An Updated Analysis of Northern Hemisphere Submonthly Retrograde Waves

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ABSTRACT

This study performs an updated analysis of Northern Hemisphere retrograde disturbances that were first identified by classical observational studies as one of the dominating coherent structures in the higher latitudes on the submonthly time scale. Analyzing 8–30-day bandpass-filtered data based on reanalysis, a set of criteria on the phase and amplitude of zonal wave-1 Fourier coefficients of geopotential height anomalies at 250 mb (1 mb = 1 hPa) and 60°N are used to identify strong retrograde-wave events in the spirit of Madden and Speth. The new catalog of retrograde-wave events from 1979 to 2017 is used to extract basic statistics and structures of retrograde waves across all major events. The results broadly agree with those reported in the classical observational studies, reaffirming the robustness of the phenomenon. The new catalog can be used to aid further studies on the mechanisms and predictability of retrograde waves. As an example, an analysis of isentropic potential vorticity over the Pacific sector for selected retrograde-wave events reveals the common occurrence of an extrusion of low-PV air into the higher latitudes, followed by a westward shift of the low-PV patch and vortex shedding. Future directions of research surrounding the retrograde-wave phenomenon are discussed.

1. Introduction

A class of large-amplitude westward-propagating waves in the midlatitudes of Northern Hemisphere were first identified in observational studies by [Branstator \(1987\)](#), [Kushnir \(1987\)](#), and [Madden and Speth \(1989\)](#). These retrograde disturbances generally attain maximum amplitudes poleward of the midlatitude jet. They exhibit a deep equivalent barotropic structure that extends through the whole troposphere and lower stratosphere. The time scale of the retrograde disturbances, measured by the periods of their long-wave Fourier components, is typically 2–3 weeks. A strong retrograde-wave event can span multiple cycles of circumglobal propagation of the long waves. An extraordinary event in the 1979/80 winter saw sustained westward propagation over 2 months ([Branstator 1987](#); [Madden and Speth 1989](#)). The potential influences of large-amplitude retrograde waves on extended-range weather prediction were suggested by the classical studies but have not been explored further.

Despite the potential importance of the phenomena in applications, relatively little has been advanced in observation and theory on submonthly retrograde waves after the aforementioned classic studies. (We postpone a brief survey to [section 3](#).) This work aims to provide an updated observational analysis of the retrograde waves. Using longer records of reanalysis, we establish or reaffirm the statistics of spatial and temporal structures of the retrograde disturbances. The analysis also produces a new catalog of major retrograde-wave events that covers 1979 to the present. The catalog may form a useful basis for future studies on the dynamics and predictability of the retrograde waves. As an example, the structures of potential vorticity associated with selected major retrograde-wave events from the catalog are analyzed.

2. A new catalog and statistics of retrograde-wave events

a. Identifying retrograde-wave events from reanalysis

Using long-term reanalysis, retrograde disturbances are identified following the framework of [Madden and Speth \(1989\)](#) (also [Speth et al. 1992](#)) based on the footprint of those disturbances in the zonal wavenumber 1 component of geopotential height anomalies. After updating the classical catalog of retrograde-wave events,

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an EOF analysis is performed to extract more detailed spatial patterns beyond zonal wavenumber 1. These analyses use the ERA-Interim dataset (Dee et al. 2011) for the period from January 1979 to December 2017. The main analysis is derived from the four-times-daily geopotential height at multiple pressure levels (but focusing on 250 mb; 1 mb = 1 hPa) with a $2.5^\circ \times 2.5^\circ$ grid resolution. Although reanalysis data with a higher spatial resolution are available, for our purpose of analyzing the long waves the given resolution is adequate.

The data are first averaged daily to remove diurnal variation. The mean annual cycle, defined as the annual mean plus the first two (annual and semiannual) harmonics, is extracted from the daily data by standard multiyear averaging and Fourier analysis. The daily geopotential height anomaly is defined as the departure from this mean annual cycle.

To focus on submonthly (approximately 1 week to 1 month) time scales, the time series of the daily geopotential height anomaly at each grid point is further processed with a bandpass filter that consists of an 8-day low-pass and a 30-day high-pass filter, as detailed in the appendix. After bandpass filtering, the first 72 days of 1979 and the last 72 days of 2017 that are not properly filtered are discarded. The ensuing analyses (except the analysis on potential vorticity in section 3) use exclusively the bandpass-filtered data. Since the filter removes much of the high-frequency short waves, it also has the effect of smoothing in space. Also, stationary waves are excluded from the data after the removal of the mean annual cycle and bandpass filtering.

b. Update of the catalog of retrograde-wave events

Following Madden and Speth (1989), the zonal wavenumber-1 Fourier component of geopotential height anomaly at 60°N and 250-mb level is chosen as the key index for detecting retrograde waves. Using a set of criteria designed in the spirit of Madden and Speth (1989) (but with modifications), a retrograde-wave event is identified in two steps:

- 1) If the 5-day running average of the amplitude of the wave-1 component exceeds the threshold of 60 m and the phase of the wave-1 component exhibits westward propagation during the whole 5-day window for averaging, the given day at the center of the 5-day window is said to satisfy the “retrograde-wave condition.”
- 2) A retrograde-wave event is established if the “retrograde-wave condition” given in step 1 is satisfied for at least 8 consecutive days and, further, the crest of the wave-1 Fourier component travels westward by at least half of the latitude circle over the span of the entire event (which could be longer than 8 days).

FIG. 1. Hovmöller diagrams of wave-1 component of geopotential height anomaly along the latitude circle at 60°N , over the period of 1 Dec 1979–31 Mar 1980: (a) 30-, (b) 250-, (c) 500-mb levels. Contour intervals are 120 m for 30 mb and 60 m for 250 and 500 mb. Red and blue are positive and negative values, and zero contours are in black. (d) As in (a)–(c), but for the wave-1 component of the anomaly of surface pressure. Contour interval is 4 mb.

Our criteria include a threshold for the amplitude of the geopotential height anomaly, which was not adopted by Madden and Speth (1989). The effect of the threshold is mainly in excluding the events in boreal summer with clear westward propagation but smaller amplitudes for the wave-1 component. The exclusion is meaningful if one is interested in applications in weather prediction, as large-amplitude events are likely to have greater impacts on the predictability of weather by the interaction between long waves and short waves. Also, we set the threshold value to 60 m partly for historical reasons. As will be shown, with this choice our criteria yield approximately the same retrograde-wave events in wintertime for 1980–87 as those originally documented in Madden and Speth (1989).

An application of our selection criteria readily recovers the strong retrograde-wave event in 1979/80 winter as prominently featured in Branstator (1987) and Madden and Speth (1989). Figures 1a–c show the Hovmöller diagrams of time versus longitude, from 1 December 1979 to 30 March 1980, for the wave-1 component of geopotential height anomalies at selected pressure levels. The green horizontal bars in Fig. 1b mark the beginning and end of the main retrograde-wave event (detailed in Table 1 as the first event of 1980), which spans from the second week of January to the middle of March. Consistent with previous studies (Branstator 1987; Madden and Speth 1989), the wave-1 geopotential height anomaly exhibits an equivalent barotropic structure; its amplitude increases with height from the middle

TABLE 1. The retrograde-wave events, organized by year, as identified by criteria 1 and 2 in the text. Each event is described by its start date, followed by duration and period in days in parentheses.

Year	Starting date (duration, period)						
1979	15 Mar (15, 16)	17 Aug (17, 19)	1 Nov (10, 19)	14 Nov (16, 21)			
1980	5 Jan (76, 20)	25 Jul (29, 19)	5 Oct (12, 17)	27 Oct (27, 20)	3 Dec (11, 14)	29 Dec (21, 14)	
1981	27 Jan (16, 21)	11 Mar (31, 16)	13 Apr (13, 15)	20 May (11, 18)	23 Nov (26, 18)		
1982	5 Jan (20, 20)	30 Jan (36, 19)	30 Nov (14, 17)	24 Dec (15, 20)			
1983	28 Feb (10, 13)	24 May (8, 15)					
1984	5 Jan (42, 21)	25 Feb (10, 20)	13 Oct (12, 19)				
1985	13 Jan (18, 17)	11 Apr (21, 18)	21 May (18, 17)				
1986	22 Feb (20, 15)	6 Apr (20, 22)					
1987	20 Jan (16, 15)	16 Feb (63, 19)	25 Sep (14, 16)	4 Nov (10, 17)	28 Nov (9, 17)	13 Dec (23, 22)	
1988	10 Feb (14, 17)	3 Mar (21, 16)	3 Apr (12, 21)	27 Apr (13, 20)	6 Jun (14, 22)	1 Oct (31, 16)	
1989	21 Feb (30, 16)	6 Apr (16, 20)	19 Jun (10, 15)	20 Nov (16, 17)	12 Dec (23, 20)		
1990	11 Feb (19, 15)	21 Mar (52, 18)	6 Nov (8, 16)				
1991	21 Jan (22, 19)	4 Apr (24, 20)	26 May (8, 15)	17 Oct (22, 19)	15 Nov (9, 16)	15 Dec (13, 16)	
1992	9 Mar (14, 16)	2 May (13, 16)	6 Dec (20, 19)				
1993	13 Jan (14, 16)	16 Feb (39, 19)	3 Apr (19, 16)	9 May (12, 17)	7 Oct (11, 15)		
1994	17 Feb (11, 19)	3 Apr (19, 22)	3 Oct (17, 18)				
1995	18 Jan (59, 17)	25 Mar (9, 13)	20 Apr (18, 13)	8 Nov (9, 17)	25 Nov (11, 18)	12 Dec (25, 18)	
1996	26 Jan (28, 15)	27 Feb (23, 22)	28 Mar (11, 16)	15 Nov (17, 26)	3 Dec (15, 19)	21 Dec (13, 26)	
1997	4 Mar (15, 15)	11 Apr (13, 12)	17 Oct (21, 15)	12 Dec (8, 15)			
1998	21 Feb (21, 15)	18 Sep (13, 14)	21 Oct (15, 18)	1 Dec (46, 17)			
1999	17 Jan (17, 18)	14 Mar (21, 16)	17 Sep (14, 18)				
2000	29 Mar (20, 14)						
2001	10 Mar (21, 19)	14 Apr (12, 23)	18 Sep (15, 20)	24 Dec (24, 22)			
2002	24 Mar (20, 22)	29 Apr (11, 18)	23 Jul (10, 18)	12 Dec (16, 15)			
2003	8 Jan (22, 21)	26 Feb (23, 21)	15 Apr (17, 17)	26 Oct (46, 21)			
2004	18 Feb (22, 17)	16 Nov (13, 14)	28 Dec (18, 18)				
2005	27 Feb (10, 15)	19 Mar (17, 18)	16 Apr (20, 17)	9 Oct (19, 21)	14 Nov (20, 14)	7 Dec (17, 15)	
2006	16 Jan (8, 16)	19 Feb (13, 17)	5 Mar (27, 17)	1 May (14, 17)	27 Nov (11, 16)		
2007	21 Jan (9, 15)	6 Feb (28, 20)	18 Mar (11, 16)	8 Apr (21, 15)	17 May (9, 15)	9 Jun (12, 14)	30 Aug (9, 18)
2008	29 Jan (15, 15)	17 Mar (18, 24)	2 Dec (19, 15)				
2009	14 Jan (13, 15)	30 Jan (10, 18)	19 Mar (20, 15)	18 May (18, 15)	28 Aug (22, 17)	20 Sep (27, 18)	1 Dec (21, 18)
2010	17 Jan (23, 18)	11 Feb (16, 23)	6 Mar (15, 25)	26 May (10, 19)	5 Dec (52, 18)		
2011	3 Feb (29, 17)	19 Mar (22, 17)	10 Nov (14, 19)	30 Nov (9, 15)			
2012	8 Jan (12, 18)	3 May (9, 13)	3 Oct (30, 18)	13 Dec (19, 25)			
2013	3 Jan (14, 20)	9 Mar (8, 15)	13 May (8, 14)	15 Sep (13, 15)	3 Oct (16, 20)	14 Nov (11, 19)	
2014	6 Feb (17, 22)	4 Mar (29, 16)	27 Apr (12, 17)				
2015	13 Jan (9, 15)	11 Mar (19, 19)	8 Jun (14, 17)	24 Sep (25, 16)			
2016	5 Feb (17, 23)	3 Mar (24, 17)	6 May (17, 18)	28 Dec (12, 15)			
2017	13 Jan (11, 18)	4 Feb (26, 21)	9 Mar (14, 21)	30 Apr (21, 18)			

troposphere to the lower stratosphere. With the equivalent barotropic structure, the wave-1 component also leaves a footprint in the surface pressure. Figure 1d shows the Hovmöller diagram of the wave-1 component of the anomaly of surface pressure, processed in the same way as geopotential height. The hemispherically confined wave-1 perturbation in surface pressure exerts a mountain torque on Earth's equatorial bulge, which can be related to Earth's wobble. This aspect was analyzed by Feldstein (2006).

In Fig. 1, over the period that shows westward propagation, phase coherence is found from the surface to lower stratosphere with little phase shift. In contrast, outside the main retrograde-wave event (e.g., in the middle of December 1979, when the wave-1 component

is stationary or slightly eastward propagating), this vertical phase coherence is absent. [A decomposition of the wave-1 height anomaly into standing and traveling components for the 1979/80 winter can be found in Fig. 1 of Watt-Meyer and Kushner (2015).]

Table 1 summarizes all retrograde-wave events from 1979 to 2017 that satisfy criteria 1 and 2. For each event, we list the starting date, duration of event, and the period (rounded to a whole day) of wave-1 component averaged over the event. From the table, the retrograde-wave event in January–March 1980 remains one of the most prominent episodes in the last four decades. The updated catalog broadly agrees with the shorter one in Table 1 of Madden and Speth (1989) within the overlapping period from 1980 to 1987. Figure 2 compares the

FIG. 2. A comparison of the retrograde-wave events documented in Table 1 of Madden and Speth (1989) and in our Table 1, for 1980–87. Each year is represented by a pair of stripes (the top stripe is from Madden and Speth and the bottom stripe is from this work) that indicate the durations of the events. The date of the year is marked on the abscissa. Blue-colored segments indicate a general agreement between the two catalogs.

events from the two catalogs, with the blue color indicating a close match between the two. The majority of the events that were identified by Madden and Speth (1989) but missing in the new catalog are those with relatively small amplitudes, due to the extra threshold of amplitude in criterion 1. Most of those events occur in

FIG. 3. A composite of the wave-1 geopotential height anomalies as a function of latitude and pressure, from the days listed in Table 1. It uses bandpass-filtered daily data at 14 pressure levels from 1000 to 30 mb. The contours are the amplitude with a 25-m contour interval. The relative phase, defined as the phase difference with respect to the reference value at 60°N, 500 mb, is shown as phase dials. It is adjusted such that the dial points upward at 60°N, 500 mb, and a counterclockwise rotation of the dial indicates a westward shift of the ridge or trough.

boreal summer and autumn when the amplitude of the wave-1 component is generally low.

Although Table 1 is based on the analysis at 250 mb, due to the equivalent barotropic structure a similar list

FIG. 4. Monthly averaged amplitudes of wave-1 and wave-2 geopotential height anomalies at 60°N as a function of month of the year. The construction uses all bandpass-filtered daily data from 1979 to 2017. (a) Wave-1, 250 mb; (b) wave-2, 250 mb; (c) wave-1, 500 mb; (d) wave-2, 500 mb.

FIG. 5. (a) Percentage of days in a month that are identified as part of a retrograde-wave event in Table 1, using the data at 250-mb level. (b) As in (a), but with the screening of retrograde-wave events performed at 500 mb.

of events could be obtained if the selection criteria are applied to a different level between the middle troposphere and the lower stratosphere. Since the baseline amplitude of the wave-1 geopotential height anomaly increases with height (e.g., see Fig. 4 for the statistics at

250 vs 500 mb), it is natural to adjust the threshold amplitude in the selection criteria if a level other than 250 mb is considered. For example, applying criteria 1 and 2 to 500 mb but with a lowering of the threshold of amplitude to 50 m yields a similar list of retrograde-wave events (not shown). Given the overlap of information across different vertical levels, we suggest that it is sufficient to identify retrograde-wave events using the observation at 250-mb level.

Using all days listed in Table 1, we create a composite of the amplitude and relative phase of the wave-1 geopotential height anomaly as a function of latitude and height (pressure), as shown in Fig. 3. The figure uses the daily geopotential height anomalies from 14 vertical levels of reanalysis from 1979 to 2017, all processed with the bandpass filter. The overall picture, characterized by an equivalent barotropic structure with a small phase tilt with height, is similar to classical results in Madden and Speth (1989) and Branstator (1987).

The wave-1 index associated to Table 1 is but one of many possible choices. An alternative index would be the projection coefficient of the leading EOF/complex EOF (CEOF) (without restricting to the wave-1 component) as analyzed by Branstator (1987) and Kushnir (1987). [See Fig. 5 of Kushnir (1987) for an example of

FIG. 6. (a) Histogram of the amplitude of the wave-1 component of geopotential height anomaly at 250 mb, using all days that are retained in Table 1. (b) As in (a), but for 500 mb. The bin width is 10 m. The abscissa is amplitude (m), and the ordinate is the number of days that fall within each bin.

FIG. 7. (a) Histogram of the phase of wave-1 geopotential height anomalies from all days listed in Table 1, using the 250-mb data. The phase is defined as the longitude where the maximum (ridge) of the wave-1 component is located. (b) As in (a), but for the 500-mb level. The bin width is 30° . The abscissa is essentially longitude, and the ordinate is the number of days that are sorted into each bin.

an alternative construction of the “catalog,” for 1957–80.] With the wave-1-based criteria, our selection of the events might be biased in favor of those that have a stronger footprint on the wave-1 component. It would be interesting to compare the catalogs created from different approaches in future work.

c. Statistics and extreme events for retrograde waves

Figure 4 shows the seasonal cycle of the amplitudes of the wave-1 and wave-2 geopotential height anomalies at 60°N , at the 250- and 500-mb levels. The statistics are based on all bandpass-filtered daily data from 1979 to 2017, before screening was performed to retain only the retrograde-wave events. The long-wave components generally have larger amplitudes in boreal winter. Figure 5a shows the percentage of days within each month that are selected into the list in Table 1, based on the wave-1 index at 60°N and 250 mb. Figure 5b is similar to Fig. 5a but for the 500-mb level, and with the selection of retrograde-wave events performed separately by reducing the threshold of amplitude in criterion 1 to 50 m. Figure 6a shows the histogram of the amplitude

of the wave-1 component at 60°N and 250 mb from the days that are included in Table 1, and Fig. 6b is its counterpart at 500 mb.

Figure 7a shows the histogram of the phase of wave-1 component at 60°N and 250 mb, for all days that are included in Table 1. Figure 7b is a similar plot but for the 500-mb level. Here, we define the phase as the longitude where the ridge (maximum of geopotential height anomaly) is located, thus the abscissa in each panel of Fig. 7 is simply the longitude. Since (by our selection criteria) the wave-1 component propagates westward around the latitude circle, the distribution of phase is relatively uniform. Nevertheless, a peak is found in the histogram just west of date line. We will revisit this point in section 3 using potential vorticity maps.

To extract the spatial structure of retrograde waves, we perform EOF analyses for the bandpass-filtered geopotential height anomaly based on the days that are listed in Table 1. Although Table 1 was based on the wave-1 index at 60°N and 250 mb, in the following analysis the EOFs are calculated for the geopotential height field that includes other Fourier components.

FIG. 8. The first two EOFs of the geopotential height anomalies truncated to zonal wavenumber 3, from 20° to 90°N, using all days listed in Table 1. The calculations are performed separately at (top) 30, (middle) 250, and (bottom) 500 mb. The percentage of variance explained by the EOF (for the respective pressure level) is also indicated in each panel. Red and blue indicate opposite signs, and contour intervals are arbitrary. The abscissa and the ordinate are longitude and latitude, respectively.

Figure 8 shows EOF 1 and EOF 2 calculated at 30, 250, and 500 mb, separately, for the geopotential height anomaly between 20° and 90°N that includes only zonal wavenumber-1, -2, and -3 components. An area weight, the square root of the area of the grid box, is multiplied to the geopotential height before the calculations. The percentage of variance explained by an EOF is indicated in each panel. Figure 9 is similar to Fig. 8, but with all zonal wavenumbers (including the zonal mean) retained in the geopotential height anomalies.

Speth et al. (1992) noted that there also exist westward-propagating long waves in the high latitudes of the Southern Hemisphere. They compared the retrograde-wave events in the Southern and Northern Hemispheres in the 1980s and found no clear correspondence between the two. To confirm this, we perform additional computations of EOFs for the global domain, as shown in Fig. 10. Except for considering the global domain, the setup for Fig. 10 is identical to Fig. 8 (i.e., with only wavenumbers 1–3). All of Figs. 8–10 show a

robust phase quadrature of the dominantly wave-1 structure, concentrated in the higher latitudes of Northern Hemisphere, as the leading pair of EOFs. [As noted before, due to our selection criteria these EOFs are more dominated by the wave-1 component compared to the EOFs/CEOFs in Branstator (1987) and Kushnir (1987).]

Guided by Table 1, in Fig. 11 we present the time evolution of the projection coefficients of geopotential height anomalies onto the EOF 1 and 2 at 250 mb in Fig. 8, over four winters (1979/80, 1983/84, 1994/95, and 2010/11) that include some of the prominent retrograde-wave events. Each panel shows one winter from 1 November to 30 April, with the retrograde-wave events from Table 1 marked by red bars. To visualize those events, Fig. 12 shows the Hovmöller diagrams over the same period for the four winter seasons. This is yet another demonstration of the extraordinary persistence of westward phase propagation associated with the 1979/80 event.

FIG. 9. As in Fig. 8, but with the calculations performed using geopotential height anomalies that contain all zonal wavenumbers.

3. Further discussion and potential vorticity picture

The catalog in Table 1 serves as not only an update of classical observational studies but also a useful guide for future studies on the dynamics of submonthly retrograde waves, of which few exist. Branstator and Held (1995) and Huang and Robinson (1995) related the retrograde waves to the leading unstable normal mode of the zonally asymmetric basic state at an upper-tropospheric level. Lau and Nath (1999) showed the consistency between the observed westward propagation speed and the dispersion relation of external Rossby waves and the dominance of the “beta term.” Mo (1999) speculated on the possible role of tropical forcing. Those studies were published in the last century and considered only limited aspects of the phenomenon. The most interesting, however, is the study of Polvani et al. (1999), which briefly examined potential vorticity associated with retrograde disturbances in a shallow-water model simulation. A comparison of PV and streamfunction (related to our geopotential height) in one of their simulations reveals the possibility that the retrograde disturbances (as seen in streamfunction) are

the manifestation of a poleward extrusion of low-PV air into higher latitudes (poleward of the Pacific jet), followed by a westward shift of the low-PV patch and vortex shedding.

Although based only on numerical simulations, the potential vorticity picture in Polvani et al. (1999) is appealing because it could help correct the retrograde-wave phenomenon to known dynamic paradigms related to wave breaking and vortex shedding. This motivates us to take a first look at potential vorticity structures in observation associated with selected retrograde-wave events from Figs. 11 and 12.

Daily isentropic potential vorticity data are obtained from the ERA-Interim archive. Unlike the filtered geopotential height anomaly, we analyze the total PV field without any further processing. The bandpass filtered geopotential height anomalies at 250 mb are compared to total PV at the 315-K isentropic surface, which is close to the 250-mb level in the higher latitudes in boreal winter. Figure 13 shows a sequence of daily PV versus geopotential height anomaly for 23, 24, 26, 27, and 31 December 2010 that are selected from the prominent 2010/11 event. While the geopotential height

FIG. 10. As in Fig. 8, but with the calculations performed for the global geopotential height anomalies truncated to wavenumber 3.

exhibits a pattern of westward-propagating long waves dominated by the westward shift of a large positive height anomaly, the PV picture shows an extrusion of low-PV air into the higher latitudes, followed by a westward migration and shedding of a vortex. One finds a clear correspondence between the shedded vortex (which contains low PV) and the positive height anomaly, an anticyclone. The PV extrusion occurs at around the date line, and the subsequent migration and shedding of vortex occurs west of the date line. Frequent occurrences of this sequence would be consistent with the “peak” in the histograms in Fig. 7. Recall that the figure shows the distribution of the location of the *ridge* of wave-1 geopotential height anomalies.

It is interesting to note that the phenomenon of blocking can also be broadly associated with a poleward extrusion of low PV into the higher latitudes (e.g., Hoskins 1997), but the blocked high is stationary and the associated negative PV anomaly presumably does not exhibit a significant westward shift nor shedding of vortex. How different large-scale dynamical conditions lead to the two types of behavior—stationary versus migrating—will be worth future investigations.

Figure 14 shows the sequence of PV versus geopotential height anomaly for 3, 6, 7, 8, and 10 January 1980, with 6 January being the start of the great 1980 event. Similar to Fig. 13, the geopotential height anomalies exhibit an asymmetry with stronger positive anomalies, which correspond to low PV coming from lower latitudes. The structure of PV is more complicated in this case. Nevertheless, by 10 January one sees a hint of the separation of the extruded low-PV patch from its lower-latitude origin, and the nearly separated low-PV air begins to shift westward in the higher latitudes.

Figure 15 shows yet another example of the sequence from 11 to 15 February 1995. With differences in detail, the common features among Figs. 13–15 are (i) poleward extrusion of low PV over the Pacific sector, (ii) westward shift of the low-PV patch (once it reaches the higher latitudes), and (iii) formation of detached vortex. As low PV is roughly associated with positive height anomalies, the sequence of (i) to (ii) is reminiscent of the classical statistics in Figs. 3 and 4 of Kushnir (1987), which used geopotential height without restricting it to low wavenumbers. The wave-1 index used for creating Table 1 picks up the “smeared out version” of the

FIG. 11. The projection coefficients of daily 250-mb geopotential height anomalies onto the first two EOFs at that level as given in the middle row of Fig. 8. Blue and red are the coefficients for EOF 1 and EOF 2, respectively. Units are arbitrary. The periods are for the winter–spring season (1 Nov–30 Apr) of (top to bottom) 1979/80, 1983/84, 1994/95, and 2010/11. The dates are indicated on the abscissa.

phenomenon, mainly the westward propagation in (ii). Nevertheless, because (i)–(iii) tend to occur together, Table 1 still usefully retains the “sequence” of the phenomenon in the listed retrograde-wave events.

The PV analysis in Figs. 13–15 enables us to examine the “fine structures” of the flow associated with the broader long-wave pattern in geopotential height. To understand mechanisms, future work is needed

FIG. 12. Hovmöller diagrams of wave-1 geopotential height anomalies along the latitude circle at 60°N, from 1 Nov to 30 Apr for (left to right) 1979/80, 1983/84, 1994/95, and 2010/11. Red and blue are positive and negative values, and zero contours are in black. Contour interval is 60 m.

FIG. 13. Maps of (left) total potential vorticity on 315-K isentropic surface and (right) bandpass-filtered 250-mb geopotential height anomaly for the sequence of (top to bottom) 23, 24, 26, 27, and 31 Dec 2010. The domain covers 30°–80°N, 80°E–60°W. The contour interval for potential vorticity is 1 PVU ($1 \text{ PVU} = 10^{-6} \text{ K kg}^{-1} \text{ m}^2 \text{ s}^{-1}$), with the darkest blue color corresponding to the areas below 1 PVU. The contour interval for geopotential height anomalies is 60 m. Red and blue are positive and negative values, and zero contours are in black.

to connect those fine structures to relevant forcing. The longitude where the low-PV extrusion occurs is approximately the exit of the Pacific jet. A further analysis to clarify this relation will help connect the retrograde waves to the (instability of) seasonal-mean basic state, as envisioned by early studies of Branstator and Held (1995) and Huang and Robinson (1995), but in a more general nonlinear setting (e.g., Polvani et al. 1999) to interpret the breakdown of the jet and subsequent evolution of potential vorticity.

Figures 13–15 illustrate a great degree of variation in the detailed PV structures—vortices and filaments—across different retrograde-wave events. The longitude where the “poleward extrusion of low PV” occurs varies from event to event. A composite of multiple retrograde-wave events would smear out those detailed structures. With their simpler structures, a more robust composite can be made for the geopotential height anomalies, for example, at a given phase of the wave-1 component. Using all events in Table 1, we found that

such a composite is typically similar to the leading EOFs (if taken at their respective phases) in Figs. 8–10, and for brevity the results are not shown.

Table 1 shows that retrograde-wave events as strong and long lasting as the January–March 1980 episode are not abundant. Figures 13–15 further indicate non-trivial variability in the detailed structures among those major events. As such, future investigations on the mechanisms of the retrograde waves might benefit from analyzing more samples from numerical simulations. In this context, we note that validations of the retrograde-wave phenomena in GCM simulations have been performed in very few studies (Kushnir 1987; Lau and Nath 1999; May 1999; Doblas-Reyes et al. 2001). The results in this paper could provide a basis for more validations.

4. Concluding remarks

This work produces the basic statistics of submonthly retrograde waves as an update of classical observational

FIG. 14. As in Fig. 13, but for the sequence of (top to bottom) 3, 6, 7, 8, and 10 Jan 1980.

studies. The structures and statistics of the retrograde waves as deduced from the longer reanalysis dataset broadly agree with known results in the classical papers. This attests to the robustness of the classical analyses as well as the phenomenon itself.

This paper is intended to be the beginning of a series of studies toward better understandings of the dynamics and predictability of the retrograde waves. Motivated by the results in section 3, a more in-depth analysis of the potential vorticity structure is underway. It will aim to connect retrograde waves to mechanisms for wave breaking and vortex shedding. In applications, we will explore the role of the retrograde waves in facilitating troposphere–stratosphere connection and in influencing the climate of the Arctic. Notably, the recent work of Long and Robinson (2017) shows that traveling wave-1 component contributes significantly to the wintertime eddy heat flux into the Arctic region.

Although classical studies have speculated on the influence of the retrograde waves on extended-range weather prediction, detailed quantifications of this influence are lacking. As the first steps forward, a recent work of H.-P. Huang (2019, unpublished manuscript)

confirms enhanced week-2 predictability in ensemble weather forecast during the prominent retrograde-wave event from January to March 1980. Recently, Stan and Krishnamurthy (2019) used multichannel singular spectral analysis to identify a submonthly mode of oscillation that resembles the high-latitude retrograde waves. They explored the possibility of incorporating this mode in a statistical model for submonthly prediction. In these contexts, the catalog in Table 1 can be used to help expand the study of predictability and to connect the enhanced predictability to the dynamical structures of the retrograde waves.

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FIG. 15. As in Fig. 13, but for the sequence of (top to bottom) 11, 12, 13, 14, and 15 Feb 1995.

APPENDIX

The Bandpass Filter

The bandpass filter combines a pair of standard nonrecursive 8-day low-pass and 30-day high-pass filters. In physical space, the weight for the low-pass (LP) filter is

$$f_{\text{LP}}(n\Delta t) = \frac{2 \sin(\omega_c n\Delta t)}{\omega_s n\Delta t}, \quad (\text{A1})$$

and that for the high-pass (HP) filter is

$$f_{\text{HP}}(n\Delta t) = \frac{2[\sin(\omega_s n\Delta t/2) - \sin(\omega_c n\Delta t)]}{\omega_s n\Delta t}, \quad (\text{A2})$$

where Δt is sampling interval ($\Delta t = 1$ day for daily data), $\omega_s = 2\pi/\Delta t$, and ω_c is the cutoff frequency given as $\omega_c = 2\pi/(8 \text{ days})$ for the LP filter and $\omega_c = 2\pi/(30 \text{ days})$ for the HP filter. For an M -point filter, the index n runs from $-(M-1)/2$ to $(M-1)/2$, and the weighted sum of the original data over that range yields the filtered data at $n = 0$. In actual applications, each of the filters is modified by a Hamming window,

$$w(n\Delta t) = \begin{cases} 0.54 + 0.46 \cos[2\pi n\Delta t/(M-1)], & \text{if } |n| < (M-1)/2, \\ 0, & \text{otherwise.} \end{cases} \quad (\text{A3})$$

Put together, the fully defined filters are $F_{\text{LP}}(n\Delta t) = f_{\text{LP}}(n\Delta t)w(n\Delta t)$ for the low-pass filter and $F_{\text{HP}}(n\Delta t) = f_{\text{HP}}(n\Delta t)w(n\Delta t)$ for the high-pass filter.

Our analysis uses a 25-point LP filter and a 121-point HP filter. The response functions for the filters are shown in Fig. A1. Over the critical window of 2–3 weeks,

almost 100% of the amplitude is retained. The response function for the LP filter drops to 0.08 at 6 days, effectively suppressing the high-frequency short waves. On the low-frequency side, the response function of the HP filter drops to 0.22 at 35 days, and 0.1 at 39 days. As the LP and HP filters are applied successively to

FIG. A1. The response functions of the high-pass (blue) and low-pass (red) filters. The two dashed vertical lines mark $\tau = 8$ and 30 days.

the daily data, the end points in the time series that are not properly filtered are discarded. The excluded points are the first 72 days of 1979 and the last 72 days of 2017.

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