Advances in the Researches of the Middle and Upper Atmosphere in China in 2012–2014

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ABSTRACT

In this report we summarize the research results by Chinese scientists in 2012–2014. The focuses are placed on the researches of the middle and upper atmosphere, specifically the researches releated to ground-based observation capability development, dynamical processes, the property of circulation and chemistry-climate coupling of the middle atmospheric layers.

KEY WORDS

Middle and upper atmosphere, Composition, Structure, Dynamics, Infrastructure, Monitoring campaign

1 Introduction

The researches of the middle and upper atmosphere in the context of COSPAR undergo smoothly in the past two years from 2012 to 2014 in China. From the aspect of linking the climate change to the middle atmospheric processes, a national research program focusing on the researches on stratospheric processes, in particular on the role of the processes in the weather and climate of the eastern Asia, has been conducted[1]. Here we review the primary research results during the years. While the readers who have interests in the previous advancements before 2012 are suggested to refer to Chen *et al.*[2] and the references therein.

2 Development in Infrastructure and Monitoring Campaign

In July of 2011, a new Mesosphere-Stratosphere-Troposphere (MST) radar was set up in the Atmospheric Observing Station of Xianghe, Institute of Atmospheric Physics, Chinese Academy of Sciences. The radar consists of 24×24 tri-unit rectangle phase antenna array and radar host system. Main specifications include: operational frequency 50 MHz ($\lambda = 6$ m), pulse width 1~10 μs, pulse repetition period 80–800 μs, emission peak power $\geqslant$172 kW, antenna array area 9110 m^2, power-aperture product 3.1×10^8 $W{\cdot}m^2$, antenna beam width $\leqslant$4.5°, detecting limit 3.5–25 km, 60–90 km and 150–1500 m, measureable maximum radial velocity $\geqslant$ 35 $m{\cdot}s^{-1}$, radial velocity precision $\leqslant$ 0.2 $m{\cdot}s^{-1}$, mimimum time resolution 20 min.

Since the Xianghe MST radar has been built, it has been continuously operated over two years, while the data has been accumulated for over 700 days excluding thunderstorm weather. The MST radar has three detection modes, for lower, middle, and upper atmospheric measurements, respectively. The measured parameters include 3-D wind, echo Signal-to-Noise Ratio (SNR), echo power spectrum, backscatter power, and atmospheric structure constant of refractive index, and these data can be used to study the lower ionosphere, meteoric ionization, tropopause, gravity waves, tidal waves, and wind shear.

A lidar system for middle atmosphere profiling has been being developed in the key Laboratory of middle Atmosphere and Global Environment Observation (LAGEO) of the Chinese Academy of Sciences since 2010. The lidar system includes a flashlamp-pumped Nd:YAG laser (550 mJ, 30 Hz) as transmitter, a 1 m telescope as receiver, and a detector & control unit, all installed inside a mobile container. In August 2013, MARMOT (Middle Atmosphere Remote Mobile Observatory in Tibet) Campaign was conducted at the site located at the Lhasa campus (3650 m a.s.l) of the Institute of Tibetan Plateau Research, CAS. Our lidar took ground-based measurements on the middle atmosphere densities and temperatures from 30 up to 70 km under the clear sky condition, with the time resolution of 1 min and the vertical resolution of 50 m.

A network including the sodium wind/temperature lidar, the Rayleigh lidar, the FP wind interferometer, the all-sky imager, the Medium-Frequency radar and Meteor radar in the Langfang (39.4°N, 116.7°E) Near-space Atmospheric Observatory of the CAS/NSSC (National Space Science Center, the Chinese Academy of Sciences), operated routinely during 2012–2013, and collected abundant middle atmospheric data.

A new Rayleigh Doppler lidar probing the atmospheric winds from 30–70 km was developed in the NSSC/LNSER (Lab of Near-Space Environment Research), as well as a space-based global atmospheric wave imager[3].

A SpectroMeter of Atmospheric RadiaTion (SMART) was developed and installed at the Xinglong station of the National Astronomical Observatories in Hebei province, China, which was supported by the Meridian Project. Zhu *et al.*[4] found that the rotational temperature derived from SMART was consistent with the spatial average temperature of NRLMSISE00 empirical model at height 83–91 km and the average temperature of TIMED/SABER from April to May in seven years at height 83–91 km, with some discre-pancies. This indicated that the new instrument and the retrieval method of the rotational temperature could give reasonable results of the airglow emission of OH and the temperature of mesopause.

Li *et al.*[5] report a narrowband high-spectral resolution sodium temperature/wind lidar recently developed at the University of Science and Technology of China (USTC) in Hefei, China (31.5°N, 117°E). Based on the design of the Colorado State University (CSU) narrowband sodium lidar with a dye laser-based transmitter, the USTC sodium temperature/wind lidar was developed with a number of technical improvements that facilitate automation and ease of operation. The power aperture product and the uncertainties of typical measurements for the temperature and wind of the lidar system are estimated to be 1.0 K and 1.5 $m{\cdot}s^{-1}$, respectively, at the sodium peak (*e.g.*, 91 km); and 8 K and 10 $m{\cdot}s^{-1}$, respectively, at both sodium layer edges (*e.g.*, 81 km and 105 km). The initial data collected since November 2011 has demonstrated the reliability and suitability of these high resolution and precision datasets for studying the wave perturbations in the mesopause region.

Guan *et al.*[6] provided a new method for pile-up calibration for high power-aperture lidar sounding. It is proposed to take PMT and High Speed Data Acquisition Unit as an Integrated Black-Box, and to use a new experimental method for identifying and removing SIN from the raw lidar signals. With this new method, they calculated atmospheric temperature in a wide range from our high power-aperture lidar data, which agrees well with the measurements of TIMED satellite.

Since 2003, an ozonesonde system with dual-Electrochemical Concentration Cell (ECC) has been successfully updated by the Institute of Atmospheric Physics, Chinese Academy of Sciences. This type of ozonesonde has high precision, stability, programmed procedure to launch, and consistency. IAP/CAS has also developed ground receiving system, including signal emission system, signal receiving system, and data collection, processing, and display. The signal emission and receiving system has a strong anti-interference ability to reduce data loss. The unit of data collection, processing and display is easy to operate, with high speed and smooth running performance. Inter comparison of this type ECC ozonesonde of the IAP has been made with world-wide used ECC ozonsonde carried by same balloons for a few times. The results show a good consistency. The deviate between them is less than 0.5 mPa below 10 km, and less than 1 mPa above 15 km, with lower values for IAP ozonsonde. IAP ozondesonde has been launched for tens of times both in Beijing and Changchun, which shows good accuracy, stability and reliability.

A few types of stratospheric zero-pressure balloon systems, with payloads from several to hundreds kilograms, are developed at the LAGEO. These systems were used for many times as platforms for scientific experiments, such as dropsonde, stratospheric solar radiation measurement, and stratospheric solar panel performance test. The development group has been engaged in scientific design, unit innovation, system assembly, laboratory adjustment and field experiment, and has made many achievements in critical technology, including GPS dropsonde, dropsonde controlling device, satellite data communication and power supply of payloads.

3 Composition and Structure of the Middle and Upper Atmosphere

Yi *et al.*[7] reported on the first simultaneous three-lidar observations of sporadic metallayers. Case studies indicate that the sporadic layering events can be observed generally in three neutral metal atom species (Na, Fe and Ca) or two neutral atom and one ion species (Na, Fe and Ca^+). The density enhancements of all the sporadic metal atom and ion species occurred in overlapping altitude range and moved following almost the same track, indicating that the sporadic metal layers are usually a mixture of multiple metal atom and ion species, meanwhile suggesting that all these metal species in amixture are products of the same or similar source processes. Some strong multi-metal sporadic layering events were found to manifest a regular altitude relation that the Na_s is the highest, the Fe_s is a few to tens of hundreds of meters lower than the Na_s, while the Ca_s is a few hundred meters lower than the Fe_s, and the Ca_s^+ is the lowest. This altitude sequence coincides well with the boiling-point dependent differential ablation in the thermal ablation theory. For those weak multi-metal sporadic events, the altitude relation becomes complicated.

Xue *et al.*[8] reported two thermospheric sodium layers observed at a low-latitude station, Lijiang (26.7°N). With the help of the adjacent ground-based and space-borne ionospheric radio observations, they suggested that the formation of the thermospheric sodium layers was related with an “Es-Thermoshoeric sodium layer” chain formed through the tidal wind shear mechanism. Dou *et al.*[9] (2013) studied the latitudinal distribution and correlation of SSL and Es, using four sodium lidars of the Chinese Meridian Project located at Beijing (40.2°N), Hefei (31.8°N), Wuhan (30.5°N) and Hainan (19.5°N), respectively. The SSLs at four lidar sites showed evident summer enhancements and correlated well with Es. The co-observations of SSLs at three lidar site pairs, *i.e.*, Hefei-Beijing, Hefei-Wuhan, and Hefei-Beijing, indicated that a large-scale SSL extending horizontally for at least a few hundred kilometers. Moreover, the SSLs were better correlated for the Hefei-Wuhan and Hefei-Haikou pairs than the Hefei-Beijing pair, which suggested a difference in the dynamical/ chemical process in MLT between the Beijing and the other sites.

Based on the long-term observation data obtained by Meridian Project lidars at Beijing, Hefei and Hainan, Gong *et al.*[10] analyzed the seasonal variations of background sodium layer, including the column abundances, the peak heights, and the RMS widths, over China. All these seasonal variations are different at these three sites, which could be correlated with the change of temperature of background atmosphere. Wang *et al.*[11] reported very special phenomena in the sodium layer, a total of 17 events in Beijing lidar data. Except the normal sodium layer at 80–105 km, another sodium layer was present at 105–130 km, suggested a double sodium layer.

Wang *et al.*[12] incorporated an empirical model of Subauroral Polarization Streams (SAPS) into the TIEGCM to simulate the effect of SAPS on the global thermosphere and ionosphere during a moderate geomagnetic active period. They found that Joule heating by the SAPS and the redistribution of this heat by dynamic processes were the primary mechanisms for the simulated global neutral temperature changes. The strong ion drag effect in the subauroral SAPS channel drove large changes in thermospheric winds. The response of neutral temperature and wind to SAPS was more significant at higher altitudes and exhibited seasonal/hemispheric asymmetry. Ma *et al.*[13] analyzed the ionospheric F_2 region peak electron densities (N_mF_2) observed from 11 ionosonde stations in the East Asian-Australian sector from 1969 to 1986. They found that, averaged over all stations and for 18 years, the normalized standard deviation of the midday ~27 day variations of N_mF_2 was 8% and that of the midnight variations was 10%. Moreover, the ~27 day variations in solar radiation and geomagnetic activity are the main drivers of the ionospheric ~27 day variations at middle and high geomagnetic latitudes. At geomagnetic low latitudes, the contribution of the ~27 day variation in solar EUV radiation was greater than that of the ~27 day variation in geomagnetic activity. Xu *et al.*[14] analyzed the ionosonde data of ionospheric F_2 layer peak electron densities (N_mF_2) from 33 stations in three longitude sectors from 1969 to 1986. They found that there is a periodic oscillation in daytime N_mF_2 with a period of 4 months (terannual). Further analysis showed that the terannual oscillation might be related to the nonlinear interaction between the annual and semiannual oscillations.

Xu *et al.*[15] (2012) used the OH nightglow emission rates from TIMED/SABER and a theoretical model of the OH nightglow to distinguish the dominant mechanism for the nightglow. They concluded that the chemical reaction $O_3 + H \rightarrow OH\ (v \leqslant 9) + O_2$ leads to population distributions that are consistent with the measurements. The contribution of the reaction $HO_2 + O \rightarrow OH(v \leqslant 6) + O_2$ to the nightglow is not needed to reproduce the measurements above 80 km. They also showed that the quenching rate of OH (v) by O_2 is smaller and that the removal by O is larger than currently used for the analysis of SABER data. Gao *et al.*[16] combined the emissions of the 557.7 nm green line airglow from ISUAL/FORMOSAT-2, MSISE-00 model and TIMED/SABER measurements to derive the density distributions of the atomic oxygen. The May observations showed that emission rate and O atom density have peak at heights of about 90 km over 10º – 20º latitudes in the Northern Hemisphere (NH). The November observations showed that strong peaks of emission rates and O atoms are at heights of about 95 km at mid-latitudes in both hemispheres. Gao *et al.*[17] studied the longitudinal structures of the global distribution of 1.27 μm O_2 nightglow brightness observed by the TIMED/SABER satellite. They found that the O_2 airglow is dominated by wave 4 structure at latitudes between equator and 20ºS/N in both hemispheres during most seasons. At mid-latitudes around 40ºS/N, the wave 1 structure is observed for most seasons with a small contribution of wave 2 during the June solstice.

Since 2011, several field sites for routine observation of TLEs (Transient Luminous Events) in the mesosphere have been established. In 2012, Yang and Feng reported the first observation of Gigantic Jet (GJ) in the mid-latitude area of mainland China. Different from previous reports, negative Cloud-to-Ground (CG) strokes dominated both before and after the GJ event in their observation, and negative CGs dominated throughout the lifetime of the GJ-producing storm, which indicates the variety in the lightning activity of GJ-producing thunderstorms. Interestingly, the two storms in this study produced different TLE phenomena. The one that produced the gigantic jet only produced this GJ event, whereas the other storm only produced 5 red sprites. This observation enriches the understanding of GJ-producing thunderstorms, and the reported GJ event was also the one that was ever reported to occur at the highest latitude (35.6°N, 119.8°E) in association with summertime thunderstorms. The characteristics of sprite-producing thunderstorms were also examined[18–19].

Chen *et al.*[20] studied the responses of the thermospheric density and CHAMP satellite's orbit to the long-duration, less intensive geomagnetic activity that is related to Corotating Interaction Regions (CIRs), and to the stronger storms related to CME. They found that the satellite orbit decay rates during CME-storms are usually larger than those during CIR-storms. However, the total thermospheric density changes and satellite orbit decays for the entire periods of CIR-storms were much greater than those for the CME-storms. Xu *et al.*[21] studied thermospheric mass densities at ~480 km (GRACE) and ~380 km (CHAMP). They found that there are strong longitude variations in the daily mean thermospheric mass density. These variations are global and have the similar characteristics at the two heights under geomagnetically quiet conditions (*Ap* <10). The positive density peaks locate always near the magnetic poles. The high density regions extend toward lower latitudes and even into the opposite hemisphere. They suggested that heating of the magnetospheric origin in the auroral region is most likely the cause of these observed longitudinal structures. Chen *et al.*[22–23] compared the thermosphere densities between GRACE/ CHAMP satellites data with NRLMSISE-00 model and developed a new correction method of the low earth orbital neutral density prediction.

Xu *et al.*[24] analyzed the longitudinal structure of temperature in the lower thermosphere based on the observations by TIMED/SABER and by MIPAS. Control simulations by TIME-GCM reproduced similar features of the longitudinal variations of temperature in the lower thermosphere. Comparison of two model runs with and without auroral heating confirms that auroral heating causes the observed longitudinal variations. The multiyear averaged vertical structures of temperature observed by the two satellite instruments indicate that the impact of auroral heating on the thermodynamics of the neutral atmosphere can penetrate down to about 105 km. Gong *et al.*[25–26] investigated the GNSS radio occultation ionosphere calibration methods and compared the COSMIC temperature data with the TIMED/ SABER temperature data for validations.

Yuan *et al.*[27] analyzed the nighttime horizontal neutral winds in the middle atmosphere (~87 and ~98 km) and thermosphere (~250 km) derived from a FPI (Fabry- Perot Interferometer) at Xinglong station. The wind data covered the period from April 2010 to July 2012. They studied the annual, semiannual and interannual variations of the midnight winds at ~87 km, ~98 km and ~250 km for the first time and compared them with Horizontal Wind Model 2007 (HWM07). The consistency of FPI winds with model winds is better at ~87 and ~98 km than that at ~250 km. The seasonally averaged zonal winds at ~87 and ~98 km typically have smaller variations than the model's throughout the night. The consistency of FPI zonal wind with model wind at ~250 km is better than the meridional wind.

Using multiyear (2002–2011) wind observations from the TIDI/TIMED, Ling *et al.*[28] report on the typical structures and variations of the zonal mean zonal wind in the MLT region from 80 to 105 km in the meridian at 120ºE. Comparisons between TIDI measurements and empirical models indicate that TIDI is in good agreement with models in the extratropic regions especially at middle and high latitudes, but significant differences occur mainly in the tropic regions. In the altitudes of TIDI's coverage from 80 to 105 km, monthly zonal winds are always westward over the tropical regions, forming an easterly band centered at the equator. Results from multiyear observations show complicated variations in the MLT tropical easterlies. The averaged width of easterlies is 37.5º and corresponding variation is about 14º.

Saunders *et al.*[29] described that spectroscopic measurements of the evolution of the ferric (Fe^{3+}) ion originating from amorphous ferrous (Fe^{2+})-based silicate powders dissolved in varying wt% sulphuric acid (30%–75%) solutions over a temperature range of 223–295 K. Complete dissolution of the particles was observed under all conditions. In addition, the chemistry climate model simulations indicate a meteoric mass input rate of about 20 ton/day would result in the measured Fe content in lower stratospheric aerosol. A heterogeneous uptake coefficient 0.01 is required to account for the observed two orders of magnitude depletion of H_2SO_4 vapour above 40 km. The formation of the summertime ozone-valley over the Tibetan plateau was attributed to two facts from satellite analyses, lower ozone in the Asian summer monsoon anticyclone caused by the strong convective transport from the boundary layer, and shorter air column over the Tibetan plateau[30]. 10-year ozone sounding data was used to analyze the long-term change trend of ozone over Beijing, by combining the Lagragian chemical transport model, and it was found that the tropsoheric ozone increasing trend of 3.0% a^{-1} over Beijing is attributed to photochemical reactions[31].

During the summer monsoon seasons in 2009–2013, the campaign on measuring the atmospheric composition in the tropopause layer with balloon-borne water vapor, ozone, and particle sounding units including the ECC ozonesonde, frost point hygrometer (FHP or CFH), and Compact Optical Backscatter Aerosol Detector (COBALD), were conducted at Kunming and Lhasa[32]. The water vapor from 0–25 km detected with high precision by the CFH/FPH shows a few cases of super saturation in the upper troposphere. The back-scattered signal of cirrus/aerosol by the COBALD shows the distribution of RHi both in and out of cirrus layer, which helps to investigate the microphysic processes in cirrus.

Total ozone observation by Dobson spectrometer has been in operation by IAP/CAS at Xianghe and Kunming, which has joined the WOUDC since 1979 and 1980, respectively. The measurements are continuous, and the data have been cited by international colleagues for many times, and the data quality was considered to be good. Since 2002, ozonesonde developed by LAGEO/IAP has been launched once every week, which provides the unique quasi-operational ozonesonde sounding over the Eastern Asian continent. The ozone vertical data make it possible to study the climate change in this region[31].

4 Dynamics of the Middle and Upper Atmosphere

4.1 Response to the Oscillations at Low Altitude

Liu *et al.*[33] reported the first observations of PMSE by Super DARN Zhongshan radar in Antarctica and presented a statistical analysis of PMSE from 2010 to 2012. The seasonal variations of occurrence were consistent with those before, with an obvious enhancement at the beginning of summer and a maximum several days after summer solstice. The special features of diurnal variations were observed because of high geomagnetic latitude of Zhongshan Station, which was that the maximum was near local midnight and the secondary maximum appeared 1–2 h after the local noon. The results proved that the auroral particle precipitation plays a fairly important role in the PMSE occurrence.

Using TIMED/SABER temperature data, Gan *et al.*[34] investigated the global distribution, seasonal, and inter annual variations of the lower Mesospheric Inversion Layers (MILs). The contribution of the semiannual oscillation and diurnal migrating tide at low latitudes and the composite planetary wave at middle latitudes to the lower MILs are estimated. Huang *et al.*[35] studied global climatological variability of quasi 2 day waves form SABER observations. Based on Arecibo incoherent scatter radar measurements, Gong *et al.*[36] reported the analysis of “midnight collapse,” a large drop in the F-layer peak height around midnight. The study indicates that besides meridional wind, electric field and ambipolar diffusion also play important roles and the former can be the most dominant factor in some cases. Gong *et al.*[37] further analyzed the response of the F region and topside ionosphere to a strong geomagnetics storm that occurred during the period of 5–6 August 2011 over Arecibo. The meridional wind is extremely enhanced at the early stage of the storm. During the storm, the vertical ion drift caused by the meridional wind is positively correlated with that caused by the electric field, which is opposite to the quiet time relationship. The disturbed vertical ion drifts result in large ionospheric perturbations in the F and topside regions.

Using the measurements of horizontal wind profiles from the University of Illinois meteor radar in Maui, Hawaii (20.7°N, 156.3°W) and the European Centre for Medium-Range Weather Forecasts (ECMWF) interim data set, Li *et al.*[38] found that the mesospheric SAO near 80–90 km, is out of phase with the stratospheric SAO. The mesospheric SAO easterly is strong during the easterly phase and weak during the westerly phase of the stratospheric Quasi-Biennial Oscillation (QBO) near 10 hPa (30 km), suggesting the modulation of the mesospheric SAO by the stratospheric QBO. The mesospheric QBO is in phase with the stratospheric QBO and out of phase with the QBO-like oscillation near 1 hPa. The GW and the QTDW likely contribute to the QBO modulation of the mesospheric SAO. The different winter easterly wind in the tropical upper stratosphere during the QBO westerly phase and during the easterly phase may impact the upward propagation of westward-propagating GWs originated in the middle latitudes, and thus the westward GW forcing in the upper mesosphere of northern subtropics.

Using the middle atmosphere temperature data set observed by the Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) satellite experiment between 2002 and 2012, and temperatures simulated by the Whole Atmospheric Community Climate Model version 3.5 (WACCM3.5) between 1953 and 2005, the influence of El Niño-Southern Oscillation (ENSO) on middle atmosphere temperature during the Northern Hemisphere (NH) wintertime were studied by Li *et al.*[39]. For the first time, a significant winter temperature response to ENSO in the middle mesosphere was observed. Analysis of the WACCM3.5 residual mean meridional circulation response to ENSO reveals a significant downwelling in the tropical mesosphere and upwelling in the NH middle and high latitudes during warm ENSO events, which is mostly driven by anomalous eastward gravity wave forcing.

Chen *et al.*[40] reported their investigation results on the dynamical responses of the mid-latitude MLT to the Sudden Stratospheric Warming (SSW) events with Wuhan (30°N, 119°E) MF radar wind data and the Langfang MF radar wind data and Aura/MLS temperature data. They revealed that the MLT mean wind at mid-low latitudes got reversed when the major warming events occurred, and the stratospheric and mesospheric gradient winds over low and mid latitudes have obvious responses to SSW.

4.2 Atmospheric Processes

Li *et al.*[41] analyzed a bore event that was observed using an OH all-sky airglow imager (ASAI) at Xinglong (40.2ºN, 117.4ºE), on the night of 8–9 January 2011. Simultaneous observations by a Doppler meteor radar, a broadband sodium lidar, and TIMED/SABER OH intensity and temperature measurements were used to investigate the characteristics and environment of the bore propagation and the possible relations with the Na density perturbations. They showed that a thermal-Doppler duct exists near the OH layer that supports the horizontal propagation of the bore. Simultaneous Na lidar observations at Yanqing (40.4ºN, 116.0ºE) suggest that there is a downward displacement of Na density during the passage of the mesospheric bore event. Xiao *et al.*[42] reported the short-term variability and summer averages of the mean wind and tidal oscillations in the MLT during the summer months of 2009 with the Langfang MF radar data.

Wang *et al.*[43] studied the activities of mid-latitude Planetary Waves (PWs) in the Troposphere and Lower Stratosphere (TLS) with radiosonde data. It was found strong PWs mainly appears around subtropical jet stream in winter, which indicates that the subtropical jet stream might strengthen the propagation of PWs or even be one of the PW excitation sources. Using the refractive index, they found that whether the PWs could propagate upward to the stratosphere depends on the thickness of the tropopause reflection layer. They also got the PW zonal and vertical propagation parameters through a case study.

Xu *et al.*[44] studied the thermal forcing of the semidiurnal, terdiurnal, and 6-h components of the migrating tide induced by ozone heating in stratosphere and lower mesosphere evaluated from Aura/MLS observations. The results showed that, during the solstice season, the maximum forcing of the diurnal and terdiurnal component occurs in the summer hemisphere while the maximum forcing of the semidiurnal and 6 h components occurs in the winter hemisphere.

By analyzing a mesospheric horizontal wind data set measured during 1991–2006 by the Medium Frequency (MF) radar at Kauai, Hawaii (22°N, 160°W), Gu *et al.*[45] found that the QTDW over Hawaii is amplified twice a year, with the January and July events most likely being the representation of zonal wave numbers 3 and 4 modes, respectively. The amplitudes of the QTDW during January in both wind components and the QTDW during July in meridional component are nearly in phase with the solar cycle by lagging 1 or 2 years. However, the QTDW during July in zonal wind is more antiphase with the solar cycle. The enhanced QTDW oscillation in January 1998 is likely related to the strong El Niño event during 1997/1998. Additional enhancement of the QTDW with a short period was observed during the major sudden stratospheric warming in January 2006.

Seasonal and interannual variations of the Quasi-Two-Day wave s=3 (W3) and s=4 (W4) modes were studied[46] with global temperature and wind data sets during 2002–2012, observed respectively by the Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) and TIMED Doppler Imager (TIDI) instruments onboard the Thermosphere Ionosphere and Mesosphere Electric Dynamics (TIMED) satellite. The amplitudes of W3 and W4 are significantly enhanced during austral and boreal summer respectively. Strong W3 amplitudes were observed during January 2006 which is most likely related to the strong Sudden Stratosphere Warming (SSW) event induced by the intensive winter planetary wave activity. In January 2008 and 2009, unusually weak W3 but strong W4 oscillations were observed, corresponding to the much weaker summer easterly jets (westward wind) than those in other years. This suggests that relatively weak summer easterly may not be able to provide sufficiently strong barotropic/baroclinic instability to amplify W3 but is favorable for the amplification of W4.

Jiang *et al.*[47] compared the winds at ~87 km from an FPI at Xinglong station (40.2ºN, 117.4ºE) with those from a meteor radar at Beijing station during April–May of 2010. The variations of FPI wind at 87 km mostly have the similar track to meteor radar wind at 87 km except for some quantitative differences. They found an obvious 5-day wave in meridional winds observed by both FPI and meteor radar. Using meteor radar data, Xiao *et al.*[48] investigated the features of the quasi-16-day waves in the MLT region over Langfang.

Based on the long-term observation data obtained by a sodium lidar at Beijing, Gong *et al.*[49] analyzed the seasonal variations of gravity waves, including their occurrence frequency, vertical wavelength, and period. The maximum of wave occurrence frequency is in June, while the minimum is in winter. They attributed this behavior to the function of wave sources and background atmospheric winds. The unambiguous power spectrum and angular spectrum of the gravity waves in the first imaging observation experiment in the mesopause region in China on 5 January 2009, at Langfang were analyzed[50].

Wu *et al.*[51] used an 11-year (1998–2008) temperature and wind data set to examine gravity wave activity and their seasonal and interannual variations over Annette Island (55.03°N, 131.57°W). Maximum wave energy amplitudes occur near winter of each year in the troposphere and near summer of each year in the stratosphere. Specifically, the maximum wave energy amplitudes in the troposphere show a close correspondence with the maximum occurrence rate of dynamical instability. In addition, the maximum wave energy amplitudes in the stratosphere also show a close correspondence with the maximum occurrence rate of convective instability. Zhang *et al*.[52] proposed a broad spectral data-analyzing method to study the altitude and seasonal variability of gravity wave-associated dynamics, and momentum and heat fluxes of gravity waves, turbulent energy dissipation rate and diffusion coefficient can be directly calculated. By using the radiosonde data from Miramar Nas during 1998–2008, the primary statistical features of gravity wave parameters and their seasonal variation were presented. The derived heat flux can explain the frequently observed tropospheric inversion in winter, and the derived turbulence parameters and their altitude variations are in good agreement with radar observations reported elsewhere. Based on 11 year radiosonde observations over 92 United States stations locating in the latitude range from 5°N to 75°N, Zhang *et al*.[53] investigated latitudinal distribution of gravity wave parameters and reveal the important role of background atmosphere in excitation and propagation of gravity waves. The analysis suggests the profound climatological impacts of gravity waves on the background atmosphere. The wave-induced force tends to decelerate the zonal jet at middle latitudes and produces a negative vertical shear in the northward wind closely above the tropopause altitude. The wave heat flux tends to cool the atmosphere around the tropospheric jet altitude and contributes significantly to the forming of tropospheric inversions at middle latitudes. Based on daily radiosonde observations at 25 stations during 1973–2010 and using a bulk Richardson number approach to determine heights, estimates of trends in planetary boundary layer height over Europe were presented by Zhang *et al*.[54]. The study indicates that daytime height variations show an expected strong negative correlation with surface relative humidity and strong positive correlation with surface temperature at most stations.

Xue *et al*.[55] extended the gravity wave parameterization scheme currently used in the Whole Atmosphere Community Climate Model (WACCM), which was based upon Lindzen's linear saturation theory, by including the Coriolis effect to better describe the Inertia-Gravity Waves (IGW). They performed WACCM simulations to study the generation of equatorial oscillations of the zonal mean zonal winds by including a spectrum of IGWs, and the parametric dependence of the wind oscillation on the IGWs and the effect of the new scheme. These simulations demonstrated that the parameterized IGW forcing from the standard and the new scheme are both capable of generating equatorial wind oscillations with a downward phase progression in the stratosphere using the standard spatial resolution settings in the current model.

Liu *et al*.[56] used a nonlinear numerical model to simulate the propagation of small amplitude GWs with various wavelengths in different non-isothermal atmospheres. They showed that the GW vertical wavelength undergoes sharp changes above the stratopause and mesopause region. The variations of GW path, vertical wavelength and horizontal phase velocity are not synchronized in a non-isothermal atmosphere as in an isothermal atmosphere. But the variations relative to the initial parameters at a reference height are similar for different initial vertical wavelengths.

Liu *et al*.[57] studied the momentum deposition in the thermosphere from the dissipation of small amplitude Gravity Waves (GWs) in a numerical model. The model solves the nonlinear propagation and dissipation of a GW packet from the stratosphere into the thermosphere with realistic molecular viscosity and thermal diffusivity for various Prandtl numbers. They showed that GW vertical wavelength decreases in time as a GW packet dissipates in the thermosphere, in agreement with the ray trace results. Simulations in a non-isothermal atmosphere showed that the net vertical wavelength profile is a competition between its decrease from viscosity and its increase from the increasing background temperature.

Based on austral winter mesospheric wind observations from three closely deployed Antarctic Peninsula stations (King George Island, Palmer, and Rothera), Qian *et al*.[58] reported their findings of mesospheric wind disturbances induced by gravity waves. The mesospheric winds to the west of the Antarctic Peninsula below 88 km are affected by gravity waves, while the winds on the east side of the peninsula are unperturbed. The gravity waves are most likely generated by orographic features of the peninsula. Because the strong westerly stratospheric wind filters out all eastward propagating waves, only westward propagating waves can reach the mesosphere on the west side of the peninsula. This data set shows the strong gravity wave effect on small scales. Hence, the mesospheric wind data at one station may not be representative of the region for global waves like tides. Small local features can greatly affect the mesospheric winds and may impact the interpretation of global waves. Moreover, the results suggest that high-density deployment of mesospheric wind instruments may be needed in some cases.

Chen *et al*.[59] simulated the stratospheric Gravity Waves (GWs) activity accompanying an upper-tropospheric jet stream with a meso-scale weather forecast model, *i.e*., the WRF-ARW. For the case of Northeast Cold Vortex, *i.e*., the cut-off-low weather system that develops in the northeastern China in June 2010, the simulation reproduces the key features of the development of the cold vortex, as well as the upper tropospheric jet stream evolving at around 9 km height. The results further reveal that pronounced stratospheric GWs are generated by the jet stream as they emerge from the exit region of jet stream. These GWs exhibit 2-d structure, and propagate preferentially in the upstream of the background winds which is just over the jet stream. Spatio-temporal spectral investigation results show that the predominant waves exhibit horizontal wavelength of ~700 km, period of 9–12 h, and vertical wavelength of 4–5 km. The presence of the jet stream results in strong vertical shear in background flow in the lower and middle stratospheric range over the jet stream. The shear further results in wave dissipation as the momentum flux of the GWs declines with height. Inhibition of GW propagation is disclosed by the great attenuation of GW momentum flux at around 18–20 km where the transition of easterlies and westerlies happens. It is anticipated that the upward propagating GWs may approach their critical level in the region thus deposit all their momentum fluxes there. Consequently, the bulk GWs drag on the mean flow in 11–20 km height range is estimated to be around 0.86 $\mathrm{m{\cdot}s^{-1}{\cdot}d^{-1}}$.

Chen *et al*.[60] conducted a simulation study on the generation of stratospheric Gravity Waves (GWs) due to typhoon. The meso-scale model (WRF) is applied to a typhoon case, the Matsa in 2005. An 8-day model run that covers the major stages of the Matsa's development reproduces the key features of the typhoon. For example, good agreements in the typhoon's track, the intensity, and the spiral clouds, as well as mean state of stratosphere, are seen between the simulation results and the observation. Simulation results clearly show that with typhoon propagates northwestward, pronounced stratospheric GWs are generated continuously in the vicinity of Matsa. The GWs exhibit the typical curve-like wave fronts away from the Typhoon Matsa, and propagate preferentially in the upstream of the background winds. These characteristics reflect that the stratospheric GWs are closely associated with the typhoon, and thus the GWs are referred to as Tropical Cyclone related Gravity Waves (TC-GWs). The results also show that these waves should have a rather large horizontal scale so that the outmost wave fronts can be seen at the distance of ~1000 km to the typhoon center in the horizontal plane of 20 km. This is consistent with the phenomenon of stratospheric TC-GWs with ~1000 km horizontal scale disclosed by the previous observational analysis results.

Using the output dataset of the simulation, Chen *et al*.[61] further examined the spatial structures and the temporal variations of the GWs through a three dimensional (3-D) spectral analysis, *i.e*. the spectrum with respect to two horizontal wavenumbers and frequency. And the momentum flux carried by the GWs was derived. Spectral investigation results show that the Power Spectral Density (PSD) of the GWs exhibits a single-peaked spectrum, which consists primarily of a distinct spectrum at horizontal wavelength of ~1000 km, time period of 12–18 h, and vertical wavelength of 7–9 km. This spectrum is different from the spectra of GWs generated by deep convections disclosed by the previous researches. Both the PSD and momentum flux spectrum are prominent in positive k_h portion, which is consistent with the fact that the GWs propagate in the upstream of mean flow. Large momentum flux is found to be associated with the GWs, and the net zonal momentum flux is 0.7845×10^{-3} Pa at 20 km height, which can account for ~26% of the momentum flux that is required in driving the QBO phenomenon.

5 Nonlinear Dynamics Investigation

Nonlinearity is a ubiquitous aspect of the dynamics of atmospheric waves in the middle and upper atmosphere. Nonlinear interaction among atmospheric waves is an important mechanism responsible for many observational phenomena, such as the short-term tidal variability and the universal spectrum of gravity waves. Both observational and numerical studies of wave nonlinearity have made great progress. By using a fully nonlinear model, Huang *et al*.[62] confirmed that the third-order interaction of gravity waves can significantly take place. The general characteristics of energy exchange in the third-order interaction are consistent with those in the second-order interaction. The third-order resonance arises through direct interaction of waves that satisfy the corresponding resonant conditions. There is not a second-order harmonic or an intermediate forced mode involved in nonlinear interaction. The match relationships of interacting waves were examined[63]. The resonant waves satisfy the wavenumber and frequency resonant conditions, thus the resonant excitation shows a reversible feature. In nonresonant interaction, three waves mismatch mainly in the vertical wavelengths but match in the horizontal wavelengths, and their frequencies also tend to match throughout the interaction. The match and mismatch of waves are explained according to the dispersion relation of gravity waves and energy exchange to the greatest extent. However, the match relationships are distinguished from the results of weak interaction theory. In the weak interaction theory, the wave vectors are required to satisfy the matching condition but the frequencies are permitted to mismatch and oscillate, hence, the interacting waves do not obey the dispersion relation any more, which is difficult to explain in the weak interaction theory. The dissipation in the mesosphere and lower thermosphere does not influence the match relationships[64]. The dissipation seems neither to prevent the interaction occurrence nor to prolong the period of wave energy exchange, which is different from the theoretical prediction based on the linearized equations. The match relationships and dissipative effects revealed in numerical experiments are helpful in further investigating interaction of gravity waves in the middle atmosphere based on experimental observations. Nonlinear interaction can effectively spread high frequency spectrum of gravity waves, and play a significant role in limiting wave amplitude growth and transferring energy into higher altitudes[65]. Adopting a nonlinear time-dependent numerical model, Huang *et al*.[66] studied the interaction of gravity waves with a time-varying tide. The simulations show that when a gravity wave packet propagates in a time-varying tidal- wind environment, not only its intrinsic frequency but also its ground-based frequency would change significantly. The combination of the increased ground-based frequency of waves and the transient nature of the critical layer induced by the time-varying tidal wind creates favorable conditions for gravity waves to penetrate their originally expected critical layers. Therefore, the gravity waves have an impact on the background atmosphere at much higher altitudes than expected. On the other hand, the observational studies also revealed some features of interactions among the planetary waves, tides and gravity waves. Based on the thermospheric neutral wind observed by Arecibo incoherent scatter radar, Huang *et al*.[67] found that the tide-gravity wave, tide-planetary wave and tide-tide interactions frequently occur. The sum and difference interactions between the diurnal tide and gravity wave always occur simultaneously, and can persist for several days though they are highly intermittent. A nonlinear interaction event of the Quasi 2-Day Wave (QTDW) and the diurnal and semidiurnal tides from meteor radar measurements at Maui was reported by Huang *et al*.[68]. The analysis shows that the significant nonlinear interactions among the QDTW and the tidal components happen. Two quasi 16 h modes with periods of 16.2 h and 15.8 h generated in the interactions of the QTDW with the diurnal and semidiurnal tides can clearly be distinguished because of the slight deviation of the QTDW period from 48 h. The study demonstrates that the wave-wave interaction is a mechanism responsible for the variability of the semidiurnal tide, and both the nonlinear interaction and the background flow changes induced by the strong QTDW are responsible for the variation of the diurnal tide. In the interaction event of the 16-day wave and the diurnal tide, Huang *et al*.[69] revealed that not only a second-order interaction occurs strongly, but also a third-order interaction takes place significantly. The beat of the diurnal tide with the secondary waves leads to substantial modulation of the diurnal tide at period of 16 days. These observational and modeling studies provide us great insight into nonlinear dynamics of atmospheric waves.

6 Interaction between the Stratosphere and the Troposphere

Kong and Hu[70] investigated the influence of Northern-Hemisphere winter stratospheric circulation anomalies on the Ural Blocking High. Using the NCEP/NCAR reanalysis over the period of 1958–2010, composite analysis on the Ural Blocking High relative to the respective positive and negative stratospheric NAM anomalies are conducted. They found that during negative stratospheric NAM anomalies the Ural Blocking High has higher frequencies of occurrence, longer life cycle, stronger amplitude, and have stronger influences on Northern China. E-P flux analysis demonstrates that during negative stratospheric NAM anomalies, the vertical component of E-P fluxes over Ural Mountain region is stronger than that during positive NAM anomalies, suggesting that stratospheric circulations during negative NAM anomalies prefers upward wave propagation.

Using the NCEP/NCAR dataset over 1958–2010, Wan *et al*.[71] performed statistical and composite analyses on the characteristics and three dimensional structures of the Northeastern Cold Vortex (NCV) for stratospheric northern-hemisphere annular mode anomalies. It shows that northeastern cold vortex has more frequent occurrences and longer duration during negative stratosphere NAM anomalies than that during positive NAM anomalies. Composite results show that the northeastern cold vortex is stronger during negative stratospheric NAM anomalies than that during positive NAM anomalies. It is also found that during negative stratospheric NAM anomalies the northeastern cold vortex is more closely related to downward, eastward and equatorward propagation of stratospheric anomalies, indicating that negative stratospheric NAM may enhance formation and development of NCV and lead to colder weather in Northeastern China.

To evaluate whether stratospheric signals can be used in long-term weather prediction or short-term climate prediction in wintertime, Jia *et al.*[72] made four intraseasonal climate predictions in winter 2011–2012, using the index of stratospheric Northern Annular Mode (NAM). They presented prediction results and comparison with observations and summarized lessons that they learned from these attempts of predictions, including both successes and failures. Four predictions were made on November 7, 2011, January 2, 2012, Feburaray 1, 2012, and Feburary 27, 2012. Each time, they first made prediction of the polarity of the tropospheric NAM over the winter season, based on the sign of NAM at 10 hPa and its downward propagation. Then, they predicted surface temperature changes associated with the change of NAM polarity. Among the four predictions, the last three predictions successfully captured the polarity of NAM and surface temperature tendency in North China, which were well verified by the observations in following weeks. The second prediction was particularly successful. The prediction experiences of winter 2011–2012 suggested that stratospheric NAM signals are indeed useful for improving prediction skills for long-range weather or short-term climate variability in winter.

Luo *et al.*[73] used various observations and a General Circulation Model (GCM) and found that the downward cross-tropopause mass transport is evidenced before Meiyu onset, which is mainly caused by the sharp meridional gradients in the tropopause pressure over the Meiyu area. After Meiyu onset, the upward cross-tropopause transport intensifies due to enhanced convections. The strongest upward transport in the UTLS occurs northeast of the Meiyu region, within the core of the upper tropospheric westerly jet.

Shu *et al.*[74] examined the effect of the stratospheric semiannual oscillation (SAO) and Quasi-Biennial Oscillation (QBO) on the equatorial double peak in observed CH_4 and N_2O. They found that the interannual variations in stratopause double peak of equatorial long-lived tracer mixing ratio (which is associated with the strength of the SAO westerlies) was not only modulated by the QBO phase, but was also significantly influenced by the interannual variation in the gravity waves. By contrast, the effect of the chemical process on the double peak is insignificant.

Shang *et al.*[75] investigated the relative importance of the direct and indirect effects of 11 a solar variations on stratospheric temperature and ozone. In the tropical lower stratosphere, the solar spectral variations in the chemistry scheme play a more important role than solar spectral variations in the radiation scheme in generating temperature and ozone responses. In the upper stratosphere, the maximum solar responses in ozone and temperature caused by both chemical and radiative effects occur at different altitudes.

The winter stratospheric and tropospheric circulations are dynamically coupled through the interaction of mean flow with upward propagating planetary waves. However, using the three-dimensional Eliassen-Palm (EP) flux as a measure of the wave activity, recent work of Wei and Chen[76] indicated that anomalous stratospheric polar vortex in late winter (February) is closely associated with the downward wave flux at the lower stratosphere, especially over the North America and North Atlantic region. The wave flux budget analysis showed that a warm February polar vortex year is usually preceded by a strong stratospheric wave flux convergence (causing stratospheric warming) in January and is accompanied by a wave flux convergence in February. A consistently weak downward wave energy flux occurs for all the extremely warm years at the lower stratosphere. The cold February, on the other hand, is characterized by a stronger downward wave flux at the lower stratosphere. This result highlights the modulation effect of the internal dynamical processes on the final state of the polar vortex in late winter, although external factors such as the QBO, solar cycles, and El Niño can influence the polar vortex.

Wei and Bao[77] found that, for East Asian winter climate, there are two basic modes in the stratosphere on interannual timescale which dominate most of the total surface air temperature variance. The second mode features a seesaw pattern between the northern and southern East Asia, which is highly correlated with the strength of the stratospheric polar vortex. Further study indicated that this seesaw pattern in temperature is associated with the path of the East Asian winter monsoon[78]. When an anomalous polar vortex propagates downward, this may induce anomalous Arctic Oscillation (AO) and Siberian high in the lower troposphere, leading to the emergence of a north-south temperature seesaw pattern in East Asia. A case study of a severe cold event over the Eurasian continent during the winter of 2011/2012 confirmed this process[79].

Investigating the current EAWM indices, Chen *et al*.[79] reported their findings in that the AO and the El Niño and Southern Oscillation (ENSO) are the two important factors influencing the East Asian winter climate. The AO is a prominent mode of low frequency variability in the extratropical northern hemisphere, which features an out-of-phase oscillation in sea level pressure between the polar region and the mid-latitudes, While the ENSO is a dominate mode of the tropical Pacific air-sea coupling system on an interannual timescale. All previous research has documented the individual impact of the ENSO or AO. Their combined effects may be different compared to an individual effect. With the warm/cold phases of the ENSO as a background, the impacts of monthly variation in the AO on the winter climate anomalies in East Asia are studied[80]. The combined effects of ENSO and the AO indicate that the winter climate anomalies are mainly influenced by the AO in northern China and by the ENSO in southern China, when an El Niño couples with a negative AO month or a La Niña couples with a positive AO month. These climate anomalies in China are consistent with the mechanisms proposed in previous studies. However, most of China presents a different pattern of climate anomalies if an El Niño couples with a positive AO month or a La Niña couples with a negative AO month, with the exception of the temperature anomalies in northern China, which are still affected dominantly by the AO. Further analysis suggests that the causes are attributed to the differences in both the stratosphere-troposphere interaction and the extratropics-tropics interaction. In the former cases, zonal symmetric circulation prevails in the winter and the extratropics-tropics interaction is weakened. Thus, the influences of the ENSO and the AO on the East Asian climate mainly present linear combination effects. On the contrary, an annular mode of atmospheric circulation is not favored in the latter cases and the extratropics-tropics interaction is strong. Hence, the combined effects of the ENSO and the AO on the winter climate in East Asia present nonlinear characteristics.

Recent works revealed that both the relations of East Asian climate to the ENSO and AO are modulated by the 11-year solar cycle[81–83]. The results indicate that the ENSO and East Asian climate relationship is robust and significant during winters with Low Solar (LS) activity, with evident warming in the lower troposphere over East Asia, which can be closely linked to the decreased pressure gradient between the cold Eurasian continent and the warm Pacific. However, during High Solar (HS) activity winters, the surface temperature anomalies are much less closely associated with ENSO. On the other hand, during winters with High Solar activity (HS), robust warming appeared in northern Asia in response to a positive AO phase. This result corresponds to an enhanced anticyclonic flow at 850 hPa over northeastern Asia and a weakened East Asian trough at 500 hPa, which implies that the cold waves affecting East Asia are relatively inactive. However, during winters with Low Solar activity (LS), both the surface warming and the intensities of the anticyclonic flow and the East Asian trough are much less in the presence of a positive AO phase. These findings extend earlier ones by emphasizing the modulation effect of solar cycle on the AO&ENSO and the East Asian winter climate relationship, which has practical use for climate prediction.

Hu *et al*[82] reported their investigation results on the characteristics of the boreal spring stratospheric final warming and the associated interannual and interdecadal variability. Using NCEP/DOE reanalysis II data in 1979–2010 to define the onset of the SFW event, they observed that a SFW event occurs from the middle and lower stratosphere, *i.e*, 10–50 hPa, with a 13-day temporal lag between the top and the bottom level. During the 32-year period, significant interannual variability of the timing the SFWs has been observed, as the earliest SFW occurs during mid March, the latest SFW may occur during late May. Composite estimation results show that the early/late SFW events in boreal spring correspond to a quicker (slower) transition of the stratospheric circulation, with the zonal-mean zonal wind reducing about 20 $\text{m}\cdot\text{s}^{-1}$ at 30 hPa within 10 days around the onset date. Meanwhile, their results further indicate that, after the breakdown of the stratospheric polar vortex, the polar temperature anomalies always exhibit an out-of-phase relationship between the stratosphere and the troposphere for both the early and late SFW events, which implies an intimate stratosphere-troposphere dynamical coupling in spring. In addition, there exists a remarkable interdecadal change of the onset time of

SFW in the mid 1990s. On average, the SFW onset time before the mid 1990s is 11 days earlier than that afterwards, corresponding to the increased/decreased planetary wave activities in late winter-early spring before/after the 1990s.

Based on estimation results by using multiple reanalysis datasets, Ren *et al.*[83] suggested that there are delayed effects of ENSO on the extratropical stratosphere. Their results show that the maximum response of the stratosphere to ENSO appears in the next winter season following the mature phase of an ENSO event, rather than in the concurrent winter of ENSO peak. Specifically, the stratospheric polar vortex tends to be anomalously warmer and weaker (colder and stronger) in both the concurrent and the next winter season following a warm (cold) ENSO event. However, the polar anomalies in the next winter are much more significant than that in the concurrent winter. We also showed that, because of the thermal anomalies of ENSO in the tropical troposphere, ENSO can affect the atmospheric thermal structure from the tropics to the extratropics, from the troposphere to the stratosphere and from the winter to spring and to the summertime after the peak phase of ENSO, which in turn causes the anomalous planetary-wave activity and the interannual variability of the mass circulation in the stratosphere. The delayed coupling between ENSO and the stratospheric circulation anomalies is the most significant in the central timescale (3–5 year) of ENSO.

By using the atmospheric general circulation models, the factors that influence the variation of stratospheric circulation in interannual, decadal and the long-term timescale were investigated. Ren and Yang[84] found that the strengthening of the polar vortex is mainly caused by the increased radiation cooling effect due to greenhouse gases, although the temporal variations of planetary-wave activities and the variations of stratospheric polar vortex oscillation are closely coupled in the interannual and decadal time scales.

Xie *et al.*[85] investigated that the effects of El Niño Modoki events on the Tropical Tropopause Layer (TTL) and the stratosphere. They found that canonical El Niño events are associated with the leading mode of the EOF analysis of the OLR and upper tropospheric water vapor anomalies, while El Niño Modoki events correspond to the second mode. El Niño Modoki events have a reverse effect on middle-high latitudes stratosphere, as compared to typical El Niño events. This effect is resulted from a complicated and nonlinear interaction between Quasi-Biennial Oscillation (QBO) signal of east phase and El Niño Modoki signal and only occurs when QBO is in its east phase.

Wang *et al.* found that increases in N_2O of 50%–100% between 2001 and 2050 result in a reduction in ozone mixing ratios of maximally 6%–10% in the middle stratosphere. However, the total ozone column still shows an increase in future decades. N_2O increases have significant effects on ozone trends at 20–10 hPa in the tropics and at northern high latitude, but have no significant effect on ozone trends in the Antarctic stratosphere. The chemical effect of N_2O increases dominates the ozone changes in the stratosphere while the dynamical and radiative effects of N_2O increases are insignificant on average. To interpret the recent measurements of extraterrestrial elements that have accumulated in polar ice cores, Dhomse *et al.*[86] used a 3-D Chemistry-Climate Model (CCM) to investigate the transport of Meteoric Smoke Particles (MSPs) from the upper mesosphere. The strongest MSP deposition is predicted to occur at middle latitudes, providing a significant source of Fe fertilization to the Southern Ocean. The model also predicts substantially more deposition in Greenland than in Antarctica.

Hu and Xia[87] showed observational evidence that the record loss of Arctic ozone is due to the extremely cold and persistent stratospheric polar vortex in the winter of 2010–2011. The polar vortex was as usual in early winter, but was intensified twice in middle January and middle February, respectively, and remained anomalously strong and stable until early April, 2011. Record low polar temperatures and record high subpolar zonal winds occurred in February and March. Stratospheric wave activity was anomalously weak because waves were refracted equatorward by the anomalously strong polar night jet. With such an extremely cold and isolated environment, Arctic stratospheric ozone was largely depleted in March and early April, 2011. Corresponding to Arctic ozone depletion, the stratospheric Northern-Hemisphere Annular Mode (NAM) displayed anomalously strong high-polarity, and the positive stratospheric NAM propagated downward and led to anomalously strong positive NAM in the troposphere and near the surface.

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