Revisiting the connection between variations in the Tsushima Warm Current and winter rainfall along the coast of Japan

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Abstract
Enhanced autumn transport via the Tsushima Warm Current (TWC) has been reported to increase winter rainfall along Japan's northern coast. However, observations reveal a significantly weakened correlation after 2006. Although enhanced transport via the Eastern channel of the Tsushima Strait affects rainfall by enhancing latent heat flux along Japan's northern coast, the role of oceanic flows in varying sea-surface temperatures has weakened since 2006. Stronger northwesterly winds co-occur with enhanced surface heat loss that overwhelms the impact of the TWC. Our findings imply that atmospheric conditions should be considered when using TWC transport as a precursor for winter rainfall.

Keywords Tsushima Warm Current · Winter rainfall · Japan Sea · Sea surface temperature

1 Introduction

The northern coast of Japan receives some of the heaviest snowfalls globally, mainly because cold, dry northwesterly continental winds blow over the warm Japan Sea during winter (Fig. 1). These winds cause evaporation and heat transfer from the ocean, leading to intense snowfall in this area (e.g., Yasunaga and Tomochika 2017; Takahashi 2020; Tachibana et al. 2022). The Tsushima Warm Current (TWC) is a crucial component of this phenomenon, serving as a major heat source that maintains the warm surface temperature of the Japan Sea. The TWC carries warm subtropical water into the Japan Sea through the Tsushima Strait, establishing a region of warm sea-surface temperatures (SSTs) south of approximately 38°N.

Hirose and Fukudome (2006) (hereafter referred to as HF6) identified a significant correlation between interannual variations in autumn TWC transport and winter rainfall. That study indicated that the TWC can play an important role in

inducing interannual variations in winter conditions around the Japan Sea, and the process of enhanced TWC transport increasing rainfall along the northern coast of Japan in the subsequent winter, offered a potential mechanism that could improve the seasonal prediction of winter rainfall. However, their analysis covered only the 9-year period from 1997 to 2005 due to limitations in the availability of TWC transport data. Examination of a longer time series is needed to elucidate further the connection between TWC transport and rainfall.

This study was motivated by our finding of a significant shift in the correlation between autumn TWC transport and winter rainfall after 2006 (Fig. 2a–c). Detailed information regarding the dataset and analysis is provided in the following section. From 1997 to 2005, a robust correlation coefficient of 0.71 was obtained, consistent with the findings of HF6. However, in the subsequent period from 2006 to 2017, the correlation weakened substantially to 0.21. This abrupt drop in the correlation coefficient indicates a potential shift, or the need to refine our understanding of the relationship between TWC and rainfall.

The mechanism underlying the connection of TWC transport with winter rainfall, as suggested by HF6, involves excess TWC transport warming SSTs in the Japan Sea in autumn. This warming process takes several months, as TWC water must spread into the interior of the sea. Warmer SSTs lead to enhanced evaporation and heat input into the

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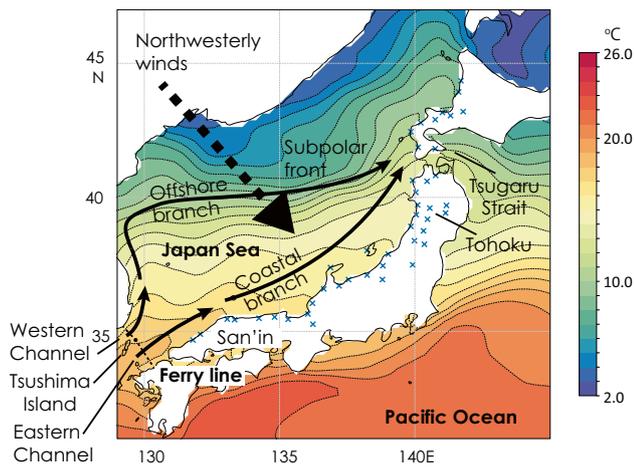
Fig. 1 Schematic of the two TWC pathways. Crosses indicate the locations of AMeDAS stations. Color gradient indicates climatological NDJ SSTs

atmosphere in winter, increasing rainfall. Determining whether excess TWC transport leads to enhanced winter rainfall through this mechanism requires evaluation of the occurrence of intermediary processes.

We will show that the connection between TWC transport and winter rainfall is largely controlled by the coastal branch

of the TWC, which passes through the eastern channel (EC) of the strait. This branch tends to flow adjacent to the coast, where heavy rainfall occurs. The abrupt change in the correlation between autumn TWC transport and winter rainfall occurred, because the variation in the TWC transport from 2006 to 2016 was largely controlled by transport through the western channel (WC) (Fig. 2d), which is uncorrelated with winter rainfall. Furthermore, atmospheric winds likely played a larger role than TWC transport during that period. These winds were associated with colder atmospheric temperatures that enhanced surface cooling and overwhelmed the warming effect of TWC transport. In Sect. 2, we describe the dataset used for analysis. In Sect. 3, we explore the impact of each branch of the TWC in detail, based on correlation and regression analyses. A summary and discussion are presented in Sect. 4.

2 Data and methods

2.1 Tsushima Warm Current transport

The monthly TWC transport dataset of Utsumi (2018) was used. This dataset was derived from direct measurements obtained using an acoustic Doppler current profiler (ADCP)

Fig. 2 Correlation between autumn (ASON) TWC transport and winter (DJF) rainfall accumulation at AMeDAS stations along the Japan Sea coast for **a** 1997–2005 and **b** 2006–2017. Stations with p values < 0.1 are shown as large circles. **c** Autumn TWC transport for detrended and original values are shown as solid and dashed lines, respectively. Station-averaged DJF rainfall accumulations are shown as histograms, with detrended and original values presented as black-outlined and cyan bars, respectively. **d** Autumn TWC transport through the western channel (WC) and eastern channel (EC) and total transport. Dotted lines in (**c**) and (**d**) indicate the boundary between the two analysis periods
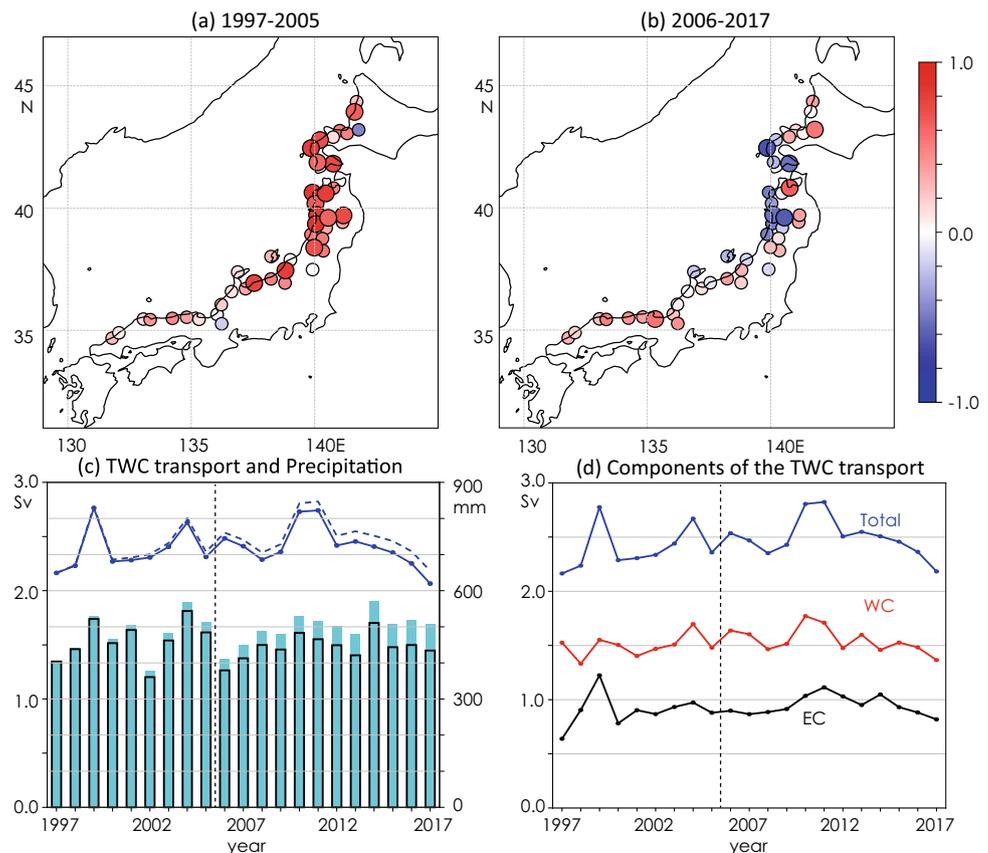
mounted on a ferryboat that traverses the Tsushima Strait (Fig. 1) and is an updated version of the Takikawa et al. (2005) dataset used in HF6. The transport values discussed hereafter are average values from August to November (autumn). Annual variations from 1997 to 2017 are shown in Fig. 2c. Due to poor sampling, the climatological monthly value was used in place of data for October 2001.

The pathway of the TWC bifurcates in the Japan Sea to form two branches, one coastal and one offshore (Fig. 1). The coastal branch flows along the northern coast of Japan, while the offshore branch flows along the eastern coast of Korea and becomes a zonal jet in the interior of the Japan Sea. We estimated the magnitudes of the coastal and offshore branches through estimation of the transport across the EC and WC of the Tsushima Strait, located east and west of Tsushima Island, respectively.

2.2 Snow and rainfall

Precipitation data obtained from 44 AMeDAS stations along the northern coast of Japan were used to evaluate the amounts of snow and rainfall (Fig. 1; Japan Meteorological Agency 2024a). This dataset integrates both rainfall and snowfall amounts; hereafter, we refer to the data as rainfall. Winter rainfall is defined as the average of hourly measurements from December to February (DJF) between 1997 and 2018. The designated year is associated with December and includes January and February of the subsequent year.

2.3 SST, latent and sensible heat fluxes, and surface wind

The JOFURO3 V1.1 (Tomita et al. 2019) monthly dataset was used to evaluate SSTs, latent and sensible heat fluxes, and surface winds and atmospheric temperatures from 1997 to 2017. This dataset was selected, so that the five variables would be consistent. NDJ averages were used for SSTs following HF6, which identified high correlations with both TWC transport and winter rainfall. A lag of a few months following TWC transport is consistent with the time needed for the warm TWC water to spread into the Japan Sea, and can be used to determine whether oceanic flow initiates SST changes beginning in autumn. DJF averages were used for latent and sensible heat fluxes and surface winds and atmospheric temperatures to match those of rainfall, which occur on shorter atmospheric timescales. In contrast with the TWC transport and rainfall data, JOFURO3 does not include data for January and February of 2018, such that 3-month averages are available only until 2016. For all analyses presented hereafter, significance was evaluated at a threshold of p value of <0.1, unless otherwise noted. Variations in transport, rainfall, SST, heat flux, and surface wind and atmospheric temperature were detrended and then analyzed separately for the periods 1997–2005 and 2006–2017.

3 Impact of the TWC on SST and latent heat flux

3.1 Period from 1997 to 2005

Regression analysis of SSTs relative to EC transport in 1997–2005 revealed a predominantly warming signal throughout the Japan Sea, particularly along the coast of Japan and subpolar front (Fig. 3a). This warming signal persisted from early autumn to winter (Fig. S1a–c). Regression analysis of latent heat flux indicated enhanced values in regions with a warming signal (Fig. 3d). The correlation between EC transport and the average winter rainfall across all AMeDAS stations was high at 0.61. These results align well with the mechanism proposed by HF6, in which excess transport leads to warmer SSTs, increased heat flux, and increased rainfall.

Regression analysis of SSTs relative to WC transport also showed a warming signal for the Japan Sea (Fig. 3b). The main difference from EC transport was that the warming signal occurred in the interior of the Japan Sea rather than along its coast. Analysis of latent heat flux indicated enhanced values in regions where warming was observed (Fig. 3e), implying that variations in WC transport can enhance rainfall. However, the correlation coefficient of WC transport with winter rainfall was 0.46 and had low statistical significance, as suggested by the weak correlations obtained at many AMeDAS stations. Rainfall appeared to be more weakly connected to WC transport than to EC transport.

Regression analysis of SSTs and latent heat flux relative to total TWC transport showed a spatial pattern combining those of EC and WC transport (Fig. 3c, f). Maximum latent heat flux was found along the coast of Tohoku, aligning well with the region of enhanced rainfall. This latitude is where the subpolar front is located, which lies along the pathway of the offshore branch. A northern shift in the frontal axis due to variations in the offshore branch can create an SST warming signal, in addition to that caused by variations in the coastal branch. For 1997–2005, the strong correlation between TWC and rainfall was driven primarily by excess transport in the coastal branch of the TWC, with a possible additional impact from the offshore branch contributing to warmer SSTs and evaporation over the Japan Sea.

3.2 Period from 2006 to 2017

Regression analysis of SSTs relative to EC transport for 2006–2017 revealed a different SST response pattern for the period 1997–2005. The warming signal was limited

Fig. 3 Regression maps of NDJ-averaged SSTs relative to **a** EC, **b** WC, and **c** total TWC transport in 1997–2005. **d**–**f** As in (**a**–**c**), but for DJF-averaged latent heat flux. The correlation between TWC transport and rainfall at each AMeDAS station is shown as a circle. Dotted regions and large circles indicate *p* values < 0.1
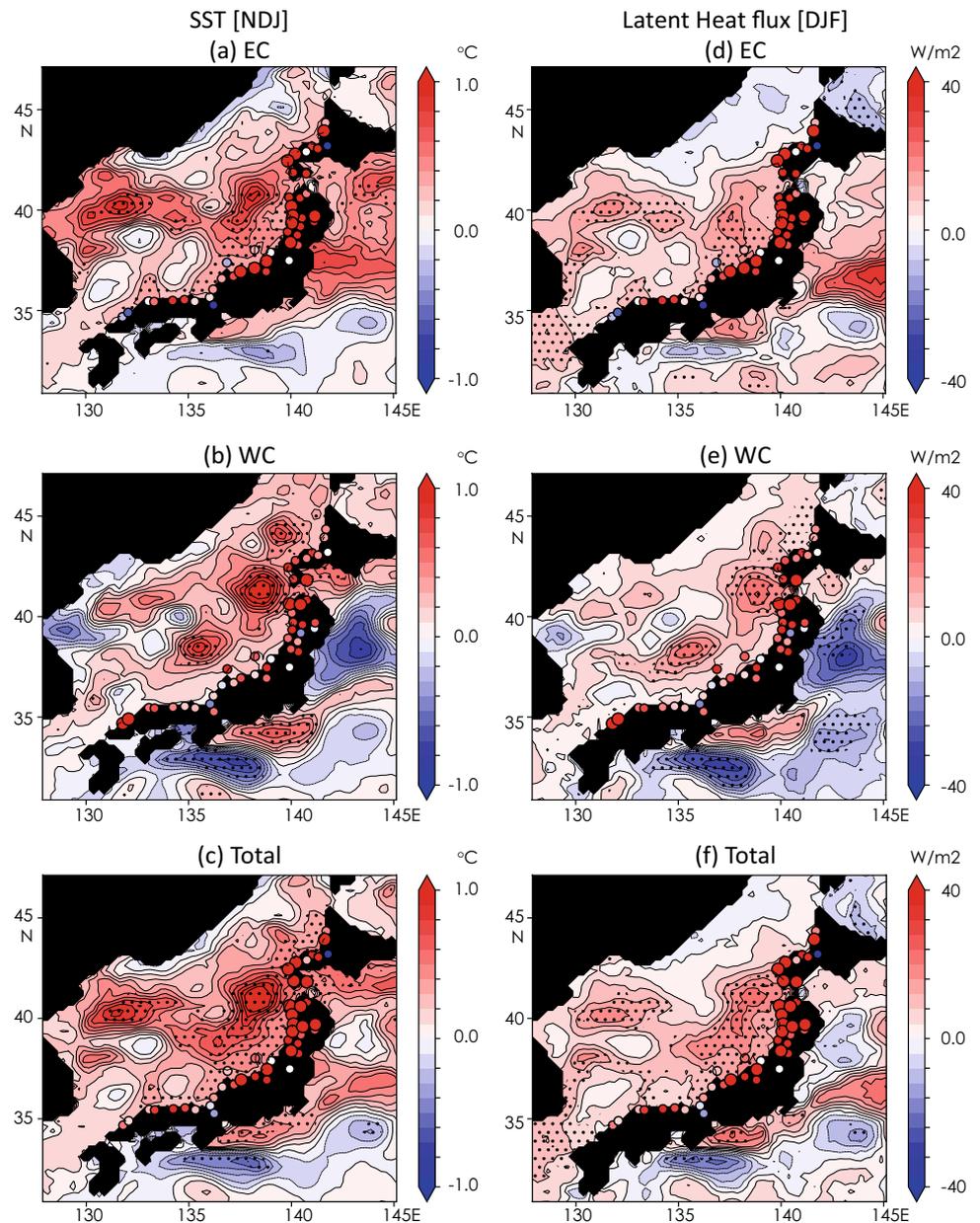
to areas within 36–38°N, while areas near the Tsushima Strait and the subpolar front exhibited a cooling response (Fig. 4a). This cooling response appeared to align with the weakened correlation between TWC transport and winter rainfall observed after 2006. However, regression analysis of latent heat flux relative to EC transport still showed enhanced evaporation over a large area (Fig. 4d). This result implies that increased EC transport continued to enhance winter rainfall in 2006–2016. Indeed, the correlation coefficient between EC transport and rainfall of 0.55 indicated a good correlation. As strong northwesterly continental winds cooled SSTs, enhanced EC transport co-occurred and provided additional heat transport through the EC and along the pathway of the coastal branch, which may have mitigated

cooling. We discuss the impact of winds in Sect. 3.3. Similar spatial patterns of an enhanced evaporation signal associated with excess EC transport were observed during both periods along the coast of Japan. This region contains the main pathway of the coastal branch, supporting the possibility that the observed response was induced by this branch.

Regression analysis of SSTs relative to WC transport showed a patchy warming pattern over a large area of the Japan Sea (Fig. 4e). Except in the area near the Tsushima Strait, no robust features associated with enhanced latent heat flux were found. The correlation coefficient between WC transport and winter rainfall shifted to −0.06, with low statistical significance, indicating that no strong connection existed.

Fig. 4 As in Fig. 3, but for 2006–2016
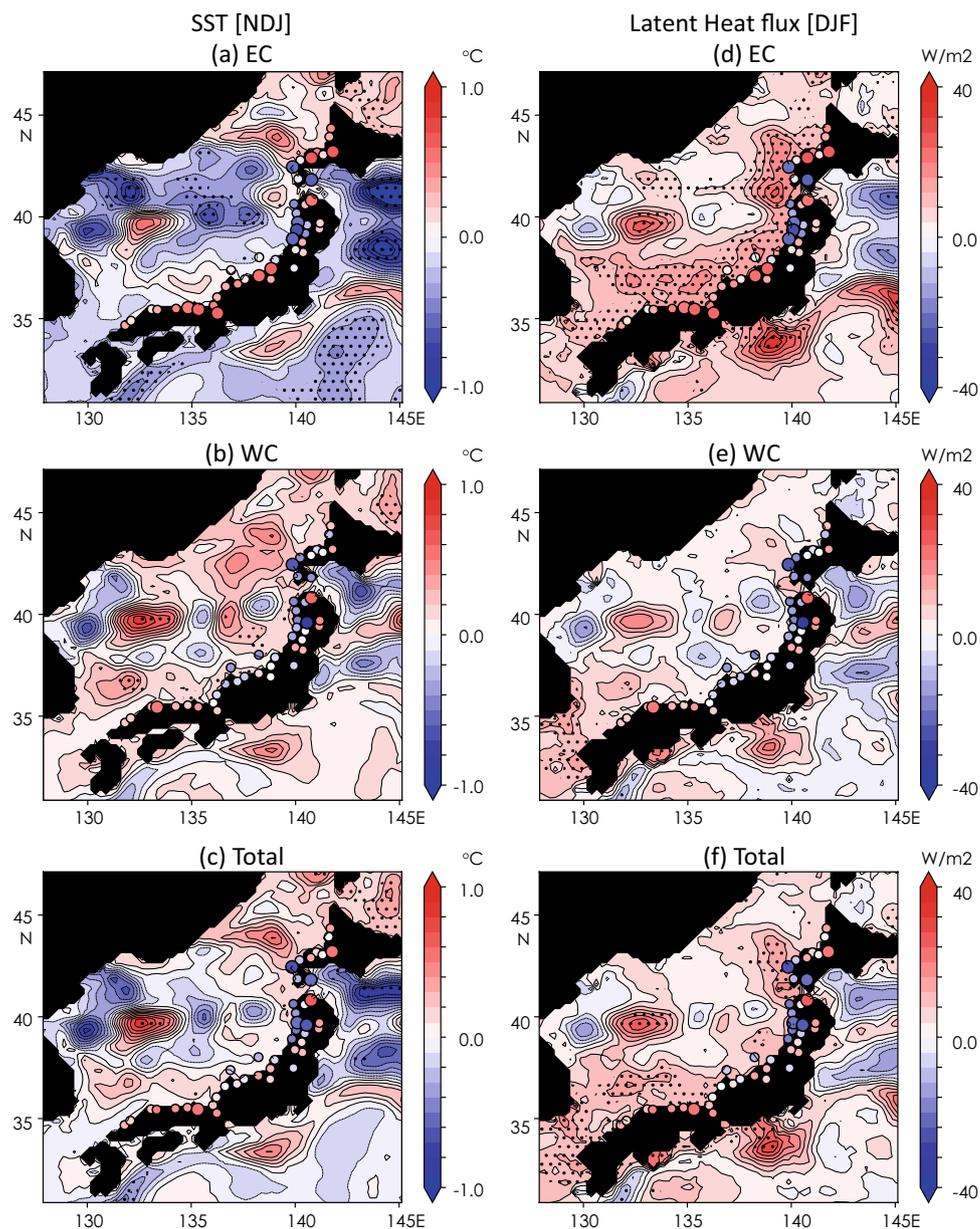
Regression analysis of the relationships of SSTs and latent heat flux relative to total TWC transport indicated contributions to the spatial pattern from both EC and WC transport (Figs. 3c, f; 4c, f). However, EC transport exerted a greater influence on rainfall, with WC transport playing a secondary role. The variations in TWC transport in 2006–2017 were induced primarily by the WC transport component, as evidenced by the strong correlation (0.90) between the two transport values, with a regression coefficient of 0.59 (Fig. 2d). The correlation between TWC transport and EC transport was also high (0.85), but with a lower regression coefficient (0.41). Consequently, the correlation between TWC and rainfall weakened abruptly after 2006.

A possible explanation for the basin-wide cooling response observed in the Japan Sea to enhanced EC transport in 2006–2016 (Fig. 4a) is an increased influence of surface winds on SSTs. As described in Sect. 3.3, northwesterly continental winds strengthen when EC transport increases, which co-occurred with lower atmospheric temperatures in 2006–2016, but not for 1997–2005 (Fig. S3a, d). In addition to latent heat flux, enhanced surface cooling was induced through sensible heat flux during 2006–2016 (Fig. S2d–f), but weak for 1997–2005 (Fig. S2a–c). As a result, the cooling response gradually strengthened from early autumn to winter in 2006–2016 (Fig. S1d–f), which was distinct from the warming signal that persisted from early autumn to winter in 1997–2005 (Fig. S1a–c).

3.3 The role of surface winds

Variations in the atmosphere also play a crucial role in controlling rainfall. Studies have shown that variations in winter snowfall along the northern coast of Japan are strongly correlated with the Monsoon Index (MOI) (e.g., Matsumura and Xie 1998). The MOI is derived from the zonal pressure difference between the Siberian High and Aleutian Low (Hanawa et al. 1988) and represents the strength of northwesterly continental winds during winter (Japan Meteorological Agency 2024b). We obtained correlation coefficients between MOI and the average winter rainfall across all AMeDAS stations of 0.78 for 1997–2005 and 0.72 for 2006–2017, in line with the findings of past studies.

Notably, variations in EC transport exhibited a strong correlation with the MOI, with correlation coefficients of 0.59 for 1997–2005 and 0.65 for 2006–2016. Regression analysis of the effect of surface winds on EC transport also indicated that higher EC transport tended to occur with the strengthening of northwesterly continental winds blowing toward the islands of Japan during 1997–2005 and 2006–2016 (Fig. 5a, d). These results indicate that both excess EC transport and increased wind contributed to enhanced latent heat flux and, consequently, rainfall. Enhanced latent heat flux along the northern coast of Japan in 2006–2016 was likely induced primarily by increased wind, as SST cooling was observed (Fig. 4a). We found that lower atmospheric temperatures co-occurred with increased wind in the period 2006–2016 (Fig. S3d), enhancing sensible heat flux (Fig. S2d). Combined with latent heat flux, this cooling overwhelmed the warming induced by oceanic flow. Changes in atmospheric temperatures, rather than wind, appear to have played the primary role in the enhanced sensible heat flux, as this increase was weaker during 1997–2005, despite stronger winds. Thus, the enhanced EC transport during 2006–2016 mitigated the magnitude of atmospherically forced SST cooling, rather than directly increasing SSTs. The strong correlations among EC transport, MOI, and rainfall are a notable finding that requires further investigation. Some lead time is needed for excess EC transport to induce winter rainfall, and the difference in spatial scale between the coastal branch of the TWC and the northwesterly continental winds indicates that another process may connect the two phenomena.

Regression analysis of surface winds relative to WC transport revealed no enhancement of the northwesterly continental winds during either 1997–2005 or 2006–2016 (Fig. 5b, e). Winds were stronger on the northern side of the Japan Sea in 1997–2005 and on the western side in 2006–2016 and were directed primarily toward the southwest. Winds parallel to the coast are unlikely to have caused increased rainfall on land. The correlation between the MOI and WC transport was non-significant, consistent with the poor correlation of WC transport and rainfall.

Regression analysis of surface winds relative to total TWC transport revealed intensification of the northwesterly continental winds during 1997–2005 but not during 2006–2016 (Fig. 5c, f). The spatial pattern showed a combined impact of variations induced by EC and WC transport in 1997–2005, which correlated well with increased rainfall. In 2006–2016, the spatial pattern resembled that induced by WC transport, in accordance with the weakened correlation between TWC transport and rainfall during this period. This northeasterly wind reflected TWC transport variation induced primarily by WC transport during 2006–2016, rather than the changes in wind direction associated with the MOI. Regression of surface winds onto the MOI revealed a similar spatial pattern to that found for EC (Fig. 5a, b). Nevertheless, the northeasterly wind direction may have been partly responsible for the spatial variation in rainfall (Fig. 4f); negative correlations were detected along the Tohoku coast, where changes in wind characteristics were mild, and weakly positive correlations were detected along the San'in coast, where wind grew stronger.

4 Summary and discussion

The goal of this study was to assess factors that may have contributed to the abrupt weakening of the correlation between variations in autumn TWC transport and winter rainfall along the northern coast of Japan after 2006. Observations show that the correlation was strong (0.71) in 1997–2005 but weakened (0.21) in 2006–2017.

Correlation and regression analyses revealed variation in the coastal branch of the TWC to be the key factor connecting the TWC with rainfall. The correlations between variations in EC transport and rainfall were 0.61 in 1997–2005 and 0.55 in 2006–2017, remaining high across both periods. Enhanced latent heat flux also occurred along the pathway of the coastal branch, implying a mechanism underlying the excess rainfall. Variations in WC transport, in contrast, showed weak correlation with rainfall and implied no strong connection. Regressed surface winds also became more consistently oriented parallel to the coast and may have changed the spatial pattern in rainfall. The abrupt weakening of the lagged correlation between variations in TWC transport and rainfall was likely caused by the domination of TWC transport variation by WC transport variation during 2006–2017. Variation in TWC transport and its partitioning appeared to be controlled by non-local processes, as they exhibited non-significant correlations with local winds along the Tsushima Strait, which can affect the gradient of sea-surface height across the strait. This finding is consistent with those of past studies which suggested that interannual variability in TWC transport is induced remotely from the Pacific and Kuroshio (e.g., Lyu and Kim 2005; Qiao et al. 2023).

Fig. 5 Regression maps of surface winds relative to **a** EC, **b** WC, and **c** total TWC transport during 1997–2005. Color gradient indicates wind speed. **d**–**f** As in (**a**–**c**), but for 2006–2016
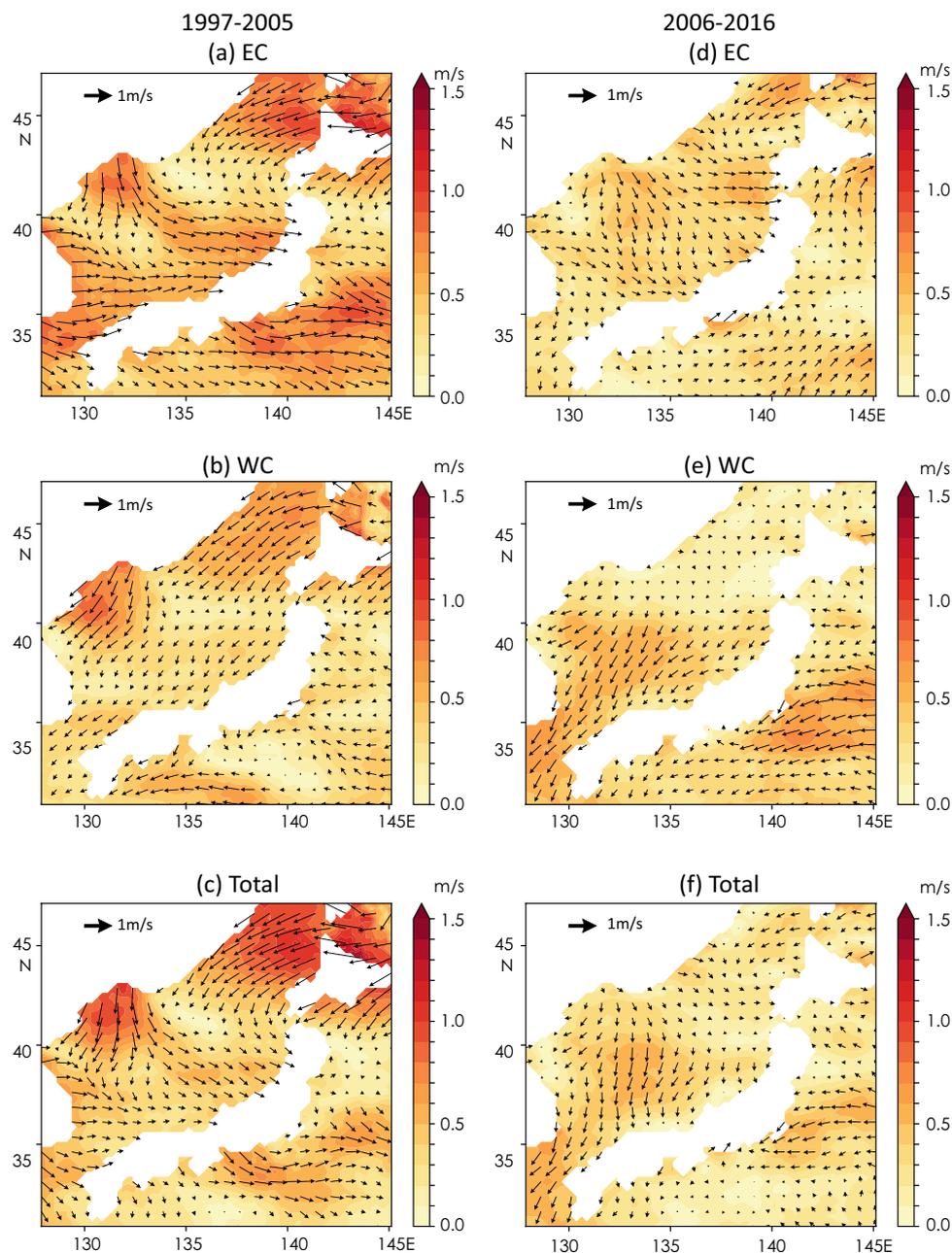
We further found that excess TWC transport did not necessarily lead to enhanced SST warming within the Japan Sea. SST warming persisted from autumn to winter during the period 1997–2005, whereas SST cooling strengthened toward winter in 2006–2016. Changes in the atmospheric wind field consistently affected rainfall, as evidenced by the strong correlations between the MOI and rainfall for both periods. Stronger SST cooling occurred during 2006–2016 as lower atmospheric temperatures co-occurred with increased surface winds, leading to enhanced sensible and latent heat fluxes that overwhelmed the impact of the TWC. This relationship implies a stronger impact of northwesterly continental winds on enhanced latent heat flux along the pathway of the TWC, and thus rainfall, in 2006–2016, rather than changes in SSTs. The role of the coastal branch of the TWC is to mitigate SST cooling and support enhanced latent heat flux along the northern coast of Japan, contributing to rainfall; however, the mechanism connecting the coastal branch and northwesterly continental winds remains unclear. Hirose et al. (2009) suggested that SST warming in the Japan Sea can affect regional climate conditions associated with the western Pacific teleconnection pattern. However, a similar relationship between the coastal branch and the wind field was observed during 2006–2016, when there was no

widespread SST warming in the Japan Sea. Investigation of the interactions of the TWC, particularly the coastal branch, with basin-scale atmospheric circulation is needed and is planned as the next step after this study.

Declarations

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