0254-6124/2016/36(5)-738–15 *Chin. J. Space Sci.* 空间科学学报

CHEN Zeyu, XU Jiyao, HU Xiong, CHEN Hongbin, CHEN Wen, WEI Ke, BIAN Jianchun, TIAN Wenshou, ZHANG Shaodong, REN Rongcai, DOU Xiankang. Advances in the researches of the middle and upper atmosphere in China in 2014—2016. *Chin. J. Space Sci.*, 2016, **36**(5): 738-752. DOI:10.11728/cjss2016.05.738

Advances in the Researches of the Middle and Upper Atmosphere in China in 2014—2016

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Abstract In this report the research results by Chinese scientists in 2014—2016 are summarized. 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 chemical process, Observation infrastructure

Classified index P 351

1 Studies on Airglow Radiation

Gao *et al.*[1] analyzed the vertical structure of OH day-glow using the data from observations by the Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) instrument on the Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics (TIMED) satellite from January 2002 to June 2014. They found that there is a double-layer structure in the distributions of 12-year averaged OH airglow emission, [O_3], and [H] during the daytime. The upper layer of OH day-glow is located in the mesopause region (~88 km) at a similar altitude to that of the OH nightglow. The lower layer is situated in the range of 70—85 km. The double-layer structure of OH day-glow emission is a long-

Received May 31, 2016

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term stable structure and is mainly caused by photochemical processes involving $[O_3]$. It is also modulated by background atmospheric temperature and [H]. Liu *et al.*[2] studied the rotation temperature derived from OH airglow emission spectra at OH (8—3) band, which were observed by the ground-based spectrometer from December 2011 to December 2013. The comparison between OH rotation temperature and SABER temperature showed that the mean rotation temperature of OH (8—3) band is 203.0±11.2 K with 5.5 K warmer than SABER's. Both have obviously seasonal variations, *e.g.*, the annual amplitude of 10.8 K, the semiannual amplitude of 2.7 K. Liu *et al.*[3] used the OH (9—4, 8—3, 6—2, 5—1, and 3—0) band airglows to evaluate Einstein coefficient by comparing the ground-based temperature derived from five sets of Einstein coefficients and SABER/TIMED temperature. They showed that of the five sets of coefficients, the rotational temperature derived with Langhoff *et al.*'s set is most consistent with SABER. Based on these comparisons, they get a set of optimal Einstein coefficients for rotational temperature derivation. The use of a standard set of Einstein coefficients will be beneficial for comparing rotational temperatures observed at different sites.

2 Studies on Thermosphere

Geomagnetic storm can be clarified to two classes: Coronal Mass Ejections (CMEs) driven storms and the Co-rotating Interaction Regions (CIRs) driven storms. Chen *et al.*[4] carried out a statistical study to assess the relative importance of each kind of storm to satellite orbital decay. They showed that CIR storms have a slightly larger effect on total orbital decay than CME storms do in a statistical sense. During the declining phase and the minimum years of a solar cycle, CIR storms occur frequently and quasi-periodically. These storms have a large effect on thermospheric densities and satellite orbits because of their relatively long duration. Xu *et al.*[5] studied the latitudinal, longitudinal, and height dependences of the multi-day oscillations of thermospheric densities observed by CHAMP and GRACE satellites during 2002—2010 and the globally averaged thermospheric densities from 1967 to 2007. They find that the main multi-day oscillations in thermospheric densities are 27-, 13.5-, 9-, and 7-day oscillations. The high correlation coefficients between the density oscillations and the $F_{10.7}$ or Ap index indicate that these oscillations are externally driven. The multi-day, periodic oscillations of thermospheric density exhibit strong latitudinal and longitudinal variations in the geomagnetic coordinate and oscillate synchronously at different heights. Jiang *et al.*[6] investigated the responses of the lower thermospheric temperature to the 9-day and 13.5-day oscillations of recurrent geomagnetic activity and solar radiation. They found that the zonal mean temperature in the lower thermosphere oscillated with periods of near 9 and 13.5 days in the height range of 100—120 km. These oscillations were more strongly correlated with the recurrent geomagnetic activity than with the solar EUV. The amplitudes of 9-day and 13.5-day oscillations increase with latitudes and altitudes. Simulation results from NCAR-TIME-GCM reproduced these oscillations and indicated that recurrent geomagnetic activity is the main cause of the 9-day and 13.5-day variations in the lower thermosphere temperature, and the contribution from solar EUV variations is minor. Liu *et al.*[7] investigated the climatology of multiday oscillations with periods of 4—19 days using three-year (2010—2013) observations of thermospheric winds (at ~250 km) during declining solar phase by Fabry-Perot Interferometers (FPIs) at Xinglong (XL, 40.2°N, 117.4°E) and Millstone Hill (MH, 42.6°N, 71.5°W). They found that these oscillations occur more frequently in the months from May to October and coincide with the summertime preference of middle-latitude ionospheric electron density oscillations. Oscillations with periods of 4—19 days exhibit annual and semiannual variations and are correlated to both the Solar Wind speed (SW) and Kp. These studies indicate that the oscillations in the thermospheric neutral winds may possibly be influenced by CIRs, the related high-speed solar wind, and the recurrent geomagnetic activity. Liu *et al.*[8] analyzed an 11-year (1989−1995 and 2010−2013) nighttime thermospheric wind (at ∼250 km) data set from FPI at MH to investigate multiday oscillations (6−30 days) in the thermospheric nighttime winds. They found that there exist prominent quasi 27-day oscillations in the thermospheric zonal wind during solar maximum and quasi 13.5-day oscillations in the zonal wind occur during the solar maximum and increasing phases. The multiday oscillations in the thermospheric winds are more correlated with Kp and SW than $F_{10.7}$. Further analyses illustrated that the zonal wind is more sensitive to SW than the meridional wind. Sun *et al.*[9] analyzed the simultaneous observations from an all-sky imager, a GPS monitor, a digisonde and a Fabry-Perot Interferometer (FPI) at Xinglong (40.4°N, 30.5°N magnetic latitude), China, on 17, 18 February 2012. They find the evolution (generation, amplification, and dissipation) of mesoscale Field-Aligned Irregularity structures (FAIs) (∼150 km) associated with a Medium-Scale Traveling Ionospheric Disturbance (MSTID) event. The mesoscale FAIs had an obvious northwestward relative velocity to main-body MSTIDs. The direction of this relative velocity was roughly parallel to the depleted fronts and was mostly controlled by the intensity of the depleted fronts. A northeastward polarization electric field within a depleted airglow front can play a controlling role in the development of the mesoscale FAIs. Chen *et al.*[10] studied the O^+ field-aligned ambipolar diffusive velocities V_d and fluxes Φ_d in the topside ionosphere using the observed profiles observed by incoherent scatter radar experiment conducted at Millstone Hill (288.5°E, 42.6°N) from 4 October to 4 November 2002. Two geomagnetic storms took place during this period. By comparing V_d and Φ_d during different phases of the two storms and quiet times, they proposed that storm time variations in diffusive velocity were more likely the results of storm time changes in the plasma vertical profile, rather than the cause of these plasma density changes. Yao *et al.*[11] compared the meridional and zonal winds derived from the Kelan FPI wind model with those based on Meteor Radar wind observations in Beijing (39.92°N, 116.39°E), and those calculated from horizontal wind models, *i.e.*, HWM93 and HWM07, at Kelan. They found that the Kelan FPI wind patterns agreed well with the Meteor Radar winds and the HWM07 model results, but less well with the HWM93 model in the mesopause region. The comparison indicates that there were large discrepancies between the Kelan FPI winds and the HWM07 model results, which were mainly due to differences in the annual variation in the nighttime meridional wind.

3 Solar Effect on the East-Asian Monsoon System

Solar radiation is the primary energy source for the motion of the atmosphere, and the most important interdecadal timescale is the 11-year solar cycle. During winters with High Solar activity (HS), robust warming appeared in northern Asia in response to a positive AO phase[12]. However, during winters with Low Solar activity (LS), the surface warming was much less in the presence of a positive AO phase. Possible mechanism for this 11-year solar cycle modulation is suggested to be the indirect influence of solar activity on the AO structure. On the other hand, the relationship between the EAWM and the EASM is also modulated by the 11-year solar cycle[13]. The EAWM-ENSO relationship depends on the solar cycle with more robust relationship in the LS categories. There tends to be a much stronger EASM after a weak EAWM associated with ENSO during the LS phases than during the HS phases. Different evolution of SST anomalies in the HS and LS years are further demonstrated, and thus explain why a closer EAWM-EASM relationship is established during LS years than HS years. These findings extend earlier ones by emphasizing the modulation effect of solar cycle on the AO&ENSO and the East Asian climate relationship, which has practical use for climate prediction.

4 Dynamical Processes in the Middle Atmosphere

4.1 Tides

Xu *et al.*[14] studied the nonlinear interaction between Stationary Planetary Waves (SPWs) and tides in the stratosphere and mesosphere using the global temperature data from 11 years (2002—2012) SABER/TIMED observations. The holistic behavior of the nonlinear interactions between all SPWs and tides is analyzed from the point of view of energetics. The results indicate that the intensities of nonmigrating diurnal, semidiurnal, terdiurnal, and 6 h tides are strongest during winter and almost vanish during summer, synchronous with SPW activity. Thus nonlinear interactions between SPWs and tides in the stratosphere and the lower mesosphere may be an important source of the nonmigrating tides that then propagate into the upper mesosphere and lower thermosphere. Liu *et al.*[15] studied the global structure and seasonal variations of the migrating 6 h tide from the stratosphere to the lower thermosphere using 10-year of SABER/TIMED temperature data. The amplitudes of the migrating 6 h tide increase with altitudes. In the stratosphere, the migrating 6 h tide peaks around 35°N/°S. The migrating 6 h tide is stronger in the southern hemisphere. Annual, semiannual, 4 and 3-month oscillations are the four dominant seasonal variations of the tidal amplitude. Both ozone heating in the stratosphere and the background atmosphere probably affect the generation and the seasonal variations of the migrating 6 h tide. In addition, the non-linear interaction between different tidal harmonics is another possible mechanism. Liu *et al.*[16] examined modulations of the temperature migrating diurnal tide (DW1) by latitudinal gradients of zonal mean zonal wind using the temperature data from SABER/TIMED and Empirical Orthogonal Function (EOF) analysis. The result shows that latitudinal gradient of zonal mean zonal wind increases with altitudes and displays clearly seasonal and interannual variability. These variations are in a similar manner as the DW1. The resembling spatial-temporal features suggest that in the upper tropic MLT probably plays an important role in modulating semiannual, annual, and quasi-biennial oscillations in DW1 at the same latitude and altitude. Yu *et al.*[17] studied seasonal variations of MLT tides using meteor radar chain. The seasonal variations of different tides in the mesosphere and lower thermosphere are investigated from wind observations of a meteor radar chain on the basis of Hough mode decomposition. Pronounced Semiannual Oscillation (SAO) is presented in the diurnal component, while latitude-dependent seasonal variation is found in the semidiurnal and terdiurnal components. At the low/mid-latitude stations, the semiannual/annual oscillation is relatively stronger. Hough mode decomposition is utilized to extract the dominant tidal modes of each decomposed component. It is found the (1, 1) mode dominates the diurnal component with apparent SAO, (2, 4) mode of the semidiurnal component is strong in the autumn and winter months (after the September equinox). Ren *et al.*[18] studied the influence of DE3 tide on the equinoctial asymmetry of the zonal mean ionospheric electron density. Through respectively adding September DE3 tide and March DE3 tide at the low boundary of GCITEM-IGGCAS model, we simulate the influence of DE3 tide on the equinoctial asymmetry of the zonal mean ionospheric electron density. The influence of DE3 tide on the equinoctial asymmetry of the zonal mean electron density varies with latitude, altitude and solar activity level. Compared with the density driven by September DE3 tide, the March DE3 tide mainly decreases the lower ionospheric zonal mean electron density, and mainly increases the electron density at higher ionosphere. In the low-latitude ionosphere, DE3 tide drives an Equatorial Ionization Anomaly structure (EIA) at higher ionosphere in the relative difference of zonal mean electron density, which suggests that

DE3 tide affect the longitudinal mean equatorial vertical $\boldsymbol{E} \times \boldsymbol{B}$ plasma drifts. Although the lower ionospheric equinoctial asymmetry driven by DE3 tide mainly decreases with the increase of solar activity, the asymmetry at higher ionosphere mainly increases with solar activity. However, EIA in equinoctial asymmetry mainly decreases with the increase of solar activity. Li *et al.*[19] studied yearly variations of the stratospheric tides. The three main tidal components, *i.e.*, the migrating components DW1, SW2 and the non-migrating component DE3, at the two stratospheric altitudes (20 and 43 km) and in the latitude range between $\pm 60°$, are obtained from the temperature data of National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR) during the interval from 1979 to 2010. The yearly variations of the main tidal components may demonstrate that the CFSR reanalysis data can be used as a supplementary observation in the investigation of the stratospheric tidal components. Li *et al.*[20] studied the variability of nonmigrating tides. This paper deals with the variability of the nonmigrating tides detected from the observation of the SABER instrument onboard the TIMED satellite during the 11-year solar period from 2002 to 2012. We found that the properties of the spatial distribution and large time-scale variation of the DE3 component are similar to those of the previous works, which used the interpolated data with 2-month resolution. Practically, the higher-resolution data were used to reveal the day-to-day variability of the DE3 component. The day-to-day variability of the DE3 component may be explained by the variance of the absolute amplitudes and the contribution of the wave phases, and the later seems to play more important role.

4.2 GWs

Chen *et al.*[21] simulated generation of stratospheric gravity waves in upper-tropospheric jet stream accompanied with a cold vortex over Northeast China in June 2010, using WRF ARW. The results reveal that pronounced stratospheric GWs are generated by the jet stream as they emerge from the exit region of jet stream.

To identify oceanic regions for which convection is a major source of Gravity Waves (GWs), Jia *et al.*[22] analyzed the correlation between sea surface temperature and absolute values of Gravity Wave Momentum Flux (GWMF) deduced from satellite data. Convective GWs are identified at the eastern coasts of the continents and over the warm water regions formed by the warm ocean currents, in particular the Gulf Stream and the Kuroshio. Potential contributions of tropical cyclones to the excitation of the GWs are discussed. Convective excitation can be identified well into the mid-mesosphere. In propagating upward, the centers of GWMF formed by convection shift poleward. Some indications of the main forcing regions are even shown for the upper Mesosphere/Lower Thermosphere (MLT).

Jia *et al.*[23] investigated the GW variability during the Sudden Stratosphere Warming (SSW) in 2008 and 2009 using the COSMIC temperature profiles together with zonal wind and geopotential height data from NCEP/NCAR reanalysis. GWs were enhanced at the edge of the polar vortex where the background wind was strong, whereas the areas with the largest GW amplitudes did not always correspond with those with the strongest background wind. In 2008, the magnitudes of the zonal mean GWs enhancements during the downward progression were relatively stable, whereas a clear reduction was detected as the GW enhancement was progressing downward in 2009.

Xu *et al.*[24] developed a no-gap OH airglow all-sky imager network for the first time in northern China since February 2012. The network is composed of 26 all-sky airglow imagers that make observations of OH airglow gravity waves and cover an area of about 2000 km east and west and about 1400 km south and north. In the study, the authors reported a series of Concentric Gravity Wave (CGW) events nearly every night during the first half of August 2013. Further analysis on two representative CGW events illustrated that on CGW was likely launched by a single thunderstorm. The temporal and spatial analyses indicate that the CGW horizontal wavelength agrees with the GW dispersion relation within 300 km from the storm center. Another CGW event was launched by two very strong thunderstorms on 9 August 2013. These CGWs have multi-scales with horizontal wavelength ranging from less than 10 km to 200 km.

Liu *et al.*[25] studied the diurnal variations of turbulence parameters (turbulence kinetic energy and turbulence diffusivity) in the tropical oceanic upper troposphere. This study used the four times per day radio sounding data on the Kexue#1 scientific observation ship of South China Sea Monsoon Experiment (SCSMEX) in 1998 and the concurrent mesoscale convective systems derived from TRMM (Tropical Rain-fall Measuring Mission) satellite. They found that the diurnal variations of turbulence parameters averaged over May and June are strongly correlated with the diurnal variations of MCS with correlation factors of 0.79 and 0.94, respectively. This indicates that the turbulence and its diurnal variations over the tropic oceanic upper stratosphere region are highly related to the MCS. Liu *et al.*[26] simulated GWs breaking and their contributions to the formation of large winds ($\geqslant 100\,\mathrm{m{\cdot}s^{-1}}$) and wind shears ($\geqslant 40\,\mathrm{m{\cdot}s^{-1}{\cdot}km^{-1}}$) in the Mesosphere and Lower Thermosphere (MLT). They showed that the momentum deposited by breaking GWs accelerates the mean wind. The resultant large background wind increases the GW's apparent horizontal phase velocity and decreases the GW's intrinsic frequency and vertical wavelength. Both the accelerated mean wind and the decreased GW vertical wavelength contribute to the enhancement of wind shears. This, in turn, creates a favorable condition for the occurrence of GW instability, breaking, and momentum deposition, as well as mean wind acceleration, which further enhances the wind shears. Liu *et al.*[27] performed 64 numerical experiments to simulate GWs with different wavelengths propagating in the migrating diurnal and semidiurnal tidal background. They found that both migrating diurnal and semidiurnal tides strongly modulate the occurrence of GW breaking, and the resulted large winds and wind shears. The simulated large winds and wind shears are in good agreement with those from the rocket-sounding chemical release measurements. Moreover, the occurrence of large wind shears highly depends on the phases of migrating tides in local time, which is in agreement with the reported lidar observations. This study revealed that the nonlinear interactions between GWs breaking and the migrating diurnal and semidiurnal tides may play an important role in driving the large winds and wind shears in the MLT region and their local time dependence. Liu *et al.*[28] used a 6-year (2007—2013) temperature data set from SOFIE/AIM to extract GWs in the polar stratosphere and mesosphere of both hemispheres. They showed that GWs are stronger in the winter than in the summer and exhibit strong annual variation. GWs are stronger in the Southern Polar Region (SPR) than in the Northern Polar Region (NPR) except in the summer months. This is likely because there are stronger and longer-lasting zonal wind jets in the SPR stratosphere. The longitudinal variations of PE in the winter polar stratosphere are consistent with the elevated regions. The correlations between GW potential energy and the column Ice Water Content (IWC, an indicator of the polar mesosphere cloud) exhibit longitudinal and annual variations.

Wei *et al.*[29] found that orographic wave excited by the TP propagate upward into the stratosphere and breaks near 150 hPa, leading to a strong attenuation of momentum flux and the release of energy into basic flows. Meanwhile, vertical turbulent mixing is extremely increased and turbulent exchange coefficient enhances by more than eight times during a short period (within 1 hour). Large turbulent mixing process causes air transports from the troposphere to the stratosphere.

4.3 Planetary Waves

Liu *et al.*[30] studied 5-day Planetary Waves (PWs) in the polar stratosphere and mesosphere using the temperature and column Ice Water Content (IWC) of

Polar Mesospheric Clouds (PMCs) measured simultaneously by the Solar Occultation for Ice Experiment (SOFIE) onboard NASA's Aeronomy of Ice in the Mesosphere satellite from 2007 to 2014. They found that the 5-day PWs in temperature are stronger in the polar winter stratosphere and mesosphere and exhibit substantial interhemispheric asymmetry. The strength of 5-day waves coincide with those of the eastward jet in each hemisphere. This indicates that the 5-day PWs might be generated from barotropic/baroclinic instability in the polar stratosphere. In the same study, the authors also showed that the phase shifts of W1 5-day PW in temperature relative to that in IWC have a mean of $-2.0\,$h ($0.3\,$h) with a standard deviation of $3.8\,$h ($4.2\,$h) in the northern (southern) polar region. This indicates that the formation of the W1 5-day PW in PMCs is controlled mainly by the W1 5-day PW in temperature and influenced by other factors.

Extending the broad spectral method proposed by Zhang *et al.* and applying 11-year (1998−2008) of radiosonde data from 92 stations in the Northern Hemisphere, Zhang *et al.*[31] investigated latitudinal, continuous vertical and seasonal variability of Medium- and High-frequency Gravity Waves (MHGWs) parameters in the lower atmosphere (2−25 km). The latitudinal and vertical distributions of the wave energy density and horizontal momentum fluxes as well as their seasonal variations exhibit considerable consistency with those of inertial gravity waves. Despite the consistency, the MHGWs have much larger energy density, horizontal momentum fluxes and wave force. The derived intrinsic frequencies are more sensitive to the spatiotemporal variation of the buoyancy frequency, and at all latitudinal regions they are higher in summer.

Gan *et al.*[32] reported the seasonal variations of the westward propagating 6.5-day planetary wave in the Mesosphere and Lower Thermosphere (MLT). A case study (around Day 130 in Year 2003) revealed an extraordinarily strong 6.5-day wave event. They found that intensive dissipation of 6.5-day wave in the mesopause region induced an extra meridional circulation, which could result in a net upward and downward transportation of atomic oxygen and molecular nitrogen, thus, the depletion of thermospheric O/N_2 ratio. Using meteor radar, radiosonde and satellite observations over 20°N and NCEP/NCAR reanalysis data during 81 days from 22 December 2004 to 12 March 2005, Huang *et al.*[33] observed a quasi-27-day oscillation propagating from the troposphere to the mesosphere. The oscillation attains a large amplitude of about $12\,\mathrm{m\cdot s^{-1}}$ in the eastward wind shear region of the troposphere. When the wind shear reverses, its amplitude rapidly decays, and the background wind gradually evolves to be westward. They further suggested that the quasi-27-day oscillation may be an atmospheric response to forcing due to the convective activity with a period of about 27 days in the tropical region.

Using extended Canadian Middle Atmosphere Model (eCMAM), Gan *et al.*[34] validated the migrating and non-migrating diurnal tidal modes with SABER temperature observation. It is found that the major tidal modes in temperature were well simulated by eCMAM with realistic lower atmosphere physics, parameterizations of gravity wave in the middle atmosphere and ion drag in the ionosphere. The simulated diurnal tides exhibited consistent spatial structure and seasonal and inter-annual characteristics compared with 11-year observations, indicative of further utilization of tidal-related research. Using observation data from the Wuhan University (WHU) VHF radar in 2012, Huang *et al.*[35] studied the primary features of the DT and its variability in the lower atmosphere over Chongyang (114.14°E, 29.53°N). They found that dominant diurnal oscillations exist in the lower atmosphere at middle latitudes, and the diurnal tide shows remarkable height, season, and short-term variability. The background wind could be responsible for diurnal tide height and season variability. The short-term variation in the tidal source and the coupling with planetary waves could be responsible for short-term variability of diurnal tide.

5 Stratospheric Processes

5.1 Sudden Stratospheric Warming

Shuai *et al.*[36] reported a study on the Elevated Stratopause (ES) events in the winter of 2006, 2009 and 2010 at 70°N. The studies are based on the SABER/TIMED temperature measurements in the period from 2003 to 2011. Their results indicated that the ES events occur only after the major Sudden Stratospheric Warming (SSW) accompanying with the polar vortex splitting. They suggested that in the ES events, enhancement of gravity wave activity could be observed at ~80 km between late January and early February, corresponding to the ES occurrence height and time.

Hu *et al.*[37] investigated the boreal spring Stratospheric Final Warming (SFW) and its interannual and interdecadal variability. They found that the earliest SFW occurs in mid-March whereas the latest SFW happens in late May. The early/late SFW events in boreal spring correspond to a quicker/slower transition of the stratospheric circulation. The earlier breakdown of the Stratospheric Polar Vortex (SPV), as for the winter Stratospheric Sudden Warming (SSW) events is driven mainly by wave forcing; and in contrast, the later breakdown of the SPV exhibits more characteristics of its seasonal evolution. In addition, the SFW onset time before the mid-1990s is 11 days earlier than that afterwards. Hu *et al.*[38−39] then demonstrates relationship between intensity and occurrence of major stratospheric Sudden Warming Events (SSWs) in midwinter and the seasonal timing of Stratospheric Final Warming events (SFWs) in spring. Specially, early spring SFWs that on average occur in early March tend to be preceded by non-SSW winters, while late spring SFWs that on average take place up until early May are mostly preceded by SSW events in midwinter. Planetary wave activity and western Eurasian high may play a role.

Pogoreltsev *et al.*[40] suggested that nonlinear interaction between planetary waves and mean flow could provide a favorable condition for the Sudden Stratospheric Warming (SSW) initiation. Their results demonstrated that the nonlinear wave-wave and wave-mean flow interactions could play an important role before and during SSW.

Xue *et al.*[41] investigated the modulation effect of QBO on the connection between ENSO and the summer South Asian High (SAH). Their results suggested that the boreal summer SAH was more significantly influenced by preceding ENSO events in the easterly phase of the QBO than in the westerly phase. This change in the ENSO-SAH relationship in the different QBO phases was attributable to the change in the ENSO-induced sea surface temperature anomalies over the tropical Indian Ocean. This result highlights the modulation effect of the QBO on the impacts of ENSO events, and the QBO should be taken into consideration when ENSO is used to predict the Asian monsoon variations.

Guo *et al.*[42] found double-core structure of ozone valley over the Tibetan Plateau and presumed its possible mechanisms. From Microwave Limb Sounder (MLS) ozone (O_3) data, a double core structure of the ozone valley over the TP is found with one depletion center in upper stratosphere named the upper core, and another depletion center, named the lower core, is observed in the upper troposphere/lower stratosphere. The analysis indicates that the zonal deviation of ozone at the upper core is nearly −1 DU while its counterpart's deviation at the lower core is nearly −15 DU. Large scale atmospheric circulation and terrain effects play an important role in the ozone valley at the lower core. In contrast, photochemistry reactions of odd chlorine including Chlorine atoms (Cl) and Chlorine monoxide (ClO) dominate the ozone valley at the upper core.

Zhang *et al.*[43] reported that the Total column Ozone Low (TOL) over the TP during winter and spring is deepening over the recent decade. Based on the analysis of multiple regression model, the thermal dynamical processes associated with the TP warming accounts for more than 50% of TCO decline during winter for the period of 1979—2009. According to the Chemistry-Climate Model (CCM) simulations, the increases in NO_x emissions in East Asia and global tropospheric N_2O mixing ratio for the period of 1979—2009 contribute to no more than 20% reductions in TCO during this period.

Xie *et al.*[44] found that El Niño Modoki has had a significant effect on tropical ozone since the 1980s, alongside that of the QBO, and canonical El Niño. Based on EOF analysis, it was found that the leading mode of TCO variability, accounting for ~28% of the variance, is associated with El Niño Modoki events, and the other modes are related to the QBO and canonical El Niño. Since El Niño Modoki activity leads tropical ozone changes by 3—4 months, it could serve as a predictor for tropical ozone variations. Xie *et al.*[45] revealed that the continuous expansion of the area of the Indo-Pacific Warm Pool (IPWP) since the 1980s represents an increase in the total heat energy of the IPWP available to heat the tropospheric air. This process lifts the tropical cold-point tropopause height and leads to the observed long-term cooling trend of the tropical tropical Cold-Point Tropopause Temperature (CPTT). In addition, Modoki activity is an important factor in modulating the interannual variations of the tropical CPTT through significant effects on overshooting convection.

Wang *et al.*[46] revealed that the Carbon Oxide (CO) surface emissions explain most of the semi-annual oscillation signals in the tropical upper troposphere, with the remainder being attributed to dynamical and chemical processes. The CO Annual Oscillation (AO) in the lower stratosphere primarily results from combined effects of dynamical and chemical processes while the dynamical and chemical processes make opposite contributions to the CO AO signals. CO surface emissions tend to weaken the amplitude of the CO annual cycle in the tropical lower stratosphere, while the annual variations in the meridional component of the BD circulation can amplify the annual variations of CO above 30 hPa.

5.2 Stratosphere Climate Change Simulation

Hu *et al.*[47] used a state-of-the-art general circulation model and found that, in the Southern Hemisphere, the stratospheric ozone depletion leads to a cooler and stronger Antarctic stratosphere, while the stratospheric ozone recovery has the opposite effects. In the Northern Hemisphere (NH), the impacts of the stratospheric ozone depletion on polar stratospheric temperature are not opposite to that of the stratospheric ozone recovery; *i.e.*, the stratospheric ozone depletion causes a weak cooling and the stratospheric ozone recovery causes a statistically significant cooling. Particularly interesting is that stratospheric ozone changes have opposite effects on the stationary and transient wave fluxes in the NH stratosphere.

Wang *et al.*[48] investigated the impact of the assumed N_2O increases on stratospheric chemistry and dynamics using a series of idealized simulations with a CCM. In a future cooler stratosphere the net yield of NO_y from N_2O is shown to decrease in a reference run following the IPCC A1B scenario, but NO_y can still be significantly increased by extra increases of N_2O over 2001—2050. Meanwhile, the ozone depleting potential of N_2O varies with the time period and is influenced by the environmental conditions.

Shang *et al.*[49] showed that CH_4 emission increases will accelerate the BD circulation. However, the BD circulation in the tropics at 100 hPa weakens as CH_4 emissions increase in East Asia and strengthens when CH_4 emissions increase in North America. A 50% increase of CH_4 emissions in North America has a greater influence on the stratospheric ozone increases than the same CH_4 emissions increase in East Asia. CH_4 emission increases in East Asia and North America reduce the concentration of tropospheric hydroxyl radicals and increase the concentration of mid-tropospheric ozone in the Northern Hemisphere mid-latitudes.

Zhang *et al.*[50] revealed that the longitudinal dependence of mid-latitude ozone anomalies associated with ENSO events during the period of January—February—March is found to be related to planetary waves. The wave trains affect ozone in the Upper Troposphere and Lower Stratosphere (UTLS) by modulating the mid-latitude tropopause height and cause Total Ozone Column (TOC) anomalies by changing the vertical distributions of ozone. In addition, changes in synoptic-scale Rossby wave breaking can also influence ozone through modulating eddy-driven meridional circulation in the UTLS. Based on the above mechanisms, Zhang *et al.*[51] further found that the maximum response of the TOC to ENSO shifts northward from southern China in winter to northern China in summer. The seasonal shift of the center of TOC anomalies is related to the seasonal shift of the location of East Asia westerly jet, accompanied by tropopause height changes and anomalous circulation induced by Rossby wave trains along the jet. The differences in the TOC between El Niño and La Niña events can cause up to 6%—10% clear-sky erythemal UV changes over the middle and lower reaches of the Yangtze River in winter and the northwestern Tibetan Plateau (TP) during spring.

Hu *et al.*[52] showed that increases in SST and the SST meridional gradient could intensify the subtropical westerly jets and significantly weaken the northern polar vortex. Global uniform SST increases produced a more significant impact on the southern stratosphere than the northern stratosphere, while SST gradient increases produced a more significant impact on the northern stratosphere. The asymmetric responses of the northern and southern polar stratosphere to SST meridional gradient changes were found to be mainly due to different wave properties and transmissions in the northern and southern atmosphere.

Using E-P flux in quasi-geostrophic spherical coordinates and its transformation form weighted by zonal annular total mass[53]. Subsequently, Shi *et al.*[54] reported recent latitudinal-structure changes in the boreal Brewer-Dobson circulation. The global ozone chemistry and related trace gas data records for the stratosphere data (GOZCARDS) show that the tropical lowermost stratospheric WV increased by 18% per decade during 2001—2011 and the boreal mid-latitude lower stratospheric HCl rose 25% per decade after 2006. This may result from a slow down of the tropical upwelling and a speedup of the mid-latitude downwelling, which is also supported by composite analysis of Eliasen-Palm Flux (EPF), zonal wind and regression of temperature on the EPF from the ERA-Interim data.

5.3 STE Processes

Using reanalysis datasets, Wei *et al.*[55] indicated that the relationship between the second mode of East Asian Winter Monsoon (EAWM) and the Stratospheric Polar Vortex (SPV) increased suddenly since the late 1980s. The SPV-related circulation and planetary wave activities are intensified in the latter period. The global warming and ozone depletion are further suggested to cause this change.

Reflection of stratospheric planetary waves and its impact on tropospheric cold weather over Asia during January 2008 was investigated by Nath *et al.*[56]. They found that a wave packet emanating from Baffin Island/coast of Labrador propagated eastward, equatorward and was reflected over Central Eurasia and parts of China, which in turn triggered the advection of cold wind from the northern part of the boreal forest regions and Siberia to the subtropics. Extreme cold weather occurred in the wide region of Central Eurasia and China during the second ten days of January 2008. Nath *et al.*[57] further studied the impact of planetary wave refection on tropospheric blocking over the Urals-Siberia region in this event by employing time-lagged singular value decomposition analysis on the geopotential height field. The results clearly showed that around mid-January, the upward component of the high-latitude wave guide was very weak, it was only the downward component that could have contributed to the development of the blocking high over the Urals-Siberia region.

Shi *et al.*[58] studied stratosphere-troposphere exchange caused by a deep convection in warm sector and abnormal subtropical front of a cutoff low over East Asia in June 2009, using cloud profile radar data from Cloudsat, temperature of black body from FY-2C, atmospheric compositions from Aura/MLS, meteorological data from the ECMWF and HYSPLIT4 trajectory model. The analysis shows that intense stratosphere-troposphere exchange occurs in the abnormal subtropical front zone due to the convective injection into stratospheric intrusions. On the scatter plot of ozone and water vapor these are two special gathering areas with both high (low) concentrations of the two species. Chen *et al.*[59] simulated a typical cold vortex over northeast China during 19−23 June 2010 using WRF model and investigated the stratosphere-troposphere exchange process through Wei formula. Results showed that the Cross-Tropopause mass Flux (CTF) induced by the cold vortex was controlled by Stratosphere-to-Troposphere Transport (STT). The time evolution of the CTF exhibited three characteristics: (i) the predominance of the STT during the pre-formation stage; (ii) the formation and development of the cold vortex, in which the CTF varied in a fluctuating pattern from Troposphere-to-Stratosphere Transport (TST) to STT to TST; and (iii) the prevalence of the STT during the decay stage.

Xu *et al.*[60] found that the higher orography has a significant influence on the STE processes with its effect having an evident diurnal variation. In the morning and evening time, the upward motions due to forcing lift of the high orography are strong and inhibit the STE. In the afternoon, the thermal effects of the high orography enhance and the turbulent mixing above the height of the orography of 2.5 km is critical, with an increase of 1% when the average orographic height rises 100 m.

Yang *et al.*[61] found, using WRF model, that deep convection over the TP can inject dust aerosols into the stratosphere. When there is no overshooting convection, vertical motions cannot transport aerosols directly into the lower stratosphere. However, small scale diffusion and mixing processes can slowly transport aerosols in the upper troposphere into the lower stratosphere using a few hours of time. Zhang *et al.*[62] reported that vertical transport of dust aerosols is closely related to background horizontal winds. In the absence of the cloud microphysical processes, when a deep convergence zone of northerly and southerly winds forms over the TP, the vertical motions resulted from the convergence could transport dust aerosols, originated from the Taklimakan desert, to the lower stratosphere with an evident inclined transport pathway. Tian *et al.*[63] showed that the distributions of water vapor over the TP from 2005 to 2008 are characterized by a minimum over the southern TP from March to April, and a maximum over the southern TP from July to October near tropopause region at 100 hPa. The low water vapor at 215 hPa over the center of the TP is related to the sinking of dry air from the UTLS region.

5.4 Studies on the Troposphere

Liu *et al.*[64] found that the effects of the QBO on tropical tropopause and OLR are most significant in winter and autumn while relatively insignificant in spring and summer. The tropical tropopause height and temperature anomalies associated with the QBO exhibit a belted distribution in the tropics while the OLR anomalies have both positive and negative anomalies along the equator. The buoyancy frequency anomalies and Convective Potential Energy (CAPE) anomalies associated with the QBO are spatially in accordance with the QBO-induced OLR anomalies, suggesting that the QBO can affect tropical convective activities through modulating the static stability and the CAPE in the tropical troposphere.

Based on the satellite observations and reanalysis data, Shi *et al.*[65] showed the distribution of Cloud Top above the Tropopause (CTAT) events and its effect on water vapor and temperature structures in the Upper Troposphere and Lower Stratosphere (UTLS) over East China. The maximum frequency of CTAT in boreal summer is located in Asian monsoon region. Meanwhile, the maximum frequency of CTAT in mid-latitudes is located in Northeast Asia. Composite analysis suggested that “dry above-moist below” and “cold above-warm below” structure in the UTLS along 15°−35°N over East Asia-West Pacific region may be associated with tropical cyclones, the opposite structure in the UTLS along 35°—50°N may be related to extratropical cyclones.

Zheng *et al.*[66] analyzed the variation of tropical tropopause height in 1919—2011. The results indicate an increase linear trend of tropopause height contributed by tropical convection, total ozone and tropospheric air temperature. With the linear trend removed, tropical tropopause varies significantly at periods of 18.2, 28.6 and 40 months. 18.2-month variation may be related to ozone and tropospheric temperature induced by monsoon. 28.6-month variation may be attributed to the quasi-biennial variation of ozone induced by the lower stratospheric zonal wind. 40-month period is mainly responsible for ENSO.

Zhang *et al.*[67] presented the intense interaction between the Tropopause Inversion Layer (TIL) and the Inertial Gravity Wave (IGW) activities using a high vertical resolution radiosonde data set at a midlatitude station for the period of 1998—2008. It is found that the TIL not only could inhibit the upward propagation of IGWs from below but also imply the possible excitation links between the TIL and IGW. The results also indicate that the enhanced wind shear layer just 1 km above the tropopause may result in the IGW breaking and intensive turbulence. The effect of the IGW-induced intensive turbulence could significantly cool the tropopause, which makes the tropopause colder and sharper and finally forms the TIL.

Zhang *et al.*[68] studied the diurnal variation of the Planetary Boundary Layer Height (PBLH) by using the eight-times-daily sampling data from an intensive radiosonde observation campaign at Yichang (111°E, 30°N), China in August 2006 and January 2007. It was found that the PBLH in both summer and winter months showed diurnal changes and the daily cycle was deeper in summer; the morning rise began at 07:00 LT/10:00 LT in summer/winter and the evening transition occurred at 19:00 LT in both seasons; the maximum height occurred in the afternoon for most cases, except some peaks found in the winter night.

6 Development of Infrastructure

Based on the 1 min backscatter ratio R profiles from the all-day lidar measurements in Wuhan, China (30.5°N, 114.4°E), Kong and Yi[69] calculated the hourly Convective Boundary Layer (CBL) height with the variance method. The computed CBL height sequence displays the regular diurnal cycle of the CBL top. The diurnal variation of the CBL height shows an obvious seasonal dependence which coincides with the annual variation of the local surface temperature. The surface fine particle concentration generally has a more complex diurnal cycle than that expected from the CBL-dilution/CBL-accumulation effect. They suggested that the seasonal behavior of the surface fine particle concentration mainly depends on the seasonal variation in available volume (determined by the CBL height) for aerosol dispersion.

A spectrally resolved Raman lidar has been built by Liu and Yi[70] to measure atmospheric N_2 Stokes vibrational-rotational Raman spectra. The lidar applies a double-grating polychromator with a reciprocal linear dispersion of $\sim 0.12\,\mathrm{nm\cdot mm^{-1}}$ for the wavelength separation and a 32-channel linear-array photomultiplier tube for sampling the spectral signals. A comparison shows an excellent agreement between the lidar-measured and theoretically-calculated spectra. A new temperature retrieval approach without needing a calibration from reference temperature data has been developed. The temperature derived from the new lidar and method is comparable to that from local radiosonde.

Acknowledgement Thank to Dr. Ling Chao from the CAS/IAP for his effort on text compilation.

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