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Analysis of water temperature variability in the Gulf of Eilat*

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1. Objectives

To analyze the time series of temperature profiles for the Gulf of Eilat in order to reveal any long-term trends and, if possible, assess the interannual variability.

2. Methods

The analysis is based on historical observations of water temperature and salinity in the Gulf of Eilat, which are organized in a database developed by the Interuniversity Institute for Marine Sciences at Eilat. The database has an on line interface (http://132.64.212.80/PeacePark/index.html) which allows the user to select and download the necessary data. We used this interface to download all temperature and salinity data available as of May 2004 in the "Sea Water Chemistry" and "CTD" datasets.

Data description.

The "Sea Water Chemistry" dataset contained 3,960 records of observations carried out during the period from 17 July 1975 to 14 December 2003. The "CTD" dataset contained 150,318 records of observations carried out during the period from 14 July 1988 to 14 December 2003. Each record contains date/time and space coordinates as well as values of the observed parameters at that point. 8.4% of the records have observation times defined as 00:00. Apparently the actual time of the observation was not recorded. The space coordinates in the records are defined by the fields "Depth" and "Station_ ID". The latter could be related to the station description table which is also available. The set of observed parameters varies from record to record. The "Sea Water Chemistry" dataset has salinity data for 99.9% of records while only 24% of records have temperature data. The "CTD" dataset has salinity data for 99% of records and all records contain temperature data.

These two data sets were merged and all records were combined in order to mark out records relating to a cast of measurements disregarding whether it is a bottle cast or CTD cast. Each group of records which has identical "date/time" field and "Station_ID" field is marked with a "Cast_ID" which is unique in our database. The total number of casts accepted for processing was 34,000. Most of the casts (32,992) are not casts in the

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Data provided by the Interuniversity Institute for the Marine Sciences at Eilat.

traditional oceanographic sense of this term. These data belong to time series which were measured by a bottom mounted CTD at “Data station – 164” during period from 28 February 2001 to 23 December 2001 with a 10 min time interval (Fig. 1).
These observations could be useful for estimating the variability on time scales ranging from several hours to several weeks. However we excluded these data from cast ensemble analyzed below for investigating the seasonal and long-term variability of the temperature in the Gulf of Eilat. We also excluded from the analysis 353 casts in which the number of measurement levels is less than 3 and where depth of the deepest level is less than 40m.

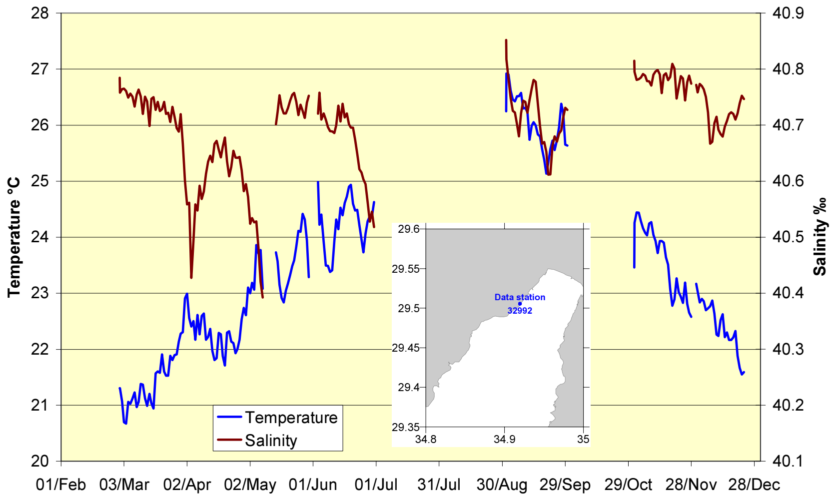

Figure 1. Time series of water temperature and salinity at the “Data station 164” during 2001. Measurements from a bottom mounted CTD (depth 0.6-2.1 m).

<u>Data quality control.</u>
For the 640 casts accepted for the long-term analysis we implemented a two step procedure of data quality control:

- testing the temperature and salinity profiles for the presence of static instabilities;
- analyzing the temperature and salinity profiles for the presence atypical vertical distributions.

Although analysis of salinity was not direct objective of this investigation, nevertheless we also carried out the quality control of salinity profiles since they are needed to calculate potential temperature and density. As a result of the first step of the quality control we found 88 casts with a decrease of potential density with depth of more than 0.05 kg/m^3 between two adjacent levels. During the second step we visually and subjectively checked all profiles with an emphasis on the casts flagged during the first step of the quality control. A summary of the quality control is shown in Table 1.

Table 1. Results of data quality control applied to 640 casts accepted for the analysis of water temperature variability in the Gulf of Eilat.

	Number of available casts	Number of rejected casts	Number of accepted cast with levels marked as bad or suspicious
Temperature data	493	12	29
Salinity data	637	34	77

Most of the rejected salinity profiles came from the "Sea Water Chemistry" dataset. A large number of these profiles had no temperature data at the corresponding levels. Therefore they could not be checked for static stability. It is possible that the water samples for these profiles were taken during the upcast from bottles placed on the CTD rosette. By comparing these profiles with other salinity profiles we marked as incorrect any observations with obvious discrepancies in both the shape of the profile and the salinity values (for example see Fig. 2). All data marked as incorrect or suspicious were not used in the investigation.

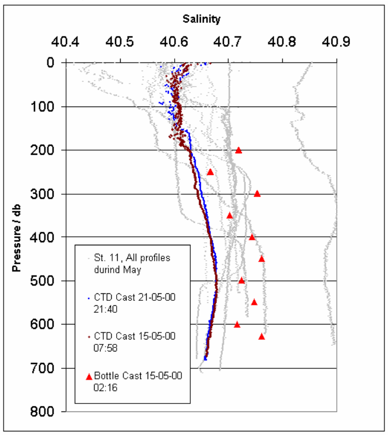

Figure 2. Example of significant discrepancies between the salinity profiles measured at the same station with a time interval of only several hours between observations. Data from the "Sea Water Chemistry" dataset (red triangles) were flagged as incorrect.

<u>Time and space distributions of profiles selected for the analysis.</u>

The water temperature observations in the Gulf of Eilat database cover the years from 1975 to 2003 (Fig. 3). Prior to 1988 all measurements were conducted with reversing thermometers mounted on bottles. These observations have a relatively low vertical resolution (50-100 m) since the bottles were located on "standard levels". Since 1988 most temperature measurements have been conducted with various types of electronic temperature profilers. The vertical resolution of these profiles varies from 0.5 m to 2 m.

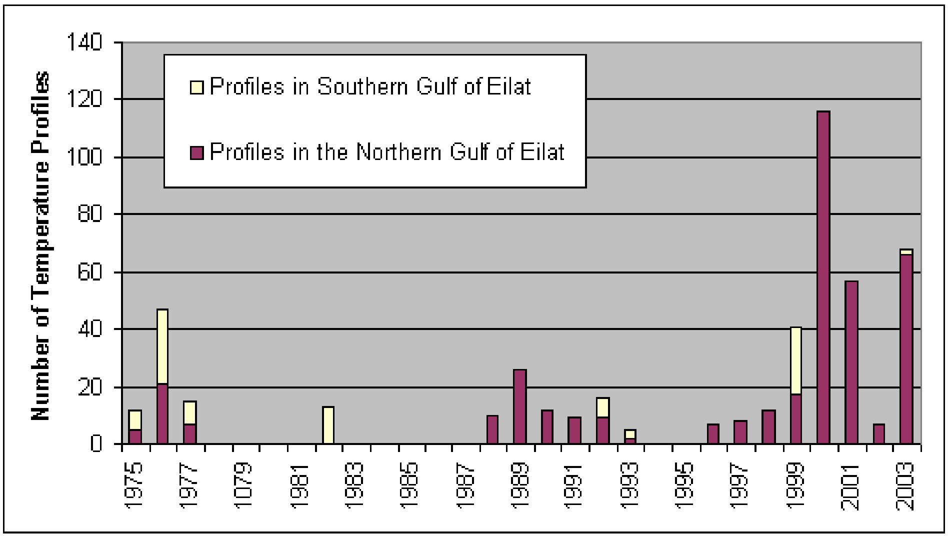

Figure 3. Yearly count of temperature profiles measured in the Gulf of Eilat from 1975 to 2003. The gulf was divided into the Southern and the Northern parts along latitude 29.45°N (Fig. 4).

The observations that were carried out in the Southern part of the gulf (Fig. 4a) can be divided into four main subsets:

- 1975-1977 - 41 stations along gulf (Fig. 5). Paldor and Anati (1979) used this data set to investigate the seasonal variability of the gulf's thermohaline structure;
- 1-7 February 1982 - 13 stations from the "Tiran II" cruise (Fig. 6);
- 22-27 November 1992 - 7 stations of the "Reeflux" cruise (Fig. 7), with a repetition of the three northern stations on 12 February 1993;
- 21-26 February 1999 - 24 stations of R/V Meteor cruise (Fig.8).

Of the total number of observations, 80% were carried out in the northern part of the gulf (Fig. 4b). The maximum number of profiles (271) is located within the square that includes Station A.

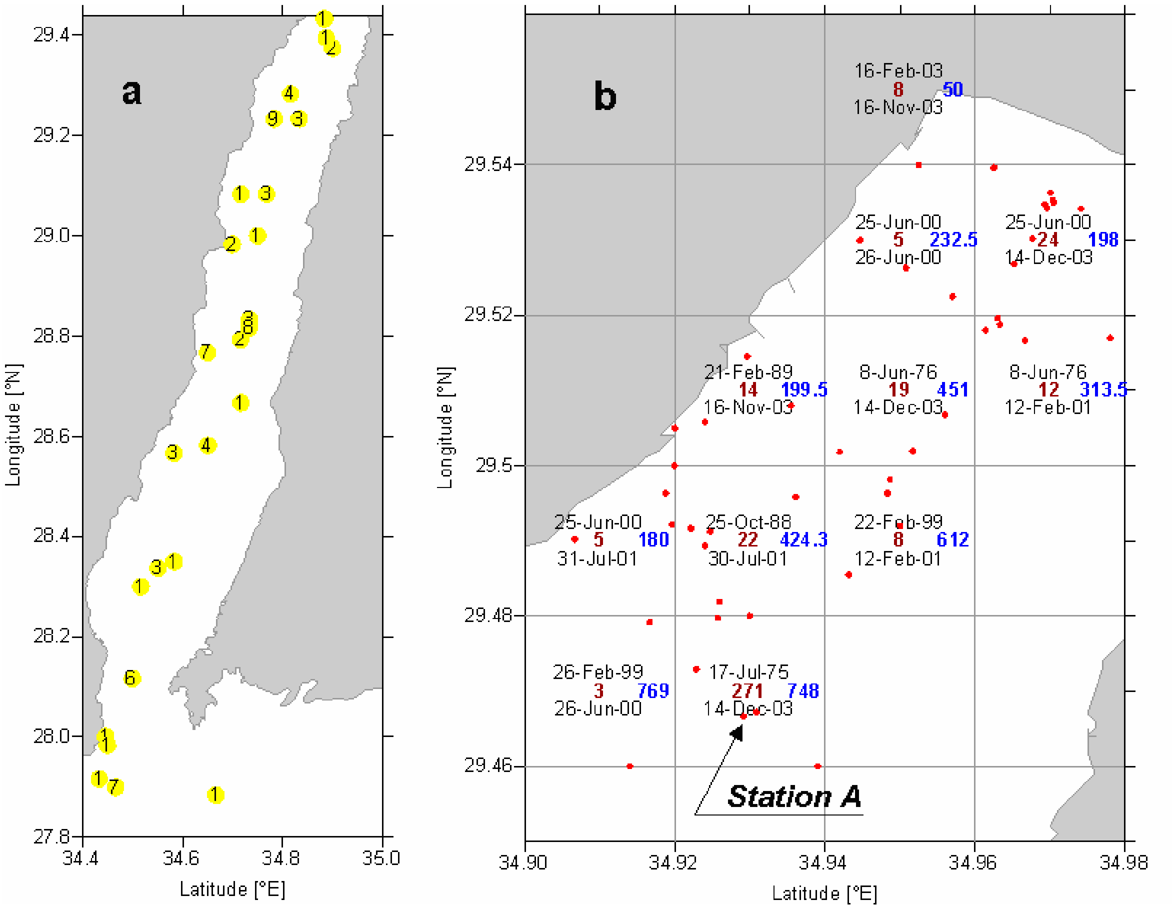

Figure 4. Location of temperature profiles in the Southern Gulf of Eilat (a) and the Northern Gulf of Eilat (b). For the Southern part (a) the number within the yellow circle is the count of profiles carried at the station during the entire period. For the Northern part (b) the red circles are the positions of the stations. Summaries of the profile distributions are shown for each 0.02°x0.02° square which contained observations. The number in the center of a square is the count of profiles carried out within that square; the upper date is the date of the first observation while the lower date is the date of the last observation; the blue number is the maximum depth of observation within the square.

4. **Results**

General view of the water temperature structure.

To obtain a general view of the temperature structure we constructed four along-gulf sections (Figs. 5-8) for four different periods (Fig. 5 - February 1977; Fig. 6 - February 1982; Fig. 7 - November 1992; and Fig. 8 - February 1999). In these sections north is to the left. The first two sections have the most southerly stations located outside of the Strait of Tiran. One can clearly see the differences between the temperature structures within gulf and in the northern part of the Red Sea. The gulf has a two layer stable structure with a thermocline between them. The depth of the thermocline is significantly shallower in November (200 – 250 m, Fig. 7) as compared to February (300-500 m, Figs. 5, 6, and 8). The deep layer is permanently colder than the upper layer. The Red Sea waters at the depths corresponding to the deep layer of the gulf are always warmer than the gulf waters. All sections show a high level of homogeneity in the deep layer (temperature range less than 0.05°C) and monotonic decrease of water temperature from south to north in the upper layer (about 0.5°C).

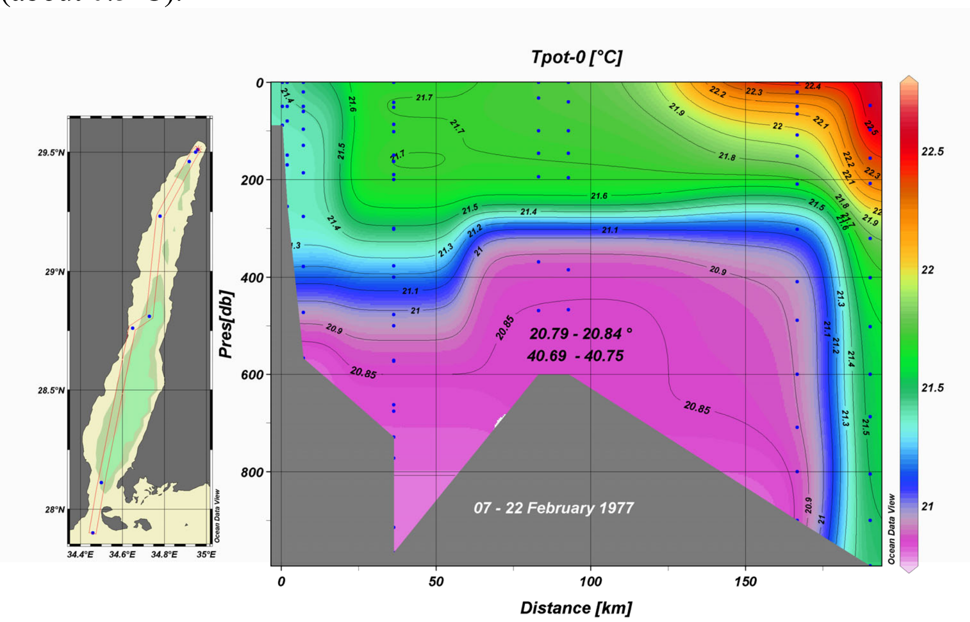

Figure 5. Potential temperature on a section along the Gulf of Eilat during 07-22 February 1977. (North is to the left. Ranges for the deep layer potential temperature and salinity are indicated by a large italic font).

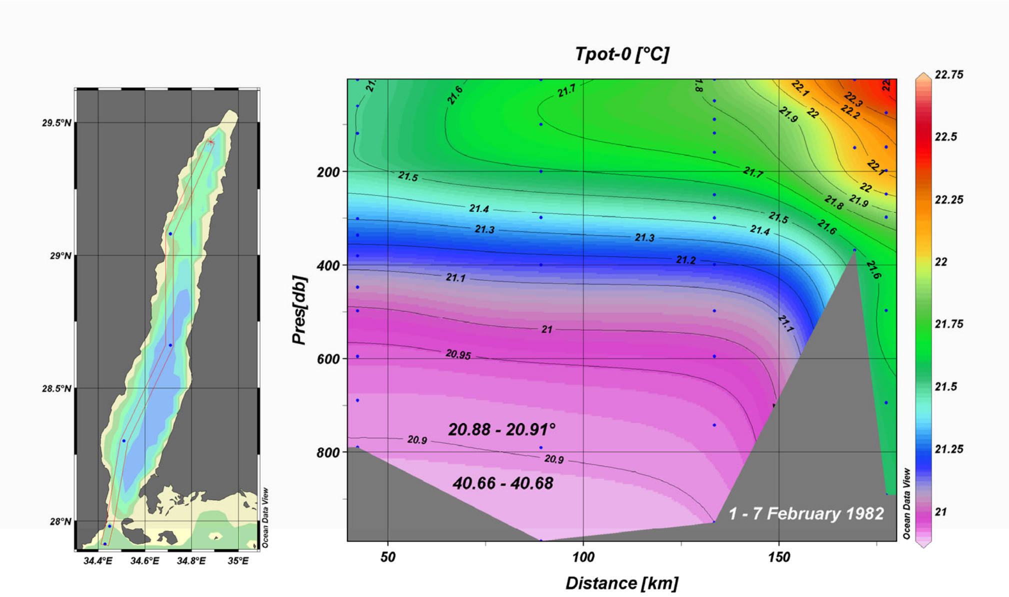

Figure 6. As in Fig.5 except for the Tiran II cruise, 1-7 February 1982.

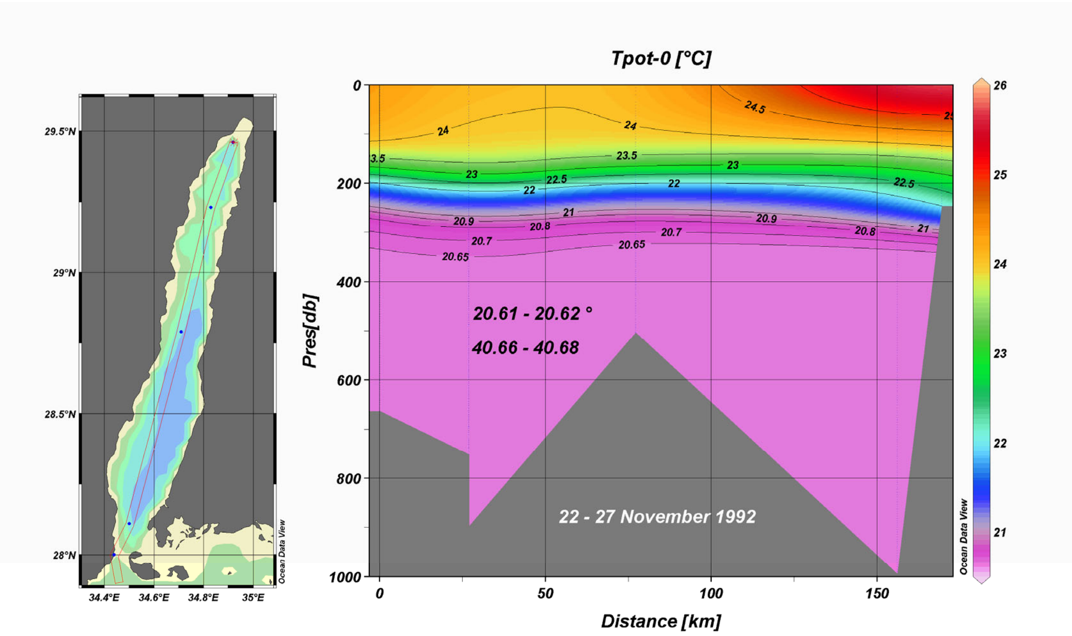

Figure 7. As in Fig. 5 except during 22-27 November 1992.

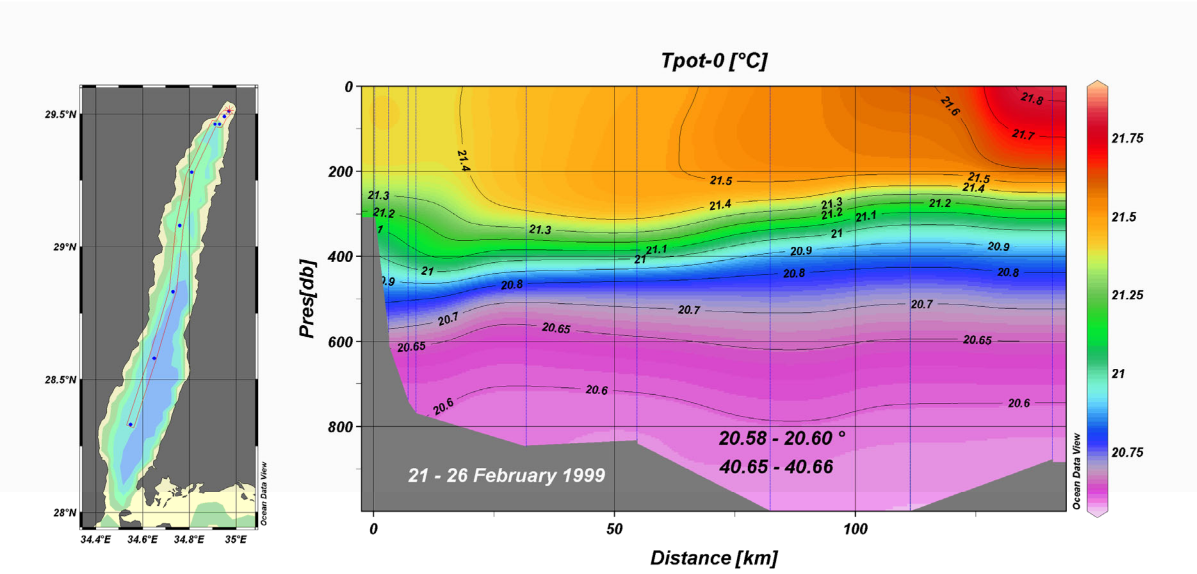

Figure 8. As in Fig.5 except for the R/V Meteor cruise, 21-26 February 1999.

Seasonal variability

To estimate the seasonal variability we used only the observations at stations which are located northward of latitude 29.45°N (Fig. 3b). For the northern part of the gulf we assume the absence of significant horizontal gradients. After interpolation of all profiles to standard levels and averaging within individual months, we grouped data according to the date of observation regardless of the year (Fig. 9). The distributions for each level were approximated by polynomial functions of order 6. Figure 10 shows the seasonal changes of potential temperature on different levels of the northern part of the gulf.

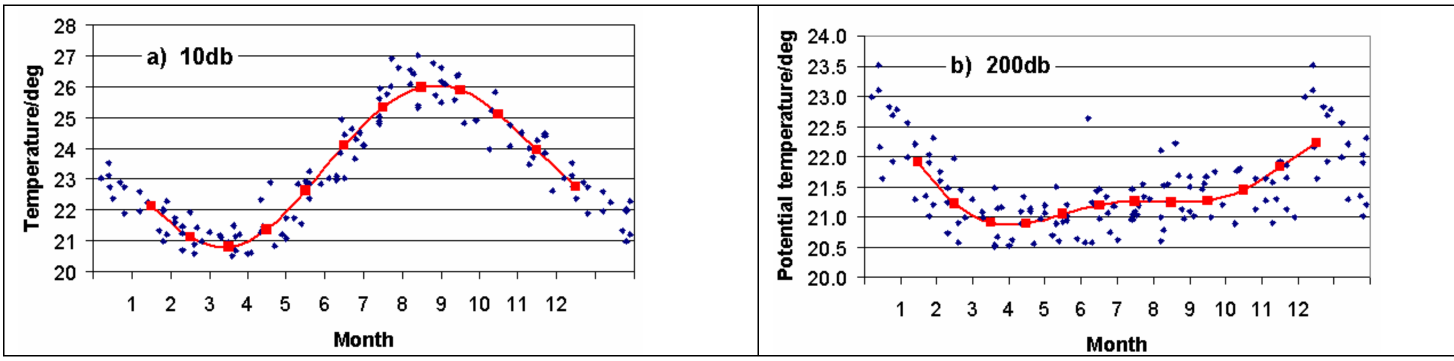

Figure 9. Examples of polynomial approximations of climatic seasonal changes of the water temperature for different levels of the northern part of the Gulf of Eilat.

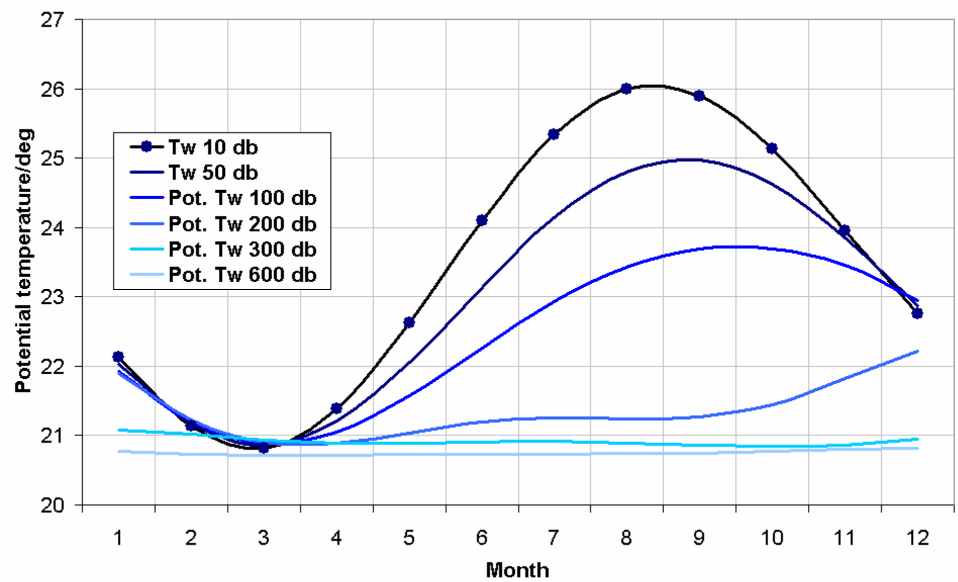

Figure 10. Seasonal changes of potential temperature for different levels of the northern part of the Gulf of Eilat.

The seasonal minimum of the temperature in the northern part of the Gulf of Eilat is observed during March, when the water column is well mixed to at least 300 m by winter convection. The seasonal maximum within the upper mixed layer (UML) is observed in August. The summer UML is usually at least 10-20 m deep while in winter (from the middle of November until the end of March) it is at least 50 m deep. The seasonal thermocline during summer is extends to 200 m (Fig. 11) where the maximum temperature is reached in December when the seasonal thermocline is eroded by winter mixing. Winter convection typically reaches 250 – 450 m (Fig. 11) but the observation also show several cases where the water column on the northern slope of the gulf (station A) was mixed to the bottom (about 700 m).

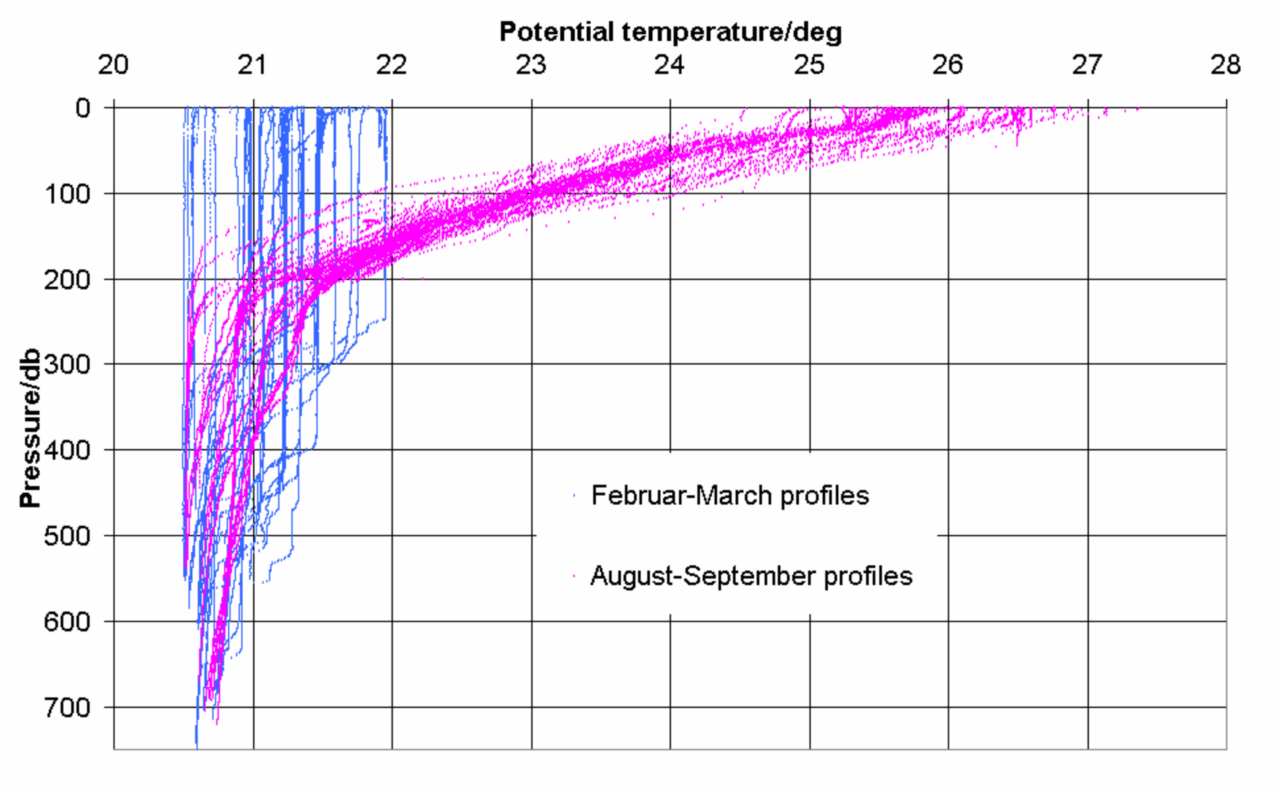

Figure 11. Typical temperature profiles for winter and summer period in the northern part of the Gulf of Eilat.

<u>Interannual changes in the intensity of the winter convection.</u>

As an objective criterion for defining the depth of the UML we used a condition of homogeneity of potential temperature. The ensemble of winter profiles shown in Figure 12 indicates that the limit of fluctuations of potential temperature within the UML of 0.05°C is appropriate for this purpose.

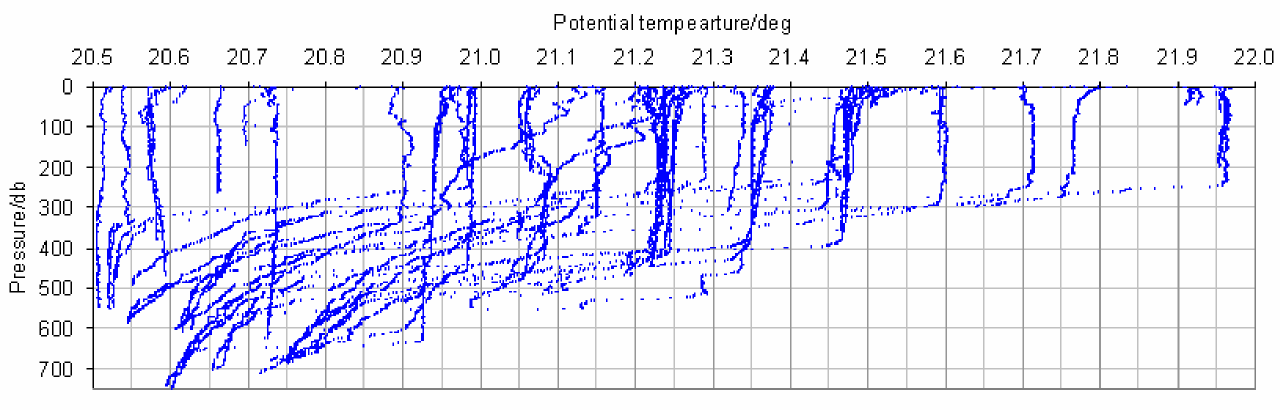

Figure 12. Ensemble of winter vertical profiles of potential temperature in the northern part of the gulf. Fluctuations of potential temperature within UML are less than 0.05° C
To avoid cases where winter convective mixing was interrupted by short daytime heating of the surface layer, we analyzed vertical fluctuation of potential temperature starting from a depth of 50 m.

Figure 13 shows fluctuation of the UML depth derived from potential temperature profiles observed at Station A (plus two additional profiles from the R/V Meteor cruise measured in February 1999 in vicinity of Station A).

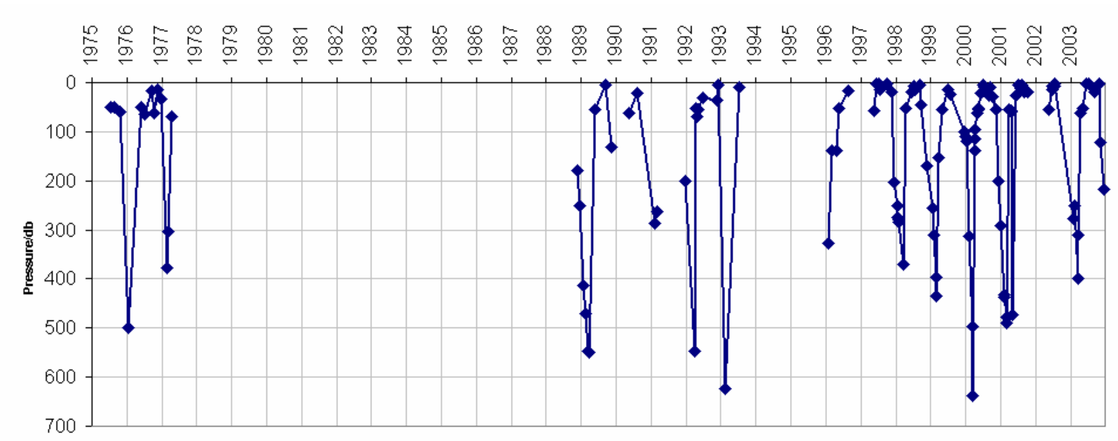

Figure 13. Depth of the upper mixed layer (UML) on the slope of the northern part of the Gulf of Eilat (Station A) derived from the analysis of available vertical profiles of potential temperature. (Fluctuations of potential temperature within the UML are less than 0.05°C).

There are four cases when winter mixing was significantly deeper than climatic penetration (about 250-450 m). These were observed during the winters of 1989 (550 m), 1992 (550 m), 1993 (630 m), and 2000 (630 m). Unfortunately even after 1989 we have no data for following winters: 1990, 1994, 1995, 1997, and 2002.

Long-term tendencies and interannual variability

To estimate the long-term variability in the temperature of the upper layer we used data collected at the 50 db level. We assume that at this depth, long period signals in water temperature fluctuations are masked less by mesoscale and synoptic variability then in the near surface layer.

Figure 14 shows the temperature fluctuations that include seasonal variability. The positive linear trend (0.02°C/year) calculated for this data could not be accepted as significant in the 95% confidence interval since the annual increment of the trend (-0.01 ÷ 0.05) includes the null value (Draper and Smith, 1981).

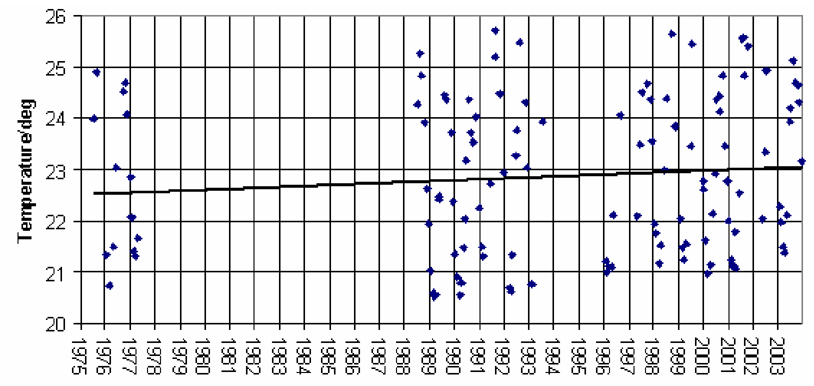

Figure 14. Long-term variability of temperature at a depth of 50 db (the northern part of the gulf). The time series include seasonal variability. The positive trend is not significant.

We then estimated the long-term temperature tendencies in the upper layer for time series which were formed separately from winter measurements and from summer measurements. These experiments also confirm that the fluctuations of temperature in the upper layer do not exhibit any significant long-term tendency.

To investigate water temperature fluctuations within the low layer of the Gulf of Eilat we have chosen the level of 500 db (Fig. 15).

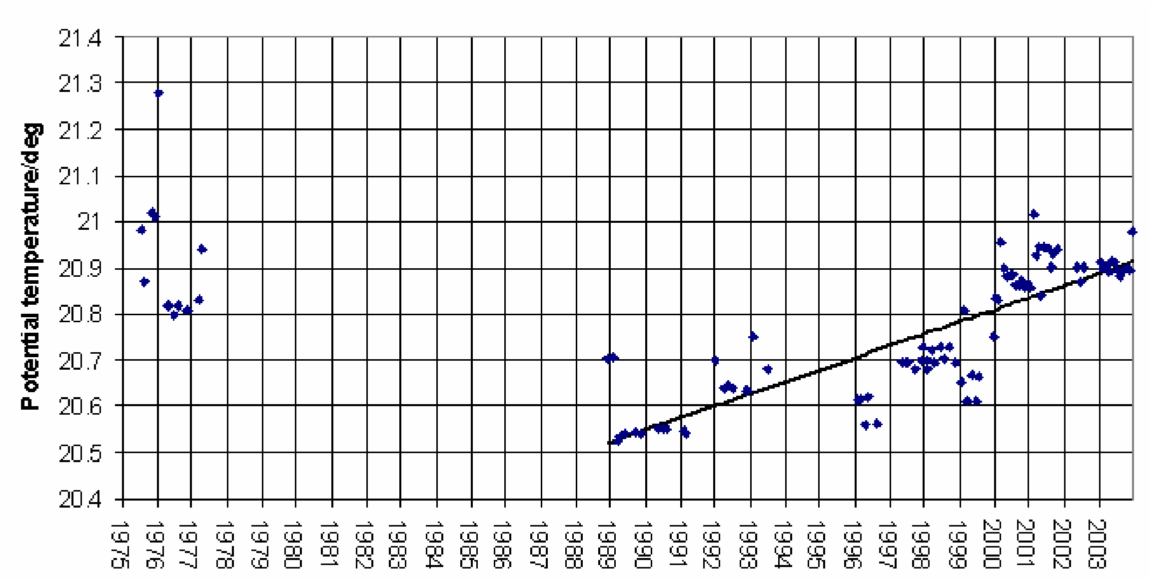

Figure 15. Long-term variability of temperature at a depth of 500 db (the northern part of the gulf). The positive trend for the period 1989-2003 is significant.

The climatic mean temperature for this level is about 20.8°C. During the first period of observation (1975-1977) the temperature was slightly higher then the climatic value, but after a 10 year gap in the observations, the potential temperature of deep the water dropped to its lowest observed value of 20.52°C. From 1989 to 2003 the deep water of the gulf exhibits a stable positive trend with annual increment about 0.03° C per year. The null hypothesis for the annual increment is rejected at the 99% level of confidence.

5. Discussion

The variability of the thermohaline structure of the Gulf of Eilat is defined by the variability in intensity of two major processes: winter convection and horizontal circulation (the latter includes water exchange through the Strait of Tiran). During a normal winter the convective mixing does not penetrate deeper than 300-400 m. The deep water mass, sealed from the atmospheric influence, slowly increase its temperature due to weak turbulent mixing with the upper layer. Intensive evaporation slowly increases salinity in the upper layer. Relatively severe winters in the gulf region occur periodically as result of variability of the large scale atmospheric circulation or as result large scale fluctuations in the transparency of the atmosphere (Genin et al., 1995). Intensification of the winter convection during a severe winter leads to intensive dense water formation in the north part of the gulf. These waters spread southward along the slope and ventilate the deep water mass. The surplus of the deep water outflow into the Red Sea may intensify the horizontal circulation. The last mechanism advects water with relative low salinity in the upper layer from south to north (Wolf-Vecht et al, 1992). Apparently most intense renewal of the deep water occurred during the winter of 1989 when the surface water temperature reached a very low value of 20.5°C. The water column during the winter was mixed to the bottom at least in the northern part of the gulf. It is interesting to note that the minimum of potential temperature in the deep water mass (about 20.50°C) was reached in the winter of 1989 (coldest profile in Fig. 12) but not in winter 1992 as suggested by Genin et al. (1995). Salinity during that winter was also relatively low, but it was not the winter with the lowest salinity.

6. Conclusions

- The Gulf of Eilat has a stable two-layer structure. The upper layer includes the upper mixed layer (UML) and the seasonal thermocline. For typical conditions the UML depth varies from 20-50 m during the summer to 250-450 m during the winter. The seasonal maximum of temperature in the UML (26 ± 1°C) is reached during August-September while the seasonal minimum (20.8 ± 0.3°C) occurs in the middle of March. The typical depth of the lower boundary of the thermocline during the summer is 200 m. At the 200 m level the maximum seasonal temperature occurs inDecember.
- **The main conclusion relevant to this task is that the temperature of the upper layer does not exhibit any significant long-term tendencies.**
- The deep-water layer of the Gulf of Eilat apparently forms as result of slope convection in the northern part of the gulf. The lowest potential temperature of the deep layer (20.52°C) was observed during the winter of 1989.
- Since the winter of 1989, the water temperature at a depth of 500 db exhibits a long-term increase, which could be approximated by a linear trend with annual increment of about 0.03° C per year. This trend is statistically significant.

7. Open questions

- A possible reason for the long-term increase of the deep-water temperature could be a positive trend in the salinity of the upper layer. In this case during each normal winter the deep water mass will be mixed by convective mixing with water, which is warmer then during the previous winter. Unfortunately the quantity and quality of salinity data are not sufficient to reveal such tendencies in salinity.

- Given the available data, we cannot prove that the fluctuations of water temperature on the northern slope of the gulf reflect fluctuations in the core of the deep water mass of the gulf. It is quite possible that the variability of water properties at Station A is much stronger then in other regions of the gulf.

8. References

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