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Key Points:
- Winter sea surface temperature variability was strongly influenced by the East Asian winter monsoon before 1990, but not after 1990
- Spring-to-winter reemergence, rather than classical winter-to-winter reemergence, replaced the winter monsoon after 1990
- Interannual variability of spring sea surface temperature is the main controlling factor for the latter period

Major Driver Leading to Winter SST Variability in the Kuroshio Recirculation Gyre Region and Its Decadal Changes: Refreshening Versus Spring-Initiated Reemergence Processes

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Abstract The analyses using reanalysis data and one-dimensional ocean model during the past decades (1963–2012) revealed that the epoch-dependent refreshening and reemergence mechanisms alternatively influenced the winter sea surface temperature (SST) in the Kuroshio recirculation gyre region. During 1971–1985, the refreshening mechanism due to the strong East Asian winter monsoon significantly contributed to the interannual winter SST variability, consistent with previous works. In contrast, the spring-initiated reemergence process better explains the winter SST variability for 1991–2005, a period corresponding to a declined winter monsoon. The classical winter-to-winter reemergence did not occur during either studied period; thus, the observed spring-to-winter reemergence is an original feature in the Kuroshio recirculation gyre region. The winter monsoon-related strong atmospheric forcing and prominent year-to-year variability of spring SST are important prerequisites for the regional refreshening and reemergence of the winter SST anomaly, respectively.

Plain Language Summary Based on the reanalysis data and one-dimensional ocean model, we showed that the interannual variability of the winter sea surface temperature (SST) in the gyre region south of the Kuroshio are controlled by two different mechanisms depending on the epoch before and after the 1990 regime shift. Before 1990, the strong East Asian winter monsoon mostly determined the interannual winter SST variability. In contrast, the spring-initiated reemergence process, which is a recurrence of previous spring SST anomaly, appears to be the main factor affecting the winter SST variability after 1990. Normally, the reemergence mechanism initiates from the winter; however, we have discovered here an original reemergence mechanism initiating from spring in the study region.

1. Introduction

Recent studies have demonstrated that the main mechanism explaining the winter sea surface temperature (SST) variability in the western North Pacific changed around 1990. During the 1970s and 1980s, the winter SST can be correctly predicted by the 1- or 2-month-leading index of the East Asian winter monsoon (EAWM; Pak et al., 2014), whereas the contribution of ocean dynamics to the winter SST variability increases after 1990 (Park et al., 2012), especially in the Kuroshio recirculation gyre (KRG) region (130°–150°E, 26°–31°N). Sugimoto and Kako (2016) also showed that the mixed layer depth (MLD) was mainly controlled by surface cooling in the late 1970s and 1980s in the region south of the Kuroshio Extension, while the MLD variability after 1990 was associated with the westward propagating Rossby waves (Qiu, 2003; Sugimoto & Hanawa, 2009). These findings consistently support the hypothesis that the ocean dynamics play an important role in determining the interannual-to-decadal winter SST variability after 1990 in the western North Pacific, while the atmospheric forcing dominated before 1990. Park et al. (2012) and Pak et al. (2014) emphasized that the weakened atmospheric influence after 1990 was related to the sudden weakening of the Siberian high (SH). On the contrary, approaches investigating the decadal change of the ocean dynamics are rare in the literature.

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One of the important processes affecting the winter SST variability is the reemergence process (Kwon et al., 2010). The reemergence is a recurrence of the winter SST anomaly through the entrainment of thermal anomalies formed in the deep mixed layer in the previous winter without persisting through the intervening summer due to a large difference in seasonal MLD (Alexander et al., 1999; Alexander & Deser, 1995; Sugimoto & Hanawa, 2007; Timlin et al., 2002). Hanawa and Sugimoto (2004) pointed out that the western North Pacific (141°–159°E, 27°–33°N and 157°E–179°W, 37°–45°N) is one of the important reemergence areas. Sugimoto and Kako (2016) also reported that the vertical entrainment is one of important processes for determining decadal temperature tendency in the mixed layer of the region south of the Kuroshio Extension (141°–155°E, 30°–37°N). In contrast, Qiu (2000) and Vivier et al. (2002) observed small contributions from the vertical entrainment in the nonseasonal temperature tendency of the mixed layer for the elongated longitudinal domain (139°–180°E). On the other hand, the winter SST is also strongly influenced by turbulent air-sea interactions. If there is a prominent year-to-year variability of atmospheric forcing especially in winter, the mixed layer thermal state is reinitialized by concurrent turbulent heat fluxes. We call this process as the "refreshening" mechanism, which can be considered as a synonym of prevalent atmospheric forcing, whereas the reemergence mechanism is related to the mixed layer dynamics.

Given these various hypotheses concerning the main process controlling winter SST variability, the purpose of this study is to investigate the physical processes associated with the decadal change of the main factor controlling the winter SST variability in the KRG region where both the atmospheric and oceanic influences are evident.

2. Data and Method

To investigate the decadal changes of the relationship between winter atmospheric forcing variables and upper-ocean thermal variability over the past decades (1963–2012), we used the monthly surface atmospheric variables from the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP) reanalysis 1 (Kalnay et al., 1996) and oceanic potential temperature from the reanalysis data of the Data Assimilation System of KIOST (Korea Institute of Ocean Science and Technology) (DASK) v1.5 (Kim et al., 2015). The oceanic temperature at the first vertical level (5 m) is used as the SST in the subsequent analyses. The subsurface temperature profiles are used to investigate the temporal evolution of the temperature anomalies through the reemergence processes. The ocean temperature from DASK are cross-validated using long-term monthly gridded observational and reanalysis data, such as Simple Ocean Data Assimilation (SODA) v2.2.4 (Giese & Ray, 2011), EN4 quality controlled ocean data (EN4) v4.2.1 (Good et al., 2013), and Ensemble Coupled Data Assimilation (ECDA) v3.1 (Chang et al., 2013). The JFM (January–March) SST from DASK has a similar variability in the KRG region as those from other supplementary products, with a minimum correlation ($r = 0.88$) with EN4 and a maximum correlation ($r = 0.93$) with SODA. In addition, the interannual-to-decadal NCEP NDJ (November–January) turbulent heat flux (Q_{tur}) variability in the KRG region is very similar to that from Objectively Analyzed air-sea Fluxes (Yu & Weller, 2007; $r = 0.98$) or European Centre for Medium-Range Weather Forecasts Re-Analysis-40 (Uppala et al., 2005; $r = 0.95$). Therefore, the subsequent analyses are not significantly affected by the selection of data sets. The sign convention for heat flux is positive downward (into the ocean). Since the winter upper-ocean thermal variability in the western North Pacific is under the influence of atmospheric forcing variability, the SST is compared with an index representing the EAWM variability. To achieve this, we use the SH index, area-mean sea level pressure anomalies from Trenberth and Paolino (1980) over the SH center (85°–105°E, 45°–55°N). The SH index is a yearly time series averaged over the winter months (NDJ) and has been normalized by the standard deviation over the 1971–2005 period. We use 3-month averaged values in order to reduce any high-frequency month-to-month noise.

The decadal change of the main process influencing winter SST variability in the KRG region across 1990 is investigated using a one-dimensional (1-D) ocean model based on Regional Ocean Modeling System v3.7 (Haidvogel et al., 2000) assuming hydrostatic and Boussinesq approximations. The 1-D simulation is designed to reproduce the decadal changes of the major drivers controlling winter SST variability under the absence of the horizontal advection and wave propagation. The model solves the evolution of temperature profiles in the 30 levels of an *s*-coordinate system (Song & Haidvogel, 1994), driven by heat fluxes and wind stresses estimated by bulk formula (Fairall et al., 1996) with NCEP meteorological

variables. The initial temperature profile was taken from DASK and averaged over the KRG region. Note that there is no freshwater flux and the profile of salinity was fixed to 34 psu. The model uses the Mellor-Yamada level-2.5 closure (Mellor & Yamada, 1982) to determine vertical diffusivity. The model bathymetry is fixed to 500 m, which is much deeper than the winter MLD in the KRG region. Using the initial temperature profile from every April during 1971–2005, the model integrates the temperature profile up to the following March. After 1 year of integration, the temperature profile is reinitialized with the April temperature of the subsequent year and integrated up to March of the following year. The evolution of reemergence is investigated with the integrated temperature profiles. The reason for using April as the start will be clear in the subsequent section.

The analysis in this study is mainly based on linear correlation and regression analyses. The linear correlation coefficient is estimated after removing linear trends, although their impact on the main results is insignificant. The regression coefficient is the correlation coefficient multiplied by the ratio of standard deviation between the target and predictor. The confidence limit of each correlation coefficient is estimated based on a two-tailed t test with $N-2$ (N: data length) degrees of freedom at a given significance level. To investigate decadal changes in atmospheric and oceanic variables, in addition to their temporal dependence, analyses of 15-year moving time series are conducted. It should be noted that the moving standard deviation is obtained after removing the linear trend within each 15-year window in order to consider only the interannual variability and its decadal modulation.

3. Epoch-Dependent Processes Controlling the Winter SST Variability

According to Park et al. (2012) and Pak et al. (2014), the winter air-sea interaction in the western North Pacific changed considerably around 1987/1988. Therefore, we separately investigate the relationship between the SST and atmospheric variables during two contrasting periods: 1971–1985 and 1991–2005. During 1971–1985, a significant correlation is observed between the JFM SST and NDJ Q_{tur} in the KRG region and marginal seas around Korea, China, and Japan (Figure 1a). The negative correlation between sign-reversed JFM SST and 2-month-leading NDJ Q_{tur} is the result of atmosphere-ocean interactions (Wu et al., 2006; Wu & Kinter, 2010), indicating that larger amounts of heat released from the ocean (negative Q_{tur} anomaly) cause a negative SST anomaly 2 months later. On the other hand, the significant relationship between JFM SST and NDJ Q_{tur} is practically absent during 1991–2005 in most regions of the western North Pacific (Figure 1b). These features are consistent with the results of previous studies (Pak et al., 2014; Park et al., 2012; Sugimoto & Kako, 2016) showing a clear decadal shift around 1990 in the winter air-sea interaction.

To investigate the atmospheric features related to the cooling of the winter SST in the KRG region, the regression coefficients of NDJ surface air temperature and wind vectors on the sign-reversed JFM SST anomalies averaged in the KRG region are obtained for the two contrasting periods. The regression map of atmospheric variables during 1971–1985 supports the fact that the winter SST variability in the KRG region is influenced by 2-month-leading cold air carried by the EAWM (Figure 1c). Strong negative air temperature and northwesterly anomalies are observed over Korea and Japan, extending into the KRG region. Therefore, the strong relationship between SST and Q_{tur} (Figure 1a) can be interpreted as a result of the cooling (warming) of the ocean by strong (weak) cold air outbreaks associated with the EAWM (Jensen et al., 2011; Talley et al., 2003). In contrast, the influence of the EAWM is not obvious during 1991–2005 (Figure 1d). It appears that the cold SST anomaly in the KRG region is more related to the westerly located north of 30°N. Anomalous southward Ekman transport in association with the westerly anomaly might be considered as a major factor resulting in cooling of the winter SST in the KRG region during 1991–2005. However, according to Sugimoto and Kako (2016), the Ekman heat advection plays a minor role in determining the behavior of the mixed layer temperature, although their analysis region (141°–155°E, 30°–37°N) is slightly northeast of the KRG region defined here (130°–150°E, 26°–31°N). Therefore, other ocean dynamics should be considered to explain the winter SST variability in the KRG region during 1991–2005 when the atmospheric influence is weak.

The KRG region, where the nonstationary relationship between winter SST and Q_{tur} is observed, is very close to the area of the local reemergence (141–159°E, 27–33°N) defined by Hanawa and Sugimoto

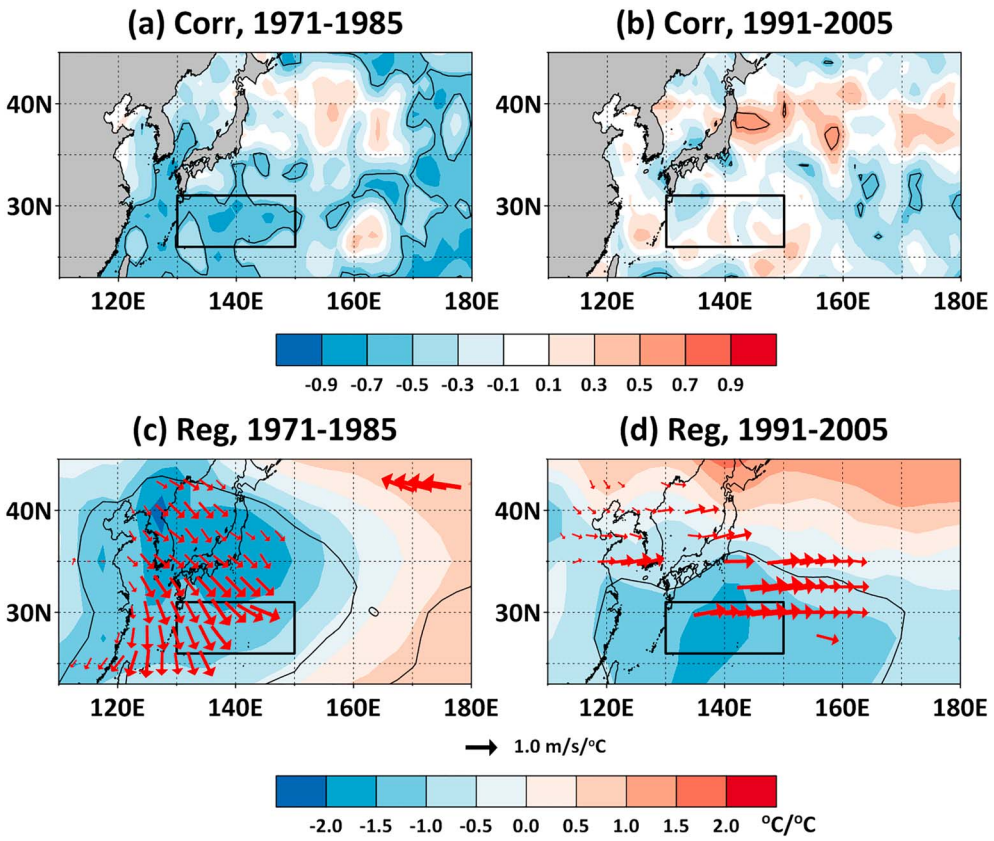


Figure 1. Spatial distribution of (a, b) correlation coefficients between sign-reversed JFM SST and local NDJ turbulent heat flux (Q_{tur}) and (c, d) regression coefficients of NDJ surface atmospheric temperature (color) and surface wind (arrows) on the sign-reversed JFM SST averaged over the Kuroshio recirculation gyre region (indicated by the black rectangle) during (a, c) 1971–1985 and (b, d) 1991–2005. The black contours indicate the significant correlation at 95% confidence level. JFM = January–March; SST = sea surface temperature; NDJ = November–January.

(2004). The existence of the local reemergence process can be analyzed from the lag correlation of the SST time series (Hanawa & Sugimoto, 2004; Timlin et al., 2002). The lag correlation for JFM SST decreases with increasing time lag and becomes insignificant for a time lag of several months (Figures 2a and 2b). During 1991–2005, the correlation coefficients with SST anomalies in the preceding spring season from February–April to May–July are significant at a 95% confidence level using data from various sources, whereas during summer (July–September to September–November), no significant correlation is observed (Figure 2b). Such a significant lag correlation in spring and its absence in summer can be regarded as evidence of local reemergence. On the other hand, during 1971–1985 all the lagged correlation coefficients for JFM SST are systematically insignificant before October–December (Figure 2a), suggesting that the reemergence process has a negligible impact on the winter SST variability. In addition, the correlation coefficients between JFM SST and Q_{tur} also show a period dependency. During 1971–1985, a significant positive correlation is observed during autumn to winter (September–November to JFM; Figure 2a), while there appears to be no significant correlation during 1991–2005 (Figure 2b). Considering the timings of a maximum correlation of Q_{tur} during 1971–1985 and of SST during 1991–2005, the influence of atmospheric forcing and reemergence processes can be safely estimated by correlating JFM SST with NDJ Q_{tur} and AMJ (April–June) SST, respectively.

The temporal evolution of the subsurface structure in association with the reemergence is observed from the lead-lag correlation of temperature profiles with JFM SST. For 1971–1985 (Figure 2c), a significant positive correlation at the 90% confidence level is confined to the winter season up to almost 200 m of depth. The positive correlation extends backward through the subsurface layer (50–100 m)

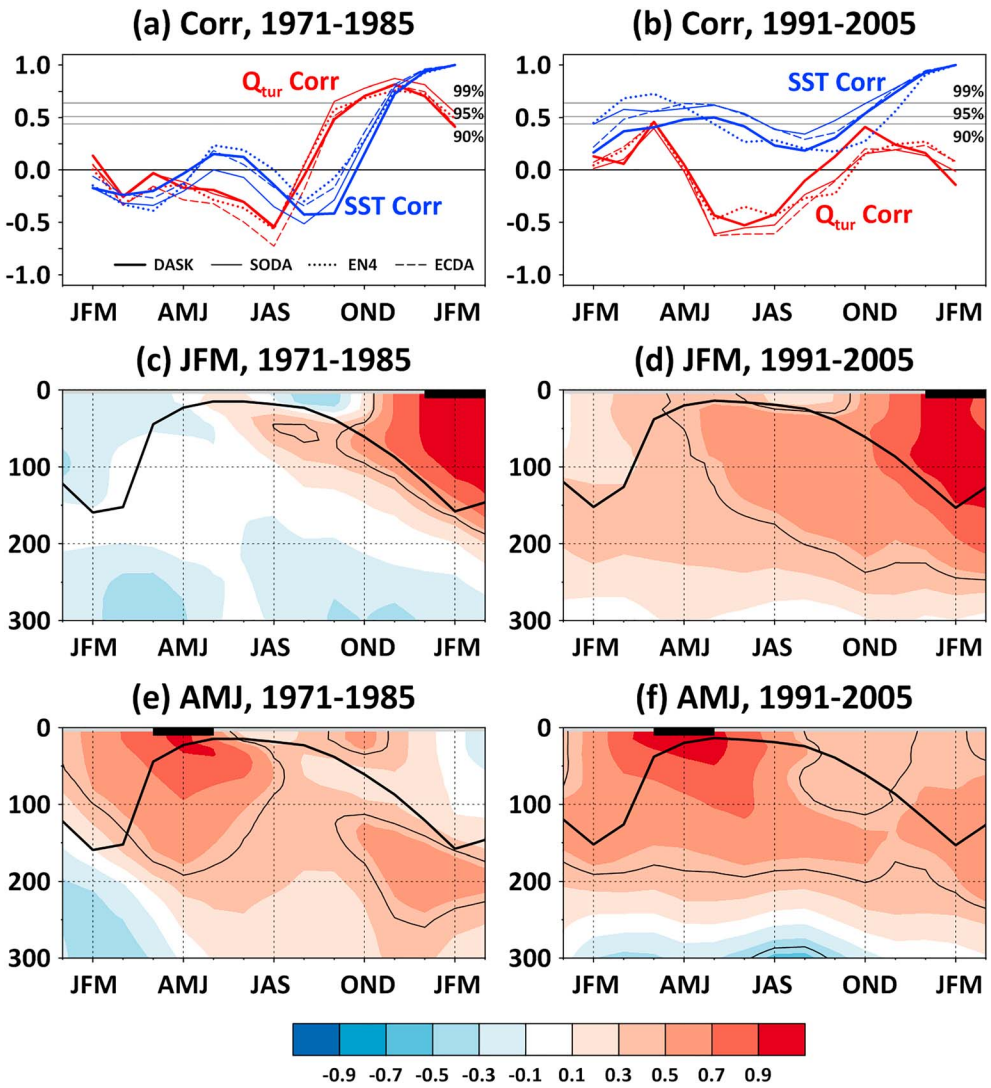


Figure 2. (a, b) Correlation coefficients of JFM SST with 3-month averaged Q_{tur} (red) and SST (blue) during (a) 1971–1985 and (b) 1991–2005 in the Kuroshio recirculation gyre region. Sources of SST data are indicated. Confidence intervals at 90%, 95%, and 99% are marked with gray lines. (c–f) Lead-lag correlation coefficients of temperature as a function of season (*x* axis) and each depth (*y* axis, m) with (c, d) JFM SST and (e, f) preceding AMJ SST during (c, e) 1971–1985 and (d, f) 1991–2005 overlaid with mixed layer depth and significant correlation at 90% confidence level marked with thick and thin solid contours, respectively. SST = sea surface temperature; JFM = January–March; AMJ = April–June; JAS = July–September; OND = October–December.

during summer and autumn, although it is not significant. On the other hand, for 1991–2005 (Figure 2d), the JFM SST and the preceding AMJ SST are significantly connected through the subsurface layer, but with insignificant correlation during intervening summer. This continuous linkage between JFM SST and the preceding AMJ SST indicates that the reemergence originating in spring controlled the winter SST during 1991–2005. A possible reason for the spring, instead of winter origin, for the reemergence will be described in section 4. Similar evidence for the epoch-dependent reemergence process is observed from the forward correlation with AMJ SST (Figures 2e and 2f). The subsurface signal is observed for both periods, but the outcropping of significant correlation in JFM only occurs for 1991–2005 (Figure 2f). For 1971–1985, there appears to be no significant correlation in winter (Figure 2e), suggesting that the upwelled oceanic heat anomalies by winter mixing more than compensate the preexisting thermal structure, such that SST anomalies are completely refreshed by strong atmospheric forcing (Hanawa & Sugimoto, 2004).

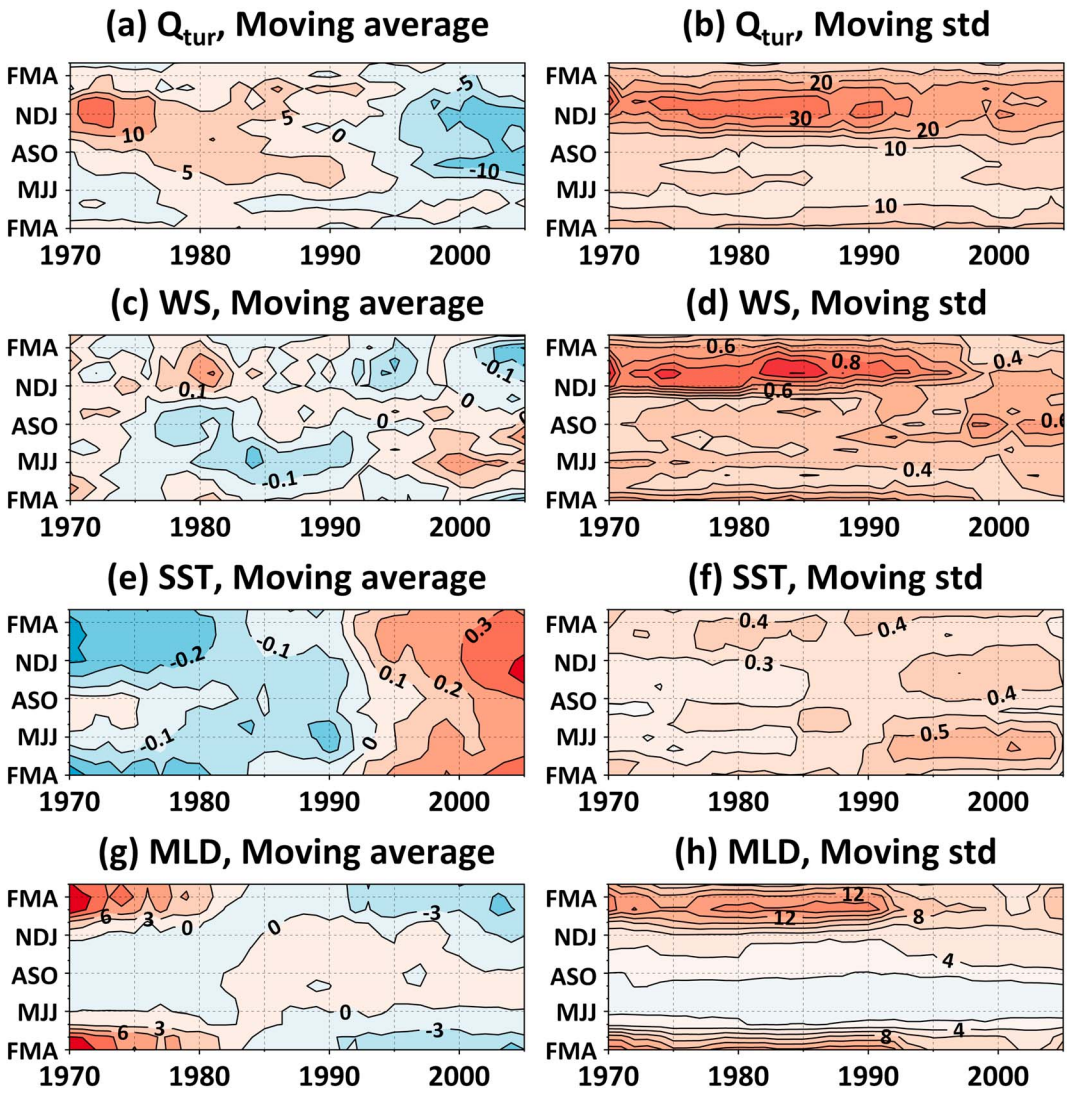


Figure 3. The 15-year (a, c, e, g) moving average and (b, d, f, h) moving standard deviation of anomalous (a, b) Q_{tur} (W/m^2), (c, d) WS (m/s), (e, f) SST (°C), and (g, h) MLD (m) of each season in the Kuroshio recirculation gyre region. The 15-year moving average (standard deviation) at a certain year is the average (standard deviation) of the time series within the window of ±7 years relative to the corresponding year. WS = wind speed; SST = sea surface temperature; MLD = mixed layer depth.

4. Underlying Mechanisms for Epoch-Dependent Changes

The refreshening and reemergence processes alternatively control the winter SST variability depending on the epoch in the KRG region, although this is not the first report of period-dependent reemergence processes. Sugimoto and Hanawa (2007) previously showed the period dependency of the occurrence of remote reemergence in the central North Pacific. They noted that the occurrence of remote reemergence depends on the background conditions in the subtropical mode water formation; a high mode water formation rate, deep MLD, significant upper-ocean heat anomaly, and strong heat flux release are shown to be very important for the occurrence of reemergence. In our case, the turbulent heat release from the ocean is more vigorous for most seasons during 1991–2005 corresponding to our reemergence period (Figure 3a). However, in spring (especially AMJ) when the reemergence heat anomaly begins in the KRG region, the heat release during the later period (1991–2005) is not significantly different from that of the earlier period (1971–1985). Moreover, the MLD during the winter and spring seasons is significantly shallower during the later period compared to the earlier period (Figure 3g), which is contrary to the prediction by Sugimoto and Hanawa

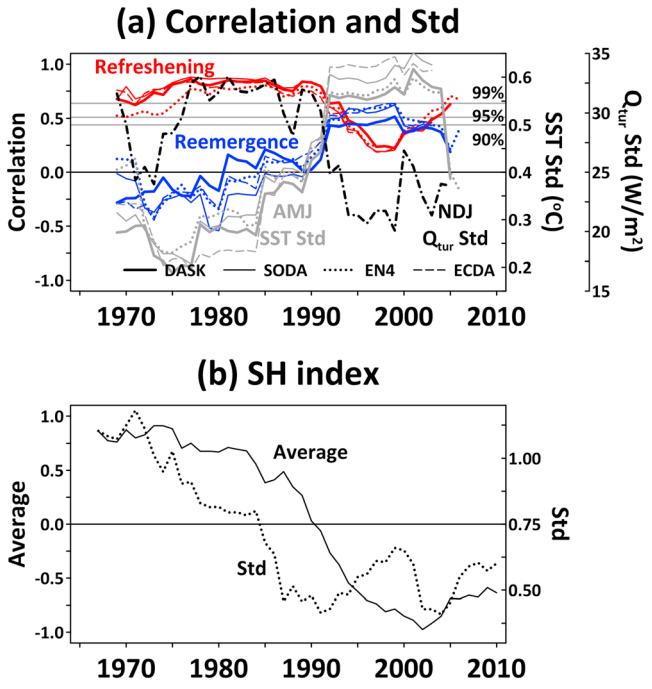


Figure 4. (a) The 15-year moving correlation coefficients of JFM SST with NDJ Q_{tur} (red) and preceding AMJ SST (blue) in the Kuroshio recirculation gyre region obtained from various SST data sets (as indicated). The 15-year moving standard deviation of AMJ SST (gray) and NDJ Q_{tur} (black dash-dotted line) are also overlaid. Confidence intervals of the correlation coefficients at 90%, 95%, and 99% are marked with gray lines, respectively. The 15-year moving correlation at a certain year is the correlation between two time series within the window of ±7 years relative to the corresponding year. (b) The 15-year moving average and standard deviation of the NDJ SH index. JFM = January–March; SST = sea surface temperature; NDJ = November–January; AMJ = April–June; SH = Siberian high; DASK = Data Assimilation System of KIOST; SODA = Simple Ocean Data Assimilation; EN4 = EN4 quality controlled ocean data; ECDA = Ensemble Coupled Data Assimilation.

(2007). Therefore, the main cause of the epoch-dependent change in the main process driving winter SST variability in the KRG region needs a different explanation.

As the interannual variability of winter SST results from the combined effect of air-sea interaction (turbulent heat flux) and ocean dynamics, the decadal modulation of interannual Q_{tur} variability can be used as an indicator for tracing the underlying mechanisms of the epoch dependency. Indeed, the 15-year moving standard deviation of winter Q_{tur} is significantly weaker after 1990 (Figure 3b), indicating that during 1971–1985, the thermal anomaly tends to be easily refreshed by strong year-to-year variability of Q_{tur}, while the refreshening barely influences the winter SST during 1991–2005. The decadal change in winter Q_{tur} variability is related to atmospheric variables, such as wind speed (Figure 3d) and surface air temperature (not shown). Note that the SH intensity and its interannual variability experienced significant decline across 1987/1988 (Figure 4b). Although Q_{tur} is the result of the air-sea interaction, the variability of winter SST shows insignificant differences between the two studied periods (Figure 3f). Therefore, the changes in the epoch-dependent factor should be associated with the decadal change in the SH-related winter atmospheric forcing. The variability of winter MLD also shows a similar decadal change as other variables, such as Q_{tur} and wind speed, showing a significant decrease after 1990 (Figure 3g).

In contrast to the typical local reemergence in other regions, showing a winter-to-winter reemergence (Hanawa & Sugimoto, 2004), a spring-to-winter reemergence is most evident during 1991–2005 in the KRG region (Figures 2b and 2d). Under a similar strength of external forcing, a larger SST anomaly tends to be sustained for a longer period, until the following winter, resulting in reemergence. Indeed, the moving standard deviation of SST is larger after 1990; in particular, the largest SST variability is found in AMJ (Figure 3f) when reemergence initiates. The moving standard deviation of SST during winter is systematically weaker than that during spring, which may explain why the winter-to-winter reemergence is not observed even in the 1991–2005 period. Although the MLD in spring is relatively shallow, the anomalous SST can be transferred to the subsurface layer via vertical diffusion (Hosoda et al., 2015). A possible cause of the larger SST variability during 1991–2005 might have been related to the increased variability of the westward propagating Rossby wave signal after 1990 in association with the positive phase of the West Pacific teleconnection pattern (Sugimoto & Kako, 2016), although further analysis is necessary.

In summary, after 1990, a significant decrease (increase) in the interannual variability of NDJ Q_{tur} (AMJ SST) is observed, which has caused a regime shift around 1990 from the refreshening to reemergence mechanisms for the winter SST variability (Figure 4a). The abrupt changes around 1990 of interannual NDJ Q_{tur} (black dash-dotted line) and AMJ SST (gray lines) variabilities appear to be related to the change in SH intensity and ocean dynamics, respectively.

Finally, the epoch-dependent occurrence of the reemergence mechanism is supported by the 1-D model (Figure 5). Although the subsurface thermal anomaly is set to start from April for both periods, significant reemergence feature does not occur before 1990 when the winter atmospheric forcing (or refreshening) is dominant but occurs during the weak winter monsoon period after 1990 (Figures 5c and 5d). Moreover, the period after 1990 corresponds to the period when the AMJ SST variability is significantly stronger compared to the period before 1990 (see Figures 3f and 4a). The track of the maximum correlation originating from April SST of the 1-D simulation, which only considers surface forcing and vertical diffusion, crosses the MLD forming a significant correlation in the subsurface layer in subsequent months (Figures 5c and

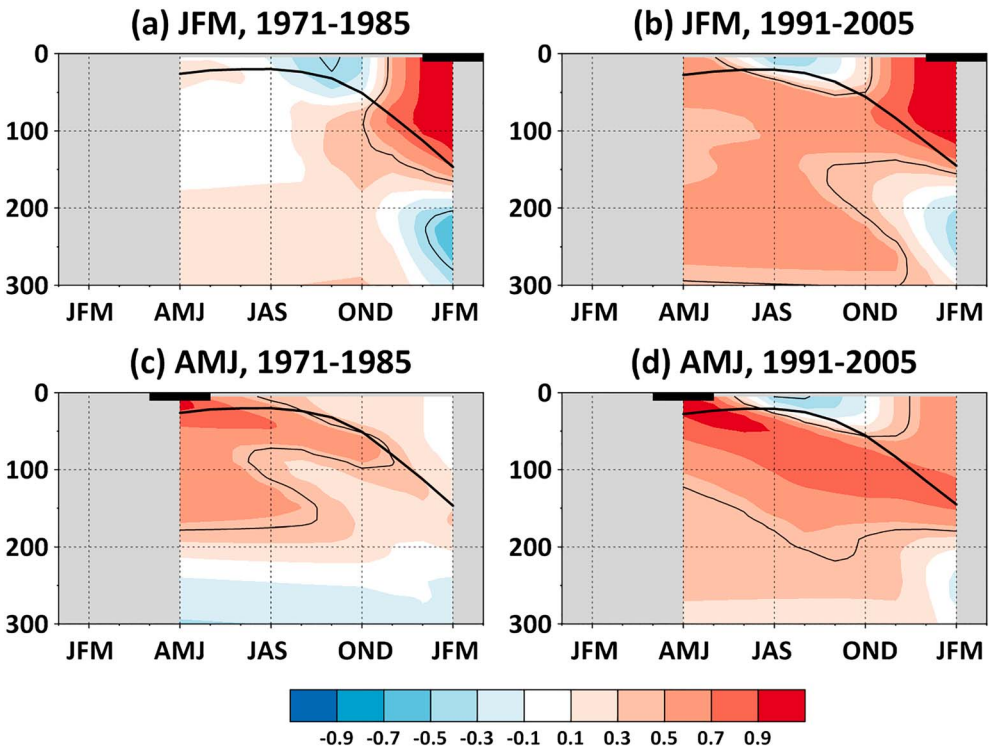


Figure 5. Lead-lag correlation coefficients of model temperature as a function of season (*x* axis) and each depth (*y* axis, m) with (a, b) JFM SST and (c, d) preceding AMJ SST during (a, c) 1971–1985 and (b, d) 1991–2005 overlaid with mixed layer depth and significant correlation at 90% confidence level marked with thick and thin solid contours, respectively. SST = sea surface temperature; JFM = January–March; AMJ = April–June; JAS = July–September; OND = October–December.

5d). This is an evidence that the vertical diffusion is a possible mechanism for transferring SST anomalies to the subsurface layer even in the shallow MLD seasons.

5. Discussion

Based on the analyses of the reanalysis/observational data and 1-D model experiment for 1963–2012, the winter SST variability in the KRG region is shown to be controlled by atmospheric forcing during the strong EAWM period before 1990, consistent with the findings of previous studies, whereas it is rather the spring-initiated reemergence process that controls the winter SST variability during the declined EAWM period after 1990. Although Park et al. (2012) proposed an increasing oceanic influence after 1990, no definitive mechanisms for the oceanic influence were proposed in that study. In addition, the spring-to-winter reemergence process evidenced here is new and appears to be a unique feature in the KRG region. The stronger SST variability in the preceding spring, rather than the preceding winter, has been used to evidence a spring-initiated reemergence. However, the cause of the stronger spring SST variability after 1990 is unknown and requires a further investigation.

Most of the KRG region in this study corresponds to the ocean interior region where the horizontal advection has a negligible impact, while a part of the KRG region is on the pathway of the strong Kuroshio. However, the decadal shift of the main driver of the winter SST variability in the KRG region has been reproduced without horizontal advection using 1-D model experiment. We have shown that the strong winter atmospheric forcing variability and strong year-by-year anomaly of spring SST are important necessary conditions for the refreshening and reemergence mechanisms, respectively. The 1-D model proves those conditions could make the epoch-dependent main drivers control the winter SST variability. But they may be a part of the full mechanisms; thus, ultimately the fully coupled climate model study is necessary. The budget analysis for the SST or SST tendency will be also useful for future study.

Acknowledgments

The DASK reanalysis data set was uploaded to http://las.kiost.ac.kr, and the reanalysis data sets of SODA and ECDA were taken from https://www.atmos.umd.edu/~ocean and https://www.gfdl.noaa.gov/ocean-data-assimilation-model-output, respectively. The EN4 ocean gridded data set was downloaded from https://www.metoffice.gov.uk/hadobs/en4. The NCEP Reanalysis I data sets were taken from https://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.html. The turbulent heat flux data sets of Objectively Analyzed air-sea Fluxes and ECMWF Re-Analysis-40 were obtained from http://oaflux.whoi.edu and https://apps.ecmwf.int/datasets/data/era40-moda/levtype=sfc, respectively. The sea level pressure data set from Trenberth and Paolino (1980) was downloaded from https://rda.ucar.edu/datasets/ds010.1. This work was supported by the National Research Foundation of Korea grant NRF-2016M1A2A2948277 funded by the Korean government (MSIT). S.-W. Yeh was funded by the Korea Meteorological Administration Research and Development Program under grant KMI2018-03211. S. Nam was partly supported by the Ministry of Oceans and Fisheries, Republic of Korea ("Deep Water Circulation and Material Cycling in the East Sea", 20160040) and NRF of the Korean Ministry of Education via SGER program (NRF-2015R1D1A1A02062252), Republic of Korea.

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