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Non-Convective High Winds Associated with Extratropical Cyclones

John A. Knox[1]*, John D. Frye[2], Joshua D. Durkee[3] and Christopher M. Fuhrmann[4]

[1]*Department of Geography, University of Georgia*
[2]*Department of Geography, Kutztown University*
[3]*Meteorology Program, Department of Geography and Geology, Western Kentucky University*
[4]*Department of Geography, University of North Carolina at Chapel Hill*

Abstract

Non-convective high winds are a damaging and potentially life-threatening weather phenomenon that occurs in the absence of thunderstorms, tornadoes and tropical cyclones. The vast majority of non-convective high wind events develop in association with extratropical cyclones in mid-latitude regions. Interest in non-convective high winds is growing due to their societal impact, gaps in the scientific understanding of the triggering mechanisms for these events, and possible future changes in their frequency and intensity caused by climate change. In this article, non-convective high winds are examined first in terms of their historical and cultural significance and climatological characteristics. Then, four possible mechanisms for the development of non-convective high winds in extratropical cyclones are discussed and critiqued: topography; the isallobaric wind; tropopause folds associated with stratospheric intrusions and dry slots; and sting jets associated with marine frontal cyclones. Evidence for past and future trends in non-convective high wind event frequency and intensity is also briefly examined. New avenues for future work in this emerging area of research are suggested that unite applied and basic research as well as climatological and case-study perspectives.

Introduction

Non-convective high winds are an underrated, yet damaging and deadly weather phenomenon that is attracting increasing interest. Although less familiar than their convective counterparts (i.e. thunderstorms, tornadoes, tropical cyclones) in many parts of the world, these wind events occur in a number of regions globally in the mid-latitudes, including: the East Coast of North America (Ashley and Black 2008), the Great Lakes region of the USA and Canada (Figure 1; Lacke et al. 2007; Niziol and Paone 2000), the northern Great Plains of the USA (Kapela et al. 1995), the Pacific Northwest of the USA and Canada (Mass and Dotson 2010), the open waters of the North Pacific and North Atlantic (Von Ahn et al. 2005), Western Europe (Figure 2; Browning 2004; Wernli et al. 2002), the Mediterranean basin (e.g. Tripoli et al. 2005), the Black Sea (e.g. Yarovaya et al. 2008), and the coast of southeastern Australia (e.g. Buckley and Leslie 2000). It is likely that future research will reveal that these winds occur in other regions as well.

In the relatively limited contemporary research literature on this subject, non-convective high winds are not rigorously defined in terms of intensity. Some studies (e.g. Lacke et al. 2007) attempt to employ the typical US National Weather Service (NWS) thresholds for high wind events, i.e. sustained (peak 1 min) 10-m-elevation winds of 40 mph

Fig. 1. A wind-driven wave on Lake Michigan overtops a 35-foot (11-m) lighthouse at South Haven, Michigan during the 'Witch of November' non-convective high wind event on 10 November 1998. See Table 1 for more information about this event and the extratropical cyclone that caused it. Photo by Taya Kashuba, Kalamazoo Gazette.

(18 m/s) for at least 1 h; or a gust of 58 mph (26 m/s) for any duration. Other studies (e.g. Von Ahn et al. 2005) use hurricane-force maximum winds of 74 mph (33 m/s) as measured by satellites (Figure 3), ships or buoys as a threshold. Still other studies simply refer to 'strong' or 'damaging' winds (e.g. Browning 2004; Kapela et al. 1995) without any specific definition or threshold, although 40 m/s recurs in the European literature as a benchmark (e.g. Baker 2009).

These wind events are usually associated with extratropical cyclones. Niziol and Paone (2000) examined 52 non-convective high wind events in the Buffalo, NY area over a 20-year period, for which the composite 850-hPa geopotential height pattern revealed a low just to the north over southern Canada. Lacke et al. (2007) confirmed and extended this relationship between non-convective high winds and low pressure using surface wind and pressure data from 38 first-order weather stations across the Great Lakes region in a 44-year climatology. Lacke et al. found a median sea-level pressure (SLP) of 1000.8 hPa for sustained non-convective high winds, and a median SLP of 993.5 hPa for non-convective high wind gusts. From a natural hazards perspective, Ashley and Black (2008) determined that more than 83% of all non-convective wind fatalities in the USA are associated with the passage of extratropical cyclones.

Extratropical cyclones over open waters may intensify (Angel and Isard 1997) and acquire some quasi-tropical characteristics (e.g. Reed et al. 2001). In this review article, however, we will focus much of our attention on events associated with classic frontal

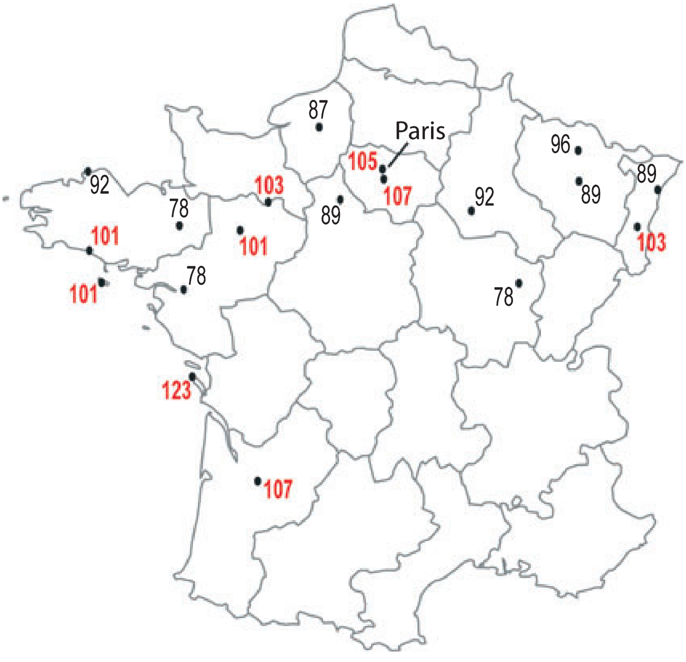

Fig. 2. Maximum wind gusts (in mph; gusts ≥100 mph in red) across France due to extratropical cyclone 'Lothar' on 25–26 December 1999. Data from Météo-France.

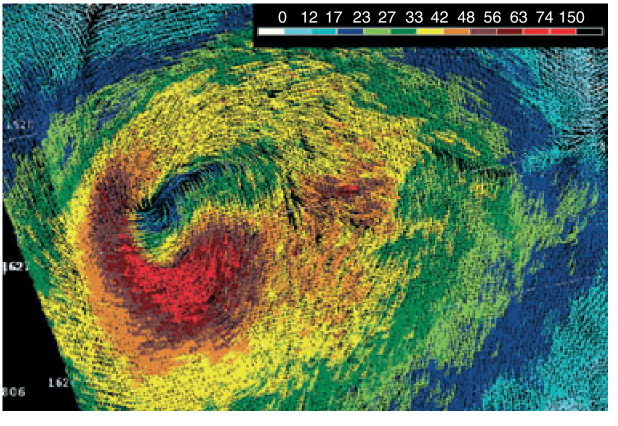

Fig. 3. NASA QuikSCAT satellite data from 1600 UTC 1 December 2004, indicating near-surface winds in a North Atlantic extratropical cyclone as measured by scatterometer. Wind speed is in knots (colour bar in upper right). The strongest (hurricane-force) winds are depicted as red wind barbs. From Von Ahn et al. (2005); figure courtesy Joan Von Ahn, NOAA/NWS.

cyclones. Non-convective high winds due primarily to topography (e.g. gap winds) are not discussed in this article.

Although other types of windstorms have a higher profile in many parts of the world (e.g. tornadoes and hurricanes in the eastern and central USA), non-convective high winds are in many ways comparable in terms of societal impact. They have the potential to be deadlier than hurricane winds or non-tornadic thunderstorm winds (Ashley and

Black 2008), and can account for more property and crop damage than thunderstorm winds or tornadoes in a typical year (Lacke et al. 2007). Europeans are generally more aware of non-convective wind hazards because of 'European windstorms' that have a long history of causing nautical disasters. More recently, several exceptional windstorms in Great Britain and northwestern Europe during the past quarter-century have stimulated interest among non-specialists and specialists alike (see examples in Fink et al. 2009). Total insurance losses in Europe associated with these storms have averaged over 1 billion Euros (approximately $1.5 billion) per year over this period (Browning 2004). In addition to direct wind deaths and damage, the action of wind on water can combine with other factors and lead to high seas and seiches that can cause additional extraordinary damage and loss of life. For example, the 1953 North Sea flood, caused by levee failures during an intense extratropical cyclone, inflicted as many confirmed fatalities in the Netherlands (1835; Sterl et al. 2009) as did Hurricane Katrina in the US Gulf Coast in 2005 (1833; Beven et al. 2008).

The purpose of this article is twofold: (i) to summarize and assess the current state of research on this emerging topic; and (ii) to unify our understanding of non-convective wind events in both pure and applied research areas. As justification for the latter, a perusal of the bibliography of this article reveals that much of the work performed in North America has been applied research, often climatological and often published in government documents, technical memos, or journals not typically read by academics internationally. Meanwhile, in Europe a sizable body of research, mainly case studies of exceptional events, exists mostly in academic journals. Of late, there has been a rapid expansion of applied research on this subject related to wind energy and insurance interests. In many instances, research on one side of the Atlantic reveals a lack of awareness of work done on the other side; and insurance-industry research tends to focus on Europe because of the greater economic impact there. We intend for this review article to bridge these divides and provide readers from a wide range of backgrounds and interests with a comprehensive and unified understanding of non-convective wind events, although admittedly with a bit of a US accent.

Non-Convective High Wind Events: Historical and Cultural Perspectives

Historically, interest in non-convective high winds has been spurred by individual events often linked to nautical disasters. The medieval 'Ballad of Sir Patrick Spens' (Abrams et al. 1979, 396–397) tells a possibly true story of a Scottish shipwreck on the North Sea during winter in the late 13th century, presumably due to a 'deadlie storme'. The 'Great Storm' of 14 November 1854 on the Black Sea surprised and sank the British fleet during the Crimean War. Combined with the *Royal Charter* Storm of 1859, these two storms spurred the development of daily weather forecasts in 1861 by Admiral Robert FitzRoy, formerly captain of *The Beagle* (Cox 2002, ch. 10). Similarly, the 'Witch of November gales' of the Great Lakes, the 'Nor'easters' of the East Coast, and the 'Big Blows' of the Pacific Northwest have caused innumerable shipwrecks in North America. Table 1 summarizes some of the most significant non-convective wind events of modern times across the globe.

Two North American events in Table 1 possess particular cultural importance and multiple connections to atmospheric science. The November 1975 Great Lakes extratropical cyclone helped sink the ore freighter *Edmund Fitzgerald* and its crew of 29 sailors on Lake Superior (Hultquist et al. 2006; Stonehouse 1977). The shipwreck inspired Canadian singer–songwriter and sailor Gordon Lightfoot to compose and record a

Table 1. Some notable non-convective high wind events associated with extratropical cyclones. Fatalities and damage estimates (at time of event) are often incomplete and generally include all aspects of the storm, not just non-convective wind effects.

Date	Location	Min. SLP (hPa)	Max. wind gust (m/s)	Fatalities	Damage	Comments	Authors
North America							
9 January 1880	Pacific Northwest	<955	31	>3	N/A	'The Storm King'; limited meteorological observations; numerous trees experienced windthrow probably exacerbated by antecedent rainfall	Read (2004)
7–11 November 1913	Great Lakes	968	40	>250	$5 million	'White Hurricane'; high winds accompanied by heavy snow squalls; wave heights reached 35 feet, contributed to the destruction of nineteen shipping vessels	Brown (2002) Deedler (2005a)
10–12 November 1940	Great Lakes; Upper Midwest	971	36	154	$2 million	'Armistice Day Storm'; destroyed five major vessels on Lake Michigan, resulting in the death of 66 sailors; high winds and waves on the banks of the Mississippi River claimed the lives of about two dozen duck hunters	Kean (2003)
24–30 November 1950	Eastern USA	978	49	353	$66.7 million	Areally extensive storm that impacted 22 states across the USA; the storm was a test-bed for early research into numerical weather prediction	Smith (1950) Phillips (1958) Kistler et al. (2004)
6–8 March 1962	US mid-Atlantic Coast	989	38	40	$300 million	'Ash Wednesday Storm'; also the 'Great Atlantic Storm'; wind and waves resulted in the most extensive coastal erosion in modern history along the US East Coast	Dolan (1987)

Table 1. (Continued)

Date	Location	Min. SLP (hPa)	Max. wind gust (m/s)	Fatalities	Damage	Comments	Authors
12 October 1962	Pacific Northwest	960	71	46	$230 million	'The Big Blow'; born from the remnants of major typhoon that crossed the north Pacific Ocean; considered the most powerful extratropical cyclone in US history	Read (2005)
3–5 October 1963	Beaufort Sea coast, Alaska	976	33	0	$3.25 million	Most severe storm in Beaufort Sea coast history; nineteen buildings in Barrow destroyed, drinking water contaminated by storm surge	Lynch et al. (2003)
9–10 November 1975	Great Lakes	976	33	31	N/A	Storm connected with the sinking of the ore freighter *Edmund Fitzgerald* on Lake Superior; popularized in modern culture by Canadian folk singer Gordon Lightfoot	Holden (1991) Knox and Ackerman (1996) Hultquist et al. (2006)
1–5 February 1976	New England USA; Canadian maritimes	957	52	N/A	$22 million	'The Groundhog Day Gale'; major beach erosion and inland flooding across New England; major flooding in the bays along the coast of Newfoundland; at least one freighter lost	Desplanque and Mossman (1999)
25–27 January 1978	Great Lakes	956	45	70	N/A	'The Great Blizzard' and 'Cleveland Superbomb'; some of the lowest extratropical cyclone surface pressures ever recorded in the contiguous USA and eastern Canada. Cleveland, Ohio all-time-low pressure record broken by 13 hPa	Blackburn (1978) Wagner (1978) Salmon and Smith (1980) Hakim et al. (1995) Deedler (2005b)

Table 1. (Continued)

Date	Location	Min. SLP (hPa)	Max. wind gust (m/s)	Fatalities	Damage	Comments	Authors
5–7 February 1978	New England USA	984	41	13	$1 billion	High winds and record snowfall produced one of the most memorable blizzards in US history; tides 3–4 feet above normal; coastal flooding and erosion; numerous lighthouses damaged	Kocin and Uccellini (2004) NCDC (1978)
30–31 October 1991	Eastern North America	972	35	5	$200 million	'The Perfect Storm'; a strong coastal cyclone joined with the remnants of Hurricane Grace; wave heights reached 35 feet; long-duration event (114 h) with high wind and waves extending over 3500 km of coastline	Davis and Dolan (1992)
29 November 1991	Southern California	1003	34	17	N/A	High winds over the San Joaquin Valley produced a major dust storm that resulted in multiple collisions involving 164 cars along sections of Interstate-5	Pauley et al. (1996)
12–13 March 1993	Eastern USA	960	45	300	$6 billion	'Superstorm' or 'Storm of the Century'; blizzard conditions in New England; high winds, westerly gales behind cold front across mid-Atlantic and southern USA; coastal erosion from Florida to New England	Kocin et al. (1995)
10 November 1998	Great Lakes	963	42	10	$40 million	'Witch of November'; exactly 23 years to the day of the 1975 storm that sank the *Edmund Fitzgerald*	Iacopelli and Knox (2001)
10–11 August 2000	Barrow, Alaska	989	33	0	$7.7 million	Record winds at Barrow; $6 million dredge destroyed, 40 buildings unroofed; Prudhoe Bay recorded near-100-year storm surge	Lynch et al. (2003)

Table 1. (Continued)

Date	Location	Min. SLP (hPa)	Max. wind gust (m/s)	Fatalities	Damage	Comments	Authors
25–27 October 2010	Upper Midwest U.S.	955	35	1	N/A	One of most intense extratropical cyclones on record in lower 48 United States; widespread high winds across upper Midwest	http://www.crh.noaa.gov/mpx/?n=10oct2627
South America							
23–24 August 2005	Uruguay	992	>45	10	N/A	Powerful extratropical cyclone with high winds and heavy rainfall; considered the country's worst storm in nearly half a century; thousands of felled trees and damaged homes; tens of thousands without electricity	Padgett et al. (2005) NCDC (2005)
Europe							
24 November–3 December 1703	UK	973	54	>10,000	N/A	'The Great Storm'; considered the worst natural disaster in the UK; thousands of lives lost at sea; at least a dozen Royal Navy ships lost	Lamb and Frydendahl (1991) Wheeler (2003)
6–7 January 1839	West Coast of Ireland	918	>50	100–300 (est.)	>£200 million	'The Night of the Big Wind'; one of the strongest storms in history to affect the Irish coast; 42 ships were damaged or capsized; tremendous agricultural damage; inspired a popular Irish novel and song/poem of the same name	Shields and Fitzgerald (1989) Forsythe et al. (2000) Sweeny (2000)
25–26 October 1859	West Coast of Great Britain	960	>33	>800	N/A	'The *Royal Charter* Storm'; worst windstorm of the 19th century in the British Isles; over 100 ships sunk including the *Royal Charter* (over 400 dead) on the Wales coast; inspired FitzRoy's attempt to issue storm forecasts	Cox (2002, ch. 10) McKee (2000)

Table 1. (Continued)

Date	Location	Min. SLP (hPa)	Max. wind gust (m/s)	Fatalities	Damage	Comments	Authors
31 January–1 February 1953	UK; The Netherlands	966	56	>2000	£1 billion	'The North Sea Flood'; high winds and tidal waves caused dyke and sea wall failures and massive flooding; numerous ships and ferries lost at sea	Lamb and Frydendahl (1991) Sterl et al. (2009)
13–14 August 1979	UK	979	36	15	N/A	High winds produced massive waves through the English Channel during the 28th Fastnet yachting race; 24 of the 303 yachts participating in the race were lost or abandoned	Pedgley (1997)
15–16 October 1987	England; France	952	>50	18	£2 billion	Known as 'The Great Storm'; millions of felled trees; highest winds occurred during the overnight hours; poorly forecasted by the UK Meteorological Office	Burt and Mansfield (1988) Browning (2004)
27 February 1990	Switzerland	948	>60	64	$5 billion	'Vivian'; high winds toppled 5 million m^3 of timber in Switzerland alone; severe damage and disruption caused by wind-blown trees and debris	Schüepp et al. (1994)
3 December 1999	North Sea	953	51	6	£1.4 billion	'Anatol'; high winds produced record storm surge along the northern Danish and German coast; the strongest storm to hit Denmark in the 20th century	Ulbrich et al. (2001) Pearce et al. (2001)
24–26 December 1999	France; Germany; Switzerland	974	58	50	£3.1 billion (Lothar & Martin)	'Lothar'; damage reported at Notre Dame in Paris and the park of Versailles; over 2000 acres of timber chips produced from felled trees	Ulbrich et al. (2001) Pearce et al. (2001) Wernli et al. (2002)

Table 1. (Continued)

Date	Location	Min. SLP (hPa)	Max. wind gust (m/s)	Fatalities	Damage	Comments	Authors
27 December 1999	France; Spain	965	40	>150	See above	'Martin'; extensive tree damage, coupled with damage from Anatol and Lothar, caused major disruptions to transportation; millions without power regionally up to 1 week	Ulbrich et al. (2001) Pearce et al. (2001)
7–9 January 2005	UK; Scandinavia	956	46	>17	>£1 billion	'Gudrun' (Norway) and 'Erwin' (Germany); 75 million m^3 of felled trees throughout Scandinavia; record flooding due to wind-driven waves in western UK (Carlisle, England)	Baker (2009)
15–19 January 2007	Western Europe	964	63	47	£4 billion	'Kyrill'; major disruption of air, land, and sea transportation; millions without power; as many as 62 million trees uprooted	Fink et al. (2009)
26–28 February 2010	Western Europe	966	54	At least 62	€1.5–3 billion	'Xynthia'; 5th deadliest winter storm in Europe in past 60 years; storm surge with 8-m waves in coastal France; millions without power in France and Portugal	http://www.knmi.nl/cms/mmbase/attachments/81817
Mediterranean							
14 November 1854	Black Sea	N/A	N/A	N/A	N/A	Surprise storm during Crimean War 3 weeks after 'Charge of the Light Brigade' wrecked British and French warships, sinking winter supplies; 'enormous losses on land and sea'	Cox (2002, chs 10 and 11)
25–29 September 1979	Black Sea	992	25	N/A	N/A	Nearly stationary mesoscale cyclone over southwest Black Sea led to delays of cruise ships from the Crimea and Odessa to Istanbul	Yarovaya et al. (2008)

Table 1. (Continued)

Date	Location	Min. SLP (hPa)	Max. wind gust (m/s)	Fatalities	Damage	Comments	Authors
19–22 December 1979	Western Mediterranean	982	30	N/A	N/A	Rapidly deepening 'bomb' cyclone followed unusual track northward from Africa to east of Balearic Islands; many trees uprooted and some seashore buildings affected on islands	Homar et al. (2002)
9–10 November 2001	Algeria	989	33	740	N/A	Devastating flooding rains and windstorm in Algiers caused by storm resembling US 'Storm of the Century'	Tripoli et al. (2005)
Australia and New Zealand							
10 April 1968	North Island, New Zealand	N/A	51	53	N/A	'The Wahine Disaster'; Cyclone Giselle converged with a strong extratropical cyclone near Wellington, NZ; connected with the capsizing of the passenger ferry *Wahine* in Wellington Harbour; significant damage to forests on the North Island	Hill (1970) Shaw (1983)
25–28 December 1998	Southeastern Australia	978	47	6	N/A	High winds produced heavy surf during the 54th Sydney-to-Hobart Yacht Race; subsequent rescue effort the biggest peacetime marine rescue in Australia's history	Buckley and Leslie (2000)

meteorologically astute and haunting ballad on the subject (Knox and Ackerman 1996). Lightfoot's song, the 1976 international hit 'The Wreck of the *Edmund Fitzgerald*', and the lingering mystery surrounding the wreck have elevated the *Fitzgerald* story into a mythic '*Titanic* of the Great Lakes' (Ackerman and Knox 2007, ch. 10). Ironically, this storm was employed by Hoskins and Pedder (1980) in their celebrated application of quasigeostrophic Q-vector theory without any reference to the wider significance of the storm, or even a base map to indicate its location. Later, Hultquist et al. (2006) performed a high-resolution numerical investigation of the storm, accurately simulating exceptional winds and seas in the location of the shipwreck (Figure 4).

A hybrid extratropical–tropical cyclone on Halloween 1991 that led to twelve deaths in fishing vessels off the USA and Canadian East Coast similarly passed into legend, via the bestselling book *The Perfect Storm* (Junger 1997) and 2000 film of the same name. It received its nickname, now broadly used in a variety of contexts throughout the English-speaking world, from Boston NWS meteorologist and former National Hurricane Center forecaster Bob Case. In another unusual intersection of culture and science, the film's Oscar-nominated visual effects included compelling computer-generated ocean wave imagery co-created by former atmospheric science professor John Anderson, a fluid dynamics expert then working at Lucasfilm's Industrial Light and Magic.

In addition to nautical tragedies involving freight or fishing, two yacht-race disasters were also precipitated by non-convective high wind events. During the August 1979 Fastnet race in England (Pedgley 1997; Rousmaniere 1980), over 100 yachts were knocked over or capsized in 50-foot (15-m) seas caused by hurricane-force wind gusts in the rear of an intense extratropical cyclone, causing fifteen fatalities and necessitating the largest peacetime rescue operation in the Royal Navy's history. Nineteen years later on Boxing Day 1998, the Sydney-to-Hobart race was similarly disrupted by an intense extratropical cyclone with wind gusts to 106 mph (47 m/s). Over half of the competing yachts retired from the race due to high winds and 80-foot-plus (25-m) waves; six sailors died despite Australia's largest-ever peacetime rescue mission (Buckley and Leslie 2000; Mundle 1999).

Non-Convective High Wind Climatologies

The first comprehensive climatological study of extratropical cyclones with strong winds appears to have been by the Canadian government meteorologist Lewis (1987). Lewis examined 100 storms with sustained (1-min mean) winds greater than a threshold of 55 mph (25 m/s) that traversed the Great Lakes between 1957 and 1985. He determined that about 0.25% of ship observations of wind made on the Great Lakes during November, December and January exceeded this threshold. Angel (1996) reanalysed Lewis's results and found that 92% of the 100 storms were extratropical cyclones; 83% of these cyclones occurred in November through March.

Lamb and Frydendahl (1991) employed historical synoptic weather maps, ship observations and a variety of non-meteorological data (e.g. church records, port records, farm diaries) to analyse the great windstorms of the past 500 years in Great Britain and the seas and coasts of northwest Europe. A total of 166 storms dating back to the 16th century were analysed and ranked according to a storm severity index, which accounts for wind speed, areal coverage of damaging winds and duration. Although an upward trend in storm intensity in the North Sea region has been suggested since about 1950, their study appears to suggest even greater storminess in past centuries.

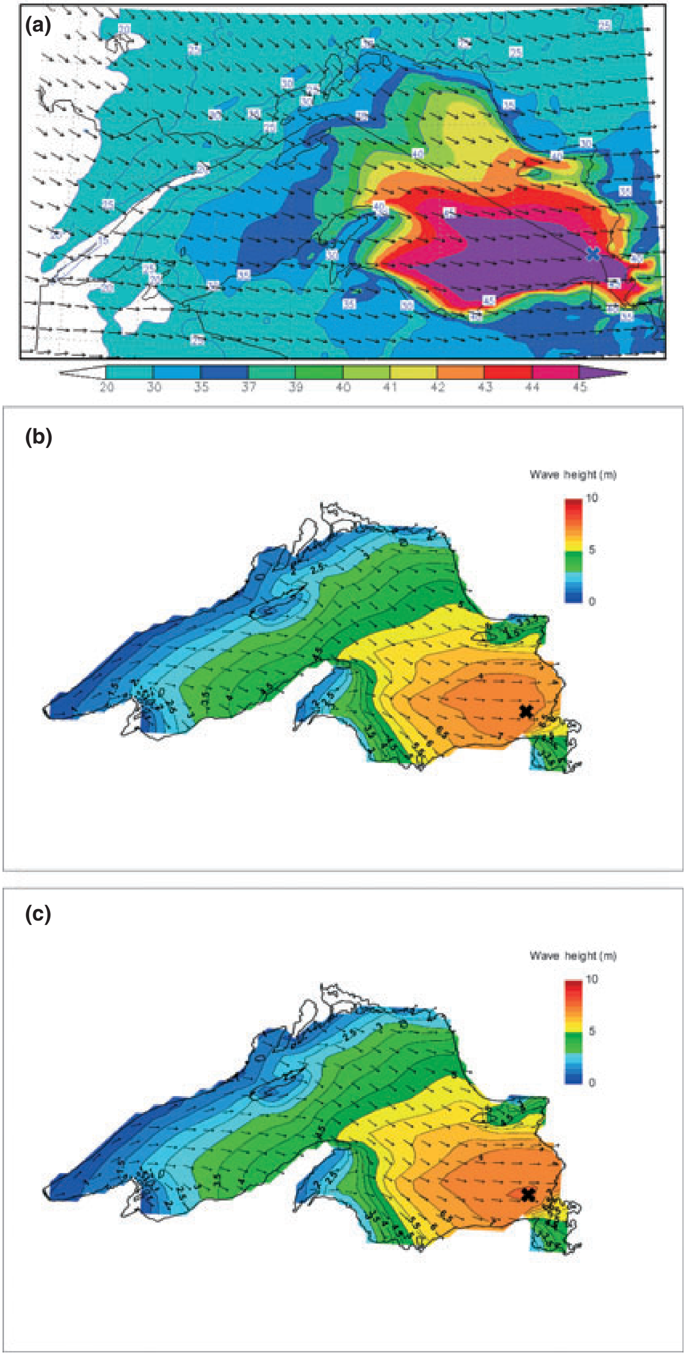

Fig. 4. High-resolution simulation results for the November 1975 '*Edmund Fitzgerald*' storm and its impact on Lake Superior: (a) wind speed (in knots, shaded) at 0000 UTC 11 November 1975; (b) significant wave heights at the same time as in (a); and (c) significant wave heights at 0100 UTC 11 November 1975, approximately 40 min after the shipwreck (location indicated by an 'x' on each plot). Simulated winds at the shipwreck site at 0100 UTC are >45 knots (22.5 m/s) and significant wave heights are 25.6 feet (7.8 m). From Hultquist et al. (2006); figure courtesy Tom Hultquist, NOAA/NWS.

Feren (1990) explored explosive cyclogenesis in the eastern portion of Bass Strait, which separates Australia and Tasmania, from 1970 to 1989. Feren focused on storms that produced very high waves (at least 17 feet, or 5 m). His results indicate a maximum in frequency of these events during June through August, i.e. Southern Hemisphere winter.

More recent climatologies have focused on the timing and meteorological characteristics of these events. Niziol and Paone's (2000) 20-year analysis for Buffalo, NY found a peak in the frequency of events in January and a preference for winds from the southwest-to-west direction, along Lake Erie. Martin and Konrad (2006), examining strong wind gusts over 8 years in the Southeast USA (of which only 8% were convective in nature), discovered a March peak. Their analysis also revealed a south–southwest to west–southwest directional preference at several surface observing stations. A more comprehensive 44-year climatology for the Great Lakes region by Lacke et al. (2007) indicated that while only 0.04% of all observations met the NWS sustained-wind high wind criterion, at least 70% of these winds were from the south-through-west direction (Figure 5). Despite the 'Witch of November' lore; however, Lacke et al. (2007) determined that the most common timing for these events in the Great Lakes has been during March or April. Von Ahn et al.'s (2005) climatology of 120 North Atlantic and North Pacific hurricane-force extratropical cyclones over a 2.5-year period yielded an estimate of roughly twenty events per basin per year, with a peak in frequency in December in the North Pacific and a January peak in the North Atlantic.

The climatology of non-convective winds has also been studied in the context of fatalities. Ashley and Black (2008) found a bimodal peak (November and March) in the number of deaths attributable to non-convective high winds in the USA from 1980 to 2005. The spatial distribution of fatalities (Figure 6) highlights the US East Coast, Great Lakes and Pacific Northwest as well as major population centres elsewhere. About 24 deaths occurred annually in the USA due to non-convective high winds during 1980–2005, with most fatalities (91%) occurring in vehicles (often due to trees felled onto vehicles), while boating, or outdoors.

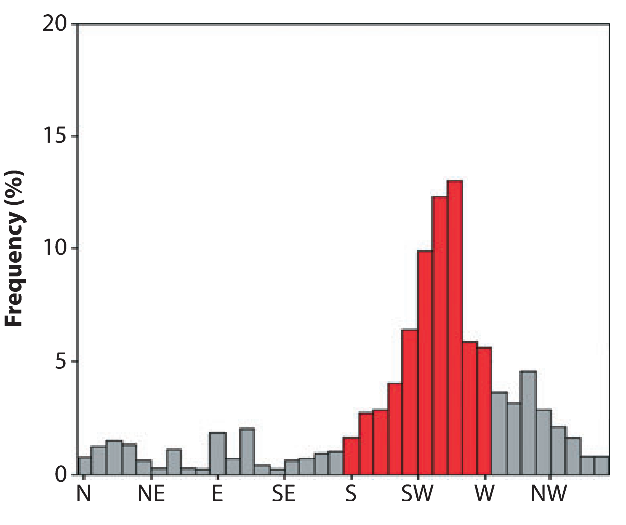

Fig. 5. Distribution of non-convective high (sustained) wind observations as a function of cardinal direction, as observed in the US Great Lakes region during the period 1967–1995. Winds from the south-through-west direction are highlighted in red. Modified from Lacke et al. (2007).

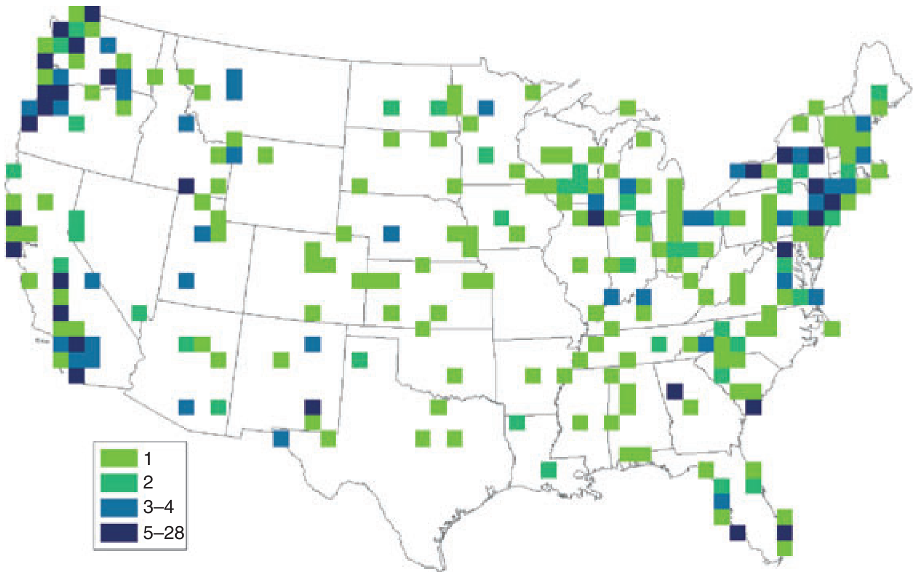

Fig. 6. The number of non-convective high wind fatalities in the lower 48 United States during the period 1980–2005. Figure courtesy Alan Black.

In summary, the climatological evidence to date indicates that non-convective high wind events preferentially occur during winter or early spring, but the death toll seems to be shifted somewhat earlier into the late fall. Several studies reveal a preference for winds from the southwest quadrant of the compass.

Physical Explanations for Non-Convective High Winds

There is no one universally accepted explanation for non-convective high winds associated with extratropical cyclones. Early work on storms predated the modern era of atmospheric dynamics and generally did not focus on ultimate causes as much as practical prediction, as in FitzRoy's case (Cox 2002, 81). By World War II, it became known that strong winds are found aloft in baroclinic zones, as per the thermal wind law (Holton 2004, 70–75). However, exactly how, when and where these winds are brought to or created at the surface is still the subject of research.

Strong surface winds are normally accompanied by steep surface pressure gradients, as required by geostrophic balance (Ackerman and Knox 2007, ch. 6). Steep pressure gradients are, in turn, possible in the vicinity of strong extratropical cyclones, for example in the vicinity of cold fronts. But how and where these pressure gradients are created and/or altered by other processes is not yet completely understood. Instead, each new event in the USA stimulates a range of explanations by different NWS forecast offices, from 'gradient winds' to tropopause folding. In Europe, a growing body of research has converged on an exceptional type of extreme wind event, the 'sting jet', pertinent to marine cyclones. In this section, we survey the state of research on this topic, examining different hypotheses one by one.

Kapela et al. (1995) summarized the ingredients leading to strong post-cold frontal winds in the northern plains of the USA. Their checklist, based on forecast experience dating to the 1980s, included: a tight SLP gradient, a strong 500-hPa vorticity maximum, a large isallobaric gradient, subsidence, cold-air advection, a steep lapse rate, a 'dry slot' in water vapour satellite imagery, an upper-tropospheric jet streak and small directional wind shear. Using this ingredients-based checklist as a general guide, we now turn to the most commonly discussed hypotheses for non-convective high winds.

TOPOGRAPHY

Kapela et al. (1995) did not mention topography, which is not particularly relevant on the homogeneously flat Great Plains. However, differences in elevation and surface roughness, particularly near coastal regions, have been hypothesized as a contributing factor in non-convective high wind events by several researchers.

Niziol and Paone (2000) linked the preference for southwesterly and westerly high winds at Buffalo to the presence of Lake Erie to the southwest of Buffalo. The authors hypothesized that Buffalo's location on elliptically shaped Lake Erie may play an important role in the stratification of wind direction, by channelling the wind at its narrowing eastern end. However, Lacke et al. (2007) demonstrated that the same preference for southwesterly winds exists throughout the Great Lakes region, independent of upwind topographic or geographic features.

Crupi (2004) and Hultquist et al. (2006) both suggested that the topography of the Upper Peninsula of Michigan played a role in non-convective high winds on Lake Superior. In the former, a funnelling of air through a canal was hypothesized to contribute to an April 1997 event (Crupi 2004). In the latter, an acceleration of winds was noted over south-central Lake Superior during the *Fitzgerald* storm (see figure 4, from Hultquist et al. 2006) that was 'likely enhanced' by coastal convergence just north of the high terrain of the Huron Mountains (maximum elevation 1979 feet or 603 m) and the Keweenaw Peninsula (maximum elevation <1640 feet or 500 m). However, Tripoli et al. (2005) ruled out topographic influences on the development of the November 2001 Algerian cyclone and wind event via a series of numerical simulations that alternately included or excluded African topography.

Three other studies for other regions have also downplayed the role of topography. Mass and Dotson (2010) have summarized the mixed results of research on interactions between Pacific Northwest cyclones and the terrain of that region, noting that 'major questions remain' regarding the role of topography in coastal wind enhancement. Pauley et al. (1996) ascribed a lesser, secondary role to topography (via mountain waves and a topographically induced low) in the generation of a deadly dust storm due to non-convective high winds in central and southern California. Homar et al. (2002) also determined that orography played only a weak role in the development of a deep cyclone with 67 mph (30 m/s) gusts over the western Mediterranean in December 1979.

In summary, although topography certainly can play a role in extreme wind events associated with extratropical cyclones, it is evident from the research as well as the many occurrences of extreme winds over the oceans that it is neither essential nor even a primary cause.

ISALLOBARIC WIND

A common explanation for non-convective high wind events in NWS discussions is the isallobaric wind, defined as the wind generated when the Coriolis force exactly balances a locally accelerating geostrophic wind (Glickman 2000). This wind is directed towards locally falling pressures and is normal to lines of equal pressure *change*, or isallobars. The larger the gradient of pressure change, the faster the isallobaric wind. As a result, the isallobaric wind can be sizable on the flanks of intense, rapidly intensifying, and/or quickly propagating extratropical cyclones.

Richwien (1980), in an early examination of the *Fitzgerald* storm, attributed the high winds on Lake Superior to the combination of gradient and isallobaric winds. This assertion was based on calculations made at one point in the vicinity of the shipwreck. Later, Crupi (2004) made similar calculations and inferences for an April 1997 wind event near Houghton, Michigan. Based on the results of two case studies of non-convective high winds in New York state in February 1997, Niziol and Paone (2000) noted that 'many of the processes conducive to high winds that occur higher in the atmosphere are reflected in … surface pressure rise/fall couplets that contribute to an isallobaric component of the wind'. More recently, NWS meteorologists have linked isallobaric winds to the damaging ($1.5 billion) windstorm in the US Ohio Valley in September 2008 associated with the extratropical transition of Hurricane Ike (Stoppkotte et al. 2009).

The isallobaric wind is prone to misuse, however. From the time of Haurwitz (1946), it has been noted that the isallobaric wind is but one (and not necessarily the dominant) component of the ageostrophic wind, and that it is usually calculated in a very approximate manner. Also, the isallobaric wind must be added vectorially to other wind components; it is not necessarily parallel to the geostrophic or gradient wind in intense cyclones. For these reasons, caution must be applied in attributing non-convective high winds to isallobaric winds. However, Kwon and Lim (1999, figure 9) have shown that the combination of isallobaric and advective ageostrophic winds does lead to a *net* meridional lower-level ageostrophic wind in the southwest quadrant of an unstable-mode (as opposed to a neutral-mode) baroclinic low, where many non-convective high wind events occur (see below). Therefore, there still appears to be merit in considering isallobaric contributions as a mechanism for non-convective high winds associated with extratropical cyclones.

TROPOPAUSE FOLDS

Other mechanisms for non-convective high winds pertain to the vertical structure of the extratropical cyclone. As noted by Browning (1997, 1999), 'dry intrusions' of subsiding air from the upper troposphere and lower stratosphere have been long associated with extratropical cyclones and very strong surface winds (see Pedgley 1997 and citations therein). These dry intrusions – referred to as 'dry slots' in satellite imagery – are, in turn, often linked with tropopause folds (Figure 7) in rapidly intensifying cyclones (see Uccellini 1990 for a review). While these intrusions rarely reach the surface, they can extend downward to approximately 700 hPa in some of the cases listed in Table 1 (e.g. Pauley et al. 1996; Tripoli et al. 2005). Unfortunately, the precise details of the connection between the subsiding air at upper levels and high winds at the surface have not been fully elucidated in many instances, other than to allude to 'the downward transfer of high-momentum air' (Kapela et al. 1995).

One line of research on non-convective high wind mechanisms focuses on mixing of high-speed air to the surface associated with the dry slot. In a study of a severe wind event in the UK in 1991 associated with a Scandinavian cyclone, Browning and Reynolds (1994) inferred that high-momentum stratospheric air descended to the boundary layer and was then transferred to the surface via shear instabilities. Three different studies focusing on events in California (Pauley et al. 1996) and the Great Plains (Goering et al. 2001; Schultz and Meisner 2009) determined that descent of strong winds aloft,

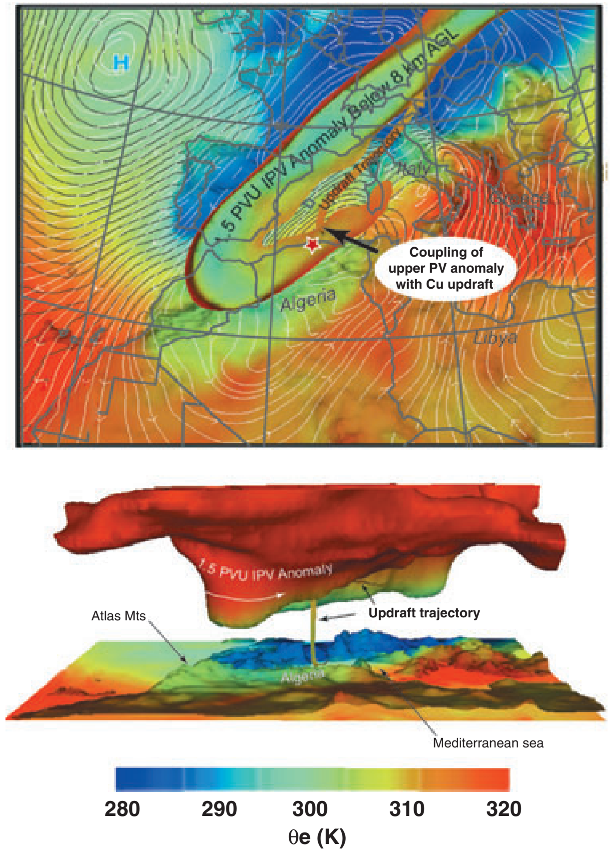

Fig. 7. Simulation of the tropopause fold [the 1.5 isentropic potential vorticity (IPV) unit surface] associated with the Algerian flood and windstorm on 0800 UTC 10 November 2001. The location of Algiers is indicated with a star in the top image. Wind streamlines at 1-km mean sea-level elevation are shown in white, while mean sea-level pressure is contoured in black (only over water) at 1-hPa intervals. Equivalent potential temperature θ_e is shaded; higher values of θ_e indicate stratospheric origins. From Tripoli et al. (2005), American Meteorological Society.

combined with mixing due to solar heating of the planetary boundary layer below, led to high wind events at the surface.

Along these lines, Iacopelli and Knox (2001) found that a 'mesoscale dry hook' in satellite imagery was collocated in time and space with reports of surface wind gusts and damage during the 1998 'Witch of November' storm in Wisconsin (Figure 8). They hypothesized that a convectively neutral layer from near the base of the tropopause fold to the surface over western Wisconsin allowed for the transport of high-momentum air all the way to the surface. Iacopelli and Knox also noted that the highest wind gusts were accompanied by rain and snow on the back side of the cyclone, which could provide localized downdrafts capable of transporting strong winds to the surface. We look at the possible contributing role of instability and convection in more detail below.

THE 'STING JET' HYPOTHESIS

Since at least the early 1970s, US meteorologists have identified certain regions of extratropical cyclones that are prone to high surface winds at different stages of cyclone development (Smigielski, cited in Parke 1986, figure 11). This schema places high winds in

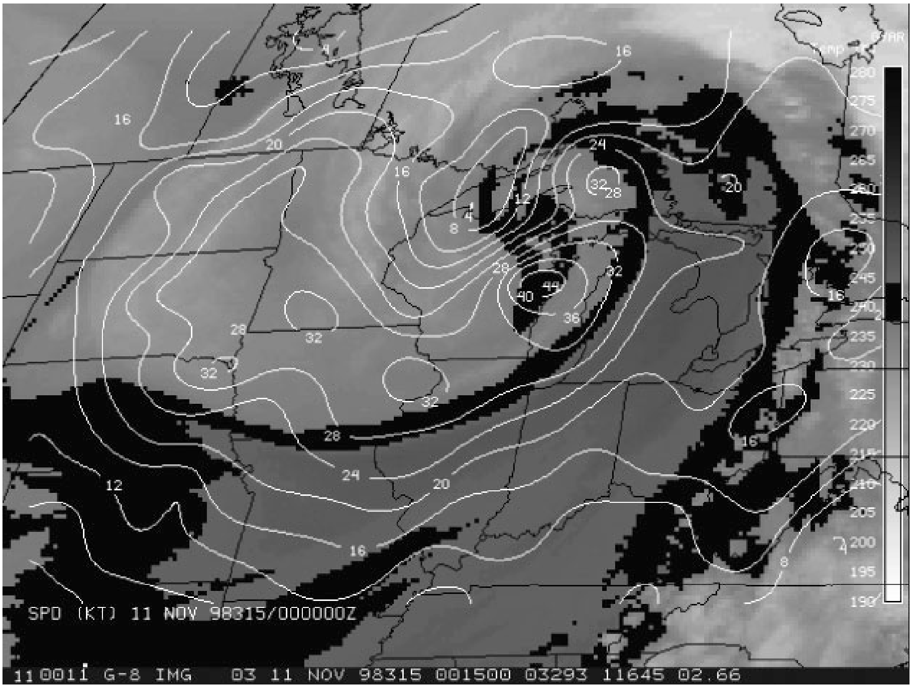

Fig. 8. GOES-8 Imager water vapour satellite imagery of the 'Witch of November' non-convective high wind event at 0015 UTC 11 November 1998. Radiances bracketing 240 K have been darkened to emphasize the 'mesoscale dry hook' in the upper troposphere over eastern Wisconsin. Wind gust reports (in knots) at 0000 UTC are contoured, highlighting the collocation of the mesoscale dry hook and highest surface wind gusts. From Iacopelli and Knox (2001).

the southern semicircle of the occluded low centre at its maximum intensity. Later, Grønås (1995) described in more detail a similar pattern in relation to the marine frontal cyclone conceptual model of Shapiro and Keyser (1990), in which the traditional occluded front is replaced with a bent-back warm front and warm seclusion. Noting the occurrence of a low-level jet on the outer side of the seclusion in a very intense Norwegian cyclone in January 1992, Grønås referred to this region of high wind as 'the poisonous tail' of the bent-back front, recalling his own forecasting experiences in Norway in the late 1960s.

In the past decade, research in Europe on non-convective high wind events has coalesced around this feature, which Browning (2004) has memorably labelled the 'sting jet' in analogy with the sting of a scorpion's tail. In his article, Browning analysed the October 1987 'Great Storm' observationally and inferred the presence of multiple banded structures in a hooked cloud head tip which were associated with high wind gusts. Browning (2004) concluded that 'upright and slantwise convection … may have played a role in the local enhancement of the already strong winds' – the enhancement leading to a sting jet. This work coincided with observational research by Reid and Vaughan (2004) indicating the ability of convection to mix stratospheric and boundary-layer air rapidly. In a follow-up article to Browning (2004), Clark et al. (2005) analysed high-resolution operational model output and confirmed the association between slantwise circulations and a sting jet descending from 650 hPa, beneath the dry intrusion rather than directly associated with it. Clark et al. distinguished between the sting jet and the warm and cold conveyor belts of the cyclone, noting differences in both location and altitude (Figure 9).

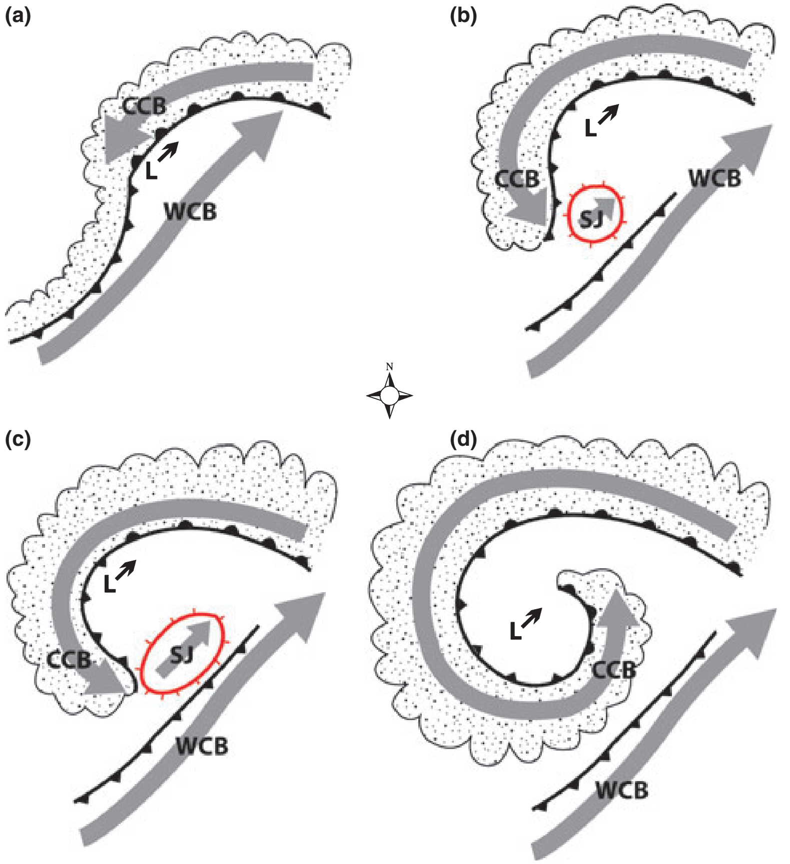

Fig. 9. Conceptual model of the near-surface flows in a marine extratropical cyclone, emphasizing the sting jet (SJ, in red). (a) Early stage of frontal wave cyclone development. L denotes low-pressure centre with direction of movement shown by thin arrow. Grey arrows show the storm-relative low-level jets; WCB is the warm-conveyor-belt jet and CCB is the cold conveyor-belt jet. (b) Frontal fracture phase, when the sting jet first appears at the surface. (c) As the cloud head wraps around the cyclone, the SJ region extends. (d) Eventually the SJ disappears and the dominant low-level wind in this region is due to the CCB. Modified from Clark et al. (2005), ©Crown copyright 2005, the Met Office.

Recently, Parton et al. (2009) provided direct observations of sting jet winds in the mid-troposphere gleaned from an October 2002 cyclone whose cloud tip passed directly over a wind profiler site in Wales. Their observations and complementary modelling simulations confirmed the existence of a sting jet in a marine cyclone exhibiting a bent-back warm front. The sting jet was associated with vertical circulations compatible with slantwise convection caused by conditional symmetric instability (CSI; Schultz and Schumacher 1999). Baker (2009) has also presented evidence of a sting jet in the intense 'Gudrun'/'Erwin' cyclone in the northern UK in January 2005, although in this case the sting jet was not responsible for the strongest low-level winds. However, the applicability of the sting jet hypothesis is so far limited to marine cyclones.

Past and Future Trends in Non-Convective High Wind Occurrences

Extreme winds are a very active area of research with regard to climate change. Because the rapid pace of work quickly renders any review obsolete, and in light of the considerable uncertainties associated with this subject in both the past and future, we limit the discussion here to a brief overview.

Instrumental and documentary evidence of storminess along the Atlantic coast of western Europe (Clarke and Rendell 2009 and references therein; see also Hanna et al. 2008) implies more or less unchanged patterns of high winds in this region over the past 150 years. However, other work (Paciorek et al. 2002) has revealed significant upward trends in extreme winds in both the north Atlantic and north Pacific basins from 1950 to 2000. Angel and Isard (1998) found that strong cyclones with central pressures ≤992 hPa more than doubled in frequency in the US Great Lakes region from 1900 to 1990, presumably leading to stronger winds. McCabe et al. (2001) subsequently obtained results similar to Angel and Isard's for the Northern Hemisphere mid-latitudes from 1959 to 1997. In the Southern Hemisphere, fewer but larger extratropical cyclones have formed in the mid-latitudes since the 1950s, and have been more intense in some regions, particularly to the south of Australia (Simmonds and Keay 2000).

Firm conclusions are not yet possible with regard to future predictions of extreme winds. Della-Marta et al. (2008), surveying a range of modelling results, stated that 'confidence in future wind-storm changes is low, although it seems likely … [according to IPCC] that there will be an increase in extreme winds over the north Atlantic and central Europe'. On the one hand, modelling studies such as Leckebusch et al. (2006) and Knippertz et al. (2000) have projected significant increases in the occurrence of extreme winds over parts of Europe, especially northwest Europe, during the 21st century. These extremes would be associated with a higher frequency of more intense extratropical cyclones (Leckebusch et al. 2006, figure 10) and would occur southward of centres of changing extreme cyclone activity, consistent with the location of non-convective high winds discussed in the previous section. On the other hand, Pryor et al. (2006), using downscaling techniques, found no substantial changes in near-surface wind speeds in the 21st century for northern Europe. In short, there is great uncertainty regarding future trends in non-convective high winds.

In the event that high winds become more common and more extreme in the future, the implications for society could be significant. Leckebusch et al. (2007), using the same modelling results as Leckebusch et al. (2006), estimated that storm-related losses to the UK and Germany could increase by up to 37% due to a greater number of extreme windstorms. Insurance-industry estimates of wind damage associated with climate change are somewhat lower, but are still in the billions of dollars per year in the UK alone (Association of British Insurers 2009).

An important factor in any such estimate is the increasing vulnerability due to rising population and development in the paths of these winds. As Pielke and Landsea (1998) and Pielke et al. (2008) have shown with regard to hurricanes in the USA, steep upward trends in damage can be attributed to these societal factors, not to changes in the frequency and intensity of the meteorological phenomenon itself. Thus, even in the absence of an increase in non-convective high winds, the human cost from these events could rise sharply in the future.

Conclusion and Avenues for Future Work

Non-convective high winds associated with extratropical cyclones occur across the globe. They cause fatalities and property damage on scales rivalling other, often better-known weather phenomena. It is our hope that this review article places non-convective high wind events in broader conceptual and geographical frameworks, bridging artificial cultural and scientific divides.

These events exhibit relatively consistent patterns in climatologies and case studies, from the persistence of southwest quadrant winds in the US Great Lakes to the collocation of highest winds with the tip of the comma cloud in European 'sting jet' cases. However, to date no one physical mechanism has been identified as causing non-convective high winds. Several different near-surface and mid-to-upper-tropospheric processes have been proposed, with the sting jet hypothesis gaining the most attention and momentum in recent years in the analysis of European marine cyclones.

There is some evidence for increased extreme winds associated with extratropical cyclones during the past half-century. Some, but not all, analyses of future climate project increased frequency and intensity of high wind events during the next century, due to changes in extratropical cyclone characteristics in a globally warmed world. Confidence in these predictions is low. If the predictions verify, however, the societal consequences could be very significant – especially given the increased societal vulnerability due to rising population and development.

Future research should benefit from bridging the artificial divides noted above. One such divide is between the climatological work carried out on non-convective high winds in North America and the many recent case studies of such events in Europe. Intercomparison of the research performed on both sides of the Atlantic may bear additional fruit. For example, the schematic for sting jets in Figure 9 seems to suggest a strong preference for south-through-west non-convective high winds, as found by Lacke et al. (2007) for the US Great Lakes region. Does this suggest that many or most such events in the Great Lakes are in fact sting jets? The Shapiro–Keyser cyclone model was developed for marine cyclones, not continental cyclones, and warm seclusions are not common in inland cyclones. But it is true that in at least one case, the Great Lakes have induced hurricane-like characteristics in an extratropical cyclone (Miner et al. 2000). Thus, the possible generalization of the sting jet hypothesis to other regions outside of Europe, and the cross-fertilization of climatological and case-study research on this subject are two promising avenues for future work. Additional research to elucidate the sting jet/CSI relationship, and to determine the relative importance of CSI versus other processes such as evaporative cooling, is also likely to clarify our understanding of these events.

Another area for future work that is currently being explored (Durkee et al. forthcoming) involves the quantitative comparison of different mechanisms for causing non-convective high winds. If no one mechanism is dominant in every instance, then it should be useful for researchers and forecasters alike to be able to differentiate between events that are, for example, primarily low-level and isallobaric in nature versus those with significant contributions from vertical advective processes (e.g. subsidence, tropopause folds, and/or sting jets).

With regard to trends in non-convective high wind events, a high priority for future research should be resolving conflicting results from general circulation model simulations and downscaling techniques. Additional palaeoclimate research using proxies for wind may also shed some light on past trends in extratropical cyclones and high winds during changing climatic conditions.

Pursuit of these avenues for future work should improve our understanding and forecasting of non-convective high winds. These improvements, we hope, will lessen the tragic consequences for those who find themselves, like the crew of the *Edmund Fitzgerald*, 'in the face of a hurricane west wind'.

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Short Biographies

John Knox is an assistant professor of geography in the atmospheric sciences program at the University of Georgia (UGA) in Athens, Georgia. His research interests focus on atmospheric and climate dynamics, including non-convective high winds, clear-air turbulence forecasting and inertial instability. Knox's research has been funded by NSF, NOAA and NASA and has appeared in leading atmospheric science journals. Knox received the 2010 T. Theodore Fujita Research Achievement Award from the National Weather Association. He is also the co-author of the award-winning introductory college-level textbook *Meteorology: Understanding the Atmosphere* (2007). Prior to coming to UGA, Knox taught at Barnard College and Valparaiso University. He received a BS in mathematics from the University of Alabama at Birmingham and earned a PhD in atmospheric sciences from the University of Wisconsin-Madison, and was a post-doctoral fellow at Columbia University in conjunction with the NASA/Goddard Institute for Space Studies.

John Frye is an assistant professor of Geography at Kutztown University of Pennsylvania. His research interests are land surface–atmosphere interactions, weather impacts on society, climate variability, and remote sensing applications in meteorology and climatology. His research has been published in *Journal of Applied Meteorology and Climatology*, *Monthly Weather Review*, *Journal of Climate*, and *Theoretical and Applied Climatology*. He earned a BS in journalism and an MS in geography from Ball State University and a PhD in geography from the University of Georgia.

Joshua Durkee is an assistant professor in the meteorology program at Western Kentucky University's Department of Geography and Geology. He received a BS in geography from Western Kentucky University, and MS and PhD degrees in geography from the University of Georgia. His research interests include synoptic and mesoscale meteorology/climatology, hydroclimatology, atmospheric circulation and teleconnections, remote sensing and GIS applications in the atmospheric sciences, and education assessment and reform in the atmospheric sciences.

Christopher Fuhrmann is Research Climatologist for the NOAA-Southeast Regional Climate Center and doctoral candidate in Geography at the University of North Carolina-Chapel Hill. His research interests are in synoptic climatology, weather and society, climate and human health, winter weather, and climate variability and change. He holds a BA in geography from UNC-Chapel Hill and an MS in geography from the University of Georgia.

Note

* Correspondence address: Dr John A. Knox, Department of Geography, University of Georgia, 210 Field Street, Athens, GA 30602, USA. E-mail: johnknox@uga.edu.

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