Sting Jets and other processes leading to high wind gusts:
wind-storms “Zeus” and “Joachim” compared

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> *“It is very difficult to predict,*
> *especially the future”*
> ***Niels Bohr***

Introduction

On Monday, 6th March 2017, a major wind-storm, named **‘ Zeus’** by the media, hit France. This low system brought absolute record wind gusts. It was one of the most violent that the country had known for years. In Brittany (“Finistère”), the level of the wind speed was unexpected and surprised lots of forecasters on shift at that time. As a consequence, this event gave us the opportunity to better understand the mechanisms that are at the source of highest gusts and in particular, to discuss the concept of the **“Sting Jet”**, raised in association with this type of hazard more and more often in the last few years. This article describes the wind-storms **“Zeus”** (*6/03/2017*) and **“Joachim”** (*16/12/2011*) and **explores the different processes leading to high wind gusts**.

Characterisation of the wind-storms “Zeus” and “Joachim”:

Indicators, given by the Climatology Division of Météo France, allow us to characterize wind-storms and compare them with each other (Tempêtes en France métropolitaine, Météo France, 2017). On an historical level, the previous wind-storm most comparable to “Zeus” was “Joachim”. The comparison of these systems is very instructive. The table below (Table 1) provides a summary.

Both cyclones were the result of a **“Baroclinic Development”**. They both had similar moving speeds (about 80 km/h) and pressure drop rates (above 1 hPa per hour), from 1005 to 990 hPa in 12 hours in the case of **“Zeus”**, and from 995 to 965 hPa in 24 hours in the case of **“Joachim”**. “Explosive cyclone development” is the phrase sometimes used to describe the development of these systems. Nevertheless, **“Zeus” was smaller in size** than **“Joachim”** (which suggests a speeding-up of overall processes involved in this case). An analytical approach (*Santurette and Joly, 2002*) highlights the differences between both (**Figure 1**) when the systems had reached maturity.

“Joachim” is typical of the ***first stage (I) of development of the conceptual cyclone model of Shapiro and Keyser*** (1990) (**Figure 2, a**). The cold and warm fronts are well structured and are of “Ana” type. They join on the inside of the low. This is a “Norwegian” configuration. Note the two branches of the upper jet stream (brown arrows). The cyclone is located on the left exit of the upstream jet streak, and on the right entrance of the downstream jet streak. A dynamic potential vorticity (PV) anomaly (black line) precedes the surface low. The isobars are quite regularly spaced. Note that the model “analysis” (brown lines) is close to the observations.

	“Zeus”	“Joachim”
Maximum gusts at maturity of the systems *phase I*	*190 km/h*, Ouessant-Stiff *193 km/h*, Camaret (absolute record) 06-07 H, 6/03/2017, Western France	*212 km/h*, Puy de Dôme (1415m) *139 km/h*, Clermont-Ferrand 06-08 H, 16/12/2011, Centre France
Other significant gusts *phase II*	*144 km/h*, Chambéry-Aix 14-15 H, 6/03/2017, Eastern France	
Other significant gusts phase *III*	*184 km/h*, Dramont *174 km/h*, St Cézaire sur Siagne (absolute record) 00 H, 7/03/2017, South-eastern France	
Affected Surface (% of the Country)	32%	31%
“Lamb (1991)” Index	595	618
“Storm Severity Index” (SSI)	54	50

▲ *Table 1: Characteristics of the wind-storms.*

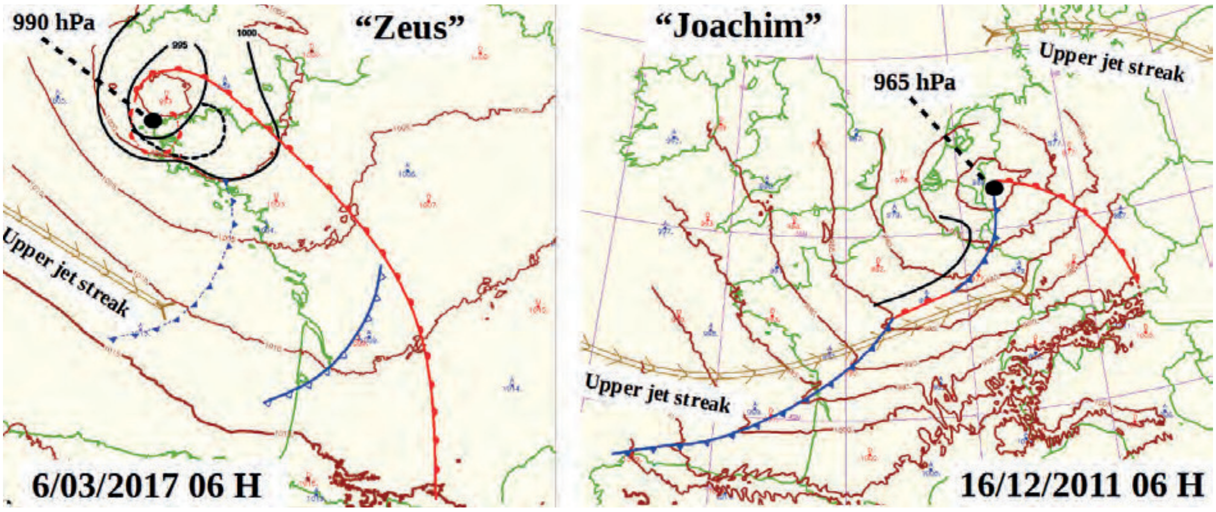
"Zeus" is typical of the ***last stage (IV) of development (Shapiro-Keyser model)***. The warm front partially encircles the low-pressure core (back-bent warm front). The cold front is of "Kata" type. The cyclone is located on the left exit of a single upstream jet streak. A "PV" anomaly overhangs the surface low (black dashed line). **The isobars** (black lines) **are tightened on the "equatorial side" of the low** (manual "analysis"). Note that the model "analysis" (brown lines) is not low enough compared to the observations. Nevertheless the main characteristics of the system seem to be properly modelled. The distinction between the stages of extra-tropical cyclone development (*Shapiro-Keyser model*) is essential because of the consequences on "**Conveyor Belts**" (explained below). Moreover, it is important to notice that, when mature, **"Joachim"** never goes beyond the first stage, but **"Zeus"** comes rapidly, if not directly, to the last stage (but without undergoing the interim stages).

Characterisation of the gusts:

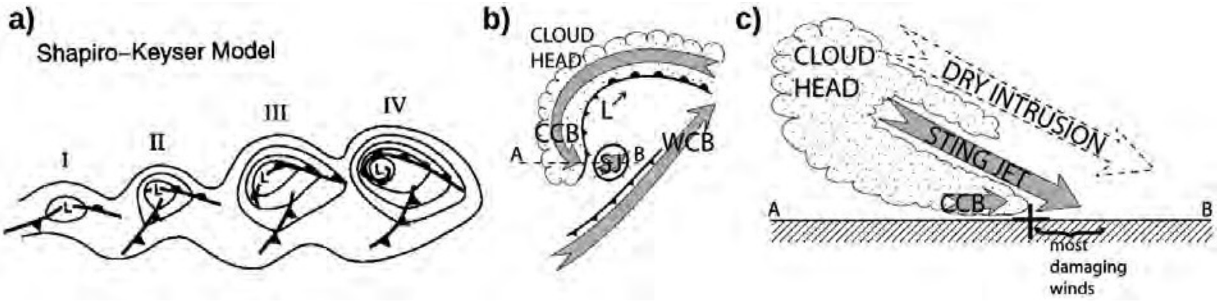
For a few years, the wind gusts predicted by numerical models, have used the parameter **"Turbulence Kinetic Energy"** (TKE). The formula (with ARPEGE/AROME -Météo France-) is close to : $W_{gusts} = W_{mean} + \alpha * \sqrt{TKE}$, α depending on the model. These relevant fields allow us to view the structures of the gusts (**Figure 3, top**).

In the case of **"Joachim"**, the highest gusts were essentially connected to the cold front and were linked to the presence of a strong low level jet (**80** kts) at an altitude of 1500m (vertical cross section **C-D**, bottom). This is the **warm conveyor belt** (WCB) (**Figure 2, b**). In the case of **"Zeus"**, the highest gusts were located on the **equatorial side** of the surface low with a peak very close to the centre of the cyclone, next to the back-bent warm front where the isobars were tightest. These gusts were linked to the presence of a strong low level jet (**90** kts) at an altitude of 1000m (vertical cross section **A-B**, bottom). This speed may have been underestimated by the model in accordance with remark 1. Note how the strongest "isotachs" extend toward the surface with a peak of TKE. These features refer to the concepts of **cold conveyor belt** (CCB) and **sting jet** (SJ) (**Figure 2, b and c**) discussed below.

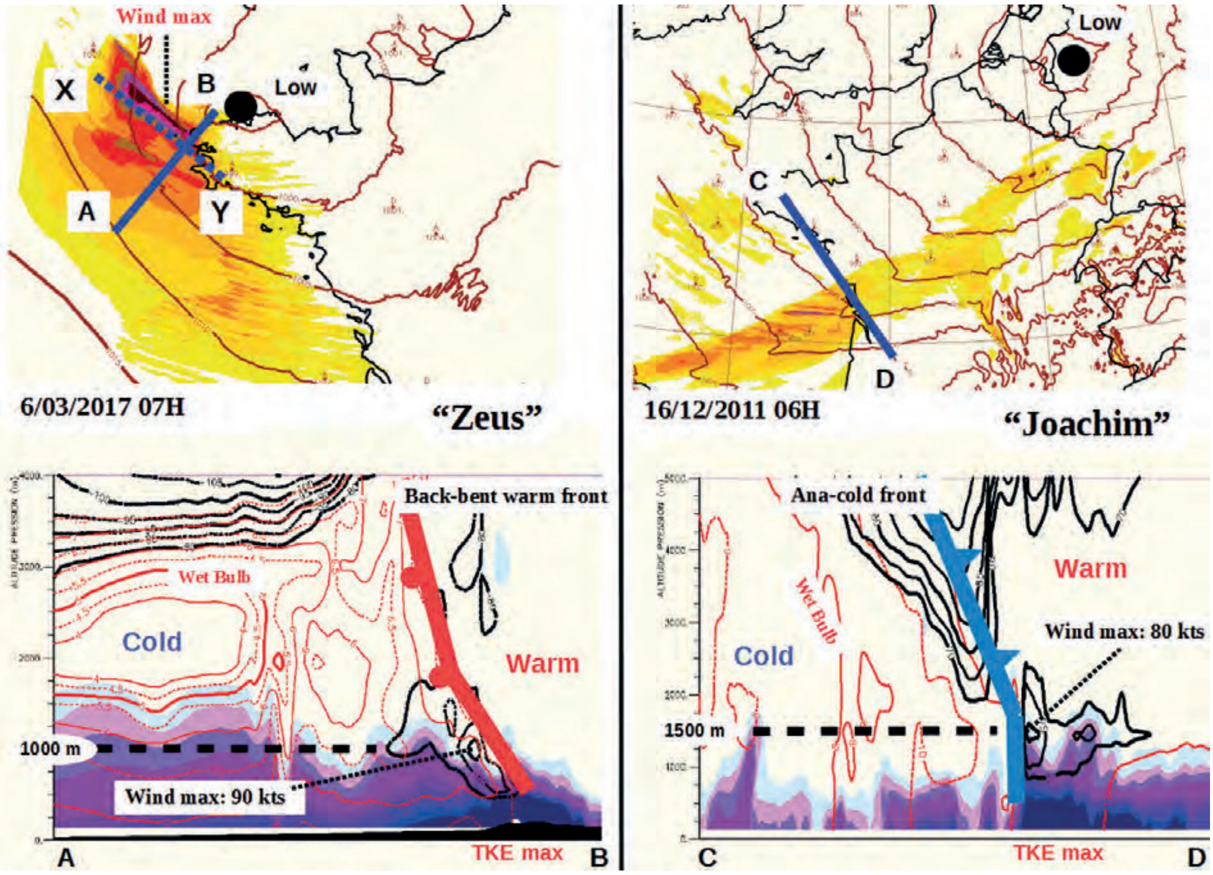
Already note that the geometric configuration of the gusts has consequences on their predictability. For a system like **"Joachim"**, a small forecast error in



▲ *Figure 1: Graphical view (ANASYG) of the wind-storms.*



▲ *Figure 2: Conceptual view of an extra-tropical cyclone. Based on Shapiro and Keyser (1990) and Schultz and Browning (2017).*



▲ *Figure 3: Gusts (threshold 100km/h, shading) and vertical cross-sections associated with the wind-storms.*

position and intensity of the low would lead to a small inaccuracy of wind estimation (almost the same regions would be affected with more or less the same level of wind speed). For a system like **"Zeus"**, a similar small forecast error could lead to missing the level of the highest gusts and the areas affected. There is no doubt that issuing accurate warnings is easier in the first case than in the second...

The Sting Jet in question:

It has been known for a long time that the most damaging winds of an extra-tropical cyclone are often located on the equatorial side of the low (Schultz and Browning, 2017). Some metaphorical expressions used to describe this phenomenon are "poisonous tail" or "the sting at the end of the tail". The concept of the sting jet was introduced by Browning in 2004 (Browning, 2004). The author associates the notion with a slantwise jet, coming from the mid and upper levels and descending toward the surface, leading to damaging gusts (Figure 2, c). Some characteristics of a sting jet can be found with "Zeus". Satellite and radar pictures display special features (Figure 4).

The water vapour image (top left) shows an axis of strong subsidence overhanging the equatorial side of the surface low (marker +) in front of the upper cloud head (marker C) of the system. This dry and subsiding air mass moves along the north side of the upper jet streak and is accompanied by a dynamic PV anomaly (marker A) and the upper cold front (marker B).

The E-View RGB composite image (top right) clearly shows the trace of the thick warm front, on the "polar side" of the surface low (marker +). The winding of low cloud, trace of the back-bent warm front (marker D) in front of the upper cloud head (marker C), on the equatorial side of the surface low distinctly appears. Subsidence, previously mentioned, prevents mid and high cloud development in this region. Finally, note the signature of the kata-cold front near the surface (marker E) and the upper levels (marker B).

The radar images (bottom) show continuous moderate rain associated with the warm front. The ring-shaped echoes mark the surface low. At 06 H, note the occurring of a narrow hook-shaped band of precipitation (marker F) eponymous of a sting jet. Indeed, this observation is concomitant with the highest wind gusts. Afterwards, the cyclone fills as it drifts eastwards over land. As a consequence, and

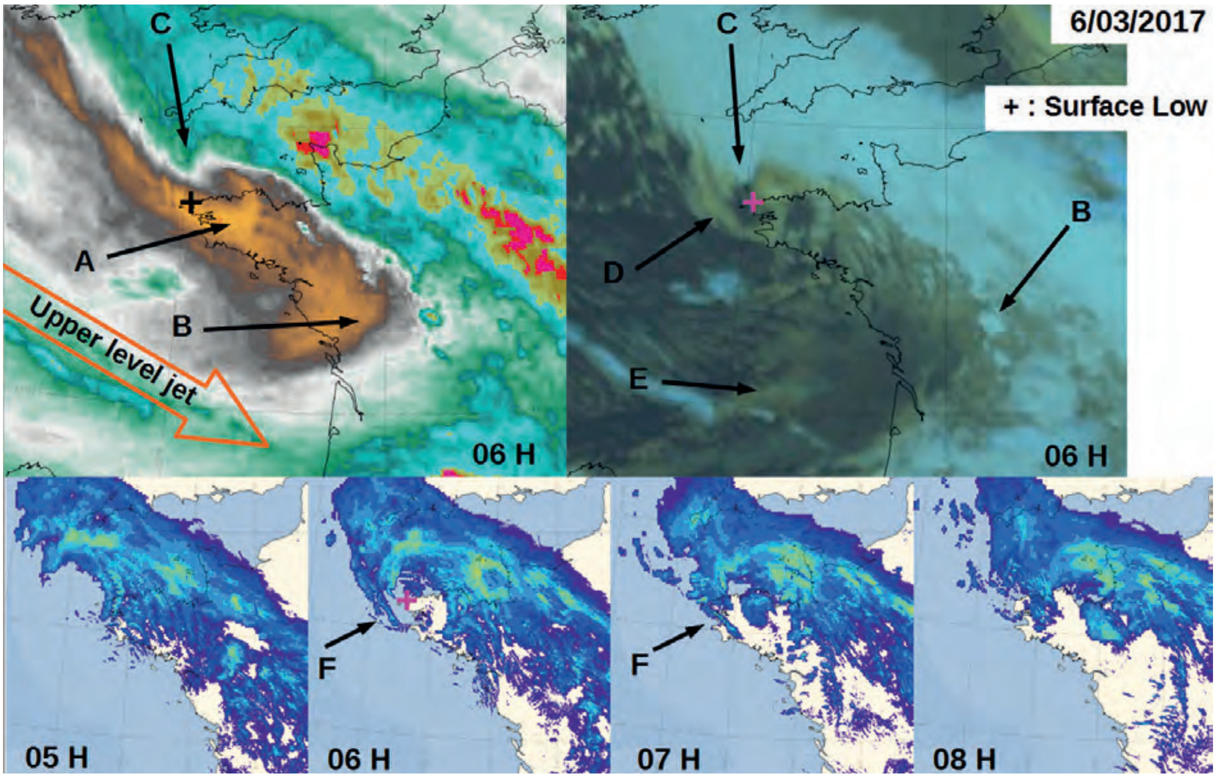


Figure 4: Satellite and radar images of wind-storm **"Zeus"** *at maturity of the system.*

because of increasing friction, gusts tend to decrease and precipitation echoes become unstructured.

The vertical cross-section (**X-Y from figure 3**) along the axis of the highest gusts (**Figure 5**) shows the vertical velocity (blue curves). A slantwise subsidence tends to overhang the low level jet previously identified (**Figure 3**). It is probably the signature of the **sting jet**, but we should point out that verification would require the computation of backward Lagrangian trajectories, in order to know the origin of air parcels in the region of maximum wind (*Coronel, 2016*).

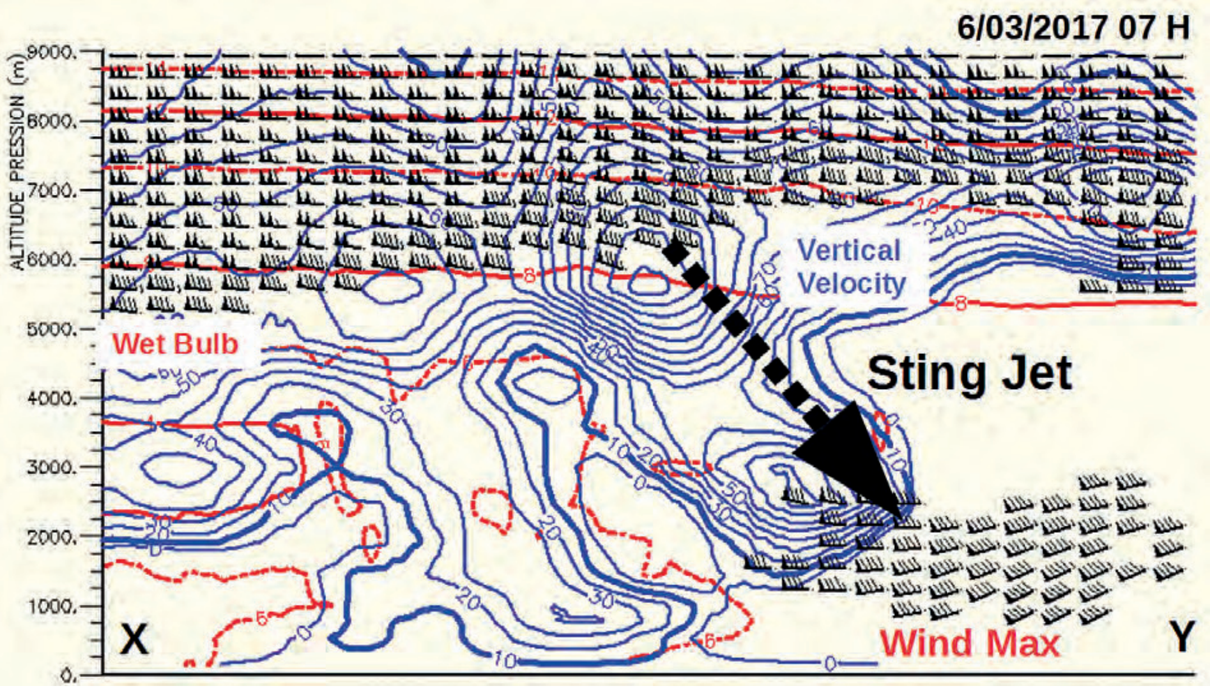


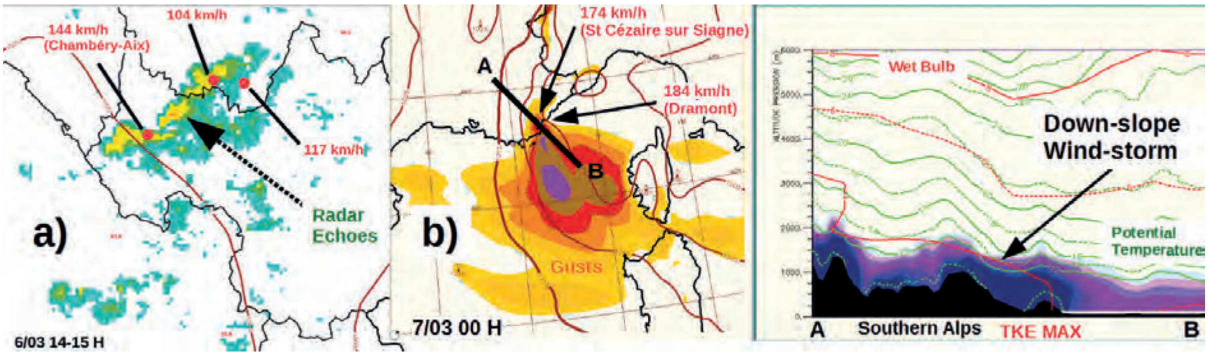
Figure 5: Vertical cross-section, wind-storm **"Zeus"**.

Other processes leading to high wind gusts:

Significant wind gusts can also occur outside the maturity period of a cyclone.

During *phase II* (**Table 1**), **“Zeus”** was weakening. The outstanding value measured in Chambéry-Aix was caused by a stormy episode (**Figure 6, a**). The convective aspect explains the level reached. Gusts associated with thunderstorms can take several forms: down-bursts (micro-bursts, macro-bursts) or even tornadoes. These are generally isolated, so as a result, are particularly hard to forecast. To issue accurate warnings is troublesome.

During *phase III* (table1), **“Zeus”** was moving away towards Mediterranean regions. On the back of the system, a dry subsiding air stream fell into place over the Southern Alps. Mountain waves produced the “down-slope wind-storm” phenomenon with record gusts (**Figure 6, b**). Windward higher-pressure and leeward lower-pressure are well represented by tightened isobars along the relief. Consequently Potential Temperatures (green curves) dive on the lee side. It has to be said that (global and limited area) models have proved successful in predicting this type of event, even if the exact intensity remains difficult to assess. Accurate warnings are generally issued.



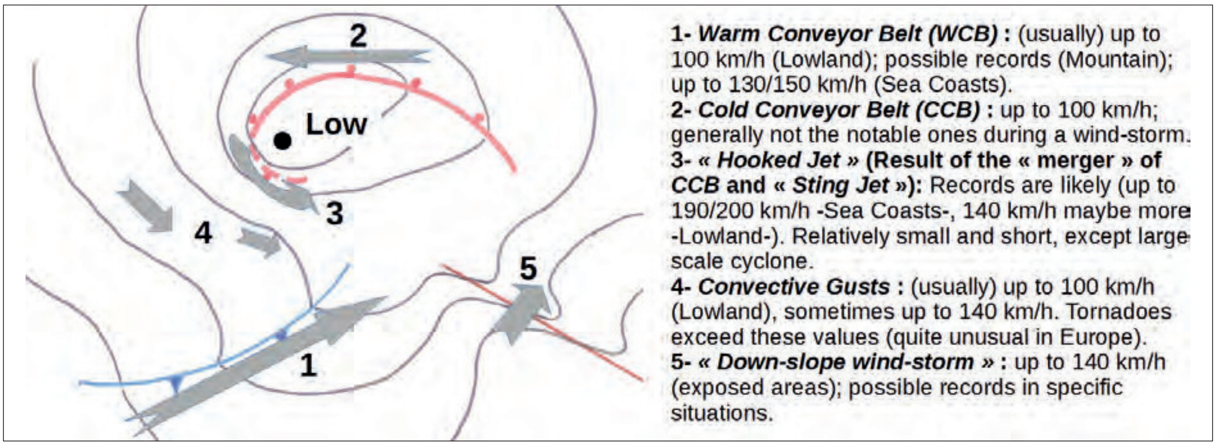
▲ *Figure 6: Gusts during phases II and III of wind-storm* **“Zeus”.**

Conclusion:

The examination of the wind-storms **“Zeus”** and **“Joachim”** has provided an analysis of the main processes leading to high wind gusts in European countries. Indeed, these systems constitute the base form of two families of extra-tropical cyclones: on the one hand, the ones with strengthening winds on the equatorial side of the low (**“Zeus”**), because of the simultaneous presence of the “cold conveyor belt” (CCB) and probably a sting jet (SJ), and, on the other hand, the ones with strengthening winds near the ana-cold front (**“Joachim”**), in conjunction with the “warm conveyor belt” (WCB). Moreover, convective gusts and down-slope wind-storms (mountain waves) can also occur. **Figure 7** gives a summary of these occurrences.

It is important to mention that the use of the term **sting jet** has become quite ambiguous because it refers both to <u>damaging wind gusts (generally) over a small area in a short period of time and a slantwise circulation due to subsidence from mid and upper levels towards low levels</u> (this last definition being selected in this paper, **Figure 5**). Yet, as a recent study (*Coronel*, 2016) suggests: **“The strongest wind gusts do not seem to be connected directly to the sting-jet air streams (in most cases)”**. Indeed, it is the combination of both a cold conveyor belt and a sting jet (increasing momentum within the boundary layer) that leads to the highest gusts. Moreover, concerning the location of the sting jet, it seems that the sting jet takes place above the cold conveyor belt, rather than beyond it. This study says: **“This differs from the 1987 storm studied by Browning (2004) […], for which the sting jet extends beyond the cold-conveyor-belt jet”**. In that respect, diagram (**Figure 2, c**) could be updated and the term ***“Hooked Jet”*** could be used to name this occurrence. In any event, the expression “*Jet d’Occlusion*” (“Occlusion Jet”) which is often used in French to describe that type of hazard should not be used here (as there is no question of an occluded front in this case). Let us remember that the **tightening of the isobars** on the equatorial side of a cyclone at the last stage (*Shapiro-Keyser Model*) next to the back-bent warm front is a potential marker of this type of event.

In an operational context, forecasters have to be attentive to all processes leading to high wind gusts. To be able to identify these processes as



1- ***Warm Conveyor Belt (WCB)* :** (usually) up to 100 km/h (Lowland); possible records (Mountain); up to 130/150 km/h (Sea Coasts).
2- ***Cold Conveyor Belt (CCB)* :** up to 100 km/h; generally not the notable ones during a wind-storm.
3- **« *Hooked Jet* » (Result of the « merger » of *CCB* and « *Sting Jet* »):** Records are likely (up to 190/200 km/h -Sea Coasts-, 140 km/h maybe more -Lowland-). Relatively small and short, except large scale cyclone.
4- ***Convective Gusts* :** (usually) up to 100 km/h (Lowland), sometimes up to 140 km/h. Tornadoes exceed these values (quite unusual in Europe).
5- **« *Down-slope wind-storm* » :** up to 140 km/h (exposed areas); possible records in specific situations.

▲ *Figure 7: Configuration of high wind gusts connected to extra-tropical cyclones. Surface isobars and fronts. Brown line symbolises the relief.*

soon as possible, allows forecasters to better manage their predictability and to better qualify uncertainty. In that sense, Ensemble Prediction Systems (EPS), at large and small scales, are really helpful. Finally, forecasters of the 21st Century experience a new challenge when facing the risk of an extreme weather event: among a set of numerous forecasts, there could be one forecast member, at least, which simulates the "right solution". The purpose is to obtain the greatest possible benefit from numerical models whilst avoiding false alarms.

Note:

All times are UTC.

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