A Major Midlatitude Hurricane in the Little Ice Age

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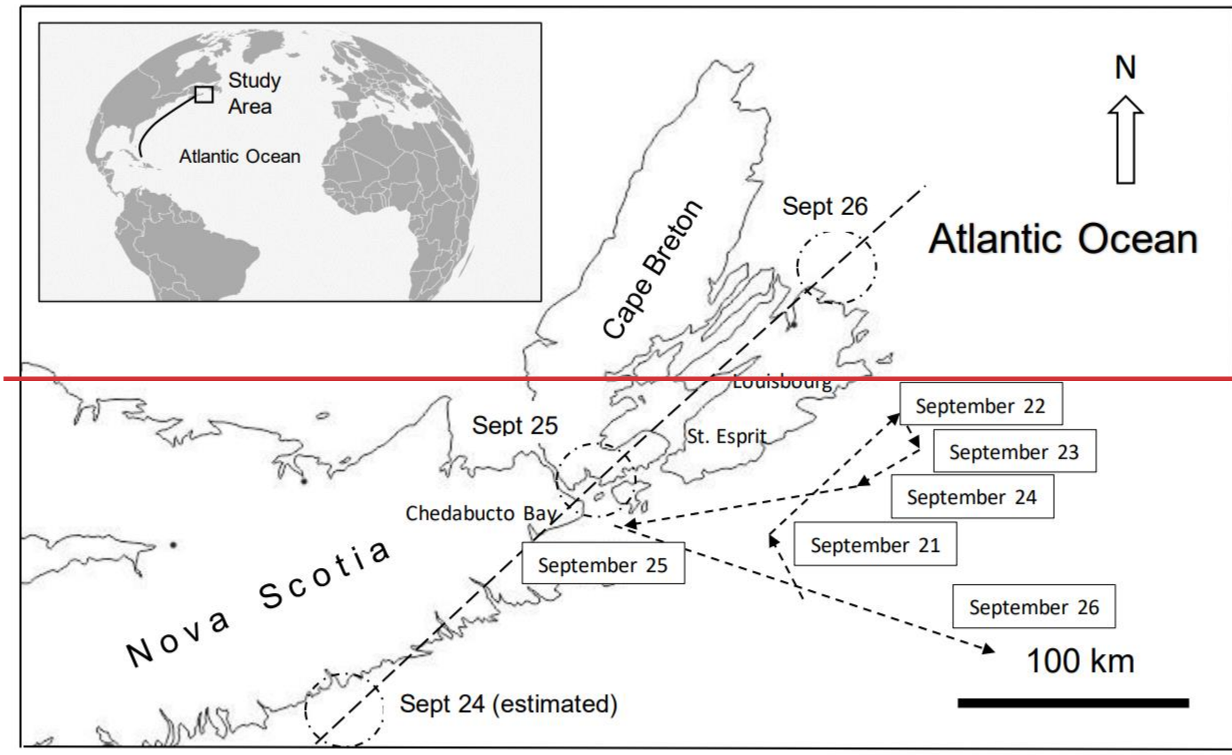
Abstract

~~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.~~ An unusually severe hurricane (Louisbourg Storm) struck Nova Scotia Canada in[JD1] 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. Predictions of warmer midlatitude sea surface temperatures could see powerful hurricanes intensify into higher latitudes later into the fall, potentially recreating the strong contrasts that triggered the intensity of the Louisbourg Storm.

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



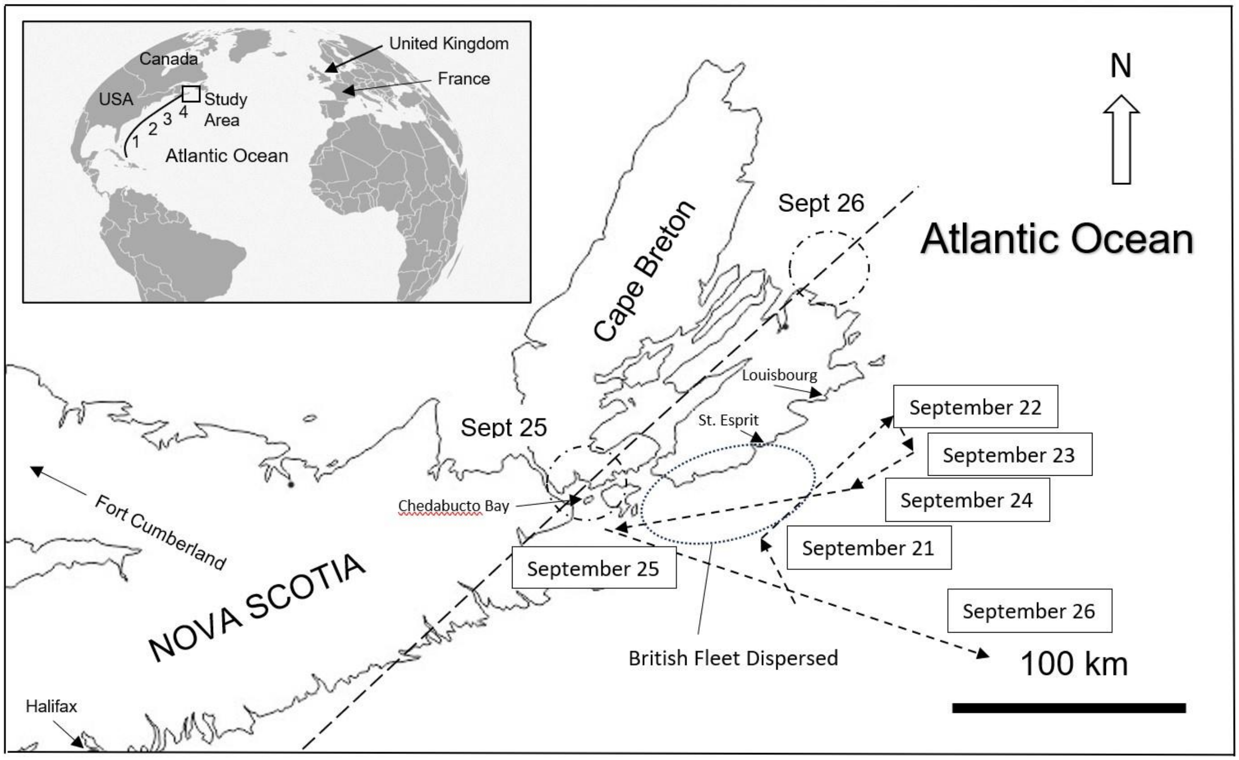


Figure 1. Study location in Nova Scotia, Canada. Arrow length and orientation represents the distance and direction traveled by the British fleet on September 21-26, 1757. September 25 and 26 shows the path of the *Invincible* south of the wider dispersal of the British fleet after being scattered by the storm (dotted oval). The storm's location off New England is estimated (off map). ~~Dashed line is the~~The estimated storm track (dashed line) shows ~~with~~ eye locations for the 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 showing its location off Florida (1), off North Carolina (2), off New England (3) and off Cape Breton Canada (4) based on records noted in the text. Fort Cumberland is 70 km toward 293 Azimuth~~.~~

~~The~~[JD2] ~~British blockade~~British fleet placed 49 sailing battleships and warships in the path of a storm descriptions of damage to ships and coastal infrastructure, and extreme storm surge[JD3] suggest was more intense than any landfalling storm in Canadian waters since modern records began in 1851 (Landsea et al. 2004, Finck 2015[JD4]). This suggests it had the intensity of a major hurricane at landfall (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).

Hurricanes are fueled by sea surface temperature~~s~~ (SST~~s~~) over 28C. They rapidly lose energy as they move north over ~~over~~ cooler midlatitude waters where half undergo extratropical transition which releases tropical energy (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 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 ~~were~~ 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, 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 conditions that dampen hurricane energy. Donnelly et al.'s (2015) historic storm reconstruction from Mattapoisett Pond, Massachusetts, and Oliva et al.'s (2017) 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[JD5].

This study utilizes ~~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 from both English and French fleets, ~~and~~ British Admiralty records, and official documents of both nations, and compares the derived ~~interpreted~~ storm metrics to those of modern systems that tracked across the same bathymetry. ~~to ascertain if it was a major hurricane~~. Characterizing its intensity ~~supports~~ tests historical descriptions ~~and proxies~~ of an unusually severe storm~~s~~ and ~~sets the stage for~~may help establish a more detailed understanding of LIA hurricane climatology[JD6].

2.0 Methodology[JD7]

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. All logs were consistent in content and format. Letters and logbook entries written in ink were copied exactly from cursive in multiple handwriting styles to a more readable format, 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 Beaufort Wind Force Scale covers winds up to hurricane threshold. The logs of British ships at sea and French ships moored in Louisbourg Harbour contained: (1) dates and times, (2) position~~s~~, (3) bearing~~s~~, (4) wind direction~~s~~, (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.

2.2 Proxy 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 proxy climate patterns 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 reaching the midlatitude eastern seaboard. Atmospheric circulation patterns for 1757 were studied to assess overarching conditions conducive to Atlantic hurricane generation.

2.3 Wind Speed[JD8]

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,' 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

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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**

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 '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 interpret 'hard' squalls as the upper end of the spectrum in the way adjectives were used to create the historic Beaufort scale (Wheeler and Wilkinson 2004). ~~We place 'hard squalls' at the upper end of the spectrum.~~ 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 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. A major hurricane is Category 3 (178-208 kph) or stronger. Wind speeds derived from log entries were plotted from the first southeasterlies noted off Nova Scotia on September 22, 1757, 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 provide an estimate of sustained 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 upper deck) approximate the 10 m height above ground level for modern hurricane wind speed measurements[JD9]. ~~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 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.

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. Longitude entries were deduced to be based on a zero meridian at Louisbourg Lighthouse (Fig. 2). 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*, *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 Eighteenth Century[JD10] century navies knew hurricanes common to in the Caribbean sometimes reached North America's eastern seaboard. The modern Saffir-Simpson

~~Hurricane Wind Scale~~scale provides a 1 to 5 storm intensity rating based on a hurricane's maximum sustained wind speed averaged over one minute. Since no such real time wind force measurement existed in 1757, this study has adopted Virot et al.'s (2016) engineering analysis of critical hurricane wind speeds ~~that~~ needed to break trees ~~provided~~ ~~a basis~~ ~~for estimating~~ as a model for estimating ~~winds that broke~~ threshold wind speeds needed to break ships' masts ~~in the Louisbourg Storm~~. Ships' logs indicate they maintained course relative to prevailing storm winds. This placed vessels at a highly oblique angle 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.[JD11]. 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 describing 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[JD12].

2.5 Wave Height

Wave height was estimated using ship dimensions including the distance of from the keel to the upper deck, the amount of freeboard between the waterline and the upper deck, and the estimated depth of water to submerge the upper deck and tear away or destroy ships' boats 60' (18 m) long and weighing as much as three tons. Other references to height such as sailors being swept off spars 80' (24 m) above the waterline provide an estimate of peak wave heights. Vessel motion renders these estimates the least reliable, though warships were designed for stability as floating gun platforms and to return to an 'even keel' as quickly as possible after firing. Waves estimates in Louisbourg Harbour are the least reliable since they are a combination of wave height and storm surge that threw vessels drawing up to 26' (8 m) on shore.

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. 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. ~~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, (2) the historic town within the Fortress, and (3) St.

Esprit where the British warship HMS Tilbury was stranded in water depths it could not normally nevigate 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.

3.0 The Little Ice Age Storminess (LIA[JD13])

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^{o}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). 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.

~~Canada's~~ The Scotian Shelf on ~~the~~ 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 higher sea surface temperatures (SSTs) closer to shore. Sediment cores from the Emerald Basin off Nova Scotia show 1600 years of cold Labrador Current temperatures ~~show~~ and a sudden and sustained warming from around 1850 into the present (Keigwin et al. 2003). 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.

~~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 seasonal weather detail not captured by ~~unavailable in~~ annual to multidecadal proxy trends. Anomalous midlatitude coastal ~~SST~~ sea surface temperatures (SSTs) ~~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 temperatures ~~In~~ 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 ~~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 unusually hot ~~seasonal~~ temperatures across the northern hemisphere known to intensify midlatitude hurricanes existed in the summer of 1757[JD14].

~~The one hurricane recorded in 1757 by Chenowith[JD15] (2006) was first seen off Florida and followed the coastline past Cape Hatteras to New England on September 22-24 (Ludlum 1963).~~ The 1757 hurricane noted by Poey (1855) and Ludlum (1963) was confirmed as a hurricane 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 36°45'N 70° 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, broke the main mast and was accompanied by a 'great sea' (September 23/24 *in* 1757ADM 52/1105).

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 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[JD16].

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, 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.

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 at the bow of each ship. 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.

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[JD17].

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.

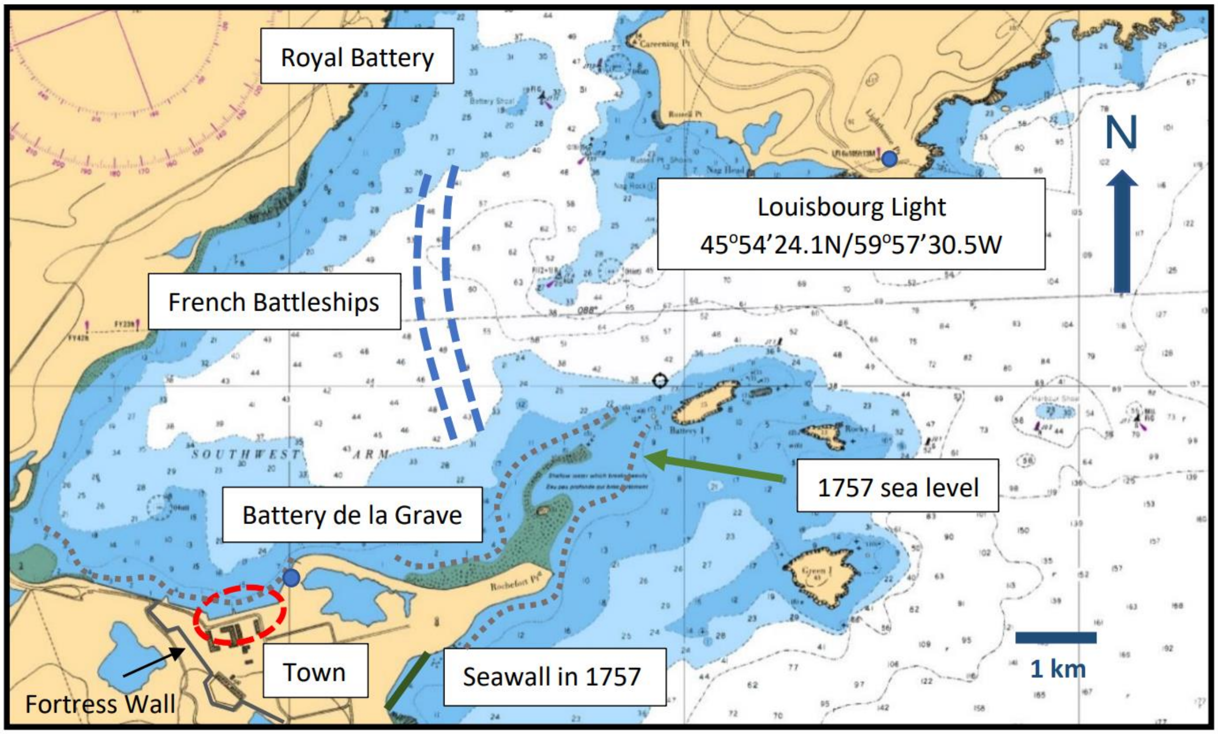


Figure 2. Louisbourg Harbour showing the French fleet anchorage, Louisbourg Lighthouse, Royal Battery, Battery de la Grave Guardhouse, and the southeast seawall overlain on chart image © Canadian Hydrographic Service (2011) Chart Guyon Island to Flint Island 1:37,866 [Issued 2022-11-26]. Shoals (shaded) relative to ship hull displacements of 5.8-7.0 m (19 to 23') give a general sense of the scale of waves and surge needed to throw battleships on shore and destroy the southeast facing seawall[JD18].

On September 25 fresh southeast gales rose to excessive hard gales with very heavy rain[JD19]. 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 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 104 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. 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. *Newark's* 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 (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, with many sailors drowned (McLennan 1918).

At sea, by 10 a.m. the British fleet was dangerously close to the breakers at St. Esprit. Many sailors were sure they were lost. *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 noted 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 had turned to blow from the west at 11:30 a.m. but had strengthened. *Eagle* recorded 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.

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[JD20]).

6.0 Storm Metrics[JD21]

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 cause structural failure in masts was estimated. Virot et al. (2016) determined the critical wind force needed to break trees of average integrity is 151 kph irrespective of species with a +9% factor for large diameter trees. 165 kph 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). To achieve the critical wind speed of 165 kph, taken as a minimum due to the factors noted, *Invincible's* motion must be considered.

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°) against EbS (101°) 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 and SE surface currents estimated at 3.49 kph based on currents of 0.97 m/s based on currents there during SE winds from 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. Ephemeral squalls of 40-60 kph added to sustained winds of 170.62 kph suggests peak winds might have reached 211-231 kph. Admittedly an imperfect solution, it assumes a minimum critical force. It does not consider the inherently superior structural integrity of masts plus their reinforcement by rigging, suggesting major hurricane threshold winds (178 kph) could have been met even without considering squalls.

~~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 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 *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 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 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.

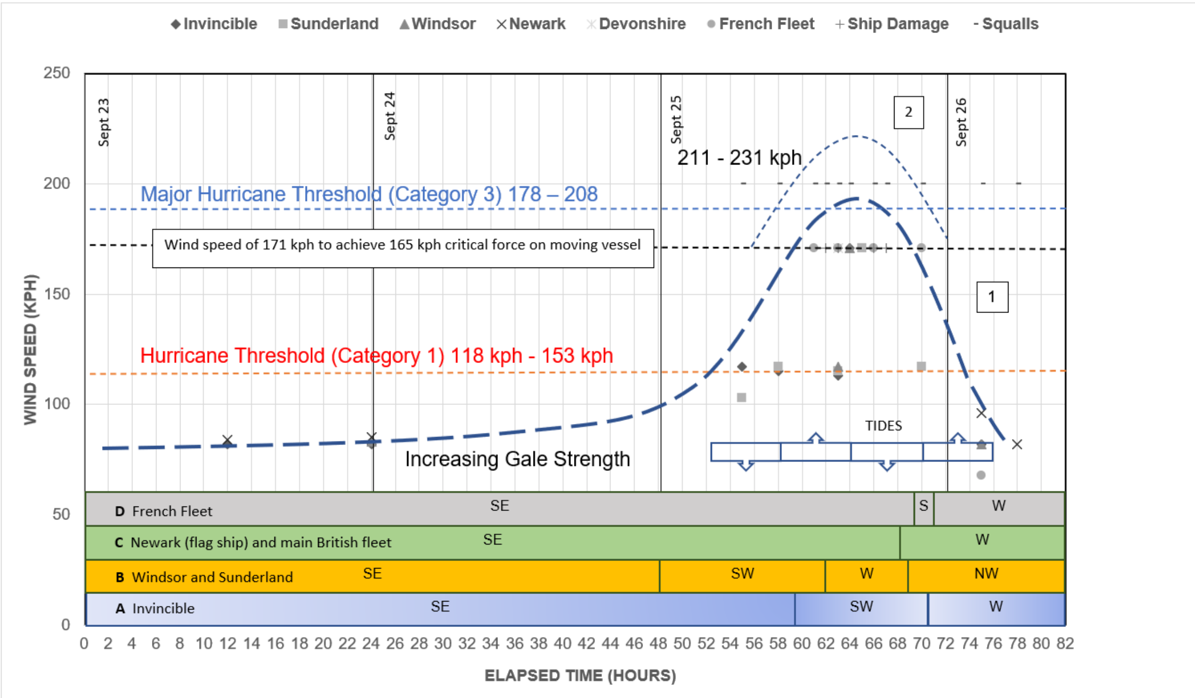
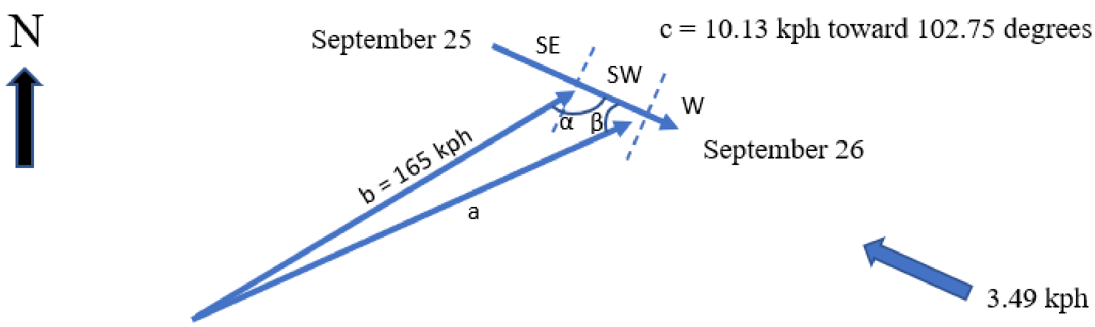


Figure 3. Hurricane wind evolution with time. The time sequence shows the arrival of southeast winds (Beaufort Scale) intensifying to hurricane winds (118 kph), peaking to sustained 171 kph critical wind force with increasing squalls, followed by a rapid decline to gale force westerlies. The horizontal 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. 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. Southernmost (blue) through southern (orange), off St. Esprit (green) and Louisbourg (grey) show the general distribution of

ship logs (*see* Table 3). *Invincible* sailed past *Windsor* and *Sunderland* during the storm and into the SW winds they had encountered earlier.



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. Correction for Vessel Motion. *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 SE winds from 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.

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 extratropical cyclone wind fields (Fig. 7). 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 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 rampart 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 (35°N 53°W) 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 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 very detailed account based on 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 larger, more powerful waves caused its damage.

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; 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. 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. 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.

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. 5). 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.

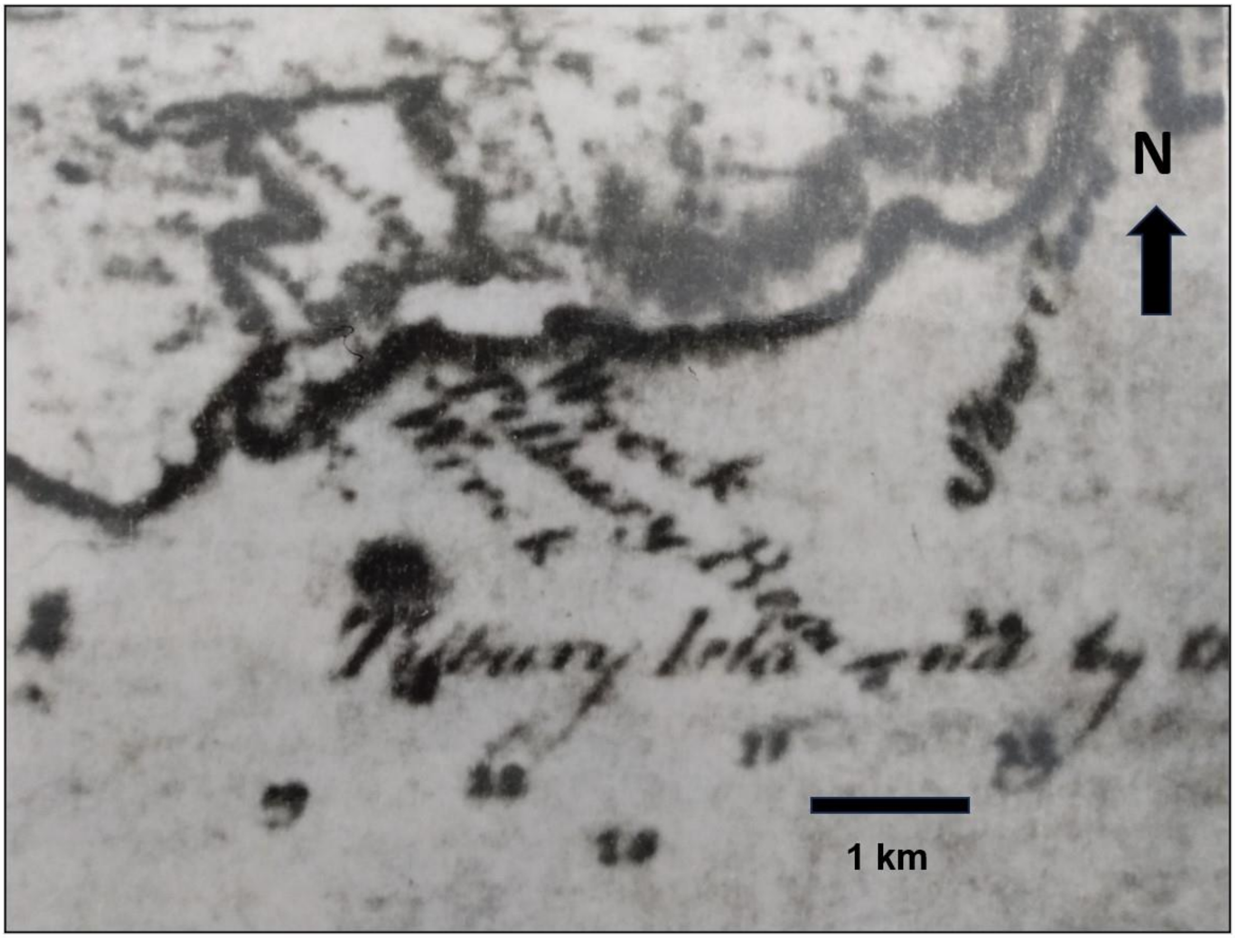


Figure 5 Excerpt from a historic chart of Cape Breton Island showing the general St. Esprit study area and *HMS Tilbury* wreck site, from Mowat (1776), depicted in Figs. 6a,b[JD22][JD23]. The faint dotted line right of Barnsley Lake, named for Tilbury's captain, marks a parish boundary.

The historic navigation chart (Fig. 5) showed parish boundaries marked by fieldstone walls of historic St. Esprit (Fig. 6a, 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 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. 6b) allowing native warriors to reach it.

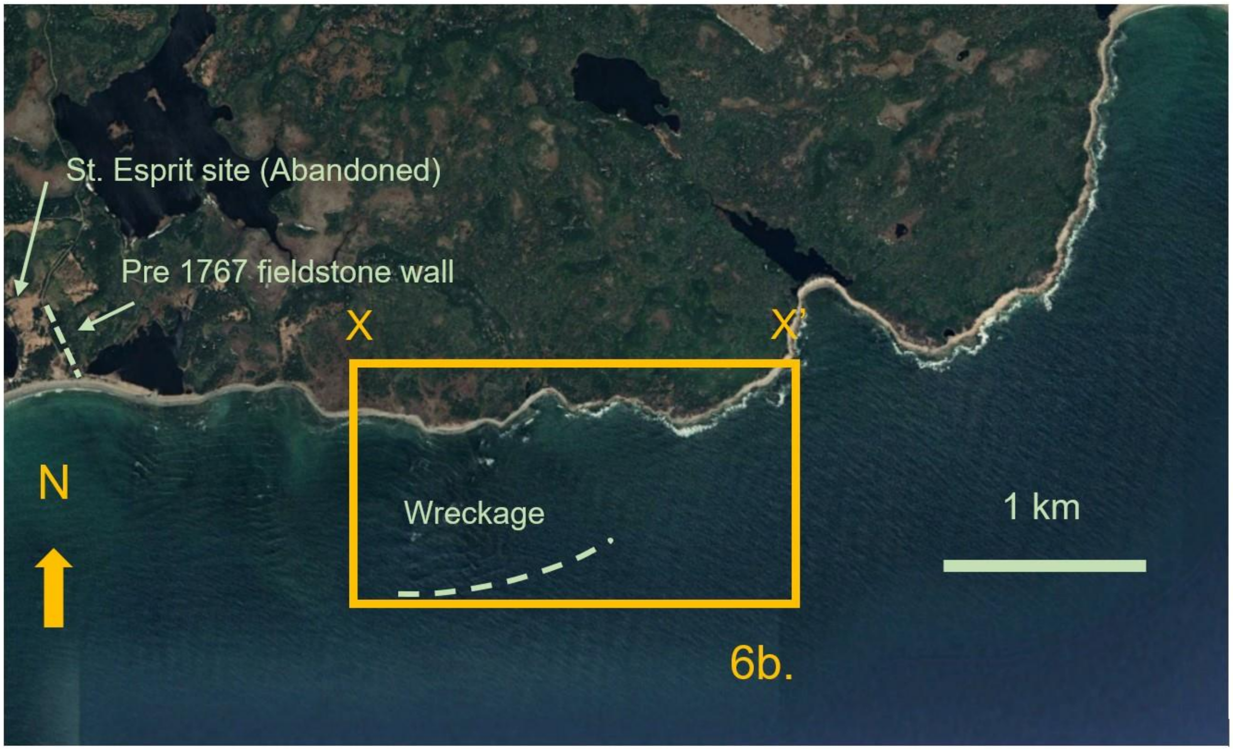


Figure 6a. Location of Tilbury shipwreck. Inset map X – X' (45º38'31.21" N 60º27'41.99" W to 45º38'31.61" N 60º26'05.28" W) corresponds to Fig. 6b. Dashed line is bedrock reef (breakers). Image © Google Earth Pro 7.3.6.9345 (2022) St. Esprit, Nova Scotia Canada. 45º38'31.54" N 60º27'37.76" W Eye alt 4.50 km TerraMetrics © 2023 MaxarTechnologies © 2023.

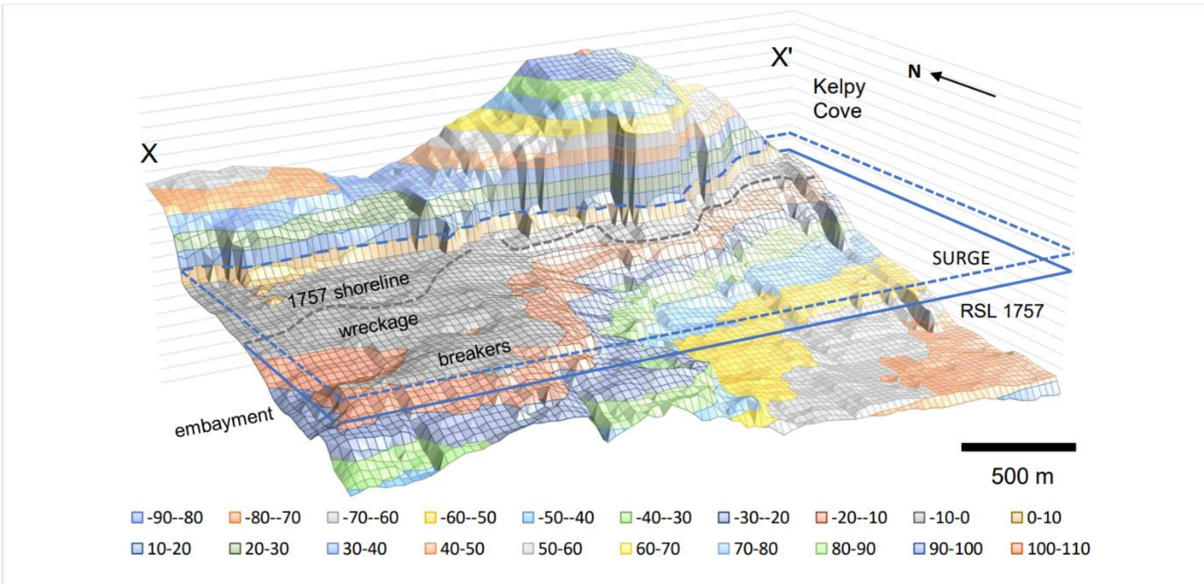


Figure 6b. Bathymetry of Tilbury site at lowest low water adjusted for 1757 relative sea level (solid line) and minimum surge (dashed line) needed to float Tilbury. Coastal retreat of 27 m (90') calculated from historic sea level gives the 1757 shoreline. Topographic and bathymetric data were kept in Imperial units 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. 6a.

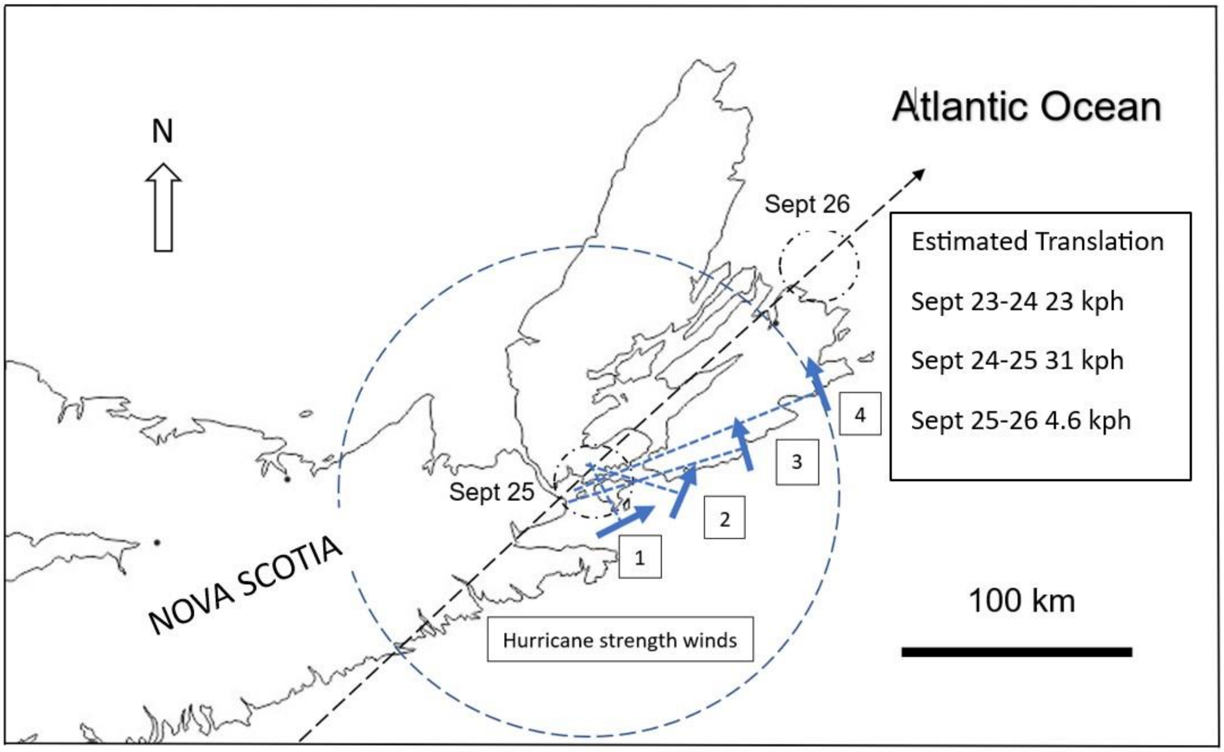


Figure 7. Eye location and estimated translation speed. Plots of wind vectors on September 25 at: (1) Invincible, (2) Windsor and Sunderland, (3) Newark and most of the British fleet, French ships at Louisbourg Harbour. Normal lines taken to wind vectors cluster at the eye. Estimated translation rates are based on the storm off North Carolina, New England and Chedabucto Bay on the dates shown, showing increased translation typical of midlatitude cyclones, yet a similar wind vector reconstruction for September 26 gives an eye location entering the Gulf of St. Lawrence, suggesting the system slowed over Cape Breton after landfall.

~~***7.1 Wind Speed***~~

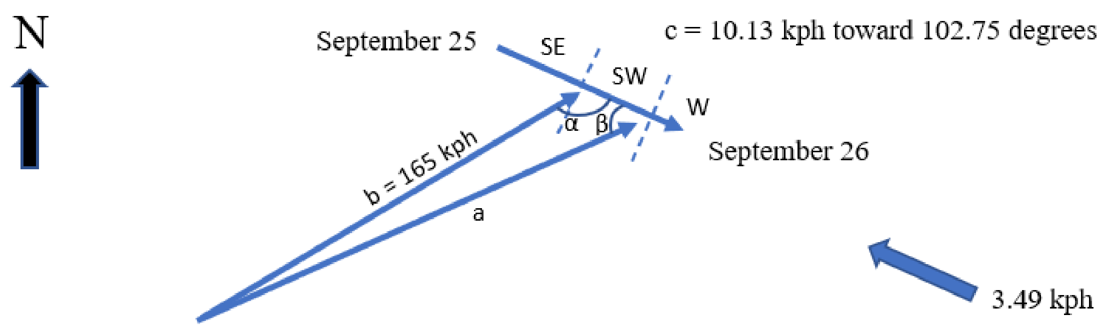
~~Masts were constructed from single fir and pine trees into the 1770's and selectively harvested in North America, Great Britain and the Baltic (Lavery 1984). Virot et al. (2016) determined the wind force to break trees is 151 kph irrespective of species and a +9% factor for large diameter trees gives 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 (230º) against EbS (101º) winds on September 24 (Fig. 1). On September 24-25 the ship's displacement was 98 km toward 256.7º (22.5 km S; 96 km W). 6 km SE (135º) of Ile Chedabucto Bay it faced W (270º) 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 (225º). 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[JD24] 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.



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

$a^2 = b^2 + c^2 - 2bc \cos \alpha$

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

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

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

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 102.75º indicates speed relative to surface currents was 10.13 kph. Image not to scale.

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; 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. (*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.

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 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[JD25].

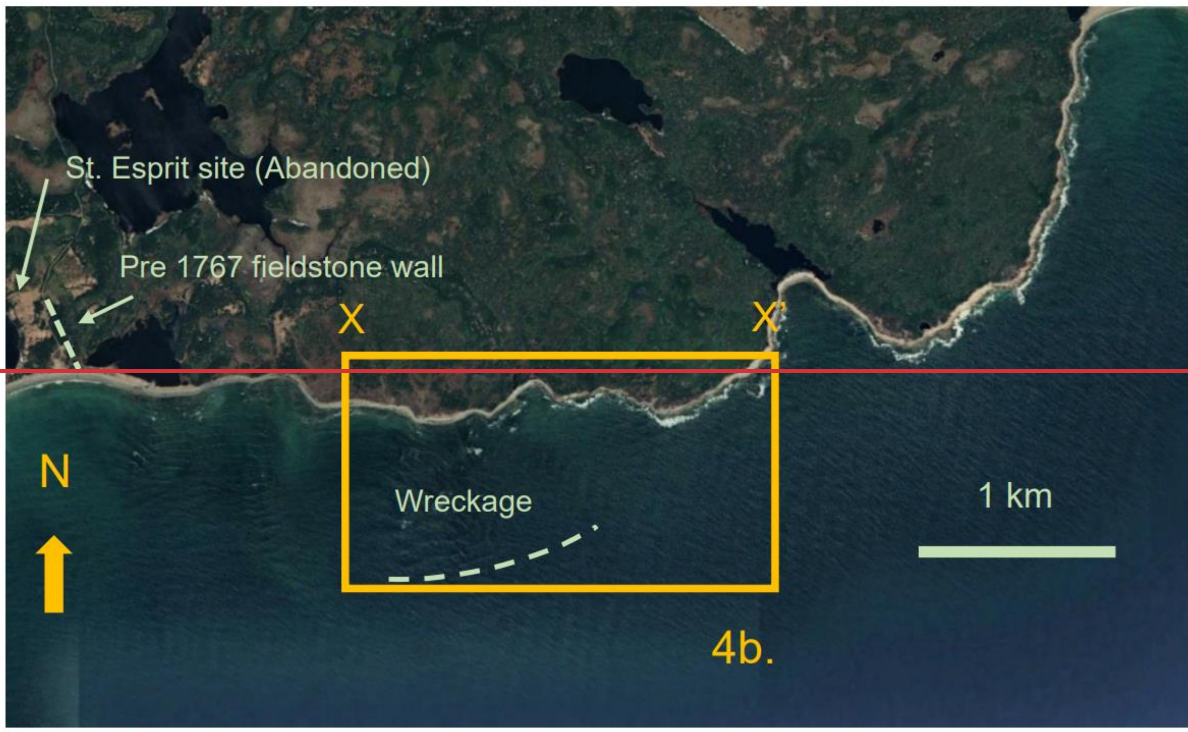


Figure 5a. Location of Tilbury shipwreck. Inset map X – X’ (45º38’31.21” N 60º27’41.99” W to 45º38’31.61” N 60º26’05.28” W) correspond to Fig. 5b. Satellite image © Google Earth Pro 7.3.6.9345 (2022) St. Esprit, Nova Scotia Canada. 45º38’31.54”N 60º27’37[JD26].76”W Eye alt 4.50 km TerraMetrics © 2023 MaxarTechnologies © 2023

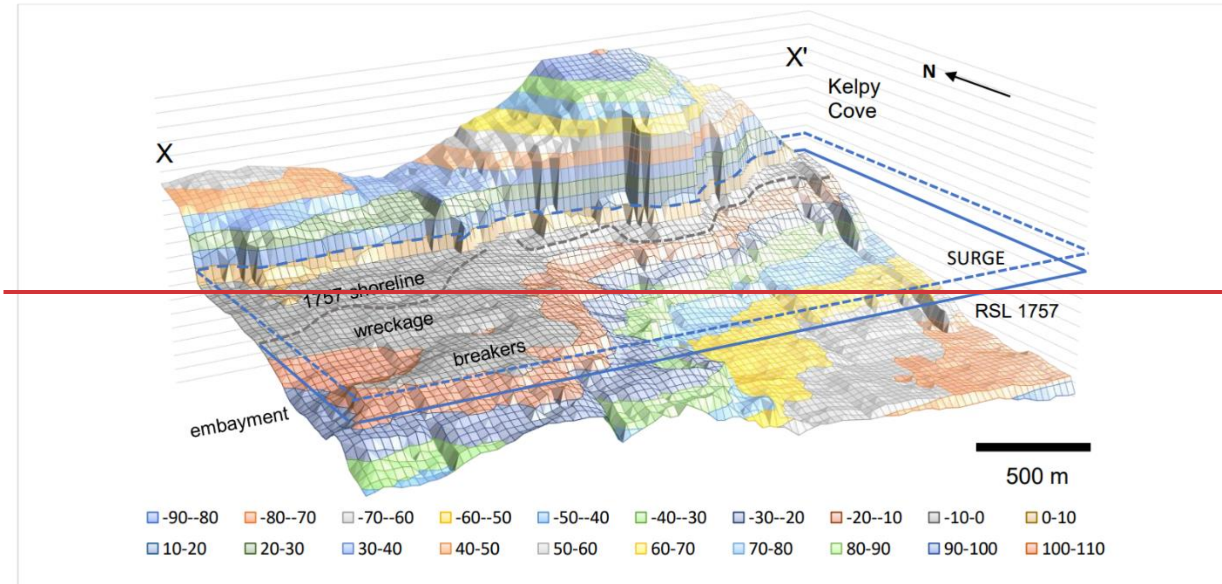


Figure 5b. Bathymetry of Tilbury site at lowest low water adjusted for 1757 relative sea level (solid line) and minimum surge (dashed line) needed to float Tilbury. Coastal retreat of 27 m (90') calculated from historic sea level gives the 1757 shoreline. Topographic and bathymetric data are in feet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

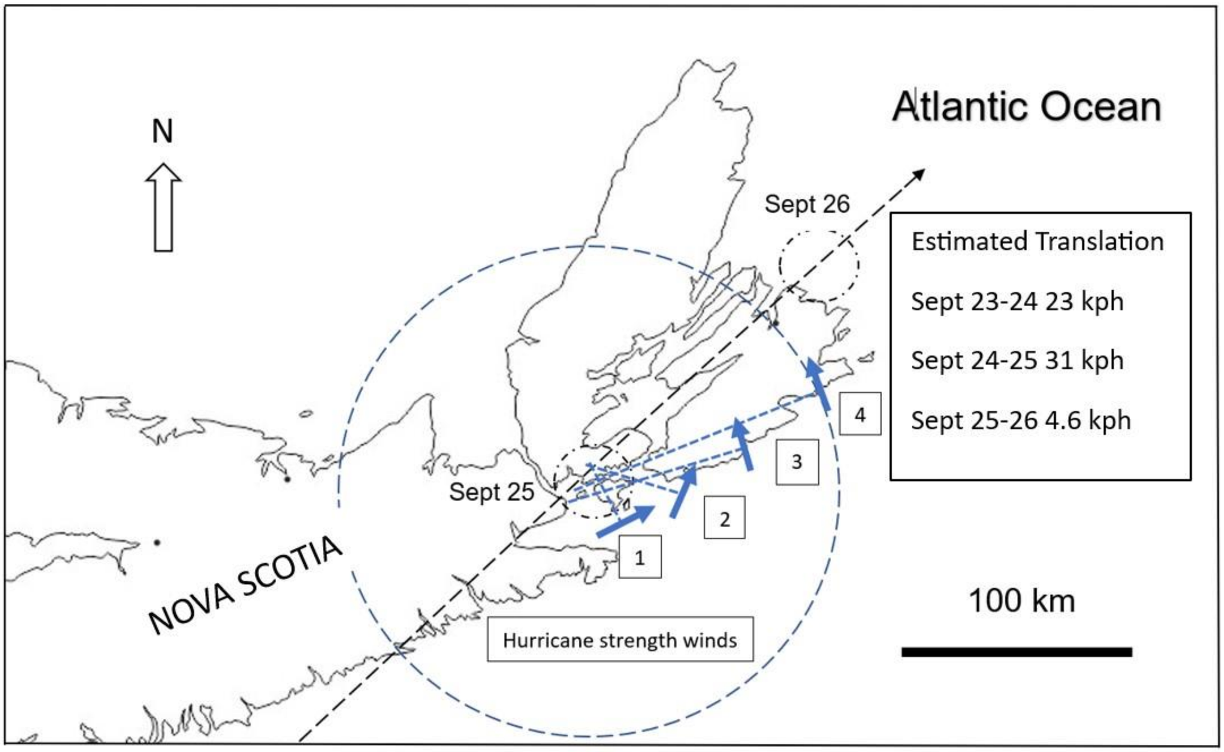


Figure 7. Eye location and estimated translation speed. Plots of wind vectors on September 25 at: (1) Invincible, (2) Windsor and Sunderland, (3) Newark and most of the British fleet, French ships at Louisbourg Harbour. Normal lines taken to wind vectors cluster at the eye. Estimated translation rates are based on the storm off North Carolina, New England and Chedabucto Bay, showing normal increased speed typical of midlatitude storms, yet plots of wind vectors for September 26 give an eye location entering the Gulf of St. Lawrence, suggesting the system slowed over Cape Breton after landfall.

~~9.0~~ 7.0 Modern ~~Storms~~ Analogs from the Scotian Shelf

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 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~~[JD27] ~~provides a database of Atlantic tropical cyclones (www.nhc.noaa.gov/data).~~ In 1969 Category 5 Hurricane Camille generated a 7.3 m (24') ~~surge~~ 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). ~~Laura in 2020 had a 5.2 m (17.2') surge.~~ 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. ~~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,~~ In 2018 Hurricane Dorian (Cat 5) slowed to 2 kph 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[JD28].

~~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 speed 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~~ 31 kph over water to 4.6 kph after ~~at~~ landfall between September 25-26 may have enhanced surge height, similar to Dorian's impact on ~~over~~ the Bahamas as it slowed, resulting in the exceptional surge height at Louisbourg. ~~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.~~ The key metrics of wind speed, wave height and surge are summarized in Table 4.

Storm	Year	Date	Peak Wind (kph)	Significant Wave Height (m)	Peak Wave Height (m)	Surge (m)
Louisbourg	1757	25-Sep	171 - 231	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 171 kph based on the critical force needed to break main and mizzen masts and break away and carry off topmasts and may have reached 231 kph with squalls. 'Peak wind' is presented as the range between sustained and maximum wind speeds.

8.0 ~~10.0~~ Discussion

Metrics[JD29] 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 index and ENSO conditions for Atlantic hurricanes to form and track up the Atlantic coast of North America into the northern midlatitudes. The already low NAO index also decreases later in the season and may have helped stay over the Gulf Stream which allowed it to 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. Longer, colder LIA winters skewed mean average temperature profiles but 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 likely existed over smaller areas for shorter periods but historical records clearly show tropical cyclones developed even during the coldest part of the LIA.

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 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 20 000 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 171 kph determined for *Invincible* to achieve 165 kph at the mast is an underestimate. Sustained winds likely exceeded the 178 kph (Cat 3) major hurricane threshold even without considering squalls of 40-60 kph. 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 which provided greater accuracy in the distribution of wind vectors. 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. 1,3, 7). Peak damage and squalls above hurricane winds lasted 9 hours and hurricane force winds noted by the British ships lasted 15 hours as the center of the storm passed the coast (Fig. 3). In comparison, Hurricane Juan crossed Nova Scotia in only 3 hours while Fiona crossed the province in under 6 hours, supporting the interpretation derived from eye locations (Fig. 7) that the Louisbourg Storm slowed over land, possibly by encountering a blocking cold air high. The British warship Tilbury was driven into water depths at St. Esprit it could navigate only under a storm tide. Tidal reversal mid storm stranded the ship near shore (Figs. 3, 6a,b).

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. A table of wind directions for the second half of September 1757 (Table 2) shows that, with the exception of the storm, prevailing winds appear to have been continental westerlies.

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. Unlike the modern analogs, storm surge at Louisbourg reflects conditions one hundred kms from landfall (Fig. 7).

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 to strike Nova Scotia. Atlantic tropical cyclone extratropical transition is triggered by the interaction of autumn continental westerlies pushing strongly baroclinic air eastward toward intensifying tropical cyclones tracking north into the higher midlatitudes of the North American eastern seaboard when SSTs peak in late

September into October. This is consistent with climatic drivers interpreted by Dezileau et al. (2011) and Jackson et al. (2019) to explain historic European LIA storminess. Storm intensity normally drops following extratropical transition, but not always (Hart and Evans 2001). The National Hurricane Center (NHC) uses sea surface temperatures plus storm asymmetry in satellite images to indicate 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 short period. The lack of eye asymmetry of the storm at landfall on September 25 based on the convergence of normal lines to vectors at ship locations (Fig. 7) suggests it may have had largely tropical characteristics at landfall. It leads to questioning at what point was it 'tropical' (hurricane) vs. 'extratropical' given the NHC's 1 to 2-day range? It was likely both in the coastal zone. The storm's 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 based on an analysis of all Atlantic tropical cyclones over a century. It shows that systems can continue to see tropical intensification north of strongly baroclinic conditions that trigger transition, resulting in an explosive release of energy and post-transition intensification. Their analysis shows this typically involves hurricanes from south of 20 N that retained an intensely tropical character into the higher midlatitudes. In fact, their analysis of past Atlantic hurricanes shows that the region most conducive to this process in the entire North Atlantic basin lies immediately south of Cape Breton, Nova Scotia, where the Louisbourg Storm was in 1757.

9.0 Conclusions

In 1757 continental westerlies, colder and earlier than today in the LIA, juxtaposed a cold higher pressure air mass against a large, intensifying hurricane approaching Cape Breton. The resulting explosive release of energy gave the Lousibourg Storm its highly destructive power. Its unusual intensity required only an incremental change in the accepted climatology of Atlantic cyclone extratropical transition, that being the early arrival of colder LIA continental westerlies driving a steeper temperature gradient. The storm slowed over Nova Scotia as it encountered a blocking air mass, indicated by the short distance between eye locations on September 25 and 26, and by the duration of hurricane force winds (15 hours) over the coast, which may have been enhanced by the storm's large diameter of hurricane force winds. The slowing storm drove an unusually high surge at high tide. Tidal reversal stranded the *Tilbury* close to the historical shoreline. Fall westerlies arriving earlier in the LIA would have expanded southward sooner and allowed an intensifying hurricane to enter a zone more baroclinically favourable for transition. In the future, instead of an earlier arrival of colder continental westerlies in fall, a warming North Atlantic could drive tropical intensification in to higher latitudes later into the autumn to trigger increasingly destructive storms over coastlines that have seen a meter of sea level rise and extensive coastal growth since the Louisbourg Storm nearly rewrote history two and a half centuries ago. It is a reminder that the past can inform the present, and the future.

~~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[JD30].

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 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.

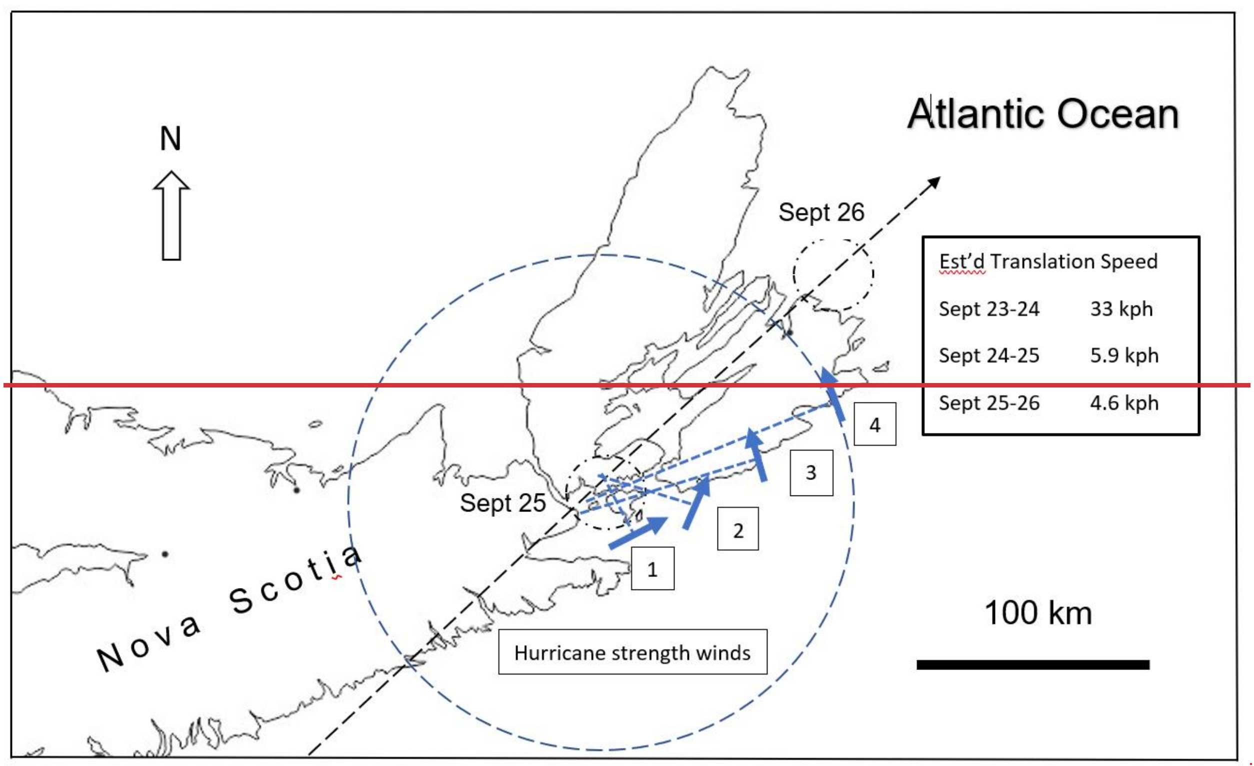


Figure 6. Hurricane eye position on September 25-26, 1757. Normal lines drawn from wind vectors at different ship locations converge at the eye. Successive eye locations give the

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.

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 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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