Seasonal Variability of Upwelling and Downwelling Surface Current Patterns Near a Small Coastal Embayment

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By

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1 Introduction

Embayments are common coastal features whose morphology and orientation can produce complex spatial patterns in local and regional surface currents (Largier 2020). Since 1974, oceanographers have observed these surface patterns using high-frequency radar (HF radar or HFR), a technique which makes use of Bragg scattering and the Doppler effect to determine the velocity of surface currents from reflected HF radio waves (Paduan & Washburn 2012). Surface currents in coastal embayments often form complex spatial patterns of significant ecological importance which can be studied using HFR-derived measurements of the current field. Some ecological processes mediated by surface currents include the development, fate, and transport of harmful algal blooms (Matson et al. 2020); frontogenesis and localized upwelling (Walter et al. 2017); the dispersal of buoyant pollutants (Coulliette et al. 2007); and larval dispersal and connectivity (Paduan & Washburn 2012; Nidzieko and Largier 2013). The latter is especially important to the design and assessment of marine protected areas (Zelenke et al. 2009).

In eastern boundary current systems, seasonal coastal upwelling is the dominant driver of variability and helps shape the complex surface patterns observed in and around embayments (i.e., “upwelling bays,” cf. Largier 2020). Paduan et al. (2018) investigated typical upwelling-driven current patterns in Monterey Bay, a large coastal embayment (along-shore width ~35 km, cross-shore length ~25 km) located in Central California. They compared traditional averages of surface current patterns over the summer upwelling season and winter non-upwelling season to those averaged conditionally during upwelling and downwelling events and found that conditional averages resulted in significantly more structure and intensity in the current patterns. However, as noted by Largier (2020), the size, orientation, and topographic features of a
particular coastal embayment can significantly impact the resulting circulation patterns. Moreover, the circulation patterns in smaller embayments (defined here as having width and length scales that are 20 km or less, but still greater that the local baroclinic Rossby radius of deformation, cf. Largier 2020) are significantly understudied relative to larger embayments, despite their ubiquity and importance on local dynamics in eastern boundary current upwelling systems (e.g., Walter et al. 2018).

Here, we apply the conditional averaging technique of Paduan et al. (2018) to investigate the upwelling-driven circulation in a small coastal embayment located in Central California [San Luis Obispo (SLO) Bay]. We also investigate the intra-upwelling season variability by examining the oceanic response to both traditional and conditional averages using a more detailed description of upwelling seasonality (Walter et al. 2018, see Section 3.1) that goes beyond the generalized upwelling and non-upwelling seasons. Implications of the findings are discussed.

2 Data and Methods

2.1 Description of Study Site and Upwelling Seasonality

SLO Bay is a small embayment on the California Central Coast located approximately 80 km north of Pt. Conception, a major marine biogeographical boundary. The embayment is defined by both Pt. Buchon and Pt. San Luis headlands to the northwest, which partially shelter the bay, and Pt. Sal to the south. Largier (2020) classifies SLO Bay as a “small bay” whose circulation patterns are dominated by an “upwelling shadow” or region sheltered from prevailing upwelling-favorable winds by a headland (cf. Walter et al, 2018). Local diurnal wind forcing has also been found to significantly affect circulation within the bay (Walter et al. 2017).
While coastal upwelling is traditionally considered a bimodal process (i.e., the summer upwelling season and the winter non-upwelling season), this generalized framework does not capture details relevant to marine ecosystems (Garcia-Reyes and Largier 2012; Walter et al. 2018). Using both the mean monthly upwelling favorable wind stress and the monthly standard deviation, Walter et al. (2018) present a tuning of the annual cycle and a more detailed description of the upwelling seasonality for the SLO Bay region. The upwelling season is refined to include a Peak Upwelling season (April and May) and Upwelling Relaxation season (July, August, and September) and the non-upwelling season to a Winter Transition season (October and November) and Winter Storms season (December, January, and February), with March and June considered “upwelling transition periods.” The Peak Upwelling season is characterized by the largest mean upwelling-favorable winds, although they are also highly variable due to the frequent wind relaxations, as well as the presence of cold, nutrient rich water, and an increase in chlorophyll concentrations throughout the water column. During the Upwelling Relaxation, the mean upwelling winds decrease significantly with less variability, and water-column stratification intensifies while chlorophyll concentrations remain elevated near the surface. During the Winter Transition season, the mean upwelling winds continue to decreased until they reach their minimum during the Winter Storms Season, although by this time the monthly variability as increased substantially due to synoptic variability (i.e., storms). During this time, vertical temperature and chlorophyll gradients start to erode due to increased vertical mixing, and the distribution becomes more uniform vertically with minimum chlorophyll levels. A more detailed description of this intraseasonal variability and the oceanic response can be found in Walter et al. (2018). This study is the first investigation of seasonal surface current patterns in this ecologically important region.
2.2 Surface Current Data

Hourly HFR measurements of the surface current velocity field from October 1, 2011 to December 31, 2019 were downloaded from the UCSD THREDDS data server (https://hfrnet-tds.ucsd.edu/thredds/catalog.html) within the region bounded by 121.25°W to 120.5°W and 34.83°N to 35.25°N (Figure 1). The percent coverage of HFR data in the domain is shown in Figure 1. Times when the spatial coverage throughout the domain was less than 90% were excluded from further analysis (Figure 1b; see also Figure 2 for times that were excluded). Since the focus of this analysis is on the upwelling- and downwelling-driven circulation, we low-pass filtered (33h) the data following Paduan et al. (2018) in order to eliminate strong tidal flows and diurnal-wind driven currents in this region (Walter et al. 2017) that may not be completely removed with the ensemble conditional averaging described below.

![Figure 1](image_url)

**Figure 1.** (a) Percent coverage of HFR data from October 1, 2011 to December 31, 2019 across the SLO Bay domain. (b) Percent coverage across the domain when restricting to times when at least 90% of all spatial points have data available. The locations of HFR sites and NDBC Buoy #46011 are indicated by a circle and triangles, respectively. The boxes labeled 1, 2, and 3 are the areas used to calculate the spin-up time (see Data and Methods section). Representative depth contours (m) are also shown.
Figure 2. Temporal coverage of (a) HFR-derived surface current velocity and (b) upwelling winds. In (b), times where wind data are available are shown in gray and times where both wind and current data are available in black. (c) Times when upwelling favorable winds exceed 5 m/s (red, upwelling events) or are less than -3 m/s (blue, downwelling events) are superimposed on the times corresponding to overlapping wind and current availability (black) from (b).

2.3 Offshore Wind Data

To assess regional wind-driven upwelling, hourly offshore winds were obtained from the National Data Buoy Center (NDBC) Buoy #46011 (Figure 1a, ~35 km offshore of SLO Bay). Equatorward upwelling favorable winds were calculated using the local coastline orientation (150° from true north; Figure 1a, cf. Walter et al., 2018) such that positive quantities denote upwelling favorable and negative indicate downwelling favorable. These winds were also filtered using a 33-hr low-pass filter following Paduan et al. (2018). In order to pair upwelling winds with HFR velocities, the timestamps of the filtered winds were interpolated onto those of the filtered surface currents (Figure 2). Upwelling events were then defined as periods when upwelling winds exceeded 5 m/s for at least 48 hours and downwelling or relaxation events as periods when upwelling winds were less than -3 m/s for at least 24 hours (Figure 3), following Paduan et al. (2018).
Figure 3. Example time series of upwelling favorable winds from April 2016 (Peak Upwelling season). Upwelling events are defined as periods when the upwelling winds exceeded 5 m/s (red dashed line) for at least 48 hours.

2.4 Conditional Averaging Process

Upwelling conditional averages and the associated standard error patterns were calculated for the Peak Upwelling (April & May) and Upwelling Relaxation (July to September) seasons, as well as the full upwelling season from March to September. Downwelling conditional averages and standard error patterns were calculated for the Winter Transition (October & November) and Winter Storm (December to February) seasons, as well as the full non-upwelling season (October to February). For comparison, the traditional average and standard error pattern for each of the aforementioned time periods were also calculated. Additionally, the divergence of the flow field for traditional and conditional averages for each season was also computed. Frozen flow field trajectories for the conditional and traditional averages for each of the aforementioned periods and seasons were also computed by placing particles at an initial spatial position and advecting the particle’s position using a fourth-order Runge Kutta scheme and the fixed (i.e., traditional or conditional average), interpolated velocity field at each hourly timestep for a total of 6 days.
2.5 Spin-up Times

In order to determine the spin-up time required to reach a quasi-steady state for the conditional averages, the average kinetic energy of the points in boxes 1-3 (Figure 1) was computed as a function of the time since the start of an upwelling event over all upwelling events, following Paduan et al. (2018) (Figure 4). The approximate time required to reach a steady state was approximately 2 days. The kinetic energy remained at a quasi-steady state, and there were a sufficient number of events to compute a representative average until around six days after the start of an upwelling event. The conditional averages for upwelling were further refined by including only times within this two- to six-day range. Downwelling events were conditionally averaged over the first three days of an event. Major results and current patterns were not significantly influenced by small changes to the conditional-averaging windows.

![Figure 4. Average kinetic energy of the boxes in Figure 2 (left axis) calculated in days since the start of an upwelling event (upwelling winds > 5 m/s). Shown with vertical dashed lines is the quasi-steady state period over which conditional averages are calculated (i.e., 2-6 days), where the kinetic energy has remained quasi-steady and there are a sufficient number of events (right axis) for the averages.](image-url)
3 Results

3.1 Upwelling Circulation Patterns

The traditionally and conditionally averaged surface current fields for the full upwelling season (March to September) are shown in Figures 5a and 5b, respectively. In both cases, an upwelling jet is visible across the mouth of the bay and advects towards the shore near the southern end of the bay. The upwelling jet is somewhat more prominent in the conditionally averaged current field compared to the traditionally averaged field. In Figures 5c and 5d, a region of strong convergence can be observed where waters from inside the northern region of the bay meet the upwelling jet. This convergence zone also lines up with the location of the upwelling shadow front [see e.g., Figure 9 in Walter et al. (2018)]. There is also a strong nearshore divergence zone at the southern end of the jet where some currents advect onshore and others continue south. This divergence is slightly amplified in the conditionally averaged current field, a result of the enhanced magnitude of the upwelling jet and its shoreward advection. Figures 5e and 5f show similar particle trajectories in both the traditional and conditional averages. More particles are entrained in the upwelling jet in the conditional average, however, highlighting the potential for greater retention.

For the Peak Upwelling season (April and May), the upwelling jet is an even more prominent feature in both the traditional and conditional averages (Figure 6a, 6b). However, it is stronger in the conditional average, especially in the nearshore. The divergence pattern is similar for both the traditional and conditional average (Figure 6c, 6d). The magnitude of the nearshore divergence is increased in the conditional average, which corresponds to the more defined southern boundary of the upwelling jet observed in the conditionally averaged current field. This augmented divergence corresponds to a stronger, southward flow that separates from the...
upwelling jet sooner than in the traditional average (6a, 6b). While the particle trajectories shown in Figures 6e and 6f are generally similar, retention of waters within the bay is diminished in the conditional average, as the increased strength of the upwelling jet and nearshore divergence zone results in the advection of a greater number of particles past the bay.

In both the traditional and conditional averages for the Upwelling Relaxation season (July, August, and September), the upwelling jet is still visible, but reduced in magnitude. In general, the strength of the current field is diminished compared to the Peak Upwelling season and the upwelling season in its entirety (Figure 7a, 7b). The jet is, however, amplified in the conditional average in the Upwelling Relaxation season, as are the magnitudes of the currents. In Figures 7c and 7d, the nearshore divergence is significantly enhanced in the conditional average than the traditional averaged, as is the convergence in the northern region of SLO Bay. This is the most noticeable difference in divergence patterns observed for any of the upwelling seasons investigated. In the particle trajectories (Figure 7e, 7f), this manifests as a pronounced split just north of Pt. Sal (southern end of SLO Bay) between the waters retained within the bay and those advected past it to the south. For comparison, the traditionally averaged trajectories fan out and displace more uniformly from their release points at a slower rate. There is also a significant westward component to these trajectories which is present in the conditional average, but absent in the Peak Upwelling Season and full upwelling season trajectories. This westward velocity component leads to reduced retention of particles within the bay compared to the other upwelling seasons and is one of the more prominent intraseasonal differences observed. Generally, it should also be noted that both the traditional and conditional averages for the entire upwelling season are influenced more by the Peak Upwelling season averages (Figure 6) than the Upwelling Relaxation season averages (Figure 7).
Figure 5. (a, b) Traditional and conditional averages of surface current data for the full upwelling season (March to September). (c, d) Divergence patterns overlaying the averaged current fields. (e, f) Frozen flow field trajectories overlaying the averaged current fields. For comparison, the green trajectories in both (e, f) correspond to particles advected in SLO Bay by the traditionally averaged flow field, while pink trajectories do not advect into the bay by the traditionally averaged flow field. The release points of the particles are indicated by a black “x.” For all panels, the traditionally averaged quantities are on the left, while the conditionally averaged quantities are on the right. Each particle’s position was updated every hour for 100 hours, or until the particle advected outside of the HFR coverage.
Figure 6. Same as Figure 5, but for the Peak Upwelling season (April and May).
Figure 7. Same as Figure 5, but for the Upwelling Relaxation season (July, August, and September).
3.2 Downwelling Circulation Patterns

Whereas the traditionally averaged current field is reminiscent of that of the Upwelling Relaxation season (Figure 7a), the most prominent feature of the full non-upwelling season (October to February) is the reversal of the currents in the conditional average (Figure 8a, 8b). In the conditional average, the upwelling jet is no longer present and the currents inside and outside of the bay are poleward (Figure 8b). The nearshore poleward flow is strongest near Pt. Buchon, with weaker poleward advection along the outer edge of SLO Bay. The traditionally and conditionally averaged divergence fields both display a very weak nearshore divergence zone near the southern end of the bay (Figure 8c, 8d). There is also a region of convergence near Pt. Buchon which corresponds to the strong poleward flow visible in Figure 8b. The traditionally averaged particle trajectories (Figure 8e) are similar to those of the Upwelling Relaxation season (Figure 7e), but with reduced magnitude and a greater westward component. Since the direction of the flow is reversed in the conditional average, particles were released off of Pt. Sal instead of in the northern region of the bay (Figure 8f). The conditionally averaged trajectories show a prominent flow separation just outside the southern end of SLO Bay with some particles retained within the bay and the rest advected northward. It appears that retention in the bay is reduced in the conditional average, but due to the flow reversal, it is more difficult to compare the traditionally and conditionally averaged trajectories and retention.

The general structure of the traditionally and conditionally averaged current fields for the Winter Transition season (October and November) is similar to that of the non-upwelling season as a whole (Figure 9a, 9b). The traditional average displays a weak westward flow, whereas the conditional average shows a northward flow that is weak within the bay but intensifies as it nears Pt. Buchon. As in the entire non-upwelling season, this intensified flow corresponds to a zone of
relatively strong convergence in the conditional average, which is not present in the traditional average (Figure 9c, 9d). For the traditional average, the degree of retention is very low, as most of the surface currents advect westward out of the bay (Figure 9e). Retention appears to increase in the conditional average, but as with the non-upwelling season as a whole, it is difficult to assess to what degree due to the flow reversal (Figure 9f).

For the Winter Storms season (December, January, and February), while there is some semblance of an upwelling jet and onshore advection in the traditionally averaged current field, it is significantly weaker than in the upwelling season (Figure 10a). The conditionally averaged currents show the expected poleward flow near Pt. Buchon, which is stronger here than in the Winter Transition season (Figure 10b). Similar to the divergence zone that forms near Pt. Sal during the upwelling seasons, there is a modest increase in the strength of the divergence in the traditional average (Figure 10c). There is also a region of increased convergence near Pt. Buchon as was observed for the Winter Transition season and the entire non-upwelling season (Figure 10d). The traditionally averaged particle trajectories support the observation of a weak current field, although there is a strong degree of retention in the northern portion of SLO Bay (Figure 10e). This contrasts with the conditionally averaged trajectories, in which there is no retention whatsoever as the particles that enter the bay after passing through the Pt. Sal divergence zone eventually exit after reaching a convergence zone in the middle of the bay (Figure 10f).
**Figure 8.** Same as Figure 5, but for the non-upwelling season (October to February). For the conditionally averaged frozen flow field in (e, f), particles are released near Pt. Sal instead of in the northern region of SLO Bay.
Figure 9. Same as Figure 8, but for the Winter Transition season (October and November).
Figure 10. Same as Figure 8, but for the Winter Storms season (December, January, and February).
3.3 Standard Error Plots

To assess the uncertainty of the traditional and conditional averages for the March to September upwelling season and October to February non-upwelling season, the standard error of each average current field was computed (Figure 11). The magnitudes of the standard error fields are at least an order of magnitude smaller than their respective current fields, so the averages computed can be considered representative. The standard error patterns for the conditional averages are greater than those of the traditional averages, which is expected since the conditional averages were calculated from fewer data points than the traditional averages. The standard error computed for the conditionally averaged non-upwelling season is greater than that of the conditionally averaged upwelling season, again due to the sample size (Table 1).

Figure 11. Standard error patterns of traditional (a, c) and conditional averages (b, d) for the March to September upwelling season (a, b) and October to February non-upwelling season (c, d).
<table>
<thead>
<tr>
<th>Season</th>
<th>Number of Upwelling Events</th>
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<td>Upwelling (March - September)</td>
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<td>Upwelling Relaxation (July - September)</td>
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<td>Non-upwelling</td>
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<td>Winter Transition (October - November)</td>
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<td>Winter Storms (December - February)</td>
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### 4 Discussion

#### 4.1 Upwelling Seasonality

The seasonality of coastal upwelling has long been established, with many studies considering a summer upwelling season and a winter non-upwelling season. Taking a conditional average of the HFR-derived surface current field based on upwelling-favorable winds reveals patterns that are obscured by a traditional average of these seasons (Paduan et al. 2018). Moreover, we show that applying the same conditional averaging with the more detailed seasonality proposed by Walter et al. (2018), which documents significant intraseasonal variability in both the upwelling and non-upwelling season, additional current patterns and features are revealed. In comparing the results of Paduan et al. (2018) to those of this study, it is important to note the morphological differences between Monterey Bay and SLO Bay. While both bays are flanked by upwind and downwind headlands, Monterey is several times larger than SLO Bay and has a width and length that are closer to one another (“square bay”), whereas the width of SLO Bay is greater than twice its length (“wide-open bay”) (Largier 2020). Paduan et al. (2018) showed that for upwelling events that reached quasi-steady state, a strong cyclonic flow developed within Monterey Bay and a pronounced, southward-flowing jet formed across...
the mouth. In SLO Bay, a similar upwelling jet can be seen in the conditionally averaged current field for the broader upwelling season, along with significant onshore advection (Figure 5). However, a full cyclonic eddy does not develop, presumably due to the geometry of the bay. The presence of a downwind headland, the size of an embayment, and local bathymetry are likely important in inhibiting the formation of a fully-developed eddy (Largier 2020). Examination of the current patterns for the upwelling season as defined in Walter et al. (2018) reveals that upwelling events occurring in the Peak Upwelling season appear to contribute more to the spatial patterns observed in the full upwelling season than upwelling events occurring during the Upwelling Relaxation season. During the full non-upwelling season, a strong poleward flow develops in both Monterey Bay and SLO Bay. Interestingly, there is much less intraseasonal variation for downwelling events, with the main difference being that the flow intensifies during the Winter Storms season compared to the Winter Transition season and the full downwelling season. The intraseasonal differences observed during the full upwelling season indicate the importance in upwelling seasonality to circulation patterns in SLO Bay.

**4.2 Upwelling Dynamics in Small Upwelling Shadow Embayments**

Small embayments (length and width scales ≤ 20 km) are ubiquitous in eastern boundary current upwelling systems, comprising just under 40% of all the bays classified by Largier (2020). Of these, roughly 70% are classified as being dominated by either an upwelling shadow or upwelling trap. Despite their ubiquity, these bays are understudied, and thus the results here could serve as a baseline for understanding and interpreting the circulation patterns in other small upwelling bays. The results presented here provide further evidence for the development and reinforcement of an upwelling shadow in the northern region of SLO Bay, as described by Walter et al. (2018). The headland north of SLO Bay shelters the northern region of the bay from
upwelling-favorable winds, resulting in the retention of surface waters on the landward side of
the upwelling jet. The lack of exchange within this retention zone leads to vertical stratification
and the development of a warm surface layer, forming a marked thermal gradient between the
waters within the bay and the cold waters in the upwelling jet outside the bay (Figure 12) (Walter
et al. 2018). The resulting upwelling shadow front leads to increased residence times and solar
heating of surface waters within the bay (Walter et al. 2017). The significant temperature
difference across the front corresponds to the zone of convergence observed during the full
upwelling season, as well as the Peak Upwelling and Upwelling Relaxation seasons (Figure 6c,
6d). We propose that the upwelling jet and shoreward circulation comprise a positive feedback
mechanism by which the upwelling shadow and front are reinforced. At the start of an upwelling
event, Ekman transport driven by upwelling-favorable winds lowers the sea level near the coast
and causes the thermocline to shoal towards the surface. The resulting alongshore flow that
develops in the presence of the headland forms a separated upwelling jet that moves across the
mouth of the bay and advects onshore, effectively trapping waters inside the bay (although there
still may be lateral exchange of colder waters at depth, cf. Walter et al. 2017) and leading to
frontogenesis. The retention in the bay results in a trapped warm surface layer, thereby
increasing the baroclinic pressure gradient force and reinforcing the convergent zone along the
front. These frontal systems are maintained for days to weeks until the next wind relaxation,
although some upwelling shadow bays have been shown to exceed the timescale of synoptic
upwelling-relaxation cycle variability. These convergent upwelling fronts can also be modulated
by local diurnal wind forcing (Walter et al. 2017) and are sites of increased internal wave activity
(Walter et al. 2016).
4.3 Ecological Ramifications

Retention during upwelling events may increase the rate of larval recruitment within the bay, while the poleward flows observed during downwelling events may provide an opportunity for species which are planktonic or have planktonic larval stages to expand their range (Nidzieko and Largier, 2013; Largier, 2020). It is possible that the bay may serve as a “stepping stone” refuge for poleward expanding species. While surface flows can stimulate plankton transport, the upwelling front can also act as a barrier to dispersal. Surface convergence can aggregate phytoplankton, and enhanced stratification in the upwelling shadow means that the bay has the potential to act as a bloom incubator, thereby increasing the risk of respiration-driven hypoxia (Ryan et al. 2008; Walter 2017). Knowledge of the surface currents associated with upwelling and relaxation events can also help track the dispersal of buoyant pollutants (e.g., oil, agricultural runoff), as well as the fate and development of harmful algal blooms previously observed at this site (see e.g., Barth et al. 2020). Future work will assess the time-dependent circulation during the upwelling spin-up and spin-down phases of the upwelling-relaxation cycles.
5 Conclusion

Upwelling in coastal embayments is important to a variety of physical and biological processes. Despite their ubiquity, circulation patterns in small bays (width and length scales ≤ 20 km) in eastern boundary current upwelling systems are relatively understudied compared to their larger counterparts. In this study, we apply a conditional averaging technique to investigate upwelling- and downwelling-driven circulation in a small coastal embayment located in Central California. We also investigate intraseasonal differences in the current patterns in SLO Bay. This is the first study investigating seasonal patterns in surface currents in and around SLO Bay. Conditional averaging reveals distinct intraseasonal differences and features that are obscured by traditional seasonal averages when examining the upwelling jet separation and onshore advection, divergence patterns, and particle trajectories. We show that the upwelling circulation and resulting upwelling jet separation and onshore advection reinforce a convergent upwelling shadow front at this site, with important ecological ramifications. While tuned specifically for SLO Bay, these findings can be used as a baseline for similar small upwelling bays and highlight the importance of conditional averages (versus traditional temporal averages) and coastal upwelling seasonality beyond the bimodal upwelling and non-upwelling description.

6 Acknowledgements

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analysis skills and oceanography knowledge he has imparted to me will continue to serve me well in my future studies and career.

References


