Prolonged Northern-Mid-Latitude Tropospheric Warming in 2018 Well Predicted by the JMA Operational Seasonal Prediction System

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Abstract
During summer 2018, zonally averaged tropospheric temperatures were higher than normal in the northern mid-latitudes, and this contributed to the extreme warmth experienced in eastern and western Japan. These northern-mid-latitudes warm anomalies, along with enhanced convective activity in the northern subtropics, persisted from autumn 2017 until autumn 2018. This paper demonstrates that both the persistent zonal pattern, and the circulation anomaly pattern, that developed during summer 2018 are well predicted by a reforecast experiment using an operational seasonal prediction system. As variation in zonally averaged convective activity in the northern subtropics is statistically closely related to northern-mid-latitude tropospheric warming in all seasons, we hypothesize that the former is likely to be a key influence on the latter. We found a weakening of northern-mid-latitude tropospheric warming in a sensitivity experiment in which tropical Pacific sea surface temperatures (SSTs) are nudged to the climatology and enhancement of convective activity in the northern tropics is weakened. These results suggest that SST anomalies in the tropical Pacific, which are well predicted by our reforecast experiment, contribute to the successful prediction of northern-mid-latitude tropospheric warming.

(Citation: Kobayashi, C., and I. Ishikawa, 2019: Prolonged northern-mid-latitude tropospheric warming in 2018 well predicted by the JMA operational seasonal prediction system. SOLA, 15A, 31–36, doi:10.2151/sola.15A-006.)

1. Introduction

In early July 2018, extremely heavy rainfall occurred over wide areas of Japan, with western regions being particularly affected (Tsuguti et al. 2018). Thereafter, extremely high temperatures persisted across eastern and western Japan (Shimpo et al. 2019). Eastern Japan experienced the highest summer average temperature since statistical records began in 1946 (Shimpo et al. 2019). The hot summer was attributed in part to higher than normal zonally averaged tropospheric temperature anomalies in the northern mid-latitudes (Shimpo et al. 2019). Several extreme heat events were observed in the Northern Hemisphere during summer 2018, with record high temperatures in Europe, East Asia, and southwestern USA (NOAA 2018; JMA 2019). These extreme weather events have also been linked to higher than normal zonally averaged tropospheric temperatures in the northern mid-latitudes as a background condition. In this study, we investigate the factors that influence the formation and maintenance of prolonged tropospheric high-temperature anomalies in the northern mid-latitudes by conducting a reforecast experiment and sensitivity experiments using the JMA Seasonal Prediction System (JMA/MRI-CPS2; Takaya et al. 2018).

2. Data and methods

We use the Japanese 55-year Reanalysis (JRA-55; Kobayashi et al. 2015) dataset to provide estimates of atmospheric conditions, NOAA Climate Data Record (CDR) of Monthly Outgoing Longwave Radiation (OLR), Version 2.7 (Lee and NOAA CDR Program 2018) to serve as an index of convective activity, and sea surface temperature (SST) data from the Centennial In Situ Observation-based Estimates of the Variability of SSTs dataset (COBE-SST; Ishii et al. 2005) to give an indication of oceanic conditions. Monthly anomaly data of these observational datasets, which are deviations from the climatology (30-year average values over the period 1981–2010), are compared with the reforecast anomaly data defined below to check the accuracy of the reforecast.

The reforecast experiment consists of two sets of 5-member, 1-month reforecast ensembles, one set starting from October 18 and the other set from October 28 in 2017. These atmospheric and oceanic initial fields are taken from the JMA operational system. Two sensitivity experiments are performed to investigate the effect of SST anomalies on tropospheric temperature anomalies. In the first experiment (GLBCST), SSTs in the atmosphere–ocean coupled model are nudged towards the SST climatology over the whole global ocean. The restoring coefficient for SST nudging is 2400 Wm$^{-2}$ K$^{-1}$, which corresponds to a 1-day relaxation time for temperature in a 50-m mixed layer. The reforecast anomalies are defined as differences between the reforecast and the GLBCST. The second experiment (TPACCST) is the same as GLBCST except that the model SSTs are nudged to climatological values only in the tropical Pacific (125°E–90°W, 30°N–20°S). The model results are shown as 10-member ensemble mean in this paper unless otherwise stated.

3. Observed northern-mid-latitude tropospheric warming in 2018

Figures 1a, 1b, 1c, and 1d shows a Hovmöller plot of zonally averaged 200-hPa geopotential height anomalies, time series of SST anomalies averaged over the NINO 3 region (5°S–5°N, 150°W–90°W), and the seasonal mean 200-hPa height anomaly pattern and SST anomaly pattern during the boreal summer of 2018. We use the 200-hPa height anomaly as an index of tropospheric temperature anomalies. The seasonal mean 200-hPa height (Fig. 1c) anomaly was positive over nearly all of the northern mid-latitudes. The positive anomalies were largest over Mongolia and northern China, in the vicinity of Alaska Bay, in the vicinity of the Labrador Peninsula, and in the southern part of the Scandinavian Peninsula. The positive anomalies of the northern mid-latitudes were remarkably large in the zonally averaged field and persisted from the autumn of 2017 (Fig. 1a).

A La Niña event took place between autumn 2017 and spring 2018, before ENSO became neutral during summer 2018 (Fig. 1b). In the tropical Pacific during summer 2018, the SSTs north of the equator showed positive anomalies, but the SSTs south of the equator showed negative anomalies (Fig. 1d). This SST anomaly pattern persisted from spring to early autumn 2017. In the Atlantic Ocean, the SST anomaly pattern exhibited a tripolar structure, with a negative anomaly in the northern subtropics, a positive anomaly in the mid-latitudes, and a negative anomaly in high-latitude regions (Fig. 1d).
4. Reforecast experiment

In Figs. 1e, 1f, 1g, and 1h we show anomaly patterns from the reforecast experiment that correspond to the observational results shown in Figs. 1a, 1b, 1c, and 1d. These fields are expressed as differences from the results of the GLBCST experiment. In the reforecast experiment, initialized in late October 2017, the high-temperature anomalies in the northern mid-latitudes that persist from autumn 2017 to summer 2018 are well predicted, in that the broad pattern of the strong positive anomalies around 35°N from boreal autumn 2017 to spring 2018 and the northward shift of the positive anomalies in summer 2018 are in good agreement between the observation and the model (Figs. 1a and 1e). This experiment also accurately predicts the intensification of zonally averaged positive anomalies in summer 2018 (Figs. 1a and 1e) and the regional distribution of positive anomaly areas in the northern mid-latitudes in summer 2018 (Figs. 1c and 1g). The fact that the observed positive anomalies of the northern mid-latitudes in summer 2018 are well reproduced in the model experiment initialized half a year earlier suggests that this feature had long-term predictability. As seen by the verification of the operational
5. Possible drivers of persistent northern-mid-latitude tropospheric warming

We next discuss the factors affecting the formation and persistence of positive tropospheric temperature anomalies in the northern mid-latitudes. The persistence of this pattern for around six months is highly unlikely to result from the atmosphere’s memory alone. Rather, it is likely that the memory of the atmosphere’s external boundary—namely, the ocean conditions—helps to sustain the atmospheric anomaly pattern. As the reforecast experiment successfully simulated the atmospheric and oceanic conditions in 2018, it is possible that the SST anomaly pattern predicted by the experiment influences the formation and continuation of the northern-mid-latitude warm anomalies via the convective activity anomalies.

Figure 2 shows OLR anomalies in 2018 and the corresponding results from the reforecast experiment. The seasonally averaged OLR anomalies from the boreal summer of 2018 show active anomalies of convection in the subtropics of the North Pacific around 15°N, especially over the Philippine Sea (Fig. 2a). Convection was inactive at around 5°S near the International Date Line, indicating a pattern with active anomalies on the northern side and inactive anomalies on the southern side of about 5°N. These characteristics were also observed in the zonally averaged OLR anomalies (Fig. 2b). The zonally averaged OLR anomaly

![Fig. 2. Observed OLR anomalies in 2018 and corresponding results from the reforecast experiment. (a) Seasonal mean observed OLR anomalies in JJA (June, July, August) 2018. The contour interval is 10 Wm^{-2}, with zero lines omitted. (b) Zonally averaged observed OLR (black line) and its anomalies (red line, right axis) in JJA 2018 with climatological OLR (grey line). (c) Time–latitude section of zonally averaged observed OLR anomalies (contour interval 2 Wm^{-2}). (d–f) As for (a–c), but for the difference between the reforecast experiment and the GLBCST experiment (reforecast minus GLBCST). Note that the negative OLR anomalies indicate positive anomalies of convective activity. Dots represent statistically significant difference at the 95% confidence level from the climatology (a, c) and from the GLBCST experiment (d, f).]
pattern, active in the north and inactive in the south, was clear from the end of 2017 and continued until the summer 2018 (Fig. 2c). The characteristics of the OLR anomaly pattern were well represented in the reforecast experiment (Figs. 2d, 2e, and 2f).

To confirm the statistical relationship between convective activity in the subtropics and the northern-mid-latitude temperature anomalies, we show the regression and correlation coefficient maps between the seasonal-mean 200-hPa height anomalies and the seasonal-mean zonally averaged convective activity in the northern subtropics (10°N−20°N; Fig. 3). The statistics were calculated for the period 1981–2016. The sign of the zonally averaged OLR anomalies was reversed to allow their use as an index of convective activity. The regression map for the boreal summer (June, July, August; JJA) shows that the variation of zonally averaged tropical Pacific contribution to the formation of the tropospheric temperature anomalies in the northern mid-latitudes. In particular, there are regions that are sensitive in East Asia (Fig. 3c). This means that when zonally averaged subtropical convection is active, the 200-hPa height in the northern mid-latitudes tends to become a positive anomaly, in boreal summer, especially over East Asia. The strong connection between subtropical convective activity and the 200-hPa height in the northern mid-latitudes is apparent during all seasons (Figs. 3a, 3b, 3c, and 3d). This suggests that the persistent enhancement of convective activity in the northern subtropics during 2018 is related to the continuation of positive anomalies in the 200-hPa height in the northern mid-latitudes.

We next investigate whether the SST anomaly pattern over the tropical Pacific had an effect on the continuation of the northern-mid-latitude warming via the convective activity, by exploring differences between the reforecast experiment and the TPCAST experiment (reforecast minus TPCAST; Fig. 4). The difference in 200-hPa height in summer 2018 is positive over almost all of the tropics, and over most of the northern mid-latitudes, except Central Asia (Fig. 4b). This implies that the SST anomalies in the tropical Pacific contribute to the formation of the tropospheric warm anomalies in the northern mid-latitudes. The zonally averaged 200-hPa height has a large positive value around 30°N at the beginning of the reforecast, with positive values continuing in the northern mid-latitudes until summer 2018 (Fig. 4a). The difference in convective activity, both in the spatial distribution and in the time–latitude section, also shows the same sign to the anomaly pattern in the reforecast experiment (Figs. 4c, 4d, and 4e). These results suggest that SST anomalies over the tropical Pacific play an important role in the formation and maintenance of northern-mid-latitude warming and subtropical convective activity anomalies.

6. Summary and discussion

Northern-mid-latitude tropospheric temperature was remarkably high between autumn 2017 and autumn 2018. The persistent northern-mid-latitude tropospheric warming and the spatial anomaly pattern of the air temperature in summer 2018 were well predicted by our reforecast experiment run on the JMA operational seasonal prediction system. Observed positive anomalies of convective activity (negative anomalies of OLR) in the northern subtropics over this same period were also successfully predicted in the reforecast experiment, as were the prominent features of the SST anomaly pattern.

Analysis of the statistical relationship between convective activity and tropospheric warming indicates that convective activity anomalies in the northern subtropics are closely related to temperature anomalies in the northern mid-latitudes during the boreal winter, spring, and summer seasons. Therefore, the convective activity anomalies are likely to be a key factor driving the persistent positive temperature anomalies in the northern mid-latitudes. In our sensitivity experiment, in which tropical Pacific SSTs were nudged to the climate SST, there was a weakening of tropospheric temperature anomalies in the northern mid-latitudes and anomalies in convective activity over the northern subtropics. These results suggest that the SST anomaly pattern had a relatively long period of accurate predictability and contributed to the successful prediction of the zonally averaged temperature anomalies in the northern mid-latitudes.

A similar situation to summer 2018 occurred in 2010, when northern-mid-latitude tropospheric warming continued during
the boreal summer. In a case study of the 2010 event, Kobayashi (2014) showed that convective activity anomalies, driven by SST anomalies in the subtropics, contributed to the northern-mid-latitude temperature anomalies. This relationship is consistent with the situation in summer 2018 explored in this work. Kobayashi (2014) further pointed out the possibility that transient waves probably contribute to the persistence of the northern-mid-latitude warming. Meanwhile, Kornhuber et al. (2019) showed that the hemisphere-wide wavenumber 7 circulation pattern was amplified in summer 2018, and the locations of the extreme weather events that occurred in the mid-latitudes were consistent with the phase positions of the teleconnection pattern. Although our study does not clarify the role of wave activity—as the anomalies associated with the subtropical convective activity caused by the SST anomaly in the tropical Pacific would generate temperature and zonal wind anomalies in the mid-latitudes—it is possible that the circumglobal teleconnection pattern was formed in the mid-latitudes through a change in the waveguides of the planetary waves, as pointed out by Branstator (2002).

We have focused here on the effect of the tropical Pacific SST on the northern-mid-latitude tropospheric temperature, and the influence of SST anomalies in other oceanic regions remains unclear. As seen by the insufficient amplitude of difference in the northern-mid-latitude tropospheric warming between the two experiments (reforecast and TPACCST), the tropical Pacific SST alone cannot explain the full anomaly in the reforecast experiments. This discrepancy is considered at least partly related to the insufficient amplitude of OLR difference in the tropical Pacific between the two experiments. It is possible that other oceanic regions affect the tropical Pacific OLR anomaly in the TPACCST experiment, though the mechanism responsible for the tropical Pacific OLR anomaly remains to be solved. Furthermore, why the SST anomaly pattern occurred and had such long-term predictability remains unresolved. Such a long memory is likely to involve processes in the subsurface ocean. In future work, we will explore the mechanisms behind this long-term predictability.

Acknowledgements

The authors are grateful to the anonymous reviewers for their constructive comments. The authors thank Mr. Takaya for providing the execution environment of JMA/MRI-CPS2 in the MRI supercomputer system.

Edited by: R. Kawamura

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*Manuscript received 20 March 2019, accepted 19 May 2019* *SOLA*: https://www.jstage.jst.go.jp/browse/sola/