Advances in Researches on the Middle and Upper Atmosphere in 2010—2012

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Abstract

This article summarizes the researches on the middle and upper atmosphere by Chinese scientists in 2010–2012. The focuses are placed on the advances in construction of ground-based remote sensing facilities, the mean state and long-term changes in the middle atmosphere circulation, the prevailing dynamical processes, and the coupling of the middle atmospheric layers.

1 Introduction

The middle and upper atmosphere is the path linking the solar and the terrestrial system. Increasing concerns arise on its mean state and variations. The Chinese Meridian Project aiming at monitoring the solar-terrestrial link and space weather in the Eastern hemisphere, as well as the sun-earth climate connection study has finished its construction phase of ground-based remote-sensing network. A subsequent evaluation project on the quality of data from the network was conducted, which yielded substantial positive assessment results. During the two-year period, a number of studies were carried out on the dynamical and chemical processes and the long-term changes in the middle and upper atmosphere.

Section 2 introduces the advances in deploying research facilitates and the associated research results. It is followed by the introduction to the study on the upper atmosphere (Section 3). Then, the main researches on the middle atmosphere processes are introduced in Section 4, in term of the mean state and long-term changes in the middle atmosphere circulation, the prevailing dynamical processes, and the coupling of the middle atmospheric layers.

2 Construction of Ground-based Remote Sensing Facilities

A narrowband high-spectral resolution sodium lidar for mesopause temperature and wind was developed at the University of Science and Technology of China (USTC) in Hefei, China (31.5°N, 117°E) [1]. Applying the same pattern as that of the Colorado-State-University narrowband sodium lidar with dye laser-based transmitter, the USTC lidar was deployed in October 2011. And a number of technical improvements in facilitating automation and operation, were made with a home constructed Pulse Dye Amplifier, automatic beam-steering system, star-tracking program and electronic timing control. The lidar is capable of detecting the temperature and horizontal wind with high temporal (15 min) and vertical (2 km) resolution in the mesopause region (80–105 km). During clear nighttime, the typical precision is about 0.6 K and 0.8 $m\cdot s^{-1}$ for the temperature and wind at 91 km, respectively. Since November 2011, the USTC lidar has been being in operation, and mesopause temperature and wind within 12 h period for 25 nights are obtained, which show large disturbances in temperature and wind during winter time at Hefei, China.

Using the double edge technique, a Rayleigh Doppler lidar for wind measurement in the stratosphere (0–40km) was also developed in the USTC. The technique works by measuring the differences between the Doppler-shifted atmospheric echo and the outgoing laser pulse, then instantaneous wind information are retrieved. A FPI with three channels is used as the frequency discriminator to detect the Doppler shift of the Rayleigh backscatter. The horizontal wind in the upper troposphere and stratosphere (0–40km) within 30 min temporal, 150 m (troposphere) /500 m (stratosphere) height intervals was measured during a field campaign in Urumqi from July 2010 to November 2011, and a good consistency with local radio soundings were reported[2].

A new mobile sodium Wind/Temperature lidar was developed in China by Laboratory for Near-Space Environment Research (LNSER), National Space Science Center (NSSC), Chinese Academy of Sciences in 2010. The retrieval algorithm of wind and temperature is validated by a simulation study[3], and the sodium Doppler free saturation spectrum is measured and applied to locking the lidar's absolute frequency[4-5]. Using the lidar observations, the sodium density variation in a 9-h period, and the temperature in the mosopause regions were reported[6-7].

For the operation of the MF radar at Langfang (39°N, 116°E), application of the FCA algorithms to the four-receiving-antenna and the three-receiving-antenna system were evaluated with regard to MF radar wind retrievals, respectively[8]. The MF radar observations of the electron density were used to show the response of the lower ionosphere to the solar eclipse on June 22, 2009[9]. A simulations of the Martian radio occultation experiments with the one-way dual-frequencies regime between YH-1 spacecraft and the Phobos Grunt space craft, and the one with the one-way single frequency regime between the YH-1 spacecraft and the Deep Space Station on the earth, were presented[10-11].

On June 3, 2010, the first launch of meteorological rocket of the Meridian Project was successful at the Hainan rocket launch site (19.5°N). Jiang *et al.*[12] analyzed the vertical profiles of atmospheric temperature and wind recorded by the rocket and its supportive balloons. The comparisons among the vertical profiles of atmospheric temperature and wind with SABER/TIMED temperature measurements and the modeling results of MSIS00 and HWM07 showed general consistency.

The wind at mesopause region and in the thermosphere at Xinglong station (40.2°N,117.4°E) of the National Astronomical Observatories in Hebei Province were observed by a Fabry-Perot Interferometer (FPI) funded by the Meridian Project in China[13]. Three 38-day data sets of horizontal wind from April 5, 2010 to May 12, 2010 show that there exists clear day-to-day variation that is consistent with the data from HWM93. Xiao *et al.*[14] constructed a new middle atmospheric empirical model extending from 20 km to 70 km with the abundant TIMED/SABER data using a three-layer feed-forward artificial neural network based on the Back-Propagation (BP) algorithm. The responses of the upper stratosphere on the SSW event were revealed with the COSMIC radio occultation data[15].

3 Study on the Upper Atmosphere

The O^+ field-aligned diffusive velocities and fluxes in the topside ionosphere were calculated by using electron density profiles observed by COSMIC radio occultation measurements[16]. The results show that daytime diffusive fluxes change gradually with altitude from downward to upward. A transition height was found below h_mF_2 +80 km. The largest value of upward diffusive flux and velocity during daytime occur at geomagnetic latitudes from 10° to 20° above h_mF_2 + 80 km, whereas during nighttime the maximum downward flux occurs at geomagnetic latitudes from 30° to 40°. Diffusive fluxes are roughly symmetric around the magnetic equator during equinoxes, but asymmetric during solstices.

Ionosonde data from 33 stations in three longitude sectors from 1969 to 1986 were used to study the seasonal variations of h_mF_2[17]. The results reveal a 4-month period terannual oscillation in daytime h_mF_2. There is a good phase match between the annual and semiannual oscillations and the terannual oscillations. The amplitude of the terannual oscillation is also correlated with the product of the amplitudes of annual and semiannual oscillations. Thus, it was suggested in Ref. [13] that the terannual oscillation might be related to the nonlinear interaction between the annual and semiannual oscillations. In addition, the terannual oscillation is stronger in the midlatitude region in the Northern Hemisphere than in the Southern Hemisphere.

Moreover, h_mF_2 from the same data set were used by Ma *et al*.[18] to investigate the effect of about 27-day solar rotation on the ionosphere. Different analysis methods were applied to determine quantitatively the sources of the observed 27-day variations of h_mF_2 and their related contributions to these variations. The results show that the 27-day variations in solar radiation are the main drivers of the ionospheric 27-day variations. At geomagnetic low latitudes, the contribution of the 27-day variation in solar EUV radiation is greater than that in geomagnetic activity. However, the contribution from geomagnetic activity become more significant and is even larger than the contribution of solar radiation at higher latitudes, especially at midnight.

The nighttime equatorial mass anomaly (NEMA) at 385 km was investigated using observations by the accelerometer onboard the CHAMP satellite between 2002 and 2007[19]. NCAR/TIME-GCM results suggest that the likely cause of both the NEMA and thermosphere midnight temperature maximum phenomena are the superposition of diurnal and semidiurnal migrating tides of modes up to wavenumber 6.

Using the thermosphere densities observed by the CHAMP and GRACE satellites and their orbital parameters, Xu *et al*. [20] investigated the effect of periodic oscillations in thermosphere densities (7–27 days) caused by solar rotation and periodic magnetic activity on satellite orbits during 2003–2005. The response of the Mean Radius of the satellite orbit Per Revolution (MRPR) to the oscillations in the Mean atmospheric Density Per Revolution (MDPR) increases linearly with oscillation periods. Moreover, there is a phase difference of $\pi/2$ between the oscillations of MRPR and MDPR. These features are in good agreement with our theoretical analysis. The response of thermosphere density during some big earthquakes was studied by Zeng *et al*.[21] using in-situ measurement data. They showed that the abnormal atmospheric density decrease over the center region of the earthquake source on the earthquake day. During the period about 1–3 days before the strong earthquake, the decrease of upper atmospheric density exists and reaches the valley on the earthquake day.

The simultaneous and common-volume Na and Fe lidar measurements at Wuhan were conducted. Fe and Na meteor trails were analyzed. And, the discrepancy and relevancy, the characteristics and variations, and the formation mechanism of the metal layers were studied. Ma and Yi[22] reported the seasonal/annual characteristics of the high-altitude sporadic metal atom layers on the basis of extensive Na and Fe lidar measurements at 30°N during the past several years. It was found that the extremely high sporadic Na and Fe layers above 105 km occurr mostly during summer. They have long durations (a few hours) and broad layer widths (much larger than 2 km). Their absolute peak densities could be comparable to or even larger than those of the corresponding main layers in a few nights. By using all the raw data profiles including sporadic layers, the authors also observed that at 30°N, the Na and Fe layers both exhibit evidence for summer topside extension, which is consistent with the earlier observations for K and Ca at different latitudes. The summer topside extension of mean metal atom layers might represent a universal phenomenon that is alike for different atom species, different geographic locations and different measurement years. The extremely high sporadic metal atom layers above 105 km occurring during summer give rise to the phenomenon.

Chen and Yi[23] reported the average properties and small-scale variation features of the mesospheric Na and Fe layers at 30°N from extensive simultaneous and common-volume Na and Fe lidar measurements at Wuhan, China. The annual mean Na and Fe density profiles were derived. The mean Na and Fe profiles preserve the sharp gradients present in most individual density profiles near the layer bottom. The Na and Fe densities in the lowest several kilometers of the layers consistently exhibit nearly the same time variations. A clear distinction between the Na and Fe time variations always appears in an altitude range near 90 km whereas a relatively weak positive correlation between them persistently occurs also in an altitude range near 100 km. The universal relations between the time variations of Na and Fe densities at the different altitudes provide an insight into the unanswered metal layer formation mechanism.

Zeng and Yi[24] first conducted extensive simultaneous and common-volume Na and Fe lidar observation investigation on meteor trails. The mean input fluxes from the lidar meteor trail measurements are 1.5×10^5 atom · $cm^{-2}\cdot s^{-1}$ for Fe and 1.4×10^4 atom$\cdot cm^{-2}\cdot s^{-1}$ for Na. Only 8 two-element trails were detected from a total of 210 h simultaneous and common-volume Na and Fe lidar measurements. The observed two-element meteor trails yield the mean Fe/Na abundance ratio of ~9.0. These trail features suggest a role of differential ablation. Xie and Yi[25] conducted Na lidar measurements of atom meteor trails with an integration period of 3.2 s at Wuhan (30.5°N, 114.4°E), China. A total of 125 Na meteor trail events were registered from 166 hours (16 nights) of lidar data. These Na trails show peak densities ranging from 4040 to 39170 cm^{-3} with a mean of 16430 cm^{-3}, while their occurrence altitudes vary from 77.2 to 111.6 km with a distribution centroid at 92.6 km. The upper edge of the Na trail altitude distribution resembles that of the altitude profile of the simultaneously observed mean Na layer. In particular, the trail altitude histogram maximum occurs around the mean Na layer peak. This is consistent with early lidar observations of K and Fe trails, which shows that meteoroids entering the atmosphere tend to yield more atom meteor trails detectable by ground-based lidars around the peak of the regular metal layers than elsewhere. It was found that the formation of the Na_s layers is usually accompanied by a bunch of Na meteor trails, and that they occurr near the altitude of the Na_s layer peak.

Combining the observations by the FORMOSAT-3/COSMIC constellation, a meteor radar at Wuhan (31°N, 114°E), and a sodium fluorescent lidar at Hefei (31.8°N, 117.3°E), the formation of the SporadicSodiumLayers (SSLs) in the mesopause region was investigated, a possible relationship between the Sporadic Sodium Layers, Meteors and enhanced electron density was proposed by Dou *et al*.[26]. Statistically, it was observed that the seasonal dependence of SSL correlates well to the annual variation of the sporadic E layers (Es), and is also consistent with seasonal meteor deposition except for February and March. It suggests that a “meteor-Es-SSL” chain could be reasonable if the recombination process are taken into consideration. Detailed study on the relationship between the electron density profiles by the COSMIC radio occultation and the observations of SSLs by the lidar illustrated that the appearance of Es accompanying SSL (*i.e.*, 56.3%) is three times greater than that in the “normal” sodium layer. It also indicates that tides play an important role in causing the lower SSLs, which might be able to carry the upper dense electrons and ions in the Es layer formed by wind shear to the lower altitudes through downward phase propagations.

The long term and global observations of the 2.0 μm OH Meinel brightness by TIMED/SABER from February 2002 to December 2008 were analyzed by Xu *et al*.[27]. The results show that migrating and nonmigrating tides have large effects on the nighttime OH airglow emission. The OH airglow emission rate is positively correlated with temperature below 94 km and negatively correlated above. The longitudinal dependency of OH airglow brightness is caused by the superposition of stationary (D_0), westward wavenumber 2 (DW2), and eastward wavenumber 3 (DE3) nonmigrating diurnal tides. Using the same data set, the global distribution of the SAO, AO, and QBO in the OH nightglow peak emission rate and height as well as the intensity were studied by Gao *et al*.[28]. The latitudinal variations of the SAO, AO, and QBO in the peak emission rate are similar to those in the intensity. However, the peak emission rate and peak height of SAO are generally in antiphase. The peak emission rate and intensity of SAO are generally in phase.

The OH and O_2 airglow emission rate data observed by the TIMED/SABER from 2002 to 2009 were used by Gao *et al*.[29] to investigate their global distributions of temporal variations of OH and O_2 nightglow emissions. The results indicate that the OH nightglow emission is stronger than the dayglow emission, whereas the O_2 nightglow emission is weaker than dayglow emission. Furthermore, the OH nightglow at the equinoxes has one peak at the equator and with a peak height around 85 km. The O_2 nightglow at the equinoxes has three peaks, lying at 30° in the spring and autumn hemispheres and at the equator. In addition, the responses of OH and O_2 nightglow emissions to the SSW (Stratospheric Sudden Warming) event in 2009 was analyzed by Gao *et al*.[30] using the TIMED/SABER data. They showed that the mesospheric cooling accompanies the warming stage of SSW events, the brightness and thickness nightglows decrease noticeably and the peak heights of the emissions ascend. On the contrary, the nightglows exhibit opposite variation during the recovery stage of the mesosphere. Gao *et al*.[22] proposed that these emission variations are mainly caused by perturbations in temperature and the transport of O in the MLT region.

The OH nightglow emission rates, temperature, and ozone obtained from TIMED/SABER observations, along with a theoretical model of the OH nightglow were used to distinguish the dominant mechanism for the nightglow[31]. They showed that the chemical reaction $O_3 + H \rightarrow OH (v \le 9) + O_2$ leads to population distributions of vibrationally excited states that are consistent with the measurements. The contribution of the reaction $HO_2 + O \rightarrow OH (v \le 6) + O_2$ to the nightglow is not needed to reproduce the measurements above 80 km. Moreover, Xu *et al*.[23] 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.

4 Processes in the Middle Atmosphere

4.1 Mean Circulation and Long-term Changes

Long-term temperature profile datasets obtained by Rayleigh lidars at three different northern latitudes within the Network for the Detection of Atmospheric Composition Change (NDACC), *i.e.*, Mauna Loa Observatory at Hawaii (MLO, 19.5°N), Table Mountain Facility in California (TMF, 34.4°N) and Observatoire de Haute Provence in France (OHP, 43.9°N), were used to derive the middle atmosphere temperature trend and their responses to the 11-year solar cycle[32]. The lidar trends agree well with earlier satellite and rocketsonde trends in the stratosphere but a substantial discrepancy was found in the mesosphere. The cooling trend in the upper stratosphere at OHP during 1981–1994 (23 K/decade) was much larger than that during 1995–2009 (≤ 0.8 K/decade), coincident with the slightly increasing upper stratospheric ozone density after 1995. Significant temperature response to the 11-year solar cycle was found. At OHP a wintertime negative response in the upper stratosphere and a positive response in the middle mesosphere were observed during 1981–1994 but the opposite behavior was found during 1995–2009. This behavior may not be a direct solar cycle response at all, but likely related to an "apparent response" to decadal variability (*e.g.* volcanoes, "modulated random" occurrence of sudden stratospheric warmings) that is more complex.

Using the measurements of horizontal wind profiles made by the University of Illinois meteor radar in Maui, Hawaii (20.7°N, 156.3°W) from May 2002 to June 2007, Li *et al.*[33] reported that the mesospheric SAO, with the winter westerly near 80-90 km clearly stronger than the summer westerly, is out of phase with the stratospheric SAO near 1 hPa (~50 km). 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 has an amplitude of ~5 $m \cdot s^{-1}$ near 80 km. It is in phase with the stratospheric QBO near 10 hPa and out of phase with the QBO-like oscillation near 1 hPa. The correlation of the Gravity Wave (GW) and the Quasi-Two Day Wave (QTDW) activities with the mesospheric SAO and QBO suggests that the GW drags and the QTDW Eliassen-Palm flux divergences likely contribute to the QBO modulation of the mesospheric SAO. The winter easterly wind in the tropical upper stratosphere pushes further into the Northern subtropics during the QBO westerly phase than during the easterly phase. This may have impacts on the upward propagation of westward-propagating GWs originated from the middle latitudes, and thus the westward GW forcing in the upper mesosphere of Northern subtropics.

Seasonal and Inter-annual variability in the GWs activities in the middle atmosphere temperature and wind are investigated by using ~10 years (January 1997 to June 2007) temperature profiles taken by the Jet Propulsion Laboratory Rayleigh lidar at Mauna Loa Observatory, Hawaii (19.5°N, 155.6°W), the seasonal and inter-annual variability of gravity waves (GWs) variance in the upper stratosphere (35–50 km) and lower mesosphere (48–63 km) were evaluated[34]. A seasonal variability with maximum in winter and minimum in summer was observed in the upper stratosphere, suggesting the dominance of the Annual Oscillation (AO). In the lower mesosphere, the seasonal oscillations of GW variance are dominated by a Semiannual Oscillation (SAO), likely due to the selective filtering of GWs by the tropical upper stratospheric SAO wind. Modulation of GW variance by the Quasi-Biennial Oscillation (QBO) is clear only for the long vertical wavelength band in the upper stratosphere, and not in the lower mesosphere. The United Kingdom Met Office (UKMO) zonal mean zonal wind further supports that enhanced GW activity in the upper stratosphere corresponds with the westerly shear phase of the zonal wind at 10 hPa (~30 km), and suppressed activity corresponds with the easterly shear phase. During the strong El Niño event in the winter of 1997/1998, enhanced GW activity was observed only in the lower mesosphere and not in the upper stratosphere. Additional enhancement of GW variance, especially clear in the upper stratosphere, was also found during 2001–2002 and winter 2005/2006.

4.2 Thermal Tides and Gravity Waves

The global distribution of atmospheric ozone observed by Aura/MLS from August 2004 to December 2008 was used to calculate the diurnal component in the ozone heating rate by Xu *et al.*[35]. According to the Hough modes and their Annual (AO), Semiannual (SAO), and Quasi-biennial (QBO) variations of ozone heating, a new parameterization of the diurnal component of the heating rate was developed. The horizontal wind observed by a meteor radar at Fuke, China (19.5°N, 109.1°E) during spring months was analyzed by Jiang, *et al.*[36]. They showed that there are quite strong tides in the mesopause region of Fuke. Comparisons of the observed tides and GSWM02 showed that Fuke diurnal tide agrees well with the model except for many differences occurring in semidiurnal tide.

The basic structure parameters of Lower Tropospheric Inversions (LTIs) were derived from 10 years of radiosonde observations over 56 United States stations[37]. Seasonal and longitudinal variability of these parameters were presented and the formation mechanisms of LTI were also discussed. It was found that LTI seems to be a common feature over the continental United States. Detailed analyses revealed that dynamical instability induced by strong zonal wind shear is responsible for LTI in winter, spring and autumn; the frontal system tends to generate LTI in summer. Since the higher occurrence rate, larger temperature jump and larger thickness of LTI occur in winter, it is believed strong zonal wind shear plays a more important role in the formation of LTI.

Using rawinsonde measurements with high vertical resolution, the gravity waves accompanying a Tropical Cyclone (TC) were investigated for two cases, the TC Faxai that develops in the northwestern Pacific in December 2001, and the TC Dina in the southern tropical Indian ocean in January 2002. Conventional and wavelet methods were combined to characterize the Gravity-waves (GWs) produced by the two intense TCs in the Upper Troposphere and Lower Stratosphere (UT/LS)[38]. Analyses revealed large contribution of GWs induced by TCs to wave energy densities in the UT/LS. An increase in total energy density of about 30% of the climatological energy density in austral summer was estimated in the LS above Tromelin during TC Dina. Four distinct periods in GW activity in relation with TC Faxai stages was observed in the UT. Globally, GWs have periods of 6 h–2.5 days, vertical wavelengths of 1–3 km and horizontal wavelengths <1000 km in the UT during the evolution of TCs. Horizontal wavelengths are longer in the LS and about 2200 km during TCs. Moreover, location of GW sources is below the tropopause height when TCs are intense otherwise varies at lower tropospheric heights depending on the strength of convection.

Focusing on the process of GWs induced by a tropical cyclone, Chen *et al*.[39] conducted a simulation with a typhoon case, the Typhoon Masta in the northwestern Pacific in 2005, by using a meso-scale model (WRF) with high vertical resolution. An 8-day model run covering the major stages of the Matsa's development reproduced 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. The simulation results clearly show that along with the northwestward propagation of the typhoon, pronounced stratospheric GWs are continuously generated in the vicinity of Matsa. The GWs exhibit typical curve-like wave fronts away from the typhoon, and propagate preferentially in the upstream of the background winds. These characteristics reflect that the stratospheric GWs are closely associated with the typhoon. Consistent with that revealed by using the rawinsonde data in Ref. [38], the simulated stratospheric GWs exhibit substantial long horizontal scale as the outmost wave fronts can be seen at the distance of ~1000 km to the typhoon center in the horizontal plane at 20 km height.

The excitation, nonlinear propagations and interactions of gravity waves were studied systematically by using nonlinear dynamic models. Applying a second-order fully nonlinear numerical scheme, Huang *et al*. [40] investigated the characteristics of reflection and transmission of atmospheric gravity wave packets in a vertically sheared horizontal wind. When the leading edge of incident wave arrives at the reflecting level predicted by the linear theory, the wave reflection begins to occur. In the reflection process, the reflection and incident waves are superposed with obvious phase staggering. Some spectral components of the incident wave can penetrate through the evanescent region and produce a transmitted wave. The simulation shows that the reflection loop predicted by the linear theory is not a common phenomenon in the wave reflection. Several groups of simulated cases indicate that the reflection and transmission coefficients depend on not only the parameters of the incident wave but also the strength and thickness of the evanescent region. The reflection coefficient increases but the transmission coefficient decreases with the relative evanescent thickness growth, and once the strength and thickness of the evanescent region are large enough, the wave hardly penetrates through the sheared wind zone, and the reflection coefficient approaches a constant value, too. These results suggest that the effects of wave reflection and transmission should be correctly included in the parameterization of gravity waves to attain more realistic middle atmospheric climatology from general circulation models.

By applying the same scheme, Huang *et al*.[41] also studied sum non-resonant interaction of gravity waves. They found that sum non-resonant interaction not only can happen in the atmosphere, but also has a considerable energy exchange magnitude, which is comparable to that of resonant interaction. Despite the lack of the resonant condition restriction, the effective energy exchange due to the non-resonant interactions depends on the detuning degrees of interactions.

The basic features of the atmospheric structures and disturbances in the troposphere, the low stratosphere were studied by using the data from routine and intensive radiosonde multi-station observations. Zhang *et al*.[42] derived the latitudinal and seasonal variations of gravity wave potential energy density, kinetic energy density, and total energy density in the troposphere and lower stratosphere segments from radiosonde observations over United States. The latitudinal variation of potential energy density in the lower stratosphere is in good agreement with satellite observations. Their analysis reveals that GW energy properties exhibit distinctive latitudinal and seasonal variations. The upward-propagating GW energy in the troposphere is larger than that in the lower stratosphere at low latitudes but the opposite holds true at high latitudes. The transition latitude, where the upward-propagating energies in the two altitude regions are the same, occurs at 35°N throughout the year. Their analysis indicates that the region around tropopause is an important source region, especially at latitudes below 35°N. Their studies strongly suggest that in order to fully understand the global GW activity in the lower atmosphere, the GW kinetic energy and its geographical and seasonal variations should be included.

The gravity waves (GWs) in the troposphere and lower stratosphere were studied by analyzing the temperature profiles with height resolution 50m obtained from the Beijing Observatory over the year 2002[43]. The results show that although the individual vertical wavenumber spectra reveal a considerable variability in both slope and amplitude, the seasonal mean spectra observed in the troposphere completely obey the linear saturation model.

The morphological features of GWs in the mesopause region were studied by analyzing the OH airglow imager data obtained from an All-Sky Airglow Imager (ASAI), which is installed at Xinglong (40.2°N, 117.4°E) in northern China[44]. It was showed that GWs occur more frequently in summer than that in winter. The bands propagate mostly in southwestward in winter, while almost all bands propagate northeastward in summer. Another ASAI with double channels has been installed at Langfang (39°N, 116°E) nearby Beijing in 2010. With the OH airglow imager data, three cases of quasi monochromatic gravity waves were analyzed in details by Tu *et al.*[45].

The seasonal variations of GW activity and spectra were revealed from the measurements of sodium temperature lidar at São José dos Campos (23°S, 46°W) [46]. The total temperature perturbation and temperature vertical power spectra have semiannual maxima occur near the equinoxes. They also found that there is a good agreement between monochromatic wave induced temperature perturbations and sodium concentration perturbations, and that the wave parameters derived from temperature data and sodium concentration data are comparable. The global morphologies of stratospheric GW activity were revealed from the temperature profile data of COSMIC GPS radio occultation by Xiao *et al.*[47]. They investigated the influences of the origins and the background winds and the modulation of the planetary waves on the GW activities.

By introducing the Coriolis effect into a GW parameterization scheme based upon Lindzen's linear saturation theory, the description of the effect from Inertia-Gravity Waves (IGWs) were improved in a GCM simulation[48]. Applying the new GW parameterization scheme with the Whole Atmosphere Community Climate Model (WACCM), simulations on the generation of the equatorial oscillations of the zonal mean zonal winds were conducted. The simulations demonstrate 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. The period of the oscillation is dependent on the strength of the IGW forcing, and the magnitude of the oscillation is dependent on the width of the wave spectrum. The new parameterization affects the wave breaking level and acceleration rates mainly through changing the critical level. QBO can be internally generated with the proper selection of the parameters of the scheme. The characteristics of the wind oscillations thus generated are compared with the observed QBO. These experiments demonstrate the need to parameterize IGWs for generating the QBO in GCMs.

4.3 Dynamical Coupling Between the Stratosphere and the Troposphere

Wang *et al.*[49] studied the characteristics of high-latitude planetary waves in the troposphere and lower stratosphere by using the data from radiosonde observations at three stations in USA. It was found that strong planetary waves exist in two regions. One is around tropopause, and the other is in the polar night jet in winter. Planetary waves around the tropopause are complex and no obvious season variability can be observed. The quasi 5-day and 10-day PW are the weakest and strongest, respectively. Significant PWs in the polar night jet occur only in winter, with smaller amplitudes than those around the tropopause, and only obvious quasi 10-day and 16-day PWs remain.

A case study for the cold December 2009 in northern hemisphere showed that the cold condition over mid-latitudes including East Asia can be accounted for by the extreme negative Arctic Oscillation (AO) at surface level, which is the lowest for the past 31 years. The negative AO in December is closely associated with the downward propagating anomalies from the stratosphere. During this process there are anomalously vertical propagations of planetary waves[50]. Further research indicated that the stationary wave propagation across Eurasian continent tends to be enhanced after mid-1970s, whereas they propagate less into the stratosphere. These interdecadal variations of stationary wave propagation may account on the enhanced Ural blocking-East Asian winter climate relationship[51].

Wei *et al.*[52] reported that the evolution of the East Asian winter monsoon has an evident changes after 2000. Results show that the winter monsoon setup has been postponed. In mid winter, the monsoon breakdown process has accelerated, while it tends to be revival in late winter. These changes have been shown to be related to large scale circulation changes in the stratosphere via the variation of planetary wave activities.

Both the responses of the planetary wave activities and the zonal-mean zonal flow to ENSO events were investigated based on the ERA-40 reanalysis data from the European Centre for Medium-Range Weather Forecasts[53]. During El Niño winters, the planetary waves in the stratosphere tend to propagate more upward and poleward. Its interaction with mean flow induces a dipole pattern in zonal-mean zonal winds, with accelerated westerly winds at low-middle latitudes and decelerated westerly winds at high latitudes. Further study on three-dimensional Eliassen-Palm fluxes presented strong correlations between the SST anomalies in the North Pacific and the vertical Eliassen-Palm fluxes in Decembers of 1958–1976 and 1992–2006[54]. However, these correlations between the interannual variations of the SST anomalies and the penetration of planetary waves into the stratosphere are much less during the decadal sub-period 1976–1992 in the positive phase of the Pacific Decadal Oscillation (PDO) and the decadal cold SST anomalies in the North Pacific. Interannual variations of the polar jet in the lower stratosphere in January are strongly associated with SST anomalies in the Aleutian Low region in December for the years with positive PDO index. This sub-period corresponds well with that of the violation of the Holton-Tan relationship between the equatorial Quasi-Biennial Oscillation (QBO) and the stratospheric circulation in the extra-tropics. These findings give evidences of a large impact of the decadal SST variations in the North Pacific on wave activity in early winter due to changes of thermal excitation of planetary waves during distinct decadal periods.

Using re-analysis data from multi sources, the temporal and spatial relationship between ENSO and the extratropical stratospheric variability in the Northern Hemisphere were investigated[55-56]. Ren *et al*.[55] found that the two phenomena are significantly correlated at the timescale of 3–5 years. Specifically, the stratospheric polar vortex tends to be anomalously warmer and weaker in both the concurrent and the subsequent winter following a warm ENSO event, and vice versa. Generally, the polar anomalies in the subsequent winter are much stronger and with a deeper vertical structure than that in the concurrent winter. The authors further showed that the delayed stratospheric response to ENSO is characterized by poleward and downward propagation of temperature anomalies, suggesting an ENSO-induced interannual variability of the global mass circulation in the stratosphere. Particularly, in response to the developing warm ENSO event, there exist warm temperature and positive isentropic mass anomalies in the midlatitude stratosphere since the preceding summer. The presence of an anomalous wavenumber-1 in the concurrent winter, associated with an anomalous Aleutian high, results in a poleward extension of warm anomalies into the polar region, and thus a weaker stratospheric polar vortex. However, the midlatitude warm temperature and positive isentropic mass anomalies persist throughout the concurrent winter till the end of the next summer. In comparison with the concurrent winter, the strengthening of poleward heat transport by an anomalous wavenumber-2 in the next winter results in a much warmer and weaker polar vortex accompanied with a colder midlatitude stratosphere. Ren *et al*.[56] further showed that the lagged relationship between ENSO and the winter stratosphere exhibits a clear seasonality due to the seasonality of ENSO and the phase-locking of stratospheric variability to the annual cycle.

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