Large Scale Air Sea Interaction in the Northern
Hemisphere from a View Point of Variations of
Surface Heat Flux by SVD Analysis

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Abstract

Large scale relationships between surface heat flux (defined as the sum of sensible and latent heat fluxes at sea surface) and the atmospheric circulation in the Northern Hemisphere during the northern winter have been examined, using the singular value decomposition (SVD) analysis. The dominant heat flux anomaly pattern in the North Pacific has large amplitude in the western and the central part of the subtropical gyre, and the one in the North Atlantic exhibits a north-south seesaw in the western Atlantic. These patterns are closely related to the dominant atmospheric circulation anomaly patterns known as the teleconnection patterns, i.e., the dominant surface heat flux pattern in the North Pacific is related to the Pacific/North American (PNA) teleconnection pattern and the one in the North Atlantic is tied to the Western Atlantic (WA) pattern (Wallace and Gutzler, 1981). Variations with a time scale of a few years are dominant in time coefficients of the leading SVD modes for both oceans. Decadal scale or trend-like variation is also seen in those for the North Pacific but is not apparent for the North Atlantic.

We also investigated the relation between the surface heat flux and the time rate of change of sea surface temperature (SST tendency). Local correlation coefficients between them are generally high but not close to unity. This suggests that the SST tendency is determined not only by the surface heat flux but also by other processes such as horizontal temperature advection and vertical mixing in the upper ocean. The spatial patterns of the first SVD mode for the surface heat flux and the SST tendency in each ocean are quite similar. They also resemble the heat flux patterns of the first SVD mode paired with atmospheric variables such as 500 hPa height in each ocean. This indicates that the dominant pattern of the SST tendency in each ocean is organized by the dominant large scale atmospheric circulation pattern such as the PNA teleconnection pattern.

1. Introduction

It is widely recognized that the heat exchange between the ocean and the atmosphere plays an important role in determining the structure of anomalies in the atmosphere and ocean and their time variations. The large scale climatology of the heat flux at the sea surface has been studied for a long time (e.g., Budyko, 1976; Hsiung, 1986; Oberhum-
estimated fluxes were based on mean products and derived variables in the COADS MST which had been calculated from individual observations. He assessed random and bias errors, i.e., errors that vary randomly with time and those due to systematic bias, in the computed fluxes and showed that a few tens of Wm$^{-2}$ of random error could be expected for the latent heat flux, and about 10 Wm$^{-2}$ for the sensible heat flux. However, he concluded that bias-like error was not serious. He performed a rotated EOF analysis on the surface heat flux for the North Pacific and the North Atlantic and looked at relations between the leading EOFs and the sea level pressure (SLP) field. Since he examined rotated EOFs, the variance of each mode was confined within small regions compared to the analysis domain (i.e., the North Pacific and North Atlantic oceans).

Cayan (1992b) investigated relations between the surface heat flux anomalies and several meteorological variables in order to find favorable conditions for large surface heat flux anomalies. He found that strong surface heat flux anomalies are associated with surface winds from preferred directions. For example, surface heat fluxes in the North Atlantic during winter are strongly enhanced during periods of northerly winds which bring cold and dry air from the polar region. He also showed the non-rotated EOF patterns of the SLP field and their relation to the surface heat flux and to other variables in each ocean. Each EOF mode was shown to be strongly related to the flux field along the southwestern flank of the SLP pattern.

Cayan (1992c) examined the relation between the surface heat flux and the SST tendency, i.e. the time rate of change of SST, in both oceans. Correlation coefficients between the surface heat flux and the SST tendency at each grid point show relatively high values (about 0.8) over the eastern North Pacific and in the middle latitude North Atlantic. Spatial patterns of the leading modes in a canonical correlation analysis for the North Atlantic resembled the rotated EOFs of the surface heat flux shown in Cayan (1992a) but the corresponding modes over the North Pacific were quite different from one another. He also examined the relation between the SST tendency and the vertical mixing, which was expressed in terms of the cube of the wind speed. He concluded that in most regions of both oceans the surface heat flux is more important in determining the SST tendency than is the vertical mixing.

Although Cayan’s works are quite comprehensive, the circulation patterns alof that are related to the dominant surface heat flux anomaly patterns are not shown and some of the results such as the rotated EOFs of the heat flux and the canonical correlation analysis between the heat flux and the SST tendency are not easy to interpret physically.

In the present study, we will examine the relation between surface heat flux (the sum of the sensible and latent heat), the atmospheric circulation, and the SST tendency over the northern oceans based on our own flux data. We will use the surface heat flux data rather than the net energy flux (the sum of the surface heat flux and the long- and short-wave radiation fluxes) because, so far, it has been hard to make quantitative estimates of the error of the radiation fluxes, especially the long-wave radiation flux. However, we have performed the same analyses as those presented in following sections based on our own net energy flux data and have confirmed that the results presented in the following sections and those obtained based on the net energy fluxes are almost identical.

Singular Value Decomposition (SVD) analysis will be used as an analysis tool. We will concentrate our attention on the dominant large scale structures in the surface heat flux and related atmospheric circulation anomalies during the northern winter.

The presentation is as follows. In Section 2, the data source and the procedures used in generating the surface heat flux data set will be shown. A brief description of the SVD analysis will be given in Section 3. Results of SVD analysis between surface heat flux, 500 hPa height, SLP, 1000–500 hPa thickness, and the time rate of change of SST will be presented in Section 4. A discussion of the results will be presented in Section 5.

2. Data

2.1 Surface heat flux and SST data sets

In the present study, the term ‘surface heat flux’ denotes the sum of the sensible and latent heat fluxes at the sea surface. The surface heat flux data set used in the present study is comprised of $5^\circ \times 5^\circ$, monthly mean data sets for the North Pacific and the North Atlantic for the period 1950 through 1986. The surface heat fluxes over the North Pacific for the period 1950 through 1979 were calculated by Iwasaka (1988). Those for the period 1980 through 1986 and over the North Atlantic were calculated by Tanimoto (1993) in the same manner. The sensible and latent heat fluxes were computed from individual observations contained in the Comprehensive Ocean-Atmosphere Data Set (COADS) CMR.5 data file. The bulk formulae with the coefficients proposed by Kondo (1975) were used in the computation. The coefficients were dependent on air-sea temperature difference and wind speed for conditions of wind speed less than 10 ms$^{-1}$. Unlike in other studies, the fluxes were calculated based on individual observations, not monthly mean meteorological observations or monthly mean values of their product. This so called ‘sampling method’ (Hanawa and Toba, 1987) is the most suitable way to compute the flux using bulk formulae because the bulk trans-
Transfer coefficients are generally based on 10–20-minute average values of surface meteorological variables.

The data processing procedure is as follows: first the fluxes were calculated from individual marine meteorological observations. The computed individual fluxes were then averaged to form 10-day means on a 2.5° × 2.5° latitude-longitude grid. Both spatial and temporal interpolation and smoothing were applied to the gridded data. Finally the 10-day mean 2.5° × 2.5° gridded data were averaged to form a monthly mean 5° × 5° grid. In the present study, a positive value of the surface heat flux implies a heat transfer from ocean to atmosphere. See Iwasaka and Hanawa (1990) for details of the procedure.

The SST data sets for both oceans were also calculated from the COADS CMR.5 data in the same manner as the surface heat flux. The SST tendency, i.e., the time rate of change of SST, at the j-th grid in the i-th month was calculated as follows:

\[
\Delta SST_j(t_i) = \frac{SST_j(t_{i+1}) - SST_j(t_{i-1})}{2} \text{ (K \cdot month}^{-1}).
\]

The 1950–86 mean value of each variable was computed for each grid point for each calendar month as its climatology. The climatology was then subtracted from the individual monthly mean values to construct the anomaly data set.

Figure 1 shows the seasonal mean climatology and the standard deviation of the surface heat flux over the northern oceans during the northern winter. The northern winter is defined as the season from December through March in the present study. This definition is adopted in order to include the meteorological and oceanographic winters because winter is usually defined from December through February in meteorology, while in oceanography the season from January through March is treated as winter in the sense that winter is the coldest season. The largest positive values, i.e., the maximum heat transfer from ocean to atmosphere of more than 300 W m\(^{-2}\) are observed in the regions of the Gulf Stream and the North Atlantic Current and the Kuroshio and the Kuroshio Extension.

Although the surface heat flux estimated using the bulk formula contains substantial error (e.g., Blanc, 1987), the error may not seriously affect the structure of the spatial distribution of the climatology shown in Fig. 1. Nor should the results of the analyses presented in following sections be affected by the error as long as the variations of the flux anomaly are considered, because we removed time mean error when we calculated the anomaly by subtracting the climatology.

Based on the central limit theorem, the random error of the surface heat flux at each grid point was evaluated from the sample standard deviation and the number of observations used to calculate the
heat flux for the grid point. In the middle latitude western parts of the oceans, the error is relatively small despite the large variance in these regions. This is because the sampling density is fairly large due to the fact that the main ship routes are concentrated in these regions. In the rest of the oceans, the sampling density is small but the variations of the heat flux are also small. Thus, the error is expected to be small. In the present study the monthly random error is as high as 20–30 Wm$^{-2}$ in the latent heat flux and less than 10 Wm$^{-2}$ for the sensible heat flux in the western oceans and the errors are smaller over the rest of the oceans. The magnitudes of the errors are comparable to those of Cayman's (1992a) heat fluxes.

2.2 Atmospheric data

Monthly mean NMC 500 hPa height and SLP data on a 445-point grid covering the Northern Hemisphere poleward of 20°N were used to investigate the relation between the surface heat flux and atmospheric circulation anomalies. 500 hPa height data are used because the height field is located at almost the middle of the troposphere, representing the general circulation of the atmosphere very well. These data were calculated from a twice-daily NMC analysis on a 1977-point grid point data. The period of both data sets is from 1950 through 1986. Their climatologies and anomalies were calculated in same manner as in the flux anomaly calculation. Monthly mean 1000–500 hPa thickness, which was computed from the 500 hPa height and SLP data, was also used.

3. Analysis methods

In the present study, we used singular value decomposition (SVD) analysis as an analysis tool. The method is used to find relations between left and right fields (such as the surface heat flux and the 500 hPa height) by decomposing the covariance matrix of the two fields into singular values and two sets of paired orthogonal vectors, one for the left field and one for the right field. SVD maximizes the covariance between the expansion coefficients of the leading pattern in the left and right fields. The concept of the analysis is similar to that of canonical correlation analysis (CCA) but the two fields are decomposed into two sets of orthogonal spatial patterns and their time coefficients in SVD while two sets of orthogonal time series and the corresponding spatial patterns are produced in CCA.

In application, SVD may be more convenient than CCA because one can obtain a unique solution for almost any pair of fields and it is numerically stable in calculation, while conventional CCA requires the preprocessing of the data to avoid failure in calculating the inverse matrix. However, one should be aware that the SVD analysis does not necessarily give meaningful results unless the effective sample size is much larger than the equivalent number of spatial degrees of freedom of the analysis fields. Thus, one must examine the statistical and physical meanings of the results of the SVD analysis.

SVD analysis yields some statistics which can be used as measures of the strength of the relationship between two fields. In the present study, we will use three statistics. The first quantity is the squared covariance fraction (hereafter referred to as $SCF_k$, where $k$ indicates the mode number). $SCF_k$ indicates the percentage of the total squared covariance explained by the $k$-th SVD mode, defined as:

$$SCF_k = \frac{\pi_k^2}{\sum_{i=1}^{n} \pi_i^2} \times 100 \%,$$

where $\pi_k$ is the singular value of the $k$-th SVD mode, and $n$ is the number of modes. Because SVD analysis decomposes the covariance matrix into singular values and sets of orthogonal patterns, the sum of the squared singular values is equal to the total squared covariance of the two fields. Thus, $SCF_k$ is a measure of the relative importance of that SVD mode in the relationship between the two fields.

The second statistic is the normalized root-mean-squared covariance fraction $NCF_k$,

$$NCF_k = \sqrt{\frac{\pi_k^2}{\sum_{i} \sum_{j} \sigma_i^2 \sigma_j^2}} \times 100 \%,$$

where $k$ refers to the mode number, $\pi_k$ is the singular value of the mode, which is the covariance explained by that mode, and $\sigma_i^2$ and $\sigma_j^2$ are the variances of the $i$-th grid point of one field and that of the $j$-th grid point of the other field, respectively. The normalized root-mean-squared covariance $NCF_k$ is the ratio of the squared singular value of the mode to the maximum possible total squared covariance of the matrix. Therefore, $NCF_k$ gives a measure of the absolute importance of the SVD mode in the relationship between the two fields.

The third statistic is the correlation coefficient ($\rho_k$) between the time series which represent the time variations of the mode in the two fields. $\rho_k$ is an indicator of the similarity between the time variations of the patterns of the two fields.

In order to test the statistical significance of the SVD modes, confidence levels of the $SCF$ and $NCF$ are estimated from probability distributions of the $SCF_1$ and $NCF_1$ for a covariance matrix between two uncorrelated fields. Here, the probability distribution is computed based on 100 realizations of SVD analysis between the two fields considered in the study, but one of them is randomly shuffled in the time sequence. The method of estimating the
Table 1. Summary of SVD analysis for the surface heat flux, SST and SST tendency fields over the North Pacific, and the hemispheric 500 hPa height, 1000-500 hPa thickness and sea-level pressure fields, paired as indicated. The squared covariance fraction (SCF, %), correlation coefficient between the time series of the two fields ($\rho$, x100), and the normalized squared covariance fraction (NCF, %) of the first SVD mode of each pair are shown (SCF/$\rho$/NCF).

<table>
<thead>
<tr>
<th>500 hPa Height</th>
<th>Thickness</th>
<th>SLP</th>
<th>(\Delta)SST</th>
<th>SST</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat Flux</td>
<td>59/83/14</td>
<td>54/80/12</td>
<td>59/84/14</td>
<td>55/76/13</td>
</tr>
<tr>
<td>(\Delta)SST</td>
<td>45/74/10</td>
<td>41/71/8</td>
<td>47/75/9</td>
<td></td>
</tr>
<tr>
<td>SST</td>
<td>63/66/13</td>
<td>58/69/12</td>
<td>62/63/11</td>
<td></td>
</tr>
</tbody>
</table>

Table 2. Same as in Table 1, except for the North Atlantic.

<table>
<thead>
<tr>
<th>500 hPa Height</th>
<th>Thickness</th>
<th>SLP</th>
<th>(\Delta)SST</th>
<th>SST</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat Flux</td>
<td>52/86/16</td>
<td>53/82/14</td>
<td>53/83/16</td>
<td>61/72/14</td>
</tr>
<tr>
<td>(\Delta)SST</td>
<td>56/66/11</td>
<td>50/61/9</td>
<td>55/64/11</td>
<td></td>
</tr>
<tr>
<td>SST</td>
<td>47/59/10</td>
<td>45/63/10</td>
<td>54/54/10</td>
<td></td>
</tr>
</tbody>
</table>

probability distribution generates an unrelated time series but retains the appropriate number of degrees of freedom in the spatial domain.

Since each SVD mode has two time series which represent the variations in the two fields, two kinds of spatial patterns can be obtained; one is called a heterogeneous regression pattern, which shows regression pattern of one field based on the time coefficient of the mode in the other field. The other one is called a homogeneous regression pattern, which indicates the spatial pattern of the variations associated with the time coefficient of the mode in the same field. Because the heterogeneous regression patterns show how the two fields are related to one another and how much of the amplitude of the variations is explained by the SVD mode, we will show the heterogeneous regression maps in the following sections.

A brief mathematical discussion of SVD analysis is given in the Appendix. The reader should refer to Bretherton et al., (1992) for further details and to Wallace et al., (1992) for examples of the application of the SVD analysis.

4. Results

We performed SVD analysis between the surface heat flux, and the SST tendency in the North Pacific and the North Atlantic with the full hemispheric 500 hPa height, 1000-500 hPa thickness, and the SLP anomaly fields during northern winter (i.e., from December through March). The 95% confidence level for the SCF was 38-40 % and that of the NCF was about 5.2-5.6 % for each pair of variables for each ocean. The 95% level for $\rho$ varies from about 0.45 for SST with atmospheric variables to about 0.66 for the surface heat flux with them. For example, the 95% level of the SCF for the surface heat flux in the North Pacific with 500 hPa height was 38.5 %, that of the NCF was 5.4 %, and that of $\rho$ was 0.66, and for the North Atlantic the corresponding levels were 40.0 %, 5.5 % and 0.67, respectively. The test shows that only the first mode for each pair of variables for each ocean was well beyond the 95 % significance level and the higher modes (less than 30 % for SCF$_2$ and 4 % for NCF$_2$ for each pair for each ocean) were not significant. Thus, we are going to present only the first SVD mode for each pair of variables.

A summary of the statistics for the first SVD mode is shown in Table 1 for the North Pacific and in Table 2 for the North Atlantic. Generally, for each pair for each ocean more than half the squared covariance is explained by the first SVD mode, i.e., SCF$_1$ for each pair of fields is more than 50 %. A strong relation between the surface heat flux and the atmospheric variables (more than 0.8 for $\rho_1$) can be expected, since surface heat flux is determined by surface wind speed and air-sea temperature difference or specific humidity difference.

4.1 Relation between surface heat flux in the northern oceans and atmospheric circulation in the Northern Hemisphere

Figures 2a, 2b, and 2c show heterogeneous regression maps for the first SVD mode between the surface heat flux anomaly over the North Pacific and the hemispheric 500 hPa height, 1000-500 hPa thickness, and SLP anomaly fields, respectively. Time coefficients for the first SVD mode of the paired 500 hPa height and the surface heat flux are shown in Fig. 3. Variations of the time coefficients for the other pairs of variables shown in Fig. 2 are almost identical to those shown in Fig. 3.

The regression pattern of 500 hPa height (Fig.
Fig. 2. Heterogeneous regression maps for the first SVD mode between the heat flux over the North Pacific and (a) 500 hPa height, (b) 1000-500 hPa thickness, and (c) SLP. In each panel, the regression pattern of the surface heat flux is expressed by shading, and contour lines show the pattern of the atmospheric variable. Dashed lines indicate negative values and thin solid lines indicate the zero contour. The density of the shading changes every 10 Wm$^{-2}$ and is proportional to the magnitude of the absolute value of the regression coefficients and the signs can be inferred from the labels on the maxima and minima. The contour interval is 20 m for 500 hPa height (a), 10 m for thickness (b), and 1 hPa for SLP (c).

2a) resembles the Pacific/North American (PNA) pattern, but the primary center of action over the North Pacific is located slightly to the southwest of that defined in Wallace and Gutzler (1981) and the pattern is more elongated toward the east coast of the Eurasian Continent. The thickness pattern (Fig. 2b) is similar to the 500 hPa height pattern but has large amplitude in a band extending eastward from the East China Sea to the central North Pacific. The SLP regression map (Fig. 2c) shows
Fig. 3. Time coefficients of the first SVD mode between the heat flux over the North Pacific and the 500 hPa height. The upper panel shows the time coefficients of the 500 hPa height and in the lower, those of the heat flux are presented. The coefficients are normalized by their standard deviation.

a monopole oscillation-like pattern covering the entire North Pacific. The center of action is located around 45°N, 165°W.

The regression patterns of the surface heat flux, indicated by the shading, are virtually identical in the three decompositions. These patterns have large amplitude of one polarity from the western boundary region to about 160°W between 30–40°N and another active region with opposite polarity is seen in the eastern North Pacific and the west coast of Canada, with an extremum off the Canadian coast. A similar pattern was obtained from conventional EOF analysis of the surface heat flux over the North Pacific (Iwasaka, 1988). Thus, the heat flux pattern associated with the first SVD mode is the most coherent large scale pattern in the North Pacific in its own right.

The time coefficients of the dominant surface heat flux patterns and those of the atmospheric variables show variations with several time scales, i.e., intraseasonal, a few years, and decadal variations or trends, but a time scale of several years is dominant in both time series (Fig. 3). One might expect a signal related to El Niño/Southern Oscillation (ENSO) to be dominant over the time series since the 500 hPa height pattern shows a PNA-like pattern. However, the ENSO signal does not seem to dominate in the time series, as can be seen in Fig. 3. On the other hand, a decadal-scale variation can be detected, i.e., negative values are often found in the 1960s while positive ones are seen in the 1980s. Similar decadal signals in the SST fields have been reported for the Pacific ocean by many researchers. For example, Tanimoto et al. (1993) showed the leading EOF of the low-pass filtered SST, for which the time coefficient presented a similar trend except for the late 1950s and the first half of the 1970s, i.e., negative SST anomalies in the central North Pacific in the 1950s, while the sign of the anomalies is reversed in the 1980s. These decadal signals may be related to each other, but rigorous assessment of the quality of the heat flux data is needed before discussing decadal variations or trend-like phenomena. Thus, we are not going into further discussion.

Heterogeneous regression maps of the first SVD modes between the surface heat flux over the North Atlantic and the hemispheric fields of the three atmospheric variables are shown in Fig. 4. Time coefficients of the first SVD mode between 500 hPa height and the surface heat flux are presented in Fig. 5. Variations of time coefficients for other pairs of variables shown in Fig. 4 are almost the same as those shown in Fig. 5.

The SLP pattern (Fig. 4c) exhibits a north-south oscillation-like pattern with one center of action located over Greenland and the other around 30°N over the central Atlantic. This pattern is quite similar to the North Atlantic Oscillation (NAO) pattern (van Loon and Rogers, 1978). The 500 hPa height pattern (Fig. 4a) shows a wavetrain-like structure extending from the North American continent to Europe but the primary centers of action are located in the North America and the North Atlantic sector. This pattern resembles the Western Atlantic (WA) pattern (Wallace and Gutzler, 1981). The thickness pattern (Fig. 4b) is quite similar to the 500 hPa height pattern.

The surface heat flux patterns, which are virtually identical in the three decompositions, have two regions in which magnitude of surface heat flux is large; one from the Canadian coast to around 20°W north of 40°N, and the other extending from the Gulf of Mexico to 60°W in the 20–40°N belt. The former is located between the two centers of action of the NAO pattern. The heat flux pattern resembles the thickness pattern.

Year-to-year variations with a time scale less than 10 years are dominant in the time series of the surface heat flux patterns and those of the atmospheric variables of the first SVD mode (Fig. 5). The ENSO signal is not seen in the time series. In contrast to the North Pacific, decadal variations or trend-like signals are not apparent.

The results obtained for both the North Pacific and the North Atlantic indicate that the large scale anomaly pattern in the surface heat flux is consistent with the large scale atmospheric circulation anomaly, i.e., the northwesterly winds blowing off
Fig. 4. Same as Fig. 2, except for the North Atlantic.

Fig. 5. Same as Fig. 3, except for the North Atlantic.
the continent over the western ocean in the lower troposphere and the strengthening of the surface westerly over the ocean sector are conducive to enhanced fluxes.

For both the North Pacific and the North Atlantic, the patterns of the first SVD mode shown above quite strongly resemble the correlation pattern of the heat flux with the expansion coefficient time series of the first conventional EOF mode of SLP shown in Figs. 3 and 4 of Cayan (1992b). However, the surface heat flux patterns do not resemble the rotated EOF pattern of the surface heat flux in Figs. 12 and 13 of Cayan (1992a), i.e., the leading rotated EOFs exhibit patterns with much smaller spatial scale than the heterogeneous patterns presented here. This is because the varimax rotation of EOFs tend to emphasize localized features in the variance field.

4.2 Relation between surface heat flux and SST tendency

The distributions of local correlation coefficients between the surface heat flux and SST tendency are presented in Fig. 6. The correlation coefficients are calculated for each grid point. In almost the entire analysis region, the coefficients are negative, i.e., the anomalous SST tendency is negative when an anomalous heat loss from the ocean occurs. The 95% confidence level for the correlation coefficient is about 0.27 if the number of degree of freedom is assumed to be the number of years of data used in the present study, i.e., 37. In the figure, absolute values of correlation coefficients above 0.3 are indicated by shading. Fairly high correlation coefficients (−0.6 to −0.7) are found at latitudes around 30°N in the eastern North Pacific and the western North Atlantic.

Magnitudes of the coefficients in Fig. 6 are slightly smaller than those reported by Cayan (1992c). This may be partly due to the difference in definition of the northern winter, i.e., we have defined the northern winter as the season from December through March while his definition is from December through February. Differences in procedures used in computing the fluxes may also contribute.

SVD analysis was applied to the surface heat flux and SST tendency fields to reveal dominant coherent patterns in the interaction between them. $SCF_1$, $p_1$, and $NCF_1$ are summarized in Table 1 for the North Pacific and in Table 2 for the North Atlantic. Heterogeneous regression maps are shown in Fig. 7 for the North Pacific and in Fig. 8 for the North Atlantic. The patterns of both fields resemble one another well and are similar to those of the surface heat flux of the first SVD mode paired with the atmospheric variables (Figs. 2 and 4). Their time coefficients are also similar to those shown in Figs. 3 and 5. For the North Pacific the maximum re-
gression coefficients are found south of the Japan Islands, while those of SST tendency appear around the date line in middle latitudes in the North Pacific. In the North Atlantic, the surface heat flux and SST tendency patterns are quite similar.

Results of canonical correlation analysis (CCA) between the SST tendency and the surface heat flux over the North Pacific shown in Cayan (1992c) are quite different from the results of SVD between them shown here, despite the similarity of the analysis methods. In Cayan (1992c), the spatial patterns of the CCA results seem to be more similar to those of the rotated EOFs of the heat flux, i.e., variances are confined within small regions compared to the size of the ocean basin and their structures are not easy to understand physically. The reason for these differences is not clear. It seems that our results show a physically more meaningful pattern of the relationship between the surface heat flux and the SST tendency.

4.3 Relation between the atmospheric circulation and SST tendency

Results of SVD analysis between the SST tendency and the atmospheric variables are also shown in Tables 1 and 2. Heterogeneous regression patterns of the first SVD mode between the SST tendency and 500 hPa height for the North Pacific are shown in Fig. 9a and those for the North Atlantic in Fig. 9b. For the North Pacific, the atmospheric pattern shows the character of the PNA pattern well and the pattern of SST tendency is very similar to that of the surface heat flux pattern shown in Fig. 2a, i.e., the pattern shows large amplitude of one polarity in a southwestern region extending eastward from Japan to about 160°W between 30° and 40°N and another active region of opposite polarity over the eastern North Pacific, with a maximum off the Canadian coast. Results for the North Atlantic shown in Fig. 9b exhibit a WA like pattern in the 500 hPa height field. As in the results for the North Pacific, these patterns are quite similar to those for the surface heat flux paired with atmospheric variables shown in Fig. 4. These patterns are expected from the results presented in the previous sections.

5. Discussion and conclusion

The results presented in this study, together with the EOF analysis of the surface flux presented in Iwasaka (1988), indicate that the dominant surface heat flux anomaly patterns over the northern oceans during winter are closely related to large scale atmospheric variations in SLP, 500 hPa height, and 1000–500 hPa thickness. The atmospheric anomaly structures are related to the east-west gradient of SLP over the western oceans, which is closely related to northwesterly (southeasterly) wind anomalies. The anomalous winds, acting upon the climatological mean north-south temperature gradient, imply anomalous cold advection at the ocean surface directly above the regions of enhanced fluxes and vice-versa. Thus, the corresponding thickness patterns have such structures that the region in which the surface heat flux anomaly is positive (anomalous heat supply from ocean to atmosphere) coincides...
with the region of the negative thickness anomaly. At the same time, these structures are related to the eastward extension and enhancement of the climatological mean westerly jet streams in the upper troposphere. These atmospheric anomaly patterns are associated with the PNA and WA teleconnection patterns. The relation between the surface heat flux and the atmospheric circulation presented in this study is quite different from that in the atmosphere-ocean system in the equatorial region. The surface heating in the equatorial region is often modeled in such a way as to induce vertical motions in the atmosphere, resulting in adiabatic cooling which tends to compensate the surface heating (e.g., Gill, 1980).

Time variations of the dominant surface heat flux patterns and related atmospheric circulation patterns show intraseasonal and interannual variations with a time scale of less than 10 years over both the North Pacific and the North Atlantic oceans. However, the ENSO related signals do not seem to be dominant over the year-to-year variations. A decadal or trend-like signal can be seen in the North Pacific sector but is not significant in the North Atlantic. The decadal signal in the North Pacific may be related to those of the SST in previous studies (e.g., Tanimoto et al., 1993) but details of the time variations are not similar. On the other hand, in the North Atlantic it is hard to see such a long time scale variation. We do not intend to have further discussion on the decadal signal in the North Pacific nor on the difference in the variations of such a time scale between the North Pacific and the North Atlantic, because we need to assess rigorously the significance of the decadal signals in the surface heat flux and the atmospheric data before discussing such decadal phenomena.

The dominant atmospheric patterns that are closely related to the surface heat flux patterns look quite different from one another, i.e., the PNA pattern shows an east-west dipole like feature, while the WA pattern shows a north-south dipole. However, in the western region of both ocean basins, the atmospheric patterns show similar north-south dipole-like features. The difference in the atmospheric patterns may be caused by geographic differences between the North Pacific and the North Atlantic sectors, e.g., the zonal scale of the oceans, existence of the Rocky Mountains downstream of the westerly jet over the North Pacific while there are no major mountains extending in the meridional direction downstream of
the North Atlantic. Discussing the causes or mechanisms which form and maintain the teleconnection patterns is beyond the scope of the present study.

The relation between the SST tendency and the surface heat flux shown in Figs. 4 and 5 seems somewhat weaker than one may have expected. Although the surface heating is important in the formation of the SST anomaly as discussed in Cayan (1992c), the weakness of the relationship implies that other processes such as horizontal temperature advection in the upper ocean, vertical mixing with deeper water, and variations in cloudiness are also important. The sensitivity of the rate of change of SST to surface heat flux anomaly depends upon the thickness of the surface mixed layer of the ocean, which varies from place to place and is generally very deep south of the western boundary currents.

The relationships between the surface heat flux, the atmospheric variables, and SST tendency shown in the SVD analyses indicate that the dominant SST anomaly patterns over the northern oceans are organized by the atmospheric forcing, as suggested by previous studies (e.g., Davis, 1976; Iwasaka et al., 1987; Wallace et al., 1992). That is, the dominant SST anomaly pattern over the North Pacific is forced by the PNA teleconnection pattern and that over the North Atlantic is forced by the WA pattern, through air-sea heat exchange and other processes such as vertical mixing and horizontal advection in the mixed layer of the ocean induced by the surface wind.

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Appendix

A1. Singular value decomposition analysis

If $A$ is an $n \times m$ matrix, of rank $r$, where $r \leq \min(n, m)$, then the matrix can be decomposed as follows (e.g., Yanai and Takeuchi, 1983):

$$A = \sum_{j=1}^{r} \mu_j u_j v_j'$$

where $\lambda_j = \mu_j^2$ is the $j$-th non-zero eigenvalue of matrix $AA'$ ($A'$ is the transposed matrix of $A$), $u_j$ and $v_j$ are the vectors which satisfy following conditions;

(i) $Au_j = \mu_j u_j$ and $A'v_j = \mu_j v_j$,

(ii) $A'A v_j = \lambda_j v_j$ and $A v_j = \mu_j u_j$,

and

(iii) $AA' u_j = \lambda_j u_j$ and $A' u_j = \mu_j v_j$,

$$(j = 1, \ldots, r).$$

The equation (a1) is called the singular value decomposition of the matrix $A$ and $\mu_j$ is the $j$-th singular value of the matrix. The singular values are labeled in descending order. It is obvious from the conditions (ii) and (iii) that the set of vector $u_j$ and that of $v_j$ are orthogonal sets.

In SVD analysis, the matrix $A$ is the covariance matrix of two fields whose $(k,l)$-th element is

$$c_{kl} = \frac{1}{T} \sum_{t} \{z_k(t) - \bar{z}_k\}\{s_l(t) - \bar{s}_l\},$$

where $z_k$ is the time series of the $k$-th grid point of the $z$ field ($1 \leq k \leq m$), $s_l$ is that of $l$-th grid point of $s$ field ($1 \leq l \leq m$), and the overbars denote their time mean values. If the $z$ and $s$ fields are the same, SVD analysis is identical to EOF analysis of the field. The maximum number of singular values of the matrix $A$ in (a1) is the same as the rank of the matrix if all the singular values are different from each other. (a1) and (a2) indicate that the $z$ and $s$ fields are interchangeable in the analysis.

The vectors $u_j$ and $v_j$ in (a1) represent spatial patterns of variations for the $z$ and $s$ fields, respectively and the squared singular value $\mu_j^2$ is equal to the squared covariance of the variations represented by $u_j$ and $v_j$. Thus, the $SCF_j$ defined in the text is a measure of the relative importance of the SVD mode in the relationship between the two fields. However, even if the $SCF$s of the leading SVD modes are large, it does not imply that the two fields are closely related to each other when the total squared covariance of the two fields is small. For example, when two fields are not correlated but the length of their time series is limited, the covariance could be non-zero, resulting in non-zero singular values.

Therefore, the $NCF_j$ is introduced as a measure of the absolute importance of the SVD mode. Here, the absolute importance denotes the ratio of the squared covariance of the SVD mode to the total squared covariance of the matrix, as defined in the
text. Squared covariance attains its maximum possible value when two time series are perfectly correlated with each other, and the value is equal to the product of the variances. Thus, the maximum possible total squared covariance is given as

\[ \sum_{k} \sum_{l} \sigma^2(z_k)\sigma^2(s_l), \]

where \( \sigma^2 \) indicates the variance of the time series for each grid point of each field.

As mentioned in the text, two kinds of spatial patterns can be obtained, i.e., heterogeneous and homogeneous patterns, for each mode for each field. Both show virtually identical structures if the correlation of two time series of the SVD mode, \( \rho \), is high. However, when the correlation is small, they may be quite different from one another and the structures of the patterns may depend on the paired fields and their nature.

A2. The effective sample size and the equivalent number of spatial degrees of freedom

The number of singular values, in other words, the number of the SVD modes, is equal to the rank of the covariance matrix to be decomposed. As can be seen from (a1) and (a2), the rank is limited by the minimum of the numbers of the grid points and the sample size, which can be changed arbitrarily by changing the sampling interval and spatial resolutions without consideration of the nature of the fields. However, these changes in sampling do not necessarily increase the number of independent data. Therefore, a kind of number of degree of freedom inherent in the fields should be considered when one discusses the statistical significance of the results. This is the idea of the effective sample size and the equivalent number of spatial degrees of freedom.

In the present study, the sample size is not long enough to consider all modes of the SVD be significant. Thus, we performed a statistical test and discussed the physical meanings of the patterns, as mentioned in the text.

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海面熱フラックス変動から見た北半球における大規模大気海洋相互作用について

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海面熱フラックス（潜熱フラックスと顕熱フラックスの和）と北半球の大気大循環との関係を北半球の冬季について特異値分解（SVD）解析で調べた。その結果、北太平洋で卓越する熱フラックスアノマリーのパターンは、大きなアノマリーが北太平洋西部から亜熱帯循環系に沿って中央部に伸びるパターンとなっていった。一方北大西洋で卓越するパターンは、西部で南北振動的なアノマリー分布を示した。これらの卓越する熱フラックスのパターンは、大気大循環のテレコミュニケーションパターンと密接に関係している。すなわち、北太平洋で卓越する熱フラックスパターンはPNAパターンと、北大西洋ではWAパターン（Wallace and Gutzler, 1981）とそれぞれ対応している。両海洋とも卓越する変動パターンでは数年程度の時間スケールの変動が目立っている。しかし、10年以上の長周期変動は北太平洋については認められたが、北大西洋では現れていない。

また、海面熱フラックスと海面水温の時間変化率との関係についても調べた。両者の相関を各格子点毎に計算したところ、一般に相関は有意であるものの係数の絶対値は1より小さい。このことは海面水温時間変化率が海面熱フラックス変動だけでなく、海洋上層での温度の水平移流や鉛直混合などによっても変化することを示している。海面熱フラックスと海面水温時間変化率とのSVD解析によると、両海域とも、第1SVDモードにおけるそれぞれの量の空間パターンは互いに極めて類似している。そしてそれらの空間パターンは、海面熱フラックスと500 hPa高度場などのSVD解析で得られた海面熱フラックスの空間パターンともよく似ている。これらのことから、北太平洋・北大西洋とも卓越する海面水温変動パターンは大気大循環のテレコミュニケーションパターンによって組織化されていることを示している。