Influence on the Middle Atmosphere of the 27-Day and 11-Year Solar Cycles: Radiative and/or Dynamical Forcing?

Marie-Lise Chanin, Philippe Keckhut

J. Geomag. Geoelectr., **43**, Suppl., 647–655, 1991

Influence on the Middle Atmosphere of the 27-Day and 11-Year Solar Cycles: Radiative and/or Dynamical Forcing?

Marie-Lise CHANIN and Philippe KECKHUT

Service d'Aéronomie du CNRS, BP 3-91371 Verrières le Buisson, France

(Received September 6, 1990; Revised November 27, 1990)

Results from Rayleigh lidar during the last solar cycle indicate a highly significant correlation with the solar flux both on the scale of the 11-year and 27-day cycles. The height profile of the response to solar variability for both cycles presents a succession of positive and negative correlations which are difficult to explain on the basis of a purely radiative and photochemical forcing. The similarity between the response as a function of height seen from lidar data and as a function of latitude seen from radiosondes and satellites data for both cycles provides a strong support to the hypothesis of dynamical forcing proposed by several authors. It leads to the conclusion that such an effect can only be simulated by three dimensional fully coupled models.

1. Introduction

The purpose of this paper is to present experimental results in support of the hypothesis of the dynamical nature of the middle atmosphere response to solar variability. It leans on the complementary results obtained either locally from lidar data giving access to the height structure of the atmospheric response or globally from radiosonde and satellite data providing the latitudinal structure of the atmospheric response. The lidar data base used in this paper was obtained between 1979 and 1989 at two mid-latitude sites: OHP (44°N, 6°E) since 1979 and Biscarosse (44°N, 1°W) since 1986 and has been described in other publications (CHANIN and HAUCHECORNE, 1984; CHANIN *et al.*, 1987; HAUCHECORNE *et al.*, 1991).

2. The 11-Year Solar Cycle

LABITZKE and VAN LOON (1988) have shown that the response of the atmosphere in the winter stratosphere at the 30 hPa level (24 km) not only changes sign with the phase of the QBO but also reverses from high to middle latitudes. From 2 sites at 80°N and 44°N corresponding to highly significant correlation with the solar cycle according to that paper, a study of the vertical structure of the response of the middle atmosphere was performed by LABITZKE and CHANIN (1988), which was later extended up to the lower thermosphere by CHANIN *et al.* (1989). Those studies indicated an alternance between positive and negative correlations as a function of both the QBO and the altitude and pointed out the existence of a negative response of the atmosphere to solar flux in the upper stratosphere and around the mesopause and above.

The separation of the data set according to the phase of the QBO was shown by VAN LOON and LABITZKE (1990) not to be necessary to obtain over large areas a statistically significant response to solar activity. In the same way the height response as observed from the lidar data at 44°N, for the period 1979–1989, for all seasons and independently of the sign of the QBO shows that the stratospheric response to solar variability (represented by the 10.7 cm flux) is negative (–4 K) in the upper stratosphere whereas it is positive in the mesosphere with a maximum response of 10 K at 65 km (Fig. 1). The correlation with the solar flux are shown to be significant well above the 95% confidence level (HAUCHECORNE *et al.*, 1991). The lidar data by themselves seem to indicate a possibility for the solar response to change sign and become negative around 80 km; this is confirmed and strongly supported by the recent paper of NEUMANN (1990). Using the OH temperature data obtained at Wuppertal (50°N, 7°E), close enough to the lidar sites to be compared with the lidar data, Neumann obtained a negative response of –0.04 K/unit of solar flux. This confirms for all seasons the negative correlation which was obtained in the winter from lidar and incoherent radar data in a previous work (CHANIN *et al.*, 1989).

The succession of in phase and out-of-phase response as a function of altitude is suggesting the role of planetary wave forcing, as already mentioned in CHANIN *et al.* (1989) and CHANIN (1989a and b). Several arguments are supporting this interpretation in term of a dynamical forcing: the fact that the response to solar flux is stronger in winter than in summer is the opposite to what would be expected from a radiative forcing; the role of the QBO, i.e. the influence of the change of direction of stratospheric winds, is likely to affect wave propagation; the negative response of the temperature in the high stratosphere, at the mesopause and in the low thermosphere, where the absorption of UV flux by O_3 and O_2 should lead to a positive response, seems rather difficult to explain in term of photochemistry and radiation alone. Several ideas of mechanisms have been suggested in the past to explain a dynamical coupling between upper and lower atmosphere and their connection to solar forcing (HINES, 1974; GELLER and ALPERT, 1980; CALLIS *et al.*, 1985), but the detailed mechanisms are still debated.

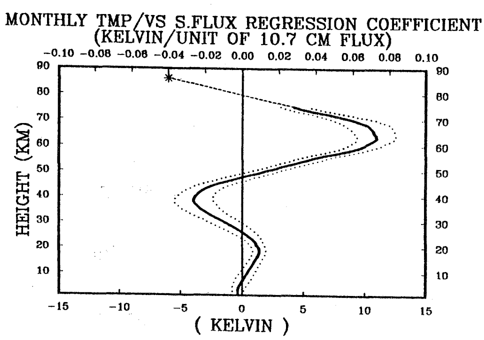

Fig. 1. Response of the temperature to a change in solar flux during the period 1979–1989: the altitude range below 30 km is obtained from radiosonde at a nearby site, the range 30–80 km is provided by the lidar data at OHP (44°N, 6°E) and BIS (44°N, 1°W) and the star at 86 km is from NEUMANN (1990). The lower abscissa gives the amplitude of the response in K, the higher one the response in K/unit of solar flux The dots indicate the ±1 σ error bar.

If this solar-induced response would be due to a dynamical forcing coherent with solar radiation, one should find a signature on dynamical parameters, for example on the zonal wind. Long-term variation of the upper stratospheric and mesospheric circulation has not been well determined until now, due to the sparse number of data. However a recent study by KODERA and YAMAZAKI (1990), using a Japanese rocket data set extending from 1973 to 1987, brings a quite convincing proof of an 11-year signature on the zonal wind at 40°N near 1 hPa (48 km). However the correlation is highly amplified if one considers only the years of west QBO as shown on Fig. 2 based on the above mentioned paper, even though the point was not emphasized by the authors. It is clear that the correlation of the zonal wind with the 10.7 cm radio solar flux is largely improved during the west phase of the QBO (0.94 ± 0.08 instead of $0.44 + 0.39$ for the whole data set) and that the variability around the 11-year variation is due to the years of East QBO.

As already observed by LABITZKE and VAN LOON (1988), observational results favor the winters of west QBO for giving a highly significant correlation with the solar cycle. Such change in the zonal wind (100 ms^{-1} as shown in Fig. 2 from KODERA and YAMAZAKI (1990)) could induce a variable transmission of the atmosphere due to filtering effects for the upward propagating waves which are thought to be responsible of the solar signature observed in the middle atmosphere. In the same paper, the authors, using the December NMC zonal wind at 40°N and 1 hPa between 1979 and 1987, indicate that the solar-induced effect seems to be mainly localised at mid latitude in the stratosphere, but suggest a reversed response in the troposphere and at high and low latitudes (see Fig. 4 of KODERA and YAMAZAKI, 1990).

Long sequence of data to study the influence of the 11-year solar cycle on the middle atmosphere do not exist yet and it would be premature to affirm the existence of a definite relationship; but those results on both temperature and wind, if confirmed, cannot be explained with purely radiative and photochemical mechanisms (see GARCIA *et al.*, 1984).

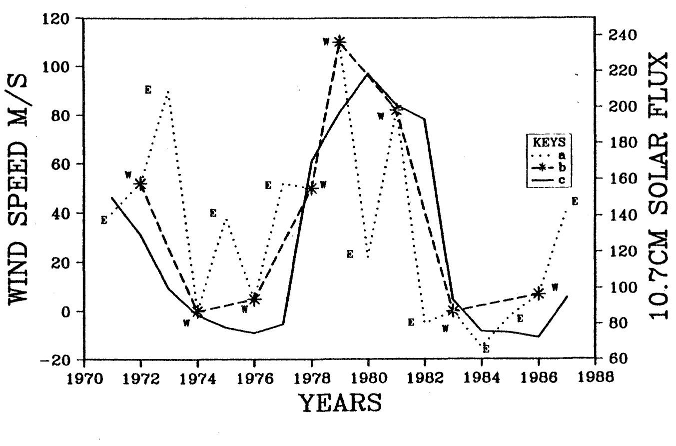

Fig. 2. Time evolution of the mean eastward wind component taken at 1 hPa at 40°N, 142°E in December from KODERA and YAMAZAKI (1990) (a). The sign of the QBO was added on the data set and the variation for years of Westward QBO given in (b). The December mean 10.7 cm radio solar flux is given in (c).

3. The 27-Day Cycle

The response of the atmosphere to short term changes in solar UV associated with the 27-day rotation period of the sun should be easier to detect, as measurements on many more such cycles can be made. Satellite data during the last maximum of solar activity have already shown that temperature and ozone responds to the variations of the flux at 205 nm. Recent results obtained locally from the lidar data are presented and compared to the global results given by the satellite data.

A more detailed description of the lidar data analysis related to the 27-day influence will be given elsewhere (KECKHUT and CHANIN, 1991). One of the difficulties in this study is to identify the 27-day period in the large variability observed during winter under the influence of planetary waves with periods ranging from 10 to 60 days. For that purpose the data are filtered for periods in the 20 to 40 days range.

The temperature data base consists of 8 years of lidar mean nightime temperature profiles with a good coverage in time (100 profiles per year per site) and an accuracy better than 1 K at 50 km and extends from 1981 to mid-1989. The recent period corresponding to high level of solar activity has not yet been used. The series of individual data was interpolated to provide one profile per day. The solar flux parameter used for the whole period is the 10.7 cm flux. However, for studying short time series the solar flux at the Lyman-α line as measured on board SME was preferentially used for all the data within the period 1982 to 1987 (ROTTMAN, 1983; MOUNT and ROTTMAN, 1985).

The spectral study was performed by applying to both the solar and the temperature data set the method of the wavelet transform recently developed by GROSSMAN and KRONLAND-MARTINET (1988) and, to confirm the significance of the peaks in the spectral decomposition, the cross spectral estimates were carried out using the time-series method described by JENKINS and WATTS (1968). The statistically significant coherence is given by the peak exceeding the 95% confidence level. The phase lag between both time series is deduced from the phase of the cross spectral analysis.

As observed from SME solar data (P. SIMON, 1989) only periods of high solar activity give a large enough 27-day amplitude of the solar U.V. flux. The selection of the time series to be studied was done by looking at the cross spectra between the two wavelet transforms of the 10.7 cm flux and the temperature. The level of coherence reaches large enough values for 7 periods of 3–4 months within the whole data base. For each of these periods it was verified that the peak observed around 27 days in the spectral analysis of the temperature series was significant. Therefore correlation coefficient, amplitude and phase lag were calculated for those 7 periods: two examples of the results are given in Figs. 3 and 4, where the line on either side represents the 95% confidence level. Two different types of response to the Lyman-α variation are seen. For 3 out of the 7 periods, the sign of the temperature deviation changes as a function of altitude, the negative response occurring between 40 and 60–70 km. This large and highly significant negative correlation (or positive correlation with a half-period phase lag) occurs very abruptly at well defined levels. Such alternance of positive and negative response to a change of solar UV is not without similarity with the response to the 11-year cycle. However, if one assumes that the response could only be positive, it leads to a phase lag as large as 15 to 20 days, whereas such an interpretation cannot stand for the response to the 11-year cycle. It should be mentioned, even though the number of cases is very small, that the situation shown on Fig. 3 has only been observed when the QBO is in its west phase. In the case of East QBO (4 out of 7 cases) the response is positive at all

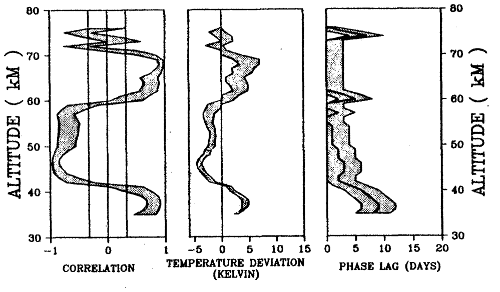

Fig. 3. Correlation coefficient, temperature deviation and phase lag for the response of the atmosphere from 35 to 75 km to the 27-day variability of Lyman-α during the period of January–February–March 1983.

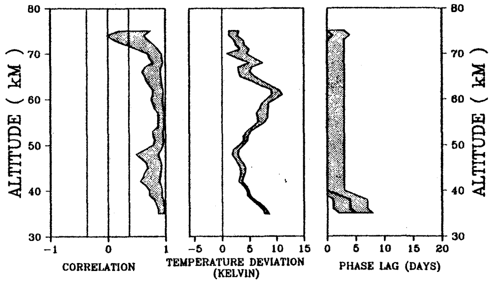

Fig. 4. As for Fig. 3 for the January–February–March 1982.

heights (Fig. 4) or when negative, it is below the level of significance. The phase lag in those 4 cases in less than 5 days at all heights. One should also note that the amplitude of the response, independently of the sign of the QBO, is of the order of a few K and as large as 5 K in 3 cases. The same comments apply to summer (3 cases) and winter (4 cases) periods, but the summer response is slightly smaller in amplitude.

The lidar results are not in contradiction with the study based on SAMS temperature performed by KEATING *et al.* (1985, 1987) and HOOD and CANTRELL (1988). The amplitude of the response seen by SAMS in 1979–1980 is between 1 and 2 K and the phase lag ranges from 14–16 days below 40 km (i.e. out of phase) to around 6 days between 40 and 60 km. But one has to keep in mind that these results were obtained for zonal mean values of temperature profiles which are of poor height resolution compared to the lidar profiles; this may act to smooth out the abrupt phase change and decrease the amplitude. Furthermore those results were obtained at equatorial latitudes.

On the other hand, our results—as on a certain way the SAMS results—are quite in disagreement with the models (BRASSEUR *et al.*, 1987). First the response is not localised in the height range 40–60 km, its amplitude is slightly larger and—if the response is assumed to be positive—the phase lag is much larger and changes abruptly with altitude.

4. Discussion

4.1 Role of ozone

A discussion on the response of the middle atmosphere temperature to a change in solar flux cannot be carried out without having in mind that, through the absorption of solar UV radiation, ozone heats up the middle atmosphere and is responsible of the temperature maximum at the stratopause level. Furthermore, the circulation and transport of ozone in the middle atmosphere depends on the temperature which on the other hand influences the chemical equilibrium of ozone and minor species.

Therefore, the temperature-solar flux relationship cannot be decoupled from the ozone response to solar flux and its impact on temperature. We know that ozone responds positively to solar UV variation and varies in phase with it, as seen from the response of LIMS data to 13.5 days UV variation (GILLE *et al.*, 1984) and from SBUV data response to the 27-day cycle (KEATING *et al.*, 1985; BRASSEUR *et al.*, 1987; HOOD, 1986; HOOD and CANTRELL, 1988). We also know that the ozone temperature relationship is either positive or negative depending on the dominant processes regulating the ozone equilibrium: schematically it would be dynamical below 30 and above 70 km, and chemical between 30 and 70 km. This may be at the origin of the change of sign in the temperature-solar flux relationship observed by lidar and presented in Fig. 3. However, if the influence of the sign of the QBO is confirmed by further studies, one will still have to understand the role of the QBO in this relationship. New results concerning the influence of QBO on ozone vertical profiles may bring a new insight on the impact of dynamics on this issue (MCCORMICK *et al.*, 1989): a clear signature of the QBO is seen on the SAGE II ozone concentration in the stratosphere extending at least up to mid latitude and a rapid change in the phase of the relationship with QBO is observed around 28 km; as suggested by the authors, it may be due to the competition between transport and photochemical effects.

As mentioned earlier one knows very little about the variability of the mean zonal wind at mid latitude in the upper stratosphere, but due to the change of radiative heating related to the ozone change, it would not be surprising to find a 27-day modulation in the mean wind which could be an amplification mechanism and could explain why the response of the temperature depends on the sign of QBO.

4.2 Latitude versus altitude response

A recent study by HOOD and JIRIKOWIC (1991) of the SAMS temperature and SBUV ozone and solar 205 nm flux measurements around 1.5 hPa (45 km) has extended the previous work on these data to mid and high latitudes, giving a new insight into the possible mechanism involved. Figure 5 reproduced from this paper shows the latitude dependence of the zonal mean SBUV ozone and SAMS temperature deviations for a 7-month period centered in the 1981–1982 North Hemisphere winter together with the SBUV solar 205 nm flux. At low latitude the ozone maxima are in phase with the solar flux, whereas the temperature is approximately out of phase with ozone. At high latitude the variations are for both ozone and temperature out of phase with the variations at low latitude. At mid latitude on a zonal mean the phase shift of one parameter relative to the other and to the solar flux is less clear. Such results had somehow been observed by CHANDRA (1985) from Nimbus 4 during the 1970–1972 period, and are obviously related to dynamics.

HOOD and JIRIKOWIC interpret these results as due to the interaction of a travelling and a stationary wave and suggest that solar UV variations may force or modulate travelling waves

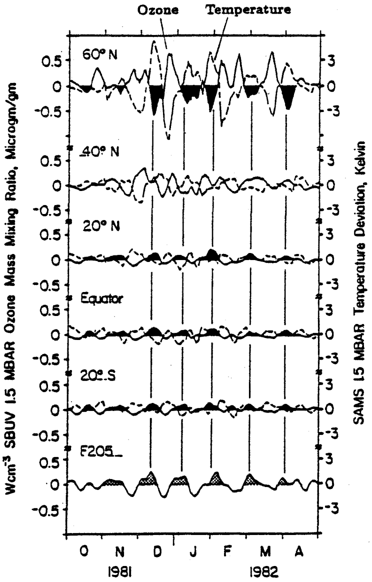

Fig. 5. Example of the latitude dependence of zonal mean SBUV ozone and SAMS temperature deviations from a 35-day running mean, for a 7-month period centered on the 1981–1982 N. H. winter. The deviation from the 35-day running mean of the SBUV solar 205 nm flux is shown in the lower paper for comparison (from HOOD and JIRIKOVIC, 1991).

with periods near 27 (and 13) days in the upper stratosphere. Such wave interaction would explain both the change of phase between the low and high latitude observed by satellite and the change of phase between the stratosphere and the mesosphere as seen by lidar. Both effects could be generated by a change in the mean wind field at mid latitude which would induce a change in meridional circulation, producing opposite effects in the stratosphere and the mesosphere.

The satellite data are covering a too short period to show a QBO influence, but the fact that the lidar observations seem to be QBO dependent is in support of the possible role of a change in the zonal wind as suggested by HOOD and JIRIKOWIC.

4.3 Models simulation

As mentioned earlier, the two dimensional radiative photochemical models (GARCIA *et al.*, 1984) have only predicted a modest change of the temperature in relationship with the 11-year solar cycle. A maximum positive effect of about 1 K at 50 km is in obvious disagreement with the observations which indicate a minimum of variability around 50 km and a response of opposite sign and of much larger amplitude in the stratosphere and mesosphere, at least for our mid latitude site. However, such results are also confirmed at other sites of both high and low latitudes (MOHANAKUMAR, 1989).

The one dimensional models have also been used to reproduce the 27-day response (BRASSEUR *et al.*, 1987; HOOD and JIRIKOWIC, 1991) and the observations are not in a satisfactory agreement either, supporting the view that the stratospheric response to short term solar UV variations is partly induced by a dynamical forcing which cannot be represented in a one dimensional radiative photochemical model.

EBEL *et al.* (1988) have applied a global three dimensional mechanistic model to show that dynamical effects can be generated in the stratosphere by imposing weak perturbations at stratopause heights to simulate the solar forcing. The fact that the forcing is rather small (1.5 K) and localized at the equator may explain why the signal is very weak at mid latitude; on the other hand the general features including the role of QBO are quite well reproduced and such a work supports the idea that perturbations can propagate even to the low atmosphere.

5. Conclusion

Observational evidence exists on the influence of the solar UV flux variation on the whole middle atmosphere both for the 11-year and 27-day solar cycles. Even though it is clear that observations are still insufficient, they indicate that radiative photochemical models cannot reproduce the amplitude and phase of the observations. Furthermore a first evidence that the mean wind may be influenced by the solar flux and that the sign of the QBO, i.e. the tropical wind in the low stratosphere, leaves a signature on both ozone and temperature, are pleading in favor of the role of dynamic in solar forcing. The simultaneous observations of ozone, temperature and winds and their variations in relationship with both the 11-year and 27-day cycles and as a function of both altitude and latitude are absolutely needed to better describe the response of the atmosphere to solar changes and help identifying the involved mechanisms. It would then likely require a radiative, photochemical and dynamical fully-coupled three dimensional model to simulate the radiative and dynamical atmospheric behaviour.

This work was supported by the CNRS programme PAMOY under grant n° 90 A 35010.

REFERENCES

BRASSEUR, G., A. De RUDDER, G. M. KEATING, and M. C. PITTS, Response of the middle atmosphere to short-term solar ultraviolet variation: 2. Theory, *J. Geophys. Res.*, **92**, 903–914, 1987.

CALLIS, L. B., J. C. ALPERT, and M. A. GELLER, An assessment of thermal, wind and planetary wave changes in the middle and lower atmosphere due to 11-year UV flux variations, *J. Geophys. Res.*, **90**, 2273–2282, 1983.

CHANDRA, S., Solar-induced oscillations in the stratosphere: a myth or reality?, *J. Geophys. Res.*, **90**, 2331–2339, 1985.

CHANIN, M. L. and A. HAUCHECORNE, Lidar studies of temperature and density using scattering, *Map Handbook*, **13**, 87–89, 1984.

CHANIN, M. L., N. SMIRES, and A. HAUCHECORNE, Long-term variation of the temperature of the middle atmosphere at mid latitudes: dynamical and radiative causes, *J. Geophys. Res.*, **92**, 933–941, 1987.

CHANIN, M. L., A review of the 11-year solar cycle, the QBO, and the atmosphere relationship, *MAP Handbook*, **29**, 27–32, 1989a.

CHANIN, M. L., Variability of the atmospheric structure with solar flux, *Proceedings of the 28th Liége Intern. Astr. Coll.*, 275–285, 1989b.

CHANIN, M. L., P. KECKHUT, A. HAUCHECORNE, and K. LABITZKE, The solar activity, QBO effect in the lower thermosphere, *Ann. Geophys.*, **7**, 463–470, 1989.

EBEL, A., M. DAMERIS, and H. J. JAKOBS, Modelling of the dynamical response of the middle atmosphere to weak external forcing: influence of stationary and transient waves, *Ann. Geophys.*, **6**, 501–512, 1988.

GARCIA, R., S. SOLOMON, R. G. ROBLE, and D. W. RUSH, Numerical response of the middle atmosphere to the 11-year solar cycle, *Planet. Space Sci.*, **32**, 411–423, 1984.

GELLER, M. A. and J. C. ALPERT, Planetary wave coupling between the troposphere and the middle atmosphere as a possible sun-weather mechanism, *J. Atmos. Sci.*, **37**, 1197–1215, 1980.

GILLE, J. C., C. M. SMYTHE, and D. F. HEATH, Observed ozone response to variations in solar ultraviolet radiation, *Science*, **225**, 315–317, 1984.

GROSSMANN, A. and R. KRONLAND-MARTINET, Time and scale representations obtained through continuous wavelet transforms, in *Signal Processing*, 475–482, edited by Elsevier Science Publishers, 1988.

HAUCHECORNE, A., M.-L. CHANIN, and P. KECKHUT, Climatology and trends of the middle atmospheric temperature (33–87 km) as seen by Rayleigh lidar over the south of France, *J. Geophys. Res.*, **96**, 15297–15309, 1991.

HINES, C. O., A possible mechanism for the production of sun-weather correlation, *J. Atmos. Sci.*, **31**, 589–591, 1974.

HOOD, L. L., Coupled stratospheric ozone and temperature responses to short-term changes in solar ultraviolet flux: an analysis of Nimbus 7 SBUV and SAMS data, *J. Geophys. Res.*, **91**, 5264–5276, 1986.

HOOD, L. L. and S. CANTRELL, Stratospheric ozone and temperature responses to short-term solar ultraviolet variation: reproducibility of low-latitude response measurements, *Ann. Geophys.*, **6**, 525–530, 1988.

HOOD, L. L. and J. J. JIRIKOWIC, Stratospheric dynamical effects of solar ultraviolet variations: Evidence from zonal mean ozone and temperature data, *J. Geophys. Res.*, **96**, 7565–7577, 1991.

JENKINS, G. M. and D. G. WATTS, In *Spectral analysis and its applications*, edited by Holden day, 1968.

KEATING, G. M., G. P. BRASSEUR, J. Y. NICHOLSON, III, and A. De RUDDER, Detection of the response of ozone in the middle atmosphere to short-term solar ultraviolet variation, *Geophys. Res. Lett.*, **12**, 449–452, 1985.

KEATING, G. M., J. Y. NICHOLSON, III, D. F. YOUNG, G. BRASSEUR, and A. De RUDDER, Response of middle atmosphere to short-term solar ultraviolet variations: 1. Observation, *J. Geophys. Res.*, **92**, 889–902, 1987.

KECKHUT, P. and M. L. CHANIN, Middle atmosphere response to the solar rotation as observed by lidar, on press in *Geophys. Res. Letters*, 1991.

KODERA, K. and K. YAMAZAKI, Long-term variation or upper stratospheric circulation in the Northem hemisphere in December, *J. of the Met. Soc. of Japan*, **68**, 101–105, 1990.

LABITZKE, K. and M. L. CHANIN, Changes in the middle atmosphere in winter related to the 11-year solar cycle, *Ann. Geophys.*, **6**, 643–644, 1988.

LABITZKE, K. and H. VAN LOON, Association between 11-year solar cycle, the QBO, and the atmosphere. Part I: the troposphere and stratosphere on the northern hemisphere in winter, *J. Atm. Terr. Phys.*, **50**, 197–206, 1988.

MCCORMICK, M. P., J. M. ZAWODNY, R. E. VEIGA, J. C. LARSEN, and P. H. WANG, An overview of SAGE I and II ozone measurements, *Planet Space Sci.*, **37**, 1567–1586, 1989.

MOHANAKUMAR, K., Influence of solar activity on middle atmosphere associated with phases of equatorial QBO, *MAP Handbook*, **29**, 39–42, 1989.

MOUNT, G. and G. ROTTMAN, Solar absolute spectral irradiance 118–300 nm, *J. Geophys. Res.*, **90**, 13031–13036, 1985.

NEUMANN, A., QBO and solar activity effects on temperatures in the mesopause region, *J. Atm. Terr. Phys.*, **52**, 165–173, 1990.

ROTTMAN, G. J., 27-day variations observed in solar U.V. (120–300 nm) irradiance, *Planet. Space Sci.*, **31**, 1001–1007, 1983.

SIMON, P. C., Variabilities in solar UV irradiances during cycle 21, *Proceedings of the 28th Liege Intern, Ast. Coll.*, 245–253, 1989.

VAN LOON, H. and K. LABITZKE, Associating between the 11-year solar cycle and the atmosphere. Part IV: The stratosphere not grouped by the phase of the QBO, *J. of Climate*, **3**, 827–837, 1990.