What is a sting jet?

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Windstorms from extratropical cyclones cause over €3.5 billion in losses per year across Europe (Barredo, 2010), and the number is expected to increase under climate change, particularly in central Europe (e.g. Leckebusch and Ulbrich, 2004; Schwierz *et al.*, 2010; Donat *et al.*, 2011). These strong winds have been reported to occur within four principal locations within extratropical cyclones (Clark *et al.*, 2005; Parton *et al.*, 2010; Hewson and Neu, 2015): within the warm sector as part of the warm conveyor belt, around the low centre as part of the cold conveyor belt, descending along the tropopause fold, and at the end of a back-bent front which wraps around the low centre in some cyclonic storms.

This article focuses on the wind maximum located equatorward of the low centre at the end of a back-bent front. As shown in Figure 1, this wind maximum is due to one or both of two jets: the cold-conveyor-belt jet (CJ) and the sting jet (SJ). Such wind maxima are often found (but perhaps not exclusively) in typically marine cyclones that exhibit the evolution of the Shapiro–Keyser cyclone (Shapiro and Keyser, 1990). The back-bent front, or bent-back front, is sometimes referred to as a bent-back occlusion or bent-back warm front. The bent-back front develops as the storm approaches its mature phase as the westward extension of the warm front whose temperature gradient is advected cyclonically around the low centre (e.g. Bjerknes, 1930; Bergeron, 1937; Takayabu, 1986; Neiman and Shapiro, 1993).

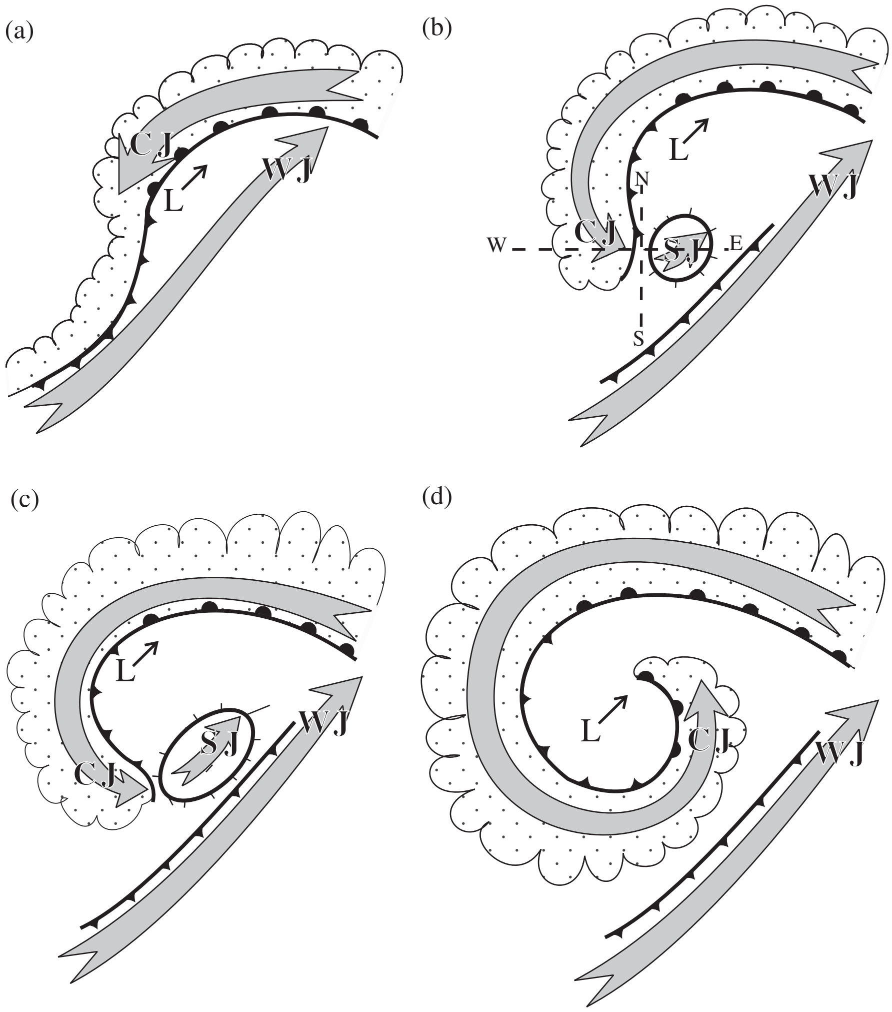

Figure 1. Conceptual model of the near-surface flows in an extratropical cyclone in the Northern Hemisphere. (a) Early stage of frontal-wave cyclone development. L denotes low-pressure centre with direction of movement shown by thin arrow. Grey arrows show the system-relative low-level jets; WJ is the warm-conveyor-belt jet and CJ the cold-conveyor-belt jet. (b) Frontal fracture phase, when the sting jet (SJ) first appears at the surface and the back-bent front forms. (c) As the back-bent front and cloud head wraps around farther the SJ region extends. (d) Eventually the distinct SJ disappears and the dominant low-level wind in this region is due to the CJ. Positions of cross-sections shown in Fig. 18 in Clark et al. (2005) are marked in (b). (Figure and caption adapted from Clark et al. (2005).)

Writing about the wind maximum equatorward of the low centre, Grønås (1995, p. 734) described the forecasting practice of Norwegian meteorologists:

As a young forecaster in the late 1960s, I was informed that the strongest winds ever recorded in our region have been linked to back-bent occlusions. Such a structure has been called 'the poisonous tail' of the back-bent occlusion (after F. Spinnangr, who in 1939 succeeded S. Pettersen [sic.] as head of the Western Norway Forecasting Office).

To pay homage to this early work by the Norwegians, Browning (2004) referred to *the sting at the end of the tail* in association with the most devastating winds from the Great Storm of October 1987. In the last sentence of Browning (2004), he coined the term *Sting Jet* (capitalised in the original) to represent a phenomenon that had not been described previously: a mesoscale wind maximum associated with descent from the mid-troposphere that formed along the bent-back front, close to the tip of the cloud head (e.g. Bottger *et al.*, 1975). Although Grønås (1995) made clear the link between the back-bent front and the wind maximum, he did not indicate that descent was necessary for the wind maximum. In any case, his analysis was based upon a model simulation with 18 levels and 50km horizontal grid spacing, which probably would have been too coarse to resolve Browning's descending sting jet. Thus, we interpret Grønås (1995) to mean that the poisonous tail of the bent-back front implied just a wind maximum; it did not imply anything about its cause or indeed that it would necessarily have been a sting jet as defined by Browning, who coined the term *sting jet* to represent a specific descending airstream responsible for the strongest winds in this region.

Since the term *sting jet* has been introduced, it has been used by a number of researchers (e.g. more than 55 peer-reviewed journal articles cite Browning (2004) as recorded by the Web of Knowledge). It is also frequently used by forecasters (see, for example http://www.bbc.co.uk/weather/feeds/24744462; https://twitter.com/bbcweather/status/681790965170962432; http://www.estofex.org/cgi-bin/polygon/showforecast.cgi?text=yes&fcstfile=2010033106_201003292357_1_stormforecast.xml; and http://www.theweathernetwork.com/news/articles/significant-storm-to-hit-bc-with-heavy-rain-wind-snow/64728) and has even become a term popular in the media (e.g. *Sting jet technology means no more hurricane mishaps for Michael Fish*, http://www.theguardian.com/uk/2012/oct/16/sting-jets-hurricane-michael-fish). As the term *sting jet* has become more popular, there has been an increasing tendency to use the term in circumstances that may not justify it, simply to denote strong winds equatorward of a low centre (e.g. https://www.washingtonpost.com/news/capital-weather-gang/wp/2015/12/14/bering-sea-bomb-cyclone-ties-record-for-strongest-storm-in-north-pacific/).

The fact that not all wind maxima equatorward of the low centre, near the tip of the cloud head, are associated with sting jets has perhaps been missed by some people. Having commonly accepted terminology that everyone agrees with is essential to good scientific communication (Schultz, 2009, pp. 96–97), so inconsistent usage of terminology risks confusion within the meteorological discipline. Thus, the purpose of this article is to outline what is known about wind maxima near the tip of the cloud head in extratropical cyclones and advocate the use of a consistent criterion for applying terminology.

The wind maximum has more than one source

Browning (2004) identified four regions of strong winds in his mesoanalysis of the Great Storm of October 1987, which he labelled A, B, C and D. Regions A and B were associated with convection ahead of the region of strongest winds and are not discussed further here. Region C was composed of the descending air of the sting jet, whereas region D was composed of air associated with the cold conveyor belt, the separate synoptic-scale airstream that travels with relatively little vertical motion underneath the warm and bent-back frontal zones that encircle the low centre (e.g. Carlson, 1980; Browning, 1990; Schultz, 2001). Regions C and D added up to form the single biggest surface wind maximum associated with the Great Storm. In other words, Browning (2004) extended Grønås's concept of a wind maximum near the end of the back-bent front by introducing the term *sting jet* to focus on just a specific part of the more general wind maximum described by Grønås (1995). This point by Browning (2004) has been inadvertently missed by some later readers. The spatial and temporal relationship between the surface manifestation of the sting jet and the low-level jet associated with the cold conveyor belt is shown in Figure 1. Both these jets occur west of the low-level jet associated with the warm conveyor belt.

More recent research has confirmed the previous finding that the maximum of wind speed near the tip of the cloud head of some extratropical cyclones is sometimes composed of two different airstreams (i.e. both a sting jet and a cold conveyor belt), having two separate source regions. Smart and Browning (2014) showed an example during which a sting jet produced a strong surface wind maximum lasting for only a couple of hours before the cold conveyor belt became the source of the strongest surface wind gusts in the cyclone. This result is reminiscent of that by Baker (2009) for another storm. The two airstreams may combine to form what appears to be a single wind maximum at the surface, although detailed analyses can often resolve separate maxima attributable to each source. In a different cyclone, Martínez-Alvarado *et al.* (2014b) again showed the different origins, and also chemical compositions, of these airstreams. No sting jet air originates in the stratosphere, as has been incorrectly portrayed in the literature (see, for example http://news.bbc.co.uk/1/hi/sci/tech/7044050.stm; and https://rgsweather.com/2016/03/29/stormkatie-stingjet-wind-analysis-reigate/; http://www.weathercast.co.uk/weather-news/news/ch/bf9d4d7ab7f0895a46533dcf2d8e543c/article/the_20th_anniversary_of_the_great_storm.html).

Clark *et al.* (2005) showed that some sting-jet air in the Great Storm accelerated from 20 to 50ms^{-1} in 4h while descending from 640 to 870hPa. More recently, sting-jet air was shown to have accelerated from about 5 to over 40ms^{-1} as it descended as much as 200hPa in both an idealised (Slater *et al.*, 2015) and a real extratropical cyclone (Slater *et al.*, 2016). According to Schultz and Sienkiewicz (2013), the descent of the sting jet is due to the decent of air within the bent-back frontal zone undergoing strong frontolysis (Figure 2). However, the frontolysis does not account for the acceleration, which is more likely to be due to the air descending into a region of stronger pressure gradient near the surface as it travels around the low centre (e.g. Slater *et al.*, 2015; 2016). In some cyclones, the descent may be enhanced by the release of conditional symmetric instability (e.g. Gray *et al.*, 2011).

Only a fraction of cyclones has a sting jet. One estimate is that 39–49% of the strongest extratropical cyclones over the North Atlantic have sting jets (Martínez-Alvarado *et al.*, 2012; 2014a). For storms that do, the origins of the descent, and the importance of descent in affecting the strength of the winds at the surface, still elicit much controversy. At first sight, it might be tempting to assume that the importance of descent is in bringing down high momentum from aloft, as suggested by Neiman and Shapiro (1993). As explained below, this assumption might be relevant in transporting momentum through the boundary layer (e.g Vaughan et al., 2014; Browning *et al.*, 2015), but, in the free troposphere, the air that becomes the sting jet starts off with low momentum (Clark *et al.*, 2005; Slater *et al.*, 2015; 2016). The question therefore remains as to the cause of the acceleration of the sting-jet air as it descends within the free troposphere. Although Browning (2004) originally hypothesised that local moist processes are important in the formation of a sting jet, through either evaporative cooling or the release of conditional symmetric instability, later work has shown mixed results. Some researchers have found evidence to support the importance of these localised moist processes to the sting-jet formation and intensity (e.g. Clark *et al.*, 2005; Gray *et al.*, 2011; Martínez-Alvarado *et al.*, 2014b; Browning *et al.*, 2015), but others have described cases in which the importance of moist processes was questionable (e.g. Schultz and Sienkiewicz, 2013; Baker, 2014; Baker *et al.*, 2014; Smart and Browning, 2014; Slater *et al.*, 2015; 2016; Coronel *et al.*, 2016).

Evaporative cooling is believed to be important in sting jets sometimes not so much in accounting for the acceleration of the sting jet as in reducing the static stability. This evaporative cooling facilitates the transport of high momentum associated with an already developed sting jet in the free troposphere down through the boundary layer to the surface (Browning *et al.*, 2015). Another way to weaken the static

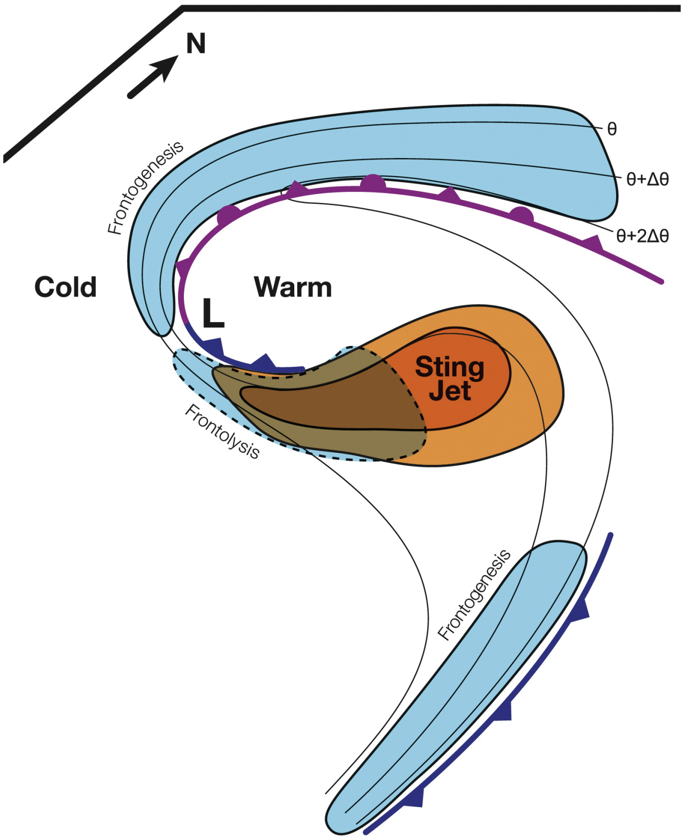

Figure 2. Conceptual model for the location of a sting jet (orange shading) in a Shapiro–Keyser cyclone in the Northern Hemisphere, highlighting regions of lower-tropospheric frontogenesis (blue shading surrounded by solid lines) and frontolysis (blue shading surrounded by dashed lines). Thin lines are lower-tropospheric (e.g. 925hPa) isentropes (θ, θ + Δθ, θ + 2Δθ), frontal symbols are conventional, and L marks the position of the surface low centre. (Figure and caption from Schultz and Sienkiewicz (2013). © American Meteorological Society.)

stability is through surface fluxes of heat and moisture (e.g. Neiman and Shapiro, 1993; Schultz and Sienkiewicz, 2013; Slater *et al.*, 2016). The relative importance of these various processes likely varies from storm to storm. Whatever the cause and importance of the descent, however, *the defining characteristic of the sting jet is its descent.*

Discussion

The term *sting jet* was introduced to emphasise a phenomenon that is different from other established wind maxima in cyclones, *different in kind and not just in degree*. In other words, *the new labels, sting jet and cold conveyor belt jet, represent phenomena that are dominated by different mechanisms.* Those wishing to use the term *sting jet* to describe a wind maximum equatorward of the low centre near the tip of the cloud head at the end of the bent-back front must be sure that the conditions of descent from the midtroposphere are met. We ought to reserve the term *sting jet* specifically for the descending airstream, not for the overall wind maximum equatorward of the low centre more generally, which is what Grønås would have been referring to when he wrote about 'the poisonous tail' of the back-bent front. The overall wind maximum may be composed of air coming from both the descending sting jet and the cold conveyor belt. Sometimes the strongest winds are associated with one and sometimes the other. From their study of many extratropical cyclones, Hewson and Neu (2015) found that the wind maximum from the sting jet, when it occurs, appears earlier in the evolution of the cyclone than that from the cold conveyor belt.

Until the last 15 years, most researchers and forecasters used the old forecasting nugget that the strongest winds in an extratropical cyclone would be where the strongest pressure gradient is (e.g. Brown and Levy, 1986; Neiman and Shapiro, 1993; Steenburgh and Mass, 1996). On the synoptic scale and with the low resolution of surface observations over the ocean, this nugget certainly worked well enough. With today's high-resolution modelling and detailed diagnostic packages that are able to quantify the acceleration terms in the momentum equation along with backward trajectories showing the path of air through the cyclone, researchers have tools at their disposal that enable them to be more precise about the relative importance of physical processes leading to surface wind-speed maxima. In fact, in many different cases, the surface wind maximum is actually *downstream* of the region of maximum pressure gradient, which is consistent with the along-flow pressure gradient accelerating the wind (e.g. Slater *et al.*, 2015).

Although the presence of strong surface divergence is a symptom of a descending sting jet (Smart and Browning, 2014), it is not always possible by viewing horizontal maps alone to know for sure the causes of the wind maximum. There are signals in satellite imagery that may indicate the descent of air in a sting jet, such as a small clearance in the boundary-layer cloud cover just ahead of the tip of the cloud head that wraps around the bent-back front (e.g. Browning and Field, 2004), but definitive evidence of the existence of the sting jet requires trajectories and/or other diagnostics (e.g. Smart and Browning, 2014; Slater *et al.*, 2015; 2016).

The question might be raised as to why the diagnosis of a sting jet matters in practical terms – it matters because the winds in the sting jet, through being characterised by different and perhaps smaller-scale mechanisms, may be more challenging for numerical models to reproduce than the winds in the cold conveyor belt. According to Hewson and Neu (2015), the strongest surface winds encountered in extratropical cyclones tend to be associated with sting jets (although not always; Smart and Browning, 2014), but these are the very situations that are particularly difficult to forecast.

The most egregious and indiscriminate use of the term *sting jet* is by journalists, though meteorologists are not immune from this. One of the authors is reminded of the misuse of the term *supercell* following its introduction in the 1960s (Browning, 1962). A particular type of severe local storm was given the distinct name *supercell* because it differs from ordinary cells not just in degree but also in kind – that is to say, it has a different dynamical structure and involves different processes. Yet, long after the term was introduced, it was common for the term to be used indiscriminately to refer to a convective storm simply because it was very intense. The misuse was accentuated because of the level of popular interest aroused by severe storms. We hope that these lessons can be learned more quickly in the case of the sting jet.

In summary, we ought to reserve the term *sting jet* specifically for the descending air stream, not more generally for the wind maximum near the tip of the cloud head equatorward of the low centre.

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