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The Annapolis Sea Breezes

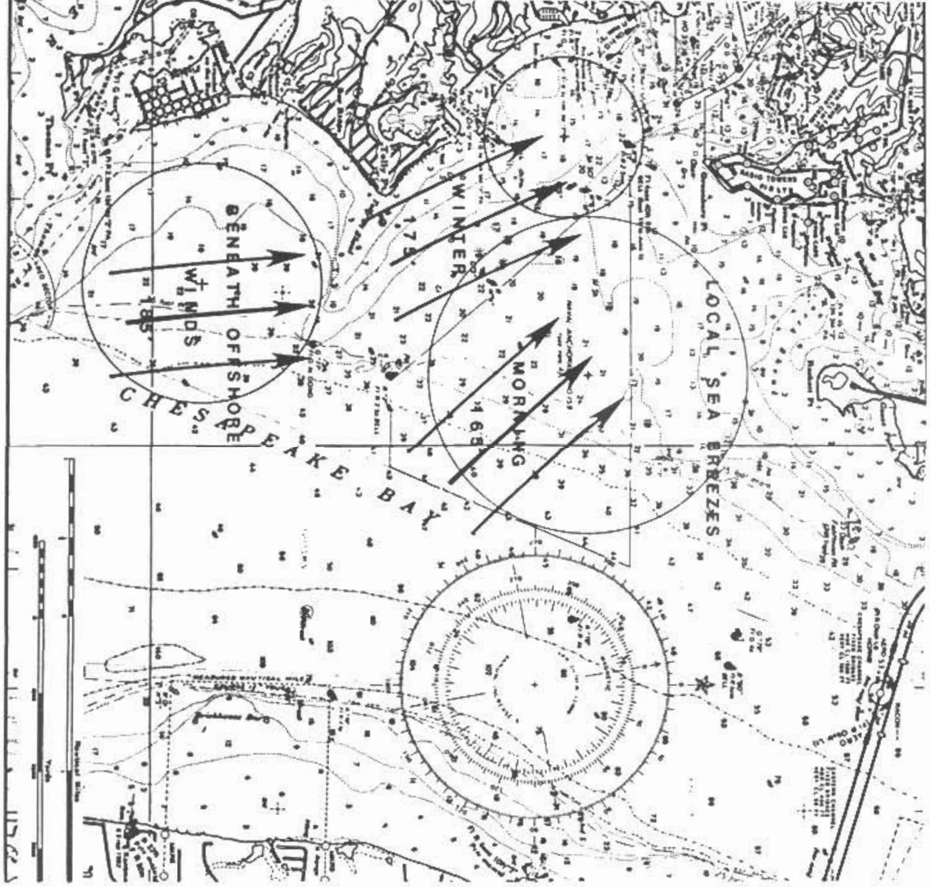
Three different sea breezes occur at Annapolis: a local (primary or secondary) sea breeze onshore from mid-Bay into the Severn, a Bay sea breeze from the ocean beyond the Virginia Capes to the Susquehanna, and a direct ocean sea breeze which crosses the Eastern Shore and comes offshore onto the Bay. The local and the ocean sea breezes are either primary sea breezes developing under a radiation, advection, and/or subsidence inversion or secondary sea breezes flowing onshore beneath a warmer opposing gradient wind. The Bay sea breeze is an amalgamated sea breeze, flowing in combination with an aligned gradient wind. Its velocity and direction are dependent upon the gradient wind with which it is amalgamated.

The Local Primary Sea Breeze

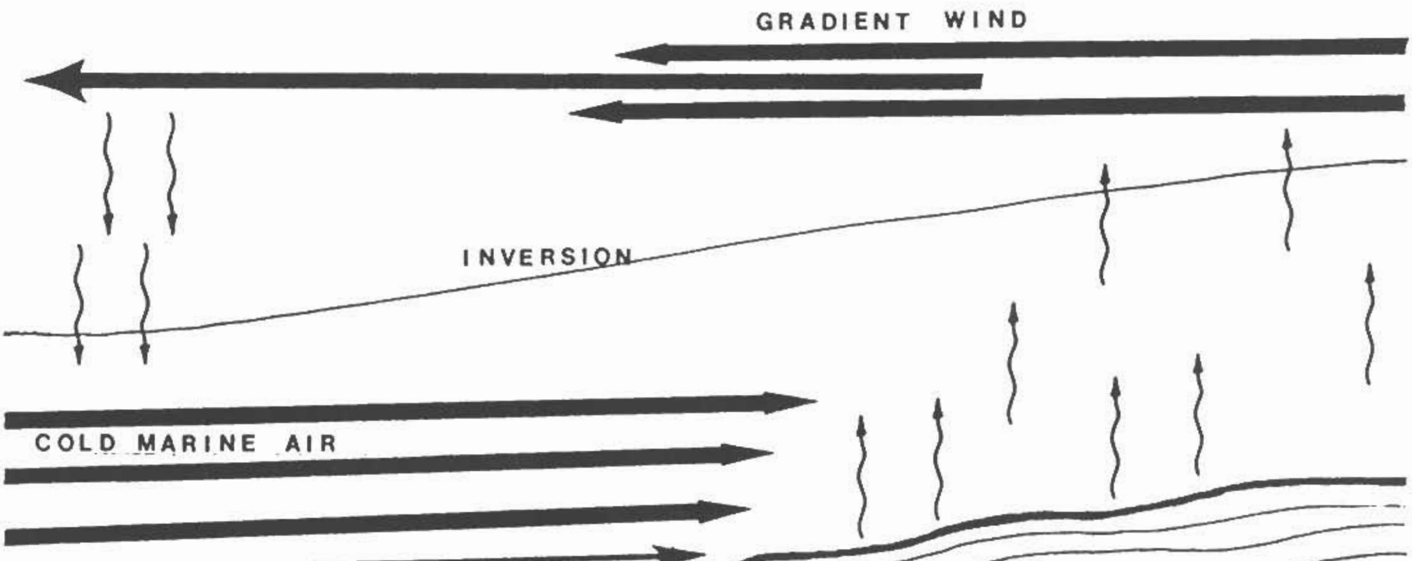
During the summer when the subsidence inversion of the Bermuda High extends over the entire U.S. east coast local primary sea breezes develop at the mouths of rivers on both sides of the Bay, but are conspicuously absent where long stretches of bluffs block access to the inland heating sites. Primary sea breeze circulations develop best where the elevated banks of a river such as the Severn direct both the low-level onshore and the upper-level offshore flows to the particular sites ashore and overwater that need replenishment.

In summer at Annapolis under a combined radiation and subsidence inversion, a local sea breeze appears in the early morning calm as a dark line of disturbed water progressing up-Severn from inside Thomas (or even Greenbury) Point. Within minutes of its appearance the advancing flow ruffles the entire surface shoreward of the initial line, crosses the shoreline, and flutters the leaves as much as a mile inland. Overwater the initially detected gusts, descending elements of upper level flow, are stronger and more veered than the subsequently evident steady, low level flow. Air rising through the cool marine air of the sea breeze front halts at the inversion, flows offshore aloft, sinks onto the dome of subsiding air a thousand yards offshore, and replenishes the surface onshore flow.

Within Annapolis harbor the basic direction of the local (primary or secondary) sea breeze, confined by the high banks of the Severn, is directly upriver at 165°. In the racing area beyond Greenbury Point, the flow is backed, initially flowing from about 145°, occasionally reaching 165°. Because the inversion lid confines the rising air to a low level and the sea breeze front extends but a short distance inshore, the pressure drop ashore is modest and the velocity of the primary sea breeze is minimal. These are homogenous flows with few oscillations, rarely exceeding six knots in velocity, but they provide excellent smooth water sailing.



LOCAL SEA BREEZE



In summer the primary sea breeze is a morning wind only, appearing under a radiation inversion before 8:00 am and disappearing before noon. It should be expected on clear days in settled conditions on the third or fourth day after a cold front passage, when a subsidence inversion has reformed, and when the gradient wind is light and in the southerly quadrant.

On clear warm days in winter a primary sea breeze often appears at midday under an advection inversion and builds until late afternoon. The usual cool, dry, buoyant cP air facilitates insolation and readily creates a very high near-surface lapse rate. Because the gradient wind on such days is much warmer than the Bay water, amalgamation is incomplete even when the two winds are closely aligned. Large patches of each move alternately down the course providing highly irregular oscillating shifts and dramatic variations in velocity. It is important to determine which wind is present at the mark ahead and to move upwind in that flow as directly as possible.

The Secondary Sea Breeze

The Local Secondary Sea Breeze

Secondary sea breezes (those developing in opposition to and displacing offshore gradient winds) are produced by the same thermal gradient and therefore typically appear from the same direction and at the same velocity as primary sea breezes. However, at Annapolis, because they are facilitated by the high lapse rates associated with cool, dry northerly gradient winds, they are often stronger and more veered. They develop when the offshore flow is weak (usually less than 12 knots) and becomes, with the diurnal heating of the land, warmer than the Bay water and its overlying near-surface marine air. They typically appear on sunny days at midday or in early afternoon. They are heralded by a standard sequence: the dying of the gradient wind, a "pre-sea breeze shift" in the gradient wind, the development of a zone of calm offshore, and finally, beyond the zone of calm, the appearance of the sea breeze as a line of dark ruffled water advancing shoreward.

At Annapolis the secondary sea breeze typically appears with light offshore northerly, northeasterly, and westerly gradient winds. In summer, when the offshore gradient flow is warm and light, it may also appear with northwesterlies. In winter and spring when the Bay water is cold, the secondary sea breeze is local - consequent to a thermal gradient between the mid-Bay water and the heating western shore (8-10 knots at 145°-165°). In summer and fall when the Bay water is warm, the secondary sea breeze is the ocean sea breeze, marine air from the relatively cold Atlantic ocean advancing in a sea breeze front across the Eastern Shore and coming offshore onto the Bay (10-16 knots at 165°-180°).

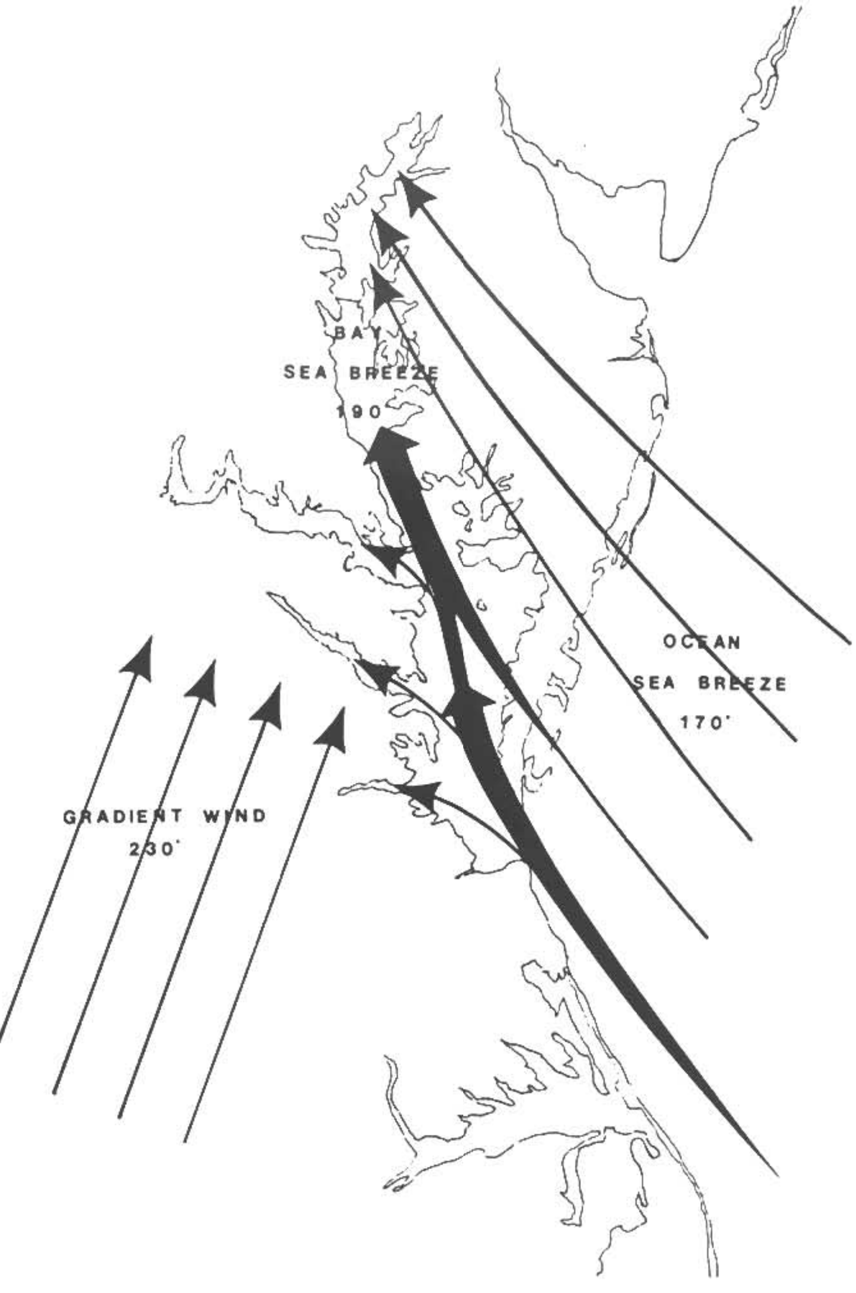
The Pre-Secondary Sea Breeze Shift

Shifts in the gradient wind precede the appearance of secondary sea breezes (sea breezes developing in the presence of and undermining offshore gradient winds) wherever they develop. These shifts are usually backs, not veers. As the offshore gradient wind is lifted from the surface and diminished, one should usually look for a back and sail left toward it before the calm develops. Only after the calm develops - in the zone of convergence between the two winds - should one look for and sail toward the sea breeze. Sometimes, however, in some places, including Annapolis, in advance of the sea breeze, instead of backing, the gradient wind veers!

When I reviewed my records of secondary sea breeze behavior throughout the world, I recognized that the venues at which secondary sea breezes occur can be divided into three categories: those - Chicago, St. Petersburg, Charlotte Harbor, Association Island, and Western Australia - at which the gradient wind typically backs (in W.A. veers) prior to the appearance of the breeze, those - Long Island Sound, Annapolis, Milwaukee, and Kingston - at which it either backs or veers, and those -Rochester and the Algarve - at which it typically veers. Backing is far more common - occurs at more venues and more commonly at those venues. At Annapolis, particularly in spring, backing is common, but in summer and fall veering is more likely.

As an airflow dies, it backs (in the northern hemisphere) due to a reduction in Coriolis Force. The surface layer of a gradient wind opposed and slowed by an invading sea breeze should, therefore, back. But the angle at which an airflow flows off the shoreline creates an important additional effect. As it leaves the friction of the land, the surface layer accelerates - diverges - beneath the layer of air above and away from the adjacent segment which is flowing overland. If an airflow comes offshore obliquely in the quadrant backed to a perpendicular to the shoreline - with water on its right, its accelerating overwater segment veers away from shore and diverges from the air flowing overland to its left. Divergence reduces local pressure and thereby facilitates sea breeze invasion which, veering as it accelerates, backs the gradient flow (as much as 90') toward or into alignment. This phenomena accounts for the ready amalgamation of sea breezes with gradient winds flowing with water on their right and the formation of strong sea/lake breezes at sites such as Buzzard's Bay, Kingston, and along the northern California coast.

If, however, the gradient wind flows obliquely offshore in the quadrant veered to a perpendicular to the shoreline - with water on its left, its accelerating overwater segment veers toward shore and converges with the slower (backed) segment moving overland to its right. Downdraft gusts of the turbulent overland segment will occupy the near-shore surface until, in late morning, the colder overwater segment undermines the warming overland air and lifts it from the surface. The result is a sudden veer which is typically followed (after several minutes or hours) by the reappearance of the backed overland segment or by the sea breeze.



This shift is typical of the southwester blowing obliquely offshore with water on its left at Rochester and the easterly (the Levante) blowing obliquely offshore with water on its left along the south coast of Spain and Portugal. At these sites the convergence of the overland and overwater segments increases the near-shore pressure and a veer to the overwater segment typically precedes the appearance of the sea breeze. This shift is more likely to occur in summer or fall when the water is warm and the marine layer easily penetrable.

The surface layer of a northwester flowing obliquely off the Chesapeake's north/south oriented western shore with water on its left also splits into an overwater and an overland segment (particularly along straight segments of the shoreline such as Gibson Island). As it flows south in the open Chesapeake, the overwater segment accelerates, veers, and turns right toward protruding points of the western shore. The colder, denser overwater air will cross narrow peninsulas such as Broad Neck, undermine the heated overland segment, and, gaining thermal turbulence (induced by the heated land), appear suddenly, strong and veered, on near-shore waters such as Whitehall Bay.

If (in summer or fall) the morning northwester is weak (less than 12 knots) and/or warm (warmer than the water) and at midday is diminishing, expect a series of shifts: Phase I - A net back due to a preponderance of backed oscillations ("dying begins") -330° → 315°. Phase II - A sudden persistent (for minutes or hours) veer to the overwater segment of the gradient wind - 315° → 360° accompanied by an increase in velocity. Phase III - A progressive veer - 360° → 30°-50° - accompanied by a decrease in velocity to near calm as the sea breeze appears off the Eastern Shore. Phase IV - A sudden veer as the sea breeze invades across the zone of convergence calm - 45° → 145°-165°. Phase V - (if the sea breeze dominates) - A progressive velocity veer as the ocean sea breeze strengthens - 165° → 180°.

<u>Lessons</u>: 1. If a secondary sea breeze is expected (if, in the presence of an unstable offshore gradient wind, the land surface temperature rises significantly above the water surface temperature) and the gradient wind is flowing offshore with water on its right, expect the pre-sea breeze shift to be a back.

2. If a secondary sea breeze is expected, but the gradient wind is flowing offshore with water on its left, expect the pre-sea breeze shift (at least near-shore) to be a veer.

The Ocean Sea Breeze

Another primary or secondary sea breeze present at Annapolis is the ocean sea breeze, an onshore flow from the Atlantic Ocean toward the east coast of the U.S. which comes ashore on and crosses the peninsula of the Eastern Shore. In spring and early summer this flow is indistinguishable from the Bay sea breeze. In the lower Bay, of course, the ocean sea breeze is the Bay sea breeze coming into the Bay through the Capes. There it is soon joined, however, by an overland sea breeze that, after crossing the southern Eastern Shore, accelerates flow into the rivers of the western shore. In summer and early fall, particularly in the northern Bay, when the Bay water is too warm to promote or maintain a local or Bay sea breeze, the ocean sea breeze often appears as a separate wind. At Annapolis it is often recognized as an "anchor breeze", appearing in late afternoon immediately after the Race Committee, for lack of wind, cancels racing. As the boats head for home, a strong cool wind from approximately 165°-185° appears and sends them planing up the river. This wind typically persists well into the evening.

By mid-summer the water and the marine air over the Bay are scarcely colder than the air over the land and the warm, moist mTg air which, on the back of the Bermuda High, has been advected over the area is so stable that separation and lift-off do not occur. In the absence of a significant synoptic gradient, in the light and flukey days of summer, the sailors drift for hours awaiting a Bay sea breeze which usually fails to materialize. No air cold enough to create the lapse rate and buoyancy required and no protective inversion is available - except from over the ocean.

Along the ocean coast protected by the subsidence inversion the cold marine air moves onto the low level coastal plain and into a primary sea breeze front that crosses the Eastern Shore. Advancing at 10-12 knots this front crosses the upper Eastern Shore in about 4-5 hours. It typically arrives in the rivers of the Eastern Shore at about 3:00 PM and at Annapolis at about 4:00. A dark line of ruffled water, a sudden shift, and a sudden increase in velocity dissipate the sputtering southwesterly gradient flow. In the fall with the Bay relatively warm in places like the Wye River, it may appear as early as noon as a gusty 8-12 knot flow from 140°-160°. Its direction is markedly channeled by the topography, aligning itself with almost every segment of the winding rivers.

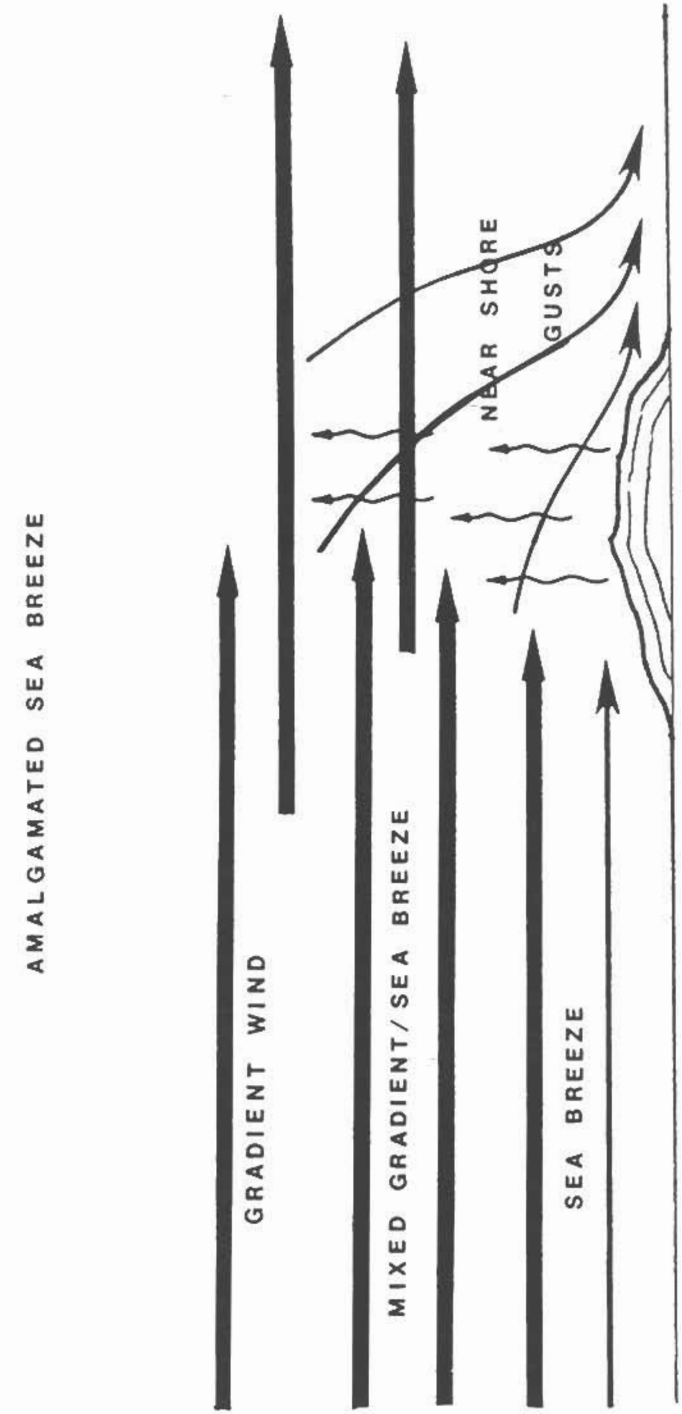
The ocean sea breeze is strongest within the Eastern Shore where thermal turbulence is marked. It is stronger on the eastern side of the Bay where it comes offshore onto the surface in gusts of upper level flow. It gradually decreases in velocity and gustiness as it moves across the Bay. Even in the Severn, however, it may retain a velocity of 16-18 knots. It backs with distance toward the western shore of the Bay, to leeward, veers with distance to windward. In a long distance race in late afternoon the stronger, veered flow along the eastern shore of the Bay should be sought.

An offshore sea breeze is strongest, most subject to channeling, and most variable in strength and direction in the gusting zone near the windward shore.

The Chesapeake's Amalgamated Sea Breezes

The Bay Sea Breeze

The Chesapeake Bay sea breeze develops in the presence of southerly or southwesterly flow in the western periphery of the Bermuda High. In summer beneath the subsidence inversion a portion of the Atlantic Coast's ocean sea breeze flows into the Chesapeake Bay at its sea level access site between the Virginia Capes. But, as the land behind the Chesapeake's 6,000 mile shoreline begins to



heat and the sea breeze accelerates between the Capes into the Lower Bay, it leaves the subsidence inversion behind. Thermal turbulence ahead of the sea breeze front destroys the preexisting inversion and the marine air, burrowing under the warm gradient flow, forms a new one. Confined beneath the warm air, the sea breeze front accelerates toward the upper Bay and its tributaries. As it extends inland, however, thermal and mechanical turbulence cause an increasing penetration of the interface and the frontal inversion also disintegrates.

Early in the day the sea breeze is composed of air that has lain in the estuary and has been gradually heated during the morning. Later in the day after this air has been pushed inland, the sea breeze is composed of ocean air, far colder and denser than the morning air, drawn in through the Virginia Capes and brought northward. In late afternoon it acts like water, channeling around promontories and into tributaries.

Amalgamation of a sea/lake breeze and a gradient wind requires that the two flows be aligned within 45° of one another and be of a similar temperature (and density). The closer the gradient wind direction is to the sea breeze direction, the stronger will be the resultant flow at the surface. In the lower bay the interface between the cold ocean air and the gradient wind is sharply defined. Farther north the marine air has become (or was already) warmer and both mechanical and thermal turbulence have increased. Here the interface has disappeared and the flow has become a continuum whose character and direction vary with height from almost all sea breeze at the bottom, through veered sea breeze with gradient flow at moderate elevation, to all gradient wind aloft.

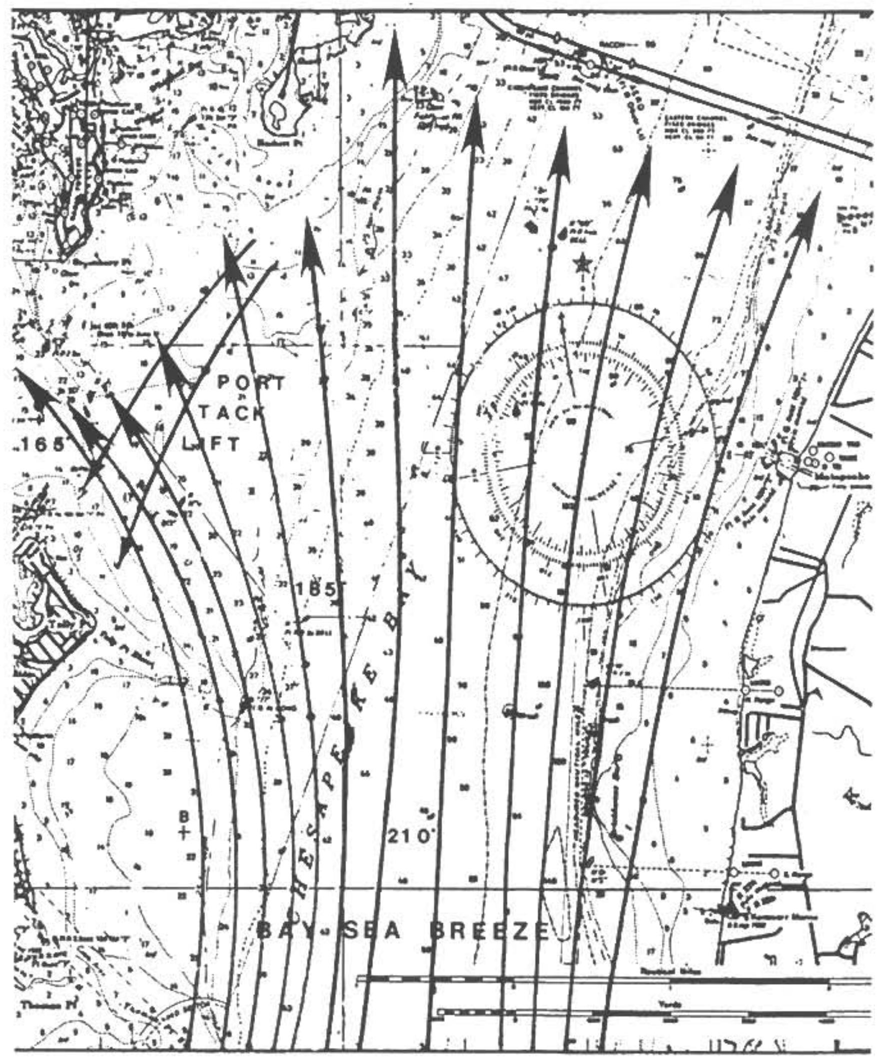
Because the Bay sea breeze, at least in the upper Bay, is an amalgamated flow, it is often far stronger than the local sea breeze. In contrast to the latter it never appears in association with offshore winds and it is never presaged by a diminution of the gradient wind flow. In the lower Bay (and sometimes in the upper) it typically appears out of morning calm - burrowing inland beneath a radiation/advection inversion. In the upper Bay the gradient flow typically appears first and the sea breeze appears as a modification of whatever gradient flow has been extant.

Incorporation of the sea breeze may result in a rapid increase in velocity but, its influence gradually increasing with insolation, only a gradually progressive persistent shift.

The Upper Bay Sea Breeze

As the ocean sea breeze heads inland between the Capes toward the heating sites, it flows to the northwest into the major rivers of the western shore and turns northward into the largest river of all, the Chesapeake Bay. It deviates in concordance with the Bay's shorelines and even more markedly into its tributary rivers and creeks. The gradient wind, however, (flowing from some direction between southeast and southwest) only amalgamates with the portions of the sea breeze flow with which it is aligned. The result is a marked variation in surface wind velocity at different sites.

In the lower Bay the direct access of the sea breeze to the large rivers of the



western shore and the confinement afforded by the low level frontal inversion result in a high velocity, southeast inflow aligned with and composed largely of marine (sea breeze) air. But farther north (where the sea breeze and gradient wind are well mixed) high velocity appears in those tributaries aligned with the gradient flow (approximately southwest/northeast) and low velocity in those perpendicular to the gradient flow.

Amalgamated sea breezes amalgamate to varying degrees, but never completely. On their initial approach to land the sea breeze flow is almost alone at the surface; farther up a bay or estuary the amalgamation is greater and the surface flow becomes a mixture of the two winds.

The great mass of heating land to the west and north exerts a constant pull to the west (in excess of the pull to the east) and causes the surface flow to turn more readily and with greater velocity into the rivers of the western shore than into the rivers of the Eastern Shore. The bay sea breeze channels into each tributary, deviating to become a westerly in some Eastern Shore rivers and an easterly in some western shore rivers. In late morning it may appear in mid-Bay off Bloody Point from 210', deviate into Eastern Bay at 235°, and be flowing from 270° at Tilghman's Point inside Eastern Bay. The Bay sea breeze may also come overland across Kent Island and similar barriers onto the inland waters of the Eastern Shore as an accelerated flow veered to 260° or more by the acceleration and the thermal turbulence. The surface flow also accelerates and veers as it channels through the narrow segments of the Bay, such as those opposite Cove Point and opposite Sandy Point, just north of Annapolis.

Parallel-to-shore winds separate into overwater and overland segments as the portion of the wind flowing over the minimal friction of the water accelerates and veers away from the relatively slow and backed overland segment. The Bay sea breeze is strengthened along much of the western shore as the segments of the parallel-to-shore, southerly amalgamated flow (with water on the right) diverge from each other and diminished along the eastern shore as the near-shore segments (with water on the left) converge toward each other.

Within the harbors and rivers of the western shore the backed overland segment of the gradient flow amalgamates poorly with and diminishes the veering sea breeze. Offshore, along the trajectory of the main shoreline and the tips of the protruding peninsulas, the veered overwater segment of that flow amalgamates well and strengthens the veering sea breeze. In a Bay sea breeze the strongest, steadiest wind is found along the western side of the open Bay. Only in late afternoon when thermal turbulence brings down gusts of the overland ocean sea breeze is there an eastern shore advantage.

Channeling and divergence (as the amalgamated sea breeze flows parallel to shore with water on its right) produce major changes in the strength and direction of the onshore flow of a sea/lake breeze.

The Bay Sea Breeze at Annapolis

At Annapolis any gradient wind between 140° to 230° will amalgamate with the bay sea breeze, but only those between 165° and 220° will be markedly strengthened. As the sea breeze veers with increasing velocity, a backed gradient wind will become increasingly malaligned and a veered one increasingly aligned. The presence of a strong gradient flow will increase the velocity of and therefore veer the amalgamated flow. The overwater segment of the southerly gradient flow (or of the amalgamated sea breeze) is the stronger and more veered of the two segments and amalgamates with the veering sea breeze best. Consequently, at Annapolis, the strongest sea breezes are associated with gradient winds veered to 185°, up to 210° - and result in an actual surface flow in mid-Bay between 210° and 220°. At other sites on the Bay the direction of the bay sea breeze and the overwater and overland segments of the gradient wind differ so the gradient wind direction that produces the strongest amalgamated sea breeze will differ.

Channeling and Divergence Near-Shore

At the mouth of the Severn the Bay sea breeze turns from its veered-to-up-Bay trajectory of 200°-210° and backs as it turns into the Severn (veers with distance down Severn). The farther into the harbor and the closer to the southern shore of the Severn the flow extends, the more backed it becomes. An amalgamated sea breeze of 210° in mid-Bay may be flowing at 165° as it heads up the Severn past the Naval Academy. This channeled shift becomes increasingly prominent with time, the incorporation of ocean air, and the coldness and denseness of the sea breeze.

Early in the sea breeze's development it may back with distance offshore (the "fan effect"). But in summer with distance sailed on starboard tack in the Severn Sailing Association's Area "A", due to channeling around Tolley Point and to an increase in velocity as it amalgamates with the veered overwater segment of the parallel-to-shore southerly, the Bay sea breeze is usually veering. With distance sailed an port tack (as one moves across the axis of the Severn), due to channeling around Tolley Point, the wind is backing significantly and in the lee of Tolley Point, where it mixes with the overland segment, is often lighter. The farther to the west ("up harbor") one crosses on port the more backed and lighter will be the wind encountered.

The net effect is that in summer and fall (when the Bay water is too warm for the local sea breeze to be operative) starboard tack from the start or the leeward mark is usually preferred, chiefly because it avoids the detrimental channeled back to the right. An initial move left also places one in a better position to attain the stronger, divergent overwater air in which one can point higher. In late morning or early afternoon, take starboard tack offshore until a stronger flow is reached and then cross on port. The only time that this plan is clearly wrong is in the presence of a strong flood when a move offshore takes the boat into stronger adverse current.

In a sea/lake breeze one tack or the other is advantaged because of channeling or divergence.

Channeling Offshore

For those racing farther offshore at Annapolis on a beat from a leeward mark near Hackett's Point to a windward mark at the mouth of the Annapolis Channel or farther south toward Thomas Point, the racing area is characterized by shorelines converging with distance to windward (the Bay narrows opposite Tolley and Thomas Points). The Bay sea breeze in summer and the ocean sea breeze in fall is therefore diverging with distance to leeward and a boat sailing toward either shore will find on each tack with distance from the rhumb line a progressive lift.
The rule for converging shorelines is "Stick to the rhumb line, avoid the course lengthening lifts near the laylines". At Annapolis because the course is far closer to the western shore, this means go out (left) on starboard (just as it does on the inshore course) so as to stay closer to the Bay's center-line and to avoid the lift inside Annapolis Rhoads. It is impressive that this channeled shift (and the need to go left) becomes progressively more evident with time after noon as the Bay sea breeze becomes increasingly composed of cold, dense ocean air (that is more affected by channeling).

Even in the center of a water body cold surface flows such as sea/lake breezes are altered in strength and direction (channeled) as the water body narrows or widens.

Oscillations

The Bay sea breeze contains small oscillations that are due to varying amalgamation as well as to medium oscillations induced by passage over land. Near shore the effects of channeling and changes in velocity are usually far more significant than either. In the open Bay shifts should generally be treated as oscillations both because (with variations in amalgamation) return shifts to the initial wind commonly occur and because other shifts cannot be distinguished from standard oscillations. If, for instance, the wind direction detected is significantly backed to that expected from channeling and alterations in velocity, one should presume that a veer is due - and assume port tack.

Seasonal Variations in the Three Sea Breezes

The local (primary or secondary) sea breeze is evident in winter and in spring - when the Bay water is cold compared with the land - and is almost absent in summer and fall - when the Bay is almost as warm as the land. The Bay sea breeze (deriving from the cold ocean) becomes prominent in spring and diminishes in summer as the Bay gradually heats. The ocean sea breeze (indistinguishable from the Bay sea breeze in spring) becomes evident in spring and, because the ocean remains cooler than the Bay and the land, continues through the summer and into the fall. In early fall it may be the only sea breeze available. It is essential to remember the season as the sea breezes likely to be present not only differ but behave differently. Do not attempt to apply in the spring the lesson learned in the fall.

In spring all three sea breezes may be present sequentially. The initial wind, evident in mid and late morning, may be from 145°-165°, i.e., the local sea breeze. At about noon or slightly later a veer to 165°-185° with an increase in velocity may herald the arrival of the ocean sea breeze. Later (1:00 to 3:00 PM) with the incorporation of the Bay sea breeze, the surface wind will increase in speed and veer further to 210° or even 215°. During the Spring Soling Bowl of 1993 in late April it paid to go right on every one of six beats as the 10 knot local sea breeze at 165° was intermittently, but progressively, replaced by the 14-15 knot ocean sea breeze at 185° and the latter, with the incorporation of the bay sea breeze, veered intermittently, but progressively, to 215° thereafter.

Summer is the time for the Bay sea breeze. If the gradient wind is weak and deviated significantly from 190°, the Bay sea breeze will first appear as a dark line on the southern horizon marching toward the observer. If the gradient wind is strong and close to 190°, the Bay sea breeze will appear first as a shift in the gradient wind. When racing at Annapolis, if a gradient wind backed to 185° is weak and increases in velocity around midday, expect a veer; the sea breeze will be the dominant component. If a gradient wind veered to 210° is weak and increases in velocity around midday, expect a back; the sea breeze will be the dominant component. If the gradient wind is predicted to be between 185° and 220° one should expect a veer toward 220° in proportion to the increase in velocity - but only reaching 220° if the gradient wind is predicted to be 220° or if the amalgamated wind becomes very strong. Veering is always proportional to velocity and so will be greater in spring when the ocean and Bay are cold and less in summer and fall.

Sea/lake breezes vary in strength and direction with the seasons as the temperature of the water and the amount of insolation change.

Westerly Gradient Wind Mixtures

In the presence of westerly gradient winds the secondary local sea breeze may either displace the warmer offshore wind from part of the surface resulting in "two winds simultaneously" (most likely in spring or early summer when the water, is cold) or may, with an offshore wind of approximately the same temperature, diminish and mix with it in a series of oscillating shifts (most likely in the fall when the water is warm). Under the latter circumstance the shifts to the sea breeze may back the oscillating westerly flowing initially from 260°-280° to about 230°-240°. With "two winds simultaneously", the westerly will be present near shore and the sea breeze at 165°-185° offshore. One must seek an upwind position in the wind extant at the mark ahead. With mixtures between the two winds, oscillations dominate and one must stick to the tack lifted to the median until close to the weather mark when conservative tactics become appropriate.

When the gradient wind flows approximately perpendicular to the sea/lake breeze direction, the two will converge, and appear simultaneously at the near-shore surface.

Will a Sea/Lake Breeze Develop?

Every racing venue has at least two different winds — one derived from the weather system pressure gradient and one derived from local differences in temperature between the land and the water. Every racing sailor needs to know which one will be present when he is racing and whether one will be displaced (or altered) by the other during his racing. As the sea/lake breezes, in contrast to the gradient (weather system) winds, derive from an almost unvarying pressure gradient and a fixed topography, they are characterized by a predictable time and rate of development, range of velocity, and range of direction. They are the stuff of "local knowledge" with which the racing sailor is greatly advantaged and without which he is greatly handicapped.

Fixed Phenomena (affecting sea/lake breeze generation)

Temperature (degree of coldness) of the near-shore water
Responsiveness to insolation of the near-shore land
Topography of the near-shore land (presence or absence of indentations such as river mouths and shoreline height above the water.)
Presence or absence of inland elevation

The essential element is the disparity between the temperature of the water and the land (not completely revealed by the disparity between the temperature of the over water air and the over land air. A body of water tends to be colder if it is large and deep and frequently changed by tide or river current. Land tends to become hot more readily, responds better to insolation, if it is barren, dry, and flat. Land that is forested, wet, and uneven has a far greater surface area and is far more able to absorb heat without a change in temperature.

A large expanse of low-level, near-shore land facilitates inland movement of the marine air. Near-shore elevations block access of the cold, dense, marine air to the heating sites and prevent the ready establishment of a sea breeze front with a high, near-surface, lapse rate and instability. An estuary, a river mouth, or a series of inlets into the land will improve access and channel the air into one or more concentrated, stronger flows. The many rivers and creeks of the Chesapeake Bay provide ready and extensive access (at sea level) for the marine air to vast areas of only slightly elevated, heating land.

Periodic Elements —

Seasonal changes
Diurnal changes

In winter, cold water is associated with cold land. Snow or ice covering the land will negate sea/lake breeze flow, but often in winter under dry, clear skies, the land heats readily and significant onshore flow develops. In spring, the water remains cold while the land heats. In the mid-latitudes late spring, when the water is still very cold, but the land hot, is the optimal time for sea/lake breeze generation. In summer (in the absence of very cold water), sea/lake breezes are usually light (or absent) as the temperature disparity diminishes. Summer is also characterized

by the presence of warm, moist, Tropical air masses with low, near-surface, lapse rates and stability. Sea/lake breeze generation is poorest in fall as the water remains warm while the land is cooling. In summer, although the surface land temperature often exceeds 100°, the water of the Chesapeake Bay is relatively warm (75-80°), and the air temperature often approaches 100°. The warm water and the low, lapse rate diminish sea breeze generation — and account for the Chesapeake's reputation as "the light air capitol of the east coast."

Diurnal variations in heating determine the sea/lake breeze's characteristic onset in late morning or early afternoon (when the heating of the land and the near-surface air finally exceeds the critical lapse rate), its increase in velocity and veering in early afternoon, and its dying and backing in late afternoon.

Variable Elements —

Water temperature
Land temperature
Characteristics of the overlying air —
- temperature
- moisture content — maritime or continental air
- near-surface lapse rate
- stability — instability
- depth of the turbulent layer

Gradient wind direction

No sea/lake breeze will develop unless the temperature of the water is at least 2° less than the expected midday air temperature (usually measured at 7-10 meters above the ground). The midday surface land temperature is always higher than the measured air temperature but for sea/lake breeze generation, it must be significantly higher, so high that the near-surface, lapse rate is 3.5 times the adiabatic. An optimal sea/lake breeze generating condition would have the water at 75° (or less), the over water air at 77°, the over land air at 80°, and the land surface at 100°. The land is more likely to rise to such a high temperature and acquire the necessarily high, near-surface, lapse rate in the clear, dry air of a continental Polar air mass.

It is the instability or buoyancy of the advected air mass that ultimately determines whether a sea/lake breeze will develop. It must be cold enough to create a high, near-surface, lapse rate (to acquire low-level instability) and it must maintain this instability to high levels — but it must be at least slightly warmer than the water. A measured air temperature more than 10° hotter than the water will diminish or eliminate the usual sea/lake breeze. It must be dry; the heat-absorbing water vapor content will diminish surface heating by absorbing short-wave, incoming radiation and diminish the lapse rate by heating the air itself.

When the advected air has a high lapse rate to high levels, heated surface air rising within it and cooling at the lesser adiabatic rate will become progressively hotter than its surroundings and continue to rise to the top of the buoyant layer.

winter, air is drawn from the sub-arctic over Canadian snowfields, it will be, and will cause local conditions to become, cold and dry. Mid-latitude summers are warm and moist because the air mass, south of the Polar front, usually present is Tropical and mid-latitude winters are cold and dry because the air mass, north of the Polar front, usually present is Polar.

To each side of the front, large masses of air subside over and assume the character of the relatively homogeneous surface beneath — cold and dry over central Canada; hot and moist over the Gulf of Mexico. The subsidence in such an air mass, the increase in density, results in a rise in surface pressure, the formation of a "high." Centers of high pressure form, a Polar high to the north; a Tropical high to the south. Air flows out from these centers of high pressure and in toward the centers of low pressure which form along the Polar front. In the northern hemisphere, Coriolis force causes all air flow to veer resulting in a clockwise circulation around the center of high pressure and a counter-clockwise circulation around the center of low pressure.

The consequences of these interactions is that, as the Polar front migrates eastward, a given surface site will experience a series of gradient wind patterns. The frequency with which Polar or Tropical air reappears, of course, depends upon the season and the latitude of the site, but for sites across which the front migrates, most of the U.S. and Europe, a pattern emerges. If we select a site somewhere along the U.S. east coast and take the passage of a cold front as the initial event, the series begins with a northwesterly flow of cold, Polar air. The second phase appears as the continental Polar high, typically passing to the north, moves eastward and the flow on its eastern side veers to the north and northeast. When the center of the high is close and due north, the gradient flow is from the east and the advected air from off the Atlantic Ocean. The fourth phase develops when the high moves to the east of the site. Gradient flow is then from the southeast or south which advects air from the Gulf over the hot southern states. If the high moves south or, as in summer, is a Tropical (mTg) high sitting offshore, the "Bermuda High," the next (the fifth) phase will be the "southwester" — the prevailing wind of summer along the Atlantic coast.

Ahead of a low that may have formed along the Polar front, the gradient wind will also be south or southwest, strengthening the southwest flow behind the center of high pressure. This flow, ahead of the low, is accompanied by increasing cloud and thunderstorms. If the low migrates along the Polar front, the next phase over a site to its south is a warm front passage. Tropical air rides up over Polar air, accompanied by varying amounts of clouds and rain. The warm front is followed by the warm sector, the zone to the south of a low between a warm front and a following cold front. Here the gradient wind is west and may be strong, as both the high to the east and the low to the north, create a westerly gradient which is accelerated by the frontal convection. After the warm sector, the sequence begins again with a cold front passage. If, of course, the center of the low passes over the site or to its south, no warm sector is experienced and the sixth phase is the often strong easterly and northeasterly (the New England coast's "three day nor'easter")

gradient flow around the low. The cool, moist, advected air drawn in from the ocean produces thick layers of cloud (stratus and nimbostratus) and rain (or snow).

These cyclicly recurring patterns of gradient flow interact with three important additional factors: the characteristics of the advected air brought to the site, the orientation of the coast over which the gradient wind flows, and the inherent capability of that coast to generate a sea/lake breeze.

The precise qualities of local weather, the day-to-day variations, are determined by the recent experience of the gradient wind, the temperature, and moisture content of the surfaces over which the air has flown. The colder and denser the advected air, the more likely will the gradient wind flow sink to the surface and come offshore strong and turbulent. The warmer the advected air, the more likely will the gradient wind be excluded from the surface, particularly from the surface of cold water, by an inversion above the cold, dense, surface air. Dry air facilitates insolation of the surface and the development of a high lapse rate (buoyancy) and, thereby, enhances secondary sea/lake breeze generation beneath offshore flows. Moist air has the opposite effect and diminishes secondary sea/lake breeze generation.

The orientation of a coast to the gradient flow determines the interaction of that flow with a potential sea/lake breeze. If the gradient flow is southerly and the coast is "south" facing (facing the south quadrant — southeast to southwest), the potential for an amalgamated sea/lake breeze is high. If the gradient flow is southerly and the coast is "north" facing, a seconday sea/lake breeze may develop by lifting the offshore gradient flow from the surface. If the coast is "east" or "west" facing and the gradient flow is parallel to the coast, sea/lake breeze flow will be impeded.

Finally, the coast itself has inherent properties which make it more or less likely to propagate sea/lake breezes and which will determine whether, on any given day, one or the other of the three sea/lake breeze types will appear. A narrowing topographic funnel leading the marine air inshore is far more likely than an unindented coast; a river providing water-level access to the interior far more likely than a straight line of bluffs; a low-lying, barren, near-shore plain far more likely than the buildings of a large city to generate a sea/lake breeze.

Seasonal Variations at Annapolis

The Polar front migrates across the northern Chesapeake throughout the year. However, the frequency with which it invades this area and the intensity of the pressure gradients to its either side vary greatly. In winter and spring, the front is regularly at this latitude and several cold fronts may pass through in a single week. And in winter, the southward surges of cold Polar air are responding to large gradients and are deflected by equally strong surges of warm, Tropical air. In summer by way of contrast, the Polar front is typically far to the north and may not cross the Chesapeake for periods of up to four weeks. The persisting residence of

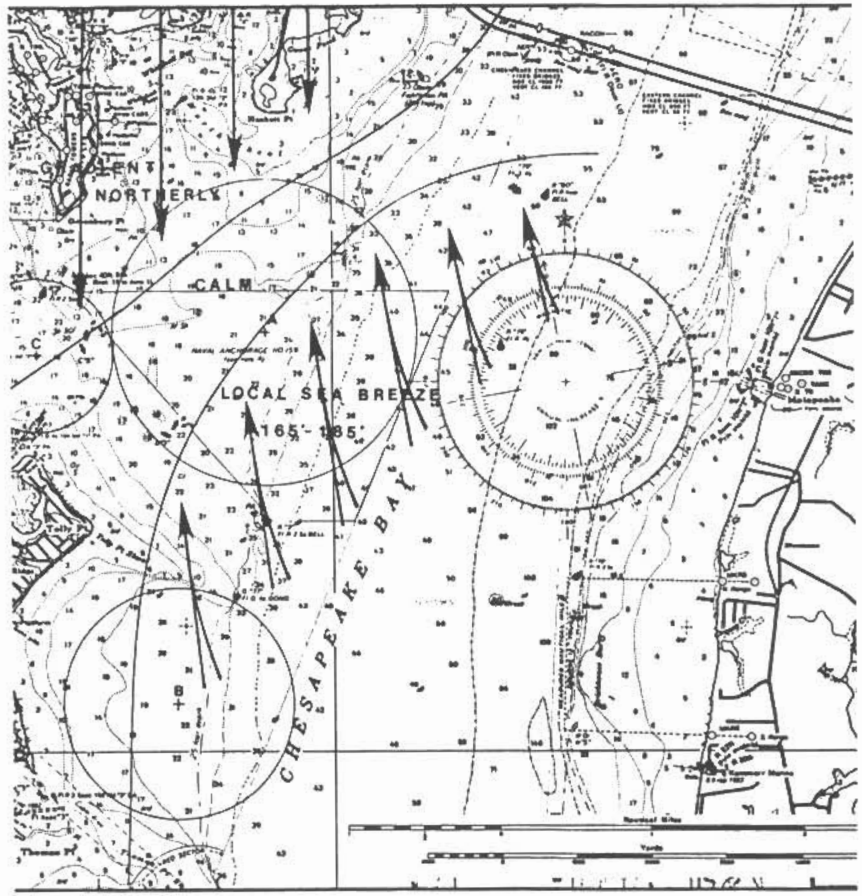
Annapolis, in an area of minimal pressure gradient to the northwest of the "Bermuda High," has unjustly earned for it the title "light air capitol of the world." The likelihood, type, and strength of the sea breeze is also subject to major seasonal variations resulting from differences in land and water temperature, gradient wind direction, and the buoyancy of the advected air.

An analysis of the relationship, between the Polar front and the surface wind flow at Annapolis, during a two-week period in June (from Wednesday, June 17th to Tuesday, June 30th, 1992), when the front makes frequent transits of the area and the sea breezes are at their strongest, is illustrative. Because the Polar front lies close and the Bay water remains cold, strong gradient winds and the strongest sea breezes of the year occur at this time.

On Wednesday, June 17th, Annapolis lay in the warm sector between high pressure centered over Long Island and low pressure centered over Lake Superior. The afternoon wind was a 8-12-knot, amalgamated, sea breeze at 180-190'. On Thursday, the cold front extending northeastward from Tennessee to the center of the low (now over Kingston, Ontario) was rapidly approaching and Annapolis experienced one of the "best sea breezes of the year" — 20 knots from 210°. On Friday morning, after the cold front had passed through (during the preceding night) and a new cold front was forming across Ohio, the wind was northwesterly at 12-15 knots. A light secondary sea breeze at 165-185° appeared in Annapolis Roads in early afternoon, resulting in "two winds simultaneously." The second cold front passed through the area Saturday morning. After a few hours of light north-northeasterly flow in the morning, the northwesterly at 15-20 knots appeared. On Sunday with the cold front offshore and High #2 centered over Lake Superior, the northerly flow continued. But this highly variable, 6-14-knot wind was associated with huge shifts caused by medium (15-20 minute) oscillations between 290° and 30° (presumably due to the splitting of the flow into two converging portions as it flowed parallel to the coast).

On Monday, the 22nd of June, with High #2 over Toronto and a cold front extending southward from a low over Lake Superior, the local wind was light northeast to east and was replaced in the afternoon by a 12-knot secondary sea breeze at 175-185°. On Tuesday with the cold front a little closer, the air was hazy, warm, and humid (mTg) and the wind light and flukey from the southeast. A light local sea breeze appeared transiently in mid-afternoon. On Wednesday, the low was over Vermont, the cold front was nearby and approaching rapidly, and we had another "best sea breeze of the year" — 20 knots from 200-210°. The cold front ahead of High #3 passed through during the night and was offshore by midday. On Thursday, the local surface wind was light and variable from the northeast until in late afternoon an 8-10-knot secondary sea breeze at 185° appeared.

On Friday, June 26th, a new low developed over North Carolina along the offshore cold front and a new cold front appeared ahead of High #4 over Chicago. The local wind was easterly and light. No sea breeze developed. The weak, new cold front passed through Annapolis on Friday night and on Saturday, the local wind was northwest at 8-12 knots with big oscillations. On Sunday, with High #4



over West Virginia and the cold front extending from Florida out into the Atlantic, the local wind was northeast to east with big oscillations and finally died away to a dead calm in late afternoon. On Monday, High #4 had dropped down to North Carolina and a new cold front, extending southward from Toronto, was approaching. A Bay sea breeze appeared in late morning strengthening to 18 knots by mid-afternoon. On Tuesday, with High #5 over northern Ontario and the approaching cold front extending east-west from Lake Huron to Maine, the Bay sea breeze appeared again at approximately 15 knots.

During this 14-day period in June, the best time of the year for sailing at Annapolis, four cold fronts passed across the Chesapeake accompanied by four cycles of the Polar front. On four of these days (after each of the cold front passages), the local wind during daylight hours was northwesterly. On only one occasion did a sea breeze (a secondary, local sea breeze) undermine this cold offshore flow. On three days, each following one day of northwesterly flow, the local wind was from the northeast and on two of those days, a secondary sea breeze replaced it. On only one day was an easterly present and it persisted throughout the day. On one other day, a southeasterly blew fitfully until it amalgamated with a Bay sea breeze. On the remaining five days, four of them, immediately preceding a cold front passage, amalgamated Bay sea breezes developed in mid-morning and persisted throughout the day. On two of these days as the cold front drove from the west to within a few hundred miles, the area experienced "the best sea breeze of the year."

Winter is characterized by primary local sea breezes facilitated by the buoyancy of the cold, dry, Polar air and protected by subsidence inversions (cold air under warm). Spring and early summer produce both secondary sea breezes under cold offshore gradient winds and the strongest of all amalgamated sea breezes. Light primary sea breezes may exist transiently under morning radiation inversions and under offshore flows in summer, but the amalgamated Bay sea breeze becomes weaker as the Bay water becomes warmer. The ocean sea breeze may appear in late afternoon as the only significant wind of the day. In fall, with the Bay as warm as the land, both local and amalgamated sea breezes are weak and infrequent. As winter begins and the Bay becomes cold, local primary sea breezes again become frequent but, as the ocean remains (relatively) warm, both Bay and ocean sea breezes are infrequent and weak.

The Sequential Phases of Gradient Wind Flow

Phase I — The Northwesterly

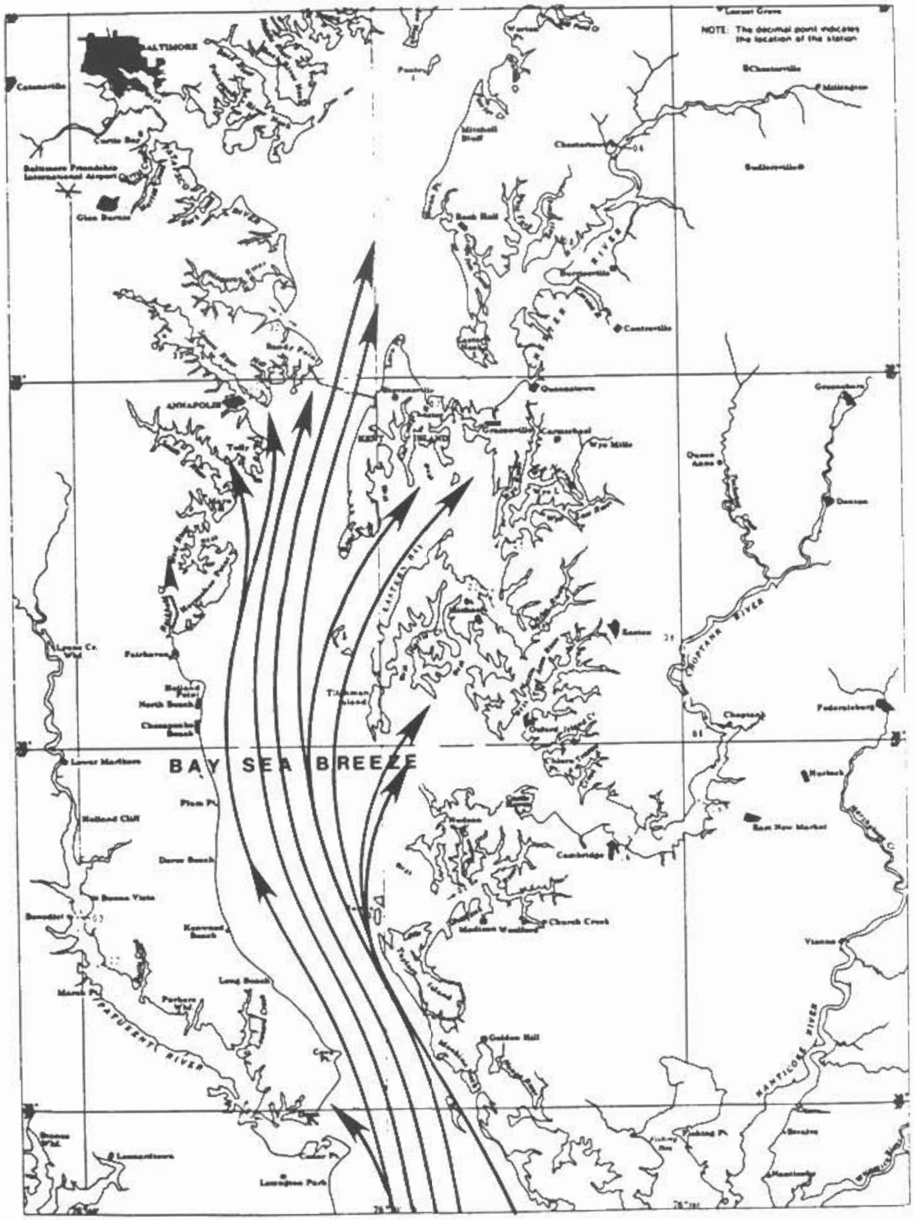
A cold front is the leading edge of a continental Polar air mass burrowing south and eastward. The cold, dense air in its periphery is running outward and south/eastward from its center under a strong gradient. The advected air is dry, cold, unstable, and buoyant (distinguished by a higher than adiabatic lapse rate) to thousands of feet above the surface. Separation occurs readily as the clear, cold air passes over the well-insolated land resulting in the continuous lift-off of convective streams, cumulus cloud formation at 3-10,000 feet, and strong downdrafts of veered, upper-level flow. Over near-shore waters on "south" and "east" facing

coasts, the northwesterly produces classic oscillating wind conditions (Category I). Amalgamated sea/lake breezes are rarely generated as the marine air is swept away by the colder, denser flow, but some enhancement of near-shore flow may be recognized on north facing coasts such as the south shore of Lake Ontario. Secondary sea/lake breezes are also unlikely as the northwest flow is typically colder and denser than, and cannot be undermined by, the marine air. However, on the second day after a cold front passage (when sometimes the gradient wind is still in the northwest), in the summer, and/or at the distant periphery of a southward surge of Polar air, the northwesterly may become warmed sufficiently to permit its lifting by unusually cold, marine air.

The northwesterlies at Annapolis are the strongest of the regular, cyclicly recurring winds. The strongest and most dramatic gusts (brought to the surface by thermal turbulence) appear near the windward shore; the flow becomes lighter and more homogeneous with distance to leeward. As gusts, composed of upper-level air flow, free of friction, are veered to the basic surface flow, a progressive veer with distance to windward is to be expected. Although medium oscillations in the wind flow and variations in the boat's position relative to the gust may cause some gusts to appear to be backed, the net effect often warrants an approach to a near-shore weather mark just below the starboard layline. However, the basic tenets of oscillating wind strategy always apply: avoid the laylines, stick to the rhumb line as the weather mark is approached, etc.

The most dramatic wind shift occurring along the U.S. east coast is that induced by the acceleration of an approaching cold front as it comes offshore onto water. Look for deepening of the billowing cumulus in the west and then the hard, dark line of ruffled water racing off the Western Shore. Keep to the right when beating in the typically preceding westerly warm sector winds. Expect the northwesterly if it arrives during daylight hours to rapidly reach its peak surface velocity and to weaken progressively for the next two days accompanied by a progressive but very gradual veer. Each day its surface velocity and gustiness will fluctuate with variations in insolation, thermal turbulence, and the incorporation of upper-level flow, reaching a peak at about 1:00 PM in winter and 3:00 PM in summer. But, particularly in summer and on the second day of northwesterly flow (as the center of the high approaches and the gradient decreases), surface velocity may actually diminish during early afternoon.

Occasionally on the second day (rarely the first), the advected air may become so warmed by its passage over heated land that the cool, marine air is able to undermine it, lift it from the surface (at least offshore), and replace the northwesterly with a secondary local sea breeze. The result is one of the two common conditions in which two winds are present simultaneously. The northwesterly, whose colder, stronger, upper-level elements are brought to the surface by thermal turbulence, will persist near shore while the sea breeze, whose coldest, heaviest elements accumulate over the deepest water and lift the gradient flow from the surface, will develop offshore. In between, where the Race Committee will undoubtedly set the course, is a zone of calm where the two winds converge



and the struggling sea breeze is displaced upward and swept offshore in the general gradient flow. Although the cold, dry northwesterly provides the high lapse rate essential to continuous stream lift-off and replenishes the ridge of high pressure at the water surface in mid Bay, its air is usually too cold to permit the marine air to invade the land.

Phase II — The Northerly/Northwesterly

A day or two after the passage of a cold front, the high (moving at approximately 300 miles per day) has moved sufficiently far eastward that the gradient flow has veered to the north or northeast. A 40-50° veer in 24 hours is only 2' per hour and is, therefore, of little significance during a half hour beat and is completely obscured by the typical 15-20° oscillations. Because the gradient, which resulted in the initial surge of Polar air, has dissipated, these winds are not as strong as the northwesterlies and because the advected air has had longer contact with warm surfaces, they are warmer. Because, by midday, at least, the temperature of the advected air becomes warmer than the marine, northeasterlies on "south" facing coasts are regularly replaced by secondary sea/lake breezes. In the eastern U.S. and Canada, the northeasterly creates the classic pre-condition for "two winds simultaneously — the sea/lake breeze offshore; the colder, stronger, upper elements of the gradient wind brought to the surface by thermal turbulence near shore.

Northeasterlies flow parallel to the U.S. east coast with water on their left and suffer from the typical consequences of such flows. The portion of the northeasterly flowing over the land is slowed by friction and; therefore, backed relative to the portion flowing over water. The resultant convergence between the two adjacent flows diminishes the net velocity of the northeasterly and results in a confused mixture of winds at the surface. At Annapolis, the result is a lighter than forecast gradient flow. In the morning, this is chiefly composed of gusts of the backed (more northerly) over land flow (brought to the near-shore surface by thermal turbulence). By midday, the veered (more easterly) over water flow has become sufficiently warmed to reach the surface. And by early afternoon, often following a period of calm, the local southeasterly sea breeze appears.

Northerly and northeasterly gradient flows are associated with the most significant effects of current at Annapolis. If the current is ebbing and the windward mark is adjacent to the 30-foot depth line, adverse current markedly disadvantages the right side of the course. In these circumstances (and in few others), current often becomes the dominant determinant of outcome. The boat must be taken inshore into the shallow water and not brought out to the right of the rhumb line until the weather mark can be laid or overstood.

Phase III — The Easterly

The gradient flow is easterly when high pressure is centered directly to the north. Along the U.S. east coast, this means that a Polar high has moved a long way from its site of origin in central Canada, that its pressure gradient has dissipated, and that its center is "nearby." Consequently, easterly gradient flow is usually weak. The moist, non-buoyant, thermostable ocean air (warmer than continental in winter; colder is summer), drawn in by the easterly, diminishes surface insolation and blocks convection. Thus, sea/lake breeze generation is impaired regardless of the orientation of a coast or its inherent characteristics. Easterly gradient flow, parallel to "north" and "south" facing coasts, is perpendicular to and blocks sea/lake breeze generation. Convergence, between the over land and over lake portions of the easterly flowing parallel to a "south" facing coast, such as along the north shore of Lake Ontario or along many segments of the Atlantic coast, is particularly detrimental.

At Annapolis (as at most sites along the U.S. east coast), the easterly produces the worst possible sailing conditions. The conditions indicated above relative to the northeasterly are even more likely with the easterly: calm interspersed with huge shifts between the gradient wind and a weak, very low-level, transiently appearing, sea breeze. Because the advected air (from the ocean) is warm and moist, both the lapse rate and the insolation are diminished and sea breeze generation is further impaired. Fortunately, the easterly is more homogeneous than the northeasterly so one does not have to struggle with two portions of the gradient wind as well as with the sea breeze. The local sea breeze, from 165-185° (in summer), if it develops, flows weakly, veers minimally (because it strengthens minimally), and dies early. The dying of either wind will be followed by a series of protracted oscillations toward the other interspersed with shifts back.

Phase IV — The Southeasterly/Southerly

As the center of high pressure moves eastward, the pressure gradient and the gradient flow become progressively weaker. Once the Polar high is off the coast, strong surface air flow depends upon the development of a sea/lake breeze. But, because the advected air, coming either off the ocean or over the southern states, is both warm and stable, it provides a poor substrate for sea/lake breeze generation. On "north" facing coasts, secondary sea/lake breezes, which might be expected to develop under the warm offshore flow, rarely do. Only on "south" facing coasts such as Buzzard's Bay, Kingston, and some portions of the Chesapeake, which are blessed with inherent facilitators of generation, are sea/lake breezes common and these are of the amalgamated variety. And even at these sites, if the gradient wind is more southeasterly than southerly, it will be backed to the southwesterly sea/lake breeze and, as the latter veers, become increasingly mal-aligned. Not infrequently, despite good alignment and inherent geographical advantages, no sea/lake breeze develops or confused oscillations between gradient wind and sea/lake breeze appear.

A strong subsidence inversion (with or without an obvious stratocumulus lid), typical of east coast summer, may be present in association with persisting high pressure and, if so, a primary sea breeze may develop beneath it. In this situation, the light, local, onshore, thermal flow may be interrupted periodically by downdrafts of gradient flow descending through melted holes in the

stratocumulus cover or, as the inversion burns off at midday, the gradient flow may replace the local sea breeze only to be replaced in turn by a large-scale amalgamated Bay sea breeze.

At Annapolis, gradient flow from all directions between northwest and east are associated with the development of secondary sea breezes — the local Annapolis sea breeze. The cool, marine air lifts the warmer, gradient flow from the surface, displaces it aloft, and replaces it at the surface. The result may be two different winds occupying different areas of the course, one wind alone, or oscillating shifts between the two, but they do not amalgamate. The secondary local sea breeze flows at 155°-175° in winter and with greater velocity at 165°-185° in spring. Southeasterly and particularly southerly flows, by contrast, are able to amalgamate with the sea breeze so that the two winds blend together in a single flow. The strength and direction of this flow will depend upon the strength and direction of the gradient component.

Southerly and southwest gradient winds and amalgamated Bay sea breezes create the second situation in which current becomes a major consideration at Annapolis. Although starboard tack offshore is often the preferred upwind course, if the current is flooding and the tack will take the boat into the strong adverse current beyond the 30-foot depth line, port tack will be preferable.

Phase V — The Southwester

Along the U.S. east coast in winter, the southwester is an ephemeral wind soon displaced by a frontal passage, but it is the prevailing wind of summer and may persist for many days in a row. The Polar front has moved northward and the Atlantic subtropical high sits over Bermuda ("the Bermuda High"). The flow around the high advects warm, moist, maritime Tropical gulf (mTg) air over the east coast and eastern Canada. Near the Polar front, particularly in the warm sector, the gradient is strong. Although the warm, moist air has a low lapse rate and diminishes sea/lake breeze generation in general, on "south" facing coasts, particularly in bays open to the southwest such as Buzzard's and Kingston, a strong amalgamated sea/lake breeze — the "smokey southwester" — forms. This is the best sailing wind of summer and sailors flock to sites where it concentrates. Because of the low lapse rate, secondary lake breezes rarely develop on "north" facing coasts beneath the southwester. On "east" and "west" facing coasts, the southwester impedes perpendicular sea/lake breeze development. When flowing parallel to a coast, the southwester is noted for its splitting into a veered, over lake flow and a backed, over land flow. The convergence between the two portions of the flow, when water is on the left, results in the characteristic diminution of the southwester at Rochester, its appearance at the surface of the lake as two separate flows, and its obstruction of sea/lake breeze generation. The divergence between the two flows, when water is on the right, results in the characteristic enhancement of the southwester in the Chesapeake and elsewhere along the Atlantic coast and its support of sea/lake breeze generation.

As the southwest wind flows along the coast, marine air is dragged into motion and incorporated within its lowest levels. As the land heats, separation and lift-off of heated air occurs, and low pressure develops at the surface of the land, an additional gradient draws the marine air ashore. As the onshore flow accelerates and veers, it becomes increasingly aligned and amalgamated with the gradient flow. The lower levels of the southwester and the marine air become homogeneously interspersed so that, at the surface, a single reasonably uniform flow develops, while aloft, the gradient wind continues unaffected at its own velocity and direction.

The upper-level portion of a primary sea breeze circulation never forms: the heated air rising above the land is swept away inshore and the depleting high pressure associated with sinking air over the water is replenished by the gradient inflow. The marine air, carried ashore in the weather system gradient, creates the high lapse rate and buoyancy necessary to continuous stream lift-off, the essential for strong sea breeze generation. Amalgamated sea breezes are the strongest sea breezes of the mid-latitudes both because of the incorporation (in spring, at least) of strong gradient flow and their facilitation of strong sea breeze development.

(See the extensive discussion of Annapolis' Sea Breezes.)

Phase VI — The Warm Sector Westerly

A warm front eventually catches up with the cP air which has invaded behind a cold front and restores the sway of mTg air to the region immediately south of the Polar front. Typically, this region, known as the warm sector, is a triangular one whose apex is a "low" located somewhere along the chain of the Great Lakes, whose eastern limit is the warm front, and whose western limit is another cold front leading another invasion of cP air. The counter-clockwise circulation around the low pressure to the north and the clockwise circulation around the high pressure to the south reinforce one another to produce a particularly strong westerly gradient. The warm, moist, Tropical air does not support secondary sea/lake breeze generation, but on appropriately oriented coasts, compressed close beneath an advancing cold front, the warm sector provides the strongest of all amalgamated sea/lake breezes. At Kingston, Buzzard's Bay, Long Island Sound, and in portions of the Chesapeake, the "south" facing coasts convert westerly gradient flow into strong amalgamated sea/lake breeze "southwesters." The warm sector, between two fronts both providing frontal lift, is characterized by convection — the creation of cumulus, altocumulus castellanus, and cumulonimbus (thunderstorm) clouds — in the moist, tropical air. The sailor must always be on the lookout for protracted oscillations due to the appearance of 5-10-mile diameter cells beneath cumulonimbus clouds with counter-clockwise surface inflow.

The warm sector facilitates Annapolis' sea breezes. The strongest sea breezes at Annapolis occur in the presence of the cold Bay water of June when, in a warm sector, an approaching cold front compresses the mTg air and creates a strong southwesterly-westerly gradient. There is sufficient insolation to generate thermal

onshore flow as well. But, because the advected air is warm and moist, look for the gradient wind to dominate with but a token shift toward the sea breeze. The direction of surface flow causes much of the flow to come over land (along the Bay's Western Shore), resulting in prominent medium oscillations. Gusts, which either derive from the upper levels of the marine air or the gradient flow, will be veered. If the gradient wind is backed to 250°, amalgamation and a strong surface flow at 200-230° will develop. If the gradient flow is veered to 250°, it will persist (sometimes in the presence of a simultaneous sea breeze) or it will die completely before, after a period of calm, being replaced by the sea breeze. Afternoon thunderstorms, with their protracted oscillations, should be expected.

The warm sector produces the second condition for two winds simultaneously (in addition to the northeasterly). In the spring with the Bay water still very cold, a warm westerly will be readily displaced from the surface offshore by the cold marine air. But, near-shore, thermal turbulence will bring (often strong) gusts of the westerly to the surface blocking access of the onshore flow to the heating sites ashore. The result is a zone of westerly (approximately 270°) flow along the south shore of Annapolis Roads and in the harbor, a local secondary sea breeze (at 165-185°) in the open Bay, and a band of calm in between. The extent of each varies so that intermittently the westerly extends into the racing area between Hackett's and Greenbury and intermittently the sea breeze extends into the harbor. The Race Committee should opt for one wind or the other — but never succeeds. If the weather mark is in the westerly but the starting line is in the sea breeze, an immediate move to the right is required so as to cross the zone of calm (above the layline, if necessary) and retain the westerly all the way to the mark. The opposite condition is less likely, but possible: If the Race Committee attempts to start nearer shore in the westerly and the sea breeze extends across the weather leg, an immediate move to the left is required. Keep an eye on the area around the weather mark; it is the wind that is extant there that you must reach before your opponents.

Phase VII — The Low Pressure Southwester

To the east of a low tracking along the Great Lakes and to the north of a warm front trailing its warm sector, the gradient flow will also be southwest (from west to south). Far from the low, the gradient is created by the center of high pressure and the gradient wind behaves as in V. above. Close to the low, cloud cover becomes complete, humidity high, and rain frequent. Under these circumstances, a sea/lake breeze will not develop. Surface flow is then the consequence of the gradient flow alone or of the frequent thunderstorms which develop in the rising air. So long as the cloud cover remains 10/10ths, the concern is for protracted oscillations associated with and emanating from cumulonimbus formations. If, however, the cloud cover is incomplete, if downdrafts of upper-level flow melt the stratus and stratocumulus formations, a sea/lake breeze may develop. One must be particularly concerned for this possibility, if the cloud cover melts over the land but not over the sea.

Beware of confusing a low pressure southwester with the classic Bay sea breeze southwester. Because the former is accompanied by clouds and rain, a shift to the sea breeze is unlikely. Look for black clouds and their accompanying downdrafts which will diminish the gradient flow initially, cause a shift toward the black cloud, and be followed by an oscillation back toward the southwester.

Phase VIII — The Low Pressure Northeasterly

When a center of low pressure develops in the Gulf of Mexico, it often migrates up and lingers off the east coast. Flow around such a low comes onshore from the east or northeast and accounts for the name given to this weather along the New England coast — "a three-day nor'easter." The gradient is often strong; winds along the coast are commonly at 20 or more knots. The advected air is from the ocean, so that in summer, it feels cold and damp. The dense cloud cover, heavy moisture, and frequent rain block insolation, separation, and sea/lake breeze generation. Because the advected air is cold, thunderstorm production is unlikely. Oscillations may be prominent to leeward of peninsulas and on lakes as the strong over land flow induces mechanical and thermal turbulence.

At Annapolis, such flows occur once or twice each summer. They are also occasionally seen in association with hurricanes migrating along the coast. Because they are composed of cool ocean air and traverse significant stretches of land en route to the Chesapeake, oscillations are evident. However, these flows are insufficiently buoyant to demonstrate any increase in velocity or veering near the weather shore. Indeed, blanketing is prominent; the warm air continues to flow at land height and does not sink to the water surface until it reaches a considerable distance offshore. Velocity to the right of the rhumb line in the open Bay will be greater than near shore in the lee of Hackett's and Greenbury Points. A velocity veer plus the improved pointing associated with greater "pressure" may advantage the right side of the course. However, as is evident in the high pressure northeaster, an ebb current will strongly advantage the inshore side of the course and if the weather mark is located near the 30-foot depth line, may be the dominant consideration.