Estimation of Water Origins within an Explosive Cyclone over the Sea of Japan Using an Isotopic Regional Spectral Model

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ABSTRACT: Moisture sources and their corresponding temperature and humidity are important for explosive extratropical cyclones' development regarding latent heating. To clarify the water origins and moisture transport processes within an explosive cyclone, we simulated an explosive cyclone migrating poleward across the Sea of Japan on 30 November 2014, by using an isotopic regional spectral model. In the cyclone's center area, a replacement of water origins occurred during the cyclone's development. During the early stage, the warm conveyor belt (WCB) transported large amounts of moisture from the East China Sea and Kuroshio into the cyclone's inner region. While in the deepening stage, the cold conveyor belt (CCB) and dry intrusion (DI) conveyed more moisture from the northwest Pacific Ocean and the Sea of Japan, respectively. Compared with the contribution of local moisture, that of remote moisture was dominant in the cyclone's center area. Regarding the water origins of condensation within the frontal system in the deepening stage, the northwest Pacific Ocean vapor, principally transported by the CCB, contributed 35.5% of the condensation in the western warm front. The East China Sea and Kuroshio moisture, conveyed by the WCB, accounted for 32.4% of the condensation in the cold and eastern warm fronts. In addition, condensation from the Sea of Japan, which was mainly triggered by the DI and induced by the topography, occurred on the west coast of the mainland of Japan and near the cyclone center. The spatial distribution of the isotopic composition in condensation and water vapor also supports the water-origin results.

SIGNIFICANCE STATEMENT: We clarified the water origins with their corresponding temperature, humidity, isotopic composition, and moisture transport processes within an explosive extratropical cyclone. Condensation with low $\delta^2\text{H}$ and d-excess in the western warm front was principally transported by the cold conveyor belt from the northwest Pacific Ocean with a cold and moist air mass, whereas condensation with high $\delta^2\text{H}$ and d-excess in the cold and eastern warm fronts was mainly conveyed by the warm conveyor belt from the East China Sea and Kuroshio with a warm and humid air mass. These results point the way toward better understanding of where the moisture evaporates, how the moisture is transported, and where the moisture condenses, which can be used for model evaluation and weather forecasting in association with explosive extratropical cyclones.

KEYWORDS: Atmosphere; North Pacific Ocean; Extratropical cyclones; Fronts; Synoptic-scale processes; Winter/cool season; Isotopic analysis; Numerical analysis/modeling

1. Introduction

Explosive extratropical cyclones are defined as when the surface central pressure falls at a rate of at least 1 mb h^{-1} for 24 h ($1 \text{ mb} = 1 \text{ hPa}$), also called meteorological “bombs” (Sanders and Gyakum 1980). Explosive cyclones, as severe weather disasters, induce heavy precipitation with devastating floods and cause great damage to human society during boreal winter, especially in the northwestern region of the Pacific and Atlantic oceans (Sanders and Davis 1988; Yoshida and Asuma 2004; Kuwano-Yoshida and Asuma 2008; Yoshiike and Kawamura 2009;

Pang and Fu 2017). In those regions, the western-boundary warm currents of the Kuroshio and the Gulf Stream play an important role in the development of explosive cyclones by supplying moisture and heat (Kuo et al. 1991; Kelly et al. 2010; Kwon et al. 2010; Booth et al. 2012; Hirata et al. 2015).

As a source of latent heating, water vapor is one key factor in the development of explosive extratropical cyclones. Water vapor is mainly transported into an extratropical cyclone system by a warm conveyor belt (WCB) (Carlson 1980; Browning and Roberts 1994; Schemm et al. 2013; Pfahl et al. 2014; Madonna et al. 2014), cold conveyor belt (CCB) (Schultz 2001; Schemm and Wernli 2014; Martínez-Alvarado et al. 2014; Hirata et al. 2015, 2018), and dry intrusion (DI) (Browning and Roberts 1994, 1996; Raveh-Rubin 2017). The WCB is a poleward ascending flow with warm and moist air prevailing in the warm sector of cyclones, and it is responsible for most of the meridional moisture transport. Booth et al. (2012) investigated the role of the WCB in the intensification of the explosive cyclone

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through its conveyance of surface moisture and heat flux from the Gulf Stream region in the warm sector of the cyclone. Another conveyor belt is the CCB, which is a low-level zonal flow with cold and relatively moist air in the poleward cold sector passing beneath the warm frontal zone. Hirata et al. (2015, 2018) proposed that the CCB plays a vital role in transporting moisture and heat from the Kuroshio warm currents to the bent-back warm front to accelerate cyclone development. The DI is a descending airstream from the vicinity of the tropopause, with cold and dry air in the western cold sector passing under the cold frontal zone of cyclones. Previous studies suggested that the DI facilitated rapid cyclogenesis and the subsequent development of cyclones through the advection of high-potential vorticity air (Young et al. 1987; Browning 1997) and interaction with the moist air ahead of the cold front (Raveh-Rubin and Wernli 2016).

In addition to data on moisture transport processes, information on moisture sources and their corresponding temperature, humidity, and isotopic composition are also important for improving our understanding of the mechanisms of cyclone intensification. Stable water isotopes have been widely used as natural tracers to investigate water origins in hydrologic and meteorologic studies based on on-site observations (Dansgaard 1964; Gat 2000; Fudeyasu et al. 2008; Li et al. 2017) and have been implemented in general and regional circulation models (Yoshimura et al. 2003; Pfahl et al. 2012; Aemisegger et al. 2015; Thurnherr et al. 2021); the isotopes can be used to validate models' performance by comparing simulated and observed isotopic results. Generally, the isotopic composition of water is controlled by environmental variables of temperature and humidity during the water's phase transitions in evaporation and condensation processes, whereas the isotopic composition of water is conserved during the moisture transport process. Moreover, regional circulation models incorporating water vapor tracers (so-called water tagging) are another powerful approach to quantify water origins in the cyclones (Sodemann et al. 2009; Winschall et al. 2014). Sodemann and Stohl (2013) emphasized that both local and remote water vapors significantly contributed to precipitation in the cyclones, and a higher proportion of remote moisture caused more intense precipitation when an atmospheric river was present. Recently, some studies have incorporated both stable water isotopes and water tagging into general circulation models to investigate the moisture sources of precipitation in East Asia (Hiraoka et al. 2011; Takakura et al. 2018). Tanoue et al. (2017) investigated the water origins of winter precipitation over Japan and identified the dominant source of precipitation induced by winter monsoons and extratropical cyclones as the Sea of Japan and the Pacific Ocean, respectively.

The aim of this study is to clarify the moisture sources and to investigate the corresponding moisture transport processes of explosive extratropical cyclones during their development. For that purpose, a regional spectral model (RSM) incorporating water vapor tracers and stable water isotopes was used to simulate an explosive cyclone developing over the Sea of Japan at the end of November 2014. In addition, the isotopic composition of precipitation was collected diurnally at Sapporo, a city on the

northernmost island of Japan, to validate the simulation results in the RSM.

The objectives of this study were (i) identification of the origins of water in the vicinity of the cyclone center during the development of the explosive cyclone; (ii) investigation of the roles of the WCB and CCB in moisture import to the cyclone's inner region during the development of the explosive cyclone; and (iii) estimation of each water origin's contribution to condensation in the frontal system of the cyclone in the deepening stage of the explosive cyclone.

The rest of the paper is organized as follows. Section 2 introduces the model used and the experimental design. Section 3 describes the simulated features of the explosive cyclone modeled in this study. Section 4 presents major water origins and corresponding transport processes within the frontal system during cyclone development. Section 5 discusses the roles of the airstreams (WCB, CCB, and DI) in moisture import to the cyclone system and the water origin and isotopic composition of condensation in the frontal system of the cyclone during rapid intensification. A summary is drawn in section 6.

2. Methods

a. Isotopic regional spectral model (IsoRSM)

The isotopic species for HDO and H_2^{18}O were incorporated into the Scripps Experimental Climate Prediction Center (ECPC) Regional Spectral Model (RSM) (Kanamitsu et al. 2005) as prognostic variables in addition to water vapor, and the model was named the isotopic regional spectral model (IsoRSM) (Yoshimura et al. 2010). In this study, an explosive cyclone traveling over the Sea of Japan at the end of November 2014 was simulated using the IsoRSM. The major physics packages used in the IsoRSM include longwave and shortwave radiation parameterizations (Chou and Suarez 1994), cloud microphysics (Slingo 1987), the relaxed Arakawa-Schubert deep convection (Moorthi and Suarez 1992), shallow convection (Tiedtke 1983), the Noah land surface model (Ek et al. 2003), a nonlocal vertical diffusion scheme for the planetary boundary layer (Hong and Pan 1998), and the orographic gravity wave drag and mountain blocking parameterization (Alpert et al. 1988).

With respect to the isotopic tracers in the IsoRSM, no isotopic fractionation occurs during the dynamic advection processes, ice and snow sublimation processes, or terrestrial evapotranspiration (100% transpiration is assumed) and runoff processes. On the other hand, thermodynamic equilibrium fractionation occurs during most of the phase transitions (such as condensation and evaporation) among water vapor, liquid, and ice (Majoube 1971a,b) under saturation conditions, whereas kinetic fractionation was considered for evaporation and isotopic exchange between open water and liquid raindrops with ambient air under unsaturated conditions (Stewart 1975; Merlivat and Jouzel 1979) and for condensation from vapor to ice under -20°C under supersaturation conditions (Jouzel and Merlivat 1984).

A spectral nudging technique is adopted to produce more realistic atmospheric circulation and to improve the IsoRSM's

simulation (von Storch et al. 2000; Kanamaru and Kanamitsu 2007). Large-scale temperature and wind fields are forced toward the reanalysis forcing fields. Conversely, small-scale details, reflecting the interplay between atmospheric circulation and local geographic features, such as topography, land–sea distribution, and land use, are not nudged in the IsoRSM. It is noteworthy that the lateral boundary-nudging zones are 5% of the sides of the domain, and the meridional wind is nudged slightly stronger, whereas the fields of humidity and isotopic composition are not spectrally nudged (Yoshimura and Kanamitsu 2008, 2009; Kanamitsu et al. 2010).

b. Colored moisture analysis based on a water-tagging approach

To clarify the water origins in an explosive cyclone system during its development, the isotopic tracers in the IsoRSM were replaced with water vapor tracers. This water-tagging method was developed by Yoshimura et al. (2004) and is called colored moisture analysis (CMA). Moisture originating from different prespecified sources is tagged with different tracers. The tagged moisture undergoes all processes (such as transportation, condensation, evaporation, and precipitation) of the atmospheric water cycle in the IsoRSM with the tracer (moisture source) information. Finally, the contribution of each tracer (moisture source) to the total moisture or precipitation can be calculated. Eight evaporative source regions for the CMA in this study are defined according to geographical borders as shown in Fig. 1 and listed as follows: East China Sea and Kuroshio region, northwest Pacific Ocean, Sea of Japan, South China Sea and Philippine Sea, East Asian continent, Pacific Ocean, Okhotsk Sea, and Indian Ocean. It should be noted that both isotopic and water vapor tracers were introduced in the model as prognostic variables, and these tracers do not interact with any physical processes of the model or affect any other model variables.

c. Simulation designs

An extratropical explosive cyclone that occurred on 30 November 2014 over the Sea of Japan was selected for this study. The cyclone developed rapidly to its mature stage late on 1 December with northward migration across the Sea of Japan. The simulation was performed over a period of 11 days from 0000 UTC 24 November to 0000 UTC 5 December 2014. The model domain covers parts of East Asia and the northwest Pacific Ocean (105.82°–178.43°E, 10.13°–63.41°N), as shown in Fig. 1. A horizontal resolution of 10 km and 28 vertical sigma levels were used. The time step for model integration was 20 s.

For stable water isotopes and CMA in the IsoRSM, the lateral boundary and initial conditions were taken from the isotopic global spectral model (IsoGSM) (Yoshimura et al. 2008) simulation. The surface boundary conditions of the sea surface temperature and sea ice distribution for the IsoRSM and IsoGSM were obtained from the National Oceanic and Atmospheric Administration Optimum Interpolation Sea Surface Temperature V2 (NOAA OISST V2) (Reynolds et al. 2002). The initial time for the IsoGSM was set at 0000 UTC

FIG. 1. Partition of prespecified tagged water source regions indicated by different colors. The domain of the isotopic regional spectral model (IsoRSM) is indicated by the inner dashed black rectangle.

1 June 2014, and the spinup period was about 6 months. Both the IsoRSM and IsoGSM used a spectral nudging technique to correct temperature and horizontal wind fields for a scale larger than 500 km at all layers and all time steps (Yoshimura and Kanamitsu 2008) based on the Japanese 55-year Reanalysis (JRA-55) (Kobayashi et al. 2015).

d. Observed isotopic data in precipitation

To evaluate the IsoRSM model, precipitation was sampled diurnally for stable isotopic analysis on the roof of the administration building at the Faculty of Environmental Earth Science, Hokkaido University, in Sapporo, northern Japan, where extratropical explosive cyclones approach frequently (e.g., Tsukijihara et al. 2019). Rainfall samples were collected using a funnel with a polyethylene vessel, whereas snow samples were collected in a bucket and melted in a plastic bag at room temperature. Collected rainfall and snow samples were weighed to obtain information on the amount of precipitation, and aliquots were poured into 6-mL glass bottles for stable isotopic analysis. These in situ observation data were available from 30 November 2014 to 18 January 2015.

The stable isotopic composition of precipitation samples was analyzed via the $\text{CO}_2/\text{H}_2/\text{H}_2\text{O}$ equilibration method using a gas bench (Thermo Fisher Scientific, United States) attached to a MAT253 (Thermo Fisher Scientific, United States, manufactured in Germany) at the Faculty of Environmental Earth Science, Hokkaido University. Analytical errors (standard deviation of reproducibility) of the internal standards were less than 2‰ and 0.2‰ for $\delta^2\text{H}$ and $\delta^{18}\text{O}$, respectively, for the entire procedure.

D-excess was defined by Dansgaard (1964) as $d\text{-excess} = \delta^2\text{H} - 8 \times \delta^{18}\text{O}$ and was widely used to reflect the atmospheric humidity condition during the evaporation process in an oceanic moisture source region (Merlivat and Jouzel 1979; Gat et al. 1994; Gat 2000). Generally, during the evaporation

FIG. 2. Comparison between model-simulated and JRA-55 results for the (a) track and (b) central pressure of the explosive extratropical cyclone that occurred on 30 Nov 2014. The locations and central pressures of the cyclone at 1800 UTC 30 Nov and at 0600 and 1800 UTC 1 Dec are marked as A, B, and C, respectively, in (a) and (b). The sampling site at Sapporo is indicated by $\times$ in (a). The time evolution of the 12-h averaged Bergeron (deepening rate) of the cyclone is indicated by a solid red line in (b).

process on the sea surface in winter, a cold and dry continent-origin air mass above the sea surface results in evaporated moisture with high d -excess; conversely, a warm and humid oceanic-origin air mass causes vapors with low d -excess.

3. Simulated features of the explosive cyclone

a. Validation of the IsoRSM simulation

To validate the IsoRSM simulation, the cyclone's track with corresponding central pressure was extracted from the JRA-55 dataset to compare with those simulated in the IsoRSM. Overall, the simulation shows good correspondence with the JRA-55 results for the time evolution of the cyclone's route and intensity, especially in the middle and late periods, as shown in Figs. 2a and 2b. However, in the early period, the simulated track shifted to the southeast as compared with the JRA-55 results. During the whole cyclone-development period, the spatial distribution of the simulated sea level pressure and precipitation showed a pattern very similar to the reanalysis results from JRA-55 and National Centers for Environmental Prediction–Department of Energy Reanalysis 2 (R2), respectively, whereas the precipitation intensity was overestimated by the IsoRSM in the frontal region according to the R2 results (not shown). Considering the time evolution of the central pressure, three time points, 1800 UTC 30 November and 0600 and

FIG. 3. Scatter diagram of the simulated and observed $\delta^2\text{H}$ in precipitation at Sapporo in northern Japan. The location of the sampling site is shown in Fig. 2a.

1800 UTC 1 December, were selected as the early, deepening, and mature stages of the cyclone and designated stages A, B, and C, respectively.

The scatter diagram of model-simulated and observed $\delta^2\text{H}$ in the precipitation at Sapporo is displayed in Fig. 3. The sample number is 108 during the 50-day observation. The simulated $\delta^2\text{H}$ values were lower than the observed results, especially for the low $\delta^2\text{H}$ values, probably resulting from the overestimated precipitation amount. The root-mean-square error between observed and simulated data is 24.52‰. The correlation coefficient is 0.71, which is statistically significant at the 0.1% level for T statistics and comparable to the results in previous studies (Ichiyangi et al. 2005; Kudo et al. 2014; Tanoue et al. 2016, 2017; Takakura et al. 2018). The isotopic composition of precipitation is mainly controlled by processes of moisture evaporation in the source region, moisture transport from the source region to the condensation region, moisture condensation, and precipitation at the observation site. Therefore, these results suggest that the IsoRSM can successfully capture all processes in the atmospheric water cycle and is made suitable for the CMA by replacing isotopic tracers with water vapor tracers to identify moisture sources in the cyclones.

b. Large-scale environment during cyclone development

The time evolution of the synoptic situation at the upper and lower troposphere for cyclone development in stages A, B, and C is displayed in Fig. 4. During the cyclone's development, an upper-level trough with a high Ertel potential vorticity (PV at 310 K) approached the cyclone from its western side (Figs. 4a–c). Meanwhile, the wind field associated with the trough showed a similar spatial distribution pattern throughout the troposphere at the upper and lower levels for each stage (not shown). At the lower level, northwesterly winds with a low θ_e (equivalent

FIG. 4. (a)–(c) Spatial distribution patterns of the Ertel potential vorticity (PV; shaded; unit of PVU and interval of 2 PVU; 1 PVU = 10^{-6} K kg⁻¹ m² s⁻¹) on the isentropic surface of 310-K potential temperature, vertically integrated moisture flux (blue vectors), 600-hPa vertical pressure velocity (magenta contour at 3 Pa s⁻¹), and SLP (black contours; units of hPa, and interval of 10 hPa with a thick contour at 1010 hPa) simulated by the IsoRSM model at 1800 UTC 30 Nov and 0600 and 1800 UTC 1 Dec. The reference arrow is 3000 kg m⁻¹ s⁻¹. Moisture fluxes of less than 400 kg m⁻¹ s⁻¹ have been suppressed. The green dot indicates the location of the cyclone center. (d)–(f) As in (a)–(c), but for the equivalent potential temperature (θ_e ; shaded; unit of K and interval of 10 K), horizontal wind (vectors), and SLP (contours) on an 850-hPa isobaric surface. The reference arrow is 50 m s⁻¹. The red dot indicates the location of the cyclone center.

potential temperature) were dominant on the western side of the cyclone and caused a baroclinic zone over the Sea of Japan, where the cyclone developed rapidly; on the other hand, southerly winds with a high θ_e were prevailing on the eastern side of the cyclone (Figs. 4d–f) and transported large amounts of moisture from southern oceanic regions to the southeast sector of the cyclone (Figs. 4a–c).

As will be revealed in section 4b, the salient poleward moisture flux zone with a high vertical pressure velocity and high θ_e , stretching northeastward from the East China Sea and Kuroshio through the northwest Pacific Ocean to the inner region of the cyclone, is intimately related to a WCB, indicating that moisture within the cyclone system was not only from the underlying region of the Sea of Japan but also had

been transported from remote areas such as the East China Sea and Kuroshio and the northwest Pacific Ocean by the WCB. In contrast, the northwesterly winds with a low θ_e and high PV from the East Asian continent correspond to a DI in the conveyor-belt model. Our results are consistent with previous studies and suggest that an upper-level trough, lower-level baroclinicity, and poleward moisture advection are favorable factors for rapid intensification of the cyclone (Yoshida and Asuma 2004; Sodemann and Stohl 2013).

c. Spatial distribution of latent and sensible heat supply

Since a latent and sensible heat supply plays a vital role in rapid intensification of the explosive cyclone (e.g., Kuwano-Yoshida and Asuma 2008; Kwon et al. 2010; Kelly et al.

FIG. 5. (a)–(c) Spatial distribution patterns of the surface turbulent latent heat flux (shaded) and 10-m horizontal wind (vectors). The reference arrow is 50 m s^{-1} . Fluxes of less than 100 W m^{-2} and wind of less than 5 m s^{-1} have been suppressed. The green dot indicates the location of the cyclone center. (d)–(f) As in (a)–(c), but for the surface turbulent sensible heat flux (shaded). Fluxes of less than 50 W m^{-2} have been suppressed.

2010; Iwao et al. 2012), the spatial distribution patterns of surface turbulent latent and sensible heat fluxes during intensification of the cyclone were investigated as described in this subsection. As shown in the upper panels of Fig. 5, as the cyclone migrated northward through the Sea of Japan, significant surface latent heat fluxes were observed around the East China Sea (Fig. 5a); these were enhanced and expanded to the Sea of Japan and Kuroshio regions during the cyclone's intensification (Figs. 5b,c). Compared with the moisture flux zone in the warm sector (Figs. 4a–c), the enhanced latent heat flux zone was located to the west of the main moisture flux zone under strengthened northwesterly winds from the East Asian continent with a cold and dry air mass (so-called cold air outbreaks). This cold and dry continental air mass facilitates intensified evaporation from the Sea of Japan and other regions in the western cold sector to moisten the airstream along the DI, whereas an intermediate

latent heat flux was observed in the warm sector under relatively weak southerly oceanic winds with a warm and humid air mass, which brought vapors from the East China Sea and Kuroshio and other warm oceanic regions to feed into the WCB. In addition, the latent heat flux was small in the northern cold sector under relatively strong oceanic winds with a cold and moist air mass, which enhanced evaporation from the northwest Pacific Ocean and other cold oceanic regions to strengthen the moisture flux zone along the CCB beneath the northeast edge of the WCB (Figs. 5a–c).

Compared with latent heat, the sensible heat showed a similar spatial distribution pattern with a smaller flux during the cyclone's development (Figs. 5d–f). The intensity of the sensible heat flux was about half that of latent heat, which is consistent with previous studies (e.g., Hirata et al. 2015, 2018). Hirata et al. (2018) emphasized that the sensible heat supply increased the water vapor content of the near-surface

saturated air by raising the air temperature and saturation mixing ratio. Therefore, during the cyclone's development, the moisture within the cyclone system may be supplied from the East China Sea and Kuroshio, northwest Pacific Ocean, and Sea of Japan as indicated by the latent heat flux shown in Figs. 5a–c, which will be examined in the next section, and sensible heat also facilitated the moisture supply process. It is worth noting the moisture uptake time and the time lag between evaporation from the ocean surface and condensation in the atmosphere. The average uptake time for whole moisture of air parcels was suggested by Thurnherr et al. (2021) to be 36 (49) h in the cold (warm) sector for Southern Ocean cyclones. However, in the northwest Pacific region, Hirata et al. (2015, 2016) showed that about 50% of the moisture (5 g kg^{-1}) in air parcels along the CCB was taken up from the underlying ocean within 12 h before condensation, which indicates that the average time lag for moisture transported by the CCB from the underlying ocean to condensation was around 6 h.

4. Major moisture sources and corresponding transport processes within the cyclone frontal system

a. Temporal variation of water origins in the vicinity of the cyclone center

The previous section suggested that large amounts of moisture were transported toward the vicinity of the cyclone center through the airstreams (such as the WCB, CCB, and DI) during the cyclone's development, and latent and sensible heat fluxes (from the East China Sea and Kuroshio, northwest Pacific Ocean, and Sea of Japan) also facilitated the process of moisture import to the cyclone's inner region. To show the water budget in the cyclone center area during the cyclone's development, the hourly evolution of precipitation, horizontal convergence of vertically integrated moisture flux, and surface turbulent latent heat flux averaged over the domain within a radius of 200 km from the cyclone center are displayed in Fig. 6a. Overall, precipitation and moisture flux convergence exhibited similar variations, increasing at the beginning of the cyclone formation and subsequently decreasing gradually during intensification of the cyclone. Compared with moisture flux convergence, surface evaporation from the underlying inner region of the cyclone was much smaller, which indicates that moisture in the vicinity of the cyclone center was mainly imported from outer regions along the moisture flux zones indicated by blue vectors in Figs. 4a–c. This corresponds well with the findings in previous studies (Sodemann et al. 2009; Sodemann and Stohl 2013).

To help identify the moisture source in the vicinity of the cyclone center during the cyclone's development, the contribution of each water origin to the total precipitable water and condensation in the center area is shown in Figs. 6b and 6c and Table 1. The total precipitable water in the cyclone's inner region showed intriguing characteristics, with an overall decreasing trend and replacement of water origins as the cyclone intensified and migrated poleward over the Sea of Japan (Fig. 6b and Table 1). When the cyclone developed in the southern Sea of Japan, in stage A, most of the total precipitable

FIG. 6. (a) Time series of hourly precipitation (blue line), horizontal convergence of vertically integrated moisture flux (green line), and surface turbulent latent heat flux (red line) averaged over the cyclone's inner region with a radius of 200 km from the cyclone center (units are mm h^{-1}). The central pressure of the cyclone is indicated by a black line. Labels A, B, and C correspond to the locations of the cyclone in Fig. 2a. (b) As in (a), but for the major oceanic origins (color bar) of the total precipitable water in mm. Different color shadings indicate the different source regions shown in Fig. 1. (c) As in (b), but for condensation (mm h^{-1}).

water was from the East China Sea and Kuroshio and from the South China Sea and Philippine Sea. In stage B, during the cyclone's migration to the northern Sea of Japan, the moisture source changed drastically, with a large decline in the East China Sea and Kuroshio and the South China Sea and Philippine Sea vapors and enhancement of the Sea of Japan and northwest Pacific Ocean vapors. During stage C, when the cyclone landed on the Asian continent from the northern Sea of Japan, the precipitable water of each origin decreased further. The time evolution of condensation for each water origin corresponds well to that of precipitable water, which indicates that both the underlying and remote moisture contributes condensation to the cyclone's inner region (Fig. 6c and Table 1).

It is notable that remote ocean vapors, such as those from the East China Sea and Kuroshio, South China Sea and

TABLE 1. Percentage of each water origin in the total precipitable water and condensation in the vicinity of the cyclone center at stage A (1800 UTC 30 Nov), stage B (0600 UTC 1 Dec), and stage C (1800 UTC 1 Dec). The area-averaged total precipitable water (mm) and condensation (mm h^{-1}) for each stage are shown in last column. Numbers without and with parentheses are the precipitable water and condensation, respectively.

Time	IO (%)	PO (%)	SCS and PS (%)	ECS and KS (%)	SJ (%)	NWP (%)	OS (%)	EAC (%)	Total amount
1800 UTC 30 Nov	3.7 (1.7)	6.7 (5.2)	20.5 (17.9)	39.4 (36.5)	10.1 (6.3)	3.4 (1.1)	0.1 (0.1)	11.3 (7.6)	31.9 (5.2)
0600 UTC 1 Dec	3.7 (2.7)	1.9 (1.8)	5.4 (5.3)	13.0 (12.7)	27.7 (21.9)	19.0 (25.8)	4.9 (2.8)	16.3 (13.5)	16.6 (2.6)
1800 UTC 1 Dec	5.0 (3.3)	2.4 (1.5)	3.1 (2.9)	7.2 (7.2)	20.3 (18.9)	8.6 (10.6)	11.2 (13.5)	25.6 (20.2)	5.3 (0.6)

Philippine Sea, northwest Pacific Ocean, and Pacific Ocean, occupied a considerable proportion of the total precipitable water and condensation in the vicinity of the cyclone center. Due to the cyclone's developing within the Sea of Japan and East Asian continent, we simply grouped the moisture into local moisture originating from the Sea of Japan and the East Asian continent and remote moisture evaporating from the other regions, except for the Sea of Japan and the East Asian continent. The proportion of remote moisture ranged from 60.8% to 86.1% (54.1% to 78.6%) for condensation (total precipitable water) in the cyclone's inner region, with a radius of 200 km during the cyclone's development (Table 1). In addition, for the larger cyclone center area with radiuses of 500 and 1000 km, remote moisture accounted for 64.3% to 78.5% (59.6% to 78.8%) of the condensation (total precipitable water) (not shown). To clarify the reasons for the replacement of water origins and the large proportion of remote moisture in the vicinity of the cyclone center, the spatial distribution of major water origins will be presented in the next subsection.

b. Spatial distribution of water vapor and condensation with their isotopic composition

Figures 7 and 8 show the spatial distribution of precipitable water and condensation from each major source region. Overall, the spatial distribution of total precipitable water corresponded well to the θ_e and moisture flux zones, and the large condensation regions were consistent with the high vertical pressure velocity areas in Fig. 4. A relatively high amount of precipitable water was observed in the southeast sector of the cyclone and along the WCB in each stage (Figs. 7a,e,i).

Regarding each water origin, during stage A, large amounts of moisture principally originating from the East China Sea and Kuroshio were transported northward along the WCB (Fig. 7c) and condensed in the vicinity of the cyclone center and warm front along the north edge of the WCB, extending southeastward from the cyclone center to the Kuroshio region (Fig. 8c); in contrast, the amount of vapor from the Sea of Japan and northwest Pacific Ocean was relatively low in the cyclone center area (Figs. 7b,d).

As the cyclone intensified and migrated poleward during stage B, near the maximum deepening rate, both the cold front and the warm front intensified (Fig. 8e). Large amounts of moisture from the northwest Pacific Ocean converged on the northeast edge of the WCB and were transported northward by the CCB into the cyclone center area (Fig. 7h), then condensed in the western warm front and the vicinity of the cyclone center (Fig. 8h). In contrast, vapors from the East

China Sea and Kuroshio, conveyed by the WCB (Fig. 7g), contributed more condensation to the cold front and the eastern warm front along the west and north edge of the WCB (Fig. 8g). In addition, the Sea of Japan vapors converged on the northwest edge of the WCB and were transported poleward by the DI (Fig. 7f), then condensed near the cyclone center and west coast of the mainland of Japan along the east edge of the DI (Fig. 8f), which was principally induced by the topography.

To further clarify the vertical structures of moisture transportation and the characteristic spatial distribution of condensation within the frontal system for each water origin, latitude–height (longitude–height) cross-sectional maps of the WCB and CCB (the CCB and DI) in stage B are shown in Fig. 9. Vapors from the northwest Pacific Ocean (Sea of Japan) transported by the CCB (DI) were distributed above (below) the western warm frontal surface of approximately 285-K potential temperature (θ) at around 140°E on the ground, where active convection occurred on the warm-air side as indicated by the high altitude of the moisture (Figs. 9f,h), leading to large condensation of the northwest Pacific Ocean vapors in the western warm front (Fig. 8h). On the other hand, vapors from the East China Sea and Kuroshio were conveyed poleward by the WCB and ascended from around 40°N along the eastern warm frontal surface of about 290-K θ (Figs. 9c,k), resulting in large condensation of the East China Sea and Kuroshio vapors in the eastern warm front (Fig. 8g). Below the eastern warm frontal surface, moisture from the northwest Pacific Ocean was transported northwestward by the CCB (Figs. 9d,l). It is noteworthy that some moisture from the northwest Pacific Ocean was distributed in the WCB because the WCB passed through the southern part of the northwest Pacific Ocean and received evaporated moisture from that region. Therefore, the WCB includes vapors not only from the East China Sea and Kuroshio but also from the southern part of the northwest Pacific Ocean.

As the cyclone intensified and moved further poleward in stage C, the spatial distribution patterns of precipitable water and condensation from each major source region were similar to those in stage B with a northeast displacement (Figs. 7j,k,l and 8j,k,l). Overall, the precipitable water and condensation were enhanced within the cyclone system, whereas in the vicinity of the cyclone center, the precipitable water and condensation were relatively low (Figs. 7i and 8i) compared to the early and deepening stages.

The isotopic composition of the condensation and water vapor also exhibited characteristic spatial variations (Figs. 10 and 11). During the cyclone's intensification, lower $\delta^2\text{H}$ and

FIG. 7. (a)–(d) Spatial distribution patterns of total precipitable water and of precipitable water from the Sea of Japan (SJ), the East China Sea and Kuroshio region (ECS and KS), and the northwest Pacific Ocean region (NWP) for the early stage at 1800 UTC 30 Nov. A red circle indicates the cyclone's inner region with a radius of 200 km from the cyclone center. (e)–(h) As in (a)–(d), but for the developing stage at 0600 UTC 1 Dec. (i)–(l) As in (a)–(d), but for the mature stage at 1800 UTC 1 Dec.

d-excess condensation values were observed in the cyclone center and western warm front than in the cold and eastern warm fronts. The $\delta^2\text{H}$ of condensation showed a decreasing trend along the cold and warm fronts toward the cyclone center, which reflects the upstream rainout effect (so-called amount effect). At the same time, water vapor along the CCB in the northern cold sector exhibited lower $\delta^2\text{H}$ and d-excess

values than that along the WCB in the warm sector. Water vapor in the cyclone center and along the warm and cold fronts with heavy condensation showed the lowest $\delta^2\text{H}$, which is attributable to the isotopic exchange between water vapors with ambient raindrops.

To further investigate the water origins of condensation in the frontal system of the cyclone in stage B, near the

FIG. 8. As in Fig. 7, but for condensation. The purple circle indicates the cyclone's inner region with a radius of 200 km from the cyclone center.

maximum deepening rate, we simply defined two condensation types: the western warm front condensation primarily induced by the CCB and the condensation in the cold and eastern warm fronts caused by the WCB, as shown in Figs. 10b and 10e. The proportion of each water origin to the total condensation in each type is given in Table 2. Approximately 32.4% of the condensation in the cold and eastern warm fronts was contributed by East China Sea and Kuroshio vapors, which were transported by the WCB, while 35.5% of the western warm front condensation was contributed by northwest Pacific Ocean vapors, which were

principally conveyed by the CCB (Table 2). For the cyclone center area, moisture from the northwest Pacific Ocean and the Sea of Japan accounted for 25.8% and 21.9% of the condensation, which was imported to the vicinity of the cyclone center by the CCB and DI, respectively (Table 1).

5. Discussion

Previous studies investigated the roles of the WCB and CCB in transporting moisture from warm currents of the Kuroshio and Gulf Stream to the cyclone's inner regions during the

FIG. 9. (a)–(d) Spatial horizontal distribution patterns of total precipitable water and of precipitable water from the Sea of Japan (SJ), the East China Sea and Kuroshio region (ECS and KS), and the northwest Pacific Ocean region (NWP) for the developing stage at 0600 UTC 1 Dec. The location of the cyclone center is indicated by a red dot. A red circle indicates the cyclone center area with a radius of 200 km. (e)–(h) Vertical distribution of the total specific humidity and of specific humidity from the SJ, the ECS and KS, and the NWP (shaded; g kg^{-1}); potential temperature θ (contours; units of K and interval of 5 K); and zonal and vertical wind (vectors; m s^{-1} for zonal wind and Pa s^{-1} for vertical wind) along an A–A' line crossing the CCB and DI at the developing stage at 0600 UTC 1 Dec. The reference arrow is 50 m s^{-1} for zonal wind. (i)–(l) As in (e)–(h), but along a B–B' line crossing the WCB and CCB. The vectors are for meridional wind (m s^{-1}) and vertical wind (Pa s^{-1}). The reference arrow is 50 m s^{-1} for meridional wind.

development of explosive cyclones (Booth et al. 2012; Hirata et al. 2015, 2018). In this study, we found that in addition to the warm current region of the Kuroshio, the South China Sea and Philippine Sea and the northwest Pacific Ocean regions also contributed substantial moisture to the vicinity of the cyclone center via the WCB and CCB. In stage A, the WCB played a more important role in importing large amounts of water vapor from the East China Sea and Kuroshio and the South China Sea and Philippine Sea to the cyclone center area. On the other

hand, as the cyclone intensified in stage B, the CCB exerted more influence on transporting moisture from the northwest Pacific Ocean to the cyclone center area (Figs. 6–8 and Table 1). The DI was also responsible for the moisture import from the Sea of Japan.

Sodemann and Stohl (2013) suggested that the replacement of water origins in the vicinity of the cyclone center during the cyclone's migration poleward was due to the consumption of previously retained moisture and the recharge of local fresh

FIG. 10. (a)–(c) Spatial distribution of $\delta^2\text{H}$ in condensation (shaded) at 1800 UTC 30 Nov and at 0600 and 1800 UTC 1 Dec. Data with condensation of less than 1 mm h^{-1} have been suppressed. (d)–(f) As in (a)–(c), but for d-excess in condensation. In (b) and (e), the upper and lower black rectangles indicate the partition of heavy condensation areas of the western warm front and the cold and eastern warm fronts at stage B (0600 UTC 1 Dec), respectively.

moisture evaporating from the underlying region. However, their explanation cannot account for the increase in the non-local moisture source from the northwest Pacific Ocean. Our results indicated that the shift in moisture transport from the WCB to the CCB could result in a replacement of water origins, especially an increase in nonlocal moisture from the northwest Pacific Ocean in the vicinity of the cyclone center (Fig. 6).

Sodemann et al. (2009) and Trenberth (1999) estimated that more than 65% of the precipitation in the extratropical cyclone was made up of nonlocal (remote) vapors. In this study, we found that 60.8%–86.1% of the condensation in the vicinity of the cyclone center was contributed by nonlocal (remote) moisture (Table 1). Although the definitions of the local moisture region (with a scale of about 500–2000 km) and precipitation area (with a scale of about 400–1000 km) differ among studies, all estimations showed the dominance and the importance of remote moisture in the cyclone system, which was transported by the WCB and CCB.

With respect to the water origins of condensation in the frontal system of the cyclone in the deepening stage, near the maximum deepening rate, when large condensation occurred, we found very intriguing phenomena: the East China Sea and Kuroshio vapors contributed more condensation to the cold and eastern warm fronts along the west and north edge of the WCB (Fig. 8g and Table 2), while the northwest Pacific Ocean vapors accounted for more condensation in the western warm front along the CCB (Fig. 8h and Table 2). At the same time, condensation exhibited lower $\delta^2\text{H}$ and d-excess values in the cyclone center and western warm front than in the cold and eastern warm fronts (Figs. 10b,e). In addition, lower $\delta^2\text{H}$ and d-excess values of water vapor were observed in the northern cold sector as compared to the warm sector (Figs. 11b,e). These characteristic isotopic distributions of the condensation and water vapor can be explained by the corresponding water origins and their evaporation conditions. In general, during the evaporation process, a high sea surface temperature causes high δ values in the vapor, while low humidity in the ambient

FIG. 11. As in Fig. 10, but for 2-m water vapor. Contours in (a)–(c) indicate 2-m air temperature ($^{\circ}\text{C}$; interval of 10°C ; white line is for 10°C and black line is for 20°C). Contours in (d)–(f) show 975-hPa relative humidity (%; interval of 15%; white line is for 65%, gray line is for 80%, and black line is for 95%).

air with a large humidity deficit in the air–sea surface interface results in high d-excess values (Dansgaard 1964; Sugimoto et al. 1988; Matsubaya and Kawaraya 2014; Li et al. 2017).

Low $\delta^2\text{H}$ and d-excess condensation values in the cyclone center and western warm front (Figs. 10b,e) were attributable to the greater amount of moisture transported along the CCB from the northwest Pacific Ocean and other cold regions with low $\delta^2\text{H}$ and d-excess values (Figs. 11b,e), resulting from a low sea surface temperature and cold southeasterly oceanic air mass with relatively high humidity during evaporation on the northwest Pacific Ocean surface in the northern part of

the warm frontal zone (Figs. 11b,e). Furthermore, moisture from remote areas with relatively heavy precipitation in the upstream region along the CCB could also lower the $\delta^2\text{H}$ of condensation. On the other hand, relatively high $\delta^2\text{H}$ and d-excess values in the cold front and eastern warm front (Figs. 10b,e) were due to increased moisture transported by the WCB from the East China Sea and Kuroshio and other warm oceanic regions in the warm sector with high $\delta^2\text{H}$ and d-excess values (Figs. 11b,e) arising from a high sea surface temperature and warm air mass with relatively low humidity during evaporation on the East China Sea and Kuroshio sea

TABLE 2. Percentage of each water origin in the total condensation in the western warm front and in the cold and eastern warm fronts at stage B (0600 UTC 1 Dec). The area-averaged condensation (mm h^{-1}) for each part is shown in the last column.

Area	IO (%)	PO (%)	SCS and PS (%)	ECS and KS (%)	SJ (%)	NWP (%)	OS (%)	EAC (%)	Total (mm h^{-1})
Western warm front	2.6	2.2	7.0	13.5	17.8	35.5	2.5	12.6	3.2
Cold and eastern warm fronts	3.2	7.6	11.1	32.4	10.2	17.6	0.3	9.5	2.1

surface in the warm sector (Figs. 11b,e). In addition, as compared to the cold front, condensation in the west coast of the mainland of Japan showed relatively low $\delta^2\text{H}$ and high d-excess values (Figs. 10b,e). This was caused by moisture along the DI that evaporated from the Sea of Japan with low $\delta^2\text{H}$ and high d-excess values under a cold and dry continental air mass during cold-air outbreaks (Figs. 11b,e), which was consistent with previous studies (Aemisegger and Sjolte 2018; Thurnherr et al. 2021).

6. Summary

This study is the first attempt to use a new approach to systematically identify water origins within the frontal system (including the cyclone center area and cold and warm fronts) of an explosive cyclone and to clarify moisture evaporation and transport processes from local and remote regions into the cyclone center area through the warm conveyor belt (WCB) and cold conveyor belt (CCB). For this purpose, an isotopic regional spectral model (IsoRSM) fitted with colored moisture analysis (CMA) with a horizontal resolution of 10 km was used to simulate an explosive cyclone developing over the Sea of Japan at the end of November 2014. According to comparisons between the IsoRSM simulated results with JRA-55 data and the observed $\delta^2\text{H}$ in precipitation at Sapporo, in northern Japan, the IsoRSM successfully reproduced the isotopic variations in precipitation as well as the track, intensity, and basic structure of the cyclone. The major findings in this study are briefly summarized as follows:

- 1) With respect to the water origins in the total precipitable water and condensation in the vicinity of the cyclone center, a replacement of water origins from the East China Sea and Kuroshio and from the South China Sea and Philippine Sea in the early stage to the Sea of Japan and northwest Pacific Ocean in the deepening stage occurred during the cyclone migration poleward across the Sea of Japan, resulting from a shift of moisture transport from the WCB to the CCB.
- 2) Regarding the active roles of the WCB and CCB in importing moisture into the cyclone system, in the early stage, during the development of the cyclone, the WCB transported large amounts of moisture from the East China Sea and Kuroshio into the cyclone's inner region. While in the deepening stage, the CCB conveyed more moisture from the northwest Pacific Ocean to the cyclone center area. Compared with the local moisture, the remote moisture was dominant in the vicinity of the cyclone center in terms of total precipitable water and condensation.
- 3) As for water origins within the frontal system, in the deepening stage, near the maximum deepening rate, vapors from the northwest Pacific Ocean, principally transported by the CCB, contributed 35.5% of the condensation in the western warm front. Moisture from the East China Sea and Kuroshio, conveyed by the WCB, made up 32.4% of the condensation in the cold and eastern warm fronts. In addition, condensation from the Sea of Japan, which is primarily transported by the DI and induced by the topography, mainly occurred near the cyclone center and on the

west coast of the mainland of Japan. The spatial distribution of isotopic composition in the condensation and water vapor also supports the water-origin results.

This study points the way toward better understanding of where the moisture is evaporated, how the moisture is transported, and where the moisture is condensed. The method based on isotopic simulation and observation can be used to evaluate physical parameterization schemes in numerical models. The findings can be used for weather forecasting, disaster preparedness with regard to heavy precipitation and flooding, and the allocation of water and energy resources in association with explosive extratropical cyclones.

Previous studies emphasized that the moisture and heat supply from warm currents and their impact on the growth of explosive cyclones were sensitive to the track of the cyclone and the geographical relationship between the cyclone and the currents (Kuo et al. 1991; Reed and Simmons 1991; Reed et al. 1993; Hirata et al. 2018). The water origins and moisture transport processes depend heavily on the cyclone track. The findings in this case study are based on the simulation of an explosive cyclone developing over the Sea of Japan. Moreover, the reproducibility of the simulated mesoscale structure, position of the cyclone, and precipitation intensity depends heavily on the model's resolution and the choice of physics packages, such as a convection scheme and planetary boundary layer scheme (Lamraoui et al. 2019). Higher-resolution simulations and further analysis of physical parameterization schemes are necessary to reproduce the cyclone more accurately. The model and analysis highlighted in this paper are not specific to this single cyclone; rather, we suggest that they be applied to additional explosive extratropical cyclones with different routes in the vicinity of Japan in order to gain a more complete understanding of water origins and moisture transport and evaporation processes with isotopic dynamics in cyclogenesis.

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