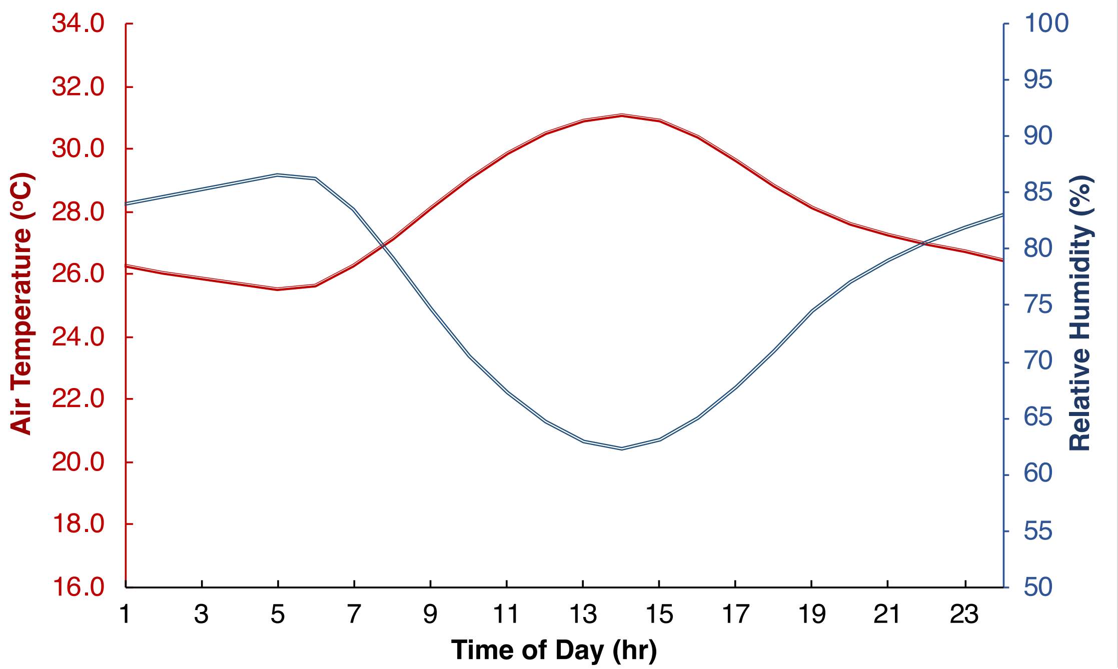
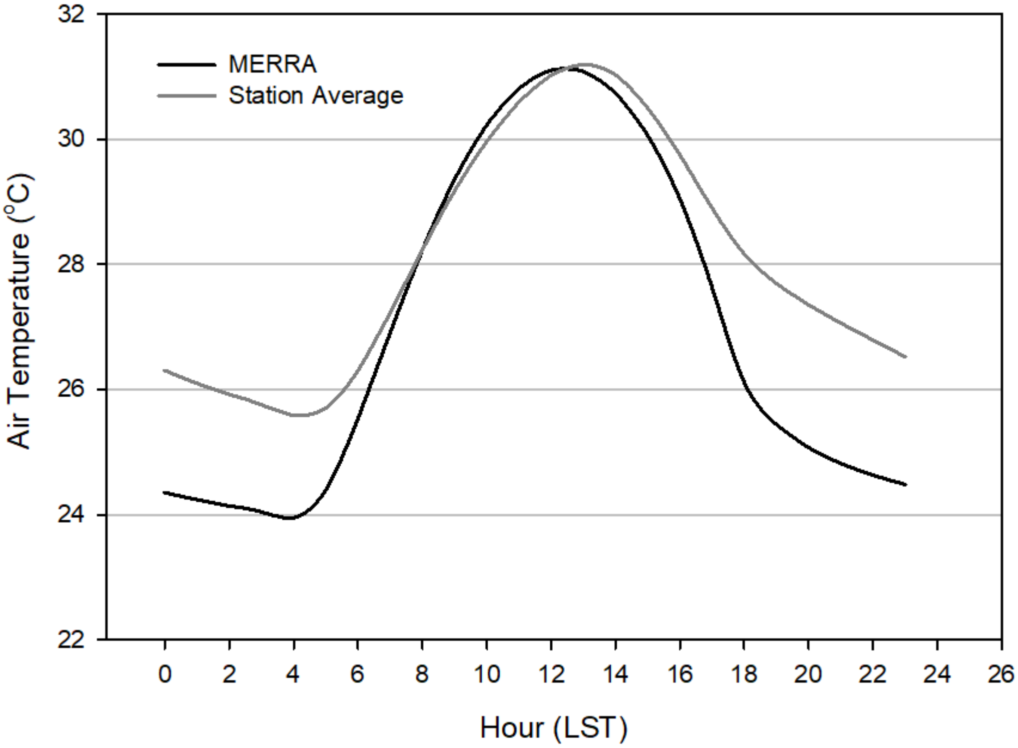
Supplemental Material: A – Average hourly temperature and relative humidity variation, 2008–2016 inclusive, within the Tokyo Metropolitan area across 20 weather stations.



Supplemental Material: B - Average 24-hr variation between MERRA temperature data and station data (from 24 weather stations) within the Tokyo Metropolitan region and the MERRA grid cell for the month of August from 2008–2016 inclusive.



Supplementary Information C:
A Brief Primer on the El Niño Southern Oscillation (ENSO)

Here we provide more in-depth information regarding the ENSO to support sections of the current paper and to provide interested readers a more detailed explanation regarding specific methods and findings. The inclusion of all such material in the paper itself is outside the scope of the given journal, yet also provides more curious readers with detailed and relevant information regarding ENSO and the atmospheric.

C.1 Planetary Ocean-Atmosphere Dynamics Heat & Cooling

The atmosphere is a complex system of several non-linear processes occurring over varying spatial and temporal scales. Like gym "battle ropes" — where moving waves from one end to another are generated by an initial perturbation — the motion of the athlete activating one end is akin to what ENSO is to the planet's weather/weather patterns. Hence, that initial movement (perturbation) activates other points (nodes) on the rope; in the atmosphere, this movement can energize regional circulations (like the PJ and WJ), which in turn influence local weather, such as Tokyo WGBT. The only main difference is that the atmosphere does not operate in a straight line (2D) like the rope but is three-dimensional.

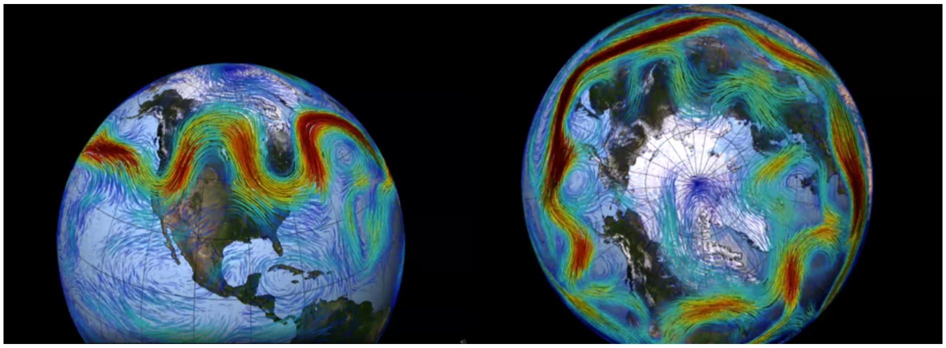
Our study finds a pronounced association between ENSO and Tokyo daytime WBGT levels in the month of August, which is rather remarkable (each geographic location is different and may not show such a strong connection). Our stochastic analysis shows that ENSO explains ~70% of Tokyo August WGBT, and this may be due to the hyper-focus on one location and at a very specific time (vs annual). Our findings, however, underscore the close inter-connectedness of the oceanic/atmospheric systems, and the coupling between large-, regional, and local scale atmospheric processes.

The Rossby wave is a key initial perturbation for planetary weather is [1]; and a central area for this activation is the swath of the Pacific where ENSO is observed [2]. While meteorological (and geophysical) sciences are still seeking to understand the cause of ENSO (e.g., the actual driver of sea-surface temperature, SST), we are able to use observed SST. Through stochastic (and modeled) means, we can then infer how these changes in SST may perturb atmospheric waves, impacting weather in remote locations at some time future time (this is known as a teleconnection, and in the popular media sometimes called the "butterfly effect"). The "flavors of ENSO" *(personal communication with Dr. Kevin Trenberth)* can change the outcome of these teleconnections; hence, meteorologists remain vigilant in studying and understanding its behavior.

The pioneering work of the late Dr. Nitta in 1987 informed the meteorological community on the potential significance of the Pacific-Japan Oscillation (which is often abbreviated as PJ) for weather in Japan [3–5]. He also noted its possible connection to ENSO—either being a derivative of it or some kind of semi-permanent circulation that has identifiable patterns in relationship to ENSO. Nitta noted that the PJO and ENSO are negatively correlated, such that the PJ is positive (negative) when ENSO is in the La Niña Phase (El Niño) phase. Other studies have followed, and closely analyzed these interactions and impacts on the regions of Japan [6–8]. Our study looks at these interactions specifically for Tokyo.

We thus point out that the physical processes behind what are described in this paper are **differences in equatorial Pacific SST that are likely exciting the Rossby wave, leading to differences regional**

circulation patterns that in turn affect local weather within that region (e.g., Tokyo ward). These are the principle drivers behind the current manuscript's analysis.



Images of Rossby waves from vantage points over the North pole and North America (NOAA, 2019) – video at: https://oceanservice.noaa.gov/facts/rossby-wave.html

C.2 How ENSO is Measured – Overview

ENSO is described by its oscillation phase (positive or negative) and intensity (see Section 2.1 of manuscript). The oscillation phase is analyzed during an observation time of five consecutive periods of 3-month running sea surface temperatures (SST) average anomalies (*i.e.,* difference from normal) (see B2.2 for JMA). ENSO intensity is determined by *how anomalous* the SSTs are from normal, based on: "Neutral" (± 0.5°C); *Weak"* (± 0.5°C to 0.9°C); *"Moderate"* (±1.0°C to 1.4°C); *"Strong"* (±1.5°C to 1.9°C); *"Very Strong"* (≥ ±2.0°C).[1] Further note that the JMA uses an observation time of 6 consecutive periods). The oscillation phase or ENSO phase during this period can give rise to separate and unique weather phenomena, when SST anomalies are ± 0.5°C. Positive (warmer) SSTs are called El Nino, and negative (cooler) SSTs are termed La Niña. Anomalies within the ±0.5°C range are called "neutral".

An ENSO year runs from October to September. The months of March, April, May (MAM) (boreal/northern hemisphere spring) form a critical transition period when the cycle may move deeper into its current phase, or transition out of the current phase and into another [9]. For this reason, national weather agencies typically issue statements for the projected ENSO tendency in April-May, for the rest of the ENSO year. This guidance typically informs on tropical cyclone/hurricanes as well as winter preparedness.

It is important to note that the above designation is the same based on the U.S. National Weather Service. The Japan Meteorological Agency (JMA), the NWS equivalent/partner in Japan, uses the same criteria as the U.S. National Weather Service, but tends to focus on NINO3 (see **Figure 1**), as that location proves significant for Japan (Wakabayashi and Kawamura, 2004). We describe this method further below.

How the Japan Meteorological Agency (JMA) Measures and Monitors ENSO

The JMA Index for ENSO only considers SST anomalies in the NINO3 region because the output here is "less noisy" than the commonly used indices for Japan's territory. However, it is unclear if this index is still used operationally. Note that the JMA Index for ENSO varies spatially and temporally the following

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[1] *"Very Strong"* is not part of the official weather service criteria, but is an additional category added in the given analysis based on personal communication with Dr. Jan Null (*personal communication*), using the same +0.5°C increment to capture events that exceeded the "strong" threshold.

ways: it is geographically truncated to 90°W to 150°W, 4°S to 4°N), with an observational period of six consecutive 3-month periods to determine trends [10,11]. Further, the JMA Index is more sensitive to La Niña events [12], and weather patterns in Japan, particularly its summer convective weather patterns (*i.e.,* precipitation or tropical cyclone activity), appear to be La Niña-sensitive [3,4].

C.3 Examples of the Pacific-Japan Index

Examples of the PJI, shown below only for DJF, indicates a general tendency observed across each ENSO season when analyzed by WGBT quartile. WGBT quartiles could be explained by the PJI Quartile analysis (Pq, not fully shown in this study), but our 35 monthly averaged data points are too coarse to truly resolve the features of the PJ, so no conclusion should be drawn from this. The PJ, being a smaller-scale feature, will need a finer temporal resolution (on the order of weeks vs months used here) to resolve.

The general observed pattern of the PJI is negative/low in a neutral phase, slightly higher in an El Niño phase, and significantly higher for an La Niña phase. We further mapped the 35°N vs 22.5°N geopotential heights of the PJI to observe which location of the layer is most dominant on the PJ, and in DJF its clearly the 35°N quadrant which is the latitude closest to Tokyo. Given our 35 years of monthly averaged PJI data, we cannot conclusively deduce this with precision, but we do see that the PJ is more resolved in neutral and El Niño years, especially in DJF. More studies are required to observe the PJ by WGBT quartile, which is includes ENSO phases.

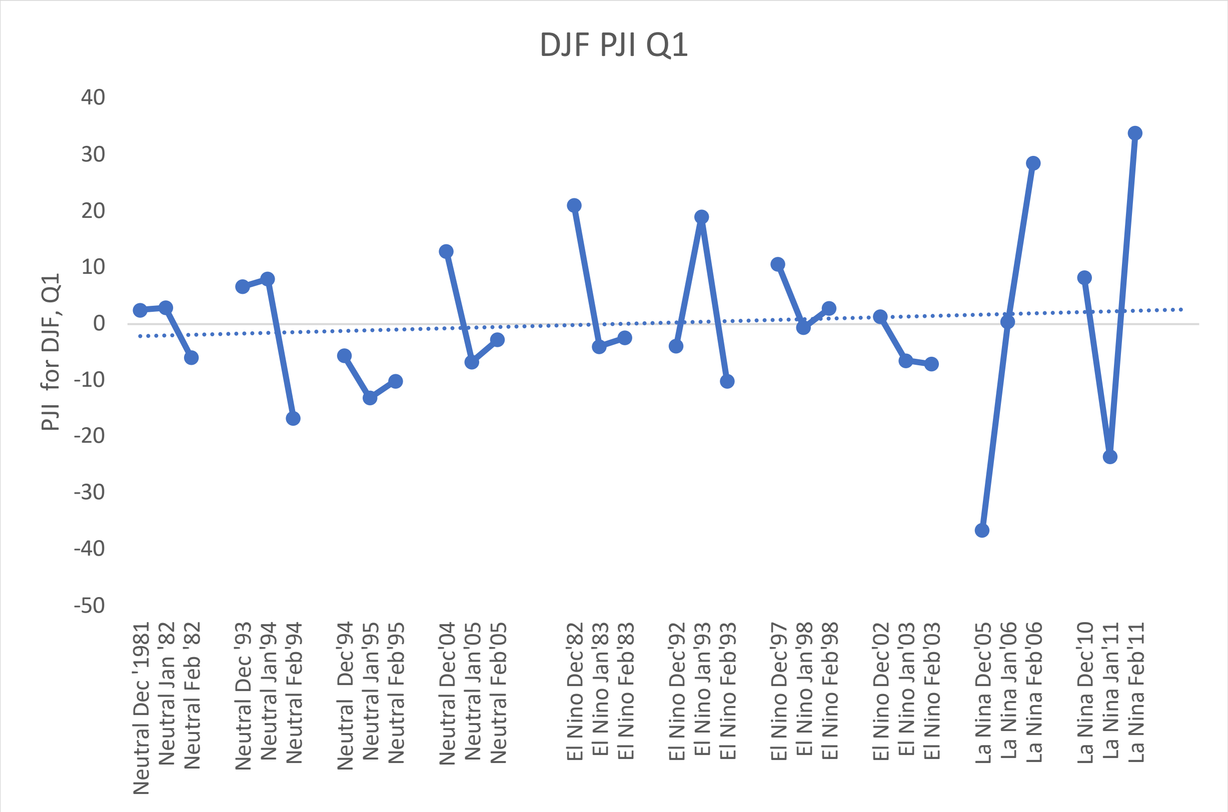


Figure C.1: Pacific Japan Index for December, January, February (DFJ) within Quartile 1 (lowest daytime August WBGT in Tokyo) by ENSO Phase (La Niña, Neutral, or El Niño).

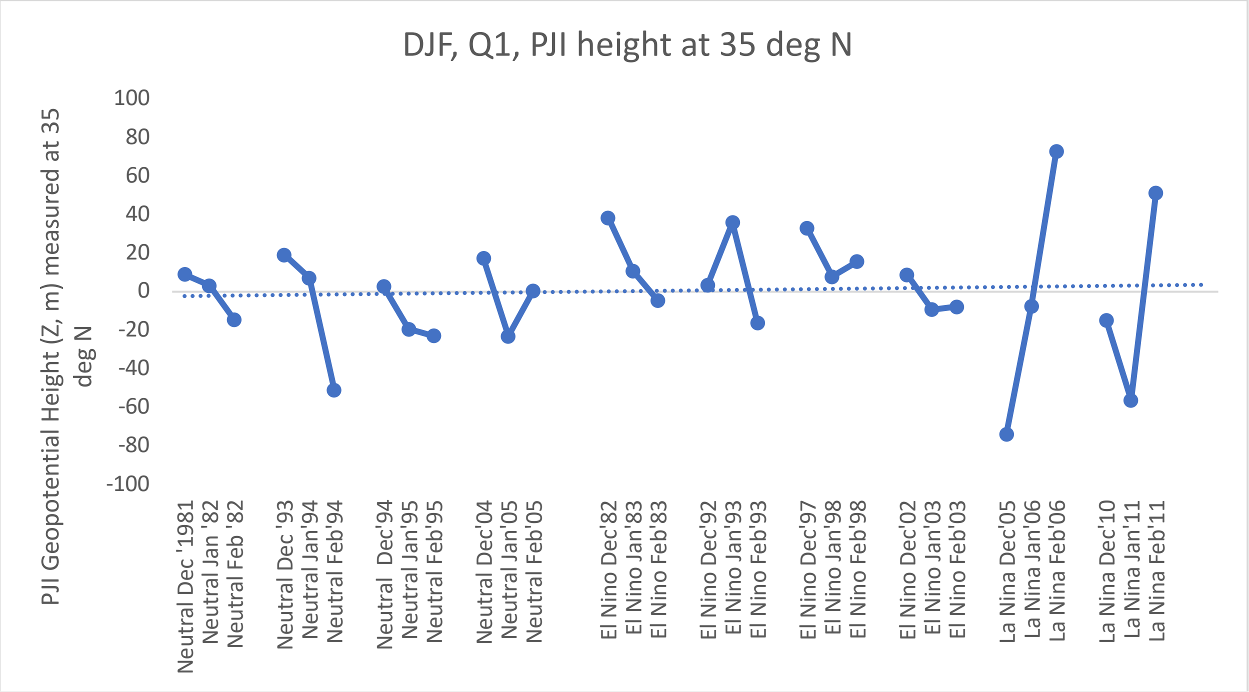


Figure C.2: Pacific Japan Index at 35°N for December, January, February (DFJ) within Quartile 1 (lowest daytime August WBGT in Tokyo) by ENSO Phase (La Niña, Neutral, or El Niño).

C.4 ENSO Effects in Japan and the Indian Monsoon

Significant Indian Monsoon events in Japan: Floods & Drought

ENSO is linked to the Indian monsoon, which has implications for Tokyo's weather. Studies have found a teleconnection between ENSO and the Indian Monsoon [13,14]. Krishanmurthy and Goswami (2000) identified that monsoon droughts are most connected with an El Niño phase, whereas floods tend to be (but not consistently) associated with the La Niña phase. The connections between (1) ENSO and the Indian Monsoon and (2) West-Asian Jet (WJ) and the Indian Monsoon are another example of the close coupling between (remote) atmospheric processes.

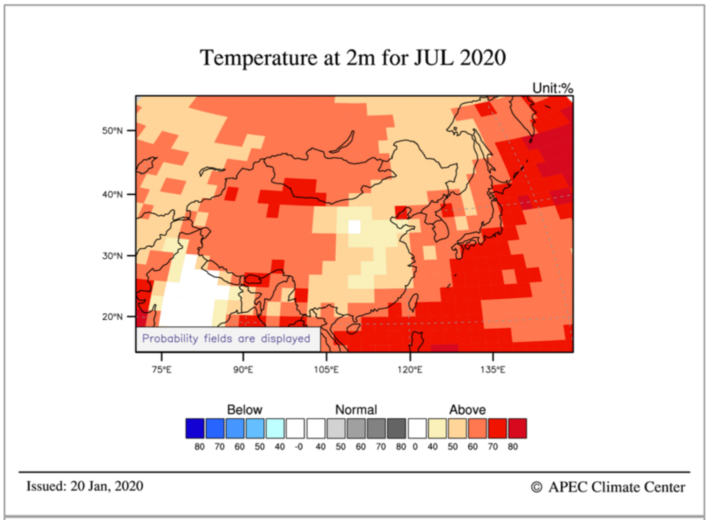
These connections are prominently demonstrated in the PCA and quartile analyses of Tables 4–6. Specifically related to the Indian Monsoon, it must be noted that **the PJI and WJI for each quartile showed a clearer pattern only when the Indian Monsoon was in "significant flood" or "significant drought" phase**. The PJ and WJ pattern for non-monsoon years in each quartile returned no repetitive pattern and is a matter of deeper atmospheric research that is beyond the scope for this present research. For example, in Quartile 3 (Table 5), there were three monsoon-related years: 1994, 2002, and 2004.

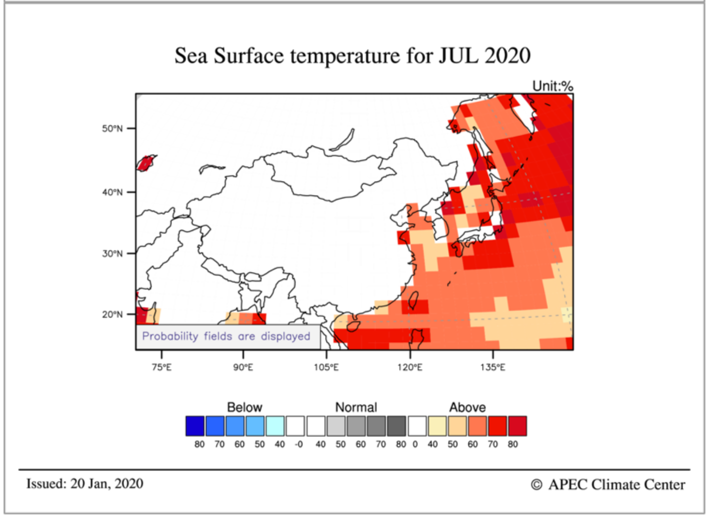
To stay in scope, we presented an overall observation of the ENSO/Indian Monsoon pattern using the Indian Institute of Tropical Meteorology data. Of the eight (8) events (out of the 36 years) with significant monsoon events, only two were in ENSO neutral phase. This finding suggests an influence of phase transitions in the ENSO region associated with the Indian Monsoon. Since the WJ showed a low explanation of August WGBT (Table 5), we infer that the monsoon plays some role, but more studies are needed to better understand the impact of the Indian monsoon on Tokyo's August WGBT.

C.5 General Trends: What to Watch for and When

Currently (early winter, 2020), neutral conditions are persistent in the equatorial Pacific. These conditions are favored through spring 2020 (~60% chance), and are expected to continue through summer 2020 (50% chance).[15] Similar predictions are provided by APCC (https://apcc21.org/ser/outlook.do?lang=en), and shown in images below, stating a strongly enhanced probability for above normal 2m air temperatures and SSTs for our area of interest in Japan in the Northwest Pacific.

The expected neutral phase falls on the tail-end of an El Niño in 2018–19. Into next summer, conditions are presenting SST anomalies lower than normal, yet not enough to indicate a La Niña. However, much more will be known for the upcoming summer season in Feb-Mar. Rossby waves become activated from December to February, which is when we start to look for trends for the upcoming summer season in the Northern Hemisphere. The SSTs in DJF in NINO3 and 3.4 regions will help indicate the ENSO set up next summer and its potential impact on Tokyo. It should be noted again that the warmest WGBT in our 36 years was a "neutral" year (1996), followed a moderate La Niña. The majority of neutral years fell into Q1 and Q2. It should further be added that our study addressed the *characterization of monthly averaged* WGBT, and caution is advised to not imply that all days will behave as the "average". The Bonin/Ogasawara High, BOH, which brings warm/humid conditions grows and decays on ~7–10 day scale, and is responsive to energy from regional circulations,[8] based on physics, approximations of its potential influences from ENSO can be more reasonably approached in MAM 2020.





https://apcc21.org/ser/outlook.do?lang=en

Supplemental Material References

1. Vega A, du-Penhoat Y, Dewitte B, Pizarro O. Equatorial forcing of interannual Rossby waves in the eastern South Pacific. *Geophys Res Lett*. 2003;30(5). doi:10.1029/2002GL015886
2. NOAA/NCEP Climate Prediction Center. El Niño Southern Oscillation: NINO3 and NINO3.4 Indicators. Teleconnections. https://www.ncdc.noaa.gov/teleconnections/enso/indicators/sst/. Published 2019. Accessed August 20, 2019.

3. Nitta T. Global features of the Pacific-Japan Oscillation. *Meteorol Atmos Phys*. 1989;41(1):5-12. doi:10.1007/BF01032585
4. Nitta T, Motoki T. Abrupt enhancement of convective activity and low-level westerly burst during the onset phase of the 1986-87 El Nino. *J Meteorol Soc Japan Ser II*. 1987;65(3):497-506.
5. Nitta T. Convective Activities in the Tropical Western Pacific and Their Impact on the Northern Hemisphere Summer Circulation. *J Meteorol Soc Japan Ser II*. 1987;65(3):373-390. doi:10.2151/jmsj1965.65.3_373
6. Wakabayashi S, Kawamura R. Extraction of major teleconnection patterns possibly associated with the anomalous summer climate in Japan. *J Meteorol Soc Japan Ser II*. 2004;82(6):1577-1588.
7. Friedlingstein P, Cox P, Betts R, et al. Climate-carbon cycle feedback analysis: Results from the C4MIP model intercomparison. *J Clim*. 2006;19:3337-3353.
8. Enomoto T, Hoskins BJ, Matsuda Y. The formation mechanism of the Bonin high in August. *Q J R Meteorol Soc*. 2003;129(587):157-178.
9. Holland GJ. Predicting el Niño's impacts. *Science (80-)*. 2009;325(5936):47.
10. Trenberth KE. The definition of el nino. *Bull Am Meteorol Soc*. 1997;78(12):2771-2778.
11. Climate Prediction Division JMA. El Niño Monitoring and Outlook. El Nino Monitoring. https://ds.data.jma.go.jp/tcc/tcc/products/elnino/elmonout.html. Published 2019. Accessed December 11, 2019.
12. Hanley DE, Bourassa MA, O'Brien JJ, Smith SR, Spade ER. A quantitative evaluation of ENSO indices. *J Clim*. 2003;16(8):1249-1258.
13. Krishnamurthy V, Goswami BN. Indian monsoon–ENSO relationship on interdecadal timescale. *J Clim*. 2000;13(3):579-595.
14. Kumar KK, Rajagopalan B, Hoerling M, Bates G, Cane M. Unraveling the Mystery of Indian Monsoon Failure During El Niño. *Science (80-)*. 2006;314(5796):115 LP - 119. doi:10.1126/science.1131152
15. NOAA. El Nino / Southern Oscillation (ENSO) Siagnostic Discussion. https://www.cpc.ncep.noaa.gov/products/analysis_monitoring/enso_advisory/ensodisc.shtml. Published 2019. Accessed October 23, 2019.