Linkages of the Weather System between over the Pacific and Arctic Regions
- Importance of the Atmospheric River -

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1. Introduction

For the purpose of improvement of 1-14 day high impact weather forecast, Winter T-PARC (Wintertime THORPEX Pacific-Asia Regional Campaign) was carried out by the lead organization of NOAA from 12 January to the end of February 2009 and continued until the end of March as WSR09 (Winter Storm Reconnaissance in 2009) campaign. As the rapidly deepening low pressure systems in the Northwestern Pacific region strongly affect downstream regions, such as Alaska, Arctic and the North-America, they have a great contribution to the improvement of the forecasting in these regions. Therefore, they were one of the main targets of the Winter T-PARC. Stagnating lows in Gulf of Alaska also affect downstream region, they were also a target for WSR09. Winter T-PARC was assigned as a part of International Polar Year (IPY) program in the United Sates. National Institute of Polar Research (NIPR) in Japan supports the Winter T-PARC as a part of Japanese IPY activities.

In this paper, we would like to discuss storm behaviors over the North Pacific Ocean and their linkages to the Arctic weather system. NCEP final objective analysis dataset (NCEPFNL) was used for this analysis.

2. Cyclone behaviors during Winter T-PARC and WSR09

Figure 1 shows Hovmöller diagram of 300hPa meridional winds (v component winds) averaged between 35N and 45N in February 2009 (left panel) and March 2009 (right panel). Dashed lines in the panel show examples of Rossby wave energy propagation paths. One can identify upper-level short wave troughs and ridges propagated around the globe (wave train) during the campaign period. As the upper-level short wave trough initiates the low pressure development over the Northwestern Pacific Ocean, one can also identify the propagation signal was enhanced there and propagated to the east.

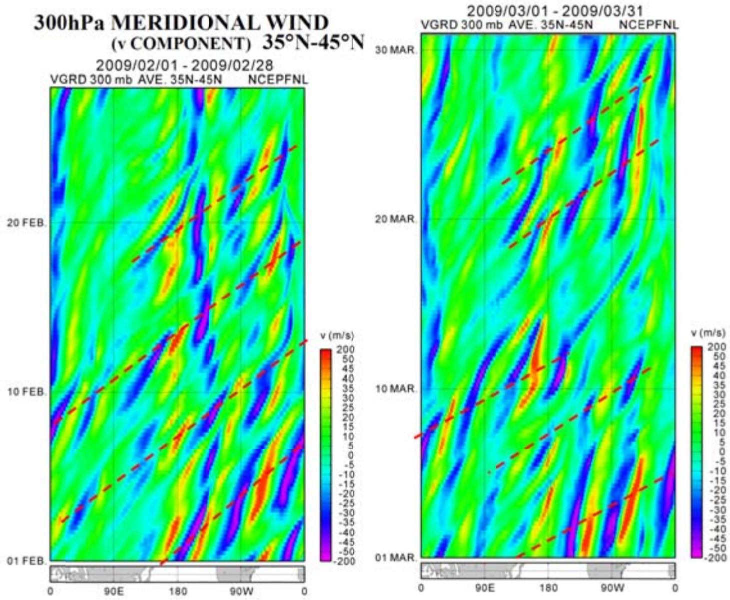

Fig. 1 Hovmöller diagram of 300hPa meridional winds averaged between 35N and 45N in latitude. Left: February 2009. Right: March 2009. Maps in the bottom show averaged area. Dashed red lines show Rossby wave energy propagation paths.

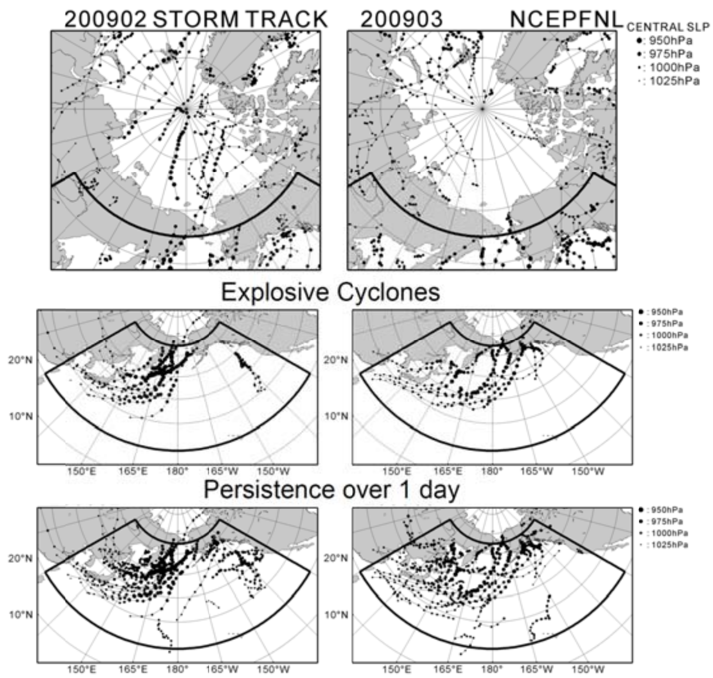

Fig. 2 Low pressure system tracks. Left: February 2009. Right: March 2009. Top: Low pressure systems persistence over 1 day in the Arctic. Middle: Explosive low pressure systems. Bottom: Low pressure systems persistence over 1day.

Hovmöller diagrams show the strong wave activity condition in February and March in 2009. Weather regimes are a little different between these two months. Figure 2 shows low pressure systems which were available to automatically track over one day (lower panels) and explosive cyclones (middle panels) over the North Pacific region, and also lows traveling in the Arctic (top panels) in February and March. The definition of the explosive cyclone is followed by Yoshida and Asuma (2004) and Kuwano-Yoshida and Asuma (2008). In February, explosive cyclones appeared over the Northwestern Pacific region near Japan, moved to the east of Kamchatka Peninsula and some cyclones continued to travel into the Arctic region through the Bering Strait. In March, cyclones also appeared near Japan, moved eastward across the central Pacific Ocean and then turned to move northward towards Alaska. After that, they stagnated over the Gulf of Alaska. In the panel, we could also identify some low pressure systems existing over the Sea of Japan and the Sea of Okhotsk. In the Arctic region in March, low pressure systems were not analyzed over the Beaufort Sea due to the high pressure systems existing there.

3. Linkages of the weather system between over the Pacific and Arctic regions

As discussed in previous section, the low pressure systems had tendencies moved northwestward and developed over the Northwestern Pacific Ocean in February 2009. In total, 5 explosive cyclones entered into the Arctic region across the 65N in latitude from the North Pacific region in February. Their lists and tracks are shown in Fig. 3. The locations which exceeded deepening rate over 1 begeron are shown with red points in the panel. For every case, we could recognize a distinct "Atmospheric River (a moisture river in the atmosphere)" after the explosive development. All of these low pressure systems showed similar life cycles. We would like to show a case of the cyclone from 14 to 22 in February as an example. We show only a case in this paper but other cases followed almost the same scenario as this case.

This low pressure system was detected near Okinawa at 18UTC 14 February 2009. It traveled to the east along the south offshore of Japan and developed rapidly in the east of Kamchatka Peninsula. The low pressure system had its minimum central SLP (sea level pressure) at 00UTC 18 and entered into Arctic region across 65N in latitude through Bearing Strait over the east of Siberia at 12UTC 19. And then, it traveled in the north offshore of Alaska over the Beaufort Sea.

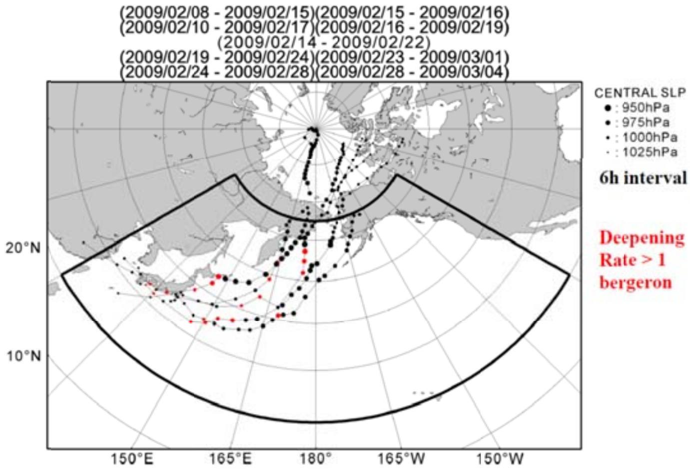

Fig. 3 Explosive cyclone tracks entered into Arctic in February 2009. Red points show locations exceeded deepening rate over 1 bergeron.

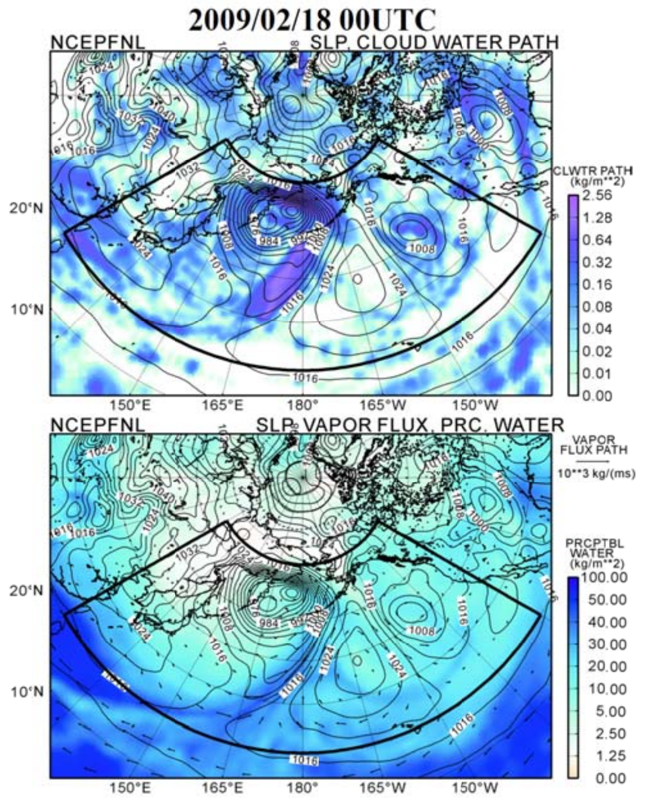

Fig. 4 Vertically integrated cloud water (upper panel), precipitable water and vertically integrated vapor flux (lower panel). Contour lines in each panel show sea level pressure (SLP).

Figure 4 shows precipitable water, vertically integrated vapor flux and SLP at 00UTC 18 February in the lower panel and the vertically integrated cloud water in the upper panel. We could clearly identify a distinct "Atmospheric River" connecting from the sub-tropical region extending to the northeastern Alaska in the lower panel. The moisture converged into the "Atmospheric River." A large amount of the vertically integrated cloud water was identified in the Atmospheric River. It means a large amount of precipitation formed there due to the strong updrafts in the river. Jets (wind speeds), winds and geopotential heights at 300hPa, 500hPa, 850hPa and surface are shown in Fig. 5. Due to the strong updrafts over the Atmospheric River, winds diverged in the upper-level, jet-streaks re-configured and clockwise circulation enhanced (Rossby wave breaking). The air descending associated with the jet-streaks and enhanced the high pressure circulation in the lower atmosphere. This anti-cyclonic circulation contributed to the moisture southward as well as eastward, and helped the moisture convergence from the east of the Atmospheric River and it became distinguished.

Figure 6 shows time series of SLP changes 6 hours interval on 19 February 2009 when the low pressure entered Arctic region. Red dots show the positions of minimum SLP (cyclone centers). The low pressure systems got into the Arctic region traveling with overtaking new low centers over the Beaufort Sea like the similar manner of the lee cyclogenesis in the mountainous region around Bearing Strait and Alaska.

Figure 7 shows jets as the same as Fig. 4 at 12UTC 19 February. The upper-level jet was meander and breaking over Alaska. The air descended in the southeastern mountainous region in Alaska and also over the Gulf of Alaska. It flew out into the south over the northeastern Pacific Ocean and it might enhance the Atmospheric River. Figure 8 shows thickness between 300hPa and 500hPa (Z_{300}-Z_{500}) (top panel), between 500hPa and 1000hPa (Z_{500}-Z_{1000}) (middle panel) and vertically integrated enthalpy ($\int \rho c_p dz$) (bottom panel). We could identify the cold air existing over the eastern Siberia and the Sea of Okhotsk and the warm air existing over the Alaska and Beaufort Sea.

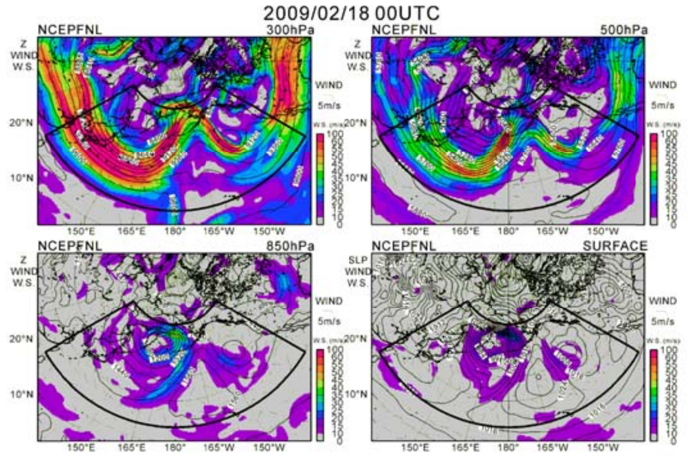

Fig. 5 Jets (wind speeds) and geopotential heights at 00UTC 18 February 2009. Left top: 300hPa. Right Top: 500hPa. Left bottom: 850hPa. Right bottom: surface.

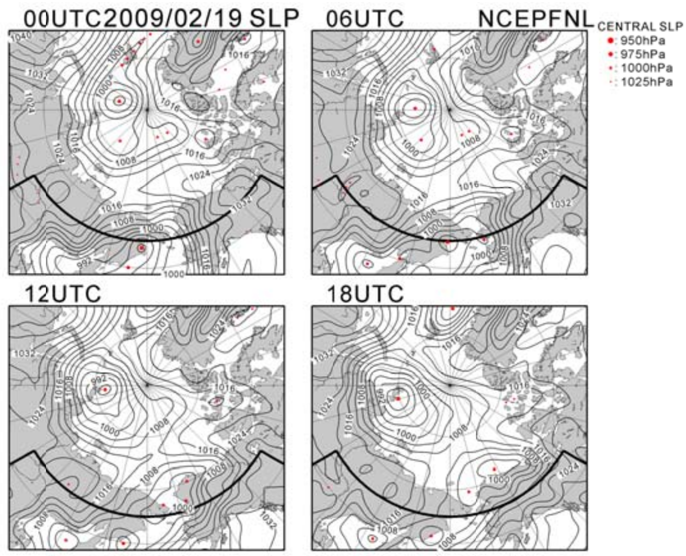

Fig. 6 Time series of SLP change 6 hours interval on 19 February 2009. Left top: 00UTC. Right top: 06UTC. Left bottom: 12UTC. Right bottom: 18UTC. Contour lines show SLP and red dots show low pressure centers.

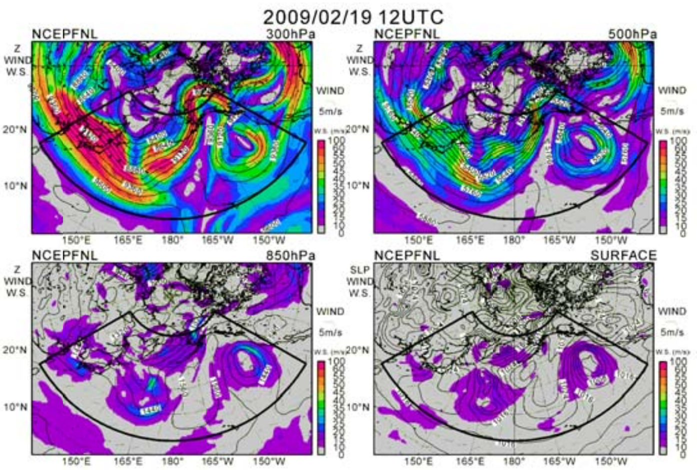

Fig. 7 As in Fig. 5, but at 12UTC 19 February 2009.

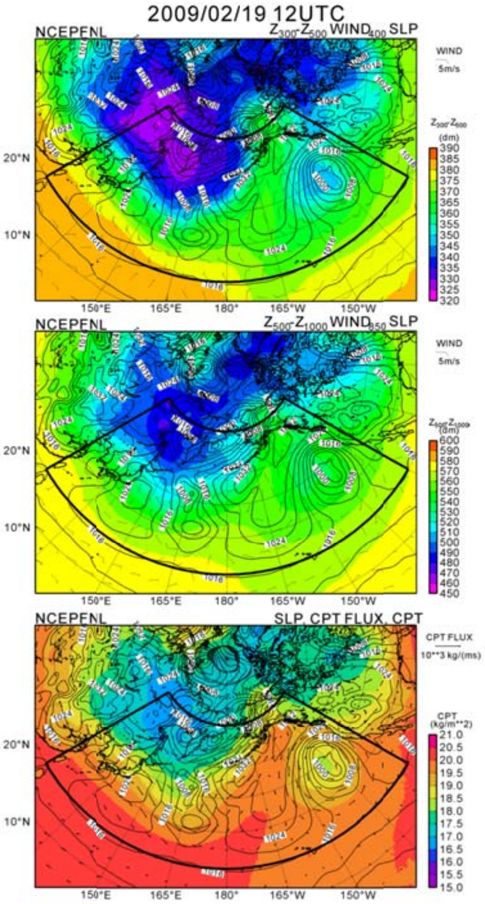

Fig. 8 Upper-level thickness (top), lower-level thickness (middle) and vertically integrated enthalpy (bottom) at 12UTC 19 February 2009

Next, we would like to discuss the weather conditions in March 2009. As discussed in section 2, low pressure systems periodically occurred, moved eastward in the central Pacific Ocean and stagnated over the Gulf of Alaska. Some low pressure systems traveled and developed over the Sea of Japan and Sea of Okhotsk. We would like to discuss a case of a stagnating low in the Gulf of Alaska from 16 to 22 in March.

The low pressure system was detected in the east of Kamchatka Peninsula at 12UTC 16 March 2009. It moved southeastward over the Bering Sea, developed in the Gulf of Alaska and stagnated there. Its maximum deepening rate exceeded over 1 bergeron due to the upper-level forcing and cold air advection from the Arctic. After the rapidly deepening, its central SLP became minimum at 00UTC 20.

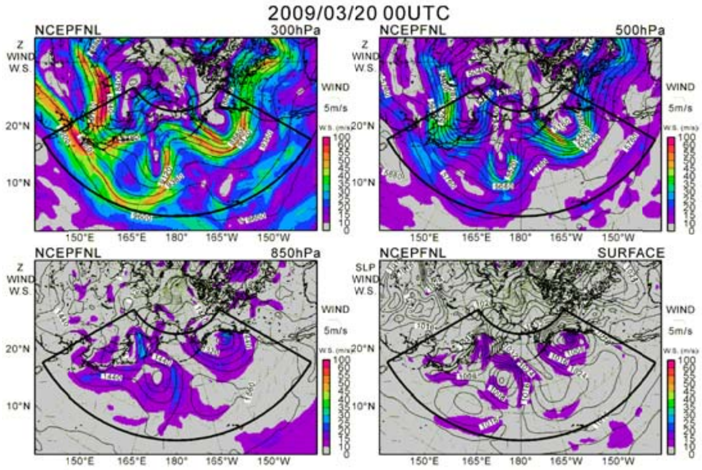

Fig. 9 As in Fig. 5, but at 00UTC 20 March 2009.

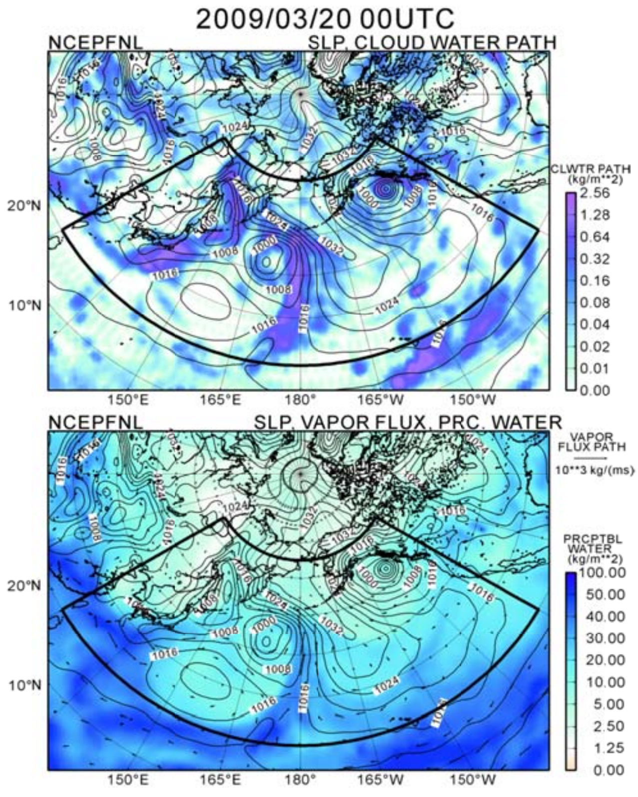

Fig. 10 As in Fig. 4, but at 00UTC 20 March.

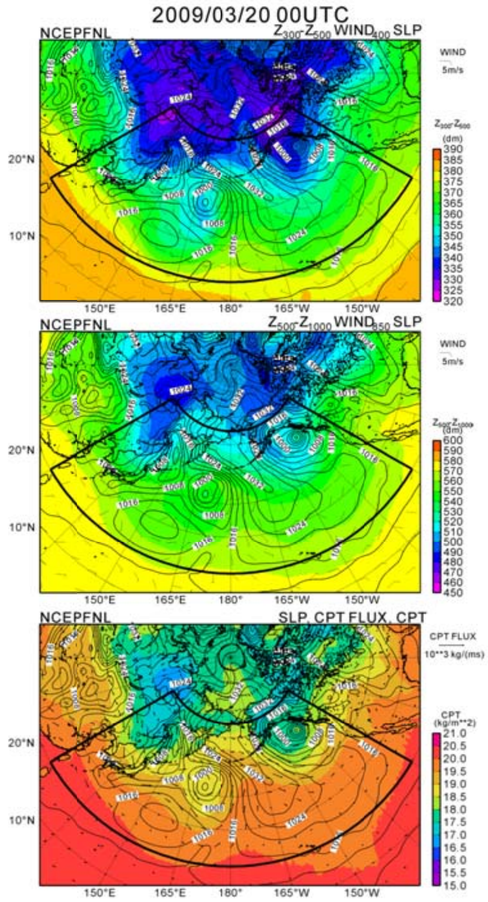

Fig. 11 As in Fig. 8, but at 00UTC 20 March.

Figures 9, 10 and 11 shows jets as the same as Fig. 5, vertically integrated cloud water and precipitable water as Fig. 4, and upper (Z_{300}-Z_{500}) and lower (Z_{500}-Z_{1000}) levels' thicknesses and vertically integrated enthalpy ($\int \rho c_p dz$) as Fig. 8 but for at 00UTC 20 March in 2009, respectively. Figure 11 shows the cold air mass existed over the eastern Siberia and the Sea of Okhotsk, and also over the Canadian Arctic Islands. The warm air mass was over the Arctic Sea. These conditions were suitable for existing the low pressure systems over the Sea of Okhotsk and Gulf of Alaska. Upper-level jet was breaking over the Bering Sea and Arctic Sea. The air descended due to the anti-cyclonic circulation of jet-streaks and flew out towards the south and it might contribute to enhance the Atmospheric River. Larger amount of vertically integrated cloud water appeared over the Atmospheric River. This means stronger updrafts existed there and it might cause Rossby wave breaking in the upper level. After this time period, a new low pressure formed in the central North Pacific Ocean, moved eastward and it stagnated over the Gulf of Alaska like previous case (Fig. 12). And another low pressure system moved over the Sea of Okhotsk to set up the similar weather condition discussed as the previous case.

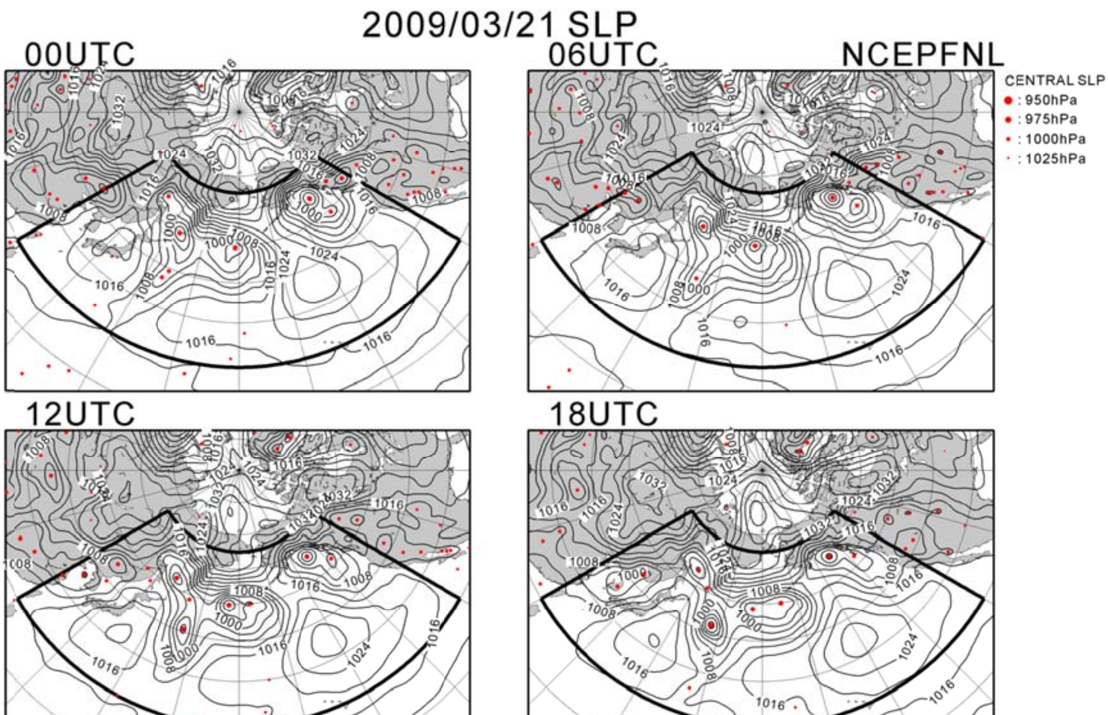

Fig. 12 As in Fig.6, but on 21 March 2009.

4. Summary

In this paper, we discussed storm behaviors over the North Pacific Ocean and their linkages to the Arctic region during Winter T-PARC and WSR09 campaigns. All of explosive cyclones entered into the Arctic region from the Pacific Ocean were associated with a distinct "Atmospheric River" of precipitable water. The river became clear after the explosively deepening. For the rapidly deepening of the low pressure system needs the upper-level forcing (short wave trough) and lower-level moisture supply to the low pressure center. It may be reasonable that all of the explosive cyclones entered into the Arctic region from the Northwestern Pacific were associated with "Atmospheric Rivers." As the explosively deepening is associated with strong updrafts, they modify the upper-level jet-streaks. Rossby wave breaking is occurred in the upper-level and it enhances descending jets and also enhances the clockwise circulation in the lower atmosphere. This anti-cyclonic circulation pushes the moisture toward south and may make clear the river. Stagnating lows in the Gulf of Alaska were also related to the "Atmospheric River." The "Atmospheric River" has a relationship to the heavy precipitation and flooding in the west coast of the North American and moisture supply to the Arctic region and higher latitudes.

5. References

Yoshida, A. and Y. Asuma, 2004: Structures and environment of explosively developing extratropical cyclones in the Northwestern Pacific region. Mon. Wea. Rev., 132, 1121-1142.

Kuwano-Yoshida, A., and Y. Asuma, 2008: Numerical study of explosively developing extratropical cyclones in the Northwestern Pacific region. Mon. Wea. Rev., 136, 712-740.