SEASONAL CYCLE OF HEAT AND SALT BALANCE IN PETER THE GREAT BAY (JAPAN SEA)

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A problem of heat balance is well developed in oceanography, and now some routine procedures exist for estimation of the balance components as direct and back radiation, and sensible and latent heat fluxes. But the problem of advective component is not solved yet, although this component could be very important. As to salt balance, most of its components are unclear, as contributions of advection, turbulent exchange, and rains. There are some papers on the heat balance of the Japan Sea (Miyazaki, 1952; Aldoshina, 1957; Radzihovskaya, 1961; Pokudov & Tunegolovets, 1975; Kondo *et al.*, 1994), and climatic atlas prepared by Maizuru Marine Observatory in 1997; there are also few papers on the salt balance, as Ito (1958), but all of them don't concern coastal areas and don't consider shelf and shallow water phenomena.

The shelf of Primorye is distinguished by sharp and abrupt changes in temperature and salinity near the coast caused by upwelling-downwelling processes induced by wind-forced advection. So, when studying the heat and salt balance in coastal area, one should take into account the wind advection. Thus, the core of this paper is the elaboration of the method of advective component estimation.

Peter the Great Bay is rather a good area for wind advection investigation because of simple wind regime. Around a year the north-northwestern or south-southeastern winds dominate with their summary frequency about 70-80% (in winter 63% of N-NW, in summer 68% of S-SE), and both these directions are approximately normal to shelf edge and coastline. So, the changes in wind direction could be considered as changes between two opposite positions: off-shore (N-NW) and on-shore (S-SE). Wind-driven currents in shallow water are directed close to wind direction, thus, the S-SE winds have to generate the currents directed generally on-shore and to cause downwelling near the coast, and N-NW winds have to generate off-shore currents and upwelling.

Theoretically, velocity of wind-driven surface current in shallow water is linearly dependent on wind velocity ($V=0.0127W/\sqrt{\sin\varphi}$). But this equation couldn't be used for estimation of the advection because advective flux is not a surface one but embraces a certain layer. Fortunately, the upwellings and downwellings are visible well in changes of upper mixed layer thickness. Of course, these changes could be caused also by changes in wavelength (depending on square of wind velocity) and possibly by some other causes not related to wind, as tides.

This scheme was tested and estimated numerically on the base of data on the thickness of the upper mixed layer obtained on meridian standard section along 132°E with stations over 10 nautical miles (Table 1, Fig. 1). If the section is approximated as a system of five 10-mile boxes (one box per station), the volume balance of mixed layer for each box between two observations is:

$$\Sigma\, dH_i = (A_i - A_{i-1})\cdot\Sigma W_S + (B_i - B_{i-1})\cdot\Sigma W_N + m\cdot\Sigma d(W^2) + \Sigma T) \qquad (1)$$

where, dH_i – box mixed layer thickness change per day;

A, B – coefficients of linear link of northward (southward) transport with S-SE (N-NW) wind;

ΣW_S, ΣW_N – accumulated velocity of south and north wind correspondingly, m/s;

m – coefficient of mixed layer thickness dependence on W^2;

$\Sigma d(W^2)$ – integrated changes of W^2 between two observations;

W – scalar wind velocity;

$\Sigma\, T$ – integrated non-wind effect on mixed layer thickness between two observations.

Boundary conditions: $A_0=0$; $B_0=0$ (no currents through the coast); $A_4=A_5$; $B_4=B_5$ (no upwelling/downwelling outside the shelf).

Solving the system for different couples of periods between observations, the values of unknown coefficients A_i, B_i, m, and also mean daily value of T were found empirically. The values of m and T change seasonally, but coefficients of water transport A and B (m^3/s through 1 cm water column) are quasi-stable in shallow boxes (Figs. 2, 3).

Table 1

Periods between observations at section along 132°E that were used for the study

April 4-April 13, 1992	August 17-September 5, 1992
April 13-April 20, 1992	August 13-September 10, 1995
April 20-April 26, 1992	May 15-July 9, 1996
April 26-May 10, 1992	September 19-September 28, 1996
May 10-June 28, 1992	June 26-August 18, 1998
June 28-August 17, 1992	

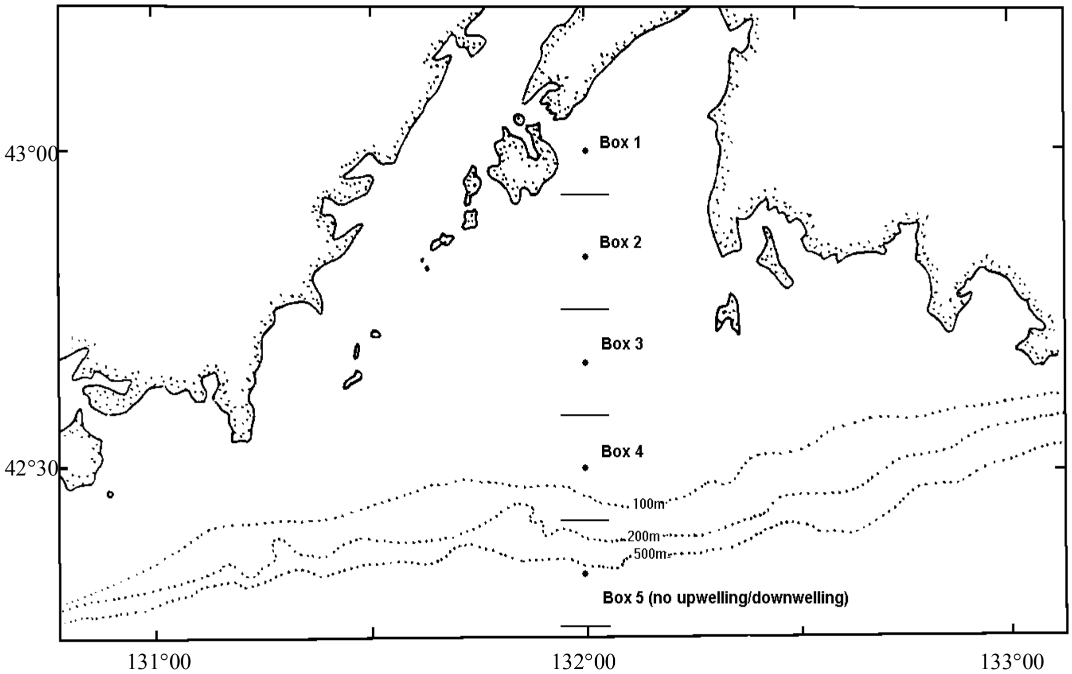

Fig. 1. Stations of the standard section and arrangement of the boxes

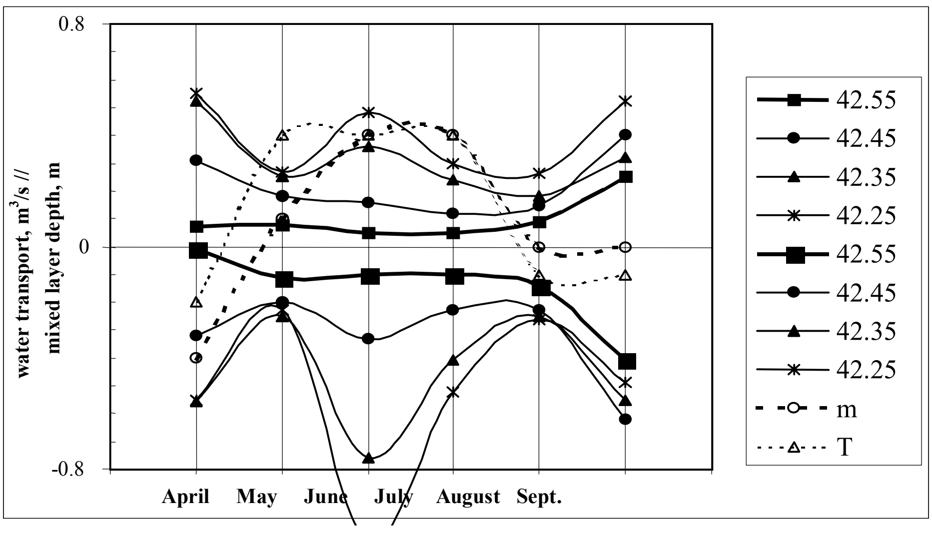

Fig. 2. Seasonal changes of Ai, Bi, m, T

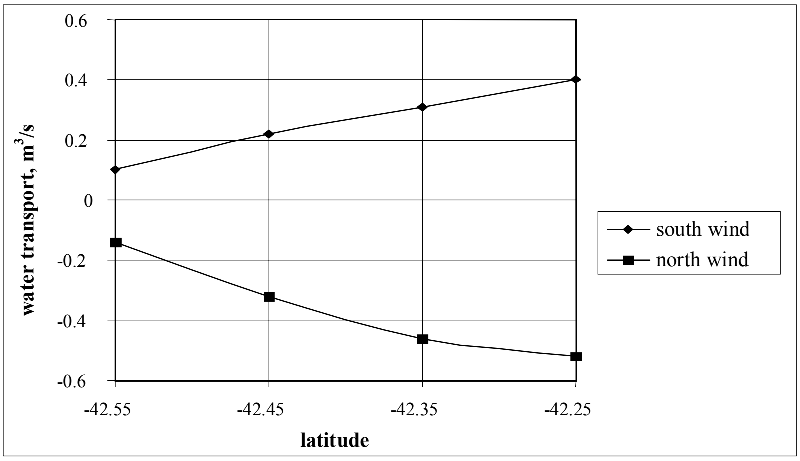

Fig. 3. Mean coefficients of water transport driven by south and north winds through the boundaries of boxes

Whole transport into or from the shallowest box causes changes in mixed layer thickness, for other boxes these changes could be calculated as difference between transports through northern and southern margins (Fig. 4).

Note that both downwelling and upwelling are the most intensive in the second box with depth about 60 m, but not in the shallowest box.

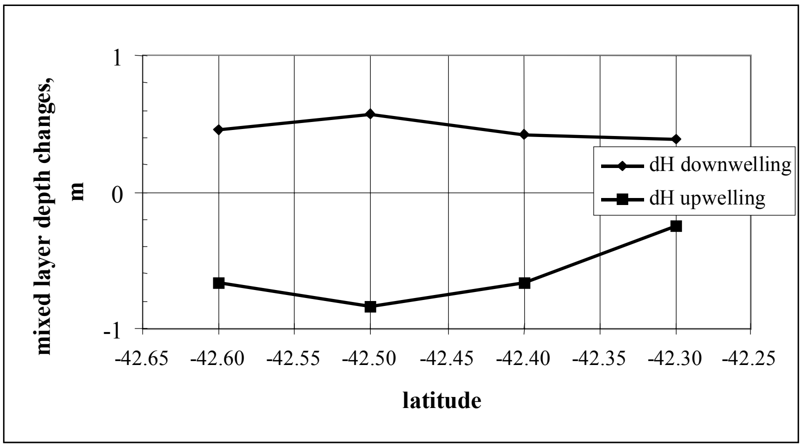

Fig. 4. Mean coefficients of changes of mixed layer thickness because of upwelling/downwelling effects in certain boxes

The links between wind conditions and upper mixed layer thickness were tested on the data obtained at the near-coast station within the shallowest box (depth 48 m). Results of the testing were satisfactory (Fig. 5) – the model simulated all general changes of the thickness.

During the warm seasons the wind-driven water transport influences heat and salt content of each box to two ways: 1) it increases (decreases) the thickness of relatively warm and brackish upper layer, and 2) it adds to upper or deeper layer the water from neighboring box, possibly, with different temperature and salinity. So far as both temperature and salinity have considerable fluctuations, for estimation of the heat and fresh water fluxes we carried out frequent (usually weekly) monitoring observations at the same near-coast station in the period from May to December. Water temperature and salinity profiles were measured at the station, and wind, cloudiness, air temperature were measured at coastal meteorological station "Vladivostok" located in 15 miles from the station. Temperature differences between the shallowest and second boxes were estimated with usage of real values for the station and climatic differences for each month. Mixed layer depth was determined as the depth of maximal gradient of thermocline.

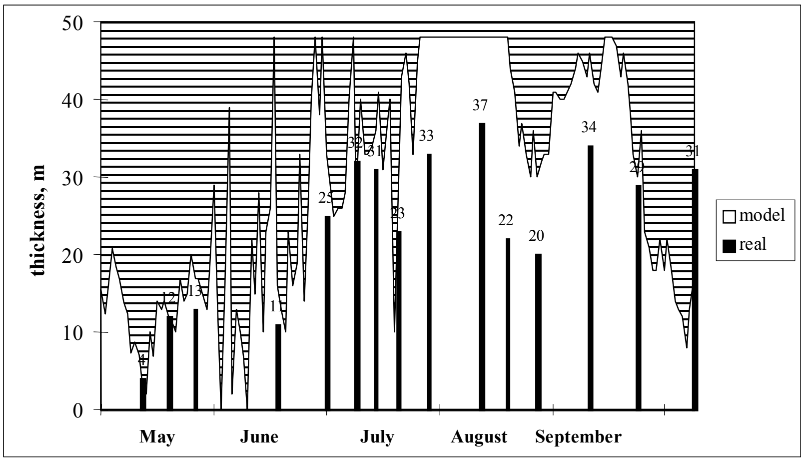

Fig. 5. Modeling of mixed layer thickness at the station in the shallowest box in 1999

Advective components of heat and fresh water balance were calculated by following procedure:

$$\Sigma\, dQ_a = \Sigma\, W_S A\ [(T_{u1} - T_{d1}) + (T_{u1} - T_{u2})] + \Sigma\, W_N B\ [(T_{u1} - T_{d1}) + (T_{d1} - T_{d2})] \quad (2)$$

$$\Sigma\, dF_a = \Sigma\, W_S A\ [(F_{u1} - F_{d1}) + (F_{u1} - F_{u2})] + \Sigma\, W_N B\ [(F_{u1} - F_{d1}) + (F_{d1} - F_{d2})], \quad (3)$$

where, dQ_a, dF_a – daily advective components of heat and fresh water balances;
$\Sigma\, W_S$ – accumulated south wind velocity;
$\Sigma\, W_N$ – accumulated north wind velocity;
A, B – coefficients for the shallowest box from Fig. 3;
$(T_{u1}–T_{d1})$, $(F_{u1} – F_{d1})$ – temperature and fresh water content differences between upper and deeper layers at station in the shallowest (1^{st}) box;
$(T_{u1} – T_{u2})$, $(F_{u1} – F_{u2})$ – temperature and fresh water content differences in upper layer between the shallowest (1^{st}) and the second boxes;
$(T_{d1} – T_{d2})$, $(F_{d1} – F_{d2})$ – temperature and fresh water content differences in deeper layer between the shallowest (1^{st}) and the second boxes.

Other components were estimated partly by routine procedure, partly by following balance equations:

$$dQ/dt = Q_r – rQ_r + Q_b + Q_e + Q_s + Q_a; \quad (4)$$

$$dF/dt = F_e + F_p + F_a + F_t, \quad (5)$$

where, dQ/dt, dF/dt – daily changes of heat and salt content;
Q_r – incoming radiation;
r – albedo;
Q_b – back radiation;
Q_e – latent heat flux caused by evaporation;
Q_s – sensible heat flux caused by turbulent exchange with atmosphere;
Q_a , F_a – heat and fresh water advection;
F_e– fresh water loss by evaporation;
F_p – fresh water supply by precipitation;
F_t – horizontal turbulent fresh water exchange (with pre-estuarine waters) caused by very high horizontal gradients of salinity.

Daily radiation balance (direct and back radiation: Q_r and Q_b) was calculated depending on latitude (42°55'N), cloudiness, air and near-surface water temperature, and dates, using the “Recommendations on calculation of components of radiation balance of ocean surface” published by USSR State Geophysics Laboratory in 1982. Sensible heat flux was estimated with usage of the empirical formula recommended by Shuleykin (1968): Q_s=5.2$W(T_A$-$T_W)$, where W is scalar wind velocity, and $(T_A$-$T_W)$ is the temperature difference between sea surface and air at 10 m above the surface. So far as we had not measured a humidity, the latent heat exchange Q_e was estimated as the rest of heat balance equations for each period between observations, that allowed to estimate the humidity deficit e using the empirical formula: $Q_e = 7.0eW$, recommended by Shuleykin (1968) as well. Fresh water decrease by evaporation F_e and fresh water turbulent exchange F_t caused by high horizontal gradients of salinity were estimated as the rest of the balance equations for the periods without rains. Then the relation between Fe and Q_e and seasonal fluctuations of F_t was determined and these two components were estimated for periods with rains. The rest of fresh water balance in these periods was interpreted as fresh water supply by precipitation *Fp*.

Estimations of all components are presented in Figs. 6, 7. Unfortunately, some estimations for autumn months (October-December) are not realistic. Of course, the latent heat flux couldn't be positive. Possibly, it means that advective component was overestimated because of considerable seasonal variability of coefficients of advection, so, it is impossible to use the values of *A*, *B* coefficients based on summertime data. Also the additional heat sources, like ice freezing or non-wind-driven advection (by eddies, for example), could be important in autumn months. Note that the estimation of latent heat flux at the Box 5 outside the shelf in November-December was more realistic: possibly, there was no ice freezing there. Anyway, so as autumn latent fluxes at coastal station were unrealistic, the values of humidity for these months weren't calculated, and there wasn't possible to estimate fresh water evaporation and fresh water supply by precipitation.

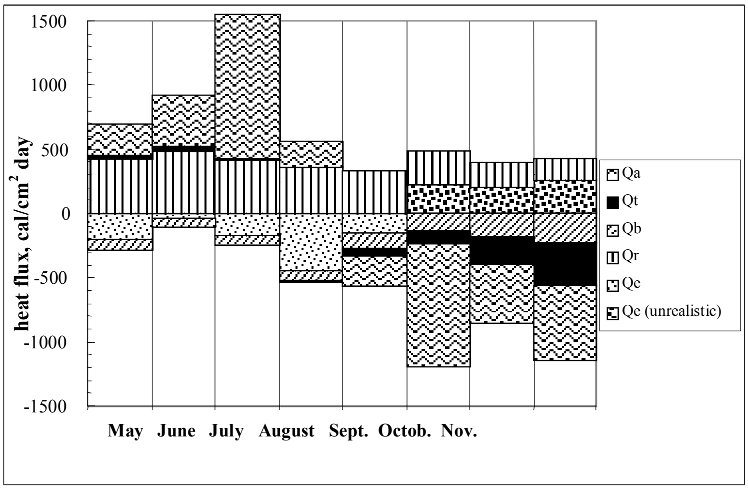

Fig. 6. Monthly averaged components of heat balance in the shallowest box in 1999

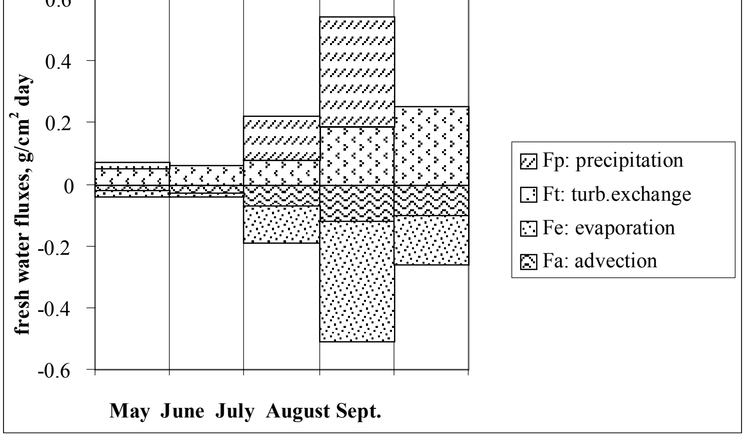

Fig. 7. Monthly averaged components of fresh water balance in the shallowest box in 1999

As for heat balance components for summer months, they look like quite realistic ones. Our indirect estimation of latent heat flux (from -50 to -500 cal/cm^{2}day) is similar to direct climatic estimations made by Radzihovskaya (1961) for the whole Japan Sea (-20 – -200 cal/cm^{2}day), and besides the highest values were obtained for extremely dry 1998 year. So, we can trust estimations of fresh water balance components in summer, based on humidity recalculated from latent heat flux values.

The prominent feature of heat balance in summer is a high importance of advective flux, mainly conditioned by upwelling/downwelling processes. When there is a summer monsoon, the advection driven by southern winds supplies 40-50% of total heat. But a considerable part of this heat is consumed by evaporation. The stronger the wind, the higher both positive advective and negative latent heat fluxes. So, the really effective heat supplier in summer is solar radiation. Winter monsoon that begins in September – October leads to simultaneously increasing of both negative advection and latent heat fluxes – as a result, the mean temperature of water column sharply decreases.

The fresh water balance hasn't been investigated yet in Peter the Great Bay, thus, any regarding information is interesting. There has to be noted the unexpected contribution of advection: it is negative (salt water advection) being driven both south and north winds! When there is a summer monsoon, the surface salt water trespasses to coastal area, when there is a winter monsoon, the salinity is increased by upwellings (Fig. 8). But fresh water is supplied permanently by horizontal turbulent exchange, and the process intensifies in late summer – autumn, when river run-off is higher. However, in rainy months precipitation is the main source of fresh water (Fig. 8).

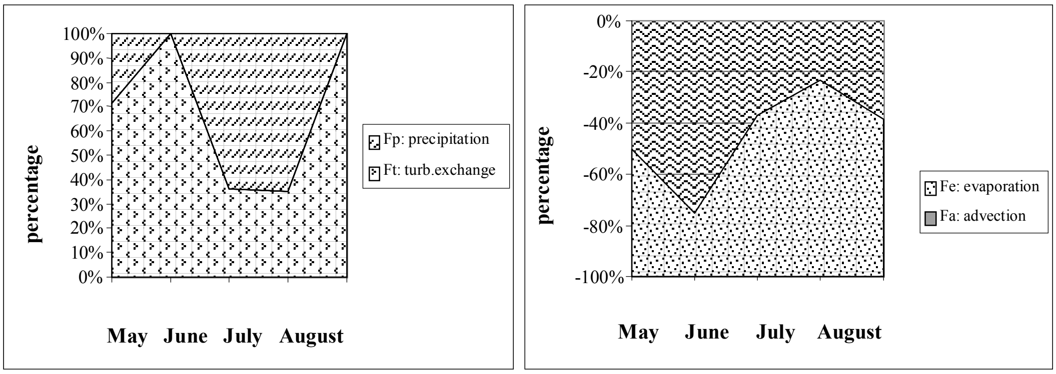

Fig. 8. Ratio of negative (left) and positive (right) contributions of fresh water balance in the shallowest box in May-September of 1999

I suppose that the results of this study are convincing arguments for a very important role of water advection both for heat and salt regime of coastal area. But the empirical model used was too rough and partly non-realistic – so we need to improve the studies of the processes in coastal zone.

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