Effects of a Coastal Front on the Distribution of Chlorophyll in Lake Tahoe, California-Nevada

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The existence of a distinct coastal zone is confirmed in Lake Tahoe (California-Nevada) by horizontal transects measuring chlorophyll and temperature simultaneously. Creation of the coastal region is influenced by bottom topography, the nature of the surface wind stress, and the difference between physical processes occurring within a Rossby radius of deformation and those occurring in midlake. Chlorophyll records from horizontal transects were decomposed by spectral analysis, and the normalized spectra from nearshore and midlake were compared. The two regions were found to differ at large scales, primarily because of differences in nutrient import, and at intermediate scales because of differences in the mixing regime. The coastal zone was observed to erode with increasing winds and weakening stratification, leading to little significant difference between nearshore and midlake chlorophyll patterns.

INTRODUCTION AND METHODS

During the summer of 1977 a series of horizontal transects was made in the midlake and coastal regions of Lake Tahoe, California-Nevada. Figure 1 is a morphometric map of Lake Tahoe that shows the locations of the transects. Analysis of temperature and chlorophyll *a* distributions revealed significant differences between nearshore and midlake values and the presence of a narrow frontal zone separating the two water masses. The frontal zone was observed to be present only during early summer and to break down with increasing winds and weakening stratification as the summer progressed.

By use of a hose-pump system [*Powell et al.*, 1975], water from a fixed depth was sampled continuously for fluorescence by a Turner Designs model 10 fluorometer, fluorescence being an indicator of chlorophyll. Fluorescence voltage is calibrated by conventional extraction methods and is linearly related to chlorophyll *a* in the range of concentrations present in Lake Tahoe. Temperature was measured by a precision thermistor mounted at the hose inlet. This hose assembly was towed at low speed (1 m/s) for a fixed distance. The depth of the hose inlet was monitored by a pressure transducer. The temperature and fluorescence signals were recorded on magnetic tape. At this towing speed, resolution is limited to scales larger than 10 m, owing to mixing of water in the hose and fluorometer noise.

THE COASTAL FRONT IN LAKE TAHOE

The presence of coastal-midlake differences in lakes has been described by several authors [e.g., *Blanton*, 1974], who have shown that the shape of the kinetic energy spectrum changes as a function of distance offshore. Previous preliminary work in Lake Tahoe had indicated that a sharp separation between coastal and midlake water masses was present, especially in early summer. The temperature and chlorophyll records in Figure 2 were taken in July from a depth of 12 m when the thermocline depth was approximately 15 m. These show several typical features encountered in the mixed layer in Lake Tahoe. There are two regions where temperature is fairly uniform, indicating thorough mixing. These are separated by a region of large temperature fluctuations. Previous work at Lake Tahoe (T. M. Powell et al., unpublished data, 1977) and in the Great Lakes [*Boyce*, 1974] has shown that this type of feature usually indicates internal waves. An associated feature occurs in the chlorophyll record that shows fluorescence increasing when temperature decreases. Owing in part to the extreme clarity of Lake Tahoe, chlorophyll increases with depth, reaching a maximum at 100 m during summer [*Richerson et al.*, 1978]. Thus any physical event that brings up colder water from below will show an increase in fluorescence as well. The last feature (right-hand side) on this transect shows quite another temperature discontinuity that appears very different from that associated with internal waves. Though the temperature drop is about the same, the temperature stays low and shows a very irregular pattern afterward. A transect done close to shore on the same day revealed a similar pattern: a lower mean temperature and a higher mean chlorophyll content with much variability in both records (Figure 3). This latter transect was always within 1 km of the shore, while the former (Figure 2) started in midlake and ended within 2–3 km of the shore (Figure 1). The similarity between the nearshore transect and the end of the midlake transect can be explained by the presence of a distinct coastal water mass, extending 2–3 km offshore.

The formation of a distinct coastal region can be associated with several physical factors. Figure 4 shows the bottom topography along the path of the coastal transect. At some points the depth is less than the depth of the thermocline, leading to the possibility of bottom irregularities affecting mixing. Although topographic features certainly cause some of the observed temperature variations, Figure 1 shows that the shallow shore areas of Lake Tahoe drop quickly to a deep flat region underlying most of the lake. Since the transect of Figure 2 indicates a coastal zone extending 2–3 km from shore, other factors also influence its formation beyond topographic effects. In large lakes it seems useful to define the coastal zone as lying within a Rossby radius of deformation [*Csanady*, 1975] of shore. An estimate of this radius for Lake Tahoe is 3–5 km. Several authors (see *Csanady* [1975] for details) have shown that physical phenomena in midlake are expected to differ

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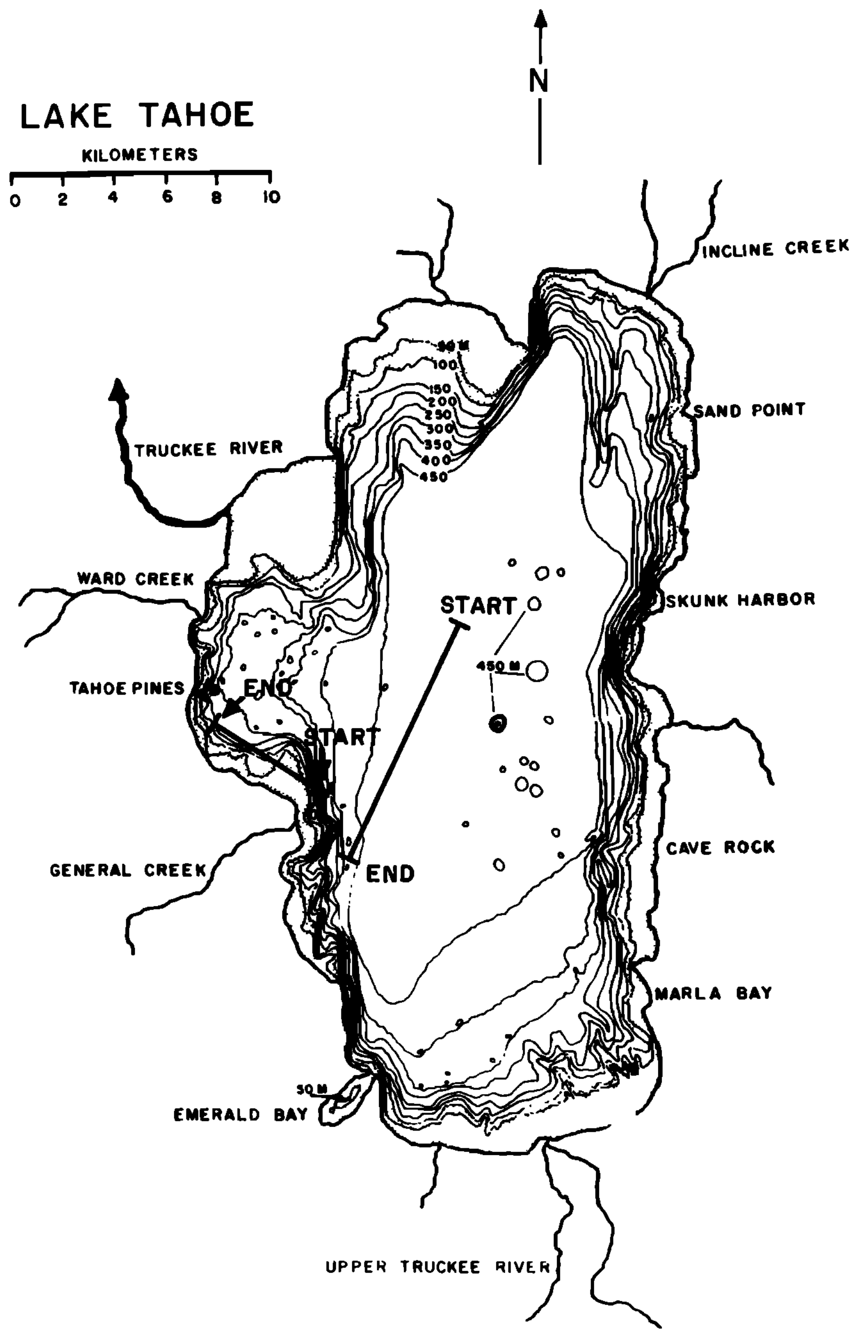

Fig. 1. Morphometric map of Lake Tahoe showing transect locations.

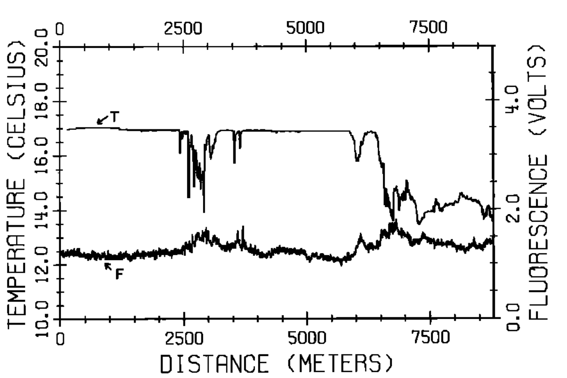

Fig. 2. Chlorophyll and temperature transect of July 26, 1977, in midlake region.

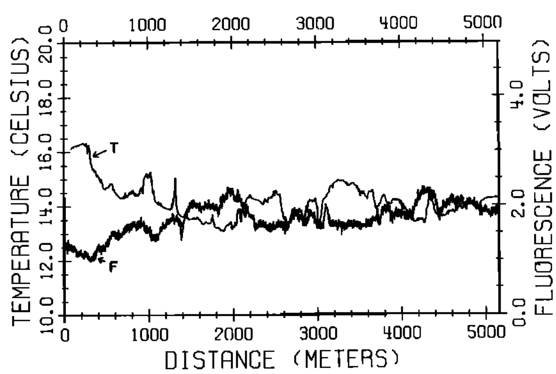

Fig. 3. Chlorophyll and temperature transect of July 26, 1977, in nearshore region.

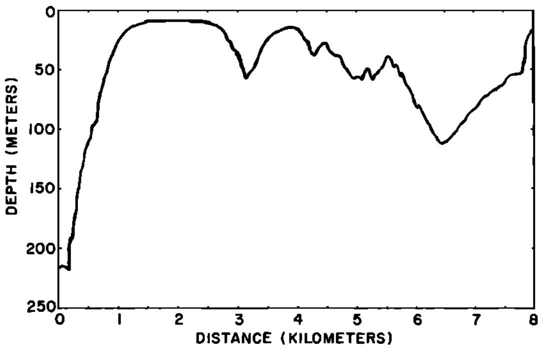

Fig. 4. Lake bottom topography from nearshore transect, July 26, 1977.

markedly from those within a deformation radius of the shore. Another factor that influences the nature of the coastal zone is the detailed pattern of the surface wind stress. Lake Tahoe is dominated in early summer by strong afternoon winds from the southwest. This can cause surface wind drift offshore of the warm upper layer of water in the coastal zone on the western shore that could lead to an upwelling of cold water. Though the details of the vertical motion in this region remain to be investigated, significantly lower mean temperatures in the coastal zone (3°C, see Figures 2 and 3) strongly suggest upwelling. Bottom irregularities could then interact with upwelling to account for the variability in temperature and chlorophyll. This picture suggests that other coastal regions of the lake with different wind conditions may exhibit different coastal patterns.

The presence of wind sufficient to cause significant upwelling would also initiate vigorous mixing; thus one would not expect such large discontinuities between the coastal zone and midlake to persist for long. However, these winds are transitory, usually lasting not more than a few hours. Also, under the strong stratification present in early summer, mixing intensity should be reduced. With mixing restricted to a shallow epilimnion and caused only by a transitory wind stress, only limited upwelling can be maintained. This allows the midlake region to retain its normal thermal structure, whereas the coastal zone is influenced by upwelling, thus creating the frontal region between them. From this process it follows that a seasonal change in wind stress and stratification should change the structure of the coastal-midlake separation.

Turbulent mixing will also be an important factor in coastal dynamics, particularly with reference to the distribution of chlorophyll. Since the midlake and coastal regions differ in wind exposure, bottom topography, and the presence or absence of land barriers, one would expect turbulence to vary between the two zones. As is shown in Figure 2, the chlorophyll distribution is highly dependent on physical processes (see also *Powell et al.* [1975]; *Denman and Platt* [1975]), and not surprisingly, turbulence will influence its distribution, possibly causing significant differences between nearshore and offshore waters.

Analysis, Results, and Discussion

The chlorophyll variance in July is an order of magnitude higher in the nearshore transect than in the midlake transect. Spectral decomposition [*Jenkins and Watts*, 1968] of the chlorophyll record shows how variance (or spatial variability) is partitioned among different length scales (more precisely, among different wave numbers). Different spectral shapes indicate that different processes are affecting the distribution of chlorophyll. It is useful to divide each smoothed spectral estimate by the total variance in the record. Spectra normalized in this manner allow for direct comparison between spectral shapes [*Denman*, 1975].

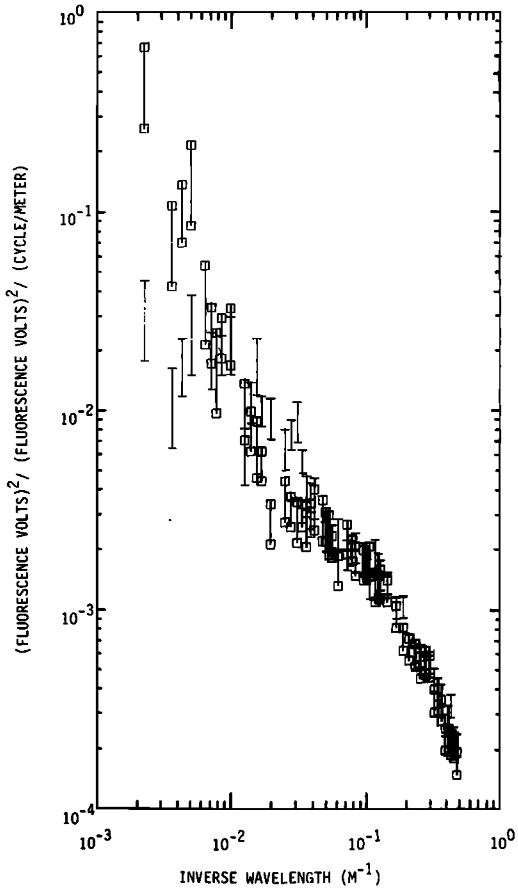

Fig. 5. Fluorescence spectra normalized to total variance from July 26, 1977. Error bars reflect 80% confidence interval. Horizontal lines indicate midlake transect; squares, nearshore transect.

Figure 5 shows two such normalized chlorophyll spectra, one from the midlake transect before it encounters the coastal front and the other from the nearshore transect. It is useful to look at three separate spectral regions: large scales, from 1 km or so to several hundred meters; intermediate scales, from a few hundred to 10 m; and small scales, less than 10 m. Upon comparing the midlake and nearshore spectra, we note that at large scales the nearshore transect has significantly more vari-

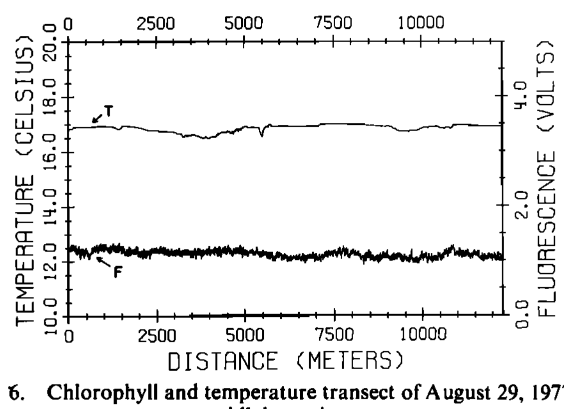

Fig. 6. Chlorophyll and temperature transect of August 29, 1977, in midlake region.

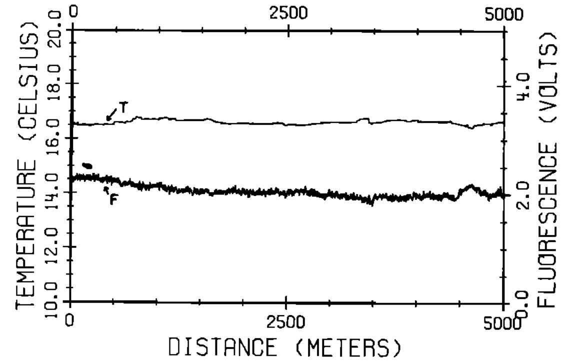

Fig. 7. Chlorophyll and temperature transect of August 30, 1977, in nearshore region.

ance. This observation is consistent with the following interpretation. First, stream inflow is a significant source of nutrients [*Goldman et al.*, 1972]. Streams in Lake Tahoe are usually separated by a few kilometers or so (large scales); if nutrients are imported to the lake by streams, phytoplankton should show increased growth at these scales. Thus variance at large scales should be increased, particularly in the coastal zone, where stream inflow should have its greatest effect. The absence of large-scale variance in the offshore zone indicates the slowness of exchange between inshore and offshore waters [*Boyce*, 1974]. Second, the relative uniformity of the temperature trace in the midlake region (neglecting the internal wave activity) in comparison to the coastal zone indicates that the midlake water mass is more homogeneous than the nearshore water mass. Thus it is not surprising that there is less relative variance in the chlorophyll spectrum at large scales in midlake.

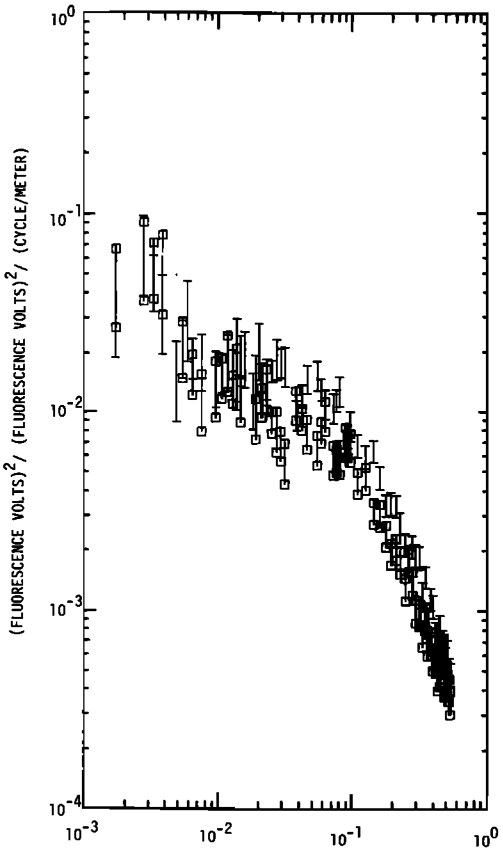

Fig. 8. Fluorescence spectra normalized to total variance from August 29 and August 30, 1977. Error bars reflect 80% confidence interval. Horizontal lines indicate midlake transect; squares, nearshore transect.

At intermediate scales the variance in both spectra falls steadily, consistent with theoretical models [*Denman et al.*, 1977]. However, the nearshore spectrum falls faster and then exhibits a plateau at a scale of 100–10 m. This discontinuity in the spectrum suggests that there is an input of momentum at these scales. The presence of boundaries and small fetch (i.e., intermediate 'eddy' sizes) in the nearshore might be the source of the increased momentum at this scale. Such an input of momentum should increase the chlorophyll variance at these scales [*Ozmidov*, 1965]. We emphasize here that the spectra in Figure 5 are normalized to the total variance. The absolute variance in the nearshore spectrum is greater than that in the midlake spectrum at every scale. Though the normalized spectra show less variance at intermediate scales in the nearshore than in midlake, the plateau in the coastal spectrum does indicate an increase of variance relative to the same region in the midlake spectrum in which variance declines monotonically. If momentum is introduced only at large scales in midlake, the simplest pictures of isotropic turbulence suggest a cascade of momentum down the spectrum to smaller scales. This results in a smooth spectrum of momentum fluctuations with a slope traditionally predicted to be $-\frac{5}{3}$ [*Monin and Yaglom*, 1975]. Then if chlorophyll can be considered a passive contaminant at these intermediate scales, its variance spectrum should also show a similar smooth shape [*Batchelor*, 1953]. This view is confirmed by the midlake spectrum that falls more uniformly between 100 and 10 m than the nearshore spectrum. Note that at both large and intermediate scales the normalized spectral levels differ by several standard deviations. Thus the contrasts between nearshore and midlake chlorophyll patterns appear to be the result of differences in physical processes in the two zones. In the nearshore zone, sources of nutrients impose substantial large-scale patterns on the chlorophyll concentration. At intermediate scales, more intense sources of momentum increase chlorophyll variance. The midlake region has weaker sources of large-scale variance in chlorophyll, owing to the slow mixing of coastal and midlake waters. The smooth cascade of variance from large scales to small scales suggests that momentum is input primarily at large scales.

The spectral shape at small scales is dominated by our data collection procedures. That the spectra are identical at these scales further confirms that only hose mixing and machine noise are being measured, rather than the actual chlorophyll distribution. Coincidentally, this result also confirms our normalization procedure, since the shape of the spectrum due to hose mixing and machine noise should always be the same if it is normalized correctly to total variance.

As was suggested earlier, changes in wind stress and stratification should affect the coastal-midlake separation. Transects were done in August, after a period of strong persistent winds. By this time the thermocline depth had increased from 15 to 23 m. The traces from both midlake and nearshore were essentially identical (Figures 6 and 7), the variation in chlorophyll and temperature being sharply reduced in comparison to the July transects. Nearshore fluorescence values were still about 50% higher than midlake values, but there was no identifiable frontal zone. The normalized spectra from the chlorophyll transects (Figure 8) show that the variance at large scales in the coastal zone has decreased, probably because of the cessation of stream inflow and its associated nutrient inputs (1977 was the driest year in 100 years in California, and all streams had dried up by mid-August at Lake Tahoe). Thus there would be no source to create large-scale phytoplankton patches. Though the spectral levels differ at intermediate scales, the shapes of the spectra from midlake and nearshore are more similar than they are in July (Figure 5). This indicates that the physical processes affecting the chlorophyll distribution at these scales are more similar in the nearshore and midlake zones, after the erosion of the front.

CONCLUSIONS AND SUMMARY

There is a distinct difference between the nearshore and midlake water masses in early summer. The coastal zone shows higher and more variable levels of chlorophyll. At large scales (greater than 100 m) it is dominated by stream inflow of nutrients and by possible upwelling events created by the particular exposure and wind patterns of the area. The midlake shows less variation at large scales, owing to the absence of stream effects and the slow exchange between midlake and coastal waters. Intermediate scales in the coastal zone are dominated by an input of momentum, created by side and bottom boundaries. Intermediate scales in midlake show monotonically decreasing variance without the plateau present in the nearshore spectrum, indicating that momentum is input primarily at large scales. As the season progresses, wind action erodes the midlake-coastal boundary, leaving the two water masses virtually identical. The nearshore spectrum now has less variance at large scales, owing to the cessation of nutrient inputs by streams. At intermediate scales the similar shapes of the coastal and midlake spectra indicate that the processes governing the chlorophyll distribution are now more similar. Thus the physical dynamics of stratified basins dominate the pattern of spatial heterogeneity of chlorophyll.

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