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1 Sting jets in intense winter North-Atlantic 2 windstorms

3 Oscar Martínez-Alvarado¹, Suzanne L Gray¹, Jennifer L Catto²
4 and Peter A Clark^{1‡}

5 ¹ Joint Centre for Mesoscale Meteorology, Department of Meteorology, University of
6 Reading, UK

7 ² School of Geography and Environmental Science Monash University, VIC 3800,
8 Australia

9 E-mail: o.martinezalvarado@reading.ac.uk

10 **Abstract.** Extratropical cyclones dominate autumn and winter weather over western
11 Europe. The strongest cyclones, often termed windstorms, have a large socio-economic
12 impact due to the strong surface winds and associated storm surges in coastal areas.
13 Here we show that sting jets are a common feature of windstorms; up to a third of the
14 100 most intense North Atlantic winter windstorms over the last two decades satisfy
15 conditions for sting jets. The sting jet is a mesoscale descending airstream that can
16 cause strong near-surface winds in the dry slot of the cyclone, a region not usually
17 associated with strong winds. Despite their localized transient nature these sting jets
18 can cause significant damage, a prominent example being the storm that devastated
19 southeast England on 16 October 1987. We present the first regional climatology of
20 windstorms with sting jets. Previously analysed sting jet cases appear to have been
21 exceptional in their track over northwest Europe rather than in their strength.

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‡ Present address: Departments of Mathematics and Civil, Chemical and Environmental Engineering,
University of Surrey, Guildford, UK

1. Introduction

Worldwide, European windstorms are second only to United States hurricanes as a traded catastrophe risk (Browning 2004). While larger-scale aspects of extratropical cyclones are generally forecast with reasonable skill, the occurrence, location, and severity of the local regions of major wind damage are not. Two regions of strong low-level winds commonly occur during the passage of a cyclone. The warm conveyor belt is a broad region of moderately strong surface winds that exists throughout most of the cyclone's life cycle in the warm sector of the cyclone (to the south of the storm centre in the northern hemisphere). When the cyclone is mature the cold conveyor belt may also produce strong surface winds if it hooks around the cloud head that can be seen curving to the northwest around the storm centre. Additionally, a third localized region of strong winds, and especially strong gusts, which may be short lived (a few hours) can exist close to the 'tail' of the cloud head hook as it wraps around the cyclone centre. This has been dubbed the 'sting at the end of the tail', or 'sting jet', by Browning (2004), terminology similar to that used by Grønås (1995) who referred to a similar feature that he called the 'poisonous tail' of the bent-back occlusion.

Sting jets are defined as accelerating, drying airflows that descend from the cloud head in the mid-troposphere (beneath the dry intrusion) towards the top of the boundary layer while conserving wet-bulb potential temperature. The descent occurs in the frontal fracture region of cyclones that follow the Shapiro–Keyser (Shapiro & Keyser 1990) conceptual model (Browning 2004, Clark et al. 2005). This region is usually relatively clear of cloud and is hence known as the 'dry slot'. Sting-jet momentum can then be transferred from the top of the boundary layer to the surface via boundary-layer processes, such as turbulent mixing, generating strong surface winds and gusts; this momentum transfer may be promoted by the weak moist static stability in the frontal fracture region.

Despite their damage potential the frequency and global distribution of sting-jet cyclones are unknown. The limited published research on sting jets to date almost exclusively consists of analyses of case studies (Browning 2004, Browning & Field 2004, Clark et al. 2005, Martínez-Alvarado et al. 2010, Parton et al. 2009, Baker 2009). The one exception is a climatology of strong mid-tropospheric mesoscale winds observed by the vertically pointing Mesosphere–Stratosphere–Troposphere (MST) radar (Vaughan 2002) located near Aberystwyth, Wales (Parton et al. 2010). Nine potential sting-jet cases were identified in seven years, but this number only represents possible sting jet events passing over Aberystwyth. Their mesoscale nature (~ 150 km across) means that sting jets are not resolved by operational weather forecast models with domains large-enough to cover storm-tracks. Nor are they represented in the even coarser resolution multi-year reanalysis datasets; hence wind climatologies based on these may miss the most damaging parts of windstorms. Furthermore, observational datasets do not provide sufficient temporal resolution over the oceans to allow exhaustive identification of these transient features.

65 To determine the climatological characteristics of sting-jet cyclones we have
66 developed a method to diagnose the precursors of sting jets (rather than the unresolved
67 sting jets themselves) from reanalysis datasets (Martínez-Alvarado et al. 2011). We
68 search for conditional symmetric instability (CSI) in the moist frontal fracture zones
69 of cyclones. The method is applied to the 100 most intense North-Atlantic cyclones
70 during 20 winter seasons (December-January-February, DJF) of the European Centre
71 for Medium-Range Weather Forecasts (ECMWF) reanalysis, ERA-Interim (Simmons
72 et al. 2007). The predicted presence or absence of a sting jet is then verified by
73 performing high-resolution, sting-jet resolving, simulations with the Met Office weather
74 forecast model (Davies et al. 2005) for 15 randomly sampled cases.

75 2. Methods

76 2.1. Reanalysis data and cyclone tracks

77 ERA-Interim is a 6-hourly, global, gridded dataset of the state of the atmosphere
78 consistent with both a numerical model derived from the operational ECMWF
79 forecasting system (IFS Cy31r1/2) and observations via a 12-hour 4D-Var data
80 assimilation cycle. In the horizontal direction the data used has been interpolated
81 from the original T255 spectral resolution onto a regular latitude-longitude grid at the
82 equivalent grid spacing of $0.7^\circ \times 0.7^\circ$. In the vertical direction it was interpolated from
83 the original 60 model levels to pressure levels between 1000 hPa and 300 hPa, with a
84 25-hPa level separation between 1000 hPa and 750 hPa and a 50-hPa level separation
85 elsewhere. Following the work by Catto et al. (2010), an objective feature tracking
86 algorithm (Hodges 1994, Hodges 1995, Hodges 1999, Hoskins & Hodges 2002) has been
87 applied to ERA-Interim. The tracks of the 100 most intense cyclones (with respect
88 to 850-hPa relative vorticity truncated to T42 resolution to emphasize the synoptic
89 scales) over the North Atlantic ocean during the winter seasons (DJF) from 1989/1990
90 to 2008/2009 have been identified.

91 2.2. Diagnostic for sting-jet precursor conditions

92 We applied a diagnostic designed to detect sting-jet precursor conditions in low-
93 resolution datasets (Martínez-Alvarado et al. 2011) to each cyclone from 0000 UTC
94 on the day before to 1800 UTC on the day after the day on which the maximum relative
95 vorticity occurred. The diagnostic for sting-jet precursor conditions (Martínez-Alvarado
96 et al. 2011) detects downdraught CSI as measured by downdraught slantwise convective
97 available potential energy (DSCAPE) in the moist frontal fracture zone. The release
98 of this CSI is a cause of sting jets and DSCAPE is present in cyclones with sting jets
99 but not present in other, equally intense, cyclones that do not have sting jets (Gray
100 et al. 2011). Insufficient model resolution does not prohibit the accumulation of CSI,
101 only its realistic release to generate a sting jet (Martínez-Alvarado et al. 2011).

102 *2.2.1. Definition of DSCAPE* DSCAPE is defined as the potential energy available
 103 to a hypothetical air parcel for descent, while conserving absolute momentum, from a
 104 pressure-level p_{top} to a pressure-level p_{bottom} , assuming that it becomes saturated through
 105 the evaporation of rain or snow falling into it from upper levels (Emanuel 1994). The
 106 pressure-levels p_{top} and p_{bottom} are prescribed: p_{top} is varied from 800 hPa to 450 hPa
 107 and p_{bottom} is kept constant, and equal to 950 hPa. Thus, DSCAPE is computed as

$$108 \quad \text{DSCAPE} = \int_{p_{\text{top}}}^{p_{\text{bottom}}} R_d (T_{v,e} - T_{v,p}) d \ln p, \quad (1)$$

109 where R_d is the dry air gas constant, p is pressure, $T_{v,p}$ is the parcel virtual temperature,
 110 and $T_{v,e}$ is the environmental virtual temperature. The integral in (1) is evaluated along
 111 a surface of constant vector absolute momentum in a similar way to that used for the
 112 calculation of SCAPE (Shutts 1990). The maximum value of DSCAPE (DSCAPE*) and
 113 associated value of p_{top} (p_{top}^*) for a vertical column is used as a representative DSCAPE
 114 value for the underlying grid point.

115 *2.2.2. Thresholds for diagnostic* A minimum threshold for DSCAPE* is imposed but
 116 this is not sufficient to discriminate CSI regions that could generate sting jets. For
 117 example, there are often large amounts of DSCAPE in dry regions such as the cyclone dry
 118 slot; DSCAPE in these regions cannot be released due to the lack of moisture required
 119 to saturate air parcels and trigger their descent. Additional conditions are imposed to
 120 restrict the regions with CSI identified to only those that are cloudy and near a cold
 121 front (and so potentially near a frontal fracture zone). The following recommended
 122 thresholds (Martínez-Alvarado et al. 2011) are imposed on relative humidity, RH, the
 123 magnitude of the gradient of wet-bulb potential temperature, $|\nabla\theta_w|$, and cross-front
 124 θ_w -advection, $\mathbf{V} \cdot \nabla\theta_w$, where \mathbf{V} is the horizontal wind vector:

$$125 \quad \begin{cases} \text{DSCAPE} > 200 \text{ J kg}^{-1}, \\ \text{RH} > 80 \%, \\ |\nabla\theta_w| > 10^{-5} \text{ K m}^{-1}, \\ \mathbf{V} \cdot \nabla\theta_w > 10^{-4} \text{ K s}^{-1}. \end{cases} \quad (2)$$

126 Mean values were used of θ_w and \mathbf{V} over layers of 100 hPa depth centred around p_{top}^*
 127 (vertically delimited by pressure levels above and below p_{top}^*). Maximum values of RH
 128 were used from within those same layers.

129 Further constraints, not included in Martínez-Alvarado et al. (2011), were imposed
 130 on the position, relative to cyclone centres, of precursor regions. Previous studies have
 131 shown that regions from which sting jets originate are typically located within a 300-km
 132 radius from a cyclone's pressure centre (e.g. Gray et al. 2011). In this study, the centre
 133 of a precursor region was required to lie within a radius of 700 km from the pressure-
 134 based cyclone position (in the full-resolution data and associated with the truncated T42
 135 relative vorticity position) in order to be considered as a potential sting-jet precursor;
 136 this encompassed the whole cloud head. Precursor regions entirely in the sector between
 137 300° and 100° relative to the direction of cyclone motion and beyond 250 km from the

138 cyclone centre were discarded as these lay along the warm conveyor belt of the cyclone
139 (CSI release may occur here but it will not lead to sting jets). Figure 1 shows a graphic
140 description of these elements. The cloudy area (cloud head and warm conveyor belt)
141 in that figure was defined by a 550-hPa relative humidity ($RH > 80\%$) composite over
142 every cyclone with CSI and every time instability was exhibited.

143 The size of the precursor region was defined by the number of connected grid
144 columns in which a parcel descending from p_{top}^* satisfies the precursor conditions. To
145 describe the shape and location of the average precursor region the central position
146 of this region for each cyclone was computed in polar coordinates, taking radial and
147 azimuthal position separately, relative to its direction of travel. The maximum upper
148 and maximum lower deviations from the central position were then calculated in both
149 the radial and azimuthal direction. These deviations were averaged over the precursor
150 regions for all cyclones to obtain a representative shape considering possible asymmetries
151 in the shape of the regions. In practice these asymmetries turned out to be small.

152 2.3. Verification of the presence of sting jets

153 In the absence of a suitable observational dataset, verification of the cyclones as having
154 had or not having had a sting jet has been achieved by performing high-resolution,
155 sting-jet resolving, simulations with the Met Office Unified Model (MetUM) (Davies
156 et al. 2005). Fifteen cyclones drawn randomly from the 100 intense cyclones were
157 simulated; the number was limited by computational cost but it is shown to be sufficient
158 to demonstrate skill.

159 2.3.1. Numerical model The MetUM version 7.1 was used to perform the sting-jet
160 resolving cyclone simulations. This is an operational finite-difference model that solves
161 the non-hydrostatic deep-atmosphere dynamical equations with a semi-implicit, semi-
162 Lagrangian integration scheme (Davies et al. 2005). It uses Arakawa C staggering
163 in the horizontal (Arakawa & Lamb 1977) and is terrain following with a hybrid-
164 height vertical coordinate and Charney–Phillips staggering (Charney & Phillips 1953)
165 in the vertical. Parameterization of physical processes includes longwave and shortwave
166 radiation (Edwards & Slingo 1996), boundary layer mixing (Lock et al. 2000), cloud
167 microphysics and large-scale precipitation (Wilson & Ballard 1999), and convection
168 (Gregory & Rowntree 1990).

169 The limited-area domain comprised 720×432 grid points (with a spacing of
170 $0.11^\circ \sim 12$ km), covering nearly all of the North Atlantic, Europe, and North Africa and
171 76 vertical levels (lid around 39 km, mid-tropospheric vertical spacing around 280 m).
172 This vertical spacing yields a vertical to horizontal scale ratio of around 1:40, consistent
173 with the ratio used by Clark et al. (2005) and resolution recommendations to resolve CSI
174 release (Persson & Warner 1991, Persson & Warner 1993). Lateral boundary conditions
175 were produced by running the MetUM in its global configuration. The global model was
176 initialized using global ECMWF operational analyses (ECMWF cited 2010) obtained at

177 a grid spacing of 0.25° and 60 vertical levels. These were interpolated to the global model
 178 resolution with 640×481 grid points (spacing $0.4^\circ \sim 40$ km meridionally) and 50 vertical
 179 levels (lid around 60 km). The limited-area model was initialized by interpolating the
 180 initial conditions produced for the global model.

181 *2.3.2. Detection of sting jets* Sting jets were identified using a three-step method
 182 (Martínez-Alvarado et al. 2010): (a) localisation and clustering of near-surface sting
 183 jet points, (b) backward-trajectory analysis (Wernli & Davies 1997) and (c) analysis of
 184 the evolution of atmospheric variables along trajectories. At the end of their descent
 185 sting jets are here defined as low-level strong, descending winds in a relatively dry
 186 region within the frontal-fracture zone hence meeting the criteria $|\mathbf{V}| > 35 \text{ m s}^{-1}$, $w <$
 187 -0.05 m s^{-1} , $\text{RH} < 80 \%$, and $\theta_{w,\min} < \theta_w < \theta_{w,\max}$ where w is vertical velocity. The
 188 θ_w values delimiting the frontal region, $\theta_{w,\min}$ and $\theta_{w,\max}$, have been set on a case-by-
 189 case basis. Clusters of points satisfying these criteria were identified and backward
 190 trajectories from these clusters computed.

191 Relative humidity, pressure and θ_w were computed along trajectories to determine if
 192 they descended from a cloudy region (i.e. the cloud head) while conserving θ_w . Specific
 193 humidity and θ were computed along trajectories to determine if evaporative cooling
 194 contributed to their descent. Saturated moist potential vorticity (MPV*), absolute
 195 vorticity (as a measure of inertial instability, and defined as $\zeta_a = f + \xi$, where f is the
 196 Coriolis parameter and ξ is relative vorticity) and moist static stability (N_m^2) (Durran
 197 & Klemp 1982) as a measure of gravitational instability of a saturated atmosphere were
 198 computed along trajectories to assess CSI.

199 3. Results

200 3.1. Sting-jet cyclone characteristics

201 The number of cyclones with a sting-jet precursor is dependent on a threshold used
 202 for the minimum size of the precursor region (defined by the number of connected
 203 grid columns in which the diagnostic is satisfied where the area of one grid box is
 204 $\sim 4000 \text{ km}^2$). This was optimized using the cases verified by high-resolution modelling
 205 and the skill of the precursor diagnostic is inferred from 2×2 contingency table (table 1)
 206 relating the presence or absence of a precursor to the presence or absence of a sting jet.
 207 Six of the fifteen cases simulated at high resolution developed trajectories consistent
 208 with the definition of a sting jet. If the minimum size threshold was set to between
 209 five and eight grid columns inclusive then five of the six sting-jet cases had precursor
 210 regions and seven of the nine cases without sting jets did not have precursor regions.
 211 The precursor diagnostic has skill for these size thresholds as this yields a p -value of
 212 0.035 using Fisher's exact test; other size thresholds yield p -values above 0.05 (i.e. the
 213 95% significance level). For minimum size thresholds yielding significant verification
 214 results, between 23 and 32 of the 100 cyclones had sting-jet precursor regions. Analysis

215 is now presented of the maximum possible number of sting jet cyclones, i.e. using a
216 minimum precursor region size of five grid columns.

217 The analysed portions of the cyclone tracks are mapped every six hours for the
218 cyclones with and without sting-jet precursors in figures 2a and b respectively. Sting-jet
219 precursors occurred only once for most of the tracks (69%) though there were tracks
220 with two (16%), three (12%) and five (3%) precursor occurrences possibly suggesting
221 multiple sting jets. The precursor regions occurred throughout the North Atlantic. The
222 analysed tracks follow the classical North Atlantic storm track (Hoskins & Hodges 2002).
223 However, a difference between the start locations of the analysed tracks with and without
224 sting-jet precursors exists: those with sting-jet precursors all originated south of 50°N
225 whereas those without originated as far north as 65°N. This may be indicative of a
226 requirement for a warm moist airmass where these cyclones form, consistent with the
227 known importance of diabatic processes in the generation of sting jets. There is a strong
228 tendency for the sting-jet precursors to occur in the 30 hours prior to the occurrence
229 of the cyclone's maximum intensity (figure 2c). This is consistent with the sting-jet
230 conceptual model in which sting jets occur during frontal fracture in stages II and
231 III of the evolution of cyclones following the Shapiro–Keyser (Shapiro & Keyser 1990)
232 conceptual model (Clark et al. 2005).

233 The frequency distribution of the maximum relative vorticity of all of the 100 most
234 intense North Atlantic cyclones, and just those with sting-jet precursors, shows that
235 there are fewer cyclones with increasing vorticity as expected (figure 3a, note that the
236 first vorticity bin contains relatively few cyclones because other cyclones with vorticity in
237 this range are not among the 100 most intense). Sting-jet precursors occur in cyclones
238 throughout the vorticity range. The 100 most intense cyclones are relatively evenly
239 distributed over the 20 winter seasons (figure 3b) with between 2 and 10 of these cyclones
240 occurring in each season; between 0 and 3 of these cyclones have sting-jet precursors
241 each year. Recent studies have found contradictory results regarding long-term trends
242 in the frequency and intensity of extreme cyclones in the second half of the 20th century
243 (e.g. Ulbrich et al. 2009). Statistically significant trends cannot be inferred from the
244 limited data presented here; however, we note that the three winter seasons in which
245 there were no sting-jet cyclones all occurred during the last six seasons analysed.

246 The locations of sting-jet precursors are shown in a system-relative reference frame
247 in figure 4a. Each precursor region has been rotated such that the direction of motion of
248 the cyclone is orientated to the right. The dots represent the locations of the gridpoints
249 within every precursor region relative to the corresponding cyclone centre. There are
250 gridpoints in areas apparently restricted (warm conveyor belt area in figure 1). However,
251 these gridpoints belong to precursor regions lying at least partly within the permitted
252 area (cloud head area in figure 1). The gridpoints span the space to the west of the
253 cyclone centre where the cloud head lies (*cf.* figures 10b and d of Catto et al. (2010)
254 which show relative humidity from composite cyclones). The average precursor region
255 (computed following the method described in section 2.2.2) lies between 279 km and
256 536 km radially (mean at 400 km) and 154° and 223° azimuthally (mean at 186°).

257 This region is shaded in figure 4a and yields an area of $126 \times 10^3 \text{ km}^2$. The precursor
258 location is consistent with the origin locations of sting jets in previous studies (Gray
259 et al. 2011, Martínez-Alvarado et al. 2011) (although these regions are all within 300 km
260 of the cyclone centre in these studies) and with the bands of updraught CSI found in
261 the cloud head of the sting-jet windstorm Jeanette (Parton et al. 2009).

262 The maximum energy available to the descending sting jet through the release
263 of CSI, measured by maximum downdraught slantwise convective available potential
264 energy in an atmospheric column (DSCAPE*), ranges from the minimum threshold
265 considered (200 J kg^{-1}) to 900 J kg^{-1} with a mode of $300\text{--}350 \text{ J kg}^{-1}$ (figure 4b). The
266 pressure level from which the descending jet has this maximum energy (p_{top}^*) is typically
267 above 650 hPa (90% of cases) with many cases at 450 hPa, which constitutes the lowest
268 pressure considered (figure 4b). These results imply that the identification of sting-jet
269 precursor regions is sensitive to these thresholds for energy and pressure and that a
270 definitive sting-jet precursor cannot be defined.

271 3.2. Sting jet characteristics

272 The characteristics of sting jets found by applying trajectory analysis to the high-
273 resolution model output are now described. The evolution of pressure, relative
274 humidity and saturated moist potential vorticity (MPV*) along one ensemble of sting-
275 jet trajectories from each cyclone are shown in figure 5. More than one ensemble of
276 trajectories satisfying the criteria for a sting jet was found in some cyclones, those
277 illustrated are chosen because they descend for similar periods and have comparable
278 ensemble sizes. The trajectories are plotted over the 10 hours prior to the time at which
279 they reach their lowest level in the atmosphere; the vertical lines mark the onset of
280 the sting-jet descent from the mid-troposphere towards the top of the boundary layer
281 (the transport of momentum from here to the surface by parameterized processes in
282 the model cannot be diagnosed from trajectories calculated using the model-resolved
283 winds). The one false-negative case (for which a sting-jet precursor was not identified)
284 was the cyclone of 12 December 1994 (bottom row in figure 5). The ensemble-mean
285 trajectory descent rate ranges from $\omega = 0.4$ to 0.9 Pa s^{-1} which compares well to
286 previous studies ($0.5, 0.8,$ and 1.3 Pa s^{-1} for windstorms Gudrun and Anna and the
287 Great October storm respectively (Gray et al. 2011)). However, the true-positive cases
288 achieve this descent rate for a minimum of 5 hr compared to just 2 hr for the false-
289 negative case. The false-negative case is also distinct in that it remains at low-levels
290 throughout its development (below the 700 hPa level). The transition from cloudy air
291 to dry air after the onset of descent is shown in the decrease in relative humidity for all
292 cases. The ensemble-mean horizontal wind speed at the end of the trajectories ranges
293 from 36 to 43 m s^{-1} (not shown) which also compares well to previous studies ($42, 35\text{--}37$
294 (values from two different models), and 48 m s^{-1} for windstorms Gudrun (Baker 2011),
295 Anna (Martínez-Alvarado et al. 2010) and the Great October storm (Clark et al. 2005)
296 respectively).

297 The existence of negative MPV*, but static and inertial stability, along a moist
298 descending trajectory implies that CSI is being released. Each sting jet has at least
299 some trajectories satisfying these criteria and, in all but the case of 26 December 1998,
300 the mean MPV* is close to zero throughout almost all of the period shown (figure 5c);
301 almost all ensemble members were statically and inertially stable (not shown). Further
302 analysis of the case of 26 December 1998 revealed that the low-level strong winds in
303 the frontal fracture region were the result of two different airstreams merging together
304 at upper levels. The first stream approached the cyclone centre from the south-west
305 at upper levels and had negative MPV*; this was the sting jet. The second stream
306 was a frontal circulation rising cyclonically around the cyclone centre and had partially
307 negative MPV* at lower levels that became positive as it ascended; this stream could
308 be releasing CSI as it ascends in the frontal circulation. As the streams met, MPV*
309 became negative in some of the upper-level trajectory parcels, while lower-level ones
310 experienced an increase in the value of MPV*. This merging of different airstreams
311 has been observed previously in a sting jet storm (windstorm Anna (Martínez-Alvarado
312 et al. 2010)) suggesting it could be a common occurrence. In windstorm Anna the sting
313 jet was of similar size (defined by the number of trajectories) to the frontal circulation,
314 whereas in the 26 December 1998 case the sting jet was much smaller than the frontal
315 circulation.

316 4. Discussion and conclusions

317 The first regional climatology of sting-jet cyclones has been produced by applying a
318 recently developed method for diagnosing sting-jet precursor regions in models incapable
319 of resolving the sting jets themselves. The method has been applied to the 100 most
320 intense extratropical cyclones that occurred in winter in the North Atlantic region
321 between 1989 and 2009. The method is demonstrated to have skill by performing high-
322 resolution sting-jet resolving weather forecasts of a sample of the cyclones.

323 Between 23 and 32% of the cyclones examined satisfied the diagnostic for the
324 sting-jet precursor (dependent on the minimum area threshold chosen for the precursor
325 region). The diagnostic depends on thresholds chosen to define the moist frontal fracture
326 region (in which sting jets occur), the minimum energy available to be released from a
327 type of atmospheric instability associated with sting jets and the highest pressure level
328 from which the sting jet can descend. Consistent with previous work, these results imply
329 that these thresholds are somewhat arbitrary; features consistent with the definition of
330 sting jets exist for a spectrum of available energies and descent levels. It is left to
331 future work to determine the relationship between these variables and the strength of
332 the resultant sting jet (measured by metrics such as surface winds, top of boundary-layer
333 winds, sting-jet extent etc.).

334 The sting-jet precursor regions cover most of the area corresponding to the southern
335 edge of the cloud head of the storm that curves around the storm centre to the northwest;
336 it is from the cloud head tip that the sting jet emanates. The precursor regions

337 occur along the entire North Atlantic storm track. However, the first points in the
338 analysed track sections (which occur the day before the time of maximum intensity of
339 the cyclones) are skewed to the south for cyclones with sting-jet precursors, relative
340 to the entire set of cyclones. This is indicative of the requirement for warm moist air
341 to fuel the diabatic processes that generate sting jets. Consistent with previous case
342 studies the precursors preferentially occur prior to the time when the cyclone reaches
343 its maximum intensity.

344 Trajectories calculated along the sting jets in the high-resolution simulations
345 demonstrate the expected characteristics of sting jets. In particular, CSI is released
346 in the descending sting jet. The sting-jet descent rates and peak horizontal wind speeds
347 at the top of the boundary layer compare well with previously analysed case studies.
348 These results suggest that sting jets are a relatively generic feature of North Atlantic
349 cyclones and that previously analysed sting jet cyclones are more exceptional in their
350 path over populated areas (which led to their identification as sting-jet storms) than
351 in the strength of their sting jets. We also note that the Great October storm was
352 exceptional in both its path and its strength (not matched by any of the high-resolution
353 simulated cyclones discussed here).

354 These results have potential impact for end-users including the insurance/re-
355 insurance industry, policy makers and engineers responsible for the design of infra-
356 structure subject to wind load (Baker 2007). More research is needed to determine the
357 relationship between metrics for the existence of sting jets (such as the instability-based
358 diagnostic applied here) and the strength of the associated observed surface winds and
359 gusts.

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366 References

- 367 Arakawa A & Lamb V 1977 *Methods Comput. Phys.* **17**, 173–265.
368 Baker C 2007 *J. Wind. Eng. Ind. Aerodyn.* **95**, 843–870.
369 Baker L 2009 *Weather* **64**, 143–148.
370 Baker L 2011 Sting jets in extratropical cyclones PhD thesis University of Reading.
371 Browning K A 2004 *Q. J. Roy. Meteor. Soc.* **130**, 375–399.
372 Browning K A & Field M 2004 *Meteorol. Appl.* **11**, 277–289.
373 Catto J L, Shaffrey L C & Hodges K L 2010 *J. Climate* **23**, 1621–1635.
374 Charney J G & Phillips N A 1953 *J. Meteor.* **10**(2), 71–99.
375 Clark P A, Browning K A & Wang C 2005 *Quart. J. Roy. Meteor. Soc.* **131**, 2263–2292.

- 376 Davies T, Cullen M J P, Malcolm A J, Mawson M H, Staniforth A, White A A & Wood N 2005 *Q. J. Roy. Meteor. Soc.* **131**, 1759–1782.
- 377
- 378 Durran D R & Klemp J B 1982 *J. Atmos. Sci.* **39**, 2152–2158.
- 379 ECMWF cited 2010 ‘ECMWF operational analysis data’. Available online from the British
380 Atmospheric Data Centre. 2006– at <http://badc.nerc.ac.uk/data/ecmwf-op/>.
- 381 Edwards J & Slingo A 1996 *Q. J. Roy. Meteor. Soc.* **122**, 689–719.
- 382 Emanuel K A 1994 *Atmospheric convection* Oxford University Press.
- 383 Gray S L, Martínez-Alvarado O, Baker L H & Clark P A 2011 *Q. J. Roy. Meteor. Soc.* **137**, 1482–1500.
- 384 Gregory D & Rowntree P R 1990 *Mon. Weather Rev.* **118**, 1483–1506.
- 385 Grønås S 1995 *Tellus* **47A**, 733–746.
- 386 Hodges K I 1994 *Mon. Weather Rev.* **122**, 2573–2586.
- 387 Hodges K I 1995 *Mon. Weather Rev.* **123**, 3458–3465.
- 388 Hodges K I 1999 *Mon. Weather Rev.* **127**, 1362–1373.
- 389 Hoskins B J & Hodges K I 2002 *J. Atmos. Sci.* **59**, 1041–1061.
- 390 Lock A P, Brown A R, Bush M R, Martin G M & Smith R N B 2000 *Mon. Wea. Rev.* **128**, 3187–3199.
- 391 Martínez-Alvarado O, Gray S L, Clark P A & Baker L H 2011 Objective detection of sting jets in
392 low-resolution atmospheric datasets. *Meteorol. Appl.* In Press.
- 393 Martínez-Alvarado O, Weidle F & Gray S L 2010 *Mon. Weather Rev.* **138**, 4054–4075.
- 394 Parton G A, Dore A & Vaughan G 2010 *Meteorol. Appl.* .
- 395 Parton G A, Vaughan G, Norton E G, Browning K A & Clark P A 2009 *Q. J. Roy. Meteor. Soc.*
396 **135**, 663–680.
- 397 Persson P O G & Warner T T 1991 *Mon. Weather Rev.* **119**, 917–935.
- 398 Persson P O G & Warner T T 1993 *Mon. Weather Rev.* **121**, 1821–1833.
- 399 Shapiro M A & Keyser D 1990 in C. W Newton & E. O Holopainen, eds, ‘Extratropical cyclones: The
400 Erik Palmén Memorial Volume’ American Meteorological Society Boston, USA pp. 167–191.
- 401 Shutts G J 1990 *Mon. Weather Rev.* **118**, 2745–2751.
- 402 Simmons A J, Uppala S, Dee D & Kobayashi S 2007 *ECMWF Newsletter* **110**, 25–35.
- 403 Ulbrich U, Leckebusch G C & Pinto J G 2009 *Theor. Appl. Climatol.* **96**, 117–131.
- 404 Vaughan G 2002 *Weather* **57**, 69–73.
- 405 Wernli H & Davies H C 1997 *Q. J. Roy. Meteor. Soc.* **123**, 467–489.
- 406 Wilson D R & Ballard S P 1999 *Q. J. Roy. Meteor. Soc.* **125**, 1607–1636.

Table 1: 2×2 contingency table after fifteen cases. Minimum size of region is 5–8 grid columns inclusive. The p -value, $p = 0.035$, was calculated using the Fisher exact probability test.

	Sting jet	No sting jet	Totals
Sting jet precursor	5	2	7
No precursor	1	7	8
Totals	6	9	15

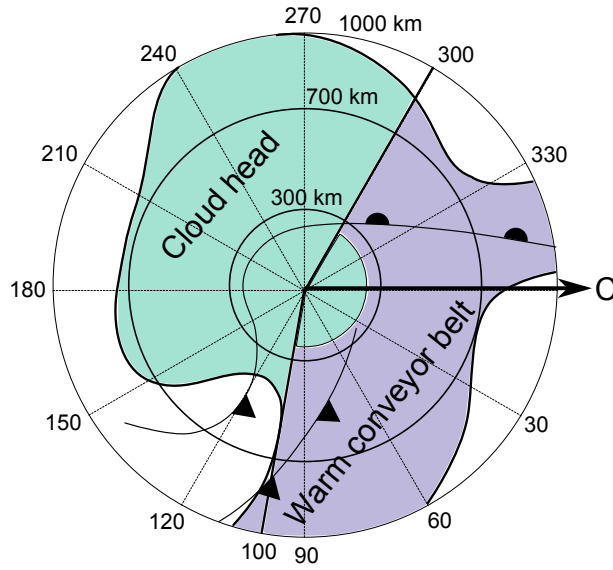


Figure 1: Cyclone elements relevant to the detection of sting-jet precursors. The pressure-based cyclone centre is located at the origin of coordinates. The black line represents a contour of cloudy air. The shaded regions show the definition of cloud head and warm conveyor belt for this purpose. The surface fronts are marked following the usual convention. Their position is only indicative. The axis C indicates the cyclone's direction of travel. See text for details.

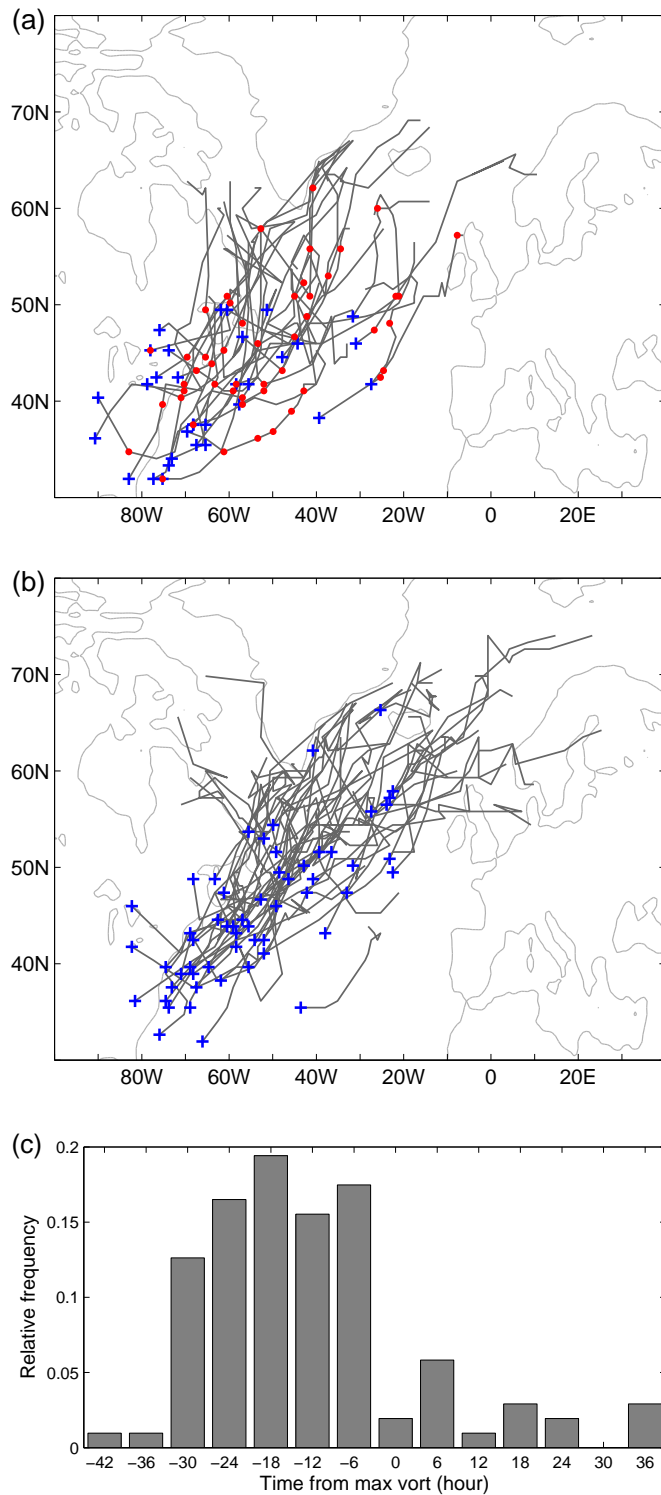


Figure 2: Track sections plotted every 6 hrs from 0000 UTC the day before to 1800 UTC the day after the day of maximum relative vorticity (at 850-hPa truncated to T42 resolution) for cyclones (a) with and (b) without sting-jet precursors. The start of the track sections are marked by a cross (+). The track points at which sting-jet precursors were identified are marked by a dot (.) in (a). (c) Distribution of sting-jet precursors with respect to the time of maximum relative vorticity.

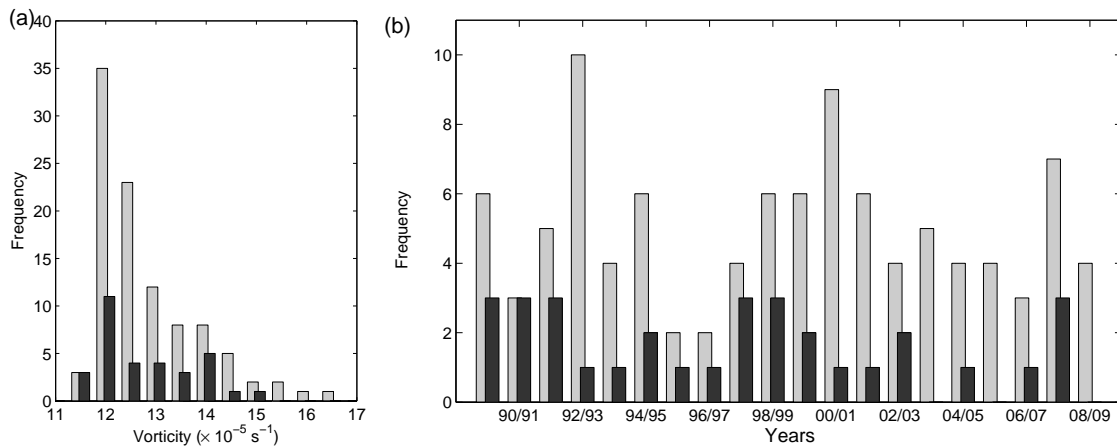


Figure 3: (a) Maximum relative vorticity distribution of all cyclones (grey) and those cyclones with sting-jet precursors (black). Bin width is $0.5 \times 10^{-5} \text{ s}^{-1}$; bin centres start at $11.5 \times 10^{-5} \text{ s}^{-1}$ and finish at $16.5 \times 10^{-5} \text{ s}^{-1}$. (b) Time distribution (by year) of all cyclones (grey) and those with sting-jet precursors (black). The 100 most intense cyclones in the North Atlantic during winter months from December 1989 to February 2009 are considered.

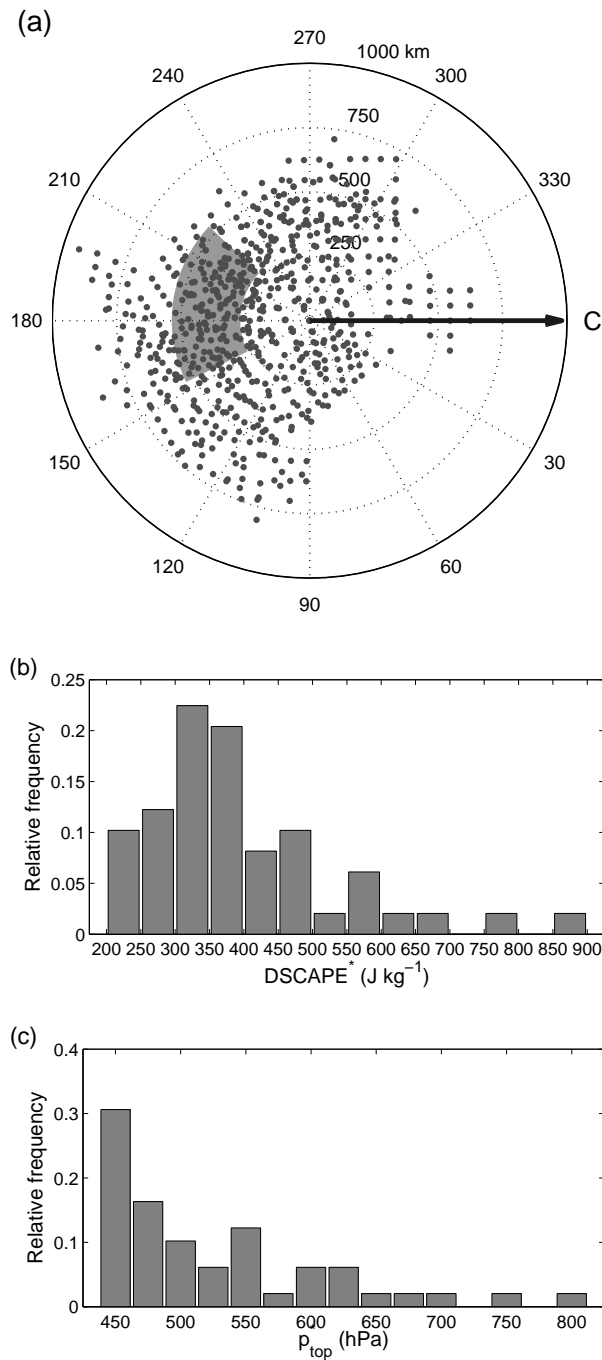


Figure 4: (a) Position of sting-jet precursor grid points (dots) within identified sting-jet precursor regions with respect to cyclone centres. The azimuth angle was measured with respect to instantaneous cyclone travel direction (C-axis). The shaded area represents the average precursor region (computed as described in section 2.2.2). (b) Frequency of sting-jet precursors as a function of the amount of CSI (as measured by maximum value of DSCAPE in a column), and (c) frequency of sting-jet precursors as a function of p_{top}^* . The 100 most intense cyclones in the North Atlantic during winter months from December 1989 to February 2009 are considered.

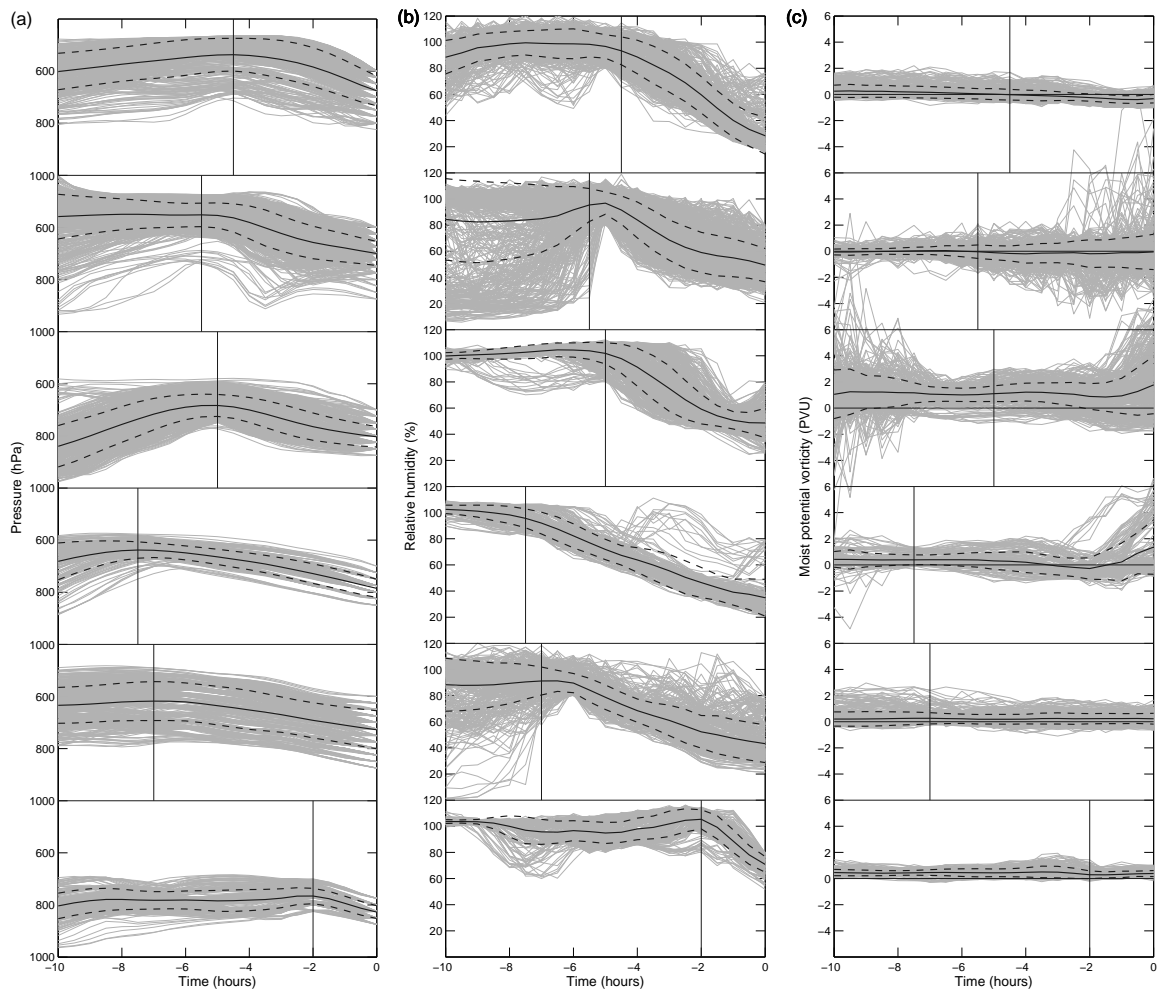


Figure 5: Trajectory analysis of the sting-jet cases found in the high-resolution simulations for (a) pressure, (b) RH and (c) MPV*, showing ensemble members (grey), ensemble mean (black solid) and \pm one standard deviation from the mean (black dashed). Vertical lines mark the onset of the sting-jet descent. Each row corresponds to a different cyclone with time zero defined as follows: (1) 0700 UTC 6 December 1994, (2) 0700 UTC 18 December 1995, (3) 0000 UTC 28 December 1998, (4) 2100 UTC 10 December 2001, (5) 0800 UTC 5 December 2002 and (6) 1400 UTC 12 December 1994.