SOMES SOUND: 
FJORD OR WELL-MIXED ESTUARY?


ABSTRACT - Somes Sound has been described as the only example of a fjord on the east coast of the United States. On a small scale, and from a morphological point of view, the Sound has key features normally associated with fjords, including pronounced subaerial topographic relief, submarine sills, and the U-shaped cross-section typical of glacially-carved troughs. However, based on its salinity distribution, which is related to the mixing and circulation processes used to characterize estuarine types from an oceanographic point of view, Somes Sound is a vertically well-mixed estuary that does not exhibit the strong stratification typical of fjords. While its geomorphology is unique, the oceanographic processes operating in the embayment are essentially the same as those in other shallow Maine estuaries with low fresh water input. In these estuaries, as well as in Somes Sound, tidal mixing is dominant over freshwater inflow in determining the circulation and the vertical stratification of the water column.

Somes Sound, a narrow cut that nearly divides Mount Desert Island in two (Fig. 1), is morphologically unique among coastal embayments and estuaries along the eastern seaboard of the United States. The coastal embayments of Maine were altered by glacial erosion of the Pleistocene ice sheets and postglacial changes in sea level creating the typical low rolling relief best characterized as a fjärd or firth coastline (Belknap et al. 1986; Kjerfve 1989). On the other hand, topographic relief in the Mount Desert region is decidedly more pronounced, and the eastern shore of Somes Sound rises at one point to more than 250 m above sea level.

In addition to the spectacular subaerial relief, the submarine topography of the Sound displays the U-shaped channel cross-section and shallow terminal sill that characterize glacially-carved and deepened valleys. Based on these and other geological characteristics, Johnson (1925) concluded that Somes Sound represents the only “possible exception to the statement that the term fjord cannot be properly applied to the coast of Maine.”

* Department of Oceanography, University of Maine, Orono, ME 04469-5741; ** Bigelow Laboratory for Ocean Sciences, West Boothbay Harbor, ME 04575
Estuaries are broadly defined as semi-enclosed coastal embayments in which sea water is measurably mixed with, and diluted by, fresh water derived from streams and other runoff (Pritchard 1967). Even within the most common descriptive category of estuaries, drowned river mouths, there is a great deal of variation in geological and oceanographic character. Various schemes have therefore been devised for the classification of estuarine types to delineate similarities and differences, and to develop archetypes from the broad spectrum of observed forms.

Perhaps the earliest classification system, and one implicit in the foregoing characterization of fjords, is a classification of estuaries based on their geomorphology. An enduring example of geomorphological classification is that of Pritchard (1952), who divided estuaries into three basic groups: coastal plain estuaries (drowned river valleys), fjords (drowned glacially-carved valleys), and bar-built estuaries (shallow embayments behind barrier beaches). A fourth group, tectonic estuaries (formed by volcanoes, faults, or landslides), is sometimes added to this list. The geomorphology (or geometry) of an
estuary can exert substantial influence over the circulation and mixing processes that ultimately determine its oceanographic character. Thus, the geologic origin of an estuarine embayment is a useful organizing theme for those systems in which geomorphological constraints are a dominant influence on the circulation and water properties within an estuary.

A classification scheme more directly tied to oceanographic conditions and the physical processes determining the circulation and mixing within an estuary, is one based on the salinity distribution. This scheme has found widespread applications due to its simplicity and more direct relationship to mixing in estuaries. In most salinity-based systems (e.g., Dyer 1973), there are four main estuarine types: highly stratified salt-wedge type estuaries, highly stratified fjord type estuaries, partially mixed estuaries, and well mixed estuaries. The last category is typically subdivided into vertically “homogeneous,” in which significant salinity differences occur only in the lateral and longitudinal directions, and sectionally “homogeneous”, in which only longitudinal gradients are important. It is interesting to note that in the salinity-based (hydrographic) classification scheme, a fjord is defined primarily on the basis of its salinity distribution, which is in part a function of the typical fjord geomorphology, rather than on the geomorphology itself.

While more sophisticated classification systems exist that may also be applied to the oceanographic classification and delineation of fjords (e.g., Hansen and Rattray 1966; Rattray 1967), their use requires specific knowledge of both circulation and stratification within the embayment. In the case of Somes Sound, although no direct current measurements are available, even order of magnitude estimates place Somes Sound well outside the circulation and stratification parameter ranges characterizing fjords.

SITE DESCRIPTION

Somes Sound is a narrow glacially-carved trough trending nearly north-south, roughly parallel to the direction of ice advance in this region (Johnson 1925). The Sound is partly cut into a granite ridge that runs east-northeast to west-southwest across Mount Desert Island. The embayment is approximately 8 km (5 mi) long and has an average width of roughly 0.8 km (0.5 mi). The width varies from a minimum of approximately 250 m (0.16 mi) at the mouth to a maximum of 1.6 km (1.0 mi) near the head.

Proceeding from south to north, the Sound consists of three subareas separated by narrows and sills: an outer basin, an inner basin, and Somes Harbor (Fig. 2). The outer basin lies between two sills, one 10 m
Figure 2. Location of CTD stations shown on a bathymetric map of Somes Sound. Soundings are in meters below mean low water.
deep at the narrow mouth composed of gravel moraines, and another 18 m deep composed of bedrock, approximately 2 km farther north and just south of the second narrows. The large inner basin extends from the second sill to the third narrows at the entrance to Somes Harbor. The deepest part of the outer basin exceeds 40 m depth, as does the larger inner basin at several locations along the western side of the channel. Somes Harbor is a small and very shallow feature with water depths reaching 10 m only within the narrow entrance channel.

The alternating sill and basin topography found in Somes Sound is common in glacial troughs. When the contrast between sill depth and basin depth is large, this type of topography can play an important role in determining oceanographic conditions. In a typical fjord, sills reduce the influence of tidal currents and tidal mixing within the basins, thereby enhancing the relative effect of freshwater inflow, and resulting in strong vertical stratification near sill depth and a relatively deep and quiescent (sometimes stagnant) lower layer.

**PREVIOUS WORK**

There have been few previous oceanographic studies of Somes Sound. Folger et al. (1972) surveyed the Sound in August, 1969, to test the idea that anoxic conditions might exist due to the restricted circulation below sill depth. Contrary to expectations, they found that waters in the basins were well mixed and well oxygenated (4.7-6.7 ml O₂ per liter of water). Based principally on sediment distributions, they also concluded that the residual deep circulation was primarily inward on the eastward side of the Sound, and outward on the westward side.

A study of the spring hydrographic (temperature and salinity) and chemical distributions of Somes Sound was undertaken by Ketchum and Cass (1986) in April, 1986, to determine springtime freshwater and nutrient inflows from streams, temperature and salinity distributions, flushing rate during spring conditions, and surface nutrient concentrations. Temperature and salinity surveys showed that the Sound was vertically well mixed. Using the measured springtime inflow from local streams and the observed salinity distribution, Ketchum and Cass (1986) used the fresh water fraction method (Bowden 1967; Dyer 1973) to estimate a spring flushing time of seven days.

**METHODS**

The present study represents the first hydrographic survey of Somes Sound using modern CTD (Conductivity Temperature and Depth) instrumentation. The survey was conducted aboard the RV Cape Hatteras on September 10, 1984, using a Neil Brown Smart CTD that derives
salinity from measurements of temperature and electrical conductance. Densities were calculated using the International Equation of State as reported by Milero and Poisson (1981). Since no measurements of river inflow were available for the study period, flushing rates for Somes Sound were estimated using a simple modification (described below) of the segmented tidal prism method of Ketchum (1951).

RESULTS

Late August through early September is traditionally the period of greatest thermal stratification in the Gulf of Maine and its coastal waters. Nevertheless, the data from Somes Sound (Fig. 3) show very little structure. Outer stations (5 & 6) show top-to-bottom temperature differences of less than 1°C, the inner stations all show vertical differences of less than 2°C, and the total temperature range over the survey is approximately 3°C. The corresponding salinity distribution is even more uniform. The maximum salinity contrast within Somes Sound (between bottom values at station 6 and surface values at station 1) is approximately 0.5 PSU (practical salinity units equivalent to parts per thousand), and the top-to-bottom differences are typically only 0.1 PSU. These temperature and salinity profiles are nearly vertically homogeneous, and are characteristic of a subclass of estuaries in which freshwater inflow is low, and tidal mixing and exchange are high.

Solar heating and freshwater runoff are the two primary factors that produce density stratification in estuaries (Dyer, 1973). In both the inner and outer basins of Somes Sound, solar heating is the more significant factor during the summer observation period. However, the data of Folger et al. (1972) show that within the semi-isolated Somes Harbor, where fresh water enters from Somes Pond, salinity contrasts can be the dominant source of density stratification even in summer. The data of Ketchum and Cass (1986) indicate that in the early spring, when solar heating is weaker and freshwater inflow is greater, salinity is the more important factor determining vertical stability (density stratification) throughout the Sound.

A quantitative expression of the relative impact of fresh and salt water sources to Somes Sound can be attained by calculation of the “fresh water fraction” defined as

\[ f = (\sigma - S)/\sigma \]

where \( s \) is the salinity of the “undiluted sea water source” outside the estuary, and \( S \) is the observed salinity at any point within the embayment. Thus the value of \( f \) is the fraction of fresh (zero salinity) water that would need to be mixed with the sea water source in order to
Figure 3. Contours of hydrographic data observed in Somes Sound in September 1984. The location of the seven CTD stations are shown in the uppermost panel. There is no evidence of the strong stratification at sill depth that typifies fjords. On the contrary, the extremely weak stratification reveals Somes Sound to be a tidally well mixed estuary.
produce the observed salinity.

The fresh water fraction was calculated for the data illustrated in Figure 3 using a $s$ value of 32.1 PSU, which was 0.1 PSU higher than the highest salinity value observed at station 7. The highest $f$ values, which occurred in the upper 3 m at station 1, reflect only 2% freshwater mixed with the coastal Gulf water. Near surface $f$ values drop to roughly 1% for stations 2-6, and to 0.5% for station 7 (outside the Sound). In comparison, calculations based on the April data of Ketchum and Cass (1986) yield near-surface fresh water fraction values in the 2%-5% range.

Estimation of estuarine flushing times, using either the fresh water fraction method, or the segmented tidal prism method (Ketchum 1951), require measurement or estimation of the volume of fresh water inflow during a tidal cycle. Since there is no routine monitoring of the small brooks that empty into Somes Sound, no data are available for our study period. Therefore, a variant of the method of the segmented tidal prism was developed that is applicable when the volume of fresh water inflow occurring over a tidal cycle makes no significant contribution to the tidal prism (intertidal volume) and instead considers only tidal range and the bathymetry. Using this method, a flushing time of $18.5 \pm 2$ days was calculated, representing the time to completely replace the water of Somes Sound by tidal mixing during late summer.

**DISCUSSION**

Based on its salinity distribution, Somes Sound is classified as a well-mixed estuary. The impact of freshwater in the inner and outer basins is extremely weak. The data of Ketchum and Cass (1986) show that even during a high runoff spring period (15-19 April 1986), Somes Sound is vertically stratified by no more than 1 PSU except near its head where stratification can increase by 1.5 PSU over the upper 5 m in Somes Harbor. During summer conditions reported here, Somes Sound is essentially a tidally-mixed embayment with only a weakly estuarine character. Our estimate of the summer flushing time of Somes Sound of 18.5 days, as well as the presence of vertically mixed water column, suggests that the high dissolved oxygen values reported by Folger et al. (1972) may be a typical summer condition.

There is precedent in Denmark for referring to shallow, well-mixed, partially submerged glacial troughs as fjords (e.g., Larsen 1980). Although Somes Sound possesses the geomorphology of such a small, shallow fjord, the geomorphological features exert no significant control over its circulation and mixing processes. In effect, the narrows and sills of Somes Sound do not substantially reduce the powerful Gulf of Maine tides. The resulting vigorous tidal mixing within the Sound is
incompatible with the strong vertical stratification and weak lower-layer circulation that are typical of fjords, and that have significant biogeochemical, sedimentological, and ecological consequences (Syvitski 1987). While the geomorphology of Somes Sound is distinct along the east coast of the United States, it operates essentially the same as other shallow embayments along the Maine coast that have low fresh water inflow. Among relatively well-studied estuaries in Maine, it is comparable in its water property distributions to the Damariscotta River estuary (McAlice 1977).

Somes Sound looks like a fjord, especially above sea level, and there is justification for retaining this geomorphological designation. However, below sea level it operates like one of the many well mixed estuaries found along the coast of Maine. Thus, Somes Sound may be considered both a fjord (from an external, geological, perspective), and a tidally well-mixed estuary (from an internal, oceanographic, perspective).

**LITERATURE CITED**


