<table>
<thead>
<tr>
<th>Title</th>
<th>Reemergence areas of winter sea surface temperature anomalies in the world's oceans</th>
</tr>
</thead>
<tbody>
<tr>
<td>Authors</td>
<td>Hanawa Kimio, Sugimoto Shusaku</td>
</tr>
<tr>
<td>Journal</td>
<td>Geophysical Research Letters</td>
</tr>
<tr>
<td>Volume</td>
<td>31</td>
</tr>
<tr>
<td>Issue</td>
<td>10</td>
</tr>
<tr>
<td>Year</td>
<td>2004</td>
</tr>
<tr>
<td>URL</td>
<td><a href="http://hdl.handle.net/10097/51460">http://hdl.handle.net/10097/51460</a></td>
</tr>
<tr>
<td>DOI</td>
<td>10.1029/2004GL019904</td>
</tr>
</tbody>
</table>
‘Reemergence’ areas of winter sea surface temperature anomalies in the world’s oceans

Kimio Hanawa and Shusaku Sugimoto
Department of Geophysics, Tohoku University, Sendai, Japan

Received 6 March 2004; accepted 21 April 2004; published 21 May 2004.

[1] Using datasets of sea surface temperature (SST), surface heat flux, upper ocean thermal data, and climatological temperature and salinity profiles, we try to detect ‘reemergence’ areas of winter SST anomalies in the world’s oceans, and describe characteristics of these areas in terms of mixed layer depth (MLD), annual mean heat flux and properties of waters formed in winter mixed layer. Eventually, seven reemergence areas are found: four in the Northern Hemisphere and three in the southern Hemisphere. All areas have a large seasonal variation of MLD, and are the regions where annual mean heat fluxes are relatively small except for two regions in the Northern Hemisphere. In the viewpoint of water properties, it is found that these areas correspond to the mode water formation regions: subtropical mode waters of the Indian Ocean, South Pacific, South Atlantic, North Pacific and North Atlantic, and North Pacific central and North Atlantic subpolar mode waters. INDEX TERMS: 4572 Oceanography: Physical: Upper ocean processes; 4283 Oceanography: General: Water masses; 4504 Oceanography: Physical: Air/sea interactions (0312).


1. Introduction

[2] The ocean plays an important role in climate variation due to its large thermal inertia. It is well known that winter sea surface temperature (SST) anomalies tend to persist beyond warming season in the mid-latitude oceans. Pioneering works by Namias and Born [1970, 1974] pointed out that winter SST anomalies in the North Pacific reappear in the next winter. Later, Alexander and Deser [1995] called this mechanism ‘reemergence’ of winter SST anomalies. Several authors have shown that reemergence occurs in the North Pacific [Alexander and Timlin, 1999; Alexander and Scott, 2001], North Atlantic [Watanabe and Kimoto, 2000; Timlin et al., 2002; Coëtlogen and Frankignoul, 2003] and the Northern Hemisphere oceans [Deser et al., 2003]. However, so far, a comprehensive study has not been done for the world’s oceans.

[3] The purpose of the present study is to detect reemergence areas in the world’s oceans and further to describe their characteristics in terms of mixed layer depth (MLD), annual mean surface heat flux, and properties of waters formed in the winter mixed layer. The remainder of this paper is organized as follows. In section 2, various kinds of datasets used are described. In section 3, reemergence areas detected in the world’s oceans are described. In section 4, characteristics of reemergence areas are described. Section 5 gives our summary and remarks.

2. The Data

[4] In the present study, we use five SST datasets to robustly detect reemergence areas in the world’s oceans: Rayner et al. [1996] (GISST), Smith et al. [1996], Japan Meteorological Agency [2001] (SAGE), Reynolds et al. [2002] and Yasunaka and Hanawa [2002]. Further, three datasets of surface heat fluxes are also used to characterize reemergence areas: Oberhuber [1988], Kalnay et al. [1996] and Josey et al. [1998] (SOC).

[5] In order to examine seasonal change of MLD and properties of waters formed in the winter mixed layer, we use gridded climatologies of temperature and salinity profiles of World Ocean Atlas 1998 [Boyer et al., 1998] (WOA98). In addition, to observe a reemergence process in a subsurface layer, the upper ocean thermal data of White [1995] are also used. Since these oceanic data are given at the standard depths, the interpolated data of 10 m by an Akima’s scheme [Akima, 1970] were prepared.

[6] The above datasets have different grid scales and data periods. However, in the present study, we did not unify both the grid scales and the data periods.

3. Reemergence Areas of Wintertime SST Anomalies

[7] So far, it is considered that mixed layer develops to the deepest depth in March (September) in the Northern (Southern) Hemisphere. However, month when the MLD is deepest naturally depends on oceanic condition and heat exchange between the ocean and the atmosphere [Takeuchi and Yasuda, 2003]. Therefore, in the present study, first we investigated the month showing the deepest MLD using WOA98. Here, the definition of MLD is the depth having the density greater by 0.125 sigma-theta than that at the sea surface. Eventually, it is found that deepest MLDS appear in February or March (August or September) in almost all areas of the Northern (Southern) Hemisphere oceans (not shown here).

[8] Next, using five SST datasets, lag correlation analysis for SST anomalies is made at each grid. The reference SST anomalies are those in the month having deepest MLD. In order to robustly detect reemergence areas, we adopt the following criterions. (1) Lag correlation coefficient has a minimum prior to reach a maximum. (2) The maximum of lag correlation coefficients exceeds a 99% significance.
level, the value of which depends on the data length of dataset used. (3) At least, three of five SST datasets satisfy the above two criterions. Therefore, reemergence areas detected in the present study are considered to be very conservative, since the above criterions are severe.

As a result, we could detect seven reemergence areas as shown in Figure 1: four areas in the Northern Hemisphere and three in the Southern Hemisphere. Among them, five areas are situated around the pole-ward and western side of the subtropical gyre, and two areas are located in the northern subtropical gyre in the North Pacific and the subpolar gyre in the Northern Hemisphere. In order to clearly show behaviors of lag correlation coefficient and seasonal change of MLD, we set seven reemergence areas as follows: Region IO (55°E–73°E, 25°S–39°S) in the Indian Ocean, Region SP (159°E–179°W, 31°S–43°S) in the South Pacific, Region SA (15°W–29°W, 31°S–43°S) in the South Atlantic, Region n-NP (157°E–179°W, 37°N–45°N) and Region s-NP (141°E–159°E, 27°N–33°N) in the northern and southern North Pacific, and Region n-NA (19°W–35°W, 41°N–53°N) and Region s-NA (45°W–65°W, 33°N–39°N) in the northern and southern North Atlantic. These regions are set conservatively within the reemergence areas shown in Figure 1.

Figure 2 shows behaviors of lag correlation coefficient and seasonal change of MLD at seven areas. It is found that there are two types of reemergence areas in terms of behavior of lag correlation coefficients. That is, in

Figure 1. Reemergence areas detected by lag correlation analyses using five SST datasets. Contours denote the areas where the lag correlation coefficients exceed the 99% significance level. See the text on regional names.

Figure 2. (Upper panels) Lag correlation coefficients of sea surface temperature in seven regions ((a) through (g)). (Lower panels) Seasonal change of MLD averaged in each of regions. Vertical bars attached to MLD mean standard deviations calculated using all grids included in each region.

4. Characteristics of Reemergence Areas in Terms of Annual Mean Heat Flux and Water Properties

Figure 4 shows a diagram of annual mean heat flux versus annual difference of MLD. Here the result of SOC surface flux [Josey et al., 1998] is shown. The results using the other two datasets also gave almost the same results, although data distributions were scattered more compared with Figure 4. We can point out that the data in Regions IO, SP, and SA in the Southern Hemisphere distribute within about ±20 W/m², and those in Regions n-NP and n-NA in
the Northern Hemisphere do within $-20$ to $-100$ W/m$^2$. On the other hand, in Regions s-NP and s-NA, they distribute within the values of $-50$ to $-200$ W/m$^2$. Regions s-NP and s-NA are situated in the areas east of large continents, where outbreak of the cold and dry air frequently occurs in winter. That is, it can be said that in Regions s-NP and s-NA, although winter SST anomalies reemerge in early fall, SST anomalies are completely refreshed due to a large amount of heat loss from the ocean. On the other hand, since heats gained by the oceans in Regions IO, SP, SA, n-NP and n-NA are consumed in the next cooling season as much as almost the same amount, winter SST anomalies can reemerge in the next winter.

Next, we examine characteristics of properties of waters formed in the winter mixed layer. Figure 5 shows a temperature-salinity (T-S) diagram of waters formed in winter mixed layer, in which water properties of known mode waters are also drawn. This diagram clearly shows the waters formed in the winter mixed layer in Regions IO, SP, SA, n-NP, n-NA, s-NP and s-NA correspond to subtropical mode waters (STMW) of the Indian Ocean (IOSTMW [Toole and Warren, 1993]), South Pacific (SPSTMW [Roemmich and Cornuelle, 1992]), South Atlantic (SASTMW [Provost et al., 1999]), North Pacific central mode water (NPCMW [Suga et al., 1997]), North Atlantic subpolar mode water (NASPMW [McCabe and Talley, 1982]), and subtropical mode waters of the North Pacific.

Figure 4. Diagram of annual mean heat flux versus annual difference of MLD for seven regions. Yellow dots are values for all grid points. Positive values of heat flux mean oceanic heat gain.
(NPSTMW [Masuzawa, 1969]) and North Atlantic (NASTMW [Worthington, 1959]), respectively. In geographical view, it is also found that these seven regions correspond well to known formation areas of mode waters [see Hanawa and Talley, 2001]. That is, it can be said that at least the formation regions of mode waters mentioned above are the reemergence areas.

5. Summary and Remarks

[15] In the present study, we tried to detect reemergence areas of winter SST anomalies in the world’s oceans. Resultantly, seven areas were found: four in the Northern Hemisphere and three in the Southern Hemisphere. All areas corresponded to the regions where winter MLD develops to some degree and has a large annual difference of MLD. The two of seven areas were those where winter SST anomalies reappeared not in winter but fall, and the rest five areas were those where reemergence occurred in the next winter. In terms of annual mean heat flux, the latter five areas were the regions showing relatively small annual mean heat flux, while the former two areas were those showing negatively large annual mean heat flux. In terms of water masses, it was found that these reemergence areas corresponded to the mode water formation areas: IOSTMW (Region IO), SPSTMW (Region SP), SASTMW (Region SA), NPSTMW (Region s-NP), NASTMW (Region n-NA), NPCMW (Region n-NP), and NASPMW (Region n-NA).

[16] Previous authors [e.g., Alexander and Timlin, 1999] have reported much wider reemergence areas in the North Pacific: latitudinal belt along 40°N (see their Figure 2). Further Co¨etlogen and Frankignoul [2003] have pointed out that the reemergence could also occur in the remote area due to the advection by the strong current such as the Gulf Stream. In the present study, as mentioned in earlier section, we set rather severe criterions to firmly and robustly detect the reemergence areas. Therefore, the areas detected in the present study are very conservative.

[17] Acknowledgments. The authors wish to express their sincere thanks to members of Physical Oceanography Group at Tohoku University for their fruitful discussion. Two anonymous reviewers gave useful comments. This study was done as part of the 21st Century Center-Of-Excellence (COE) Program, ‘Advanced Science and Technology Center for the Dynamic Earth (E-ASTEC)’, at Tohoku University.

References


K. Hanawa and S. Sugimoto, Department of Geophysics, Graduate School of Science, Tohoku University, Aoba-ku, Sendai 980-8578, Japan. (hanawa@pol.geophys.tohoku.ac.jp; sugi@pol.geophys.tohoku.ac.jp)