Spatial Patterns of Winter Precipitation in the North-Central Region (Hokuriku District) of Japan

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Abstract

This study examines dominant precipitation patterns during winter in the north-central region (Hokuriku District) of Japan, based on empirical orthogonal functions (EOFs) analysis. The pattern of the first leading component is similar to that of the mean precipitation, and the second leading component shows a dipole structure in which positive and negative regions are separated by the coast line. This dipole pattern across the coast line is robust regardless of data stratifications for the EOF calculation. Composites reveal that maritime and inland precipitation is relatively enhanced before and after the passage of a mid-level trough, respectively. In the former case, the temperature is higher and westerly or southwesterly wind prevails, while northwesterly wind dominates in the latter case. It is suggested that interactions between cold air over the land and warm air over the ocean are essentially important to the distinct precipitation patterns; offshore winds wedge the inland cold air under the maritime warm air, and intensifies the precipitation over the ocean. On the other hand, the northwesterly monsoonal flow pushes the maritime warm air onto the inland cold air, and more precipitation is brought about around the mountain range.

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1. Introduction

The winter monsoonal flow in the vicinity of Japan is characterized by a northwesterly wind, which brings large amounts of precipitation around the coastal region of the Sea of Japan and in the adjacent mountain areas (e.g., Fig. 1b in Yasunaga and Tomochika 2017). The winter precipitation is stored in the form of ice and snow in the mountain, and the melting ice and snow during other seasons provide an indispensable supply of water in the coastal region. On the other hand, heavy snowfall in the plain region sometimes paralyzes the transportation system. Therefore, gaining a better understanding of the dominant winter precipitation patterns is important to manage the water resources and minimize disaster risks.

In the present investigation, we examine winter precipitation patterns in the north-central region of Japan (Hokuriku District; see Fig. 1). There are several prior investigations on the precipitation patterns there. Akiyama (1981a) examined time and space variations in snowfall for 15 winter seasons over Niigata Prefecture (Fig. 1) and identified three dominant precipitation patterns (referred to as M-type, N-type, and P-type), based on empirical orthogonal function (EOF) analysis. Focusing on the heavy snowfall events, Akiyama (1981b) found distinctive mechanisms for M-type and P-type precipitation patterns. For M-type cases, precipitation increases in the mountain area through orographic lifting of air parcels associated with intensive surface wind perpendicular to the mountain range, whereas active convection develops over the plain due to unstable stratification in the lower level for P-type cases. Iwamoto et al. (2008) conducted a similar investigation without restricting the scope to heavy snowfall events and pointed out that M-type and P-type precipitation patterns are influenced by the topography over the extended area including Toyama Bay and Noto Peninsula (Fig. 1).

These prior results are consistent with empirical knowledge that heavy snowfall frequently occurs on the north-western side of the mountains or over the coastal areas, depending on synoptic-scale atmospheric situation. Consequently, the concept of M-type and P-type classifications has been widely accepted by weather experts and the public. However, it is important to note that previous works exclusively focused on precipitation in a limited area of Hokuriku District (only Niigata Prefecture), and it is still unclear whether some precipitation patterns dominate over the entire Hokuriku region. More importantly, the previous studies did not take precipitation over the ocean into account. Stationary snow bands have been repeatedly observed off the coast of Hokuriku District (e.g., Ishihara et al. 1989; Yoshizaki et al. 2004; Yoshihara et al. 2004; Eito et al. 2005; Ohigashi and Tsuboki 2005). Accordingly, to obtain a more comprehensive understanding of precipitation patterns, the oceanic region off the coast should be included. Finally, daily precipitation and 12-hourly sounding data were used in the previous researches. Synoptic conditions sometimes significantly change during a single day-long period, and it is likely that using such a low time-resolution results in a vague composite field. Therefore, higher time-resolution datasets would be desirable to more clearly illustrate the linkage of a certain dominant precipitation pattern with larger-scale atmospheric environments, and the usage of 1-hour precipitation data and 3-hourly analyzed field is another advantage of the present study (See the next section for more details).
2. Data and analysis method

This study utilizes radar-Automated Meteorological Data Acquisition System (AME-DAS) analyzed precipitation data in the winter months (January, February, and December) from 2006 to 2014. More specifically, 1-hour accumulated precipitation data over Japan and adjacent areas are used, which is provided by the Japan Meteorological Agency (JMA). More details of the data are found in Makihara (1996).

Due to the limitation of computer resources, the horizontal and temporal resolutions are reduced from the original 1 km × 1 km to 4 km × 4 km and from 30 minutes to 1 hour, respectively. The analysis domain covers Ishikawa, Toyama, and Niigata prefectures to 4 km × 4 km and from 30 minutes to 1 hour, respectively. The variance of EOF1 is overestimated in the present analysis due to the limitation of space, however, we will exclusively focus on EOF2 here.

3. Results and discussion

3.1 EOF analysis

Figures 2a, 2b, and 2c show spatial patterns of the first, second, and third leading components of the EOF, respectively (hereafter referred to as EOF1, EOF2, and EOF3). The pattern of EOF1 is close to that of the mean precipitation (Fig. 1), and positive values are spread throughout the entire domain. EOF2, positive and negative areas are separated by the coast line (although Noto Peninsula and Ishikawa Prefecture are included in the positive ocean area), which means that when precipitation is enhanced over the ocean, land precipitation is often inhibited (or vice versa).

In EOF3, positive and negative areas are located in the southern and northern parts of the analysis domain, and this represents the distinction between the northern and southern parts of Hokuriku District. EOF1, EOF2, and EOF3 account for about 37.8%, 8.5%, and 5.4% of the total variance, with the contribution from EOF1 being much larger than that of the other residual components (Table 1).

However, it is important to note that when no precipitation occurs at a given grid point, the anomaly is calculated as a negative mean precipitation value, and thereby, it is highly possible that the variance of EOF1 is overestimated in the present analysis (and possibly in the previous studies). More importantly, the other lower modes (e.g., EOF2 and EOF3) might be distorted by EOF1, which significantly reflects the background (mean) precipitation distribution, because the EOF components are mutually orthogonal and uncorrelated.

We conducted the same EOF analysis, stratifying cases where the precipitation (larger than 0 mm hr⁻¹) occurred over more than 20%, 40%, 60%, and 80% of the analysis domain or making use of the anomaly from the domain-mean precipitation (hereafter referred to as Frac20, Frac40, Frac60, Frac80, and Aanom, respectively). The peak area shifts offshore, and the precipitation pattern displays a more prominent peak in Toyama Bay, as the precipitation coverage increases (Figs. 2d, 2g, 2j, and 2m). According to the weather chart, coefficients of the EOF1 in Frac60 and Frac80 tend to be large in association with the passage of a distinct cyclone accompanied with warm and cold fronts or south-coast cyclone. It is found that precipitation is inhibited and enhanced over the Noto Peninsula and Toyama Bay respectively in the prominent EOF1 events (not shown). Although it is possible that such contrast is of importance in better understanding of the precipitation process, we will not further focus on the developed cyclones in the present investigation due to the limitation of space.

With regard to EOF2, the patterns are similar to that of EOF2 in the original analysis (Figs. 2b, 2c, 2h, 2k, and 2n), although EOF1 displays slightly different features. The contributions of EOF2 exceed 10% for these analyses, whereas that of EOF1 decreases by about 10–20% (Table 1). More interestingly, the spatial pattern of EOF1 in Aanom is virtually identical to that of EOF2 in the original analysis (Fig. 2p), and 14% of the total variance is accounted for by this EOF1 (Table 1). These results indicate that the structures of EOF2 (and EOF1 in Aanom) are robust, regardless of the background precipitation pattern, which the EOF2s would represent an “actual” dynamical mode that dominates under a particular atmospheric situation, although individual EOF components do not necessarily correspond to the individual dynamical mode in general. In fact, precipitation systems remain virtually stationary over the ocean, while the time-series of EOF2 coefficients are positive (e.g., Fig. 3a). On the other hand, negative coefficients of EOF2 correspond to the precipitation enhanced over the mountain region (e.g., Fig. 3b). To more clearly illustrate the distinct features, composite analysis was conducted with reference to the coefficients, which will be discussed in the next subsection.

For convenience, the cases where the EOF2 coefficients are positive and negative are hereafter referred to as “O-type” and “L-type,” respectively. The pattern of EOF3 is also found to be robust (Figs. 2c, 2f, 2i, 2I, 2o, and 2q), and it may also reflect some dynamical mode. Due to the limitation of space, however, we will exclusively focus on EOF2 here.

3.2 Composite analysis

It is well known that the precipitation histogram is far from a typical Gaussian distribution, and it is possible that two uncorrelated time-series of EOF1 and EOF2 can be nonlinearly related (e.g., Monahan et al. 2009). To avoid such complexity, the time-series associated with EOF1 in Aanom, which corresponds to EOF2 in the original analysis, are used to make a composite. However, the results are not sensitive to this.

We objectively extracted dominant O-type and L-type cases, as shown. First, the 5-point (94 hours) running-mean was calculated for the time-series of EOF1 in Aanom. Second, prominent O-type and L-type events were identified when the smoothed coefficients exceeded or fell below the standard deviation ranges, respectively. Third, the events were sorted with reference to the time duration, and the top 20 O-type and L-type events were sampled. Finally, warm cyclonic cases, in which the 500-hPa temperature at Wajima was higher than −25°C (e.g., Akiyama 1981b), and low-level precipitation events (daily precipitation at Wajima and Takada was < 20 mm) were excluded from the samples. As a result, 12 and 18 events were identified to make the composite for the O-type and L-type precipitation patterns, respectively. The duration of the selected O-type and L-type events range from 14–26 hours and 18–49 hours.

Figures 4a and 4b represent composites of temperature and horizontal wind vectors at 1000 hPa level. The temperature is higher in O-type cases than those in L-type cases. In addition, there is a distinction in the horizontal wind direction, although the wind speed shows little differences; westerly or southwesterly prevails in O-type cases, while northwesterly dominates in L-type cases. The surface observations at Wajima and Takada (Figs. 5a and 5b), which are located in the peak area of the O-type and L-type precipitation, support such distinct differences in the temperature and wind direction (The surface observations are not included in the analyzed field of the MSM).

To examine the larger-scale environmental conditions preferable to O-type and L-type precipitation patterns, composites of temperature and geopotential height in the upper levels were also made (Fig. 5). A trough is located to the west and east of Japan at the 500 hPa level in O-type and L-type cases, respectively. Namely, O-type (L-type) precipitation tends to occur before (after) the passage of a mid-level trough. Corresponding to the location of mid-level trough, the geopotential isolines are oriented to the zonal direction in the lower levels (850 hPa and 1000 hPa levels) in O-type cases. By contrast, they are directed from the northwest to the southeast in 850 hPa level and from north to the south in the 1000 hPa level in L-type cases. Assuming a geostrophic wind, a horizontal wind turning counter-clockwise with height translates to cold air advection. In fact, the L-type cases are characterized by
Fig. 2. Spatial patterns of the first, second, and third leading modes of the EOF calculated from all available time-series of precipitation (a−c), time-series of precipitation stratified with reference to the coverage (d−o), and time-series of precipitation anomaly from the domain mean (p−q). See text for more detail.
lower temperatures along the coastal region of the Sea of Japan (Figs. 4a and 4b).

The previous investigations speculated that unstable stratification associated with the passage of a mid-level cold vortex is responsible for the convection development over the plain region of Niigata Prefecture (P-type), while precipitation is enhanced over the mountain region through the topographic lift by the (northwesterly) wind orthogonal to the mountain range (M-type). Although the domain of our analysis covers a much wider area (including the oceanic region), making a direct comparison difficult, the L-type cases share similar features with the previous M-type cases, where the northwesterly wind prevails, and the topographic uplift appears to play an important role (Fig. 6b). In our O-type cases, on the other hand, a mid-level cold vortex is

|          | EOF1  | EOF2  | EOF3  |
|----------|-------|-------|-------|
| All      | 37.8  | 8.5   | 5.4   |
| Frac20   | 26.2  | 10.1  | 6.4   |
| Frac40   | 21.3  | 10.9  | 6.9   |
| Frac60   | 18.8  | 10.9  | 7.2   |
| Frac80   | 19.3  | 10.3  | 8.2   |
| Aanom    | 14    | 8.5   |       |
| Akiyama (1981a) | 49.4/52.8 | 14.4/14.6 | 5.8/6.9 |

Fig. 3. 3-hourly-snapshots of precipitation, while the coefficients of EOF2 are significantly positive (left panels) and negative (right panels).
Fig. 4. Composites of MSM temperature (shaded, unit: °C) and horizontal wind (vector) in the 1000 hPa level for the O-type (left) and L-type (right) cases.

Fig. 5. Composites of MSM temperature (shaded, unit: °C) and geopotential height (contour, unit: m) at 500 hPa (upper), 850 hPa (middle), and 1000 hPa levels (lower) for O-type (left) and L-type (right) cases.
not evident, although O-type precipitation develops ahead of the mid-level trough. Although intensive updrafts are found to be nearly stationary along the coastline (Fig. 6a), unstable stratification is not likely to account for the distinct precipitation pattern over the ocean and land, because conditions for the potential instability are satisfied in L-type cases as well as in O-type cases (Fig. S2).

Detailed mechanisms responsible for these precipitation patterns are beyond the scope of this investigation. Based on the composite analysis (e.g., Figs. 3, 4, 5, 6, and S3), however, we speculate that interactions between cold air over the land and warm air over the ocean is essentially important to the distinct features of O-type and L-type precipitation patterns, as follows.

During winter, the surface temperature is much colder over land due to its small heat capacity compared to that of ocean water. This indicates that horizontal gradients of temperature increase around the coastal region, and the offshore wind would develop under weak prevailing wind conditions. Westerly or southwesterly wind, which dominates in the lower and middle troposphere in O-type cases, would not counteract the offshore wind, and would more likely intensify the offshore wind. Therefore, the inland cold air would be wedged under the maritime warm air, like a cold front (e.g., Fig. S3a). In addition, dynamical upward motion is generally excited in the lower level, when a mid-level trough approaches. These environmental conditions would be favorable for convection systems to develop over the ocean, as seen in O-type cases.

By contrast, when intensive northwesterly monsoonal flow prevails in the lower and middle troposphere, it would push the maritime warm air onto inland cold air, like a warm front (e.g., Fig. S3b). Dynamical downward motion is generally excited in the lower level behind the mid-level trough. Accordingly, topographic lifting would be necessary to systematically form upward motion of warm air originating from the ocean, although temperature profiles satisfy unstable conditions in L-type cases (e.g., Fig. S2).

The importance of cold air advection by the offshore wind has been recognized by several previously conducted studies, in association with stationary snow bands around the coastal area of Hokuriku District. Therefore, our speculation is not special. Our association with stationary snow bands around the coastal area of Hokuriku District during winter, based on EOFs analysis. Although several previous studies have been conducted, our analysis domain covered a larger area (including the offshore oceanic region) and utilized higher time-resolution datasets. The pattern of the EOF1 was close to that of the mean precipitation, and the EOF2 showed a dipole pattern, in which positive and negative areas were found to be separated by the coast line. EOF1 and EOF2 contributed to about 37.8% and 8.5%, of the total variance, respectively. The structure of EOF2 was robust when precipitation time-series were stratified with reference to the domain coverage of the precipitation or when the anomaly from the domain-averaged precipitation was used to calculate the EOFs.

To illustrate the dipole precipitation pattern across the coastal line, composite analysis was conducted for cases where precipitation was relatively enhanced over the ocean (O-type) and the land (L-type). Composites of wind, temperature, and geopotential fields revealed that O-type and L-type events occur ahead of and behind the mid-level trough, respectively. In addition, the temperature is higher in O-type case than in L-type case, and westerly or southwesterly wind prevails in O-type case, while northwesterly wind dominates in L-type case. Although previous works paid more attention to stability in the lower level, we speculated that interactions between inland cold air and maritime warm air were essential to the distinct features of O-type and L-type cases; the offshore wind would wedge the inland cold air under the maritime warm air in an O-type case, while strong monsoonal flow would push maritime warm air onto the inland cold air in an L-type case.

4. Summary

This study examined the dominant precipitation patterns in Hokuriku District during winter, based on EOFs analysis. Although previous works have been conducted, our analysis domain covered a larger area (including the offshore oceanic region) and utilized higher time-resolution datasets. The pattern of the EOF1 was close to that of the mean precipitation, and the EOF2 showed a dipole pattern, in which positive and negative areas were found to be separated by the coast line. EOF1 and EOF2 contributed to about 37.8% and 8.5%, of the total variance, respectively. The structure of EOF2 was robust when precipitation time-series were stratified with reference to the domain coverage of the precipitation or when the anomaly from the domain-averaged precipitation was used to calculate the EOFs.

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The present investigation used observations archived and

Fig. 6. Composites of MSM vertical wind (shaded, unit: Pa·s⁻¹) and potential temperature (contour, unit: °C) at 850 hPa level for O-type (left) and L-type (right) cases.
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