NOTES AND CORRESPONDENCE

Distribution of Salinity and Temperature in the Hudson Estuary[1]

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ABSTRACT

Vertical salinity profiles in the Hudson Estuary are extremely variable, and often contain finestructure similar to that in oceanic stratification. This finestructure may be caused by the stability-dependent vertical diffusion of salt. The interpretation of *T-S* diagrams indicates that, to a first order, temperature and salinity are controlled by conservative mixing processes, and that residence time in the Estuary is approximately one or two weeks.

1. Introduction

The CIMAS program of monthly surveys of the Hudson Estuary from the inner New York Bight to Saugerties, N. Y., has been in progress since December 1973. The physical oceanographic observations on which this report is based have been made at each of the 16 stations of the survey. Biological, chemical and geological observations reported elsewhere (Weiss *et al.*, 1975) have also been included among the routine station operations.

Temperature was measured by means of an *in situ* temperature probe, and salinity was converted electrically from the output of an *in situ* induction conductivity probe, both part of the Inter Ocean 513 D Probe. On several surveys, continuous vertical profiles of salinity and temperature were automatically graphed by an X-Y_1-Y_2 plotter. In addition, temperature vs salinity graphs were automatically plotted by a second X-Y plotter.

2. Salinity profiles

Abood (1974) characterizes the mean vertical salinity profiles in the Hudson Estuary and in partially mixed estuaries in general, as cubic functions of depth with zero vertical gradients at the surface and the bottom, and a maximum gradient at mid-depth. In contrast to the classification of the Hudson as a partially mixed estuary, Howells (1972) classifies it as a "shallow, well-mixed" estuary between the Battery and Haverstraw Bay, the entire mesohaline sector. The variety of generalizations applied to the Hudson is increased still further by Simpson *et al.* (1973), who describe the stratification as a "two-layer structure" or "salt wedge" except where strong vertical mixing destroys the vertical stratification.

While the salinity profiles determined from observations at discrete depths, as described above, are informative, continuous vertical salinity profiles of the Hudson Estuary offer new insights into stratification and mixing processes, not obtained by previous, coarser sampling methods. Fig. 1 shows several continuous vertical salinity profiles recorded in December 1974. (The range of salinity from surface to bottom was approximately the same under these winter conditions as it was in July 1974 during the previous summer.) The most striking characteristic of these profiles is the fact that each is representative of a different estuary type, and some are not classifiable as any of the usual types. Each of the large variety of profiles in Fig. 1 has been observed on numerous occasions; none is an isolated rarity in the Hudson Estuary. Clearly none of the simple generalizations referred to in the preceding paragraph is adequate as a general representation of the instantaneous continuous vertical salinity profile in the Hudson Estuary.

The profiles in Fig. 1 labelled KVK and ER were taken at the confluences of the two side branches with the Hudson Estuary, so they are not truly estuarine. Nevertheless, as stated above, profiles similar to those at these two stations have been observed in the Estuary proper at the same time or at other times.

The alternating high-gradient and low-gradient layers

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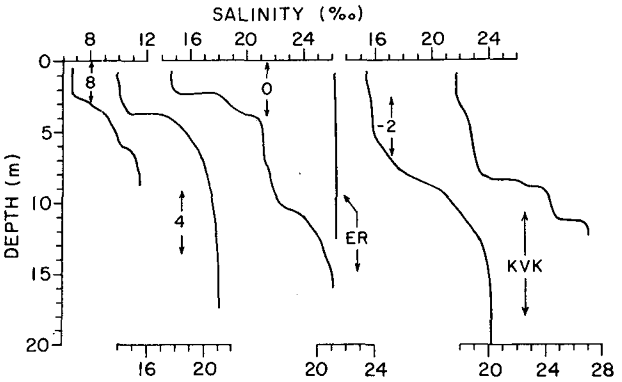

FIG. 1. Vertical salinities at six stations in the Hudson Estuary, 7–8 December 1974. Each profile taken at mid-channel is identified by its mile point north of the Battery. The profiles taken at the confluences of the Hudson Estuary with side branches at mile points −6 and 0 are labelled KVK (Kill van Kull) and ER (East River), respectively.

in profiles at mile points 0, 8, and KVK, which will be referred to here as "finestructure," are not observable by the discrete-depth sampling procedures referred to earlier in this paper. The use of continuous-profiling STD's in deep sea research has led to reports of similar finestructure in the open ocean. For example, Gregg *et al.* (1973) observed irregularities in the vertical stratification with wavenumbers around 0.1 cycle per meter in the main thermocline of the central North Pacific. We speculate that the estuarine finestructure in Fig. 1 has a genetic affinity with deep sea finestructure in stable water. While horizontal advection and other processes probably play an important role in generating and maintaining such finestructure, we speculate further that the vertical diffusion process discussed in the following paragraph also has an important role.

It can be shown by a well-known argument that, if the fluxes throughout a region tend to increase with increasing salinity gradients, diffusion processes will tend to smooth out variations, or finestructure, in the salinity profiles. This applies to small vertical salinity gradients, which correspond to low stability. Inversely, if the fluxes throughout a region would tend to decrease with increasing salinity gradient, an analogous argument can show that the variations of gradient in this region will actually increase as a result of diffusion, leading to a step-like finestructure. This applies to large vertical salinity gradients because the high stability inhibits mixing. Vertical diffusion can thus create, as well as eradicate, finestructure such as that in several of the vertical salinity profiles in Fig. 1. A detailed, quantitative treatment of this phenomenon is given by Posmentier (1977).

3. *T-S* relationships

While the spatial distribution of temperature and salinity are an important consideration, considerable additional insight can be provided by the use of *T-S* diagrams. It is well known that a body of water throughout which there is a conservative mixture of two water types is represented on a *T-S* diagram by a straight line connecting the two water types. The converse inference is usually valid, i.e., a body of water represented by a straight line on a *T-S* diagram is probably formed by conservative mixing between two water types. Exceptions to the latter inference might be expected where non-conservative processes such as precipitation, evaporation, heating or cooling take place. In the open ocean, these factors often obscure the characteristic *T-S* relationship within the upper depth of frictional influence, which is approximately 50 m in mid-latitudes. These reservations should generate initial skepticism about the use of *T-S* diagrams in studying the Hudson Estuary. Nevertheless, as we shall show, the method proves fruitful.

A *T-S* diagram of data from the Hudson Estuary is illustrated in Fig. 2. For the months shown in Fig. 2, the only data omitted are from those stations which overlap the stations shown. For example, while stations 10 and 11 are omitted from the April data because they extend along a straight line from 9 to 12, no data from station 9 have been omitted—they all fall at the same point.

Fig. 2 contains a number of noteworthy features. First, during any one sampling period the entire volume of the Estuary is represented to first order by a single straight line on the *T-S* diagram, and can therefore be described as a water mass which approximates a conservative mixture of two water types, freshwater and sea water. It should be emphasized that "entire volume" refers to *all* stations and *all* depths, combined. If any non-conservative process such as surface heating or evaporation had effects comparable to those of the mixing process, portions of the water mass would

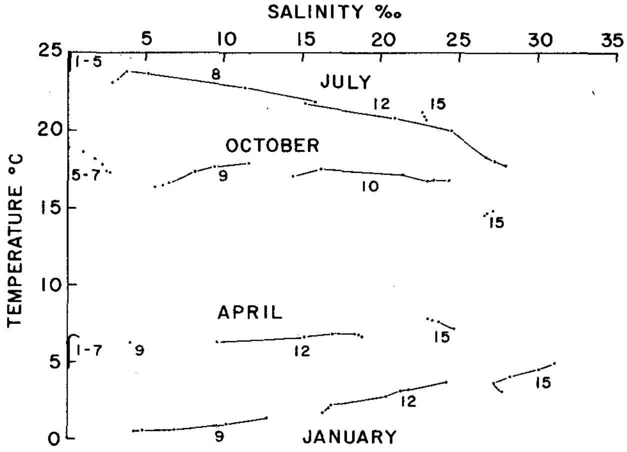

FIG. 2. *T-S* diagram of the Hudson Estuary water mass for four different months in 1974. Station numbers range from 1 at the upstream-most station (Saugerties, mile point 99) to 15 at the seaward-most station (Lower Bay, mile point −12).

necessarily deviate significantly from the straight line. (An exception to this statement could occur only if a non-conservative process acted at all depths and positions at a rate exactly equivalent to the local time derivatives of the two water types' *T-S* values—a highly improbable coincidence!) The description of the mixing process in the Hudson Estuary as "conservative" is therefore a reasonable approximation.

Although residence times may be calculated by a diffusion-advection approach, it is interesting to note that they may be approximated by interpreting the *T-S* diagram. For the purposes of this paper, residence time in the Estuary is defined as the time required for half the water in the Estuary between the Narrows and Saugerties to leave that region. If the residence time in the Estuary were one month or longer, older water would deviate toward older lines on the *T-S* diagram, and not lie on the straight line between the two current water types. The residence time is therefore significantly less than one month. On the other hand, curvature in the lines is observable, so the residence time is probably not as short as, say, three days. The residence time is therefore roughly one or two weeks. This conclusion is consistent with Stewart's (1958) observations of a lag time for flow variations of 10 days between West Point and New York Harbor.

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