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Advances in Researches on the Middle and Upper Atmosphere in 2008–2010*

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Abstract This paper summarizes the results of the researches on the middle and upper atmosphere obtained by Chinese scientists in 2008–2010. The focuses are specifically placed on the researches being associated with ground-based observation capability development, dynamical processes, the property of atmospheric circulation and the chemistry-climate coupling of the middle atmospheric layers.
Keywords Middle and upper atmosphere, Metalic and airglow layer, Atmospheric tides

1 Introduction

In China, the researches of the middle and upper atmosphere in the context of COSPAR have been undergoing smoothly in 2008–2010. From the aspect of associating climate change with the middle atmospheric processes, a national research program focusing on stratospheric processes, in particular role of the processes in the weather and climate of the eastern Asia[1], has been approved by the Ministry of Science and Technology of China. This paper reviews the primary research results during 2008–2010. Readers interested in previous research advances before 2008 are suggested to refer to Chen *et al.*[2] and the references therein.

2 Observations of the Metalic Layer and the Airglow Layer

Substantial improvements in lidar techniques were made, which yielded new observational analysis results. Combining three lidars that operate respectively at the scheme of N_2-vibrational Raman backscatter, standard Rayleigh scattering and the Fe-Boltzmann florescence, Yu and Yi[3] acquired the temperature profiles from near the ground to about 100 km. Using 195 h long observation data at Wuhan as were measured simultaneously by a Fe-florescence lidar and a Sodium-lidar pointing to common-volume, Yi *et al.*[4] revealed a ubiquitous features of the Fe and Sodium layers on their top and lower borders. They reported that the lower boundary of the layers of the two species propagated almost along the same track, which suggests that the lower boundary of Fe and Na layer are both controlled by the same processes. Specifically, they also found that the lower boundary of the Fe layer is at a slightly higher altitude than that of the Sodium layer by 0.2 km. Furthermore, using multi-year measurements by the Sodium and the Fe lidars, a complete seasonal pattern of the noc-

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turnal mesospheric Na and Fe layers at Wuhan was constructed by Yi *et al.*[5].

Dou *et al.*[6] reported their Sodium lidar observation results of the Sporadic Sodium Layers (SSLs) during the past 3 years at a mid-latitude location (Hefei, China, 31.8°N, 117.3°E). From 64 SSL events detected in about 900 h of observation, an SSL occurrence rate of 1 event every 14 h at the location was obtained. This result, combined with previous studies, reveals that the SSL occurrence can be relatively frequent at some mid-latitude locations. Statistical analysis of the main parameters for the 64 SSL events was performed. By examining the corresponding data from an ionosonde, a considerable correlation was found with a Pearson coefficient of 0.66 between seasonal variations of SSL and those of sporadic E ($E_{\rm s}$) during nighttime. By comparing observations from the University of Science and Technology of China (USTC) lidar and from Wuhan Institute of Physics and Mathematics (WIPM) lidar (Wuhan, China, 31°N, 114°E), the minimum horizontal range for some events was estimated to be over 500 km.

Gao *et al.*[7] developed a method for deriving the peak density of atomic oxygen in the MLT region from atomic oxygen [OI] 558 nm nightglow intensity. By using this method, the peak density of atomic oxygen was derived from the 558 nm airglow data observed at the ISTP SB RAS Geophysical observatory in 2000–2004. The results show that nocturnal variation of the 558 nm airglow intensity changes with season and has peaks in March, June and October, and larger values in the winter months. The nocturnal and the seasonal variations of the peak density of atomic oxygen are generally similar to those of 558 nm airglow intensity. Gao *et al.*[8] developed a method to retrieve oxygen density by using the OH airglow observation. The retrieval uncertainties of the oxygen density were analyzed.

The seasonal and latitudinal differences of the correlations between daytime ionospheric F_2 peak electron density ($N_{\rm m}F_2$) and solar activity indices were analyzed using data from 15 ionosonde stations at different geomagnetic latitudes during 1969–1990 by Ma *et al.*[9]. The results show that the characteristics of the correlations between $N_{\rm m}F_2$ and solar activity indices have significant seasonal and latitudinal variations and hemispheric asymmetry. At middle and high latitudes, there is a clear saturation trend in $N_{\rm m}F_2$ as solar activity increases in summer. But there is no apparent saturation trend in winter. At higher latitudes and in the Northern Hemisphere, there is even a trend of nonlinear increase of $N_{\rm m}F_2$ with solar activity. The analysis results indicate that thermospheric global circulation is probably an important factor that introduces seasonal, latitudinal, and north south differences in the correlations between $N_{\rm m}F_2$ and solar activity indices. They also used CHAMP Radio Occultation (RO) measurements to study the O^+ field-aligned diffusive velocities and fluxes in the topside ionosphere. The velocities and fluxes from January 2002 to December 2003 at low- and mid-latitudes were statistically analyzed. The results show that during the daytime, diffusive fluxes changed gradually from downward to upward as altitude increases. The largest values of the upward diffusive fluxes and velocities occurred at around geomagnetic latitude.

3 Dynamical Processes in the Middle Atmosphere

3.1 Researches on Gravity Waves

Using fully nonlinear atmospheric kinetic equations, Zhang and Yi[10] simulated the response of the wave number spectra of atmospheric Gravity Waves (GWs) to different excitation sources. The simulations reproduced the primary features of the observed GW universal wave number spectra. Their results also suggest that the random character of the wave sources plays an important role in the formation of the observed universal GW-spectra. Huang *et al.*[11] numerically investigated the reflection of GWs in the background zonal winds with latitudinal shear. Their results suggest that the dynamical effects due to the shear should be considered in the study of the QBO and SAO phenomenon. Using numerical simulation, Huang *et al.*[12] further investigated the resonant interaction under the sum resonant conditions in the atmosphere. They argued that the interactions were important in determining the atmospheric wave spectrum and played a significant role in the momentum budget well in the thermosphere. A detuning degree of interaction was proposed, which may be applied to measure whether or not the effective energy exchange occurs in the nonlinear interactions of gravity waves. These researches can help to improve the current Gravity Wave Drag (GWD) parameterization. By developing a GWD parameterization scheme with continuous wave spectrum, Huang *et al.*[13] successfully simulated a more realistic equatorial Quasi-Biennial Oscillation (QBO).

Two intensive radiosonde campaigns were implemented in Yichang in August 2006 and January 2007. The eight-times-daily radiosonde measurements during the campaigns were applied to investigate characteristics of dynamical and thermal structures and Inertial Gravity Waves (IGWs) in the Troposphere and Lower Stratosphere (TLS). Zhang and Yi[14] argued that the wind shear associated with tropospheric jet was the dominant source for IGWs in both the troposphere and lower stratosphere. Results from analyzing the campaign data show that the occurrence of a second inversion layer can be closely associated with the presence of intense IGWs propagating in winter tropospheric jets[15]. Huang *et al.*[16] further investigated the activity of diurnal tide and Planetary Waves (PWs) in the Troposphere and Lower Stratosphere (TLS) over Yichang. The spectral analyses reveal that some waves with period of around 24 h are generated by the interactions between diurnal tide and PWs, with the tidal amplitudes being modulated by the PWs.

The study on the interaction between gravity waves and tides was performed by using a compressible nonlinear two-dimensional gravity wave model[17]. The numerical results show that tidal wind reduces the vertical wavelengths of the GWs when it is in the same direction as the wave propagation, and thus increases the perturbative shear and the likelihood of instability and wave breaking, especially for waves with shorter vertical wavelengths. Below the critical level, the breaking of GWs can increase the amplitude of diurnal tidal wind due to the momentum deposition. It is interesting that the gravity wave breaking not only accelerates the mean winds, but also increases the amplitudes of the diurnal tide at various altitudes.

By developing a parallel computation scheme, the propagation of GWs were simulated by a two-dimensional[18] and a three-dimensional model[19]. The Kelvin-Helmholtz (KH) billows in GW propagation were simulated explicitly by using the two-dimensional model[20]. The simulation can resolve the braid structures and overturning of KH billows, caused by nonlinear interactions between GWs and mean flow. And the results provide support to the findings of airglow studies, that the propagation of GWs into the MLT region from below is an important source of the KH billows. The results also demonstrate that before the KH billows evolve, the mean wind is accelerated greatly by GWs; while by contrast, as the KH billows evolve and mix with mean flow, the mean wind and its peak value decrease.

Combining conventional and wavelet methods with GPS winsonde data, Chane-Ming *et al.*[21] investigated the GWs in the Upper Troposphere and Lower Stratosphere (UT/LS) region due to intense Tropical Cyclones (TCs). Analyses reveal 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 6–60 h, 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. Convective activity over the basin and GW energy density are modulated by mixed equatorial waves of 3–4 days, 6–8 days and 10–13 days confirmed by Hövmöller diagram, Fourier and wavelet analyses of OLR data. Moreover, location of GW sources is below the tropopause height when TCs are intense, and otherwise varies at lower tropospheric heights depending on the strength of convection. Finally, the maximum surface wind speeds of TCs Dina and Faxai can be linearly estimated with total energy densities.

Yuan *et al.*[22] investigated the character of vertical wavenumber spectra of ozone fluctuations, to assess the possible roles of gravity wave field in ozone fluctuations, by using 12 ozone fluctuations obtained during June–August 2003. Their results indicate that mean spectral slopes in the wavenumber range from 4.69×10^{-4} to 2.50×10^{-3} cycle/m are about -2.91 in the troposphere and -2.87 in the lower stratosphere, which is close to the slope of -3 predicted by current gravity wave saturation models, indicating that the observed ozone fluctuations can be ascribed primarily to atmospheric gravity waves. Mean vertical wavenumber spectra in area-preserving form reveal that dominant vertical wavelengths is about 2.6 km in the troposphere and about 2.7 km in the lower stratosphere.

3.2 Researches on Atmospheric Tides

Chen and Lu[23] developed a numerical scheme to calculate Hough functions based on Laplace's tidal equation. The Eigen values and the Hough functions associated with each of the 39 tidal components, including the components falling in three primary frequencies, viz., diurnal, semidiurnal and terdiurnal, and in zonal wavenumber range $[-6, 6]$, were all calculated. As examples, the results of the Hough functions associated with the migrating diurnal and semidiurnal tides were presented to show the correctness of the structure of these functions. And the results of the corresponding Eigen values show that substantial accuracies in these values are maintained, which suggests that the current results are sufficiently applicable for conventional applications.

Using the TIMED/SABER temperature during 2002–2006, Chen and Lu[24] investigated the global structures of the eastward propagating diurnal tide of zonal wavenumber 3 (DE3) with the application of Hough Mode Decomposition (HMD) method. The HMD analysis results show that the DE3 tide is primarily dominated by two leading propagating Hough modes, *i.e.*, $(-3, 3)$ and $(-3, 4)$ modes; while the influences of the other Hough modes including trapped modes can be neglected. Based upon the HMD analysis results, they first reported the maximum of the tidal activity in the MLT region. The results show that the DE3 tide exhibits annual unimodal distribution with the maximal amplitude occurring at 110 km in late summer (around July each year). Moreover, characteristic 2-year period variation was observed in the $(-3, 3)$ Hough mode. And this type of interannual variation is further reflected in the tidal amplitude at 110 km height. For example, corresponding to the 2-year variation of the $(-3, 3)$ mode, the DE3 tidal amplitude exhibits two substantially enhanced activities with maximal amplitude exceeding 12 K in 2002 and 2004 respectively. Moreover, current investigation results indicate that the influence of the second propagating Hough mode, $(-3, 4)$ mode, is important, in particular at heights below 100 km, where the DE3 amplitudes exhibit anti-symmetric distribution with respect to the equator. The $(-3, 4)$ mode exhibits bimodal distribution over a yearly course, which dominates the DE3 tide in the lower mesosphere. For example, two maximal DE3 activities were observed in late-winter-to-early-spring and late-autumn-to-early-winter respectively: the first maximum is seen in the south of the Equator, and the second maximum is in the north of the equator.

A new method of extracting zonal mean and tides from satellite observation was put forward. Using TIMED temperature data, seasonal variations of the migrating diurnal tide were estimated, and the associating diurnal tide in equilibrium wind was derived[25]. The results show that there are strong Quasi-Biennial Oscillation (QBO) signatures in the amplitude of the diurnal tidal temperature in the tropical region and in the wind near $\pm 20°$. The magnitude of the QBO in the diurnal tidal amplitude reaches about 3 K in temperature and about 7 m/s (Northern Hemisphere) and 9 m/s (Southern Hemisphere) in meridional wind. Throughout the mesosphere, the amplitude of the diurnal tide reaches maximum during March/April of the years when the QBO in lower stratospheric wind is in the eastward phase. The TIMED global temperature observed by SABER and the wind observed by TIDI were used to investigate the damping of the diurnal tide[26]. This damping was approximated by an Equivalent Rayleigh Friction (ERF). The results show that during some periods the ERF coefficient can be very large over narrow vertical regions of about 5 km. The magnitude and shape of the vertical profiles change with latitude and season. The peak in the vertical profile of ERF is larger and located at a higher altitude in summer than in winter and the ERF coefficients at 40° are stronger than at 20° in both hemispheres. The global distribution of atmospheric ozone observed by Aura/MLS was used to calculate the diurnal component in the ozone heating rate[27]. The heating was decomposed into Hough modes and the annual (AO), semiannual (SAO), and quasi-biennial (QBO) periodicities of each Hough mode were presented. The results show that the majority of the O_3 heating goes into the symmetric $(1, -2)$, (1, 1) and $(1, -4)$ modes. The largest propagating mode (1,1) and the largest trapped mode $(1, -2)$ have obvious SAO signatures near 47 km, where the heating magnitude is largest. The strongest annual variation takes place in the $(1, -1)$ mode near 45 km at the Dec./Jan. solstice. A new parameterization of the diurnal component of the heating rate, covering the vertical range from 10 km to 70 km, was developed based on the seasonal variations in each Hough mode.

Jiang *et al.*[28] used the wind data obtained by the Maui meteor radar (20.75°N, 156.43°W) to study the 8 h tide. The results show that the 8 h tide is a regular and distinct feature over Maui. The meridional component of this wave is significantly larger than the zonal component. The meridional component exhibits a semiannual variation in amplitude, with peaks near the equinoxes, whereas the variation of the zonal component does not show this seasonal characteristic. They also analyzed tidal waves of the low latitudes of China by using the meteor radar at Fuke, China (19.5°N, 109.1°E)[29]. The observed tides were compared with the linear tide model (Global Scale Wave Model, GSWM02), and the results show that Fuke diurnal tide agrees well with the model, but there are many differences between Fuke semidiurnal tide and the results from model.

3.3 Researches on Planetary Waves in the Upper Atmosphere

The planetary waves were analyzed by using six ground-based Radar observations[30]. The strong mesospheric 6.5-day wave event that occurred during April–May 2003 was studied in detail. The analysis shows that the latitudinal structure of the mesospheric 6.5-day wave during April–May 2003 is basically in agreement with the theoretical Rossby mode $(s, n) = (1, -2)$. The main wave periods and the altitude distribution of large amplitude of this wave event varied with latitude. Downward propagating wave phases were also observed, indicating that the wave event originated in the lower atmosphere and propagated upward to the upper region.

4 Circulation and Chemistry-climate Coupling in the Middle Atmosphere

Recent studies on the relations of the variability of the East Asian Winter Monsoon (EAWM) to planetary wave activities have achieved important progress. Chen *et al.*[31] found that in the Northern Hemisphere winter the variations of the two waveguides of planetary wave propagation have an out-of-phase oscillation on interannual timescales. If the polar waveguide is strengthened, then the low latitude waveguide may be weakened, and vice versa. And it was also found that the oscillation of these two waveguides is closely related to the interannual variations of Northern Annular Mode (NAM), which can lead to interannual variabilities of the EAWM via anomalous planetary wave activities. This relationship between the planetary wave activity and the EAWM on interannual timescale is strongly modulated by the tropical Quasi-Biennial Oscillation (QBO) of zonal wind in the stratosphere. Using observational data from 1957 to 2002, Wang *et al.*[32] analyzed the interdecadal variations of the EAWM and their association with the quasi-stationary planetary wave activity. It was found that the EAWM experienced significant weakening around late 1980 s. In the meantime, both the propagation and amplitude of quasi-stationary planetary waves experienced obvious interdecadal variations, which are closely related to those of the EAWM. Anomalous propagation of waves may weaken the East Asian jet stream. And reduced amplitude of waves may weaken both the Siberian high and the Aleutian low, thereby reducing the pressure gradient in between. Hence, the EAWM is weakened. The most recent work of Wang *et al.*[33] also suggests that interdecadal variations of planetary wave propagation may account for the enhanced Ural blocking-East Asian winter climate relationship.

Chen and Wei[34] investigated anomalous propagation of planetary waves and its roles in the impact of the stratosphere on the East Asian winter climate, particularly on intraseasonal timescales. They found that the variability of planetary wave activity is closely associated with the low frequency variations of stratospheric polar vortex. The anomalous polar vortex in the stratosphere may have a downward influence on the short-term climate in the troposphere via the interaction with the planetary waves. In addition, this downward influence is particularly significant over East Asia. The interannual variations of the winter stratospheric polar vortex were further investigated by Chen and Wei[35] through an EOF analysis. The leading mode (EOF1) reflects the intensity variation of the polar vortex and is characterized by a geopotential height seesaw between the polar region and the mid-latitudes. The second one (EOF2) exhibits variation in the zonal asymmetric part of the polar vortex, which mainly describes the stationary planetary wave activity. As the strongest interannual variation signal in the atmosphere, the QBO has been shown to influence mainly the strength of the polar vortex. On the other hand, the ENSO cycle, as the strongest interannual variation signal in the ocean, has been shown to be mainly associated with the variation of stationary planetary wave activity in the stratosphere. Possible influences of the stratospheric polar vortex on the tropospheric circulation were also documented on interannual timescales.

The breakup of the stratospheric polar vortex and the role of planetary waves were investigated with focus on the differences between the southern and northern hemispheres[36]. Strong activities of planetary waves were found before the breakup and the wave activities declined quickly afterwards. It is suggested that the upward planetary wave propagation determines the exact time of breaking. The long-term trend indicates that the breaking time of the stratospheric polar vortex has been postponed in both hemispheres, especially since the mid- 1990 s.

Hu and Pan[37] analyzed results from AMIP simulations which were forced by observed time-varying SSTs. It was found that all AMIP simulations demonstrate warming trends in the Arctic lower stratosphere. It also shows a weakened Arctic polar vortex, in responding to the polar warming. Empirical Orthogonal Function (EOF) analysis shows a downward trend toward the negative polarity of an annular-like mode. Further analyses indicate that the Arctic stratospheric warming is associated with increasing wave activity and enhanced wave-flux convergence in the extratropical stratosphere, suggesting that the polar warming is caused by enhanced wave-driven adiabatic heating due to SST increases.

Hu and Fu[38] reported their finding of the evidence of significant stratospheric warming over Southern Hemisphere high latitudes and large portions of the Antarctic polar region in winter and spring seasons, with a maximum warming of 7–8°C in September and October, using satellite Microwave Sounding Unit observations for 1979–2006. It was found that this warming is associated with increasing wave activity from the troposphere into the stratosphere, suggesting that the warming is caused by enhanced wave-driven adiabatic heating. It is shown that the stratospheric warming in Southern Hemisphere high latitudes has close correlations with Sea Surface Temperature (SST) increase, and that general circulation model simulations forced with observed time-varying SSTs reproduce similar warming trend patterns in the Antarctic stratosphere. The simulated stratospheric warming is closely related to increasing wave activity in the Southern Hemisphere. These findings suggest that the stratospheric warming is likely induced by SST warming. As SST warming continues, resulting from greenhouse gas increase due to anthropogenic activity, the stratospheric warming would also continue, which has important implications for the recovery of the Antarctic ozone hole.

The temporal and spatial variation processes of the Polar Vortex Oscillation (PVO) in both the Northern and Southern Hemisphere were investigated by applying the daily re-analysis data and the Isentropic Potential Vorticity theory[39−40]. It was found that the dominant timescale of the PVO in the Northern Hemisphere (NH) is about 120 day, while the Southern Hemispheric (SH) PVO exhibits a dominant timescale of as long as about 220 day. The NH PVO basically manifests the intra-seasonal variability of the NH polar vortex, while the SH PVO is mostly the reflection of the inter-annual variability of the SH polar vortex. And the NH PVO exhibits much stronger variability than its counterpart in the SH. However, accompanying the occurrence of the PVO events, the temporal and spatial variations of the associated circulation anomalies are quite similar between the two hemispheres. They both exhibit systematic pole-ward and simultaneous downward propagations in the stratosphere, and also equatorward propagation of the temperature anomalies in the troposphere. Specifically, the stratospheric anomalies need about 55–60 days in NH and about 100–110 days in SH to travel from the deep tropics to the polar region. The arrival of the propagating anomalies in the pole is responsible for the occurrence of the PVO events and corresponds to the opposite signed anomalies and the equatorward propagation in the troposphere. Moreover, based on the theory of mass circulation, a global mass circulation paradigm was proposed. Particularly, the compensatory coupling between the upper warm and the lower cold branch of the global mass circulation accounts for the meridional and vertical coupling of the circulation anomalies associated with the PVO. The paradigm also helps to explain the out-of-phase relationship of the temperature anomalies from the stratosphere to the troposphere, and the variations of the extra-tropical surface pressure during the PVO events. Using the dataset, Ren *et al.*[41] reported that ENSO and the PVO are intimately related mainly on the timescale of 3–5 years, and show a lagged coupling relationship. Specifically, following warm/cold ENSO event, the extra-tropical stratosphere tend to be warmer/colder 9–11 months later, or exhibiting a weaker/stronger polar vortex and polar jet. The mutual reproduction of the ENSO-related SST patterns by the lagged PVO variations and the PVO-related spatial patterns by the leading Nino3 index confirms this lagged coupling relationship. The ENSO-induced variability of the PVO also exhibits similar poleward and downward propagations in the stratosphere, indicative of the variability of the mass circulation on the interannual timescale.

Using a detailed fully coupled chemistry-climate model, Tian *et al.*[42] investigated the effect of increasing stratospheric water vapor on ozone depletion and temperature change. They found that increasing stratospheric water tends to accelerate the recovery in the northern high latitudes and delay it in the southern high latitudes. The modeled ozone recovery is more significant between 2000–2050 than between 2050–2100, driven mainly by the larger relative change in chlorine in the earlier period. Xie *et al.*[43] studied the radiative effect of ozone and GHG changes on the Stratosphere and Troposphere Exchange (STE) and found that increasing ozone is likely to warm the tropopause and cause more tropospheric water vapor entering into the stratosphere. Their results also show that Sea Surface Temperature (SST) changes associated with increasing atmospheric Greenhouse Gases (GHG) have a profound impact on the STE. Without corresponding SST changes, the radiative effects of the CO_2 doubling on the STE are less significant than a global 15% O_3 increase.

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