Home

Advances in the Researches of the Middle and Upper Atmosphere in China

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Abstract

In this report we summarize the research results by Chinese scientists in 2016–2018. The focuses are placed on the researches of the middle and upper atmosphere, specifically the researches associated with ground-based observation capability development, dynamical processes, and properties of circulation and chemistry-climate coupling of the middle atmospheric layers.

Key words

Middle and upper atmosphere, Dynamical and micro-physical-chemical process, Observation infrastructure

1. Development of Infrastructure

A solid-state sodium (Na) Doppler lidar developed at YanQing Station, aiming to simultaneous wind and temperature measurement of mesopause region, was reported by Xia *et al*.[1] The 589 nm pulse laser was produced by two injection seeded 1064 nm and 1319 nm Nd:YAG pulse lasers using the Sum-Frequency Generation (SFG) technique. They developed an all-fiber-coupled design for seeding laser unit, absolute laser frequency locking, and cyclic three-frequency switching necessary for simultaneous temperature and wind measurements. The all-fiber-coupled injection seeding configuration together with the solid-state Nd:YAG lasers makes the Na Doppler lidar more compact and greatly reduces the system maintenance. A preliminary observational result obtained with this solid-state sodium Doppler lidar was also given.

A wind measurement Doppler Lidar system was developed by Du *et al*.[2] Its injection seeded laser was used to generate narrow line-width laser pulse. The frequency of the seed laser was locked to iodine molecular absorption line 1109, with long-time (44 h) frequency-locking accuracy being about 1MHz. Experiments of wind measurement by lidar at Yanqing (Beijing) was done, and the results showed that the middle and low atmospheric wind field can be detected by the Doppler wind lidar.

Jiao *et al.*[3] introduced the Beijing Na–K lidar. This lidar has two laser beams: one dye laser emits a 589-nm laser beam for Na layer detection; the other dye laser emits a 770-nm laser beam for K layer detection. This lidar has a sufficient Signal Noise Ratio (SNR). The structure and details of K layer can be effectively distinguished from a single original echo. This lidar not only can supplement the lack of Na and K layer observation at this latitude region, but also provide evidence for the atmospheric sciences and space environment monitoring.

A mobile Doppler lidar system had been developed to simultaneously measure zonal and meridional winds and temperature from 30 to 70 km (Yan *et al.*[4]). Comparison of the lidar results with the temperature of the Sounding of the Atmosphere using Broadband Emission Radiometry (SABER), the zonal wind of the Modern-Era Retrospective Analysis for Re-search and Applications (MEARA), and radiosonde zonal wind shows good agreement, indicating that the Doppler lidar results are reliable.

2. Structure and Composition in the Middle Atmosphere

Equatorial Plasma Bubbles (EPBs) is the ionospheric irregularities in the F region. Statistical characteristics and evolution of the EPBs were studied using OI 630nm red line airglow observations from the ground-based all-sky imagers over low latitudes of China. Three years' airglow images from the all-sky network of 4 imagers were used to analyze EPBs' the characteristics (Sun *et al.*[5], 2016). These are the first statistical features of EPBs, including the occurrence rates, zonal drift velocities, Polarward Magnetic Latitude Extensions (PMLEs), distances between adjacent EPB depletions, longitudinal extensions of the EPBs, tilt angles of EPB depletions with respect to the geographic North-South (N-S), and influences of solar $F_{10.7}$ on EPB occurrence rate and PMLE in East Asia. In addition, the evolutions of some EPBs events were studied using multi-observation data sets. One event occurred on 4-5 November, 2013 is studied (Sun *et al*[6], 2017). Through 2 all-sky imagers observations, a group of EPBs was identified, and their evolution processes, including generation, development, and dissipation are analyzed in detail by combination with observations from a Digisonde, a VHF radar, and the C/NOFS satellite. This is the first time that a EPB group that evolved from the bottom-side large-scale wave-like structure was simultaneously observed by multi-instruments. Another two interesting EPBs cases on 4–5 October (Case 1) and 29–30 September 2013 (Case 2) were analyzed using 2 all-sky imagers located in the magnetically equatorial region (Wu *et al.*[7], 2017). The EPBs in case 1 showed planar wave-like structures. Zonal wind velocities and conductivity at different geographical latitudes lead to their tilt angle with respect to the geomagnetic meridian before midnight. They first time observed a full evolution process of a rotating EPB and fossil EPBs merging using all-sky imagers. Meanwhile, different shapes of EPB were identified, and each of them corresponds to different physical and chemical evolution processes. The morphological features of EPBs and their full evolution processes are studied, and it is indicated that the latitudinal change of zonal drift velocities of EPBs should be the main reasons of these unusual shaped EPBs.

Furthermore, a corona is the uppermost part of an atmosphere that extends outward from the exobase and gradually fades into interplanetary space. The corona structure on Titan was studied using a large data set acquired by INMS instrument on board Cassini (Jiang *et al.*[8], 2017). The result indicates that on average, Titan possesses a subthermal rather than suprathermal corona. A careful examination reveals that the variability in corona structure is not very likely to be solar driven.

Four nightglow NO 5.3 μm, O_2 1.27 μm, OH 2.0 μm and 1.6 μm emission have been observed by SABER onboard TIMED satellite since January 2002. The responses of the above nightglow emissions to solar radiation were analyzed (Gao et al[9], 2016). The quantitative linear regression fit between the nightglow emissions and the $F_{10.7}$ were calculated. The peak intensity heights of the 13 year average global mean NO, O_2, OH-2 and OH-1 nightglows are 123.6±0.2 km, 89.8±0.05 km, 88.1±0.02 km, and 86.6±0.02 km, respectively. The influence of solar radiation on the nightglows at lower heights is weaker than the ones higher above. The intensities and peak emission rates of the four global mean nightglow emissions are highly correlated to solar radiation. Meanwhile, the responses of nightglow emissions to solar radiation change with latitude.

The dayglow is greatly influenced by solar activities. So, the effect of Solar Proton Events (SPEs) on the daytime O_2 and OH airglows and ozone and atomic oxygen concentrations in the mesosphere was studied using data from TIMED/SABER (Gao *et al*[10], 2017). Five events were selected according to the given criteria. It is the first time that the responses of OH airglow and atomic oxygen to solar proton events are studied. The results indicate that both dayglow and daytime ozone and atomic oxygen in the mesosphere decrease in all SPEs. The SPE affects both O_2 and OH dayglow emissions in the mesosphere strongly, and therefore, they can be used as a tracer of the impacts of the SPE on the atmosphere. This study can make us understand the effects of solar proton event on O_2 and OH airglow emissions and ozone and atomic oxygen further.

Wang *et al*.[11] analyzed the two years' data of Na-K lidar at Yanqing station (40.41°N, 116.01°E), and found that: The K layer shows considerable semiannual seasonal variations: The column and peak densities vary semiannually with maxima in winter and summer. The centric height displays semiannual variation, reaching maxima in spring and autumn. The seasonal behavior of the K layer in Beijing is similar to that in other K lidar sties. However, the unexpected difference is that the column and peak densities of the K layer are extremely large in winter, compared to the maximum values in summer.

Jiao *et al*.[12]found a kind of peculiar sodium layer in lower thermosphere, from Haikou (19.99°N, 110.34°E) lidar data, and call them: the Thermospheric Convective Sodium Layer (TCSL). It is the first time convective sodium layer observed in the lower thermosphere region (105–120 km). Most of the apogees of the TCSL events are higher than 108 km. A TCSL event lasts several hours and is composed of several convective structures, with each vertical shape lasting 5–30 min. The TCSL has potential regional feature and appears to be related to the Es, winds, and field-aligned ionospheric irregularities.

Jiao *et al*.[13] presented the first simultaneous observation of mesopause sodium (Na) and potassium (K) layer by a Na-K lidar at the South Hemisphere site, São José dos Campos (23.1°S, 45.9°W). On 21 November 2016, sporadic layers in both Na and K layer occurred in main layer height with obvious descending variations with time, which seems like tidal induced. Notably, the peak K/Na ratio slowly increased with time. And Na layer and K layer showed different processes along with time with K density reaching its maximum 1 h later than that of Na.

Xun *et al*.[14] reported a lower Thermospheric-enhanced Na layer (TeNL) case from Yanqing lidar data. The density of TeNL was constantly enhanced in the whole night. Its peak density increased from 250cm^{-3} to 1500 cm^{-3}. From the data of an ionosonde and a meteor radar, which are closed to Yanqing station, they calculated vertical velocity of ions and the production rate of radiative recombination, and explained the formation mechanism of TeNL. The Na^+ converged by wind shear mechanism. Furthermore, the thermospheric sodium layers were neutralized from converged Na^+ layers.

Jiao *et al*.[15] presented the comprehensive statistical analyses of sporadic K (Ks) layer parameters, by using Yanqing lidar data. The seasonal distribution of Ks occurrence was obtained, with two maxima observed in January and July, respectively. However, good correlations between Es and Ks in case by case study were found. They also found that four Ks events with peak altitudes lower than 90 km were associated with large and sharp temperature increases in five comparative examples.

Jiao *et al*.[16] found the Highly concentrated layers of atomic K from Yanqing Na-K lidar data. The K density exceeds 1100 cm^{-3} (at least 4 times higher than reported elsewhere), and the K/Na ratio is superchondritic by a factor of 3–4. A model with detailed metal ion chemistry, supported by ancillary measurements from a nearby ionosonde and meteor radar, was used to show that these K layers can be produced from a strong sporadic E layer (critical frequency > 11 MHz) that descends from above 100 km. This allows most of the Na^+ ions to be neutralized before the remaining ions are dumped around 90 km, where the higher pressures and colder temperatures facilitate the formation of $K{+}N_2$ and $K{+}CO_2$ cluster ions. These cluster ions then undergo dissociative recombination with electrons to form K.

Lu *et al*.[17] (2016) reported a special case observed in the continental United States where the regular negative CG strokes might also generate sprite events through a subsequent impulsive charge transfer of sufficient strength. The electric field perturbation of these two adjacent lightning strokes can be sufficiently superimposed so that the total electric field change can drive the formation of sprite. Yang *et al* (2017a[18], 2017b[19]) also reported a similar case where two consecutive positive CG strokes occurred to product a red sprite.

Lu *et al*.[20] (2017) examined the broadband (< 1 Hz to 30 kHz) lightning sferics associated with 395 sprites observed near North America by the Imager of Sprites and Upper Atmospheric Lightning (ISUAL) onboard the FORMOSAT-2 satellite in a 12-year period from 2004–

2015. Their analysis indicates that the ISUAL dataset contains a significant fraction (69, or 18%) of negative sprites, which were predominantly (>80%) observed over oceanic and coastal thunderstorms mostly in tropical areas.

Yang *et al*.[21] (2018) reported the observation of a GJ over a Mesoscale Convective System (MCS) in the mid-latitude region in eastern China. The GJ was observed over a relatively weak radar reflectivity region ahead of the leading line, and the maximum radar echo top along the GJ azimuth was lower than the tropopause in the same region, significantly different from past studies that indicate summer GJs are usually associated with convective surges or overshooting tops.

Polar Mesospheric Clouds (PMCs) are considered a sensitive indicator for detection of global climate change and inter-hemispheric coupling. CIPS instrument on the AIM satellite provides an opportunity to study the longitudinal variation in PMC (Liu *et al*.[22], 2016). 8-year (2007–2014) PMC albedo observations were examined. The results show that seasonal averaged PMC albedo, and the PMC albedo averaged over eight PMC seasons are always low (65% of the rest of the hemisphere) in the longitude range of 60°W to 150°W in the southern polar region. This persistent longitudinal variation in PMC albedo does not occur in the northern polar region. The persistent structures were determined by fluctuations with the zonal wave numbers 1 through 4. The result from a 0-D model with H_2O and temperature from MLS inputs is generally consistent with the observed low PMC albedo in South Hemisphere (SH). Tidal analyses using the SABER temperatures indicate that the non-migrating semidiurnal tides with modes of S0, W1, and E1 might be the main drivers of the persistent longitudinal variations of PMC albedo in the SH. Non-migrating tides are much weaker in the NH and consistent with the observed lack of longitudinal variability in PMC albedo.

Xiao *et al*.[23] investigated the spatial and temporal changes of atmospheric density at 38°N in 20–100 km based on TIMED/SABER by the method of global gridding and mathematical statistics. A self-regression model was established for the atmospheric random disturbances. Model simulations were taken and compared with the lidar-observed density data, showing that the modeling method is feasible.

Yi *et al*.[24] (2016) estimated the mesopause temperatures using a low latitude meteor radar data at Kunming Station (25.6°N, 103.8°E), China. The meteor radar temperatures are in good agreement with SABER temperatures and exhibit clear seasonal variations with dominant spectral peaks at annual, semiannual, quasi 90-day and terannual oscillations. Further, Yi *et al*. (2017a[25], 2017b[26]) reported the first observations of 6.75, 9 and 13.5 day sub-harmonics of the solar rotational period (27 day) in neutral mesospheric density estimated using observations from the Davis meteor radar (68.5°S, 77.9°E; magnetic latitude, 74.6°S), Antarctica in the declining phase of solar cycle 23 and 24. They suggested these periodic variations were due to the modulation of periodic recurrent geomagnetic activity connected to Corotating Interaction Regions (CIRs) in the solar wind high-speed streams. The periodic oscillation in density shows a strong anti-correlation with periodic changes in the Auroral Electrojet (*AE*) index. These results provide new insight into solar-terrestrial coupling at mesospheric heights, as well as provide a new explanation of some "planetary wave period" oscillations in the mesosphere. Yi *et al*.[27] (2018) reported an inter-hemisphere high latitude mesospheric density response to geomagnetic storms. A superposed epoch analysis indicated that geomagnetic storms can significantly influence mesospheric density causing a greater than ~10% decrease in the auroral zones, and a ~5% decrease at higher mid-latitudes. The actual mechanism of how Magnetosphere-Ionosphere-Thermosphere (MIT) coupling during geomagnetic activity influences density at mesosphere heights is complex, and is still unclear for the moment. This raises a challenge to modeling work aimed at understanding the physical and chemical processes in the mesosphere during geomagnetic activity.

Yu *et al*.[28] (2017) presented on a statistical basis that lightning and thunderstorm activities can affect the metal layer. A statistically significant enhancement of metal Na layer above thunderstorms was found. The lightning-induced enhancement of metal layer above thunderstorms may be related. Thunderstorm-induced GWs (Gravity Waves) or electrical effects may be responsible.

Using seven years', from 2006 to 2013, sodium lidar observations over Hefei, China (31.80°N, 117.3°E), Qiu *et al*.[29] (2017) attempted to propose a possible mechanism for the formation of Sporadic Sodium Layers (SSLs or NaS). They analyzed the relationship between low temperature (<150 K) and SSL occurrence and detect a statistically significant link that the low temperature (<150 K) occur in three days before an SSL with an occurrence rate of 93.4% (57/61). The sharp decrease of water vapor concentration nearby before an SSL and the recover after the SSL are also detected frequently. Based upon these evidences and some case studies, they proposed an icy dust reservoir in the formation of an SSL. The icy dust could form in the extremely cold mesopause region where the temperature falls below 150 K and it will absorb sodium atoms to form a solid sodium metal film as a sodium reservoir. The icy dust will then sublimate rapidly when meeting with warm air (e.g., 150 K < T < 190 K) and leave behind the solid metal atom film. The remanent sodium film might release vapor sodium atoms finally by some means through high temperature (*e.g.*, >190 K and sometimes even >230 K) and form a sporadic sodium layer. Although not conclusive and highly uncertain, the icy dust reservoir model not only provides a good explanation for the observed characteristics of SSLs; it is also in good agreement with many other observations, such as the simultaneous sporadic sodium and iron layers, the behavior of SSLs on small time scale, the deviation of the sodium density profile of SSLs from the normal one, and the sharply decreased scale height above the peak of the sodium layer. These results further suggest that the icy dust might be a viable option of sodium reservoir for the formation of SSLs.

Zhang *et al.*[30] (2017) investigated the influence of the Arctic Oscillation (AO) on the vertical distribution of stratospheric ozone in the Northern Hemisphere in winter and found that positive ozone anomalies exist at low latitudes (0°–30°N) and negative ozone anomalies exist in the northern midand high latitudes during positive AO phases. Their analysis indicates that anomalous dynamical transport related to AO variability primarily controls these ozone changes.

Suo *et al.*[31] (2017) made a comparison of ozone depletion in 1997 and 2011 in the Arctic stratosphere and found that the magnitudes of Total Column Ozone (TCO) anomalies over the Arctic in 1997 and 2011 both could be up to ~ –80 DU and the ozone decreases between200 hPa and 30 hPa accounted for ~80% of the TCO anomalies. They argued that the two extremely low Arctic TCO events were possibly related to La Niña activity, which resulted in a stronger Arctic polar vortex, a lower stratospheric temperature, more polar clouds, and eventually more ozone chemical loss. They also emphasized the role of the positive sea surface temperature anomalies in the North Pacific in 2011 in causing the extremely low TCO over the Arctic.

Wang *et al.*[32] (2016) found that the Quasi-Biennial Oscillation (QBO) in the tropical stratospheric CO mixing ratios has a phase change at 30 hPa. They showed that the CO QBO is primarily resulted from combined effects of dynamical and chemical processes associated with CO, while the QBO phase change at 30 hPa is resulted from the combined effects of dynamical and chemical processes which lead to a reverse of the CO vertical gradient in the tropical stratosphere at 30 hPa. They also found that the chemical processes associated with CO not only have a weakening effect on the amplitude of the CO QBO, but also lead to a QBO phase difference by 3 months between zonal wind QBO and CO QBO at 10–30 hPa.

Guo *et al.*[33] showed that the Ozone Valley over the Tibetan Plateau (OVTP) from NCEP-CFSR (Climate Forecast System Reanalysis) dataset became strong in the summers of 1979–2009, whereas it became weak according to ERA-Interim and JRA-55. The OVTP strengthening in NCEP-CFSR may have been caused by South Asian High (SAH) intensification, a rising tropopause, and increasing ozone over non-Tibetan Plateau areas (27°–37°N, <75°E and >105°E). Analogously, the OVTP weakening in ERA-Interim and JRA-55 may have been affected by weakening SAH, descending tropopause, and decreasing non-TP ozone.

Shi *et al.*[34] validate the ozone products from the Microwave Limb Sounder (MLS) onboard the Aura satellite over the Tibetan plateau using Electrochemical Concentration Cell (ECC) ozonesonde data of 2016 for Ngari, Tibet. The MLS version four ozone profiles have lower standard deviation in the middle stratosphere (38–10 hPa), whereas the ozonesonde profiles have lower standard deviation in the upper troposphere and lower stratosphere region (200–83 hPa). There are statistically significant differences between these two datasets in most of the stratosphere (10–83 hPa).

Wan *et al.*[35] detected the double core of Ozone Valley (OV) over the Qinghai-Xizang Plateau in summer in the WACCM3 output and showed that the OV core near the UTLS is well performed in location. Intensity of the OV core is a little bit stronger than the observation. However, simulation is not good enough in the upper stratosphere. The upper stratosphere OV core from model output is stronger and biased to eastside. Successful simulation of atmospheric circulation is the reason for the well performance of the UTLS OV core which is mainly controlled by dynamic transport. The poor simulation of the upper OV is caused by the bad copy the chlorine and nitrogen compounds which may be resulted from the circulation differences between model output and observation.

It is well-known that the height of the maximum ozone heating rate is much higher than the height of the maximum ozone concentration in the stratosphere. However, it lacks an analytical expression to explain it. Using a simple theoretical model, Zhang *et al*.[36] has calculated the height of maximum ozone heating rate and found that strong absorption of ozone causes the incoming solar flux to be largely attenuated before reaching the location of the maximum ozone concentration. By comparing with the exact radiative transfer calculations, the heights of the maximum ozone heating rate produced by the theoretical model are generally very close to the true values. The location of the maximum ozone heating rate is sensitive to the solar spectral range.

3. Climate and Modeling

Gan *et al*.[37] (2017) reproduced the 11-year solar cycle effect on the temperature in the mesosphere via the extended Canadian Middle Atmosphere Model (eCMAM30). They suggested that the alternate structure in temperature was attributed to the anomalous residual circulation generated by the wave-mean flow interaction. Using ISR at Arecibo, Gong *et al*.[38] (2017) found that the negative ion ratio in a latitude range from 65 to 85 km inferred by previous ISR studies is overestimated. They improved the processing method that could produce more accurate the negative ion ratio results. Gong *et al*.[39] (2016a) presented the first direct comparison of the vertical electric fields in the E and F regions. They concluded that Electric fields in the E region and F region are not the same as commonly assumed. They improved the data processing method and obtained E region electric field with minimal assumptions. Using the Hainan coherent scatter phased array radar, Chen *et al*.[40] (2017) observed two cases of midday F region irregularities in geomagnetically quiet condition at low latitude. The irregularities were observed with small Doppler velocities, narrow spectral widths, and northward drifting tendency. They reported that the daytime irregularities were fossil structures and most likely the remnant of previous night's bubbles.

Wei *et al*. (2016[41]) performed a comparison between models with and without well-resolved stratosphere on the simulation of the East Asian winter climate. Their results revealed that the Fifth Coupled Model Inter-comparison Project (CMIP5) models with model top above the stratopause had a better simulation of the distribution of surface air temperature, sea level pressure and precipitation than the models with a low-top below the stratopause. The discrepancy of the East Asian winter climate between High-Top (HT) and Low-Top (LT) CMIP5 models is also evident in the future projection under higher (RCP85) and midrange (RCP45) emission scenarios. They also suggested that insufficient representation of the stratosphere might lead to underestimation of the anthropogenic global warming in regional scale and hence had the potential to lead to insufficient response action and mitigation measures. Cai *et al*.[42] (2017) further assessed the abilities of the CMIP5 and CMIP3 models to simulate the boreal winter stratospheric polar vortex. The results showed that the HT models with a High Vertical resolution (HVer) of the stratosphere, and NonorOgraphic Gravity wave drag (NOG), rank higher in both the temporal scoring system and the spatial scoring system. The extreme cold polar vortex bias, which was found in the CMIP3 models, vanishes in the CMIP5 models with HT, HVer, and NOG but persists in the other CMIP5 models. A dynamical analysis revealed that the heat flux propagating into the stratosphere is stronger in models with HT, HVer, and NOG, but these propagations are still weaker than those in the ERA40 reanalysis, indicating the lack of variability in the current CMIP5 models.

Zhang *et al*.[43] (2016) found that the Arctic polar vortex shifted persistently towards the Eurasian continent and away from North America in February over the past three decades. Their analysis reveals that this vortex shift induces cooling over some parts of the Eurasian continent and North America which partly offsets the tropospheric climate warming there in the past three decades. More recently, Zhang *et al*.[44] (2018) identified a 'Eurasia-North America Dipole' (ENAD) mode in the Total Column Ozone (TCO) over the Northern Hemisphere with negative and positive TCO anomaly centres over Eurasia and North America, respectively. They further showed that there exists a positive trend in this mode in the past three decades, which is closely related to the polar vortex shift towards Eurasia and this trend in late winter is likely continues in near future in multiple chemistry-climate-model simulations.

Huang *et al.*[45] studied the radiative impacts of the stratosphere on troposphere and surface climate, using abrupt CO_2 quadrupling experiments of the Coupled Model Inter-comparison Project phase 5 (CMIP5), with a focus on stratospheric temperature and water vapor. It is found that the stratospheric temperature change has a robust bullhorn-like zonal-mean pattern due to a strengthening of the stratospheric overturning circulation. This temperature change modifies the zonal mean top-of-the-atmosphere energy balance, but the compensation of the regional effects leads to an insignificant global-mean radiative feedback (-0.02 ± 0.04 W·m^{-2}·K^{-1}). The stratospheric water vapor concentration generally increases, which leads to a weak positive global-mean radiative feedback (0.02 ± 0.01W·m^{-2}·K^{-1}). The stratospheric moistening is related to mixing of elevated upper-tropospheric humidity, and, to a lesser extent, to change in tropical tropopause temperature. Our results indicate that the strength of the stratospheric water vapor feedback is noticeably larger in high-top models than in low-top ones. The results here indicate that although its radiative impact as a forcing adjustment is significant, the stratosphere makes a minor contribution to the overall climate feedback in CMIP5 models.

The global warming simulations of the General Circulation Models (GCMs) are generally performed with different ozone prescriptions. Xia *et al.*[46] found that the differences in ozone distribution, especially in the Upper Tropospheric and Lower Stratospheric (UTLS) region, account for important model discrepancies shown in the ozone-only historical experiment of the Coupled Model Intercomparison Project Phase 5 (CMIP5). These discrepancies include global high cloud fraction, stratospheric temperature, and stratospheric water vapor. Through a set of experiments conducted by an atmospheric GCM with contrasting UTLS ozone prescriptions, we verify that UTLS ozone not only directly radiatively heats the UTLS region and cools the upper parts of the stratosphere but also strongly influences the high clouds due to its impact on relative humidity and static stability in the UTLS region and the stratospheric water vapor due to its impact on the tropical tropopause temperature. These consequences strongly affect the global mean effective radiative forcing of ozone, as noted in previous studies. Our findings suggest that special attention should be paid to the UTLS ozone when evaluating the climate effects of ozone depletion in the 20th century and recovery in the 21st century. UTLS ozone difference may also be important for understanding the intermodal discrepancy in the climate projections of the CMIP6 GCMs in which either prescribed or interactive ozone is used.

Xia *et al.*[47] (2017) investigated the climatic impact of Stratospheric Ozone Recovery (SOR), with a focus on the surface temperature change in atmosphere–slab ocean coupled climate simulations. It is found that although SOR would cause significant surface warming (global mean: 0.2 K) in a climate free of clouds and sea ice, it causes surface cooling (–0.06 K) in the real climate. The results here are especially interesting in that the stratosphere-adjusted radiative forcing is positive in both cases. Radiation diagnosis shows that the surface cooling is mainly due to a strong radiative effect resulting from significant reduction of global high clouds and, to a lesser extent, from an increase in high-latitude sea ice. Our simulation experiments suggest that clouds and sea ice are sensitive to stratospheric ozone perturbation, which constitutes a significant radiative adjustment that influences the sign and magnitude of the global surface temperature change.

Xie *et al.*[48] studied 3-Dimension VARiational (3DVAR) assimilation method to achieve the near space global atmospheric temperature field at 20–100 km, of which the observation data was taken from TIMED\SABER temperature data and the background data was taken from WACCM model. The evaluation analysis indicated that the errors of the near space global atmospheric temperature field get a general decrease after 3DVAR assimilation, with the maximum error decreasing from 17 K to 7 K. The application of this 3DVAR assimilation algorithm can provide more accurate initial fields to near space atmospheric environment forecast model.

4. Dynamics in the Middle Atmosphere

Gravity Waves (GWs) are disturbances of the atmosphere with horizontal wavelengths of several kilometers to several thousand kilometers. GWs can be generated by many sources, *e.g.*, wind jets, deep convection, and flow over topography. Variation of global GWs is studied using GW Potential Energy (PE) per unit mass derived from SABER temperature profiles (Liu *et al.*[49], 2017). We find a significant positive trend of GW PE at around 50°N during July from 2002 to 2015. Both the monthly and the deseasonalized trends in of GW PE are significant near 50°S. Specifically, the deseasonalized trend of GW PE has a positive peak of 12%–15% per decade at 40°S–50°S and below 60 km, which suggests that eddy diffusion is increasing in some places. The response of GW PE to solar activity is negative in the lower and middle latitudes. The response of GW PE to QBO is negative in the tropical upper stratosphere and extends to higher latitudes at higher altitudes. The response of GW PE to ENSO is positive in the tropical upper stratosphere.

In the past few years, a ground-based all-sky airglow imager network over China has been constructed by the middle and upper atmosphere research team in the State Key Laboratory of Space Weather, Chinese Academy of Science. The network contains 15 stations, and has two channels, one is OH airglow, and another is OI 630nm red line airglow. Gravity wave propagating characteristics over mid-latitude region of China are studied using the OH airglow all-sky imagers network (Wang *et al.*[50], 2016). We find that propagations of the waves prefer to different directions in different seasons. In combined with TRMM satellite and ECMWF data sets, the convective activity at the south of observation sites and filtering effect of background wind might make the gravity waves prefer to polarward propagation in summer , while the jet streams near tropopause might determine the equatorward and parallel to equator propagation during winter.

The Tibetan Plateau (TP), known as “Third Pole” of the Earth, has important influences on global climates and local weather. 3 year OH airglow images (November 2011 to October 2014) from Qujing (25.6°N, 103.7°E) are used to investigate the TP effect of orographic features on the geographical distributions of Gravity Wave (GW) sources (Li *et al.*[51], 2016). Along with meteor radar and TIMED/SABER observations, three types of GWs (freely propagating, ducted, or evanescent) were identified. We find that almost all GWs propagate southeastward in winter and the GW propagation directions in winter are significantly different from other airglow imager observations at northern middle latitudes. Using backward ray-tracing analysis, we find that most of the mesospheric freely propagating GWs are located in or near the large wind shear intensity region (~10 km–~17 km) on the southeastern edge of the TP in spring and winter. The averaged value of momentum flux is $11.6\pm5.2\,m^2\cdot s^{-2}$ in winter and $7.5\pm3.1\,m^2\cdot s^{-2}$ in summer. This work will provide valuable information for the GW parameterization schemes in general circulation models in TP region.

Guo *et al.*[52] analyzed the seasonal variations of atmospheric temperature and gravity waves between 35–70 km in Beijing by Rayleigh lidar data. The profile of averaged gravity waves potential energy density and dissipation in different seasons were given over Beijing area.

Wang *et al.*[53] studied the quasi-monochromatic gravity waves parameters in the mesopause over Langfang based on the 60h sodium fluorescence Doppler lidar data during 2011–2013. The result showed that vertical wavelengths (horizontal wavelengths) and observed periods are mainly distributed from 6 km to 9 km (200 km to 800 km) and 2 h to 7 h ,with the mean values 6.6 km (727.8 km) and 7.4 h respectively. Wang *et al.*[54] retrieved quasi-monochromatic inertia gravity waves over Hainan rocket launch site(19.5°N,109°E) from wind and temperature data detected by the first meteorological rocket of the Meridian Space Weather Monitoring Project. The GW parameters such as propagation, intrinsic period, wavelength and group velocity were analyzed.

Ba *et al.*[55] studied Na atoms transportations induced by gravity wave dissipation in the mesopause region from sodium fluorescence Doppler lidar data at Langfang station. The results suggested the activities of gravity wave dissipations accumulate Na atoms at near 91 km and make the mean Na production rate significantly increase between 88 and 92 km. Gravity wave dissipations play an important role in the formation of Na layer structure in the mesopause region. Ba *et al.*[56] simulated the vertical wind perturbations with the vertical wind and zonal wind profile data obtained by the Na fluorescence Doppler lidar at Langfang. The observation data showed the perturbation magnitude of vertical wind and horizontal wind is about $10\,m\cdot s^{-1}$, and the perturbations of vertical wind are much larger than those of the background vertical wind.

Xiao *et al.*[57] showed the global morphology of near space atmospheric fluctuation based on the quantitative results of the temperature standard deviations using TIMED/SABER temperature data. In the lower altitude between 20 km and 70 km, temperature standard deviations are generally 1–10 K, which are mostly related with atmospheric gravity waves. They also showed temperature standard deviations in the upper altitude between 20 km and 70km are generally 10–30 K. The travelling planetary waves (quasi-2-days, quasi-6.5-days) contribute significantly to the total atmospheric fluctuation.

Cheng *et al*.[58] studied the Sporadic Sodium Layers (SSL) caused by atmospheric gravity waves over Langfang (39°N,116°E) from the sodium fluorescence Doppler lidar and the meteor radar detection data. The results showed that the accumulation and joint action of the strong horizontal wind shear and vertical wind field direction caused by the atmospheric gravity wave increases the density of sodium atoms and form the SSL.

Zhang *et al*.(2017a[59]) found that the mean slopes of the horizontal wind spectra in the troposphere are systematically less negative than the canonical slope of -3 based on the 12-year radiosonde data over a mid-latitude station. This is the first time that the statistical results of the vertical wind fluctuation spectra are revealed. Latitudinal and seasonal variations of those spectra in the troposphere and lower stratosphere were further investigated using the 11-year radiosonde data from 92 United States stations in the Northern Hemisphere by Zhang *et al*. (2017b[60]). They discovered that the vertical wind spectrum is much shallower than the horizontal wind spectrum over a wide latitude region for the first time. These studies suggested that the gravity waves dynamical propagation might be the main cause of the universal spectrum. In low latitudes, long-term activities of the gravity waves were statistically analyzed by Li *et al*.[61] (2016) using the 14-year radiosonde data from 16 stations at latitudes between 14.33°S to 29.37°N. Low-frequency oscillations of the quasi-biennial oscillation, 11-year solar cycle and a 35.2 month oscillation were observed in the gravity wave energy densities, which indicates interactions between oscillations or modulation from the background zonal wind. In the Mesosphere and Lower Thermosphere (MLT) region, simultaneous upward and downward propagating Inertia-Gravity Waves (IGWs) were observed by Huang *et al*.[62] (2017) at Andes Lidar Observatory. The observed downward propagating IGWs indicates that the instability arising from the multiple-perturbation superposition might have a significant influence on wave saturation and amplitude constraint in the MLT region.

Using temperature profiles provided by the Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC) Global Positioning System (GPS) satellite constellation, an eight-year series (2007 to 2015) of Gravity Wave (GW) potential energy in the stratosphere (18–30 km) around the Tibetan Plateau (TP) were investigated, Zeng *et al*.[63] (2017) found that with increasing altitude, the GW potential energy (E_p) values in the stratosphere caused by convection decreases. The importance of GWs that are stimulated by topography is enhanced in this area. In the TP, which was considered to lack strong topographical GW activity, clear activity existed in the spring and winter of all studied years. Based on the latitudinal zone of the TP, the distribution of GW potential energy is highly consistent with the elevation of the local topography. The activities of topographical GWs are strongly filtered as they propagate upward to the area of zero speed wind. The analysis indicates that in the TP, clear orographic GW excitation exists and propagates upward to the upper stratosphere, where it is greatly influenced by the wind.

Jia *et al*.[64] (2016) used observational data from an all-sky airglow imager at Xinglong (40.2°N, 117.4°E), a sodium lidar at Yanqing (40.4°N, 116.0°E) and a meteor radar at Shisanling (40.3°N, 116.2°E) to study the propagation of a mesoscale gravity wave. They found the imager identified a mesoscale gravity wave structure in the OH airglow that had a wave period of 2 hours, propagating along an azimuthal direction (clockwise) with an angle of 163°, a phase speed of 73 m/s, and a horizontal wavelength of 566 km. Simultaneous measurements provided by the sodium lidar also showed a perturbation in the sodium layer with a 2-hour period. Based on the SABER/TIMED and radar data, they estimated that the momentum flux and the energy flux of the gravity wave were approximately 0.59 $m^2 \cdot s^{-2}$ and 0.22 $mW \cdot m^{-2}$, respectively. Ray-tracing analysis showed that the gravity wave was likely generated in the center of Lake Baikal owing to the existence of a jet-front system in the upper troposphere at that time.

Zhao *et al.* (2016[65], 2017[66]) used a mobile Rayleigh Doppler wind lidar of the University of Science and Technology of China, which was developed in 2013, to study the gravity waves within 15 to 60 km altitude region. The observation locations cover the northwest (midlatitude) of China, *i.e*., Delingha (37.371°N, 97.374°E), Xinzhou (38.425°N, 112.729°E), and Jiuquan (39.741°N, 98.495°E). They found that the inertia gravity waves and mountain waves existed at the same time, and the typical features of the gravity waves in the stratosphere were reported.

Using the parameterization based on Lindzen's linear saturation theory, Yu *et al*.[67] (2017) improved the parameterization of Inertial Gravity Waves (IGW) by importing a more realistic IGW phase speed spectrum, and spontaneously generate the Quasi-Biennial Oscillation (QBO) in the Whole Atmosphere Community Climate Model (WACCM). A series of numeric simulations were performed to test the sensitivity of QBO-like oscillation features to the phase speed spectrum and the settings of parameterized IGWs. All of these simulations are capable of generating equatorial wind oscillations in the stratosphere based on standard spatial resolution settings. Central phase speeds of the "double-Gaussian parameterization" affect QBO magnitudes and periods, and the momentum flux of IGWs determines the acceleration rate of zonal wind. Furthermore, stronger IGW forcing can lead to a propagation of the QBO-like oscillation to lower altitude. The temporal intermittency factor of the parameterization also prominently affects the QBO period. Stratospheric QBO-like oscillation with obvious improvements are generated using the new IGWs parameterization in a long time simulation.

Yang *et al*.[68] investigated the seasonal variations of tides of the Mesospheric and Lower Thermospheric (MLT) winds within 80~100 km altitude regions using the wind data from the observation of China Langfang (39.4°N,116.7°E) Meteor Radar (MR). The results showed that both diurnal and semidiurnal tide dominates the zonal and meridional wind. WACCM4 (Whole Atmosphere Community Climate Model, version 4) can reproduce the seasonal variation of tides, but underestimate the amplitudes.

Planetary Waves (PW) during SSW event were also studied using the 5 meteor radars at low and middle latitude of northern hemisphere near 120°E (Zhu *et al*.[69], 2017). It was indicated that the enhanced quasi-16-day waves was prior to the warming, and the PW amplitude reached the maximum when the polar temperature reached its peak. Furthermore, the reanalysis data showed that the PW propagated from lower latitude to the pole, and the zero-wind line moved from low latitude to the high. The above evidences indicate the coupling and interaction between SSW and PW.

The impact of stratospheric planetary wave reflection on tropospheric weather over Central Eurasia during 2013 Sudden Stratospheric Warming (SSW) event was investigated by Nath *et al* .(2016a[70]). They found that the 2013 SSW event is excited by the combined influence of WaveNumber 1 (WN1) and WaveNumber 2 (WN2) planetary waves, which makes the event an unusual one. An extraordinary development of a ridge was observed over the Siberian Tundra and the North Pacific during first development stage (last week of December 2012) and later from the North Atlantic in the second development stage (first week of January 2013), and these waves appeared to be responsible for the excitation of the WN2 pattern during the SSW. The wave packets propagated upward and were then reflected back down to central Eurasia due to strong negative wind shear in the upper stratospheric polar jet, caused by the SSW event. Waves that propagated downward led to the formation of a deep trough over Eurasia and brought extreme cold weather over Kazakhstan, the Southern part of Russia and the Northwestern part of China during mid-January 2013.

Using multiple reanalysis datasets, Nath *et al*. (2016b[71]) found an increasing trend and westward shift in the number of PV intrusion events over the Pacific. The increased frequency can be linked to a long-term trend in UT equatorial westerly wind and subtropical jets during boreal winter to spring, which are driven by the warming-induced strengthening of Walker circulation and regional changes in Hadley circulation on multi-decadal timescale (Nath *et al*., 2017a[72]). The multi-decadal strengthening in the Pacific Walker circulation is consistent with the global mean temperature rise. In addition, these intrusions brought dry and ozone rich air of stratospheric origin deep into the tropics. Hence, a long-term increasing trend in ozone flux over the northern hemispheric were observed in outer tropical (10°–25°N) central Pacific that results from equatorward transport and downward mixing from the mid-latitude upper troposphere and lower stratosphere during PV intrusions. However, on the interannual timescales, the intrusion frequency is mainly related to convection associated with El Niño/Southern Oscillation (ENSO) with more events under La-Niña and less under El-Niño conditions (Nath *et al*., 2017b[73]). This may result from stronger equatorial westerly ducts and subtropical jets during La-Niña and weaker during El-Niño. Their results further suggest that tropospheric ozone concentration and subtropical intrusions account ~65% of the co- variability (below 5 km) in the outer tropical (10°–25°N) central Pacific Ocean, particularly during La-Niña conditions. Another important phenomenon is the teleconnections related to ENSO, which is closely associated with the extratropical climate impacts from the tropics. In this process, the stratospheric polar vortex plays an important role in modulating Northern Hemispheric climate anomalies. A recent study of Ding *et al.*[74] (2017) investigated the combined impacts of the Pacific decadal oscillation and two types of La-Niña on climate anomalies in Europe, and their results suggest that the modulating effects of the background state on the planetary wave propagation should be considered in the seasonal forecasts.

Huang *et al.*[75] (2017) investigated the dominant Planetary Waves (PWs) in the lower atmosphere over Xianghe (117.00°E, 39.77°N) using observation data from the Beijing Mesosphere-Stratosphere-Troposphere (MST) radar in the period of December 2013 to November 2014. They found that the PWs show quasi-standing structure in vertical direction and the prevailing eastward propagation in horizontal direction. The Quasi-16-day and quasi-10-day waves present similar seasonal and height variations and contribute significantly to the construction and maintenance of tropospheric jet. Huang *et al.*[76] (2017) studied the annual and interannual variations of 6.5 day waves (6.5DWs) during 2002-2016 using the Thermosphere Ionosphere Mesosphere and Dynamics/Sounding of the Atmosphere using Broadband Emssion Radiometry (TIMED/SABER) measurements. They suggested that the annual variations of the 6.5DWs were different in stratosphere, mesosphere and the lower thermosphere. Long-term variations in 6.5DWs were mainly related to AO and SAO. Using the TIME-GCM model, Gan *et al.*[77] (2016) found the 6-day wave could produce 6-day oscillation in the ionosphere via dynamo modulation. The tidal-6 day wave interaction results in the ionospheric short-term variability.

Shi *et al.*[78] showed that during 9–14 January 2014, the modulating effects helped strengthen upward and eastward wave activity fluxes over the Atlantic region and enhance the Pacific high in the stratosphere in its early stage. Later in 19–24 January, the downward wave activity fluxes over the east Pacific due to the modulating effects were beneficial to downward development of the stratospheric high over the Pacific and the formation of a blocking high over the west coast of North America in the troposphere accompanied by a strong adjacent cold low on the east side. These circulations benefit the southward invasion of polar cold air reaching the lower latitudes of east North America, leading to the cold wave outbreak.

Huang *et al.*[79] (2017) investigated the connections between tropospheric blockings and the stratospheric polar vortex variations. Their results show that the blocking frequency decreases over the Euro-Atlantic sector and increases over the western North Pacific during the onset and maturation stages of strong polar vortex events. The changes of the blocking frequency during the growth stage of weak polar vortex events are almost opposite to those during strong vortex events. This study also reveals that the nonlinear wave interference have a considerable contribution to the weakening of the upward wave fluxes in the stratosphere after the central date of weak vortex events and this is not emphasized in previous literatures.

Yang *et al.*[80] investigated the responses of zonal winds in the stratosphere, mesosphere and lower thermosphere to SSWs based on the data at ~40°N at different longitudes during different Stratospheric Sudden Warming (SSW) events. Moreover, simulations by the Specified Dynamics version of the Whole Atmosphere Community Climate Model (SD-WACCM) were taken to explain different responding specifics of zonal wind to SSW events. Their results indicated that different phases of PWs would lead to the different zonal wind along with longitudes and the different amplitudes and phases in different SSW events can lead to the different zonal wind responses.

Gong *et al.* (2016b[81]) presented an analysis of the thermospheric Midnight Temperature Maximum (MTM) during a major SSW event using the Incoherent Scatter Radar (ISR) observation at Arecibo. The observed MTM is suggested to be generated by an upward propagating terdiurnal tide associated with the SSW. They provide the first and direct observation evidence to support the model studies. Ma *et al.*[82] (2017) reported an analysis of the Quasi 2 Day Waves (QTDWs) during the 2013 SSW using a meteor radar chain measurements. This is the first time that an enhancement of the QTDWs in the mid-latitudes in the Northern Hemisphere during a SSW is observed. They found that the amplification of the QTDW amplitudes during the SSW at the low latitudes is the most prominent. To the same SSW event, Chen *et al.*[83] (2016) analyzed the mid-latitude ionospheric responses using eight ionosondes and a meteor radar. They reported that the observed quasi-16 day waves are amplified in MLT winds and modulate the semidiurnal tides in F_2 layer critical frequency. Aside from the planetary wave, atmospheric Kelvin waves during SSW events were investigated by Jia *et al*.[84] (2016) using ERA-Interim reanalysis data and verified with COSMIC temperature data. They concluded that the Kelvin wave activity shows obvious coupling with the convection localized in the India Ocean and western Pacific region. Their results indicate that the enhanced meridional circulation driven by the extratropical planetary wave forcing during SSW events leads to tropical upwelling, which further produces temperature decrease in the tropical stratosphere.

Shi *et al*.[85] revealed that a stratospheric sudden warming event from 17 February to 15 March 2005 (SSW05) (1) consisted of three stages: a prior minor warming (MnW05), a late Final Warming (FW05), and a warming stagnation between MnW05 and FW05; (2) the wave 3 first decreased total upward EP fluxes by more than 30% at 100 hPa, resulting in warming stagnation, and then increased upward EPFs by greater than 50%, leading to FW05; and (3) the anomalies of wave-3 activity fluxes were associated with the pattern of Atlantic blocking high in the latter two stages. The interactions between the wave 3 and wave 1 partitioned the zonal upward channel of total wave activity fluxes from one longitudinal region into two longitudinal regions and affected SSW05.

5. Stratosphere-troposphere Exchange

Wang *et al*.[86] (2016) studied the variations of tropopause and Tropopause Inversion Layer (TIL) in the Arctic region during a Sudden Stratospheric Warming (SSW) in 2009 with MERRA reanalysis data and GPS/COSMIC temperature data. Their work showed that during the SSW in 2009, the tropopause height in the Arctic decreased accompanied with the tropopause temperature increase and the TIL enhancement. The variations of the tropopause and TIL were larger in higher latitudes. The variations of the tropopause and TIL were associated with the variations of the residual circulation and the static stability due to the SSW. Larger static stability appeared in the upper stratosphere and moved downward to the narrow region just above the tropopause. The descent of strong downward flow was faster in higher latitudes. The static stability tendency analysis showed that the strong downward residual flow induced the static stability change in the stratosphere and around the tropopause. Besides, the strong downwelling in the stratosphere was mainly induced by wave2, which led to the tropopause height and temperature changes due to the adiabatic heating. Around the tropopause, a pair of downwelling above the tropopause and upwelling below the tropopause due to wave2 contributed to the enhancement of static stability in the TIL immediately after the SSW.

Hu *et al*.[87] found that the tropical Cold-Point Tropopause Temperature (CPTT) trends during 1979–2014 are zonally asymmetric; that is, over the tropical Central and Eastern Pacific (CEP; 20°S–20°N, 160°E–100°W), the CPTT shows an increasing trend of 0.22 $K\cdot decade^{-1}$, whereas over the rest of the tropical regions (non-CEP regions) the CPTT shows a decreasing trend of $-0.08\ K\cdot decade^{-1}$. Model simulations suggest that this zonal asymmetry in the tropical CPTT trends can be partly attributed to Walker circulation changes induced by zonally asymmetric changes of the Sea Surface Temperatures (SSTs). The increasing (decreasing) SSTs over the western Pacific (CEP) result in a larger zonal gradient in sea level pressure over the tropical Pacific and intensified surface easterlies. The increased pressure gradient leads to enhanced convection over the Indo-Pacific warm pool and weakened convection over the CEP, facilitating a stronger Walker circulation. The downward branch of the intensified Walker circulation induces a dynamical warming over the CEP and the upward branch of the intensified Walker circulation induces a dynamical cooling over the non-CEP regions below 150 hPa.

Yang *et al*.[88] found that the second (first) tropopause is easier to be observed over the Tibetan Plateau (TP) than that over the plain area in June–September (October–May). The first Tropopause Height (TH1) over the TP is higher than that over the plain area in boreal winter (November–March), while the second Tropopause Height (TH2) over the TP is higher in each month, and from April to September it is even higher than that over the tropics. The maximum differences of both TH1 and TH2 between the TP and tropics appear in boreal middle summer.

Chen and Tao[89] analyzed the distribution characteristics of substances (cloud cover, ozone, cloud ice, water vapor) in Tropical Tropopause Layer (TTL) region and showed that: (1) The ozone concentration of the TTL region (abundant typhoon activity) is relatively lower; (2) The cloud ice and water vapor concentrations increase in the TTL region during the typhoon period, whose concentration centers locate around the typhoon center; (3) The typhoon activity contributes to the increasing of cloud cover in TTL region, there is an extreme value; (4) Vertical upward movement caused by the typhoon results in the stratosphere-troposphere exchange, and thus has a major impact on the distribution of trace substances in the TTL region.

Wei *et al.*[90] (2016) analyzed the stratosphere and troposphere exchange associated with an orographic gravity wave event occurred over Tibetan Plateau. Their results showed that the orographic wave propagated upward into the stratosphere and breaks near 150 hPa, leading to a strong attenuation of momentum flux and a significant increase in the vertical turbulent mixing. They found that the turbulent exchange coefficient enhances by more than eight times during a short period (within 1 hour) in this gravity wave event which causes air transport from the troposphere to the stratosphere.

Xie *et al.*[91] (2016a) investigated the transport of surface emissions from high population density regions into the stratosphere. Their results showed that the average proportion of a tracer entering the stratosphere compared with its total release is 2.6% for Southeast Asia, followed by 1.7% for Australia, 1.4% for Southwest Asia, 1.0% for Africa, 1.0% for South America, 0.9% for East Asia, 0.7% for North America, and 0.3% for Europe. Xie *et al.*[92] (2016) further analyzed stratospheric water vapor variations in the middle and upper stratosphere over the past two decades. They found that water vapor variations below 10 hPa are mainly resulted from upward transport of the water vapor from the lower stratosphere. Meanwhile, the water vapor variations in the upper stratosphere have an 11-year period controlled by the solar cycle as well as a 2-year cycle regulated by the Quasi-Biennial Oscillation (QBO).

Based on data from 16 Chemistry-Climate Models (CCMs) and separate experimental results using a state-of-the-art CCM, Hu *et al.*[93] examined the trends in the Brewer–Dobson Circulation (BDC) during the second half of the 20th century (1960–2000) and the first half of the 21st century (2001–2050). From the ensemble mean of the CCMs, the BDC exhibits strengthening trends in both the 20th and 21st centuries; however, the acceleration rates of tropical upwelling and southern downwelling during 2001–2050 are smaller than those during 1960–2000, while the acceleration rate of the northern downward branch of the BDC during 2001–2050 is slightly larger than that during 1960–2000. The differences in the extratropical downwelling trends between the two periods are closely related to changes in planetary-wave propagation into the stratosphere caused by the combined effects of increases in the concentrations of greenhouse gases and changes in stratospheric ozone.

Tian *et al.*[94] (2017) analyzed the Cross-Tropopause Mass Flux (CTMF) and long-term trends in Stratosphere-Troposphere Exchange (STE) over the Tibetan Plateau (TP) and its surroundings. Their results showed that the gross CTMF over the TP accounts for 2.96% of the global total STE. They also found that the gross CTMF over the TP exhibits a strong negative trend in winter during the period 1979–2009, implying that the downward transport increases over the TP in the past three decades. They argued that the strong negative trend of gross CTMF in winter over the TP may be resulted from the combined effects of the rising tropopause height and weakening Asian winter monsoon.

Pulse signals in the stratospheric mass circulation include “PULSE_TOT”, “PULSE_W1”, and “PULSE_W2” events, defined as a period of stronger meridional mass transport into the polar stratosphere by total flow, wavenumber-1, and wavenumber-2, respectively. Yu *et al.*[95] found a robust relationship between two dominant patterns of winter Cold Air Outbreaks (CAOs) and PULSE_W1 and PULSE_W2 events. Cold temperature anomalies tend to occur over Eurasia with the other continent anomalously warm during the 2 weeks before the peak dates of PULSE_W1 events, while the opposite temperature anomaly pattern can be found after the peak dates; and during the 1–2 weeks centered on the peak dates of PULSE_W2 events, a higher probability of occurrence of CAOs is found over both continents. These relationships become more robust for PULSE_W1 and PULSE_W2 events of larger peak intensity. The specific pattern of CAOs associated with PULSE_TOT event is found to be a combination of the CAO patterns associated with PULSE_W1 and PULSE_W2 events.

Yu *et al.*[96] confirmed that the negative stratospheric Northern Annular Mode (NAM) and PSM index (total mass in the polar stratospheric cap, 60°–90°N, above the isentropic surface 400 K) have a nearly indistinguishable temporal evolution and a similar red-noise-like spectrum with a decorrelation timescale of 4 weeks. The DMT index (total diabatic mass transport across 400 K from the polar stratosphere into the troposphere below) tends to be positively correlated with the PSM with a red-noise-like spectrum, representing slow radiative cooling processes giving rise to a de-correlation timescale of 3–4 weeks. The AMT (total adiabatic mass transport across 60°N into the polar stratosphere cap) is nearly perfectly correlated with the day-to-day tendency of PSM, reflecting a robust quasi 90° out-of-phase relation between the AMT and PSM at all frequency bands.

Li and Tian[97] (2017) investigated the impact of two types of El Niño events, *i.e.*, eastern Pacific El Niño (EP-El Niño) and central Pacific El Niño (CP-El Niño) events, on the duration of major and minor Sudden Stratospheric Warmings (SSWs) in Northern Hemisphere winter (November to February) and they found that the duration of both major and minor SSWs during CP-El Niño is shorter than that during EP-El Niño. The analysis also revealed that EP-El Niño tends to induce positive phases of PNA and WP teleconnections, while CP-El Niño induces negative-phase WP teleconnection, while positive phases of the PNA and WP teleconnections tend to strengthen wavenumber 1, which accounts for the longer SSW duration during EP-El Niño than during CP-El Niño.

Tian *et al*.[98] (2017) found that the SST variations across the East Asian marginal seas (5°S-35°N, 100°–140°E) rather than the tropical eastern Pacific Ocean, where ENSO occurs, have the most significant correlation with the southern high-latitude lower-stratospheric ozone changes in austral spring. Their analysis revealed that planetary waves originating over the marginal seas in austral spring can propagate towards southern middle to high latitudes via teleconnection pathway and hence insert an influence on the southern polar stratospheric ozone. Their model simulations indicates that approximately 17% of the decreasing trend in the southern high latitude lower-stratospheric ozone observed over the past 5 decades can be accounted by the increasing SST trend over the East Asian marginal seas.

Xie *et al*.[99]. (2016) provided evidence from both observations and model simulations that ARctic Stratospheric Ozone (ARSO) changes are correlated with ENSO changes, with the ARSO leading ENSO by more than one year. They proposed that ARSO-induced circulation anomalies propagate downward to affect the North Pacific Oscillation (NPO) and Victoria Mode (VM) of the North Pacific, and hence modulate the ENSO cycle. Subsequently, Xie *et al.*[100] (2017) found that the ARSO changes in March have the strongest connection with North Pacific SST variations in April.

Li *et al*.[101] (2017) investigated the connections between the first two primary components of the Sea Surface Temperature (SST) anomalies over the North Pacific and the Stratospheric Sudden Warmings (SSWs) in the Northern Hemisphere winter. They showed that the winter SSW duration is more correlated to the second Primary Component (PC2) than the first Primary Component (PC1). On the other hand, the SSW event occurs more frequently and the winter SSW duration is longer during the positive phases of PC2 than the negative phases of PC2. They pointed out that SST anomalies of PC2 are capable of producing a feedback on the PNA and the WP teleconnections and hence, have an impact on the variability of SSWs.

Rao and Ren[102] revealed that, different from ordinary El Niño, warm SST anomalies appear earliest in the western tropical Pacific and precede the super El Niño peak by more than 18 months. In the previous winter, relative to the mature phase of El Niño, as a precursor, North Pacific Oscillation-like circulation anomalies were observed. A Pacific–North America (PNA) teleconnection appeared in the extratropical troposphere during the mature phase, in spite of the subtle differences between the intensities, as well as the zonal position, of the PNA lobes.

Hu *et al*.[103] found that, during 1958–1978, El Niño generated an anomalous Aleutian low in the mid troposphere extending from northeastern Eurasia to the northeastern Pacific with the most significant center in the northwestern Pacific. The anomalous Aleutian low resulted in a marked increase in planetary wavenumber 1 but a weak decrease in wavenumber 2 from the upper troposphere to lower stratosphere. The planetary wave converged at the high latitudes in the stratosphere and brings about a significantly weakened polar vortex. In contrast, during 1979–2015, the wintertime El Niño-related Aleutian low shifted eastward into the northeastern Pacific. This variation in tropospheric El Niño teleconnection led to a dramatic decrease in planetary wavenumber 2 but a relatively weak increase in wavenumber 1. Furthermore, the magnitude of the decrease of wavenumber-2 EP flux was comparable to the increase of wavenumber-1 EP flux in the stratosphere. Consequently, the stratospheric response lessened dramatically, showing a less disturbed and slightly enhanced polar vortex.

Rao and Ren[104] revealed that the Tropical Atlantic Ocean (TAO) SST forcing has significant effects on the northern winter stratosphere, but these effects vary from early to late winter in a way that explains the overall insignificant effect when the seasonal average is considered. The stratospheric polar vortex is anomalously weaker/warmer in November–December, stronger/colder in January-March, and weaker/warmer again in April-May during warm TAO years. The varying impacts of the TAO forcing on the extratropical stratosphere are related to a three-stage response of the extratropical troposphere to the TAO forcing during cold season.

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