

Numerical Study on a Polar Mesocyclone Development in a Shear Zone over the Japan Sea

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1. Introduction

A significant number of polar lows and polar mesocyclones (PMCs) are observed over the Japan Sea (e.g. Ninomiya 1989, Asai 1988), which is located at the lowest latitude among other regions such as the Norwegian Sea, Barents Sea, and Weddell Sea where polar lows are frequently generated. Most of the PMCs over the Japan Sea develop in the vicinity of Japan Sea Polar Air mass Convergence Zone (JPCZ; Asai 1988). JPCZ is accompanied by strong low-level convergence, which causes active cumulus convection. It is also associated with strong cyclonic shear. Barotropic shear instability due to this strong shear has been considered to be a dominant mechanism of PMC's development in JPCZ (Nagata 1993), although baroclinic instability and diabatic heating due to active cumulus convection have been pointed out to play some role. There have been a number of studies on PMCs. However, a PMC development from the initial formation stage of the JPCZ has not been studied yet, which is the subject of the present study.

2. Overview of observed PMC

When a cold air outbreak from the Eurasian Continent occurred on 30 December 2010, a west-east oriented cloud band was formed in the northwestern part of the Japan Sea (Fig. 1a) and moved southward. Several vortices appeared in the cloud band (Fig. 1b) and finally one of these vortices developed into a PMC which had a horizontal scale of $\sim 150\text{km}$ and cloud-free eye (Fig. 1c). After the PMC landed the Japanese islands and dissipated, a well-developed JPCZ was formed (Fig. 1d).

A short-wave trough was moving eastward in a cold vortex accompanied by extremely cold air below -42°C over the base of Korea Peninsula. This is a common situation in which a JPCZ and PMCs develop.

3. Numerical model

Japan Meteorological Agency Non-hydrostatic Model (JMA-NHM) with horizontal resolution of 2km is used in the present study. JMA meso analysis is used for initial and boundary data. The numerical simulation is performed for 48 hours starting from 09UTC on 29 when the cloud band had not appeared. No cumulus parameterization is used and MYNN model is used for the boundary-layer parameterization.

4. Simulation result

Fig. 2 shows pseudo infrared images produced from the simulation results. A comparison of Fig. 2 with Fig. 1 shows that the simulation reproduces quite well the movement and development of the PMC.

Fig. 3 shows a time evolution of maximum relative vorticity at 20m above the sea level (hereafter ASL).

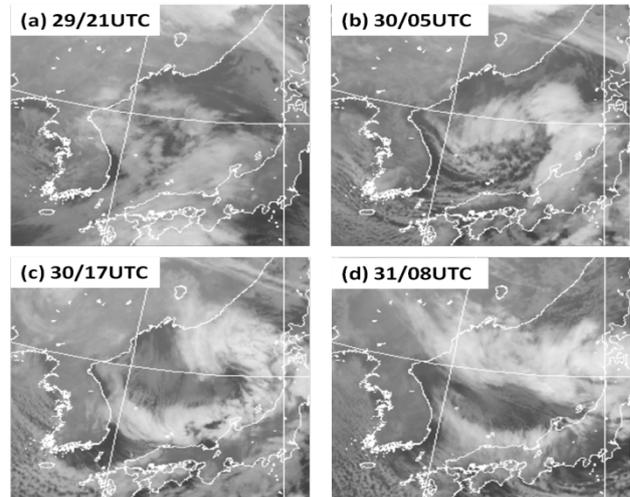


Fig.1. Satellite infrared images of PMC

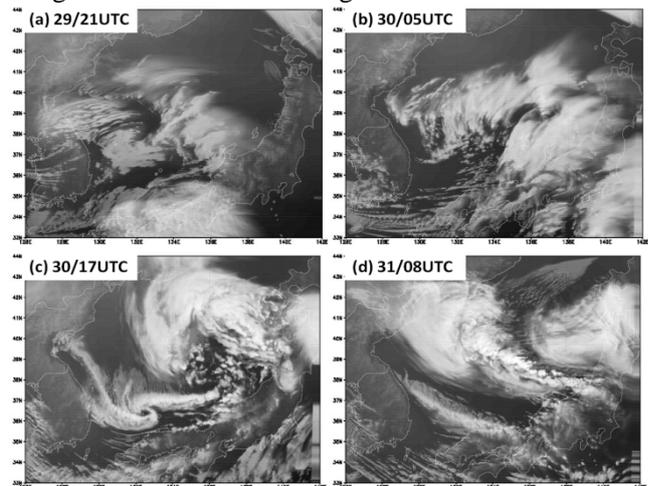


Fig.2. Pseudo infrared images of simulated PMC

Based on Fig. 3, we divide the evolution of the maximum vorticity into 5 stages: the shear zone formation stage (29/12~16UTC), the development restraining stage (29/16~20UTC) in which vorticity increase little in spite of the presence of horizontal shear, the first development stage (29/20UTC~30/02UTC) in which numbers of small vortices appear within the shear zone, the second development stage (30/02~10UTC) in which the size of vortices become larger and vorticity increases rapidly, and the mature stage (30/10~ 21UTC) in which only a single PMC is present.

In the first development stage (30/00UTC), a shear zone having a width of about 8km exists and it is accompanied by a number of vortices. The interval of the vortices is about 30km , which is rather smaller than 64km (8 times the width of shear zone) predicted from a linear theory of shear instability. An energy budget analysis for the vortices (Fig. 4) shows that the horizontal shear production

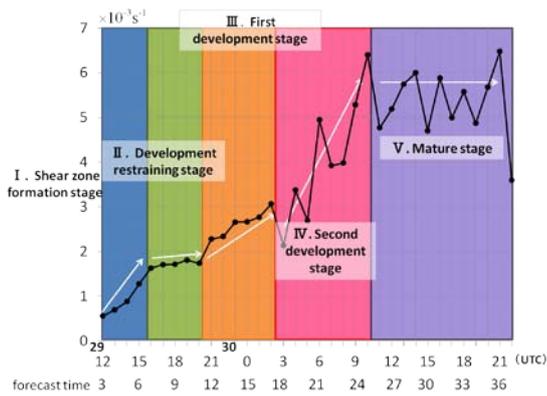


Fig.3. Maximum relative vorticity at 20m ASL.

(HSP) is large below 600m ASL where horizontal shear is large, while buoyancy production (BP) is extremely large around 1700m ASL. Thus the vortices acquire their energy mainly through BP which is closely related to intense updrafts of cumulus convection.

In the second development stage (30/09UTC), the width of the shear zone becomes about 16km and the interval of vortices increases to about 100km, which is now consistent with the linear theory. Energy budget analysis shows that HSP is dominant at this time (Fig. 5). This is because the shear zone has increased its depth due to air mass transformation.

In the mature stage (30/17UTC), a single PMC with a diameter of about 100km exists. The PMC has a cloud-free eye (Fig. 2c). Fig. 6 shows vertical cross section through the center of the PMC. Intense updrafts corresponding to PMC's eye-wall and a meridional circulation accompanying convergence at low-level and divergence at upper-level exist. Weak dry downdrafts are found at the center, which form a cloud-free eye and a warm core through adiabatic heating. These structures resemble those of hurricanes.

5. Summary and conclusion

A polar mesocyclone (PMC) observed over the Japan Sea was studied by a numerical simulation using a high-resolution non-hydrostatic model. The simulation reproduces quite well the movement and development of the PMC. An energy budget analysis indicates that the PMC acquired its energy through buoyancy production in the early development stage, but mainly through horizontal shear production later. Warm core and cloud-free eye structure are formed in the mature stage of PMC, which resemble those of hurricanes, so thermal instability such as CISK and WISHE may be important in this stage. More case studies are required to examine how typical a PMC development like this case is and to deepen our understanding of PMCs.

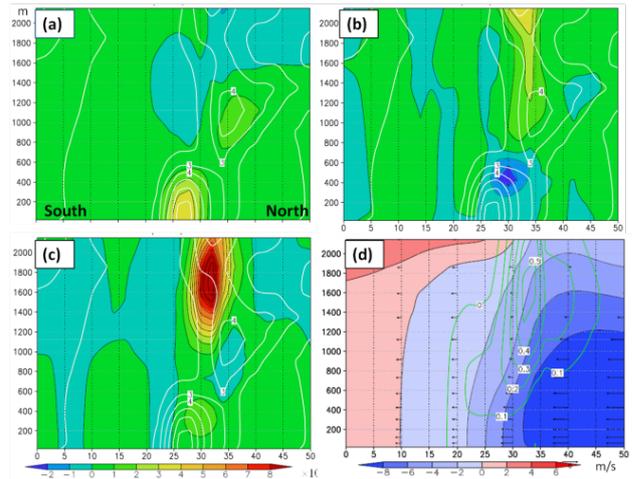


Fig.4. (a)-(c) eddy kinetic energy (white contour lines) and energy production terms (color shade): (a) horizontal shear production (HSP), (b) vertical shear production (VSP), (c) buoyancy production (BP). (d) horizontal wind component perpendicular to the shear zone(color shade) and vertical wind (green contour) at 30/00UTC

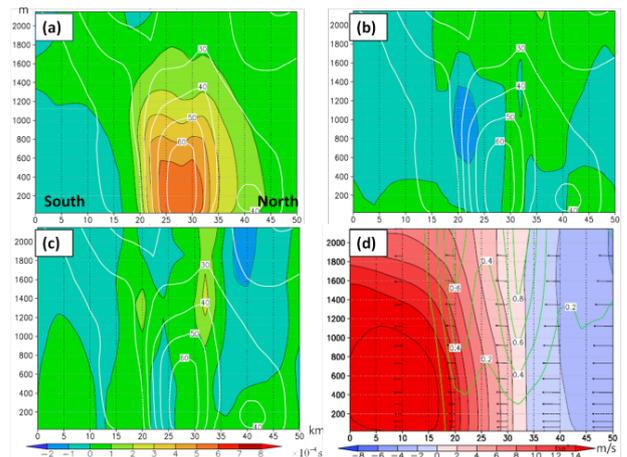


Fig.5. Same as Fig.4. except for at 30/09UTC

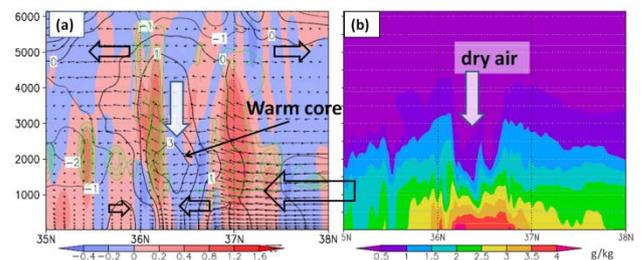


Fig.6 North-south vertical cross section of the PMC at 30/17UTC: (a) vertical wind (color shade) and potential temperature anomaly from horizontal average (contour), and (b) mixing ratio of water vapor.

References

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