Winter Circulation in the Western Gulf of Maine: Part 2. Current and Pressure Observations

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ABSTRACT

The wintertime circulation in the western Gulf of Maine has been studied with a moored current, temperature and pressure array which was deployed from November 1974 to January 1975. These observations have been interpreted with three additional data sets: coastal sea level records, Portland Lightship meteorological data, and offshore hydrographic transect data which describe the evolution of the density field on weekly time scales. The observed mean currents are consistent with the idea of a cyclonic Gulf of Maine gyre. The subtidal current fluctuations were coherent in the vertical at each mooring but incoherent between the moorings which were separated by about 50 km in both the alongshore and offshore direction. Furthermore, the currents showed only weak coherence with the winds.

The pressure field was highly coherent over the whole Gulf of Maine. Therefore, estimates of the pressure gradient vector inside and outside the 100 m isobath were made using coastal subsurface and bottom pressure records. The alongshore pressure gradient for the deeper water was found to be quite coherent with the winds for periods between 25 and 200 h. The relation of the pressure gradients and the winds in the shallower water suggests the development of a transient coastal boundary layer.

The incoherence between the observed current and pressure gradient fields is due in part to the existence of geostrophic currents associated with a highly variable density field. The density field variability is caused by incomplete mixing of three water masses: advected Scotian shelf water, deeper more saline slope water, and local winter water which is formed in the region of the experiment.

1. Introduction

The general circulation patterns of the Gulf of Maine have been inferred from hydrographic, drift bottle and sea bed drifter data obtained by Bigelow (1927), Bumpus (1973) and Bumpus and Lauzier (1975). The principal feature of that picture is a two-gyre system consisting of the counterclockwise Gulf of Maine gyre and the clockwise Georges Bank gyre. The more recent observational data reviewed by Bumpus (1976) generally support Bigelow’s description of a seasonal gyre system which reaches its maximum intensity in late May.

There are scattered direct current observations which are consistent with the idea of a Gulf of Maine gyre. One set of results from a long-term nearshore current meter array located in about 20 m of water off Hampton, New Hampshire, is described by Normandeeau Associates (1975). These nearshore currents are highly coupled with the local meteorological forcing and show the associated variability in the alongshore component. Tidal currents are generally more evident when the winds are weak. Longer term mean currents are consistent with the idea of a southwestward drift in the western Gulf of Maine. Butman et al. (1977) report that preliminary results from a moored array experiment conducted on and around Georges Bank seem consistent with the motion of northeast drift on the northern side of the Bank.

The bathymetric configuration of the Gulf of Maine, which is shown in Fig. 1, suggests that its dynamics may be more similar to those of a semi-enclosed sea than an open continental shelf. Csanady (1974) has developed a barotropic model of the Gulf of Maine in which he considers the effects of topography, mean sea surface slopes, wind stress and bottom friction. A double-gyre circulation results from the wind stress associated with northeasterly storms which he argues are the most effective in producing significant wind stress.

In this paper we explore the effects of the passage of winter storms on the circulation in the western
Gulf of Maine in terms of observed meteorology, hydrography, bottom pressures and Eulerian currents. In Section 2 we describe the field experiment. Section 3 contains a summary of the individual current and pressure results with an intercomparison of these results with the winds. Section 4 is a discussion of the influence of baroclinic currents on these observations.

2. Description of experiment

A joint moored array and hydrographic experiment was conducted in the western Gulf of Maine during the period from November 1974 to January 1975. The principal goal of this experiment was to determine the effect of the passage of wintertime storms on the general circulation in the western gulf.
The purpose of the hydrographic program was to document the wintertime evolution of the density field within the study area. The details of those hydrographic results are summarized by Brown et al. (1977) and Brown and Beardsley (1978). A series of offshore XBT and Nansen cast transects were made during the relatively calm periods between storms. Surface temperatures measured with a quartz thermometer were used to improve the accuracy of the deeper XBT measurements. The observed salinity field was less well-resolved than the temperature field but found to be more uniform. In fact, we found that the density variability depended principally on temperature variability during this experiment. Therefore, spatially interpolated values of salinities have been used with XBT temperatures to improve the resolution of the density field.

The principal result of the hydrographic study was the observation of intermittent vertical overturning which may be caused by the surface cooling effect of offshore winds. Brown and Beardsley (1978) have suggested that the vertical mixing associated with such overturning may be an important process in maintaining the overall salt balance in the Gulf of Maine and adjacent continental shelf regions. Locally this mechanism is important in producing the observed vertical homogeneity of the density field. We will show here that the existing horizontal density gradients were large enough to support significant vertical geostrophic shears.

The moored array component of the experiment consisted of three subsurface moorings, each of which contained at least two current meters and one bottom-mounted pressure/temperature recorder. The locations and configuration of the moorings are shown in Fig. 1. The details of the moorings and current statistics are summarized in Table 1.

The alongshore element (moorings 1 and 3) of the array was located near the 100 m isobath. On each of these moorings an AMF vector averaging current meter (VACM) was set at 33 m, and an EG&G type 102 film current meter (FCM) was set at 68 m depth. Mooring 2 was located about 75 km offshore in about 190 m of water, and had a VACM at 33 m and FCM's at 68 and 118 m. A self-contained strain-gage pressure/temperature recorder (described by Wunsch and Dahlen, 1974) was deployed on a separate bottom anchor at each mooring site.

Auxiliary data were obtained from various sources in order to assist in the interpretation of the moored array observations. Hourly sea level values were obtained from the National Ocean Survey for the coastal stations indicated in Fig. 1. Three hourly values of meteorological parameters were obtained for a number of coastal stations as well as the Portland Lightship.

### 3. Results: Moored array

The results from the moored array experiment were the first long-term measurements of current and bottom pressure obtained beyond the 100 m isobath in this region. So although we are principally interested in the subtidal fluctuations in currents and pressures, important new tidal information was also obtained. The important harmonic constituents for each of the stations are listed in Table 2 which is found in the Appendix. The $M_2$ tidal ellipse characteristics are summarized there also. These results have been used by Greenberg (1977) to help verify a numerical tidal model of the Gulf of Maine and Georges Bank region.

The variance analysis found in the Appendix shows that only $-1\%$ of the recorded bottom-pres-

### Table 1. Summary of the western Gulf of Maine moored array. Current statistics are shown to the right. The means have been computed from 50 daily averaged samples (N) over the common period 21 November 1974–9 January 1975 and are presented with the standard error $\sigma = \sigma(Z/N)^{1/2}$ where $\sigma$ is the standard deviation of the subtidal current fluctuations and $Z_{\sigma}$ is the nondimensional zero crossing of the autocorrelation function. The larger standard errors for the Cashes Ledge mean currents is due to the longer time scales of the currents observed there.

<table>
<thead>
<tr>
<th>Mooring location</th>
<th>Instrument ID</th>
<th>Water depth (m)</th>
<th>Instrument depth (m)</th>
<th>Instrument type</th>
<th>East</th>
<th>North</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$\bar{u}$ (cm s$^{-1}$)</td>
<td>$\sigma_{\bar{u}}$ (cm s$^{-1}$)</td>
</tr>
<tr>
<td>1. Monhegan</td>
<td>11</td>
<td>98</td>
<td>33</td>
<td>VACM</td>
<td>-7.5 ± 2.1</td>
<td>6.5</td>
</tr>
<tr>
<td>43° 40.3' N</td>
<td>12</td>
<td>68</td>
<td>68</td>
<td>FCM</td>
<td>-3.7 ± 1.3</td>
<td>4.0</td>
</tr>
<tr>
<td>69° 22.7' W</td>
<td>13</td>
<td>98</td>
<td>98</td>
<td>T/P</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Cashes Ledge</td>
<td>21</td>
<td>190</td>
<td>33</td>
<td>VACM</td>
<td>-7.1 ± 4.6</td>
<td>9.9</td>
</tr>
<tr>
<td>43° 10.5' N</td>
<td>22</td>
<td>68</td>
<td>68</td>
<td>FCM</td>
<td>-3.4 ± 1.4</td>
<td>4.3</td>
</tr>
<tr>
<td>69° 05.0' W</td>
<td>23</td>
<td>118</td>
<td>118</td>
<td>FCM</td>
<td>-1.3 ± 1.1</td>
<td>3.4</td>
</tr>
<tr>
<td>24</td>
<td></td>
<td>190</td>
<td>190</td>
<td>T/P</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Cape Porpoise</td>
<td>31</td>
<td>98</td>
<td>33</td>
<td>VACM</td>
<td>-1.1 ± 1.4</td>
<td>5.4</td>
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<tr>
<td>43° 12.9' N</td>
<td>32</td>
<td>68</td>
<td>68</td>
<td>FCM</td>
<td></td>
<td></td>
</tr>
<tr>
<td>70° 16.6' W</td>
<td>33</td>
<td>98</td>
<td>98</td>
<td>T/P</td>
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</table>
Table 2. Harmonic constituents for the three bottom pressure stations. The amplitudes have been converted from pressure by multiplying by \((\rho g)^{-1} = (1.026 \text{kg m}^{-3} \cdot \text{m}^2 \text{s}^{-2})^{-1} = 0.9950\). G is the Greenwich epoch. \(P_i\), \(\nu_i\) and \(K_i\) have been inferred from \(K_1\), \(N_2\), and \(S_2\), respectively.

<table>
<thead>
<tr>
<th>Station</th>
<th>Monhegan (1)</th>
<th>Cashes Ledge (2)</th>
<th>Cape Porpoise (3)</th>
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<tr>
<td>Latitude</td>
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<td>43° 10.9’ N</td>
<td>43° 12.9’ N</td>
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<tr>
<td>Longitude</td>
<td>69° 22.7’ W</td>
<td>69° 05.0’ W</td>
<td>70° 16.6’ W</td>
</tr>
<tr>
<td>Dates</td>
<td>19 Nov 74–16 Jan</td>
<td>20 Nov 74–16 Jan</td>
<td>16 Nov 74–28 Jan</td>
</tr>
<tr>
<td>Julian hours</td>
<td>75</td>
<td>75</td>
<td>75</td>
</tr>
<tr>
<td>Water depth</td>
<td>656423–6657785</td>
<td>656429–657809</td>
<td>656331–658097</td>
</tr>
<tr>
<td></td>
<td>98.3 m</td>
<td>193.6 m</td>
<td>101.1 m</td>
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<table>
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<tr>
<th>Constituents</th>
<th>Amplitude (cm)</th>
<th>G (deg)</th>
<th>Amplitude (cm)</th>
<th>G (deg)</th>
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<td>0.00</td>
<td>199.57</td>
<td>0.00</td>
<td>199.44</td>
<td>0.00</td>
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<tr>
<td>(M_n)</td>
<td>1.75</td>
<td>94.5</td>
<td>7.40</td>
<td>69.3</td>
<td>3.08</td>
<td>76.8</td>
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<td>(M_s)</td>
<td>1.86</td>
<td>149.5</td>
<td>2.68</td>
<td>34.0</td>
<td>1.73</td>
<td>185.7</td>
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<tr>
<td>(K_1)</td>
<td>13.33</td>
<td>199.8</td>
<td>12.77</td>
<td>200.1</td>
<td>13.29</td>
<td>202.6</td>
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<tr>
<td>(O_1)</td>
<td>10.86</td>
<td>183.2</td>
<td>10.47</td>
<td>183.8</td>
<td>10.60</td>
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<td>(P_1)</td>
<td>4.83</td>
<td>199.2</td>
<td>4.63</td>
<td>199.5</td>
<td>4.82</td>
<td>202.0</td>
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<td>(J_1)</td>
<td>.74</td>
<td>241.5</td>
<td>.66</td>
<td>223.3</td>
<td>1.63</td>
<td>225.2</td>
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<td>(NO_3)</td>
<td>1.83</td>
<td>203.2</td>
<td>1.84</td>
<td>201.3</td>
<td>1.28</td>
<td>193.3</td>
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<td>(Q_1)</td>
<td>2.13</td>
<td>183.8</td>
<td>1.95</td>
<td>181.8</td>
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<td>200.0</td>
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<td>(M_2)</td>
<td>13.96</td>
<td>99.8</td>
<td>120.47</td>
<td>98.4</td>
<td>126.35</td>
<td>103.5</td>
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<td>27.00</td>
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<td>67.9</td>
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<td>127.8</td>
<td>20.30</td>
<td>125.7</td>
<td>21.81</td>
<td>132.1</td>
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<td>(L_2)</td>
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<td>117.8</td>
<td>8.15</td>
<td>116.6</td>
<td>8.66</td>
<td>114.2</td>
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<tr>
<td>(\nu_s)</td>
<td>6.80</td>
<td>68.8</td>
<td>6.27</td>
<td>66.8</td>
<td>6.72</td>
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<td>(K_2)</td>
<td>6.11</td>
<td>129.6</td>
<td>5.62</td>
<td>127.5</td>
<td>6.04</td>
<td>133.9</td>
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<tr>
<td>(M_2)</td>
<td>3.50</td>
<td>311.0</td>
<td>3.21</td>
<td>313.5</td>
<td>2.99</td>
<td>329.0</td>
</tr>
</tbody>
</table>

Recorded variance (cm²) 9634 8179 8895
Residual variance (cm²) 99 103 117
Ratio 0.0103 0.0126 0.0132

Pressure variance is nontidal. In order to investigate the part of the residual variance at subtidal frequencies, all current, sea level and bottom-pressure data have been low-passed using the PL33 filter described by Flagg, et al. (1976). This filter has its −6 dB point at 0.03 cph (0.727 cpd) or 33 h period.

a. The current field

The observed mean vector current for each instrument is shown in Fig. 1. The flow direction indicated by the alongshore array is consistent with Bigelow’s (1927) conceptual picture of a basinwide cyclonic gyre. The low-passed current records are compared in Fig. 2. A cursory look indicates some vertical but little horizontal similarity. Daily averages of the low-passed currents are displayed as progressive vector diagrams (PVD’s) in Fig. 3. The 33 m PVD’s are similar in shape to the deeper PVD’s and reveal that the flow at the Monhegan (1) and Cape Porpoise mooring (3) are more or less consistent with the direction of the 50-day mean flow (shown vectorially in Fig. 1), while the current at the Cashes Ledge mooring (2) appears to be composed of two rather distinctly different flow patterns: a westward flow during late November and early December which then turns toward the northwest from mid-December through early January. This distinct transition in the flow pattern will be discussed later in terms of an evolving density field and the associated baroclinic velocity field.

The scales of the subtidal fluctuations in the current field were investigated by performing rotary cross spectra according to the method described by Gonella (1979). This method permits a coherence computation of vector fields in a way which is independent of the orientation of the coordinate system chosen. The vertical rotary coherence and phase between 33 m and 68 m currents at the Monhegan mooring (1) and at the Cashes Ledge mooring (2) are shown in Fig. 4. Significant coherence exists at both of the locations for periods >50 h. The phase indicates downward propagation of energy from the 33 to the 68 m level. The horizontal rotary coherence and phase between 33 m currents on the three separate moorings is displayed in Fig. 5. There is very little indication of significant coherence between any pair of currents at 33 m depth.
b. The pressure field

Time series of atmospheric pressure were obtained for Boston, Portland, and Eastport, Maine, to construct subsurface pressures at nearby coastal sea level stations. The problem of using atmospheric pressures at remote stations has been explored by calculating the coherences shown in Fig. 6. These results agree with those of Mooers et al. (1976) who concluded that atmospheric pressure differences at stations separated by less than 150 km are insignificant for purposes such as ours.

The pressure time series are shown in Fig. 7 and consist of the three bottom pressure (BP) records at Monhegan Island, Cashes Ledge and Cape Porpoise, and subsurface pressures (SSP) from Sandwich, Massachusetts, Portsmouth, New Hampshire, Portland and Bar Harbor, Maine, and Yarmouth and Halifax, Nova Scotia. Subsurface pressures were formed at the coastal stations by adding the atmospheric pressure (AP) to the sea level (SL) (in pressure equivalent units). Boston AP has been used to construct the Sandwich and Portsmouth SSP; Portland SPP was formed from Port-
land AP and SL, while Eastport AP was used in the formation of Bar Harbor, St. John, Yarmouth and Halifax SSP records.

The relationship between atmospheric pressure, sea level, SSP and bottom pressure fluctuations is demonstrated in Fig. 8. The energy associated with AP fluctuations is one-third to one-half of the equivalent SL fluctuations. The reduction of SSP energy relative to SL energy must be due in part to the inverted barometer response of sea level as suggested by the approximate antiphase of AP and SL. However, the secondary importance of this process is indicated by the marginal coherence between atmospheric pressure and sea level. Apparently AP fluctuations are not responsible in this case for most of the variance in sea level fluctuations. SL fluctuations, which constitute the principal part of the SSP signal, are in fact related to local wind-stress fluctuations as will be shown later. In Fig. 8 it is also shown that the bottom pressures are slightly less energetic than, but highly coherent with the Portland SSP record.

The visual correlation between the SSP records shown in Fig. 7 suggests much greater horizontal coherence than found with the moored current data. We investigated this observation quantitatively with the calculation of SSP coherences and phases which are summarized in Fig. 9. Coherences are seen to decrease with station separation. The general decrease of coherences with frequency is interrupted by an increase for frequencies near 0.04 cph due to an incomplete removal of the tides which of course are extremely coherent. The phases though small and statistically insignificant
shore PG's were estimated on the basis of Bar Harbor SSP minus Portsmouth SSP and Monhegan BP minus Cape Porpoise BP, respectively. These PG's were resolved into orthogonal components in the alongshore direction (54°T) and cross-shore direction (144°T), and the components are shown in Fig. 11 for the I and O regimes.

The coherence spectra between corresponding inshore and offshore PG components, which are shown in Fig. 12, indicate a low coherence between the inshore and offshore regimes. This is especially puzzling since the coherence between the alongshore PG $(\delta p/\delta y |_I)$ and Yarmouth–Sandwich PG shown in Fig. 13 is high. The fact that $\delta p/\delta y |_O$ shows a higher coherence with the Portland–Portsmouth PG suggests that the choice of alongshore and off-

show a tendency for southwestern stations to lead northeastern stations.

Very high coherences (0.98) and small phases (1–3°) are found between the bottom pressure stations. This result is consistent with the SSP picture and suggests that pressure gradient estimates may be made using pressure differences. The fluctuations of the alongshore and cross-shore pressure gradient components (PG) were estimated for regimes inshore (I) and offshore (O) of the 100 m isobath from the combined SSP and bottom pressure measurements shown in Fig. 10. A pseudo-bottom pressure record called MOCBP was constructed from the average of Monhegan BP and Cape Porpoise BP for the location MOCBP shown in Fig. 10. The I and O cross-shore PG's were estimated on the basis of Portland SSP minus MOCBP and MOCBP minus Cashes Ledge BP, respectively. The I and O along-

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An accumulated linear instrumental drift of about 0.22 db has been removed from the observed series.

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Fig. 4. Rotary spectra, vertical coherence and phase between 33 and 68 m currents in the western Gulf of Maine. The spectral energy at the Monhegan mooring (1), 33 m (○) and 68 m (○ — ○), and the Cashes Ledge mooring (2), 33 m (● — ●) and 68 m (● — ●), are shown above. The vertical coherence and phase between 33 and 68 m are shown below for Monhegan mooring (1) (solid line) and the Cashes Ledge mooring (2) (dashed line). The 95% confidence levels are shown for 10 degrees of freedom. The phase uncertainty corresponds to a coherence of 0.9.

Fig. 5. Rotary spectra, horizontal coherence and phase between 33 m currents in the western Gulf of Maine. The spectral energy at the Monhegan mooring (1) (solid), the Cashes Ledge mooring (2) (dotted) and the Cape Porpoise mooring (3) (dashed) are shown above. Below are shown the horizontal coherence and phase for the Cashes Ledge-Monhegan (dashed), the Cape Porpoise-Monhegan (solid) and the Cashes Ledge-Cape Porpoise (dotted) pair. The 95% confidence levels are shown for 10 degrees of freedom. The phase uncertainty corresponds to a coherence of 0.9.
shore directions in this southwestern end of the Gulf of Maine may be difficult. This problem will be addressed later.

A direct measurement of the mean pressure gradient cannot be made with bottom pressure gages because of the relatively large uncertainty in the relative depths of the two gages. However, Scott and Csanady (1976) have presented an indirect method which can be used to estimate the mean pressure gradient in the southwestern coast during late winter, 1974. Six hourly current, and wind data obtained in December 1974, off Hampton Beach, New Hampshire by Normandeau Associates, Inc. (supplied by Hartwell, personal communication) was first vector-averaged to produce a daily time series of current and wind-stress components aligned toward 13°T, the approximate orientation of the coastline and local topography. The current data was obtained at a depth of 12 m in water 18 m deep. The current meter site was located at 42°53.7'N, 70°47.4'W, approximately 1.8 km offshore of the mouth of the Hampton River. Wind data were obtained with a meteorological station located on Hampton Beach. Following Scott and Csanady (1976), a linear regression analysis of the alongshore near bottom current \( V_b \) and the kinematic wind stress \( \tau_u \) data yielded (with 95% confidence)

\[
\tau_u = a + bV_b = -0.05 \pm 0.10 + (0.17 \pm 0.04)V_b.
\]

Scott and Csanady (1976) identify the coefficient \( a \) with the mean alongshore pressure gradient. While this method is open to criticism (see Beardsley and Winant, 1979), we tentatively conclude that the mean alongshore gradient was not measurably different from zero. The uncertainty in this calculation corresponds to an estimated uncertainty of \( \pm 0.6 \times 10^{-7} \) in equivalent sea surface slope, which is sufficiently large to obscure any small mean surface slopes. For comparison, other mean alongshore slope estimates made off Long Island (see Scott and Csanady 1975; Beardsley et al., 1977 and New Jersey (by EG&G, 1976) indicate a mean northward rise of sea surface along the coast with a slope of roughly \( 10^{-7} \).

Sturges (1977) has suggested that the amplitude of this slope varies seasonally in phase with the alongshore wind stress, so that the sea surface slope is a maximum during winter. Thus, while it seems reasonable to conclude that this mean slope surface is a persistent winter feature in the mid-Atlantic Bight, the Hampton Beach observations suggest that the mean winter alongshore surface slope may be considerably smaller within the western Gulf of Maine.

c. Intercomparison of currents, pressures and winds

The unusually small horizontal coherence scales found here for the currents are anomalous in comparison with other shelf observations made in the mid-Atlantic Bight, where a significant part of the current variance was coherent with the regional winds and reflected the large meteorological spatial scales. We will now explore the relationship between the wind, current and pressures in the western Gulf of Maine.

The Portland Lightship (PLS) wind stress shown in Fig. 2 has been computed using PLS winds and a constant drag coefficient of \( 1.2 \times 10^{-3} \). The 67-day mean PLS wind stress was found to be 0.25 dyn cm\(^{-2}\) directed toward the southeast. This stress value compares with 0.80 dyn cm\(^{-2}\) toward the southeast found by Saunders (1977) for this area using 32 years of ship reports which were heavily weighted by PLS data. This comparison suggests that rela-
tively mild winter conditions existed during our moored array experiment. Statistically no significant coherence was found between the cross-shore and the alongshore components of the wind stress. Noble and Butman (1978) found this to be generally true for the entire northeast shelf region.

The coherence between 33 m currents and the PLS wind stress is shown in Fig. 14 while the coherence between PG's and PLS wind is shown in Fig. 15. Only the lower frequency counterclockwise components of the 33 m currents at Monhegan (1) show much coherence with the wind stress. The current there lags the wind stress by roughly 90°. This lack of coherence contrasts with the high coherence shown in Fig. 15b between alongshore wind and PG components in the offshore regime at frequencies between 0.005 and 0.03 cph (periods between 200 and 35 h).

4. Results: Geostrophic currents

One of the more interesting questions raised by these observations is why the pressure gradient field is more strongly related to the regional winds than the observed currents. The rough bottom topography in the western gulf is probably responsible for generating small-scale currents at the deeper levels but this seems an inadequate explanation for upper level current fluctuations especially near Cashes Ledge. We believe a substantial part of the incoherence between pressure gradients and currents is caused by smaller horizontal scale currents which balance the density field. The anomalous appearance of the Cashes Ledge mooring (2) PVD in Fig. 3 led to the following consideration of the evolution of the density field.

As expected for the winter season, the density field was found to be locally well mixed in the
vertical throughout most of the experiment. Brown and Beardsley (1978) have shown that much of the mixing occurs in connection with temperature-induced overturning of the offshore waters in the western Gulf of Maine. On the other hand, significant horizontal density gradients did exist. The changes of the density field are reflected in the sequences of surface dynamic heights shown in Fig. 16. The dynamic height pattern for 5–6 December 1974 is very suggestive of a baroclinic eddy pair with an approximate wavelength of 30 km. This scale compares favorably with the calculated 35 km internal radius of deformation. A reversal feature seen in the Cashes Ledge PVD in Fig. 3 near this date is consistent with the advection of such eddy-like features past the mooring by the observed “mean” southwestward or westward currents. The dynamic height field on 20 December is characterized

![Image of graph showing coherence and phase spectra](https://via.placeholder.com/150)

**Fig. 8.** The energy density, coherence and phase spectra of Portland atmospheric pressure, sea level equivalent pressure and SSP fluctuation as well as Cape Porpoise (3) bottom pressures. The 95% confidence limits correspond to 20 degrees of freedom. The phase uncertainty for coherences of 0.9 and 0.8 is shown.

![Image of graph showing coherence and phase spectra](https://via.placeholder.com/150)

**Fig. 9.** The energy density, coherence and phase spectra for several SSP stations around the perimeter of the Gulf of Maine. The energy density spectra are representative. Horizontal separations are indicated in a column to the right. The 95% confidence limits correspond to the 20 degrees of freedom. The phase uncertainty for coherences of 0.9 and 0.8 are indicated.

by strong along-front geostrophic flows (20 cm s⁻¹) and the appearance of onshore flow near the Cashes Ledge mooring. The latter two pictures on 29 December and 3 January are similar in their suggestion of onshore flow at Cashes Ledge.

The geostrophic currents based on the observed density field have been crudely estimated for the region near the Cashes Ledge mooring (2). The two alongshore stations nearest Cashes Ledge have been used to estimate the onshore geostrophic current relative to 100 db. These currents are compared with the onshore currents observed at Cashes Ledge in Fig. 17. The two current estimates are in good agreement at depths <100 m. Salinity intrusions at greater depths can lead to a geostrophic current profile with a deep minimum consistent with the ob-
Fig. 10. Bottom pressure (open circles) and SSP (solid circles) sites in the western Gulf of Maine used to estimate pressure gradients. A pseudo-bottom pressure (see text) is located at MOCP. The orthogonal alongshore (54°T) and the cross-shore (144°T) directions were chosen on the basis of the shape of the coastline and the 100 m isobath which is shown.

Fig. 11. Alongshore and cross-shore pressure gradient components and winds. The alongshore (54°T) and cross-shore (144°T) pressure gradient components (see text) for the I regime \( \frac{\partial p}{\partial y} |_I \) are compared with the respective components \( \frac{\partial p}{\partial y} |_O \) in the O regime. For reference, the alongshore (\( u \)) and the cross-shore (\( v \)) components of the winds at the Portland Lightship are shown.

Fig. 12. The energy density, coherence and phase spectra for the inshore (I) and the offshore (O) pressure gradient components (see text). The 95% confidence limits correspond to 20 degrees of freedom. The phase uncertainty for a coherence of 0.6 is shown.

served current profile. Therefore, although the choice of a 100 m level of no motion was chosen somewhat arbitrarily, it may roughly coincide with an actual velocity minimum. These two sets of density observations were made after the current at the Cashes Ledge mooring turned onshore (see Fig. 3) and became well developed. Thus we suggest that during the latter part of December, the Cashes Ledge currents were geostrophically balanced and generally reflect the variability in the horizontal density gradient field.

In an attempt to provide some perspective to these western Gulf of Maine observations, we have computed the surface dynamic heights relative to 100 db for the entire Gulf using the widely spaced temperature and salinity data presented by Colton et al. (1968). The seasonal variability of the geostrophic currents is shown in Fig. 18. The
principal features of this circulation include the alongshore flow along the outer continental shelf and slope, the inflow into the Gulf of Maine from the inner Scotian shelf, and the development of the cyclonic Gulf of Maine gyre in late spring.

Of particular interest here is the onshore flow in the western Gulf of Maine region found to occur in the December panel in Fig. 18. This December 1964 picture is similar to the observations presented here for 1974 and suggests that the onshore geostrophic flow may be a rather general feature of the winter circulation pattern in the western Gulf. The December 1974 surface density picture shown in Fig. 19 suggests that water flowing into the Gulf from the Scotian shelf interacts with a developing mass of extremely dense water in the western Gulf to form the alongshore density gradient. Brown and Beardsley (1978) discuss the likely formation of this dense water by surface cooling by offshore flow of cold and dry polar air.

The geostrophic transport through the section extending from the 50 m isobath south of Cape Sable to the northeast peak of Georges Bank has been calculated and is presented in Fig. 20. A 100 db level of no motion was used where possible and was chosen to correspond to the reference level chosen by Drinkwater et al. (1978) who have made a similar computation of the alongshelf geostrophic transport though the Halifax section shown in Fig. 19. Their monthly average transport estimates are also shown in Fig. 20 for a transect (stations 1–6) across the whole shelf and for a transect (stations 2–3) across the inner part of the shelf. The crude similarity of these transport curves suggests that much
of the water confined to the inner Scotian shelf may enter the Gulf of Maine around Cape Sable with a small (order one month) phase lag.

5. Discussion

In summary the results of a winter 1974–75 moored current and pressure experiment in the western Gulf of Maine indicate that the mean currents are consistent with the idea of a cyclonic Gulf of Maine gyre. Subtidal current fluctuations at vertically separated levels are coherent while currents separated horizontally by about 50 km in both alongshore and offshore directions are incoherent. Furthermore, the currents showed an unexpectedly weak coherence with local winds.

The pressure and pressure gradient fields were found to be coherent over much larger horizontal distances than the currents. In contrast to the current observations the longshore pressure gradient and local wind fluctuations are very coherent.

The discrepancy between current and pressure gradient horizontal coherent scales and the poor coherence between winds and currents are the principal results from the moored array measurements. We have presented some evidence that suggests that a relatively energetic baroclinic component of the Eulerian current field, to which bottom pressure measurements are not very sensitive, may be responsible for degrading the horizontal coherence of moored currents. The further suggestion is
that the baroclinic currents are incoherent with the winds and thus the poor wind/current coherence.

The cause of the baroclinic current fluctuations is not known but we can speculate about several possibilities. The unusually rough bottom topography in this region of the Gulf of Maine may interact with the along-coast flow to produce baroclinic eddies. Huppert and Bryan (1976) have studied the velocity perturbation field due to the interaction of a bump and a mean flow in a rotating frame in terms of a parameter $N h_m / U_0$, where $N$, $U_0$ and $h_m$ are the characteristic buoyancy frequency, velocity and vertical topographic scale, respectively. Their analytical results show nonlinear and linear dynamics for $N h_m / U_0 \ll 1$ and $\gg 10$, respectively. For $N h_m / U_0 \approx 1$ a Taylor column forms above the topographic feature, eddies shed and move downstream, and for $N h_m / U_0 \approx 10$ the eddy stays near the top of the feature. Because the conditions in the western Gulf of Maine cover the range $1 < N h_m / U_0 < 10$, we are unable to say whether or not particular eddies generated by the topography remain near the generating topographic feature. Given the rich spectral character of the bottom topography in this region it is possible that although this mechanism may be important it would be difficult to identify individual eddies.

![Fig. 16. Surface dynamic height distribution for the study area in the western Gulf of Maine. The results from a series of 1-day hydrographic cruises were used to construct these pictures which show contours of dynamic height at intervals of 0.005 dynamic meters relative to 100 m. The large dots are Nansen cast stations, the small dots are XBT stations and the triangles are mooring locations. Densities have been calculated for XBT stations on the basis of interpolated salinity values (see text).](image)

![Fig. 17. An intercomparison of the geostrophic shear predicted by the observed density field and the mean observed currents. The estimates of the onshore component of the geostrophic currents relative to the 100 m isobath for 29 December 1974 (cruise 12, ⬤) and 3 January 1975 (cruise 14, ▲) are shown. The 2-day mean values of the onshore current (350°T) at the Cashes Ledge mooring (2) bracketing cruise 12 (○) and cruise 14 (▲) are shown also.](image)
The similarity of this western Gulf of Maine region to the northwestern Mediterranean Sea in terms of winter water formation provides tempting avenues of speculation. For instance Gascard (1978) describes one mechanism whose basis is the baroclinic instability of the frontal zone associated with the western Mediterranean gyre. This mechanism is attractive because it reinforces the wind-induced buoyancy production and is consistent with observations of deep vertical mixing and eddy production are explained by the model.

Since the dynamical role of topography in the relatively shallow Gulf of Maine is probably more important than in the Mediterranean it would be naive to draw a direct analogy between the two situations. However, an investigation of both mechanisms is suggested with perhaps an initial summertime (stratified) study to assess the importance of topography alone in generating baroclinic turbulence.

Acknowledgments. We want to acknowledge the key role played by Bill Richardson who helped with the design of the experiment and encouraged our participation. We also want to thank the crew of the USCGS Spar, commanded by Capt. J. C. Midgett, for deploying and retrieving the moored array. F. Faller and the crew of the Portland Lightship kindly provided local meteorological data and P. Bedard at Nova University furnished the VACM's. This work has been patiently supported by the National Science Foundation through Grants DES75-03992 and OCE76-02190 to W.B. and Grants DES74-03001 and OCE76-01813 to J.V. and R.B.

Fig. 18. The seasonal evolution of the surface dynamic heights in the Gulf of Maine. The seasonal sequence begins in the lower left panel and proceeds clockwise. The dynamic heights in units of dynamic meters relative to the 100 db surface are computed from the temperature and salinity data presented by Colton et al. (1968). Arrows indicate current direction only.
Fig. 19. The surface sigma-τ distribution in the Gulf of Maine for 3–18 December 1964. They have been computed from temperature and salinity data presented by Colton et al. (1968). The Cape Sable hydrographic section is indicated along with the six stations of the Halifax section (O).

Fig. 20. Geostrophic volume transports on the Scotin shelf. The volume transport relative to the 100 m surface (where possible) at the Cape Sable section (O) estimated from Colton et al. data are compared with the average monthly transports at the Halifax section; stations 1–6 (O) and stations 2–3 (+) (see text) according to Drinkwater, et al. (1978).

APPENDIX

Tidal Elevations and Currents

A harmonic analysis has been performed on the bottom pressure records by DeWolf (1977) at the Bedford Institute of Oceanography. The results of that analysis are summarized in Table 2, where the

<table>
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<th>Major axis (cm s⁻¹)</th>
<th>Orientation (°T)</th>
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<td>2.4</td>
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<td>(4.4)</td>
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Table 3. The observed M₂ current ellipse characteristics for the western Gulf of Maine experiment. The values in parentheses are the characteristics for M₂ tidal currents predicted by a numerical tidal model of the Gulf of Maine and the adjacent continental shelf developed by Greenberg (1977). The ratio of the major and minor axes of the current ellipse is the ellipticity e. The orientation of the major axis of the ellipse relative to north is shown.
amplitude converted to centimeters of seawater and the Greenwich epoch for constituents with amplitudes >1 cm are given. The residual variance is determined from the time series with the tides removed and represents about 1% of the recorded variance.

The M2 (or semidiurnal) tidal current ellipses have been determined on the basis of the Fourier coefficients for each current meter record and have been summarized in Table 3.

REFERENCES


DeWolf, D., 1977: Tidal measurement program of the Bay of Fundy-Gulf of Maine tidal regime. [Unpublished manuscript].


