5.7 **Structure and Environment of Polar Meso-cyclones over the Sea of Japan: Composite Analysis and Numerical Experiments**

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1. Introduction

Polar mesocyclones (hereafter PMCs) are meso-α- and meso-β-scale cyclonic vortices that develop in the poleward of the main polar front over the north Atlantic, north Pacific and Antarctic oceans in winter. The Sea of Japan is located at the lowest latitude among the oceans where PMCs develop frequently.

There have been extensive studies on PMCs. However, there have been only a few composite analyses of their time-evolving environment (e.g., Blechschmidt et al. 2009; Mallet et al. 2013; Yanase et al. 2015). These studies used relatively low-resolution dataset, and targeted meso-α-scale PMCs.

In the present study we will clarify the time-evolving environment for the development of PMCs including meso-β-scale vortices over the Sea of Japan by composite analyses using objective analysis data. Then using the time-evolving composite fields as the initial and boundary conditions, we preform numerical experiments to examine if a PMC is reproduced. If we succeed in reproducing the PMC, we examine factors important for the PMC development using sensitivity experiments.

2. Geographical distribution and movements of PMCs

First, we used JMA Mesoscale Analysis (MA), which has time resolution of 3 hours and horizontal resolution of about 10km, for 6 cold seasons between 2009 and 2015 to examine geographical distribution and movements of PMCs. Tracks of PMCs are determined objectively using the method of Watanabe et al. (2016). Two regions of active PMCs are found to exist in the Sea of Japan (Fig. 1): One is the northeastern part and the other the northwestern part. In the present paper, the PMCs in the northeastern part will be described in detail

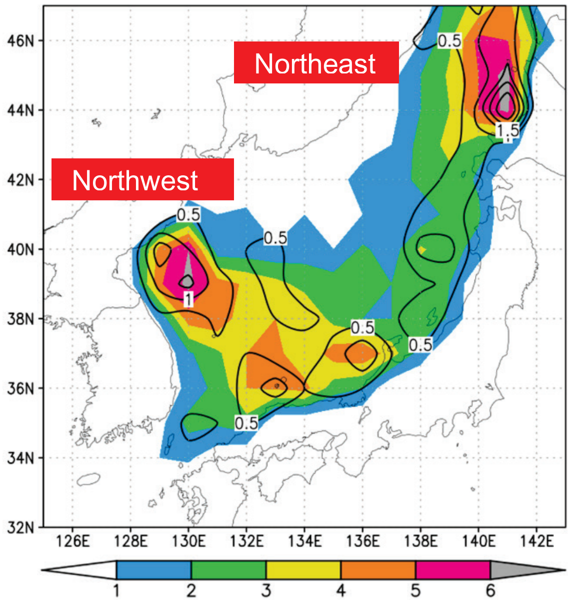

Fig. 1: Average numbers of tracks (color shading) and PMCs reaching the maximum intensity (contour) within a 1° ×1° grid in 6 cold seasons.

3. Composite Analysis

The composite analysis were made using JMA Global analysis (GA). Figure 2 shows tracks of 22 seasons. The reference time T=0 for composite analysis is taken as the time when a PMC is closest

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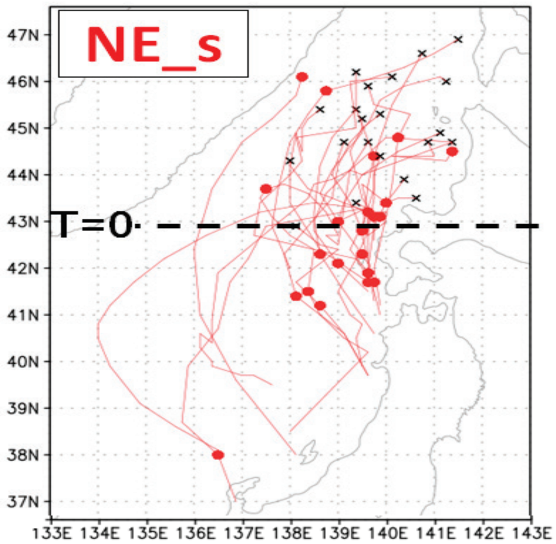

Fig. 2: Tracks of 22 PMCs in the northeastern part during the 6 cold seasons. The cross mark and solid circle show the locations of genesis and maximum vorticity, respectively.

to 43N line (dashed line in Fig. 2). Then each physical variable was simply superposed and averaged by fixing the latitude and longitude for every 6 hours to obtain the composite. Note that the mean field is PMCs in the northeastern part during the 6 cold defined by a 14 days average around T=0, and anomalies by deviations of the composite field from the mean field

Figure 3 shows horizontal distributions of total and anomaly sea-level pressure (Fig. 3a), and anomalies of temperature and geopotential at 500hPa (Fig. 3b) at T=0. At T=-48 h, a precedent synoptic low (hereafter SL) is located to the east of Hokkaido and Siberian high over the Eurasian continent. An upper cold vortex (hereafter UCV) is located over the Eurasian Continent. At T=-24 h, the precedent SL moves eastward, but a surface trough extends westward to the northeastern part of the Sea of Japan. The UCV reaches the eastern coast of the Eurasian continent (Note that the figures corresponding to Fig.3 for T=-48, -24 and 24 h are not shown).

At T=0, a new SL is generated over the Pacific Ocean to the southeast of the Japan islands. A

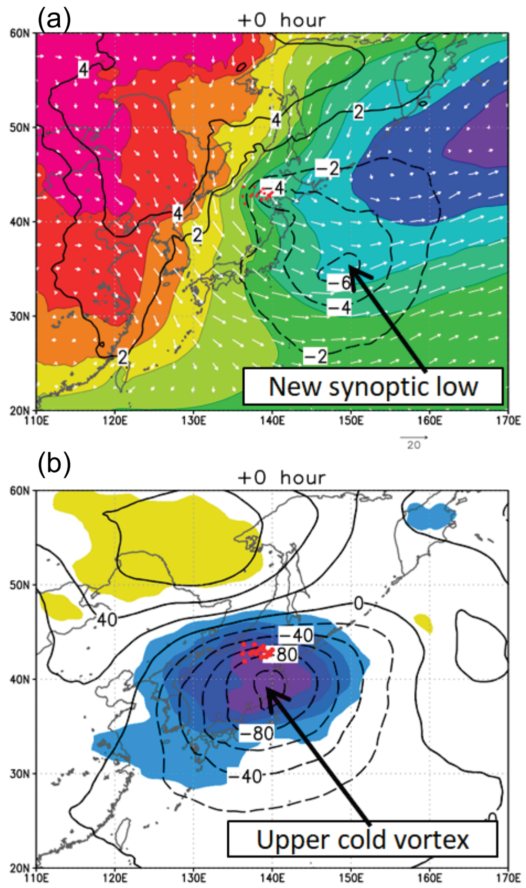

Fig. 3: Horizontal distributions of (a) total (color shading) and anomaly (contour) sea-level pressure, and (b) anomalies of temperature (color shading) and geopotential (contour) at T=0. Red dots indicate the locations of PMCs.

pressure depression is also seen where the PMCs are concentrated. The UCV is now located right south of the PMCs. Twenty-four hours later (T=24 h), both the UCV and the new SL move away to the east of Japan islands. The PMCs make landfalls on the Japan islands and dissipate.

4. Numerical simulation

In order to examine how representative the time-evolving composite fields are, we have made a numerical experiment using the time-evolving composite fields as the initial and boundary conditions. The model used for the simulation is JMA Non-hydrostatic Model (Saito et al., 2007). The horizontal resolution and grid numbers are 10km and 350x250. A total of 40 vertical grid points are distributed from the surface up to 15,540 m, with grid intervals varying from 40m at the surface to 802m near the upper boundary. An explicit three-ice bulk scheme (Ikawa et al. 1991), Kain–Fritsch convective parameterization (Kain and Fritsch 1990; Kain 2004) and the MYNN level-3 boundary layer parameterization (Nakanishi and Niino 2006) are used. The composite of the NOAA 0.25° daily Optimum Interpolation Sea Surface Temperature (OISST; Reynolds et al. 2007) data at T=0 h is used for the SST and the distribution of sea ice. The calculation was started at T=-48 h and continued for 72 hours.

The simulation turned out to nicely reproduce a PMC (Fig. 4) which resembles a typical PMC such as found on 21 January 1997 (Yanase et al. 2002), demonstrating that the composite gives a representative environment of PMCs, and that a PMC can develop spontaneously when a favorable environment is given. The vertically-integrated condensed water shows a comma-shaped pattern at T=6 h, but it changes into a spiraliform at T=18h. This seems to correspond to a decrease in baroclinicity in the environment (e.g., Yanase and Niino 2007).

The simulated PMC has a warm core (not shown). In order to examine the cause of the warm core, 98 parcels are distributed in the warm core at the level of 850 hPa at T=6 h, and their backward trajectories for 24 hours are obtained (Fig. 5). A majority of parcels come from Mamiya Strait near the surface. The potential temperature and water vapor mixing ratio of the parcels increase by 10K and 1.5g/kg, respectively, during the last 12 hours due to heat and moisture fluxes from the sea surface.

Since a PMC was successfully reproduced in the control experiment (CNTL), we now examine effects of condensational heating, SST and topography along the east coast of the Eurasian continent by four sensitivity experiments: The first is DRY experiment in which moisture is removed after T=-24 h when the PMC is formed in the CNTL. The second

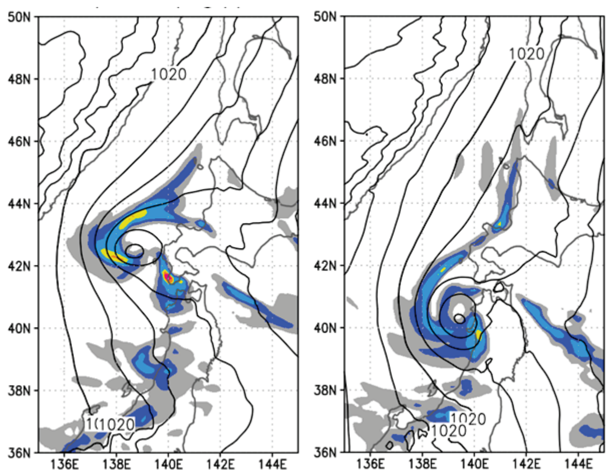

Figure 4: Sea-level pressure (contours; interval 2 hPa) and vertically integrated condensed water content (color; kgm21): (a) T=6 h and (b) t=18 h.

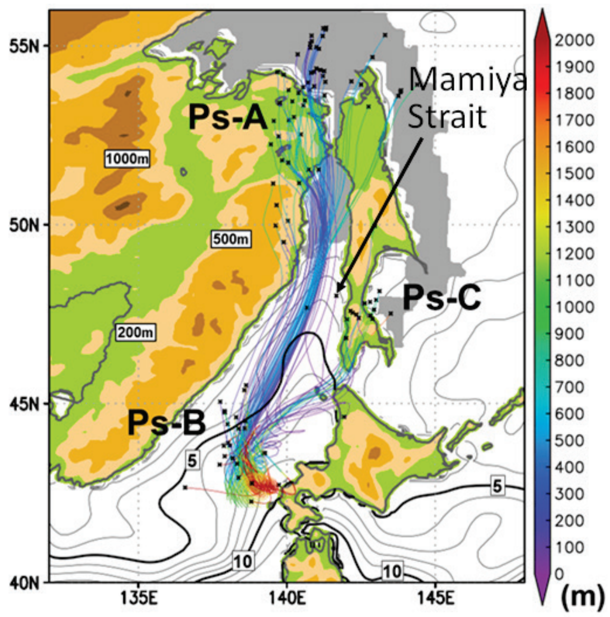

Fig. 5: Twenty-hours backward trajectories of particles placed in the warm core of the PMC at 850 hPa level at T=6 h. The colors on the trajectories show height, and the black solid dots show the position at T=-18h.

is another DRY experiment in which moisture is removed after T=0 h when the PMC is at a development stage. The third is a low-SST experiment in which SST between the west of Hokkaido and Mamiya Strait is lowered by 5K. And the fourth is no mountain experiment in which the topography higher than 100m along the east coast of the Eurasian continent (Sikhote-Alin mountains) is removed.

Figure 6 shows time evolutions of vertical vorticity near the PMC center between 850-950 hPa for each experiment. For the CNTL, the vertical vorticity continuously increases. When moisture is removed at T=-24 h, a PMC was not formed (not shown). When moisture is removed at T=0 h, the PMC develops for 3 hours, but starts to weaken after that. These demonstrate that condensational heating is essential for genesis and development of the PMC.

When the SST is lowered, the development of the PMC is significantly suppressed. When the mountains along the coastline of the continent are removed, the development is also suppressed because the cold air over the continent directly flows into the PMC without being heated and moistened from the sea surface, showing the importance of the airmass transformation through Mamiya Strait.

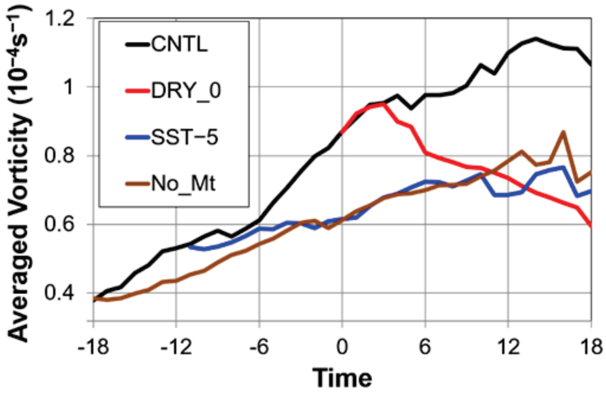

Fig. 6: Time series of average vorticity within 150-km radius from the center of the PMC between 950 and 850 hPa for each experiment.

5. Summary

The general characteristics of the structure and environment of polar mesocyclones (PMCs) over the Sea of Japan are examined using composite analysis and numerical simulations. PMCs are detected using an objective tracking method and classified according to their genesis location and direction of movement. This paper has mainly reported the results for PMCs in the northeastern part of the Sea of Japan (Watanabe et al. 2017a). The composite analysis using Japan Meteorological Agency (JMA) Global Analysis shows that the synoptic-scale environment associated with the PMCs is characterized by a cold trough moving eastwards in the upper levels and a negative sea level pressure anomaly to the east that causes a cold air outbreak at low levels.

A numerical simulation using a non-hydrostatic model with a horizontal grid size of 10 km, in which the initial and boundary fields are given by the composite field of the Global Analysis does successfully reproduce a PMC similar to observed PMCs. It is noted that mesoscale structures are almost smoothed out in the initial and boundary fields, demonstrating that the synoptic environment almost determines the genesis location and moving direction of the PMCs. Also performed are sensitivity experiments to examine the roles of condensational heating, distribution of sea surface temperature, and the topography of the Sikhote-Alin mountains at the east coast of the Eurasian continent. The results of the sensitivity experiments show that condensational heating is crucial for the genesis and development of the PMCs. It is also shown that the high SST in the Mamiya Strait (Strait of Tartary) and the Sea of Japan to the west of Hokkaido Island, and the topography of the Sikhote-Alin mountain region provide favorable conditions for the PMCs that develop over the northeastern Sea of Japan.

A similar composite analysis and numerical experiments are done for the PMCs in the northwestern part of the Sea of Japan (Watanabe et al. 2017b). For these PMCs, the blocking of the cold monsoon by the Changbai Mountains as well as condensational heating is found to be crucial.

Acknowledgements

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