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A major midlatitude hurricane in the Little Ice Age

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Abstract

An unusually severe hurricane struck Nova Scotia during the Seven Years' War (1756-1763), causing exceptional damage to the ships of two naval fleets. Its impact was so much greater than that of modern storms that it warranted detailed study. Quantitative storm attributes were extracted from hourly entries in logs of multiple ships scattered by the hurricane. Wave height and wind data at multiple ship locations characterized storm intensity which was compared to storm surge calculated at two coastal sites. A comparison to modern Atlantic hurricanes suggests it was a major hurricane, likely Cat 4 intensity at landfall making it more powerful than any modern (post-1851) storm despite the colder climate of the Little Ice Age (LIA c1300-1850). Mean annual and multi-decadal climate trends did not capture the weather (days to weeks) that fueled this storm. Understanding its climatology and that of other major LIA midlatitude hurricanes can improve our understanding of natural variability and potential future impacts under warming oceans.

1.0 Introduction

On September 25, 1757, a powerful hurricane struck the coast of Cape Breton Island, Nova Scotia, Canada (Fig. 1). There would have had no record of the 'Louisbourg Storm' had it

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not coincided with a British naval blockade of France's Fortress Louisbourg during the Seven Years' War (1756-1763). Three French naval squadrons at Louisbourg and the blockading

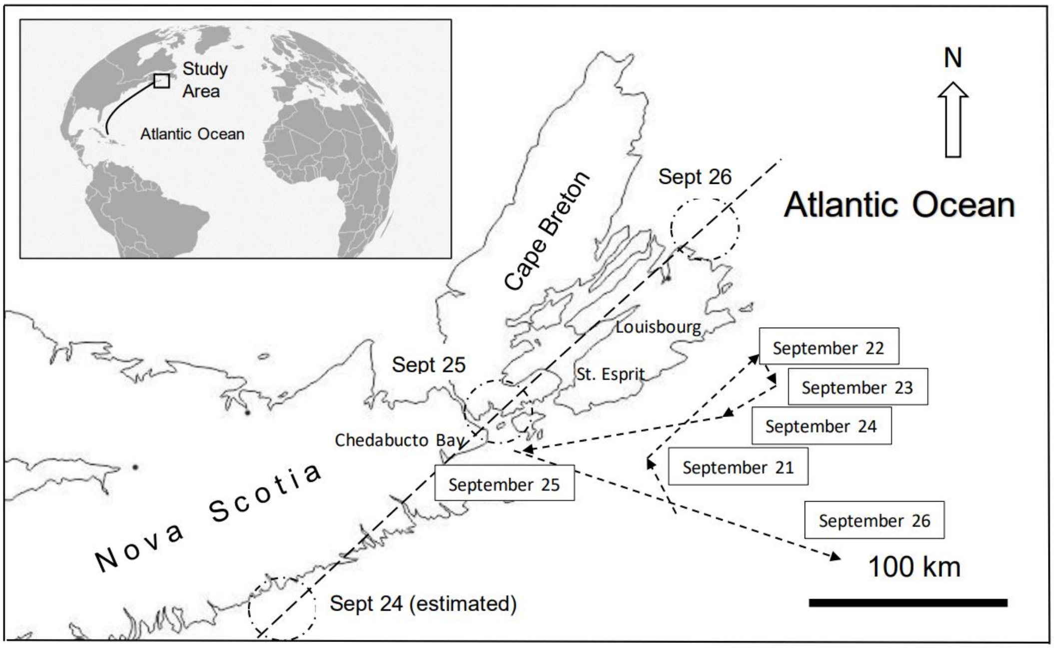

Figure 1. Study location in Nova Scotia, Canada. Arrow length and orientation represent the distance and direction traveled by the British fleet on September 21-26, 1757. Dashed line is the estimated storm track with eye locations for dates shown calculated from log entries of winds except for Sept. 24 which is estimated from logs plus Fort Cumberland winds. Inset shows the study area relative to the North Atlantic and the hurricane track based on historic records.

The British blockade placed 49 sailing battleships and warships in the path of a storm descriptions suggest was a major hurricane (Category 3+ on the Saffir-Simpson Hurricane Wind Scale). This would make it more intense than any landfalling storm in Canadian waters since modern records began in 1851 (Landsea et al. 2004, NOAA HURDAT data *in* Finck 2015), yet it struck during the colder climate of the 'Little Ice Age' (LIA; c1300-1850).

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Hurricanes are fueled by sea surface temperatures (SSTs) over 28C. They rapidly lose energy over cooler midlatitude waters where half undergo extratropical transition (Hart and Evans 2001). Modern tropical cyclone intensity is characterized in real time with instruments carried by aircraft, satellites and at ground stations. In contrast, pre-industrial metrics must be derived from historical observational records. Subjective interpretation and geographic bias can make them less reliable than instrumental data (e.g., Jones and Mann 2004), yet they offer a temporal resolution unavailable in scientific proxies, and they straddle the end of the LIA and the rise of modern anthropogenic emissions. Oliver and Kington (1970) and Lamb (1982) first explored their suitability for weather research. Naval logbooks were subsequently found to be a superior source of historical weather data given that hourly ship observations were systematically recorded in real time with a consistent terminology. Logbook data have been compiled to assess historical atmospheric circulation patterns (e.g., Garcia et al. 2001, Garcia-Herrera et al. 2005a, Wheeler et al. 2010, Barriopedro et al. 2014). CLIWOC, the Climatological Database for the World's Oceans, was compiled from British, French, Dutch and Spanish naval logbooks. It established a common historical wind force terminology to document ocean surface atmospheric circulation patterns between 1750 and 1850 (Garcia-Herrera et al. 2005b).

To date, pooled historic naval records were used to identify longer-term regional circulation patterns and extend the multidecadal climate signal into the industrial period (e.g., Garcia-Herrera at al. 2005a, b, Wheeler et al. 2010, Barriopedro et al. 2014). In contrast, this study takes advantage of an unusual concentration of warships in the path of a single hurricane to characterize its intensity. It seems counterintuitive that the colder LIA climate would generate more powerful midlatitude Atlantic cyclones than in the modern era, yet historical records show the LIA to be generally 'stormier' with unusually powerful midlatitude hurricanes despite

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conditions that dampen hurricane energy. This study seeks to take advantage of a unique historical data set to characterize the intensity of the Louisbourg Storm using spatial and temporal weather metrics extracted from ship logbooks and Admiralty records, and compare interpreted storm metrics to those of modern systems to ascertain if it was a major hurricane. Characterizing its intensity supports historical descriptions and proxies of unusually severe storms and sets the stage for more detailed LIA hurricane climatology.

2.0 Methodology

The logs of British ships at sea and French ships in Louisbourg Harbour contained: (1) dates and times, (2) positions, (3) bearings, (4) wind directions, (5) wind speed terms that evolved into the Beaufort Wind Scale (e.g., Garcia-Herrera et al. 2005a, b; Wheeler 2005; Wheeler et al. 2010), and (6) descriptions of sea state. In the 18th Century navigation and weather data were entered in the log starting at noon which marked the start of the sea day. Britain adopted the Gregorian calendar in 1752. In 1757 ships relied on a local meridian for longitude. British Admiralty records are preserved in England: Admiralty Correspondence and Papers (ADM1/481, 1488, 2294) cover storm damage to British vessels on the 'Halifax Station' in 1757, Fleet Lists (ADM8/31, 32) at the National Archives at Kew (UK), as are Royal Navy Master's (ADM 51/409, 633,1075) and Captain's (ADM 52/578,819,1064) logbooks. Lieutenant's logs (ADM51) kept at the National Maritime Museum, Greenwich, were often incorporated into Captain's logs with addenda. Master's and Captain's logs of the Royal Navy warships *Invincible*, *Windsor*, *Sunderland*, *Eagle*, *Terrible*, *Grafton*, *Newark*, and *Captain*, plus ancillary official correspondence, were used in this study. All logs were consistent in content and format. Letters and logbook entries written in cursive at sea were transposed, compiled into a time sequence and cross referenced. Logs from French warships *Fleur de Lys*, *l'Abenaquise*,

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Tonnant, *l'Inflexible* and *Dauphin Royal* translated from French describe conditions in Louisbourg Harbour (McLennan 1918). Wind directions from gimballed ships' compasses reference magnetic north. Bearings and wind directions used the 32 points of the compass (Smyth 1867, Blake and Lawrence 1999) and were translated to azimuths. The Beaufort Wind Force Scale covers winds up to hurricane threshold. 18th Century navies knew hurricanes common to the Caribbean sometimes reached North America's eastern seaboard. The modern Saffir-Simpson Hurricane Wind Scale provides a 1 to 5 storm intensity rating based on a hurricane's maximum sustained wind speed over one minute. Since no such real time wind force measurement existed in 1757, Virot et al.'s (2016) critical hurricane wind speeds that break trees provided a basis for estimating winds that broke ships' masts in the Louisbourg Storm.

3.0 The Little Ice Age (LIA)

Matthes (1939) named the LIA to explain European glacier expansion during a historically colder climate period. Heightened climate variability saw deeply cold winters and cooler mean annual temperatures primarily in the northern hemisphere (e.g., Kreutz et al. 1997, Mann 2002, Jones and Mann 2004). It may have been triggered by late 13th Century volcanic eruptions and a cooling feedback process sustained by Arctic sea-ice expansion (Miller et al., 2012). North Atlantic mean annual SSTs were 1-2°C cooler than today (e.g., Keigwin, 1996, Winter et al. 2000, Richey et al. 2009, Saenger et al. 2009, Cronin et al. 2010, Bertler et al. 2011, Mazzarella and Scaffeta 2018, Gebbie 2019). The Maunder Minimum, the coldest part of the LIA, (MM; 1645-1715) saw greater 'storminess' during polar air breakouts from Europe correlating to more frequent easterly gales in the English Channel and Approaches in 1685-1750 (Wheeler et al. 2010). Concentrated storm horizons in coastal dunes across western Europe and in Brittany and on France's Mediterranean coast correlate to the coldest part of the LIA

(Dezileau et al. 2011, Van Vliet-Lanoe et al. 2014, Sicre et al. 2016, Jackson et al. 2019). Dezileau et al. (2011) attributed LIA storminess to cold-enhanced lower tropospheric baroclinicity modifying prevailing westerlies. In the northwest Atlantic, Donnelly et al. (2001) described major hurricane deposits in New England coastal sediments dating to 1635, 1638 and 1815. Ludlum's (1963) compilation of historical northwest Atlantic hurricanes and tropical storms includes the LIA's major 'Independence Hurricane' that struck New England on August 29, 1775 and the 'Newfoundland Hurricane' of September 9, 1775, a storm that left 4000 dead to become Canada's deadliest hurricane (Ludlum 1963, Ruffman 1996).

Canada's Scotian Shelf on the Atlantic seaboard (Fig. 1) is dominated by the cold, south-flowing, low-salinity Labrador Current. It originates in the Davis Strait of the Canadian Arctic and hugs the coast to the start of the midlatitudes at Cape Hatteras, North Carolina where it meets, mixes with, and redirects seaward the tropical, north-flowing more saline Gulf Stream. The Labrador Current plays a critical role in hurricane extratropical transition (Hart and Evans 2001). Sediment cores from the Emerald Basin off Nova Scotia show 1600 years of cold Labrador Current temperatures show a sudden and sustained warming from 1850 to the present (Keigwin et al. 2003). Landsea et al. (2004) and Chenowith (2006) show a sharp increase in the number and percentage of historical Atlantic tropical cyclones striking eastern Canada since 1850 with higher storm frequency correlating to rising SSTs (Vecchi and Knutson 2008).

Historical records offer detail unavailable in annual to multidecadal proxy trends. Anomalous midlatitude coastal SST warming over days to weeks, conditions that fuel tropical cyclones, are not likely to appear in annualized data weighted by colder, sustained LIA winters. Jacoby and D'Arrigo's (1989) North American northern and Arctic temperature reconstruction shows above normal temperatures in the 1750's. Lieutenant John Knox recorded unusually high

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temperatures In Halifax on July 20, 1757, which fellow officers found hotter than Gibraltar and the Mediterranean (Knox 1769). This coincided with a heat wave in Britain and southwest Europe from July into early August that set records lasting into the 21st Century (The London Chronicle, July 23-26, 1757; London Magazine, November 1758 p. 563-4). London on July 16-26 had an average high of 41.2C (Nature Notes, 24 August 1882, p. 415). This does not assume weather conditions in Europe fueled a hurricane tracking into Atlantic Canada, but demonstrates that seasonal temperatures across the northern hemisphere known to intensify midlatitude hurricanes existed.

The one hurricane recorded in 1757 by Chenowith (2006) was first seen off Florida and followed the coastline past Cape Hatteras to New England on September 22-24 (Ludlum 1963). Benjamin Franklin's observations of this specific storm led him to conclude that hurricanes "are produced by currents of cold winds rushing from the north along the Atlantic coast and mingling with the warm winds produced by the gulf-stream" (Warden 1819). It passed New England on September 23-24 (Boston Herald, Oct. 17, 1757, Ludlum 1963) and struck Nova Scotia as the Louisbourg Storm on September 25, 1757. Its arrival at Fort Cumberland on the Nova Scotia border 200 km inland late September 22 included 'violent rain' and 'constant heavy rain' into the 23rd. Knox's journal on the 27th describes September 24-26 with … 'I never saw such storms of wind and rain as we have had for some days past…' followed by 'windy, showery and very cold' weather on the 27-28th and 'dry, cold windy weather' on the 29th, followed by frost and snow by mid-October (Knox 1769).

4.0 Historical Context

Great Britain's 'Grand Plan' for the Seven Years' War (1756-1763) North American campaign (Syrett 2008) began with John Campbell, the 4th Earl of Loudoun, appointed

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Commander-in-Chief of the British military in North America. His adversary was Louis-Joseph de Montcalm-Grozon, Marquis de Montcalm de Saint-Veran, commander of French forces in North America. To attack Montcalm at Quebec without leaving a powerful French fortress at his rear, Loudoun needed to first seize Fortress Louisbourg in Nova Scotia. On May 22 to 25, 1757, troops boarded 134 transport ships in New York to rendezvous at Halifax with a fleet departing Britain under Vice Admiral Frances Holbourne. Pitt's brief removal as Prime Minister delayed the fleet but his return to power with a coalition government saw it depart Cork, Ireland, on May 8, 1757. The delay allowed France to reinforce Louisbourg with three naval squadrons ahead of the British arrival. On May 23 five French battleships and a frigate under Chevalier Joseph de Beauffremont arrived from the West Indies, followed on June 15 by four battleships and two frigates under Joseph Francois de Noble du Revest from Toulon. On June 20 nine battleships and two frigates under Vice Admiral Emmanuel-Auguste de Cahideuc (Comte Dubois de la Motte) arrived from Brest. 4000 French troops bolstered a garrison of 3200 plus 300 Acadians and Mi'kmaq warriors (McLennan 1918, Stoetzel 2008). Holbourne's arrival at Halifax on June 30 bolstered Loudoun's force to create an army of 12 000. *HMS Gosport* arrived on August 5 with letters intercepted from a French schooner captured off Newfoundland detailing Louisbourg's reinforcement. It rendered the attack on the fortress untenable. Loudoun returned to New York and on September 11, 1757 Holbourne sailed his fleet north to blockade Louisbourg (Fig 1).

5.0 The Louisbourg Storm

Historic references include ship structure whose specifications are presented in metric converted from Imperial units. Square rigged ships' masts are, bow to stern, fore, main and mizzen. Heavy canvas sails were the sole means of propulsion.

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On September 21, Holbourne's 80-gun flagship *Newark* recorded fresh westerly gales followed by fair weather and light breezes then calm with fog on the 22nd. At Louisbourg an officer on the 28-gun frigate *Fleur de Lys* saw a low mist enter the harbour. *Invincible* also noted the mist which dissipated on the 23rd under a rising southeast breeze. *Newark* and *Fleur de Lys* found the breeze veered to the southeast and intensified into moderate gales. On the 24th *Invincible* and *Newark* reported increasing cloud, haze and rain under freshening southeast gales. French naval officers, expecting a storm, moored the fleet in two lines off Royal Battery (Fig. 2) with 4 x 2-ton anchors at the bow of each ship. The British fleet at sea secured masts and rigging and naval guns, weighing as much as 3 tons apiece, for heavy seas and strong winds.

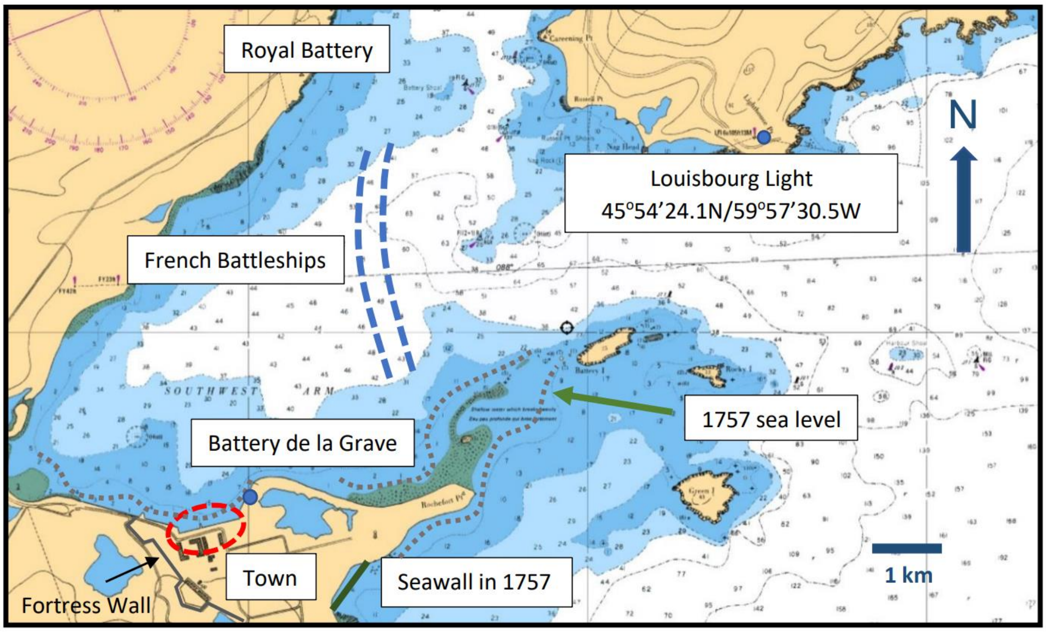

Figure 2. Louisbourg Harbour showing the French fleet anchorage, Louisbourg Lighthouse, Royal Battery, Battery de la Grave Guardhouse, and the southeast seawall overlain on chart image © Canadian Hydrographic Service (2011) Chart Guyon Island to Flint Island 1:37,866 [Issued 2022-11-26]. Shoals (shaded) relative to ship hull displacements of 5.8-7.0 m (19 to 23')

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give a general sense of the scale of waves and surge needed to throw battleships on shore and destroy the southeast facing seawall.

On September 25 fresh southeast gales rose to excessive hard gales with very heavy rain. *Windsor* also recorded heavy rain and mist under intensifying strong gales and hard squalls. At 7 *Sunderland* faced very hard gales that rose to extreme hard gales by 10. At 12 *Invincible* faced strong gales, torrential rains and a 'great sea.' At 2 a.m. *Invincible* faced an 'excessive hard gale' and 'a hurricane of wind' and mountainous waves. Topsails used to control ships in severe weather were 'blown to rags' and *Sunderland*'*s* main staysail was torn off. Waves 'made a free passage over…' the 70-gun *Devonshire* and smashed in *Lightning's* stern gallery. The wind carried off the 8-gun *Cruiser* sloop's mizzen mast and three sailors were swept away. *Cruiser* dumped its guns being 'very near foundering having been underwater several times.'

Windsor noted extreme gales, severe squalls, heavy rain and a great sea. Canvas tarpaulins were stripped off deck gratings, allowing waves and rain to flood the ships with up to 2.5 m (9') of water in the hold despite the pumps in operation. *Windsor* and *Sunderland* sailed S across SSW winds. *Grafton's* three-ton 7 m (30') rudder was torn off the ship. *Invincible*'s rudder was likewise damaged and saved only by its preventer chains. Sails were torn away. Flexural strain opened *Invincible's* hull planking and snapped the gun deck's iron reinforcing brackets, allowing the entire deck supporting tens of tons of artillery to drop several inches.

Sunderland's foretopmast, reinforced by 10 x 5 cm (2") rope shrouds plus stays, was torn off the ship and carried into the night with two sailors. *Invincible* was thrown onto her 'beam ends' (side), forcing it to heave overboard 10 x 12-pounder upper deck guns and carriages weighting roughly 20 tons to right the ship. *Invincible's* main yard was ordered taken down but before it could be done the wind broke the 38" (1 m) diameter mainmast 20' (6 m) above the

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deck. The falling mast tore down the foretopmast and mizzen mast and crushed the starboard gunwale. The wreckage pulled the ship over and swept sailors John Guttredge and Samuel Kivby into the sea. *Invincible's* crew cut the tangled mass away before it sank the ship.

The French officer at La Grave Battery (Fig. 2) led his men to safety when seawater rose over their knees (Chevalier de Johnstone 1758). French warships drifted in port while offshore the sea swallowed the British 14-gun *Ferret* sloop with its 104 crew. Around 6 a.m. *Invincible* saw five British ships dangerously close to shore. *Eagle* was blown onto its beam ends and jettisoned 10 upper deck guns and cut down its mizzen mast to right the ship. *Captain's* foretopmast was torn off and caried off with two topmen. *Lightning* drifted toward offshore breakers less than 200 m away. As Captain Faulkner ordered *Windsor's* guns jettisoned he saw that *Invincible* had lost all but its lower foremast and bowsprit.

Sunderland was swept by 'a very heavy large sea' that 'passed freely over us.' Barges lashed to the decks of *Windsor* and *Invincible* were smashed and swept overboard. *Sunderland* cut down its main topmast and threw guns overboard to right the ship. Its 61 cm (24") diameter mizzen mast broke off under the wind. Anchors did not slow its drift toward the offshore breakers. The mainmast was cut down and the ship stopped near the breakers under a kilometer from shore. The 74-gun *Terrible* also stopped near the breakers. *Eagle's* foretopmast was cut down to lessen the strain on the ship. It sailed past the breakers. *Newark's* anchor cable was cut and guns went overboard to regain control and also cleared the offshore reef. Dawn's light revealed a signal flag raised at the French fishing village of St. Esprit to give the British crews hope (Bristol Journal, November 12, 1757).

French warships at Louisbourg drifted under severe winds and waves. The 70-gun *Dauphin Royale* fired a gun in distress when its anchor cables snapped. It struck the 80-gun

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Tonnant, destroying its bowsprit, figurehead and cutwater, and damaging *Tonnant's* rudder and poop deck. The two ships snagged *l'Abenaquise's* anchor cables and the three entangled ships were heaved on shore at Royal Battery (Fig. 2). The *l'Abenaquise* frigate along with 25 merchant ships, 50 schooners and 80 small vessels were driven ashore, many high and dry, and many sailors drowned (McLennan 1918). By 10 a.m. the British fleet was close to being driven onto the breakers at St. Esprit. *Grafton* struck a rock but floated free and managed to anchor. *Windsor* and *Eagle* were able to avoid them by sailing south. *Eagle's* Captain Palliser saw *Nottingham* or *Tilbury* near shore, landward of the breakers with its bow in with its foremast and mizzen mast gone. It was afloat and attempting to wear (turn). Waves striking the coast tore down stone seawalls at the fortress and reached lakes 10 km inland. Seawater flooded the streets of Louisbourg, 'something never before seen' (Chevalier de Johnstone 1758).

Tonnant 'floated with the tide and the wind veered south, then west at 11 a.m. At 11:30 *Windsor* noted the wind had strengthened from the west. At noon *Eagle* recorded weakening squalls. On *Sunderland* massive waves swept sailor George Lancey off the fore yard 24 m (80') above the keel. By 3 p.m. waves at Louisbourg fell enough that *l'Inflexible* sent sailors to assist other ships. French captains petitioned 74-year-old Admiral Dubois de la Motte to attack the British but his orders to defend Louisbourg had been met and he kept his ships in port. James Johnstone, a Scot serving as a French officer, felt that five French warships could have captured the entire British fleet (Chevalier de Johnstone 1758). This sentiment was shared by Lady Anson, daughter of a confidante of Lord Newcastle with whom Pitt had formed his coalition government, in an October 31, 1757 letter to the First Lord of the Admiralty, her husband George Anson (Anson 1757). On September 27th a boat arriving at Louisbourg from St. Esprit announced that *Tilbury* had wrecked with over 120 lost. Four schooners with 160 French troops

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were unable to counter the heavy seas so they marched to the site across flooded land. Mi'kmaq warriors gaining the wreck informed the shipwrecked sailor they would not be harmed since the storm had brought them to their shores (Moreau St. Mery *in* McLennan 1918).

6.0 Wave Height

Wave height is a function of wind speed and duration, fetch and bathymetry. Comparison to ship dimensions provides an estimate. *Sunderland's* and *Devonshire's* bows were sufficiently submerged to tear away ships' boats lashed to the deck. As the ship crested each wave the 12.2 m (40') from the keel to the upper deck (Lavery 1983) provides a height estimate with another 3-6 m (15-20') needed to flood the deck and tear away 18 m (60' long) 3 ton boats. *Lightning*'s stern gallery windows 40-50' above the keel were destroyed by wave strikes from astern, suggesting significant wave heights of 12.2 m (60'). A sailor washed out of the fore yard by a wave infers a maximum wave height of 25 m (80') or more.

7.0 Wind

In this study the Beaufort Wind Force Scale is used to describe wind speeds from gale to hurricane force (63-118 kph). The Saffir-Simpson Hurricane Wind Scale describes hurricane winds greater than 118+ kph with peak windspeeds averaged over one minute defining hurricane intensity Categories 1-5. Wind speeds derived from log entries were plotted from the first southeasterlies to the diminishing westerlies at the storm's end. A best-fit windspeed curve passing through hurricane threshold speeds reach sustained critical wind force that broke masts, tore away sails and rolled ships onto their sides. Ephemeral squalls of 1 min duration above threshold winds under the one-minute duration of the Saffir-Simpson scale reflects Category 3-4 hurricane intensity. The hurricane threshold of 118 kph plus 'hard squalls' of 60+ kph is

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sufficient to mee the threshold wind speed of a major hurricane (178 kph), yet sustained winds pushed battleships onto their sides and tore away large diameter, reinforced masts.

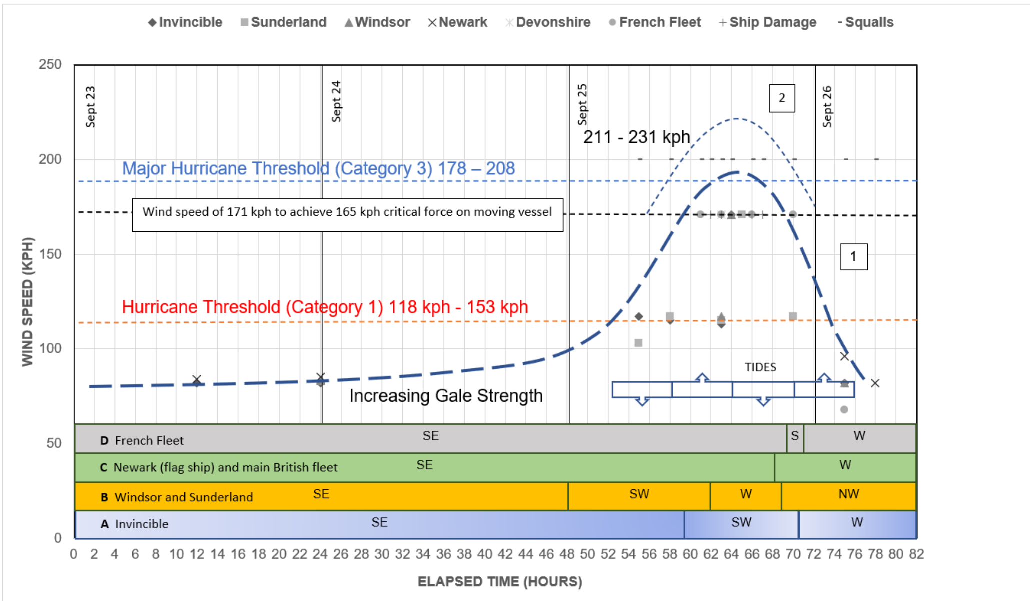

Figure 3. Hurricane wind evolution with time. The time sequence shows the arrival of southeast winds (Beaufort Scale) intensifying to hurricane winds (118 kph), peaking to sustained 171 kph critical wind force with increasing squalls, followed by a rapid decline to gale force westerlies. The horizontal axis is divided into days (noon) and 2-hour intervals. The vertical scale is wind speed in kph. A best fit curve [1] is typical of windspeeds as a hurricane passes a fixed point. A best fit curve for squall frequency [2] in ships' logs adds ephemeral wind speed increases to sustained winds. 171 kph is considered the minimum critical wind force considering the superior materials integrity of masts and their reinforcement with rigging. Wind directions represent, north to south, winds affecting: French ships at Louisbourg, British ships near St. Esprit, *Windsor* and *Sunderland* south of St. Esprit, and *Invincible* closest to the eye.

7.1 Wind Speed

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A 'gale' (Beaufort Force 8) was originally between a breeze (Force 2) and a violent storm (Force 11) and established a benchmark (Table 1). A 'near gale,' its diminutive (Smyth 1867) corresponds to a 'moderate gale.' Wheeler et al. (2010) categorized 'strong gale,' 'hard gale,' 'blew hard' and 'storm' as stronger than 'fresh gale.' Adjectives 'stiff' and 'fresh' indicate winds stronger than a gale (Force 9) while 'severe' or 'hard' reflect a 'storm' (Force 10). 'Excessive' and 'extreme' hard gale, necessarily stronger than a 'hard gale,' appears to correspond to 'violent storm' (Force 11) which does not appear in the logs. 'Hurricane' (Force 12) is mentioned in both French and British records.

Table 1. Logbook Beaufort Terms and Associated Windspeeds (kph).

Logbook Term	Beaufort Scale	Rating	Wind (kph)
Hurricane	**Hurricane**	**12**	**118+**
Excessive / Extreme Hard Gale	**Violent storm**	**11**	**103-117**
Severe / Hard Gale	**Storm**	**10**	**89-102**
Strong / Stiff Gale	**Strong Gale**	**9**	**75-88**
Gale	**Gale**	**8**	**62-74**
Moderate Gale	**Near Gale**	**7**	**50-61**
Strong / Stiff Breeze	**Strong Breeze**	**6**	**39-49**

'Squall' is a historical term for an increase in wind speed sustained above threshold for at least one minute. The National Oceans and Atmospheric Administration (NOAA) defines it as a sudden increase by at least 16 knots (33 kph) and sustained at over 22 knots (41 kph) for one minute. Environment and Climate Change Canada (ECCC) defines squalls as increases of 34 knots (63 kph) or more above prevailing winds sustained for over a minute. The World Meteorological Organization (WMO) uses 8 m/s and 11 m/s (29 and 40 kph) above threshold for over one minute while the American Meteorological Association (AMA) notes squalls are of

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'several minutes' duration. In considering these definitions 'squall' is taken to be a sudden increase in wind speed of 40-60 kph above threshold and sustained for at least one minute. We place 'hard squalls' at the upper end of the spectrum.

Masts were constructed from single fir and pine trees into the 1770's and selectively harvested in North America, Great Britain and the Baltic (Lavery 1984). Virot et al. (2016) determined the wind force to break trees is 151 kph irrespective of species and a +9% factor for large diameter trees gives 165 kph. It assumes structural defects from a longer life offset the advantage of size, yet masts were selected based on a lack of defects. Masts were not free-standing but reinforced to transfer wind energy from the sails to the hull. *Invincible's* masts were secured by 16 x 5 cm (2") hemp shrouds per side, each tensioned with paired deadeye blocks, the lower block in an iron band bolted to the ship's frame. *Invincible's* 1 m (38") diameter lower mainmast stepped against the ship's keelson rose 35.7 m (117') through two decks. Above it stood a 21.3 m (70') 51 cm (20") diameter topmast and above that the 10.7 m (35') 28 cm (11") diameter topgallant mast (Lavery 1984, 1988).

7.2 Wind Direction

French ships anchored at Louisbourg faced consistent SSE winds veering to westerlies on the 26th. *Invincible* sailed SW under SE winds, but it faced a gradual wind directional change to SW under a NE-tracking cyclone. *Sunderland* and *Windsor* sailed south across SSW winds, while ships to their north by St. Esprit led by *Newark* faced SSE winds. *Invincible* was among the southernmost ships, the first to face hurricane winds and suffered the most damage (Fig. 3). It sailed SW½W (230°) against EbS (101°) winds on September 24 (Fig. 1). On September 24-25 the ship's displacement was 98 km toward 256.7° (22.5 km S; 96 km W). 6 km SE (135°) of Ile

Chedabucto Bay it faced W (270°) winds and SE surface currents estimated at 3.49 kph based on currents of 0.97 m/s recorded there during Hurricane Juan in 2003 (CBCL Report 2015).

On September 25 to 26 *Invincible* sailed 159 km toward 102.75 degrees. The ship spent 11 hours under SE winds and another 11 hours under SW winds. The last 2 hours it drifted west under jury rig. The strongest winds were SW (225°). Cosine Law (Figure 4) gives a wind speed of 170.62 kph to achieve 165 kph at the mast on the moving vessel. The 5.62 kph difference infers vessel motion played only a minor role in reaching critical force yet is still 18% of the Saffir-Simpson Category 3 wind force range. Squalls of 40-60+ kph added to 170.62 kph yields 211-231 kph winds sustained for one minute, or Category 4 intensity. Normal lines drawn to anticlockwise wind vectors tangential to concentric cyclone wind bands converge at the eye and lack the asymmetry of extratropical cyclones (e.g., Hart and Evans 2001). Successive eye locations show the hurricane's track from landfall on Canso Peninsula and crossing Cape Breton before entering the Gulf of St. Lawrence.

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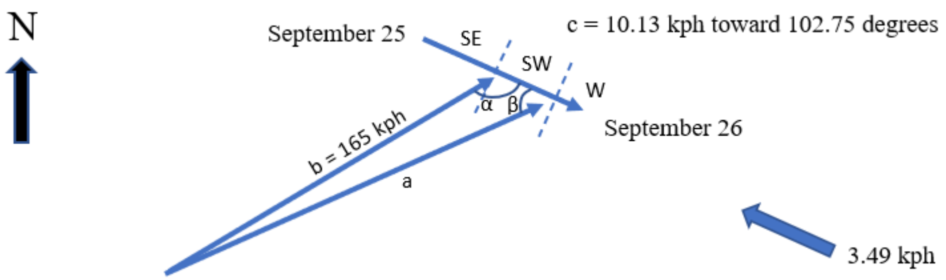

Using Cosine Law, we solve for velocity a where α is 122.25 degrees:

$a^2 = b^2 + c^2 – 2bc \cos α$

$a^2 = (165)^2 + (10.13)^2 – 2 \times (165 \times 10.13) \times \cos (122.25)$

$a^2 = 27{,}225 + 102.62 – 2 \times (1671.45) \times (-0.5336)$

$a^2 = 27{,}327.62 + 1783.77$

a = 170.62 kph from 227.75 degrees (where b = 165 kph and β = 55 degrees)

Figure 4. *Invincible* drifted 159 km toward 102.75° between September 25 and 26 over 24 hours. It experienced SE (11 hours), then SW (11 hours) and finally W winds (2 hours). This solution focuses on the 11 hours the ship was under SW winds, the strongest winds closer to the center of the cyclone (Fig. 3). During elapsed hours 59-70 the vessel sailed toward 102.75 under a SW wind (225°) at an average of 6.64 kph based on the total displacement of 159 km toward 102.75°. The incident angle between the wind and the ship displacement vectors is 122.25°. A surface current in Chedabucto Bay during Hurricane Juan (CBCL Report, 1995) of 0.97 m/s (3.492 kph) is assumed to be a reasonable estimate for this study. The resultant of 6.64 kph toward 102.75° indicates speed relative to surface currents was 10.13 kph. Image not to scale.

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8.0 Surge

Surge is a rise in sea level due to atmospheric pressure and storm winds and is proportional to a tropical cyclone's intensity and translation rate. Coastal surge is a reasonable estimate of storm intensity and can serve as a test of intensity derived from wind data.

8.1 Louisbourg Harbour

A Parks Canada coastal erosion study at Fortress Louisbourg National Historic Site revealed iron mooring rings set in the remains of a seawall. Modern high tide compared to these rings established historical high tide 0.90 m (3') of sea level rise since 1757 (Duggan 2010). La Grave Battery (Fig. 2) is 2.0 m (6.6') above sea level (asl; Google Earth mid-tide datum), so sea level rise plus flooding to sentries' knees (0.5 m) yields a 3.4 m (11') mid-storm surge. Historic buildings along the waterfront (Fig. 2; 45°53'33.57" N 59°59'07.89" W) are 5 m (16.4') asl while the first street, Rue Royale, is 7 m (22.9') asl. Seawater flooding the town streets at the lowest levels and adjusted for sea level rise indicates 5.9 m (19.4') to 7.9 m (21.4') of surge. *Tonnant* 'floated with the tide' when the wind veered south at 11 a.m. (*Fleur de Lys* log *in* McLennan 1918). Louisbourg's 12-hour tidal cycle and assuming low tide around 10 a.m. gives a high tide at 4 a.m. coinciding with storm landfall and creating a storm tide (Fig. 3). Backing out the 1.5 m (5') tidal range gives a 4.4-6.4 m (14.4-21') peak surge, consistent with the earlier surge of 3.4 m (11') at La Grave.

8.2 Tilbury Wreck Site

HMS Tilbury was a 58-gun square-rigged warship lost on the coast in the storm. *Eagle's* captain saw either *Tilbury* or *Nottingham* shoreward of the breakers near St. Esprit, 45 km south of Louisbourg. It was deduced to have been *Tilbury* since *Nottingham* survived the storm with a different array of masts than seen on this ship.

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Tilbury's gundeck was 147' (45 m) with a 42' (13 m) beam. It displaced 1888 tons, drew 18.1' (5.5 m) and its length to beam ratio of 3.5:1 provided warships the stability required of a floating gun platform (Lavery 1983). *Tilbury's* wreck offers a chance to estimate surge at a second location. This necessitates an exploration program to locate the wreck using historical research and a marine magnetometer survey. 'Wreck' on a 1776 chart and parish boundaries marked by fieldstone walls located historic St. Esprit (Fig. 4a, b). Storm (2002) used Zinck's (1975) image of an 18th Century 6-pounder British naval gun at 'Tilbury Rocks' to view Tilbury's wreckage in 4 m (15') from a boat in 1969. *Tilbury*'s location remained undisclosed under treasure trove laws and a letter from the British High Commission in 2006 reminded the Minister of Foreign Affairs Canada of the wreck's sovereign immunity and the wreck location remained undisclosed, forcing the present study to conduct a search.

For this exercise, Ship Lists of Royal Navy vessels in Nova Scotia in 1757 were consulted. Surviving logs of ships that had been in the hurricane were copied, translated and cross-referenced to position the fleet up to September 26 (Fig. 1). Longitude entries were deduced to be based on a zero meridian at Louisbourg Lighthouse (Fig. 2). A draft hydrographic chart (Hanson 1954) was digitized and gridded with missing data interpolated. Paired depths and locations were entered in a spreadsheet and a grid-plot of local bathymetry supported a marine proton magnetometer survey of Tilbury Reef isobaths following best practices for submerged archaeological sites (Cornwall Council Report 2010-R012). Dipole targets were investigated by divers who identified mid-18th Century wreckage including a 6-pounder British naval gun *in situ* in 3 m (10') depth near the 6-pounder on shore, both interpreted to be from *Tilbury's* forecastle. In 1757 *Tilbury* bow was observed at the time as 'bow in' near shore (2.1 m / 7' 1757 bathymetry), landward of the breakers and 'attempting to wear' (turn) in water sufficiently deep

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for its 18’ displacement as it was seen to be afloat and under sail. Adding in the hydrographic survey datum offset of 0.6 m (2’) between lowest low tide at St. Esprit and the Google Earth WGS84 (World Geodetic Standard 1984) mid-tide datum for Louisbourg suggests a minimum 4.0 m (13’) surge at St. Esprit. Post-storm relaxation flow stranded the *Tilbury* (Fig. 4b) and allowed native warriors to reach it.

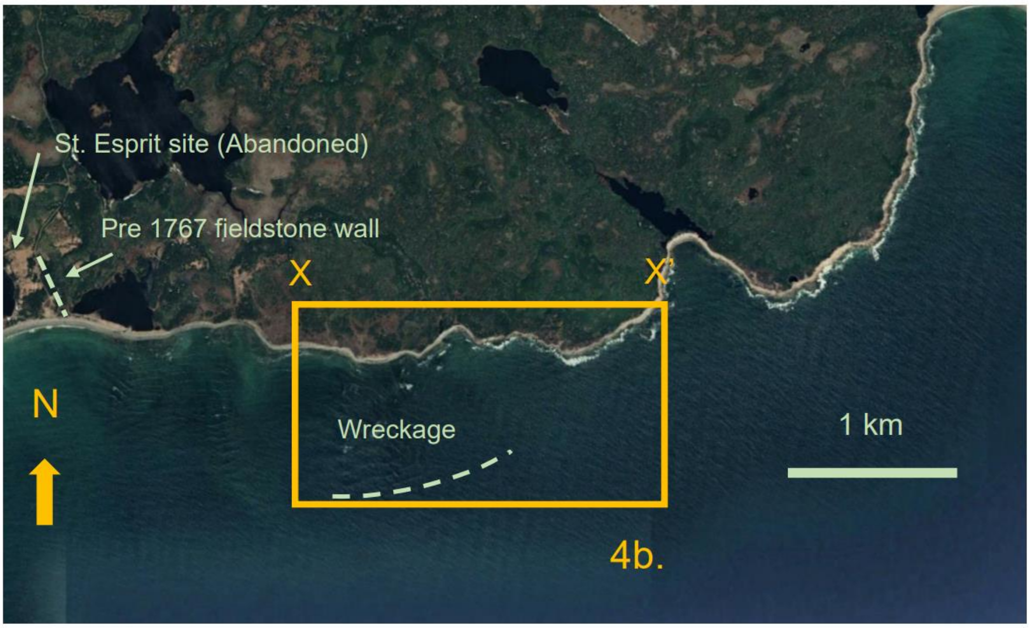

Figure 5a. Location of Tilbury shipwreck. Inset map X – X’ (45°38’31.21” N 60°27’41.99” W to 45°38’31.61” N 60°26’05.28” W) correspond to Fig. 5b. Satellite image © Google Earth Pro 7.3.6.9345 (2022) St. Esprit, Nova Scotia Canada. 45°38’31.54”N 60°27’37.76”W Eye alt 4.50 km TerraMetrics © 2023 MaxarTechnologies © 2023

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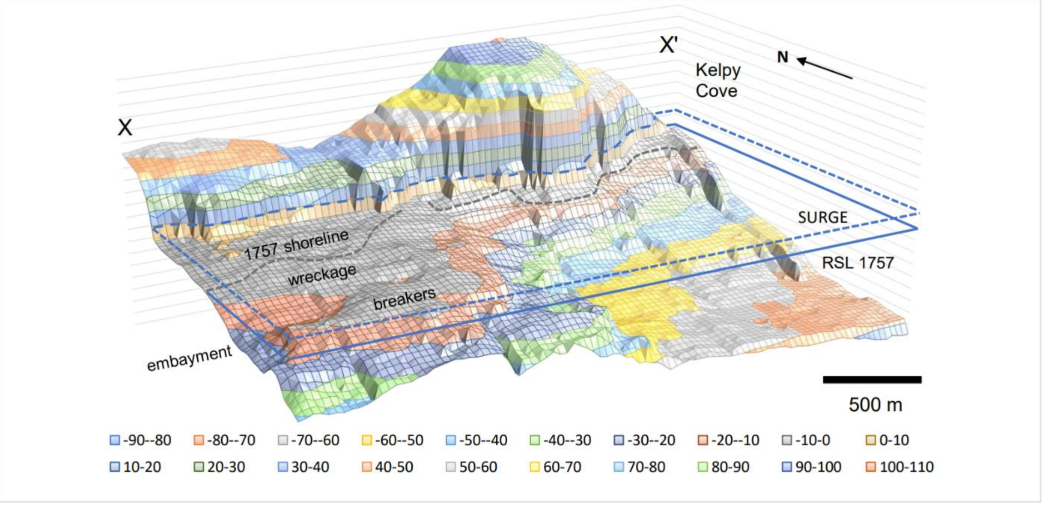

Figure 5b. Bathymetry of Tilbury site at lowest low water adjusted for 1757 relative sea level (solid line) and minimum surge (dashed line) needed to float Tilbury. Coastal retreat of 27 m (90') calculated from historic sea level gives the 1757 shoreline. Topographic and bathymetric data are in feet for comparison to Tilbury's displacement.

9.0 Modern Storms

On September 29, 2003, Hurricane Juan struck Nova Scotia with peak winds of 165 kph (Category 2), a significant wave height of 10 m (32'), a maximum wave height of 19.9 m (65') and a surge at landfall near Halifax of 1.5 m (4.9') (Lixion 2003). On January 20-22, 2000, an extratropical meteorological 'superbomb' that developed off Cape Hatteras struck Nova Scotia with peak winds of 25-30 m/s (90-108 kph), a significant wave height of 12 m (39'), a peak wave height of 19 m (62') to 23 m (77') at drilling rigs near Sable Island (JD pers. obs.) and a 1.4 m (4.6') surge at landfall near St. Esprit (Lalbeharry et al. 2009). Both cyclones produced similar sea states and surge which can be compared to the Louisbourg Storm. On September 24, 2022, Category 3 Hurricane Fiona began extratropical transition as it crossed the Scotian shelf. A cold

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trough over Nova Scotia directed its landfall to the Canso Peninsula. Winds of 140 kph in Nova Scotia reached 177 kph in Newfoundland and Labrador. Significant and peak wave heights were 17 m (56') and 30 m (98') and surge reached 2.4 m (8').

NOAA provides a database of Atlantic tropical cyclones (www.nhc.noaa.gov/data). In 1969 Hurricane Camille generated a 7.3 m (24') surge while Katrina in 2005 produced a storm tide of 8.2 m (27'). Laura in 2020 had a 5.2 m (17.2') surge. The first two were Category 5 hurricanes and Laura was a powerful Category 4 with a 2.7-4.0 m (9-13') surge spanned 130 km from Beaumont to Lake Arthur, Texas. In 2018 Hurricane Dorian (Cat 5) slowed to 2 kph over the Bahamas creating an 8.5 m (28') surge (Avila et al. 2020). Hurricane Juan's translation before landfall was 1-5 m/s (4-18 kph). Compared to North Atlantic hurricane translation rates of 17.7-19.3 kph (11-12 mph) the Louisbourg Storm slowing from 33 kph over water to 4.6 kph at landfall may have enhanced surge height, similar to Dorian over the Bahamas. The most intense rain, wind and surge of the right front quadrant enhanced storm impact on the coastline due to the slowing storm's oblique track down the axis of the island.

10.0 Discussion

On September 25, 1757, sailors '50 years afloat had never seen the sea so awful' and described 'a most terrible hurricane' (Chevalier de Johnstone 1758). The Louisbourg Storm delayed the capture of Louisbourg and delayed Britain's North American campaign. If the French fleet had seized the stricken British ships, a doubled naval force with 4000 French troops would have captured Halifax, changing the balance of naval power in North America and likely the outcome of the war.

On September 22, 1757, one day before the hurricane passed New England, southeast winds and heavy rains struck Fort Cumberland. On September 23 the British fleet at sea and the

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French fleet in Louisbourg harbour noted a wind direction change to the southeast. By the evening of September 25 winds reached hurricane force and lasted 16 hours, peaking in intensity at 4 a.m. and causing maximum ship damage. British ships off St. Esprit and French ships 45 km north at Louisbourg faced SE winds. British warships *Windsor*, *Sunderland* and *Invincible* south of the main fleet passed from the hurricane's front right quadrant's SE winds to SSW winds in its rear right quadrant (Fig. 6). They contain a hurricane's maximum winds, surge and rainfall.

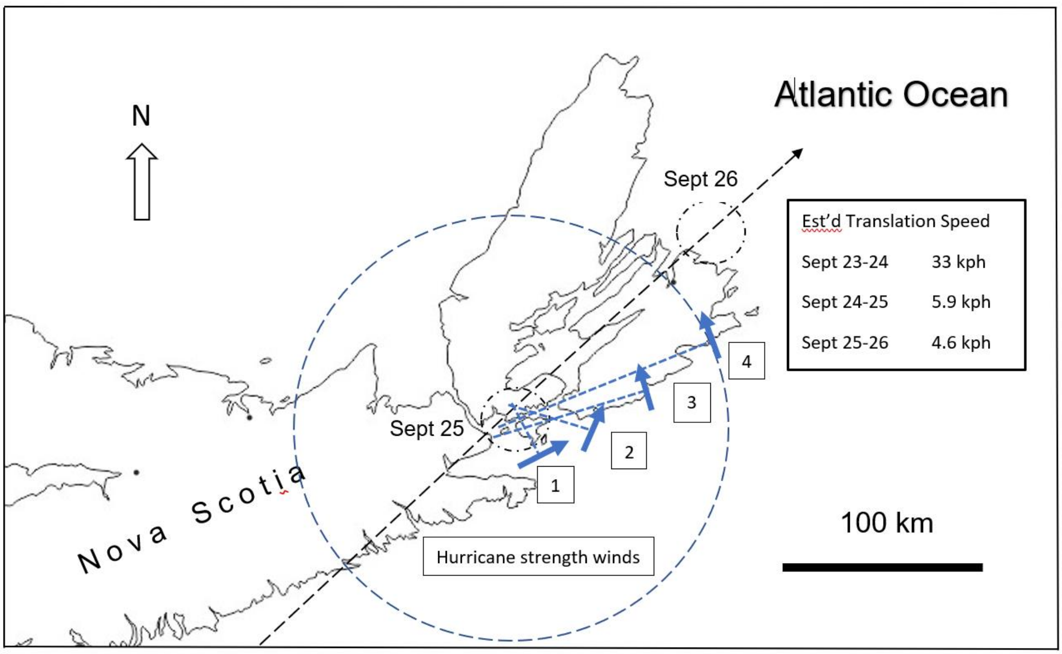

Figure 6. Hurricane eye position on September 25-26, 1757. Normal lines drawn from wind vectors at different ship locations converge at the eye. Successive eye locations give the storm track and allow translation speed to be estimated. 1. Invincible, 2. Windsor and Sunderland, 3. Newark and most of the British fleet, 4. French fleet at Louisbourg on September 25. Dashed circle is a reconstruction of the storm center on September 26 using the same method.

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Invincible was closest to the strongest winds at the eyewall which seems to be reflected in the greatest ship damage. *Sunderland* and *Windsor*, respectively, recorded WNW and NWbW winds as the storm passed, while *Invincible* drifted 159 km under SWbW to W winds. The storm crossed the Canso Peninsula and Chedabucto Bay, entered central Cape Breton and returned to the Gulf of St. Lawrence on September 26. Hard squall winds of 60+ kph added to the threshold of 118 kph alone would make the Louisbourg Storm a major hurricane. However, the severe damage to ships from sustained winds of 171 kph plus frequent squalls at this time of 40-60+ kph yields wind speeds of 221-231 kph, or Cat 4 on the Saffir Simpson scale. Surge height at Louisbourg greatly exceeds surge of all three modern Scotian Shelf analogs and while consistent with surge from various Category 4-5 hurricanes, it was still 100 km from landfall.

A blocking air mass over North America driven by the early onset of colder, more baroclinic autumn air fits the description by Benjamin Franklin. A hurricane following the coast drew energy from warm Gulf Stream waters which helped it intensify as it tracked north. Landfall slowed its translation of 33 kph over the ocean to 4.6 kph over land, possibly enhancing surge height further enhanced by a rising tide at landfall. An apparently symmetrical wind field suggests an inherently tropical system at landfall. Still, interaction with colder drier air under prevailing westerlies soon after based on weather observations at Fort Cumberland, and the unusual intensity of this system at landfall could argue for thermal energy release in the earliest stages of extratropical transition. The lack of any record of this storm in Newfoundland and Labrador or Quebec likely indicates it dissipated over the Gulf of St. Lawrence.

11. Conclusions

The Louisbourg Storm provides an unusual opportunity to characterize the intensity of a midlatitude LIA Atlantic hurricane. Historic records and proxy studies suggest more severe

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hurricanes made midlatitude landfall in the colder climate of the LIA than today which appears to be counterintuitive to the conditions needed for hurricane intensification in the midlatitudes. The Louisbourg Storm's intensity was characterized from empirical spatial and temporal data extracted from the logs of British and French naval vessels scattered across its path. The wind speed and direction indicate a large cyclone that appears to have intensified just prior to crossing the Scotian Shelf and may have been sustained by unusually warm coastal waters in the days to weeks prior. Our interpretation that the Louisbourg Storm was a major hurricane is supported by an exceptional coastal surge typically associated with Category 4-5 hurricanes. This storm was therefore more intense than any tropical cyclone in Canadian waters since the end of the LIA. It suggests that annual to multidecadal LIA climate studies may not capture the sub-seasonal (days to weeks) natural variability that can fuel exceptionally severe hurricanes in the midlatitudes. This indicates further research into the climatology of intense LIA hurricanes is warranted in order to determine what those forcing mechanisms might imply for hurricanes intensifying higher into the midlatitudes later in autumn given projections of warming oceans.

Data

Data used in this study can be made available under reasonable timelines

Author contributions

Both authors contributed to the study conception and design. Data collection and analysis were by John Dickie. Grant Wach supported scientific resources through the Basin and Reservoir Lab and commented on draft versions with both authors approving the final manuscript.

Competing Interests

The authors have no relevant financial or non-financial competing interests to disclose.

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ADM 51/633 Captain's Log HMS Newark (1755 Jul 31–1760 Apr 1)

ADM 51/1075 Captain's Log HMS Windsor (1755 Jun12–1759 May 20)

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