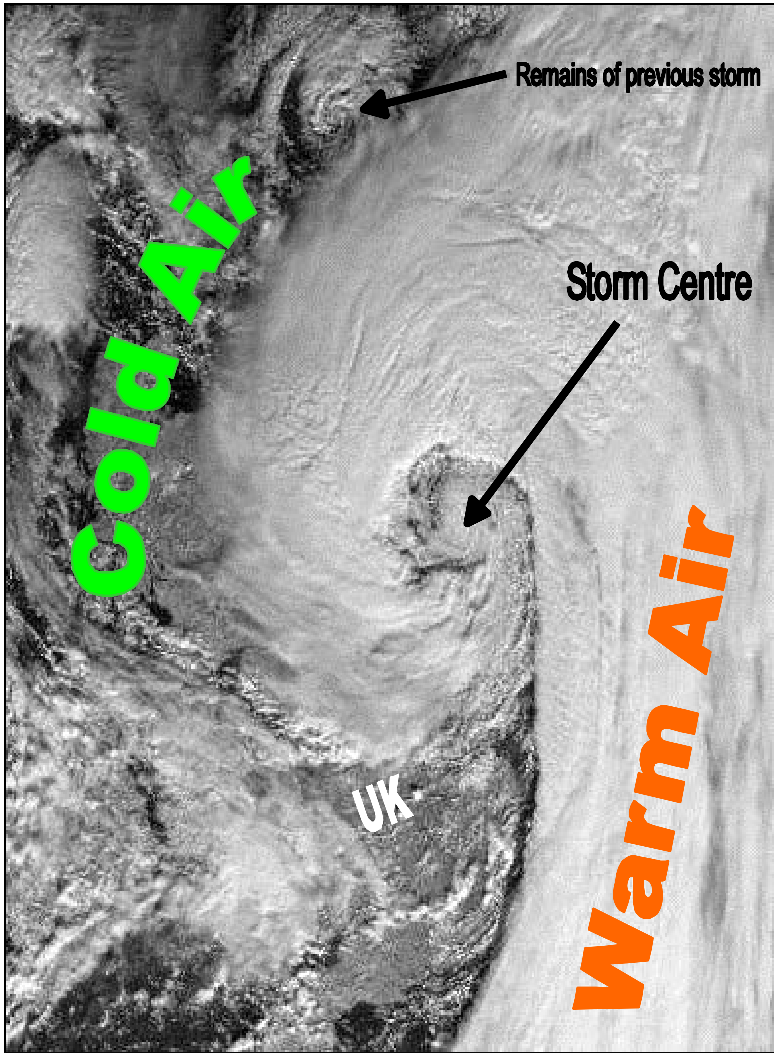

Cyclonic Windstorms – Morphology, Predictability and Model Representation

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Cyclones, windstorms and the IMILAST project

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ABSTRACT

By way of introduction to the TELLUS thematic cluster on outcomes of the IMILAST project (Intercomparison of MId-LAtitude STorm diagnostics), this paper presents the results of new research that is fundamental for the correct interpretation of IMILAST results. Specifically we investigated the mesoscale structure of cyclonic windstorms, and the representation of those windstorms in re-analysis data. The paper concludes with an overview of the project itself. Twenty-nine historic windstorms are studied in detail, using wide-ranging observational data, and on this basis a conceptual model of the life cycle of a typical windstorm-generating cyclone is developed. The model delineates three wind phenomena, the warm jet, the sting jet and the cold jet, and maps out the typical damage footprint left by each. Focussing on the boundary layer, the physical processes at work in each jet zone are investigated. These include the impact of near-surface stability and exposure on gust strength. Based on numerous cases, a generic description of the sting jet is provided, with many new features highlighted. This phenomenon looks to be unique in that exceptional gusts can be realised well inland because destabilisation is activated from above. We next investigate how well the widely-referenced ERA-Interim re-analysis, that has been a primary data source for IMILAST, can represent windstorms. In many ways, performance is suboptimal. Compared to a benchmark manually-analysed dataset, windstorm-generating cyclones generally do not deepen rapidly enough. In part, this is a resolution limitation. For one medium-sized cyclone, it is shown, using other models, that horizontal resolution of order 20 km or better is required to capture the most damaging winds. In the context of IMILAST, which has used data at resolutions ≥80 km, this is a fundamental result. For this and other reasons, caution is clearly needed when inferring storm behaviour and severity from model-based metrics.

Keywords: cyclone life-cycle, conceptual model, sting jet, cyclone tracking, windstorm footprint, satellite imagery, re-analyses, boundary layer, convective instability, evaporation

Layout of talk

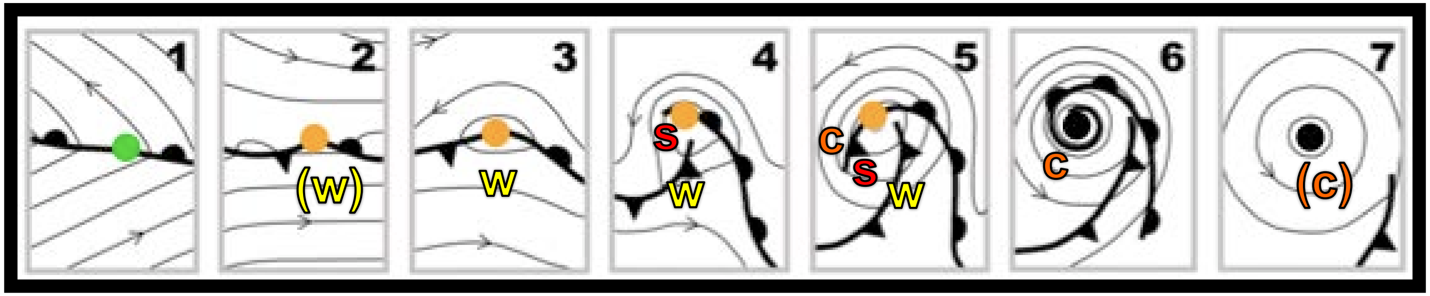
- **Deriving a conceptual model of extra-tropical windstorms**
  - **Method**
  - **Key characteristics**
- **The role of stability - focus on the Boundary Layer**
  - **What makes a Sting Jet different?**
- **How can the conceptual model be used to improve real time forecasts?**
- **How are windstorms represented in ERA-Interim**
  - **Is storm intensity scaleable?**

- **Summary**

Deriving a Conceptual Model - Data Sources

- **Iterative process based on a (15 year!) study**
- **Used 29 Cyclonic windstorms over Europe (22 from IMILAST)**
- **Each Storm was (re-)examined using:**
  - **Standard synoptic analysis charts (mainly from UK Met Office)**
  - **Surface observations**
  - **Satellite imagery sequences**
  - **And, where possible:**
    - **Data/results from related publications**
    - **Radar / Soundings / Profilers, etc…**
- **A conceptual model, showing storm footprints and temporal evolution, and a key characteristics table resulted**

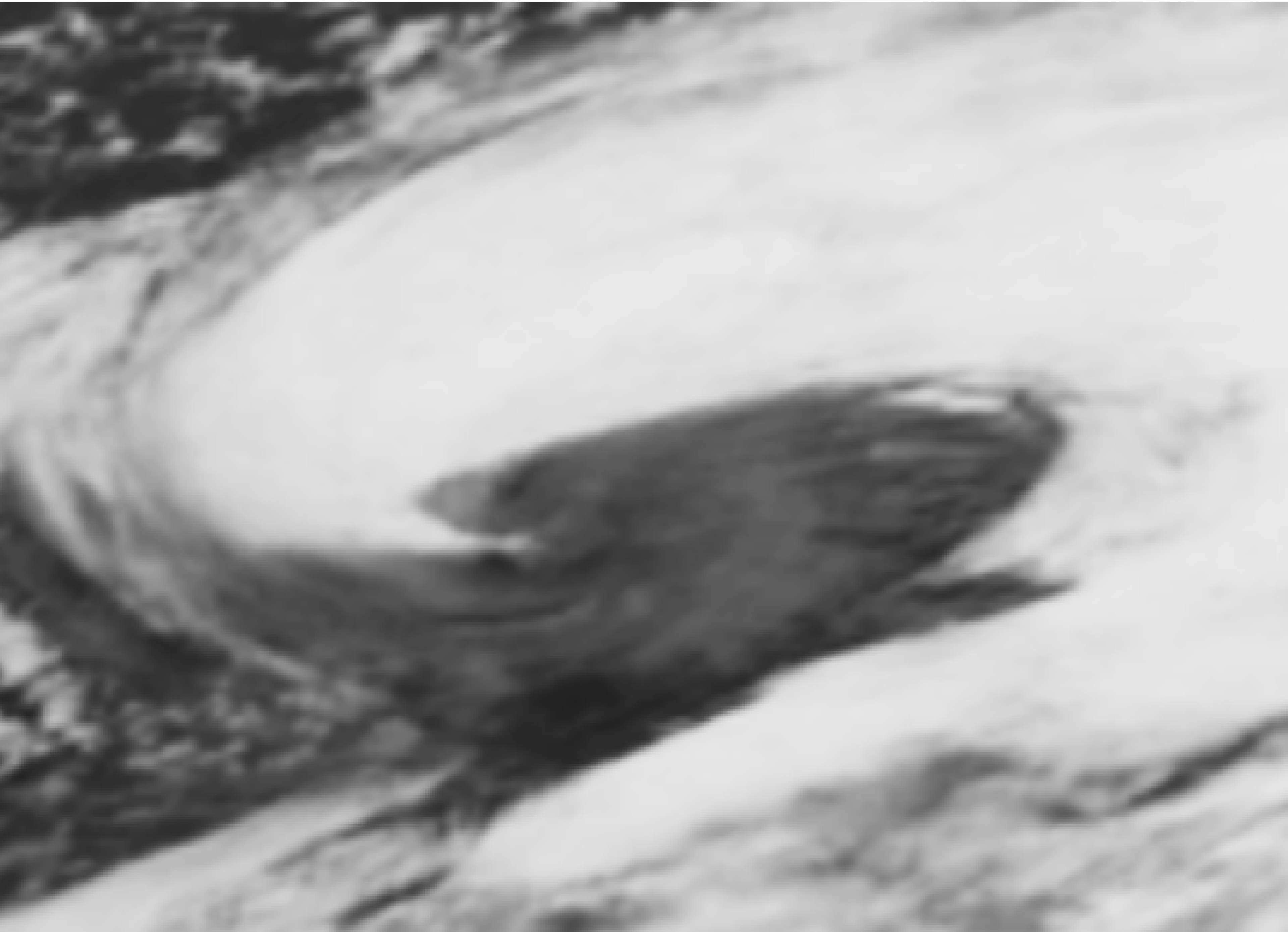
Approach



- Starting point = above cyclone lifecycle model
- For each windstorm document probable cause of the peak (damaging) gusts recorded over land

W = Warm Jet S = Sting Jet C = Cold Jet

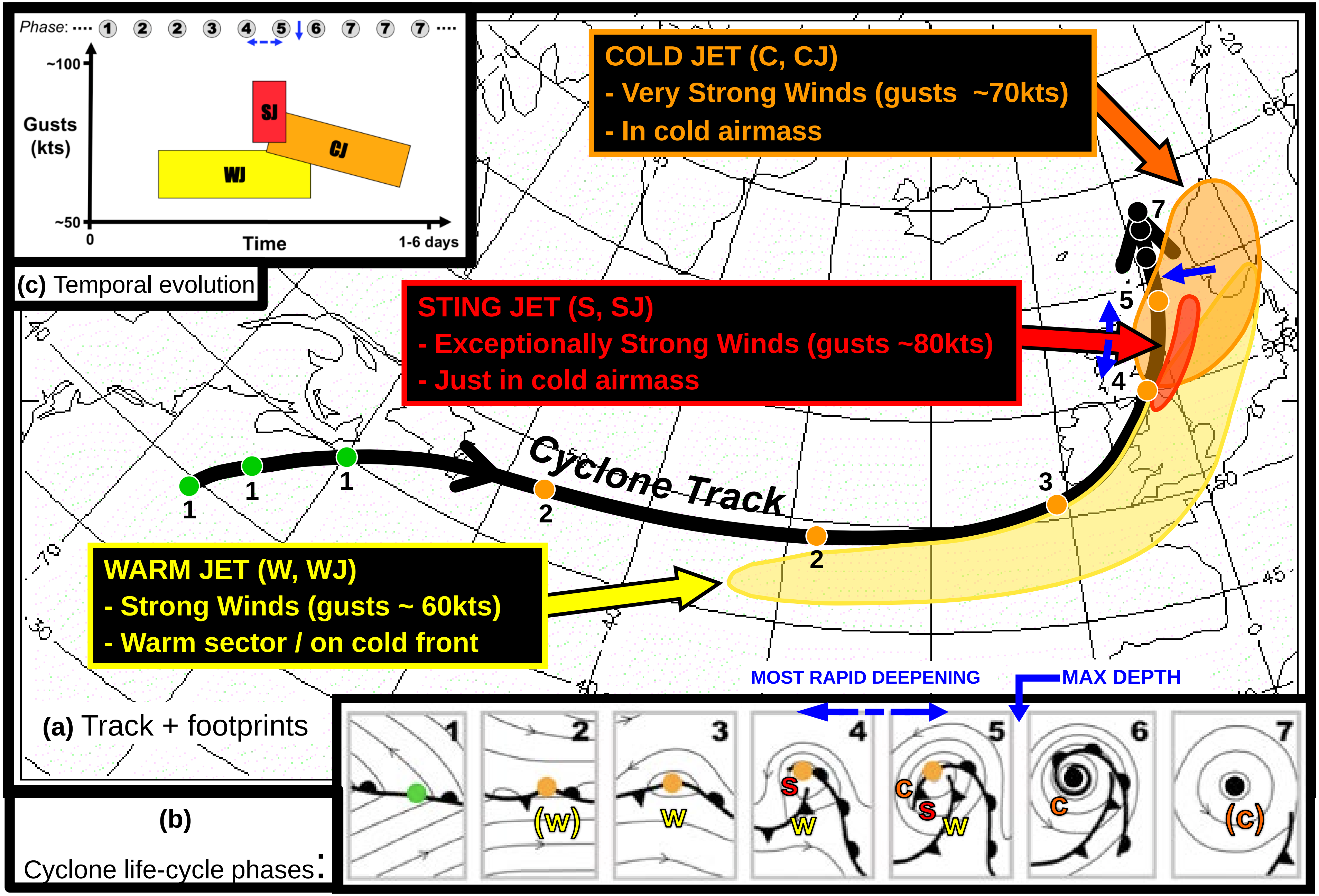
- Mostly based on gust location relative to fronts on synoptic charts
- BUT disentangling Sting Jet from Cold Jet cases required much more work, using multiple data sources, as available. Satellite imagery key..



Classification Results for 29 storms

Name of Storm	First impact date	Main countries affected	Storm type (over land)
Daria	25/1/90	GB,NL,DK	W C
Vivian	26/2/90	IE,GB,DE,BE,CH,AT,NL	W C
"Venice92"	9/12/92	IT	W
Lili (ET)	28/10/96	IE,GB,DE	C
Yuma	24/12/97	IE,GB	(S) C
Anatol	3/12/99	DE,DK,SE	S C
Lothar	26/12/99	FR,CH,DE,AT	W (S)
Martin	28/12/99	FR,CH,DE	C
Oratia	30/10/00	GB	W S C
Torsten	11/11/01	DZ, ES	C
Jeanette	27/10/02	GB,NL,BE,DE,PL,CZ	C
Quimburga	20/11/04	CZ,AT,SK	(W) C
Dagmar	17/12/04	FR	C
Erwin	08/01/05	GB,DK,DE	W S C
Gordon (ET)	20/09/06	ES,IE,GB	(W) C
Renate	03/10/06	FR	S C
Kyrill	18/10/07	GB,DE,CH,AT,DE,PL,CZ	W C
Paula	25/01/08	DE,PL.CZ,AT	W C
Klaus	24/01/09	PT,ES,FR	C
Xola	23/12/09	PT	S C
Xynthia	28/2/10	FR,DE	(S) C
Ulli	03/01/12	GB	S C
October87	15/10/87	GB,FR	S C
Herta	3/2/90	FR,BE,DE	(S) C
Petra	15/7/10	GB	S
Friedhelm	08/12/11	GB	C
Christian	28/10/13	GB,NE,DK,DE,SE	S C
Xaver	05/12/13	GB,NE,DK,DE	C
Ulla	14/02/14	GB,FR	W C

Windstorm Conceptual Model



Key points

- **The conceptual model represents the life-cycle of a ‘typical’ cyclonic windstorm over the North Atlantic**

- **Model should be considered very malleable:**
  - **Cyclone track obviously varies with case. Scales vary too.**
  - **All 3 footprints will not be present over land for all cyclones - there may be only one** →

W C
W C
W
C
(S) C
S C
W (S)
C
W S C
C
C
(W) C
C
W S C
(W) C
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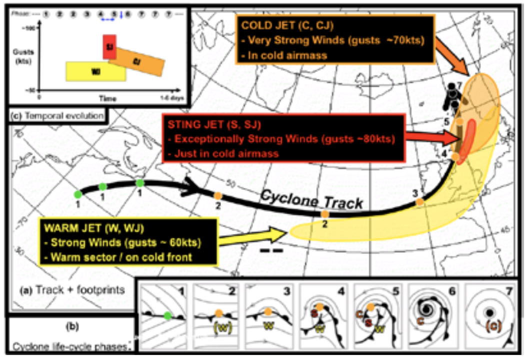
S C
C
W C



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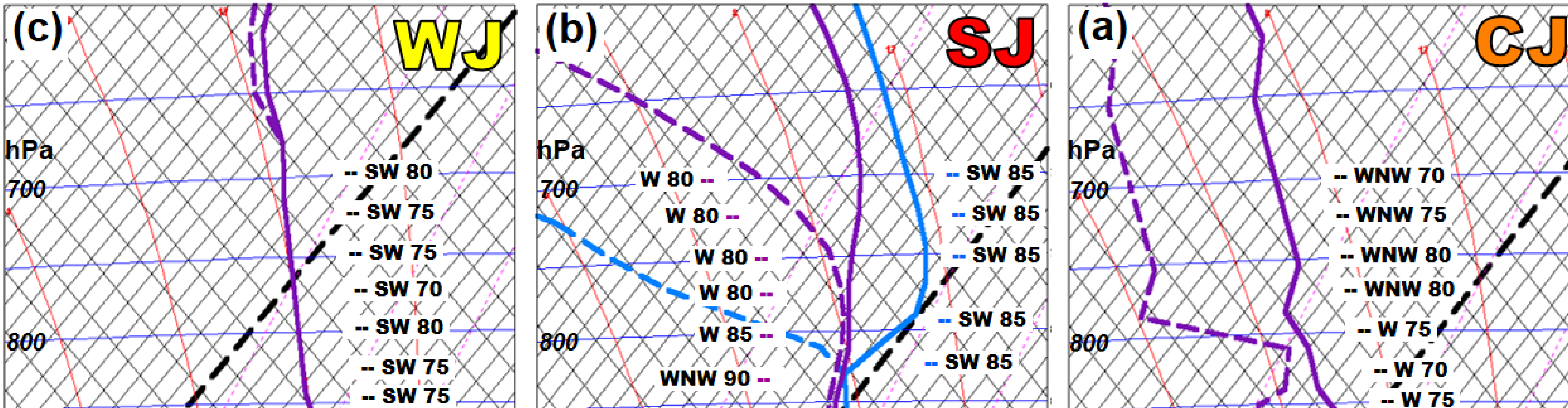
Boundary layer – the Effects of Stability



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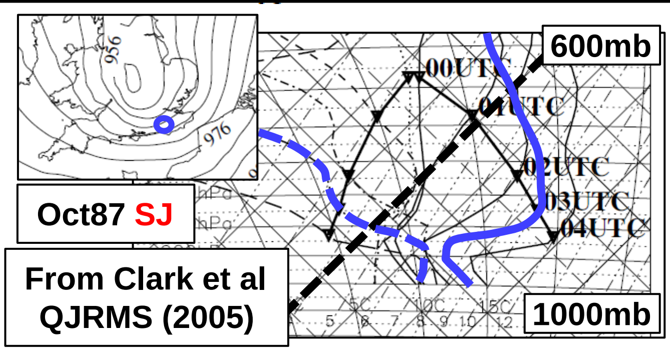
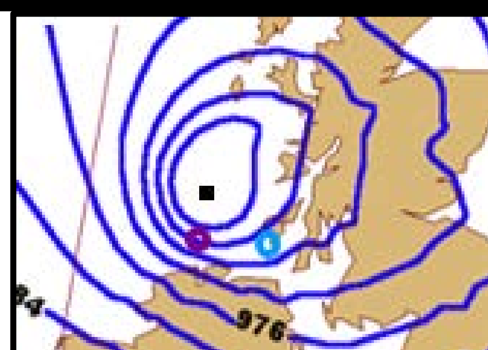
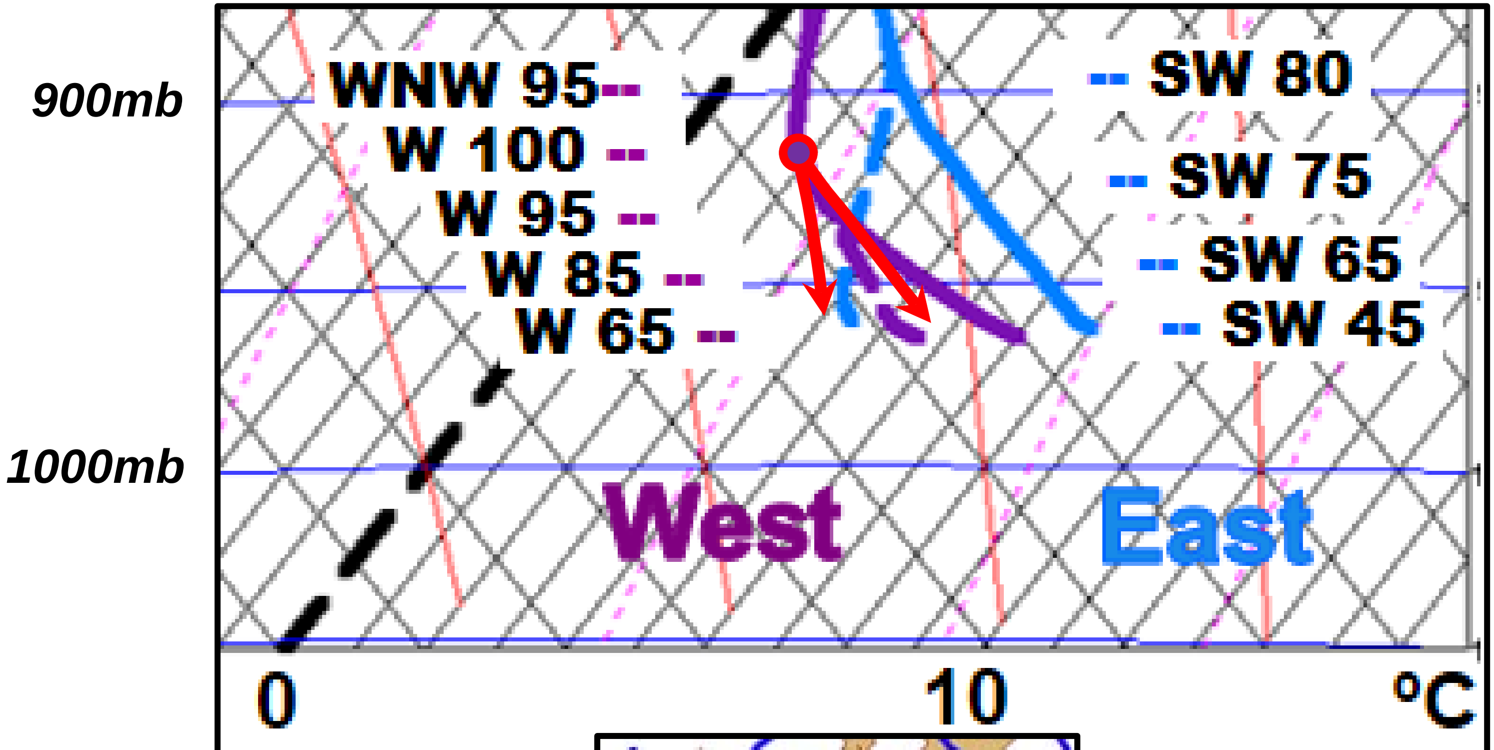
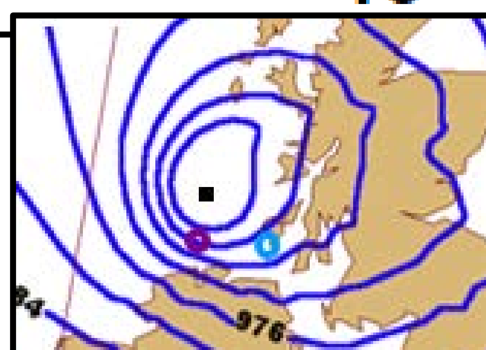




Sting Jet – Downward momentum transfer





ECMWF

“Xola” case - low level jet (at very low levels!)

From Pinto & Silva, 2010 (IPMA report, Portugal)

0447UTC

Cross-section of velocity along filament of cloud head tip

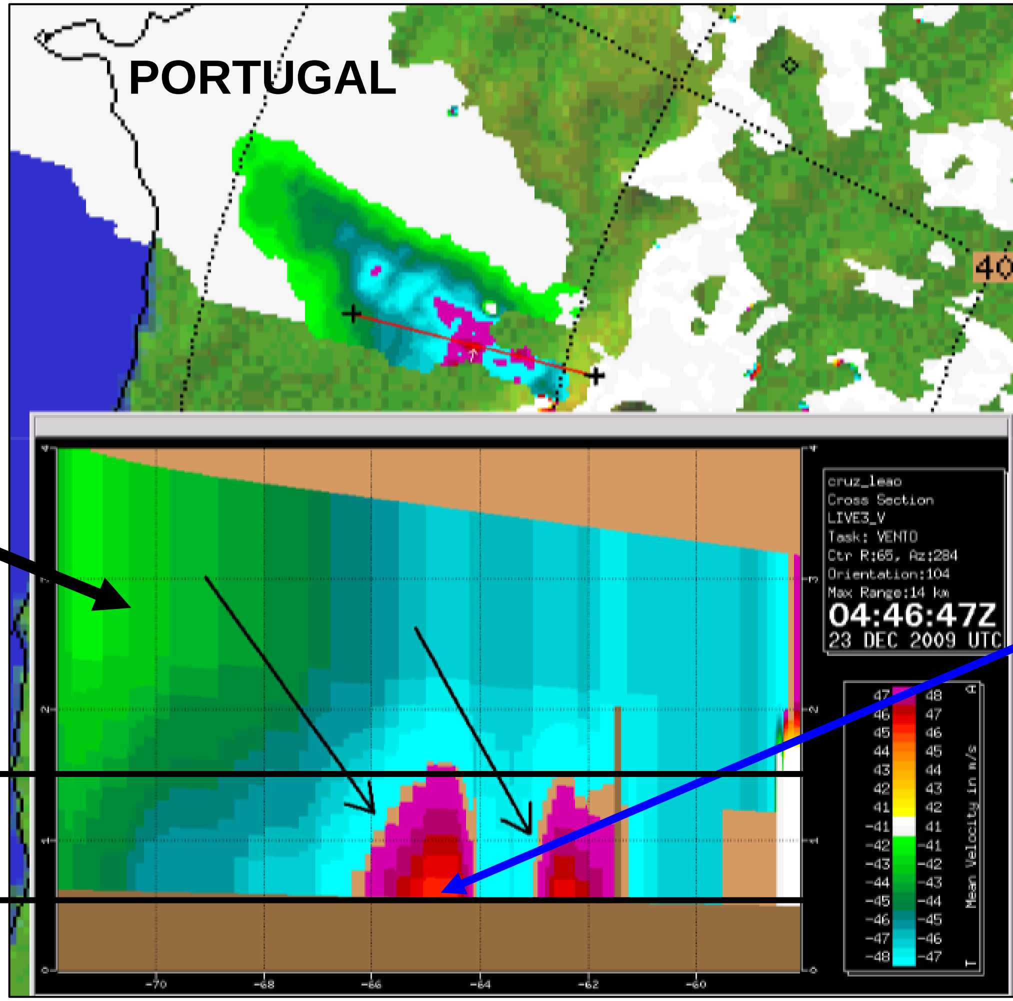
~110kts

~850mb

550m

z

x



Suggests acceleration downwards into boundary layer – 850mb speed not so relevant!

Key Point

- **Buoyancy forces in the sting jet environment promote downward momentum transfer, whereas in the cold jet and warm jet environments default behaviour is for buoyancy forces to inhibit this momentum transfer**
- **So this is a unique feature of the Sting Jet, allowing very strong gusts to be realised at non-exposed inland sites**
- **So sting jets can impart much more damage inland**

How can better understanding improve real time forecasts ?

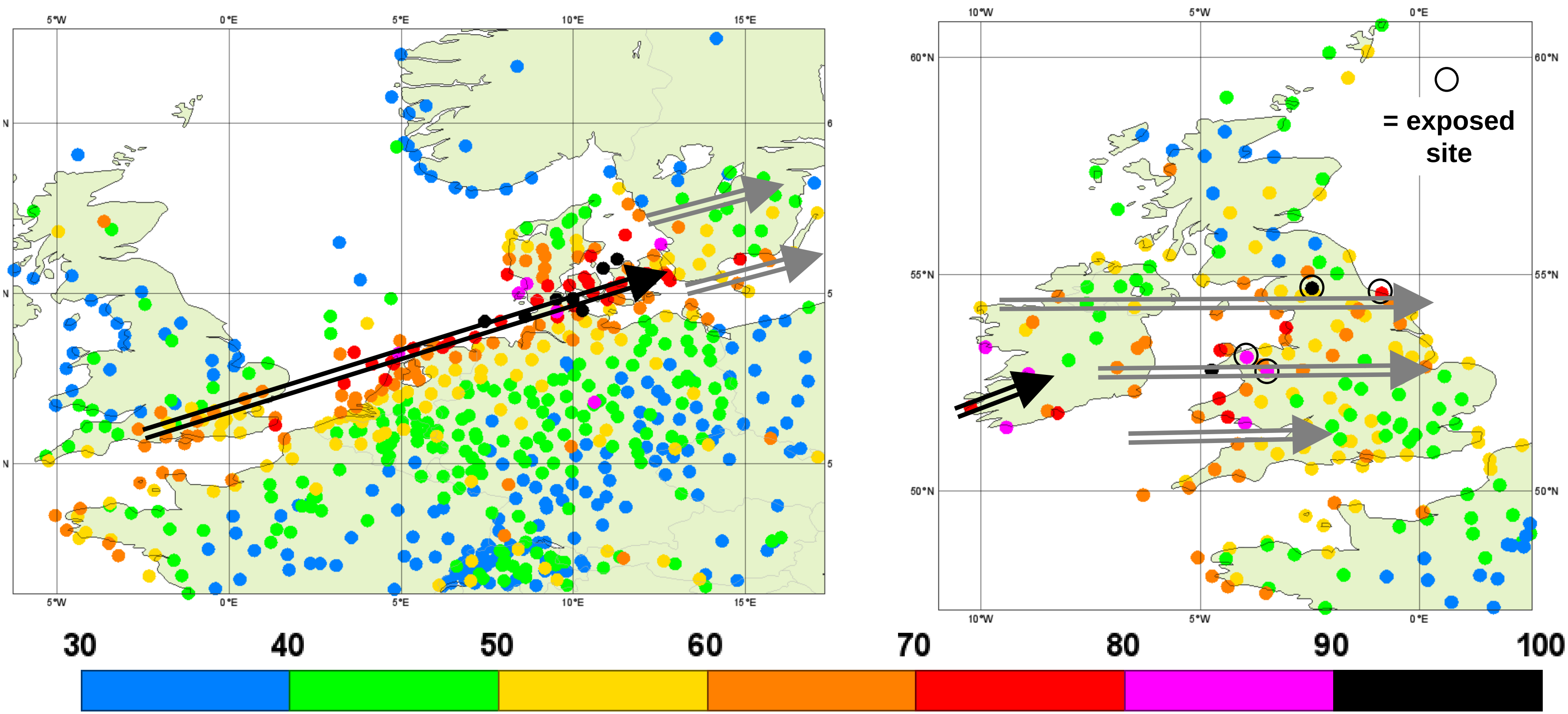
- **Compare:**
  - **Windstorm Christian, 28 Oct 2013 (no sig warnings for Copenhagen)**
  - **EG: Max gust Copenhagen airport: 70 kts**

- **With:**
  - **Windstorm Tini, 12 Feb 2014 (red warning issued for NW England)**
  - **EG: Max gust at Rosthern (Manchester, NW England): 52 kts**

Could use of the conceptual model and related concepts have improved these warnings ?

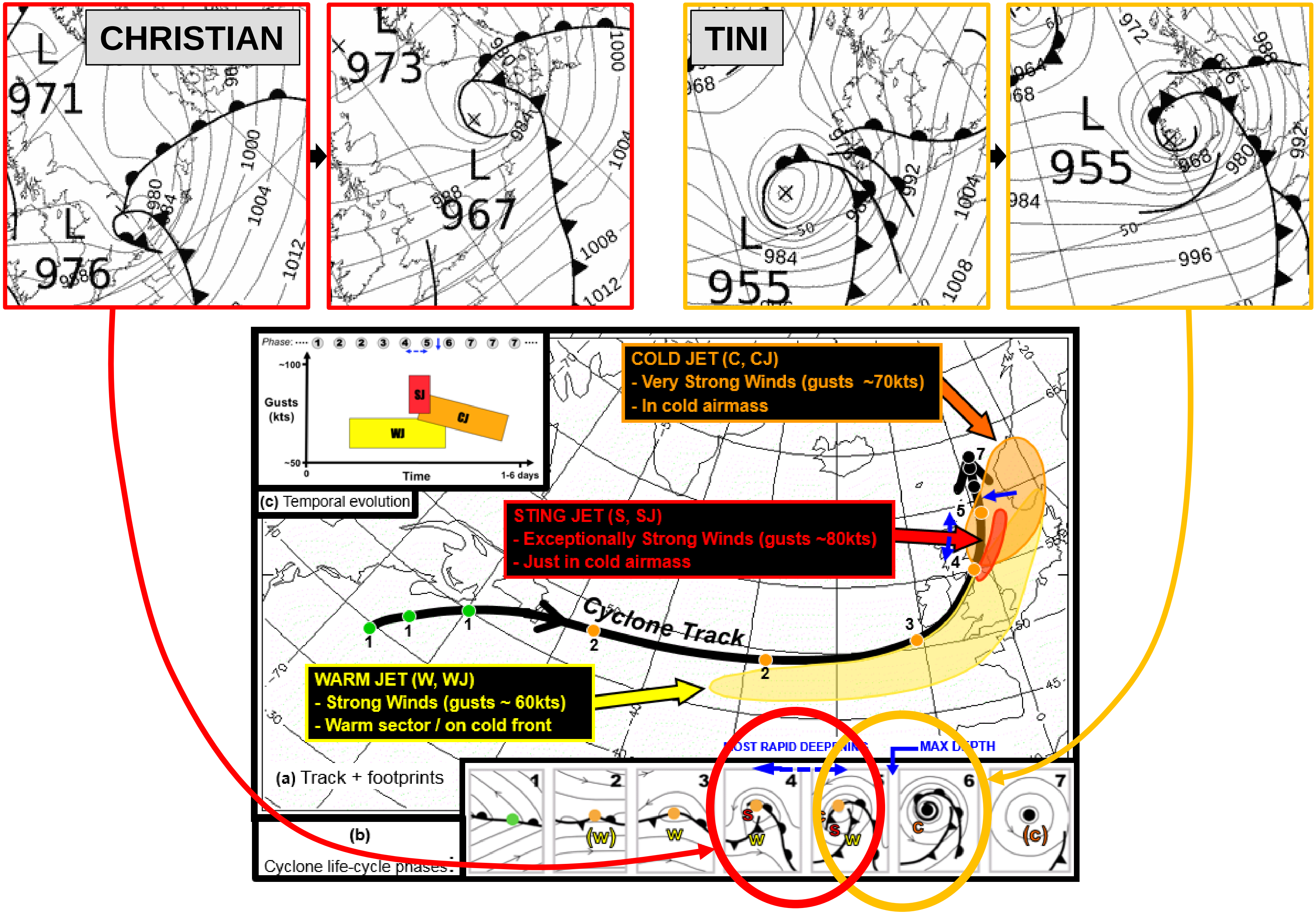
Max Gusts (kts)

SJ → CJ →



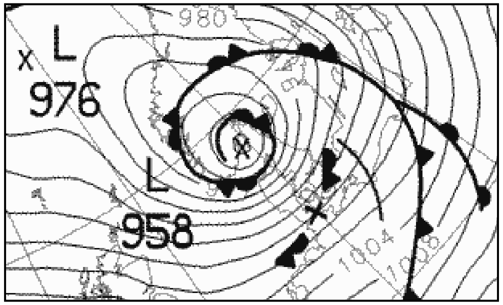
Christian – 28 Oct 2013

Tini – 12 Feb 2014


CHRISTIAN
TINI
COLD JET (C, CJ)
- Very Strong Winds (gusts ~70kts)
- In cold airmass
STING JET (S, SJ)
- Exceptionally Strong Winds (gusts ~80kts)
- Just in cold airmass
WARM JET (W, WJ)
- Strong Winds (gusts ~ 60kts)
- Warm sector / on cold front
Cyclone Track
Phase:
Gusts (kts)
Time
1-6 days
(c) Temporal evolution
(a) Track + footprints
(b)
Cyclone life-cycle phases:
MAX DEPTH

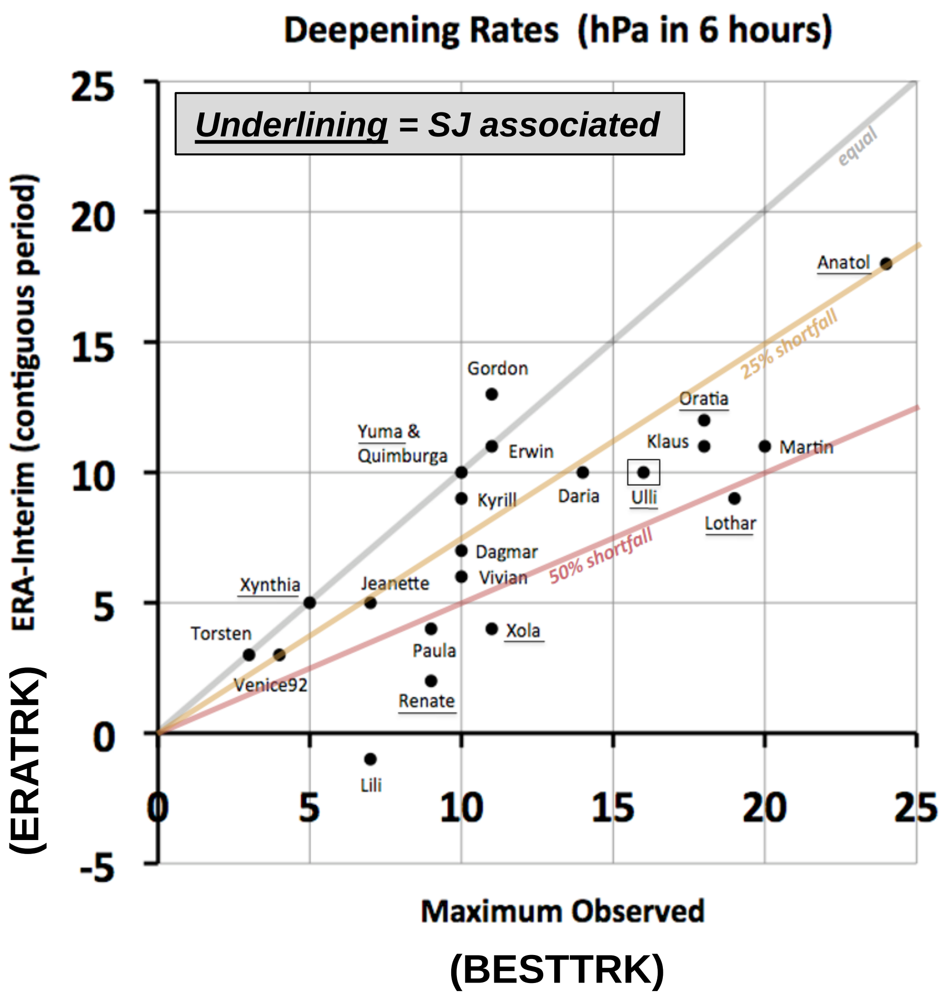
ECMWF

Windstorms in ERA-Interim

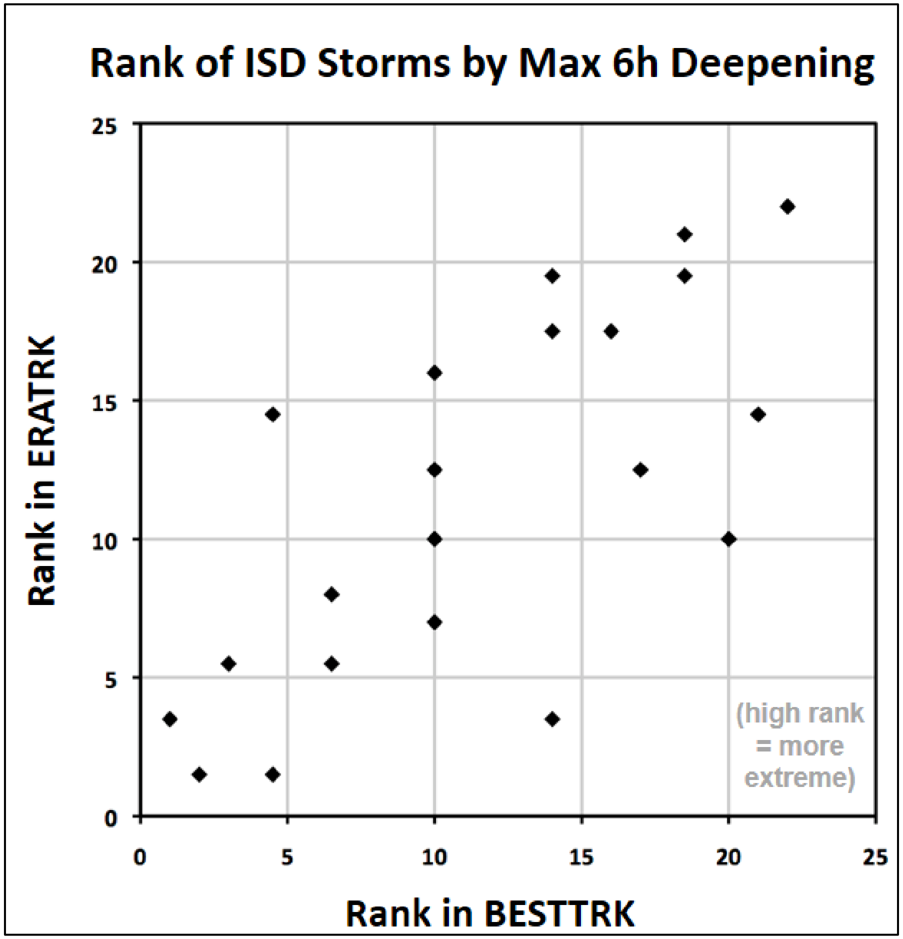


- **ERA-Interim a key input dataset for IMILAST**
- **How well does it represent windstorms?**
- **Use the 22 IMILAST storms to test**
- **Focus on <u>time of most rapid deepening</u>, and the deepening rates represented:**
  - **links to the damaging winds – in SJ phase and early part of CJ phase**
- **To test, we created a BEST-TRACK dataset:**
  - **used Met Office operational analyses, with further manual QC, and DWD equivalents as a consistency check (✓)**
- **And an ERA-TRACK dataset:**
  - **Based on manual tracking of the same cyclones in mslp fields**

Windstorms in ERA-Interim - Results

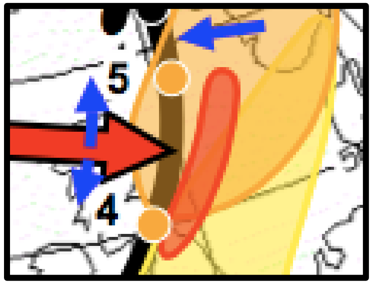


- But do the storms in ERA-I still 'scale' ?

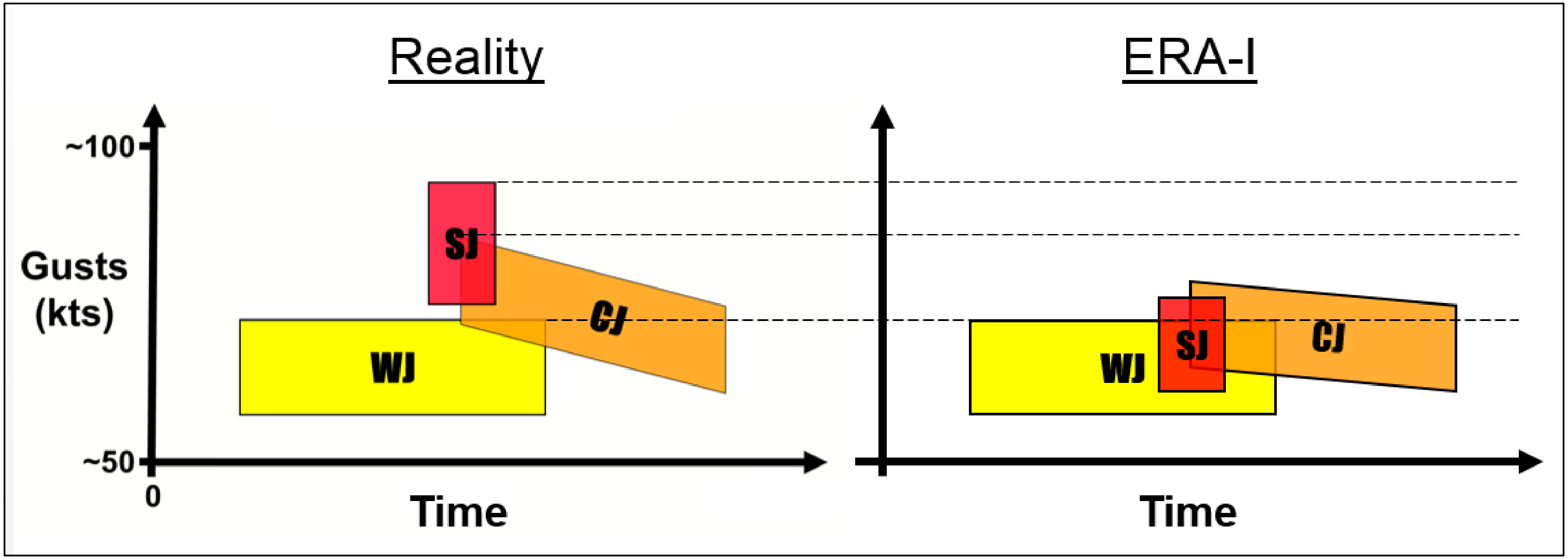


Key Points *(for the IMILAST windstorms)*

- **ERA-I cyclones generally not deep enough**
- **MSLP errors show much variability – 17hPa too shallow in ERA-I for Lothar**
- **Generally errors greatest at the end of period of maximum 6h deepening**
  - **This is when the strongest winds occur**
  - **Commonly also when a sting jet, if there is one, is observed**
  - **So strongest winds, in ERA-Interim (means and gusts), tend to be under-estimated**
- **Mapping true intensity onto ERA-I intensity brings limited success.**
  - **Because storm size matters**
  - **So re-scaling re-analyses & Climate runs has its limitations**



Gust levels for a "medium-sized" cyclone



For smaller cyclones correspondence is worse
For larger cyclones correspondence is better

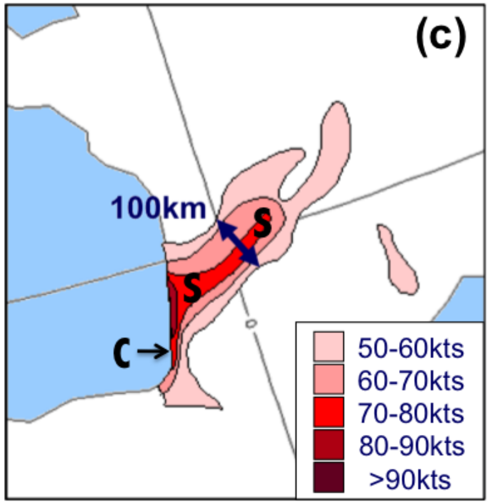
ECMWF

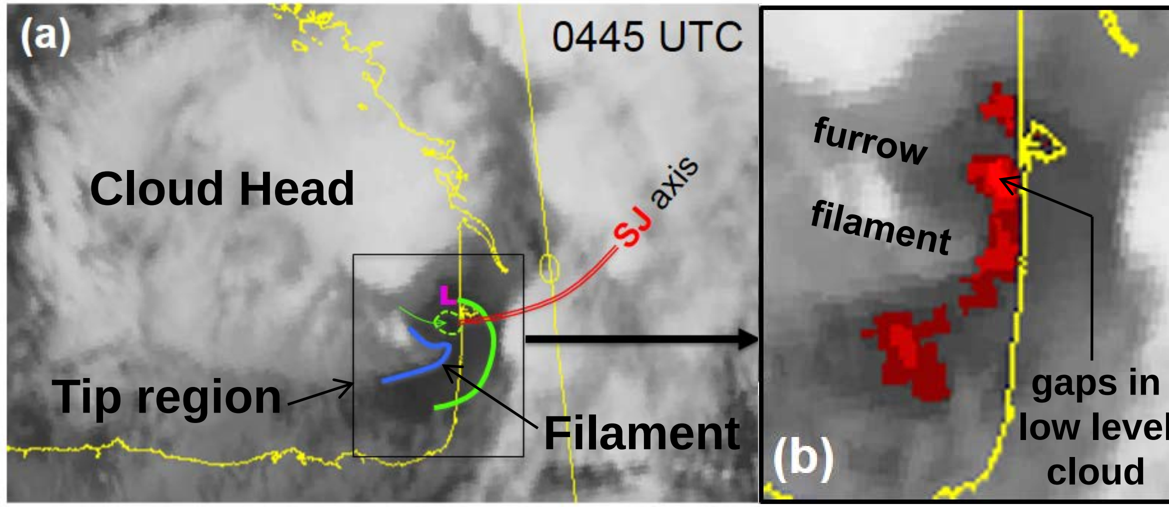
Summary

- 29 windstorms studied in detail using observations
- For discrimination of Sting Jets (SJs) imagery signatures were the main data source used
- Many WJ, SJ and CJ examples were uncovered – a generic conceptual model has been constructed.
- Conceptual Model can help with real time forecasting.
- SJs are particularly damaging for inland sites – buoyancy promotes downward momentum transfer (unlike WJ/CJ)
- ERA-Interim generally underestimates windstorm intensity, mainly because of its resolution – problems most acute for SJs and small systems. Re-scaling is problematic.
- ERA5 to come in 2016? Resolution 32 or 40km. Should be much better than ERA-I, though will still have limitations.
  - Ideally one wants 10-20km horizontal resolution (or better)

Imagery signatures

Windstorm "Renate" – Oct 2006



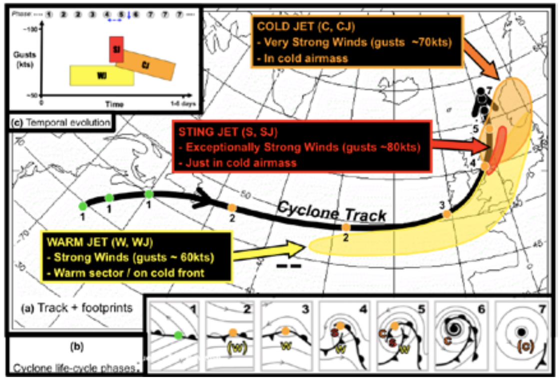


- **Following Browning's study (QJRMS, 2004), we look for**
  - **a) a cloud head with a well-defined tip region**
  - **b) evidence that peak gusts occurred downwind of the tip region**
  - **c) evidence of evaporating cloud filament(s) in the tip region**
- **If these are satisfied a Sting Jet is deemed to be present. If not then the cause is a Cold Jet. But both may co-exist.**

Sting Jet – Some Characteristics

- **Very rare phenomena, many very deep cyclones do not have SJs associated.**
- **Small (intense) cyclones can have SJs associated.**
- **Gust intensity maintained inland (unlike WJ/CJ) because no restoring force to counteract downward momentum transfer**
- **Gusts are maximised downstream of gaps/furrows in the tip of the cloud head**
- **Tends to occur during and just after most rapid deepening**
- **Damage footprint widths in range ~20-200km**
- **Damage footprint length up to ~800km**
- **Duration of phenomena ~1 to 12h**
- **Onset can be extremely rapid – lower tropospheric wind strength can increase by ~10m/s per hour**

Gust Mechanisms



- Key question: **What facilitates downward propagation of momentum, to give strong gusts at the surface (and can model gust parametrisation capture this process well)?**

- WJ **– inhibited by stable airmass; convective activity at cold front or in warm sector can elevate gusts, but gusts usually not that strong**

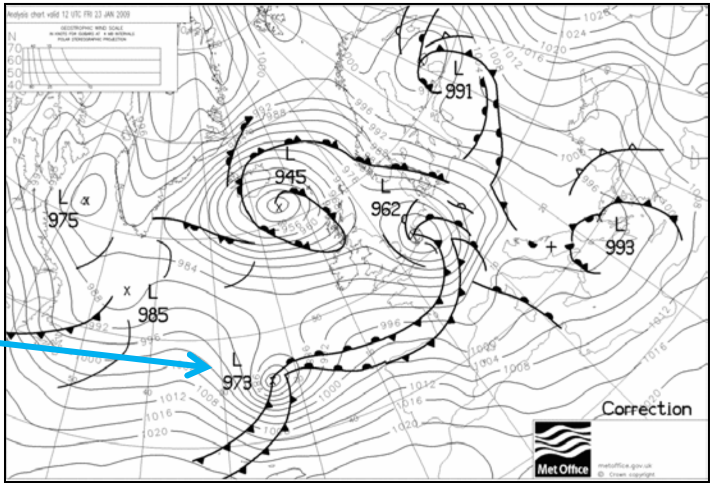
- CJ **– more unstable profiles are typical, especially on coasts in onshore flow (SST triggering). Inland gusts more muted, unless daytime insolation destabilises (uncommon in winter). Swathe typically ~ 100-600 km wide**

- SJ **– believed to be destabilised from above, by evaporative cooling of particulate in region of strongly forced descent, so strong gusts can occur inland as much as on coasts. Swathe typically ~ 20-150km wide.**

Best-Track data

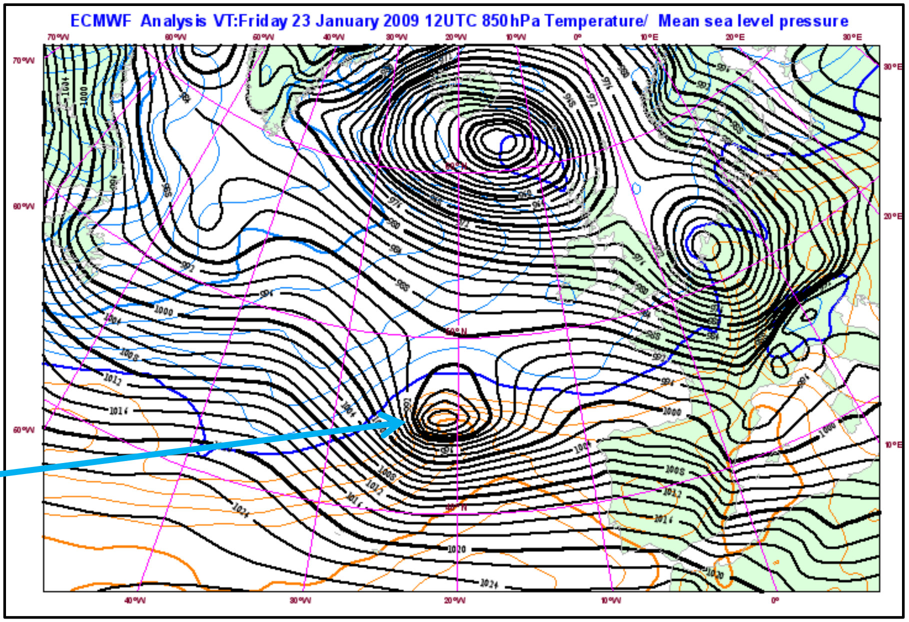
- We enlisted an independent analyst, at the Met Office in Exeter, to construct this dataset (Rob Wilbraham)
- They recorded central pressure, latitude and longitude for all times in each cyclone's life cycle (6-hourly) using
    - Recent past: Met Office surface analyses, with separate reference to surface observations on occasion
    - Older cases: Hand drawn synoptic charts overlaid on observations
- Further QC adjustments involved checking against reports from published case studies, and re-visiting again surface observations where necessary

"Klaus"



ERA-Interim equivalent

- **MSLP (and 850mb temperature) fields were plotted for all times when one of the 22 cyclones was in existence**
- **Position and central pressure of each such cyclone were recorded**
- **Discrepancies in position were generally small (<2 degrees latitude), and so analysis has focussed on comparing central pressure values**
- **Given correspondence between windstorm severity/existence & time of max depth/deepening, in the conceptual model, for intercomparison we focus on these times**

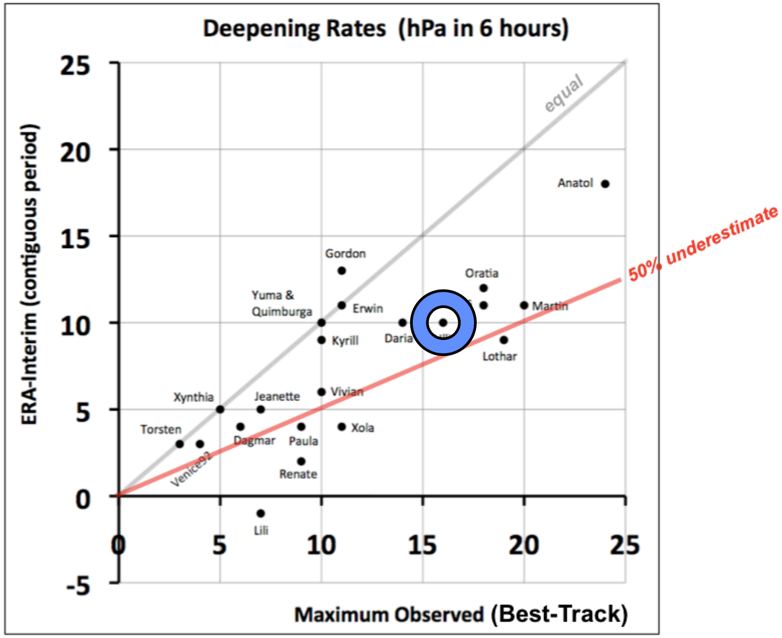


"Klaus"

ECMWF

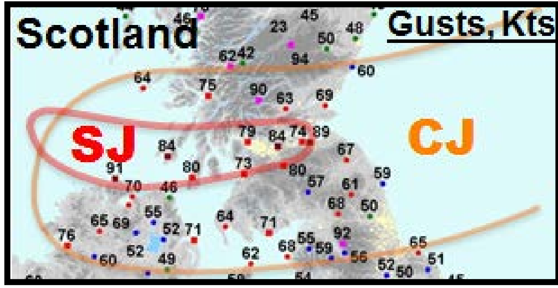
- So what about other models, with different resolution ?

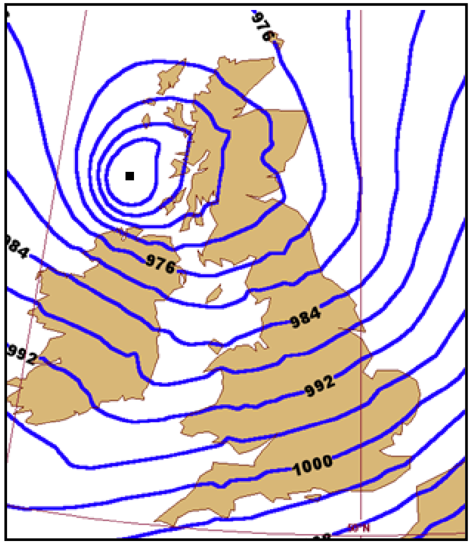
- Use a case study to illustrate…



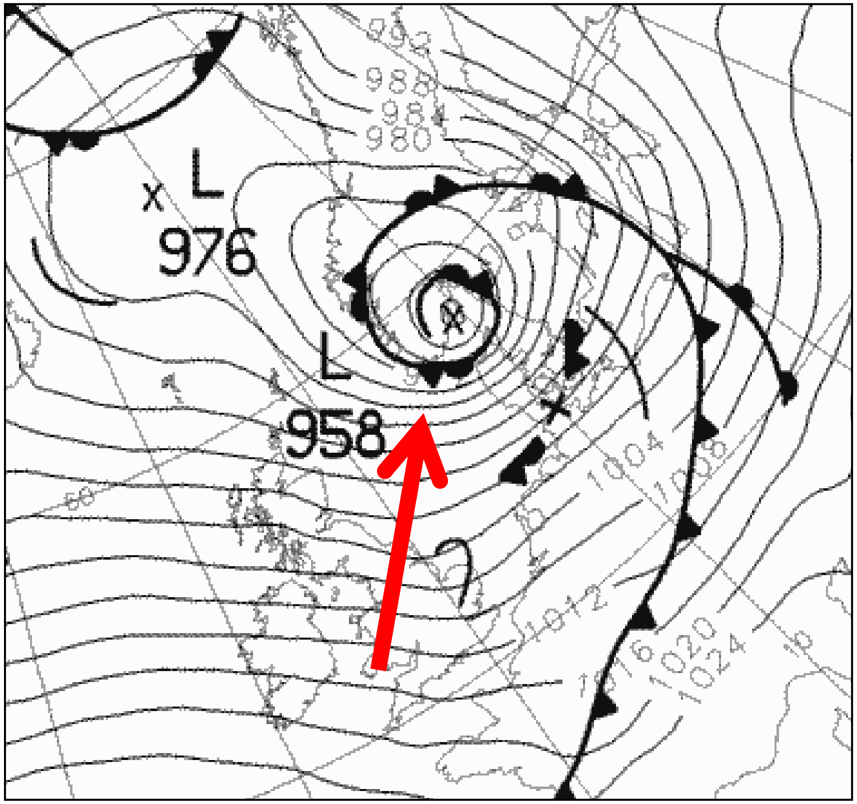
ECMWF

Cyclone Ulli – 3 Jan 2012

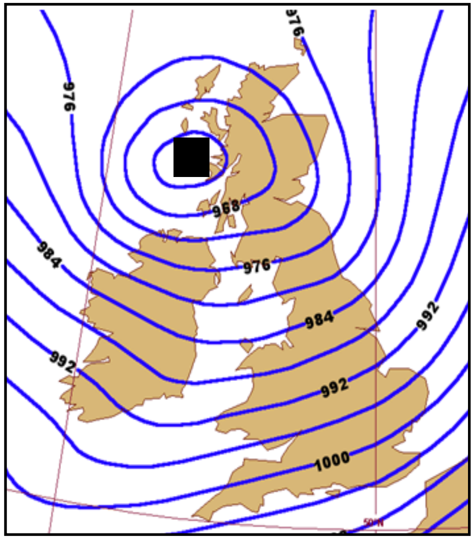




ECMWF (16km) HRES 6h forecast – good representation



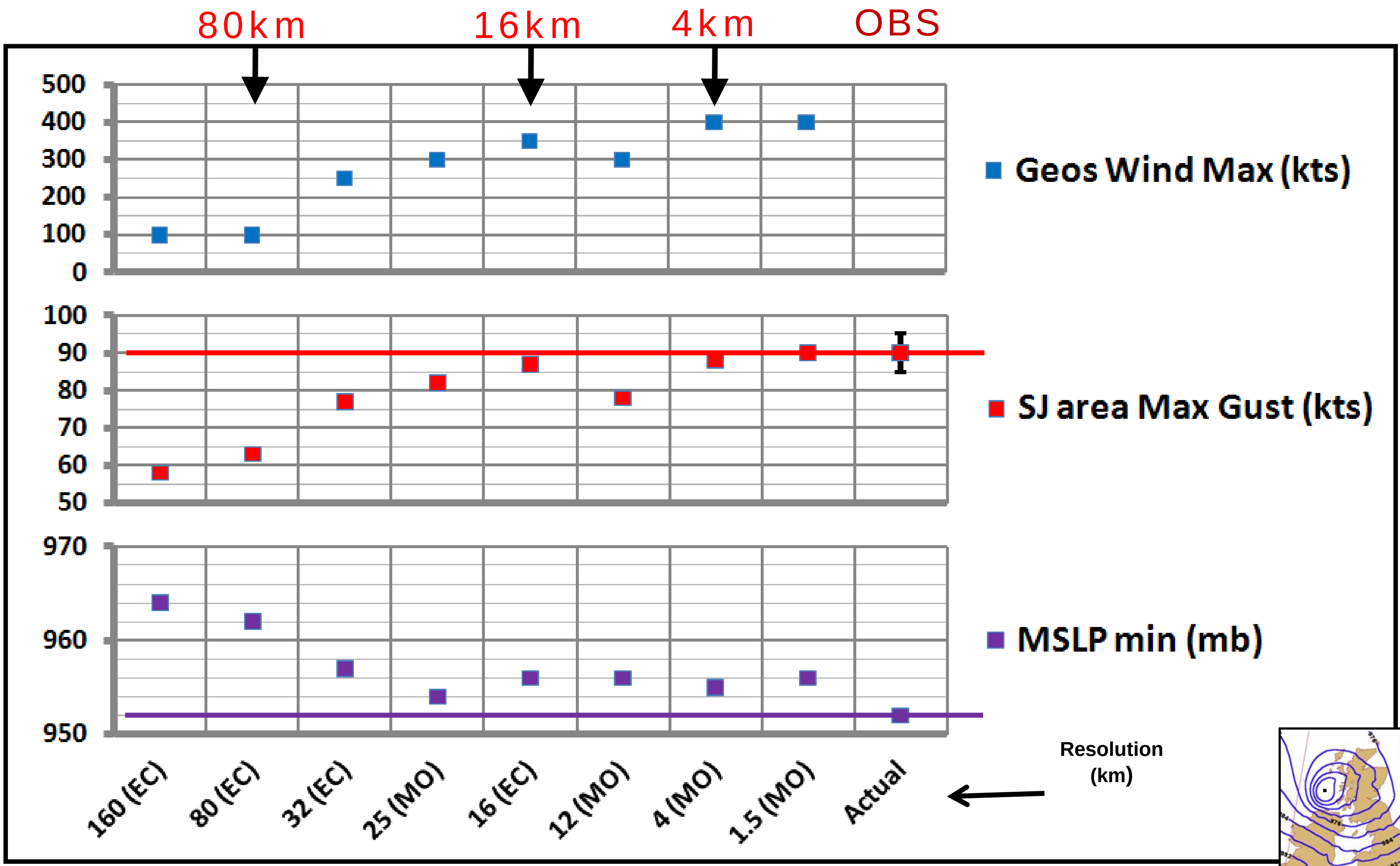
18h later – evidently this was not a particularly small cyclone

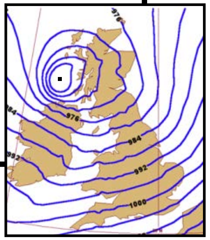


ERA-I (80km) – minimum mslp, gradients, wind gusts all poor

ECMWF

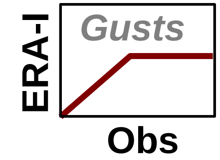
Multiple Models – Ulli – 3 Jan 2012





ECMWF

Implications



- When tracking extreme cyclones, and identifying max winds, we cannot expect model values will match reality – intensity will often be underestimated if model resolution > ~10km
- Especially true for (a) small cyclones, and (b) when a Sting Jet is present
- The problem is resolution – so unreasonable to expect that re-calibration would work in a reliable way, due to saturation
- For global climate simulations extremes will be worse still (RCMs may be better)
- A full appreciation of the nature of windstorms is needed by those using these models, who look at climate trends. Resolution-related uncertainties are very large (and are compounded by innate uncertainty in storm tracks themselves).

Summary

Summary

- A conceptual model built up over many years, using observational data, highlights the morphology of cyclonic windstorms
- 3 different damage swathes can be present, which relate to fronts, deepening and stability. 8 probable sting jet cases identified.
- Best-Track datasets (position and pressure) have been put together for 22 severe European windstorms
- Comparison with (80km) ERA-Interim shows model under-representation of extreme deepening, and the associated very strong winds (e.g. "Sting Jet")
- So blind acceptance of re-analysis and climate model data is dangerous! Ideally we want 10km resolution or better (though even then gust parametrisation can still be problematic).
- "ERA-5", in 1-2 years time (40km resolution or better), will be a significant improvement, but will still be unable to represent well many of the smaller extreme windstorms