Intensity of climate variability derived from the satellite and MERRA reanalysis temperatures: AO, ENSO, and QBO

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ARTICLE INFO

Article history:
Received 14 June 2012
Received in revised form 12 November 2012
Accepted 6 January 2013
Available online 23 January 2013

Keywords:
MERRA
AMSU
Climate indices
AO
ENSO
QBO

Abstract

Satellite measurements (Atmospheric InfraRed Sounder/Advanced Microwave Sounding Unit-A, Moderate resolution Imaging Spectoradiometer) and the Modern Era Retrospective-analysis for Research and Applications (MERRA) reanalysis have been utilized to analyze the relative influence of the climate variability (AO: Arctic Oscillation, ENSO: El Niño-Southern Oscillation, QBO: Quasi-Biennial Oscillation) on the zonal-mean temperature and wind variations over the globe from September 2002 to August 2011. We also extended the usage of MERRA data for the period of 1979–2011; furthermore, three climate indices of AO, NINO3.4, and QBO were used as the corresponding climate indicators. The correlations between the temperature anomalies and the climate indices indicate that the tropospheric temperature variability in the mid-latitude (30–60N) linked to both AO and ENSO has been more pronounced over ocean than over land. However, the low stratospheric temperature variability in the mid-latitude is mainly associated with ENSO and QBO. The north–south symmetric patterns over the globe are seen in the wind anomaly distributions for ENSO and QBO, but not for AO. The ENSO events are globally vigorous but also localized during the recent 9 years compared with those based on the period of 1979–2011. The tropospheric warming and stratospheric cooling phenomena during this period are more remarkable in the recent 9 years, although according to IPCC (2012), their linkage to the ENSO variability is still uncertain. The ENSO is found to have more significant impact on the tropospheric and low stratosphere temperature variability over the tropics in the recent period, consistent with more active zonal wind meridional circulations. The discrepancies between satellite observations and MERRA are also discussed. The estimated relative impact of the three major concurrent large-scale climate phenomena on regional temperature variability can be of great use in its long-term predictability.

1. Introduction

Major sources of interannual variability in the atmospheric circulation over the globe are the El Niño-Southern Oscillation (ENSO) and the Arctic Oscillation (AO), particularly in the boreal winter (Yadav et al., 2009), and the Quasi-Biennial Oscillation (QBO). Numerous research papers have demonstrated atmospheric variability in connection with ENSO over the globe (e.g., Philander, 1990; Treberth and Hurrell, 1994; Zhang et al., 1997; Yang et al., 2002; Brönnimann, 2007, Manzini, 2009), AO (e.g., Thompson and Wallace, 1998, 2000; Thompson et al., 2000; Wallace, 2000), and QBO (e.g., Holton and Tan, 1980; Labitzke and van Loon, 1988; Salby et al., 1997; Randel et al., 1999; Baldwin and Dunkerton, 2001). ENSO is a coupled ocean–atmosphere phenomenon influencing tropical and extra-tropical regions through atmospheric oscillations and teleconnections (e.g., WMO, 2010). The AO is defined as the difference in the sea level pressure (SLP) between the northern hemispheric mid-latitudes and the Arctic; it is also a ‘positive phase’ with relatively high pressure over the former region (e.g., Wallace, 2000; WMO, 2010). The ENSO and AO are known to cause the largest climate perturbations (Jevrejeva et al., 2003), and generally have a great impact on the mid-latitude climate in the troposphere and low stratosphere, together with the role of QBO in the upper atmosphere. The QBO is an interannual...
oscillation of the zonal winds and temperatures in the tropical stratosphere with an approximate 2-year periodicity (e.g., Randel et al., 1999), and the observed QBO characteristics have been described by Holton (2004). Most of the earlier studies on climate change concentrated on surface variables (e.g., temperature and wind) that are important to human beings (Trenberth and Hurrell, 1994). Therefore, understanding the temporal and spatial relationship of the three major phenomena and the estimation of their relative impacts in terms of some meteorological variables (i.e., temperature and wind) are essential in explaining the climatic variability over the globe.

Variations in the atmospheric and surface temperatures are the basis of studying the intensity of the global climate changes, as shown in previous studies (IPCC, 2012). According to the model intercomparison by Scaife et al. (2009), climate models are able to reproduce both the Southern Oscillation (SO) and global warming to some extent; however, they are not able to reproduce the North Atlantic Oscillation (NAO). The NAO and AO have been considered to be the representation of the same basic phenomena (Wallace, 2000; Yadav et al., 2009). Scaife et al. (2009) suggested that poor NAO simulation from climate models is possibly due to the lack of troposphere–stratosphere interactions. In order to better understand and confirm the important climate phenomena, reliable and consistent temperature observations are required in various vertical layers, such as the mid-troposphere (~500 hPa) and low stratosphere (~50 hPa) as well as in the surface skin (hereafter called ‘skin’). In this study, satellite-derived temperature data of the three layers over the globe from the past 9 years (September 2002 to August 2011; Case 1) are utilized, based on the data of the Atmospheric Infrared Sounder (AIRS)/the Advanced Microwave Scanning Sounder Unit-A (AMSU-A; hereafter named AMSU) (e.g., Susskind et al., 2003; Mostovoy et al., 2005) and MODerate-resolution Imaging Spectroradiometer (MODIS). We further exploited the model Modern-Era Retrospective Analysis for Research and Applications (MERRA) reanalysis during the 33 year period (January 1979–December 2011; Case 2). We can check the effect of satellite data (AIRS/AMSU and MODIS) assimilation on the climate analysis by comparing the results for the two periods.

In the global domain, the relative influence of the three major climate phenomena (AO, ENSO, and QBO) on the monthly mean temperature variations has been poorly known. Because of the importance as indicators for thermal variability in the climate system, the climate indices related to the three phenomena can be utilized to understand the long-term predictability for temperature and their impact on climate change together with the model simulations (e.g., Scaife et al., 2009; Ineson and Scaife, 2009). Specifically, to better understand the global relationship between thermal and climate variability, it is necessary to investigate the correlation (or regression) of time series between monthly zonal-mean temperature (or wind) anomalies and climate indices, in connection with the AO (e.g., Thompson and Wallace, 2000; Thompson et al., 2000), ENSO, and QBO.

In this paper, we address the relative impacts of the three phenomena in terms of zonal-mean temperature and wind variability using the MERRA reanalysis (Rienecker et al., 2011) during Case 2 as well as the satellite data for Case 1. The MERRA was obtained from the state-of-the-art global data assimilation systems which are suitable for climatological studies. The comparison in temperature variability between the two periods is important, for instance, because the frequency and intensity of the ENSO events have changed with time (Müller and Roeckner, 2006; Brönnimann, 2007; Yeh et al., 2009; Lee and McPhaden, 2010). Furthermore, the ENSO impact on mid-latitude circulation patterns and the NAO variability is expected to be more pronounced in the future winter climate, based on the experiments of a coupled atmosphere-ocean climate model (Müller and Roeckner, 2006).

This paper is presented as follows. In Section 2, the data and method are described, introducing satellite observations and the MERRA reanalysis. The climate variability based on the two datasets is described in Sections 3 and 4, respectively. Tropospheric and stratospheric temperature trends from the MERRA in relation to the climate variability are shown in Section 5. The discrepancies between satellite and MERRA data are discussed in Section 6. Conclusions are presented in Section 7.

2. Data and method

For Case 1, we used four satellite-observed datasets taken over the globe (Table 1). The satellite data from AIRS/AMSU were utilized to examine skin temperatures. In addition, we analyzed skin temperatures from the MODIS observations. The AMSU temperature data at the heights of 500 hPa and 50 hPa were also used to analyze the thermal state of mid-troposphere and low stratosphere, respectively (e.g., Olsen, 2007). The MODIS data, which have a higher spatial resolution than the one from the AIRS/AMSU data, have been rearranged in the same grid of 1° × 1° (~100 km × 100 km) for comparison of the two datasets over the globe. The spatial resolutions of the MODIS land and ocean surface skin temperature are 5 km × 5 km and 4 km × 4 km, respectively. Since the high resolution MODIS data are converted into the low resolution for the comparison, there is no impact due to rebinning the grid on our analysis. According to Lee et al. (2012), the two datasets on a 1° × 1° grid are in agreement within ~1.7 K in the 50N–50S region on an annual average basis. In this study, annual and seasonal cycles were removed by using monthly mean temperature anomalies in order to correlate the temperature and climate indices.

The satellite Level 3 (L3) gridded data obtained from radiometer measurements of MODIS and AIRS/AMSU-A (hereafter AMSU-A named AMSU) onboard the EOS Aqua satellites were utilized in this study. The polar orbiting Aqua satellite, which provides observational data twice a day, has Local Equatorial Crossing Times (LECTs) of 1:30 am (descending) and 1:30 pm

### Table 1

<table>
<thead>
<tr>
<th>OBS temperature</th>
<th>Temp type</th>
<th>Area</th>
<th>Spatial resolution</th>
<th>Number of OBS</th>
<th>Satellite sensor</th>
<th>LECT</th>
<th>Abbreviation</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>MODIS SST</td>
<td>Skin</td>
<td>Globe</td>
<td>5 km × 5 km</td>
<td>2/day</td>
<td>Aqua MODIS</td>
<td>01:30/13:30</td>
<td>T_{skin} (MODIS_SST)</td>
<td>Olsen (2007)</td>
</tr>
<tr>
<td>MODIS SST temp profile at 24 levels</td>
<td>Air</td>
<td>Globe</td>
<td>4 km × 4 km</td>
<td>2/day</td>
<td>Aqua MODIS</td>
<td>01:30/13:30</td>
<td>T_{skin} (MODIS_SST)</td>
<td>Olsen (2007)</td>
</tr>
<tr>
<td>AIRS/AMSU skin temp</td>
<td>Skin</td>
<td>Globe</td>
<td>1° × 1°</td>
<td>2/day</td>
<td>Aqua AIRS/AMSU-A</td>
<td>01:30/13:30</td>
<td>T_{skin} (AIRS/AMSU)</td>
<td>Olsen (2007)</td>
</tr>
</tbody>
</table>
L3 products of AIRS/AMSU (AIRX3STM) and MODIS have been derived from Version 5 retrieval algorithm (e.g., Olsen, 2007 for AIRS/AMSU; Wan, 2009 for the MODIS Land Surface Temperature). AMSU is composed of 12 channels within the 50–60 GHz portion of the oxygen band for thermal information (Chahine et al., 2001). The AIRS/AMSU data have a resolution of 1° × 1° over both land and ocean. According to the AIRS document (Harris, 2007), the AIRS/AMSU monthly L3 products can be used for an analysis of long-term climate trends with the lowest possible systematic errors. On the other hand, the MODIS data have spatial resolutions of 5 km × 5 km over land and 4 km × 4 km over ocean (e.g., Wan, 2005, 2009; Wang et al., 2008; Coll et al., 2009). MODIS data products used in our study are as follows: L3 version 5 monthly Land Surface Temperature (LST) data as MYD11C3.5, and Ocean L3 version 4 Standard Mapped Image (SMI) data for Sea Surface Temperature (SST). The AIRS/AMSU instrument has been designed to obtain mean temperatures for tropospheric layers with 1 km thickness at an accuracy of 1 K (e.g., Olsen, 2007), while the accuracy of the MODIS LST is better than 1 K for the clear-sky condition (Wan et al., 2004). The satellite-observed trend estimates have been verified with independent ground-based measurements from surface-stations, buoy, and radiosondes around the Korean Peninsula (Yoo et al., 2011).

MERRA, developed by the Global Modeling and Assimilation Office (GMAO) of NASA, is a satellite era reanalysis. The Goddard Earth Observing System Version 5 (GEOS-5) is the assimilation system used to produce MERRA data that span the period of January 1979–present. Besides the conventional data sources, such as weather stations, balloons, aircraft, ships, and buoys, observational inputs to MERRA include satellite data such as TIROS Operational Vertical Sounder (TOVS) radiances, Aqua/Atmospheric Infrared Sounder (AIRS) radiances, Special Sensor Microwave Imager (SSMI) radiances, Geostationary Operational Environmental Satellites (GOES) sounder bright temperatures, and the Solar Backscatter Ultraviolet instrument (SBUV/2) ozone (Rienecker et al., 2011). The MERRA reanalysis is performed at the native horizontal resolution of 2°/3° longitude by 0.5° latitude, and at 72 levels up to 0.01 hPa (Rienecker et al., 2011). We used monthly assimilated fields of atmospheric temperatures and winds from the implementation of the Incremental Analysis Update (IAU; Bloom et al., 1996) corrector, which are provided at a reduced horizontal resolution of 1.25° by 1.25° at 42 pressure levels.

For the correlation analysis between thermal and climate variability, we utilized the AO (NOAA, 2011a; Thompson and Wallace, 1998), NINO3.4 (NOAA, 2011b; Brönnimann, 2007) and QBO at 50 hPa indices as the atmospheric components of AO, ENSO, and QBO (NOAA, 2011c), respectively. Here, the thermal variability was derived from both satellite observations and the MERRA reanalysis. The AO is characterized by the leading Empirical Orthogonal Function (EOF) mode of the northern hemisphere sea-level pressure (Fyfe et al., 1999) whereas the NINO3.4 index represents the average SST anomaly over the region (120–170W, 5N–5S) (e.g., Müller and Roeckner, 2006). In this study, the three climate indices during the periods of Cases 1 and 2 were obtained from NOAA.

In this study, we used the linear correlation method in order to examine the inter-relationship between temperature and climate variability.
indices (AO, NINO3.4, and QBO), and the ‘simple’ linear regression is used for analyzing the influence of each climate index on wind (e.g., von Storch and Zwiers, 1999). The main purpose of this study is to address the relationship between temperature and the climate indices. In addition, the regression analyses of wind on each climate index have been utilized to additionally support the issue. The method we used in this study, simultaneous correlation/regression only reveals the linear relations. Lead/lag relation is not considered here. Thus, “relative impacts” means which index shows most strong linear correlation/co-variation.

3. Correlation between satellite-derived temperatures and climate indices

The values of the correlation coefficient (CC) in the monthly zonal-mean anomaly time series between satellite-derived temperatures and climate indices (i.e., AO, NINO3.4, and the QBO at 50 hPa) were examined in order to analyze the temperature variations for Case 1, linked to the climate variability at the three vertical layers (skin, mid-troposphere, low stratosphere) over seven global areas divided by latitudes (Table 2). Here the ‘*’ and ‘o’ symbols indicate statistically significant cases at the 95% and 99% confidence levels respectively. The coefficients were also calculated over three separate areas of ‘Ocean and Land’, ‘Ocean’, and ‘Land’, respectively. Fig. 1 is a graphical representation of Table 2 for the case of ‘Ocean and Land’ only.

From the statistical analysis of satellite temperature variation with climate indices, it is found that in the mid-latitude (30–60N) of the northern hemisphere (NH), AO and ENSO have more significant influence on the layers from skin to mid-troposphere (500 hPa) over ocean than over land (Table 2 and Figs. 1 and 7). On the other hand, ENSO and QBO are more pronounced in the low stratosphere without reflecting the surface boundary effect (Table 2). The surface oceanic effect in the troposphere is expected due to the contributions of the Pacific/North American (PNA; Horel and Wallace, 1981) index in the Pacific for ENSO (Fig. 7b and e) and the NAO index in the Atlantic for AO (Fig. 7a and d), respectively. In the NH mid-latitude belt (Ocean and Land), the correlations between the satellite-derived temperature and AO are found to be positive ($r = 0.28–0.37$ significant at the 99% confidence interval) from the skin to mid-troposphere, and negative ($r = 0.14$ not significant) in the low stratosphere (Fig. 1a and Table 2). The AO has the largest impact on skin temperatures in the NH tropics, particularly in the land region ($r = -0.47$ $-0.55$); however, this tendency is not clear in the mid-troposphere (Table 2).

In the low stratosphere over the NH mid-latitude (Ocean and Land), the satellite-derived temperatures are highly correlated with ENSO ($r = 0.49$) and QBO ($r = 0.44$) (Table 2 and Fig. 1b and c). The positive CC in the low stratosphere of the NH mid-latitude during ENSO is consistent with Manzini (2009), who explained the correlation in terms of the relationship between ozone and temperature, together with the planetary waves emerging from the troposphere into the stratosphere during northern winter. According to Manzini (2006, 2009), the large scale, extratropical tropospheric response to ENSO also enhances planetary wave propagation from the troposphere into the stratosphere, resulting in the warming over the high latitudes of both hemispheres. The dynamical connection between the ENSO and the low stratosphere over the high latitudes in both hemispheres during the winter was also suggested by Manzini (2009), and its effect was shown to be more significant in the North Pole than in the NH mid-latitude. However, the effect is not substantial in the North Pole in this study probably due to the use of data for the whole months of each year, not focusing just on the winter months (Fig. 1b). In our study, the effect of ENSO in the low stratosphere occurs globally in a symmetric pattern with respect to the equator, showing a significant CC value ($r = 0.29$) over the 30–60S latitude band.

The meridional CC variations of the temperature versus three climate indices in the tropospheric layers (i.e., skin and mid-troposphere) are generally out of phase with those in the low stratosphere, indicating the coupling between troposphere and stratosphere. In particular, the coupling and teleconnections during the ENSO have been reviewed and presented by numerous studies in literature (e.g., Brönnimann et al., 2004; Brönnimann, 2007; Manzini, 2009; Ineson and Scaife, 2009; Cagnazzo and Manzini, 2009; Randel et al., 2009; IPCC, 2012). According to the review of Brönnimann (2007), the increase of planetary wave activity entering from the troposphere to the stratosphere decelerates the zonal mean flow and accelerates the poleward flow during El Niño winters, leading to an enhanced Brewer–Dobson
circulation and a poleward ozone transport in the late winter polar region. In the teleconnection, the role of ozone concentrations on the stratospheric temperature trends has been discussed by Randel and Cobb (1994), Randel et al. (2009), Ramaswamy et al. (2001), and Brönnimann et al. (2004).

Although the ENSO effect on the skin and mid-tropospheric temperatures in the NH mid-latitude of ‘Ocean and Land’ is weak ($r=-0.17 \sim -0.22$) compared to that of the AO ($r=0.28 \sim 0.37$), the cases of $T_{\text{skin}}$(MODIS) and $T_{500}$ hPa(AMSU) are still significant at the 95% significance level. Here, $T_{\text{skin}}$(MODIS) and $T_{500}$ hPa(AMSU) represent MODIS skin temperature and AMSU mid-troposphere (i.e., 500 hPa) temperature, respectively (see also Table 1). In summary, the tropospheric temperature variation in the NH mid-latitude is linked primarily to AO, and secondarily to ENSO and QBO suggesting the considerable effect of surface oceanic boundary for the ENSO and AO cases. These results suggest that the climate indices in the latitude belt should be utilized as indicators for long-term thermal variability with teleconnections of the above major climate events.

The thermal variability in the three atmospheric layers (skin, mid-troposphere, low stratosphere) over the ‘Ocean and Land’ of the tropics (30N–30S) has been substantially affected by ENSO (Table 2 and Fig. 1b), as noted in earlier studies (e.g., Trenberth and Hurrell, 1994; Zhang et al., 1997; IPCC, 2012). In these studies, the teleconnections for ENSO are more remarkable over ocean than over land. This tendency is clear in the AIRS/AMSU

**Fig. 2.** Correlation coefficients between monthly zonal-mean temperature anomalies and the (a) AO, (b) NINO3.4, and (c) QBO at 50 hPa indices, based on the MERRA reanalysis data over the globe from September 2002 to August 2011 (Case 1). White solid (dashed) lines stand for positive (negative) correlation coefficients at the 5% significance level. (d)–(f) Same as in Fig. 2(a)–(c), but for the period from January 1979 to December 2011 (Case 2).
surface temperature ($T_{20}$) in our study, as depicted in Table 2. Note that over the tropics north of the equator, AO influences significantly at the 99% level on thermal variability of the skin and the low stratosphere but not for the mid-troposphere (Fig. 1a).

In addition, during the recent 9 years, the AO and ENSO phenomena have affected the tropospheric and low stratospheric thermal states, respectively, in temperature variability over the NH mid-latitude. Since the troposphere and the low stratosphere in the mid-latitudes interact with each other through upward propagating Rossby waves, depending on the low stratospheric polar vortex (Thompson and Wallace, 1998; Wallace, 2000; Liu et al., 2004; Bond and Harrison, 2006; Cagnazzo and Manzini, 2009; Cohen et al., 2010; Scaife, 2010), the dynamical relationship between AO and ENSO has to be understood in order to predict thermal trends more accurately in the mid-latitude. Possible mechanisms in the interaction between the ENSO and NAO over the Atlantic Ocean have been discussed by Müller and Roecker (2006). As mentioned in previous studies (Holton and Tan, 1980; Holton, 2004), the QBO remarkably influences the low stratosphere over the globe, particularly in the NH tropics and mid-latitude (Table 2).

4. Temperature and wind variability from the MERRA reanalysis

In order to examine the differences in thermal characteristics associated with the interannual climate variations of the AO, ENSO, and QBO, we constructed the CC between monthly zonal-mean temperature anomalies and climate indices during the periods of Cases 1 and 2, respectively; the first dataset corresponds to the overlapping period with the satellite data, i.e., September 2002 to August 2011 (Fig. 2a–c), and the second corresponds to the entire duration of the reanalysis data from January 1979 to December 2010 (Fig. 2d–f). The distinctive features in the CC patterns due to temperature variability in the two periods are expected to provide further insight into the interannual changes observed in the relationships. The thermal circulation with climate variability can be analyzed better by utilizing both temperature correlation and wind regression with respect to climate indices, as shown by previous studies (e.g., Thompson and Wallace, 2000; Thompson et al., 2000). The regression relationship between monthly zonal-mean zonal wind anomalies and the indices in the meridional distribution has also been portrayed in Fig. 3. Positive and negative CC (or regression) threshold values significant at the 0.05 (or 95%) level are plotted with solid and dashed white contours, respectively.

The CC values in the anomaly time series between MERRA temperature and climate indices indicate that tropospheric temperature variability in the mid-latitude (30–60N) is linked to both the AO and the ENSO (Fig. 2a,b and d,e). However, the low stratospheric temperature in the latitudinal belt is mainly associated with ENSO and QBO, respectively (Fig. 2b,c and e,f). The warm anomalies in the troposphere over the tropics and in the 100–15 hPa stratosphere over the NH mid-latitude during the ENSO have been discussed in previous studies (Fig. 2b and e; Manzini, 2009; Ineson and Scaife, 2009). In particular, strong positive CCs with ENSO in the NH mid-latitudes are shown over the low stratospheric region for Case 1 (Fig. 2b), consistent with the AIRS/AMSU zonal-mean observations during the same period (Fig. 1b). These figures also suggest that the ENSO-temperature relationship has globally strengthened during the recent 9 years, particularly in the tropics and mid-latitude regions (Fig. 2b and e).

Furthermore, Case 1 shows intensified positive CC in the troposphere and negative CC in the stratosphere with a strong dipole pattern in a vertical direction over the tropics, compared to Case 2. This indicates the recently enhanced influence of ENSO on the upper and lower atmospheric temperature over the tropics, implying a more unstable tropical atmosphere due to the ENSO effect on tropospheric warming and stratospheric cooling over the region (Fig. 2b).

The teleconnections from the relationship between temperature and the three indices have also been intensified and localized in the Southern Hemisphere (SH) during the recent 9 years (Case 1; Fig. 2a–c), compared to Case 2 (Fig. 2d–f). The strong CC patterns above 100 hPa in Fig. 2c and f show that QBO dominates the stratospheric temperature variation. This effect was particularly enhanced during the recent 9 years with significant positive and negative CCs over the SH region, although the corresponding wind variations for Cases 1 and 2 remain almost unchanged (Fig. 3c and f). However, among the three major climate phenomena, the ENSO is found to latey make the most substantial impact on the tropospheric and low stratospheric temperature variability over the tropics and mid-latitude regions (Fig. 2b and d). Specifically, for Case 1 the strong dipole patterns between the warm troposphere and cold stratosphere over the tropics, and between the warm tropics and cold mid-latitudes in the troposphere can lead to reinforced Hadley circulation with steep thermal gradients (Fig. 2b).

In summary, the AO, ENSO, and QBO have affected temperature more actively for Case 1 (Fig. 2a–c) than for Case 2 (Fig. 2d–f). For the recent 9 year period, the CCs have been enhanced in the following regions: (1) AO—cold anomaly in the troposphere over the SH high latitudes (Fig. 2a). (2) ENSO—over the tropics, warm anomalies in the troposphere and cold anomalies in the 100–15 hPa stratosphere, and wave-like cold anomalies in the upward, diagonal direction from both hemispheric mid-latitude surfaces to the stratosphere over the tropics (Fig. 2b). (3) QBO—cold anomalies in the stratosphere over the SH high latitudes (Fig. 2c). The wind variability, which corresponds to that of temperature, is not clear for the AO and QBO, but quite clear for the ENSO (Fig. 3).

Fig. 3 shows the regression slopes between the monthly zonal-mean zonal wind anomalies (1000–10 hPa) and the climate indices of the AO, NINO3.4 and QBO over the globe for Cases 1 and 2, respectively, utilizing the data of the MERRA reanalysis. The white solid (dashed) lines indicate positive (negative) regression slopes at the 95% significance level. The CC and regression spatial distributions for the ENSO and QBO generally show north/south symmetric patterns over the tropics, unlike the AO (Figs. 2 and 3). The temperature and wind distributions for AO are clearly asymmetric with large anomalies and variability in the NH, due to the land/ocean contrast and topography (Fig. 2a,d and Fig. 3a,d; Thompson and Wallace, 1998, 2000). In Fig. 3a and d, the regression patterns of wind versus AO are generally similar to the ‘high phase’ AO noted in the study by Wallace (2000), (see his Fig. 4 for the years 1968–1997).

Due to the interaction between wind and the three indices, the regression values are greater for Case 1 than for Case 2 in the following regions: (1) AO—westerly anomalies in the mid-troposphere over the Arctic and in the layer from troposphere to low stratosphere over about 55S (Fig. 3a and d). (2) ENSO—westerly anomaly in the layer from mid-troposphere to low stratosphere over the tropics, and easterly anomalies in most of the atmosphere over about 60N and 60S, respectively, and in the upper stratosphere over the tropics (Fig. 3b and e). Compared to the regressions of wind with respect to either the AO or QBO, there has been a distinctive change in wind versus the NINO3.4 between Case 1 and Case 2. Although the increase of westerly anomaly in the troposphere of the tropical Pacific during the ENSO is well known in earlier studies (e.g., Horel and Wallace, 1981; Philander, 1990), the anomaly in this study is recently more
strengthened in the layer from mid-troposphere to low stratosphere for the recent 9 years (Fig. 3b). This tends to be somewhat stronger in the SH tropics than in the NH one. IPCC (2012) reported that the recent El Niño events tend to be centered more in the central equatorial Pacific than in the eastern Pacific (Yeh et al., 2009), and their intensities increased in the former region (Lee and McPhaden, 2010). On the other hand, the wind change for the two other climate indices (AO, QBO) between the two Cases is relatively weak, particularly for the mainly stratospheric phenomenon of the QBO.

The warm anomalies in the low stratosphere over the NH mid-latitudes during the ENSO (Fig. 2b and e) have been known to be associated with the polar vortex (Fig. 3b and e), of which strength can depend on the phase of the AO (Thompson and Wallace, 2000; Wallace, 2000). Thompson and Wallace (2000) reported that anomalously strong westerlies north of 45N, related with the AO, were linked to easterly anomalies around 35N and in the low troposphere over the tropics, leading to stronger trades, as shown in Fig. 3d. However, the easterly anomalies for the AO in our study are extended into the tropopause or the low stratosphere over the tropics, and furthermore, the upper atmosphere around 25S via the equator. This tendency for the AO is likely related to the warm anomalies in the 100–20 hPa low stratosphere over the tropics (Fig. 2a; for the NH winter, see also Thompson and Wallace.
(2000)). The results in Figs. 2 and 3 suggest a possible interaction between the ENSO and AO, based on thermal teleconnection and wind circulation. Müller and Roeckner (2006) reported some evidence of the interaction between the ENSO and NAO over the Atlantic Ocean.

According to Wallace (2000), who has primarily concentrated on wintertime (January–March; JFM), cold temperature anomalies in the low stratosphere due to enhanced easterlies in the tropopause (~200 hPa) around 30N can be associated with warm anomalies in the low stratosphere over the tropics. In previous studies (Thompson et al., 2000; Wallace, 2000), the AO explained over 30% of the JFM warming of the NH continents. Based on the above results, it is seen that the AO has a teleconnection in temperature from the mid-latitude surface to the low stratosphere over the tropics (Figs. 2d and 3d). The relation between temperature and wind in the meridional distribution for the AO has been comprehensively studied by Wallace (2000), and has been explained in terms of the flux of planetary waves (e.g., Rossby waves) and Brewer–Dobson stratospheric circulation. Since the Brewer–Dobson circulation affects the ozone transport from the tropics into the polar stratosphere, the amount of ozone and the temperature in the layer depend on the intensity of the circulation, implying a coupling between the tropospheric AO and the low stratospheric condition (Baldwin and Dunkerton, 1999; Wallace, 2000).

5. Tropospheric and stratospheric temperature trends from the MERRA reanalysis

Temperature trends in the layer (1000 hPa–10 hPa) have been examined for the following three periods: Period 1 (P1, September 1982–August 1991), Period 2 (P2, September 1992–August 2001), and Period 3 (P3, September 2002–August 2011) (Fig. 4). As aforementioned, ‘Period 3’ corresponds to ‘Case 1’ when the AIRS/AMSU data is available for the observational input to MERRA. This analysis may be useful to understand the influence of satellite observations on the MERRA reanalysis data as well as the decadal trends. Since the background temperature trends of both the troposphere and the stratosphere may have an influence on the relationship between temperature (or wind) and the climate indices for the two Cases (e.g., Trenberth and Hoar, 1996; Müller and Roeckner, 2006; Scaife et al., 2009), this issue has been investigated by scrutinizing the difference in temperature trends among the three periods.

Although the influence of tropospheric warming on global climate change is still an open question (Trenberth and Hurrell, 1994), there are some possible connections between them in the atmospheric climate models. For instance, Scaife et al. (2009) found a strong relationship between the Southern Oscillation (SO) and the global warming rate by comparing the climate model simulations. Trenberth and Hoar (1996) suggested that the ENSO pattern might change more likely due to global warming and an increase in greenhouse gases than natural decadal-timescale variation. Moreover, under global warming based on coupled model calculations, ENSO events tend to occur more in the central equatorial Pacific region than in the eastern Pacific (Yeh et al., 2009); further, their intensities in the former region are also increased (Lee and McPhaden, 2010). In addition, Müller and Roeckner (2006) reported that an accurate estimation of ENSO in a future climate from a coupled climate model could be limited by uncertainties due to future greenhouse gas or aerosol forcing. However, so far, various model simulations suggest that the intensities in ENSO variability, as a result of global warming and increased greenhouse gases, do not agree with each other and thus, their confidence level is low (e.g., van Oldenborgh et al., 2005; Cherchi et al., 2008; Collins et al., 2010; IPCC, 2012).

Fig. 4a shows the difference in the zonal mean temperature between Period 2 and Period 1 (i.e., P2 minus P1); the difference of P3 minus P2 is presented in Fig. 4b. Each period corresponds to a 9 year term within the past three decades, approximately for Case 2. The datasets have been rebinned by the same term, because the satellite AIRS/AMSU observations for P3 is our main concern. It can be seen that tropospheric warming and stratospheric cooling have persistently occurred in the thermal trend differences (P2 minus P1, P3 minus P2). Tropospheric warming was a little stronger in the recent period (P3) and particularly near the tropopause over the polar regions. However, the atmospheric background trends basically remained almost unchanged in the last three decades, inducing radiatively more unstable conditions from tropospheric warming and stratospheric cooling. According to IPCC (2007, 2012), the observational trend, similar to the MERRA estimate of our study, is very likely because of the combined effects of increasing greenhouse gases and stratospheric ozone depletion.

In order to examine an interannual variation of temperature associated with ENSO phenomena and volcanic eruptions, we have analyzed the zonal mean temperature anomalies of the MERRA reanalysis as a function of time and latitude at four pressure altitudes (50 hPa, 200 hPa, 500 hPa and 975 hPa) over the globe for Case 2 (Fig. 5). The altitudes approximately correspond to the layers of the low stratopause, tropopause, mid-troposphere, and surface. The characteristics of tropospheric warming in the layer of 200–975 hPa and stratospheric cooling at ~50 hPa with time are remarkable. The warming occurs in the
layer of 200–500 hPa more vividly than near the surface in the recent 9 years. This is consistent with IPCC (2007), reporting that tropospheric warming over the tropics is likely to increase with altitude. Since 1993, stratospheric cooling has become more distinct. The warming trend at \( \sim 200 \) hPa is prevailing in the tropics and mid-latitudes, but is not clear in the high latitude and polar regions. This suggests that the tropopause (that is assumed as a constant level at 200 hPa in this study) could vary with latitudes, and thus, it may correspond to the low stratosphere in the polar regions (e.g., Hartmann, 1994).

Fig. 5 also shows the major events of the ENSO and volcanic eruptions as a function of time and latitude. For instance, the two volcanic eruptions of El Chichon (17.4N, 93.2W) in August 1982 and Pinatubo (15.1N, 120.4E) in August 1991 are represented as warm anomalies at \( \sim 50 \) hPa. In addition, the tropospheric warm anomalies due to the ENSO events are seen most prominently during the 1997–1998 event. This tendency was more salient in the middle and upper tropospheric layers of 200–500 hPa than in the near surface (\( \sim 975 \) hPa). Tropospheric warming due to the major 1982–1983 ENSO was not as intense as the ones in 1997–1998 and 2009–2010. The 1982–1983 ENSO intensity would be partially masked by the tropospheric cooling due to the El Chichon volcanic eruption (Wielicki et al., 2002).

6. Comparison in the thermal trend between AMSU and MERRA; temperature versus climate indices

We used the data from both satellite AMSU observations and MERRA reanalysis in order to analyze the relative intensity in climate variability in association with the AO, ENSO, and QBO in the same domain of space-time. The satellite AIRS/AMSU data were used as observational input to the MERRA reanalysis (Rienecker et al., 2011), and thus, both datasets are partially dependent. Also, the artifact pattern due to additional AIRS/AMSU input to MERRA has not been identified in the reanalysis time series for the year 2002. However, since the two datasets also have some different basic features (e.g., weighting functions in the satellite data), it is important to interpret their results in terms of the relationship between temperature vs. climate indices. Fig. 6 shows the spatial distribution of the correlation coefficient between the low stratospheric temperature anomalies at 50 hPa and climate indices (AO, NINO3.4, QBO), derived from the AMSU and MERRA data from September 2002 to August 2011 (i.e., Case 1, Period 3). The correlation values of temperature with respect to the climate indices are shown in Fig. 6a–c and d–f for the AMSU and the MERRA reanalysis, respectively. The black solid lines indicate the correlation coefficients at the 5% significance level.

Globally, the correlation values (temperature vs. AO) of the MERRA reanalysis agree well with those of AMSU (Fig. 6a and d). They were more variable in the NH than in the SH, showing marked dipole patterns in the middle and high latitudes. However, in the tropical central and eastern Pacific Ocean, there was a disagreement
in the correlation of temperature vs. NINO3.4 (Fig. 6b and e). In detail, AMSU shows strong negative correlations over the region, while in MERRA, the negative correlations appear extensively in the belt over the tropics south of the equator. The negative correlation values of MERRA over the ocean were underestimated by \(0.2\), compared to those of AMSU. The datasets of AMSU and MERRA in the correlation (temperature vs. QBO) are in good agreement with each other, except over the tropics following the equator (Fig. 6c and f). The discrepancies in QBO between the satellite and reanalysis data also appear over the tropics. The cold and warm anomalies of MERRA are considerably greater than those of AMSU. Moreover, positive correlations of the reanalysis were overestimated by 0.2, compared to those of the satellite observation. Overall, the MERRA correlation distributions of temperature vs. three climate indices are in good agreement with those of AMSU.

Fig. 7 shows the discrepancy in the correlation between AMSU and MERRA in the mid troposphere (\(\sim 500\) hPa), which is similar to Fig. 6. In the relationship of temperature vs. AO, the spatial distribution of MERRA over the globe agrees well with that of AMSU, particularly in the NAO regions of the North Atlantic and Europe (Fig. 7a and d). The AO has an equivalent barotropic structure from the surface into the low stratosphere (Thompson and Wallace, 1998) with baroclinic eddy forcing, associated with the intensity of the polar jet and the AO index (Tanaka and Tokinaga, 2002; Seki et al., 2011). The vertical features with the baroclinic structure are also shown in our study (Table 2, Figs. 2a,d, 6a,d, and 7a,d). The correlation (temperature vs. NINO3.4) shows that positive values of MERRA over the tropical Pacific and the Indian Ocean are underestimated by 0.2, compared to those of AMSU (Fig. 7b and e). The relationship between the temperature and the QBO indicates that negative correlations of MERRA along the equatorial belt are not consistent with the positive ones of AMSU (Fig. 7c and f). Compared to AMSU, the MERRA values (temperature vs. QBO) along the belt are underestimated in the mid-troposphere, but overestimated in the low stratosphere (also see Fig. 6c and f). By and large, the MERRA
reanalysis in the correlation of temperature vs. three climate indices agrees well with AMSU, particularly in the AO case.

7. Conclusion

The main goal of this study is to utilize observations from the most satellite-rich period of recent decade. To address a potential concern on the short data record, we also conducted the same analysis with MERRA reanalysis data. The analysis not only confirms the results from shorter term satellite data, but also it provides a chance to address the potential impact of the long-term change in satellite data used in MERRA assimilation system. A number of satellite measurements (AIRS/AMSU, MODIS) and the MERRA reanalysis have been utilized to analyze the relative intensity in the climate variability (AO, ENSO, QBO) in terms of the zonal-mean temperature and zonal wind variations over the globe from September 2002 to August 2011. We also extended the usage of MERRA data for the period of 1979–2011, and three climate indices of AO, NINO3.4, and QBO were used as the corresponding climate indicators.

The teleconnections for ENSO have been globally more intensified and localized during the recent 9 years, compared with those based on the extended dataset (1979–2010). Based on the recent nine year data, the ENSO phenomena are found to have a significant impact on the tropospheric and the low stratosphere temperature variability over the tropics and are consistent with the zonal-wind meridional circulations. It is also seen that

![Fig. 7. Correlation coefficients between the AMSU 500 hPa temperature anomalies and the (a) AO, (b) NINO3.4, and (c) QBO at 50 hPa indices from September 2002 to August 2011 (Case 1). Black solid lines stand for the correlation coefficients at the 5% significance level. (d)–(f) Same as in Fig. 7(a)–(c), but for MERRA 500 hPa temperature anomalies.](image-url)
the ENSO has substantial influences on the low stratospheric temperature over the mid-latitude region.

In our study, the recent enhanced ENSO activities are important because the NAO variability is expected to become more dependent on the ENSO in future climate changes (Müller and Roeckner, 2006). Müller and Roeckner (2006) suggested that the mechanisms in the interaction between the two phenomena could include atmosphere–ocean teleconnections or a direct connection through the troposphere or stratosphere. However, in spite of more intensified ENSO in the recent period, the AO and QBO variability in this study did not increase significantly (note that we examined the data of four seasons not just the winter case). Even though we have used monthly data without seasonal separation, the results are generally consistent with previous results (e.g., Thompson and Wallace, 1998, 2000; Manzini, 2009), likely due to the larger variability of ENSO and AO during winter.

Tropospheric warming and stratospheric cooling have been obtained from the MERRA 33 year data, although their linkage to the ENSO variability is still uncertain, as addressed by the IPCC (2012). The warming is more prominent in the middle and upper troposphere than it is near the surface. The MERRA data are useful for indicating tropospheric warming induced by the ENSO events as well as low stratospheric warming from volcanic eruptions.

The MERRA data generally agree well with those of AMSU in the distribution for the correlation of temperature vs. climate indices (AO, NINO3.4, and QBO). The MERRA for the AO case is more consistent with AMSU than for the ENSO or QBO cases. The relationship between tropospheric global warming in Fig. 4 and the three major phenomena of our study is an open question due to our current limited understanding (i.e., natural and internal variability, non-linear dynamics, model parameterizations, troposphere–stratosphere coupling, and so on) and model limitations (IPCC, 2012). The interactions between the major phenomena in their extreme phases for a month (e.g., Lim and Schubert, 2011) have not been examined in our analysis. Hence, more investigations are needed for such issue. This study attempted to estimate the relative impact of the three major concurrent phenomena on regional temperature variability based on a large scale of space and time; the results of the study will be of great use in the prediction of long-term variability.

Acknowledgement

This work was supported by the National Research Foundation of Korea (NRF) grant funded by Korea government (MEST) (No. 20120000858) and the Korean Ministry of Environment as part of the Eco-Innovation Project. We would like to thank Goddard Earth Sciences Data Information and Services Center (GES DISC) for providing the AIRS/AMSU and MERRA data. We are also grateful to NASA Land Process Distributed Active Archive Center (LP DAAC) for providing the MODIS LST data.

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