Advances in Studies of the Middle and Upper Atmosphere and Their Coupling with the Lower Atmosphere

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ABSTRACT

Recent advances in studies of the middle and upper atmosphere and their coupling with the lower atmosphere in China are briefly reviewed. This review emphasizes four aspects: (1) Development of instrumentation for middle and upper atmosphere observation; (2) Analyses and observation of middle and upper atmosphere; (3) Theoretical and modeling studies of planetary wave and gravity wave activities in the middle atmosphere and their relation to lower atmospheric processes; (4) Study on the coupling between the stratosphere and the troposphere.

Key words: middle and upper atmosphere, gravity wave, planetary wave, stratosphere-troposphere exchange (STE), stratospheric ozone

1. Introduction

Studies of the middle and upper atmosphere and their relationship to the lower atmosphere play an important role in understanding the basic processes of the whole atmosphere and its response to global change as well as facilitating multiple applications for the prediction and monitoring of the atmospheric environment. In the past four years, significant progress has been made by Chinese scientists in the following areas: development of instrumentation, observations and analyses of the middle and upper atmosphere, study on middle atmosphere planetary wave propagation and gravity waves (GW), as well as study on the stratosphere-troposphere coupling. In this paper, the activities and some results are briefly reviewed.

2. Development of instrumentation for middle and upper atmosphere observation

The knowledge of the middle atmosphere is critically dependent on field observation, with space-borne, air-borne, and ground-based instrumentations. In the past four years, a series of ground-based facilities has been developed and put into operation. The Xianghe VHF/ST (Very High Frequency/Stratosphere-Troposphere) radar developed by the Institute of Atmospheric Physics/Chinese Academy of Sciences (IAP/CAS) has been successfully completed and has obtained wind profiles from 2–22 km, structure constant of air refractivity, C_n^2 profiles, as well as directional apparent reflectivity from the zenith angles of 0° to 20° which can show the backscattering mechanisms of Fresnel reflection and turbulent scattering (Lü Daren, private communication). This VHF/ST radar is the first stage of a complete MST (Mesosphere-Stratosphere-Troposphere) radar. A medium frequency (MF) Doppler radar dedicated for observing the winds and waves in the mesosphere and lower thermosphere was set up by the Wuhan Institute of Physics and Mathematics in 2002 and quasi-continuous observation has been conducted there (Hu Xiong, private communication). A new telescope with a 1-m aperture has upgraded the detecting ability of the Rayleigh and Sodium Lidar of the Wuhan Institute of Physics and Mathematics. This Lidar system is used for quasi-continuous observation of the sodium layer and for retrieving middle atmosphere density profiles (Gong Shunshen, private communication). At the Chinese

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Antarctic Expedition Station, named Zhongshan Station, the multi-channel photometer and all-sky camera for aurora observation, in cooperation with the Japanese Polar Research Institute, have collected a wealth of new data (Liu Ruiyuan, private communication).

3. Observations and analysis of the middle and upper atmosphere

3.1 *Field observation activities*

LAGEO (Laboratory for Middle Atmosphere and Global Environment Observation), IAP/CAS initialized quasi-operational ozone sounding over Beijing, China in spring 2001 for twice-weekly soundings. This project is a collaboration with the China Meteorology Bureau for advancing operational ozone observation. Up to 2003, there have been more than 150 soundings. Preliminary analysis by Wang Gengchen et al. (private communication) revealed a distinct seasonal variation about the column ozone content and, in particular, its vertical distribution. In spring, multiple peaks of ozone density appeared in the regions of the tropopause where tropopause folding exists. Further analysis is being made (Chen Hongbin and Wang Gengchen, private communication).

The mesospheric sodium layer provides a perfect tracer to investigate the dynamical and chemical characteristics of the atmosphere at these usually inaccessible altitudes. Typically, the sodium layer suffers a great number of regular and irregular variations with time scales from a few minutes to those of a seasonal span. Among them, the most drastic one is the sporadic Nas layer in the mesopause region. The formation mechanisms of the Nas layer are not well understood. To reveal the function of tides, gravity waves, and turbulence in the formation of Nas layers, more Lidar observations with a wide geographical coverage are needed. A powerful Rayleigh and sodium resonance fluorescence Lidar system was established in 2001 and is currently being operated by Dr. Yi Fan group of Wuhan University. During March to September 2001, Yi et al. (2002) observed sporadic Na layers (Nas) on 29 occasions from 275 hours of observation data . These layers tended to show a seasonal variation with a maximum occurrence rate in July. The maximum Na density was comparable with those observed at low and high latitudes. The team found that in contrast to observations from all other sites around the world, most Nas layers over Wuhan tended to occur around the peak altitudes of the normal Na layers (∼92 km). In addition, the Nas layers over Wuhan often exhibited broader layer widths than those at low and high latitudes. As for the observation of the background Na layer, Mao and Yi (2003) analyzed the observation results by using the Lidar of Wuhan University (Yi et al., 2002) in the period of March 2001 to October 2002. Their statistics revealed that the seasonal variation and the layer centroid height were very similar to those of observations over Urbana, USA (40°N, 88°W) (States and Gardner, 1999), which means that the same mechanism controls the Na layer performance over the two sites. The present results supply the performance of Nas layers over the midlatitudes and raises the problem of the primary mechanisms of geomagnetic or geographic effects (Von Zahn et al., 1987; Clemesha et al., 1988; Zhou and Mathews, 1995).

3.2 *Analysis of satellite observations of the middle and upper atmosphere*

Shen et al. (2001) used the neutral atmospheric data of the number density ratios of $n(\mathrm{He})/n(\mathrm{N_2})$ and $n(\mathrm{O})/n(\mathrm{N_2})$ observed by the Atmospheric Explorer AE-D satellite to analyze the variations during magnetic storms in November 1975. Their results indicate that the lifting of the neutral atmosphere with a higher proportion of heavier constituents (such as N_2 and Ar) leads to a relative decrease of the concentration of lighter constituents (such as He and O). In comparison, on a magnetically quiet day, the ratio of $n(\mathrm{He})/n(\mathrm{N_2})$ is smaller by about one order of magnitude at 150 km, while $n(\mathrm{Ar})/n(\mathrm{N_2})$ is larger by a little more than one order of magnitude.

Ma et al. (2001) studied the characteristics of temperature at heights of 20–80 km over China by using the Nimbus-7 SAMS temperature data from 1979–1981. Their results show an obvious difference between the temperature over China and the zonal mean temperature of the CIRA-1986 atmospheric model. Chen and Yi (2003) combined the observation data of radio soundings and Rayleigh scattering Lidar to derive density and temperature profiles in the range of 0–65 km over Wuhan (30.50°N, 114.40°E). Their results agree very well with the MSISE-90 atmosphere model. The temperature difference between the derived profiles and the model at the stratopause height is about 3 K. Gravity wave activities were observed by using their Rayleigh Lidar.

3.3 *Atmospheric ozone over China*

There are five stations over China for monitoring atmospheric ozone variation. Two of them use Dobson instruments and began observations from the end of the 1950s. Since 1979, these instruments have been in routine operation at Beijing (39.93°N, 116.40°E) and Kunming (25.02°N, 102.68°E). Based on the data of total atmospheric ozone observed over these two stations, Bian et al. (2002) analyzed the variation characteristics of atmospheric ozone content, including the long-term trend, interannual, seasonal, and intraseasonal variations. They found that (1) the long-term trends for the period of 1979/1980–2000 were –0.642 Du yr^{-1} and 0.009 Du yr^{-1} in Beijing and Kunming, respectively. These results are consistent with the results given in the WMO Global Ozone Research and Monitoring Project Report (1999). These values of the long-term trend are significantly less than the values deduced by other authors who used the same data but of a shorter time period (1980–1991) (e.g., Wei et al., 1994; Zhou et al., 1996). This difference raises the problem of how to distinguish between multi-year natural variability and anthropogenic influences. (2) They also found there exists a strong intra-seasonal variation, especially in winter, which is comparable to seasonal variations both in Beijing and Kunming. (3) They also found significant quasi-biennial oscillation (QBO) signals both in the mid-latitudes (Beijing) and low latitudes (Kunming), which are the main components (combined with the long-term trend) of the inter-annual variation.

4. Study on middle atmosphere planetary waves and gravity waves

4.1 *Middle atmosphere planetary waves*

Atmospheric planetary waves (PWs) are mainly produced in the troposphere by dynamical and thermal effects of solar radiation and earth surface imhomogeneity. In certain conditions, PWs will propagate to the middle atmosphere and play an important role in regulating middle atmosphere circulation and constituent distribution, such as ozone. To understand the function of the QBO modulation of planetary wave propagation in the middle atmosphere and its effect on the transport of ozone from its low latitude source region to high latitudes, Chen and Huang (1999) studied the PW-mean flow interactions during the different phases of the QBO with the quasi-geostrophic zonally-averaged mean flow equations and the linearized primitive equations. They found that in the linear case of steady flows, there is no feedback between the mean flow and the PWs. And the noticeable difference of the dissipating PW propagation between the easterly and westerly phases of QBO is mainly confined to low latitudes. Since PWs are often neither steady nor conservative, there always exists PW mean flow interaction and coupling. In this case, Chen and Huang (2002) found a noticeable difference between PW propagation at middle and high latitudes. In winter, there are obviously larger upward and equatorward (EP) Eliassen-Palm fluxes in the easterly phase winter than in the westerly phase. By modulating the propagation of PWs, they found that the tropical QBO introduces significant variability in the planetary wave amplitudes and the residual circulation in the Northern Hemisphere; also, in winter, the planetary wave amplitudes are shown to be greater during the easterly phase than during the westerly one.

By using the transformed Eulerian-mean equations, Chen and Huang (2002) studied the dynamics of PWs. They found from both observations and numerical simulations that in the Northern Hemisphere winter there are two waveguides for the meridional propagation of quasi-stationary PWs, viz., the high latitude waveguide and the low latitude waveguide. This is in agreement with theoretical analysis. The convergence of EP fluxes in their results reveals that the stratospheric sudden warming (SSW) is the result of anomalous planetary wave propagation along the high latitude waveguide and its interaction with mean flows. Their analysis also shows that the tropical QBO may influence the low latitude waveguide of planetary wave propagation and further modulate the high latitude waveguide through wave-mean flow interactions. They found that the modification of the planetary wave propagation by the equatorial QBO winds is shown to have an important impact on the transport circulation. It was found by their model simulation that the meridional transport is amplified during the easterly phase of the QBO. This mechanism may explain the interannual variability of ozone in the stratosphere at high latitudes.

4.2 *Sources and mechanisms of gravity waves*

Gravity waves (GWs) play an important role in the middle atmospheric circulation. It is commonly recognized that sources of the middle atmospheric GWs are mainly from the troposphere, but the detailed mechanism and quantitative description of the source mechanism are still not very clear. Based on an observation case of strong summer deep convection (a hail storm) in mid-latitude China, Chen and Lu (2001) conducted a numerical simulation for GW excitation in the lower stratosphere by deep convection with a nonhydrostatic compressive model coupled with a bulk cloud microphysics parameterization scheme. Their simulation revealed that due to the penetration of convection through the tropopause, three distinct subareas—the wave-energizing, the wave-exciting, and the wave-bearing subareas—are found to be responsible for the wave generation. The GW wave-induced momentum flux at the tropopause height is about 0.3 N m^{-2}, which is comparable to those of orographically excited GWs in winter. Since the strong convections are often generated in mid-latitude summer in East Asia, it is anticipated that there exist significant GW sources for this region, not just for the tropical area.

In fact, GWs can also be excited by stratospheric processes. Based on the data of a Stratosphere Sudden Warming (SSW) event in February 1979, Huang and Chen (2002) found that due to the upward propagation of quasi-stationary PWs, strong ageostrophic motion existing in the stratosphere, may produce a strong divergence field and strong, large-amplitude GWs. They simulated such a mechanism of GW excitation with a linear barotropic spherical-spectral model. Taking the actual geostrophic deviation at 10 hPa on 22 February 1979 as the initial disturbance, the geostrophic adaptation process of geostrophic disturbances, and the excitement and propagation of the large-amplitude GWs during SSW, were successfully simulated. Their simulation reveals that the stratospheric geostrophic adaptation process is also a GW excitation mechanism within the middle atmosphere.

Nonlinear propagation of GWs in the mesosphere is very important. So far, this kind of study has been limited to ideal conditions, i.e., isothermal and incompressible conditions (e.g., Prusa, 1996). Since the real atmosphere is nonlinear, compressible, and dissipative, it is necessary to investigate the effects of these factors on GW propagation.

Zhang and Yi (1999) made a numerical study of the nonlinear propagation of a GW packet in a compressible atmosphere by using a Full-Implicit-Continuous-Eulerian (FICE) scheme. Their results clearly show that in a non-isothermal compressible atmosphere, the GW packet propagation departs from the ray path derived from linear theory. Zhang et al. (2000) studied nonlinear effects on the dispersion and polarization relations of GW packets with the same FICE scheme. They found that the relations are the same as those from linear theory (Zhang et al., 2001a,b). Yue and Yi (2001) extended the 2D GW nonlinear propagation to three dimensional situations by using an alternative-direction-implicit (ADI) scheme. They found that this scheme is reliable. Their numerical results show that in the 3D situation, nonlinear GW propagation still maintains these characteristics which are the same as those from linear propagation. Zhang et al. (2002) studied the GW saturation mechanism in the mesosphere. Their results show that the dominant mechanism is overturning and the turbulence is the only end product.

Wu and Yi (2002) studied the nonlinear propagation of a GW packet in a 3D compressible atmosphere by using the FICE scheme. They found that in the nonlinear situation, the increase of GW wave amplitude is faster than that for linear theory, and the horizontal disturbance velocity increases greatly which may lead to an enhancement of the local ambient winds. Zhang and Yi (2002) studied the GW packet propagation in a dissipative atmosphere. They found that the molecular viscosity and its vertical imhomogeneity play an important role in nonlinear GW packet propagation.

4.3 *Wave-wave interaction in the middle atmosphere*

Over the past decade, nonlinear interactions among PWs, tides, and GWs have been widely studied and used to explain short and long term variability of the wave activities in the mesopause region (e.g., Manson et al., 1998). With German mobile SOUSY radar observation data during the MAC/SINE campaign in summer 1987 (Ruster, 1994), taken from the height range of 78–94.2 km, Xiong and Yi (2001) analyzed the nonlinear wave interaction in the mesopause range (83.4–91.2 km). They found that a 35-h wave, semi-diurnal tides, and inertial-gravity waves with a period of about 8.9 h existed at almost all heights in the zonal wind and these frequencies satisfied the resonance condition. And a 33-h wave, semi-diurnal tides, and inertial-gravity waves with a period of about 19 h in the meridional wind also satisfied the resonance condition. By using bispectral analysis, they found that the non-linear wave interactions may exist in the mesopause region, which leads to the variation of tide amplitude temporally and spatially. By using the same datasets, Liu and Yi (2003) studied the resonant nonlinear interaction between atmospheric waves in the polar summer mesopause region. They found that wave-wave sum resonant interaction and the wave dissipation due to instability are two dominant dynamical processes that occur in the mesopause region.

For studying the GW saturation processes, Wu and Xu (2000) discussed vertical wavenumber spectra of the zonal and meridional velocity fluctuation by using data provided by German scientists measured from 10 chaff rockets and found a spectral slope of –3.0, providing observational evidence of a saturated gravity wave spectrum with high resolution in the lower thermosphere. In a subsequent study, Wu et al. (2001) further discussed the mean characteristics of vertical wavenumber spectra of the scalar horizontal wind fluctuation using data measured from 33 German chaff rockets. They found that the mean vertical wavenumber spectrum was consistent with the linear saturation theory in both spectral slope and spectral amplitude. This good agreement provides further support for the linear saturation theory in a mean sense and suggests that saturation processes are present in the horizontal flow and that they act to produce turbulence. We can therefore expect that turbulence is enhanced near the polar summer mesopause. In addition, the chaff rocket system with very high vertical resolution has also been used to study the space-time structure of turbulence. Wu (1998) calculated the spectrum of the vertical velocity fluctuations in an extremely large shear layer and found that the spectrum has spectral slopes of –3.10, –1.65, and –7.11 in the buoyancy subrange, the inertial subrange, and the viscous subrange, respectively, which is in good agreement with the neutral density fluctuations. The relationship between turbulence and GW was also studied. The results indicate that enhanced turbulence has a strong link with wave field saturation.

4.4 *Coupling of dynamics and chemistry in the middle atmosphere*

The coupling between the dynamics and the chemistry in the gravity wave process is another research direction. Xu et al. (2000a) developed a dynamical-photochemical coupling model of atmospheric GWs. The model is used to study the influences of GWs on distributions of atmospheric minor species through transport and the nonlinear photochemical reactions. The simulations indicate that the effect of GWs on the distributions of atmospheric trace gases mainly depends on the nonlinear photochemical reactions in the mesopause region. The contribution of the nonlinear photochemical reactions caused by GWs can exceed the nonlinear transportation and the eddy diffusion. GWs may strongly modify the mean concentrations of atmospheric compounds near the mesopause, especially during nighttime (Xu, 2000). Xu (2000) and Xu et al. (2000b) investigated the conditions under which GWs become unstable due to photochemical heating in the mesopause region. These studies show that the GW growth rate induced by photochemistry is sensitive to the temperature and atomic oxygen concentration profiles. And the critical vertical wavelength was given. Xu et al. (2001) studied the influence of GWs on photochemical heating in the mesopause region. They discussed the balance of the variation of background temperature and of atomic oxygen density on the loss of photochemical heating induced by GWs. The results indicate that as the background temperature decreases, or as the background atomic oxygen density increases, the GW-induced loss of photochemical heating increases and the ratio between it and the background photochemical heating rate also increases. Wang et al. (2001) used a 2-D nonlinear GW model to study the propagation of a GW packet produced at the tropopause and GW breaking.

5. Studies of stratosphere-troposphere exchange (STE) and related processes

Processes of stratosphere-troposphere interaction and related dynamical, physical, as well as chemical processes have been an active research topic due to their significance to climate change and global environment.

5.1 *Global tropopause climatology and long-term variation*

Since STE occurs near the tropopause, the climatology and the spatial and temporal variation of the global tropopause height distribution itself become a significant issue (e.g., Haynes et al., 2001). Based on 40 years (1958–1997) of NCEP global data, Li Guohui (private communication) et al. analyzed the characteristics and long-term trend of the global tropopause. They found that due to the forcing of both tropical convection and extratropical wave forcing, the seasonal variation of the tropopause height reveals the character that it is not just simply higher in summer and lower in winter. In the Northern Hemisphere high latitudes, the annual variation reveals two peaks and two valleys. In the Southern Hemisphere high latitudes (65°S and southward), the tropopause height is higher in winter than in summer. All these characteristics are controlled by the general circulation pattern and radiation distribution. It is found from the analysis of the long-term trend of global tropopause height that in certain regions in the middle and high latitudes of both hemispheres, the long-term trend exists with statistical significance.

5.2 *Impact of tropopause variation on ozone distribution in the upper troposphere/lower stratosphere*

Because most atmospheric ozone resides in the lower stratosphere, small changes in ozone abundance can have a large impact on climate and the surface UV flux. The variation of the tropopause, as a transition or boundary between the well mixed, ozone-poor upper troposphere and the stratified, ozone-rich lower stratosphere, has a direct and evident effect on the distribution of ozone and its column abundance. Li et al. (2002) simulated the impact of tropopause variation on the distribution of ozone in the upper troposphere/lower stratosphere (UT/LS) using a two-dimensional model. Their results show that the annual cycle of the tropopause height has a remarkable impact on the distribution of ozone. The local change of ozone can be more than 10%. They found that the impact is mainly caused by the variation of the horizontal and vertical eddy exchange coefficients in the model due to the annual cycle of the tropopause height. Their results also show that the annual cycle of the tropopause height also remarkably affects the distributions of other trace gases, such as some long-lived species (HCl, HNO_3, NO_x, etc.) and some short-lived species (NO_2 and NO, etc.). When the tropopause height is increased (or decreased) by 1 km in winter in northern middle latitudes, the model results show that the impact on ozone distribution is evident and the local change of ozone can be more than 6%. However, they found that the impact on total ozone is relatively small; the variation is less than 5 Dobson units, i.e. less than but comparable with the statistical results of the relationship between tropopause height and total ozone, (e.g., Hoinka et al. 1996; Sternbrecht et al., 1998.

5.3 *Regional mass exchange between stratosphere and troposphere over Tibet and neighboring areas*

By using daily NCEP data of 1978–1996 and SAGE data of 1988–1993, calculations of mass exchange between stratosphere and troposphere and aerosol and ozone concentration at 100 hPa were made for Tibet and neighboring areas by Cong et al. (2001). It was found that (1) in summer, mass exchange is dominated by transport from the troposphere to the stratosphere centered over the northern Gulf of Bengal and southeastern Tibet. In winter, mass exchange is predominant from the stratosphere to the troposphere; (2) the 19-year average transport from the troposphere to the stratosphere over this area is about 14.84×10^{18} kg in summer. There exists a channel in this region for upward mass transport. Owing to pollutants in the lower atmosphere over this region, the atmospheric mass transport would increase all aerosol and other pollutant loadings near the tropopause of this region, possibly resulting in the decrease of ozone over the Tibetan area.

5.4 *Mesoscale modeling of STE over East Asia*

Four synoptic cases of strong cut-off lows for each season in eastern Asia were simulated with regional mesoscale model MM5 by Yang and Lu (2003). Their results show that there exist different mechanisms for cut-off-low-induced STE. Turbulent mixing near the jet stream is the primary contributor in the winter case. The interaction between the surface front and upper front is the primary contributor in spring. Strong convection over the ocean is the primary contributor in the summer case. In autumn, the cut-off low induced a small but broad area of descent of the tropopause, which plays an important role. According to the model trial results, they found that the tropopause is not a simple mass surface but a transition zone which can be fixed by the variation of flux following the potential vorticity. The total upward and downward fluxes in the tropopause are strong for the winter and spring cases, while weak for the summer and autumn cases. The largest net flux from the stratosphere to the troposphere appears in the spring case while the lowest appears in the summer case. The maximum ratio of upward mass and downward mass transport appears in summer, showing a strong upward transport of air mass in summer and a minimum amount in autumn.

6. Summary

In this brief paper, we reviewed the progress of middle and upper atmosphere research contributed by Chinese scientists in the past four years. Four areas have been reviewed: instrumentation for middle and upper atmosphere observation; observation and analysis of the middle and upper atmosphere; middle atmospheric planetary waves and gravity waves; and stratosphere-troposphere exchange and related processes. All these research activities will continue and be more closely linked to global climate and environment change studies.

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