Applying new 3-D jet core visualisation techniques to the study of extreme cyclones

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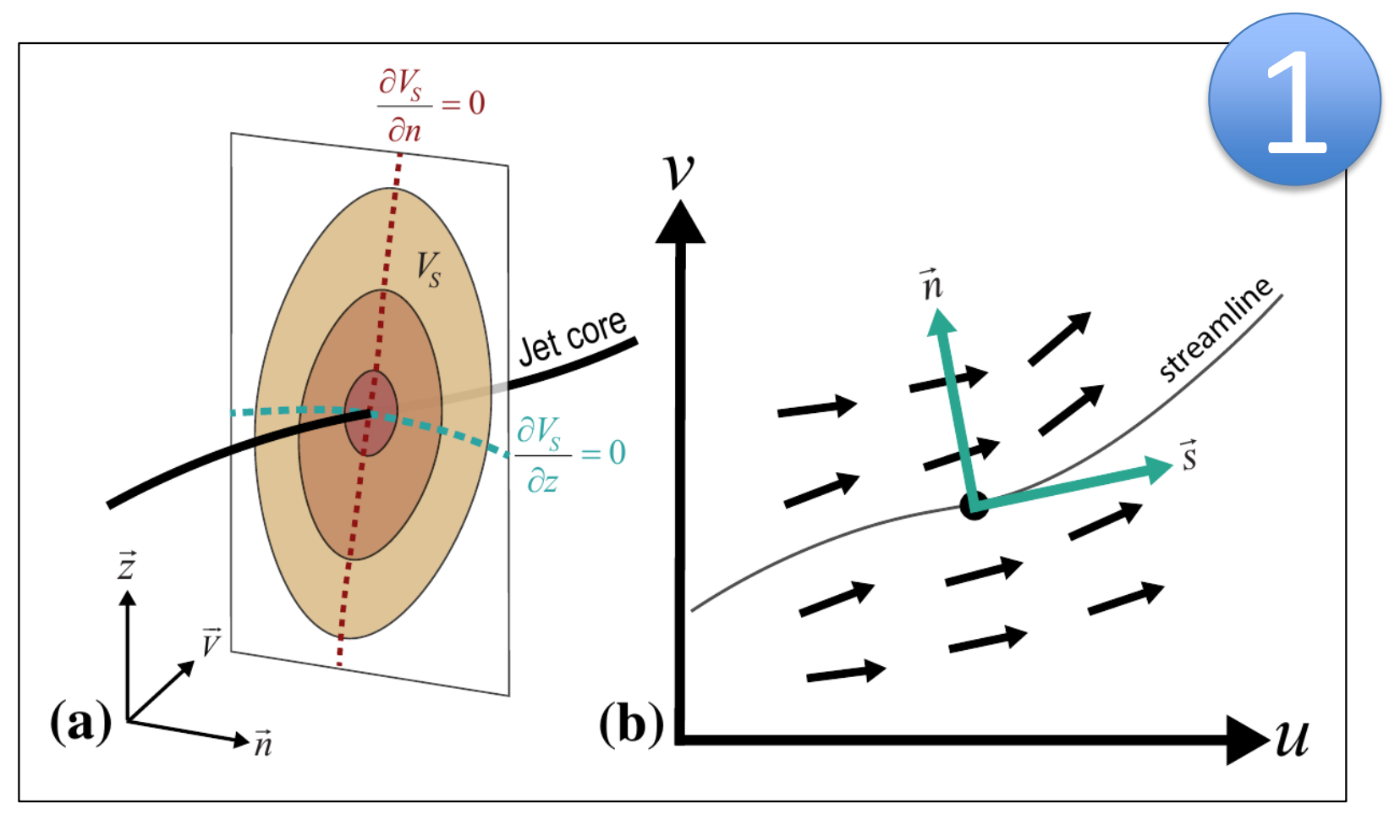
1. Introduction

Depictions of meteorological features, such as fronts and jet streams, have traditionally been in 2-D, on horizontal or vertical sections. However most of these features lend themselves to a 3-D representation, providing greater realism and potentially delivering clearer and quicker insights into atmospheric and numerical model behaviour. With hardware advances (primarily GPUs) and visualisation software that exploits those advances (e.g. the open source "Met.3D" package - https://met3d.wavestoweather.de - described in [5]) real time interactive 3-D visualisation, with fly through and animation, can now be realised on a standard desktop PC, potentially even within forecasting. Here we use Met.3D in conjunction with a new mathematical algorithm for tracing out the 3-D cores of jet streams, to investigate the structure of an extreme cyclonic windstorm "Xavier" that lead to damage and fatalities, notably in northern Germany and Poland, on 5th October 2017.

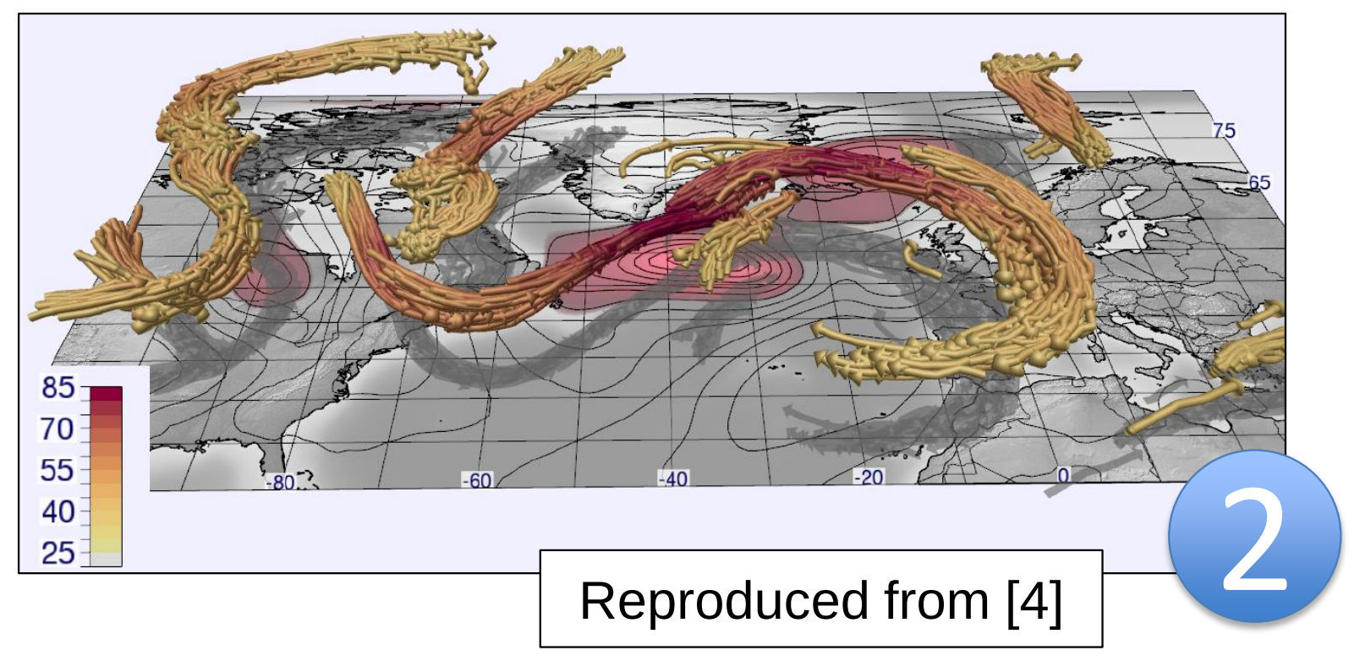
2. 3-D Jet Core algorithm

Building on a 2-D jet core algorithm described in [1] we define the jet cores to be a subset of the line segments in 3-D space that are the intersections of contorted sheets represented by the two simple equations on the left of Fig ①. The eigenvalues of a locally computed Hessian matrix are used to mask out line segments that are wind speed minima or loci of saddle points, to leave just the maxima. Additional simple masks are also applied to enforce a minimum wind speed cut-off and a maximum angle tolerance between jet core line and local 2-D wind direction. Vertical velocities are ignored. It has been found that this conceptually simple approach delivers more robust, less noisy results than classical "3-D ridge extraction" techniques – see [4]. Fig ② (a case from September 2016) shows jet core "bundles" identified in this way in 51 ensemble runs.

①



②



Reproduced from [4]

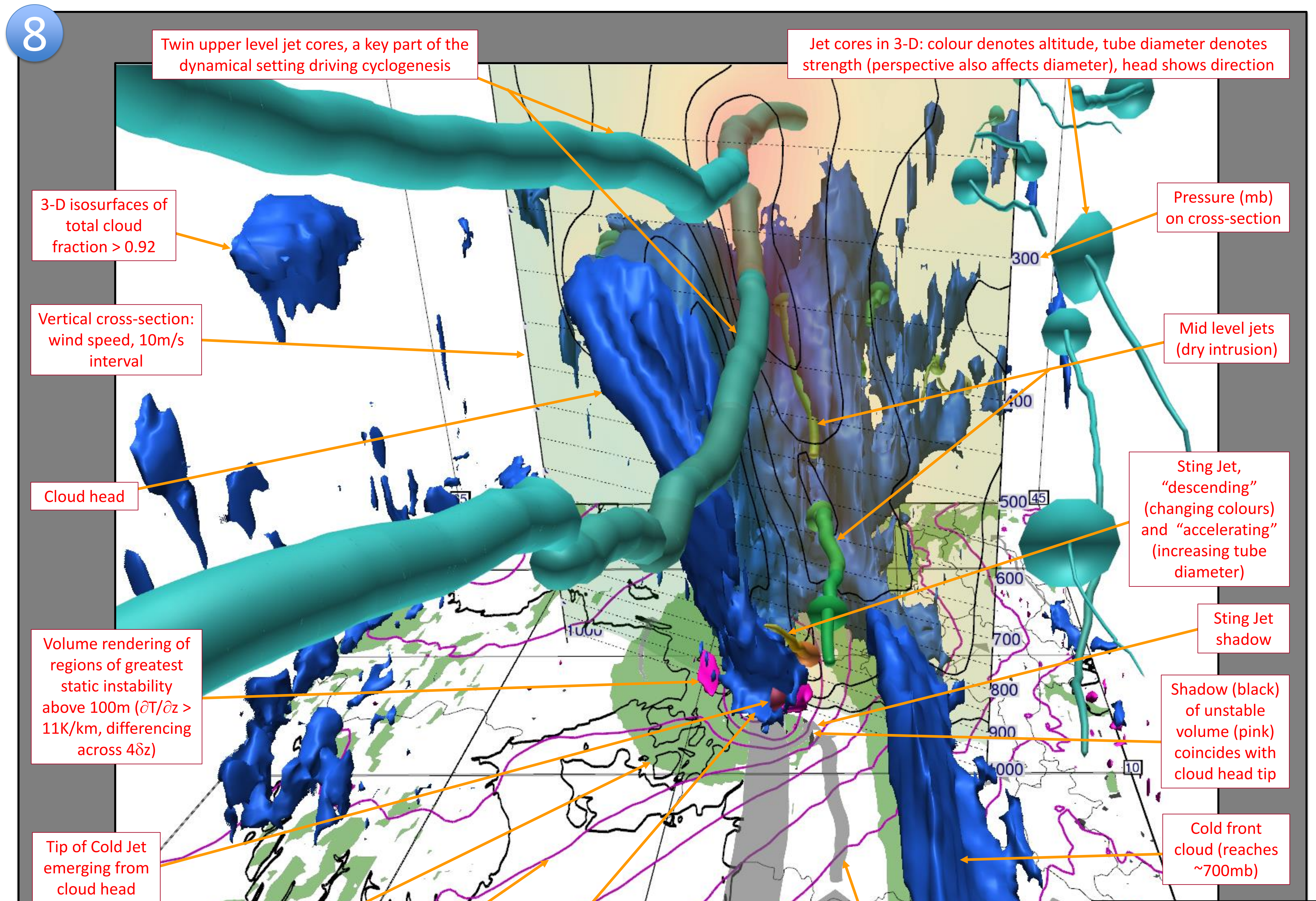
3. Case Study

Cyclonic windstorm "Xavier", shown in rotated synoptic chart form on Fig ③, delivered a swathe of very strong winds across parts of Europe during 5th October 2017 (Fig ④). Distinctive imagery signatures (not shown) suggested a Sting Jet ([2], [3]) could be responsible, as did the existence of very strong winds well inland ([3]). Swathe shape also matches the conceptual model sting jet swathe shape (red) on Fig ⑤ (from [3]).

Classical plots (Figs ⑥, ⑦) from a relatively accurate operational short range forecast by ECMWF (the European Centre for Medium Range Weather Forecasts) show very strong gusts predicted southwest of the low centre, in a region that has relatively unstable air near the surface. Next we fed 3-D output from this model run into Met.3D, to create Figs ⑧ and ⑨. Key points are:

- The Jet Core algorithm successfully identifies several jets of varying strength around the cyclone: upper-level jets, mid-level jets in the dry intrusion, Cold Jet, Sting Jet
- The Sting Jet core curves downwards and appears to descend and accelerate (albeit that a full trajectory analysis would be required to prove temporal behaviour). This is in agreement with published literature (e.g. Fig 7 in [2]), except that here **the identification is automated.**
- The lower flank of the Sting Jet tip intersects a volume of static instability (pink zone, the most substantive in the domain), which is potentially the conduit for extreme gusts to reach the surface, as proposed in [3]. Evaporation may be "fuelling" the instability.

⑧



Twin upper level jet cores, a key part of the dynamical setting driving cyclogenesis

Jet cores in 3-D: colour denotes altitude, tube diameter denotes strength (perspective also affects diameter), head shows direction

3-D isosurfaces of total cloud fraction > 0.92

Pressure (mb) on cross-section

Vertical cross-section: wind speed, 10m/s interval

Mid level jets (dry intrusion)

Cloud head

Sting Jet, "descending" (changing colours) and "accelerating" (increasing tube diameter)

Sting Jet shadow

Volume rendering of regions of greatest static instability above 100m ($\partial T/\partial z$ > 11K/km, differencing across 4δz)

Shadow (black) of unstable volume (pink) coincides with cloud head tip

Tip of Cold Jet emerging from cloud head

Cold front cloud (reaches ~700mb)

Cloud head shadow

Isobars, 4mb interval

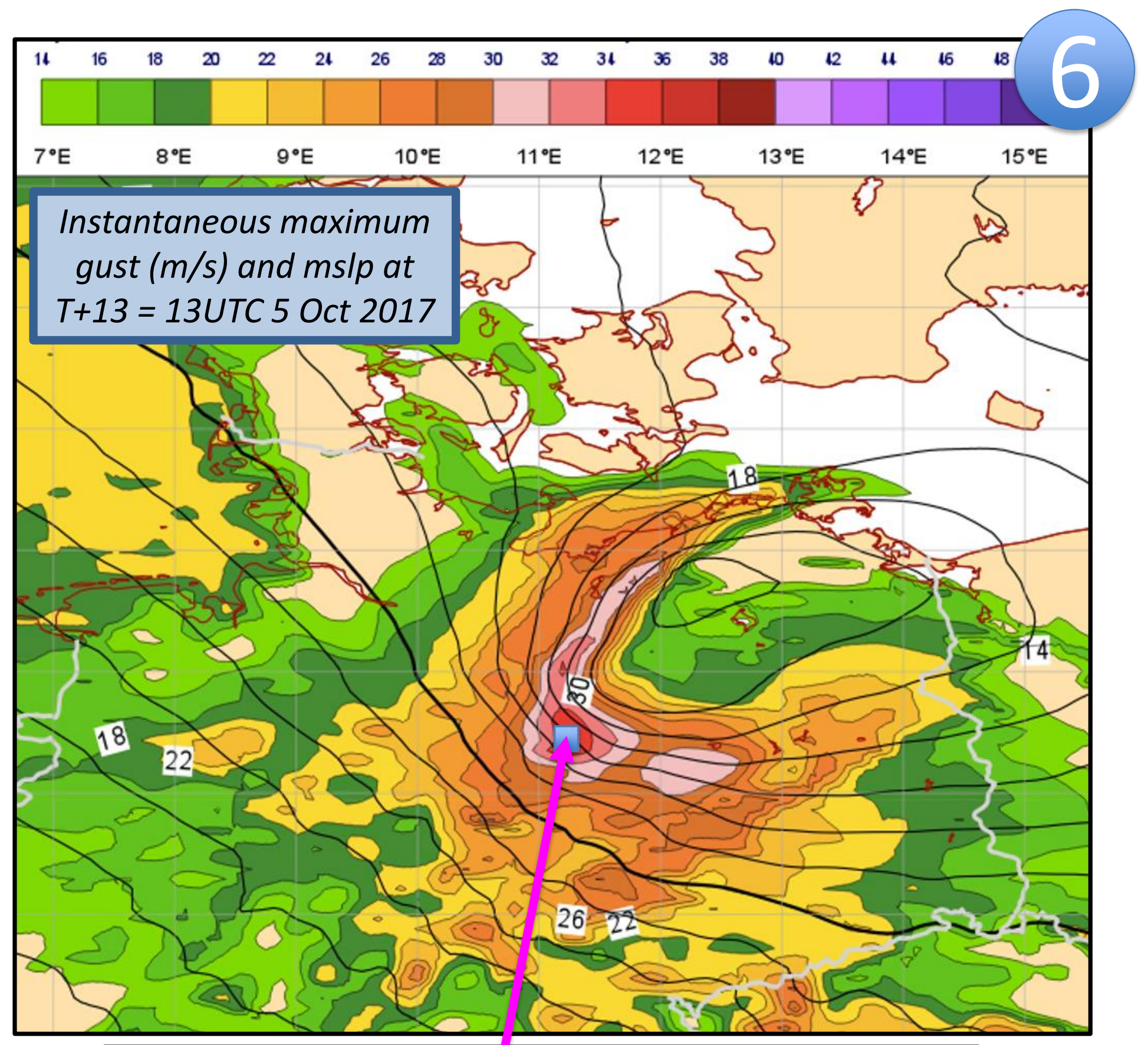
Centre of cyclone "Xavier" at surface

Overlapping shadows of upper level jets

Shadow of mid-level jet

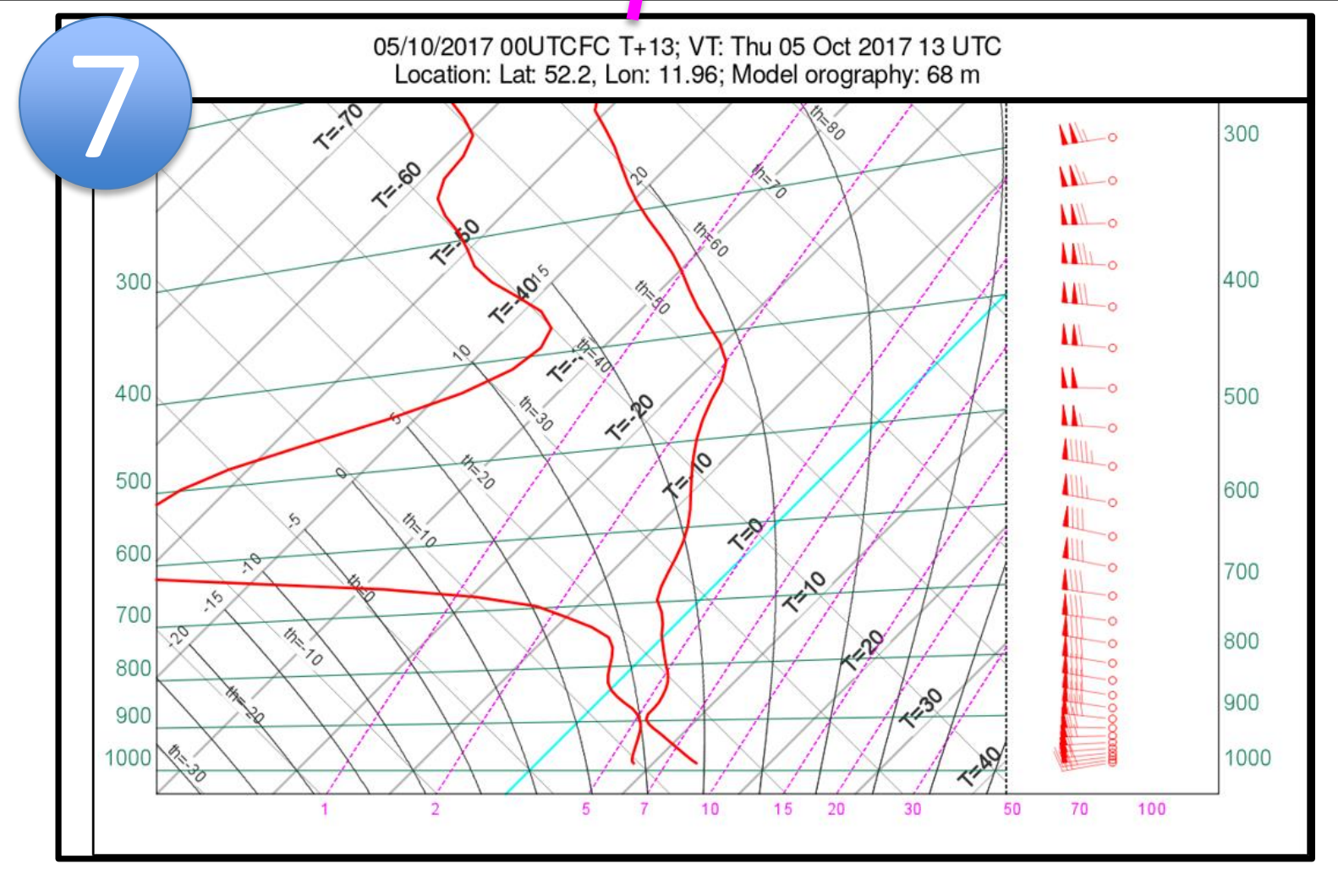
ECMWF 13h forecast for 13UTC 5 Oct 2017.
0.25° resolution, all 137 model levels utilised

⑥



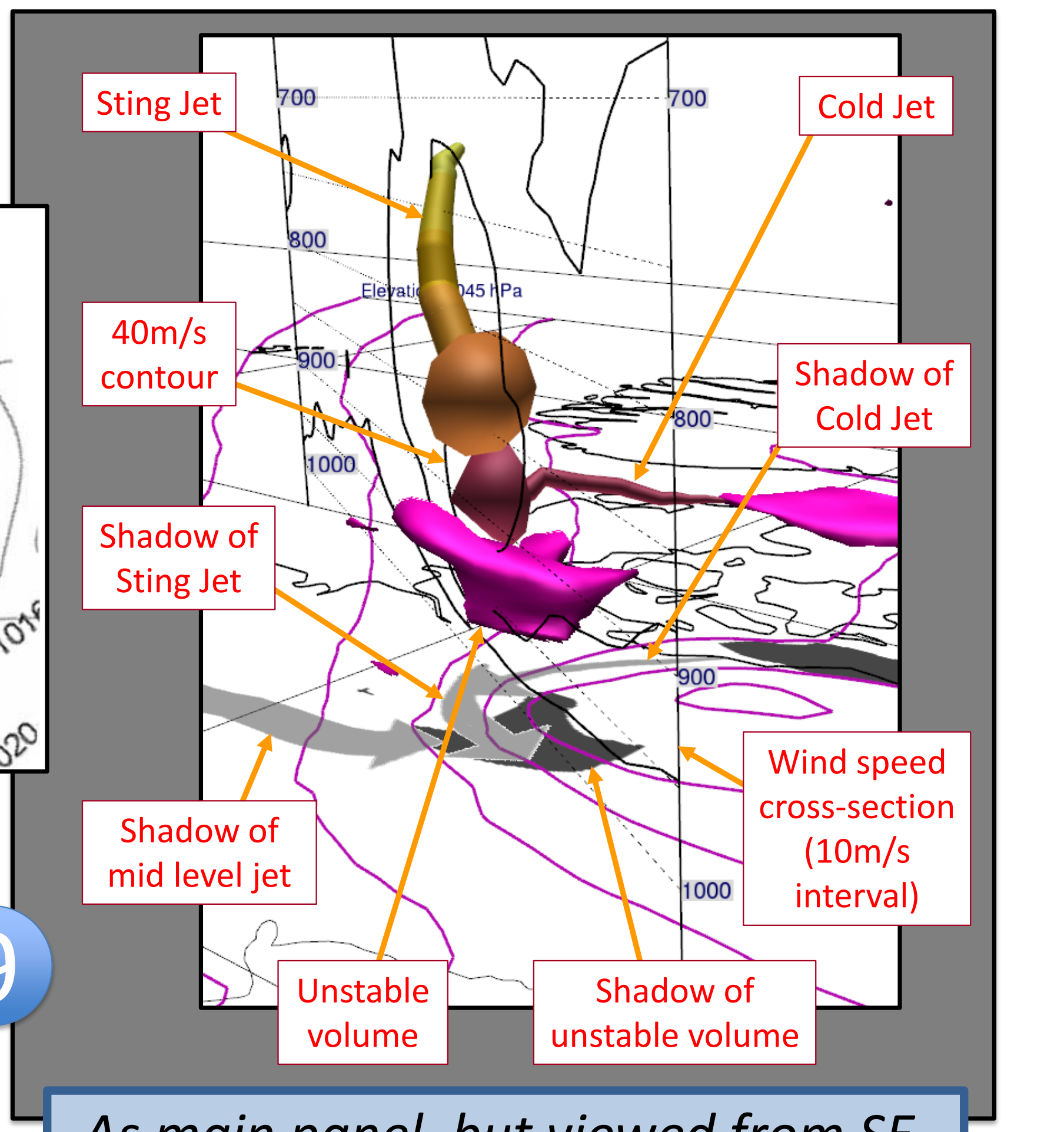
Instantaneous maximum gust (m/s) and mslp at T+13 = 13UTC 5 Oct 2017

⑦



05/10/2017 00UTCFC T+13; VT: Thu 05 Oct 2017 13 UTC
Location: Lat: 52.2, Lon: 11.96; Model orography: 68 m

⑨



Sting Jet

Cold Jet

40m/s contour

Shadow of Cold Jet

Shadow of Sting Jet

Wind speed cross-section (10m/s interval)

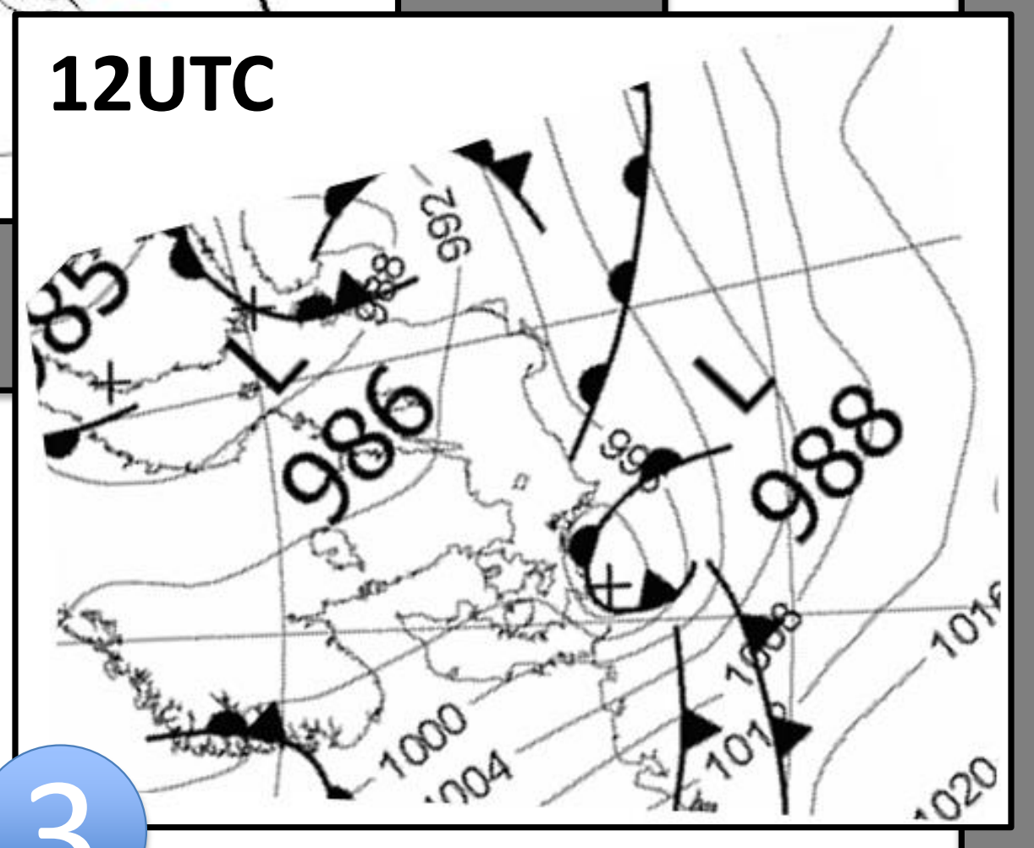
Shadow of mid level jet

Unstable volume

Shadow of unstable volume

As main panel, but viewed from SE, with cloud rendering de-activated

③



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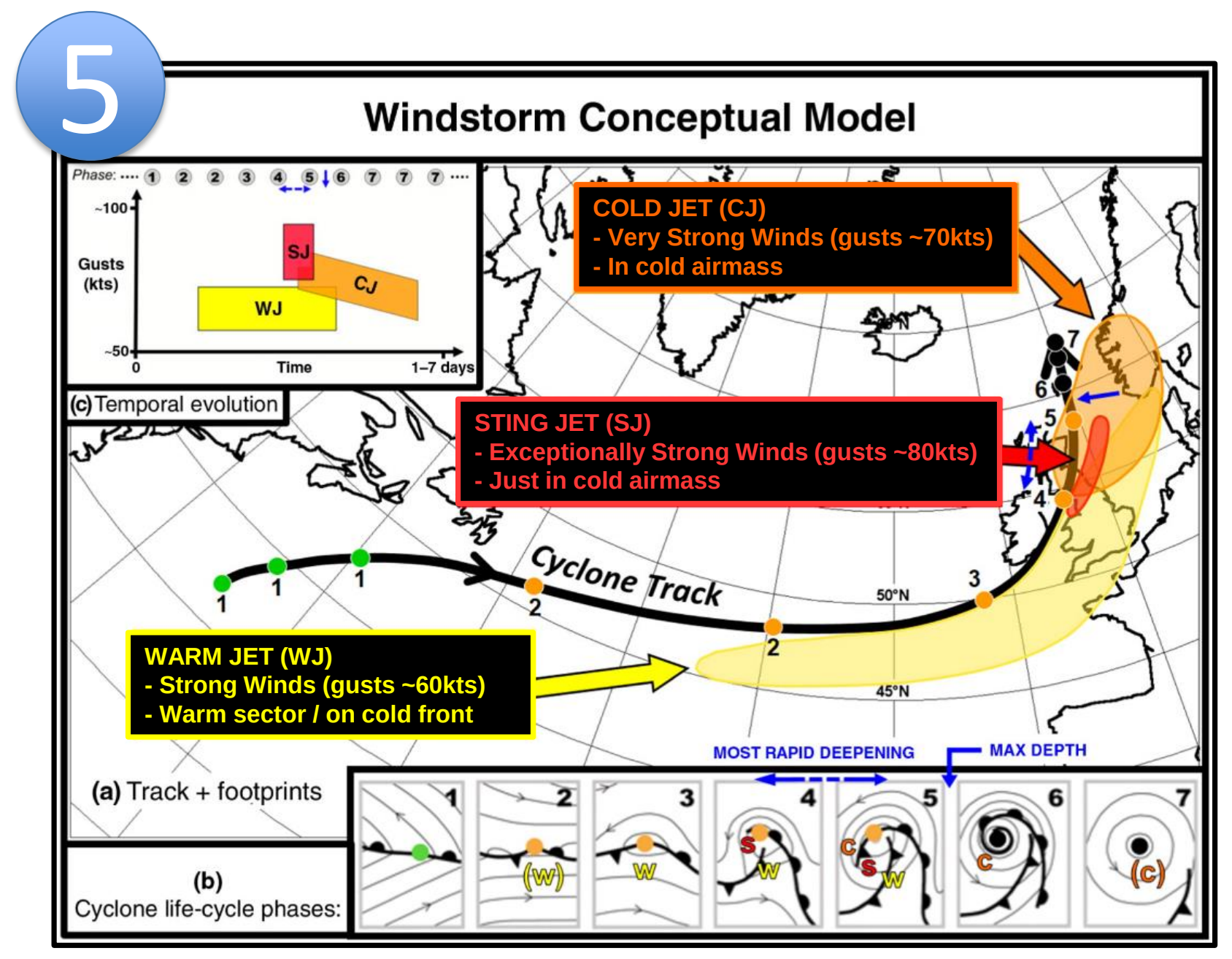


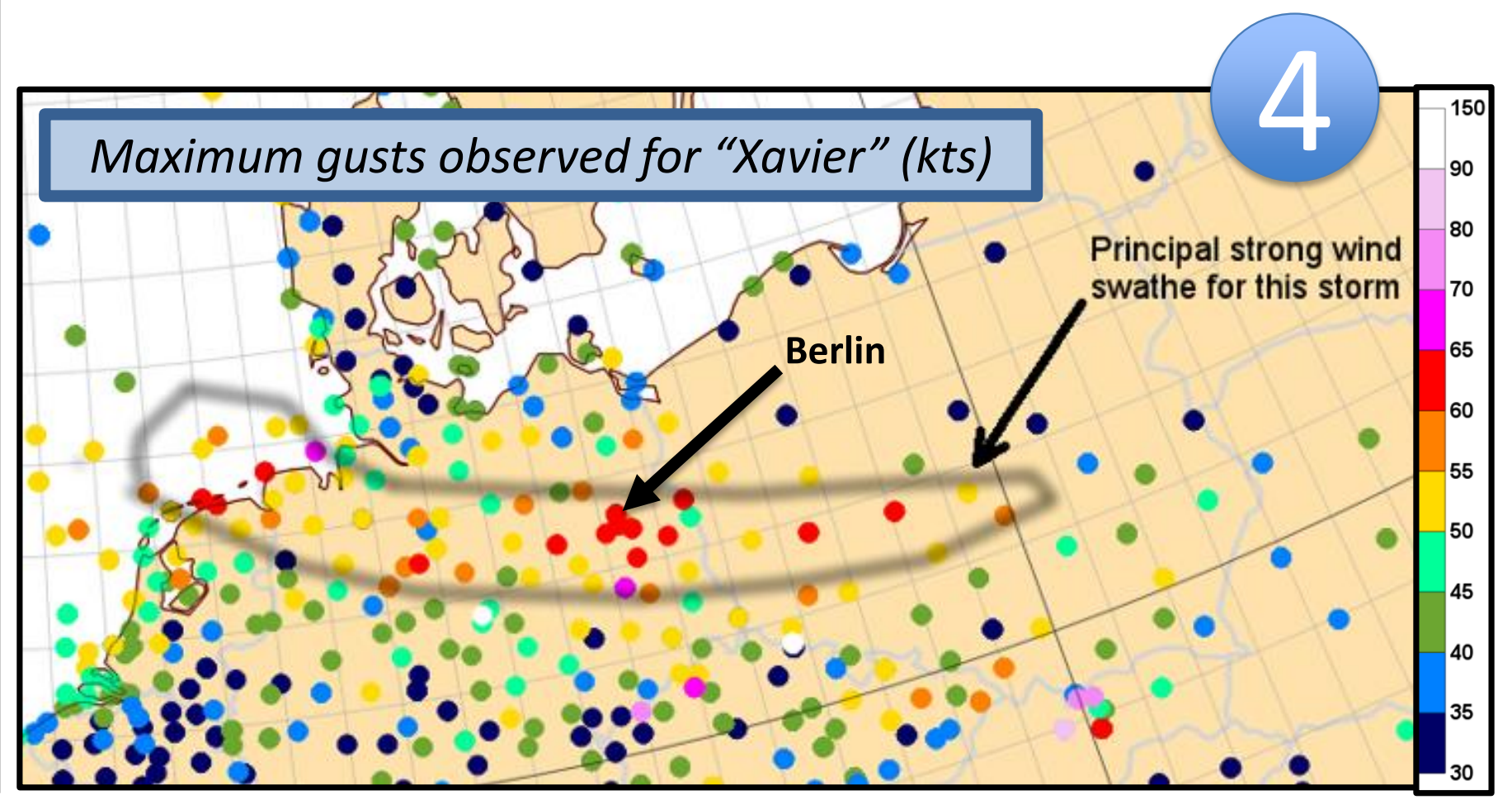
Windstorm Conceptual Model

COLD JET (CJ)
- Very Strong Winds (gusts ~70kts)
- In cold airmass

STING JET (SJ)
- Exceptionally Strong Winds (gusts ~80kts)
- Just in cold airmass

WARM JET (WJ)
- Strong Winds (gusts ~60kts)
- Warm sector / on cold front

④



Maximum gusts observed for "Xavier" (kts)

4. Discussion

Whilst this case and two others (not shown) fit some previous conceptual ideas very well, further cases must be examined; it is likely that a continuum of different behaviours will be revealed. And within cyclones there exist several types of instability (see [2]); only one is examined here. Volume rendering of other types could be useful, but model limitations must also be considered.

Achieving the 3-D visualisations shown in Figs ⑧ and ⑨ required much experimentation, adjusting the tuneable parameters for jet cores, changing the (92%) threshold for the cloud volume rendering, adjusting viewing angles, moving cross sections etc. For future work, in research or operations, saving, sharing and re-using settings will be critical. Met.3D facilitates this.

It would also be instructive to render frontal surfaces in 3-D, to provide further insights, as fronts are a fundamental component of extra-tropical cyclones. Work on this has already begun.

References

[1] G. Berry, C. Thorncroft, and T. Hewson. 2007. African easterly waves during 2004—Analysis using objective techniques. *Mon. Wea. Rev.,* **135**(4):1251–1267

[2] P. A. Clark and S. L. Gray. 2018. Sting Jets in extratropical cyclones: a review. *Q.J.R. Meteorol. Soc.* Accepted for publication.

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[4] M. Kern, T. Hewson, F. Sadlo, R. Westermann, and M. Rautenhaus. 2018. Robust detection and visualization of jet-stream core lines in atmospheric flow. *IEEE Trans. Visual. Comput. Graphics*, **24**(1):893–902.

[5] M. Rautenhaus, M. Kern, A. Schäfler, and R. Westermann. 2015. Three-dimensional visualization of ensemble weather forecasts – Part 1: The visualization tool Met.3D (version 1.0). *Geosci. Model Dev.*, 8(7):2329–2353.