Estimated Advection Heat in the East/Japan Sea

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A significant surface net heat loss appears around the Kuroshio and the Tsushima Warm Current regions. The area where the surface heat loss occurs should require heat to be supplied by the current to maintain the long-term annual heat balance. Oceanic heat advection in these regions plays an important role in the heat budget. The spatial distribution of the heat supply by the Tsushima Warm Current near the surface was examined by calculating the horizontal heat supply in the surface layer of the East/Japan Sea, directly from historical sea surface temperature and current data. We have also found a simple estimation of the effective vertical scale of heat supply by the current to compensate net heat loss using the heat supplied by the current in the surface 10m layer. The heat supplied by the current for the annual heat balance was large in the Korea/Tsushima Strait and along the Japanese Coast, and was small in the northwestern part of the East/Japan Sea. The amount of heat supplied by the current was large in the northwestern part and small in the southeastern part of the East/Japan Sea. These features suggest that the heat supplied by the Tsushima Warm Current is restricted to near the surface around the northeastern part and extends to a deeper layer around the southeastern part of the East/Japan Sea.

Key words : Advection heat, Surface heat exchange, Tsushima Warm Current

1. Introduction

The Tsushima Warm Current (TWC hereafter) flows into the East/Japan Sea (EJS hereafter) through the Korea/ Tsushima Strait (KS hereafter), and flows along the Japanese coast and the Korean coast to higher latitudes. Most of the TWC flows out through the Tsugaru Strait. A minor part of TWC flows to the north along the western coast of Sakhalin Island, then cools down and turns south(1). The TWC transfers high temperature and saline water to the EJS, and it also plays an important role in transporting fish from lower latitudes(2). The inflow of the TWC into the EJS also influences the climates of the coastal regions of Korea and Japan and contributes to the long-term annual heat balance.

It was found that annual mean surface heat loss in the North Pacific is replaced advection heat, and suggested that this mainly occurs in the surface layer up to 30 to 70m(3). Advection heat is also important in surface heat exchange in the Northwestern Pacific was claimed(4). It plays especially major roles in the TWC and the Kuroshio regions.

It was suggested that the small gain of heat in the area near Vladivostok seems to be associated with the existence of cold water flowing from the north(5).

Annual surface heat exchange in the EJS is about -51.3 W/m^2 (6), which implies that the EJS should be gradually cooled down. However, the EJS maintains its annual heat balance, which is possible due to advection heat. The heat supply into the EJS by the TWC should be as great as the heat loss across the sea surface in the EJS. This is associated with the difference between the heat inflow through the KS and heat outflow through the Tsugaru Strait and the Soya Strait. However, the spatial distribution of advection heat in the EJS has not been clearly identified.

In this paper we present the spatial distributions of advection heat in the surface layer are estimated from the historical data of sea surface temperature and surface currents. The vertical scale of advection heat can be estimated from the

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local balance between the net surface heat exchange across the sea surface and heat supply by advection heat. Finally, the horizontal distribution of the 'vertical scale' of advection heat is discussed.

2. Data and Methods

2.1 Data

The analysis is based on the historical surface current data observed by GEK (Geomagnetic Electro Kinetograph), ADCP (Acoustic Doppler Current Profiler) and ship drift from 1900 to 1993 published by the Japan Oceanography Data Center (JODC). The data were sorted by 1°x1° grids in the EJS (23-49°N, 119-157E°) (Fig. 1). The total number of observation points in our study area is 298,351. Most of the observations come from GEK and ship-drift measurements, and the data set is assumed to represent average velocity in the upper 10m depth. Representative monthly current data at each grid were obtained from averages of all available current observations belonging to the same month during 94 years in each grid. The published temperature data used were the global historical temperature data at standard depth by JODC (1943-1993) and the serial oceanographic station data of Korea Oceanographic Data Center (KODC) (1960-1995). Sea surface temperature, which is actually defined at 1m below the surface, is used in this study.

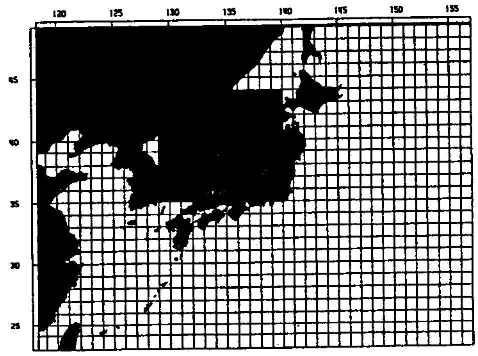


Fig.1 Domain of study area. Advection heat is computed in the shaded area, EJS.

Water is expected to be vertically well mixed near the surface. The total number of observations in our study area was 503,553. Representative temperature data values for each grid square were monthly mean temperature data. There are fewer surface current data than temperature data values (current data are about 60% of the number of temperature data points). The current data in the coastal region of Korea were especially sparse. On latitude and longitude coordinates, denoted by the subscripts i and j, spatially smoothed current data $u(i, j)$ and $v(i, j)$ at (i, j) grid were computed by averaging current data in local 3×3 grids, as follows.

$$u(i,j)=\frac{1}{N}\sum_{i=i-1}^{i+1}\sum_{j=j-1}^{j+1}u(i,j) \quad \text{and} \quad v(i,j)=\frac{1}{N}\sum_{i=i-1}^{i+1}\sum_{j=j-1}^{j+1}v(i,j) \qquad (1)$$

where u and v are eastward and northward currents, respectively, and N is the number of grids around the target grid.

We also used surface heat exchange data of short-wave radiation, long-wave radiation, sensible heat flux and latent heat flux from ASMD94 (Atlas of Surface Marine Data 1994) produced by NODC (National Oceanographic Data Center) for the estimation of advection heat in our study area. Surface heat exchange data at each grid were given by monthly mean 1°x1° grid data from the global atmosphere and oceanic data of COADS (Comprehensive Ocean Atmosphere Data Set) during 44 years from 1945 to 1989. Surface net heat exchange was computed from the difference between short-wave radiation and the sum of long-wave radiation, sensible heat flux and latent heat flux.

2.2 Method

The angle between surface current and isothermal line is estimated using the equation of state,

$$\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=k\nabla^2 T+Q \qquad (2)$$

where T is the surface temperature, $k\nabla^2 T$ is heat diffusion and Q is surface heat exchange rate. If we assume a steady state ($\partial T/\partial t=0$) and neglect surface heat exchange (Q), heat diffusion ($k\nabla^2 T$), then Eq. (2) becomes a conservation equation of heat advection.

The heat advection term can be written

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\nabla T\cdot\vec{V}=|\nabla T||\vec{V}|\cos\theta \qquad (3)$$

where $\vec{V}$ is the current vector, θ is the angle between current direction and ∇T is the temperature gradient. The relations between temperature gradient and current vector are shown in Fig. 2. When the current flows parallel to an isothermal line (Fig. 2(a), $\theta = 90^{\circ}$), no heat content change occurs. If the current flows across an isothermal line from a high to a low temperature area, then heat should be supplied by current (Fig. 2(b), $\theta > 90^{\circ}$). In this case, if the angle between the current vector and the temperature gradients increase, the advection heat is increased. By contrast, if the current flows across an isothermal line from a low to a high temperature area, then heat should be withdrawn by the current (Fig. 2(c), $\theta < 90^{\circ}$). In this case, if the angle between both terms decreases, the heat withdrawn by the current is increased.

The angle between temperature gradients and current vector can be computed by

$$\theta = \cos^{-1}\frac{\vec{V}\cdot\nabla T}{|\vec{V}||\nabla T|} \tag{4}$$

The relationship between the direction of current and isothermal line was examined using the historical monthly mean temperature and current data for each grid.

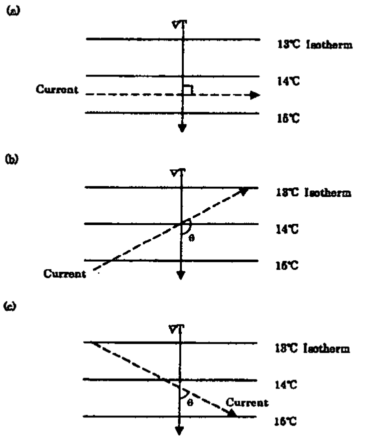


Fig. 2 Diagram of angle between current vector and temperature gradient.

The oceanic heat balance including both heat exchange across the sea surface and heat advection by ocean currents can be simply written [7] as

$$Q_{net} + Q_v = 0 \tag{5}$$

where Q_v indicates the heat supplied by ocean current, inflow of fresh water, rainfall and so on. If heat supplied from the inflow of fresh water and rainfall is very small, Q_v is able to represent advection heat, and Q_v can be estimated by net heat loss, Q_{net}, from Eq. (5).

We used monthly mean surface current data and temperature data at each grid to compute advection heat. Advection heat in the surface 10m layer (Q_{10m}) is computed from surface current and temperature data by

$$Q_{10m} = c\rho\left(u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y}\right)\times D \tag{6}$$

where c is specific heat (3.93kJ/kg\ ℃), ρ is density of water (1025kg/m^3), u and v are eastward and northward currents velocity (m/s) at the upper 10m average, and D is the surface layer thickness, 10m. Heat advection in Eq. (6) was estimated by the finite-difference method on 1°×1° grid.

3. Results

3.1 Surface heat exchange in the Northwestern Pacific

It has been reported that large surface heat loss occurs in the Northwestern Pacific [4), 8), 9)]. It is stated that The heat loss is due to the difference in temperature and vapor pressure between the Kuroshio region and the atmosphere [10)].

Figure 3(a) shows the annual mean distribution of heat supplied by solar radiation from the surface heat exchange data issued by ASMD94. The heat supplied by solar radiation is gradually reduced with increasing latitude. The spatial distributions of heat supplied through the surface in the EJS are in the range 150-170W/m^2. Figure 3(b) shows the distributions of heat discharge through surface in the Northwestern Pacific. Annual mean surface heat loss in the EJS is about 150-250 W/m^2. The spatial difference of heat loss through surface is greater than 100 W/m^2, though the heat supply difference is not so large. This is associated with high latent heat (150-170W/m^2) and sensible heat (40-50 W/m^2) of the Kuroshio and the TWC regions in winter [7), 10), 11)].

Figure 3(c) shows the annual mean surface net heat loss as a difference between surface heat supply and surface heat loss. A relatively large annual mean heat loss clearly appears around the Kuroshio and the TWC regions. If one considers only surface heat exchange, these areas should cool down. However, the maintenance of heat balance in these regions should be caused by advection heat [3), 9)]. Advection heat for annual heat balance in the EJS is larger than 100 W/m^2 in the southeastern part and less than 20 W/m^2 in the northwestern part.

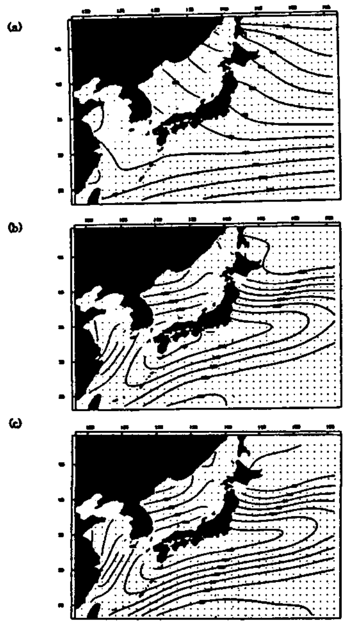


Fig.3 Annual mean distribution of (a) heat gain, (b) heat loss and (c) net heat loss through the surface in the Northwestern Pacific (unit : W/m^2).

3.2 Heat capacity variation due to surface current

The change of heat content due to currents can be quantitatively computed from Eq. (7). In that equation, if ρ, c and D are constant, heat capacity change due to current could be presented by an advection term (Eq.(4)).

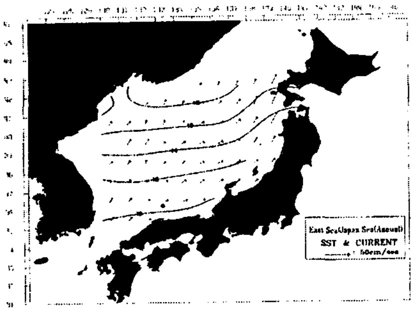


Fig.4 Spatial distribution of annual mean surface temperature and current in EJS (unit : ℃).

Figure 4 shows the annual mean distributions of surface current and temperature at each grid in the EJS. Current vectors are almost parallel to isothermal lines in the southeastern part and perpendicular to isothermal lines from high to low temperature areas in the northwestern part of the EJS and at the mouth of Tsugaru Strait. According to these results, a larger advection heat should occur in the northwestern part and a smaller one in the southeastern part of the EJS.

These predictions are confirmed in Fig. 5 which shows spatial distributions of annual mean advection heat in the surface 10m layer from surface current and temperature data calculated according to Eq. (7). Advection heat is large around the northwestern part in the EJS and at the mouth of Tsugaru Strait (> 80 W/m^2) and is small around the southeastern part of the EJS (< 10 W/m^2). The distribution pattern of advection heat shows a distinctive imbalance with net heat loss shown in Fig. 3(c).

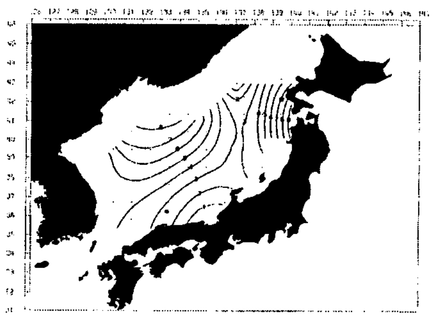
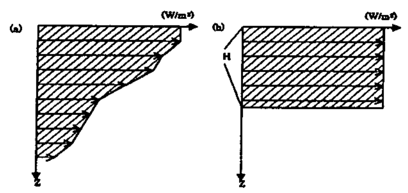


Fig.5 Spatial distribution of annual mean advection heat in the surface 10m thickness in EJS (unit : W/m^2).

It may therefore be supposed that the effect of advection heat might extend to a deep layer in the southeastern part of the EJS, while being limited to a shallow layer in the northwestern part of the EJS to compensate net heat loss. This point will be discussed in the next section.

3.3 Vertical scale of advection heat in the East/Japan Sea

It is natural to consider that current velocity will decrease downward and so advection heat should change with water depth (Fig. 6(a)). It is difficult to discover the precise vertical current profile. Advection heat in the surface 10m layer is integrated from the surface to a certain depth to match advection heat with net heat loss to maintain the heat balance at each grid location; the effective vertical scale of advection heat (*H*) can be estimated (see Fig. 6(b)).



$$\int_0^z Q(z)dz = Q_{10m} \times H$$

Fig. 6 Diagram showing the definition of effective vertical scale (*H*) by Q_{10m}, where $Q(z)$ is advection heat at depth z, Q_{10m} is advection heat in the surface 10m thickness and *H* indicates a depth where integrated value of Q_{10m} divided by *D* from surface to some depth is same as advection heat for local annual heat loss.

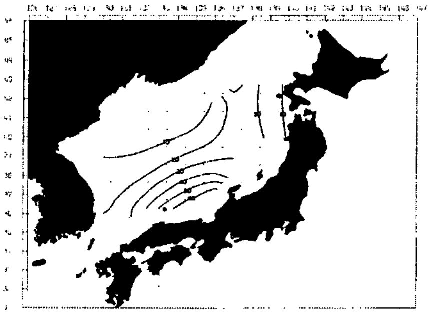


Fig. 7 Spatial distribution of vertical scale (H) estimated by annual heat balance in EJS (unit : m).

Advection heat extends to a greater depth in the southeastern part of the EJS and is restricted to a shallower depth in the northwestern part of the EJS and at the mouth of Tsugaru Strait (Fig. 7). limiting factor.

3.4 Heat supply due to current and solar radiation energy

Figure 8 shows the ratio between heat supply through sea surface (Q_S) and advection heat (Q_v) in the EJS. The heat supplied by solar radiation through the sea surface has almost uniform distributions of 150-170 W/m^2 in the EJS. By contrast, advection heat is clearly large in the southeastern part and reduces gradually toward the northwestern part of the EJS, the spatial difference being larger than 100 W/m^2. This means that advection heat is an important heat source, being about 60-70% of the heat supplied through the surface, around the southeastern part of the EJS and the Japanese coast. Around the northwestern part of the EJS, the heat content is mainly dominated by the net heat exchange across the sea surface, and advection heat in that region contributes less than 10% to the changing heat content.

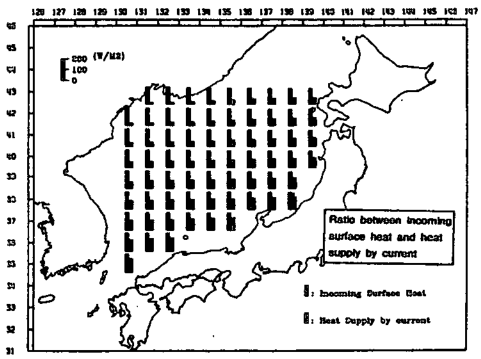


Fig. 8 Spatial distribution of the ratio between incoming solar radiation (Q_S) and advection heat (Q_v) in EJS.

4. Conclusions

Surface heat exchange data show that the annual mean heat loss is larger than the annual mean heat gain in the Northwestern Pacific. If we consider the surface heat exchange only, this area should be cooled down, but long-term annual heat balances are maintained in that region because advection heat compensates the surface net heat loss. The advection heat need to maintain the annual heat balance in the EJS is large around the KS and the Japanese coast with magnitude > 100 W/m^2 and is small in the northwestern part of the EJS with magnitude < 20 W/m^2.

A study of the distributions of isotherms and surface current vectors in the EJS shows that surface current usually flows across the isothermal line from high to low temperature areas. This is distinctly shown at the northwestern part of the EJS and around the mouth of Tsugaru Strait. The magnitude of advection heat in the surface 10m layer in the northwestern part of the EJS is greater than that at the southeastern part. In fact, advection heat in the surface 10m layer is > 80 W/m^2 in the northwestern part of the EJS, while it is < 10 W/m^2 in the southeastern part of the EJS.

The effective vertical depths associated with advection heat estimated from annual net heat loss and advection heat in the surface 10m layer, are deeper than 60 m in the southeastern part and shallower than 10 m in the northwestern part of the EJS. This suggests that the TWC in the southeastern part of the EJS occupies a deeper layer but that in the northwestern part of the EJS is limited to a relatively shallow layer.

Annual advection heat in the southeastern part of the EJS amounts to more than 60% of the heat supplied through the sea surface. Advection heat in that area is relatively important for the heat balance. By contrast, advection heat in the northwestern part of the EJS forms less than 10% of the heat supplied through the sea surface. Most of the heat exchange in the northwestern part of the EJS occurs across the sea surface.

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