Tidal and Atmospheric Forcing of the Upper Ocean in the Gulf of California

2. Surface Heat Flux

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Satellite infrared imagery and coastal meteorological data for March 1984 through February 1985 are used to estimate the net annual surface heat flux for the northern Gulf of California. The average annual surface heat flux for the area north of Guaymas and Santa Rosalia is estimated to be +74 W m$^{-2}$ for the 1984–1985 time period. This is comparable to the +20–50 W m$^{-2}$ previously obtained from heat and freshwater transport estimates made with hydrographic surveys from different years and months. The spatial distribution of the net surface heat flux shows a net gain of heat over the whole northern gulf. Except for a local maximum near San Esteban Island, the largest heat gain (+110–120 W m$^{-2}$) occurs in the Ballenas and Salsipuedes channels, where strong tidal mixing produces anomalously cold sea surface temperatures (SSTs) over much of the year. The lowest heat gain occurs in the Guaymas Basin (+40–50 W m$^{-2}$), where SSTs are consistently warmer. In the relatively shallow northern basin the net surface heat flux is fairly uniform, with a net annual gain of approximately +70 W m$^{-2}$. A local minimum in heat gain (approximately +60 W m$^{-2}$) is observed over the shelf in the northwest, where spring and summer surface temperatures are particularly high. A similar minimum in heat gain over the shelf was observed in a separate study in which historical SSTs and 7 years (1979–1986) of meteorological data from Puerto Peñasco were used to estimate the net surface heat flux for the northern basin. In that study, however, the heat fluxes were higher, with a gain of +100 W m$^{-2}$ over the shelf and +114 W m$^{-2}$ in the northern basin. These larger values are directly attributable to the higher humidities in the 1979–1986 study compared to the 1984–1985 satellite study. Significant interannual variations in humidity appear to occur in the northern gulf, with relatively high humidities during El Niño years and low humidities during anti-El Niño years. High humidities reduce evaporation and the associated latent heat loss, promoting a net annual heat gain. In the northern Gulf of California, however, tidal mixing appears to play a key role in the observed gain of heat. Deep mixing in the island region produces a persistent pool of cold water which is mixed horizontally by the large-scale circulation, lowering surface temperatures over most of the northern gulf. These cold SSTs decrease evaporation by reducing the saturation vapor pressure of the overlying air. As a result, heat loss is substantially reduced, even when humidities are low. By removing heat from the surface, tidal mixing alters the time scale of air-sea interaction and reduces or possibly even inhibits the formation of deep water masses via convection. Over climatological timescales, it may be tidal mixing that ultimately maintains the estuarine-like circulation in the northern Gulf of California, differentiating it from the Mediterranean and Red seas, which lose heat to the atmosphere.

1. INTRODUCTION

The sea surface temperature (SST) plays a significant role in the exchange of heat between the ocean and atmosphere. The outgoing longwave radiation as well as the sensible (conductive) and latent (evaporative) heat fluxes are all a function of SST. These fluxes in combination with the incoming shortwave radiation determine the net air-sea exchange. This exchange is important both for regulating climate as well as for establishing thermohaline circulations which are of particular interest in marginal and semienclosed seas.

In the northern Gulf of California (Figure 1), SST patterns are largely determined by spatial variations in the strength of tidal mixing [Paden et al., 1991]. Resonant to the semidiurnal tide, the gulf is subject to strong tidal forcing and attains ranges as large as 10 m at its northern end [Roden and Groves, 1959]. In the midrift region, several large islands restrict tidal flows between the relatively shallow northern basin and deeper basins to the south. Tidal currents in these narrow channels reach 1–3 m s$^{-1}$ [Alvarez et al., 1984; Badan-Dagon et al., 1991a] and result in the formation of internal hydraulic jumps over sills located in the Ballenas and Salsipuedes channels and between the islands of San Esteban and San Lorenzo [Badan-Dagon et al., 1991a]. During spring tides, mixing at the sills occurs over depths of 300–500 m, creating the persistent pool of cold water evident in satellite infrared imagery [Badan-Dagon et al., 1985;
Paden et al., 1991] (Figure 2). This cold water is dispersed by the large-scale circulation, reducing surface temperatures over most of the northern gulf.

The Gulf of California is also subject to strong atmospheric forcing. Isolated from the moderating influence of the Pacific Ocean by a continuous chain of mountains along the Baja California peninsula, the gulf experiences SST ranges of nearly 20°C over the year. These same mountains tend to channel the winds along the axis of the gulf. During the summer, winds blow predominantly from the southeast, bringing warm, moist tropical air into the gulf. During the rest of the year, winds tend to blow out of the northwest off the continental United States [Roden, 1964; Badan-Dangon et al., 1991b]. The dry continental air mass results in relatively high evaporation rates over the northern gulf. Initial estimates of evaporation and the associated latent heat flux suggested that the Gulf of California lost heat to the atmosphere on an annual average [Roden and Emilsson, 1979]. These estimates were based on coastal meteorological data which did not necessarily represent conditions over the open ocean. Recent heat transport estimates based on hydrographic data [Bray, 1988], however, showed that the

Fig. 1. Map of the Gulf of California showing region visible in satellite images.
northern gulf in fact gains heat from the atmosphere on the order of 22 W m\(^{-2}\). A net gain of heat was also observed in a separate study using 7 years of monthly mean meteorological data from Puerto Peñasco and SSTs from historical ship observations near the shallow northern shelf [Lavin and Organista, 1988]. The heat gain, in conjunction with evaporation, produces a warm, saline water mass, which flows out of the gulf in exchange for cold, relatively fresh water at depth. This thermohaline circulation is opposite to that observed in the Mediterranean and Red seas, which loses heat to the atmosphere on an annual average [Bunker et al., 1982].

The reduced SSTs created by tidal mixing in the gulf can have a large impact on the surface heat flux by lowering the saturation vapor pressure of the air. Heated surface waters are mixed downward, pumping heat deep into the water column, where it is less able to interact with the atmosphere. The air overlying the sea surface is cooled and therefore retains less moisture. As a result, evaporation and the associated latent heat loss are reduced. Hydrographic estimates of the freshwater flux [Bray, 1988] indicated a significantly lower evaporation rate over the northern gulf than was originally obtained using coastal meteorological data [Roden and Emilsson, 1979]. When the latent heat flux associated with the lower rate of evaporation was used with the meteorological data to calculate the net surface heat flux, the flux became negative into the ocean (+20 to +50 W m\(^{-2}\)) in agreement with the heat transport estimates [Bray, 1988].

The latent heat flux is the largest heat loss term in the surface heat flux and one of the most difficult to estimate. Bulk formulas used to estimate the latent heat flux require knowledge of the vapor pressure of the air over the open ocean and the local SST for calculating the saturation vapor pressure. When coastal data are used, the latent heat flux can be overestimated in two ways: (1) the atmosphere can be drier near the coast than over the ocean owing to the influence of the continental air mass and local orographic effects, and (2) SSTs may be warmer at the coast than over the open ocean. The latter case is particularly relevant in the northern Gulf of California, where tidal mixing in the island region decreases surface temperatures over a large area.

During a 1-year period from March 1984 through February 1985, NOAA 7 and NOAA 9 satellite infrared data were collected for the northern Gulf of California. This period coincided with three of the hydrographic cruises used in the heat and freshwater transport estimates. Winds, atmospheric pressure, and wet and dry bulb temperatures were also measured at several portable weather stations throughout the gulf and together with the satellite-derived SSTs provide an independent estimate of the net surface heat flux using a more synoptic data set.

In the first section the meteorological data are presented and the variability of the atmosphere over the gulf is examined. Next, estimates of the various heat flux components are presented, and their temporal behavior is compared with that obtained by Lavin and Organista [1988]. The integrated net surface heat flux is then calculated and compared with the heat transport estimates of Bray [1988]. Finally, the spatial pattern of the surface heat flux is presented and the role of tidal mixing in the net gain of heat is discussed.
500 m off the coast of Guaymas (25 m). The PAM stations measured wind speed and direction, air and wet bulb temperatures, and atmospheric pressure [Merrifield et al., 1987]. The stations did not function continuously owing to occasional problems with the satellite-linked data transmission. In addition, wet bulb temperature measurements were sometimes missing owing to evaporation of the instrument’s water. Data collected by the Servicio Meteorológico Mexicano (Mexican Meteorological Service or MMS) at San Felipe were used to augment measurements for the northern basin. This station was located approximately 1 km from the shore at 15 m above sea level.

Plots of the available meteorological data are presented in Figures 4–7. The atmospheric pressures reduced to sea level (sea level pressure) are presented in Figure 4. The lowest pressures occur during the summer with the largest pressures and pressure gradients occurring during the winter. Air temperatures (Figure 5) are fairly similar at the various stations, with the exception of Puerto Peñasco (P6) and San Felipe (M1) in the north which are several degrees colder during the winter. The depression in air temperature at the northern end of the gulf occurs when winter winds from the northwest advect cold, dry air over the gulf [Badan-Dangoz et al., 1991b]. This mass quickly comes into equilibrium with the ocean so that temperatures from stations further south are more representative of the marine atmosphere. Note that temperatures and sea level pressures are strongly correlated between stations throughout the year ($r > 0.90$) [Badan-Dangoz et al., 1991b].

Winds in the gulf are coherent between stations and blow predominantly along the axis, with winter rms wind speeds approximately twice those in summer (Figure 6). In the Guaymas Basin, winds measured at Isla Tortuga (P4) were twice as strong as those measured at nearby coastal stations and appear to be most representative of open-gulf conditions [Merrifield and Winant, 1989]. In the northern basin, overflight measurements in March 1984 [Candelas et al., 1985] showed wind magnitudes similar to the Isla Tortuga PAM winds, whereas the Puerto Peñasco PAM (P6) winds were much smaller. Winds measured at Isla Rasa (P2), an island off Baja California in the midrift region, also showed magnitudes similar to those measured at Isla Tortuga when data were available. It appears in general that the coastal wind measurements underestimate the wind field over the gulf during winter. During summer 1983, winds in the northern basin were smaller in magnitude and less coherent with the winds further south [Badan-Dangoz et al., 1991b]. In 1984, however, significant differences in monthly rms wind speeds between Puerto Peñasco and Isla Tortuga occurred only in the month of June (3.8 m s$^{-1}$ versus 2.3 m s$^{-1}$) owing to a slight difference in the timing of the seasonal wind reversal in the two basins. The general discrepancy between coastal wind measurements and those made offshore and the similarity between aircraft measurements in both the northern basin and Guaymas Basin to the Isla Tortuga PAM winds suggest the use of these latter winds as most representative of open ocean winds throughout the northern gulf.

Seasonality is also apparent in the water vapor content of the lower atmosphere (Figure 7). Estimates of the water vapor pressure for all stations show a pronounced annual cycle with maximum vapor pressures during late August and early September (Julian days 225 to 250). Most of the stations are similar in value, with the exception of Isla Piojo (P1) and Santa Rosalia (P3). These two stations are located
on the Baja California peninsula and are in regions that are expected to be more arid. Isla Piojo is an island located between Isla Angel de la Guarda and Baja California. This region is often characterized by cross-channel winds which erode the marine layer, permitting a greater influence of desert air in the channel [C. Dorman, personal communication, 1989]. The station at Santa Rosalia is located atop a 200-m mesa a few kilometers from the coast.

The sea surface temperatures used in the heat flux calculations were obtained from monthly mean NOAA 7 and NOAA 9 satellite infrared images for the period March 1984 through February 1985 [Paden et al., 1991]. Monthly mean images could not be constructed for the months of July or December because of atmospheric conditions over the gulf. These data were obtained from the other images using the first five gradient empirical orthogonal functions, $G_n$:

$$T_s(x, t) = b_0(t) + \sum_{n=1}^{5} b_n(t)G_n(x)$$
where the spatial means, $b_0(t)$, were estimated by fitting a seasonal signal to the existing spatial means and the mode amplitudes, $b_n(t)$, were estimated from the adjacent amplitudes by linear interpolation [Paden et al., 1991].

3. HEAT FLUX CALCULATIONS

Estimates of the surface heat flux were made from monthly mean values of wind speed, temperature, sea level pressure, and water vapor pressure using the same formulas as Lavin and Organista [1988] (see appendix). The incident solar radiation was estimated analytically using the Smithsonian formulation with corrections for albedo, cloud cover, and Sun altitude [see Reed, 1977]. The sensible and latent heat fluxes were estimated from the bulk aerodynamic formulas using exchange coefficients dependent upon the wind speed and the air-sea temperature difference [Friehe and Schmitt, 1976; Bunker, 1976]. The net longwave radiation was estimated from the satellite SSTs using the formula of N. A. Efimova [Budyko, 1974] modified for cloud cover [Reed, 1976, 1983].

Lavin and Organista [1988] have shown that estimates of the various heat flux components made using monthly aver-

Fig. 6. Daily averaged rms wind speed at Isla Rasa (P2), Isla Tortuga (P4), and Puerto Peñasco (P6). Days are numbered consecutively from January 1, 1984.

Fig. 7. Daily averaged vapor pressure at each meteorological station: Isla Piojo (P1), Isla Rasa (P2), Santa Rosalia (P3), Isla Tortuga (P4), Guaymas (P5), Puerto Peñasco (P6), and San Felipe (M1). Days are numbered consecutively from January 1, 1984.
TABLE 1. Monthly Averaged Meteorological Data

<table>
<thead>
<tr>
<th>Month</th>
<th>( T_s ) °C</th>
<th>( T_a ) °C</th>
<th>( e_r ) mb</th>
<th>( H_r )%</th>
<th>( p\times1000 ) mbar</th>
<th>( W ) m s(^{-1} )</th>
<th>( C )</th>
</tr>
</thead>
<tbody>
<tr>
<td>March 1984</td>
<td>18.5</td>
<td>19.8</td>
<td>11.0</td>
<td>53</td>
<td>11.6</td>
<td>4.1</td>
<td>0.18</td>
</tr>
<tr>
<td>April</td>
<td>20.3</td>
<td>21.0</td>
<td>14.3</td>
<td>61</td>
<td>10.1</td>
<td>3.7</td>
<td>0.18</td>
</tr>
<tr>
<td>May</td>
<td>22.5</td>
<td>25.5</td>
<td>19.9</td>
<td>74</td>
<td>8.5</td>
<td>2.1</td>
<td>0.10</td>
</tr>
<tr>
<td>June</td>
<td>26.2</td>
<td>26.6</td>
<td>24.2</td>
<td>72</td>
<td>7.8</td>
<td>2.2</td>
<td>0.12</td>
</tr>
<tr>
<td>July</td>
<td>28.9</td>
<td>28.6</td>
<td>31.0</td>
<td>79</td>
<td>8.1</td>
<td>2.1</td>
<td>0.38</td>
</tr>
<tr>
<td>Aug.</td>
<td>30.4</td>
<td>29.4</td>
<td>33.4</td>
<td>78</td>
<td>8.4</td>
<td>2.2</td>
<td>0.31</td>
</tr>
<tr>
<td>Sept.</td>
<td>29.6</td>
<td>29.1</td>
<td>29.9</td>
<td>73</td>
<td>5.9</td>
<td>3.0</td>
<td>0.15</td>
</tr>
<tr>
<td>Oct.</td>
<td>26.4</td>
<td>24.0</td>
<td>18.1</td>
<td>53</td>
<td>10.5</td>
<td>2.9</td>
<td>0.22</td>
</tr>
<tr>
<td>Nov.</td>
<td>22.1</td>
<td>19.4</td>
<td>11.8</td>
<td>45</td>
<td>14.4</td>
<td>5.1</td>
<td>0.20</td>
</tr>
<tr>
<td>Dec.</td>
<td>18.7</td>
<td>16.5</td>
<td>10.9</td>
<td>51</td>
<td>13.9</td>
<td>5.1</td>
<td>0.61</td>
</tr>
<tr>
<td>Jan. 1985</td>
<td>16.8</td>
<td>14.9</td>
<td>8.3</td>
<td>44</td>
<td>16.8</td>
<td>4.8</td>
<td>0.40</td>
</tr>
<tr>
<td>Feb.</td>
<td>17.3</td>
<td>15.9</td>
<td>8.4</td>
<td>43</td>
<td>16.2</td>
<td>5.1</td>
<td>0.35</td>
</tr>
</tbody>
</table>

Parameters are as follows: \( T_s \), spatially averaged SST from monthly mean infrared image for area north of Guaymas and Santa Rosalia; \( T_a \), air temperature; \( e_r \), water vapor pressure; \( H_r \), humidity calculated as 100 \( \times \) \( e_r / e_s \), where \( e_s \) is the saturation vapor pressure for air at the sea surface temperature, \( T_s \); \( p \), atmospheric pressure; \( W \), estimated 10-m rms wind speed at Tortuga Island; \( C \), fractional cloud cover estimated from all available satellite images.

Averaged meteorological data from Puerto Peñasco generally have an error of less than 10% when compared with estimates made using daily averaged meteorological data. These errors are similar to those obtained by Ebbesen and Reynolds [1981] for calculations of latent and sensible heat fluxes for the midlatitude and subtropical North Pacific and North Atlantic. In the Gulf of California, however, the sensible heat flux estimated from the monthly mean data had an error of approximately 20% compared with estimates made from daily mean values. This error was considered acceptable because the sensible heat flux is less than 10 W m\(^{-2} \) in the gulf, resulting in an error of less than 2 W m\(^{-2} \).

It was shown previously [Paden et al., 1991] that fluctuations in the spatially averaged SSTs for the northern basin, island region, and Guaymas Basin were all highly correlated with fluctuations in the air temperature over much of the year. The exceptions were during late fall and early winter, when winds from the northwest bring cold, dry air off the continental United States. During this period, the upper mixed layer is relatively deep, and the transfer of heat between the ocean and atmosphere occurs over a longer time scale than during the spring and summer when the upper layer is warming. The fact that the spatially averaged SSTs for each of the three regions respond so similarly to atmospheric forcing and that such a high degree of correlation exists between the different meteorological stations suggests that the atmosphere over the gulf can be treated as fairly uniform.

To calculate the surface heat flux, daily averaged values were first estimated for each meteorological variable. The available daily mean values were then averaged spatially over all stations that were representative of the open gulf. The resulting spatial means were in turn averaged over each month to obtain a monthly mean value. Data from Santa Rosalia (P3) and Isla Plojo (P1) were not used in the vapor pressure averages, since they are less representative of the marine atmosphere. Air temperatures from San Felipe and Puerto Peñasco were not used, as they tended to reflect continental values during the winter. Since there were three stations in the Guaymas basin and only two each in the island region and northern basin, data from Santa Rosalia (P3) were not used unless values at Guaymas (P5) were missing, so that each region was represented as equally as possible. The rms wind speeds were estimated solely from the Isla Tortuga PAM data, since they appeared to best represent conditions over the open ocean throughout the northern gulf.

Monthly mean values of the meteorological data are listed in Table 1. The SST values listed represent a spatial average of the data north of the Guaymas–Santa Rosalia transect where hydrographic estimates of the heat transport were made by Bray [1988]. The cloud cover was estimated from visual examination of archived satellite infrared data available at the Scripps Satellite Oceanography Facility (SSOF). Although the formulas used to estimate incident solar radiation and the net longwave radiation were originally derived using visual cloud estimates [Reed, 1977], the cloud factors estimated from the satellite images were not significantly different from previous estimates for the gulf. The annual average for the satellite-derived cloud cover was 0.27 compared with visual estimates of 0.29 at Puerto Peñasco [Lavin and Organista, 1988] and 0.26 for the gulf as a whole [Rodin and Emislou, 1979]. These results suggest that the satellite estimates of cloud cover are fairly representative of conditions in the northern Gulf of California.

4. Temporal Variability of the Surface Heat Flux

The surface heat flux was estimated for each month from March 1984 through February 1985 corresponding to the available PAM data and monthly mean SST images. Time series of the various components of the surface heat flux are presented in Figure 8 with positive values indicative of a gain of heat by the ocean. These values represent the integrated fluxes for the region north of the Guaymas–Santa Rosalia line corresponding to the area for which the heat and freshwater transport estimates were made [Bray, 1988]. The heat flux components were first calculated pixel by pixel for each image and then averaged in space to obtain a monthly mean value (Table 2). Estimates of the net annual surface heat flux made with area-averaged SSTs (Table 3) were essentially identical to those obtained using the exact SST data (Table 2), although some of the individual latent heat
Table 2. Monthly Heat Fluxes for Region North of Guaymas and Santa Rosalia Calculated With Satellite SSTs and Meteorological Data from Table 1

<table>
<thead>
<tr>
<th>Month</th>
<th>$Q_{sw}$</th>
<th>$Q_s$</th>
<th>$Q_b$</th>
<th>$Q_l$</th>
<th>$Q$</th>
</tr>
</thead>
<tbody>
<tr>
<td>March 1984</td>
<td>253.0</td>
<td>-62.6</td>
<td>-69.4</td>
<td>2.4</td>
<td>123.4</td>
</tr>
<tr>
<td>April</td>
<td>304.0</td>
<td>-69.1</td>
<td>-65.3</td>
<td>-0.2</td>
<td>169.4</td>
</tr>
<tr>
<td>May</td>
<td>353.5</td>
<td>-9.0</td>
<td>-61.3</td>
<td>3.7</td>
<td>286.9</td>
</tr>
<tr>
<td>June</td>
<td>363.2</td>
<td>-43.9</td>
<td>-54.7</td>
<td>-2.0</td>
<td>262.6</td>
</tr>
<tr>
<td>July</td>
<td>304.2</td>
<td>-64.2</td>
<td>-32.7</td>
<td>-3.9</td>
<td>203.4</td>
</tr>
<tr>
<td>Aug.</td>
<td>293.9</td>
<td>-74.0</td>
<td>-31.8</td>
<td>-5.3</td>
<td>182.8</td>
</tr>
<tr>
<td>Sept.</td>
<td>279.4</td>
<td>-98.8</td>
<td>-44.0</td>
<td>-4.9</td>
<td>131.7</td>
</tr>
<tr>
<td>Oct.</td>
<td>213.9</td>
<td>-178.7</td>
<td>-61.3</td>
<td>-11.1</td>
<td>-37.2</td>
</tr>
<tr>
<td>Nov.</td>
<td>169.2</td>
<td>-253.3</td>
<td>-70.1</td>
<td>-18.4</td>
<td>-154.6</td>
</tr>
<tr>
<td>Dec.</td>
<td>107.6</td>
<td>-167.7</td>
<td>-41.7</td>
<td>-16.1</td>
<td>-117.9</td>
</tr>
<tr>
<td>Jan. 1985</td>
<td>138.5</td>
<td>-159.8</td>
<td>-57.5</td>
<td>-13.9</td>
<td>-92.7</td>
</tr>
<tr>
<td>Feb.</td>
<td>179.1</td>
<td>-173.7</td>
<td>-61.1</td>
<td>-11.2</td>
<td>-66.9</td>
</tr>
</tbody>
</table>

Mean: 246.6 -111.4 -54.2 -6.7 74.2

Fig. 8. Monthly averaged surface fluxes for the region north of Guaymas-Santa Rosalia line: (a) incident solar radiation, (b) latent heat flux, (c) sensible heat flux, (d) long-wave radiation, (e) total net surface heat flux.

flux estimates differed significantly between the two analyses.

The temporal behaviors of the various heat flux components are similar to those obtained by Lavin and Organista [1988] using historical hydrographic data and 7 years (1979-1986) of monthly mean meteorological data from an MMS station at Puerto Peñasco. The incident solar radiation, calculated at 29°N (the center of the satellite image), has a maximum in June and minimum in December with a net annual average of +247 W m⁻² in the 1984-1985 period. The latent heat flux shows a minimum value in May and a maximum in November, compared to June and October for the Puerto Peñasco analysis. The average annual latent heat flux was higher for the 1984-1985 data set, with a net loss of 111 W m⁻² and an evaporation rate of 1.4 m yr⁻¹ compared with the 67 W m⁻² and 0.9 m yr⁻¹ estimated by Lavin and Organista [1988]. Bray [1988] also estimated an evaporation rate of 0.95 m yr⁻¹ from freshwater transport estimates. The back radiation or net longwave radiation is also seasonal, with a minimum in summer due to the increase in water vapor content of the lower atmosphere. Cloud cover further reduces the back radiation during the summer as well as in December in the 1984-1985 analysis yielding a net loss of approximately 54 W m⁻² over the year, essentially identical to the 53 W m⁻² obtained by Lavin and Organista [1988]. The sensible heat flux shows different temporal behaviors in the two analyses, with no significant differences in the total annual sensible heat flux. Lavin and Organista [1988] show a net annual sensible heat loss of approximately 3 W m⁻² compared with 7 W m⁻² for the satellite analysis.

The total net surface heat flux (Figure 8e) north of the Guaymas-Santa Rosalia line shows a gain of heat by the ocean from March through September, with a net loss of heat from October through February. The estimated net annual surface heat flux is +74 W m⁻². This value is somewhat larger than the 20-50 W m⁻² estimated by Bray [1988] using hydrographic data from different years and months. However, given the different data sets and methodologies used, these results are fairly comparable. Lavin and Organista [1988] (revised by Castro et al. [1993], hereinafter referred to as CLR) on the other hand, use the same surface heat flux formulae to estimate a net surface heat flux of +114 W m⁻² over most of the northern basin, with heat loss occurring only in the months of November and December.

The large difference between the Puerto Peñasco results and those obtained in the present study can be directly attributed to the different humidities in the two data sets.

Table 3. Monthly Heat Fluxes Calculated Using Data in Table 1

<table>
<thead>
<tr>
<th>Month</th>
<th>$Q_{sw}$</th>
<th>$Q_s$</th>
<th>$Q_b$</th>
<th>$Q_l$</th>
<th>$Q$</th>
</tr>
</thead>
<tbody>
<tr>
<td>March 1984</td>
<td>253.0</td>
<td>-52.3</td>
<td>-69.4</td>
<td>2.5</td>
<td>133.8</td>
</tr>
<tr>
<td>April</td>
<td>304.0</td>
<td>-71.6</td>
<td>-63.3</td>
<td>-0.5</td>
<td>166.6</td>
</tr>
<tr>
<td>May</td>
<td>353.5</td>
<td>-8.4</td>
<td>-61.4</td>
<td>3.6</td>
<td>287.3</td>
</tr>
<tr>
<td>June</td>
<td>363.2</td>
<td>-29.6</td>
<td>-54.7</td>
<td>-2.3</td>
<td>276.6</td>
</tr>
<tr>
<td>July</td>
<td>304.2</td>
<td>-69.4</td>
<td>-32.7</td>
<td>-3.5</td>
<td>198.9</td>
</tr>
<tr>
<td>Aug.</td>
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<td>-66.9</td>
<td>-31.8</td>
<td>-5.3</td>
<td>189.9</td>
</tr>
<tr>
<td>Sept.</td>
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<td>-97.5</td>
<td>-44.0</td>
<td>-4.5</td>
<td>133.4</td>
</tr>
<tr>
<td>Oct.</td>
<td>213.9</td>
<td>-178.5</td>
<td>-61.1</td>
<td>-11.0</td>
<td>-36.8</td>
</tr>
<tr>
<td>Nov.</td>
<td>169.2</td>
<td>-236.5</td>
<td>-70.1</td>
<td>-18.3</td>
<td>-155.7</td>
</tr>
<tr>
<td>Dec.</td>
<td>107.6</td>
<td>-169.9</td>
<td>-41.7</td>
<td>-16.4</td>
<td>-120.4</td>
</tr>
<tr>
<td>Jan. 1985</td>
<td>138.5</td>
<td>-161.0</td>
<td>-57.5</td>
<td>-13.7</td>
<td>-93.7</td>
</tr>
<tr>
<td>Feb.</td>
<td>179.1</td>
<td>-179.7</td>
<td>-61.1</td>
<td>-11.3</td>
<td>-73.0</td>
</tr>
</tbody>
</table>

Mean: 246.6 -110.1 -54.2 -6.7 75.6
The years 1977–1984 mark an extended warm period in the Pacific Ocean [Roden, 1989] which was punctuated by the occurrence of an historically strong El Niño in the winter of 1982–1983 and a more moderate one in the winter of 1977–1978. The Puerto Peñasco humidities, which were obtained by averaging available data from 1979 to 1986, show essentially no seasonal variability with a relatively high mean of 70% and a range of 66–73%. During 1984–1985, however, humidities measured at the PAM stations averaged 60% and ranged from 43% in winter to 79% in summer. Similar humidities and seasonal variability were also seen at the San Felipe MMS station in 1984 and 1985, but were not observed in the Puerto Peñasco MMS data for reasons that are not clear. Humidities reported by Lavin and Organista [1988, Figure 3] for the period 1959–1962 [from Thomson et al., 1969] also had a large seasonal signal, with a mean of only 43%. The interannual variability in humidity may occur in response to large-scale climatic variability over the Pacific Ocean. During El Niño years, wintertime humidities apparently remain high in the northern Gulf of California, similar to what is seen along the west coast of North America [Roden, 1989]. In non-El Niño years, a strong seasonal cycle seems to occur. The low humidities reported for 1959–1962 occur during a period in which the Southern Oscillation Index (SOI) is positive [Baumgartner et al., 1989], opposite to what occurs during El Niño years. The SOI is the difference in atmospheric pressure at sea level between the island of Tahiti and Darwin, Australia. This same index is approximately zero during 1984–1985 and mostly negative between 1979 and 1984, suggesting that variations in the annual mean humidity in the Gulf of California may be related to the strength of the atmospheric pressure systems over the North Pacific.

5. Spatial Variability of the Surface Heat Flux

The spatial distribution of the net surface heat flux is presented in Plate 1. These data were obtained by first calculating the net surface heat flux pixel by pixel for each monthly mean SST image and then averaging in time. The whole northern gulf appears to gain heat, with the largest gain occurring in the island region where SSTs are the coldest. Other than a small local maximum near San Esteban
Island, the largest heat gain occurs in the Ballenas and Salsipuedes Channels, with an average annual flux of $+110$ to $+120$ W m$^{-2}$. In the north a local minimum in the heat flux occurs over the shallow shelf near the coast, similar to results obtained by Lavin and Organista [1988] and revised by CLR. Using higher humidities, they estimate that the shallow shelf gains approximately 100 W m$^{-2}$ compared with 114 W m$^{-2}$ further offshore. Our calculations show a somewhat different heat gain between the two regions, with approximately 60 W m$^{-2}$ gained on the shallow shelf and 70 W m$^{-2}$ offshore. In general, however, the heat flux appears to be fairly uniform over most of the northern basin, as was hypothesized by Lavin and Organista [1988]. The smallest heat gain (40–50 W m$^{-2}$) occurs in the Guayas Basin, where SSTs are consistently higher over the year. In another study, Ripa and Marinone [1989] (revised in CLR) estimated a gain of 137 W m$^{-2}$ in the Guayas Basin based on historical hydrographic data and climatological meteorology (1941–1970) from an MMS station near Guayas. The large difference between their results and those obtained in the present study is, for the most part, due to significantly warmer air temperatures in the Guayas MMS data set. Although air temperatures during 1984–1985 may have been unusually low in comparison with the climatological mean for Guayas, it is possible that the Guayas MMS air temperatures do not represent those over the open ocean. In addition, it has been shown previously [Merrifield and Winant, 1989] that wind speeds measured at Guayas are much lower than those at Tortuga Island, where conditions are more representative of the open gulf.

The spatial pattern of the net surface heat flux is primarily determined by the pattern of the latent heat flux. The sensible heat flux and back radiation typically do not vary much in space, ranging from $-12.3$ to $+2.5$ W m$^{-2}$ and $-55.3$ to $-52.6$ W m$^{-2}$, respectively, in the northern gulf. The largest sensible heat loss and back radiation occur in the Guayas Basin with the sensible heat gain and smaller back radiation occurring over the sills in the island region. The latent heat flux, on the other hand, ranges from $-135$ to $-145$ W m$^{-2}$ in the Guayas Basin to as low as $-75$ to $-85$ W m$^{-2}$ in the Ballenas and Salsipuedes channels, with a local minimum near San Esteban of approximately $-60$ W m$^{-2}$. The latent heat loss increases with distance from the island region, attaining a value $-115$ W m$^{-2}$ in the northern basin and $-125$ W m$^{-2}$ over the shallow northern shelf.

The spatial pattern of the latent heat flux and in turn the net annual surface heat flux is a direct reflection of the SST patterns in the northern Gulf of California. Strong tidal mixing in the midriff island region produces a persistent pool of cool water that when dispersed by the large-scale circulation reduces SSTs throughout the northern basin and part of the Guayas Basin [Paden et al., 1991]. The transfer of heat to depth by tidal mixing can be seen in temperature cross sections from the Ballenas and Salsipuedes channels (Figure 9). Note the relatively warm water at depth in the channel compared with the Guayas Basin in the south. Mixing exchanges the heated surface waters for cool waters from below, maintaining the cold surface temperatures and further enhancing the flux of heat into the ocean. This positive feedback mechanism is evident in the high surface heat flux values in the channel.

### 6. Summary and Discussion

Satellite-derived SSTs and spatially averaged coastal meteorological data for March 1984 through February 1985 have been used to estimate monthly mean surface heat fluxes for the northern Gulf of California. The net surface heat flux for the area north of Guaymas and Santa Rosalia is shown to be $+74$ W m$^{-2}$. This is reasonably comparable to the $+20$–$50$ W m$^{-2}$ previously obtained from hydrographic estimates of heat and freshwater transport [Bray, 1988], given the different data sets and methodologies used. For the period 1984–1985, heat is gained over the whole northern basin, with the largest heat gain ($+110$–$120$ W m$^{-2}$) in the Ballenas and Salsipuedes channels, where tidal mixing produces a persistent pool of cold water. The magnitude of the net surface heat flux decreases with distance from the island region as SSTs become warmer. The lowest heat gain in the northern gulf ($+40$–$50$ W m$^{-2}$) occurs in the southern Guayas Basin, where SSTs are least influenced by cold water from the island region. Over most of the northern basin, the net surface heat flux is fairly uniform ($+70$ W m$^{-2}$), with a local minimum over the shallow shelf in the northwest (approximately $+60$ W m$^{-2}$). A similar pattern for the northern basin was observed by Lavin and Organista [1988] (revised in CLR) using historical SSTs and meteorological data from an MMS station at Puerto Peñasco. Their results, however, indicated a higher net surface heat flux with a gain of $114$ W m$^{-2}$ in the northern basin and $100$ W m$^{-2}$ over the shelf.

The apparent discrepancy between the two surface heat flux estimates for the northern basin is related to differences in humidity. The Puerto Peñasco MMS humidities, obtained by averaging monthly mean values over a 7-year period between 1979 and 1986, exhibit very little seasonal variability and a relatively high annual mean. In contrast, the 1984–1985 PAM humidities, which were averaged spatially, have a large seasonal signal with a lower annual mean. The Puerto Peñasco data sampled an anomalously warm period for the Pacific Basin (1977–1984) with an historically strong El Niño occurring in 1982–1983. During the El Niño, winter-time humidities remained high in the northern Gulf of California, minimizing the seasonal cycle and increasing the annual mean. In 1984, a non-El Niño year, a pronounced seasonal cycle is evident in the Puerto Peñasco PAM data as well as in the San Felipe MMS data reported by Lavin and Organista [1988]. The Puerto Peñasco MMS humidities, on the other hand, exhibit very little seasonality in 1984, with values early in the year as high as those observed during the El Niño. This discrepancy in the observations at Puerto Peñasco, as well as the inclusion of the 1982–1983 El Niño, led to higher humidities in the analysis of Lavin and Organista [1988]. Nevertheless, it is evident that large interannual variations in humidity occur in the northern Gulf of California. These data, combined with observations of extremely low humidity at Puerto Peñasco during the anti-El Niño period of 1959–1962 [Thomson et al., 1969], suggest that the interannual variability is related, either directly or indirectly, to fluctuations in the strength of atmospheric pressure systems over the Pacific Ocean.

When humidities are high, evaporation and the associated latent heat loss are reduced. It is this mechanism that Lavin and Organista [1988] used to explain the net gain of heat by the northern Gulf of California. However, the cold SSTs produced by tidal mixing play the key role in reducing the
latent heat flux by decreasing the saturation vapor pressure of the overlying air. As a result, large moisture gradients cannot form between the sea surface and the lower atmosphere, and evaporation is minimized. Mixing in the channels maintains the cold SSTs by removing heat from the surface and pumping it deep into the water column. Because the cold surface temperatures are mixed horizontally by the large-scale circulation, the latent heat flux is reduced over most of the northern basin. This mechanism of storing heat at depth will be most critical during particularly cold, dry winters (such as appear to occur during anti-El Niño years), as well as over shorter timescales when strong northwesterly winds advect cold, dry air into the gulf from the upper Sonoran Desert [Badan-Dangon et al., 1991]. It is at these times that large amounts of heat would otherwise be transferred from the ocean to the atmosphere. By promoting heat

Fig. 9. Hydrographic section through Ballenas Channel during May 1984 [Bray, 1988]. Distance in kilometers along section is relative to point at 27°N, 111°W. Vertical sections of (a) potential temperature, (b) salinity, and (c) potential density.
storage, tidal mixing alters the timescale of air-sea interaction and in so doing reduces or possibly even inhibits the formation of deep water masses via convection. While variations in humidity will certainly affect the magnitude of the net surface heat flux, it may be tidal mixing that ultimately maintains the estuarine-like circulation over climatological timescales, differentiating the Gulf of California from the Mediterranean and Red seas, which lose heat to the atmosphere.

APPENDIX: SURFACE HEAT FLUX FORMULAS

Following the notation of Lavin and Organista [1988], the flux of heat across the surface of the ocean, \( Q \) (in watts per square meter, positive downward), is represented by the sum of the net shortwave radiation (\( Q_{s-r} \)), the net longwave radiation (\( Q_b \)), the latent (or evaporative) heat flux (\( Q_e \)), and the sensible heat flux (\( Q_l \)).

\[
Q = Q_{s-r} + Q_b + Q_e + Q_l
\]

These various components are estimated as follows:

\[
Q_{s-r} = Q_s(1 - 0.62C + 0.0019\alpha)(1 - A)
\]

The clear-sky radiation, \( Q_s \), is estimated analytically using the Smithsonian formulation which depends solely on latitude and day of the year [see Reed, 1977]. This value is reduced with an albedo \( A = 0.06 \) [Payne, 1972] and corrected for cloud cover \( C \) and Sun altitude \( \alpha \) (in degrees) [Reed, 1977].

The net longwave radiation is calculated as [Reed, 1983]

\[
Q_b = -\sigma e(T_s + 274)^4(0.254 - 0.000495\epsilon_e)
\]

where \( T_s \) (in degrees Celsius) is the sea surface temperature, \( \sigma = 5.7 \times 10^{-8} \) W m\(^{-2}\) K\(^{-4}\) is the Stefan-Boltzmann constant, \( \epsilon = 0.97 \) is the emissivity of the sea surface, and \( \epsilon_e \) (in millibars) is the vapor pressure of the air. (The coefficient for \( \epsilon_e \) was misprinted in the Lavin and Organista [1988] paper and is corrected here.)

The latent and sensible heat fluxes are estimated using the bulk aerodynamic formulas. The latent heat flux is calculated [Gill, 1982]

\[
Q_e = \rho_a C_v W (q_s - q_a) L_v
\]

where \( \rho_a = 1.25 \) kg m\(^{-3}\) is the air density, \( W \) is the mean wind speed (in meters per second), \( q_s \) is the saturation specific humidity of the sea surface, and \( q_a \) is the specific humidity of air. The exchange coefficient, \( C_v \), is made dependent on the wind speed and the sea-air temperature difference following Bunker [1976] and the latent heat of vaporization,

\[
L_v = 2.5008 \times 10^{-6} - 2.3 \times 10^{-3} T_s \text{ J kg}^{-1}
\]

The sensible heat flux is calculated as

\[
Q_l = \rho_a C_p \left( 0.0026 + 0.86 \times 10^{-3} W \Delta T \right) W \Delta T < 0
\]

\[
Q_l = \rho_a C_p \left( 0.002 + 0.97 \times 10^{-3} W \Delta T \right) 0 < W \Delta T < 25
\]

\[
Q_l = \rho_a C_p \left( 1.46 \times 10^{-3} W \Delta T \right) W \Delta T > 25
\]

according to Friehle and Schmitt [1976], where \( \Delta T = (T_s - T_a) \) and the specific heat of air at constant pressure,

\[
C_p = 1004.6(1 + 0.8375q_a) \text{ J kg}^{-1} \text{ K}^{-1}
\]

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