Chapter 4—Weather Forecasting and Waves

Part 1: Weather Forecasting, Stan Honey and Ken Campbell

Key Concepts: Essentials of weather forecasting (OSR 6.02), sources, terms and definitions, logging local conditions, preparation for local anomalies.

Weather forecast models:

There are several different computer-generated models used around the world to forecast the weather. The GFS is the most commonly used model and is the U.S. global forecast model. It is free and so is often used by racers who are precluded by Racing Rule of Sailing 41 from purchasing weather data during a race. It is also one of the best models. The NAM is the US high resolution model for North America. The European weather model, ECMWF, is the EU's global forecast model and is also one of the best. The UKmet is the British global forecast model. The GEM is the Canadian global forecast model; it is not very reliable. It is well known for over-forecasting tropical lows.

Forecasts are frequently different from model to model, so it is important to match the reality of your current conditions to each weather model. It is very important to watch the weather patterns several days in advance before starting a race or cruise to get a "feeling" about the overall weather pattern and the forecast reliability.

Global Weather zones:

Understanding weather forecasting begins with understanding the overall structure of global weather. Global patterns interact with local conditions to produce the weather that affects your present situation. Global weather is an often-invisible 'sea' moving above the earth's surface in three dimensions similar to the ocean currents moving below the surface of the sea. The upper levels of the atmosphere, such as the jet stream, play an important role in what happens on the surface to affect your boat. It is crucial to understand these interactions in order to prepare for developing conditions.

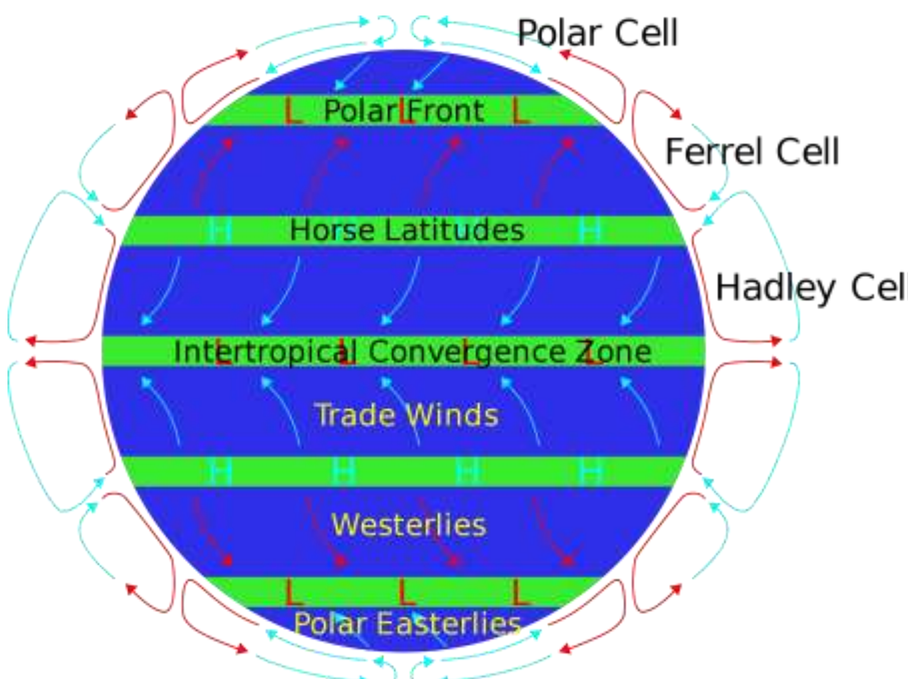


Figure 1:Credit: Burschik, Wikipedia Commons

This simplified diagram shows the major cells of air currents, rising up into the atmosphere at the equator and at 60° latitude and sinking back to earth at 30° and at the poles. In between, the major air currents respond to the Coriolis Effect, the jet stream and local conditions.

Working from the Equator and moving towards the poles, the major weather patterns can be divided into five major zones: the Inter-Tropical Convergence Zone (ITCZ), tradewinds, horse latitudes, variable westerlies, and the polar front.

- The ITCZ is also called the Doldrums or "Le Pot-au-Noir" (Pot of black). The ITCZ will shift north during the northern hemisphere summer and south during the winter. It can be squally and unpredictable or exceedingly light, so a key tactical decision when racing is where to cross it.
- The *Tradewinds* are generally delightful and enable consistent sailing. This is home to the seasonal Tropical Lows, one of the three critical types of lows, which we will discuss in detail later in this chapter.
- *T*he *Horse Latitudes* are home to semi-permanent summertime highs, such as the Pacific High and Azores High, which have a critical impact on Transpacific and Transatlantic passages. There is generally pleasant weather here, unless you are stuck in a stationary high with no wind.
- The *Variable Westerlies* are called "the variables" because they are home to another type of low, the transiting mid-latitude lows, with their associated fronts generating wind shifts from the southwest to the northwest. Of the three critical types of lows, mid-latitude lows are probably the best understood by sailors due to TV weather reports providing widespread recognition of their associated cold fronts and warm fronts.
- Most sailors can ignore the *polar front* and polar Easterlies. Volvo and Vendee sailors make certain to stay on the equator side of the polar front and stay in the Westerlies.

Weather maps:

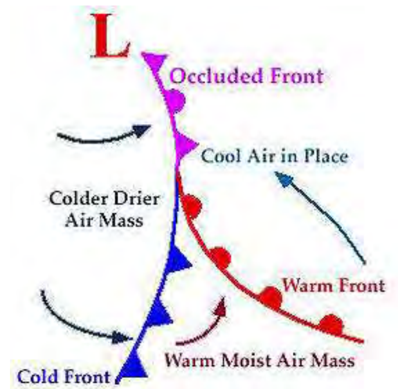
The best way to predict the weather is to understand weather maps. When viewing a weather map be sure to note the "valid time" for the features shown. While a surface analysis shows current conditions, forecasts may have a valid time of 24-hours, 48-hours, or 96-hours in the future, so the features appearing on the chart may not be evident locally until later.

The following movements occur in the Northern Hemisphere:

- Wind flows clockwise around highs. Wind descends in highs, which causes clear skies. The locations of highs are shown with a bold **H** on weather maps. The locations of highs 24 hours before/after the chart valid time are sometimes shown by a circled **X** with an arrow to/from the valid time location. (See Surface Analysis chart at end of this section.)

- Wind flows counter-clockwise around lows. Wind ascends in lows, forming clouds. The location of a low is shown with a bold **L**. The location of the low 24 hours before/after the chart valid time is sometimes shown by an X.
- Wind arrows on weather maps fly with the wind. The feathers always point towards the low pressure. It is very helpful to remember this. The arrow feathers have the following

designations: short feather = 5 knots, long feather = 10 knots each (cumulative), triangular feather = 50 knots.



From University of Illinois-Champaign, Dept of Atmospheric Science, WW2010

Fronts are drawn by humans. This is a major advantage of weather maps; they reflect human intelligence. Cold fronts are shown with triangles. Warm fronts are shown with half-circles. The movement of the front determines which is used. For example, an occluded front, which occurs when a cold front overtakes a warm front, is shown by alternating triangles and half-circles on the same side of the frontal line. Stationary fronts, which are not moving, are shown by triangles on one side of the frontal line and half-circles on the other side.

Isobars are lines of constant barometric pressure, typically depicted in millibar or hPa (hectopascal) units. Isobar spacing is conventionally in 4 mb increments. Wind speed can be inferred from isobar spacing, the curvature of the isobars, and the latitude.

Know your Lows:

There are three major types of lows: tropical lows, mid-latitude lows, and cut-off lows. It is important to understand the differences between them.

Tropical lows live in the belt of tradewinds, and are also known as tropical depressions, tropical cyclones, hurricanes, and typhoons. They are seasonal and travel east to west in the trades. The GFS weather model dramatically underestimates the strength of tropical lows, but predicts their location and movement reasonably well. It is critical to receive hurricane advisory forecasts for accurate prediction of their strength and movement.

Tropical lows derive energy from the warmth of the oceans and the release of latent heat energy from the formation of the clouds. Cold, dry air can weaken a tropical low. A concentration of thunderstorms over water temperatures of 27° C or warmer is the first sign of a tropical low forming. It is mandatory that there is no jet stream or strong winds aloft for tropical low pressure formation because thunderstorms need to develop vertically and not be torn apart by jet stream winds or wind shear.

Since the jet stream is frequently not present near a tropical low, the low's movement can be erratic and less predictable than a mid-latitude low. A tropical low is much smaller in size than a mid-latitude low, frequently only 400-500 miles across. A big tropical low might be 800-900 miles across. The strongest winds will be found within 25-50 miles of the center. Barometric pressure gradient is also much less than with a mid-latitude low.

The most dangerous side of a tropical low is the "right side" in the northern hemisphere. If the tropical low is moving east to west, this would be the north side; if it is moving from south to north, this would be the east side. Winds are strongest over a much larger area on the "right side" and the seas are also largest on the "right side." Even though sailors know that the right side of a tropical low is the dangerous side, never try to cross in front of a tropical low.

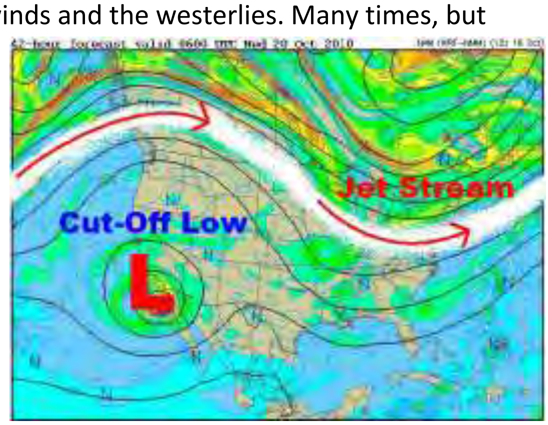
North Atlantic and northeast Pacific hurricane season is generally May to November. It peaks from late August through early October. The low is designated a tropical depression when a defined low pressure circulation exists - rather than just a cluster of thunderstorms - and when sustained wind speeds are under 35 knots. The low becomes a tropical storm, and is named, when sustained winds are 35 knots or higher over any part of the low. The low becomes a hurricane when sustained winds are 64 knots or higher over any part of the low. Tropical storms are called tropical cyclones in the western North Pacific and are given names.

Mid-latitude Lows are very different from tropical lows. Mid-latitude lows are the low pressure areas we most frequently experience in mid-latitudes, from 30° to 60° north and south. They are the traditional low pressure areas with attached fronts that move west to east in the mid-latitudes with the variable westerlies. Newly formed lows have small and intense centers. Old lows can have broad centers with light wind. Lows travel in a direction that is parallel to the isobars in the cold sector, the area between the cold and warm fronts on the equator side of the low. They move at about half the speed of the 500mb upper level wind in their vicinity. They are reasonably well forecasted by the GFS weather model.

Energy for the mid-latitude low comes from a mixing of cold and warm air, such as when east coast storms move from land to over the ocean. The greater the temperature contrast, the stronger the low can become. This is why the strongest lows in the northern hemisphere occur during late October through December, and again February through April. Warm currents like the Gulf Stream, Kurishio, East Australian (EAC), and the Agulhas can increase the temperature contrast, which makes these areas breeding grounds for strong lows. These storms can be very large - 3000-5000 miles across - which makes them very difficult to avoid completely. In the northern hemisphere, they will have a warm front to the east of the low, where east winds shift to south as the front passes. They will have a following cold front where south winds shift to west and northwest as the front passes.

As the cold and warm air mix within the low and the air mass becomes more homogeneous, the low will weaken and the winds will diminish. This is the occlusion phase of the storm's life cycle. However, even though winds diminish, the leftover seas can still be large, leaving rough conditions in spite of the diminished winds. This is the "washing machine" phase with little wind, but agitated seas.

Cut-off lows are critical for a sailor to understand. This will be on the final exam, so memorize it. Cut-off lows occur when a mid-latitude low is removed from the jet stream. They have unpredictable movement as they are "cut off" from both the easterly tradewinds and the westerlies. Many times, but not always, the low is weak and the wind field near the low is also weak. Their movement can be erratic. They sometimes move quickly, but can stay stationary for days.



From Mark Fisher, unofficialalpine.com

Cut-off lows can be extremely dangerous and should be avoided. They have their origins in the lower latitudes - south of 30N and north of 30S - and can have some tropical low pressure characteristics. They can transition into a tropical low if they remain over warm water and the jet stream is non-existent. Examples of deadly cut-offs include the Halloween Storm of 1991 (famous as "The Perfect Storm" in book and movie) with 8 mariner fatalities, the Fastnet race in 1979 with 18 fatalities, the Sydney-Hobart race in 1998 with 6 sailor fatalities, and Hurricane Sandy. These were all strong cut-off lows that mixed tropical characteristics with a mid-latitude weather system. When two extreme weather systems merge, they can result in extraordinary weather. (For an excellent review of the 1979 Fastnet Race, see John Rousmaniere's *Fastnet, Force 10: The Deadliest Storm in the History of Modern Sailing.* For an excellent book on the 1998 Sidney-Hobart race, see G. Bruce Knecht's *The Proving Ground.)*

These are some danger signs to watch: tight core at the center of the low, rapid pressure drop, significant temperature gradient on the polar side of the low, a comma shape, and fast-moving jet stream over the top which can be seen in the 500mb charts.

Squalls and thunderstorms:

There are three types of squalls/thunderstorms: those associated with a cold front or low pressure area, the "air mass" thunderstorm, and tradewind squalls.

Cold front thunderstorms develop along the leading edge of a cold front. Remember, the cold front brings a wind shift from the south or southwest into the west and northwest. The cold front also brings a change in temperature and increased dryness of the air. Thunderstorms develop vertically into the atmosphere, reaching heights of 40,000-50,000 feet. The rule of thumb is the taller the thunderstorm, the more violent the weather will be. Taller, more violent thunderstorms will be preceded by an area of high clouds that spread out from the top of the thunderstorm, moving with the jet stream. Since these higher clouds appear overhead before the thunderstorms arrive in your area, they will give you an early warning signal of an approaching squall line.

When thunderstorms develop up into the jet stream level - which moves faster than the cold front - they will move out in front of the cold front. Thunderstorms can precede the cold front by several hours. If this happens, there will be a weather lull between the squall line and actual cold front. But if the lull lasts for more than three to four hours, there could be a second squall line closer to the actual cold front.

Air mass thunderstorms form inland during the afternoon and move very little. During late afternoon and evening, when the afternoon sea breeze weakens and ends, thunderstorms will move towards the shoreline. If the thunderstorms persist long enough, they can bring squally weather to the coast around and after sunset. The Florida coast, parts of the Central American coast, Africa, and Brazil are notorious for the late afternoon and evening squally thunderstorms, especially during the summer seasons.

Tradewind squalls are typically smaller, less developed, and less violent than thunderstorms. A simple rule of thumb is: the taller the cloud, the stronger the squall will be. They generally move from east to west in both hemispheres. They are strongest two to three hours before sunrise. They are weakest from late morning thru mid-afternoon. Mid-morning showers can cause very large areas with very little wind. Squalls that form around or just after sunset can also be gusty.

Sea breezes and land breezes:

A *sea breeze* is an afternoon wind that blows onshore and can cause a significant increase in wind speed. Typically a sea breeze is preceded by a calm period during the morning. As the land warms, the sea breeze increases. Since the warming air is less dense, it rises and creates a low pressure area, which pulls cooler/denser air in from the ocean. Sea breezes can extend 30-40 miles offshore during the late afternoon. Sea breezes can be predicted by the rapid improvement in visibility when looking at the horizon out to sea, coupled with the appearance of cumulous clouds over land. A sea breeze will end quickly during the evening as the land cools and can leave a large, very light wind area within 5-10 miles of the coastline.

A *land breeze* is a late night wind that forms at the shoreline as the land cools more than the sea. Since the land must be colder than the ocean, clear nights are most vulnerable to a land breeze. Land breezes can be predicted by the rapid drying of dew on deck. Typically, a land breeze is a soft wind coming off the shoreline. But when the shoreline is elevated or mountainous, such as with the Adriatic coastline of the Balkans, the land breeze can be briefly quite strong around sunrise; 20-plus knot northeasterly and easterly winds are common late at night along the Balkan Adriatic shoreline.

Storm avoidance:

Crucial to storm avoidance is early planning and understanding the seasonal changes in storm patterns. Large mid-latitude lows will be impossible to avoid all together, but try to be as far away from the center of the low as possible. It is also helpful to be on the downwind side, but that is not always possible. If going upwind, try to limit the time on the tack heading into the low. There is an excellent discussion on hurricane avoidance from the National Hurricane Center. (See http://www.nhc.noaa.gov/prepare/marine.php)

Be sure to plan early, realize the potential for errors in predicted storm tracks, and remember hurricanes are relatively small compared to mid-latitude Lows. The GFS model dramatically underestimates the strength of hurricanes, but does a satisfactory job of predicting their movement. However, skilled and trained experts pay close attention to the forecasts for hurricane movement and strength, so it is essential to receive and consider NHC, Marine Prediction Center, and Tropical Prediction Center advisories in addition to grib (gridded binary data) file forecasts.

Sources of Weather Forecasts:

There are multiple weather forecast sources, including NOAA text/voice forecasts, NOAA graphic forecasts, NOAA and U.S. Navy forecasts in grib format, private forecasts, forecasts from non-U.S. sources, and sea-state forecasts.

NOAA text/voice forecasts are the best source of formal weather warnings, such as small craft, gale, storm, hurricane, etc. Memorize exactly what these terms mean. This will be on the final.

- *Hurricane*: 74 knots or more. Note that the wind does not have to result from a tropical storm or classic "hurricane" to cause Hurricane warnings.
- *Storm*: 48 knots or more
- *Gale*: 34 to 47 knots
- *Small Craft Advisories*: varies by location but often 25 to 33 knots

Coverage Areas: NOAA text/voice coverage areas are specified on the NOAA website. These areas vary and are much easier to understand from the coverage graphic plots than from the text descriptions of the areas. Here are some samples of coverage graphic plots.

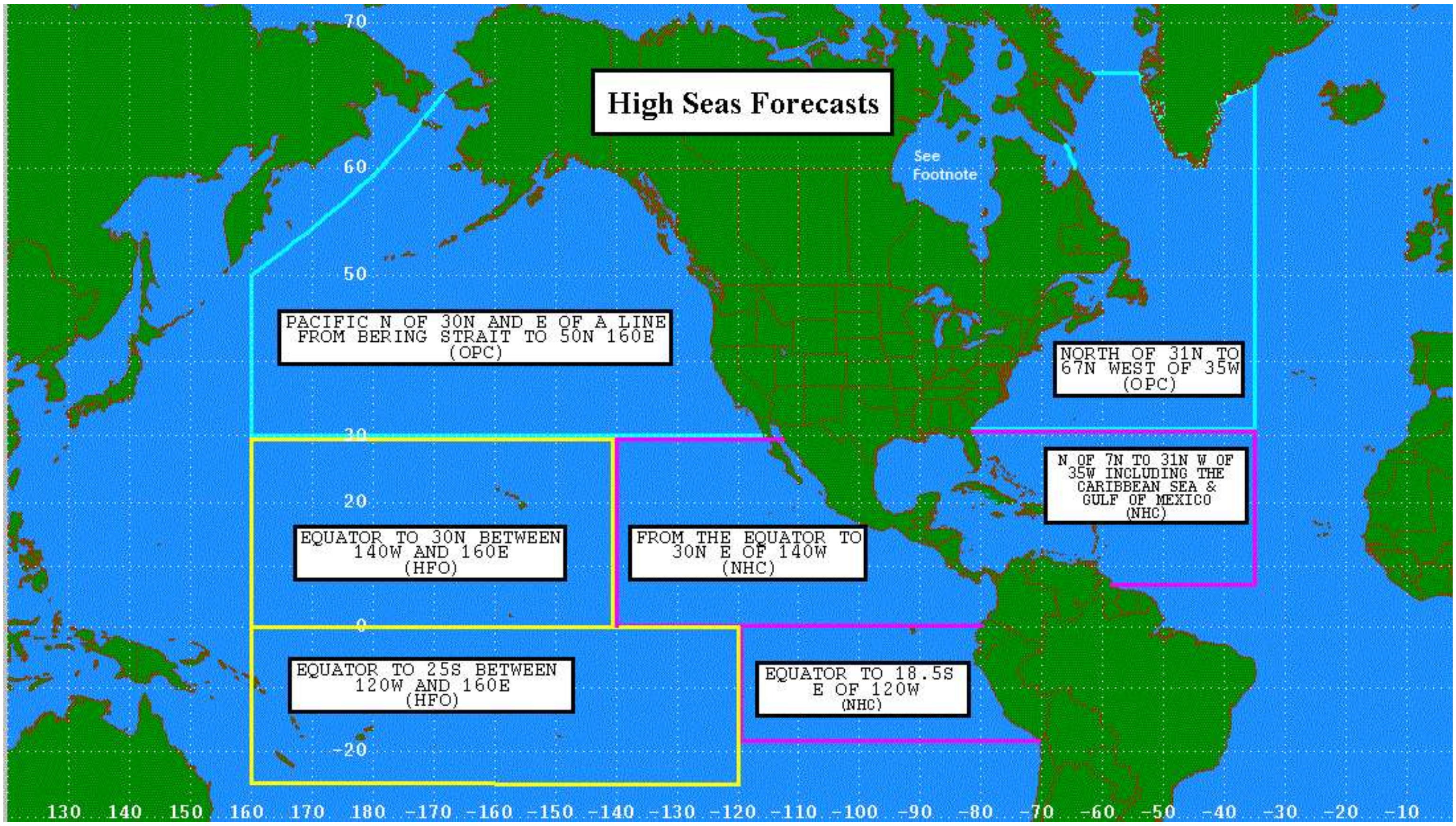
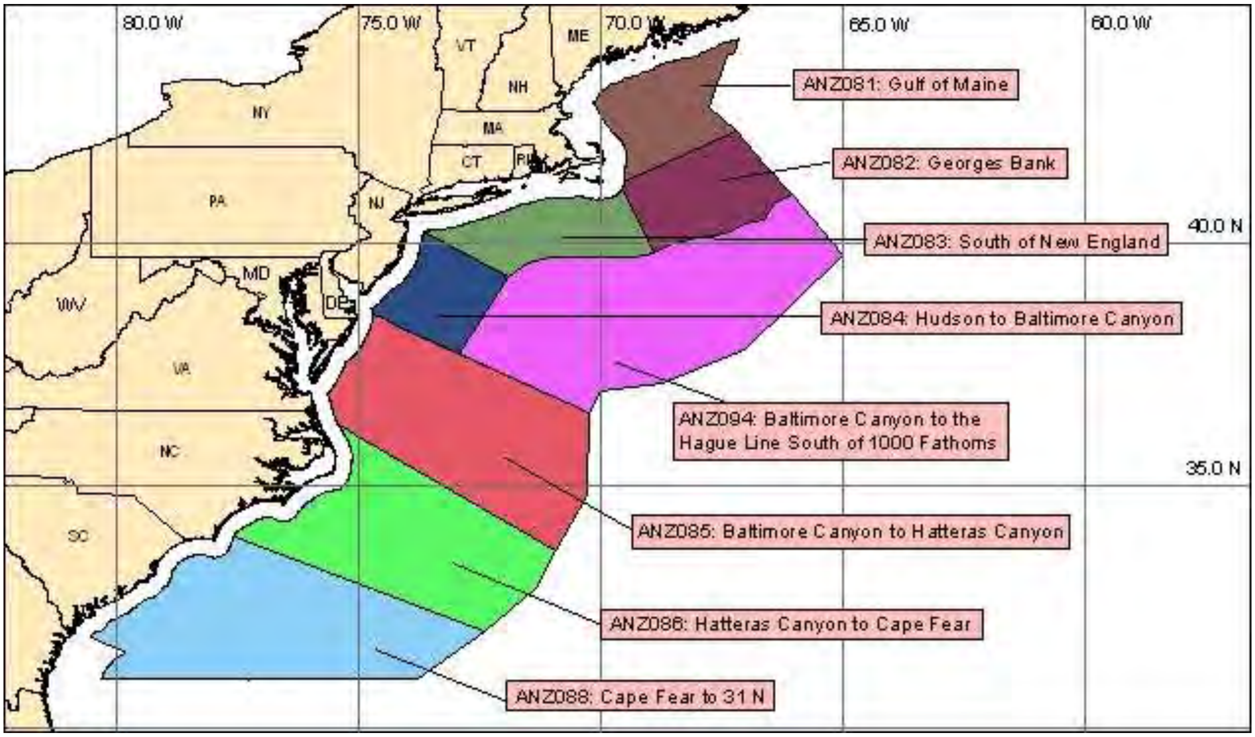
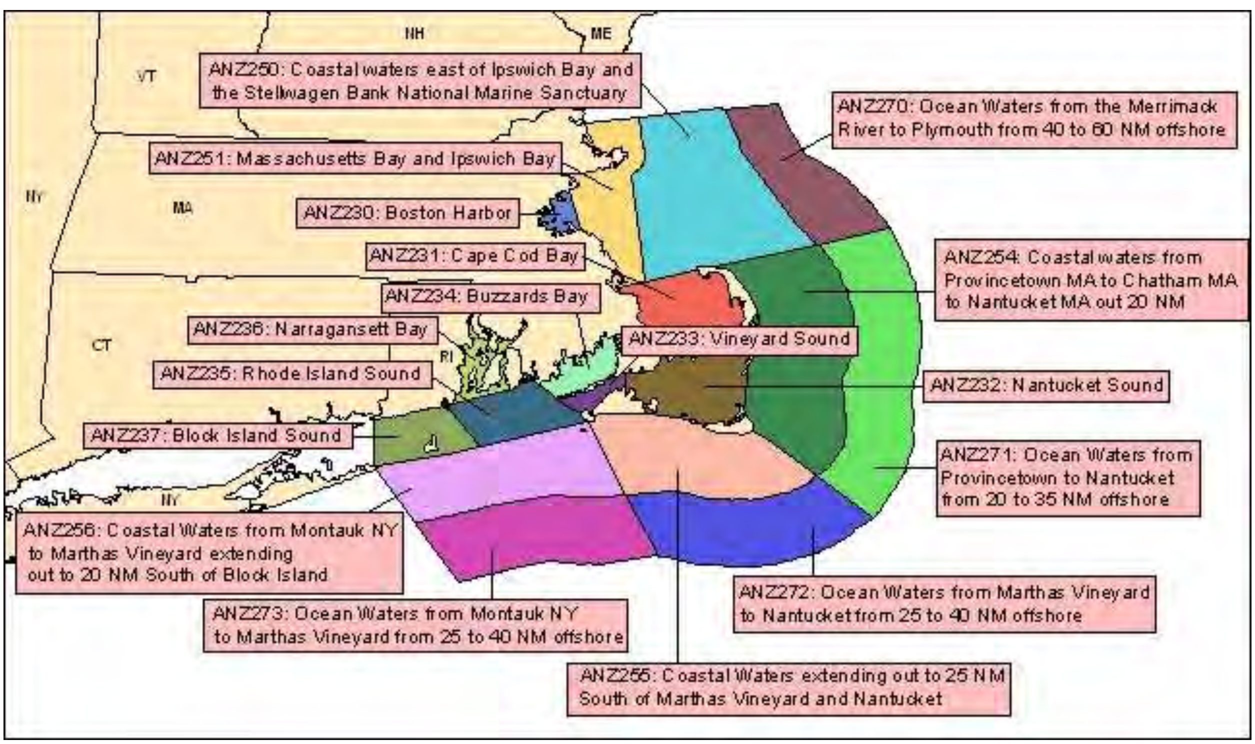


Figure 2 NOAA High Seas Forecast Areas



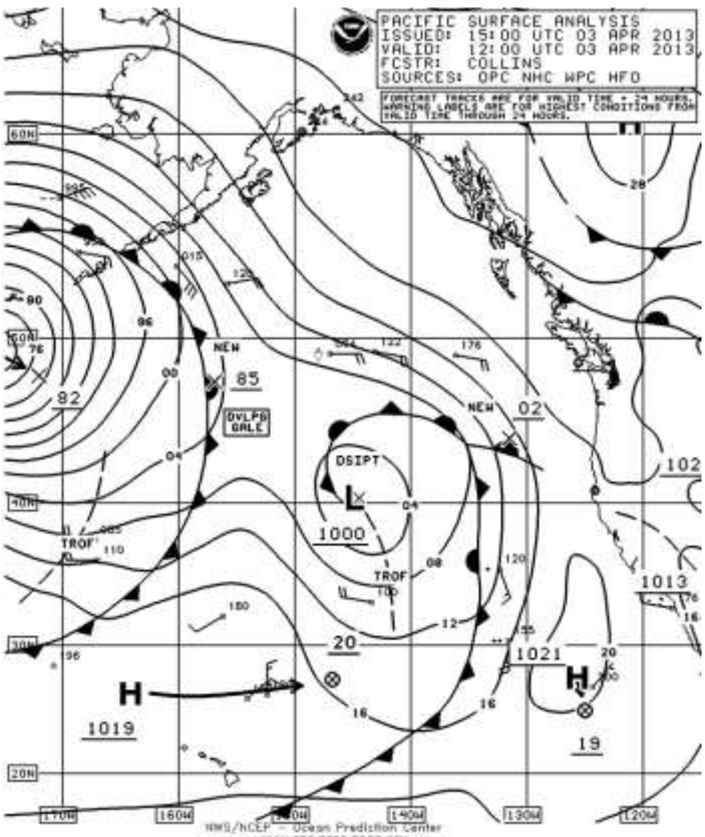
NOAA Offshore Forecast Areas (above)



NOAA Coastal Waters Forecast Areas (above)

NOAA forecasts are very good and are written by humans (as opposed to computer-generated) who do it daily so they develop valuable local knowledge. NOAA text forecasts draw clear attention to wind and sea warnings, and they are free. NOAA High Seas, Offshore, and Coastal forecasts are available via the web, FTP, email, and voice radio transmission (HF and VHF), as well as a variety of private weather services that forward them in various formats.

NOAA graphic forecasts are traditional weather maps. They include wind/wave, surface, upper air, tropical cyclone, ice, and satellite image charts. Since they are drawn by individuals, they incorporate “genuine” intelligence. Warnings are shown, such as “dvlpg gale,” front locations, and frontal types. The forecasts are available from the web, via FTP, and via traditional HF weatherfax, which can be received over SSB radio using a PC and an inexpensive interface.



In addition to these sources, NOAA has been very aggressively introducing new graphic interfaces to access their forecast data, marine and otherwise. Be resourceful and look around on the NOAA website for their latest products.

NOAA and US Navy forecasts are available in *grib format.* NOAA GFS data is available directly from NOAA if you are resourceful, but grib files are more easily retrieved from Saildocs, UGrib, Mailasail, Zygrib, Theyr, or Predictwind, all of whom provide free NOAA GFS grib data via email and/or FTP. There are other free vendors as well. During a race, unless the organizing authority changes RRS 41, it is only legal to use a free source of weather data. Grib data is terrific for routing and has worldwide coverage - which is very helpful as certain parts of the world are no longer covered with weatherfax maps - but do note that GFS grib files underestimate the strength of tropical lows and do not show the location of fronts.

Private forecasts are available through highly trained expert meteorologists who can provide specific forecasts prior to a race, as well as before and during any offshore passage. These forecasts are legal prior to the start of most races but not legal during a race, unless the organizing authority has changed RRS 41. Custom forecasts can be extremely useful to pick a departure time for a non-race offshore passage or boat delivery, and are very affordable.

Forecasts from non-US sources will likely give wind speeds based on the Beaufort scale. (See Beaufort descriptions in the following section.)

Be aware that for forecasts from any source wind gusts can exceed the forecast wind speed by 40%. Also, forecasts overlook small, but potentially severe features like thunderstorms and waterspouts.

Seastate forecasts: As noted elsewhere in this publication, the forecast "significant wave height" is the average height of the highest third of all waves. Individual waves may be more than twice the stated significant wave height. A seamanlike practice is to stay in water that is at least three times the depth of the significant wave height, or 2.5 times the sum of the forecast swell and wind-wave height.

Additional sources of weather background information include college courses, commercial maritime courses such as the USCG license course "Advanced Meteorology for Masters and Mates", and the following books:

- *Meteorology Today* by C. Donald Ahrens, a good introductory text on meteorology
- *Bernot on Breezes* by Jean-Yves Bernot, particularly useful for inshore racers
- *Weather at Sea* by David Houghton. All of Houghton's books are worth reading
- *Heavy Weather Avoidance and Route Design, Concepts and Applications of 500MB Charts* by Ma-Li Chen and Lee Chesneau, for the committed navigator

Recommended Practices:

It is best to start monitoring the weather a few weeks in advance of a race or offshore passage. See what is available online and closely follow the sources of weather information that you will have available on the passage. These sources must be free (when racing) and retrievable using the technology you will have available onboard. Review prior races and/or passages and their weather patterns if they are available.

During the passage, review the weather and your course selection four times per day when the forecasts become available. Brief the crew four times per day on the big picture, as well as the expected conditions and objectives for the next 6-12 hours. Keep a log of the sky appearance, seastate, barometric pressure, wind direction and speed. Include notes in the log of every crew briefing. Finally, always watch the sky and become a student of it.

SIDE BAR: **BEAUFORT SCALE:** The Beaufort Scale was invented in 1805 as a way to standardize descriptions of weather conditions. For each number over Force 5, consider a reduction in sail area. Photos courtesy: John Jourdane.

Force 0 – Calm: Sea surface smooth and mirror-like

Force 2 – Light Breeze 4-6 knots: Small wavelets, crests glassy, no breaking

Force 4 – Moderate Breeze 11-16 kts: Small waves 1-4 ft. becoming longer, numerous whitecaps

Force 5 – Fresh Breeze 17-21 kts: Moderate waves 4-8 ft taking longer form, many whitecaps, some spray

Force 6 – Strong Breeze 22-17 kts: Larger waves 8-13 ft, whitecaps common, more spray

Force 7 – Near Gale 28-33 kts: Sea heaps up, waves 13-19 ft, white foam streaks off breakers

Force 8 – Gale 34-40 kts: Moderately high (18-25 ft) waves of greater length, edges of crests begin to break into spindrift, foam blown in streaks

Force 9 – Strong Gale 41-47 kts: High waves (23-32 ft), sea begins to roll, dense streaks of foam, spray may reduce visibility

Force 10 – Storm 46-55 kts: Very high waves (29-41 ft) with overhanging crests, sea white with densely blown foam, heavy rolling, lowered visibility

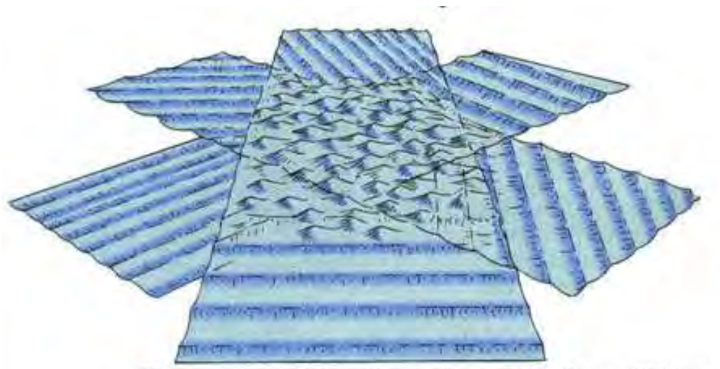
Force 11 – Violent Storm 56-63 kts: Exceptionally high (37-52 ft) waves, foam patches cover sea, visibility more reduced

Force 12 – Hurricane 64+: Air filled with foam, waves over 45 ft, sea completely white with driving spray, visibility greatly reduced (two square flags)

Part 2: Wave Development, Jim Corenman, Jim Antrim and SLH

Key Concepts: How waves develop, forecast sources, definition of SWH; what changes wave shape, height, direction; unusual waves, seamounts; effects of shoaling and lee shores

Waves develop as a result of wind blowing for a certain amount of time (duration) over a certain distance (fetch). The stronger the wind and the longer the fetch, the higher the waves become over time. Ocean waves that move beyond the place from which they were generated become deep-water swell and underlie the surface waves that are kicked up by local wind effects. Ocean swells travel great distances and inevitably encounter swells of different lengths and heights generated in other areas. In this way, a typical sea-state is made up of a mixture of deep-water swells and waves from many different sources, which all combine to form the apparent chaotic ocean surface known as the wave spectrum. Periodically the wave peaks will coincide to produce especially large waves, and at other times they will virtually cancel each other to form relatively small waves, so there is no single "wave height" that will describe all waves at a given place and time.



From geology.uprm.edu/Morelock

Wind is always changing in strength and direction. New waves are forming all the time; ripples, chop, bigger waves, and swell. They all pile on top of each other, usually from a variety of directions.
This action forms lulls, wave sets, "rogue waves" and "sneaker waves."
from Jim Antrim

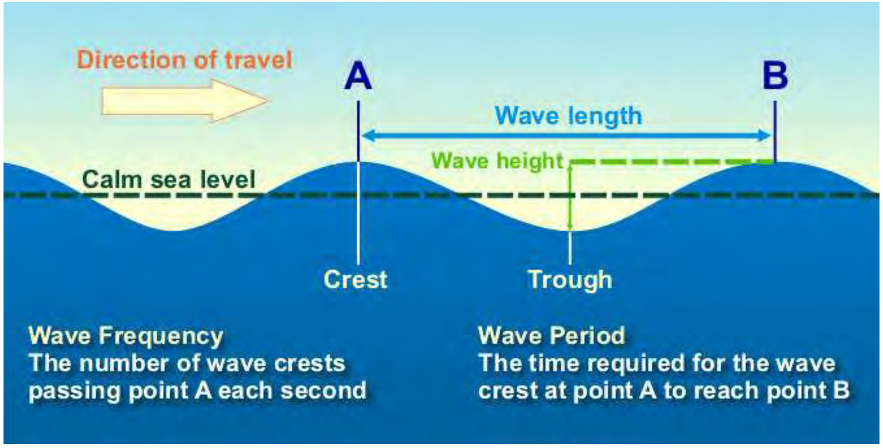
Because there is never one specific wave height, oceanographers use a statistical analysis to forecast "Significant Wave Height (SWH)," which is defined as the average of the largest one-third of all waves. This is the wave height that an experienced observer will typically report. The actual wave height at a given time and place can be much higher, as much as twice the forecast SWH. The following table shows the likelihood of actual wave heights given a forecast Significant Wave Height of 10':

Forecast "Significant Wave Height" (SWH) of **10'**
Mean Wave Height = **6.4'**
Highest 10% of waves = **12.7'**
Highest 1% of waves **16.7'**
Max wave height to be expected = **20'**

(For a fuller explanation of waves, see "Significant Wave Height, A closer look at wave forecasts" by Tom Ainsworth, NWS Juneau, Alaska http://www.mxak.org/weather/pdfs/waves.pdf).

Wind waves are independent of the swell and add to the wave height. The resulting "Combined Seas (CS)" is the square root of the sum of the squares of the swell and wind waves. The National Weather Service considers CS equal to significant wave height.

Waves are defined by four components: height (trough to crest), length (distance between crests), period (time elapsed from the passage of one crest to the next), and steepness. Steepness is the ratio between height and length, which can be approximated from period. Equal wave height and period indicate steep waves, which are a particular danger to small boats. When wave steepness exceeds 1/7, the wave will begin to break. This generally happens in 12-15 knots of wind.



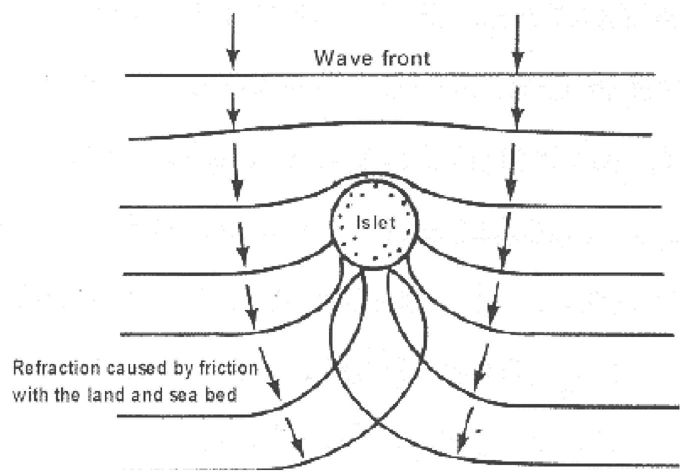
NOAA image

There are a number of influences that that can change the shape, height and direction of the deep-water swell, including reflection, refraction and current.


From CK-12, 106.0: Wave Interactions and Interference

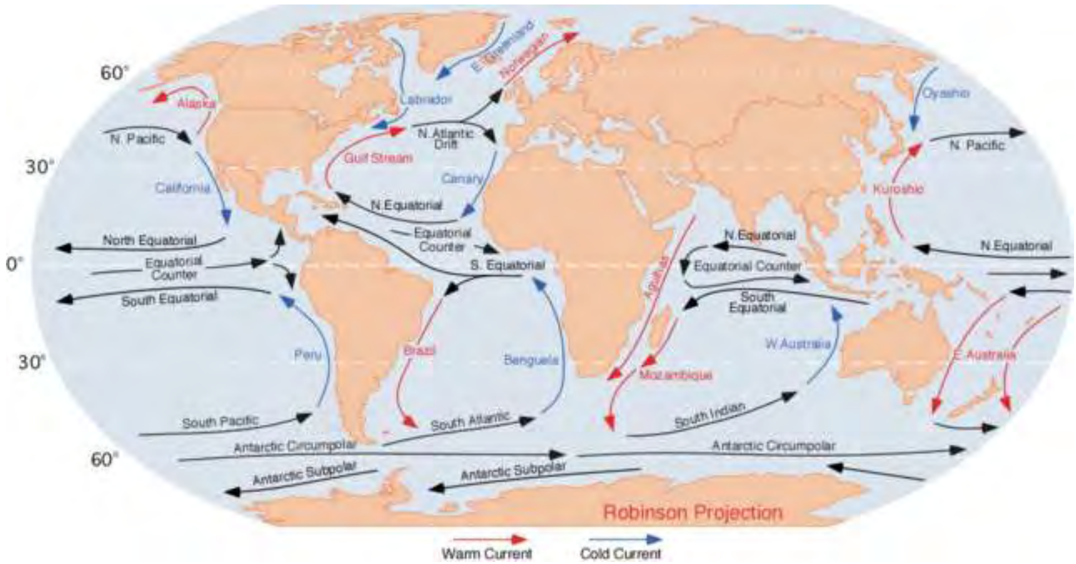
Reflected waves occur when waves bounce back from an obstruction and combine with the waves still approaching the obstruction. The phenomenon can sometimes be seen many miles off a steep shore. For example, reflected waves have been seen as far as 15 miles off the California coast where the shore falls steeply into the ocean.

Refracted waves occur as the waves are bent around projecting land. The shallower water, which is closer to land, slows the land-side of the wave, causing the wave to bend (refract). Around a headland, wave energy focuses on the tip of the point. The waves will wrap around the tip and erode the land just behind the point to form a tombolo, a very thin strip of land leading out to what would otherwise be an island. When waves rejoin on the down current side of an island, they can augment each other to form larger, sometimes breaking, waves.



From geographyfieldwork.com

Current: When current opposes the wind, waves can build quickly to steep and dangerous proportions. Common examples include the Gulf Stream, the Agulhas current, and cases where wind opposes tide, e.g., San Francisco Bay during a strong ebb.



Major currents of the World, Wikipedia

Unusual Waves, sometimes called 'rogue' waves, result from the infrequent amassing of smaller waves to form a larger than normal wave. These occur much less frequently than the 2.0 x SWH described above and often appear from a different direction than the main wave pattern. They can appear as sudden breaking seas and cause unexpected damage in an otherwise manageable sea state. Factors which contribute to exceptional seas include wind opposing current, multiple wave patterns occasionally combining to form a single breaking sea or a set much larger than the average, length of fetch, and shelving, shoaling or promontories. Exceptional waves are known to occur along the Alaska, British Columbia, Washington, Oregon, and California coastlines; in areas affected by the Gulf Stream and Agulhas currents; and in the Tasman Sea, Cape Horn, Bay of Biscay, North Sea, and southern tip of Norway and Ireland. (from John Neal)

Cortes Bank, Photo credit Keith from SurferMag.com

Underwater bathymetry: Seamounts such as the Cortes Bank, which is 100 miles off the coast of San Diego, can create 14' breakers in the middle of an otherwise calm sea. Seamounts affect surface conditions throughout the Pacific, Atlantic, and Indian oceans.

The Effects of Shoaling/Lee Shores: In shoal waters, waves change character, not just height & length. In deep water, the apparent "movement" of a wave is actually a moving pulse of pressure with individual water particles rotating within the wave crest as the pulse passes. As waves encounter shallow water and "feel the bottom," they slow down. However, the period is unchanged so the longer, open water wave becomes a slower, taller wave. The wave height increases as the depth decreases until the wave becomes unstable and breaks. As the wave breaks, the water particles no longer rotate within the wave crest, but instead rush down the face. If the breaker forms gradually (e.g., on a gently-sloping beach), then the waves will form "spilling" breakers, with the water tumbling down the sloping face of the wave. If the breaker forms quickly (e.g., a faster-moving wave and a more steeply-sloping shoreline), then a "plunging" breaker forms with the face becoming vertical, curling, and then collapsing into the trough like classic surfing waves. The plunging breaker generally incorporates more energy and can therefore be more dangerous. ("Shallow Water Waves", COMET MedEd Program, http://www.meted.ucar.edu/marine/SWW/print.htm)

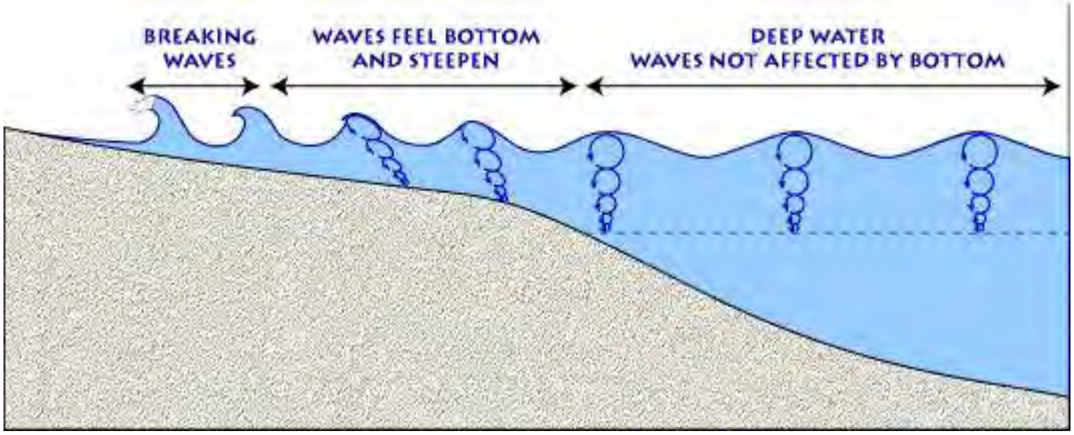


Figure From: USGS "Park Shorelines"

Breaking waves are much more dangerous than significantly larger ocean swells. The surface force of a breaking wave has the tendency to turn a boat broadside - the "log effect" - which renders the boat extremely vulnerable. A breaking wave equal in height to the beam of the boat is likely to capsize the boat.

The critical question for sailors is at what depth breakers will form when approaching a lee shore. There is a series of calculations beyond the scope of this chapter that answers that question. Factors that affect whether a wave will break in shallow water are the size and steepness of the wave, the depth of the water, and the shape of the bottom contour. Wavelength and wave period are related. For instance, the wavelength (L) of a wave with a 14-second period is 1000 ft. Depths over half of that (L/2 or 500') are considered "deep water" and depths of less than L/20 (50') are considered "shallow water" for wave dynamics. The height of a breaking wave depends on the deep-water wave steepness as well as its height, and also on the bottom slope. This is described as a "shoaling factor," which is the ratio between the deep-water wave height and the height of the breaking wave. Its value is found from an empirical nomogram from the deep-water wave steepness and the bottom slope. To find the breaking depth - the water depth where waves will break - one more term is needed, the "breaker steepness," which is a measure of the breaker height relative to the original (unchanged) period. Specifically, it is the breaker height divided by (g x period squared) where "g" (gravity) is 32 ft/sec^2. The "breaking depth coefficient" can then be found on another empirical nomogram, which again is a function of the steepness of the bottom slope. This coefficient is then multiplied by the shoaling breaker height to find the depth at which the wave will break.

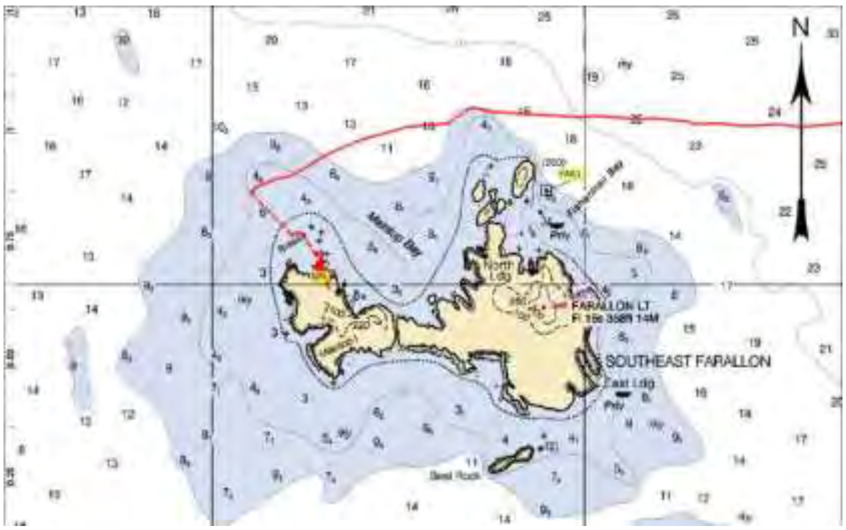
Fortunately, for the sailor approaching a lee shore, there are several simple rules of thumb to calculate safe water depth from a given weather forecast. These are specified at the end of the attached *Low Speed Chase* case study.

Bottom line: be aware of the many factors affecting wave formation and the variety of wave heights and characteristics in any given sea-state. Know how your particular boat will handle waves from the bow, the quarter, and abeam, and be ready to orient your boat to best advantage in any given sea-state. Avoid shallow water and lee shores. Remember you will not be able to see breaking waves as you approach from the deep water side.

Case Study: *Low Speed Chase*

Synopsis of events: On April 12, 2012, a normal spring sailing day in San Francisco turned tragic. The Full Crew Farallones race has one turning mark, the SE Farallon Island, 26 miles west of San Francisco near the edge of the continental shelf. The northwest corner of the island features a rock-strewn shoal with depths of less than 6 fathoms, extending 1000' offshore. In typical winds, this is a treacherous lee shore with continual breakers over exposed and partially submerged rocks. This day was no exception. The coastal waters forecast on the morning of the race was for northwest winds 15 to 25 knots, wind waves 3 to 7 feet, northwest swell 12 to 15 feet at 13 seconds.

As the Sydney 38, *Low Speed Chase*, rounded the northwest corner of the island, they bore off to a course that took them over the 4-fathom shoal in 28' of water. They encountered breaking waves when less than 0.2 nm (400 yards) off the northwest point. A set of larger than normal waves capsized the boat, throwing seven of the eight crew members into the water. The one crew who stayed on board survived. Of the seven in the water, five drowned.



LSC course over the 4-fathom shoal. The capsize happened at the 90-degree turn in their course.

The charted depth where *Low Speed Chase* was capsized was 27 feet. Had they heeded the calculations below and sailed in only marginally deeper water, they likely would have prevented the tragedy.

Foam line shows breakers forming where *Low Speed Chase* capsized.

S.E. Farallon Island viewed from Maintop Point

Actual conditions at the time of the capsize were calculated from data recorded by a Waverider buoy located 25 miles northwest, directly upwind, of the Farallones, with adjustment made for travel time over those 25 miles. It showed a significant wave height of 14.4 feet at 14.3 seconds, indicating the largest 10% of the waves could be expected to average 18 feet and the largest 1% would average 24 feet. Those on board could have predicted that 2-3 times an hour there would be a wave of up to twice the significant wave height of 14, which would be 28 feet. The shoaling effect of this point on the Farallones would increase the height of the largest wave to 31 feet and create "plunging" breakers, which become vertical, curl and collapse. This is consistent with observations reported by the survivors of *Low Speed Chase*. A common rule of thumb is that a wave will generally break in depths less than 1.3 times the height of the wave, which means it could be predicted that a few waves on this day would break in depths less than 38-40 feet of water.

There are several ways to calculate safe minimum depth from a given weather forecast. Forecasts typically include a swell forecast (i.e. waves from outside the immediate area) and wind-waves generated by the forecast winds. These are usually given as a range, and the maximum forecast for each should be used.

The mathematically-inclined could combine swell and wind-wave significant wave heights as the square-root of the sum of the squares, multiply that by 2.0 to get the largest expected wave, and then multiply that number by the 1.3x rule-of-thumb to get minimum water depth, adding some margin in case the waves are larger than forecast. Doing this for a forecasted 15 foot swell and 7 foot wind-wave would yield a minimum depth of 43 feet, to which some margin needs be added.

Stan Honey uses a simpler rule for minimum depth: 2.5x the sum of the maximum forecast swell and wind-wave heights. This sum will be larger than the square-root of the squares, which adds some safety margin. For our forecasted 15 foot swell and 7 foot wind-wave, this calculation would yield a minimum depth of 55 feet.

Another rule for minimum depth is to simply multiply the deep-water significant wave height by 3 (or 4, for some additional margin)[1], which would indicate a minimum depth of 45-60 feet for our 15 foot swell forecast.

It is unclear whether LSC could have avoided capsize at the first signs of breaking waves; there was a prior wave that broke very close to the boat. Of the 14 GPS tracks submitted by the boats racing that day, one other crossed the shoal at the same 28 foot depth and four others crossed inside the 6-fathom line. They were lucky. *Low Speed Chase* was not.

[1] "Max Ebb's Breaking Point", Latitude 38 June 2012 pg. 106-108, http://www.latitude38.com/eBooks/2012/L38201206.pdf

Credit to The COMET Program, Shallow Water Waves, 2012 Update http://meted.ucar.edu/marine/SWW

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"Shallow Water Waves: 2012 Update", Copyright 2012, University Corporation for Atmospheric Research (http://www.ucar.edu).

"Shallow Water Waves", COMET MedEd Program, http://www.meted.ucar.edu/marine/SWW/