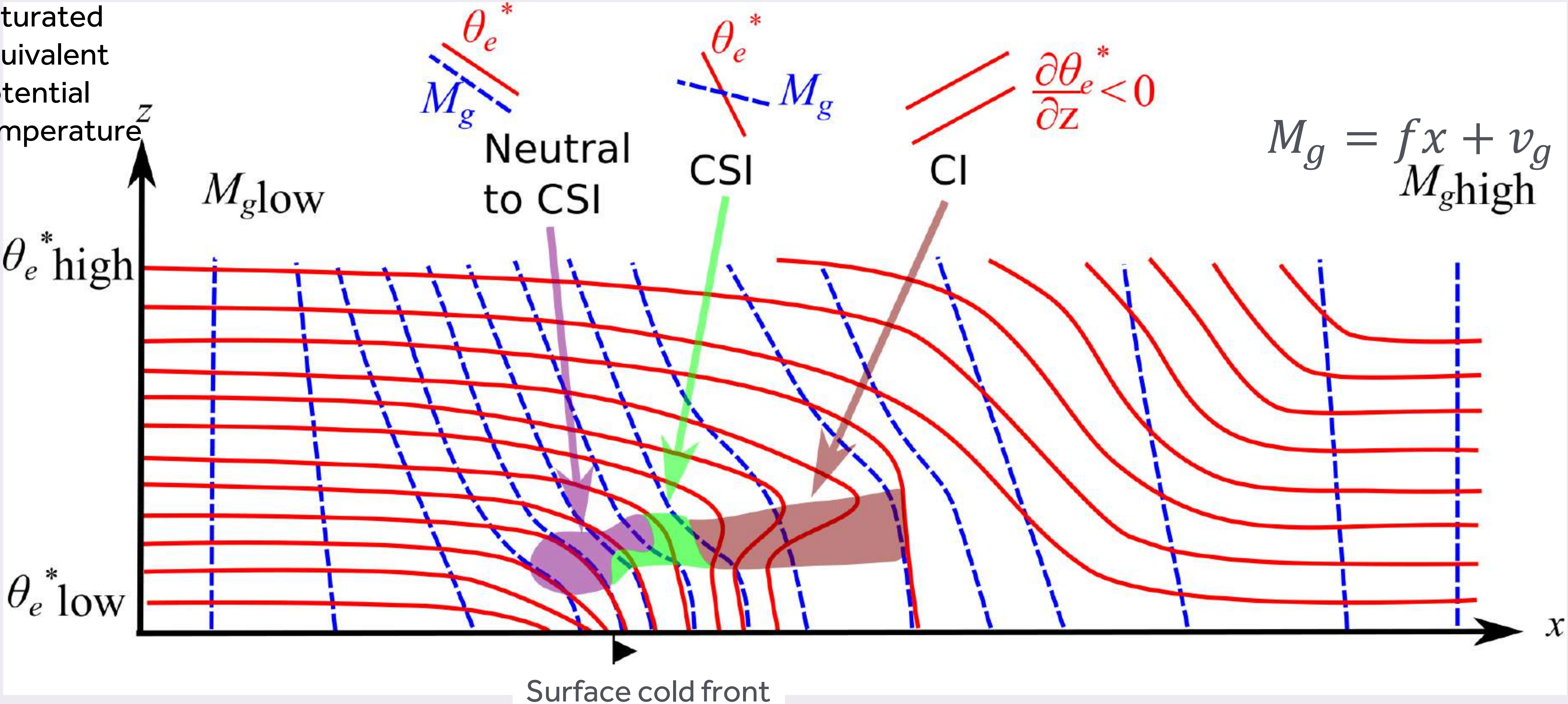
- Vertical wavelength <2km
- Likely due to the release of a type of slantwise moist instability called conditional symmetric instability (CSI) or a type of inertial adjustment called Delta-M adjustment (M for momentum).
- Processes leading to bands often not resolved by numerical weather prediction models due to insufficient vertical resolution.



Chilbolton radar range-height-indicator Doppler velocity scans (2 of 8). The principle layers of slantwise ascent are fed by upright line convection.

From Browning et al. (2001)

Rainband substructure I

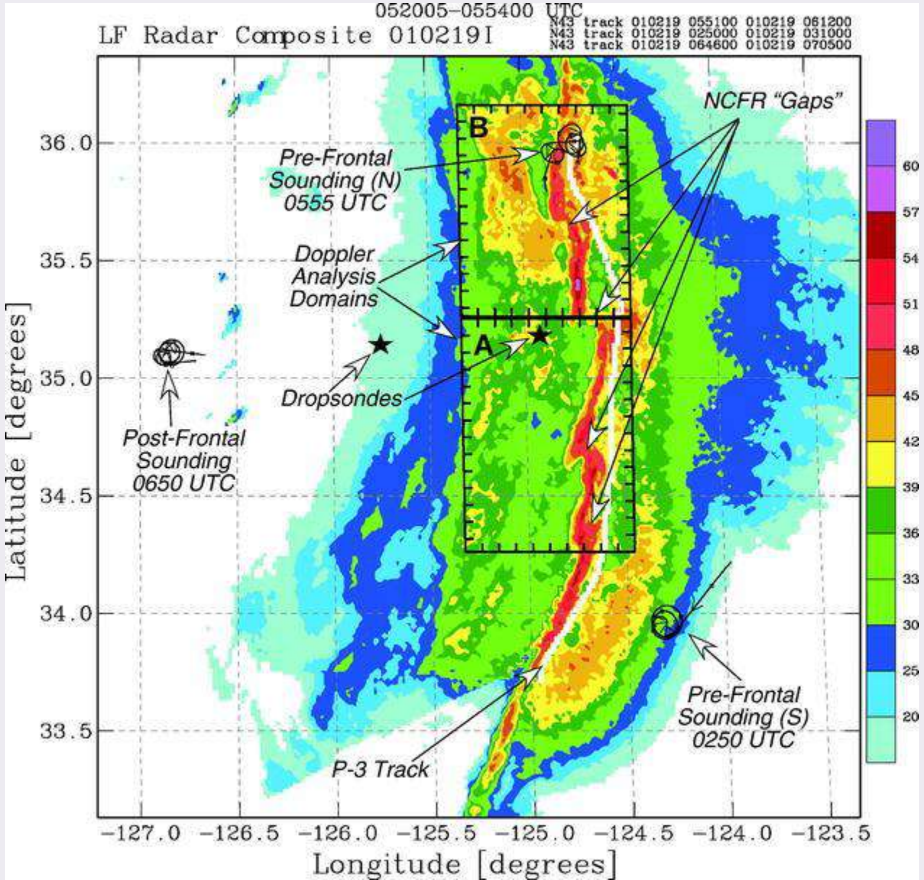


CSI = conditional symmetric instability
CI = conditional instability

From Clark and Gray. (2018)

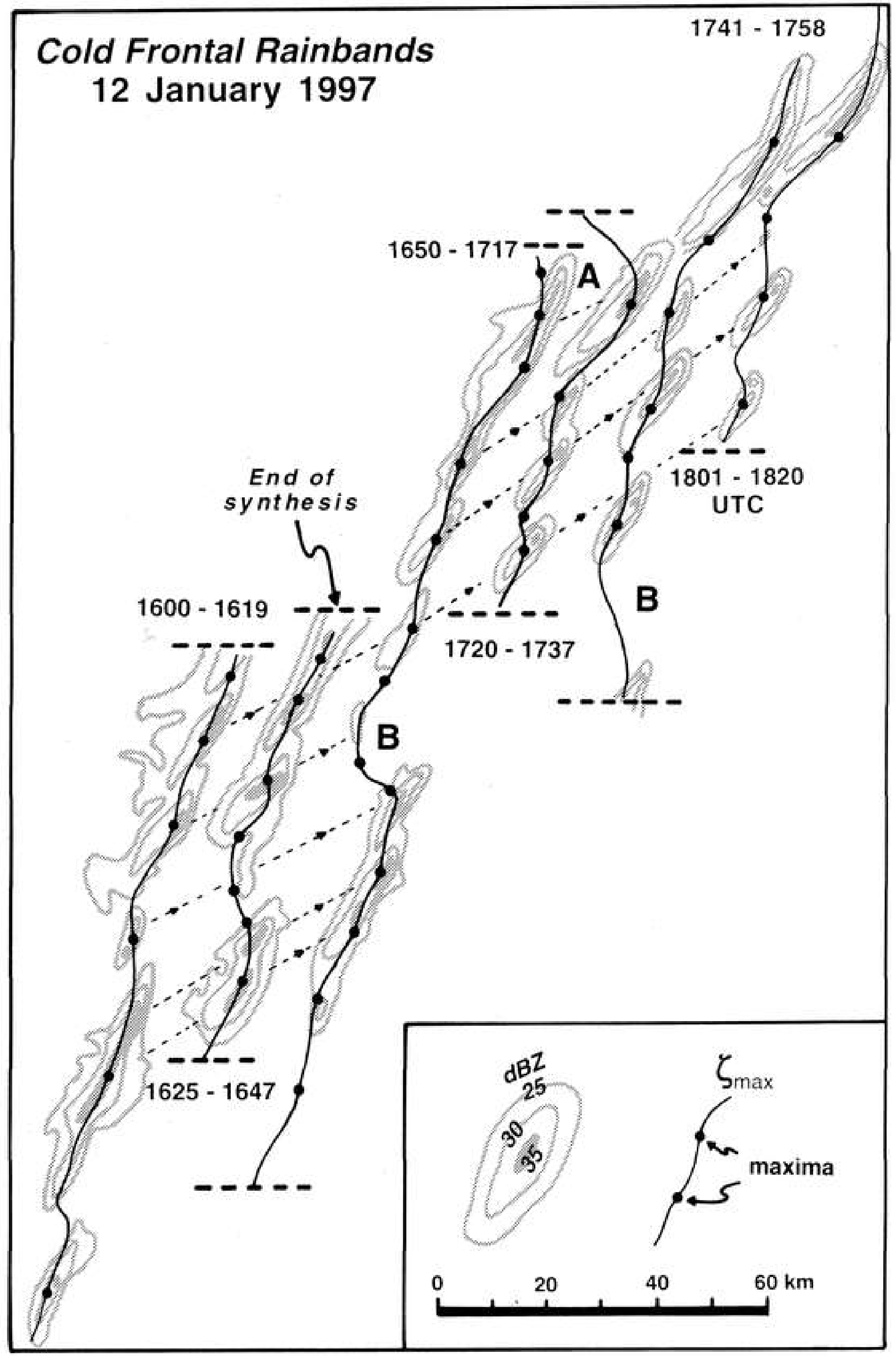
Rainband substructure II

- The narrow cold frontal rainband can be broken up into lines of weaker and stronger reflectivity corresponding to distinct shallow convective line elements (precipitation cores).
- Formation theories include density currents and shear instability in the horizontal wind.



Aircraft radar observations from Jorgensen et al. (2003)

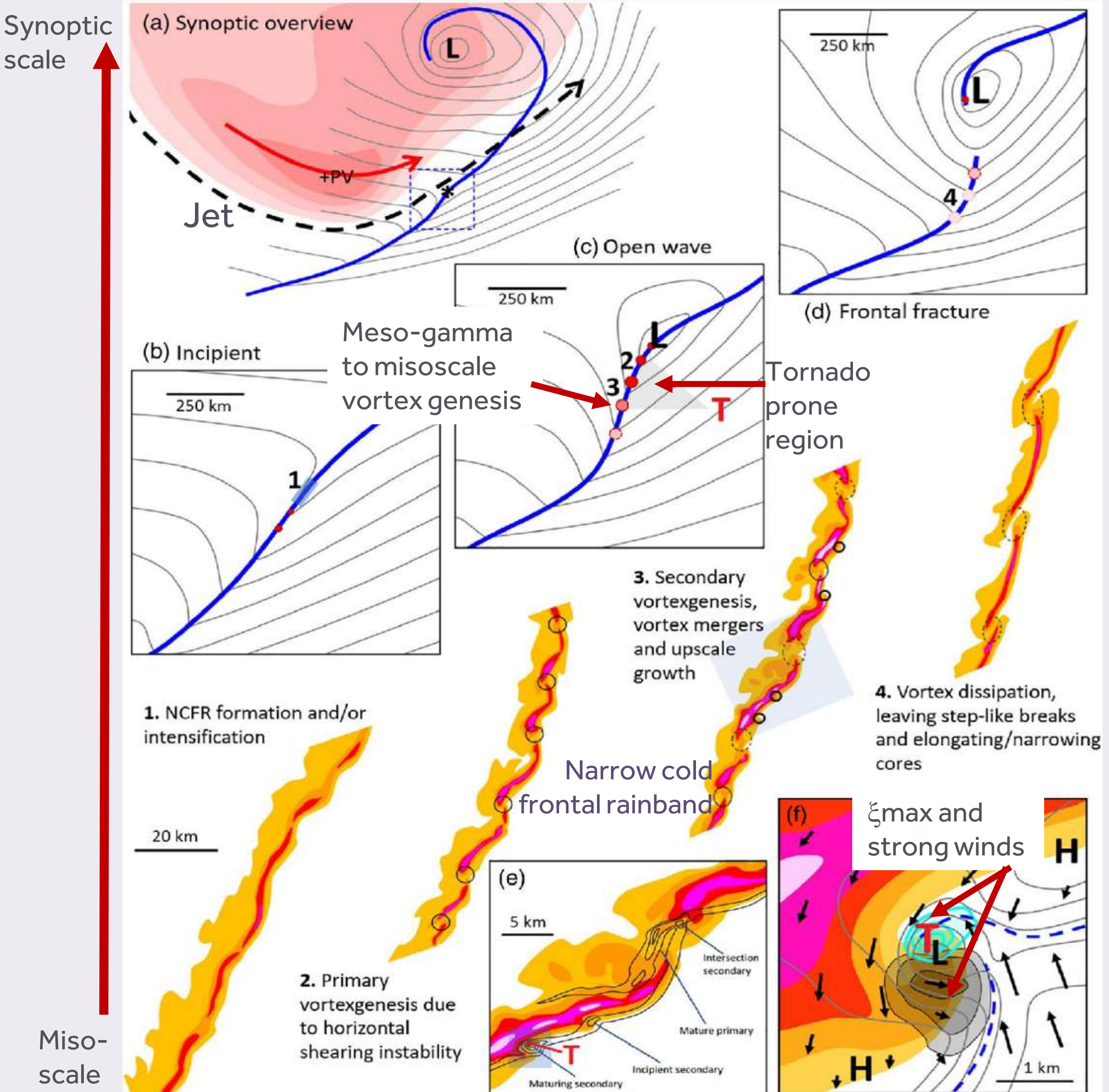
Time series of aircraft radar echoes from Wakinoto and Bosart (2000)



...link to tornadoes

- Narrow cold frontal rainbands are an important source of UK tornadoes
- UK tornadoes associated with narrow cold frontal rainbands are often connected to
1. Developing secondary cyclones (frontal waves) along trailing cold fronts
2. Strong mid- to upper-level jet streak cutting across front within an amplifying large-scale flow pattern (Clark and Parker 2020).

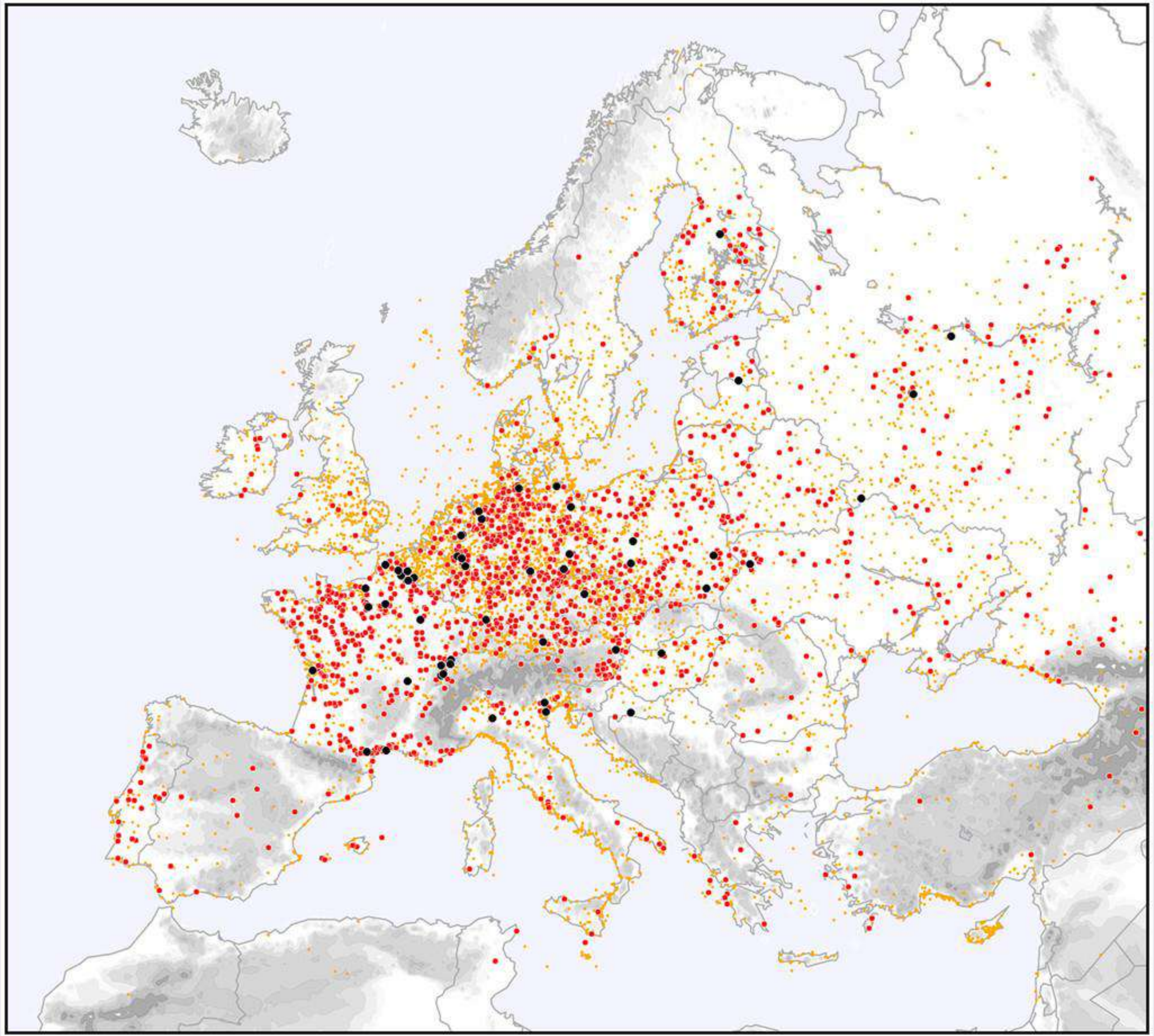
Conceptual model of shear-zone vortex genesis in a developing frontal wave
From Clark et al. (2001)



European tornadoes

Tornado reports (not just those associated with cyclones) contained in the European Severe Weather Database 1995-2006.

Orange points are weak (F0, F1) and unrated tornadoes; red points are strong (F2, F3) tornadoes; and black points violent (F4, F5) tornadoes.

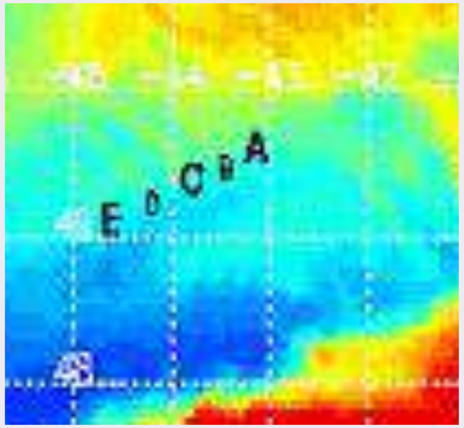


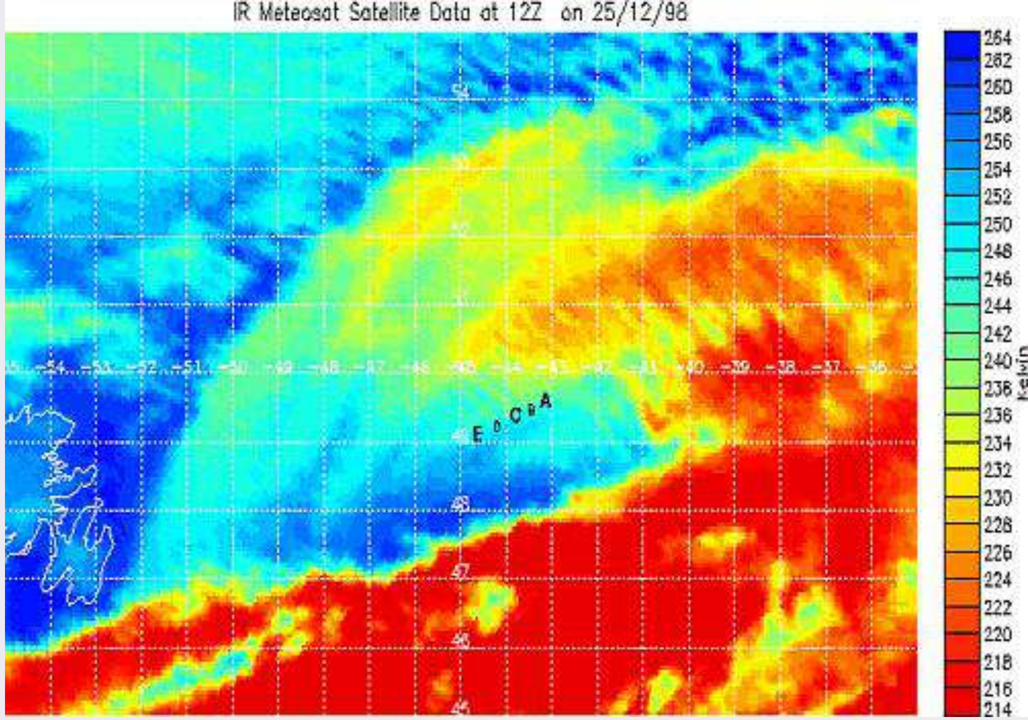
From Groenemeijer and Kühne (2014)

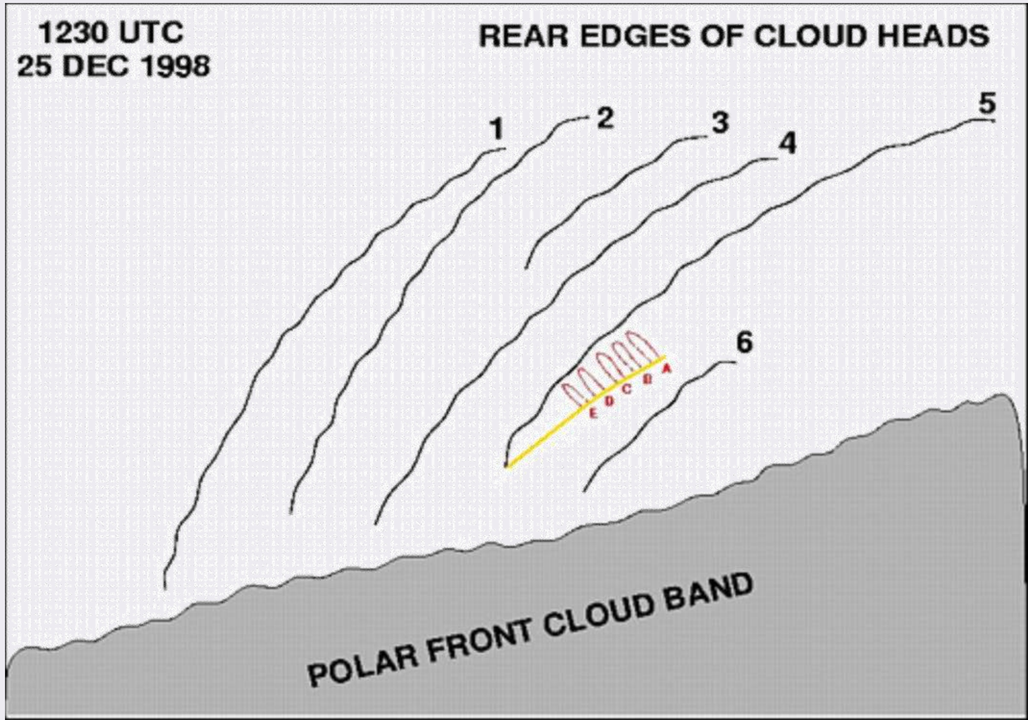
Embedded convection

Cloud striations

- Cloud-top striations can be visible within mesoscale cloud features associated with ana-cold frontal circulations and (multiple) cloud heads.
- May be due to convective rolls forming above a frontal zone.
- ~parallel to wind shear at cloud top but perpendicular to strong thermal-wind shear in underlying frontal zone.
- Often associated with rapid cyclogenesis and gusts

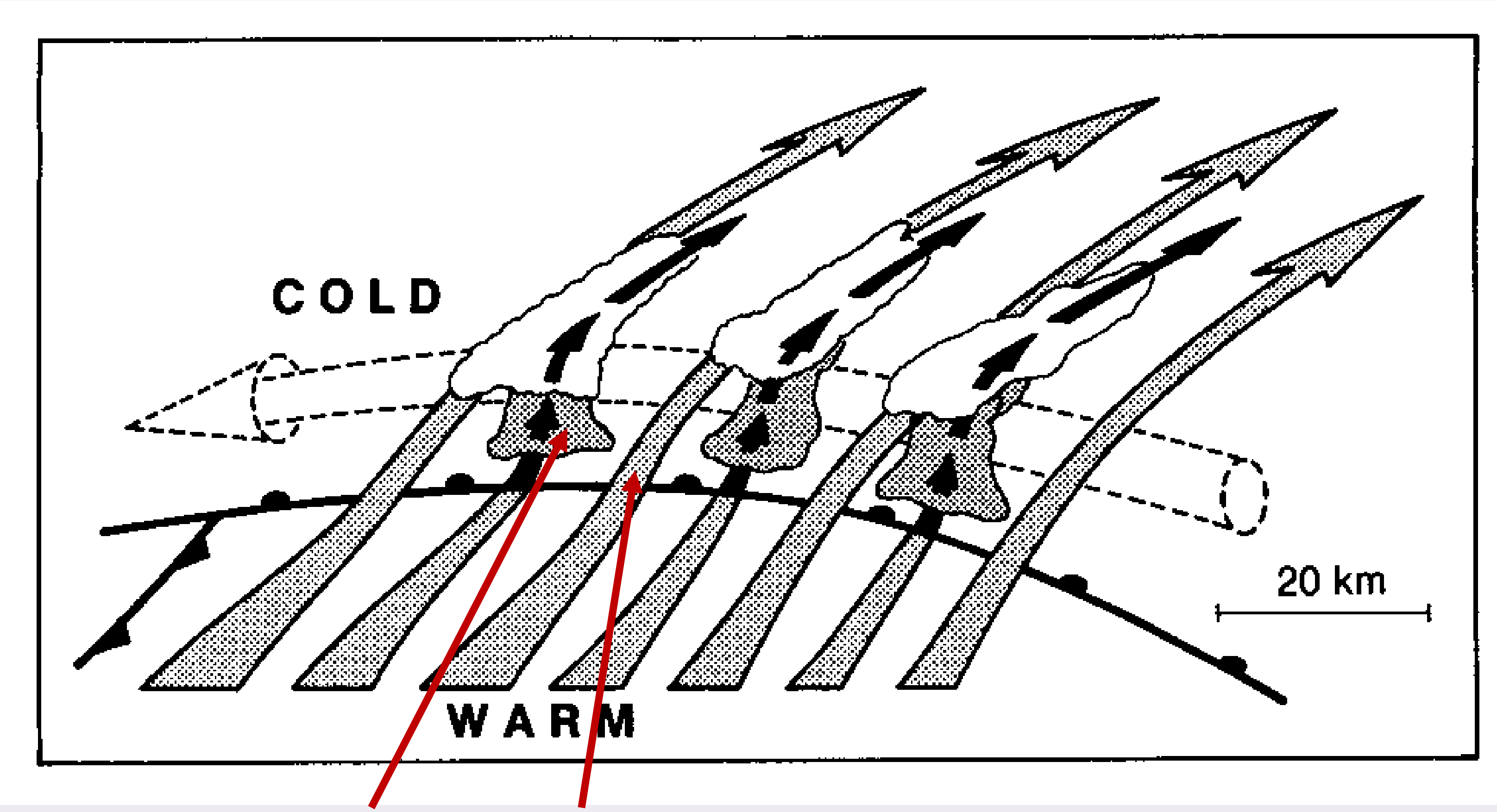






From Dixon et al. (2000)

Embedded convection

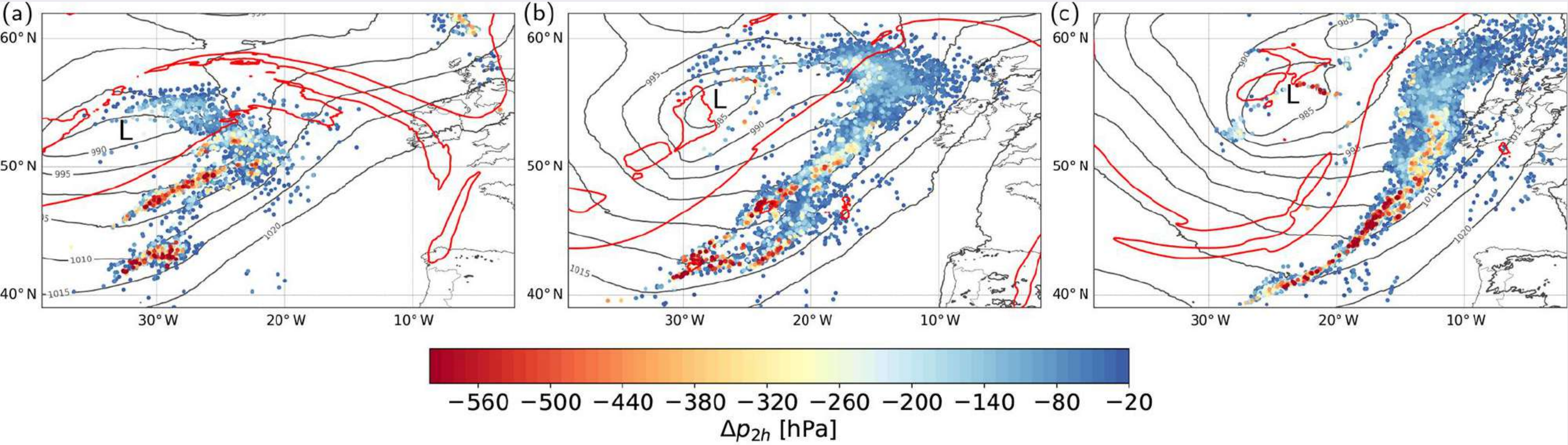


The elevator-escalator warm-frontal ascent model

Warm southerly airstream (flat, lightly stippled arrows) rises over the cold easterly polar airstream (tubular dashed arrow). Meso-convective ascent (the elevator, solid arrows) and convective clouds (stippled with white anvils) are shown at regular intervals between regions of gentler ascent (the escalator).

From Neiman et al. (1993)

Embedded convection



time

Warm conveyor belt ascent for Cyclone Vladiana.

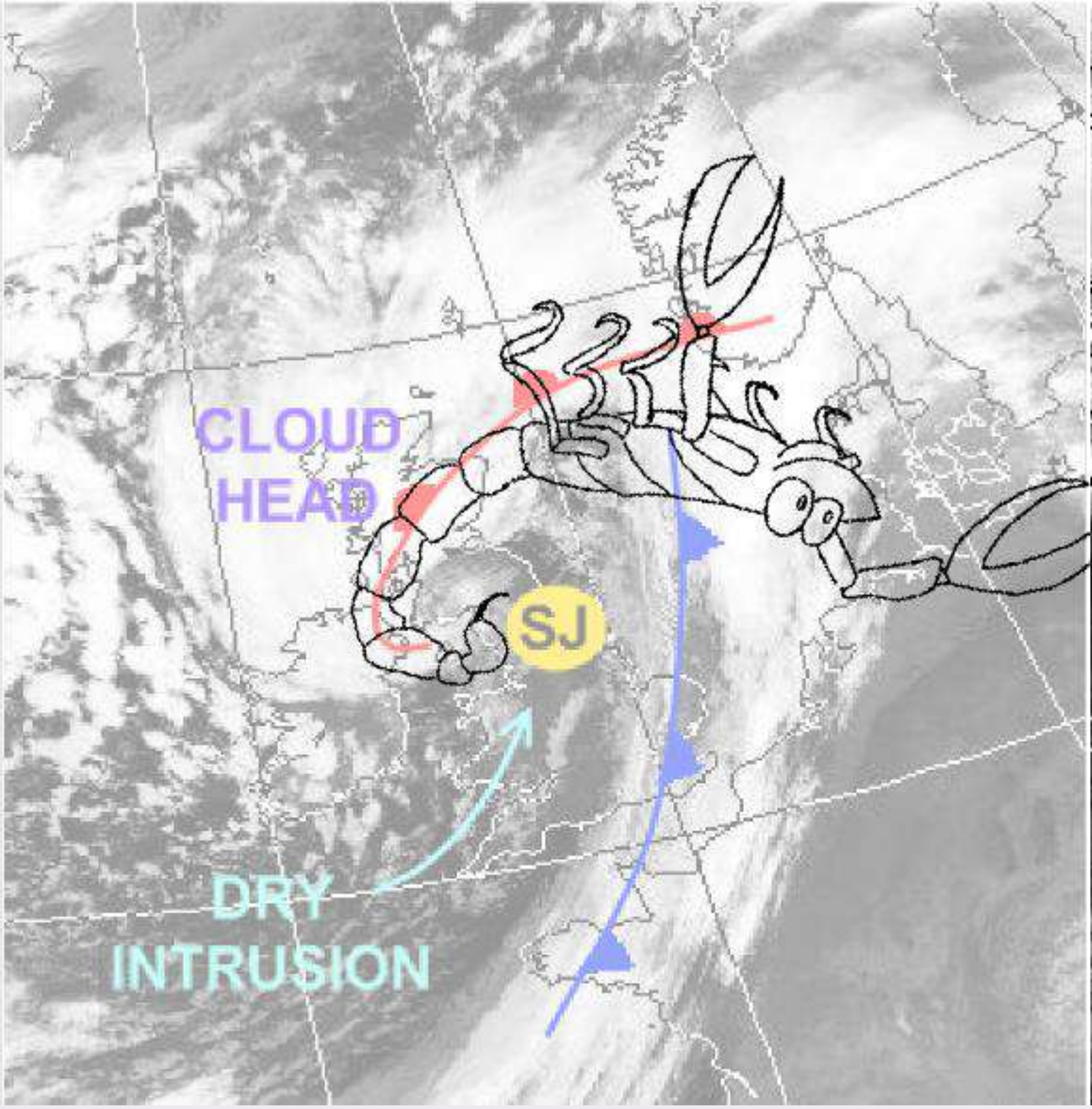
Colours indicate 2 h pressure change along ascending WCB trajectories.
Grey contours – sea level pressure and red contour 2 PVU at 320 K.

From Ortel *et al.* (2020)

Sting jets and other causes of damaging winds

Sting jets

- Transient (few hours), mesoscale (~50km spread) jets of air descending from the tip of the hooked cloud head in the frontal fracture regions of some extratropical storms.
- Can cause damaging winds (and especially gusts).
- Coined 'the sting at the end of the tail by Browning (2004)' in his study of the Great October storm of 1987.
- Since then large body of work performed on modelling, mechanisms and climatologies.
- First research aircraft flight into a sting jet storm led by Reading scientists within DIAMET project: Windstorm Friedhelm in 2011 (Baker et al. 2013, Martínez-Alvarado et al. 2014, Vaughan et al. 2015).
- Term has now entered common usage(?)



Adapted from Laura Baker by Neil Hart.

The zoo of sting-jet case studies

University of Reading

Storm name	Storm date	Impact location	Reference
Great Storm	October 16, 1987	Southern England	Browning (2004); Browning and Field (2004); Clark *et al.* (2005); Gray *et al.* (2011)
Oratia	October 30, 2000	Wales and central England	Browning (2004); Browning (2005)
Anna	February 26, 2002	Central UK	Martínez-Alvarado *et al.* (2010); Gray *et al.* (2011)
Jeanette	October 27, 2002	Wales	Parton *et al.* (2009)
Gudrun/Erwin	January 7/8, 2005	Northern UK	Baker (2009); Gray *et al.* (2011)
Unnamed	December 7/8, 2005	East of Canada	Schultz and Sienkiewicz (2013)
Friedhelm	December 8, 2011	Scotland	Baker *et al.* (2013); Martínez-Alvarado *et al.* (2014a)
Ulli	January 3, 2012	Northern UK	Fox *et al.* (2012); Smart and Browning (2014)
St Jude's Day / *Christian*	October 28, 2013	Southern England	Browning *et al.* (2015)
Tini	February 12, 2014	Ireland, Wales, NW England	Slater *et al.* (2017);Volonté *et al.* (2018)

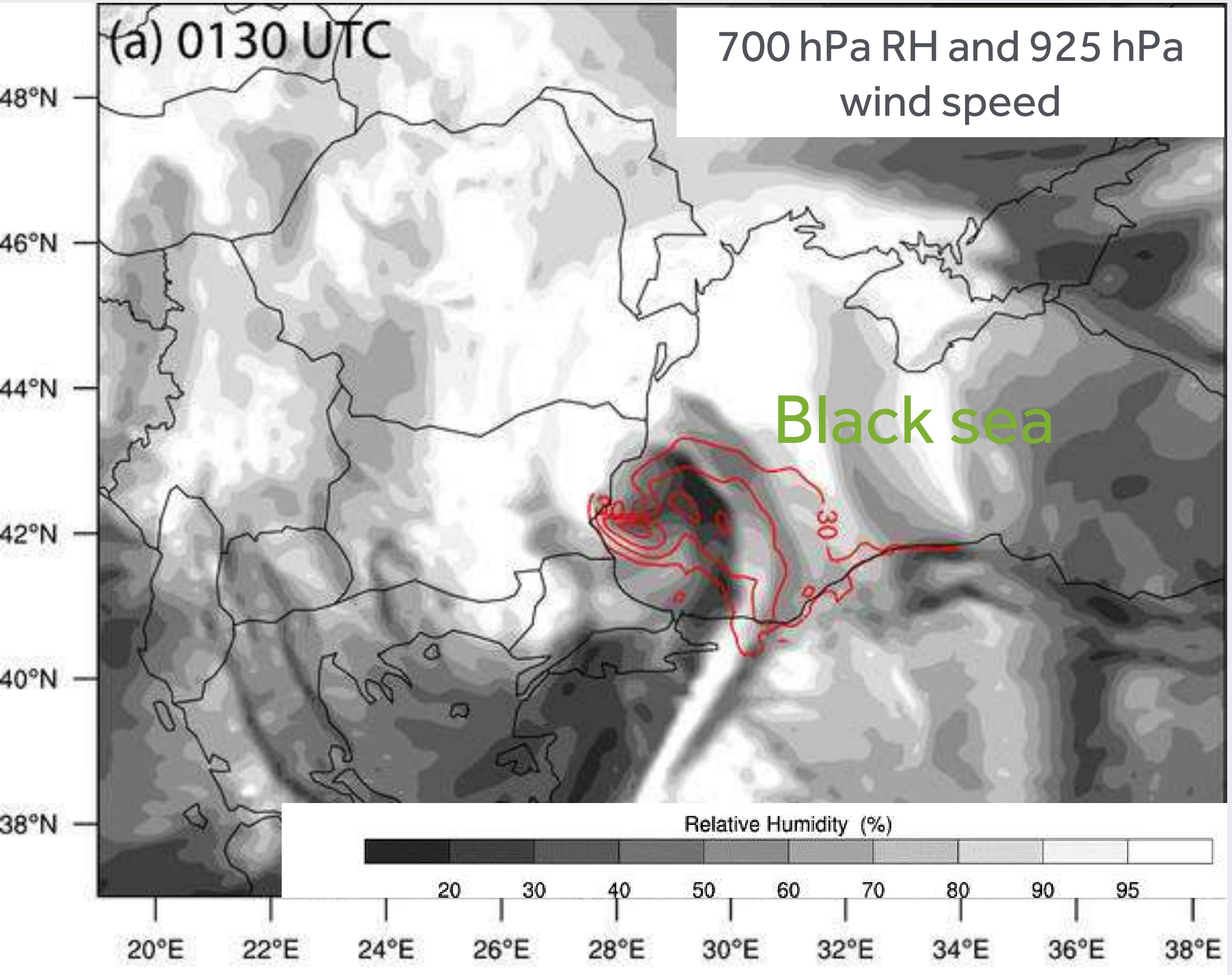
Review by Clark and Gray (2018)

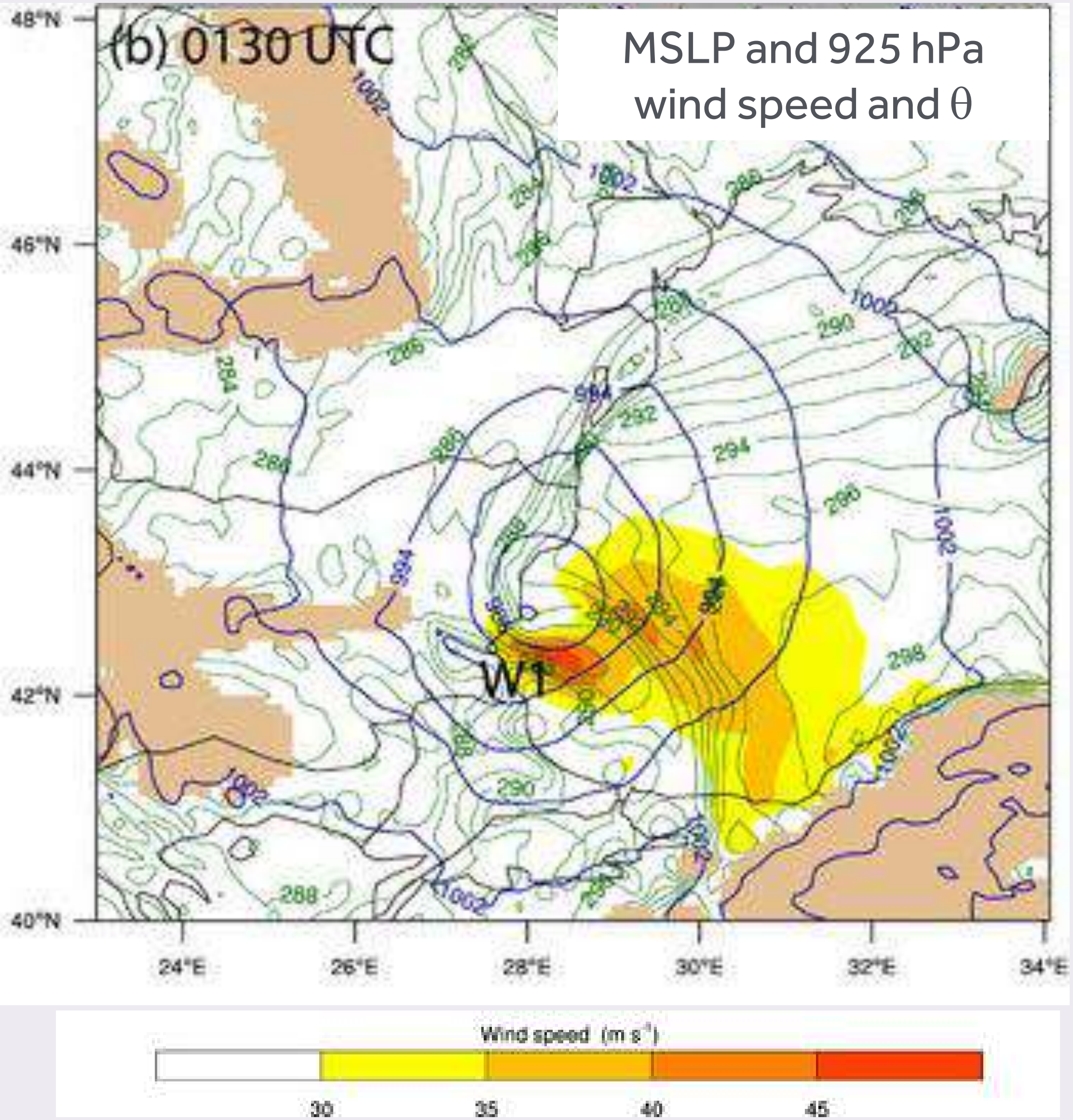
Unnamed	2/3 December 2012	Black Sea and east Romanian coast	Brâncuş et al. (2019)
Egon	12/13 January 2017	France to Poland	Eisenstein et al. (2019)
Eunice	February 18, 2022	Southern England	Volonté et al. (2023a,b)
Ciarán	November 2, 2023	Southern England/France	Charlton-Perez et al. (2024)

More recent publications

Our understanding of sting jet dynamics has advanced considerably since their first identification, but mostly through analysis of case studies of cyclones crossing the North Atlantic to affect northwest Europe

Examples: Mediterranean



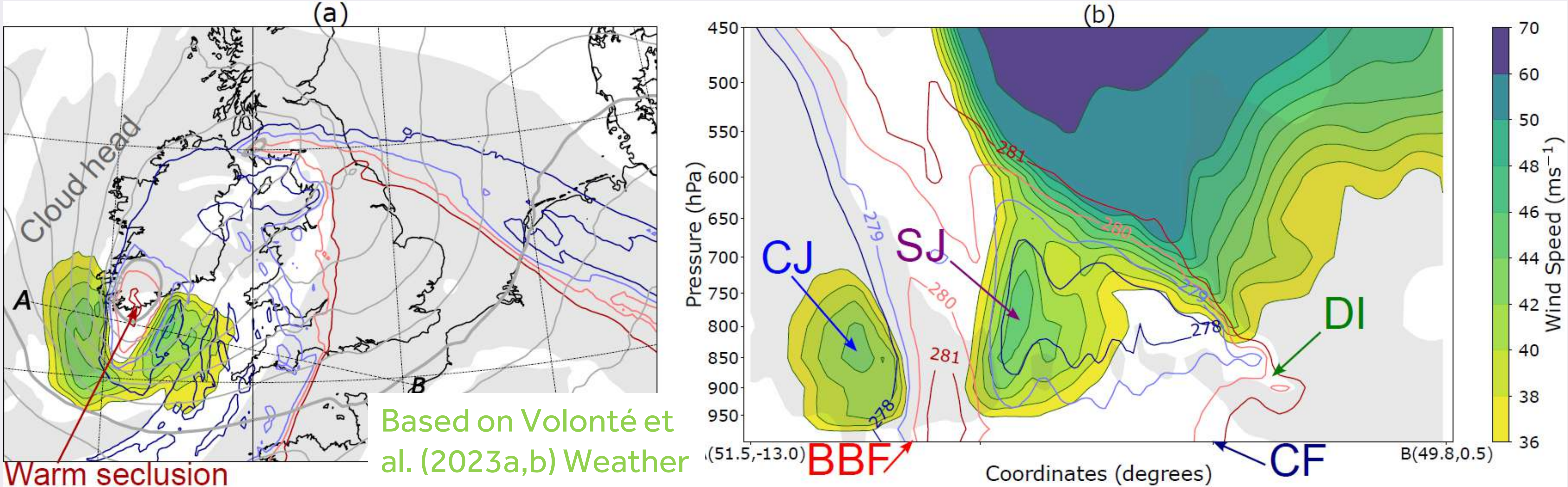


Strongest near-surface winds > 45 m/s lasted 2-4 hrs and were due to a descending SJ.
Later cold sector wind maximum was due to the CCB.

Brâncuş et al. (2018)

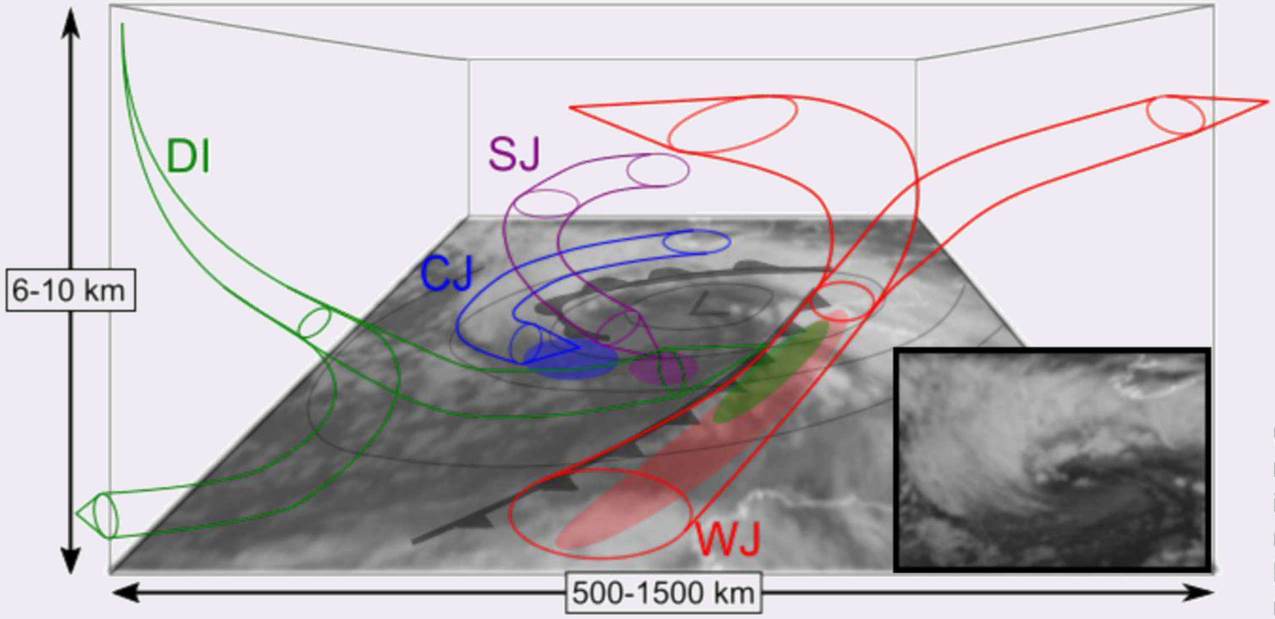
Examples: UK

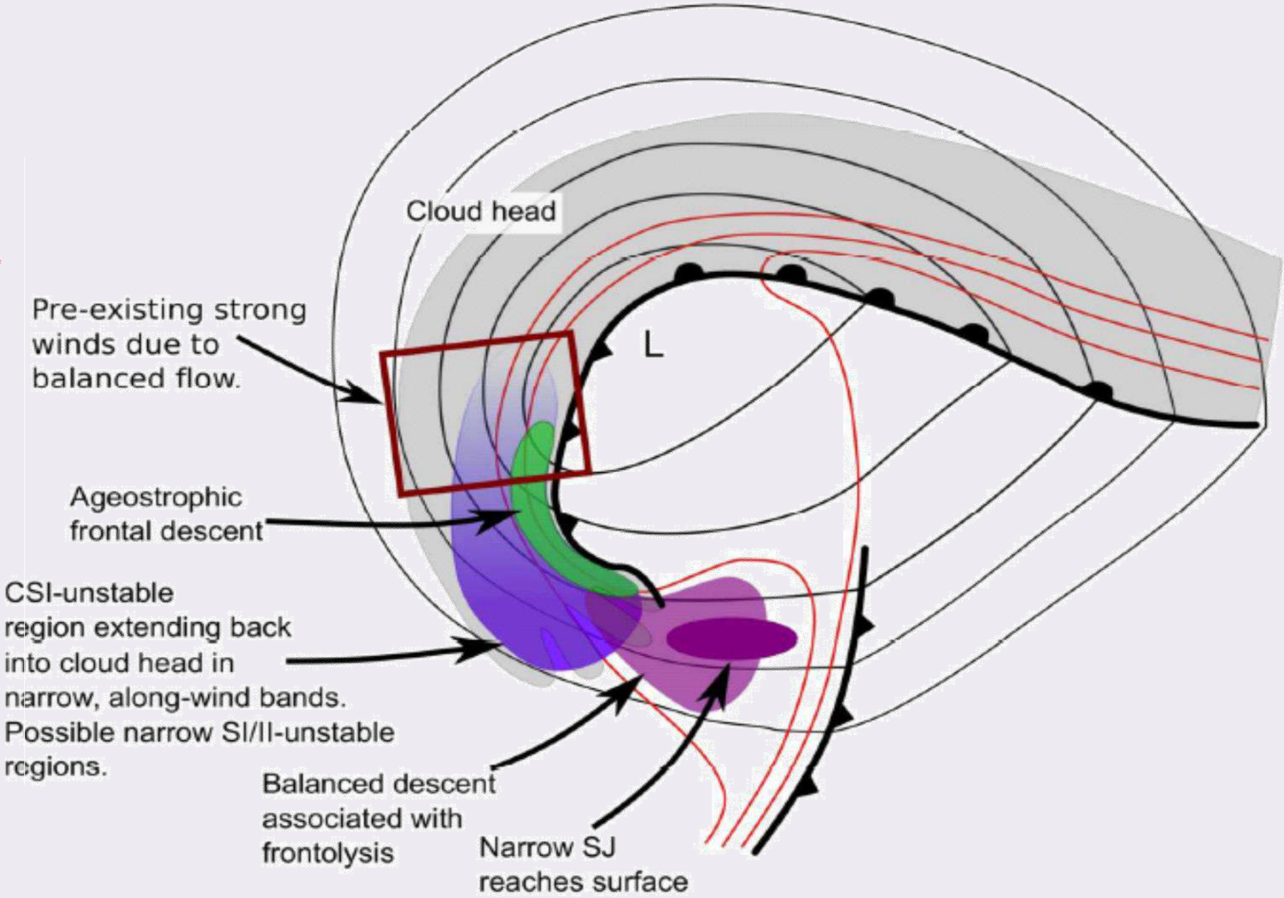
- Storm Eunice (Storm Zeynep in Germany) in Feb. 2022 was a well forecast, intense and damaging windstorm.
- Two main regions of strong low-level winds (>42 ms^{-1}).
- The more westwards region was associated with a CCB jet.
- There was evidence of mesoscale instability presence/release (CSI/SI) in the cloud head tip: this will have strengthened the SJ.



Based on Volonté et al. (2023a,b) Weather

Conceptual model





Review by Clark and Gray (2018)

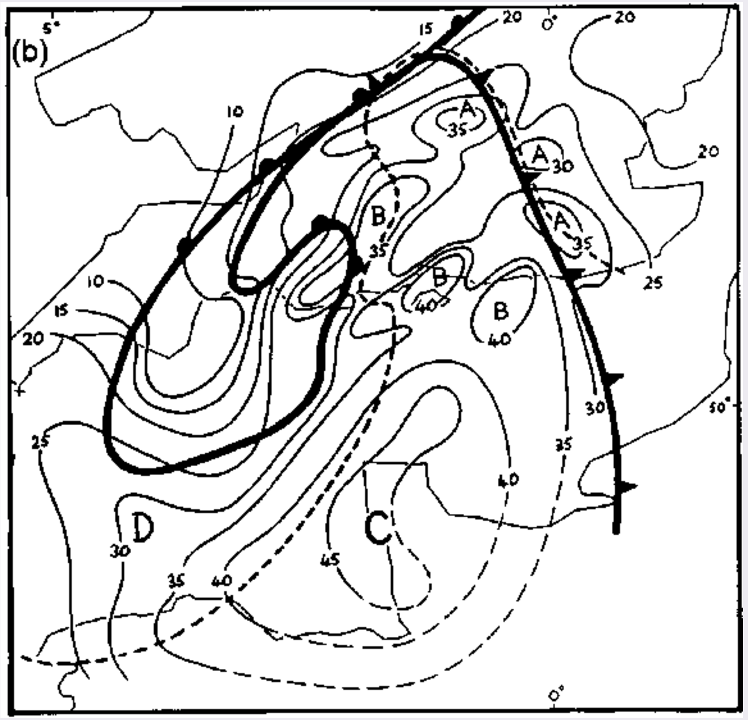
Mesoscale wind features

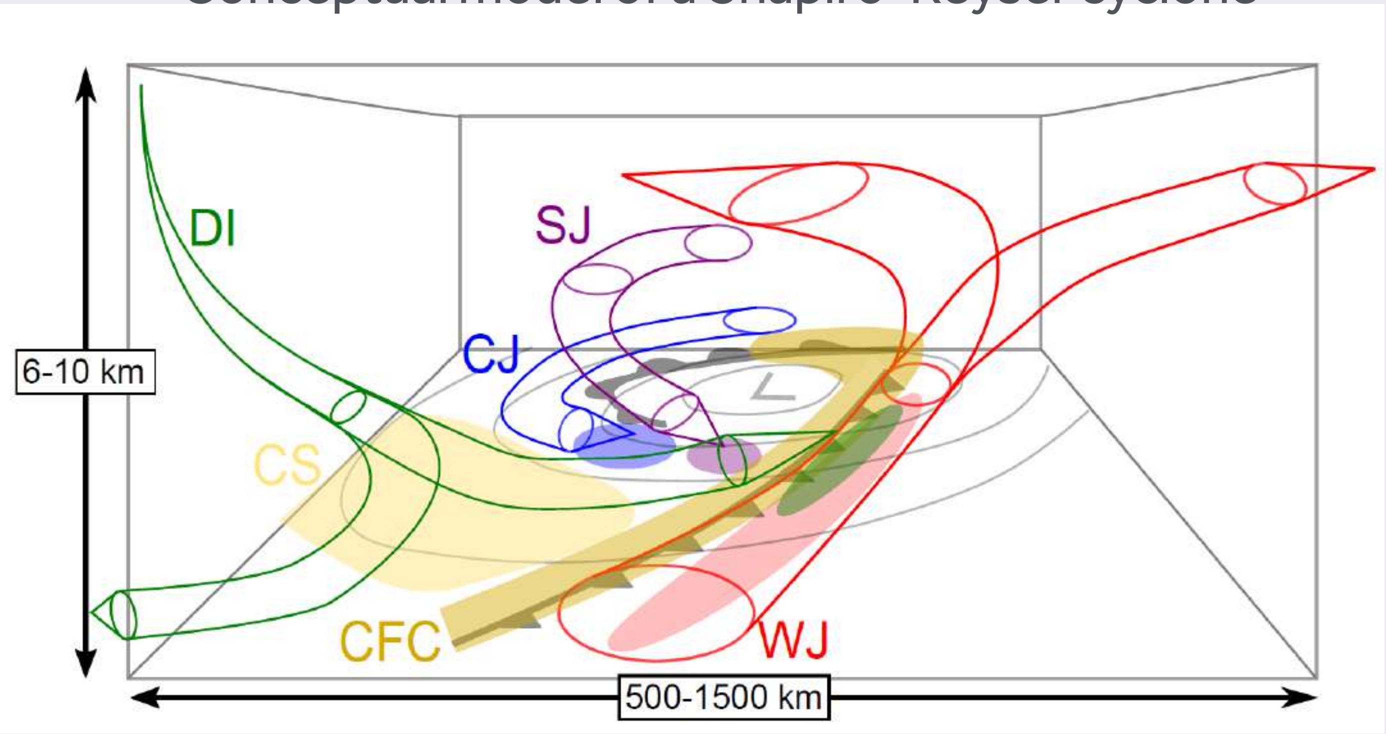
University of Reading

Conceptual model of a Shapiro-Keyser cyclone

Mesoanalysis of peak surface wind gusts in Great October 1987 storm

From Browning (2004)





Mesoscale features are often associated with strong winds and gusts e.g.,

A: localised areas of strong gusts associated with cumulonimbus clouds ahead of cold front 2.

B: localised areas of strong gusts associated with shallow non-precipitating clouds in dry slot behind cold front 2.

C: large region of v. strong winds in dry slot (sting jet).

D: strong winds due to cold conveyor belt jet.

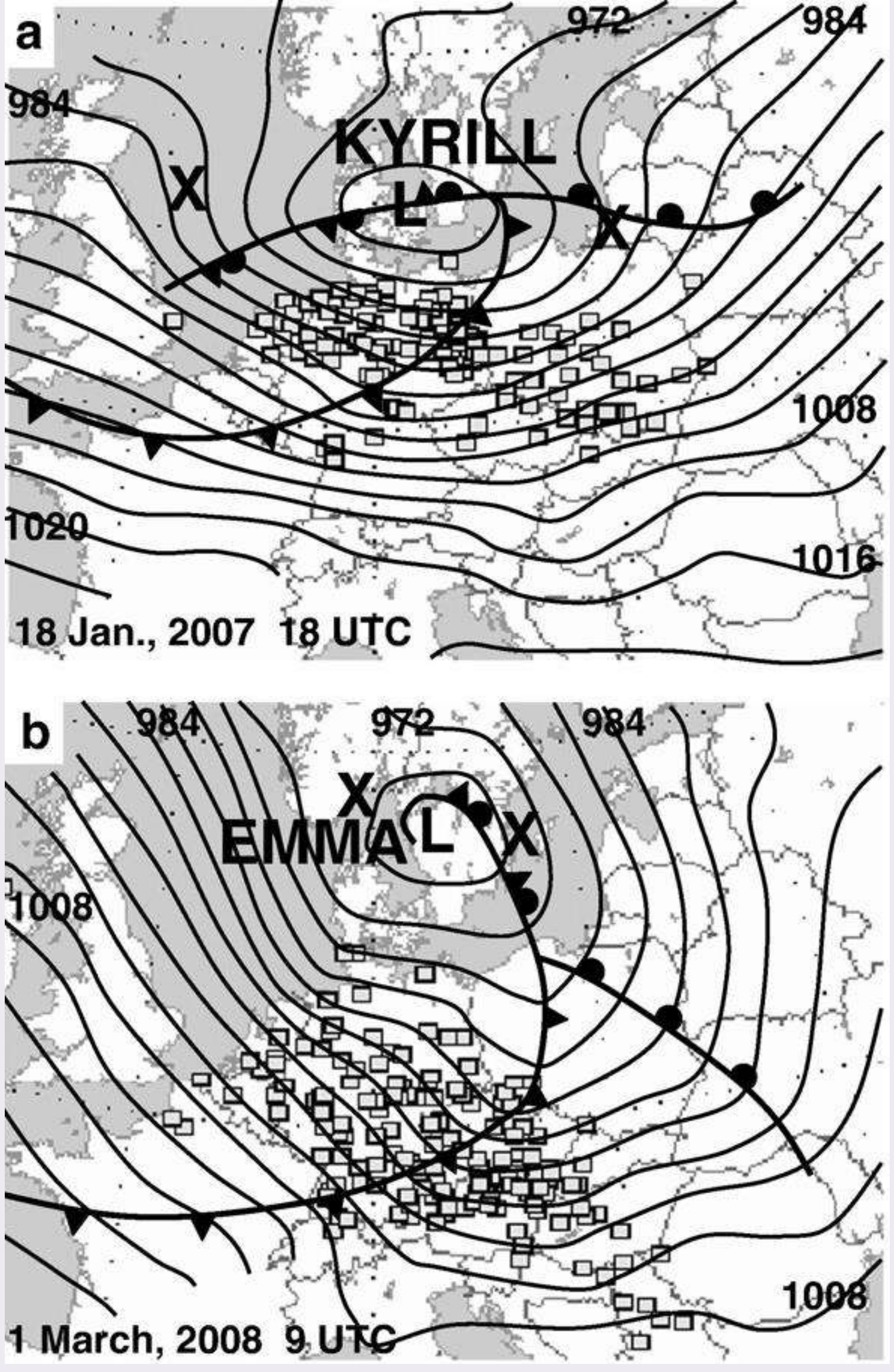
WJ – warm jet
CJ – cold jet
SJ – sting jet
CFC – cold frontal convection
CS – cold sector convection

Modified from Clark and Gray (2018) and Eisenstein et al. (2022)

Mesoscale wind features

Widespread convectively induced windstorms, called **squall lines** or **derechoes** are associated with long swaths of damaging winds can also occur associated with intense surface cyclones.

- In Kyrill and Emma (right), damaging winds were reported over a distance of 1500 km and locally reached F3 intensity
- Both derechoes formed along cold fronts that were affected by strong quasi-geostrophic forcing.
- A derecho is defined as a family of downburst clusters produced by an extratropical convective system (Johns and Hirt, 1986).



Boxes are reports of gusts > 25 m/s

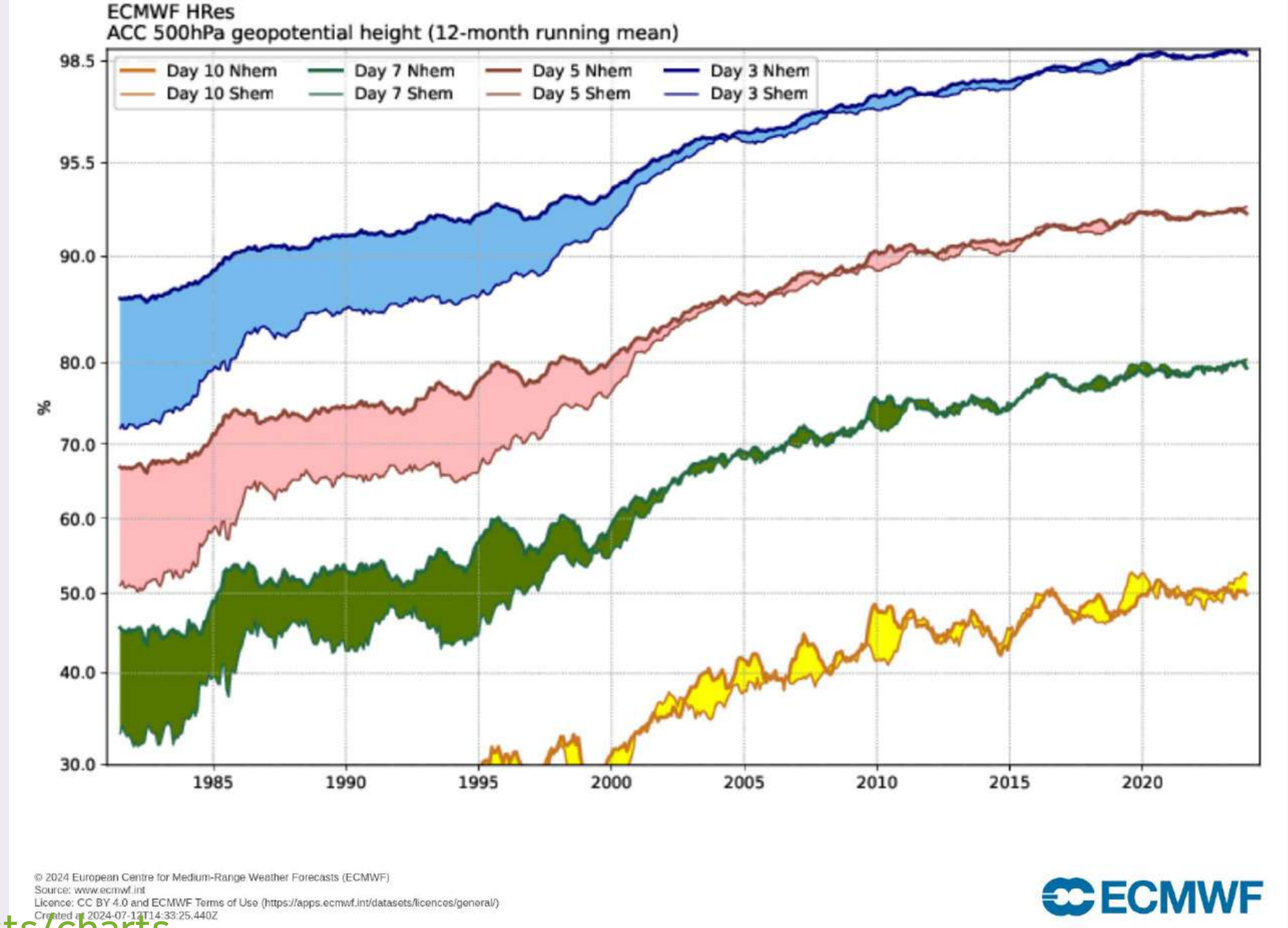
Gatzen *et al.* (2011)

Predictability across scales

Forecast skill and predictability: I

Synoptic-planetary scale: high resolution 500 hPa geopotential height forecasts

Lead time of anomaly correlation coefficient (ACC) reaching multiple thresholds



ECMWF forecasts from https://www.ecmwf.int/en/forecasts/charts

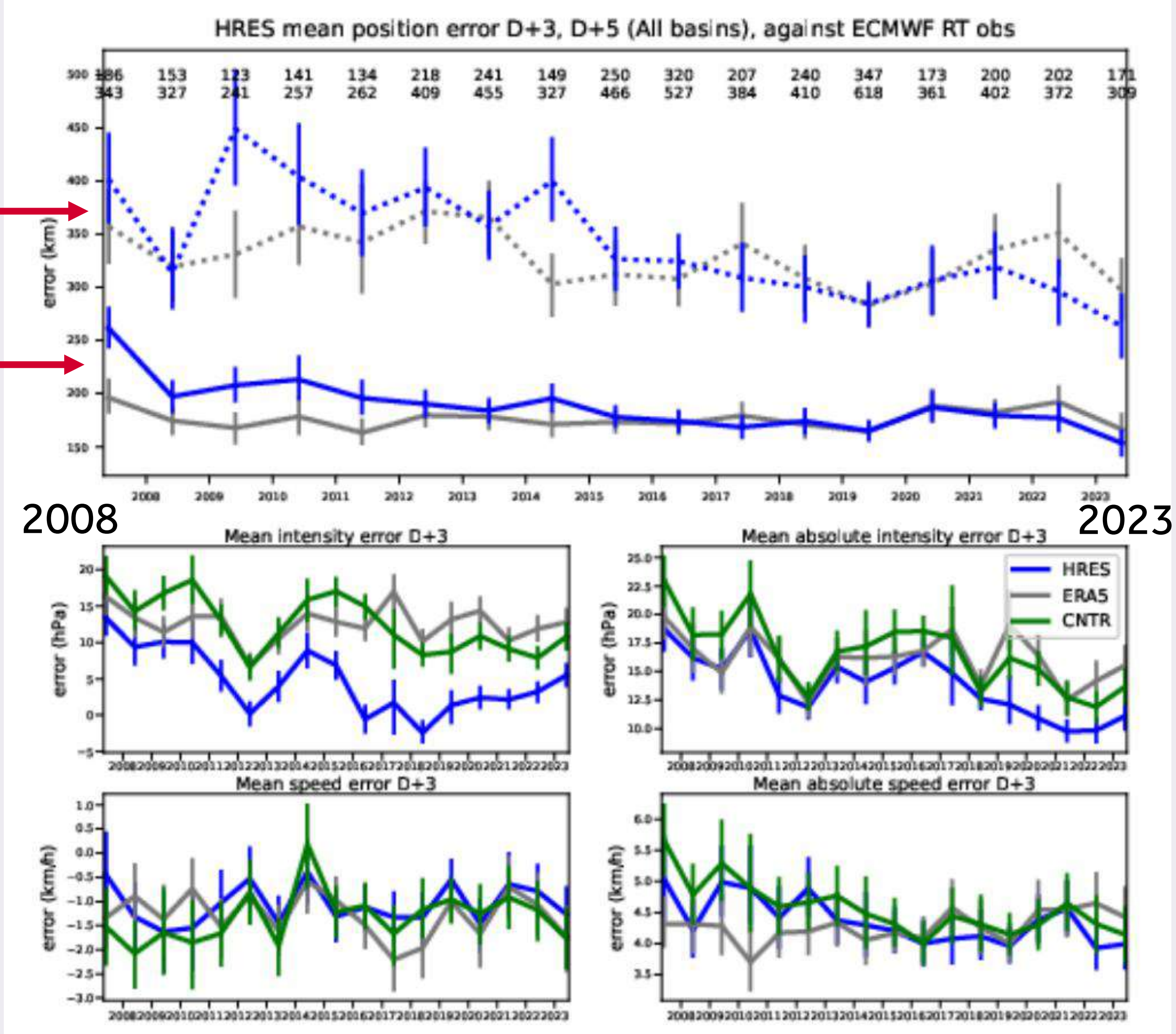
Forecast skill and predictability: II

University of Reading

Synoptic-scale: Errors of tropical cyclone forecasts

5-day forecast

3-day forecast for high-resolution forecast (blue) and ERA5 (grey) compared to observations

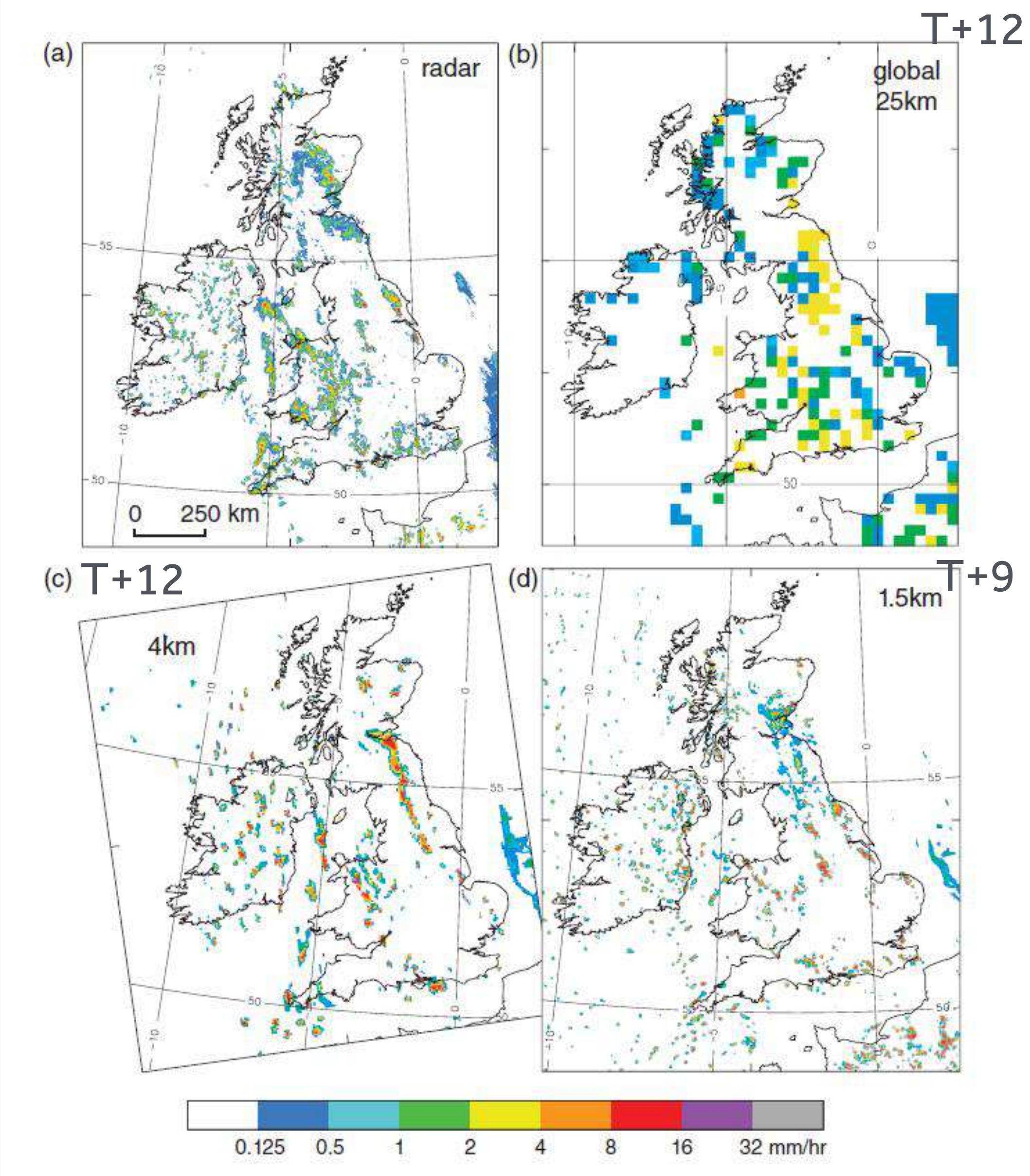


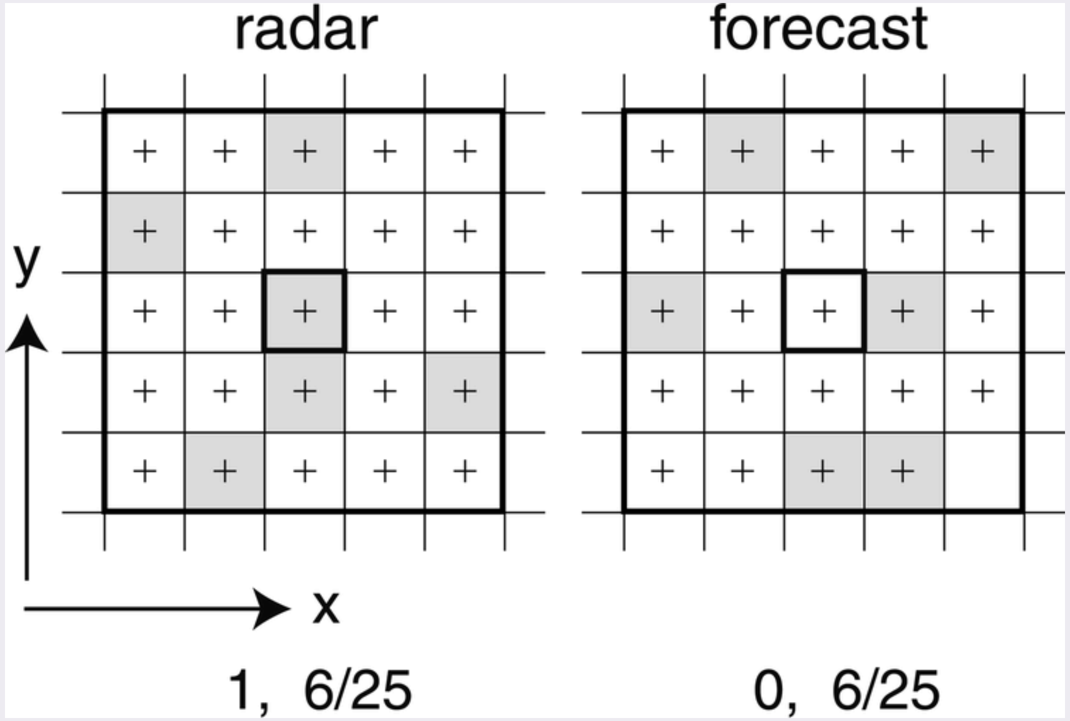
Errors in speed and intensity for 3-day forecasts

ECMWF forecasts from https://www.ecmwf.int/en/forecasts/charts

Forecast skill and predictability: III

Convective scale – isolated showers





Neighbourhood verification methods
(Roberts and Lean, 2008)

Clark et al. (2016)

Stages of error growth

University of Reading

Studies have consistently revealed upscale error growth across multiple scales.

e.g., from Baumgart *et al.* (2019) using identical twin experiments

- **0-12 hr:** dominated by differences in the convection scheme
- **0.5-2 days:** differences in the upper-tropospheric divergent wind then project these diabatic errors into the tropopause region
- **2-14.5 days:** governed by differences in the nonlinear near-tropopause dynamics
- **Up to 18 days:** error growth from the synoptic up to the planetary scale.

Summary

- Cold fronts can be classified as Ana or Kata depending on whether there is general upsliding of warm air (ana) or descent in all but the lowest layers (kata).
- Rainbands can have a wealth of associated mesoscale features: multiple bands in the horizontal, stacked vertical layers, distinct precipitation cores, tornadoes, derechos, cloud head striations.
- Line convection can be followed by slantwise convection aloft and upright convection can be triggered by slantwise ascent: elevator-escalator model.
- Sting jets are transient (few hours), mesoscale (~50km spread) jets of air descending from the tip of the hooked cloud head in the frontal fracture regions of some extratropical storms.
- Predictability varies with scale with new approaches required to measure mesoscale and convective predictability such as neighbourhood and object-based metrics.
- Also, (not shown), arc rainbands can form in the dry slot of cyclones and inertia-gravity waves can form associated with the upper-level jet.