A Major Midlatitude Hurricane in the Little Ice Age

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Abstract

An unusually severe hurricane (Louisbourg Storm) struck Nova Scotia Canada in 1757. Historic records describing storm conditions as well as damage to ships and coastal fortifications indicate an intensity beyond any modern (post-1851) Atlantic cyclones striking the same region, yet this storm struck during a cold climate period known as the Little Ice Age (LIA). Its track and timing coincided with a British naval blockade of a French fleet at Fortress Louisbourg during the Seven Years' War (1756-1763). This provides a unique opportunity to explore growing scientific evidence of heightened storminess in the North Atlantic despite a colder climate expected to suppress hurricane intensification but which research is increasingly showing to have supported North Atlantic storms of exceptional strength. Weather attributes extracted from the logs of naval vessels scattered by the Louisbourg Storm provided multiple hourly observations recorded at different locations. Wave height and wind force estimates at ship locations were compared to extreme storm surge heights calculated for Louisbourg Harbour and a shipwreck site south of Fortress Louisbourg. Comparing these metrics to those of modern analogs that crossed the same bathymetry reflects landfall intensity consistent with a powerful major hurricane. Historical records show this storm originated as a tropical cyclone at the height of hurricane season and intensified into the northern midlatitudes along the Gulf Stream. Its intensity at landfall is

consistent with established seasonal climatological models where highly baroclinic westerlies driven by autumn continental cooling encounter intensifying north-tracking tropical cyclones fueled by sea surface temperatures that peak in autumn. Stronger seasonal contrasts from earlier and colder continental westerlies in the Little Ice Age (LIA) may have triggered explosive extratropical transition from a large hurricane resulting in a more severe strike. It suggests that tropical cyclones lasting days to weeks and the conditions that generate them are likely masked by cooler historic mean-annual to multi-decadal LIA climate reconstructions.

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 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

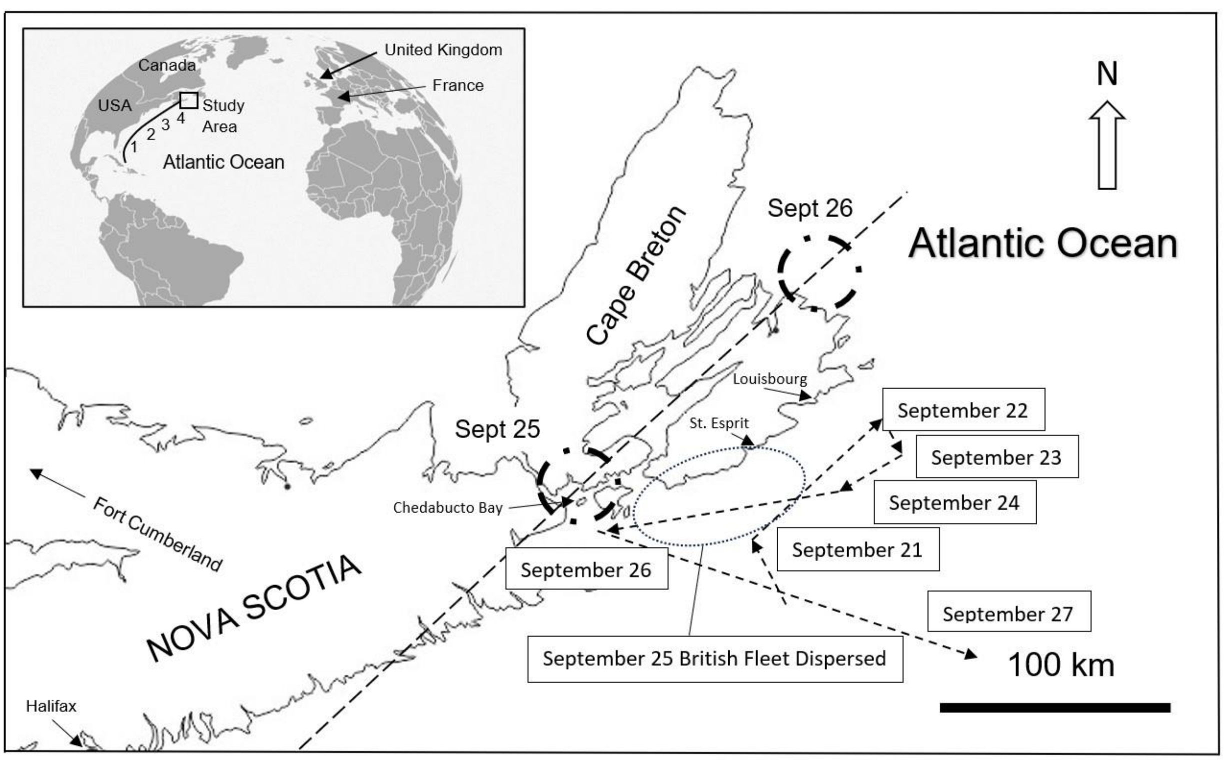


Figure 1. Study location in Nova Scotia, Canada. Arrow length and orientation represents the distance and direction traveled by the British fleet on September 21-26, 1757. September 25 and 26 show the path of the *Invincible* south of the wider dispersal of the British fleet after being scattered by the storm (dotted oval). The storm's location off New England is estimated (off map). The estimated storm track (dashed line) shows eye locations for the dates shown. Inset shows the study area relative to the North Atlantic and the hurricane track based on historic records showing its progressive northward translation seaward of (1) Florida (no date), (2) North Carolina (September 23), (3) New England (September 24) and (4) Cape Breton Canada (September 25-26). Fort Cumberland is 70 km toward 293 azimuth.

British fleet placed 49 sailing battleships and other warships (Supplemental Tables S1, S2) in the path of a storm descriptions of damage to ships and coastal infrastructure, severe flooding from rainfall and extreme storm surge suggest was more intense than any landfalling storm in Canadian waters since modern records began in 1851 (Landsea et al., 2004, Finck, 2015). This suggests it had the intensity of a major hurricane at landfall (Category 3+ on the Saffir-Simpson Hurricane Wind Scale) yet it struck during the colder climate of the 'Little Ice Age' (LIA; c1300-1850).

Hurricanes are fueled by sea surface temperatures (SSTs) over 28C. They rapidly lose energy as they move north over cooler midlatitude waters, and many tropical cyclones undergo extratropical transition which releases tropical energy at increasingly higher latitudes later in hurricane season (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 natural climate archives, 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 historical 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 historical naval records have been 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, 2005b, 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 conditions that dampen hurricane energy. Donnelly et al.'s (2001) historic storm reconstruction from Mattapoisett Pond, Massachusetts, and Oliva et al.'s (2018) historic storm reconstruction from Robinson Lake, Nova Scotia, are among a growing number of proxy studies showing that major Atlantic cyclones struck the northeastern seaboard of North America in the LIA. Since winter extratropical cyclones known as Nor'easters cannot be differentiated from

Atlantic tropical cyclones and their extratropical derivatives from proxy data alone, historical records can constrain the timing of midlatitude hurricanes and tropical storms.

This study utilizes a unique historical data set to characterize the intensity of the Louisbourg Storm using spatial and temporal weather metrics extracted from ship logbooks of both the English and French fleets, British Admiralty records and official documents of both nations, and compares the derived storm metrics to those of modern systems that tracked across the same bathymetry. Characterizing its intensity tests historical descriptions of an unusually severe storm and may help establish a more thorough understanding of LIA hurricane climatology.

2.0 Methodology

2.1 Historical Records

Eighteenth century navigation and weather data were entered hourly in the daily logs of naval vessels, resulting in reliable records suitable for historical climate research. A noon sighting of the sun fixed latitude and marked the start of the sea day. Britain adopted the Gregorian calendar in 1752 so dates in logs used for this study did not require correction. In 1757 a local meridian was used to determine longitude, deduced from logs to have been based on Louisbourg Lighthouse (Fig. 2).

Historical British Admiralty Correspondence and Papers (ADM1/481, 1488, 2294) covering storm damage to British vessels on the 'Halifax Station' in 1757 and Fleet Lists (ADM8/31, 32) are preserved 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. The first author reviewed all logs and found them to be consistent in content and format, then he copied letters and logbook entries written in cursive in multiple handwriting styles to a more readable format (Supplemental Fig. S1). These were interpreted, compiled into a time sequence and cross referenced. Logs from French warships *Fleur de Lys*, *l'Abenaquise*, *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 logs of British ships at sea and French ships moored in Louisbourg Harbour contained: (1) dates and times, (2) position, (3) bearing, (4) wind direction, (5) wind speed terms that evolved into the Beaufort Wind Scale (e.g., Garcia-Herrera et al., 2005a, 2005b, Wheeler, 2005, Wheeler et al., 2010), and (6) descriptions of sea state.

2.2 Climate Context

Major atmospheric circulation patterns that influence Atlantic tropical cyclone behaviour, specifically the El Nino Southern Oscillation (ENSO) and North Atlantic Oscillation (NAO), have been reconstructed for the historical period (e.g., Gurgis and Fowler, 2009, Trouet et al., 2012). These trends provide an overarching context since La Nina years create conditions conducive to driving hurricanes in the Atlantic, and a negative NAO allows Atlantic tropical cyclones to enter the Atlantic and potentially reach the midlatitude eastern seaboard. Atmospheric circulation patterns for 1757 were studied to assess overarching conditions conducive to Atlantic hurricane generation.

2.3 Wind Speed

Wheeler and Wilkinson's (2004) analysis of the derivation of the Beaufort scale shows terms that vary little from the logbook terms used in this study. A similar approach has been adopted here with adjectives describing primary nomenclature. 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 a 'severe' or 'hard' gale reflects a 'storm' (Force 10). 'Excessive' and 'extreme' hard gale, necessarily stronger than a 'hard gale' would then correspond to 'violent storm' (Force 11) which does not appear in the logs used here. 'Hurricane' (Force 12) is mentioned in both French and British records. '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 km h^{-1}) and sustained at over 22 knots (41 km h^{-1}) for one minute. Environment and Climate Change Canada (ECCC) defines

Logbook Term	Beaufort Scale	Rating	Wind (km h^{-1})
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**

Table 1. Logbook Beaufort Terms and Associated Windspeeds (km h^{-1}).

squalls as increases of 34 knots (63 km h^{-1}) or more above prevailing winds sustained for over a minute. The World Meteorological Organization (WMO) uses 8 m s^{-1} and 11 m s^{-1} (29 and 40 km h^{-1}) above threshold for over one minute while the American Meteorological Association (AMA) notes squalls are of 'several minutes' duration. In considering these definitions 'squall' is taken to be a sudden increase in wind speed of 40-60 km h^{-1} above threshold and sustained for at least one minute. We interpret 'hard' squalls as the upper end of the spectrum by applying the same historical adjectives used to create the historic Beaufort scale (Wheeler and Wilkinson, 2004). Heavy rains accompanying squalls noted in the logs appear to be consistent with descriptions of hurricane spiral bands.

In this study the Beaufort Wind Force Scale is used to describe wind speeds from gale to hurricane force (63-118 km h^{-1}). The Saffir-Simpson Hurricane Wind Scale describes hurricane winds greater than 118 km h^{-1} with peak wind speeds averaged over one minute defining hurricane intensity Categories 1-5. A major hurricane is Category 3 (178-208 km h^{-1}) or stronger. Wind speeds derived from log entries were plotted from the first southeasterlies noted off Nova Scotia on September 22, 1757, to diminishing westerlies at the storm's end on September 26. Ephemeral squalls of 1 min duration above threshold winds provide an estimate of total wind speed sustained for one minute or longer. Wind speeds at mid-mast height above the deck plus freeboard (distance from the waterline to the upper deck) approximate the 10 m height above ground level for modern hurricane wind speed measurements.

Eighteenth century navies knew hurricanes commonly encountered in the Caribbean sometimes reached North America's eastern seaboard. Since no real time wind force measurement existed in 1757, to measure and categorize hurricane intensity, this study has adopted Virot et al.'s (2016) engineering analysis of critical hurricane wind speeds that break trees as a model for estimating threshold wind speeds needed to break ships' masts. *Invincible's* log indicates it maintained course relative to prevailing storm winds. This placed the vessel oblique to wave crests which minimized pitch and yaw, and held masts within a stable plane of reference against which wind applied a sustained force. In addition, large vessels (74-gun third rates) with up to nine feet of flooding in the hold would have a lower center of mass that would have affected its righting moment and minimized directional variance in the wind force striking the masts. Rigging designed to stabilize the masts and transfer wind energy through the sails would likely have required a higher sustained wind force to achieve failure.

2.4 Wind Direction

Wind direction was measured using the ship's magnetic compass and entered in the ships' logs as 'points of the compass.' These entries were translated to azimuths. Compass directions are relative to magnetic north and not corrected for declination given the small study area and short time frame. Eighteenth century navigation was inaccurate but this study benefits from (1) log entries of the fleet relying on smaller vessels sent inshore to establish distance from coastal landmarks, and (2) during the storm ships were driven sufficiently close to land that their positioning entries were based on triangulation using landmarks which greatly improves accuracy. Experienced navigators were also able to correct for ship motion in their readings while the ship's position was typically determined by a Lieutenant plus one or more midshipmen and the sailing master's mate.

2.5 Wave Height

Wave height was estimated based on descriptions compared to ship dimensions and is the last accurate metric. Historic references to ship structure in Imperial Units have been converted to metric. This includes the distance from the keel to the upper deck and freeboard from the waterline to the upper deck. The depth of water needed to spill over the bow to flood the upper deck and tear away large ship's boats tethered to the deck is estimated. References such as sailors being swept off spars 24 m (80') above the waterline offers an estimate of peak wave heights. Warships were designed for stability as floating gun platforms and to return to an 'even keel' as quickly as possible after firing. Wave descriptions in Louisbourg Harbour are the least reliable since they include storm surge.

2.6 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. The surge height of modern analogs that struck Nova Scotia after tracking across the Scotian Shelf and whose intensity has been characterized with metrics derived using modern meteorological methods provides a reliable benchmark for comparison to surge calculated for the 1757 storm. In this study, storm surge at known locations and elevations above sea level were described at (1) Battery de la Grave at Fortress Louisbourg and (2) the historic town within the Fortress (Fig. 2), and (3) St. Esprit (Fig. 1) where the British warship HMS *Tilbury* was stranded in water depths it could not normally navigate given its displacement. All surge calculations were then corrected for (1) relative sea level (RSL) rise since 1757, and (2) a mid-tide RSL datum used by Google Earth versus a lowest low water (tide) datum used by the Canadian Hydrographic Service for a (draft) navigation chart used for the *Tilbury* wreck site. In addition, French records noting the tidal change at Louisbourg allowed for the timing of the tidal cycle to be backed out to determine storm surge versus storm tide.

Tilbury's wreck site offered a chance to estimate surge at a second location 45 km southwest of Louisbourg. *Tilbury*'s identity was confirmed in 1986 with the discovery of the ship's bell, most of its guns, anchors and artifacts (Storm, 2002). Locating the wreck to confirm its water depth required creating a digital bathymetric chart needed to guide a marine magnetometer survey leading to site confirmation by divers.

3.0 Little Ice Age Storminess

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 1-2ºC 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. (2015) 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). Lamb's (1991) exhaustive survey of British and European storms includes the Great Storm that devastated the British Isles on November 26, 1703. It was an extratropical cyclone equal to a Category 2 hurricane yet Wheeler (2003) notes a far more powerful Atlantic storm on December 1-12, 1792, also late in Atlantic hurricane season. Both were anomalous for a colder climate period.

The Scotian Shelf on Canada's 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 by providing a coastal buffer of cooler sea surface temperatures that effectively cut off the tropical energy of the Gulf Stream (Hart and Evans, 2001). Summer and fall bring warm water eddies from the Gulf Stream and warmer coastal SST. Sediment cores from the Emerald Basin off Nova Scotia show 1600 years of cold Labrador Current temperatures and a sudden and sustained warming around 1850 that has continued into the present (Keigwin et al., 2003) and coincides with the end of the LIA. Storm compilations by Landsea et al. (2004) and Chenowith (2006) show a progressive increase in the number of historical Atlantic tropical cyclones from 1700 and a sharp increase in the number and percentage reaching New England and eastern Canada beginning around 1850. Vecchi and Knutson (2008) in a study of data from the start of instrumental data collection in 1880 show a strong correlation between mean annual SST and storm frequency.

Historical records offer seasonal weather detail not captured by annual to multidecadal proxy trends. Anomalous midlatitude coastal sea surface temperatures (SSTs) over days to weeks, conditions that fuel tropical cyclones, are therefore not likely to appear in annualized data weighted by colder, sustained LIA winters. Northern and Arctic temperature reconstructions for temperate North America show cooler mean temperatures over the whole of the LIA (e.g., Jacoby and D'Arrigo, 1989 and Trouet et al., 2013). Trouet et al., (2013) demonstrate a multi-decadal warming to cooling trend peaking in the mid-eighteenth century.

Lieutenant John Knox recorded unusually high temperatures in Halifax Harbour 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 1757 that set temperature records that stood for over 250 years (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 unusually hot temperatures across the northern hemisphere capable of warming midlatitude SSTs that intensify midlatitude hurricanes existed in the summer of 1757.

The 1757 hurricane noted by Poey (1855) and Ludlum (1963) was confirmed as a hurricane, storm 73 in Table IV in Chenowith's (2006) re-assessment compilation. It 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 struck the British frigate *HMS Winchelsea* on September 23 to 24 at 36º45'N 70º 54'W (off North

Carolina over the Gulf Stream). The log notes gale force east then east-southeast and south winds between 10 p.m. and 5 a.m. on September 23 which, 15 minutes later, veered violently to the northeast and then northwest at 'near hurricane' intensity. It split the main sail and broke the main mast and was accompanied by a 'great sea' (ADM 52/1105).

The storm passed New England on September 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 across Nova Scotia by mid-October (Knox 1769).

4.0 Historical Context

The Seven Years' War (1756-1763) arose from unresolved issues following the Treaty of Aix-la-Chappelle that ended the War of the Austian Succession (1740-1748). It began as a European conflict between Great Britain and allies and France and its allies, but soon extended to the colonial interests of both nations in North America and India. It resulted in significant losses for France including the loss of New France, now Canada, to Great Britain (Syrett, 2008). Britain's overwhelming success in gaining territory at France's expense during the war led France to subsequently support the secession of the American colonies in 1775.

Great Britain's 'Grand Plan' for the North American campaign began with John Campbell, the 4th Earl of Loudoun, being appointed 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

The British fleet cruised off the coast of Cape Breton Nova Scotia (Fig. 1) to lure the French fleet out of Louisbourg Harbour to do battle. On September 21, the British 80-gun flagship *Newark* noted fresh westerly gales followed by fair weather and light breezes then calm with fog on the 22nd. That day an officer on the French 28-gun frigate *Fleur de Lys* saw a low mist enter Louisbourg Harbour. The mist was also seen at sea by the British *Invincible* until it dissipated under a rising southeast breeze. Britain's *Newark* and France's *Fleur de Lys* recorded that the breeze veered to the southeast and intensified to moderate gales on September 22. The *Invincible* recorded strengthening easterlies September 22-26 from otherwise prevailing westerlies through the second half of September (Table 2).

SEPT 16			SEPT 17			SEPT 18		
SW	SW	WSW	SW	W	NNW	NNW	NNW	NNW
225	225	247.5	225	270	337.5	337.5	337.5	337.5
SEPT 19			**SEPT 20**			**SEPT 21**		
NNW	NE	WNW	WSW	WSW	W	W	W	NNW
337.5	45	292.5	247.5	247.5	270	270	270	337.5
SEPT 22			**SEPT 23**			**SEPT 24**		
SE	*SSE*	*SEBS*	*SE*	*SE*	*SEBS*	*SEBS*	*SEBS*	*EBS*
135	*157.5*	*146.25*	*135*	*135*	*146.25*	*146.25*	*146.25*	*101.25*
SEPT 25			**SEPT 26**			**SEPT 27**		
EBS	SW	W	W	W	NW	SWBW	SEBS	WBS
101.25	225	270	270	270	315	236.25	146.25	258.75

Table 2. Prevailing Winds (*HMS Invincible* logbook)

Prevailing wind direction measured for each of three successive 8-hour watches per day and azimuth equivalent on the *Invincible*. Storm winds, arriving September 22, 1757, off Cape Breton, are shaded and in italics; two watches with easterlies not associated with the storm are shaded only. Mean 250.5 (WSW) prevailing wind direction six days before and five days following storm (continued westerly on 28 and 29). Mean 135 (SE) wind direction during storm. Ships off St. Esprit on September 25 saw prevailing southeasterly winds last until September 26. Ships south of St. Esprit including *Invincible, Sunderland* and *Windsor* faced southwesterly winds on September 25. 'B' stands for 'by,' a historical modifier defining a point of the compass (e.g., SWBW means southwest by west which is 11.25° west of southwest or 236.25 azimuth).

French naval officers, expecting a storm due to the southeast winds, moored the French fleet in two lines off Royal Battery (Fig. 2) with four 2-ton anchors set from the bow of each ship with four 20 cm diameter anchor cables. The southeast winds led the British ships at sea to secure masts and naval guns, weighing as much as 3 tons apiece, anticipating a storm. On the 24th *Invincible* and *Newark* reported increasing cloud, haze and rain beginning under southeast gales.

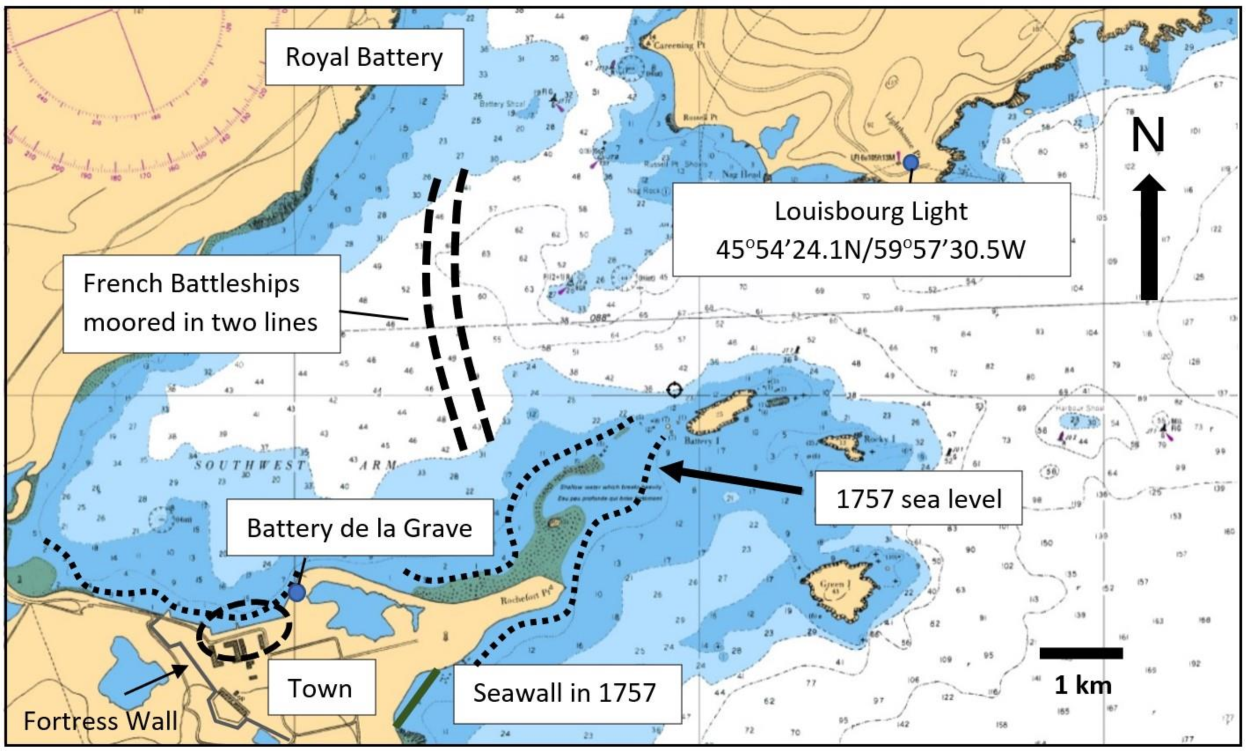


Figure 2. Louisbourg Harbour showing the French fleet anchorage, Louisbourg Lighthouse, Royal Battery, Battery de la Grave Guardhouse, and the southeast seawall overlain on chart image © Canadian Hydrographic Service (2011) Chart Guyon Island to Flint Island 1:37,866 [Issued 2022-11-26]. Shoals (shaded) relative to ship hull displacements of 5.8-7.0 m (19 to 23’) 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. The British *Windsor* noted heavy rain and mist and intensifying strong gales with hard squalls. At 7 p.m. *Sunderland* faced very hard gales that rose to extreme hard gales by 10 p.m. At 12 a.m. *Invincible* faced strong gales, torrential rains and a 'great sea.' At 2 a.m. on the 25th *Invincible* noted an 'excessive hard gale' and 'a hurricane of wind' and mountainous waves. Topsails used to control ships in severe weather were 'blown to rags.' *Sunderland's* main staysail was torn away. Waves 'made a free passage over…' the 70-gun *Devonshire* and smashed in *Lightning's* stern. The wind tore away the 8-gun *Cruiser* sloop's mizzen mast and three sailors were swept overboard. *Cruiser* was 'very near foundering having been underwater several times' and jettisoned its guns to stay afloat.

Windsor's log records extreme gales with severe squalls, heavy rain and a great sea. Canvas tarpaulins stripped off deck gratings by the wind allowed waves and rain to flood the ships which soon had up to 2.5 m (9') of water in the holds despite the pumps in full 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, also torn free, was only saved by its preventer chains. Sails on all the British ships at sea were torn away by the wind. Captain Bently later reported that *Invincible's* hull planking had opened and strain on the hull broke iron reinforcing brackets and bolts, allowing the entire gun deck and its tens of tons of heavy naval guns to drop several inches (Captain's Letters, ADM 1/1488). *Sunderland's* foretopmast, reinforced by ten 5 cm (2") rope shrouds plus stays, was torn off the ship and it disappeared into the night with two sailors. *Invincible* was thrown onto her 'beam ends' (side), forcing it to heave overboard ten 12-pounder upper deck guns and carriages, roughly twenty tons, to right the ship. *Invincible's* main yard was ordered taken down but before it could be done the wind broke off the 38" (1 m) diameter mainmast 20’ (6 m) above the deck. The falling mast tore down the foretopmast and mizzen mast and crushed the starboard gunwale. The wreckage pulled the ship onto its side and swept sailors John Guttredge and Samuel Kirby into the sea. *Invincible’s* sailors cut the tangled mass free before it sank the ship.

At Louisbourg, the French military officer at La Grave Battery (Fig. 2) led his troops to safety after the sea rose steadily above their knees (Chevalier de Johnstone, 1758). Offshore, the British 14-gun *Ferret* sloop under Francis Upton and a crew of 125 was lost with all hands. Around 6 a.m. *Invincible* noted five British ships dangerously close to shore. *Eagle* was blown onto its beam ends and jettisoned ten upper deck guns and cut down its mizzen mast to right the ship. *Captain’s* foretopmast was torn away and took its two topmen. *Lightning* found it was drifting toward offshore breakers less than 200 m away. Captain Faulkner ordered *Windsor’s* guns jettisoned. He noted *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. The wind snapped its 61 cm (24”) diameter mizzen mast as it drifted toward the offshore breakers. Anchors did not slow its drift so the mainmast was cut down. *Sunderland* stopped close to the breakers and less than a kilometer from shore (Fig. 3). The 74-gun *Terrible* also stopped its drift almost at the breakers. *Eagle’s* foretopmast was cut down to lessen the strain on the ship. It sailed southward narrowly missing the breakers (Fig. 3). *Newark* regained control after cutting the anchor cable and heaving guns overboard and barely cleared the line of breakers. Dawn revealed a signal flag had been raised by the French fishing village of St. Esprit to give the crews of the British ships hope (Knox Bristol Journal, November 12, 1757).

At Louisbourg the French fleet was pummeled by severe winds and waves. The 70-gun French battleship *Dauphin Royale* fired a gun in distress when its anchor cables snapped under the strain. *Dauphin Royale* collided with the 80-gun *Tonnant*, destroying its bowsprit, figurehead and cutwater, and damaged *Tonnant's* rudder and poop deck. The two ships crossed *l'Abenaquise's* anchor cables and the three entangled ships were heaved on shore at Royal Battery (Fig. 2) along with 25 merchant ships, 50 schooners and 80 small vessels, many high and dry and with many sailors drowned (McLennan, 1918).

At sea, by 10 a.m. the British fleet was dangerously close to the breakers off St. Esprit. Many sailors were certain they were doomed (Knox Bristol Journal, November 12, 1757). *Grafton* struck a rock but floated free and managed to set an anchor. *Windsor* and *Eagle* had been able to sail south of the main British fleet off St. Esprit. *Eagle's* Captain Palliser saw what he judged to be *Nottingham* or *Tilbury* near shore, within the breakers, its bow facing shore with its fore and mizzen masts gone. He also recorded that it was afloat and attempting to wear (turn) but lost sight of it in heavy rain.

Waves tore down sections of the French Fortress Louisbourg's massive southeast facing stone seawalls. Locals brought news of lakes 10 km inland being reached by the sea. Seawater rose to flood the streets of the Town of Louisbourg, 'something never before seen' (Chevalier de Johnstone, 1758). Eventually the beached French battleship *Tonnant* 'floated with the tide' as the wind veered south and then west at 11 a.m.

At sea the British warship *Windsor* noted the wind turned to blow from the west at 11:30 a.m. but had strengthened. *Eagle* recorded that the squalls had lessened by noon. On the *Sunderland* massive waves swept sailor George Lancey from the fore yard 24 m (80') above the keel. By 3 p.m. waves at Louisbourg fell enough that *l'Inflexible* was able to send sailors to assist other ships. French captains petitioned 74-year-old Admiral Dubois de la Motte to attack the stricken British ships off their coast 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 if they had ventured to sea could have captured the entire British fleet (Chevalier de Johnstone, 1758). This sentiment was subsequently 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 arrived at Louisbourg from St. Esprit with news that the British warship *Tilbury* had wrecked there with over 120 lost. Four schooners with 160 French troops

TIME	BRITISH AT SEA	WINDS	DESCRIPTION	FRENCH IN PORT	WINDS	DESCRIPTION
7 p.m	Sunderland	SSE	Very hard gales and hard squalls	Fleet	SE	Moored in Louisbourg Harbour
10 p.m.	Sunderland	SSE	Extreme hard gales			
10 p.m.	Windsor	SSW	Very heavy rain, intensifying strong gales			
			Hard squalls			
12 a.m.	Invincible	SW	Strong gales; great sea, torrential rain			
2-4 a.m	Invincible	SW	Excessive hard gale, hurricane of wind	La Grave Battery	SE	Sea level rises 3.4 m (11')
			seas like mountains,			
2-4 a.m.	Sunderland	SSW	topsails and staysails blown to rags	Dauphin Royale		Dauphin Royale collides with Tonnant
2-4 a.m	Devonshire	SE	Waves swept over the ship	Tonnant		Dauphn Royale and Tonnant driven across
2-4 a.m	Lightning	SE	Waves overrun and destroy stern gallery	l'Abenaquise		l'Abenaquise anchor cable and the three
2-4 a.m	Cruiser	SE	Waves sweep over the ship			entangled ships are thrown ashore at
			Guns jettisoned to avoid sinking	Royal Battery		Royal Battery
			Mizzen mast torn off ship by wind	Merchant ships		25 merchant ships thrown on shore
2-4 a.m	Windsor	SSW	Severe squalls, heavy rain, great sea	Schooners		50 schooners thrown on shore
2-4 a.m	fleet		Flooding by rain and waves	Small vessels		80 small vessels thrown on shore
	Grafton	SSE	Rudder torn off ship			
2-4 a.m	Invincible	SW	Rudder torn off ship	SE facing sea wall		Waves tear down fortress stone seawalls
		SW	Hull planking sprung; hold flooding	Lakes in region		Lakes 10 km inland flooded by the sea
		SW	Gun deck brackets/bolts snapped	Louisbourg		Seawater floods the Town of Louisbourg
2-4 a.m	Sunderland	SW	Foretopmast torn off ship			requiring at least 4.4-6.4 m (14.4-21') surge
	Invincible	SW	Driven onto its side by wind force			
		SW	Ten upper deck guns jettisoned			
		SW	Main mast snapped off which tears down			
		SW	foretopmast and mizzen mast			
		SW	Ship hauled onto its side by wreckage			
2-4 a.m ?	Ferret	SE?	Ship swallowed by the sea with all hands			
4-6 a.m	Invincible	SW	Near shore, sees five ships close to shore			
4-6 a.m	Eagle	SE	Driven onto its side by wind force			
			Jettisons guns and cuts down mizzen			
4-6 a.m	Captain	SE	Foretopmast torn off ship			
4-6 a.m	Lightning	SE	Near offshore breakers 200 m away			
4-6 a.m	Windsor	SSW	Jettisons guns to stay afloat			
4-6 a.m	Sunderland	SSW	Swept by waves			
			Barge torn off the upper deck by waves			
4-6 a.m	Windsor	SSW	Barge torn off the upper deck by waves			
	Sunderland	SSW	Driven onto its side by wind force			
		SW	Jettisons guns to stay afloat			
		SW	Mizzen mast torn off ship by wind			
		SW	Anchors at breakers 1 km from shore			
6-8 a.m	Terrible	SE	Anchors at breakers			
	Newark	SE	Clears breakers			
10 a.m.	Grafton	SE	Strikes rock near St. Esprit			
	Eagle	SE	Notes Tilbury near shore at St. Esprit			
	Tilbury	SE	Aground at St. Esprit			
	fleet	SE	Most ships dangerously close to shore			
11 a.m.	Windsor	W	Winds shifted to westerlies			
12 p.m.	Eagle	W	Squalls lessening in strength			
3 p.m	Invincible	W to NW	ship under jury rig drifting seaward	l'Inflexible	W	Waves reduced enough to assist other ships

Table 3. Timeline of Louisbourg Storm (September 25)

Timeline of storm impacts on the British fleet at sea increasingly scattered by the storm and the French fleet moored in Louisbourg Harbour. Relative ship locations, south to north, are blue, orange, green and grey. British ships were relatively static (drifting, sailing under reefed sails or at anchor) but *Invincible* sailed across storm winds to end up south of *Windsor* and *Sunderland*.

It is not known when *Ferret* sank but it had been sent ahead of the fleet prior to the storm to undertake reconnaissance of the French fleet at Louisbourg.

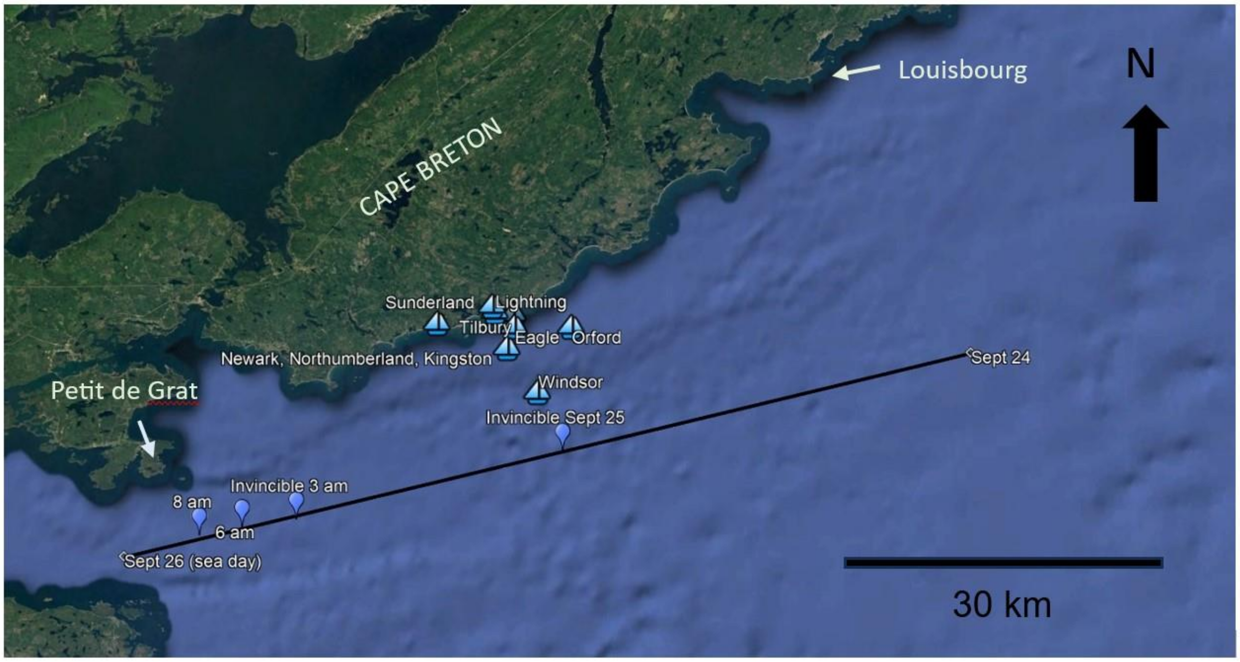


Figure 3. Location of British ships estimated for 8 a.m. September 25 (sea day). The fleet sailed in close formation until scattered by the hurricane south of Louisbourg (Fig. 1). Named ship locations reflect best estimates of ship positions based on logbook references to sightings and estimated distances and bearings to the coastline, known islands, Louisbourg, the breakers at St. Esprit and other ships. The displacement of Invincible is based on the ship's logbook entries for September 24 where the ship's position was fixed at noon with sextants to establish latitude with the sun highest in the sky marking the start of the sea day. The entry 45°36'N 0°12'E, correcting for 12' east longitude relative to Louisbourg Lighthouse as the zero meridian, corrects *Invincible's* position to 45°36N 59°45' W. *Invincible's* position on September 26 based on a bearing of NBE (11.25 azimuth) and 4 miles (5 km) from 'Peddigrah,' a phonetic spelling for 'Petit de Grat' gives 45°23'51" N 60°58'55" W. *Sunderland* halted its drift one km from shore when the anchor finally held. The southwesterly winds encountered by *Invincible, Sunderland*

and Windsor reflect the southernmost vessels sailing southwest into a northeast tracking storm. A displacement of 97.25 km toward 257.43 azimuth when the bearing was taken at 11 a.m. when the wind shifted to westerly (September 25; sea day), giving an average speed of 2.07 kmh^{-1} over 47 hours. Plotting the hourly displacement allowed the position of the ship to be estimated for noon, September 25, at the height of the storm at 3 a.m. and when the ship was dismasted at 6 a.m., and at 8 a.m. when the positions of multiple ships could be estimated when *Windsor, Sunderland* and *Invincible* were under southwesterly winds while the rest of the British ships were still recording south-southeasterly winds and when the British ship positions had been stabilized by anchoring or limiting their rate of drift. Logbook records: *Orford* 6 km from the coastline running northwest to north; *Windsor* 3 km from the breakers; *Terrible* 1.3 km from breakers and 3 km from the land to the west-northwest; *Lightning* 200 m off the breakers before halting its drift; *Sunderland* 1 km from shore after sailing SE across SW winds; *Tilbury* shoreward of the breakers; *Newark* near breakers with *Northumberland* and *Kingston* and *Windsor*; *Eagle* south of breakers until 11:30 when the breakers were 3 km to their lee. Image © Google Earth Pro 7.3.6.9345 (2022) Cape Breton, Nova Scotia Canada. Image date 12/13/2015 45°33’51.38” N 60°13’56.57” W Eye alt 132.12 km TerraMetrics © 2023 MaxarTechnologies © 2023.

were unable to counter the heavy seas so they marched to the site across land flooded by the torrential rain. Mi’kmaq warriors gained the wreck first but informed the shipwrecked British they would not be harmed since the storm had brought them to their lands (Moreau St. Mery *in* McLennan, 1918).

6.0 Deriving Storm Metrics

Storm intensity is reflected in key metrics including wind speed and direction, wave height and surge which is driven by a rise in sea level due to atmospheric pressure and sustained storm winds and is proportional to a cyclone's intensity, translation rate and the bathymetric gradient of the continental shelf.

6.1 Estimating Storm Wind Speed

The wind speed required to break *Invincible's* main mast, and other ships' mizzen masts and topmasts is estimated based on the engineering model of Virot et al. (2016) who determined the critical wind force needed to break trees of average integrity is 151 km h^{-1} irrespective of species with a +9% factor for large diameter trees. This is relevant since masts in 1757 were made from single trees. 165 km h^{-1} assumes structural defects due to longer tree life offset the structural advantage of size, yet masts were chosen for their lack of defects. Fir and pine trees of superior structural integrity were selectively harvested for Royal Navy masts into the 1770's from North America, Great Britain and the Baltic (Lavery, 1984). Masts were also not free-standing (like trees) but reinforced by rigging to effectively transfer wind energy from the sails to the hull. *Invincible's* masts were secured by sixteen 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. Its 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).

Invincible sailed SW under SE winds, but gradually encountered SW winds. *Sunderland* and *Windsor* sailed south across SSW winds while most ships of the British fleet to their north near St. Esprit faced SSE winds. *Invincible* was among the southernmost ships (Fig. 1). It sailed SW½W (230^o) against EbS (101^o) winds on September 24. During the storm its displacement was 98 km toward 256.7° (22.5 km S; 96 km W). 6 km SE (135°) of Chedabucto Bay it faced W (270°) winds.

Ephemeral squalls of 40-60 km h^{-1} added to sustained winds of km h^{-1} suggests peak winds might have reached 205-225 km h^{-1} around 6 a.m. when *Invincible's* mast broke. *Sunderland's* foretopmast broke at 7 a.m. and the mizzen mast broke at 9:30 a.m. While it is an imperfect solution, it does not consider the inherently superior structural integrity of masts plus their reinforcement by rigging, which requires only an additional strength factor to withstand an additional sustained 13 km h^{-1} to meet major hurricane threshold (178 km h^{-1}) without considering squalls.

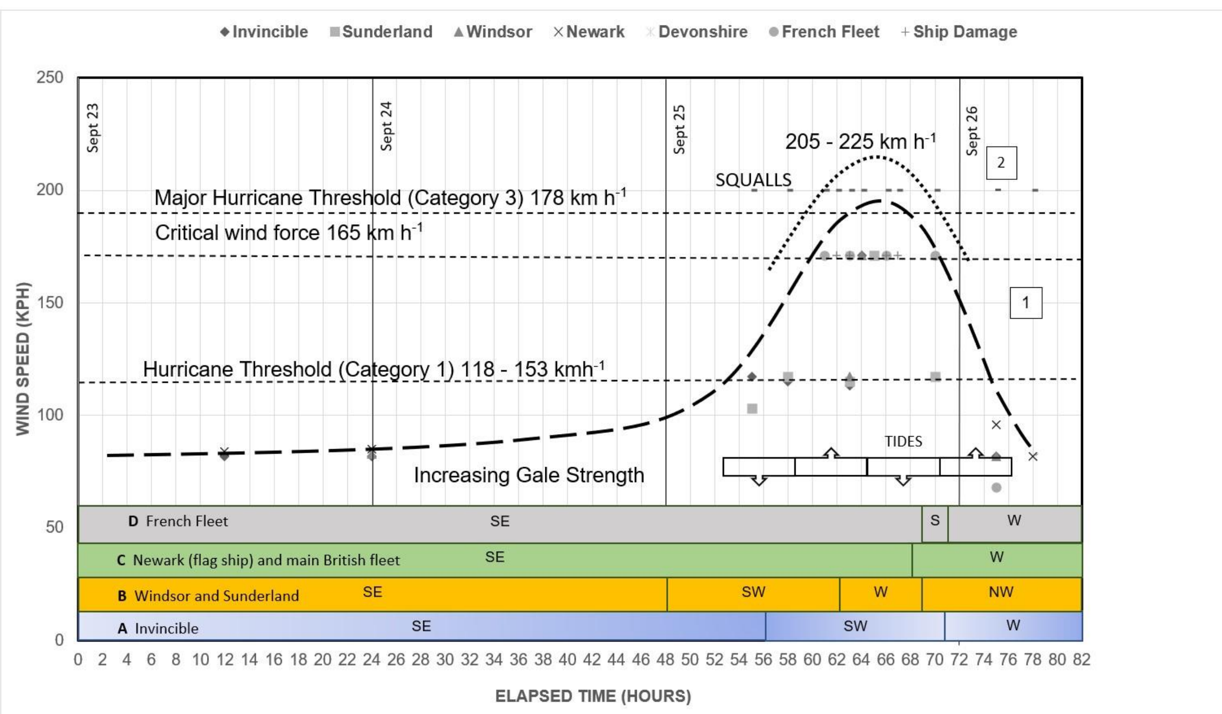
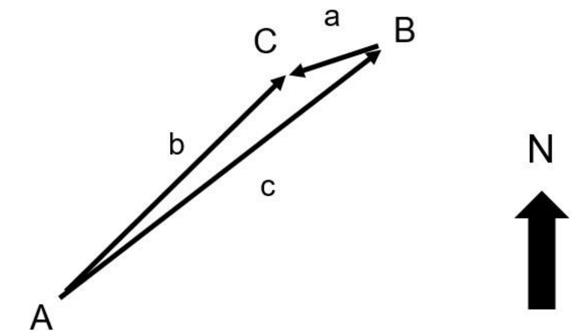


Figure 4. Hurricane wind evolution with time. The time sequence shows the arrival of southeast winds (Beaufort Scale) intensifying to hurricane winds (118 km h^{-1}) peaking to sustained 165 km h^{-1} critical wind force with increasing squall frequency, followed by a rapid decline to gale force westerlies. The horizontal axis is divided into days (noon) and 2-hour intervals. The vertical

scale is wind speed in km h^{-1}. 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 to sustained winds. 165 km h^{-1} is considered the minimum critical wind force considering the superior materials integrity of masts and their reinforcement with rigging. Peak winds lasted 9 hours while hurricane force winds impacting the fleet lasted 15 hours. 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 (Fig 1). Southernmost (blue) through southern (orange), off St. Esprit (green) and Louisbourg (grey) show the general distribution of ships (*see* Table 3). *Invincible* sailed past *Windsor* and *Sunderland* during the storm.



a = average speed of Invincible of 2.07 km h^{-1}

b = wind speed resulting from sailing close to the wind

c = southwest winds at 165 km h^{-1}

Angle B is 35° (the closest a square-rigged ship can sail into the wind)

Cosine B = 0.8192

$b^2 = a^2 + c^2 - 2ac \times \text{Cosine B}$

$b^2 = (2.07)2 + (165)^2 - 2\,(2.07)\,(165) \times 0.8192$

b = 163.31 km h^{-1}

Figure 5. Estimate of wind force at Invincible under threshold winds. Invincible, maintaining its bearing of SW½W of September 24 sailed into winds that progressively became SW (at the ship)

as the hurricane tracked northeast. Square-rigged ships cannot sail closer than 35^o into the wind. This reduced the wind speed acting on the masts by a minor amount, suggesting that squalls whose frequency corresponds to the frequency of ship damage (Fig. 4) were needed to overcome the reinforcing factors of superior mast structural integrity and rigging to achieve critical force. Not to scale.

Anticlockwise wind vectors at ship locations are tangential to concentric cyclonic wind bands. Normal lines drawn to these vectors converge to identify the location of the eye. Interestingly they lack the asymmetry diagnostic of extratropical cyclone wind fields (Fig. 8). This process, repeated to plot the eye location on September 26, 1757, indicates the storm crossed Cape Breton and entered the Gulf of St. Lawrence. Even if the wind field began to collapse, the location of the storm center suggests the system may have slowed while passing over Cape Breton Island.

6.2 Estimating Storm Wave Height

Sunderland's and *Devonshire's* upper decks were submerged after waves broke over the forecastle. The 12.2 m (40') distance from the keel to the upper deck plus an estimated 3-6 m (15-20') to break over the forecastle and tear away ship's boats lashed to the deck requires a wave height of about 18 m (60') (Lavery 1983). *Lightning*'s stern gallery 15-20 m (40-50') above the keel was destroyed by waves striking the ship from astern, also requiring waves of about 12.2 m (60'). A sailor swept out of *Sunderland's* fore yard by a wave necessitates a wave of about 25-30 m (80-90'). While carrying considerable uncertainty, these examples provide estimates of significant and maximum wave heights. Waves sufficiently large to tear down stone seawall ramparts of Fortress Louisbourg are consistent with these estimates, as are waves capable of reaching inland lakes. Descriptions of the sea state in Louisbourg Harbour by French naval officers resulting in extensive damage to ships and boats suggests waves much larger than any recorded in modern times even though wave energy from the southeast would have been partly attenuated by shoals (Fig. 2).

On September 26-28, 1818, the American frigate USS *Macedonian* met a hurricane off Bermuda (35ºN 53ºW) and suffered damage nearly identical to HMS *Invincible* in 1757 from waves of 12 m (40') (Saegesser, 1970). The dates appear to coincide with Chenowith's (2006) 'Final Storm Number 253' listed as a hurricane in Chenowith's Table IV. Damage to the ship closely parallels that described for the 1757 hurricane except that line of battle ships had a much heavier construction than a frigate. Saegesser (1970) provides a detailed account from the ship's log and ancillary damage reports, and notes that in the same storm the Dutch brig *De Hoope* lost all topmasts and spars, the brig *Ann* from Nova Scotia was abandoned at sea, the brig *Mary* from Bristol was overturned, the ship *Catherine Dawes* from Philadelphia sank and a Baltimore schooner and a Nantucket whaler were both dismasted. *Invincible's* substantially more robust build than the frigate *Macedonian* implies more intense storm conditions.

6.3 *Estimating Surge Height*

6.3.1 Surge at 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; 45º53'33.57" N 59º59'07.89" 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. on September 26 (*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. 4). 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.

6.3.2 Surge at St. Esprit (Tilbury Wreck)

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. ‘Wreck’ appears on a 1776 chart (Fig. 6). 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.

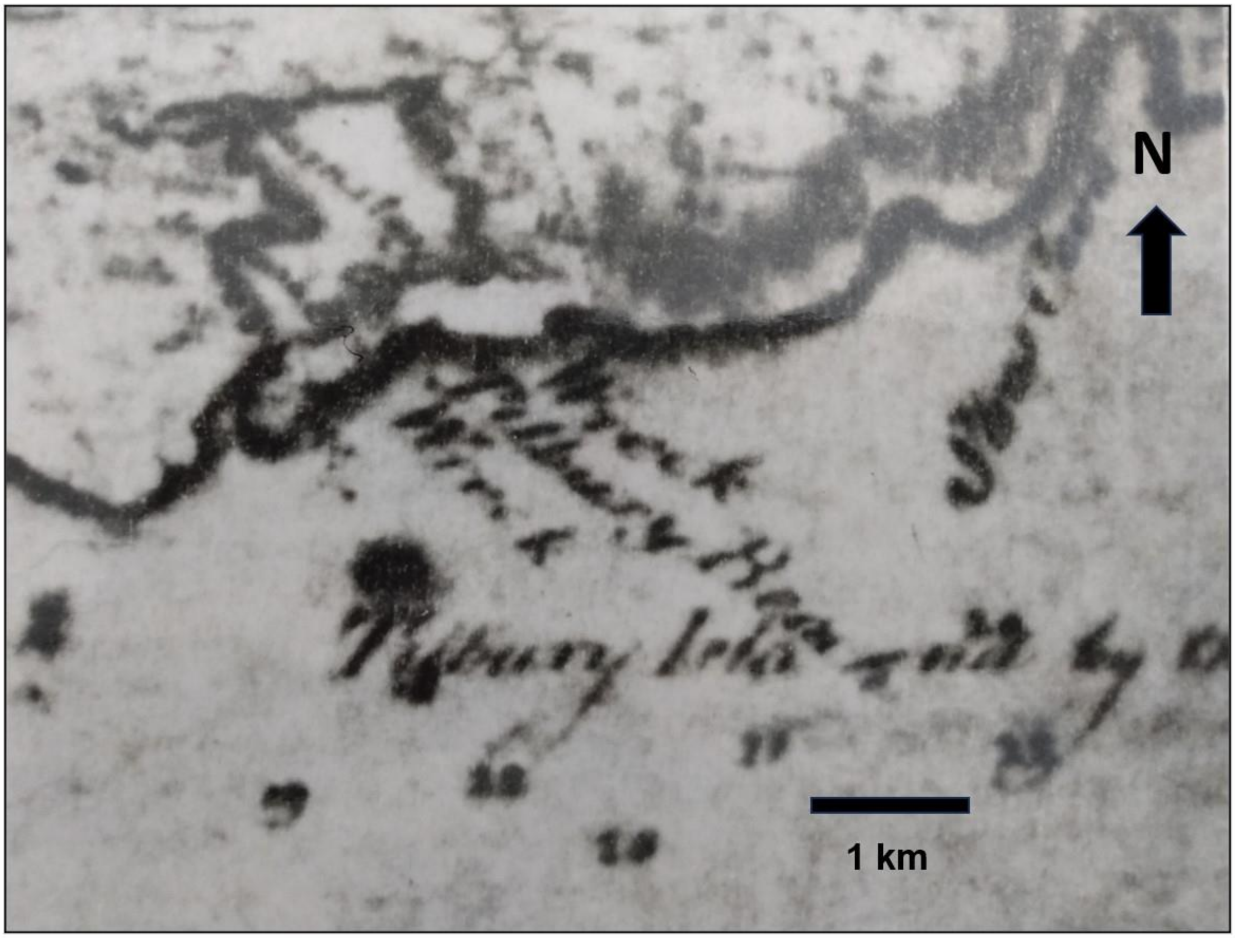
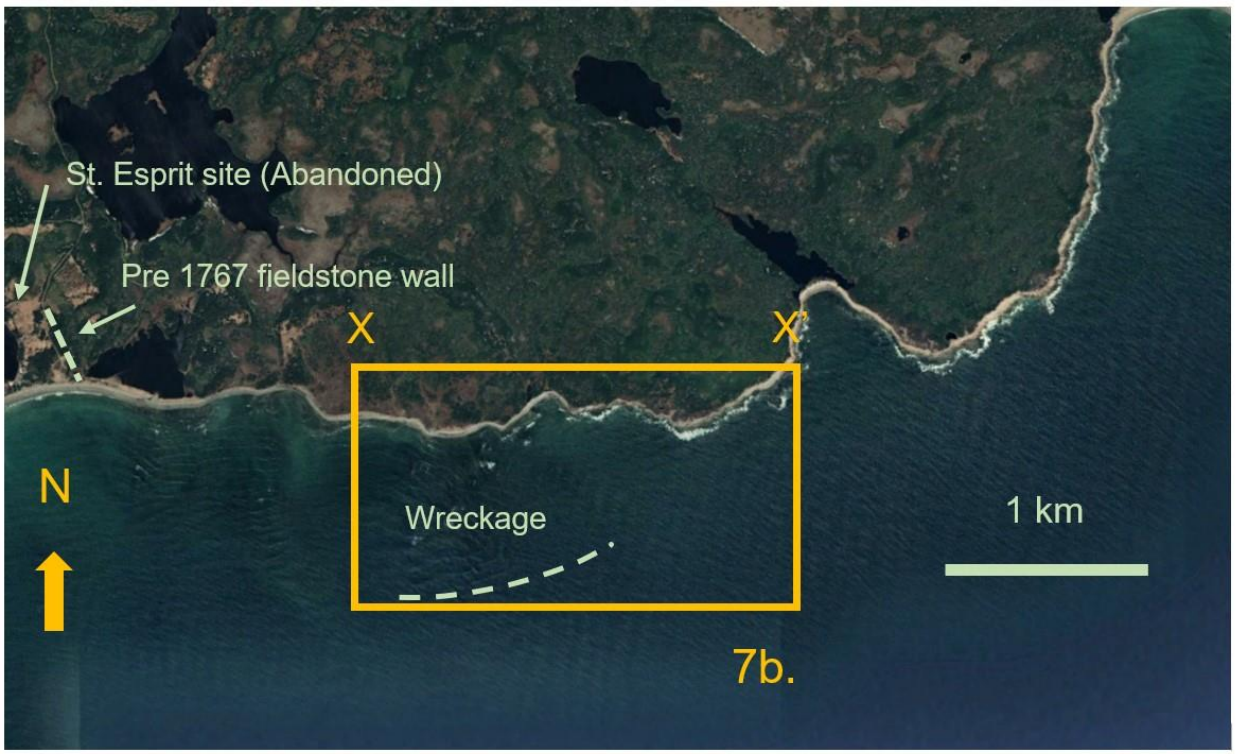


Figure 6. Excerpt from a historic chart of Cape Breton Island showing the general St. Esprit study area and *HMS Tilbury* wreck site, from Mowat (1776), depicted in Fig. 7a, b. The faint dotted line right of Barnsley Lake, named for *Tilbury's* captain, marks a parish boundary.

The historic navigation chart (Fig. 6) showed parish boundaries marked by fieldstone walls of historic St. Esprit (Fig. 7a, b) which helped identify the line of offshore breakers described in British naval logs. 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 investigated by divers led to locating a mid-18th Century 6-

pounder British naval gun *in situ* in 3 m (10’) which was 2.1 m (7’) in 1757, near the site of the 6-pounder on shore, both interpreted to be from *Tilbury’s* forecastle. In 1757 *Tilbury* was observed at the time as ‘bow in’ near shore, landward of the breakers and ‘attempting to wear’ (turn). It was in water sufficiently deep for its 18’ displacement as it was, at the time, 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. 7b) allowing native warriors to reach it.



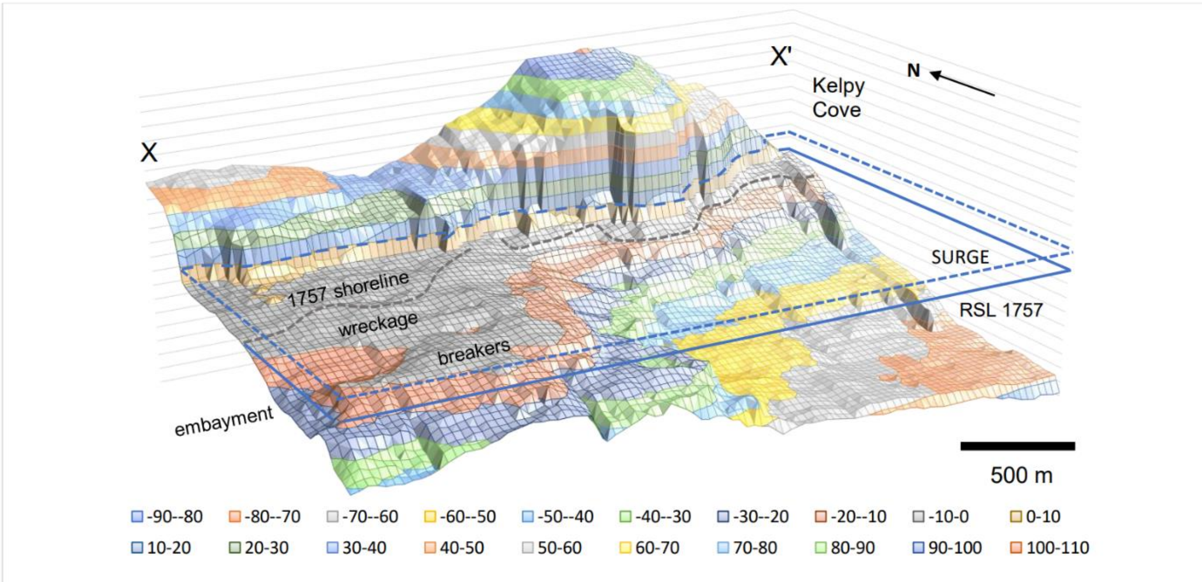


Figure 7a. Location of the *Tilbury* shipwreck. Inset map X – X’ (45°38’31.21” N 60°27’41.99” W to 45°38’31.61” N 60°26’05.28” W) corresponds to Fig. 7b. Dashed line is bedrock reef (breakers). Image © Google Earth Pro 7.3.6.9345 (2022) St. Esprit, Nova Scotia Canada. 45°38’31.54” N 60°27’37.76” W Eye alt 4.50 km TerraMetrics © 2023 MaxarTechnologies © 2023.

Figure 7b. Bathymetry of *Tilbury* wreck 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 were kept in Imperial units (feet) for comparison to *Tilbury’s* displacement. X and X’ of this block diagram correspond to the same GPS positions on the areal chart in Fig. 7a.

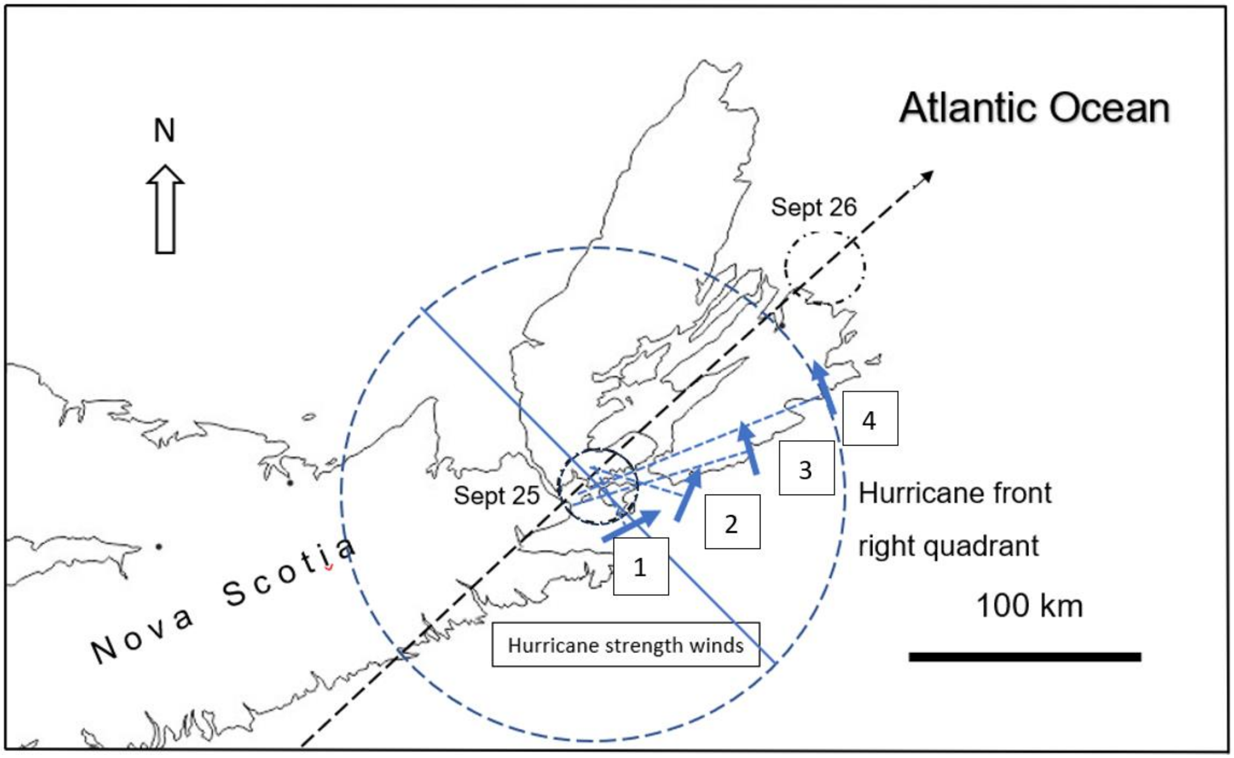


Figure 8. Eye location and estimated translation speed. Plots of wind vectors on September 25 (8 a.m.) at: (1) *Invincible*, (2) *Windsor* and *Sunderland*, (3) *Newark* and most of the British fleet, and (4) French ships at Louisbourg Harbour. Normal lines (dashed blue lines) taken to wind vectors cluster at the eye.

7.0 Modern Analogs

On September 29, 2003, Hurricane Juan struck Nova Scotia with peak winds of 165 km h^{-1} (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^{-1} (90-108 km h^{-1}), 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 trough over Nova Scotia directed its landfall to the Canso Peninsula. Winds of 140 km h^{-1} in Nova Scotia reached 177 km h^{-1} in Newfoundland and Labrador. Significant and maximum wave heights were 17 m (56') and 30 m (98') and surge reached 2.4 m (8').

In 1969 Category 5 Hurricane Camille generated a 7.3 m (24') storm tide from 1.8-3.0 m (6-10') surge (U.S. Department of Commerce Environmental Science Services Administration 1969) while Category 5 Katrina in 2005 produced a storm tide of 8.2 m (27') (Knabb et al., 2023). Hurricane Laura (Category 4) in 2020 had a peak 5.2 m (17.2') surge (Pasch et al., 2021) and a 2.7-4.0 m (9-13') spanning 130 km from Beaumont to Lake Arthur, Texas. In 2018 Hurricane Dorian (Cat 5) slowed to 2 km h^{-1} over the Bahamas creating an 8.5 m (28') surge (Avila et al., 2020). Surge from these major hurricanes cannot be readily compared to storm strikes in Nova Scotia due to different coastal bathymetry but they allow a general comparative benchmark.

Hurricane Juan's translation speed before landfall was 1-5 m s^{-1} (4-18 km h^{-1}). If the Louisbourg Storm slowed slightly as it approached Nova Scotia it may have enhanced surge height, similar to Dorian's impact on the Bahamas as it slowed which may explain the exceptional surge height at Louisbourg. The key metrics of wind speed, wave height and surge are summarized in Table 4.

Storm	Year	Date	Peak Wind (km h^{-1})	Significant Wave Height (m)	Peak Wave Height (m)	Surge (m)
Louisbourg	1757	25-Sep	205 - 225	12+	25-30	4.4 – 6.4
Unnamed	2000	22-Jan	90 - 108	12	19	1.4
Juan	2003	27-Sep	160 - 165	10	20	1.5
Fiona	2022	24-Sep	155 - 179	17	30	2.4

Table 4. Louisbourg Storm Comparison to Modern Nova Scotia Landfalling Storms. The Louisbourg Storm, a winter extratropical storm in 2000, Juan (Category 2 hurricane at landfall), and Fiona, an extratropical cyclone that transitioned from a Category 3 hurricane over the Scotian Shelf crossed the same coastal bathymetry with similar translation rates to strike Nova Scotia. Sustained winds for the Louisbourg Storm exceeded 165 km h^{-1} based on the critical force needed to break main and mizzen masts and break away and carry off topmasts and may have reached 225 km h^{-1} with squalls.

8.0 Discussion

Metrics derived from historical data captured during the Louisbourg Storm of 1757 indicate its intensity surpassed any modern (post-1851) Atlantic cyclones striking the same region. Historical records show the Louisbourg Storm originated in the tropics to pass Florida, the Carolinas and New England to strike Nova Scotia on September 25, 1757. It developed at the height of hurricane season under an optimal NAO (strongly negative) index and ENSO conditions (La Nina) for Atlantic hurricanes to form and track up the Atlantic coast of North America into the northern midlatitudes. The NAO index tends to decrease as the season progresses (Hart and Evans, 2001) and may have helped the hurricane remain over the Gulf Stream and intensify into higher latitudes. Its devastating impact on the British and French fleets and coastal infrastructure was due to an unusually violent release of energy over coastal waters. A UK and European heat wave in Europe in 1757, extreme even by modern standards, shows seasonal temperature variability could contribute to warmer SSTs and fuel tropical cyclones in the LIA. A strong correlation between SST and tropical cyclone frequency (Vecchi and Knutson, 2008) suggests that the LIA's cooler SSTs could see fewer storms per year. Mean-annual temperature data limited by temporal resolution limitations likely mask peak temperatures that must have existed over smaller areas for shorter periods since historical records (e.g., Chenowith 2006) clearly show tropical cyclones developed even during the coldest part of the LIA. A multidecadal warming-cooling trend in temperate North America peaking in the mid-1700's (Trouet et al. 2013) shows shorter-cycle warming within a cooler mean LIA. It suggests that the peak latitudes reached by midlatitude hurricane patterns should be compared to multi-decadal temperature cycles.

The large number of British warships scattered along Cape Breton's coast by the Louisbourg Storm provided a spatial resolution of wind vectors not normally available in storm reconstructions. It was partly facilitated by ships sailing across storm winds to avoid being driven ashore. The proximity of many British ships to shore (Fig. 3) and the severe surge and wave action at Louisbourg led many contemporary naval authorities of both nations to fear the catastrophic loss of the British and French fleets and almost 21 000 sailors. Only the reversal of wind direction at the last minute as the eye of the storm passed prevented a disaster.

Wind speed is the key metric used in the Saffir Simpson scale to characterize the intensity of modern cyclones. Engineering models are a standard method of determining the force required to trigger structural failure in materials. Trees lacking defects that negate size advantage were preferentially selected for masts and so likely required higher wind speeds for structural failure. Rigging not only reinforced masts but redirected wind energy to the hull. Both factors imply that the wind speed estimate of 165 km h^{-1} is an underestimate while the 178 km h^{-1} (Cat 3) major hurricane threshold requires that increased strength factor to only be equivalent to 13 km h^{-1}. Extreme winds are reflected in topmasts (along with shrouds and stays) not only being torn off two British ships but being carried off (with sailors) instead of falling to the deck. British ship positions were triangulated against known coastal landmarks, including the offshore breakers at St. Esprit, and each other. This provided greater accuracy in wind vectors for the period 8-10 a.m. Superimposing *Invincible's* location and the wind vectors that identify the eye location at the height of the storm suggests severe damage was a consequence of proximity to the eye which is the location of a cyclone's strongest winds (Figs. 1, 4, 8). Peak damage and squalls above hurricane winds lasted 9 hours and hurricane force winds noted by the British ships lasted more than 15 hours as the center of the storm passed the coast (Fig. 4). In comparison, Hurricane Juan crossed Nova Scotia in only 3 hours while Fiona crossed the province in under 6 hours (Fig. 8). The Louisbourg Storm may have slowed approaching Nova Scotia. Rough estimates of the storm position off North Carolina, New England and Nova Scotia suggest a translation speed of 33 km h^{-1} between the Carolinas and New England in 24 hours, and 19 km h^{-1} based on 42 hours to cross 800 km to land at Chedabucto Bay (Fig. 8) by 8 a.m. on September 25, crossing the remaining 113 km in 4 hours yielding an estimate of 28 km h^{-1}. There is significant uncertainty associated with these estimates, but if the hurricane slowed between New England and Nova Scotia, its location over the Labrador Current while encountering prevailing westerlies (Table 2) may have created a strong temperature gradient known to trigger extratropical transition (Hart and Evans 2001) where stronger gradients drive more rapid intensification and greater destructive power (e.g., Day and Hodges, 2018, Studholme et al., 2022, Cheung and Chu, 2023). It can therefore be argued that while modern SST warming driving steeper temperature gradients will result in more powerful storms, a similar increase in baroclinic instability from steeper temperature gradients driven by colder continental autumn circulation during the LIA interacted with an intensifying tropical cyclone. The hurricane was fueled by SSTs that peak at their most northern latitudes at the height of Atlantic hurricane season in late September and early October, consistent with the extratropical climatology of Hart and Evans (2001) and records of prevailing westerlies (Table 2) which were recorded as extremely cold following the storm. Wind plots also show that the southernmost ships of the British fleet faced southwest winds from the lower right quadrant of the hurricane. British ships to the northeast near St. Esprit faced southeast winds. The French fleet in Louisbourg Harbour also faced southeast winds and an anomalously high storm surge which allowed massive waves to drive ships on shore while the surrounding region was flooded by torrential rains, all consistent with the front right quadrant of the hurricane where the most severe impacts are felt. There was no suggestion that the air of the storm was cold, but westerlies following the storm were described at Fort Cumberland as very cold and dry.

Modern analogs show strong similarities in significant and maximum wave height, but interpreted wind speeds for the Louisbourg storm are greater than those of Category 2 hurricane Juan, a winter extratropical 'superbomb' in 2000, and the extratropical cyclone Fiona in 2022. Surge measured at three locations is consistent with the scale of surge from major hurricanes in the Gulf of Mexico and Caribbean. The 1757 surge greatly exceeds that of modern analogs that crossed the same bathymetry with similar translation speeds. This consistent basis of comparison of surge height, closely linked to storm intensity, shows the Louisbourg Storm had an intensity far beyond a Category 2 system and was equal to a major hurricane. Surge calculated independently for the lowest streets of the historic town of Louisbourg, Battery de la Grave and the *Tilbury* wreck at St. Esprit were also consistent. Even accommodating the tidal range at Louisbourg, the French battleship *Le Tonnant* drawing 25' being beached requires an exceptional surge. Unlike the modern analogs, storm surge at Louisbourg was one hundred kms from landfall (Fig. 8).

The climatology of tropical cyclones on North America's eastern seaboard renders the simple attribution of 'tropical' vs. 'extratropical' problematic. It is unlikely that a fully tropical system with wind speeds equal to a Category 4 hurricane struck Nova Scotia. Hart and Evans' (2001) climatology for North Atlantic extratropical transition of tropical cyclones showed that expansion of baroclinic conditions known to trigger transition as cooling autumn continental temperatures expanding under prevailing westerlies encounter north-trending tropical cyclones that tend to reach the highest latitudes by October when SSTs peak. Cheung and Chu (2023) modeled different concentrations of CO_2 as a forcing mechanism behind future global warming. Their model outputs showed that more destructive extratropical cyclones originating in the tropics as tropical cyclones become more frequent in response to warming. The key factors in storm destructive energy are increased wind speed and the expansion of the wind field during extratropical transition. This supports the climatology of Hart and Evans (2001) who described the collapse of the symmetric tropical wind field into an asymmetric extratropical storm during transition, and the tendency for tropical cyclones formed below 20° north latitude to maintain their tropical integrity into higher latitudes where they have a higher probability of post-transition intensification. The National Hurricane Center (NHC) uses sea surface temperatures plus storm asymmetry in satellite images to gauge the degree of transition. Hart and Evans (2001) also found that 'the NHC declaration (of extratropical transition) typically occurs early in the 1 to 2-day period … when the storm is just beginning to lose its tropical characteristics.' This is not easy to assess for the Louisbourg Storm whose energy release may have occurred over a much shorter period. The eye symmetry at landfall on September 25 is based on the convergence of normal lines to vectors at ship locations (Fig. 8) suggesting it may have had largely tropical characteristics at landfall. It leads to the question at what point was it 'tropical' (hurricane) vs. 'extratropical' given the NHC's 1 to 2-day range. The storm's unusually large size is indicated by its winds first being recorded on September 22 by both the British and French fleets at Cape

Breton on the same day it struck the British frigate *Winchelsea* off North Carolina, 1350 km to the southwest. This may have enabled it to continue to draw tropical energy from the Gulf Stream as it neared the Nova Scotia coastline. Hart and Evans's (2001) extratropical climatology shows that in some cases tropical cyclones can continue to intensify north of strongly baroclinic conditions that trigger transition, resulting in an explosive release of energy and post-transition intensification. Their analysis of past Atlantic hurricanes shows that the region most conducive to post-transition intensification in the North Atlantic basin lies immediately south of Cape Breton, Nova Scotia, which covers the track of the Louisbourg Storm in 1757.

Multidecadal climate trends for temperate North America show eighteenth century warming peaking mid century followed by cooling within a cooler mean temperature associated with the LIA (Trouet et al., 2013). This supports the early argument by Mann (2002) who argued that the LIA was a period of natural climate variability which is indicated by relatively warmer summers offset by colder winters to provide cooler mean and multidecadal LIA temperature trends. Tropical cyclones continued to transfer equatorial heat northward into the midlatitudes where they likely encountered colder LIA continental temperatures earlier in hurricane season, driving a sharper temperature contrast and greater baroclinic instability resulting in a more catastrophic energy release during extratropical transition. Oliva et al. (2017) noted the importance of various proxies to study historical Atlantic hurricanes given the importance of understanding their frequency and intensity as a benchmark against future storms. One area on the eastern seaboard of North America showing a notable data gap is Nova Scotia (Oliva et al., 2017). Not only has the population of the northeastern United States and Atlantic Canada grown since 1757, but coastal waters experienced massive shipping growth between North America and Europe. In addition, sea level rise since 1757 and projected rise increases storm surge risk to coastlines under more powerful storms. Hart and Evans (2001) identified this region as having the highest probability of post-transition intensification. Heightened temperature gradients into fall driven by warmer SSTs would not only fuel more powerful tropical cyclones reaching higher latitudes, but more intense extratropical cyclones as well.

9.0 Conclusions

In 1757 a cold air mass met a hurricane that tracked north along the Gulf Stream from the coast of Florida. The resulting explosive release of energy was likely due to extratropical transition driven by the heightened temperature gradient between colder continental and tropical maritime circulation during the LIA, giving the Louisbourg Storm its destructive power. This increase in energy requires only an incremental change in the accepted climatology of Atlantic cyclone extratropical transition. The duration of hurricane force winds (15 hours) over the coast may have been enhanced by the storm's large diameter, possibly a result of transition. The storm drove an unusually high surge at high tide. Warmer SSTs under anthropogenic forcing creating steeper autumn coastal temperature gradients could fuel future midlatitude tropical and extratropical cyclones of increasing destructive power.

Acknowledgements

The authors would like to thank William Pretel and Antoine LaChance for constructive review comments on the manuscript. Research assistance was provided by Cambria Huff (Dalhousie), John Allison (UK), the National Archives (UK) and the Public Archives of Nova Scotia. All figures were drafted by JD. Tony Sampson, commercial diver, offshore survival instructor and owner/operator of Salty Dog Sea Tours, and Steve Jennex, Dave Murphy, Steve Dugas and Dana Sheppard of Zodiac Divers coordinated marine operations and underwater exploration.

Funding

The authors declare that no funds, grants, or other supports were received during the preparation of this manuscript and that they have no financial or proprietary interests in any material discussed in this article.

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