POC_P - 4167

Summer Density Distribution Near the North-Eastern Coast of Sakhalin Based on the Parametric Modeling of Vertical Structure

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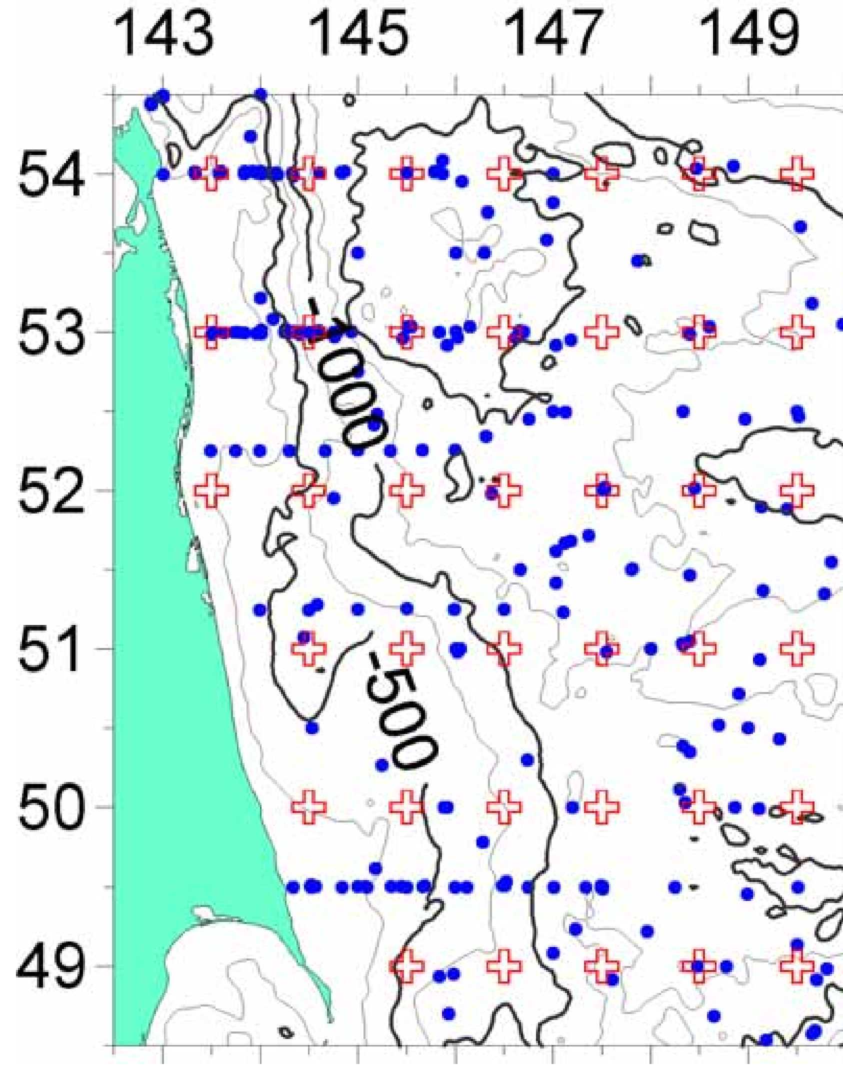
Northern near-shore areas of the region are strongly influenced by runoff of the Amur River, which leads to significant reduction in the salinity of near-surface waters and sharpening of horizontal and vertical density gradients (Muzita et al., 2003). The intermediate layer, with negative values of temperatures, in summer is located at depths from 30-60 m to 150-250 m (Itoh et al., 2003; Fukamachi et al., 2004). Another important feature is coastal upwelling induced by the prevailing southern winds during summer (Budaeva and Makarov, 1999).

The data set included **130 CTD** profiles (1-m resolution) obtained during four summer cruises of the R/V '*Professor Khromov*' (1**998–2000** and **2006**) and **120** quality-controlled profiles (**1937–1993**, mainly bottle data) from the North Pacific hydrobase (Macdonald et al., 2001) for the same season.



The mean density field was constructed on the 1° grid (38 nodes, +).
A principal element of any mapping is an averaging the data.

Any vertical density profile, obtained from observations, represent a set of pressure (or depth) and density values. In general case a form of the profile can be described by a function of two variables and some coefficients (parameters)

$$\boxed{(z_k, \rho_k) \rightarrow F(z, \rho; R) = 0, R=(r_1,\ldots,r_m)}$$

There are three basic approaches to average such a data.

(1) The first one is **isobaric (**or, **z - levels) averaging**, frequently used in oceanographic practice. The Levitus climatological Atlases (Levitus 1982,1994; Levitus et al. 1998) are based on this approach. In this case, the density is considered as some function of depth $\rho = f(z, R)$, and average density for two different profiles on the given level z_c is calculated under the following formula

$$<\rho(z_c)> = 0.5 \, [\, f(z_c, R_1) + f(z_c, R_2)].$$

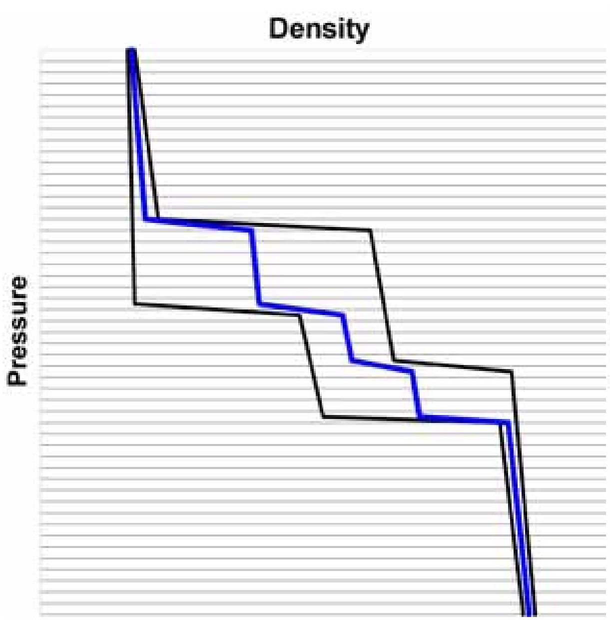
(2) If, vice versa, to consider the depth as the function of density $z = g(\rho, R)$, an average depth can be calculated at each given density ρ_c as following $<z(\rho_c)> = 0.5 \, [\, g(\rho_c, R_1) + g(\rho_c, R_2)]$. This is the base of **isopycnal averaging** from wich the new climatologies of the North Atlantic (Lozier et al. 1995) and the North Pacific (Macdonald et al. 2001) were produced.

(3) An alternative to previous approaches is to average the parameters insted of the variables: $<\rho(z_c)> = f\,[z_c, 0.5(R_1+R_2)]$ or $<z(\rho_c)> = g\,[\rho_c, 0.5(R_1+R_2)]$. Such a technique was used in the Generalized Digital Environmental Model (GDEM), which is applied by the U.S. Navy for most of its operational systems (Teague et al., 1990). For **parametric averaging** a certain model of vertical stratification is required (e.g., Chu et al. 1997, 1999, 2000, 2006; etc).

The difference between these approaches can easily be represented, considering an idealized case of quasi 3-layer stratification. (I.e., 5-segment broken line; coordinates of 6 nodes give us 12 parameters).

$$\rho = f\,(z, R)$$

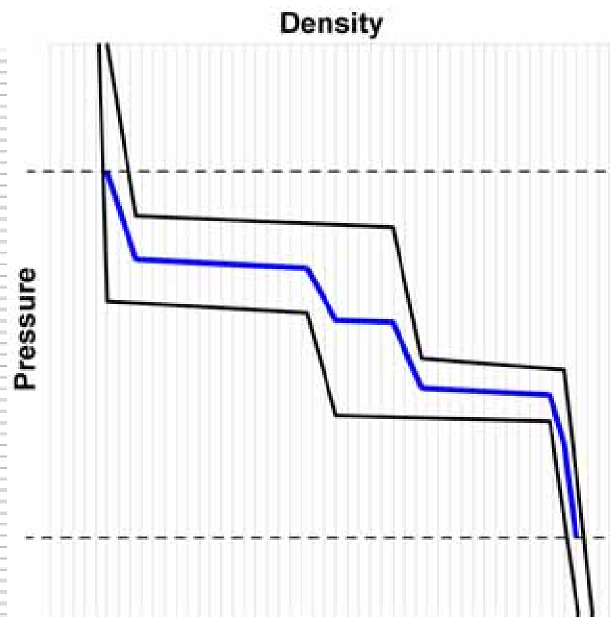
$$\rho\langle\rho(z_c)\rangle = 0.5[\,f\,(z_c, R_1) + f\,(z_c, R_2)]$$



The **isobaric** averaging gives an unexpected **fife-layer** profile with reduced vertical density gradients.

$$z = g\,(\rho, R)$$

$$\langle z(\rho c)\rangle = 0.5[\,g\,(\rho c, R1) + g\,(\rho c, R2)]$$

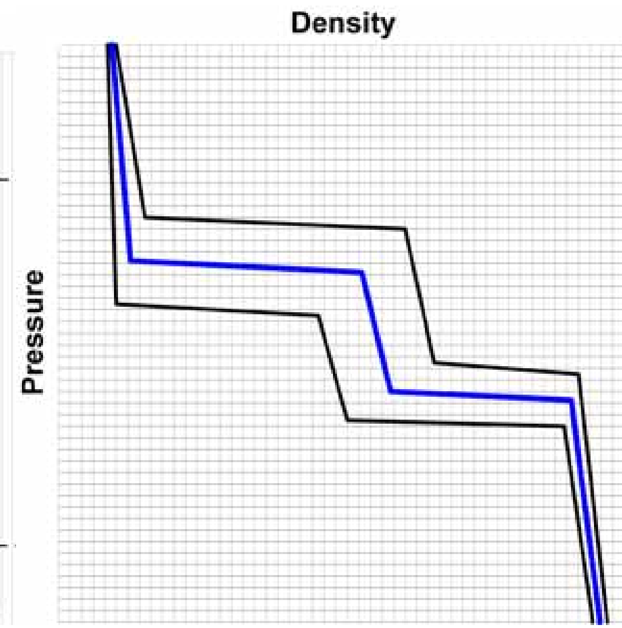


The **isopycnal** averaging is more realistic, but gives a **for-layer truncated** profile.

$\rho = f\,(z, R)$ **or** $z = g\,(\rho, R)$

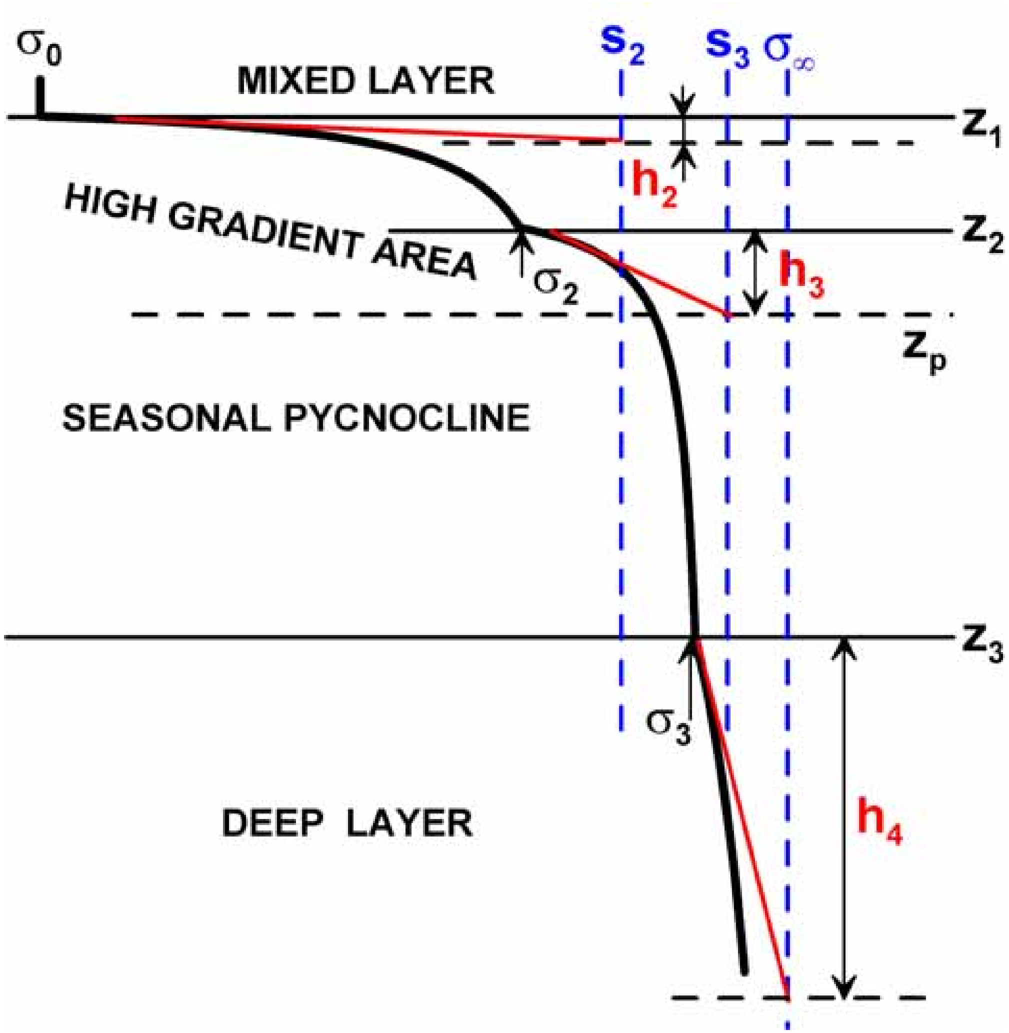
$\langle\rho(zc)\rangle = f\,[zc, 0.5(R1+R2)]$, **or**

$\langle z(\rho c)\rangle = g\,[\rho c, 0.5(R1+R2)]$



The **parametric** averaging **conserves** all principal features of stratification and gives the reasonable density gradients.

In this study we use a **<u>For-layer hyperbolic model</u>** (as special case of N-layered model from Makarov et al, submitted) which consists of a homogeneous top layer, a seasonal pycnocline (represented as two layers) and a deep layer. The additional layer in the upper part was introduced because, in the top of the pycnocline, but below the well-expressed mixed layer (3–20 m), there was at least one ‘step’ in the density curve associated with a subsurface minimum in temperature.



S_2, S_3 and $\blacklozenge_{\infty}$ are the limiting values, to which sigma-t for the corresponding layer tends asymptotically. Inclined straight lines represent tangents to the approximated curve at the top of the layers. Thus, parameters **h_n** are related to the maximum value of a density gradient in a corresponding layer

$$\gamma_2 = (s_2 - \sigma_0)/h_2, \quad \gamma_3 = (s_3 - \sigma_2)/h_3,$$

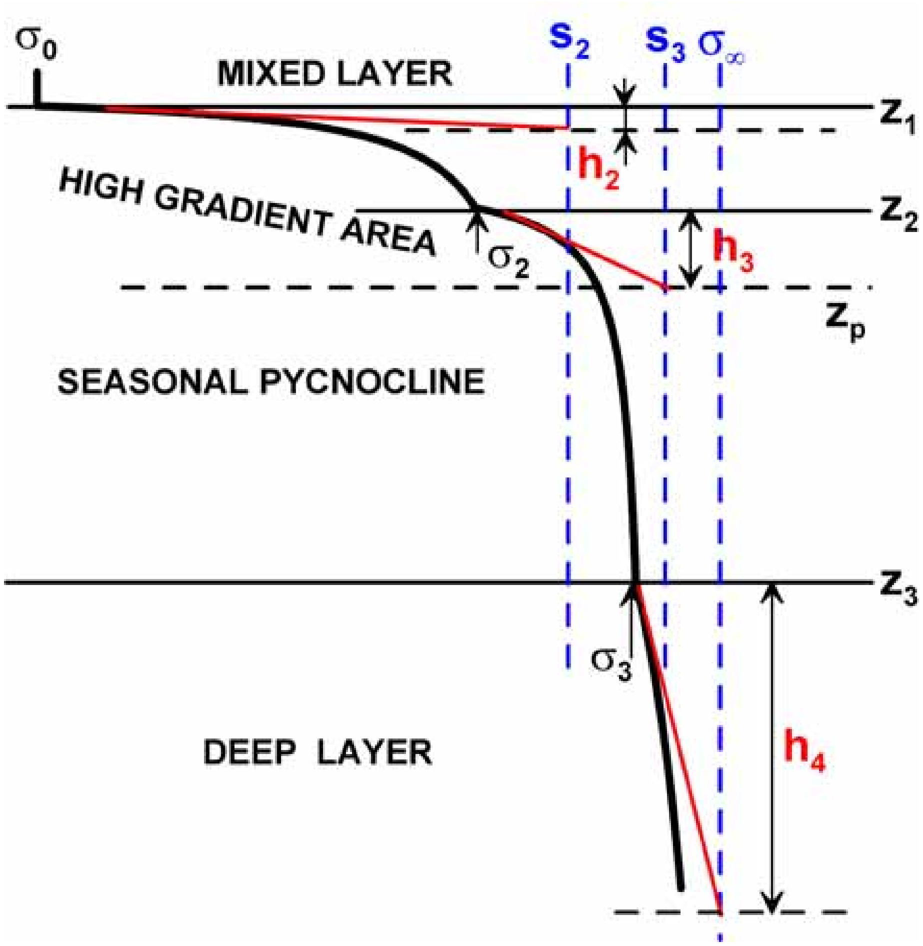
$$\gamma_4 = (\sigma_\infty - \sigma_3)/h_4$$

The lower boundary of high density gradients area can be estimated as

$$\mathbf{z_p = z_2 + h_3}.$$

Note, that the parameter σ_∞ can be used for downward extrapolation.

Thus, a vertical distribution of sigma-t on the profile has the following form:



$$\sigma(z)=\begin{cases}\sigma_0, & 0\le z\le z_1\\ s_2-(s_2-\sigma_0)/\left(1+(z-z_1)/h_2\right), & z_1<z\le z_2\\ s_3-(s_3-\sigma_2)/\left(1+(z-z_2)/h_3\right), & z_2<z\le z_3\\ \sigma_\infty-(\sigma_\infty-\sigma_3)/\left(1+(z-z_3)/h_4\right), & z>z_3\end{cases}$$

where **σ_2, σ_3** resulting from continuity conditions at the interfaces

$$\sigma_2=s_2-(s_2-\sigma_0)/\left(1+(z_2-z_1)/h_2\right),$$

$$\sigma_3=s_3-(s_3-\sigma_2)/\left(1+(z_3-z_2)/h_3\right)$$

The model has 10 unknown coefficients:

$z_1, z_2, z_3, \sigma_0, s_2, s_3, h_2, h_3, h_4, \sigma_\infty$

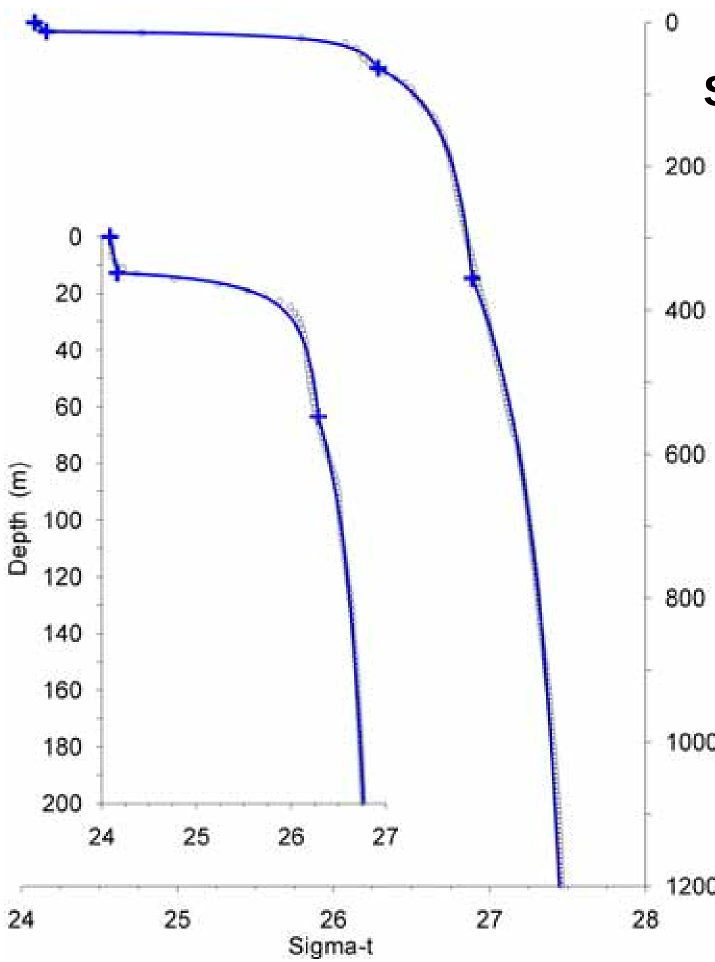
or, equally

$z_1, z_2, z_3, \sigma_0, \sigma_2, \sigma_3, \gamma_2, \gamma_3, \gamma_4, \sigma_\infty$

which should be derived by the fitting of the model to the observed data. Since the layer interfaces are also unknown, we need to use a nonlinear least squares procedure (e.g., Levenberg-Marquardt iterative method) to obtain a set of best-fit coefficients.

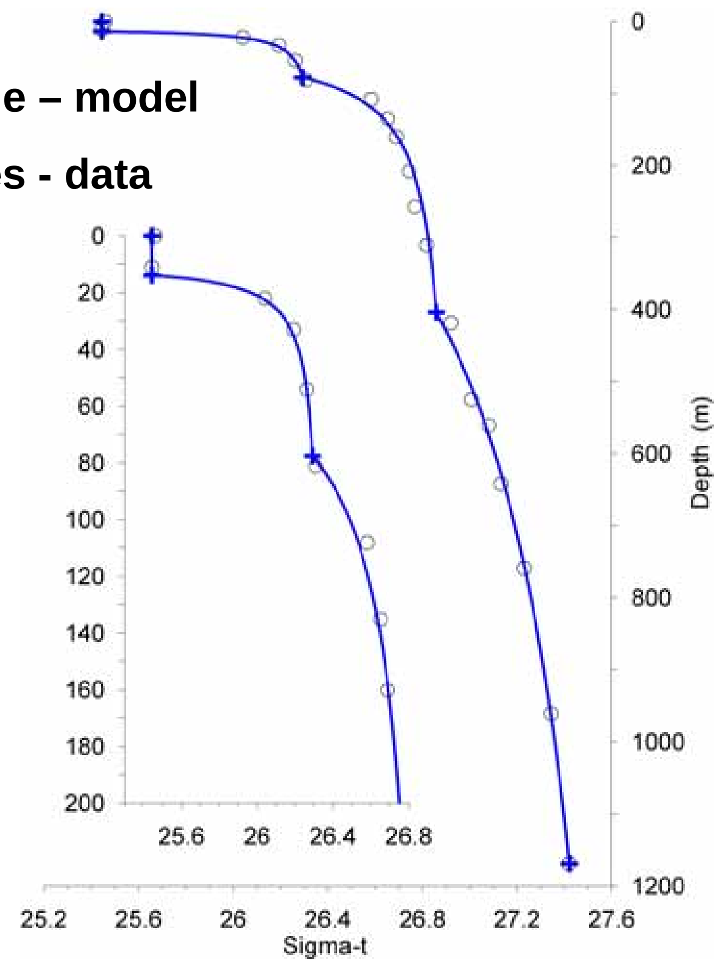
These are two examples of fitting the 4-layer model to

the CTD-profile (1-m resolution) and the Bottle sample data



Solid line – model

Circles - data

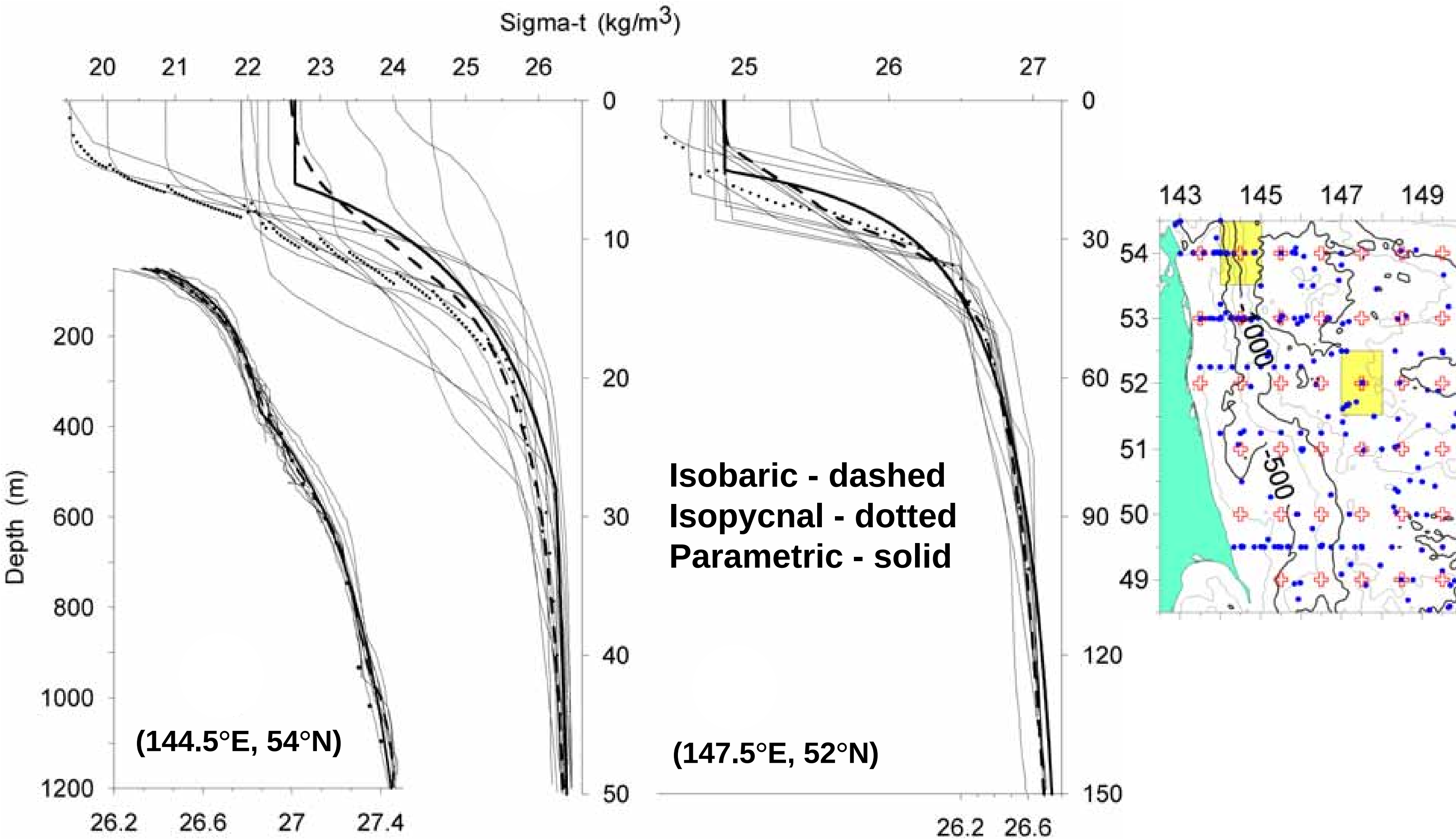


To obtain a mean profile for each 1° square, all individual profiles within this square were fitted, and then the model coefficients were averaged. The resulting 3-D mean density field is completely defined by the 380 mean parameters only.

For comparison we also calculated the mean “isobaric” and “isopycnal” profiles.

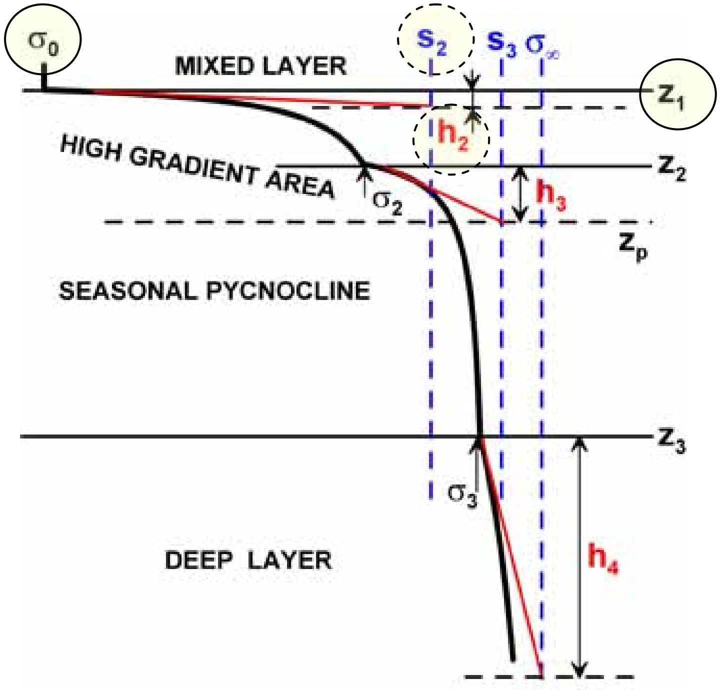
With isobaric averaging, a sharp pycnocline is fully diffused. The isopycnal averaging fails near the surface. Both are poorly suitable for calculation of mean MLD values.

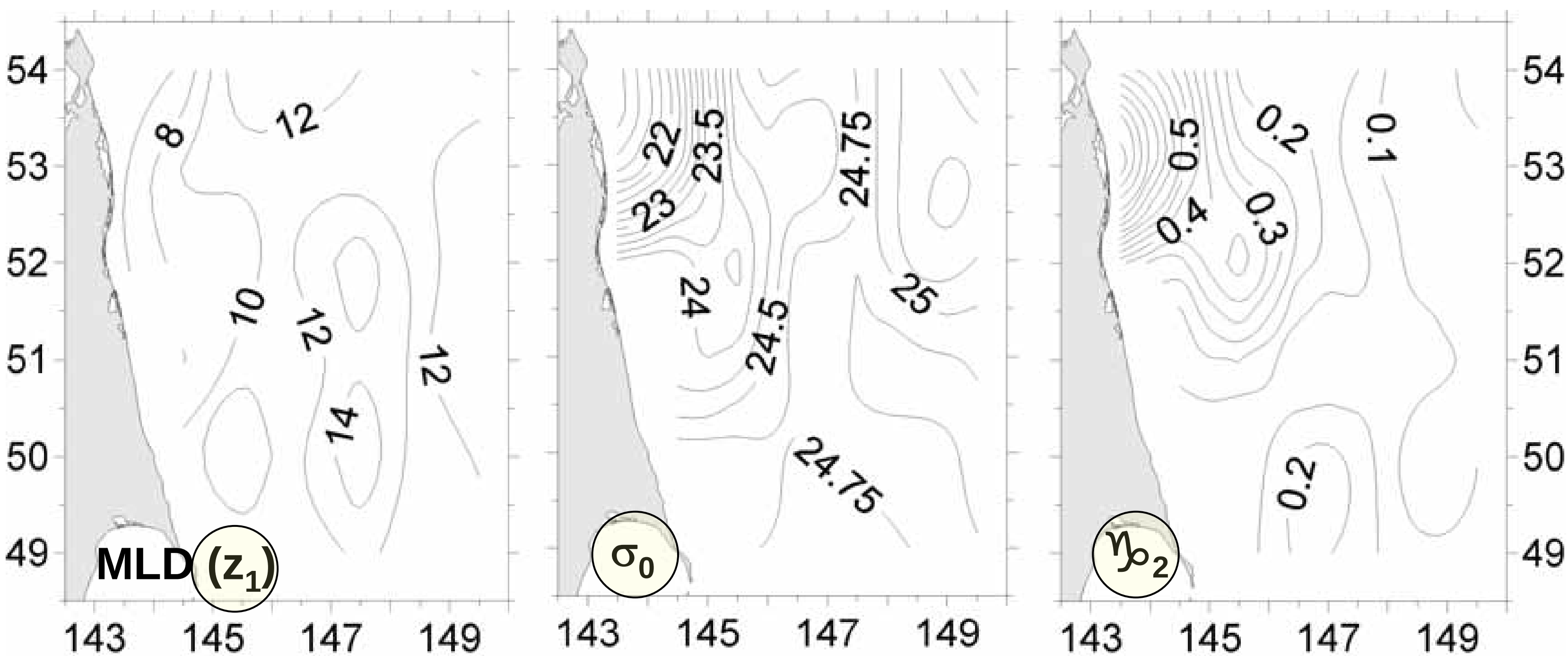
Below ~100 m the difference between all three methods becomes essentially small.



Some features of density field can be obtained directly from the model coefficients. A well-defined front (located at latitudes 52–52.5°N), which limits the southward propagation of warm waters with low salinity values, occurs in the horizontal distributions of the MLD (z_1), superficial sigma-t (σ_0), and maximum vertical density gradient in the pycnocline

$$\gamma_2 = \left(s_2 - \sigma_0\right) / h_2$$

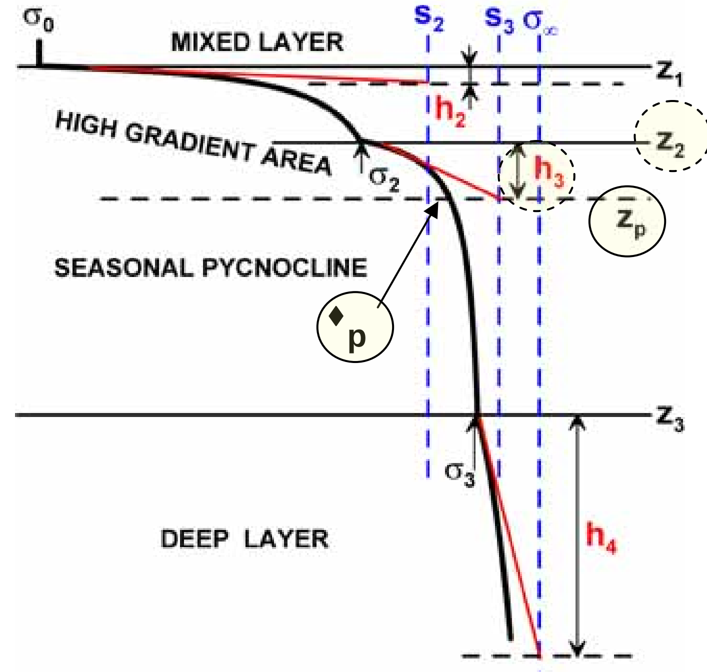


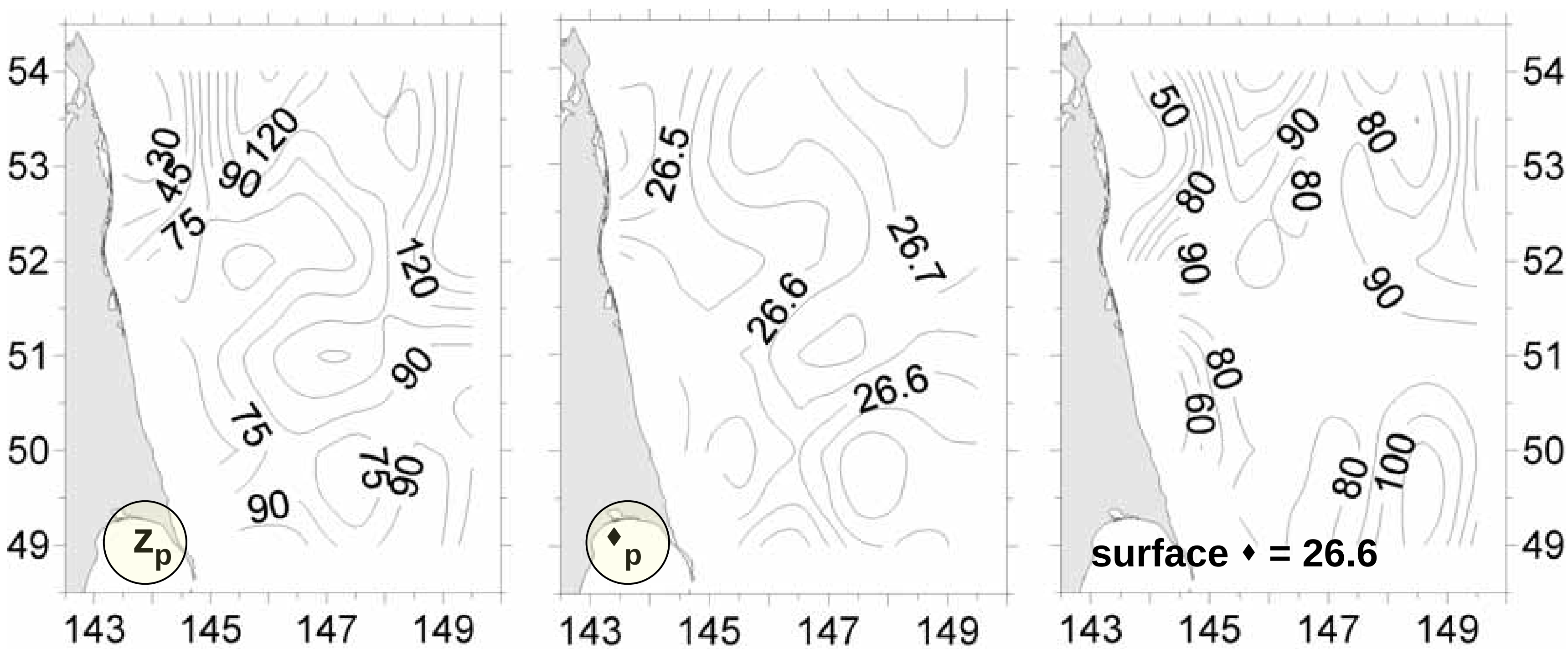


The lower boundary

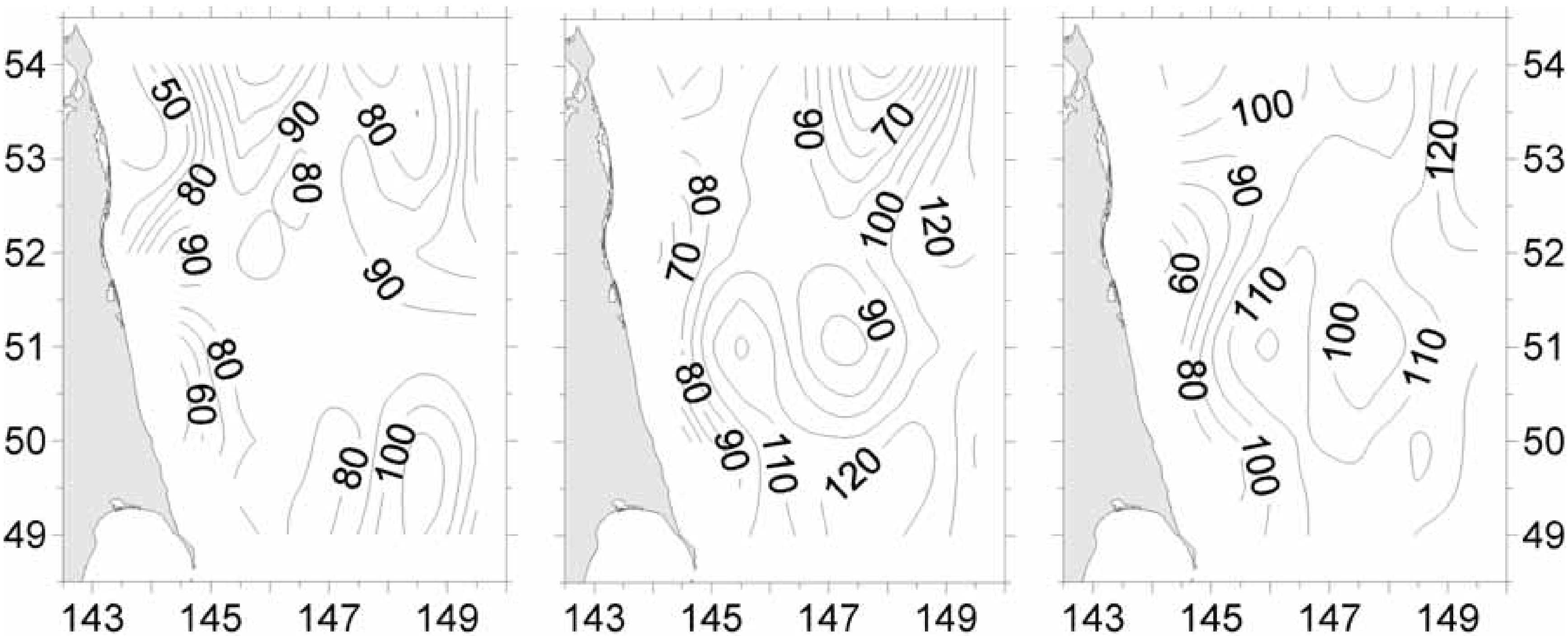
$$z_p = z_2 + h_3$$

of high vertical density gradients area, is more informative. Calculated ♦$_p$ = ♦(z_p) is quasi-uniform, with a mean value of ~**26.6**. Hence, this value can serve as a marker for the bottom of a dynamically active layer. Elevation of corresponding isopycnal surface near the continental slope indicates presence of coastal upwelling.



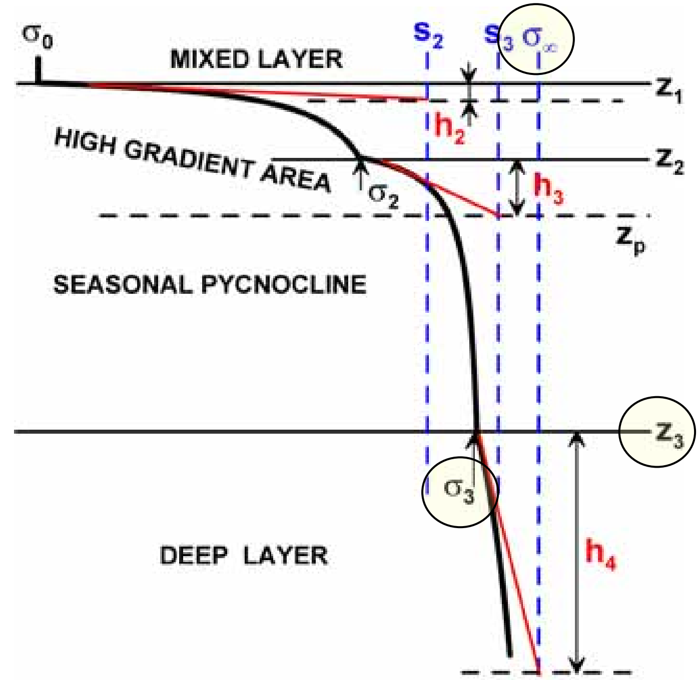


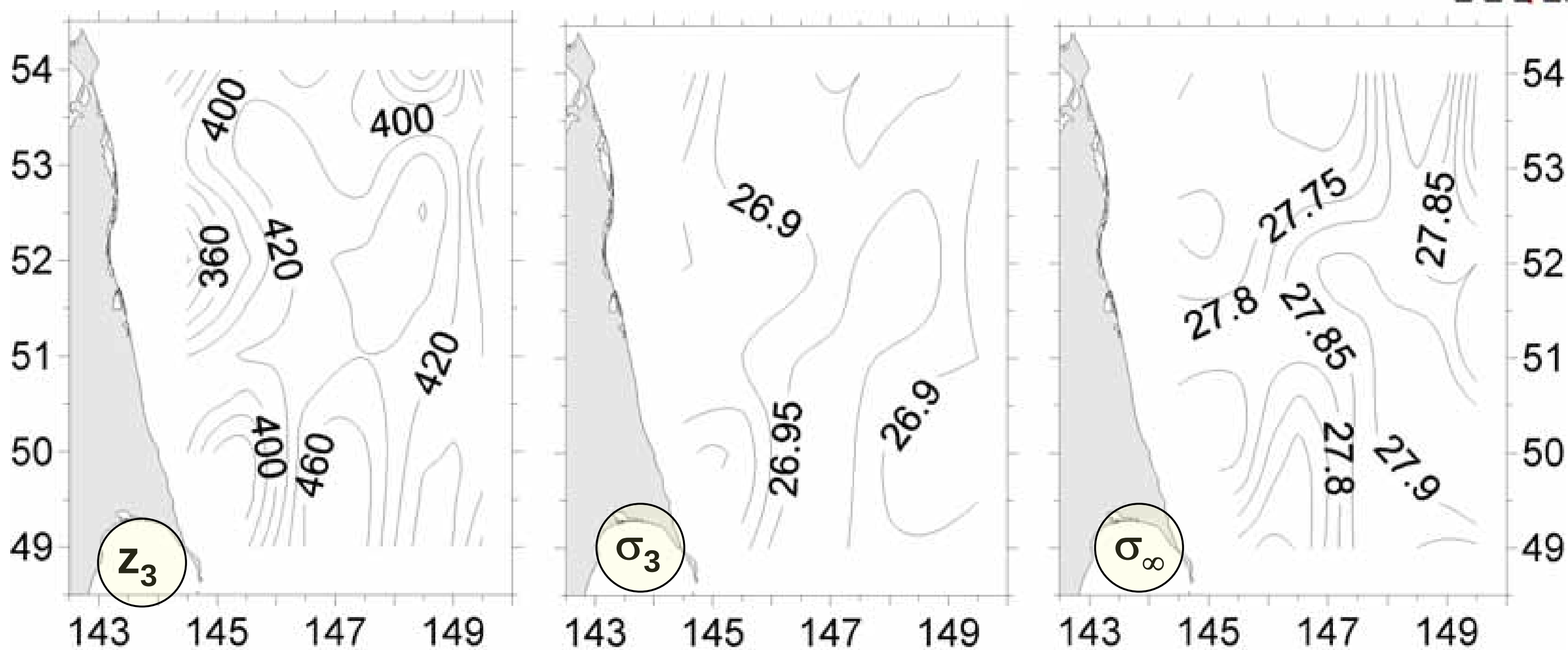
For comparison, this surface (σ = **26.6**) was calculated using parametric, isopycnal, and isobaric averaging. The obtained surfaces have noticeable, quantitative differences caused by the manner of their construction only. In the “isopycnal” case, the values of **z**(σ) obtained from individual profiles were averaged within each square. In the “isobaric” case, the mean value of **z**(σ) for each square was defined from the mean profile obtained by isobaric averaging.

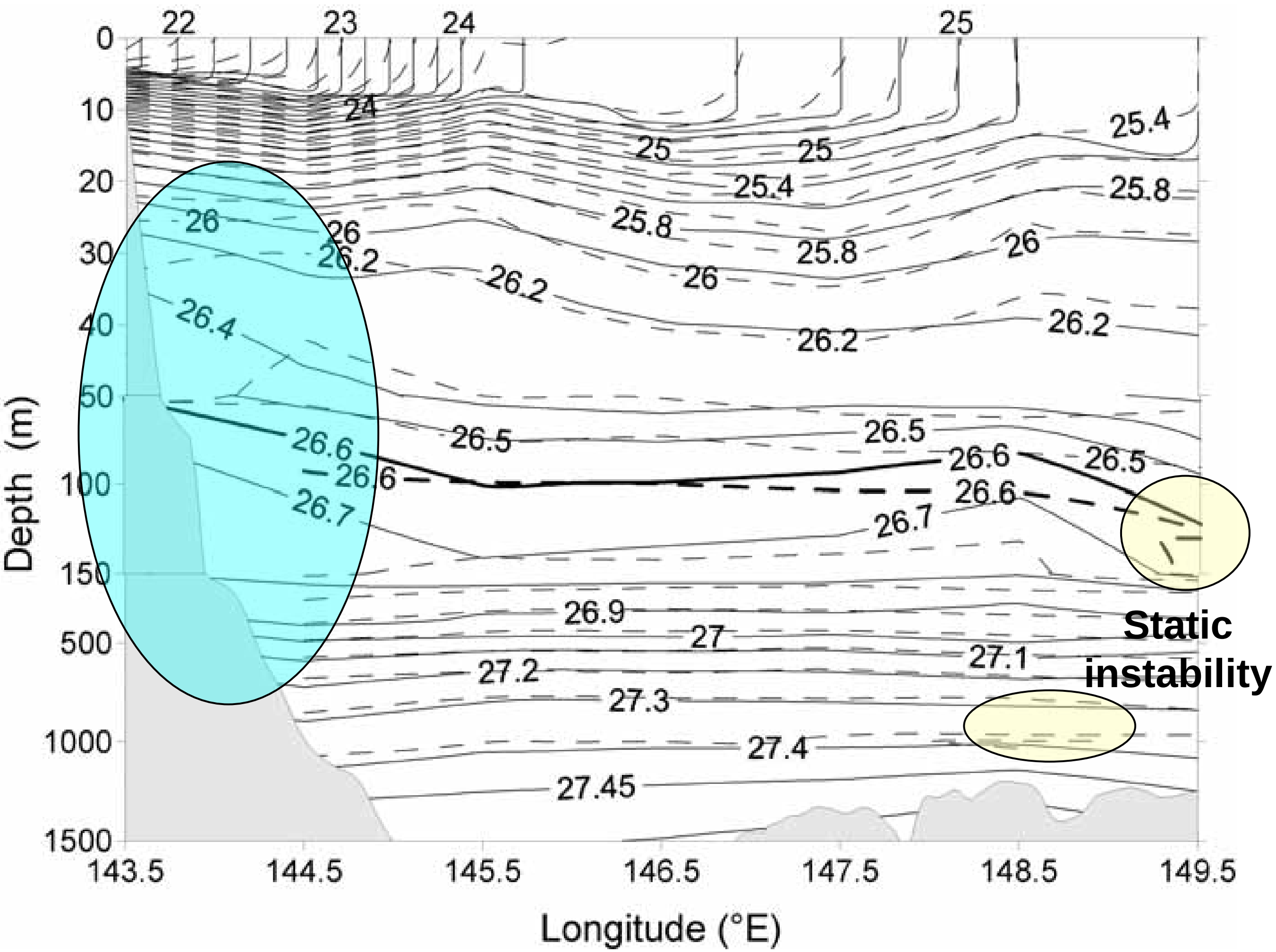


parametric **isopycnal** **isobaric**

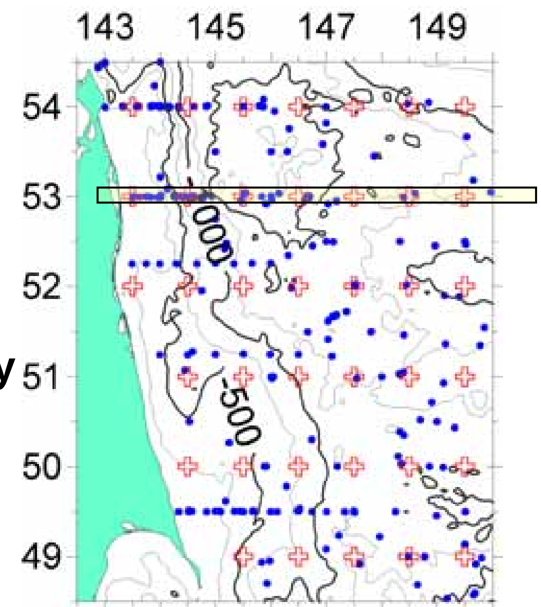
Here are shown the depth (z_3) on the top of deep layer (~400 m) and the corresponding distribution of σ_3 with mean value ~**26.9**, which can serve as another "critical" isopycnal. The field of the key extrapolation parameter σ_∞ was used at each node of the 1° grid to extend the mean profiles to the sea bottom. (The mean value for this region is ~**27.83)**.







This vertical section was constructed by using the model (solid) and isobaric (dashed) approaches.



The major differences include a different inclination in the isopycnals observed in the upper layer (0–150 m), especially near the edge of the continental shelf and slope. The averaged on *z*-levels density field shows downwelling in this area, instead of anticipated upwelling (e.g., Fukamachi et al., 2004). Some local ‘loops’ on isopycnals were detected. The appearance of static instability in the mean density can also be explained by application of averaging procedure on *z*-levels (Jackett and McDougall, 1995; Chu, 2006).

Conclusions

- Comparison of the commonly used averaging methods for near-shore area of the Sea of Okhotsk, has shown that, in case of strong stratification and high horizontal variability in density, it is preferable to use the parametric approach. The isobaric averaging can strongly deform the density structure in the upper layer (0–100m). The isopycnal approach is of little use near the sea surface.
- The piecewise analytical model of density distribution may be useful in inverse methods (e.g., P-Vector method by Chu, 2006) to determine geostrophic velocity, and in simple layered or isopycnal ocean models.
- This approach may be also used for development of various types of models, including models for other oceanographic parameters, such as temperature or salinity.