1   **A Major Midlatitude Hurricane in the Little Ice Age**

2   **John Dickie[1,2] and Grant Wach[1]**

3   [1]Basin and Reservoir Lab, Department of Earth and Environmental Sciences

4   Dalhousie University, Halifax, Canada B3H 4R2

5   [2]Corresponding Author

6   Contacts: john.dickie@dal.ca; grant.wach@dal.ca

7   **Abstract**

8   An unusually severe hurricane (Louisbourg Storm) struck Nova Scotia Canada in 1757. Historic

9   records describing storm conditions as well as damage to ships and coastal fortifications indicate

10   an intensity beyond any modern (post-1851) Atlantic cyclones striking the same region, yet this

11   storm struck during a cold climate period known as the Little Ice Age (LIA). Its track and timing

12   coincided with a British naval blockade of a French fleet at Fortress Louisbourg during the Seven

13   Years' War (1756-1763). This provides a unique opportunity to explore growing scientific

14   evidence of heightened storminess in the North Atlantic despite a colder climate expected to

15   suppress hurricane intensification but which research is increasingly showing to have supported

16   North Atlantic storms of exceptional strength. Weather attributes extracted from the logs of

17   naval vessels scattered by the Louisbourg Storm provided multiple hourly observations recorded

18   at different locations. Wave height and wind force estimates at ship locations were compared to

19   extreme storm surge heights calculated for Louisbourg Harbour and a shipwreck site south of

20   Fortress Louisbourg. Comparing these metrics to those of modern analogs that crossed the same

21   bathymetry reflects landfall intensity consistent with a powerful major hurricane. Historical

22   records show this storm originated as a tropical cyclone at the height of hurricane season and

23   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

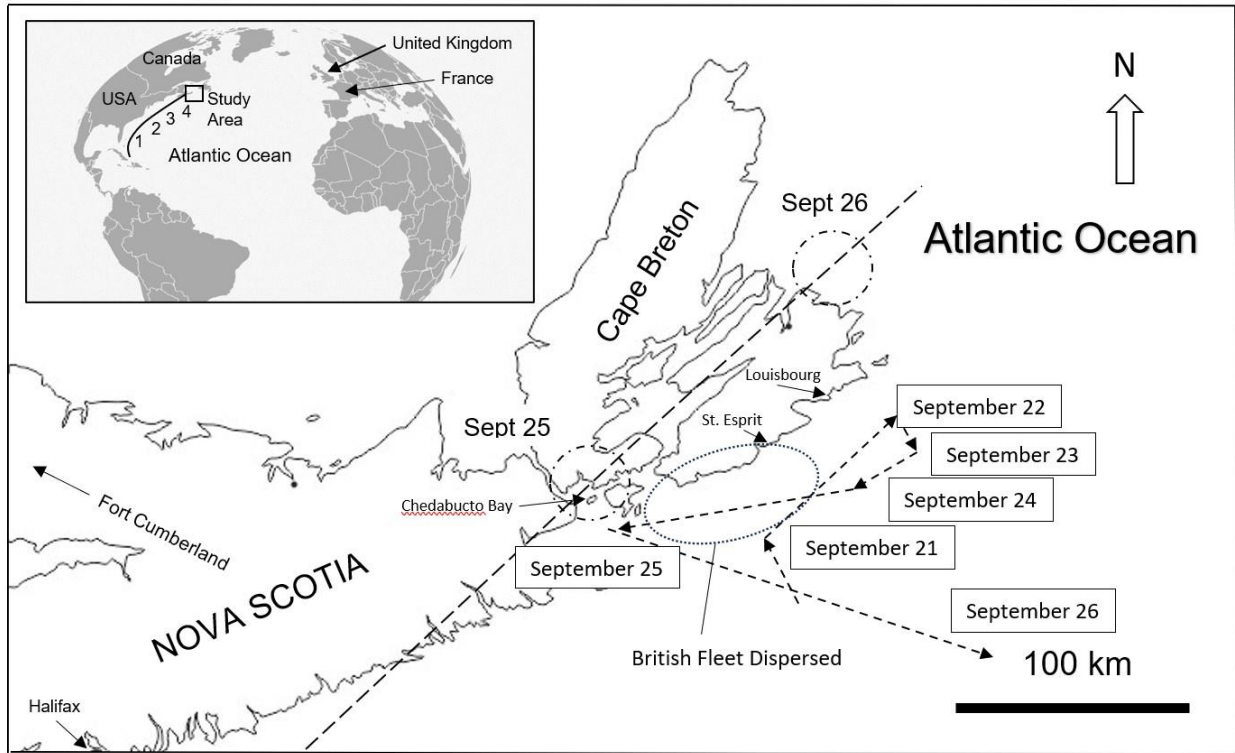



Figure 1. Study location in Nova Scotia, Canada. Arrow length and orientation represents the

distance and direction traveled by the British fleet on September 21-26, 1757. September 25 and

26 show the path of the *Invincible* south of the wider dispersal of the British fleet after being

scattered by the storm (dotted oval). The storm's location off New England is estimated (off

map). The estimated storm track (dashed line) shows eye locations for the dates shown Inset

shows the study area relative to the North Atlantic and the hurricane track based on historic

records showing its progressive northward translation seaward of (1) Florida (no date), (2) North

Carolina (September 23), (3) New England (September 24) and (4) Cape Breton Canada

(September 25-26). Fort Cumberland is 70 km toward 293 Azimuth.

British fleet placed 49 sailing battleships and warships in the path of a storm descriptions of

damage to ships and coastal infrastructure, severe flooding from rainfall and extreme storm surge

suggest was more intense than any landfalling storm in Canadian waters since modern records

52   began in 1851 (Landsea et al., 2004, Finck, 2015). This suggests it had the intensity of a major

53   hurricane at landfall (Category 3+ on the Saffir-Simpson Hurricane Wind Scale) yet it struck

54   during the colder climate of the 'Little Ice Age' (LIA; c1300-1850).

55   Hurricanes are fueled by sea surface temperature (SST) over 28C. They rapidly lose

56   energy as the move north over cooler midlatitude waters, and many tropical cyclones undergo

57   extratropical transition which releases tropical energy at increasingly higher latitudes later in

58   hurricane season (Hart and Evans, 2001). Modern tropical cyclone intensity is characterized in

59   real time with instruments carried by aircraft, satellites and at ground stations. In contrast, pre-

60   industrial metrics must be derived from historical observational records. Subjective interpretation

61   and geographic bias can make them less reliable than instrumental data (e.g., Jones and Mann

62   2004), yet they offer a temporal resolution unavailable in scientific proxies, and they straddle the

63   end of the LIA and the rise of modern anthropogenic emissions. Oliver and Kington (1970) and

64   Lamb (1982) first explored their suitability for weather research. Naval logbooks were

65   subsequently found to be a superior source of historical weather data given that hourly ship

66   observations were systematically recorded in real time with a consistent terminology. Logbook

67   data have been compiled to assess historical atmospheric circulation patterns (e.g., Garcia et al.,

68   2001, Garcia-Herrera et al., 2005a, Wheeler et al., 2010, Barriopedro et al., 2014). CLIWOC, the

69   Climatological Database for the World's Oceans, was compiled from historical British, French,

70   Dutch and Spanish naval logbooks. It established a common historical wind force terminology to

71   document ocean surface atmospheric circulation patterns between 1750 and 1850 (Garcia-

72   Herrera et al., 2005b).

73   To date, pooled historical naval records have been used to identify longer-term regional

74   circulation patterns and extend the multidecadal climate signal into the industrial period (e.g.,

75   Garcia-Herrera at al., 2005a, 2005b, Wheeler et al., 2010, Barriopedro et al., 2014). In contrast,

76   this study takes advantage of an unusual concentration of warships in the path of a single

77   hurricane to characterize its intensity. It seems counterintuitive that the colder LIA climate would

78   generate more powerful midlatitude Atlantic cyclones than in the modern era, yet historical

79   records show the LIA to be generally 'stormier' with unusually powerful midlatitude hurricanes

80   despite conditions that dampen hurricane energy. Donnelly et al.'s (2001) historic storm

81   reconstruction from Mattapoisett Pond, Massachusetts, and Oliva et al.'s (2018) historic storm

82   reconstruction from Robinson Lake, Nova Scotia, are among a growing number of proxy studies

83   showing that major Atlantic cyclones struck the northeastern seaboard of North America in the

84   LIA. Since winter extratropical cyclones known as Nor'easters cannot be differentiated from

85   Atlantic tropical cyclones and their extratropical derivatives from proxy data alone, historical

86   records can constrain the timing of midlatitude hurricanes and tropical storms.

87   This study utilizes a unique historical data set to characterize the intensity of the

88   Louisbourg Storm using spatial and temporal weather metrics extracted from ship logbooks of

89   both the English and French fleets, British Admiralty records and official documents of both

90   nations, and compares the derived storm metrics to those of modern systems that tracked across

91   the same bathymetry. Characterizing its intensity tests historical descriptions of an unusually

92   severe storm and may help establish a more thorough understanding of LIA hurricane

93   climatology.

94   **2.0 Methodology**

95   *2.1 Historical Records*

96   Eighteenth century navigation and weather data were entered hourly in the daily logs of

97   naval vessels, resulting in reliable records suitable for historical climate research. A noon

98   sighting of the sun fixed latitude and marked the start of the sea day. Britain adopted the

99   Gregorian calendar in 1752 so dates in logs used for this study did not require correction. In 1757

100 a local meridian was used to determine longitude, deduced from logs to have been based on

101 Louisbourg Lighthouse (Fig. 2).

102   Historical British Admiralty Correspondence and Papers (ADM1/481, 1488, 2294)

103 covering storm damage to British vessels on the 'Halifax Station' in 1757 and Fleet Lists

104 (ADM8/31, 32) are preserved at the National Archives at Kew (UK), as are Royal Navy Master's

105 (ADM 51/409, 633,1075) and Captain's (ADM 52/578,819,1064) logbooks. Lieutenant's logs

106 (ADM51) kept at the National Maritime Museum, Greenwich, were often incorporated into

107 Captain's logs with addenda. Master's and Captain's logs of the Royal Navy warships *Invincible*,

108 *Windsor*, *Sunderland*, *Eagle*, *Terrible*, *Grafton*, *Newark*, and *Captain*, plus ancillary official

109 correspondence, were used in this study. All logs were consistent in content and format. Letters

110 and logbook entries written in ink were copied from cursive in multiple handwriting styles to a

111 more readable format, interpreted, compiled into a time sequence and cross referenced. Logs

112 from French warships *Fleur de Lys*, *l'Abenaquise*, *Tonnant*, *l'Inflexible* and *Dauphin Royal*

113 translated from French describe conditions in Louisbourg Harbour (McLennan, 1918). Wind

114 directions from gimballed ships' compasses reference magnetic north. Bearings and wind

115 directions used the 32 points of the compass (Smyth, 1867, Blake and Lawrence, 1999) and were

116 translated to azimuths. The logs of British ships at sea and French ships moored in Louisbourg

117 Harbour contained: (1) dates and times, (2) position, (3) bearing, (4) wind direction, (5) wind

118 speed terms that evolved into the Beaufort Wind Scale (e.g., Garcia-Herrera et al., 2005a, 2005b,

119 Wheeler, 2005, Wheeler et al., 2010), and (6) descriptions of sea state.

120 *2.2 Proxy Climate Context*

121   Major atmospheric circulation patterns that influence Atlantic tropical cyclone behaviour,

122   specifically the El Nino Southern Oscillation (ENSO) and North Atlantic Oscillation (NAO),

123   have been reconstructed for the historical period (e.g., Gurgis and Fowler, 2009, Trouet, et al.,

124   2012). These proxy climate patterns provide an overarching context since La Nina years create

125   conditions conducive to driving hurricanes in the Atlantic, and a negative NAO allows Atlantic

126   tropical cyclones to enter the Atlantic and potentially reaching the midlatitude eastern seaboard.

127   Atmospheric circulation patterns for 1757 were studied to assess overarching conditions

128   conducive to Atlantic hurricane generation.

129   *2.3 Wind Speed*

130   Wheeler and Wilkinson's (2004) analysis of the derivation of the Beaufort scale shows

131   terms that vary little from the logbook terms used in this study. A similar approach has been

132   adopted here with adjectives describing primary nomenclature. A 'gale' (Beaufort Force 8) was

133   originally between a breeze (Force 2) and a violent storm (Force 11) and established a

134   benchmark (Table 1). A 'near gale,' its diminutive (Smyth, 1867) corresponds to a 'moderate

135   gale.' Wheeler et al. (2010) categorized 'strong gale,' 'hard gale,' 'blew hard' and 'storm' as

136   stronger than 'fresh gale.' Adjectives 'stiff' and 'fresh' indicate winds stronger than a gale

137   (Force 9) while a 'severe' or 'hard' gale reflects a 'storm' (Force 10). 'Excessive' and 'extreme'

138   hard gale, necessarily stronger than a 'hard gale' would then correspond to 'violent storm' (Force

139   11) which does not appear in the logs used here. 'Hurricane' (Force 12) is mentioned in both

140   French and British records. 'Squall' is a historical term for an increase in wind speed sustained

141   above threshold for at least one minute. The National Oceans and Atmospheric Administration

142   (NOAA) defines it as a sudden increase by at least 16 knots (33 kph) and sustained at over 22

143   knots (41 kph) for one minute. Environment and Climate Change Canada (ECCC) defines

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

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

145 squalls as increases of 34 knots (63 kph) or more above prevailing winds sustained for over a

146 minute. The World Meteorological Organization (WMO) uses 8 m/s and 11 m/s (29 and 40 kph)

147 above threshold for over one minute while the American Meteorological Association (AMA)

148 notes squalls are of 'several minutes' duration. In considering these definitions 'squall' is taken

149 to be a sudden increase in wind speed of 40-60 kph above threshold and sustained for at least one

150 minute. We interpret 'hard' squalls as the upper end of the spectrum in the way adjectives were

151 used to create the historic Beaufort scale (Wheeler and Wilkinson, 2004). Heavy rains

152 accompanying squalls noted in the logs appear to be consistent with descriptions of hurricane

153 spiral bands.

154   In this study the Beaufort Wind Force Scale is used to describe wind speeds from gale to

155 hurricane force (63-118 kph). The Saffir-Simpson Hurricane Wind Scale describes hurricane

156 winds greater than 118 kph with peak wind speeds averaged over one minute defining hurricane

157 intensity Categories 1-5. A major hurricane is Category 3 (178-208 kph) or stronger. Wind

158 speeds derived from log entries were plotted from the first southeasterlies noted off Nova Scotia

159 on September 22, 1757, to diminishing westerlies at the storm's end on September 26.

160 Ephemeral squalls of 1 min duration above threshold winds provide an estimate of total wind

161 speed sustained for one minute or longer. Wind speeds at mid-mast height above the deck plus

162 freeboard (distance from the waterline to the upper deck) approximate the 10 m height above

163 ground level for modern hurricane wind speed measurements.

164   Eighteenth century navies knew hurricanes commonly encountered in the Caribbean

165 sometimes reached North America's eastern seaboard. The modern Saffir-Simpson scale

166 provides a 1 to 5 storm intensity rating based on a hurricane's maximum sustained wind speed

167 averaged over one minute. Since no such real time wind force measurement existed in 1757, this

168 study has adopted Virot et al.'s (2016) engineering analysis of critical hurricane wind speeds that

169 break trees as a model for estimating threshold wind speeds needed to break ships' masts. Ships'

170 logs indicate they maintained course relative to prevailing storm winds. This placed vessels at a

171 highly oblique angle to wave crests which minimized pitch and yaw, and held masts within a

172 stable plane of reference against which wind applied a sustained force. In addition, large vessels

173 (74-gun third rates) with up to nine feet of flooding in the hold would have a lower center of

174 mass that would have affected its righting moment and minimized directional variance in the

175 wind force striking the masts. Rigging designed to stabilize the masts and transfer wind energy

176 through the sails would likely have required a higher sustained wind force to achieve failure.

177 *2.4 Wind Direction*

178   Wind direction was measured using the ship's magnetic compass and entered in the

179 ships' logs as 'points of the compass.' These entries were translated to azimuths. Compass

180 directions are relative to magnetic north and not corrected for declination given the small study

181 area and short time frame. Eighteenth century navigation was inaccurate but this study benefits

182 from (1) log entries of the fleet relying on smaller vessels sent inshore to establish distance from

183 coastal landmarks, and (2) during the storm ships were driven sufficiently close to land that their

184 positioning entries were based on triangulation using landmarks which greatly improves

185 accuracy. Experienced navigators were also able to correct for ship motion in their readings

186 while the ship's position was typically determined by a Lieutenant plus one or more midshipmen

187 and the sailing master's mate.

188 *2.5 Wave Height*

189 Wave height was estimated based on descriptions compared to ship dimensions and is the

190 last accurate metric. Historic references to ship structure in Imperial Units have been converted

191 to metric. This includes the distance from the keel to the upper deck and freeboard from the

192 waterline to the upper deck. The depth of water needed to spill over the bow to flood the upper

193 deck and tear away large ship's boats tethered to the deck is estimated. References such as

194 sailors being swept off spars 80' (24 m) above the waterline offers an estimate of peak wave

195 heights. Warships were designed for stability as floating gun platforms and to return to an 'even

196 keel' as quickly as possible after firing. Wave descriptions in Louisbourg Harbour are the least

197 reliable since they include storm surge.

198 *2.6 Surge*

199 Surge is a rise in sea level due to atmospheric pressure and storm winds and is

200 proportional to a tropical cyclone's intensity and translation rate. Coastal surge is a reasonable

201 estimate of storm intensity and can serve as a test of intensity derived from wind data. The surge

202 height of modern analogs that struck Nova Scotia after tracking across the Scotian Shelf and

203 whose intensity has been characterized with metrics derived using modern meteorological

204 methods provides a reliable benchmark for comparison to surge calculated for the 1757 storm. In

205 this study, storm surge at known locations and elevations above sea level were described at (1)

206 Battery de la Grave at Fortress Louisbourg, (2) the historic town within the Fortress, and (3) St.

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

208 navigate given its displacement. All surge calculations were then corrected for (1) relative sea

209 level (RSL) rise since 1757, and (2) a mid-tide RSL datum used by Google Earth versus a lowest

210 low water (tide) datum used by the Canadian Hydrographic Service for a (draft) navigation chart

211 used for the Tilbury wreck site. In addition, French records noting the tidal change at

212 Louisbourg allowed for the timing of the tidal cycle to be backed out to determine storm surge

213 versus storm tide.

214   *Tilbury's* wreck site offered a chance to estimate surge at a second location 45 km

215 southwest of Louisbourg. *Tilbury*'s identity was confirmed in 1986 with the discovery of the

216 ship's bell, most of its guns, anchors and artifacts (Storm, 2002). Its location remained

217 undisclosed after a letter from the British High Commission in 2006 reminded the Minister of

218 Foreign Affairs Canada of the wreck's sovereign immunity, resulting in Nova Scotia rescinding

219 the associated treasure trove license. Relocating the wreck to confirm its water depth required

220 creating a digital bathymetric chart needed to guide a marine magnetometer survey leading to

221 site confirmation by divers.

222 **3.0 Little Ice Age Storminess**

223   Matthes (1939) named the LIA to explain European glacier expansion during a

224 historically colder climate period. Heightened climate variability saw deeply cold winters and

225 cooler mean annual temperatures primarily in the northern hemisphere (e.g., Kreutz et al., 1997,

226 Mann, 2002, Jones and Mann, 2004). It may have been triggered by late 13th Century volcanic

227 eruptions and a cooling feedback process sustained by Arctic sea-ice expansion (Miller et al.,

228 2012). North Atlantic mean annual SSTs were 1-2°C cooler than today (e.g., Keigwin, 1996,

229 Winter et al., 2000, Richey et al., 2009, Saenger et al., 2009, Cronin et al., 2010, Bertler et al.,

230 2011, Mazzarella and Scaffeta, 2018, Gebbie, 2019). The Maunder Minimum, the coldest part of

231 the LIA, (MM; 1645-1715) saw greater 'storminess' during polar air breakouts from Europe

232 correlating to more frequent easterly gales in the English Channel and Approaches in 1685-1750

233 (Wheeler et al. 2010). Concentrated storm horizons in coastal dunes across western Europe and

234 in Brittany and on France's Mediterranean coast correlate to the coldest part of the LIA

235 (Dezileau et al., 2011, Van Vliet-Lanoe et al., 2014, Sicre et al., 2016, Jackson et al. 2019).

236 Dezileau et al. (2011) attributed LIA storminess to cold-enhanced lower tropospheric

237 baroclinicity modifying prevailing westerlies. In the northwest Atlantic, Donnelly et al. (2015)

238 described major hurricane deposits in New England coastal sediments dating to 1635, 1638 and

239 1815. Ludlum's (1963) compilation of historical northwest Atlantic hurricanes and tropical

240 storms includes the LIA's major 'Independence Hurricane' that struck New England on August

241 29, 1775 and the 'Newfoundland Hurricane' of September 9, 1775, a storm that left 4000 dead to

242 become Canada's deadliest hurricane (Ludlum, 1963, Ruffman, 1996). Lamb's (1991)

243 exhaustive survey of British and European storms includes the Great Storm that devastated the

244 British Isles on November 26, 1703. It was an extratropical cyclone equal to a Category 2

245 hurricane yet Wheeler (2003) notes a far more powerful Atlantic storm on December 1-12, 1792,

246 also late in Atlantic hurricane season. Both were anomalous for a colder climate period.

247   The Scotian Shelf on Canada's Atlantic seaboard (Fig. 1) is dominated by the cold, south-

248 flowing, low-salinity Labrador Current. It originates in the Davis Strait of the Canadian Arctic

249 and hugs the coast to the start of the midlatitudes at Cape Hatteras, North Carolina where it

250 meets, mixes with, and redirects seaward the tropical, north-flowing more saline Gulf Stream.

251 The Labrador Current plays a critical role in hurricane extratropical transition by providing a

252 coastal buffer of cooler sea surface temperatures that effectively cut off the tropical energy of the

253 Gulf Stream (Hart and Evans, 2001). Summer and fall bring warm water eddies from the Gulf

254 Stream and warmer coastal SST. Sediment cores from the Emerald Basin off Nova Scotia show

255 1600 years of cold Labrador Current temperatures and a sudden and sustained warming around

256 1850 that has continued into the present (Keigwin et al., 2003) and coincides with the end of the

257 LIA. Storm compilations by Landsea et al. (2004) and Chenowith (2006) show a progressive

258 increase in the number of historical Atlantic tropical cyclones from 1700 and a sharp increase in

259 the number and percentage reaching New England and eastern Canada beginning around 1850.

260 Vecchi and Knutson (2008) in a study of data from the start of instrumental data collection in

261 1880 show a strong correlation between mean annual SST and storm frequency.

262   Historical records offer seasonal weather detail not captured by annual to multidecadal

263 proxy trends. Anomalous midlatitude coastal sea surface temperatures (SSTs) over days to

264 weeks, conditions that fuel tropical cyclones, are therefore not likely to appear in annualized data

265 weighted by colder, sustained LIA winters. Jacoby and D'Arrigo's (1989) North American

266 northern and Arctic temperature reconstruction shows above normal temperatures in the 1750's.

267 Lieutenant John Knox recorded unusually high temperatures in Halifax Harbour on July 20,

268 1757, which fellow officers found hotter than Gibraltar and the Mediterranean (Knox, 1769).

269 This coincided with a heat wave in Britain and southwest Europe from July into early August

270 1757 that set temperature records that stood for over 250 years (The London Chronicle, July 23-

271 26, 1757; London Magazine, November 1758 p. 563-4). London on July 16-26 had an average

272 high of 41.2C (Nature Notes, 24 August 1882, p. 415). This does not assume weather conditions

273 in Europe fueled a hurricane tracking into Atlantic Canada, but demonstrates that unusually hot

274 temperatures across the northern hemisphere known to intensify midlatitude hurricanes existed in

275 the summer of 1757.

276   The 1757 hurricane noted by Poey (1855) and Ludlum (1963) was confirmed as a

277   hurricane in Chenowith's (2006) re-assessment compilation. It was first seen off Florida and

278   followed the coastline past Cape Hatteras to New England on September 22-24 (Ludlum, 1963).

279   Benjamin Franklin's observations of this specific storm led him to conclude that hurricanes "are

280   produced by currents of cold winds rushing from the north along the Atlantic coast and mingling

281   with the warm winds produced by the gulf-stream" (Warden, 1819). It struck the British frigate

282   HMS Winchelsea on September 23 to 24 at 36º45'N 70º 54'W (off North Carolina over the Gulf

283   Stream). The log notes gale force east then east-southeast and south winds between 10 p.m. and

284   5 a.m. on September 23 which, 15 minutes later, veered violently to the northeast and then

285   northwest at 'near hurricane' intensity. It split the main sail and broke the main mast. It was also

286   accompanied by a 'great sea' (ADM 52/1105).

287   The storm passed New England on September 24 (Boston Herald, Oct. 17, 1757, Ludlum

288   1963) and struck Nova Scotia as the Louisbourg Storm on September 25, 1757. Its arrival at Fort

289   Cumberland on the Nova Scotia border 200 km inland late September 22 included 'violent rain'

290   and 'constant heavy rain' into the 23rd. Knox's journal on the 27th describes September 24-26

291   with … 'I never saw such storms of wind and rain as we have had for some days past…'

292   followed by 'windy, showery and very cold' weather on the 27-28th and 'dry, cold windy

293   weather' on the 29th, followed by frost and snow across Nova Scotia by mid-October (Knox

294   1769).

295   **4.0 Historical Context**

296   The Seven Years' War (1756-1763) arose from unresolved issues following the Treaty

297   of Aix-la-Chappelle that ended the War of the Austian Succession (1740-1748). It began as a

298   European conflict between Great Britain and allies and France and its allies, but soon extended to

299 the colonial interests of both nations in North America and India. It resulted in significant losses

300 for France including the loss of New France, now Canada, to Great Britain (Syrett, 2008).

301 Britain's overwhelming success in gaining territory at France's expense during the war led

302 France to subsequently support the secession of the American colonies in 1775.

303   Great Britain's 'Grand Plan' for the North American campaign began with John

304 Campbell, the 4th Earl of Loudoun, being appointed Commander-in-Chief of the British military

305 in North America. His adversary was Louis-Joseph de Montcalm-Grozon, Marquis de Montcalm

306 de Saint-Veran, commander of French forces in North America. To attack Montcalm at Quebec

307 without leaving a powerful French fortress at his rear, Loudoun needed to first seize Fortress

308 Louisbourg in Nova Scotia. On May 22 to 25, 1757, troops boarded 134 transport ships in New

309 York to rendezvous at Halifax with a fleet departing Britain under Vice Admiral Frances

310 Holbourne. Pitt's brief removal as Prime Minister delayed the fleet but his return to power with a

311 coalition government saw it depart Cork, Ireland, on May 8, 1757. The delay allowed France to

312 reinforce Louisbourg with three naval squadrons ahead of the British arrival. On May 23 five

313 French battleships and a frigate under Chevalier Joseph de Beauffremont arrived from the West

314 Indies, followed on June 15 by four battleships and two frigates under Joseph Francois de Noble

315 du Revest from Toulon. On June 20 nine battleships and two frigates under Vice Admiral

316 Emmanuel-Auguste de Cahideuc (Comte Dubois de la Motte) arrived from Brest. 4000 French

317 troops bolstered a garrison of 3200 plus 300 Acadians and Mi'kmaq warriors (McLennan, 1918,

318 Stoetzel, 2008). Holbourne's arrival at Halifax on June 30 bolstered Loudoun's force to create an

319 army of 12 000. *HMS Gosport* arrived on August 5 with letters intercepted from a French

320 schooner captured off Newfoundland detailing Louisbourg's reinforcement. It rendered the

321   attack on the fortress untenable. Loudoun returned to New York and on September 11, 1757

322   Holbourne sailed his fleet north to blockade Louisbourg (Fig 1).

323   **5.0 The Louisbourg Storm**

324   The British fleet cruised off the coast of Cape Breton Nova Scotia (Fig. 1) to lure the

325   French fleet out of Louisbourg Harbour to do battle. On September 21, the British 80-gun

326   flagship *Newark* noted fresh westerly gales followed by fair weather and light breezes then calm

327   with fog on the 22nd. That day an officer on the French 28-gun frigate *Fleur de Lys* saw a low

328   mist enter Louisbourg Harbour. The mist was also seen at sea by the British *Invincible* until it

329   dissipated under a rising southeast breeze. Britain's *Newark* and France's *Fleur de Lys* recorded

330   that the breeze veered to the southeast and intensified to moderate gales on September 22. The

331   *Invincible* recorded strengthening easterlies September 22-26 from otherwise prevailing

332   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

333

334   **Table 2.** Prevailing Winds (HMS Invincible Logbook)

335 Prevailing wind direction measured for each of three successive 8-hour watches per day and

336 azimuth equivalent on the *Invincible*. Storm winds, arriving September 22, 1757, off Cape

337 Breton, are shaded and in italics; two watches with easterlies not associated with the storm are

338 shaded only. Mean 250.5 (WSW) prevailing wind direction six days before and five days

339 following storm (continued westerly on 28 and 29). Mean 135 (SE) wind direction during storm.

340 Ships off St. Esprit on September 25 saw prevailing southeasterly winds last until September 26.

341 Ships south of St. Esprit including *Invincible, Sunderland and Windsor* faced southwesterly

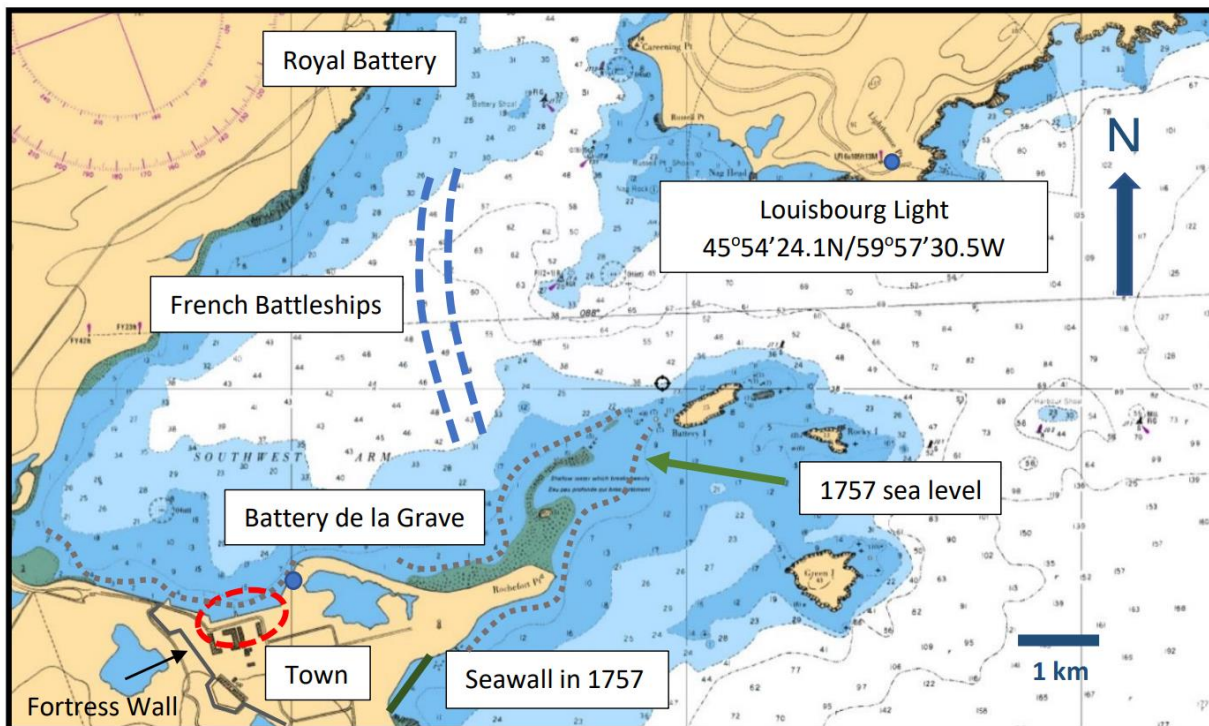
342 winds on September 25.

343   French naval officers, expecting a storm due to the southeast winds, moored the French

344 fleet in two lines off Royal Battery (Fig. 2) with four 2-ton anchors at the bow of each ship. The

345 southeast winds led the British ships at sea to secure masts and naval guns, weighing as much as

346 3 tons apiece, anticipating a storm. On the 24th *Invincible* and *Newark* reported increasing cloud,

347 haze and rain beginning under southeast gales.

348

349   **Figure 2.** Louisbourg Harbour showing the French fleet anchorage, Louisbourg Lighthouse,

350   Royal Battery, Battery de la Grave Guardhouse, and the southeast seawall overlain on chart

351   image © Canadian Hydrographic Service (2011) Chart Guyon Island to Flint Island 1:37,866

352   [Issued 2022-11-26]. Shoals (shaded) relative to ship hull displacements of 5.8-7.0 m (19 to 23')

353   give a general sense of the scale of waves and surge needed to throw battleships on shore and

354   destroy the southeast facing seawall.

355   On September 25 fresh southeast gales rose to excessive hard gales with very heavy rain.

356   The British *Windsor* noted heavy rain and mist and intensifying strong gales with hard squalls.

357   At 7 p.m. *Sunderland* faced very hard gales that rose to extreme hard gales by 10 p.m. At 12

358   a.m. *Invincible* faced strong gales, torrential rains and a 'great sea.' At 2 a.m. on the 25th

359   *Invincible* noted an 'excessive hard gale' and 'a hurricane of wind' and mountainous waves.

360   Topsails used to control ships in severe weather were 'blown to rags.' *Sunderland*'s main

361   staysail was torn away. Waves 'made a free passage over…' the 70-gun *Devonshire* and

362   smashed in *Lightning's* stern. The wind tore away the 8-gun *Cruiser* sloop's mizzen mast and

363   three sailors were swept overboard. *Cruiser* was 'very near foundering having been underwater

364   several times' and jettisoned its guns to stay afloat.

365   *Windsor*'s log records extreme gales with severe squalls, heavy rain and a great sea.

366   Canvas tarpaulins stripped off deck gratings by the wind allowed waves and rain to flood the

367   ships which soon had up to 2.5 m (9') of water in the holds despite the pumps in full operation.

368   *Windsor* and *Sunderland* sailed S across SSW winds. *Grafton's* three-ton 7 m (30') rudder was

369   torn off the ship. *Invincible*'s rudder, also torn free, was only saved by its preventer chains.

370   Sails on all the British ships at sea were torn away by the wind. Captain Bently later reported

371   that *Invincible's* hull planking had opened and broke iron reinforcing brackets and bolts,

372   allowing the entire gun deck and its tens of tons of heavy naval guns to drop several inches

373   (Captain's Letters, ADM 1/1488). *Sunderland's* foretopmast, reinforced by ten 5 cm (2") rope

374   shrouds plus stays, was torn off the ship and it disappeared into the night with two sailors.

375   *Invincible* was thrown onto her 'beam ends' (side), forcing it to heave overboard ten 12-pounder

376   upper deck guns and carriages, roughly twenty tons, to right the ship. *Invincible's* main yard was

377   ordered taken down but before it could be done the wind broke off the 38" (1 m) diameter

378   mainmast 20' (6 m) above the deck. The falling mast tore down the foretopmast and mizzen mast

379   and crushed the starboard gunwale. The wreckage pulled the ship onto its side and swept sailors

380   John Guttredge and Samuel Kirby into the sea. *Invincible's* sailors cut the tangled mass free

381   before it sank the ship.

382   At Louisbourg, the French military officer at La Grave Battery (Fig. 2) led his troops to

383   safety after the sea rose steadily above their knees (Chevalier de Johnstone, 1758). Offshore, the

384   British 14-gun *Ferret* sloop under Francis Upton and a crew of 104 was lost with all hands.

385   Around 6 a.m. *Invincible* noted five British ships dangerously close to shore. *Eagle* was blown

386   onto its beam ends and jettisoned ten upper deck guns and cut down its mizzen mast to right the

387   ship. *Captain's* foretopmast was torn away and took its two topmen. *Lightning* found it was

388   drifting toward offshore breakers less than 200 m away. Captain Faulkner ordered *Windsor's*

389   guns jettisoned. He noted *Invincible* had lost all but its lower foremast and bowsprit. *Sunderland*

390   was swept by 'a very heavy large sea' that 'passed freely over us.' Barges lashed to the decks of

391   *Windsor* and *Invincible* were smashed and swept overboard. *Sunderland* cut down its main

392   topmast and threw guns overboard to right the ship. The wind snapped its 61 cm (24") diameter

393   mizzen mast as it drifted toward the offshore breakers. Anchors did not slow its drift so the

394   mainmast was cut down. *Sunderland* stopped close to the breakers and less than a kilometer from

395   shore. The 74-gun *Terrible* also stopped its drift almost at the breakers. *Eagle's* foretopmast was

396   cut down to lessen the strain on the ship. It sailed southward narrowly missing the breakers.

397   *Newark* regained control after cutting the anchor cable and heaving guns overboard and barely

398   cleared the line of breakers. Dawn revealed a signal flag had been raised by the French fishing

399   village of St. Esprit to give the crews of the British ships hope (Knox Bristol Journal, November

400   12, 1757).

401   At Louisbourg the French fleet was pummeled by severe winds and waves. The 70-gun

402   French battleship *Dauphin Royale* fired a gun in distress when its anchor cables snapped under

403   the strain. *Dauphin Royale* collided with the 80-gun *Tonnant,* destroying its bowsprit, figurehead

404   and cutwater, and damaged *Tonnant's* rudder and poop deck. The two ships crossed

405   *l'Abenaquise's* anchor cables and the three entangled ships were heaved on shore at Royal

406   Battery (Fig. 2) along with 25 merchant ships, 50 schooners and 80 small vessels, many high and

407   dry and with many sailors drowned (McLennan, 1918).

408   At sea, by 10 a.m. the British fleet was dangerously close to the breakers off St. Esprit.

409   Many sailors were certain they were doomed (Knox Bristol Journal, November 12, 1757).

410   *Grafton* struck a rock but floated free and managed to set an anchor. *Windsor* and *Eagle* had

411   been able to sail south of the main British fleet off St. Esprit. *Eagle's* Captain Palliser saw what

412   he judged to be *Nottingham* or *Tilbury* near shore, within the breakers, its bow facing shore with

413   its fore and mizzen masts gone. He also recorded that it was afloat and attempting to wear (turn)

414   but lost sight of it in heavy rain.

415   Waves tore down sections of the French Fortress Louisbourg's massive southeast facing

416   stone seawalls. Locals brought news of lakes 10 km inland being reached by the sea. Seawater

417   rose to flood the streets of the Town of Louisbourg, 'something never before seen' (Chevalier de

418   Johnstone, 1758). Eventually the beached French battleship *Tonnant* 'floated with the tide' as

419   the wind veered south and then west at 11 a.m.

420   At sea the British warship *Windsor* noted the wind turned to blow from the west at 11:30

421   a.m. but had strengthened. *Eagle* recorded that the squalls had lessened by noon. On the

422   *Sunderland* massive waves swept sailor George Lancey from the fore yard 24 m (80') above the

423   keel. By 3 p.m. waves at Louisbourg fell enough that *l'Inflexible* was able to send sailors to assist

424   other ships. French captains petitioned 74-year-old Admiral Dubois de la Motte to attack the

425   stricken British ships off their coast but his orders to defend Louisbourg had been met and he

426   kept his ships in port. James Johnstone, a Scot serving as a French officer, felt that five French

427   warships if they had ventured to sea could have captured the entire British fleet (Chevalier de

428   Johnstone, 1758). This sentiment was subsequently shared by Lady Anson, daughter of a

429   confidante of Lord Newcastle with whom Pitt had formed his coalition government, in an

430   October 31, 1757 letter to the First Lord of the Admiralty, her husband George Anson (Anson,

431   1757). On September 27th a boat arrived at Louisbourg from St. Esprit with news that the British

432   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 seas like mountains,	La Grave Battery	SE	Sea level rises 3.4 m (11')
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

433

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*.

439   It is not known when *Ferret* sank but it had been sent ahead of the fleet prior to the storm to

440   undertake reconnaissance of the French fleet at Louisbourg.

441   were unable to counter the heavy seas so they marched to the site across land flooded by the

442   torrential rain. Mi'kmaq warriors gained the wreck first but informed the shipwrecked British

443   they would not be harmed since the storm had brought them to their lands (Moreau St. Mery *in*

444   McLennan, 1918).

445   **6.0 Deriving Storm Metrics**

446   Storm intensity is reflected in key metrics including wind speed and direction, wave

447   height and surge which is driven by a rise in sea level due to atmospheric pressure and sustained

448   storm winds and is proportional to a cyclone's intensity, translation rate and the bathymetric

449   gradient of the continental shelf.

450   *6.1 Estimating Storm Wind Speed*

451   The wind speed required to cause structural failure in masts was estimated. Virot et al.

452   (2016) determined the critical wind force needed to break trees of average integrity is 151 kph

453   irrespective of species with a +9% factor for large diameter trees. 165 kph assumes structural

454   defects due to longer tree life offset the structural advantage of size, yet masts were chosen for

455   their lack of defects. Fir and pine trees of superior structural integrity were selectively harvested

456   for Royal Navy masts into the 1770's from North America, Great Britain and the Baltic (Lavery,

457   1984). Masts were also not free-standing (like trees) but reinforced by rigging to effectively

458   transfer wind energy from the sails to the hull. *Invincible's* masts were secured by sixteen 5 cm

459   (2") hemp shrouds per side, each tensioned with paired deadeye blocks, the lower block in an

460   iron band bolted to the ship's frame. Its 1 m (38") diameter lower mainmast stepped against the

461   ship's keelson rose 35.7 m (117') through two decks. Above it stood a 21.3 m (70') 51 cm (20")

462 diameter topmast and above that the 10.7 m (35') 28 cm (11") diameter topgallant mast (Lavery,

463 1984, 1988). To achieve the critical wind speed of 165 kph, taken as a minimum due to the

464 factors noted, *Invincible's* motion must be considered.

465   *Invincible* sailed SW under SE winds, but gradually encountered SW winds. *Sunderland*

466 and *Windsor* sailed south across SSW winds while most ships of the British fleet to their north

467 near St. Esprit faced SSE winds. *Invincible* was among the southernmost ships (Fig. 1). It sailed

468 SW½W (230°) against EbS (101°) winds on September 24. During the storm its displacement

469 was 98 km toward 256.7° (22.5 km S; 96 km W). 6 km SE (135°) of Chedabucto Bay it faced W

470 (270°) winds and SE surface currents estimated at 3.49 kph based on currents of 0.97 m/s based

471 on currents there during SE winds from Hurricane Juan in 2003 (CBCL Report, 2015).

472   On September 25 to 26 *Invincible* sailed 159 km toward 102.75 degrees. The ship spent

473 11 hours under SE winds and another 11 hours under SW winds. The last 2 hours it drifted west

474 under jury rig. The strongest winds were SW (225°). Cosine Law (Figure 4) gives a wind speed

475 of 170.62 kph to achieve 165 kph at the mast on the moving vessel. The 5.62 kph difference

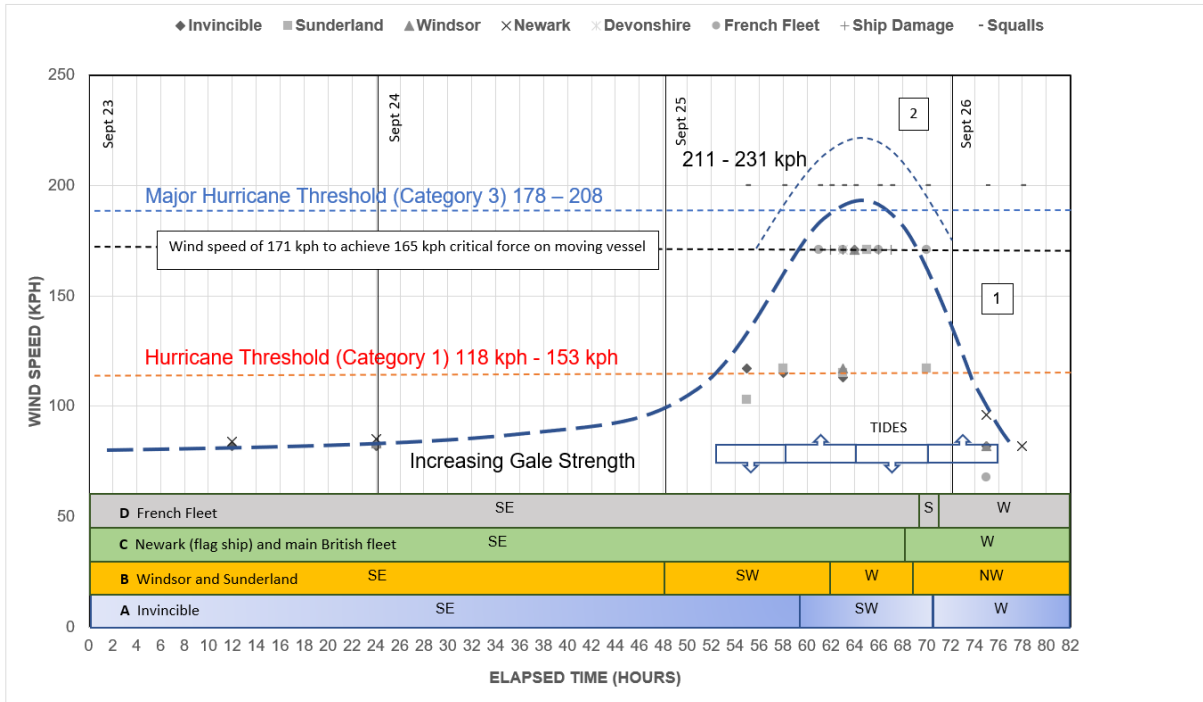
476 infers vessel motion played only a minor role in reaching critical force yet is still 18% of the

477 Saffir-Simpson Category 3 wind force range. Ephemeral squalls of 40-60 kph added to sustained

478 winds of 170.62 kph suggests peak winds might have reached 211-231 kph. Admittedly an

479 imperfect solution, it assumes a minimum critical force. It does not consider the inherently

480 superior structural integrity of masts plus their reinforcement by rigging, suggesting major

481 hurricane threshold winds (178 kph) could have been met even without considering squalls.

482

483   **Figure 3.** Hurricane wind evolution with time. The time sequence shows the arrival of southeast

484   winds (Beaufort Scale) intensifying to hurricane winds (118 kph), peaking to sustained 171 kph

485   *see* Fig. 4) critical wind force with increasing squalls, followed by a rapid decline to gale force

486   westerlies. The horizontal axis is divided into days (noon) and 2-hour intervals. The vertical

487   scale is wind speed in kph. A best fit curve [1] is typical of windspeeds as a hurricane passes a

488   fixed point. A best fit curve for squall frequency [2] in ships' logs adds ephemeral wind speed to

489   sustained winds. 171 kph is considered the minimum critical wind force considering the superior

490   materials integrity of masts and their reinforcement with rigging. Peak winds lasted 9 hours

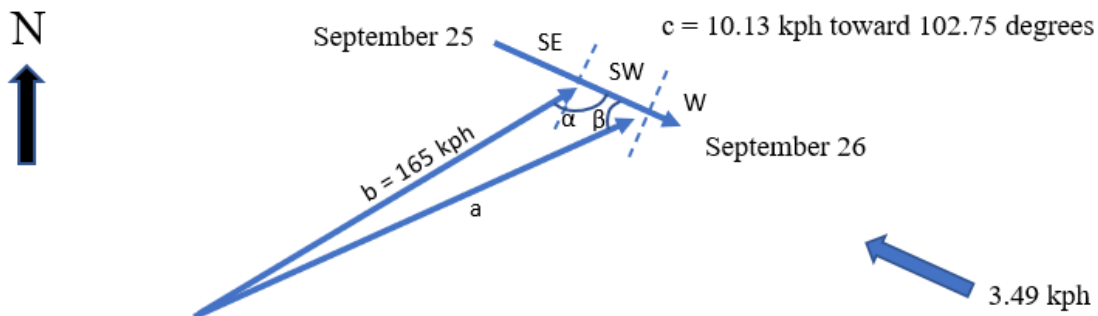
491   while hurricane force winds impacting the fleet lasted 15 hours. Wind directions represent, north

492   to south, winds affecting: French ships at Louisbourg, British ships near St. Esprit, *Windsor* and

493   *Sunderland* south of St. Esprit, and *Invincible* closest to the eye (Fig 1). Southernmost (blue)

494   through southern (orange), off St. Esprit (green) and Louisbourg (grey) show the general

495 distribution of ship logs (*see* Table 3). *Invincible* sailed past *Windsor* and *Sunderland* during the

496 storm and into the SW winds they had encountered earlier.

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

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

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

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

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

$a = 170.62$ kph from 227.75 degrees (where $b = 165$ kph and $\beta = 55$ degrees)

497

498 **Figure 4.** Correction for Vessel Motion. *Invincible* drifted 159 km toward 102.75° between

499 September 25 and 26 over 24 hours. It experienced SE (11 hours), then SW (11 hours) and

500 finally W winds (2 hours). This solution focuses on the 11 hours the ship was under SW winds,

501 the strongest winds closer to the center of the cyclone (Fig. 3). During elapsed hours 59-70 the

502 vessel sailed toward 102.75 under a SW wind (225°) at an average of 6.64 kph based on the total

503 displacement of 159 km toward 102.75°. The incident angle between the wind and the ship

504 displacement vectors is 122.25°. A surface current in Chedabucto Bay during SE winds from

505 Hurricane Juan (CBCL Report, 1995) of 0.97 m/s (3.492 kph) is assumed to be a reasonable

506 estimate for this study. The resultant of 6.64 kph toward 102.75° indicates speed relative to

507 surface currents was 10.13 kph. Image not to scale.

508   Anticlockwise wind vectors at ship locations are tangential to concentric cyclonic wind bands.

509   Normal lines drawn to these vectors converge to identify the location of the eye. Interestingly

510   they lack the asymmetry diagnostic extratropical cyclone wind fields (Fig. 7). This process,

511   repeated to plot the eye location on September 26, 1757, indicates the storm crossed Cape Breton

512   and entered the Gulf of St. Lawrence. Even if the wind field began to collapse, the location of the

513   storm center suggests the system may have slowed while passing over Cape Breton Island.

514   *6.2 Estimating Storm Wave Height*

515   *Sunderland's* and *Devonshire's* upper decks were submerged after waves broke over the

516   forecastle. The 12.2 m (40') distance from the keel to the upper deck plus an estimated 3-6 m

517   (15-20') to break over the forecastle and tear away ship's boats lashed to the deck requires a

518   wave height of about 18 m (60') (Lavery 1983). *Lightning's* stern gallery 40-50' above the keel

519   was destroyed by waves striking the ship from astern, also requiring waves of about 12.2 m

520   (60'). A sailor swept out of *Sunderland's* fore yard by a wave necessitates a wave of about 25-30

521   m (80-90'). While carrying considerable uncertainty, these examples provide estimates of

522   significant and maximum wave heights. Waves sufficiently large to tear down stone seawall

523   rampart of Fortress Louisbourg are consistent with these estimates, as are waves capable of

524   reaching inland lakes. Descriptions of the sea state in Louisbourg Harbour by French naval

525   officers resulting in extensive damage to ships and boats suggests waves much larger than any

526   recorded in modern times even though wave energy from the southeast would have been partly

527   attenuated by shoals (Fig. 2).

528   On September 26-28, 1818, the American frigate *USS Macedonian* met a hurricane off

529   Bermuda (35°N 53°W) and suffered damage nearly identical to *HMS Invincible* in 1757 from

530   waves of 12 m (40') (Saegesser 1970). The dates appear to coincide with Chenowith's (2006)

531   'Final Storm Number 253' listed as a hurricane in Table IV. Damage to the ship closely parallels

532   that described for the 1757 hurricane except that line of battle ships had a much heavier

533   construction than a frigate. Saegesser (1970) provides a very detailed account based on the ship's

534   log and ancillary damage reports, and notes that in the same storm the Dutch brig De Hoope lost

535   all topmasts and spars, the brig Ann from Nova Scotia was abandoned at sea, the brig Mary from

536   Bristol was overturned, the ship Catherine Dawes from Philadelphia sank and a Baltimore

537   schooner and a Nantucket whaler were both dismasted. *Invincible's* substantially more robust

538   build than the frigate *Macedonian* implies larger, more powerful waves caused its damage.

539   6.3 *Estimating Surge Height*

540   *6.3.1 Surge at Louisbourg Harbour*

541   A Parks Canada coastal erosion study at Fortress Louisbourg National Historic Site

542   revealed iron mooring rings set in the remains of a seawall. Modern high tide compared to these

543   rings established historical high tide 0.90 m (3') of sea level rise since 1757 (Duggan, 2010). La

544   Grave Battery (Fig. 2) is 2.0 m (6.6') above sea level (asl; Google Earth mid-tide datum), so sea

545   level rise plus flooding to sentries' knees (0.5 m) yields a 3.4 m (11') mid-storm surge. Historic

546   buildings along the waterfront (Fig. 2; 45°53'33.57" N 59°59'07.89" W) are 5 m (16.4') asl

547   while the first street, Rue Royale, is 7 m (22.9') asl. Seawater flooding the town streets at the

548   lowest levels and adjusted for sea level rise indicates 5.9 m (19.4') to 7.9 m (21.4') of surge.

549   *Tonnant* 'floated with the tide' when the wind veered south at 11 a.m. on September 26 (*Fleur de*

550   *Lys* log *in* McLennan, 1918). Louisbourg's 12-hour tidal cycle and assuming low tide around 10

551   a.m. gives a high tide at 4 a.m. coinciding with storm landfall and creating a storm tide (Fig. 3).

552   Backing out the 1.5 m (5') tidal range gives a 4.4-6.4 m (14.4-21') peak surge, consistent with

553   the earlier surge of 3.4 m (11') at La Grave.

554   *6.3.2 Surge at St. Esprit (Tilbury Wreck)*

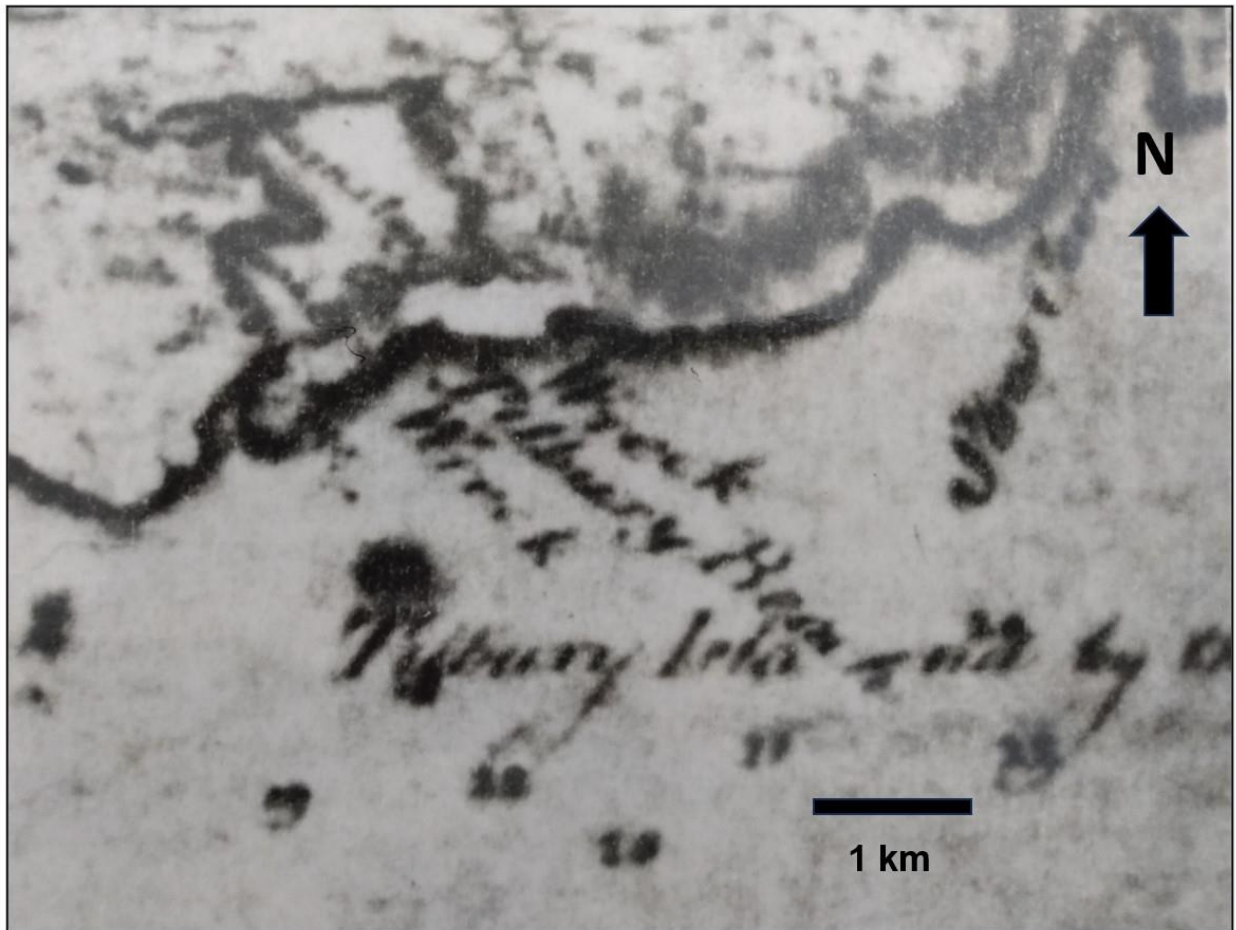
555   *HMS Tilbury* was a 58-gun square-rigged warship lost on the coast in the storm. *Eagle's*

556   captain saw either *Tilbury* or *Nottingham* shoreward of the breakers near St. Esprit, 45 km south

557   of Louisbourg. It was deduced to have been *Tilbury* since *Nottingham* survived the storm with a

558   different array of masts than seen on this ship. 'Wreck' appears on a 1776 chart (Fig. 5). Storm

559   (2002) used Zinck's (1975) image of an 18th Century 6-pounder British naval gun at 'Tilbury

560   Rocks' to view Tilbury's wreckage in 4 m (15') from a boat in 1969.

561

562   **Figure 5.** Excerpt from a historic chart of Cape Breton Island showing the general St. Esprit

563   study area and *HMS Tilbury* wreck site, from Mowat (1776), depicted in Figs. 6a,b.The faint

564   dotted line right of Barnsley Lake, named for Tilbury's captain, marks a parish boundary.

565   The historic navigation chart (Fig. 5) showed parish boundaries marked by fieldstone

566   walls of historic St. Esprit (Fig. 6a, b) which helped identify the line of offshore breakers

567   described in British naval logs. A draft hydrographic chart (Hanson, 1954) was digitized and

568   gridded with missing data interpolated. Paired depths and locations were entered in a spreadsheet

569   and a grid-plot of local bathymetry supported a marine proton magnetometer survey of Tilbury

570   Reef isobaths following best practices for submerged archaeological sites (Cornwall Council

571   Report 2010-R012). Dipole targets investigated by divers led to locating a mid-18th Century 6-

572   pounder British naval gun *in situ* in 3 m (10') which was 2.1 m (7') in 1757, near the site of the

573   6-pounder on shore, both interpreted to be from *Tilbury's* forecastle. In 1757 *Tilbury* was

574   observed at the time as 'bow in' near shore, landward of the breakers and 'attempting to wear'

575   (turn). It was in water sufficiently deep for its 18' displacement as it was, at the time, afloat and

576   under sail. Adding in the hydrographic survey datum offset of 0.6 m (2') between lowest low tide

577   at St. Esprit and the Google Earth WGS84 (World Geodetic Standard 1984) mid-tide datum for

578   Louisbourg suggests a minimum 4.0 m (13') surge at St. Esprit. Post-storm relaxation flow

579   stranded the *Tilbury* (Fig. 6b) allowing native warriors to reach it.

580

581

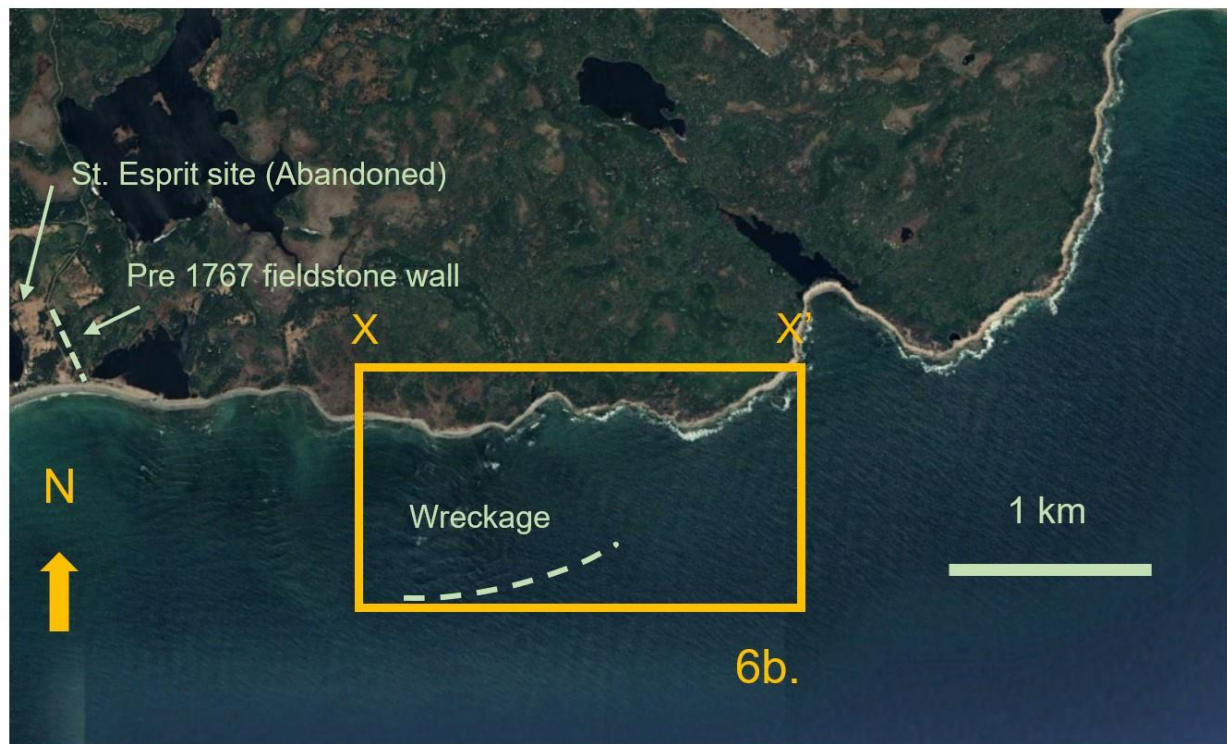
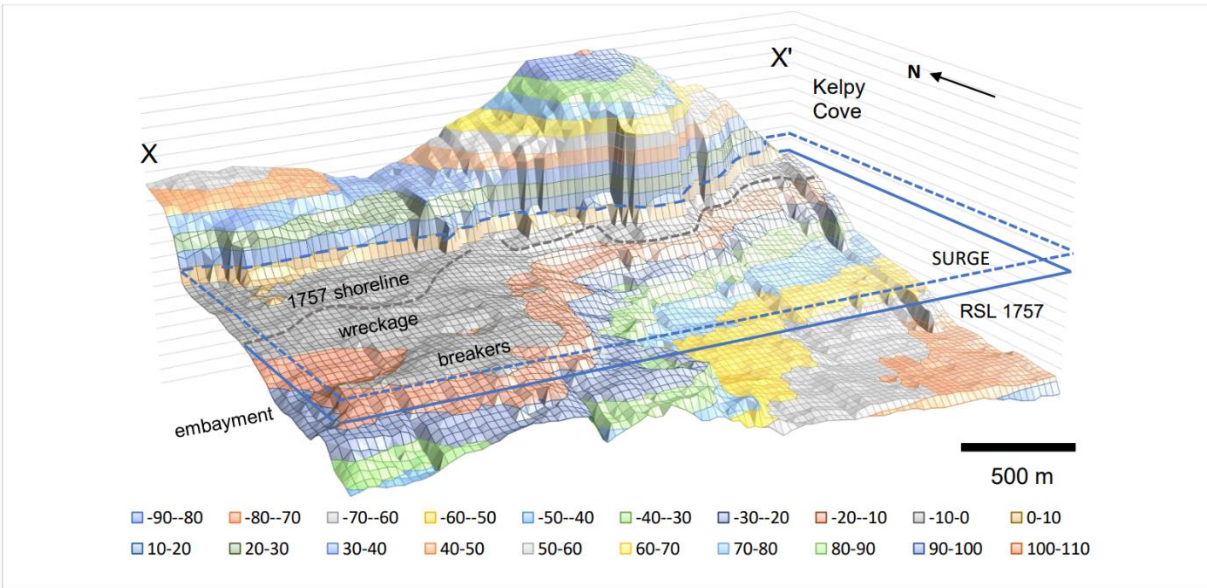



Figure 6a. Location of Tilbury shipwreck. Inset map X – X' (45º38'31.21" N 60º27'41.99" W

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* wreck site at lowest low water adjusted for 1757 relative sea

level (solid line) and minimum surge (dashed line) needed to float *Tilbury*. Coastal retreat of 27

m (90') calculated from historic sea level gives the 1757 shoreline. Topographic and bathymetric

data were kept in Imperial units 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.

593

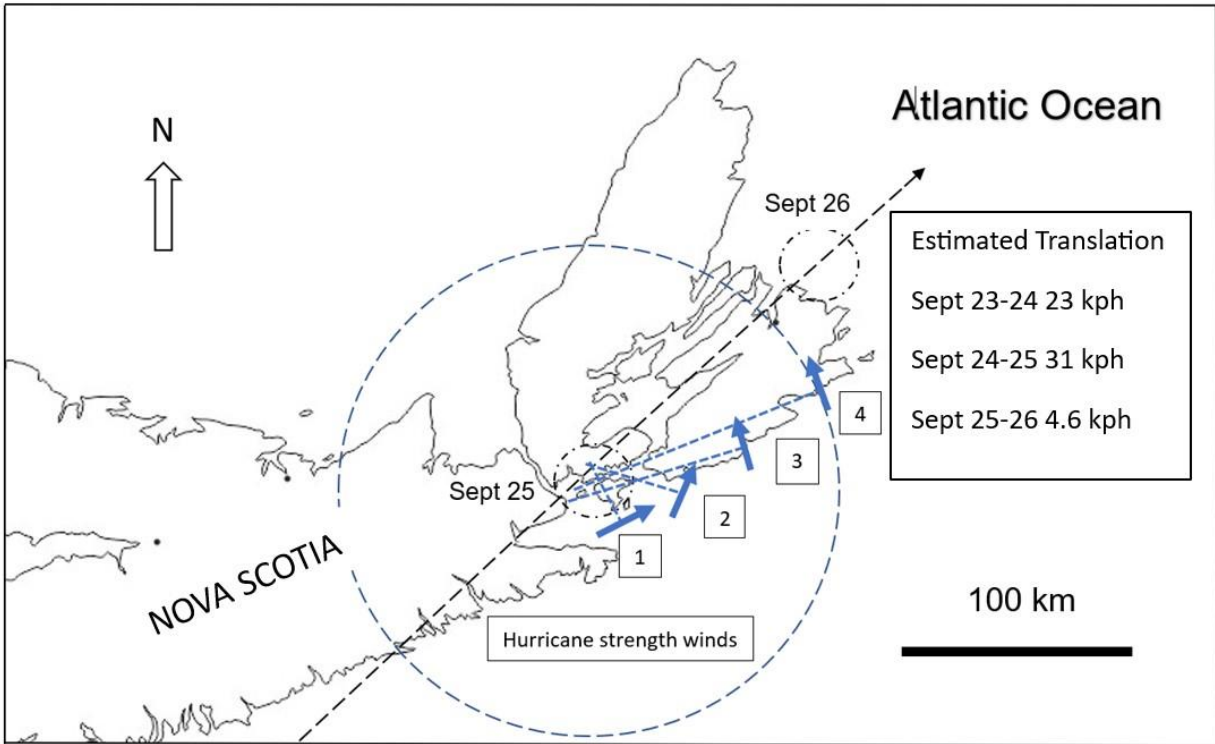



Figure 7. Eye location and estimated translation speed. Plots of wind vectors on September

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.

7.0 Modern Analogs

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

607 height of 19 m (62') to 23 m (77') at drilling rigs near Sable Island (JD pers. obs.) and a 1.4 m

608 (4.6') surge at landfall near St. Esprit (Lalbeharry et al., 2009). Both cyclones produced similar

609 sea states and surge which can be compared to the Louisbourg Storm. On September 24, 2022,

610 Category 3 Hurricane Fiona began extratropical transition as it crossed the Scotian shelf. A cold

611 trough over Nova Scotia directed its landfall to the Canso Peninsula. Winds of 140 kph in Nova

612 Scotia reached 177 kph in Newfoundland and Labrador. Significant and maximum wave heights

613 were 17 m (56') and 30 m (98') and surge reached 2.4 m (8').

614   In 1969 Category 5 Hurricane Camille generated a 7.3 m (24') storm tide from 1.8-3.0 m

615 (6-10') surge (U.S. Department of Commerce Environmental Science Services Administration

616 1969) while Category 5 Katrina in 2005 produced a storm tide of 8.2 m (27') (Knabb et al.,

617 2023). Hurricane Laura (Category 4) in 2020 had a peak 5.2 m (17.2') surge (Pasch et al., 2021)

618 and a 2.7-4.0 m (9-13') spanning 130 km from Beaumont to Lake Arthur, Texas. In 2018

619 Hurricane Dorian (Cat 5) slowed to 2 kph over the Bahamas creating an 8.5 m (28') surge (Avila

620 et al., 2020). Surge from these major hurricanes cannot be readily compared to storm strikes in

621 Nova Scotia due to different coastal bathymetry but they allow a general comparative

622 benchmark.

623   Hurricane Juan's translation speed before landfall was 1-5 m/s (4-18 kph). Compared to

624 North Atlantic hurricane translation rates of 17.7-19.3 kph (11-12 mph) the Louisbourg Storm

625 slowing from 31 kph over water to 4.6 kph after landfall between September 25-26 may have

626 enhanced surge height, similar to Dorian's impact on the Bahamas as it slowed, resulting in the

627 exceptional surge height at Louisbourg. Prevailing westerlies returned after the storm. The key

628 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 threshold

and maximum wind speeds.

8.0 Discussion

Metrics derived from historical data captured during the Louisbourg Storm of 1757

indicate its intensity surpassed any modern (post-1851) Atlantic cyclones striking the same

region. Historical records show the Louisbourg Storm originated in the tropics to pass Florida,

the Carolinas and New England to strike Nova Scotia on September 25, 1757. It developed at

the height of hurricane season under an optimal NAO 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

648 release of energy over coastal waters. Longer, colder LIA winters skewed mean average

649 temperature profiles but a UK and European heat wave in Europe in 1757, extreme even by

650 modern standards, shows seasonal temperature variability could contribute to warmer SSTs and

651 fuel tropical cyclones in the LIA. A strong correlation between SST and tropical cyclone

652 frequency (Vecchi and Knutson, 2008) suggests that the LIA's cooler SSTs could see fewer

653 storms per year. Mean-annual temperature data limited by temporal resolution limitations likely

654 mask peak temperatures that likely existed over smaller areas for shorter periods but historical

655 records clearly show tropical cyclones developed even during the coldest part of the LIA.

656   The large number of British warships scattered along Cape Breton's coast by the

657 Louisbourg Storm provided a spatial resolution of wind vectors not normally available in storm

658 reconstructions. It was partly facilitated by ships sailing across storm winds to avoid being

659 driven ashore. The proximity of many British ships to shore and the severe surge and wave

660 action at Louisbourg led many contemporary naval authorities of both nations to fear the

661 catastrophic loss of the British and French fleets and 20 000 sailors. Only the reversal of wind

662 direction at the last minute as the eye of the storm passed prevented a disaster.

663   Wind speed is the key metric used in the Saffir Simpson scale to characterize the intensity

664 of modern cyclones. Engineering models are a standard method of determining the force

665 required to trigger structural failure in materials. Trees lacking defects that negate size advantage

666 were preferentially selected for masts and so likely required higher wind speeds for structural

667 failure. Rigging not only reinforced masts but redirected wind energy to the hull. Both factors

668 imply that the wind speed estimate of 171 kph determined for *Invincible* to achieve 165 kph at

669 the mast is an underestimate. Sustained winds likely exceeded the 178 kph (Cat 3) major

670 hurricane threshold even without considering squalls of 40-60 kph. Extreme winds are reflected

671 in topmasts (along with shrouds and stays) not only being torn off two British ships but being

672 carried off (with sailors) instead of falling to the deck. British ship positions were triangulated

673 against known coastal landmarks which provided greater accuracy in the distribution of wind

674 vectors. Superimposing *Invincible's* location and the wind vectors that identify the eye location at

675 the height of the storm suggests severe damage was a consequence of proximity to the eye which

676 is the location of a cyclone's strongest winds (Figs. 1,3, 7). Peak damage and squalls above

677 hurricane winds lasted 9 hours and hurricane force winds noted by the British ships lasted 15

678 hours as the center of the storm passed the coast (Fig. 3). In comparison, Hurricane Juan crossed

679 Nova Scotia in only 3 hours while Fiona crossed the province in under 6 hours, supporting the

680 interpretation derived from eye locations (Fig. 7) that the Louisbourg Storm slowed over land,

681 possibly due to a blocking cold air high. The British warship Tilbury was driven into water

682 depths at St. Esprit it could navigate only under a storm tide. Tidal reversal mid storm stranded

683 the ship near shore (Figs. 3, 6a,b).

684   Wind plots also show that the southernmost ships of the British fleet faced southwest

685 winds from the lower right quadrant of the hurricane. British ships to the northeast near St. Esprit

686 faced southeast winds. The French fleet in Louisbourg Harbour also faced southeast winds and

687 an anomalously high storm surge which allowed massive waves to drive ships on shore while the

688 surrounding region was flooded by torrential rains, all consistent with the front right quadrant of

689 the hurricane where the most severe impacts are felt. There was no suggestion that the air of the

690 storm was cold, but westerlies following the storm were described at Fort Cumberland as very

691 cold and dry. A table of wind directions for the second half of September 1757 (Table 2) shows

692 that, with the exception of the storm, prevailing winds appear to have been continental

693 westerlies.

694   Modern analogs show strong similarities in significant and maximum wave height, but

695   interpreted wind speeds for the Louisbourg storm are greater than those of Category 2 hurricane

696   Juan, a winter extratropical 'superbomb' in 2000, and the extratropical cyclone Fiona in 2022.

697   Surge measured at three locations is consistent with the scale of surge from major hurricanes in

698   the Gulf of Mexico and Caribbean. The 1757 surge greatly exceeds that of modern analogs that

699   crossed the same bathymetry with similar translation speeds. This consistent basis of comparison

700   of surge height, closely linked to storm intensity, shows the Louisbourg Storm had an intensity

701   far beyond a Category 2 system and was equal to a major hurricane. Surge calculated

702   independently for the lowest streets of the historic town of Louisbourg, Battery de la Grave and

703   the *Tilbury* wreck at St. Esprit were also consistent. Unlike the modern analogs, storm surge at

704   Louisbourg reflects conditions one hundred kms from landfall (Fig. 7).

705   The climatology of tropical cyclones on North America's eastern seaboard renders the

706   simple attribution of 'tropical' vs. 'extratropical' problematic. It is unlikely that a fully tropical

707   system with wind speeds equal to a Category 4 hurricane to strike Nova Scotia. Atlantic tropical

708   cyclone extratropical transition is triggered by the interaction of autumn continental westerlies

709   pushing strongly baroclinic air eastward toward intensifying tropical cyclones tracking north into

710   the higher midlatitudes of the North American eastern seaboard when SSTs peak in late

711   September into October. This is consistent with climatic drivers interpreted by Dezileau et al.

712   (2011) and Jackson et al. (2019) to explain historic European LIA storminess. Storm intensity

713   normally drops following extratropical transition, but not always (Hart and Evans, 2001). The

714   National Hurricane Center (NHC) uses sea surface temperatures plus storm asymmetry in

715   satellite images to indicate the degree of transition. Hart and Evans (2001) also found that 'the

716   NHC declaration (of extratropical transition) typically occurs early in the 1 to 2-day period …

717   when the storm is just beginning to lose its tropical characteristics.' This is not easy to assess for

718   the Louisbourg Storm whose energy release may have occurred over a short period. The lack of

719   eye asymmetry of the storm at landfall on September 25 based on the convergence of normal

720   lines to vectors at ship locations (Fig. 7) suggests it may have had largely tropical characteristics

721   at landfall. It leads to questioning at what point was it 'tropical' (hurricane) vs. 'extratropical'

722   given the NHC's 1 to 2-day range? It was likely both in the coastal zone. The storm's large size

723   is indicated by its winds first being recorded on September 22 by both the British and French

724   fleets at Cape Breton on the same day it struck the British frigate *Winchelsea* off North Carolina,

725   1350 km to the southwest. This may have enabled it to continue to draw tropical energy from the

726   Gulf Stream as it neared the Nova Scotia coastline. Hart and Evans's (2001) extratropical

727   climatology based on an analysis of all Atlantic tropical cyclones over a century. It shows that

728   systems can continue to see tropical intensification north of strongly baroclinic conditions that

729   trigger transition, resulting in an explosive release of energy and post-transition intensification.

730   Their analysis shows this typically involves hurricanes from south of 20 N that retained an

731   intensely tropical character into the higher midlatitudes. In fact, their analysis of past Atlantic

732   hurricanes shows that the region most conducive to this process in the entire North Atlantic basin

733   lies immediately south of Cape Breton, Nova Scotia, where the Louisbourg Storm was in 1757.

734   **9.0 Conclusions**

735   In 1757 continental westerlies, colder and earlier than today in the LIA, juxtaposed a cold

736   higher pressure air mass against a large, intensifying hurricane approaching Cape Breton. The

737   resulting explosive release of energy gave the Lousibourg Storm its highly destructive power. Its

738   unusual intensity required only an incremental change in the accepted climatology of Atlantic

739   cyclone extratropical transition, that being the early arrival of colder LIA continental westerlies

740   driving a steeper temperature gradient. The storm slowed over Nova Scotia as it encountered a

741   blocking high, indicated by the short distance between eye locations on September 25 and 26, as

742   well as by the duration of hurricane force winds (15 hours) over the coast, which may have been

743   enhanced by the storm's large diameter. The slowing storm drove an unusually high surge at high

744   tide. Tidal reversal stranded the *Tilbury* close to the historical shoreline. Fall westerlies arriving

745   earlier in the LIA would have expanded southward sooner and allowed an intensifying hurricane

746   to enter a zone more baroclinically favourable for transition. In the future, instead of an earlier

747   arrival of colder continental westerlies in fall, a warming North Atlantic could drive tropical

748   intensification in to higher latitudes later into the autumn to trigger increasingly destructive

749   storms over coastlines that have seen a meter of sea level rise and extensive coastal growth since

750   the Louisbourg Storm nearly rewrote history two and a half centuries ago. It is a reminder that

751   the past can inform the present, and the future.

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