Biological effects of internal waves in coastal waters

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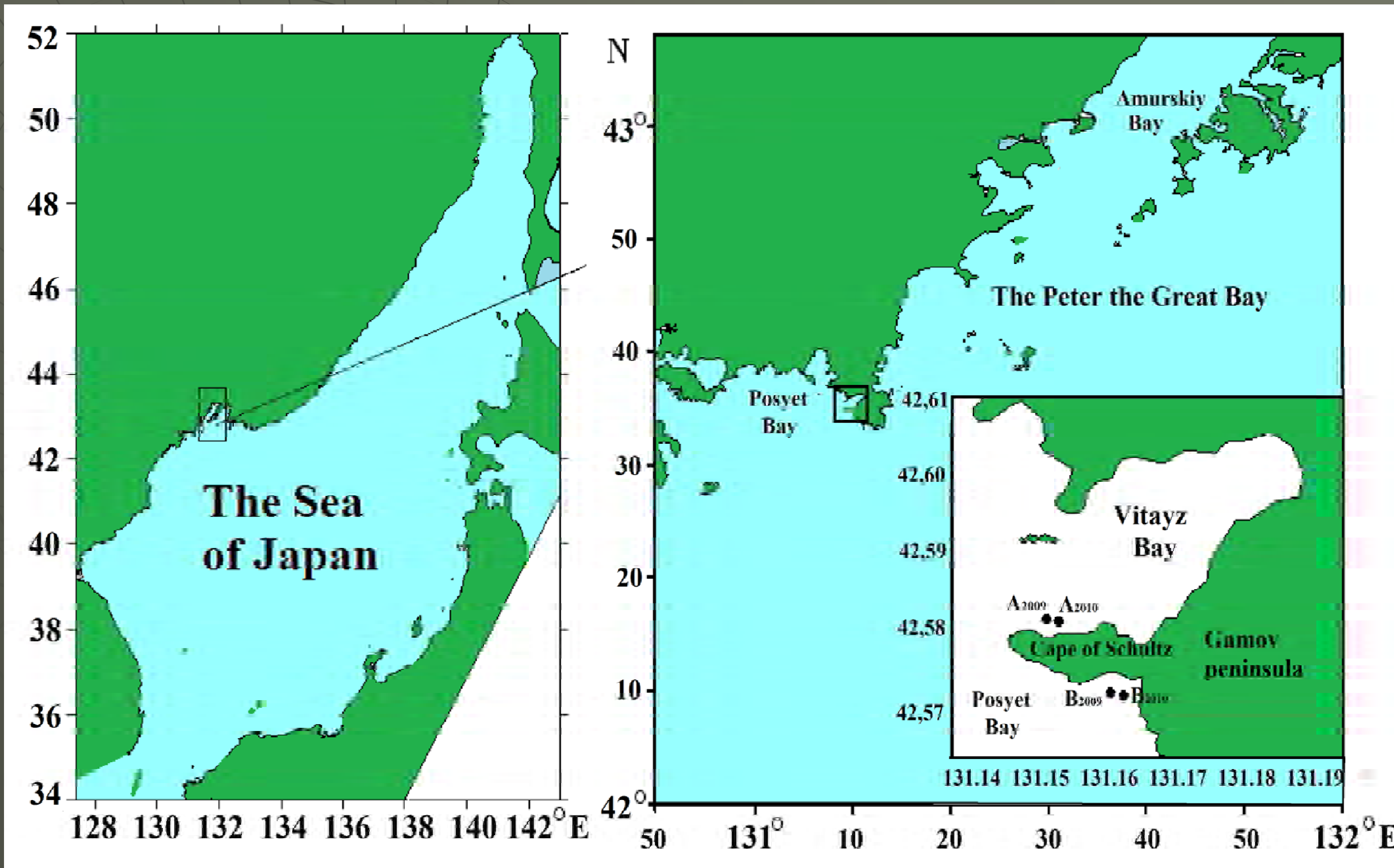
Research area and points of long-term observations



Main points

- Modeling of IW generation near the shelf break
- Experimental investigations of processes in the near-bottom thermocline
- IW and biology
- Interpretation of results

Numeric modeling

Equations

$$\left(U+W_1\right)_\tau+\left(\tfrac{1}{2}U^2+gZ+W_2\right)_\xi+\frac{P_\xi}{\rho}-\frac{1}{\rho^2}\overline{\rho' k p'_\theta}=\frac{1}{\rho}\left[\mu\left(U_\eta+W_3\right)\right]_\eta-\nu W_4 \qquad (1)$$

$$\rho C\left(T_\tau+UT_\xi\right)=\left[\lambda\left(1+\overline{z'^2_\eta}+k^2\overline{z'^2_\theta}\right)T_\eta\right]_\eta \qquad (2)$$

$$S_\tau+\left[U\left(1-S\right)\right]_\xi=0 \qquad (3)$$

$$P_\eta=-\rho g \qquad (4)$$

$$\rho\left(1+Z_\zeta\right)=\rho_0\left(1-S\right) \qquad (5)$$

$$\rho(U-c)^2k^2z'_{\theta\theta}+\rho g z'_\eta+p'_\eta=0,$$
$$p'=\rho(U-c)^2z'_\eta-\rho g z', \qquad (6)$$

$$\rho C(U-c)\left(kt'_\theta-T_\xi z'_\eta\right)=-2\left(\lambda T_\eta\right)_\eta z'_\eta-\lambda T_\eta\left(z'_{\eta\eta}+k^2z'_{\theta\theta}\right) \qquad (7)$$

$$\left[\int\rho k^{-1}W_1 d\eta\right]_\tau+\left[\int\rho k^{-1}(U-c)\left(c\overline{z'^2_\eta}+Uk^2\overline{z'^2_\theta}\right)d\eta\right]_\xi-\int\rho^{-1}\overline{\rho' p'_\theta}d\eta=$$
$$-\int\mu k^{-1}W_4 d\eta+\delta\left\{\mu k^{-1}\left[\tfrac{1}{2}(U-c)\left(\overline{z'^2_\eta}+k^2\overline{z'^2_\theta}\right)_\eta+U_\eta\left(3\overline{z'^2_\eta}+k^2\overline{z'^2_\theta}\right)\right]\right\} \qquad (8)$$

ξ, ζ, τ – horizontal Euler coordinate, vertical Lagrange coordinate and time,

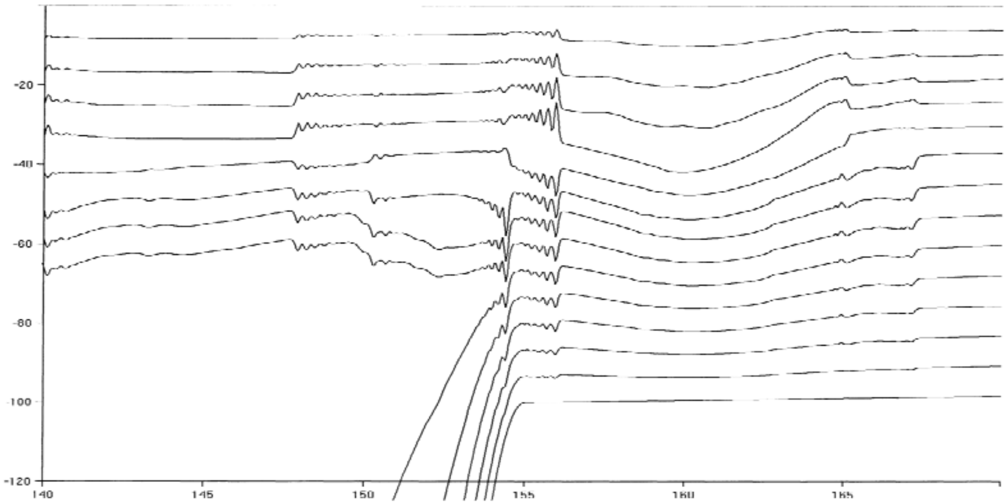
T, U и S – mean temperature of a layer, Lagrange mean horizontal velocity and mean deformation coefficient of a layer, 1-S – horizontal compression of fluid element relative to the standard state, “layer” means the aggregate of fluid particles having the same Lagrange coordinate,

ρ_0 – standard density,

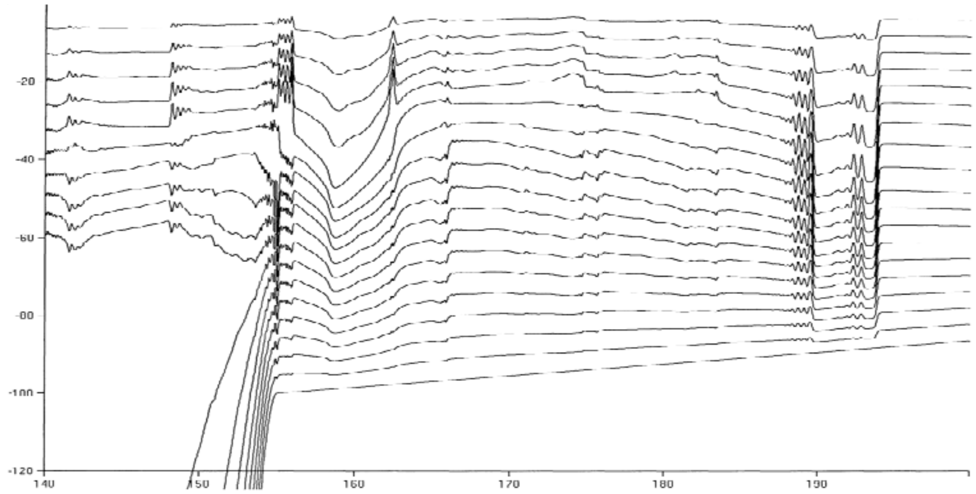
Nonlinear equations of shallow water were solved for different vertical structure of density, different continental slope steepness, different tidal current velocities.

Nonlinear transformations of propagating waves, formation of the second vertical mode, internal jumps, packets of solitons and packets of quasi sinusoidal short waves, as well as conditions for IW breaking were obtained for different initial conditions.

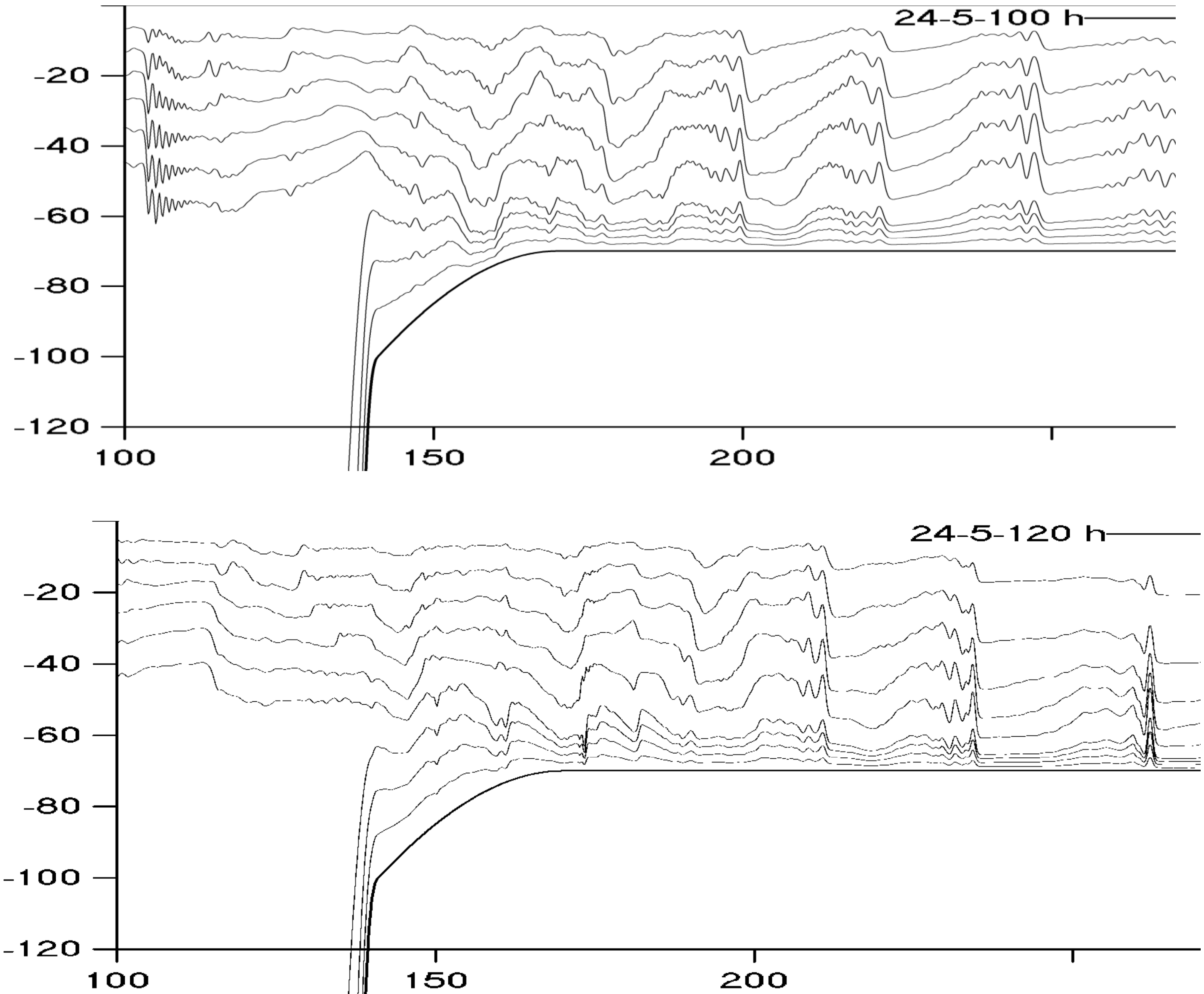
Near the shb, v = 0.4 m/s, horiz visc = 1 sqm/s.
First mode for internal tide and second mode for shorter waves.



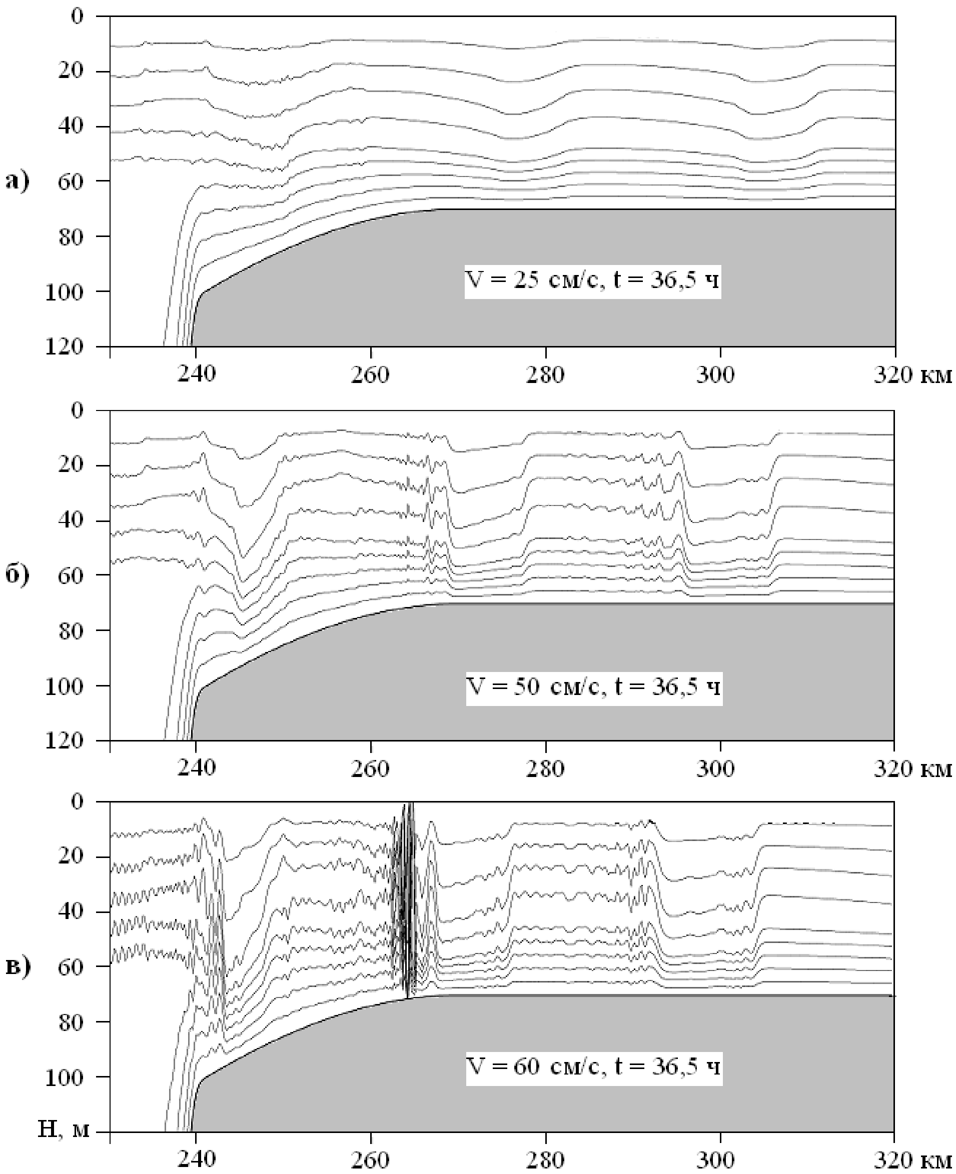
v = 0.5 m/s, vert visc = 0.002 sqm/s.
Internal jumps and packets of short waves formation

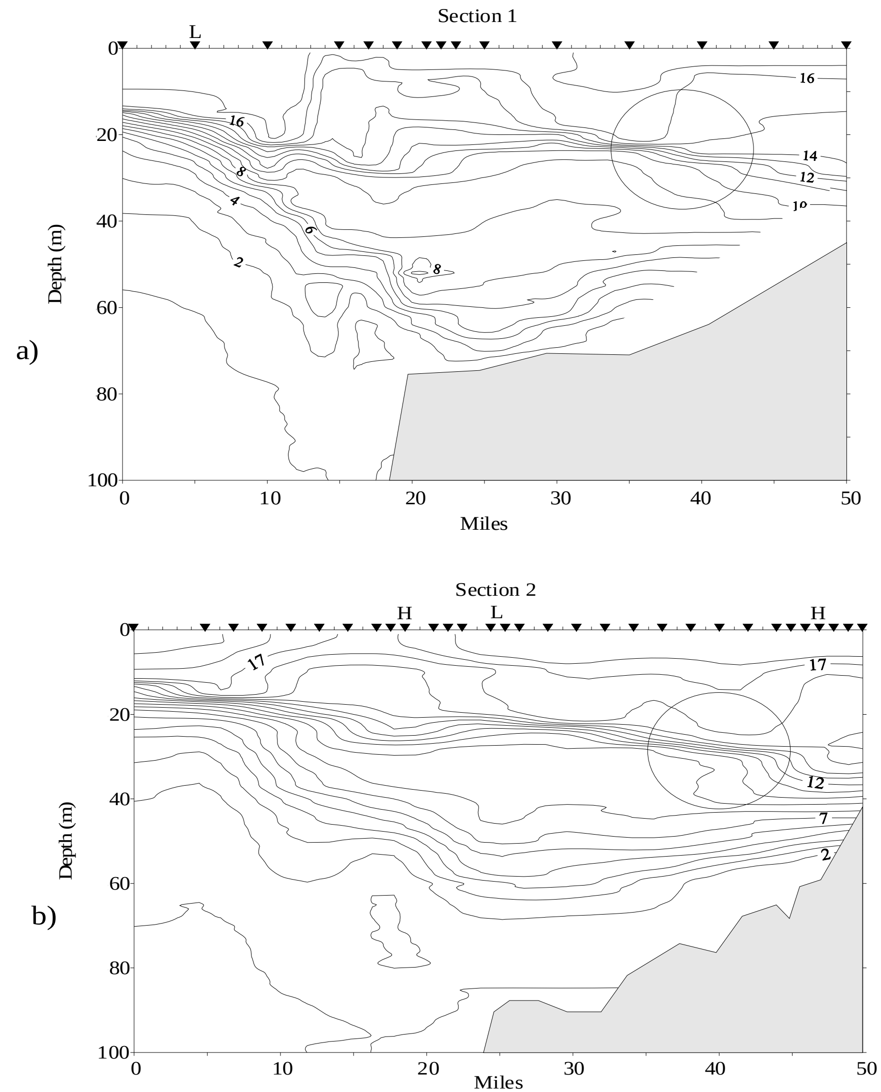


Spatial structure of IW at the moment 100 and 120 hours after throwing into action semidiurnal (tidal) fluctuations of velocity from initial rest

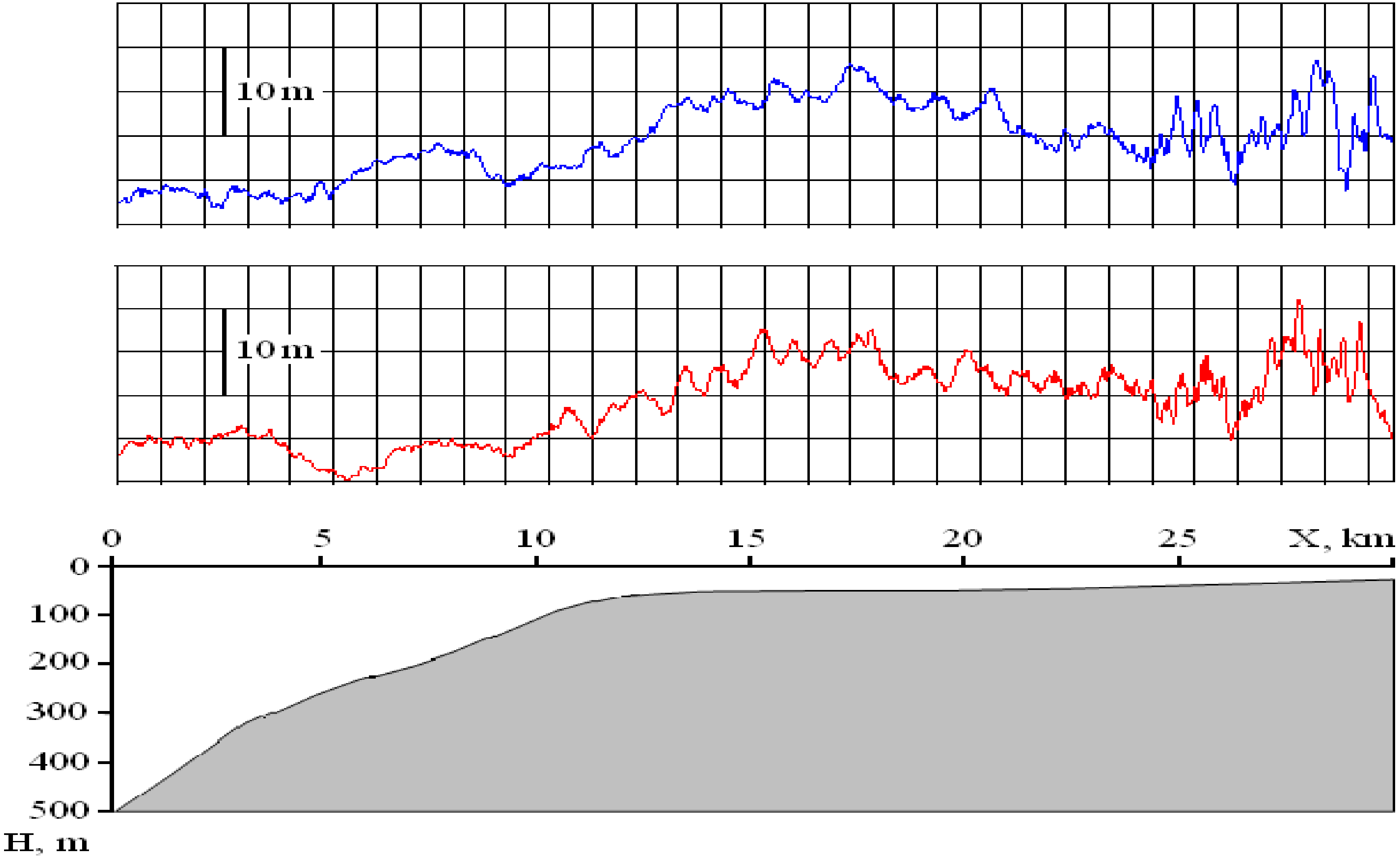


IW in the moment 36.5 h after activation of tidal currents from initial state at rest and observed thermocline structure in the Japanese Sea shelf zone





Internal waves transformation on the way from an open sea to a shore
Measurements are made with the help of a towed line sensor



To show animation

- 08-24-5 – to compare with observed IW deformation from shelf break to a shore
- 08-24-4 – Change of IW structure in time and space
- 08-24-1 – More complex: tide+inertial.

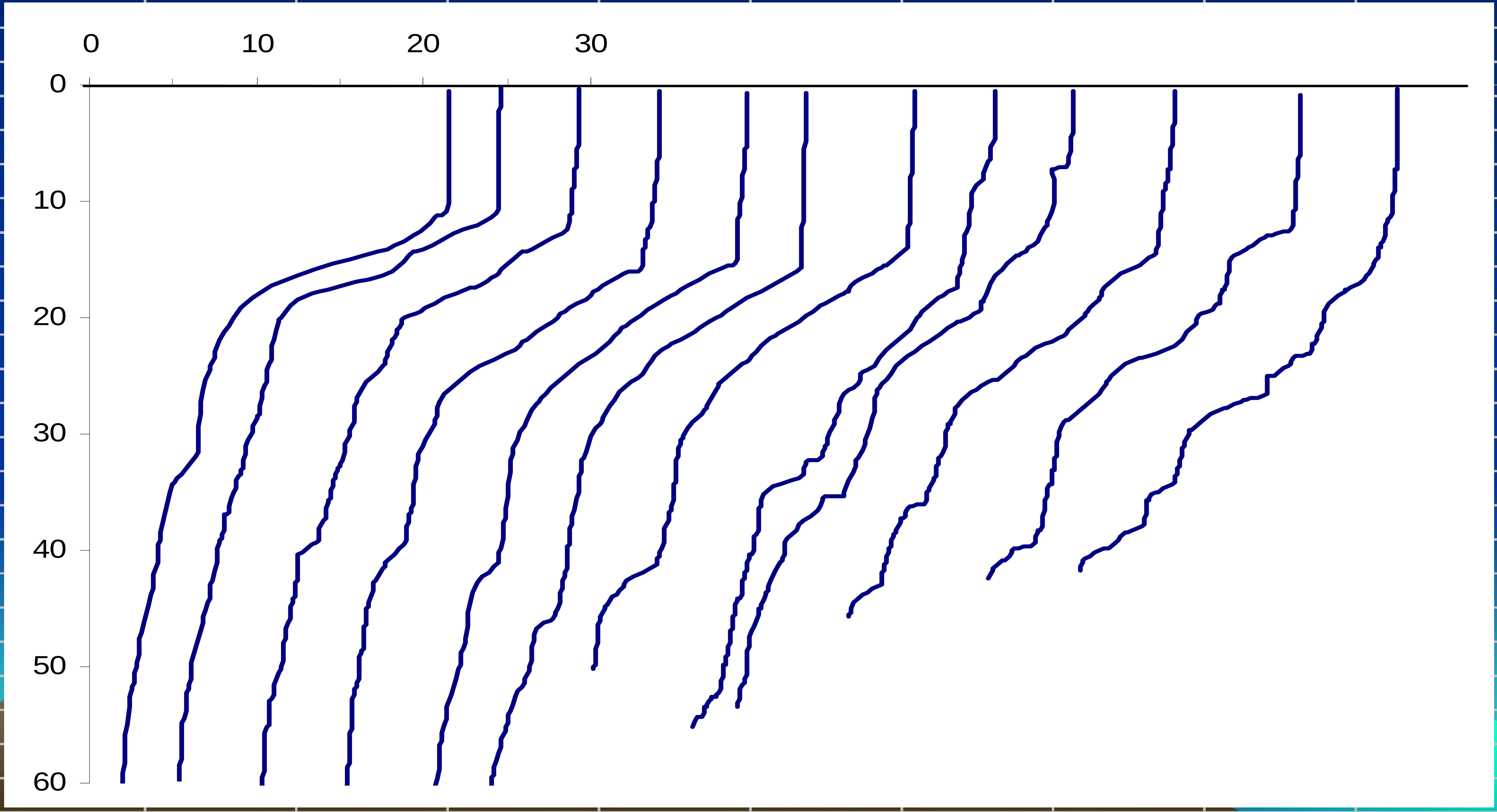
  IW shoaling with distance and time

- Far from a shore, when the lower boundary of a thermocline is far from bottom, energy of IW serves to change mean density structure and form vertical fine structure.
- The changed vertical structure parametrically changes IW properties – dispersion relations, lengths, phase and group velocities, and energy spectrum.
- These nonlinear transformations can go on practically without IW breaking till the zones, where thermocline begins to feel bottom. Waves with high amplitudes feel bottom earlier, than waves with small amplitudes.

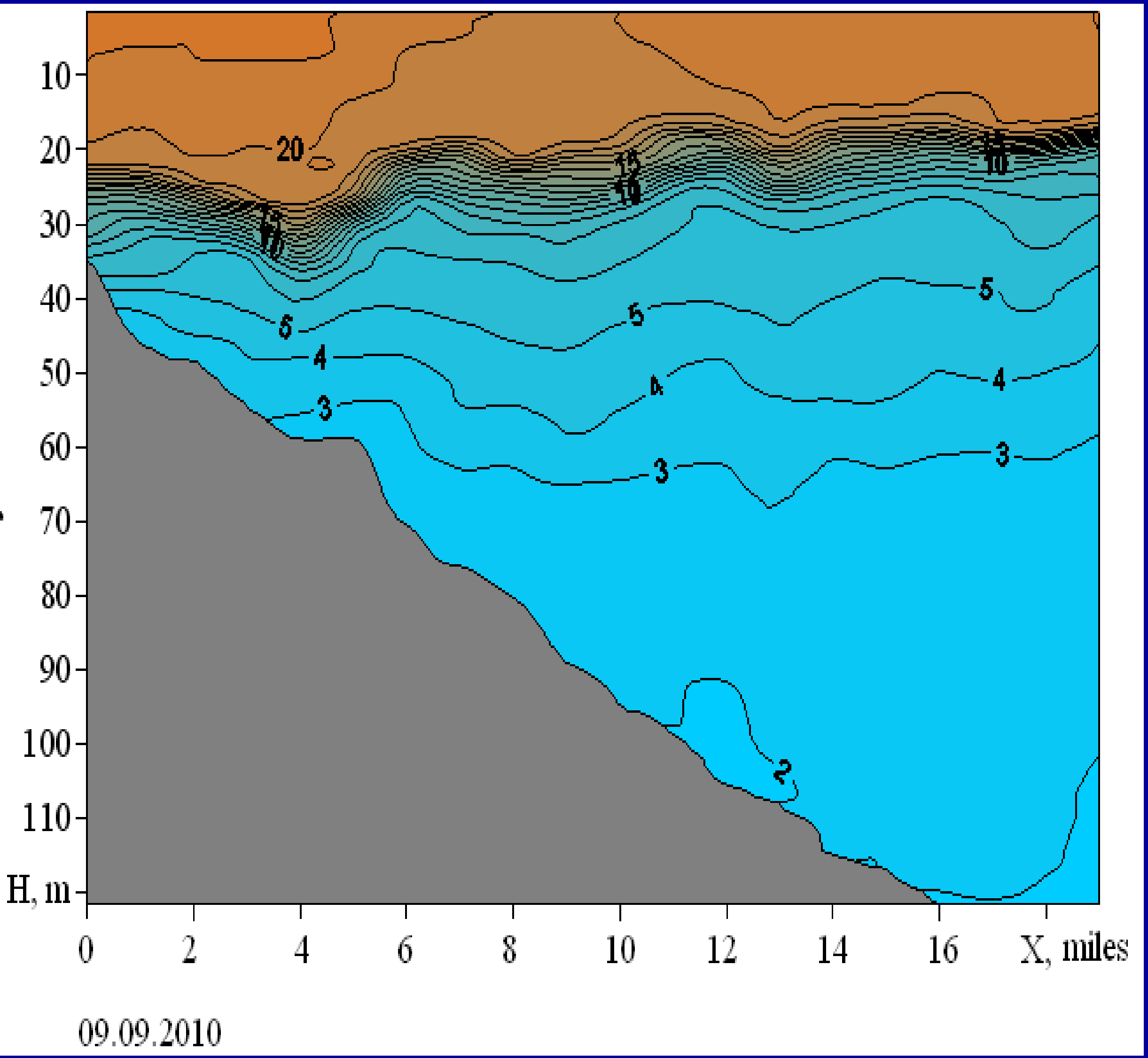
- In any case the final result is turbulent dissipation, but that wave-to-turbulence transition is not enough investigated, though it is important for many geophysical, biological and ecological processes in coastal zones.

- Our main goal was experimental study of IW transformation in the near-bottom thermocline.

Temperature profiles on transects from the shelf break to the shore (from left to right). The temperature scale is shown for the left profile, the others being sequentially shifted by 5^0 C. Distance between soundings is 1 mile.



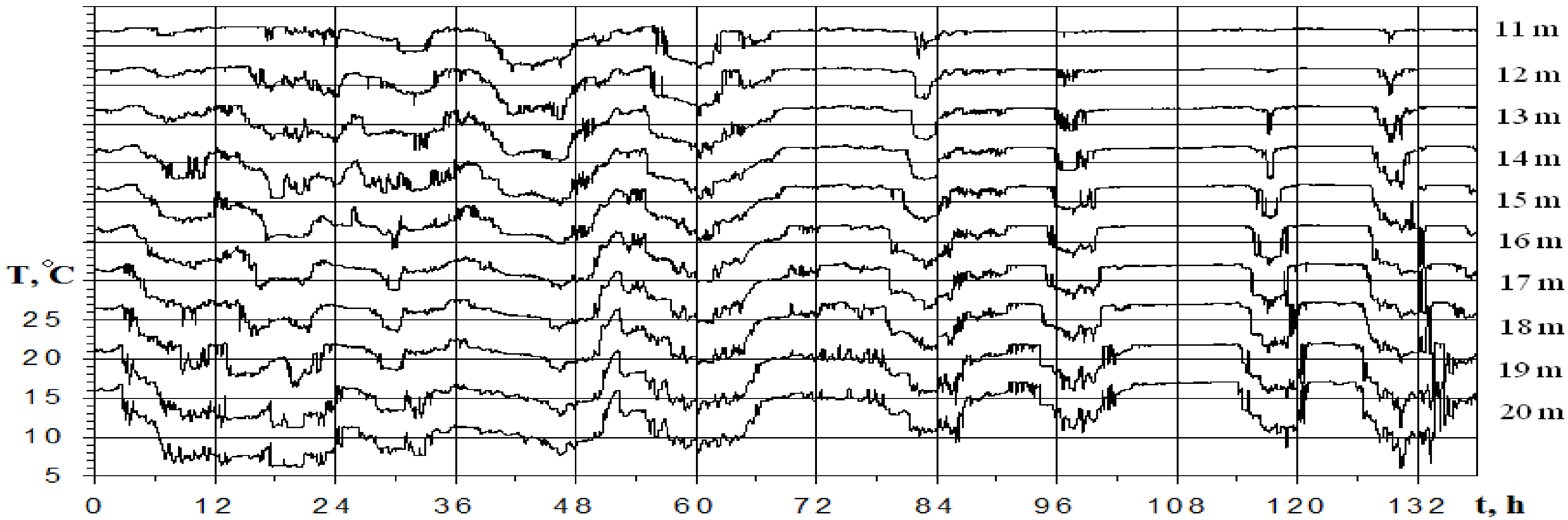
Spatial transect of temperature through the Japanese Sea shelf zone

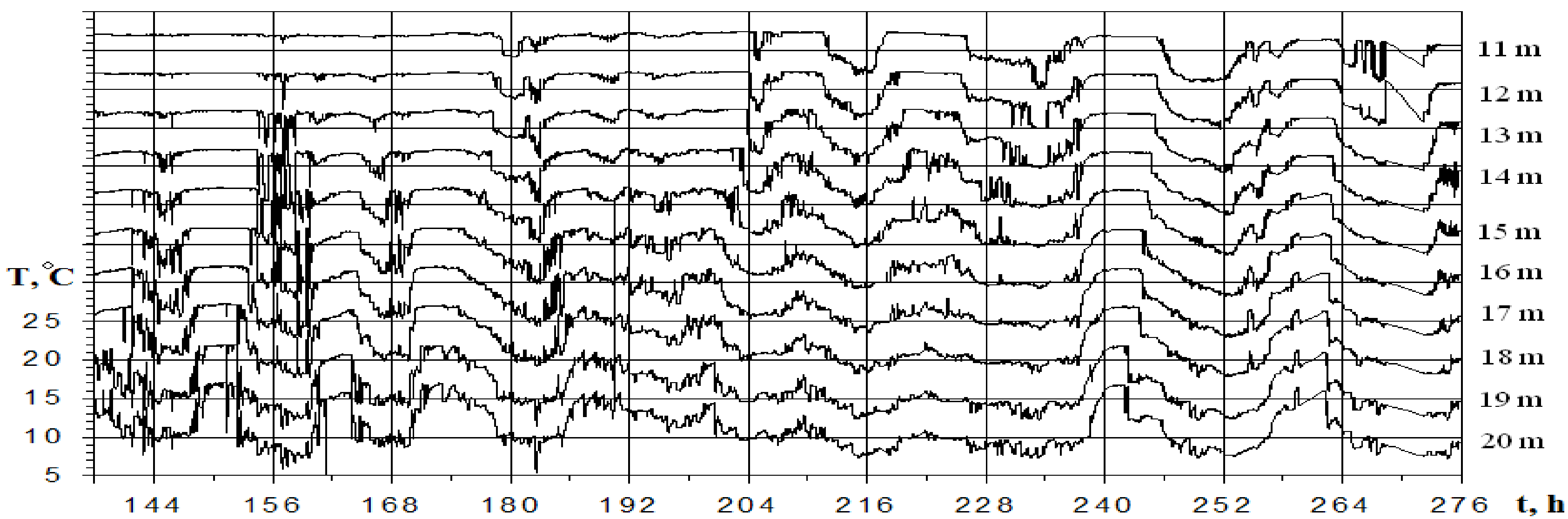


- Sharp thermocline is aproaching to the bottom, and intense internal waves must become highly nonlinear, break and dissipate their energy in rather thin near-bottom layer.

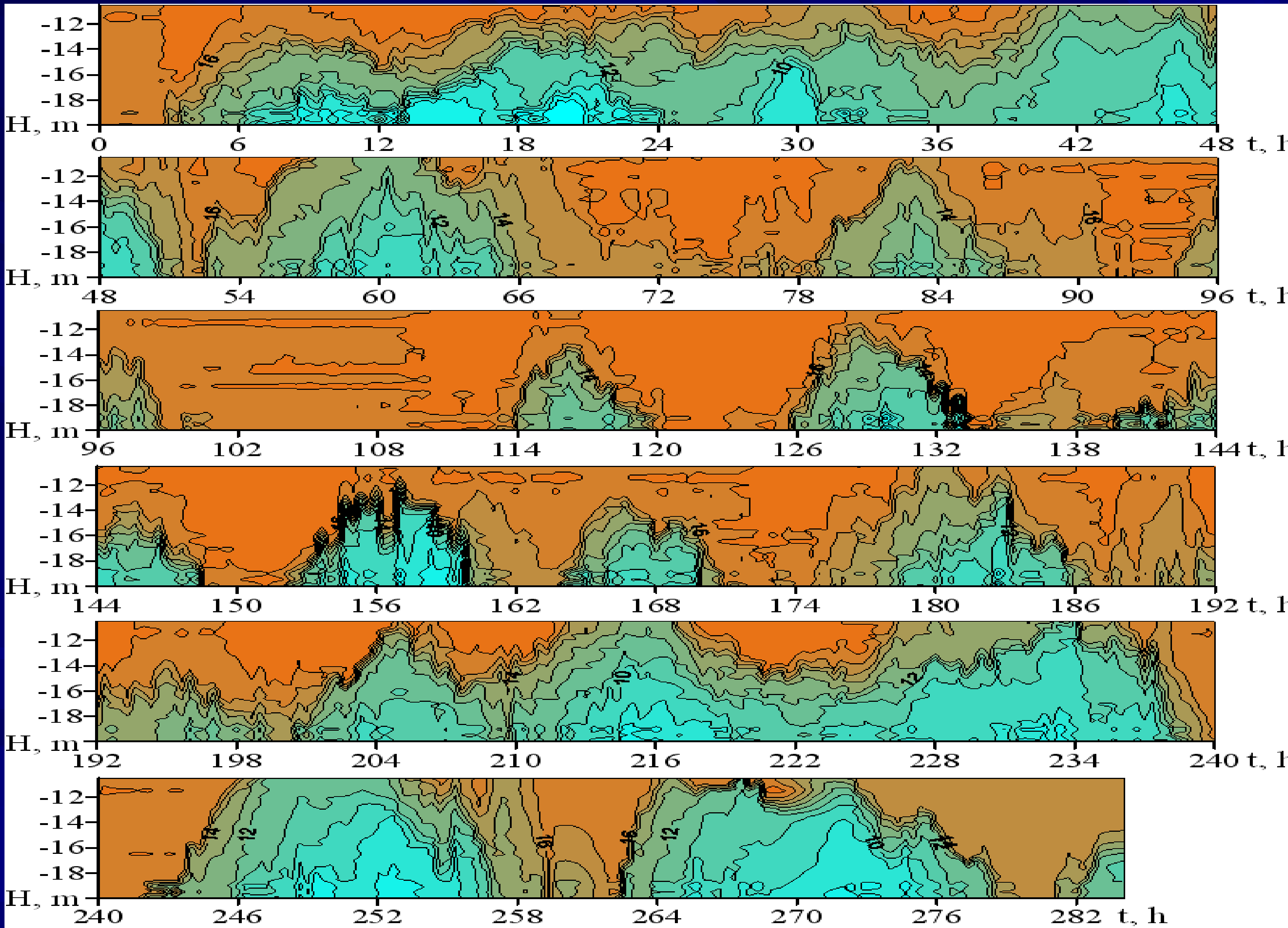
How this process is going on?

Temperature fluctuations in a 10-meter layer of the near-bottom thermocline (Sept. 2009).

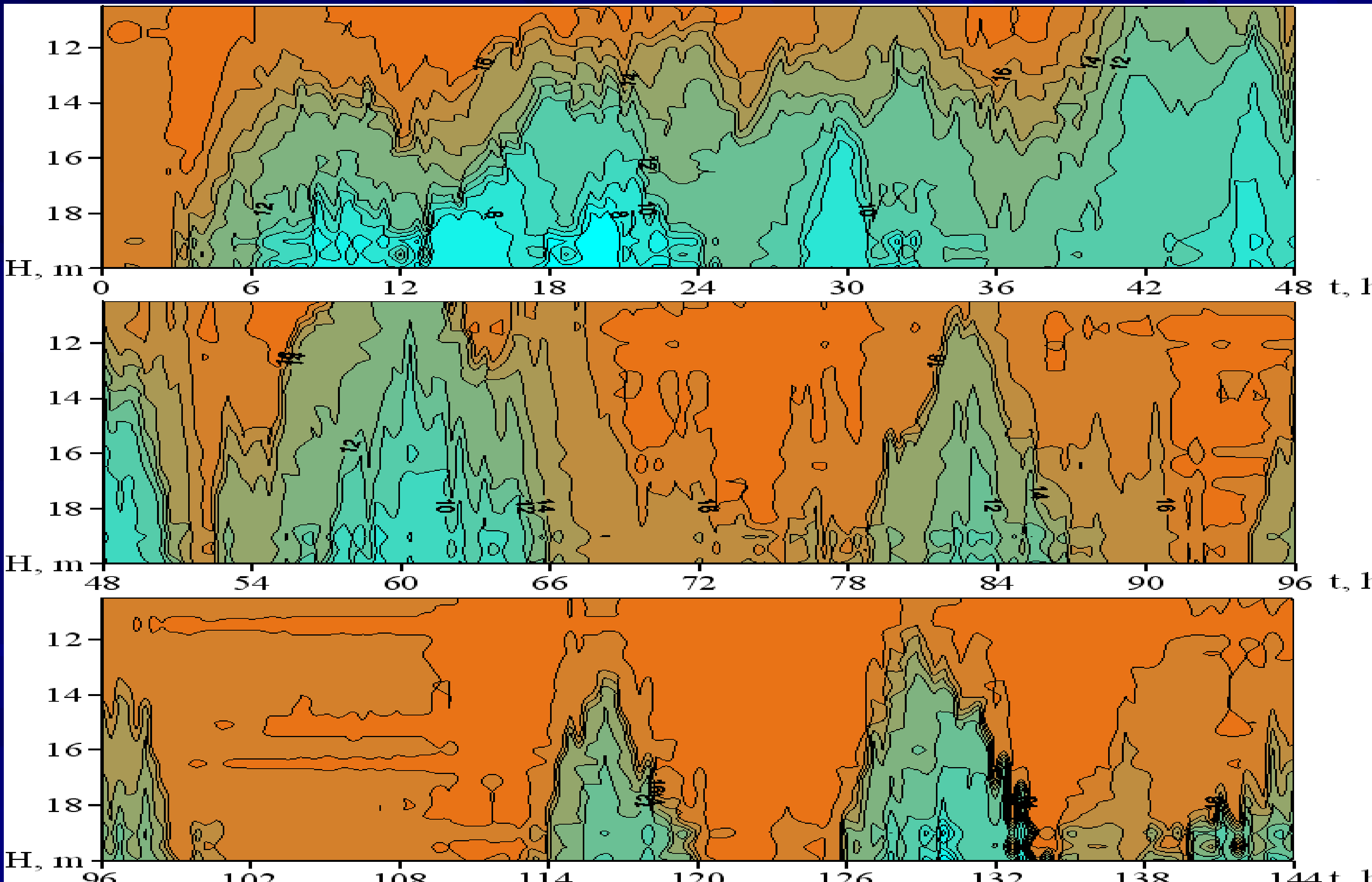




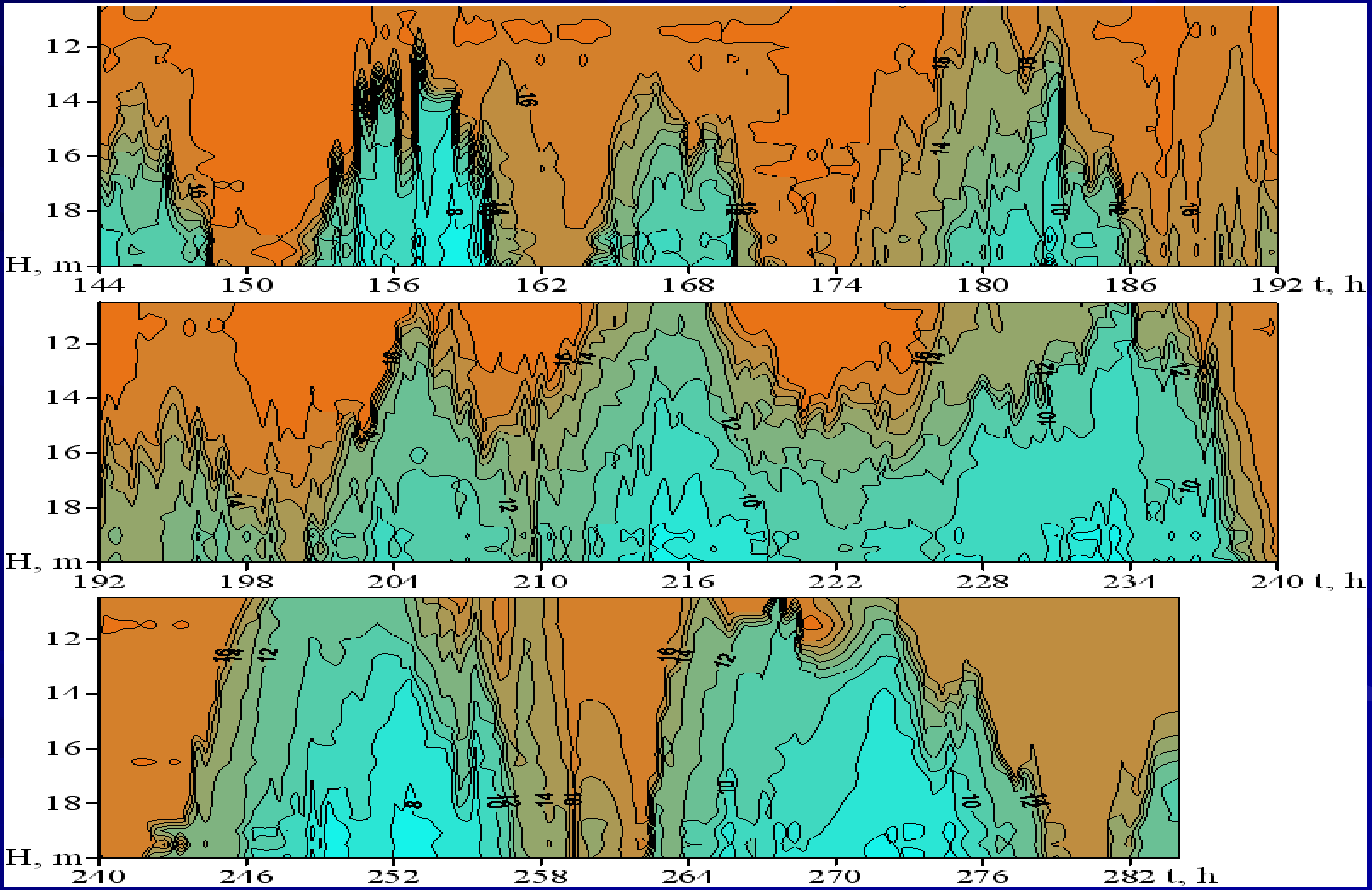
Internal waves and boluses in the near-bottom thermocline (Sept. 2009)



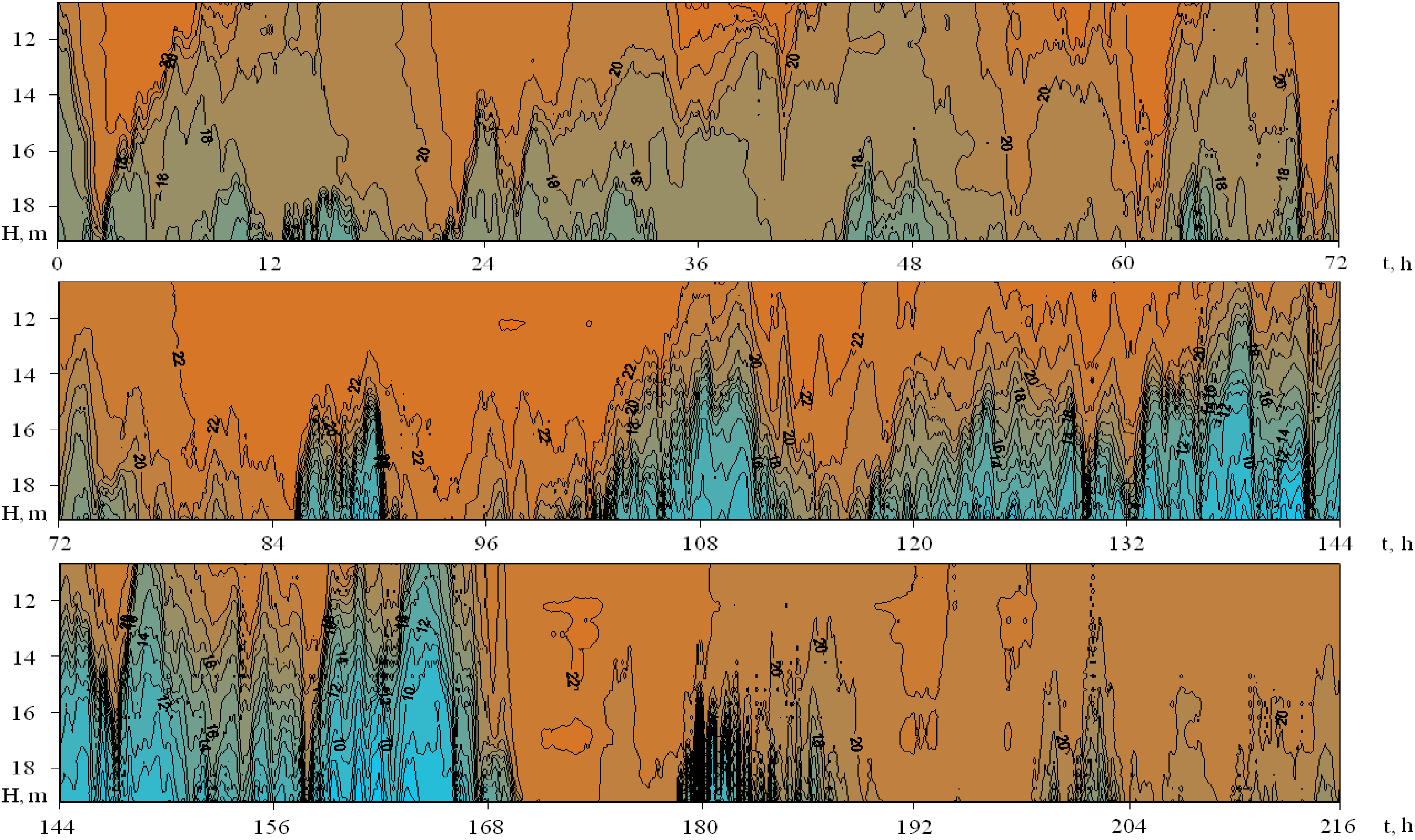
Internal waves and boluses in the near-bottom thermocline (Sept. 2009)



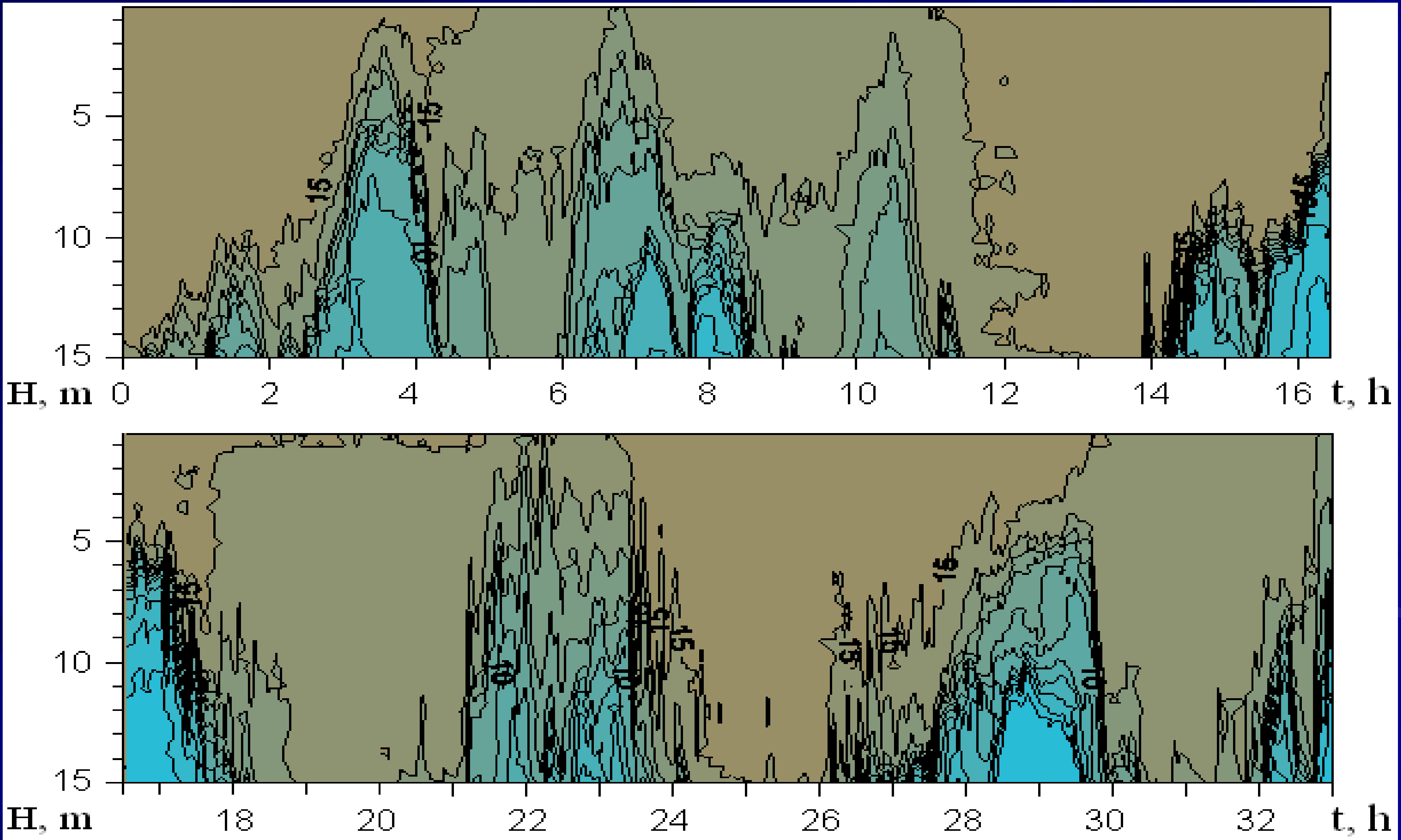
continuation



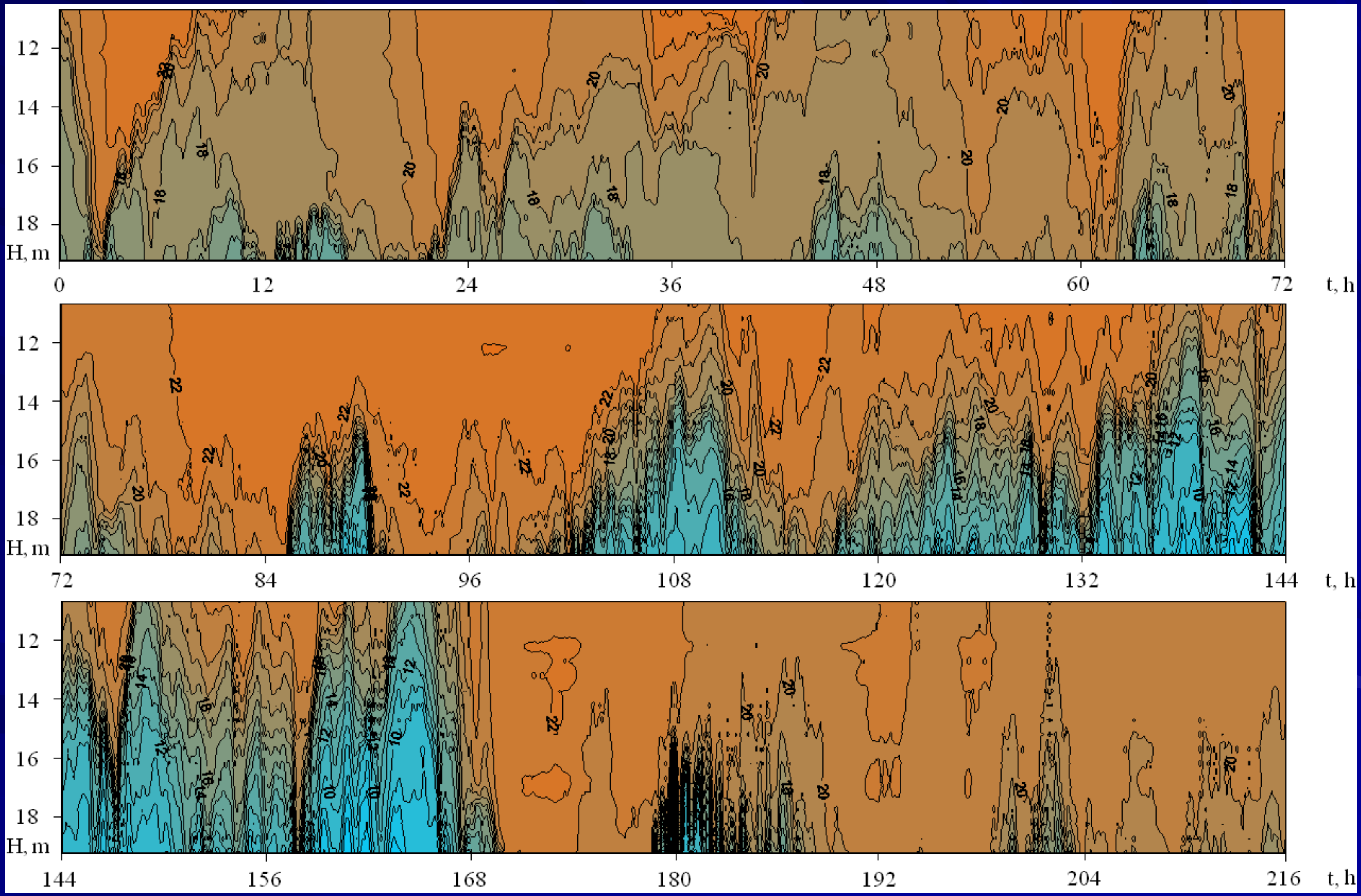
Temporal fluctuations of temperature in the 10-meter thick near-bottom layer (observations from 31.08.2010, 11:35).



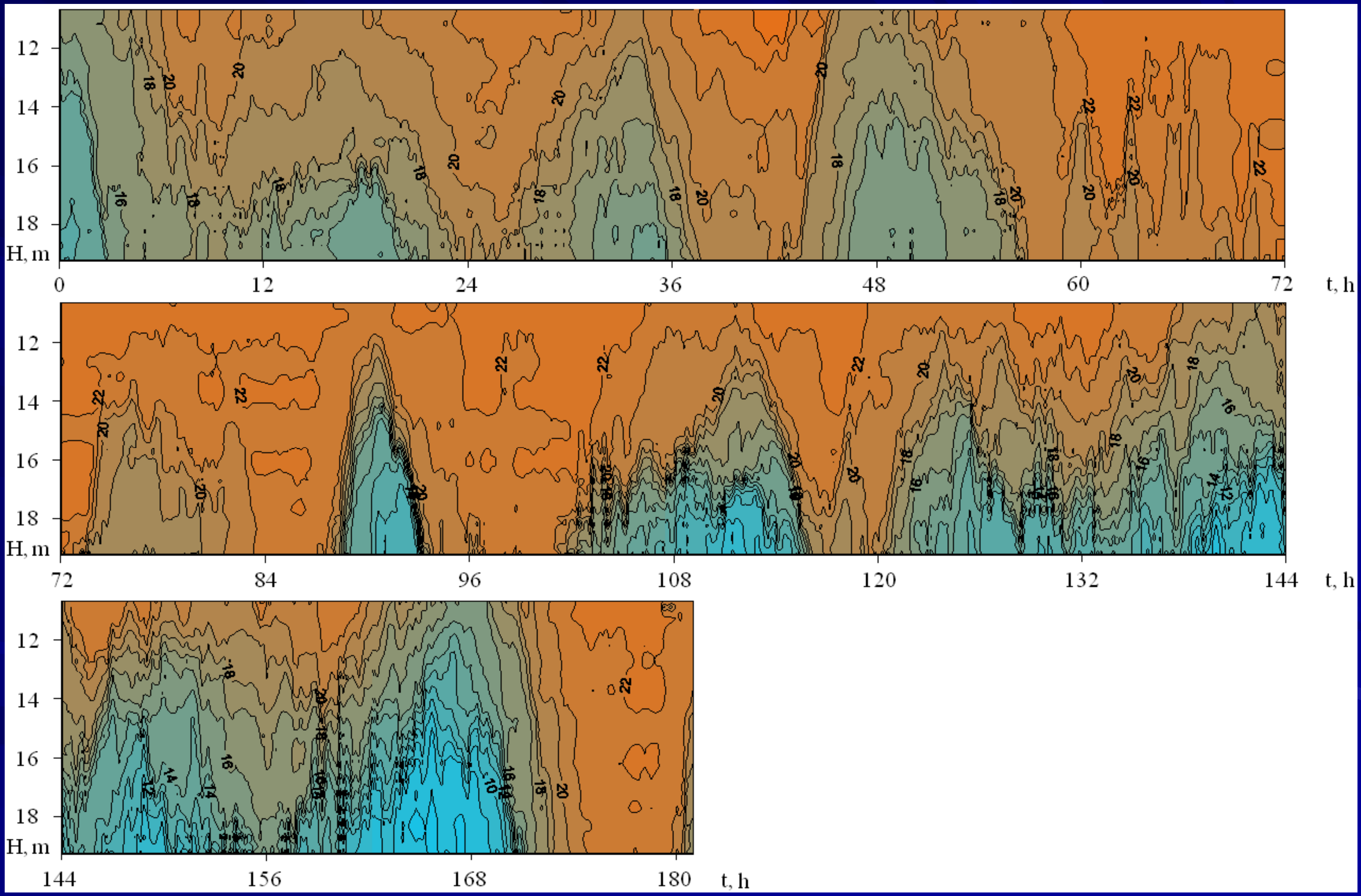
Setup and destruction of short-period internal waves in the 15m thick near-bottom layer (start at 06:22, 01.09.2011).



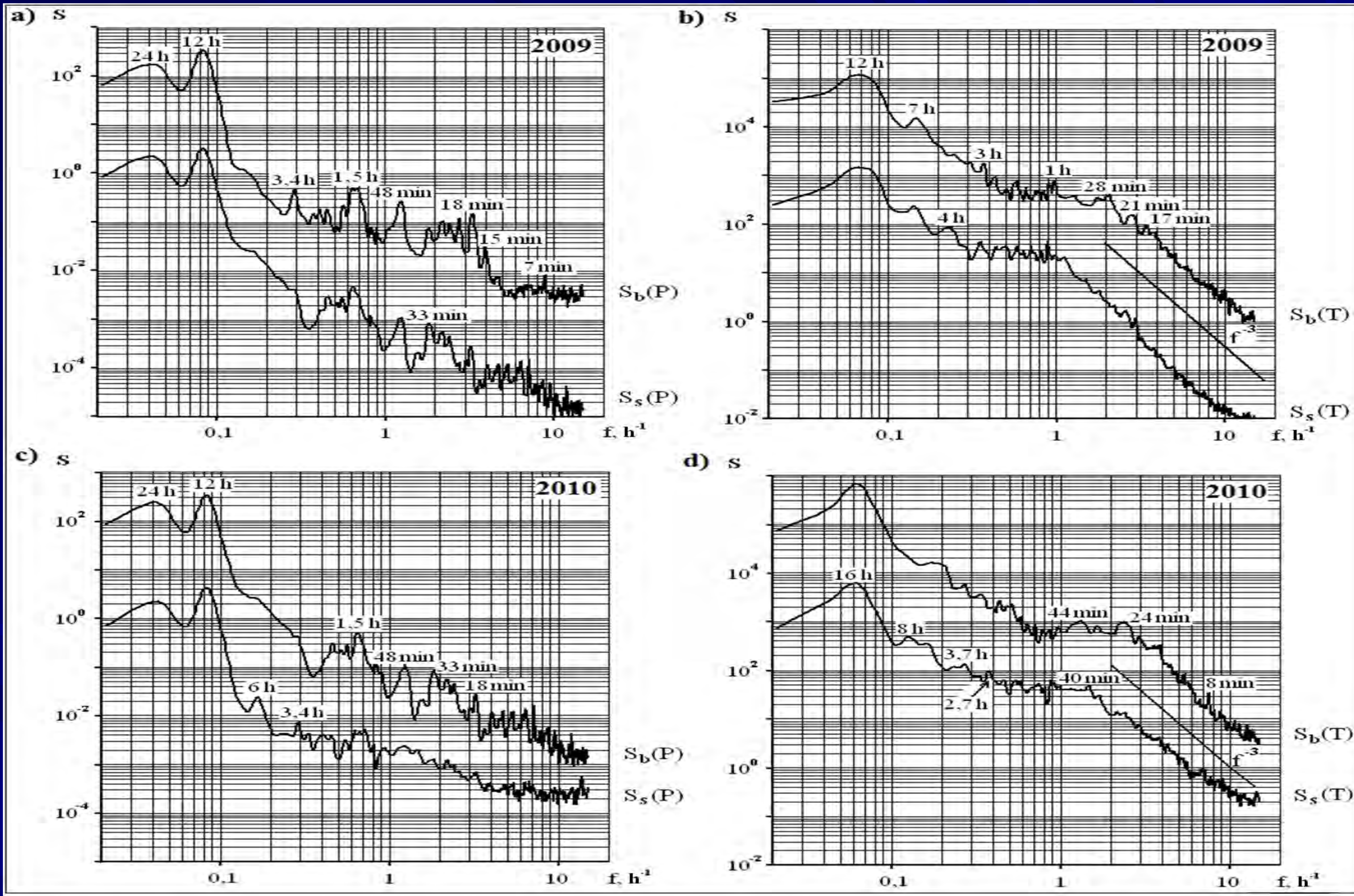
Temporal fluctuations of temperature in the 10-meter-thick near-bottom layer in the open sea (Aug-Sept 2010)



Temporal fluctuations of temperature in the 10-meter-thick near-bottom layer in the Vitiaz Bay (Aug-Sept 2010)

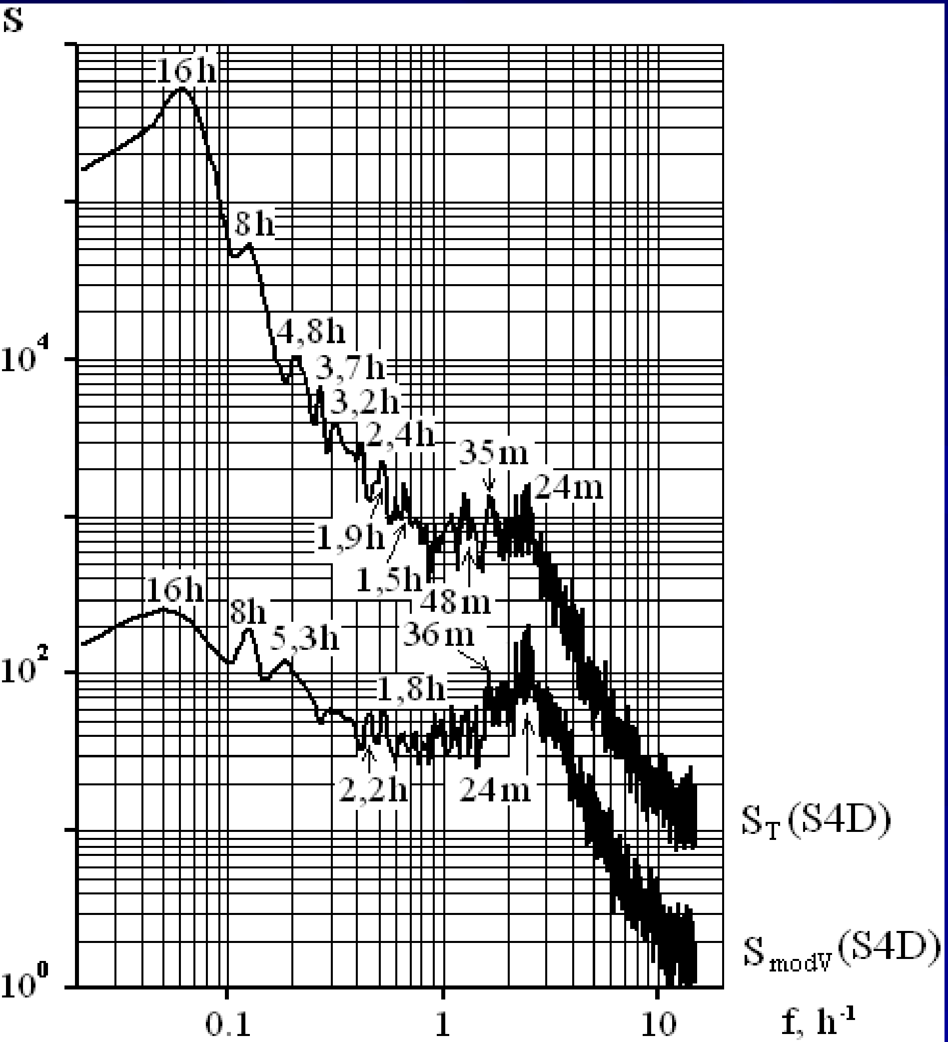


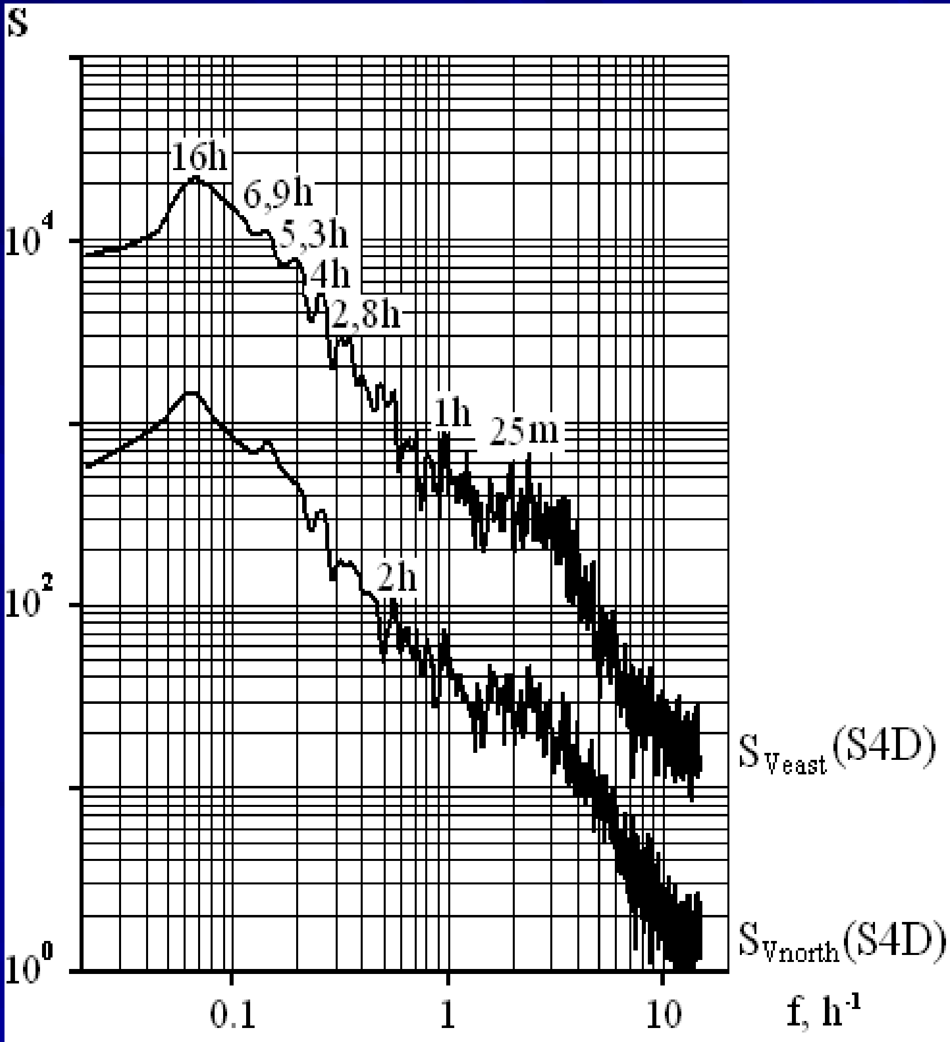
Spectra of bottom pressure and temperature fluctuations in the open sea and in the Vitiaz Bay in 2009-2010 – specific IW features



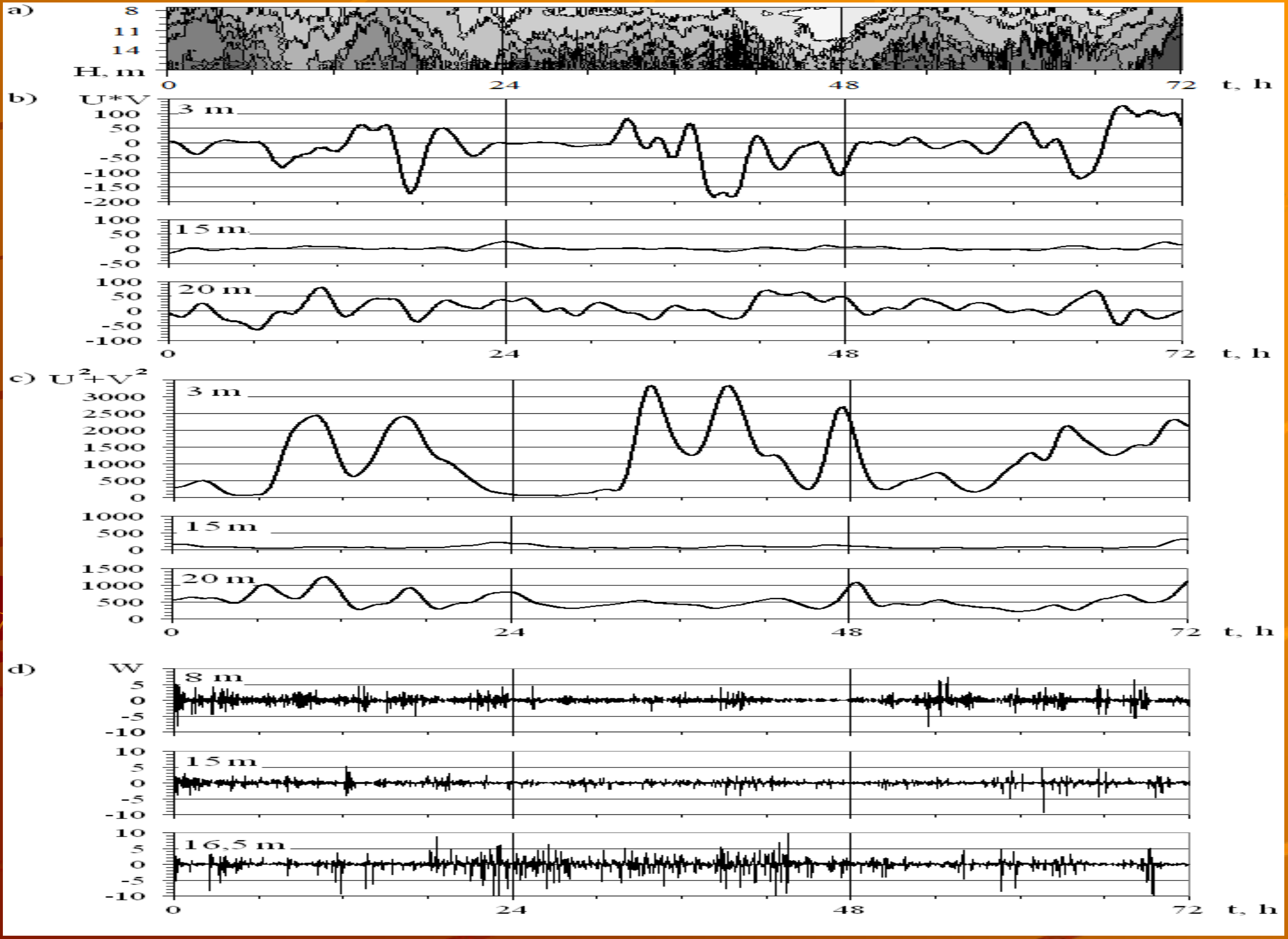
Spectra of mod(V) and temperature fluctuations

(The observed velocity field is is obviously produced by internal waves)

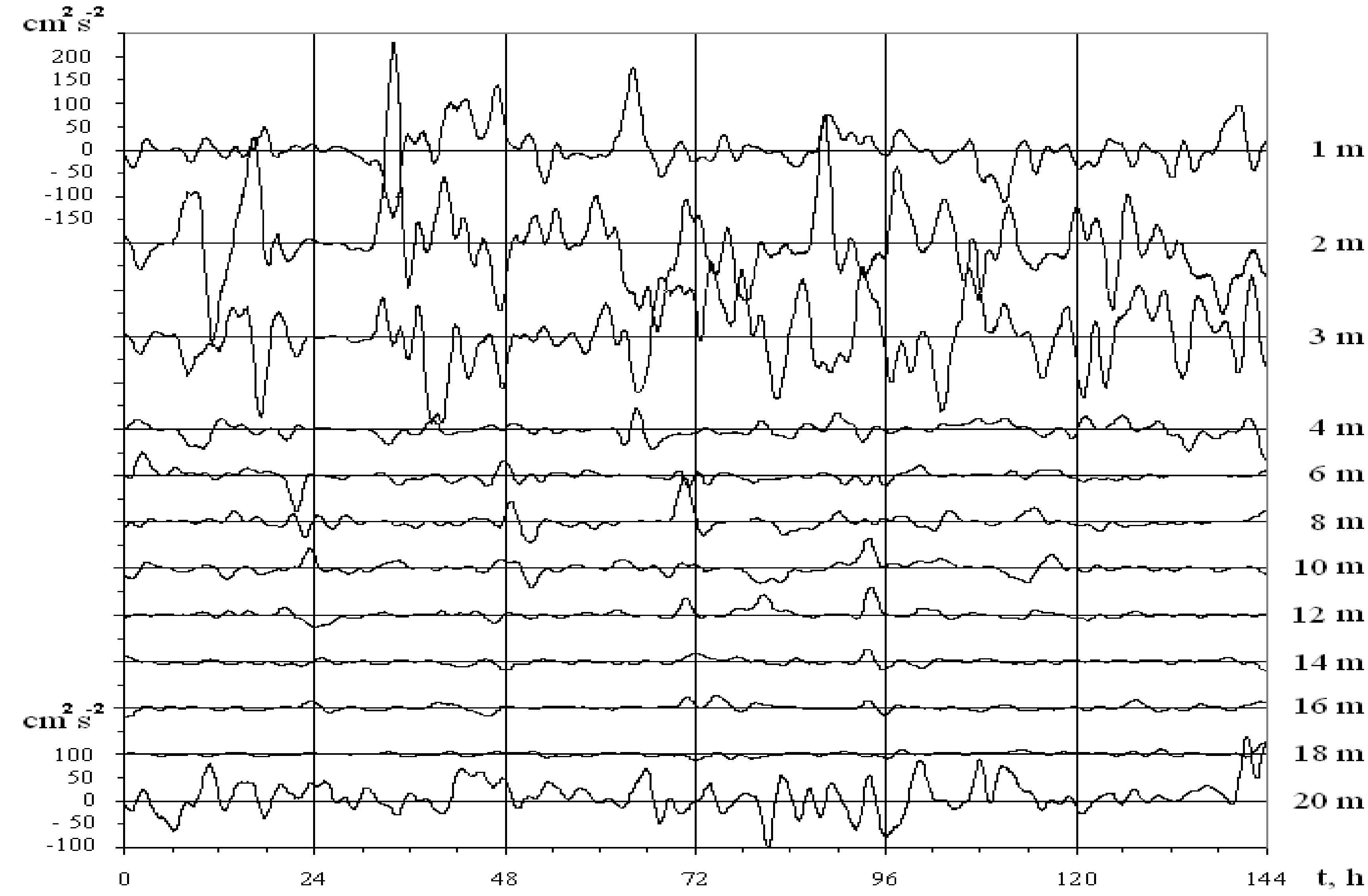




Temperature fluctuations in the near-bottom layer, fluxes of momentum and kinetic energy, and vertical velocity close to bottom



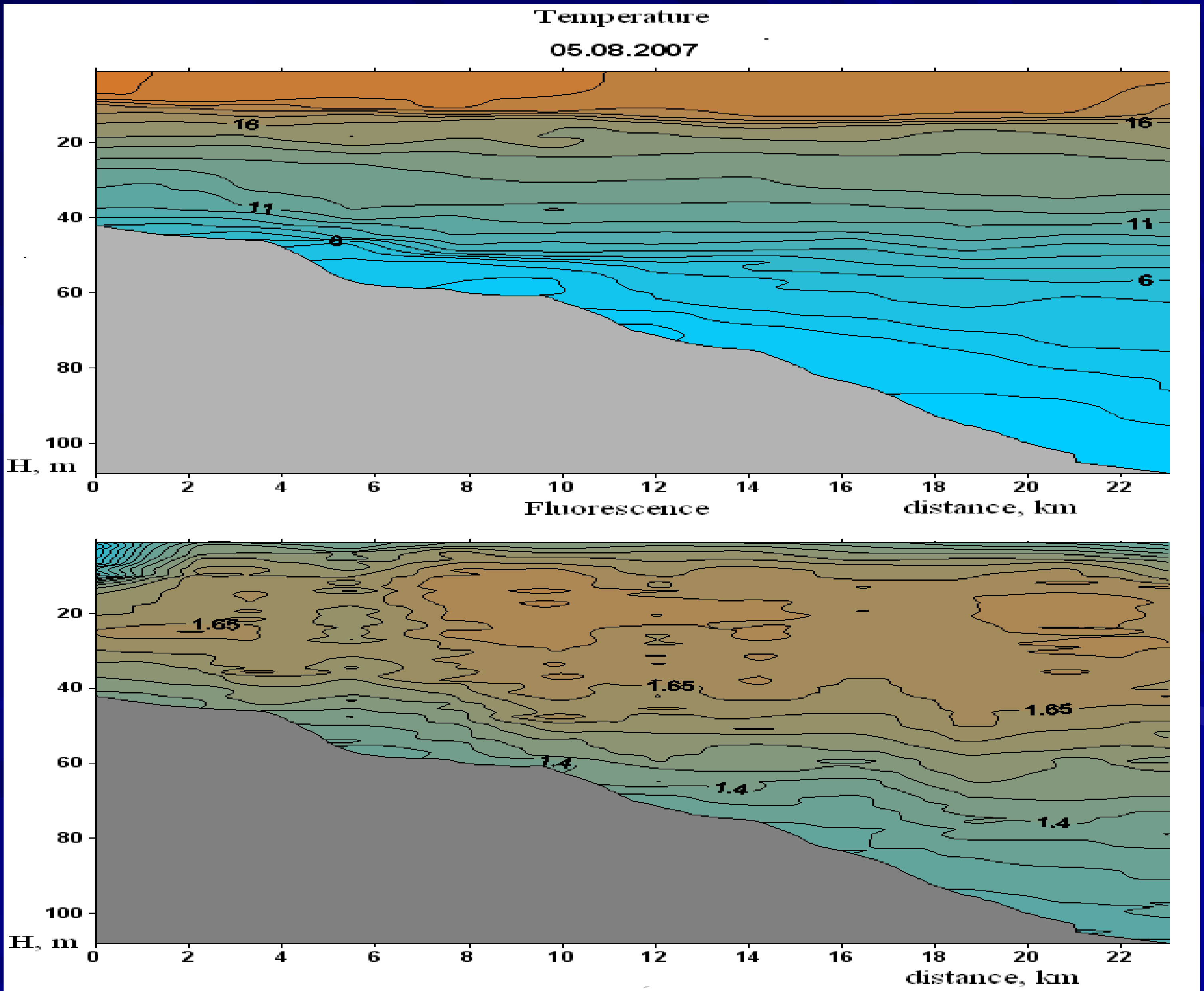
Kinetic energy of horizontal movements at different levels (bottom depth about 22 m)



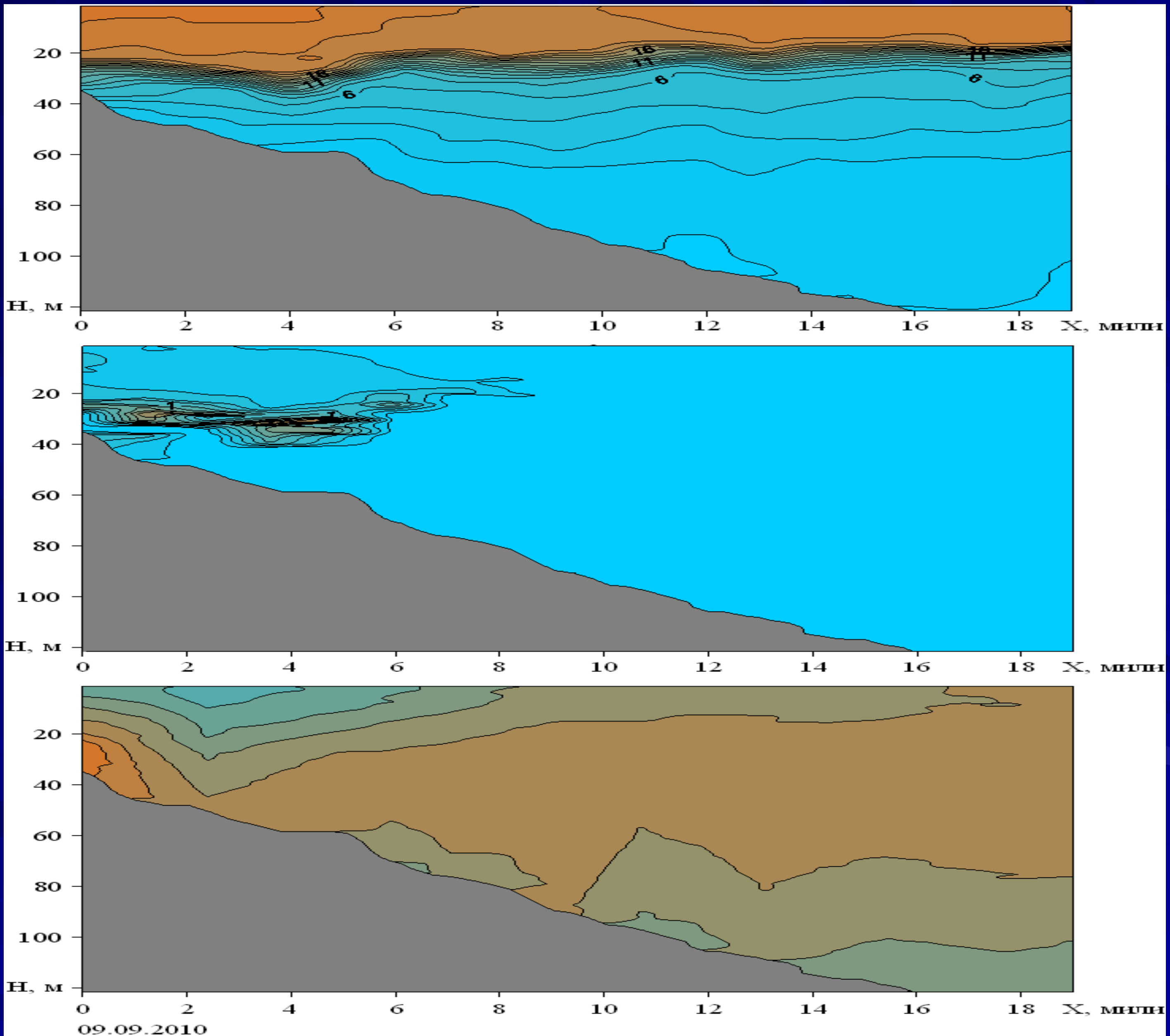
Surface wave breaking. Internal waves should break in the same way, but on longer time-space scales

- Quasiperiodical structure of amplitudes and velocities along the fronts of breaking waves is the result of intense horizontal vorticity and horizontal turbulence generation in nonlinear breaking waves

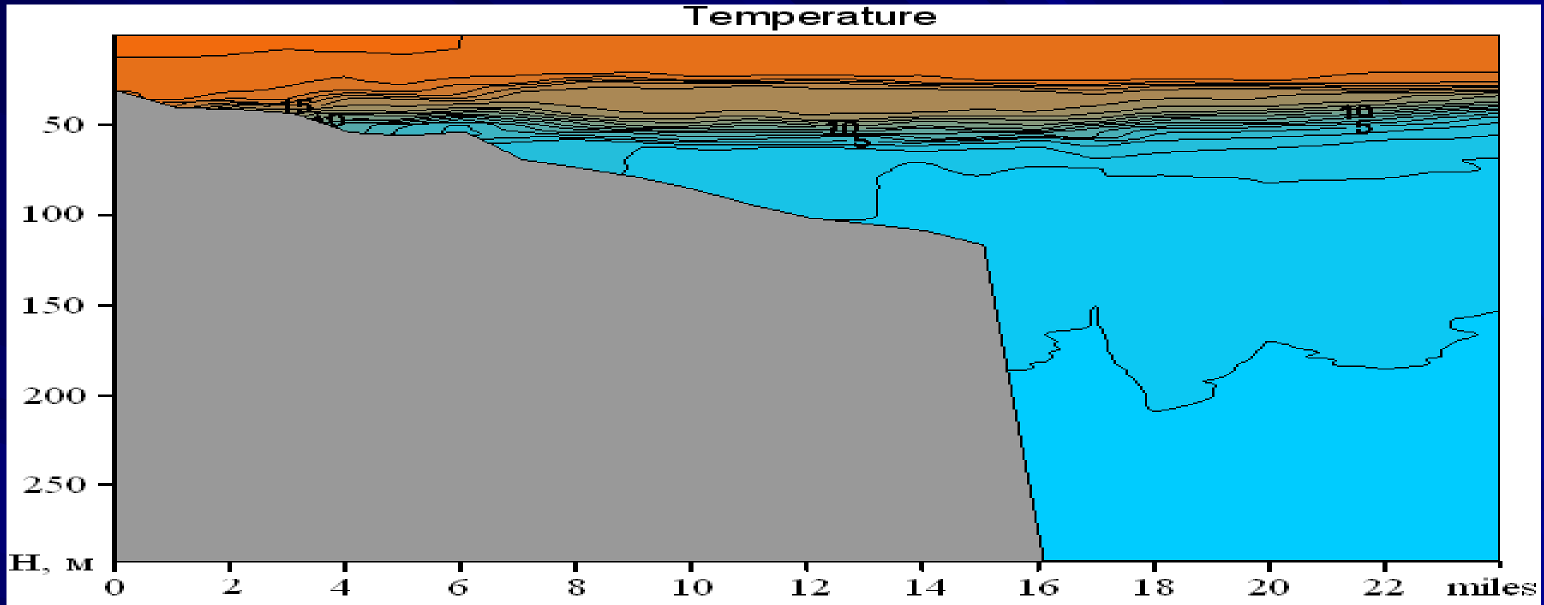
Temperature and fluorescence in the shelf zone (Peter the Great Bay)

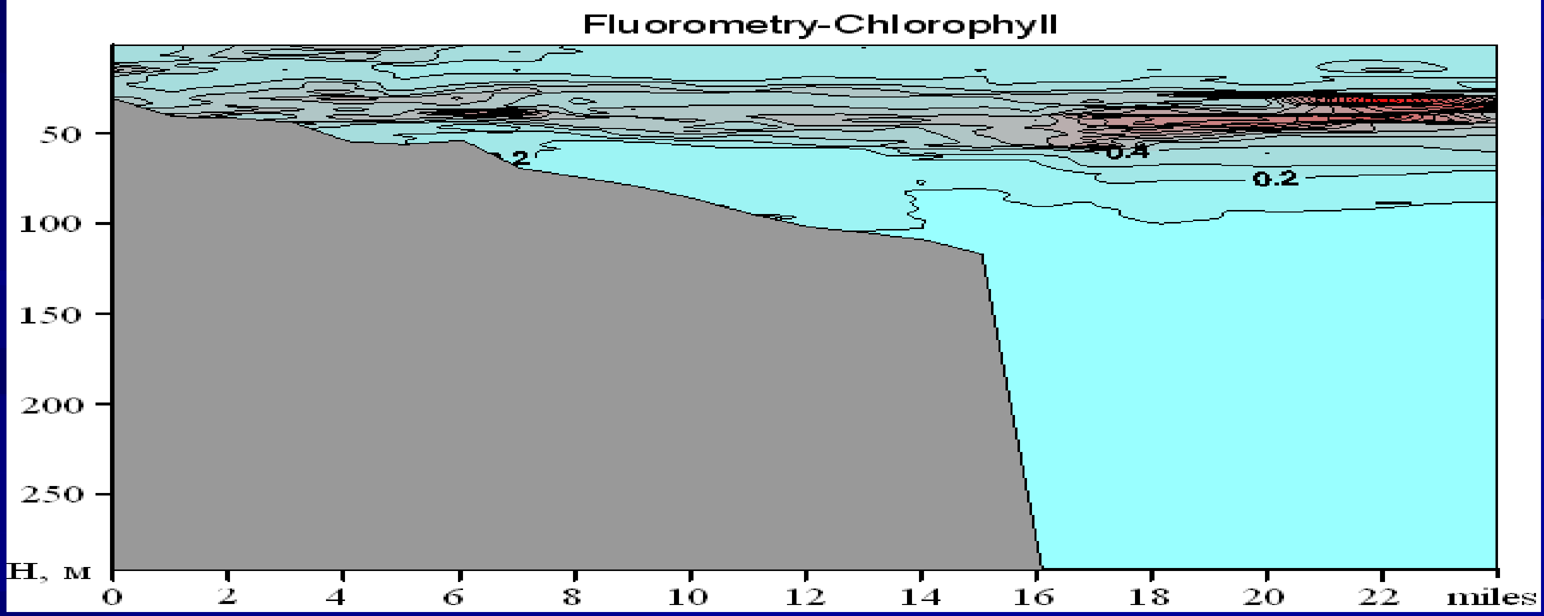


Temperature, fluorescence and turbidity spatial structure (PG Bay, 2011)

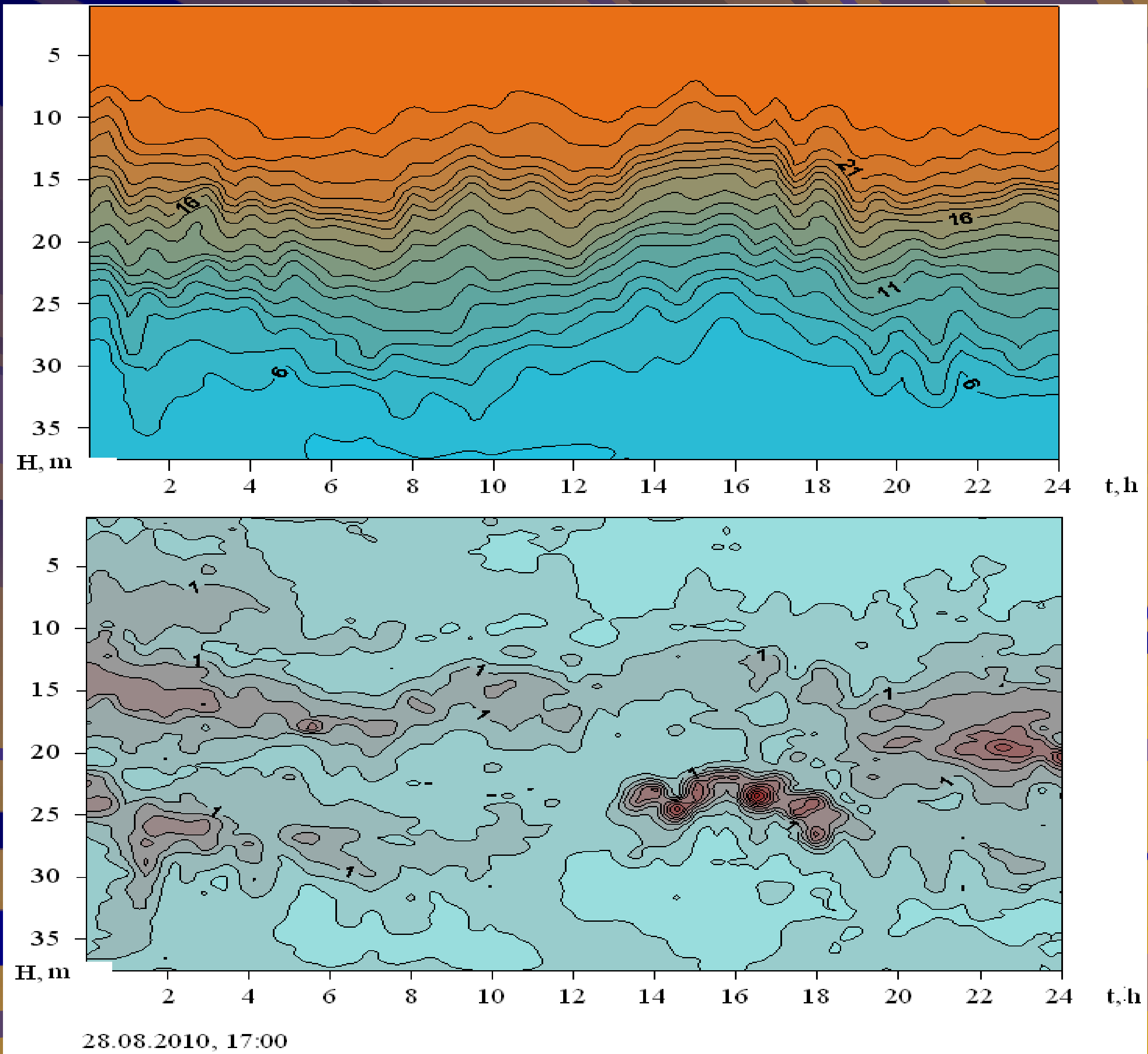


Thermocline and fluorescence in the Pete the Great Bay (Sept 2012)





Temporal fluctuations of thermocline and layers with maximum fluorescence



Conclusions

- Vertical structure of hydrophysical characteristics and vertical mixing intensity in shelf zones is to high degree defined by nonlinear interaction of internal waves with mean density structure of shelf waters
- Internal wave breaking in the near-bottom thermocline leads to generation not only three-dimensional small scale turbulence, but horizontal turbulence as well, which scales are defined by the scales of prevailing internal waves
- Resulting vertical and horizontal mixing combined with horizontal tidal movements leads a) to change in density vertical structure over the shelf zone; b) to effective transport of nutrients, oxygen and other admixtures defining productivity and ecological state of ocean shelf waters.

Thank you