Downbursts, groundings, incompetence and other hazards to 21st century merchant sailing ships

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Abstract

The safety record of commercial sailing vessels operating between 1850-2012 is analyzed, with the goal of predicting risks to modern merchant sailing ships. These risks are: sudden and invisible tornado-like winds caused by downbursts, insufficient engine power for auxiliary engines, unsafe cargo stowing and inexperienced crew. Merchant sailing ships using large, moveable underwater control surfaces that extend well below the hull (as may be required for acceptable sailing performance) may also be endangered by whale strikes.

Background

With increasing fuel prices and the onset of climate change, merchant sailing vessels are poised for a comeback. Recent work by the author shows that, based on past-10-year average fuel prices, bulk carrier vessels of 15,000-30,000 cargo deadweight tonnage (CDWT) using wind as the principal form of propulsion would have Required Freight Rates 20-40% lower than conventional ships. However, the comeback will occur without the 100 years of sailing operating experience and technological evolution that might have occurred if not for the invention of the engine. This paper will attempt to bridge the gap in development as it applies to the safety of merchant sailing vessels, by examining the historical record of ship sinkings.

Considered here are events which resulted in vessel losses in oceans and U.S. Great Lakes, and occurred between 1850-1900 (Swayze, 1992 and Hocking, 1969). Only sketchy information is usually available regarding the loss of these ships, but their story is nevertheless instructive. Recent sinking of "tall ships" between 1957 and 2012 are also considered, and much greater detail is available about their demise.

It appears from the historical record that merchant sailing ships of the past were more dangerous than today; in the 50 years from 1850 – 1900 (when most of the ships were sailing vessels), an average of 52 shipwrecks occurred per year in the U.S. Great Lakes alone (Swayze, 1992). For perspective, 41 ships over 100 GT were lost worldwide in 2019 (Allianz, 2020). Tall ship sailors of the past understood and accepted the inherent dangers of making a living on the sea. Herman Melville, in Moby Dick, expresses this understanding: *"There is death in this business of whaling - a speechlessly quick chaotic bundling of a man into eternity".*

Thanks to safety regulations introduced by governments and international organizations such as the IMO (International Maritime Organization), modern sailors accept a much smaller level of risk. The dangers to which large merchant sailing ships are subject, based on past and recent history, are identified below.

Risks from Rogue Winds

As shown by casualty records, and as might be logically inferred, most of the danger to which sailing vessels are exposed is weather-related. Hurricanes, typhoons and depressions are well-known and can normally be forecast with some precision, enabling prudent skippers to steer clear, or if necessary, take preparatory steps to ride out a storm. However, an analysis of eight tall ship losses occurring between 1957 and 2012 shows that in at least three of these vessels, more localized but more sudden winds associated with downbursts may be a far bigger threat to modern sailing vessels. These downbursts are caused by rapidly sinking air in very tall storm-clouds, usually cumulonimbus (Fujita, 1983). When the descending air reaches or approaches the surface of the earth, the flow of air spreads out horizontally, creating powerful and damaging winds. Microbursts, macrobursts, gust fronts and wind-shear are very similar: they are very rapidly moving air masses that can strike suddenly, and are all caused by downbursts.

Downbursts are respected and well-known to sailors, but it appears that there is a dangerous misunderstanding of what downburst conditions might look like. One of the survivors of the sinking of S/V Albatross recounts (Parrott, 2003), “I saw what looked like a light squall coming – just a grey uniform cloud approaching from windward…. There was no warning. She heeled us over about 45 degrees immediately… The ship hesitated and then slowly sank down on her side”. And from the S/V Pride of Baltimore sinking, a survivor recalls, “There was a line of squalls on the quarter and overcast skies on the beam. None of them appeared unduly threatening…. We were suddenly hit by a wall of wind and water with wind speeds of 70 knots and more… in what appeared to be slow motion the boat started laying over to port and in less than 60 seconds the boat was over on her side”.

A video showing a knockdown of sailing yacht Great Britain can be found at https://www.youtube.com/watch?v=Z5vA4QvaH1Q . The wind is seen to change suddenly from starboard to port, and the boat is knocked on her side within a few seconds. A crewmember explains, “We’d had a number of squalls during the day.. we’d seen another squall coming in and just thought it was going to be another squall .. all of a sudden, out of nowhere … the wind picked up… the boat went suddenly on its side. We’d never experienced that before.”

Yet another sudden increase in wind (which may have been a gust normally associated with depression storms) is documented by one of the few survivors of the sinking of sailing vessel Pamir in 1957 (Parrott, 2003), which sailed into the path of hurricane Carrie, “The wind suddenly changed direction and became shrill”, and the sails could not be furled quickly enough, necessitating them to be cut away. The survivor recalled, “With our sails cut away the gale forced us on our side until one rail was continuously underwater. Now 40-foot-high waves were smashing across our deck” (we note that the ship’s sinking was probably caused by poor stability, as cargo had been improperly stowed, preventing the ship from recovering from the roll to her side).

Fatal commercial aircraft accidents during landing and take-off led to federally-funded wind-shear research projects such as JAWS and NIMROD (Fujita, 1983), as well as Huntsville Alabama (Clark, 1988) in the 1970's – 1980's. Work by investigators showed that downdrafts associated with severe thunderstorms could cause very rapid changes in wind direction and speed known as wind-shear, as well as "tornado-like damage up to F3 in intensity" on the surface, with winds up to of 150 miles per hour, or 70 m/s (Fujita, 1983).

Fujita (1983) defines a downburst as "A strong downdraft causing an outburst of damaging winds on or near the ground". Downdrafts are caused by rapidly sinking air in tall clouds. The speed of the down-flowing air depends on temperature differences within clouds, the presence of rainfall, pressure differences between cloud tops and bases, and temperature differences between the air flowing out the base of the cloud and the surrounding air (Wolfson, 1988).

Microbursts are strong winds resulting from downbursts, with relatively small extent of horizontal flow (less than 4 km in breadth) in a direction that may be different from before the downburst, lasting for 2-5 minutes. Macrobursts cover larger areas, with 5-20 minute duration. To make matters more confusing, gust fronts are also produced by downbursts and also cause sudden increases in wind velocity and direction changes. However, gust fronts cover a much larger area than macro/microbursts, and can last from minutes to several hours. In addition, gust fronts are much gustier than micro and macrobursts. All of these phenomena may be "dry" or "wet", referring to the presence of rain. Fujita (1983) considered downbursts to be dry if they were accompanied by less than 0.01 inch of rain during the downburst period. Arbuckle (1996) defined dry downbursts in terms of the radar reflectivity of the downburst winds, with less than 35 dBZ as the upper limit of dry downbursts.

Microbursts are of great concern to aviation, since an airplane could encounter sudden wind speed changes with 180-degree differences in horizontal air flow direction as a microburst is traversed, as well as significant downward velocities – all of great concern at low altitudes. For the sailor, the difference between a microburst, a macroburst and a gust front may be academic since all of them could knock a vessel down with a sudden increase in wind speed, all are caused by downbursts, and all are plagued by the same detection problems. These phenomena will be referred to as downbursts in this report.

Fujita (1983) lists the types of clouds that can spawn downbursts:

- **Cumulonimbus** clouds may cause wet or dry microbursts which descend from the dark base of the cloud, often accompanied by lightning and hail nearby.
- **Spreading Anvil Cumulonimbus** clouds may develop dry microbursts beneath the long precipitation streaks falling from a spreading anvil of a dissipating cumulonimbus. Due to the evaporation during the long descent, practically all of these microbursts are dry. However, the outburst winds may be very strong.
- **Cumulus Congestus** clouds develop streaks of virga (rain that evaporates before striking the surface) that may have an innocuous appearance, but the virga could induce strong microbursts lasting 2 to 3 minutes.

While gusts in normal depression storms do not appear to be as large as downburst gusts, storm gusts could seriously endanger a vessel. Forristall (1985) developed equations for predicting gust strength over water, based on wave heights, height over the water surface, average wind speed, and wind speed standard deviation, from data taken on offshore oil structures in the North Sea and the Gulf of Mexico. We applied Forristall's technique using the Beaufort wind-speed scale (with given maximum wave heights), resulting in Figure 1 below. The plot shows the maximum Gust Factor (Gust Maximum/Average Wind Speed) as a function of average wind speed.

The plot shows that maximum gust factors range from 2.1 at 5 m/s to 2.5 at 30 m/s. This is in direct contrast to storm gusts over land, which show decreasing gust factors with wind speed. The increase appears to be due to the effect of waves.

By contrast, Fujita (1980) describes a microburst resulting in sudden wind increases from 15 knots to 54 knots, a gust factor of 3.6. The duration of storm gusts is seconds, while downbursts can last several minutes.

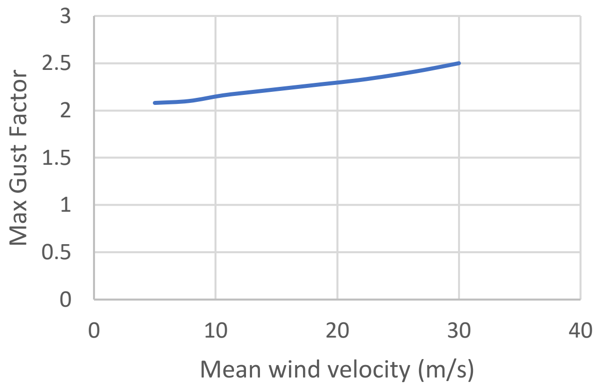

Figure 1. Maximum gust factor (gust velocity/mean wind velocity) from Forristall's method (Forristall, 1985), using data from Gulf of Mexico and North Sea, with maximum wave heights corresponding to mean wind velocity.

Figure 2. Cumulonimbus anvil cloud, photographed from International Space Station. https://www.nasa.gov/topics/earth/features/astronauts_eyes/iss016e27426.html

Information from the JAWS, NIMROD and Huntsville reports is summarized below:

1) Downbursts may be dry or wet, depending on the presence of rainfall in the moving air mass.
2) Surface winds from downbursts have roughly an equal probability of being cooler or warmer than ambient conditions.
3) The JAWS project was conducted near Denver, Colorado in May-August for 86 days, in which 182 microbursts were detected. By far, the busiest month was July. Few downbursts occur outside of this time period.
4) The highest reported wind speed was 36.6 m/s in JAWS, 31.1 m/s in NIMROD (conducted near Chicago, Illinois).
5) Microbursts occurred between 9 AM and midnight. Two high frequency peaks were observed: one at 3 PM and another at 6 PM local time, with the 3 PM downburst being the more frequent.

Rogue Wind Solutions

Downbursts/wind shear are routinely detected by Doppler weather radar at airports and on-board commercial airliners. Doppler radar has been shown to have a high probability of detection of wind shear incidents for both wet and dry downbursts (Arbuckle,1996). While Doppler LIDAR (Light Detection and Ranging) is in-use on some off-shore oil and gas structures and wind platforms for better detection of dry winds, it is not clear that the added complexity and expense of these systems is justified for sailing vessels.

The primary purpose of radars on merchant ships is collision avoidance and navigation, and IMO rules specify performance requirements for this purpose. While merchant ship radars can and are used to detect the presence of storms and estimate the severity of rainfall, there is no detection capability for downbursts.

Recommendation 1: *Doppler radar used on aircraft should be adapted for sailing merchant ships for the detection of downbursts.*

Once a strong and sudden gust is experienced, merchant sailing vessels have several options: “fall off”, (steer away from the wind, downwind), steer into the wind, or de-power the sails quickly. Given the speed with which these events can occur (as shown by the video of the Great Britain yacht knockdown), the most effective response is probably de-powering the sails.

A vessel with high stability can recover from a knockdown, but there may be harmful consequences which could compromise vessel stability, such as the shifting of cargo, free surface effects, flooding through open hatches, as well as dangers to personnel. In addition, if the vessel does not right herself quickly (as might occur if the gust is sustained or if there is some flooding), the vessel’s orientation with respect to any breaking waves cannot be controlled, risking her safety.

A conventional square-rigger cannot lower sails quickly enough, nor can Dynarig vessels in their current usage configuration. Rigid airfoil sails may be quickly released if the vertical axis of rotation of the sail is mounted ahead of the center of pressure of the sail, somewhere around the 0.25 chord point (Abbot, 1959).

<u>Recommendation 2</u>: *Future merchant sailing vessels must have a method for coping with the sudden onset of powerful winds. The sails may be de-powered either by a push-button system from the bridge or by an automatic sensor-based algorithm.*

Insufficient auxiliary engine power

General data from 63 accidents resulting in ship loss, mostly wooden merchant sailing ships with no auxiliary engines, from 1850-1900 in the U.S. Great Lakes show that the biggest source of accidents is the inability of the sailing vessels to resist being blown downwind. The records show that once a vessel is stranded on a beach or rocks, storm waves can pummel it to pieces.

This type of situation might be encountered while transiting confined waters under auxiliary engine power with furled sails. Or a vessel sailing close to shore with sails deployed may be blown ashore under the combined action of heavy wind and waves.

Requiring larger engines than needed for transiting through confined aeras may seem like an obvious conclusion, but the need to cut costs or maximize cargo-carrying capacity could influence the selection of auxiliary engines of merchant sailing vessels. For example, proposals for modern merchant sailing-ship design have included engines in the 600 – 1000 HP range (Woodward, 1975) for 15,000-45,000 cargo tons sailing vessels. The authors, in an effort to maintain as large a cargo capability as possible and to keep overall cost down, purposely selected engines just large enough to maintain 6 knot vessel speeds (to be used only in case of poor winds and for maneuvering between port and open water), and stipulated that the vessels should not enter confined waters under windy conditions. We calculate that, based on 50 knot winds, ships of these sizes would require about 7 times more power to hold their position in moderate waves and furled sails. For better maneuverability navigating in confined harbors and waterways, twin-screws and thrusters should also be considered.

In a previous study (Perez et al., 2021), we found that the increased engine power would add approximately 5% to the overall cost of a Dynarig bulk cargo sailing vessel of 15,000-45,000 ton cargo capacity. Such an increase would still result in a significantly lower RFR (required Freight Rate) for a sailing vessel, as compared to a conventional engine-powered ship. By maintaining a low fuel-use strategy, fuel costs are kept down, and the need to increase fuel tank size (which would affect cargo carrying capacity) would be minimized.

<u>Recommendation 3:</u> *Sailing vessels must have sufficient engine power to maneuver against the wind under storm conditions. Twin screws and side thrusters should be considered.*

Collisions with whales

Asgard II, a tall ship with 25 m LOA, collided with an unknown underwater object. The ship was wooden, and the collision resulted in the damaging of the hull and sinking of the vessel (MCIB, 2010).

The World Shipping Council (WSC, 2021) reports that less than 0.001% of all shipping containers transported internationally were lost at sea in 2019, or about 2260 containers. It is possible for containers to stay afloat for extended periods of time, depending on the cargo carried, although most reportedly sink somewhat quickly. These are dangers to which both sail and motor-powered ships are exposed.

The merchant sailing vessel of the future may require movable surfaces/fins extending below the vessel's normal draft (Woodward, 1975). Conventionally-designed sailing vessels over 45,000 CDWT require drafts in excess of depths normally available in ports, but this difficulty could be overcome by the use of retractable lee or centerboards. In addition, large conventionally-designed sailing vessels require mast heights too high to permit access to many port areas, but with the use of high-lift devices on the sails (flaps and slats, as used on commercial aircraft) the sails can generate much more lifting force, permitting the use of smaller sails and masts. Unfortunately, the increased lift from sail high-lift devices (as well as from Flettner rotors) comes with increased side forces, and these could be controlled by retractable leeboards or centerboards which may be susceptible to collisions with whales. While the steel hull of modern ships may not be damaged by a whale strike, a fin extending beneath the hull would be more vulnerable.

In Rockwood (2017), the authors developed an algorithm for predicting mortalities for Blue, Humpback and Fin Whales off the U.S. West Coast, for an area of 812,000 square km, during the peak whale period July-December. The authors predicted mortalities ranging from 83 – 183 whales, which is perhaps more common than merchant mariners might expect. The authors report that ships may not be aware of collisions with whales. Rockwood reports that large ships have entered port areas with a whale carcass suspended on the bulbous bow. In addition, carcasses may sink directly to the bottom before there is any indication that a collision might have occurred.

Schoeman (2020) reports that 75 species of marine animals may be victims of collisions with ships, including manatees and sharks, but most of the research on collisions has involved whales. Whales do not appear to avoid areas of heavy ship traffic, and their reaction to approaching ships is uncertain. Some whales have been observed to initiate a slow descent that is not fast enough to prevent a collision with a rapidly-moving vessel, and some may not move at all. Knudsen (2007) reports successful detection of whales with ordinary fish-finding sonar. Schoeman (2020) reports that acoustic alerting stimuli are ineffective at causing a flight response in whales.

While slower-moving merchant sailing vessels may have a greater likelihood of avoiding collisions with whales than engine-driven vessels (Gende, 2019), precautions need to be taken. A collision with a movable control surface may have a variety of undesirable effects such as fins stuck in down position or fins breaking off with damage to the vessel hull.

A release mechanism on movable control surfaces should be considered, much like the kick-up rudders on some catamarans. These rudders pivot back when a vessel runs aground and prevent the rudders from breaking off.

Recommendation 4: *Merchant sailing vessels with deep draft control surfaces should avoid areas known to be inhabited by whales, and should be deployed with sonar capable of detecting them. Underwater control surfaces should have some type of release mechanism in the event of a whale strike.*

Ignorance of Stability and other Issues

The design techniques for stable sailing vessels are well-known to naval architects, and involve ensuring that righting moments are of sufficient magnitude, preferably acting in excess of 90 degrees rolls. Tall-ships Pamir, Albatross, Concordia and Marques were likely very stable upon christening, but became unstable due to improper use or modifications (Parrott, 2003):

- Pamir (96 m): by company policy, grain loaded on Pamir had been stowed in bags which prevented shifting of the cargo. But in an effort to reduce stowage time and costs, the practice was discontinued, and grain was loaded directly into the holds without bags. A relatively small number of grain-filled bags was placed over the unbagged grain to prevent shifting. In addition, in order to increase the cargo capacity, grain was poured into ballast tanks. Properly laden, Pamir had encountered and successfully weathered hurricanes before her final voyage (Parrot, 2003), but when she encountered hurricane Carrie in 1957, which was not an especially powerful storm, the ship was rolled on her side by a strong gust, and never recovered. Later analysis determined that the grain must have shifted during the roll, making it impossible for the ship to return to an upright position. Once Pamir was on her side, waves crashed onto her deck and flooded into the vessel. 80 died, with only a handful of survivors.
- Albatross (36 m LOA) and Marques (27 m LOA): both of these vessels had begun their careers as stable, but modifications made when the vessels were repurposed raised their centers of gravity. In addition, both vessels had large hatch areas open at the time of their sinking; when wind speed increased and heeled the boat close to 90 degrees, water poured in. Had these vessels been properly analyzed for stability after their modifications, and greater attention paid to open hatches, their sinking and loss of life might have been averted.
- Concordia (58 m LOA): This vessel had sufficient stability to recover from 90-degree rolls (TSB Canada, 2010). On her final voyage, the vessel was knocked on her side by strong winds, but the open deck house door permitted water to enter the ship at a roll angle of 57 degrees, resulting in the vessel's sinking.
- Pride of Baltimore (27 m LOA): this vessel was the victim of a downburst which knocked her on her side. An open hatch permitted down-flooding to occur, which sank the vessel.

The importance of vessel stability is evident from these incidents, but it appears that even stable vessels are in danger without watertight decks. Licensing exams for deck-watch officers of merchant sailing vessels must then include thorough coverage of stability and downflooding, such as prescribed by the Nautical Institute (2014) in their International Sail Endorsement Scheme (ISES).

The ISES is used in conjunction with STCW Certificates of Competency, and ensures a thorough knowledge of topics important to the operation of large sailing vessels, not just stability. Given the current dearth of practical experience in the transport of cargo by large sailing merchant ships, the importance of practical training and testing is clear.

At the time of this writing, U.S. Coast Guard licensing requirements for Masters of self-propelled vessels (which includes sailing vessels) of unlimited tonnage who wish to add an endorsement for "Sail or Auxiliary sail" must pass a Coast Guard Exam Module for Auxiliary Sail or some other approved exam. Based on the content of a sample test (www.dco.uscg.mil/nmc/exams/additional-deck-officer-Q460-Q461), it appears that the coverage of the Coast Guard exam is aimed at sailing yachts, not large cargo-carrying sailing vessels. The Coast Guard sample test had no questions about stability, cargo stowing or multi-masted vessel storm strategies. This is an understandable omission, as large merchant sailing vessels are still emerging, but more thorough sailing endorsements like the ISES will need to be implemented.

Recommendation 5: *Licensing standards for merchant sailing ship deck-watch officers need to be improved to ensure deep understanding of vessel stability and all other aspects of operating large sailing ships.*

Recommendation 6: *Merchant sailing vessels should have sensors displaying the status of all deck hatches and openings. Remote opening/closing of hatches should be considered, as well as the use of water-tight compartments to isolate flooded areas.*

Conclusions

1) Hurricane-force winds induced by downbursts can knock a sailing vessel down without warning, but the winds may be detected with the use of ship-based Doppler radar of the type commonly used on commercial aircraft to detect wind-shear.
2) The tendency to provide only the engine power required for auxiliary low-speed engine propulsion can result in vessels without the capability to maneuver in strong winds and confined spaces, or the inability to resist running aground when sailing close to shore in very powerful winds.
3) The problem of sailing mast heights too high to permit entry into some ports may be addressed by the use of high-lift devices such as flaps and slats, which increase lift coefficients and thus require smaller sails. Flettner rotors could achieve the same result, but both of these methods result in heeling and drag forces far greater than conventional high aspect ratio sails, possibly requiring large, movable underwater appendages (centerboards or leeboards) extending below the vessel's hull. These appendages could be very vulnerable to collisions with whales, endangering the vessel. Whales may be detected and thus avoided using normal sonar devices found on fishing vessels.
4) Due to the long lapse in the use of large sailing ships for the transport of cargo, there is a dearth of practical knowledge in the operation of these vessels. One important consequence of this could be an ignorance of the importance of proper cargo stowage. Ignorance of stability and other issues important to operating large merchant sailing vessels can be addressed through better and more comprehensive licensing requirements for deck-watch officers, such as the International Sail Endorsement Scheme (ISES).

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