21 April 2021

Underlying factors of the warmest March on record in Japan

Japan experienced remarkably warm weather conditions in March 2021. According to the statistics of the Japan Meteorological Agency (JMA), its monthly mean temperature anomaly averaged over the country was +2.76 degrees Celsius above 30-year average from 1981 to 2010, and this is the highest on record since 1898 for the month (Figure 1). Reflecting such a warm condition, cherry blossom bloomed much earlier than usual years and some local observatories of JMA announced the earliest blooming on its observation record. This research aims to summarize characteristics of atmospheric circulation anomalies associated with the warmest March in Japan and discuss underlying mechanisms which contribute to enhance and maintain them. We use JMA's reanalysis dataset JRA-55 to illustrate and diagnose climate system conditions and define an anomaly as a deviation from 30-year average from 1981-2010 unless otherwise noted.

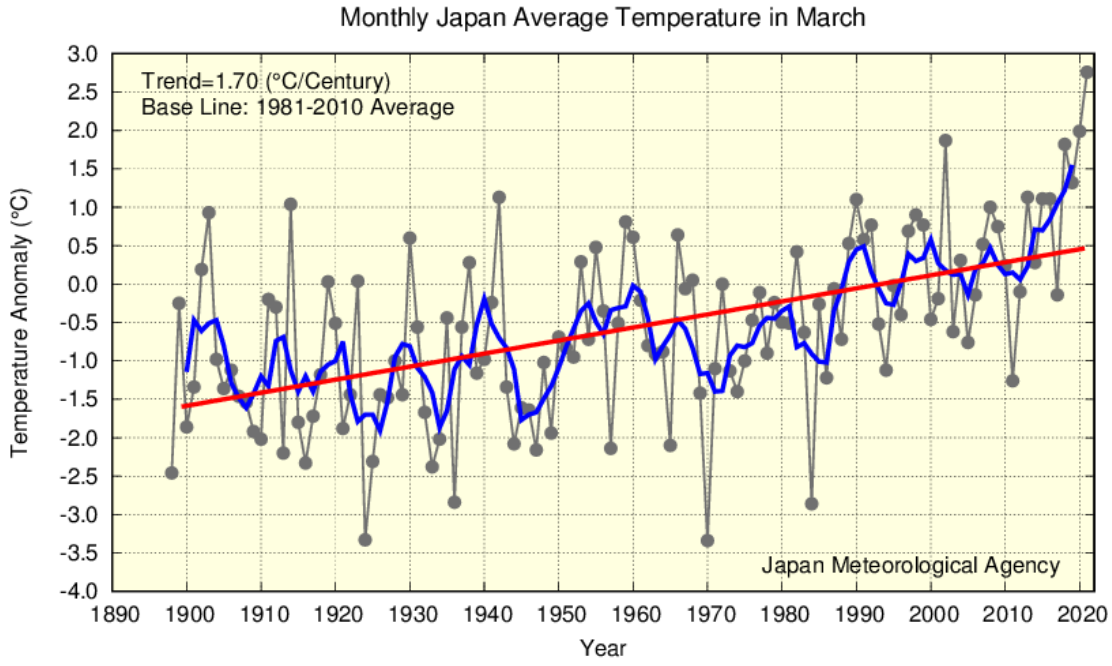

Figure 1. Monthly mean temperature over Japan for March

The most prominent characteristic of atmospheric circulation around Japan in March was an anticyclonic circulation anomaly elongated from East Asia to the North Pacific. In each field of 500 hPa geopotential height, sea level pressure (SLP) or air temperature at 850 hPa (Figure 2), remarkable positive anomalies larger than 2 standard deviations were recognized

over the region. Japan is located in the western verge of this anticyclonic circulation anomaly and southerly wind advected warm air mass there. According to thermal budget analysis, heating associated with anomalous wind played the dominant role in temperature rising over and around Japan and its magnitude reached at about 3 degrees/day (Figure 3). In association with aforementioned anticyclonic circulation anomaly, a polar front jet stream flowed around 50°N and this could contribute to keeping the cold air mass of the Arctic region in high latitude and preventing southward cold air mass outbreaks in East Asia in March 2021.

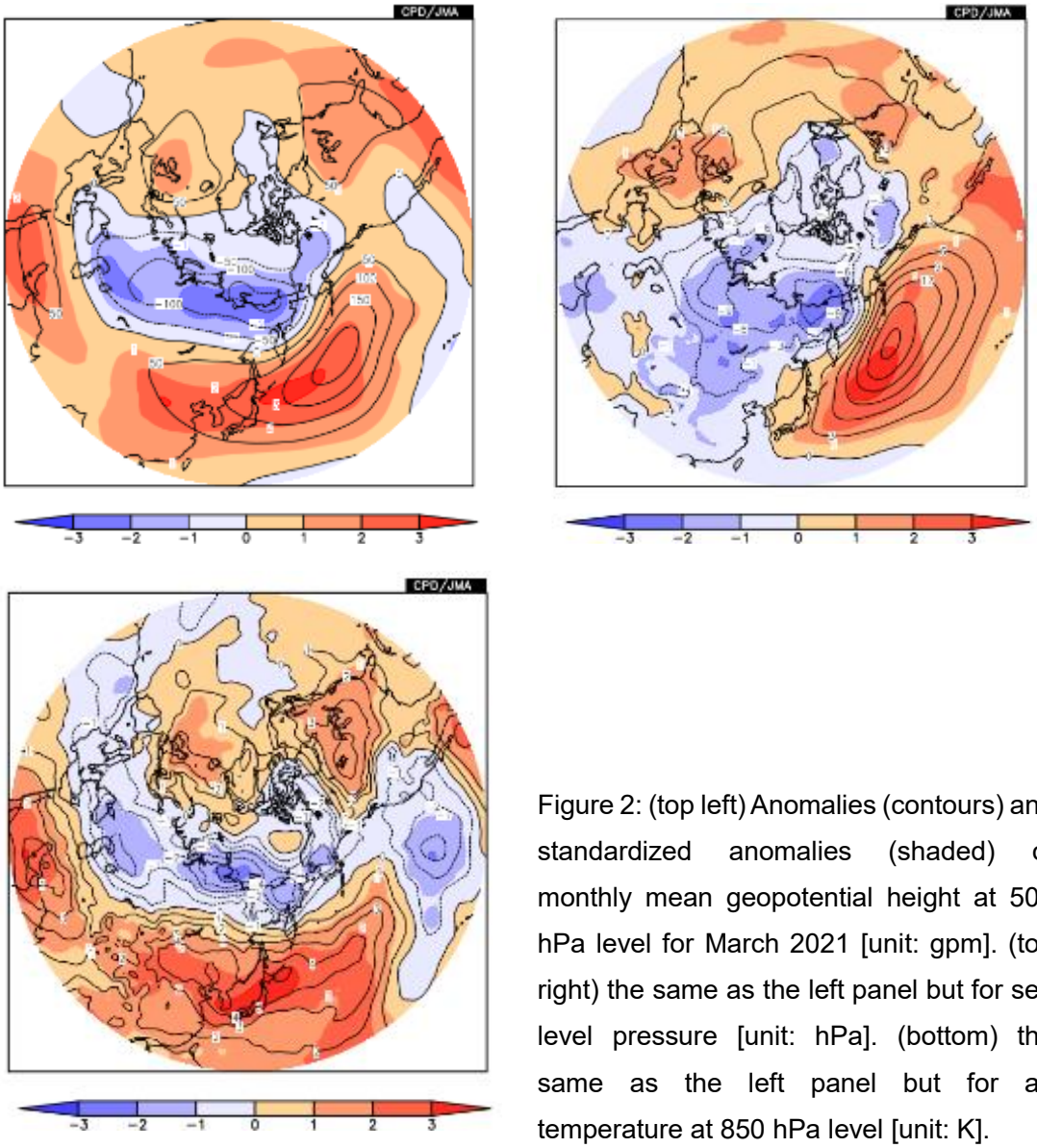

Figure 2: (top left) Anomalies (contours) and standardized anomalies (shaded) of monthly mean geopotential height at 500 hPa level for March 2021 [unit: gpm]. (top right) the same as the left panel but for sea level pressure [unit: hPa]. (bottom) the same as the left panel but for air temperature at 850 hPa level [unit: K].

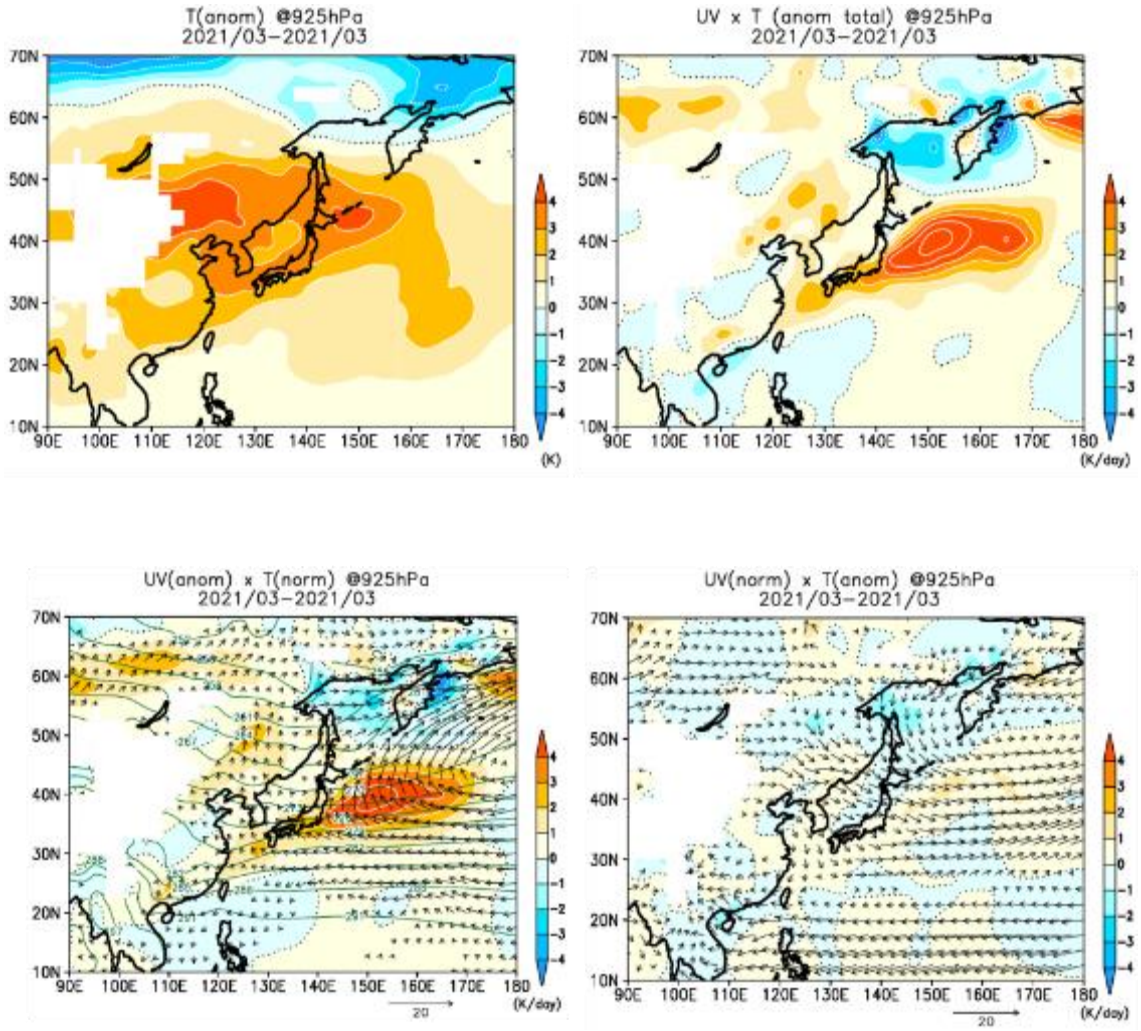

Figure 3: Result of thermal budget analysis for March 2021 at 925 hPa level.
(top left) temperature anomalies [unit: K]. (top right) temperature advection associated with horizontal wind [unit: K/day]. (bottom left) temperature advection associated with anomalous wind and climatological normal temperature field [unit: K/day]. (bottom right) temperature advection associated with anomalous temperature and climatological normal wind field [unit: K/day].

Hereafter, we focus on some details of the structure and maintenance mechanisms of anticyclonic anomaly over East Asia and the North Pacific. Figure 4 shows the vertical cross section of geopotential height and temperature anomalies averaged over 40°-50°N, where the center of the anomaly was located. Though this anomaly had an equivalent barotropic structure in and around its center, it also had a baroclinic structure over western verge of it. There, contours of geopotential height anomalies tilted westward with height and positive

temperature anomalies were even larger than those in the center of the height anomaly. Such characteristics seen in both fields strongly suggest that anomalous poleward heat flux over the area could extract the available potential energy from the mean flow, possibly leading to maintain or even strengthen this anticyclonic anomaly. To diagnose maintenance mechanisms quantitatively from a view point of energetics, we analyzed energy budgets over the North Pacific. As expected from vertical structure of anticyclonic anomalies, a strong positive baroclinic energy conversion was recognized in the western part of anticyclonic anomaly and relatively weaker barotropic energy conversion was seen around the center of the anomaly. The result of energy budget analysis in Figure 5 indicates that the baroclinic energy conversion associated with climatologically strong northward temperature gradient in the lower troposphere over the western North Pacific and poleward heat flux induced by the anticyclonic anomaly played a dominant role in maintain and even westward extension of the anticyclonic anomaly.

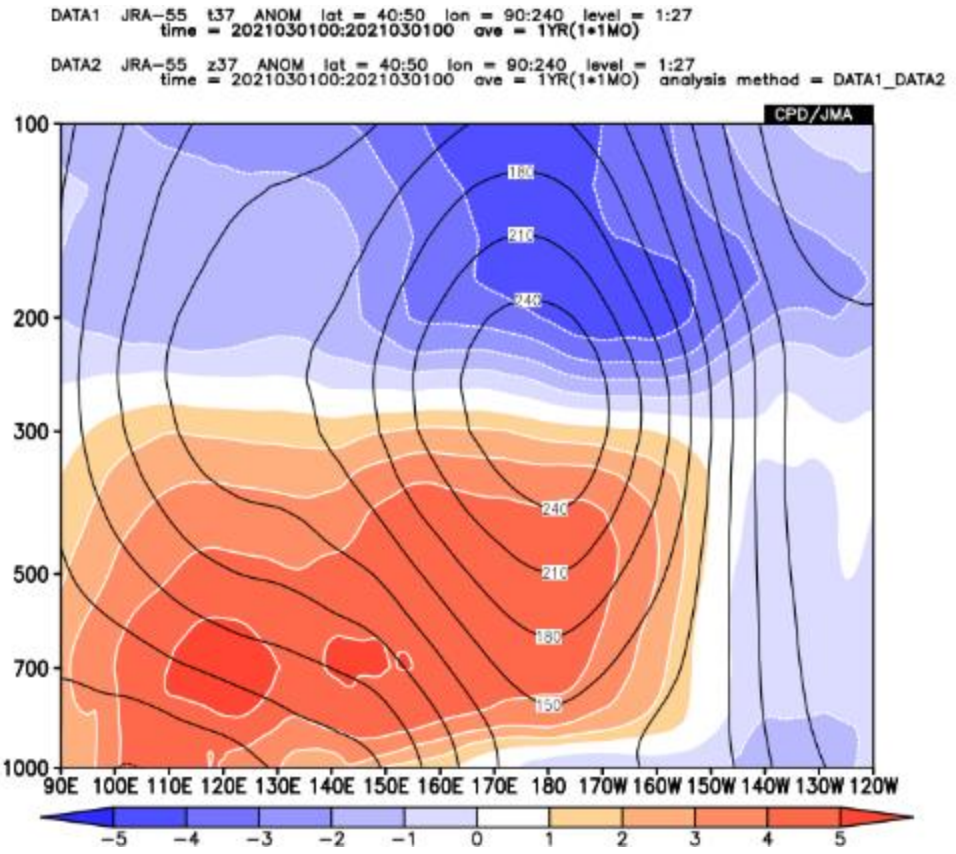

Figure 4: Vertical cross section of geopotential height [unit: gpm] (contours) and temperature [unit: K] (shades) anomalies averaged 40°-50° N.

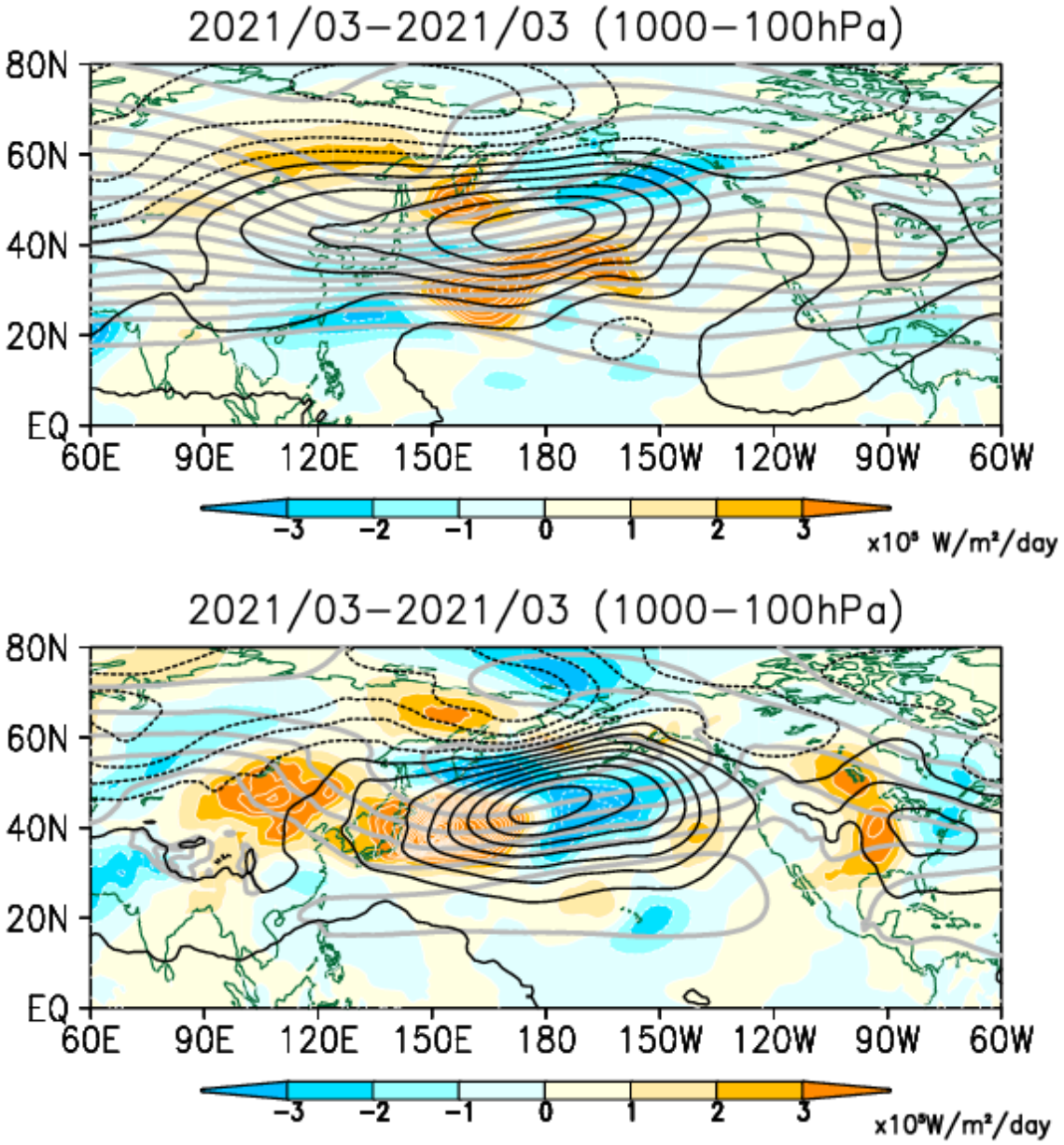

Figure 5: Result of energy budget analysis. (top) barotropic energy conversion. (bottom) baroclinic energy conversion [unit $10^5 W/m^2/day$] (shades) and anomalies (black contours) and climatological mean of geopotential height at 250 hPa (top) and 850hPa (bottom) level [unit: gpm] (grey contours). Energy conversion was vertically integrated in the troposphere (1000 - 100 hPa).

To comprehend underlying mechanisms of long-lasting circulation anomalies, it is important to diagnose an interaction between disturbances with different time frequencies. Corresponding to the anticyclonic circulation anomaly over East Asia and the North Pacific in March 2021, a polar front jet stream was clearer than climatological mean for the month

and influenced high frequency disturbances over the North Pacific. Distributions of poleward heat flux at 850 hPa level and a kinetic energy at 300 hPa level associated with high frequency disturbances, which are a good indication of storm track activities in the lower and upper troposphere respectively, clearly shows that a storm track shifted northward and its activities were enhanced. Furthermore, a diagnostic analysis of a feedback of vorticity flux from high frequency disturbances to height field behind them indicates that there was a feedback to raise geopotential height over the area south of northward-shifted storm track over the North Pacific (Figure 6).

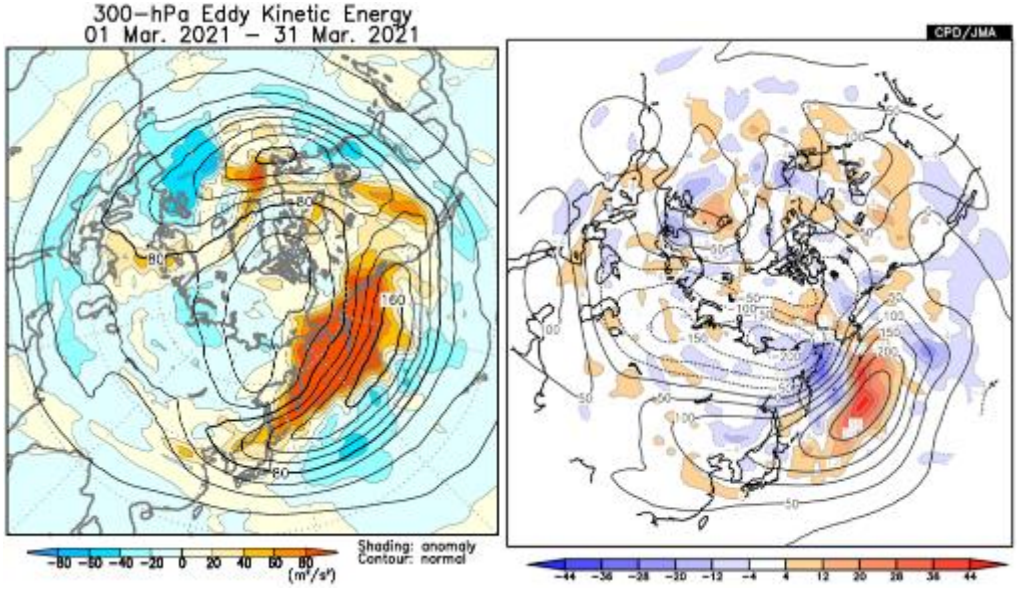

Figure 6: (left) Kinetic energy associated with high frequency disturbances (contours: show climatological normal for March and shades shows anomalies for March 2021 [unit: m^2/s^2]). (right) geopotential height tendency induced by vorticity flux associated with high frequency disturbances at 300 hPa level [unit: m/day] (shades) and geopotential anomalies at the same level for March 2021 [unit: gpm].

When we focus on zonal mean field of the Northern Hemisphere, westerly wind anomalies corresponding polar front jet streams were clear, largely contributed by the one from East Asia over North Pacific. Convergence of westerly momentum flux anomalies in the troposphere associated with both stationary and transient eddies in March 2021 shows a good correspondence with westerly wind anomalies (Figure 7). To consider possible mechanisms behind this characteristics seen in zonal mean field, we define a “wave” as a deviation from zonal wind field. Figure 8 shows geopotential height deviation from zonal mean at 300 hPa level and wave activity flux defined by Plumb (1985). As indicated in Figure 2, East Asian winter monsoon was much weaker than climatological normal in March 2021

and it is represented as the shallower trough and smaller vertical component of wave activity flux over East Asia in Figure 8. While vertical component of wave activity flux was smaller, south-east ward propagation of wave activity was clear from this trough over the North Pacific and this is coincident with westerly momentum flux convergence associated with stationary disturbances.

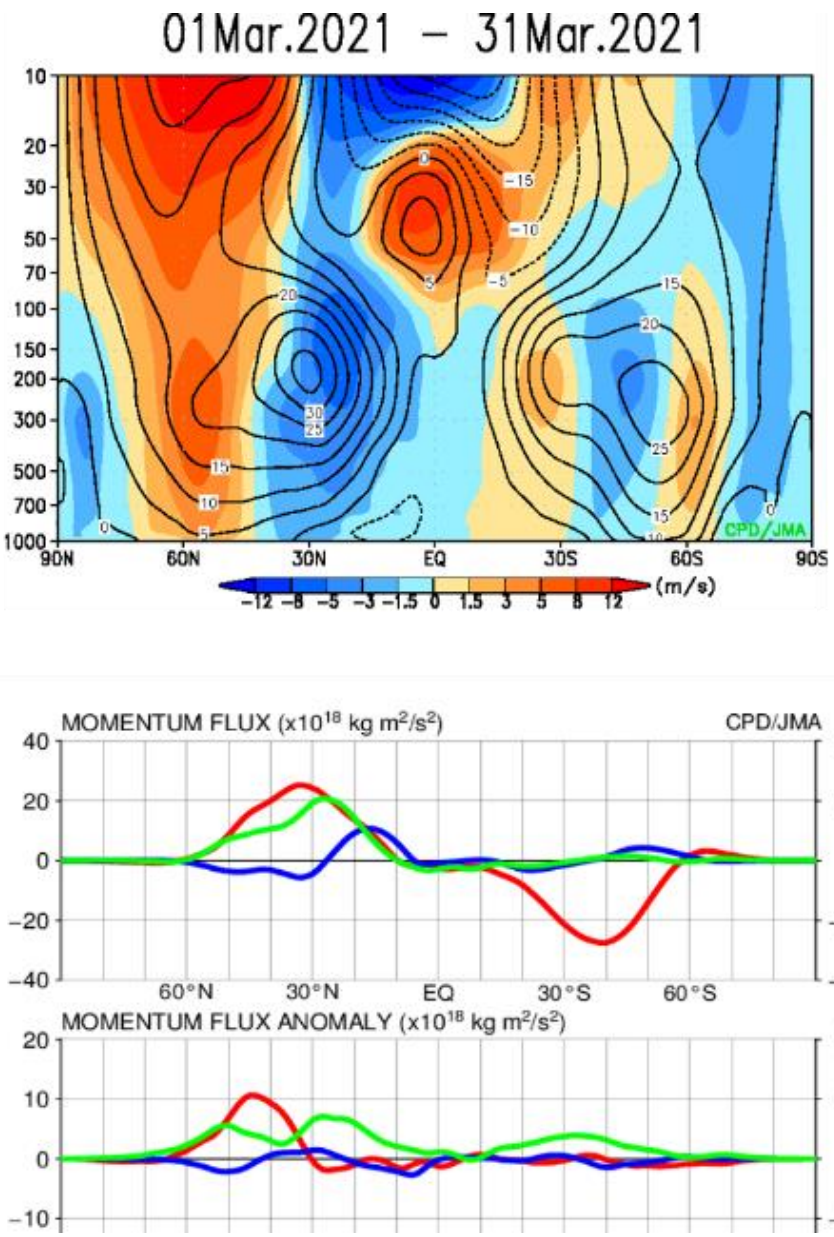

Figure 7: (top) zonal mean zonal wind (contour) and its anomalies (shades) for March 2021 [unit: m/s]. (bottom) westerly momentum fluxes and their anomalies (blue: momentum flux with meridional circulation, green: momentum flux with stationary disturbances, red: momentum flux with transient disturbances) [unit: 10^{18}kg m^2/s^2]

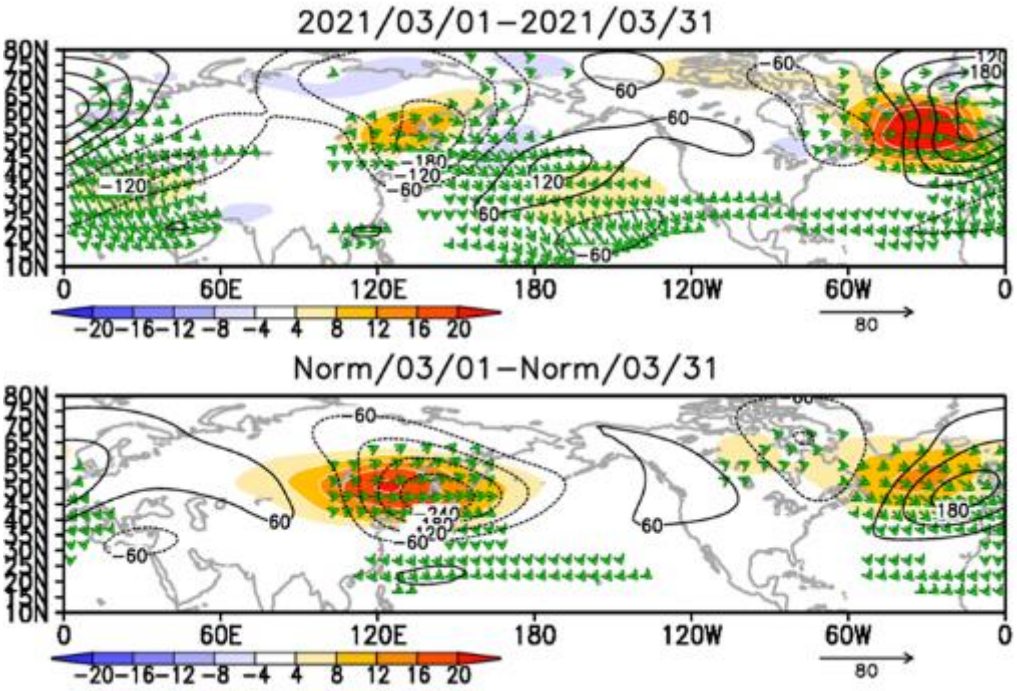

Figure 8: geopotential height deviation from zonal mean at 300 hPa level (contour) [unit: gpm], horizontal component of wave activity flux defined by Plumb (1985) at 300 hPa level (arrows) [unit: m^2/s^2] and its vertical component at 500 hPa level (shades) [unit: 10^{-2} m^2/s^2]

As mentioned before, positive anomalies of surface temperature observed over Japan and associated atmospheric circulation were over 2 standard deviations and in some places as large as 3 standard deviations, which means this could be quite a rare event to occur once in several ten years or more statistically. Through this research it is indicated that disturbances with various spatial and temporal scales and basic flow interacted to maintain and enhance circulation anomalies resulting in a record-breaking warm condition over Japan in March 2021. Certainly there is a statistically significant trend in monthly mean temperature over Japan for March as other months and this is thought to be associated with global warming, we cannot attribute the warmest March only to influences of global warming. Rather, this event highlights the importance of climate system diagnosis to deepen our understandings of mechanisms underlying climate extremes. That could lead to improvement of predictability of extreme events and eventually could lead to early warnings to which needs and necessity has been increasing year by year in the changing climate.

References

Plumb, R. A., 1985: On the Three-Dimensional Propagation of Stationary Waves. *J. Atmos. Sci.*, **42**, 217–229.

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