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STRATOSPHERIC WARMINGS - THE QUASI-BIENNIAL OSCILLATION Ozone Hole in the Antarctic but not the Arctic - Correlations between the Solar Cycle, Polar Temperatures, and an Equatorial Oscillation

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d)	QBO	d)	QBO
e)	Solar cycle	e)	Solsyklus

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8)	ABSTRACT

This report is a tutorial and overview over some of the complex dynamic phenomena in the polar and equatorial stratosphere, and the unexpected correlation that exists between these and the solar cycle. Sudden stratospheric warmings (stratwarms) occur in the polar stratosphere in winter, but not equally distributed between the two hemispheres. As a result, the ozone hole in the springtime polar stratosphere is much more severe in the Southern Hemisphere than in the Northern Hemisphere. The Quasi-Biennial Oscillation (QBO) is a dynamic phenomenon of the equatorial stratosphere. Through processes not fully understood, the phase of the QBO (easterly or westerly) influences the onset of stratwarms. In addition, a correlation between the stratospheric winter temperature over the poles and the solar cycle has been found, but only if the datapoints are ordered by the phase of the QBO. - The best explanations and figures from four recent textbooks are selected, and abstracts of most relevant publications from the six last years are collected, with the most relevant portions for these subjects highlighted. - In addition to being basic science, the understanding of these phenomena is important in the context of the ozone hole, the greenhouse effect, as well as anthropogenic and natural climate change.

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STRATOSPHERIC WARMINGS - THE QUASI-BIENNIAL OSCILLATION Ozone Hole in the Antarctic but not the Arctic - Correlations between the Solar Cycle, Polar Temperatures, and an Equatorial Oscillation

1 INTRODUCTION

At first sight, Sudden Stratospheric Warmings and the Quasi-Biennial Oscillation have only one thing in common: They are features of stratospheric dynamics, one in the polar stratosphere and one in the equatorial stratosphere. Through the ozone depletion and through an unexpected correlation between stratospheric parameters and the solar cycle, they are more connected than we understand at the surface. A better understanding of this correlation may make it easier to forecast the climate in relation to anthropogenic greenhouse gases and solar-terrestrial physics. It is well known that the dynamics of major midwinter stratospheric warmings, which occur only in the Northern Hemisphere, are an important reason for the ozone hole being less serious in the Arctic than in the Antarctic. It is also understood, but less widely known, that an increased greenhouse effect will lead to a colder stratosphere also in the Arctic, more PSC, and a more stable polar vortex, all of which can lead to a more serious ozone hole in the Arctic. Furthermore, ozone is also a greenhouse gas, contributing to warming at the surface.

Many scientists have studied these phenomena over the years, and more and more continue to do so. This report started as lecture notes for the course "The Polar Middle Atmosphere" held at the University Courses on Svalbard (UNIS) in Autumn 1998, 1999, and 2000, respectively. It is based heavily on the textbooks by Holton (1992), Andrews et al. (1987), Dieminger et al. (1996), and Labitzke and van Loon (1999). In addition, all relevant articles in scientific journals published in the six years from August 1994 to November 2000 (found in the ISI database) were included as abstracts. These abstracts are ordered with the newest abstracts first, and statements of special importance for this subject are printed in boldface. In its present form, this report may serve as an overview over the status of knowledge for colleagues in Norway and in other countries. Hopefully, it can also be a shortcut into this fascinating, intellectually rewarding, and important field for young scientists.
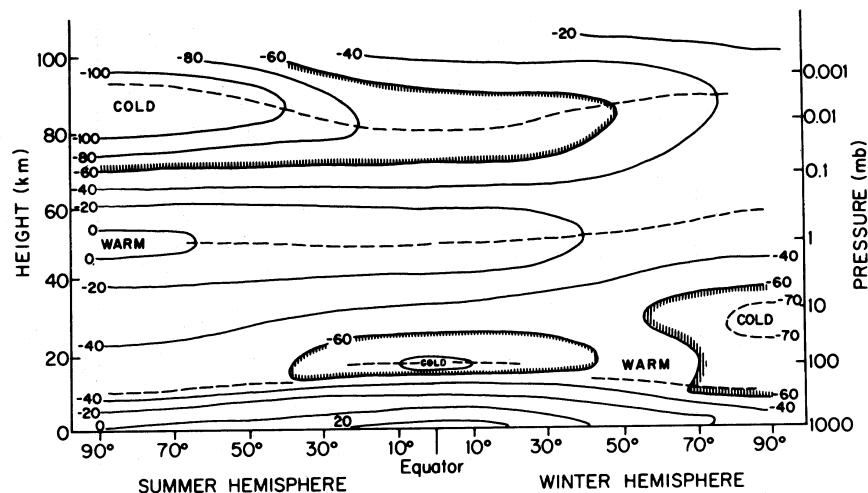

Figure 2.1   Schematic latitude-height section of zonal mean temperatures (°C) for solstice conditions Dashed lines indicate tropopause, stratopause, and mesopause levels (Andrews et al., 1987).
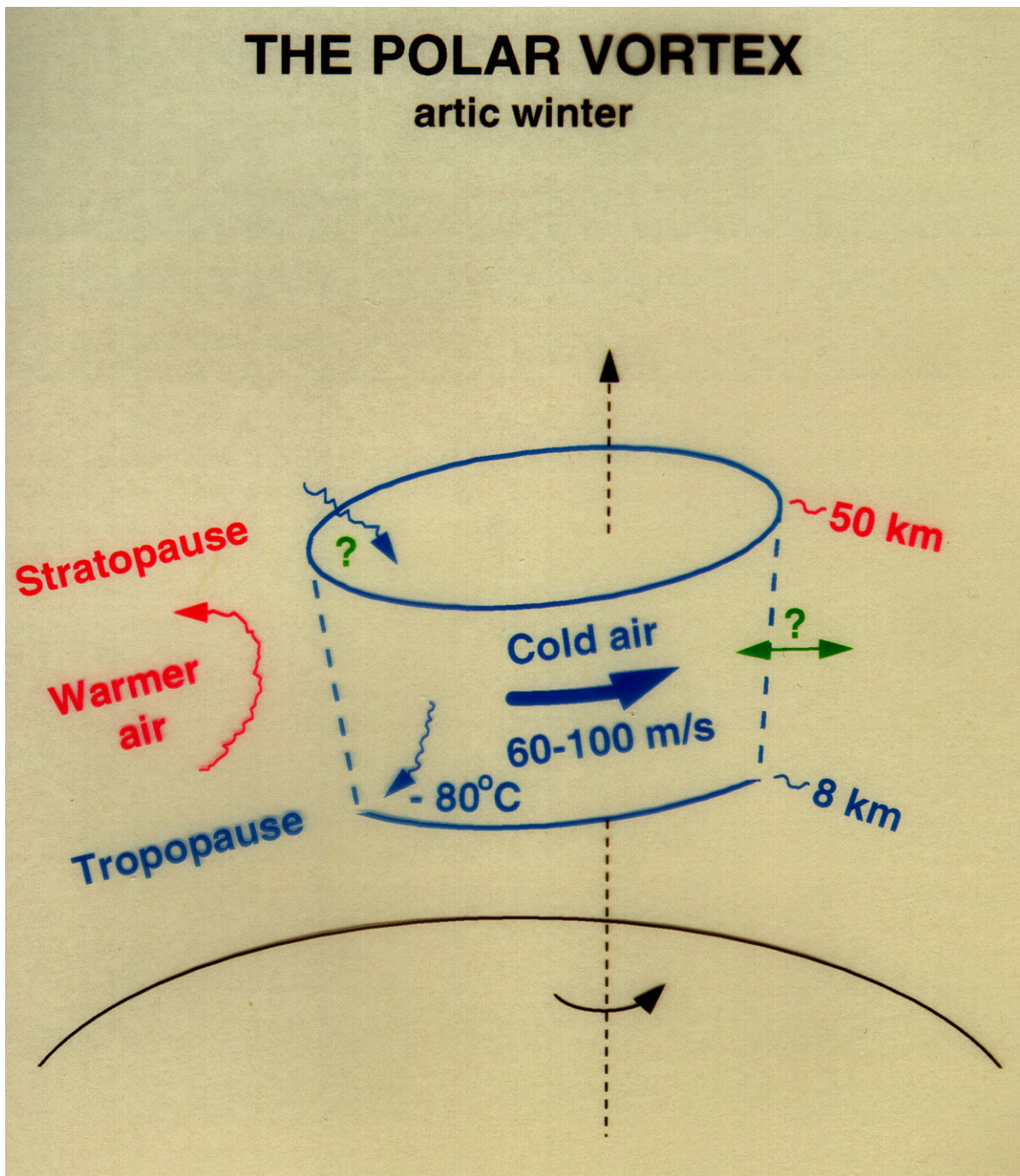
Figure 2.2   Schematic of the Arctic stratospheric polar vortex

2   STRATOSPHERIC WARMINGS

More details can be found in the textbooks by Holton (1992) in chapter 12.4, Dieminger et al. (1996), chapter IV.2, Andrews et al. (1987), chapter 6.

2.1   Phenomenology

Figure 2.1 shows a meridional cross section of the atmospheric temperature at winter solstice in the Northern Hemisphere. The zonal-mean temperature is shown. The cold air poleward of 70^0N and between 10 km and 40 km altitude is the polar vortex. Its origin is the lack of solar radiation in the polar night. Figure 2.2 shows a schematic of the polar vortex: A cold air mass between the
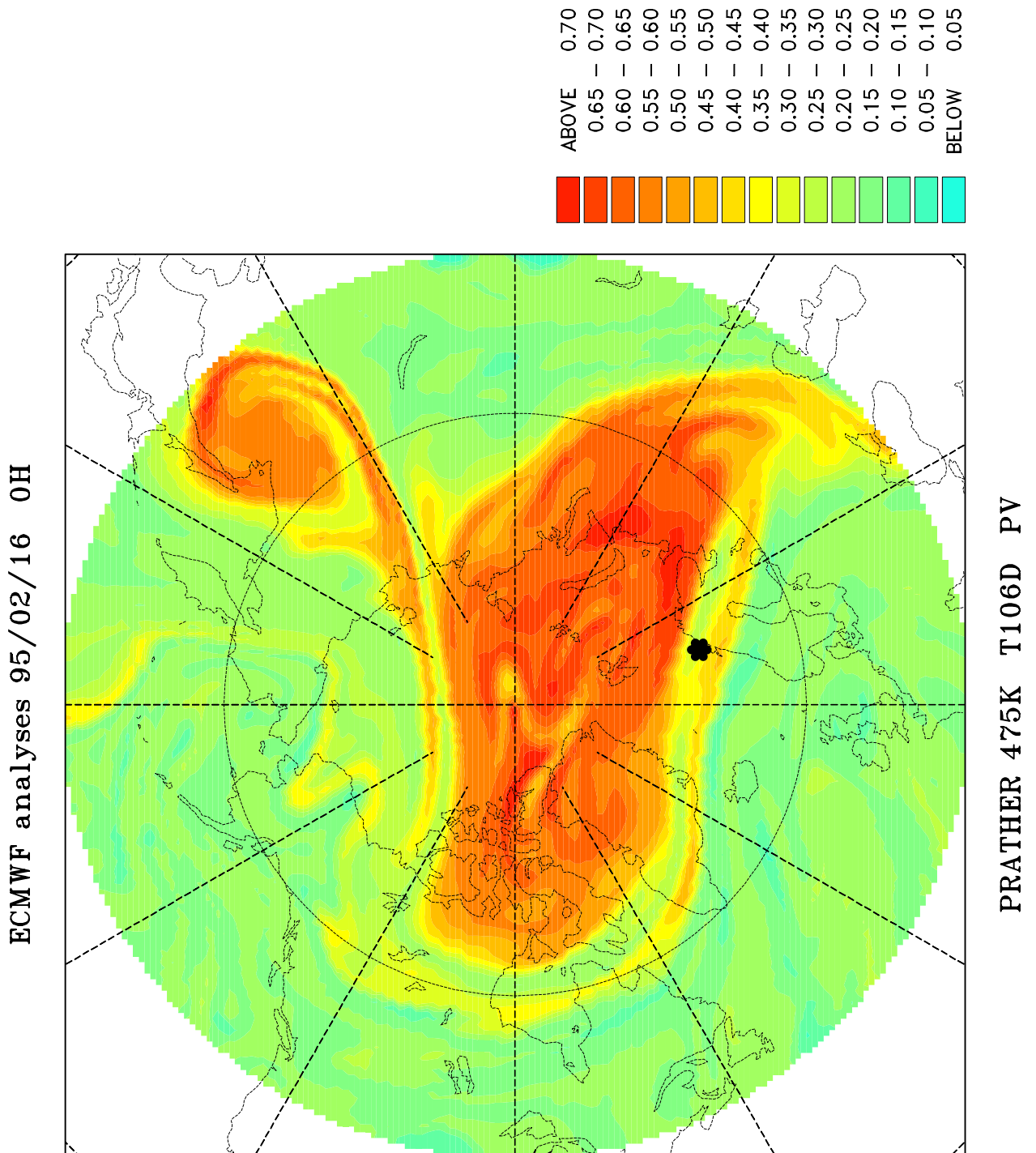
Figure 2.3   Potential vorticity at approximately 20 km altitude (475 K potential temperature) on 16 Feb 1995 in PV-units. The orange and red shades are the actual polar vortex. The symbol shows the position of ALOMAR. (Orsolini et al., 1997).

tropopause and the stratopause. Cold air is heavier than its surroundings and sinks down. The sinking air is replaced with air from lower latitudes at high altitude (through the law of continuity). The Coriolis force of the rotating Earth forces the air mass instead to rotate counterclockwise (in the Northern Hemisphere) with 60-100 m/s, completing a full rotation in 5 to 7 days. The ALOMAR ozone lidar for instance is located approximately beneath the edge of the polar vortex, and can very often sample the same air again after 5 to 7 days. The polar vortex is not as simple and symmetric as shown in Figure 2.2. Figure 2.3 shows an example of an elongated polar vortex with a smaller vortex shedding off over eastern Siberia. This figure is showing potential vorticity at the altitude level defined by a potential temperature of 475 K. The vortex has different shapes at different altitudes, i.e., it has a complex three-dimensional shape. Figure 2.4 shows a schematic of the average meridional circulation in the atmosphere. The upper part, in the stratosphere and mesosphere is known as the Brewer-Dobson Circulation.
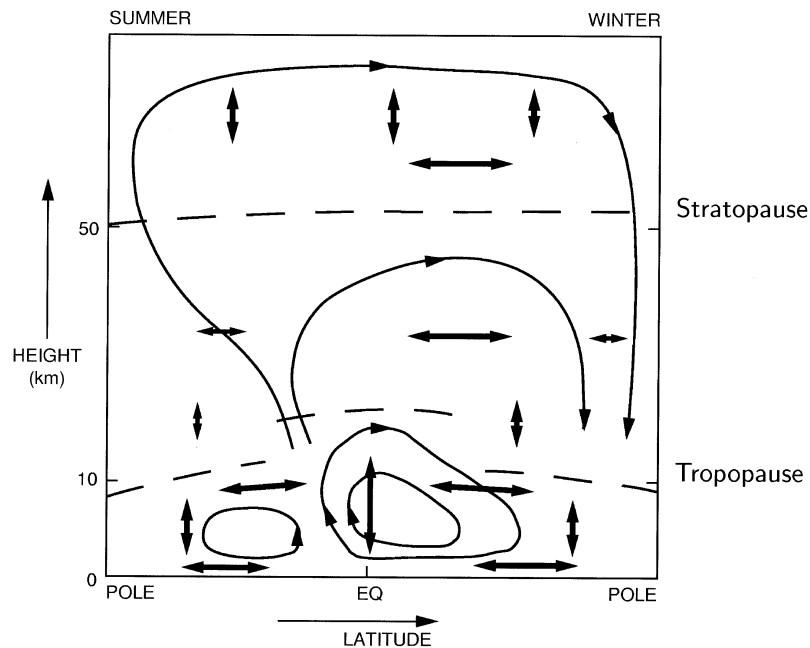

Figure 2.4   Schematic picture of the meridional circulation in the atmosphere (WMO 1985)

It is easy to see that stratospheric warmings have important consequences for the ozone hole problem. Stratospheric warmings have been known since the publication by Scherhag (1952). Figure 2.5 shows the zonally averaged temperature at 10 hPa (approximately 30 km) at 80^0N from October 1978 to May 1979. From late January to early March three stratospheric warming events are observed. Figure 2.6 shows a series of temperature profiles measured by rocket during the previous winter, 1976/77. Notice that the stratospheric temperature increases dramatically from 13 December to 28 December and 3 January, while the mesospheric temperature decreases almost just as dramatically during the same time. Stratospheric warmings and mesospheric cooling belong together, as Figure 2.7 illustrates. Figure 2.8 shows a recent example of a stratospheric warming in winter 2000/2001, measured over ALOMAR. Figure 2.9 shows the temperature at 10 hPa over the North Pole for 11 winters. The minimum of all curves shows a cooling from the beginning of November to the end of December, followed by a constant cold temperature (-80^0C) until mid-February and a strong warming trend towards the summer state. On top of this baseline there are episodic, random excursions by 30 to 70 K. The energy required for such warmings is of the order $2 \cdot 10^{21}$ J. This would require 35 hours of continuous insolation with the sun in the zenith and with a total absorption of the solar radiation in the stratosphere. As this clearly is not the case, there must be another source of energy driving the phenomenon.

2.2 Definition

A stratospheric warming ("stratwarm") is defined by a reversal of the meridional temperature gradient at 10 hPa or below poleward from 60^0 latitude (from negative to positive), see Figure 2.10, lower panel. If the warming impulse is strong enough, also the circulation – the zonal-mean zonal wind – reverses from eastward to westward as shown in the top panel of Figure 2.10. This reversal of the zonal circulation in addition to the reversal of the temperature gradient is the definition of a major stratospheric warming. When the temperature gradient reverses, but not the circulation, it is a minor warming. Contrary to one of the recent publications below (Didonfrancesco et al., 1996) the textbooks say that major stratwarms only occur in the Northern Hemisphere, never in the southern. Didonfrancesco et al. (1996) do not consider the zonal mean zonal wind, but instead only the degree of warming and the altitude range of the warming to diagnose a "major" warming. This does not agree with the generally accepted definition.
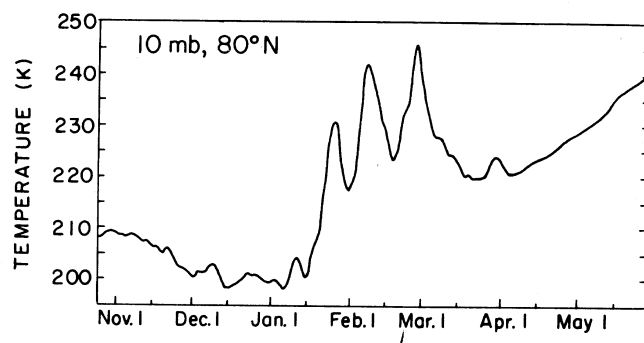
Figure 2.5   Variation of zonal-mean temperature at 10 hPa, 80°N, from October 1978 through May 1979, derived from LIMS data (Andrews et al., 1987).
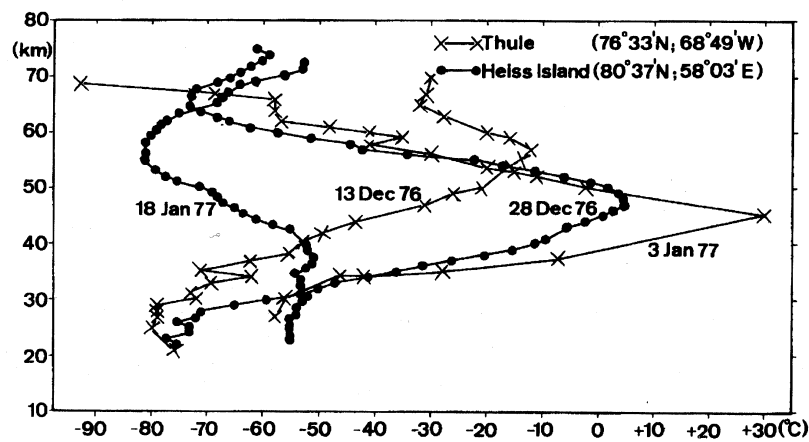
Figure 2.6   Rocketsonde measurements during the winter 1976/77 (Labitzke and Barnett, 1985).
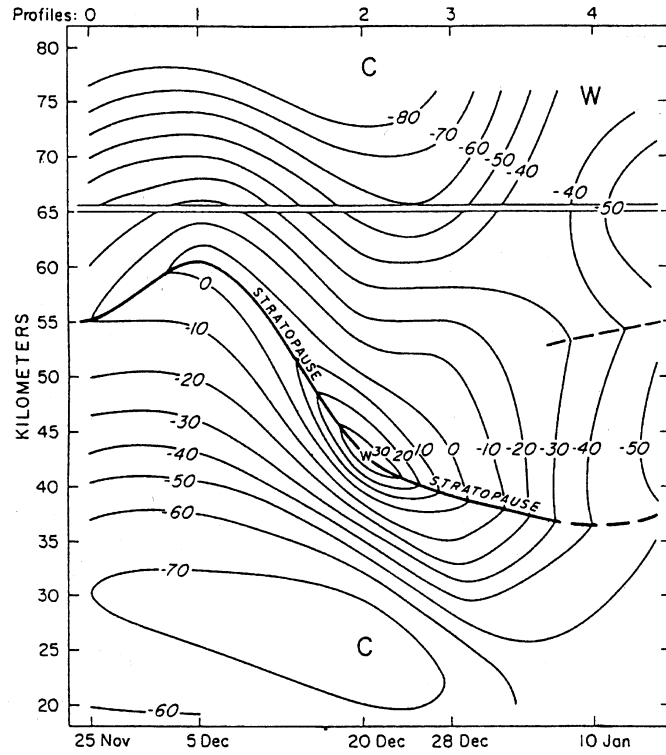
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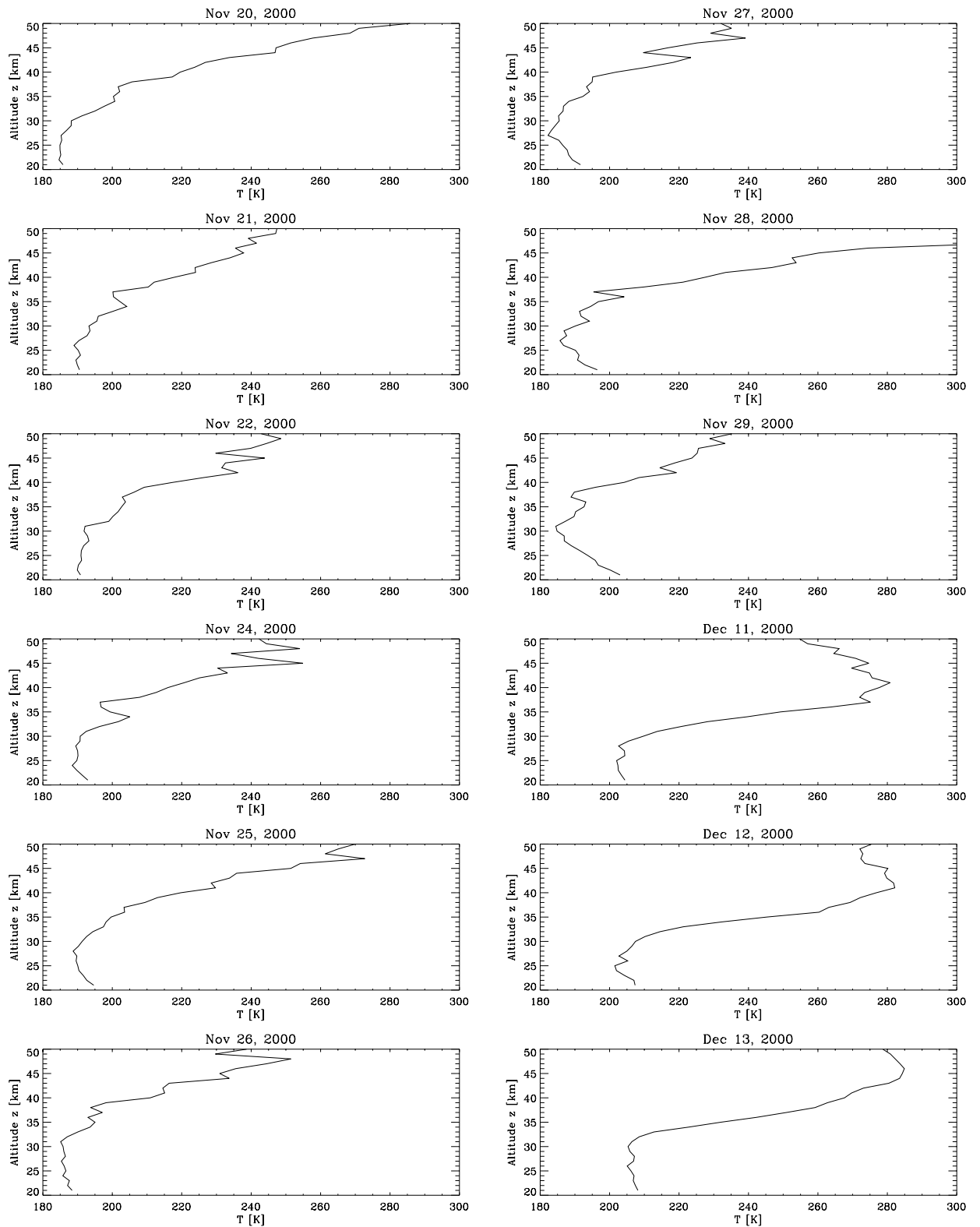
Figure 2.8   Preliminary temperature profiles from the ALOMAR Ozone Lidar (69.28°N, 16.01°E). The temperature integration was initialised at 60 km with the temperature value from the ALOMAR RMR lidar. Note the stratwarm in the last three profiles. The temperature increase at 40 km is more than 60 K.
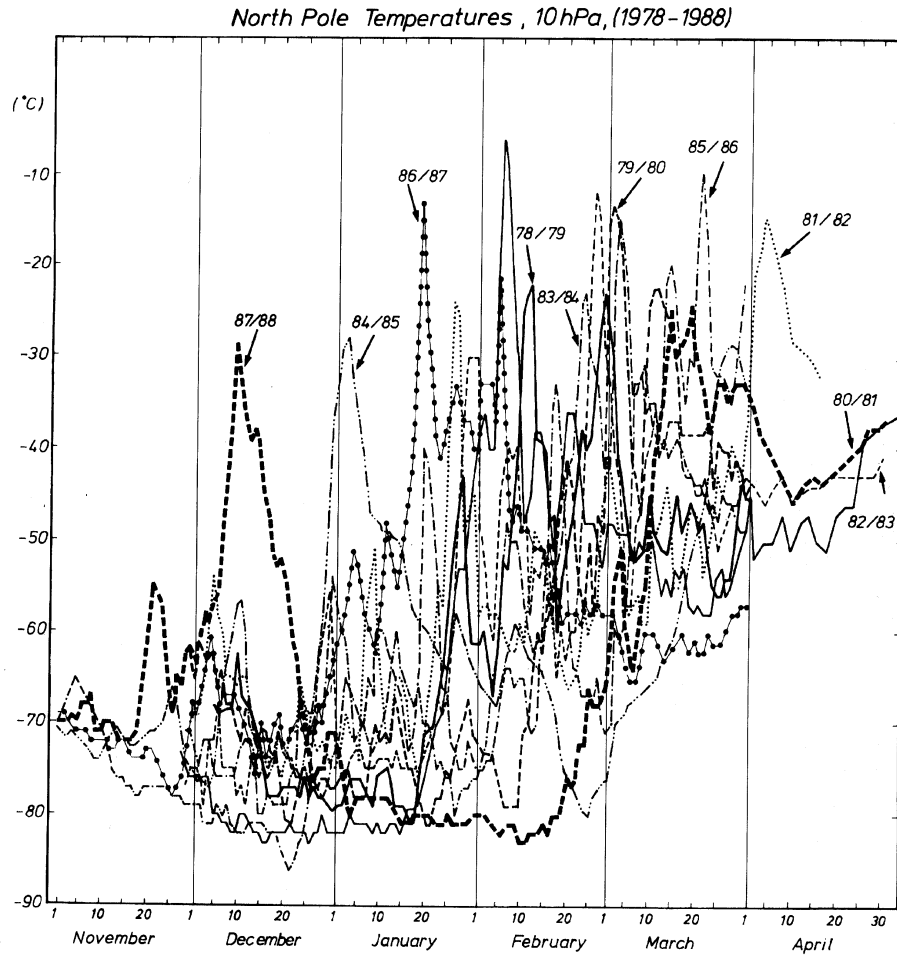
Figure 2.9   *Curves of 10-mb temperatures (°C) at the North Pole in 11 winters. From the daily analyses of the Stratospheric Research Group, Freie Universität Berlin (Labitzke and van Loon, 1996).*

2.3   Mechanism

Stratwarms have to some extent been successfully modelled by assuming the following (Figure 2.11): A transient planetary wave propagates upward from the troposphere. In Figure 2.11 its upper edge has reached the altitude z_0. The dashed line shows the Eliassen-Palm flux $\vec{F}$ of this planetary wave:

$$\vec{F} = -\rho_0 \cdot \overline{u' \cdot v'} \cdot \vec{j} + \frac{f \cdot R}{N^2 \cdot H} \cdot \rho_0 \cdot \overline{v' \cdot T'} \cdot \vec{k} \tag{2.1}$$

with ρ_0 the reference density, u', v' the horizontal perturbation velocities (eastward and northward), $f = 2\Omega \sin \phi$ the Coriolis parameter (also called the inertial frequency), R the gas constant for dry air,

$$N^2 = \frac{R}{H}\left(\frac{\kappa T_0}{H} + \frac{dT_0}{dz} \right) \tag{2.2}$$

the square of the Brunt-Väisälää frequency (also known as the buoyancy frequency), H the scale height, T' the temperature perturbation, T_0 the reference temperature, $\kappa = R/c_P$, c_p the heat capacity at constant pressure, $\vec{j}, \vec{k}$ unit vectors toward east and north, respectively, Ω the Earth's angular velocity and ϕ latitude. The full line in Figure 2.11a showing the wide layer is the Eliassen-Palm flux divergence $\vec{\nabla} \cdot \vec{F}$, which gives the zonal forcing and leads to the

acceleration of the mean zonal flow shown by the other full line in Figure 2.11a. The hatched region in Figure 2.11b shows the region where the Eliassen-Palm flux is convergent, leading to the zonal acceleration shown by the contour lines. As potential vorticity is conserved, this zonal acceleration gives rise to the poleward residual motion shown by the arrow within the hatched area, and mass continuity leads to the residual circulation shown by the arrows. This accelerates the downward motion within the vortex (and decelerates the downward motion in the mesosphere above the polar vortex), leading to a warming in the stratosphere and a cooling in the mesosphere. An adiabatic downward motion by 3 to 7 km suffices to explain the observed warmings by 30 to 70 K. Using ozone as a tracer, such downward motions have indeed been observed during stratwarms, for instance with the ALOMAR Ozone Lidar. When the dynamic forces are strong enough to split the polar vortex and push the Aleutian High between the two sub-vortices, a zonally-averaged reversal of the zonal wind poleward of 60^0 is achieved (Figure 2.12).
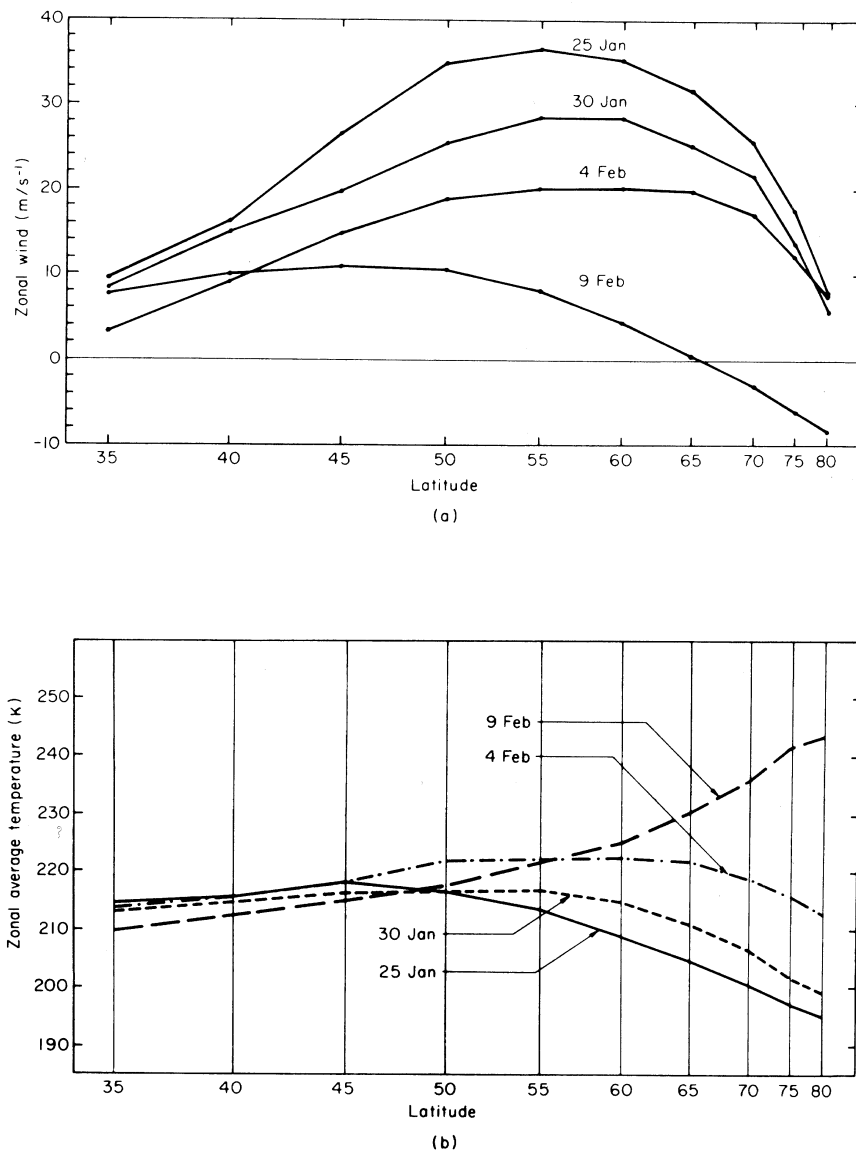
Figure 2.10   Variation with latitude and time at the 50-mb level of (a) the zonal wind and (b) the zonal mean temperature during the sudden warming of 1957 (Holton, 1992).
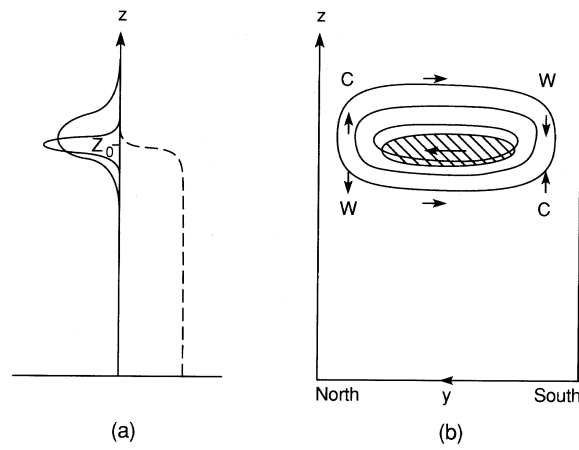
Figure 2.11 *Schematic of transient wave, mean-flow interactions occurring during a stratospheric warming. (a) Height profiles of EP flux (dashed), EP flux divergence (broad full line), and mean zonal flow acceleration (narrow full line); z_0 is the height reached by the leading edge of the wave packet at the time pictured. (b) Latitude-height cross section showing region where the EP flux is convergent (hatched), contours of induced zonal acceleration (thin lines), and induced residual circulation (arrows). Regions of warming (W) and cooling (C) are also shown (Holton, 1992).*
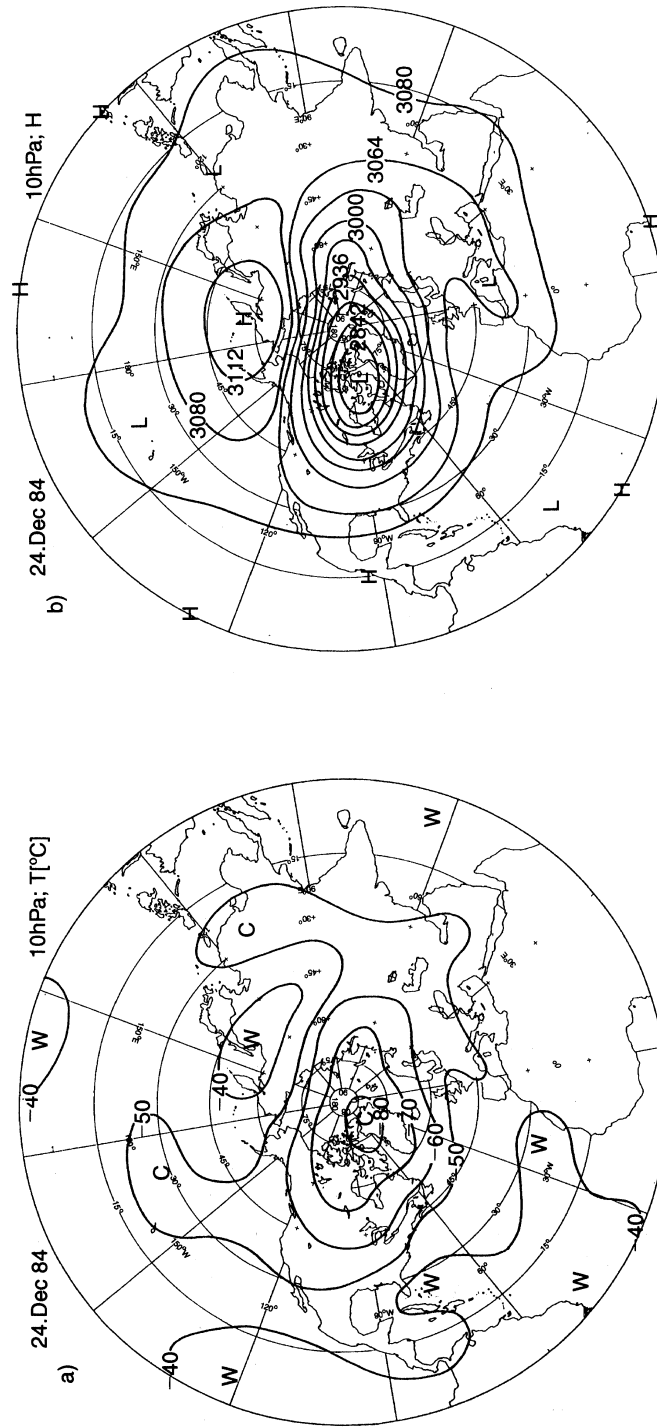
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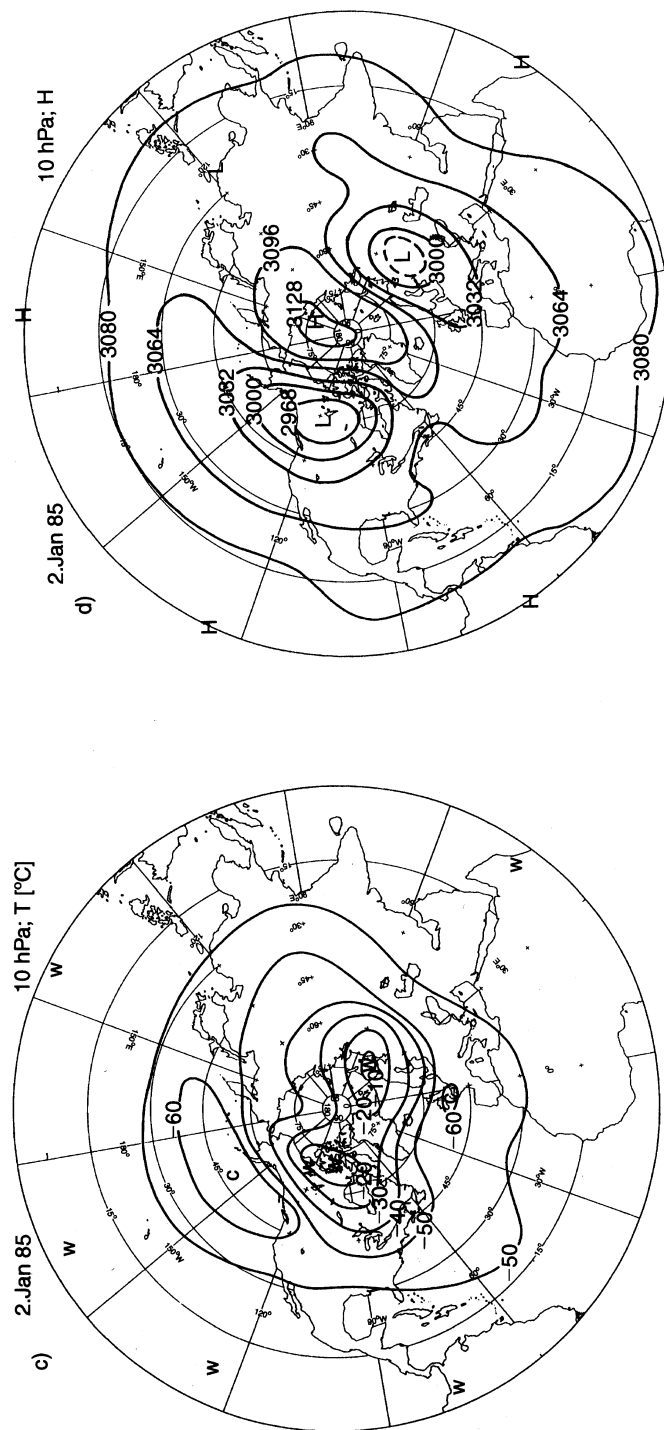
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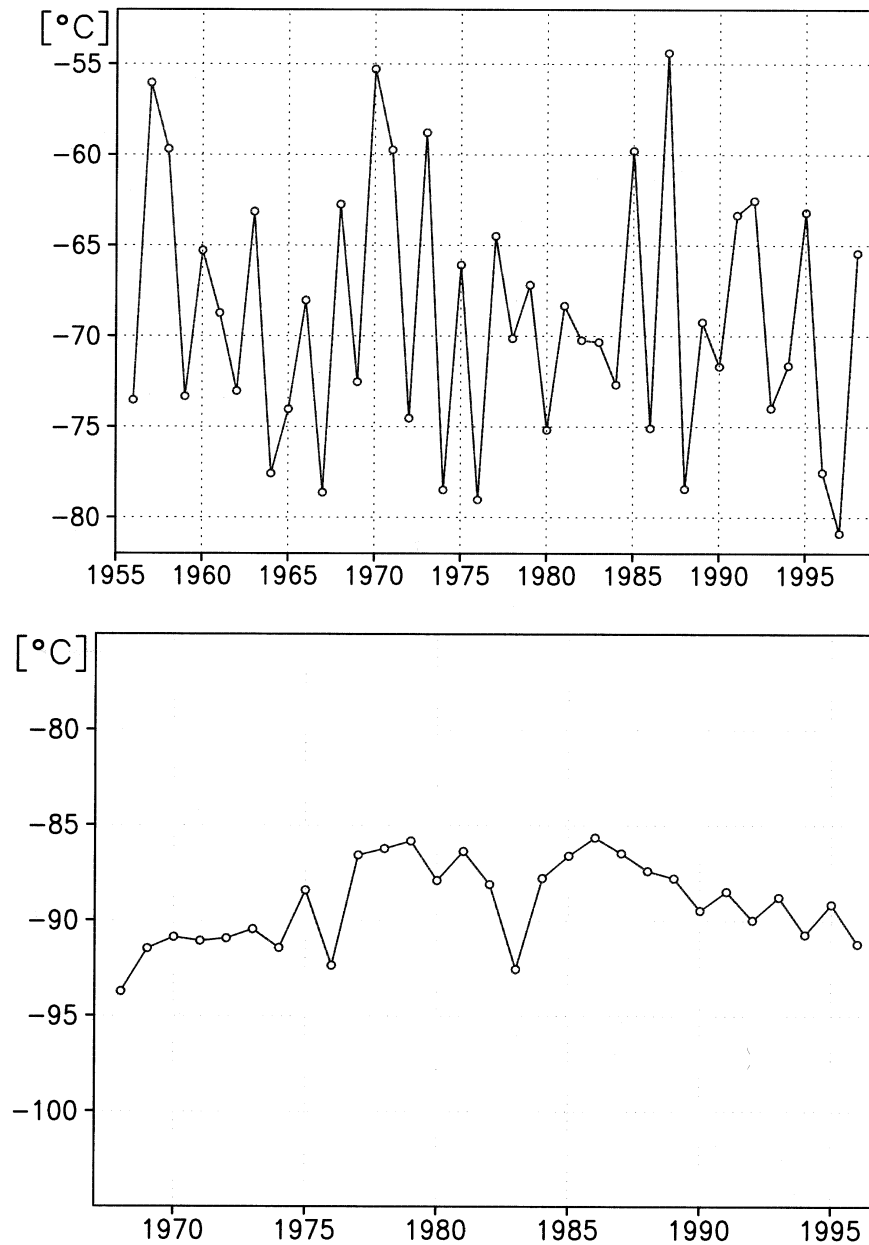
Figure 2.13 (Top) Time series of the 30-hPa temperature (°C) at the North Pole in January-February, 1956-1998. (Bottom) The same at the South Pole in July-August, 1968-1996 (Labitzke and van Loon, 1999).

2.4   Asymmetry between the Northern and Southern Hemispheres

Figure 2.13 compares the winter temperatures at 30 hPa over the poles, January-February for the North Pole and July-August for the South Pole. Note the 2.5 times larger variability from year to year over the North Pole, and an average about 20 K warmer. Due to there being more ocean on the Southern Hemisphere (and less land and mountain), there is weaker planetary wave activity over the Antarctic. As a result, the southern Polar Vortex is much stronger and there are no major stratospheric warmings (only minor stratwarms). This leads to a severe ozone hole over the Antarctic each spring, while there is only a small reduction of ozone density of the Northern Hemisphere in spring.

2.5 Recent Relevant Publications

Authors   TJ Duck, JA Whiteway, AI Carswell
Title   **A detailed record of High Arctic middle atmospheric temperatures**
Full source   Journal of Geophysical Research - Atmospheres, 2000, Vol 105, Iss D18, pp 22909-22918

Address   Duck TJ, MIT, Haystack Observ, Westford,MA 01886 USA

Abstract   Four hundred and twenty-two nights of middle atmospheric temperature observations were obtained in the High Arctic at Eureka (80 degrees N, 86 degrees W) during six wintertime measurement campaigns from 1992-1993 to 1997-1998 by using a lidar and meteorological balloons. **The measurements reveal that temperature changes of greater than 30 K occur in the stratosphere within the space of a few weeks. In a comparison with maps of wind in the Northern Hemisphere, it is clear that much of the thermal variability is associated with movements of the wintertime stratospheric vortex over the measurement site. Measurements in the vortex core show a persistently cold lower stratosphere and warm upper stratosphere. Conversely, outside of the vortex altogether the lower stratosphere is relatively warm and the upper stratosphere is cold. By separately examining measurements obtained inside the vortex core, a 25+/-2 K annual warming of the upper stratosphere in late December is apparent. This annual vortex core warming is distinctly different from planetary-wave-driven sudden stratospheric warming and the seasonal march of temperatures due to changing insolation.**
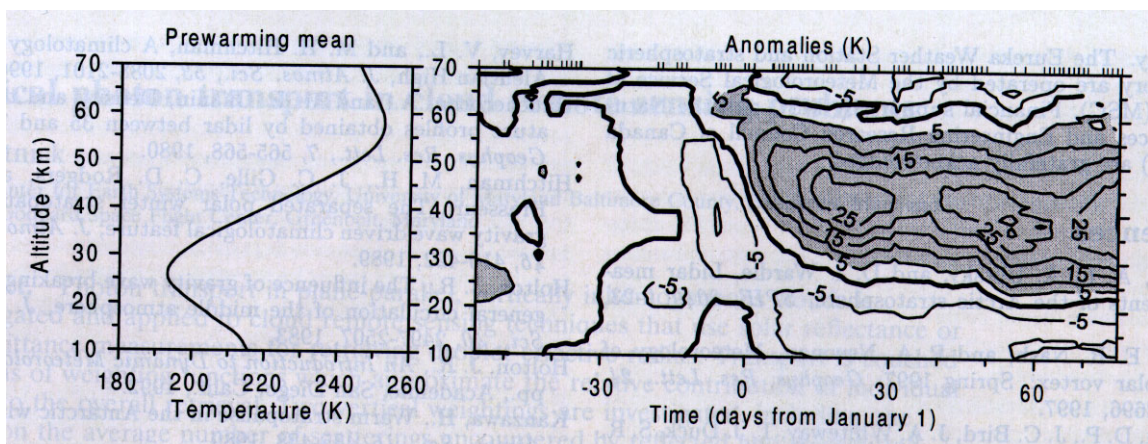
Figure 2.14   A composite presentation of all the vortex core temperature profiles obtained by lidar and radiosondes during wintertime at Eureka from 1992-1993 to 1997-1998. The profile gives the mean vortex core temperatures for measurements taken prior to December 27, and the contours show the average deviation of vortex core temperatures from that profile as a function of time. The zero Kelvin anomaly is denoted by a bold line, and temperatures over 5 K warmer than the profile are shaded. Note that, on average, a strong stratospheric warming (with a mesospheric cooling) commenced in late December (Duck et al., 2000).

Authors   P Braesicke, U Langematz
Title   On the occurrence and evolution of extremely high temperatures at the polar winter stratopause - a GCM study
Full source   Geophysical Research Letters, 2000, Vol 27, Iss 10, pp 1467-1470
Address   Braesicke P, Univ Cambridge, Dept Chem, CAS, Lensfield Rd, Cambridge CB2 1EW, ENGLAND
Abstract   Sudden warmings in the stratopause region are a well known phenomenon in middle atmosphere dynamics. **In this study, these stratopause warmings are analyzed using**

a ten-year integration of the Berlin Climate Middle Atmosphere Model. The good spatial and temporal resolution of the model allows to investigate the main properties on a statistical basis. **It turns out that strong stratopause warmings occur in almost each northern hemisphere winter.** The associated temperature maxima and the descent of the stratopause agree very well with observed events. **Two selected warmings are compared in terms of EP flux diagnostics and planetary wave amplitudes** to study the links between stratopause events and (major) warmings in the lower/middle stratosphere. **Only with supply of upward propagating wave energy from the troposphere and lowest stratosphere, stratopause warmings develop to lower stratospheric warmings.**

Authors   ST Zhou, ME Gelman, AJ Miller, JP McCormack
Title   **An inter-hemisphere comparison of the persistent stratospheric polar vortex**
Full source   Geophysical Research Letters, 2000, Vol 27, Iss 8, pp 1123-1126
Address   Zhou ST, W-NP53, 808, 5200 Auth Rd, Washington,DC 20233 USA
Abstract   Based on 19 years(1979-1998) of NCEP/NCAR reanalyses data and potential vorticity (PV) area diagnostics, we found that in the southern hemisphere (SH) the polar vortex has lasted about two weeks longer in the 1990s than in the early 1980s and the northern hemisphere (NH) polar vortex has lasted four weeks longer. The SH vortex persisted within the layer(12-22 km) with almost complete ozone loss, but did not persist at higher altitudes where ozone was not depleted. However, the NH vortex persisted in a broader vertical range not limited to the ozone-depletion layer. We show that wave activity has weakened in recent years in the NH, but not in the SH. The springtime Antarctic ozone hole seems to be the main cause for the SH polar vortex persistence, while the cause for the NH vortex persistence involves changes in polar ozone as well as changes in dynamics.

Authors   XH Wang, J Fyfe
Title   Onset of edge wave breaking in an **idealized model of the polar stratospheric vortex**

Full source   Journal of the Atmospheric Sciences, 2000, Vol 57, Iss 7, pp 956-966

Address   Fyfe J, Univ Victoria, Canadian Ctr Climate Modelling & Anal, POB 1700, MS 3339, Victoria, BC V8W 2Y2, CANADA
Abstract   A mechanism for the breakdown of vertically propagating edge waves in a Boussinesq fluid is investigated within the context of the **destruction of the polar stratospheric vortex**. Under inviscid, quasi-linear, and slowly varying conditions in a three-dimensional, quasigeostrophic contour dynamics model it is analytically predicted that planetary-scale edge wave breaking will occur if the zonal mean flow is decelerated by more than approximately one-half its initial value via a positive group-velocity-mean-flow feedback mechanism. Fully nonlinear model simulations confirm this "one-half rule" and detail the sequence of events leading to the breaking.

Authors   GL Manney, WA Lahoz, R Swinbank, A Oneill, PM Connew, RW Zurek
Title   **Simulation of the December 1998 stratospheric major warming**
Source   Geophysical Research Letters 26: 17 (SEP 1 1999)
Page(s)   2733-2736
Address   GL Manney, CALTECH, Jet Prop Lab, MS 183-701, Pasadena, CA 91109 USA
 Abstract An atypically early major stratospheric sudden warming in mid-Dec 1998 resulted in an abnormally warm and weak polar vortex through most of the 1998-99 winter. The first major warming in nearly 8 years, it was only the second major warming observed before the end of Dec, and strongly resembled the previous Dec 1987 major warming in several characteristics atypical of major warmings later in winter. **3D mechanistic model simulations reproduced most characteristics of the Dec 1998 major warming, including the magnitudes of zonal mean easterlies and temperature increases** and the 3D evolution of the

flow, paving the way for more detailed future studies of the mechanisms involved in this unusual event.

Authors   S Yoden, T Yamaga, S Pawson, U Langematz
Title   A composite analysis of the **stratospheric sudden warmings simulated in a perpetual January** integration of the Berlin TSM **GCM**
Address   S Yoden, Kyoto Univ, Dept Geophys, Kyoto 6068502, JAPAN
Abstract A 7,200-day dataset from a **perpetual January integration of the Berlin Troposphere-Stratosphere-Mesosphere General Circulation Model** is analyzed to clarify the basic nature of the dynamical linkage between the stratosphere and the troposphere. Much attention is paid to the stratospheric sudden warming events; sixty-four events are detected in this dataset, with no clear periodicity.
The 64 sudden warming events are divided into two groups according to the relative strength of planetary waves of zonal wavenumber 1 and 2 in the stratosphere, although each event has its own dynamical characteristics. Composites for each group show some general features of the stratospheric sudden warmings, including the "preconditioned" zonal mean states in the lower stratosphere and the upward propagation of the enhancement of planetary-scale waves from the troposphere to the stratosphere. In the preconditioned states the zonal mean temperature is lower than normal in the polar region, and the zonal mean zonal wind is stronger in the middle and high latitudes.
Each group shows some different dynamical behavior, not only in the stratosphere but also in the troposphere before, during and after the sudden warming events. In the group in which the wavenumber 1 component dominates, the preconditioned states are more evident and confined to lower altitudes. Such states continue even after sudden warming events near the tropopause. In the other group of wavenumber 2 dominance, signals of sudden warming descend to the upper troposphere after the events.

Authors   S Pawson, B Naujokat
Title   **The cold winters of the middle 1990s in the northern lower stratosphere**
Address   S Pawson, NASA, Goddard Space Flight Ctr, USRA, Code 910-3, Greenbelt, MD 20771 USA
Abstract Lower stratospheric temperatures in the northern winters of 1994/1995, 1995/1996, and 1996/1997 were low enough to support polar stratospheric cloud (PSC) formation for prolonged periods. While the seasonal evolution of each winter was quite different, there are some common characteristics: notably, the occurrence of extremely cold periods of long duration and the coldness of the late winter in each year. Comparison with observations over more than three decades indicate the stratosphere was atypically cold in these three years, with the largest anomalies occurring in the late winter and spring. In January and February the coldness seems to be determined by the interannual variability of the circulation, while in March the persistence of the polar vortex dominated the circulation in these three years. This may be related to the lack of major midwinter warmings in those years. Comparison with other winters shows that although the persistence of the polar vortex well into the spring is not unprecedented, this did not occur frequently in the previous two decades. Further, there is a general temperature decrease in the northern lower stratosphere, which contributed to the coldness of the three winters. Comparison of the late winter and spring of 1997 with 1967, both of which were forced only weakly by dynamics, supports the idea that this is due to a change in the radiative balance (with equilibrium at a lower temperature), although there are many caveats to this conclusion.

Authors   J Harnisch, R Borchers, P Fabian, M Maiss
Title   CF4 and **the age of mesospheric and polar vortex air**
Address   J Harnisch, Max Planck Inst Aeron, Max Planck Str 2, D-37191 Katlenburg Duhm, GERMANY

Abstract A chronology of tropospheric CF4 mixing ratios is reported for the northern hemisphere, A decline of global emissions of CF4 from 16,000 to 11,000 metric tons yr(-1) is found for the periods 1978-1990 and 1992-1998, respectively. The atmospheric chronology of CF4 is applied to determine the age of air of cryogenic air samples collected on rocket and balloon platforms. **Age values of 7 years are found inside the polar vortex between 25-44 km altitude and of 11 years between 56 and 61 km altitude**, which is significantly higher than predicted by most models currently used to assess the effects of high-flying aircraft. The results suggest that the mesosphere is more isolated from below than previously believed. A comparison of age values derived from CF4 and SF6 relative to predicted deviations constrains the atmospheric lifetime of SF6 to >5,000 years.

Authors   U Vonzahn, J Fiedler, B Naujokat, U Langematz, K Kruger
Title   **A note on record-high temperatures at the northern polar stratopause in winter 1997/98**
Address   U Vonzahn, Leibniz Inst Atmospher Phys, Schlossstr 4-6, D-18225 Kuhlungsborn, Germany

Abstract A series of lidar temperature soundings from the ALOMAR observatory in northern Norway indicated an extreme warming of a descending stratopause in February 1998. **The maximum temperature recorded during this event was +49 degrees C at 40 km altitude.** This stratospheric warming is described by means of SSU satellite radiance data and of stratospheric analyses from the Free University Berlin. Comparisons are made to a number of historical events with similar temperature observations from rocket soundings and to results from the Berlin general circulation model. **It turns out that in all cases the highest stratopause temperatures occur close to the 40 km altitude level.**

Authors   TJ Duck, JA Whiteway, AI Carswell
Title   Lidar observations of gravity wave activity and Arctic stratospheric vortex core warming
Address   TJ Duck, York Univ, Dept Phys & Astron, 4700 Keele St, Toronto, on M3J 1P3, Canada

Abstract Measurements of stratospheric thermal structure and gravity wave activity have been obtained with a Rayleigh lidar in the Canadian High Arctic at Eureka (80 degrees N, 86 degrees W) during five recent winters. **The observations reveal that an annual late December warming of the upper stratosphere occurred in the polar vortex core** and was sustained through the winter. Increased gravity wave activity was detected in the vortex jet during the warming. That these two phenomena developed in parallel suggests they are related. **It is proposed that increased gravity wave momentum deposition above the jet maximum forced flow into the vortex core where it descended and warmed adiabatically.**

Authors   SJ Reid, M Rex, P Vondergathen, I Floisand, F Stordal, GD Carver, A Beck, E Reimer, R Krugercarstensen, LL Dehaan, G Braathen, V Dorokhov, H Fast, E Kyro, M Gil, Z Litynska, M Molyneux, G Murphy, F Oconnor, F Ravegnani, C Varotsos, J Wenger, C Zerefos

Title   A study of ozone laminae using diabatic trajectories, contour advection and photochemical trajectory model simulations.
Source   Journal of Atmospheric Chemistry 30: 1 (MAY 1998)
Page(s)   187-207
Address   SJ Reid, NOAA, Aeron Lab, 325 Broadway, Boulder, CO 80303 USA

Abstract In this paper, **we show that the rate of ozone loss in both polar and mid-latitudes, derived from ozonesonde and satellite data, has almost the same vertical distribution (although opposite sense) to that of ozone laminae abundance**. Ozone laminae appear in the lower stratosphere soon after the polar vortex is established in autumn, increase in number throughout the winter and reach a maximum abundance in late winter or spring. **We indicate a possible coupling between mid-winter, sudden stratospheric warmings (when the vortex is weakened or disrupted) and the abundance of ozone laminae using a 23-year record of ozonesonde data from the World Ozone Data Center in Canada combined with monthly-mean January polar temperatures at 30 hPa**.
Results are presented from an experiment conducted during the winter of 1994/95, in phase II of the Second European Stratospheric And Mid-latitude Experiment (SESAME), in which 93 ozone-enhanced laminae of polar origin observed by ozonesondes at different time and locations are linked by diabatic trajectories, enabling them to be probed twice or more. It is shown that, in general, ozone concentrations inside laminae fall progressively with time, mixing irreversibly with mid-latitude air on time-scales of a few weeks.
A particular set of laminae which advected across Europe during mid February 1995 are examined in detail. These laminae were observed almost simultaneously at seven ozonesonde stations, providing information on their spatial scales. The development of these laminae has been modelled using the Contour Advection algorithm of Norton (1994), adding support to the concept that many laminae are extrusions of vortex air. Finally, a photochemical trajectory model is used to show that, if the air in the laminae is chemically activated, it will impact on mid-latitude ozone concentrations. An estimate is made of the potential number of ozone molecules lost each winter via this mechanism.

Authors   DT Shindell, D Rind, P Lonergan
Title   Increased polar stratospheric ozone losses and delayed eventual recovery owing to increasing greenhouse-gas concentrations
Source   **Nature** 392: 6676 (APR 9 1998)
Page(s)   589-592
Address   DT Shindell, NASA, Goddard Inst Space Studies, 2880 Broadway, New York, NY 10025 USA

Abstract The chemical reactions responsible for stratospheric ozone depletion are extremely sensitive to temperature(1). Greenhouse gases warm the Earth's surface but cool the stratosphere radiatively(2-5) and therefore affect ozone depletion. Here we investigate the interplay between projected future emissions of greenhouse gases and levels of ozone-depleting halogen species using a global climate model that incorporates simplified ozone-depletion chemistry. **Temperature and wind changes induced by the increasing greenhouse-gas concentrations alter planetary-wave propagation in our model, reducing the frequency of sudden stratospheric warmings in the Northern Hemisphere(4). This results in a more stable Arctic polar vortex, with significantly colder temperatures in the lower stratosphere and concomitantly increased ozone depletion**. Increased concentrations of greenhouse gases might therefore be at least partly responsible for the very large Arctic ozone losses observed in recent winters(6-9). Arctic losses reach a maximum in the decade 2010 to 2019 in our model, roughly a decade after the maximum in stratospheric chlorine abundance. The mean losses are about the same as those over the Antarctic during the early 1990s, with geographically localized losses of up to two-thirds of the Arctic ozone column in the worst years. The severity and the duration of the Antarctic ozone hole are also predicted to increase because of greenhouse-gas-induced stratospheric cooling over the coming decades.

Authors   JC Bird, SR Pal, AI Carswell, DP Donovan, GL Manney, JM Harris, O Uchino
Title   Observations of ozone structures in the Arctic polar vortex
Source   Journal of Geophysical Research - Atmospheres 102: D9
        (MAY 20 1997)
Page(s)   10785-10800
Address   JC Bird, York Univ, Inst Space & Terr Sci, 4850 Keele St, N York, on M3J 3K1, Canada
Abstract Lidar and balloon measurements at the new observatory, AStrO (80.05 degrees N, 86.42 degrees W), near Eureka, in the Canadian Arctic, have revealed laminations inside the ozone layer both inside and outside the polar vortex. These observations have been conducted by the lidar group of the Institute for Space and Terrestrial Science during February-March 1993 and the winters of 1993-1994 and 1994-1995. Observations of the vortex edge region were obtained as it passed over Eureka, revealing ozone profiles rich in structure. This paper discusses the observed ozone structures and their relationship to vortex filaments, the vortex edge structure, low-ozone pockets, motion of the vortex edge region in the ozone profiles, and observed temperatures. Complementing the observations are back trajectories, potential vorticity maps, and Lagrangian domain-filling potential vorticity trajectories. The relations of magnitude and thickness of the laminations to their positions relative to the vortex are revealed by presenting data as a function of potential vorticity. Mechanisms for the formation and transport of the laminae are discussed, as well as their role as a possible exchange mechanism of air masses across the polar vortex boundary. From observations of the laminations and their relation to potential vorticity, it is suggested that motion of the vortex, sometimes associated with warmings, is involved in the formation of laminations, which are subsequently advected as filamentary structures.

Authors   G Didonfrancesco, A Adriani, GP Gobbi, F Congeduti
Title   Lidar observations of stratospheric temperature above McMurdo Station, Antarctica
Source   Journal of Atmospheric and Terrestrial Physics 58: 13
        (SEP 1996)
Page(s)   1391-1399
Address   G Didonfrancesco, Enea, AMB Saf Atmo, Ctr Ric Casaccia, Via Anguillarese 301, I-00060 S Maria Galeria, Rome, Italy
Abstract Stratospheric temperatures were measured by lidar at **McMurdo station, Antarctica (78 degrees S, 167 degrees E)** during two late spring months (September-October) in 1991 and 1992, and during the period March-October in 1993 and 1994. The stratosphere was found to be quite active, with **one major and several minor warmings** occurring in 1993 and 1994, and showing the expected behaviour of a distinct region of high temperatures, formed in the polar mesosphere, descending with time and warming the stratopause region. A relative maximum of the stratopause temperature was observed in July 1994, and differences between two years in terms of the time development of average temperature in the different stratospheric layers and in terms of the average temperature variability over single months are pointed out. Monthly mean temperature profiles determined from lidar observations are compared with a reference atmosphere (CIRA86). Fair agreement, with discrepancies less than +/-4 K, in June, July and August in the middle stratosphere and just above the stratopause was found. (C) 1996

Authors   GL Manney, L Froidevaux, JW Waters, RW Zurek, JC Gille, JB Kumer, JL Mergenthaler, AE Roche, A Oneill, R Swinbank
Title   Formation of low-ozone pockets in the middle stratospheric anticyclone during winter
Source   Journal of Geophysical Research - Atmospheres 100: D7
        (JUL 20 1995)
Page(s)   13939-13950

Address   GL Manney, Caltech, Jet Prop Lab, 4800 Oak Grove Dr, Mail Stop 183-701, Pasadena, CA 91109 USA

Abstract **Microwave limb sounder observations of midstratospheric ozone during stratospheric warmings show tongues of high ozone drawn up from low latitudes into the developing anticyclone**. Several days later, an isolated pocket of low ozone mixing ratios appears, centered in the anticyclone, and extending in the vertical from approximate to 15 to 5 hPa, with higher mixing ratios both above and below. These low ozone mixing ratios during northern hemisphere warmings are comparable to values well inside the vortex and are approximate to 3 parts per million by volume lower than typical midlatitude extra-vortex mixing ratios. This type of feature is seen whenever the anticyclone is strong and persistent, including during relatively strong minor warmings in the southern hemisphere. Three-dimensional back trajectory calculations indicate that the air in the region of the low-ozone pockets originates at higher altitudes and low latitudes, where ozone mixing ratios are much higher. The air parcels studied here are typically confined together for 1 to 3 weeks before the lowest ozone mixing ratios are observed. The trajectory calculations and comparisons with passive tracer data confirm that the observed low- ozone regions in the midstratosphere could not result solely from transport processes.

Authors   W Singer, P Hoffmann, AH Manson, CE Meek, R Schminder, D Kurschner, GA Kokin, AK Knyazev, YI Portnyagin, NA Makarov, AN Fakhrutdinova, VV Sidorov, G Cevolani, HG Muller, ES Kazimirovsky, VA Gaidukov, RR Clark, RP Chebotarev, Y Karadjaev
Title   The Wind Regime of the Mesosphere and Lower Thermosphere During the DYANA Campaign .1. Prevailing Winds
Address   W Singer, Inst Atmospher Phys, D-18221 Kuhlungsborn, Germany

Abstract During the DYANA campaign, winds and tides at mesopheric and lower thermospheric altitudes were measured by 14 ground based experiments (MF radars, meteor radars and LF-drift systems). The experiments were located between 107-degrees-W and 102-degrees-E, mostly in northern mid-latitudes with well covered areas in Central and Eastern Europe. Emphasis is placed here upon the vertical profiles and height-time contours of the prevailing zonal and meridional winds with different resolution (15 d, 4 d). Generally, westerly winds are observed at heights below 95 km with a strong mesospheric variability and with longitudinal differences between the data of Central Europe, Eastern Europe, Asia and Canada. Planetary waves **and a minor stratospheric warming** in the first 10 days of February 1990 are the cause of this behaviour. **In connection with the stratospheric warming, a wind reversal to summer east winds reaching from the upper stratosphere up to 95 km is observed**. The close connection of the behaviour of the stratosphere with the observed longitudinal differences in the mesospheric response on the stratospheric warming and with the occurrence of wind oscillations (10-15 d) is discussed.

Authors   IV Bugaeva, AI Boutko, GA Kokin, YP Koshelkov, SP Perov, DA Tarasenko, GR Zakharov, GF Toulinov, D Offermann, M Bittner, U Vonzahn, ML Chanin, A Hauchecorne, I Soule, BH Subbaraya, M Gilojeda, BA Delamorena, FJ Schmidlin, KI Oyama, H Kanzawa
Title   Basic Features of Large-Scale Processes in the Middle Atmosphere During DYANA
Address   IV Bugaeva, Cent Aerol Observ, Dolgoprudnyi, Russia

Abstract Large-scale processes in the stratosphere and mesosphere were investigated for the DYANA period, mainly on the basis of rocket sounding series and satellite-based maps. It was

found that undisturbed circulation prevailed during the early winter period with low stratospheric temperatures near the Pole. Periodic warm pulses appeared in January in the upper stratosphere and an intense warming was observed at these levels in early February, the downward penetration of which (below 25-30 km) was relatively confined. **Wavenumber 1** predominated during the warming. In late February the cold cyclonic vortex was restored near the Pole and this persisted into March.

 Abstract During February and March 1993, Rayleigh lidar observations of temperature structure and gravity wave activity were carried out in the high Canadian Arctic at Eureka, Northwest Territories (80 degrees N, 86 degrees W). **A sudden warming was observed first in the upper stratosphere during late February and then at lower levels in early March.** The warming appeared to be part of a disturbance of the entire middle atmosphere with **temperature changes in the mesosphere and lower stratosphere being opposite in sign to those in the upper stratosphere**. Shorter time and length scale temperature fluctuations, observed in the upper stratosphere, are interpreted as being a result of atmospheric gravity waves. The wave amplitudes are shown to be capable of inducing convective instability. The rms perturbation and available potential energy density show substantial vertical and day-to-day variability in regions of conservative and dissipative growth rates. Vertical growth of the potential energy spectral density is seen to cease at the broadband convective instability saturated limit. There appeared to be substantially greater dissipation of gravity wave energy within the upper-stratospheric warming in comparison with the preceding and following periods.

3   THE QUASI-BIENNIAL OSCILLATION

More details can be found in chapter 12.6 of Holton (1992), Chapter III.1.5 of Dieminger et al. (1996), and chapter 8 of Andrews et at. (1987).

3.1   Phenomenology

The Quasi-biennial oscillation (QBO; "oscillation with a period of almost two years") is:
1. Zonally symmetric easterly and westerly wind regimes (Figure 3.1) alternate regularly with periods varying from about 24 to 30 months (Holton, 1992), or 22 to 34 months, with an average of about 27 months (Andrews et al., 1987), or the wind at a given level can stay in the same phase for as long as two years or as short as six months (Naujokat, 1986). Figure 3.2 shows the monthly mean zonal wind for 46 years, showing 20 periods: average 28 months.
2. Successive regimes first appear above 30 km but propagate downward at a rate of about 1 km/month.
3. The downward propagation occurs without loss of amplitude between 30 km and 23 km, but there is rapid attenuation below 23 km. Thus, there must be a process feeding energy into this oscillation in the height range 23-30 km.

4. The oscillation is symmetric about the equator with a maximum amplitude of about 20 m/s and an approximately Gaussian distribution in latitude with a half-width of about 12^0. See Figure 3.3.

The QBO was discovered in 1960 by Reed and independently in 1961 by Veryard and Ebdon (Reed et al., 1961; Veryard and Ebdon, 1961). Figure 3.4 shows that, although the QBO is very irregular, there is a tendency for the easterly wind onset (at 50 hPa) to occur in the summer months of the northern hemisphere. Figure 3.5 shows an asymmetry in the onsets of the westerly and easterly regimes: The westerlies begin at the equator and spread north and south, whereas the easterlies begin simultaneously in the whole QBO band of latitudes. This may indicate different excitation mechanisms for the two regimes.
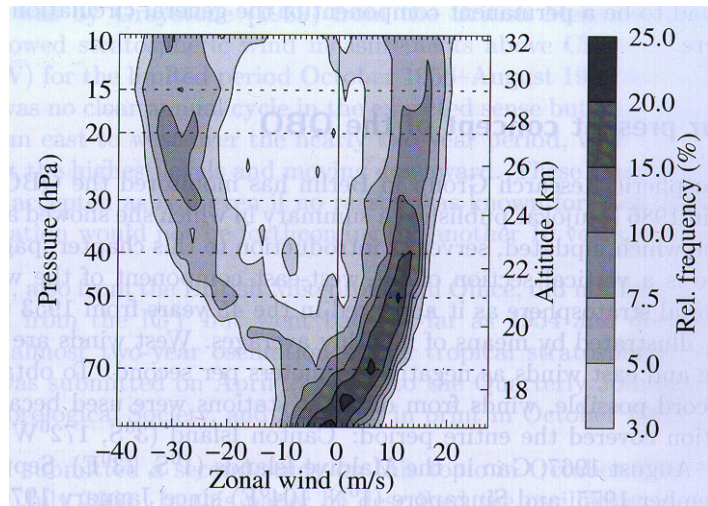
Figure 3.1   The relative frequency distribution at various heights of the monthly mean zonal winds (negative values are toward west, positive ones are toward east). 1953-1997. The monthly means are stratified in classes with a width of 2.5 ms^{-1} (Marquardt, 1998).

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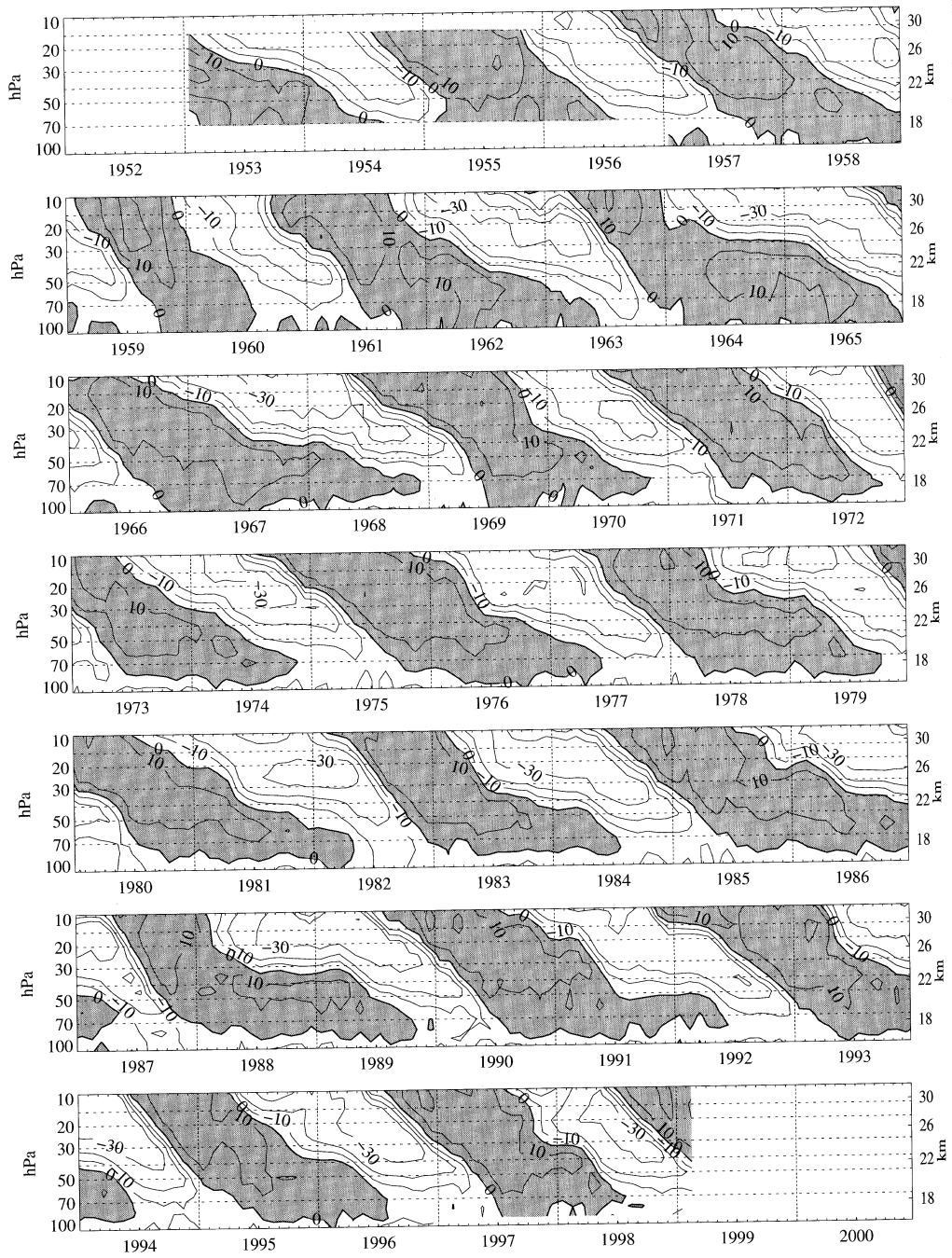
Figure 3.2   Time-height section of the monthly mean zonal wind components over the eauator (Labitzke and van Loon, 1999).
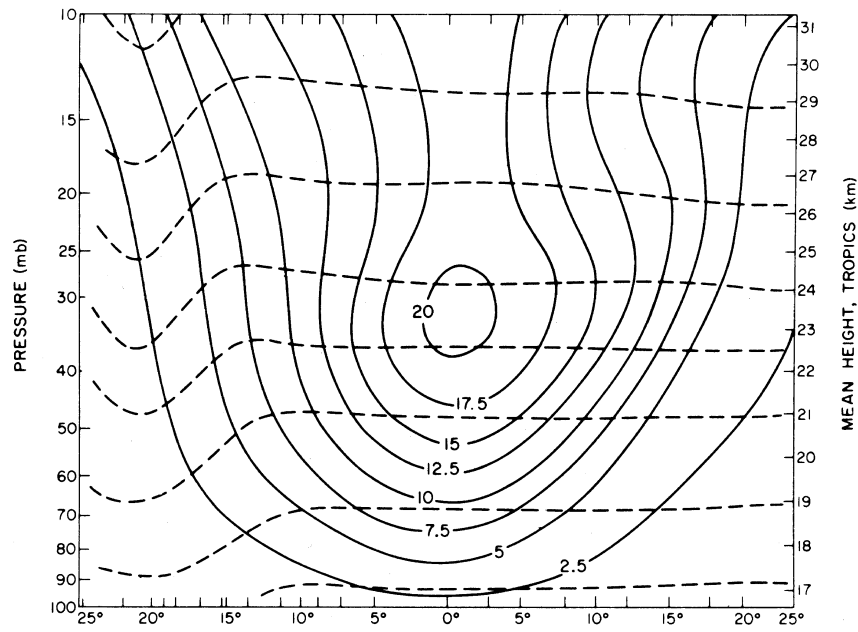
Figure 3.3 Latitude-height distribution of the amplitude and phase of the zonal wind QBO. Amplitude (solid lines) in ms^{-1}, phase (dashed lines) at 1-month intervals with time increasing downward (Andrews et al., 1987).
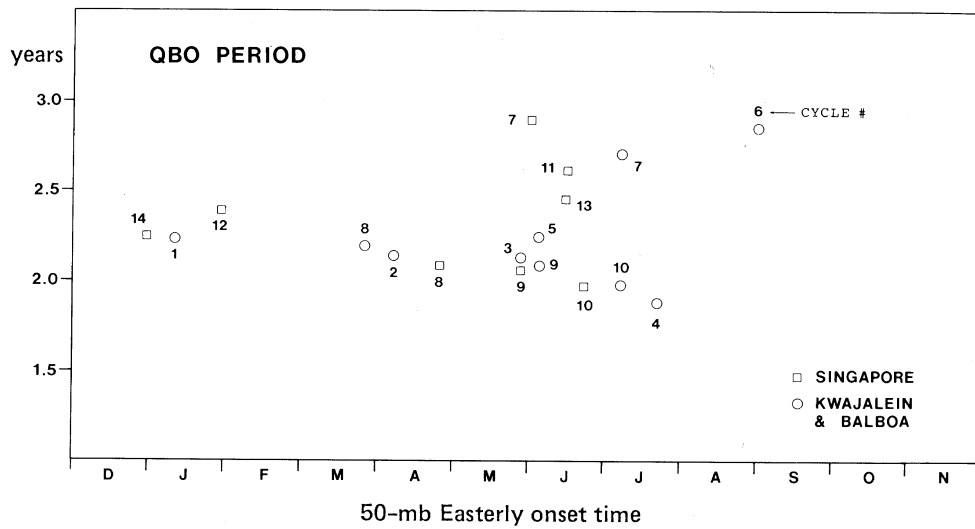
Figure 3.4 Period of QBO cycles as a function of the time of easterly wind onset at the 50-mb level. Notice the clustering of easterly onset occurrences during Northern-Hemisphere summer (Andrews et al., 1987).
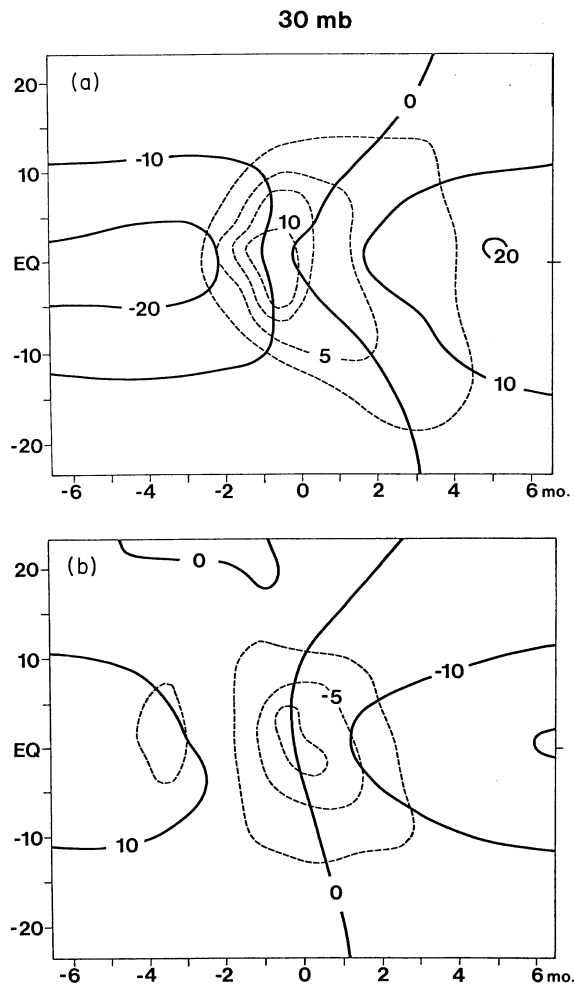
Figure 3.5   Composite latitude-time section of zonal wind at 30 hPa for westerly (upper) and easterly (lower) phases of the QBO. Zonal winds (solid lines) in ms^{-1}; acceleration (dashed lines) in ms^{-1}month^{-1} (Dunkerton and Delisi, 1985).

3.2   Unexpected correlations

The upper panel of Figure 3.6 is a plot of the 30 hPa temperature over the North pole in January/February together with the 10.7-cm solar flux. As one might have expected, there is no correlation. However, if the datapoints are ordered by whether the QBO was in its West phase (middle panel) or in its East phase (bottom panel), an unexpected correlation and anti-correlation, respectively, emerges. Figure 3.7 shows the correlation between temperatures at two NH locations and the 10.7-cm solar flux. Figure 3.8 shows a map of the correlation coefficients between the 10.7-cm flux and the 30 hPa height. Friis-Christensen and Lassen (1991) have discovered that an even better correlation is found between the length of the solar cycle and the temperatures or geopotential heights in the stratosphere (Figure 3.9). Only the winter temperatures, etc, must be ordered by the phase of the QBO. In the other seasons, the correlation is there for both phases of the QBO. - The variation of the solar constant with the sunspot number is very small (about 2 Wm^{-2}), and no one expects this to have any measurable effect on the temperature on the earth. On the other hand, the solar spectrum varies most on the UV-end, the part of the spectrum that is absorbed preferentially in the stratosphere. - As of today, no explanation is known for this correlation, and it is surprising that a strictly equatorial feature like the QBO should have any effect on the polar atmospheres. – It is possible that the stratosphere might – by coincidence - have an intrinsic frequency of something close to the 11 years solar cycle, making the stratosphere especially susceptible to changes in the 11-year

forcing. The odd phase jumps to make the two independent (this hypothesis) oscillators match might contribute to the QBO?
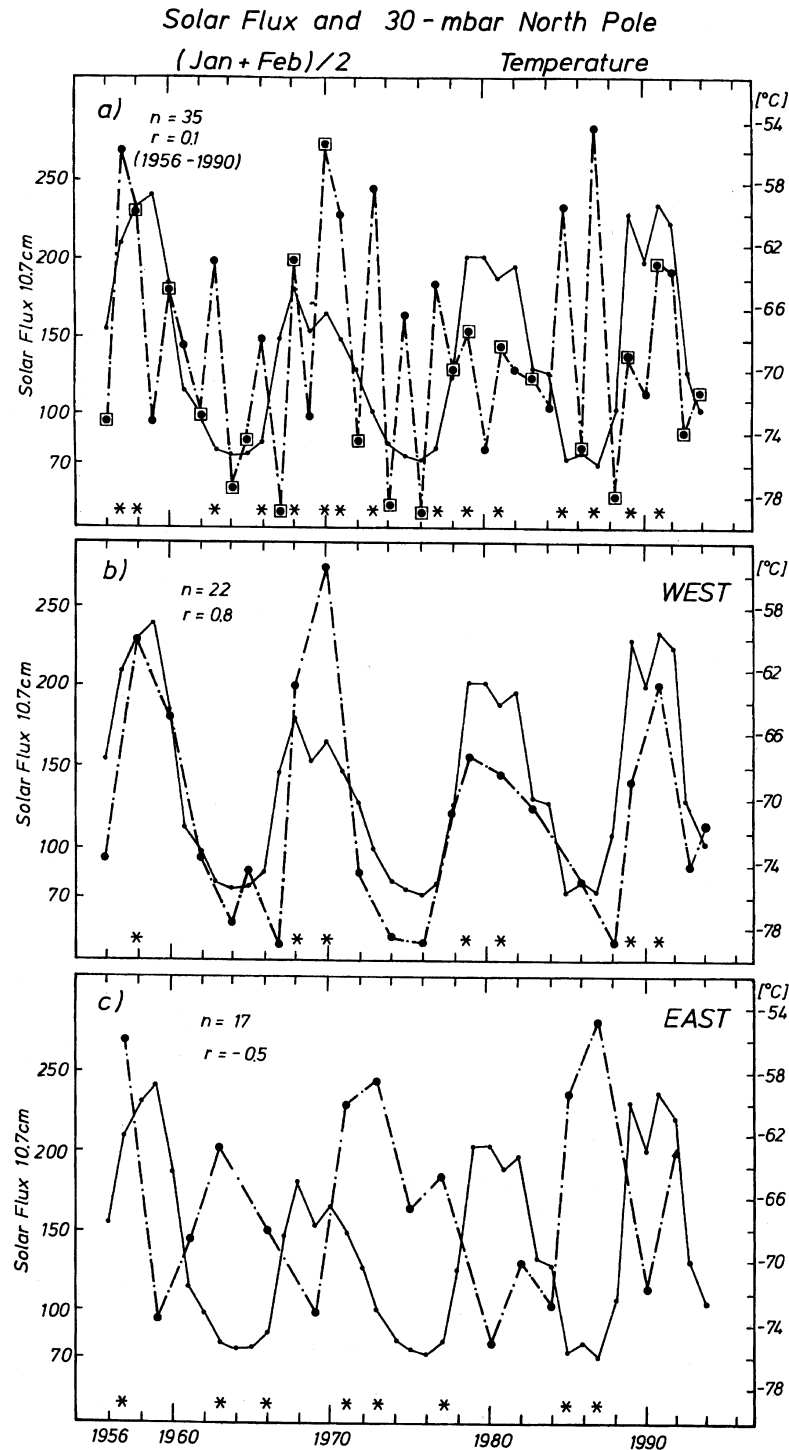
Figure 3.6 (a) Time series of the 10.7 cm solar flux (units are $10^{-22} Wm^{-2}Hz^{-1}$) for (Jan+Feb)/2 and of the mean 30-mb temperature (°C) at the North Pole for (Jan+Feb)/2. The squares on the temperature curve denote winters in the west phase of the QBO. The asterisks at the bottom are the years with the major mid-winter warmings. The number of years and the correlation coefficient between the two series are also shown. (b) The solar flux as in a. The 30-mb temperature curve at the North Pole for (Jan+Feb)/2 is drawn only for the winters in the west phase of the QBO: The asterisks denote the major mid-winter warmings which occurred in the west phase. (c) as b, but for the winters in the east phase of the

QBO; the asterisks show the major mid-winter warmings which occurred in the east phase. (After Labitzke and van Loon, 1988).
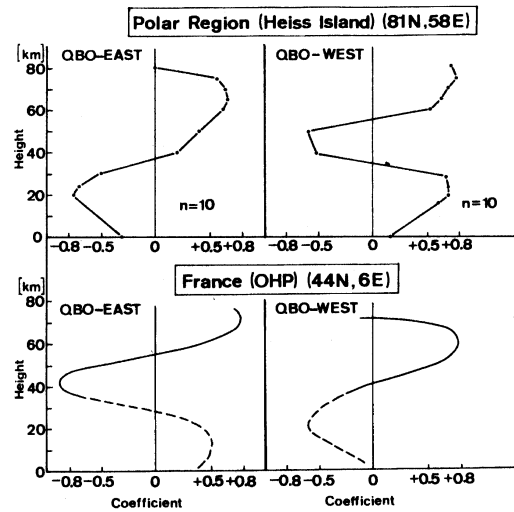
Figure 3.7   Vertical distribution of correlations between the 11-year solar cycle (10.7 cm solar flux) and averaged temperature in January and February in the East and West phase of the QBO. (a) At Heiss Island (81°N, 58°E). (b) At the Observatory of Haute Provence (44°N, 6°E) Labitzke and Chanin, 1988).
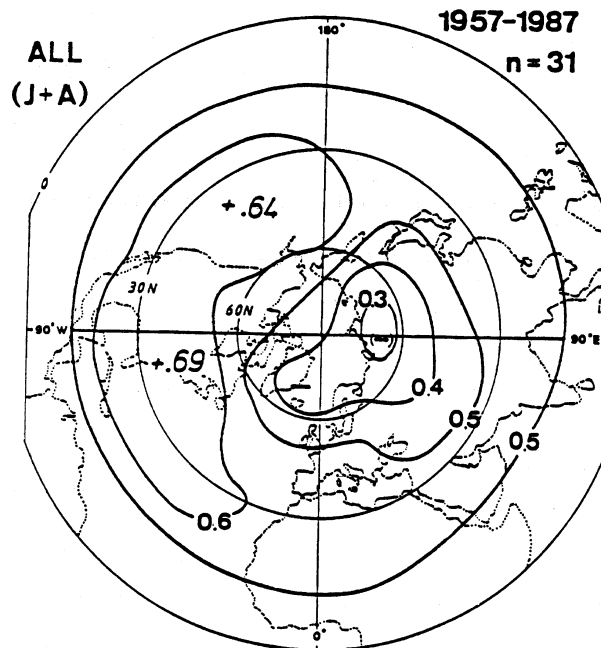
Figure 3.8   Correlation between the 10.7 cm solar flux and the 30-mb height in July-August in 31 years 1957-1987 (Labitzke and van Loon, 1989).
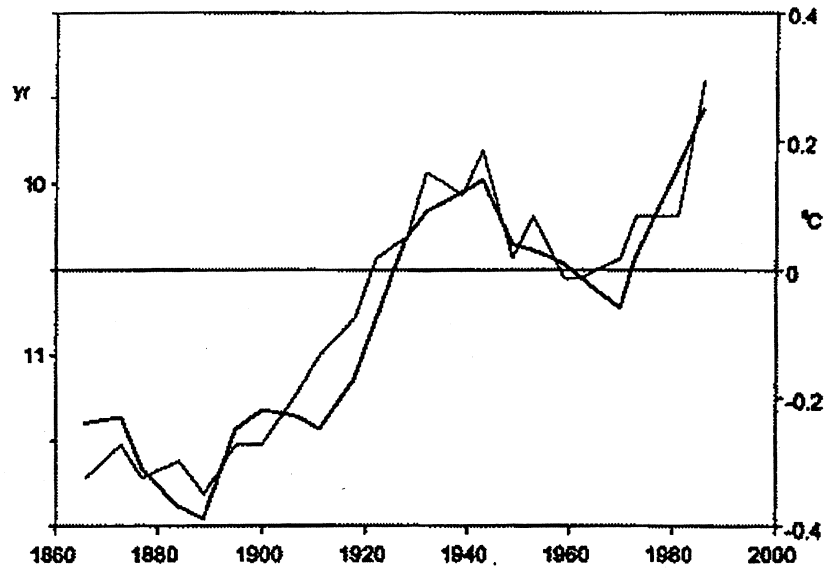
Figure 3.9   One line shows the deviation of the Northern-Hemisphere annual-mean temperature from the long-term average (right axis), the other line shows the length of the appropriate solar cycle (left axis), from 1865 to 1985 (Friis-Christensen and Lassen, 1991).

3.3   The origin of the QBO
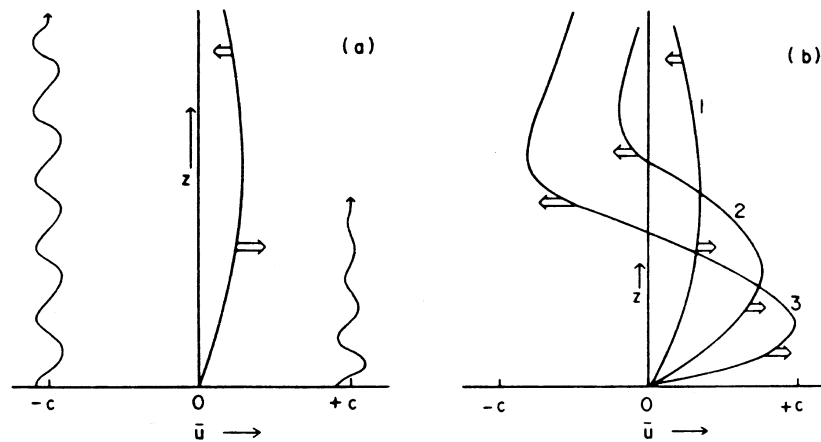
Figure 3.10   Schematic representation of the wave-driven accelerations that lead to the zonal wind QBO. Kelvin and Rossby gravity waves of phase speeds +c and –c, respectively, propagate upward and are dissipated at rates dependent on the Doppler-shifted frequency. (a) Initial weak westerly current selectively damps the Kelvin wave and leads to westerly acceleration at lower levels and easterly acceleration at high levels. (b) Descending westerly shear zones block penetration of Kelvin waves while Rossby-gravity waves produce descending easterlies aloft. Broad arrows show locations and direction of maxima in mean wind acceleration. Wavy lines indicate relative penetration of waves (from Plumb, 1982).

At least for the QBO itself we seem to have a satisfactory explanation Figure 3.10: Kelvin waves (a special class of atmospheric gravity waves) exist only in a band very close to the equator and only with a phase velocity towards the east (westerly). They are symbolized by the wavy line on the right side of Figure 3.10a. Rossby-gravity waves, on the other hand, can also have phase speeds towards the west, see the wavy line on the left side of the left panel of

Figure 3.10. At such heights where the zonal background wind becomes equal to the phase speed of an atmospheric wave, the wave is Doppler-shifted to zero frequency and thus absorbed by the background flow. This is called a critical layer absorption. The process is a little more complicated than described here, and occurs already when the phase velocity approaches the background wind speed. This process leads to any (coincidental) background wind like in Figure 3.10a to be modified by wave momentum deposition as shown by the arrows. As Figure 3.10b shows, this will lead to a steepening and downward propagation of the wave. The nonlinearity of the process and the randomness of the occurrence of the Kelvin and Rossby-gravity waves, respectively, leads to the unsteadiness of the QBO.

3.4   Recent Relevant Publications

Authors   H Zou, CP Ji, LB Zhou
Title   **QBO signal in total ozone over Tibet**

Full source   Advances in Atmospheric Sciences, 2000, Vol 17, Iss 4, pp 562-568

Address   Zou H, Chinese Acad Sci, Inst Atmospher Phys, Environm & Polar Program, Beijing 100029, PEOPLES R CHINA
Abstract   From data analysis of ozone satellite observation and general circulation, this article discusses the seasonal and interannual variations of total ozone over Tibet. Analysis has been done on Quasi-Biennial Oscillation (QBO) in interannual ozone variation over Tibet, in comparison with QBO over the tropics and non-mountain region at the same latitudes of Tibet. **The fact is shown that Tibet ozone QBO has an averaged period of 29 months, with an averaged amplitude of 8 DU. The Tibet ozone QBO is antiphase to the stratospheric wind QBO over the tropics, i.e., when the tropics 30 hPa-wind is easterly, ozone has a surplus**, and vice versa. This article also discusses the impact of atmospheric transfer on ozone QBO over Tibet.

Authors   MJ Alexander, RA Vincent
Title   Gravity waves in the tropical lower stratosphere: A model study of seasonal and interannual variability
Full source   Journal of Geophysical Research - Atmospheres, 2000, Vol 105, Iss D14, pp 17983-17993
Address   Alexander MJ, NW Res Associates Inc, Colorado Res Associates Div, 3380 Mitchell Lane, Boulder,CO 80301 USA
Abstract   A model study is presented to clarify the relationship between gravity wave properties observed in the stratosphere and the sources for the waves, presumed to be in the troposphere. The observations are balloon-borne radiosondes launched from Cocos Island in the tropical Indian Ocean (12 degrees S, 97 degrees E), and the analysis of these data is described in a companion paper [Vincent and Alexander, this issue]. **The dominant time variations in the observed gravity wave activity are annual and quasi-biennial patterns in the zonal momentum flux and kinetic energy density.** The background zonal winds at this site vary with the same periods, and these are known to be capable of causing dramatic variations in the observable properties of the waves even if the sources for the waves are constant in time. The results presented here clarify (1) the nature of the sources for the gravity waves observed in the stratosphere, (2) the limitations of the observations for observing the full range of gravity wave perturbations potentially present in the atmosphere, and (3) **the role the observed waves can play in forcing the quasibiennial oscillation (QBO) in the zonal winds at this latitude.** The stratospheric waves appear to originate near the height of the tropopause, so the source is apparently related to deep convection. No seasonal or interannual variations in the convection need be assumed to understand the observations. The waves at the tropopause appear to have a phase speed distribution that is narrowly confined near zero phase speed relative to the ground. The source is likely related to slowly propagating tropospheric

convection and the wind near the tropopause. Variations observed in the stratospheric data are caused by both the wind shear in the stratosphere and the ability of waves with these characteristics to propagate vertically without severe dissipation. Higher phase speed waves may be present and could carry significant momentum flux vertically into the stratosphere and mesosphere but would be extremely difficult to see in these radiosonde data. **The observed waves can contribute substantially to the descent of the eastward shear zones characteristic of the "westerly" phase of the QBO in the lower stratosphere zonal winds.**

Author   LJ Gray
Title   **A model study of the influence of the quasi-biennial oscillation on trace gas distributions in the middle and upper stratosphere**
Full source   Journal of Geophysical Research - Atmospheres, 2000, Vol 105, Iss D4, pp 4539-4551
Address   Gray LJ, Rutherford Appleton Lab, Didcot OX11 0QX, Oxon, ENGLAND
Abstract   The dominant tracer transport processes in the equatorial and subtropical latitudes of the middle and upper stratosphere are investigated. Distributions of water vapor in Northern Hemisphere winter from the Microwave Limb Sounder onboard the Upper Atmosphere Research Satellite are employed, together with a three-dimensional Stratosphere Mesosphere Model that incorporates a representation of the quasi-biennial oscillation (QBO). The model reproduces the observed tracer distributions, in particular a "staircase" feature that is present in northern winter of 1992 (easterly QBO phase) but not in 1993 (westerly QBO phase). This feature is highly asymmetric about the equator. The model circulation is diagnosed to show that while the induced QBO circulation in the lower stratosphere of the model is relatively symmetric about the equator, in the middle and upper stratosphere it is highly asymmetric and in the correct sense to give rise to the staircase feature. Model experiments are compared in which trajectories are advected by (1) the full three-dimensional circulation and (2) the residual mean circulation only, thereby removing the local effects of isentropic mixing by planetary waves on the trajectory distributions. These confirm the importance of advection by the QBO circulation at equatorial and subtropical latitudes. However, sharpening of the tracer gradients at the subtropical edge of the surf zone by the action of planetary waves is shown to be important in the formation of a subtropical "cliff" between 10 and 20 hPa at 20 degrees-30 degrees N. The model results also suggest that the prominence of the summer subtropical peak in easterly phase years compared with westerly phase years is not entirely due to increased summer upwelling of the large-scale global circulation caused by the stronger planetary wave driving. The depression of the winter half of the equatorial peak by the local asymmetric QBO circulation is also shown to be important.

Authors   LP Bruhwiler, K Hamilton
Title   **A numerical simulation of the stratospheric ozone quasi-biennial oscillation using a comprehensive general circulation model**
Full source   Journal of Geophysical Research - Atmospheres, 1999, Vol 104, Iss D23, pp 30525-30557
Address   Bruhwiler LP, NOAA, Climate Monitoring & Diagnost Lab, ERL, R-E-CG1, 325 Broadway, Boulder,CO 80303 USA
Abstract   The Geophysical Fluid Dynamics Laboratory's SKYHI general circulation model (GCM) including a new detailed stratospheric photochemistry module has been integrated for over 14 years with an imposed zonally symmetric momentum source designed to force a realistic quasi-biennial oscillation (QBO) in the tropical stratosphere. The GCM features an internally consistent calculation of the annual stratospheric circulation cycle and exhibits realistic extratropical stratospheric interannual variability, making it appropriate for the detailed investigation of QBO/annual cycle interactions. The simulated ozone QBO is generally realistic in the tropics and subtropics, and, in particular, the QBO in total column ozone agrees quite well with that derived from satellite observations. A detailed analysis of the

QBO modulation of the zonal-mean ozone budget has been performed. The advective effects of the QBO-induced residual mean circulation are found to be strongly dependent on season, in accord with recent results from some two-dimensional model studies [Jones et al., 1998; Kinnersley and Tung, 1998]. In addition, the QBO modulation of explicitly resolved eddy transport in the GCM is found to make a significant contribution to the ozone budget, and this helps account for the strong seasonal synchronization of the ozone QBO.

Author   JS Kinnersley
Title   Seasonal asymmetry of the low- and middle-latitude QBO circulation anomaly
Source   Journal of the Atmospheric Sciences 56: 9 (MAY 1 1999)
Page(s)   1140-1153
Address   JS Kinnersley, Univ Washington, Dept Appl Math, Box 352420, Seattle, WA 98195 USA

Abstract It is usually assumed that the circulation anomaly induced directly by the quasi-biennial oscillation (QBO) in the equatorial zonal wind is, approximately, a seasonally independent, two-cell structure symmetric about the equator and confined to the Tropics.
It is shown here using a simple two-dimensional model that although the two-cell structure exists at equinox, at solstice the summer cell disappears and the winter cell is greatly strengthened (about three times stronger than at equinox) and expanded. Strong cross-equatorial flow is induced near the shear zone where the QBO winds are easterly. This result may explain why the observed anomalies in trace gases are small in the summer hemisphere and it also reduces the need for a modulation of the planetary wave fluxes at low and middle latitudes in order to explain the modulation of the circulation there. At low latitudes, the shape of the isopleths of a modeled tracer closely resemble those observed in both easterly and westerly phases of the QBO.
The difference between the hemispheres stems from the nonlinear advection of the equatorial zonal wind anomaly into the winter hemisphere, where it leads to a large temperature anomaly due to the explicit latitudinal dependence of the thermal wind equation. An asymmetric circulation anomaly is induced both at steady state and in the transition to steady state: during transition, an asymmetric circulation works to produce the asymmetric temperature anomaly required by thermal wind balance, while at steady state the same circulation balances the Newtonian cooling induced by the (now established) temperature anomaly. Thus, in the real stratosphere, an asymmetric circulation may exist even in the absence of a large asymmetric temperature anomaly, though the circulation anomaly will eventually produce such a temperature anomaly. The poleward extent of the circulation anomaly is increased by moderate Rayleigh friction on the zonal wind poleward of about 15 degrees in the winter hemisphere. However, low-latitude friction reduces the low-latitude zonal wind anomaly and hence the circulation anomaly.

Authors   MN Sasi, L Vijayan, V Deepa, BVK Murthy
Title   Estimation of **equatorial wave momentum fluxes** using MST radar winds observed at Gadanki (13.5 degrees N, 79.2 degrees E)
Source   Journal of Atmospheric and Solar - Terrestrial Physics 61: 5 (MAR 1999)
Page(s)   377-384
Address   MN Sasi, Vikram Sarabhai Space Ctr, Space Phys Lab, Trivandrum 695022, Kerala, INDIA

Abstract A method of computing the vertical flux of zonal momentum (associated with equatorial waves) from the zonal and vertical components of the winds measured by the Indian MST radar at Gadanki (13.5 degrees N, 79.2 degrees E) is presented. The application of the method to the radar data gives flux values of 16 x 10(-3), 8.0 x 10(-3) and 5.5 x 10(-3) m(2) s(-2) for slow Kelvin (12-day period), fast Kelvin (5.33-day period) and Rossby-gravity (RG) (3.43-day period) waves, respectively, in the upper troposphere. These flux values compare quite well with the values 4 x 10(-3) m(2) s(-2) and 1 x 10(-3) m(2) s(-2) obtained from

radiosonde zonal wind and temperature data by Wallace and Kousky (1968) for slow Kelvin and RG waves, respectively. An estimate of the error in the fluxes gives a value of similar to 1.2 x 10(-3) m(2) s(-2).

Authors   MA Giorgetta, L Bengtsson
Title   **Potential role of the quasi-biennial oscillation in the stratosphere-troposphere exchange** as found in water vapor in general circulation model experiments
Address   MA Giorgetta, Max Planck Inst Meteorol, Bundesstr 55, D-20146 Hamburg, GERMANY
Abstract The tropical tropopause is considered to be the main region of upward transport of tropospheric air carrying water vapor and other tracers to the tropical stratosphere. The lower tropical stratosphere is also the region where the quasi-biennial oscillation (QBO) in the zonal wind is observed. The QBO is positioned in the region where the upward transport of tropospheric tracers to the ovenworld takes place. Hence the QBO can in principle modulate these transports by its secondary meridional circulation. **This modulation is investigated in this study by an analysis of general circulation model (GCM) experiments with an assimilated QBO**. The experiments show, first, that the temperature signal of the QBO modifies the specific humidity in the air transported upward and, second, that the secondary meridional circulation modulates the velocity of the upward transport. Thus during the eastward phase of the QBO the upward moving air is moister and the upward velocity is less than during the westward phase of the QBO. It was further found that the QBO period is too short to allow an equilibration of the moisture in the QBO region. This causes a QBO signal of the moisture which is considerably smaller than what could be obtained in the limiting case of indefinitely long QBO phases. This also allows a high sensitivity of the mean moisture over a QBO cycle to the El Nino-Southern Oscillation (ENSO) phenomena or major tropical volcanic eruptions. The interplay of sporadic volcanic eruptions, ENSO, and QBO can produce low-frequency variability in the water vapor content of the tropical stratosphere, which renders the isolation of the QBO signal in observational data of water vapor in the equatorial lower stratosphere difficult.

Author   K Hamilton
Title   **Dynamics of the tropical middle atmosphere: A tutorial review**
Address   K Hamilton, Princeton Univ, GFDL NOAA, Princeton, NJ 08542 USA
Abstract The general circulation of the tropical stratosphere, mesosphere and lowermost thermosphere is discussed at a tutorial level. Observations of the quasi-biennial and semiannual oscillations by both in situ and satellite techniques are first reviewed. The basic dynamics controlling the zonal-mean component of the circulation are then discussed The role of radiative diabatic cooling in constraining the zonal-mean circulation in the middle atmosphere is emphasized. It is shown that the effectiveness of this radiative constraint is reduced at low latitudes, allowing for the sustained mean flaw accelerations over long period of time characteristic of the quasi-biennial and semiannual oscillations in the tropics.
The current view is that the dominant driving for the equatorial mean flow accelerations seen in the middle atmosphere derives from vertically-propagating waves. This process is illustrated here in its simplest context, i.e. the Plumb (1977) model of the interaction of monochromatic internal gravity waves with the mean flow (based on earlier work of Lindzen and Holton, 1968; Holton and Lindzen, 1972). **It is shown that the dynamics illustrated by this simple model can serve as the basis for an explanation of the quasi-biennial oscillation.**
 The paper then describes some of recent developments in the theory of the quasi-biennial and semiannual oscillations, including aspects related to the inter-action between

tropics and midlatitudes in the middle atmosphere. The paper concludes with a discussion of the effects of the long period dynamical variations in the tropical circulation on the chemical composition of the stratosphere.

Authors   RP Kane, CE Meek, AH Manson
Title   **Quasi-biennial** and higher-period **oscillations in the mean winds in the mesosphere and lower thermosphere over Saskatoon**, 52 degrees N, 107 degrees W
Source   Journal of Geophysical Research - Space Physics 104: A2 (FEB 1 1999)
Page(s)   2645-2652
Address   RP Kane, Inst Nacl Pesquisas Espaciais, Av Astronautas 1758, Caixa Postal 515, BR-12201970 Sao Paulo, BRAZIL

Abstract The mesospheric zonal and meridional winds over Saskatoon (52 degrees N, 107 degrees W) show significant QBO (quasi-biennial oscillations), with periods of 2.01, 2.42, 2.30, 2.37, and 2.31 years at 94, 91, 88, 85, and 82 km, respectively, in the meridional (north) component and 2.51, 2.88, 2.52, 2.29, and 2.61 years in the zonal least) component, mostly not matching with the QBO (similar to 2.50 years) of equatorial stratospheric winds. Also, significant higher periodicities (similar to 4 years) are seen in the mesospheric winds, indicating that QBO and higher periodicities in the midlatitude mesosphere could be highly distorted forms of stratospheric wind QBO and/or may have altogether different origins (e.g., El Nino-Southern Oscillation effects).

Authors   WJ Randel, F Wu, R Swinbank, J Nash, A Oneill
Title   **Global QBO circulation** derived from UKMO stratospheric analyses
Source   Journal of the Atmospheric Sciences 56: 4 (FEB 15 1999)
Page(s)   457-474
Address   WJ Randel, Natl Ctr Atmospher Res, Div Atmospher Chem, POB 3000, Boulder, CO 80307 USA

Abstract Global circulation anomalies associated with the stratospheric quasi-biennial oscillation (QBO) are analyzed based on U.K. Meteorological Office (UKMO) assimilated wind and temperature fields. Zonal winds and temperatures from the assimilation are compared with Singapore rawinsonde data (the standard QBO reference time series), showing reasonable agreement but an underestimate of maxima in the UKMO analyses. Global structure of the QBO in zonal wind, temperature, and residual mean meridional circulation (derived from thermodynamic balance and mass continuity) is isolated, showing coherent tropical and midlatitude components. Important aspects of the QBO revealed in these data include 1) out of phase maxima in temperature (and vertical velocity) between the lower and upper stratosphere, and 2) strong seasonal synchronization of midlatitude anomalies. These characteristics are also evident in long records of satellite radiance measurements.

Author   PH Haynes
Title   **The latitudinal structure of the quasi-biennial oscillation**
Source   Quarterly Journal of the Royal Meteorological Society 124: 552 Part B (OCT 1998)
Page(s)   2645-2670
Address   PH Haynes, Univ Cambridge, Dept Appl Math & Theoret Phys, Ctr Atmospher Sci, Silver St, Cambridge CB3 9EW, ENGLAND

Abstract The theory of symmetric time-dependent meridional circulations in a radiatively damped atmosphere shows that, when the frequency sigma of the time variation of an applied body force is smaller than the radiative damping rate alpha, there are two distinct forms of response to the force. At high latitudes, the response appears primarily as a quasi-steady meridional circulation, whilst at low latitudes it appears primarily as an acceleration. The transition from 'low-latitude' to 'high-latitude' response occurs at a distance (equation missing) from the equator where N is the buoyancy frequency, D is the depth scale of the force and beta is the horizontal gradient of the Coriolis parameter at the equator.

It is argued here that this latitudinal scale may also be that of the quasi-biennial oscillation (QBO), in that the width of the region where there is a substantial QBO in the zonal wind may be determined by the radiative damping rate and the frequency of the oscillation at the equator, rather than by the latitudinal scale of the wave-momentum fluxes (provided that this latter scale is sufficiently broad). Numerical simulations of QBO-like oscillations are carried out in a two-dimensional (height and latitude) model with wave-momentum fluxes imposed independently at each latitude. Variation of the background rotation rate and the thermal damping rate between these simulations helps to elucidate the effect of these two parameters on the latitudinal structure of the oscillations. In particular, it is shown that, provided that there is weak lateral transport of momentum, the width of the oscillation does indeed correspond to the low-latitude/high-latitude transition scale given above. For this mechanism of equatorial confinement, the depth scale D is, in effect, set by the vertical phase variation of the oscillation, which is highly unrealistic in many simple QBO models.

Authors   PO Canziani, JR Holton
Title   **Kelvin Waves and the quasi-biennial oscillation**: An observational analysis
Address   PO Canziani, Univ Buenos Aires, Fac Ciencias Exactas & Nat, Dept Ciencias Atmosfera, CONICET, Buenos Aires, DF, ARGENTINA
Abstract A method is derived for estimating the Kelvin wave contribution to the vertical flux of westerly momentum in the equatorial stratosphere, which is based on temperature and geopotential perturbations. This method is used to estimate the momentum transfer due to Kelvin wave activity as derived from the cryogenic limb array etalon spectrophotometer (CLAES) temperature data set, for the onset of the westerly phase of the QBO during 1992 and the first few months of 1993, that is, during the first part of the Upper Atmosphere Research Satellite (UARS) mission, The results are compared with the zonal winds as observed by the high-resolution Doppler imager (HRDI) also flown on board UARS, and the United Kingdom Meteorological Office (UKMO) data assimilation model product, a correlative data set to the UARS mission. **The analysis shows that although the Kelvin wave momentum flux convergence is occasionally sufficient to account for the observed QBO westerly acceleration, the observed flux is sporadic in nature and virtually disappears during the second half of the sample, when the westerly vertical shear zone approaches the 100 hPa level. An estimate of the total westerly momentum flux necessary to produce the observed descent of the westerly phase of the QBO is made using the transformed Eulerian mean (TEM) formalism. The results suggest that Kelvin waves are not sufficient to force the descent of the westerly phase of the QBO. There appears to be a need far enhanced westerly forcing throughout the descent of the westerly phase of the QBO. This enhanced forcing is most likely provided by gravity waves that are unresolved by the satellite observations.** These results are in agreement with the results derived from general circulation models.

Authors   GE Bodeker, IS Boyd, WA Matthews
Title   Trends and variability in vertical ozone and temperature profiles measured by ozonesondes at Lauder, New Zealand: 1986-1996
Address   GE Bodeker, Natl Inst Water & Atmospher Res, Private Bag 50061, Omakau, Central Otago, New Zealand
Abstract A first analysis of trends in vertical ozone and temperature profiles from ozonesonde flights made at Lauder (45.045 degrees S, 169.684 degrees E) between August 1986 and July 1996, is presented. To calculate the trends and determine the magnitude of the forcing mechanisms underlying the variability in ozone and temperature, a linear least squares

regression model was applied to ozone mixing ratios, ozone number densities, and temperatures, interpolated onto 100 pressure levels from the surface (969 hPa/370 m) to 12.1 hPa (similar to 30.1 km), similar to 300 geopotential meters apart. Ozone trends indicate wintertime upper tropospheric decreases of more than -30+/-24% per decade (2 sigma), post vortex breakup trends in a-narrow altitude region above the tropopause of -20+/-20% per decade (2 sigma), and positive trends of up to 30+/-14% per decade (2 sigma) in the lower stratosphere during late winter, spring, and early summer. The predominant temperature trend is +1.5% per decade and greater above the similar to 50 hPa level during winter. Derived trends were sensitive to inclusion of tropopause height forcing which was found to influence ozone and temperature at a high level of statistical significance. **Ozone at Lauder shows significant QBO dependence throughout the lower stratosphere during winter, spring, and early summer, but little or no dependence on the solar cycle. Temperatures, however, show little dependence on QBO but were influenced by the solar cycle**. The Mt. Pinatubo eruption had little influence on Lauder ozone but significantly cooled the troposphere. The ENSO cycle in ozone and temperature was weak except at the uppermost analysis levels.

Author   S Pawson
Title   **A comparison of reanalyses in the tropical stratosphere. Part 2: The quasi biennial oscillation**
Address   S Pawson, Lawrence Livermore Natl Lab, Program Climate Model, Diag & Intercomparison, Livermore, CA USA

 Abstract Reanalysis datasets potentially offer the opportunity to examine the tropical quasi-biennial oscillation (QBO) in greater detail than in the past, including the associated meridional circulation and the links with other parts of the atmosphere. For such studies to be useful, the QBO represented by the reanalyses should be realistic. In this work, the QBO in the ERA and NCEP reanalyses is validated against rawinsonde observations from Singapore. Monthly mean data are used. In the lower stratosphere (at 50 hPa and 30 hPa) the ERA QBO is reasonable: although the wind extrema in both phases are too weak and the vertical shear and the temperature anomalies are too small. The NCEP QBO is weaker still. At 10 hPa neither reanalysis system performs well, both systems failing to reproduce the westerlies, possibly because of the proximity of the upper boundary. The Singapore wind is representative of the zonal means in the reanalyses. The weak wind extrema in the reanalyses would not support a wave-mean flow interaction theory of the QBO, because a large portion of the gravity wave spectrum which would be absorbed in reality would be transmitted beyond 10 hPa. The stronger shear zones captured in the ERA data, are associated with larger, more realistic temperature perturbations near 30 hPa. The northward velocities in the NCEP data show a more realistic structure than in the ERA reanalysis, where they are dominated by a Vertical "gridpoint wave" structure in the lowermost stratosphere. Despite the shortcomings of the reanalyses, the high correlations of the wind at 30 hPa and 50 hPa with the observations at Singapore mean that the reanalyses could potentially be used to examine the effects of the QBO away from the tropical stratosphere. Future reanalyses need to take full account of the wind shears evident in the rawinsonde observations and use models with an adequate resolution to capture these vertical scales.

Authors   II Mokhov, AV Eliseev
Title   Changes in the characteristics of the quasi-biennial oscillation of zonal wind and temperature in the equatorial lower stratosphere

Address   II Mokhov, Russian Acad Sci, Oboukhov Inst Atmospher Phys, Pyzhevskii per 3, Moscow 109017, Russia
Abstract A diagnosis of cyclic features in the temporal series, including an analysis of phase portraits and their evolution, is used to study the quasi-biennial oscillation (QBO) of wind and temperature in the equatorial lower stratosphere in the past decades. On the whole, **the amplitude and period of the QBO of zonal wind in the 20- to 15-hPa layer have increased in the past decades. The amplitude and period of the QBO of zonal wind are positively correlated**. This relation is most pronounced in the 20- to 10-hPa layer and at the 70-hPa level, and is less pronounced in the 50- to 30-hPa layer. The conditions are found for the positive correlation between the amplitude and period of the QBO in the equatorial lower stratosphere for both a two-layer thermodynamic model of the troposphere-stratosphere system and a model of the Holton-Lindzen type. **A possible relationship between the variability of equatorial QBO characteristics and other processes of climatic variability, including variations in the total ozone in high latitudes, is discussed**.

Authors   D Rind, D Shindell, P Lonergan, NK Balachandran
Title   Climate change and the middle atmosphere. Part III: The doubled CO2 climate revisited
Source   Journal of Climate 11: 5 (MAY 1998)
Page(s)   876-894
Address   D Rind, NASA, Goddard Space Flight Ctr, Inst Space Studies, 2880 Broadway, New York, NY 10025 USA
Abstract **The response of the troposphere-stratosphere system to doubled atmospheric CO2 is investigated in a series of experiments** in which sea surface temperatures are allowed to adjust to radiation imbalances. The Goddard Institute for Space Studies (GISS) Global Climate Middle Atmosphere Model (GCMAM) warms by 5.1 degrees C at the surface while the stratosphere cools by up to 10 degrees C. When ozone is allowed to respond photochemically, the stratospheric cooling is reduced by 20%, with little effect in the troposphere. Planetary wave energy increases in the stratosphere, producing dynamical warming at high latitudes, in agreement with previous GCMAM doubled CO2 simulations; the effect is due to increased tropospheric generation and altered refraction, both strongly influenced by the magnitude of warming in the model's tropical upper troposphere**. This warming also results in stronger zonal winds in the lower stratosphere, which appears to reduce stratospheric planetary wave 2 energy and stratospheric warming events**. The dynamical changes in the lower stratosphere are weakened when O-3 chemistry on polar stratospheric cloud effects are included at current stratospheric chlorine levels. Comparison with the nine-level version of the GISS GCM with a top at 10 hPa shows that both the stratospheric and tropospheric dynamical responses are different. The tropospheric effect is mostly a function of the vertical resolution in the troposphere; finer vertical resolution leads to increased latent heat release in the warmer climate, greater zonal available potential energy increase. and greater planetary longwave energy and energy transports. The increase in planetary longwave energy and residual circulation in the stratosphere is reproduced when the model top is lifted from 30 to 50 km, which also affects upper-tropospheric stability, convection and cloud cover, and climate sensitivity.

Authors   RA Vincent, S Kovalam, DC Fritts, JR Isler
Title   Long-term MF radar observations of solar tides in the low-latitude mesosphere: Interannual variability and comparisons with the GSWM
Source   Journal of Geophysical Research - Atmospheres 103: D8 (APR 27 1998)
Page(s)   8667-8683
Address   RA Vincent, Univ Adelaide, Dept Phys & Math Phys, Adelaide, SA 5005, Australia
Abstract Long-term MF radar wind measurements in the 80-100 km height range made at three equatorial and subtropical sites (Adelaide, Christmas Island, and Kauai) are used to

produce climatologies and to study interannual variability of solar tides. **Twelve years of data were available** for Adelaide and up to 6 years at the other sites and are analyzed in 30-day intervals. The climatological values are compared with the Global Scale Wave Model (GSWM). Good agreement between the measured and model amplitudes and phases is found for the diurnal tide, but the semidiurnal model values agree less well with the observations. The diurnal tidal amplitudes and phases show strong seasonal variability. Maximum amplitudes are attained in March, and subsidiary maxima are observed in July/August and October, while the phase shows an annual cycle at Adelaide and Kauai, with the phase advancing by similar to 4-6 hours from summer to winter. Amplitudes of the semidiurnal tide rarely exceed 10 m s(-1). The phases undergo rapid shifts around the equinoxes at Adelaide and Kauai, but there is a more complicated phase variation at Christmas Island. The diurnal tide shows strong interannual variability in amplitude, especially near the March equinox. **There appears to be an association with the quasi-biennial oscillation (QBO) in zonal winds in the equatorial stratosphere, with the amplitudes being larger than the climatological average in years when the stratospheric winds are eastward and smaller than average when the QBO is in its westward phase.** In contrast, the phase of the diurnal tide, as well as the semidiurnal tide, shows little systematic interannual variability.

Abstract Gravity **Waves (GW) as described with the Doppler Spread Parameterization (DSP) of Hines have been shown to produce significant Quasi-biennial and Semi-annual oscillations (QBO and SAO) in the zonal circulation at equatorial latitudes**. To elucidate the process involved, we discuss computer experiments performed without the external, seasonal variations in solar differential heating, and the conclusions are summarized here. (1) As reported earlier, two kinds of oscillations are then generated spontaneously: one at lower altitudes in the stratosphere which has a long period approaching that of the QBO, the other one at higher altitudes in the mesosphere which has a shorter period close to that of the SAO. The amplitudes of these oscillations are weaker, however, than those generated with seasonal heating. (2) When the time independent solar heating is turned off, the oscillations continue but with significantly reduced period in the mesosphere where the vertical winds driven by solar differential heating produce Doppler shifting. The associated temperature variations are then small, consistent with the one dimensional prototype calculations discussed by Lindzen and Holton. (3) When the GW momentum source is turned off above 40 km to suppress the short-period oscillation, the long-period oscillation below continues with enhanced amplitude and period. When the source is turned off below 35 km, the amplitude of the short-period oscillation increases at higher altitudes, indicative of increased acceleration. (4) The wind oscillations change systematically and dramatically with changing eddy diffusivity/viscosity (K). The amplitudes and periods of both short- and long-period oscillations decrease (increase) with increasing (decreasing) K, and above a certain value of viscosity, both oscillations completely cease. Lowering K thus helps in generating a larger and longer period QBO at lower altitudes, but can be detrimental to the SAO when the natural oscillation period increase significantly above six months. (5) Under oscillation conditions, the height variations in the GW vertical wave numbers reveal a staircase pattern reflecting the intermittence characteristic of the wave interaction. It reveals the nonlinearity of the GW interaction to be of third (odd) order, which has the distinctive property that it can feed and maintain the fundamental harmonic of the oscillation-considered a prerequisite for sustaining the oscillations without external time dependent source. In the companion paper, an analytical model of the equatorial

oscillation is presented which describes some of the trends reported here. (C) 1998 Elsevier Science Ltd. All rights reserved.

Author   TJ Dunkerton
Title   The role of gravity waves in the quasi-biennial oscillation
Source   Journal of Geophysical Research - Atmospheres 102: D22 (NOV 27 1997)
Page(s)   26053-26076
Address   TJ Dunkerton, NW Res Associates Inc, POB 3027, Bellevue, WA 98009 USA

Abstract **The role of gravity wave momentum transport in the quasi-biennial oscillation (QBO) is investigated using a two-dimensional numerical model**. In order to obtain an oscillation with realistic vertical structure and period, vertical momentum transport in addition to that of large-scale, long-period Kelvin and Rossby-gravity waves is necessary. The total wave flux required for the QBO is sensitive to the rate of upwelling, due to the Brewer-Dobson circulation, which can be estimated from the observed ascent of water vapor anomalies in the tropical lower stratosphere. Although mesoscale gravity waves contribute to mean flow acceleration, it is unlikely that the momentum flux in these waves is adequate for the QBO, especially if their spectrum is shifted toward westerly phase speeds. Short-period Kelvin and inertia-gravity waves at planetary and intermediate scales also transport momentum. Numerical results suggest that the flux in all vertically propagating waves (planetary-scale equatorial modes, intermediate inertia-gravity waves, and mesoscale gravity waves), in combination, is sufficient to obtain a QBO with realistic Brewer-Dobson upwelling if the total wave flux is 2-4 times as large as that of the observed large-scale, long-period Kelvin and Rossby-gravity waves. Lateral propagation of Rossby waves from the winter hemisphere is unnecessary in this case, although it may be important in the upper and lowermost levels of the QBO and subtropics

Authors   **K Labitzke, H van Loon**
Title   **The signal of the 11-year sunspot cycle in the upper troposphere lower stratosphere**
Source   Space Science Reviews 80: 3-4 (MAY 1997)
Page(s)   393-410
Address   K Labitzke, Free Univ Berlin, Inst Meteorol, Stratospher Res Grp, D-12165 Berlin, Germany

Abstract **The paper summarizes work by the authors over the past ten years on an apparent signal of the 11-year sunspot cycle in the lower stratosphere-upper troposphere**. The signal appears as a basic, consistent pattern in correlations between heights of stratospheric constant-pressure levels, at least as high as 25 km, and the solar cycle in which the highest correlations are in the subtropics.

The variation of the stratospheric heights in phase with the sunspot cycle are - in the areas of high correlations between the two - associated with temperature variations on the same time scale in the middle and upper troposphere. The spatial distribution of the correlations suggests that the year-to-year changes in tropical and subtropical vertical motions contain a component on the time scale of the solar cycle.

In January and February the correlations with the sunspot cycle are smallest. The smallness of the correlations is owing to the fact that they are different in the east and west years of the quasi-biennial oscillation in the equatorial stratospheric winds. The correlation pattern in the east years is the same as in the other seasons and is statistically significant. In the west years the correlations are insignificant outside the arctic, and the positive correlation in the arctic in these years is related to the fact that major midwinter breakdowns of the cyclonic vortex in the west years so far have happened only at maxima in the solar cycle.

Until recently reliable continuous series of analyses of the stratosphere were not available for the southern hemisphere. The U.S. National Centers for Environmental Prediction and the National Center for Atmospheric Research have now, however, issued a 23-year series of re-

analyzed global data which has made it possible to detect the solar signal on the southern hemisphere. It turns out to be almost the same as that on the northern hemisphere.
The correlations between total column ozone and the sunspot cycle are lowest in the equatorial regions, where ozone is produced, and in the subpolar regions, where the largest amounts are found. In the annual mean the largest correlations lie between 5 degrees lat. and 30 degrees lat. We suggest that this distribution of correlations is due to the fact that the subtropical heights of the constant-pressure surfaces in the ozone layer are higher in maximum than in minimum years of the sunspot cycle, and that the higher subtropical heights in the solar maxima depress the poleward transport of ozone through the subtropics and thus create an abundance of ozone.

Authors   RP Kane, RA Buriti
Title   Latitude and altitude dependence of the interannual variability and trends of atmospheric temperatures
Address   RP Kane, Inst NaCl Pesquisas Espaciais, Caixa Postal 515, BR-12201970 S Jose Campos, Sp, Brazil
Abstract The 4-season (12-month) running means of temperatures at five atmospheric levels (surface, 850-300 hPa, 300-100 hPa, 100-50 hPa, 100-30 hPa) and seven climatic zones (60 degrees N-90 degrees N, 30 degrees N-60 degrees N, 10 degrees N-30 degrees N, 10 degrees N-10 degrees S, 10 degrees S-30 degrees S, 30 degrees S-60 degrees S, 60 degrees S-90 degrees S) showed QBO (Quasi-biennial Oscillation), QTO (Quasi-triennial Oscillation) and larger periodicities. For stratosphere and tropopause, the temperature variations near the equator and North Pole somewhat resembled the 50 hPa low latitude zonal winds, mainly due to prominent QBO. For troposphere and surface, the temperature variations, especially those near the equator, resemble those of eastern equatorial Pacific sea-surface temperatures, mainly due to prominent QTO. In general, the temperature trends in the last 35 years show stratospheric cooling and tropospheric warming. But the trends are not monotonic. For example, the surface trends were downward during 1960-70, upward during 1970-82, downward during 1982-85 and upward thereafter. Models of green-house warming should take these non-uniformities into account.

Authors   MJ Alexander, JR Holton
Title   A model study of zonal forcing in the equatorial stratosphere by convectively induced gravity waves
Address   JR Holton, Univ Washington, Dept Atmospher Sci, Box 351640, Seattle, WA 98195 USA
Abstract A two-dimensional cloud-resolving model is used to examine the possible role of gravity waves generated by a simulated tropical squall line in forcing the quasi-biennial oscillation (QBO) of the zonal winds in the equatorial stratosphere. A simulation with constant background stratospheric winds is compared to simulations with background winds characteristic of the westerly and easterly QBO phases, respectively. In all three cases a broad spectrum of both eastward and westward propagating gravity waves is excited. In the constant background wind case the vertical momentum flux is nearly constant with height in the stratosphere, after correction for waves leaving the model domain. In the easterly and westerly shear cases, however, westward and eastward propagating waves, respectively, are strongly damped as they approach their critical levers, owing to the strongly scale-dependent vertical diffusion in the model. The profiles of zonal forcing induced by this wave damping are similar to profiles given by critical level absorption, but displaced slightly downward. The magnitude of the zonal forcing is of order 5 m s(-1) day(-1). It is estimated that if 2% of the area of the

Tropics were occupied by storms of similar magnitude, mesoscale gravity waves could provide nearly 1/4 of the zonal forcing required for the QBO.

Authors   CS Zerefos, K Tourpali, BR Bojkov, DS Balis, B Rognerund, ISA Isaksen
Title   Solar activity total column ozone relationships: Observations and model studies with heterogeneous chemistry
Source   Journal of Geophysical Research - Atmospheres 102: D1 (JAN 20 1997)
Page(s)   1561-1569
Address   CS Zerefos, Aristotelian Univ Thessaloniki, Lab Atmospher Phys, Dept Phys, Thessaloniki 54006, Greece

Abstract In the present paper we examine the effect of long-term solar variability on total column ozone using the longest available ground-based (1964-1994) and satellite (1979-1992) zonally averaged total column ozone records. Numerical Simulations with a two-dimensional (2-D) model, which incorporates heterogeneous chemistry, transport, and the representation of the long-term solar variability, are compared to the observations. Our analysis of the total column ozone records shows that the solar activity signal in total column ozone is better seen in the tropics and during periods with no volcanoes and no synergistic effects from El Nino-Southern Oscillation (ENSO) and quasibiennial oscillation (QBO). On decadal timescales the solar activity component in total column ozone is confirmed to have a relatively small amplitude (1-2% of the 1964-1994 mean). The slowly varying decadal solar activity component in total column ozone has an amplitude 3 to 5 times larger than that of the 27-day solar rotation oscillation as seen in total ozone. The observations confirm model calculations of a larger amplitude in total column ozone at solar maximum as compared to solar activity minimum conditions for the 27-day period. The heterogeneous 2-D chemical transport model results are in good agreement with the long-term ground-based observations. It is noted that in the tropics both the interannual variability of total column ozone and the long-term impact from chlorofluorocarbons (CFCs) through the action of polar stratospheric clouds (PSCs) are small and therefore the 1-2% solar activity signal in the data can be more clearly seen above the noise level at these lower latitudes.

Authors   MD Burrage, RA Vincent, HG Mayr, WR Skinner, NF Arnold, PB Hays
Title   Long-term variability in the equatorial middle atmosphere zonal wind
Source   Journal of Geophysical Research - Atmospheres 101: D8 (MAY 27 1996)
Page(s)   12847-12854
Address   MD Burrage, Univ Michigan, Space Phys Res Lab, 2455 Hayward St, Ann Arbor, MI 48109 USA

Abstract The high resolution Doppler imager (HRDI) on the Upper Atmosphere Research Satellite (UARS) has provided measurements of the horizontal wind field in the stratosphere, mesosphere, and lower thermosphere since November 1991. This data set, which spans a period of more than 3 years, has facilitated an investigation of the long-term behavior of the background circulation on a nearly global basis. At middle and high latitudes the zonal circulation is characterized by an annual oscillation. At low latitudes (+/-30 degrees) the most prominent long-term variation above the stratopause is the mesosphere semiannual oscillation (MSAO), which maximizes near the equator at an altitude of between 80 and 85 km. **Further analysis of the time series reveals an additional strong variation, with an amplitude near 30 ms(-1) and a period of about 2 years. This feature shows the same altitude and latitude structure as the MSAO and exhibits a phase relationship with the stratospheric quasi-biennial oscillation (QBO). Observations from the Christmas Island MF radar (2 degrees N, 130 degrees W) confirm the presence of this mesospheric QBO (MQBO).** These observations support recent findings from a modeling study which generates an MQBO via the selective filtering of small-scale gravity waves by the underlying winds they traverse.

Authors   P Keckhut, A Hauchecorne, ML Chanin

Title   Midlatitude long-term variability of the middle atmosphere: Trends and cyclic and episodic changes
Source   Journal of Geophysical Research - Atmospheres 100: D9 (SEP 20 1995)
Page(s)   18887-18897
Address   P Keckhut, CNRS, Serv Aeron, BP 3, F-91371 Verrieres Buisson, France

Abstract A study of variability and long-term trend detection in the middle atmosphere is performed using the temperature database obtained since 1979 by French Rayleigh lidars at 44 degrees N. A multivariable analysis is used to consider natural variability, including solar activity, quasi biennial oscillation (QBO), and volcanic eruption effects. As the solar proxy has an important role in this analysis, its choice is first discussed. Changes induced by solar activity reported here, mainly large negative correlation observed in the winter upper stratosphere, are not reproduced by numerical models without an unrealistic solar UV change. A significant warming of 6 K in the mesosphere is observed in summer 1992 and 1993. This large change could be due to aerosols injected in the stratosphere by the Mount Pinatubo eruption. Observed volcanic aerosol effects are compared with some numerical simulations and are shown to present some agreements. A long-term cooling of 0.4 K/year is observed in the mesosphere that is statistically significant but is larger than anthropogenic effects simulated in numerical models. In the upper stratosphere the small trend observed is not yet significant but in better agreement with model predictions.

Authors   GP Gobbi, C Souprayen, F Congeduti, G Didonfrancesco, A Adriani, M Viterbini, S Centurioni
Title   Lidar observations of middle atmosphere temperature variability
Source   Annales Geophysicae - Atmospheres Hydrospheres and Space Sciences 13: 6 (JUN 1995)
Page(s)   648-655
Address   GP Gobbi, CNR, Ist Fis Atmosfera, I-00044 Frascati, Italy

Abstract We discuss 223 middle atmosphere lidar temperature observations. The record was collected at Frascati (42 degrees N-13 degrees E), during the 41-month period January 1989-May 1992, corresponding to the maximum of solar cycle 22. The choice of this interval was aimed at minimizing the temperature variability induced by the 11-year solar cycle. The average climatology over the 41-month period and comparison with a reference atmosphere (CIRA86) are presented. Monthly temperature variability over the full period, during opposite quasi-biennial oscillation phases and on a short-term scale (0.5-4 h), is analyzed. Results indicate the 50-55-km region as less affected by variability caused by the natural phenomena considered in the analysis. Due to this minimum in natural noise characterizing the atmospheric temperature just above the stratopause, observations of that region are well suited to the detection of possible temperature trends induced by industrial activities.

Authors   P Mlch, J Lastovicka
Title   Total ozone response to major geomagnetic storms and changes in meteorological situations
Source   Studia Geophysica et Geodaetica 39: 2 (1995)
Page(s)   189-207
Address   P Mlch, Acad Sci Czech Republ, Inst Atmospher Phys, Bocni II-1401, CR-14131 Prague 4, Czech Republic

Abstract The total ozone response to strong major geomagnetic storms (A(p) greater than or equal to 60) in winter along the 50 degrees N latitudinal circle is studied. The results add to the recent results of Lastovicka et al. (1992) obtained for European middle latitudes (similar to 50 degrees N) and to the results of Mlch (1994). **A significant response of total ozone is only observed in winter under high solar activity/E-phase of QBO conditions (E-max) and seems to be caused by geomagnetic storm-induced changes of atmospheric dynamics**. There are two sectors along latitude 50 degrees N, which are sensitive to forcing by

geomagnetic storms both in total ozone and the troposphere - north-eastern Atlantic-European and eastern Siberia-Aleutian sectors. The total ozone response under E-max conditions manifests itself mainly as a large decrease in the longitudinal variation of ozone after the storm, which means an increase of ozone in Europe. The observed effects in total ozone consist in redistribution, not production or loss of ozone.

Authors   SD Eckermann, I Hirota, WK Hocking
Title   Gravity wave and equatorial wave morphology of the stratosphere derived from long-term rocket soundings
Address   SD Eckermann, Computat Phys Inc, Suite 600, 2750 Prosper Ave, Fairfax, VA 22031 USA

Abstract Fluctuations in vertical profiles of atmospheric temperature and horizontal wind in the 20-60 km altitude range have been isolated from meteorological rocket measurements during 1977-87 at 15 widely separated sites. The seasonal, geographical, and vertical variability of the variance of horizontal velocities, $u'(2) + v'(2)$, and relative-temperature perturbations, $T*'(2)$, were studied. The bulk of the variance of both quantities in the 2-10 km and 2-20 km vertical-wavelength bands was associated with gravity-wave motions, although in-depth study of the wave polarization shows that planetary-scale equatorial wave modes contribute to the variance at equatorial sites. Annual mean variances varied widely among the 15 stations, suggesting appreciable geographical variability in stratospheric wave activity. Whereas $u'(2) + v'(2)$ values generally increased significantly with altitude throughout the stratosphere, $T*'(2)$ values grew less substantially and often decreased with altitude at upper heights. Rotations of wave-velocity phasors with height were always more frequently clockwise than anticlockwise in the northern hemisphere, consistent with upward-propagating wave energy, yet these percentages (>50%) showed a marked semi-annual variation, with equinoctial maxima and minima at the solstices. At high latitudes (similar to 50 degrees N-80 degrees N) variances exhibited a strong annual variation, with the minimum in summer and a strong peak during winter at both lower (20-40 km) and upper (40-60 km) heights. The annual variance cycle attenuated somewhat at mid-latitudes (similar to 25 degrees N-40 degrees N), and a strong peak in August dominated the $u'(2) + v'(2)$ variations at 40-60 km. The peak was also evident in $T*'(2)$, but was smaller relative to the winter peak. At low latitudes (similar to 15 degrees N-25 degrees N) the wave morphology was broadly similar to that at mid-latitudes, apart from an additional upper-level peak in the variance in May. This peak in May occurred in some years but not in others at mid-latitude stations. At the equatorial stations (similar to 10 degrees N-10 degrees S) the low-level variance showed little systematic seasonal variability, but exhibited clear modulation over a quasi-two-year period. **Much of this variance was consistent with the Kelvin modes thought to drive the eastward phase of the stratospheric quasibiennial oscillation (QBO). However, the uniform east-west alignment of waves was inconsistent with the expected polarization of the mixed Rossby-gravity wave mode which is believed to drive the westward phase of the QBO**. At 40-60 km, the variance was strongly attenuated around April-May and November, when both $u'(2) + v'(2)$ and $T*'(2)$ decreased with height around the 40-45 km range, indicating that wave dissipation occurs here. This produced a semi-annual variation at upper heights, with maxima around January and July, which may contribute significantly to the semi-annual wave driving of the equatorial upper stratosphere. Polarization studies showed that this variance in the 2-10 km band was mostly due to gravity waves, although equatorial modes contributed during December-February.

Author   GC Reid
Title   Seasonal and interannual temperature variations in the tropical stratosphere

Address   GC Reid, NOAA, Aeron Lab, 325 Broadway, Boulder, CO 80303 USA

Abstract **Temperature variations in the tropical lower and middle stratosphere are influenced by at least five distinct driving forces. These are (1) the mechanism of the regular seasonal cycle, (2) the quasi-biennial oscillation (QBO) in zonal winds, (3) the semiannual zonal wind oscillation (SAG) at higher levels, (4) El Nino-Southern Oscillation (ENSO) effects driven by the underlying troposphere, and (5) radiative effects**, including volcanic aerosol heating. Radiosonde measurements of temperatures from a number of tropical stations, mostly in the. western Pacific region, are used in this paper to examine the characteristic annual and interannual temperature variability in the stratosphere below the 10-hPa pressure level (similar to 31 km) over a time period of 17 years, chosen to eliminate or at least minimize the effect of volcanic eruptions. Both annual and interannual variations are found to show a fairly distinct transition between the lower and the middle stratosphere at about the 35-hPa level (similar to 23 km). The lower stratosphere, below this transition level, is strongly influenced by the ENSO cycle as well as by the QBO. The overall result of the interaction is to modulate the amplitude of the normal stratospheric seasonal cycle and to impose a biennial component on it, so that alternate seasonal cycles are stronger or weaker than normal. Additional modulation by the ENSO cycle occurs at its quasi-period of 3-5 years, giving rise to a complex net behavior. In the middle stratosphere above the transition level, there is no discernible ENSO influence, and departures from the regular semiannual seasonal cycle are dominated by the QBO. Recent ideas on the underlying physical mechanisms governing these variations are discussed, as is the relationship of the radiosonde measurements to recent satellite remote-sensing observations.

Authors   SP Namboothiri, CE Meek, AH Manson

Title   Variations of Mean Winds and Solar Tides in the Mesosphere and Lower Thermosphere over Time Scales Ranging from 6 Months to 11 Yr - Saskatoon, 52 degrees N, 107 degrees W

Address   SP Namboothiri, Univ Saskatchewan, Inst Space & Atmospher Studies, Saskatoon S7N 0W0, Saskatchewan, Canada

Abstract The MF radar (spaced antenna) winds technique has been used to measure mean winds at Saskatoon (52-degrees-N, 107-degrees-W), Canada for over a solar cycle. The data from 1974 to 1991 are used to study different periods of oscillation such as 24-, 12-, 6- and 3-month oscillation etc. The mean wind and tidal data are also analyzed with a special emphasis upon solar activity and the possible influence of the equatorial quasi-biennial oscillation (QBO) on mesospheric circulation. The various analyses of the data stress the solar activity influence on mean winds and semidiurnal tidal amplitudes. While a range of periods of oscillation is observed in zonal and meridional winds during 12 yr, the zonal winds are more characterized with a 2-yr period of oscillation. At certain mesospheric heights, the 26-month period least squares fits to zonal winds as well as the frequency spectra clearly indicate a QBO of the mesospheric wind pattern. The study of the amplitudes and phases of the 24-, 12-, 6- and 3-month oscillation shows that there are trends of solar modulation in some height ranges for the 12-, 6- and 3-month oscillation.

4   RECENT PUBLICATIONS ON THE CONNECTION BETWEEN THE QBO, THE SOLAR CYCLE AND STRATWARMS

Authors   H vanLoon, DJ Shea
Title   **The global 11-year solar signal in July-August**
Address   van Loon H, Natl Ctr Atmospher Res, POB 3000, Boulder,CO 80307 USA

Abstract   During the past 41 years there has been an observable effect of the 11-year solar cycle on the temperatures and heights in the levels between the middle troposphere and 10 hPa (the highest level in the data) in July-August. Between 30 degrees S and the North Pole the temperatures and heights were higher at peaks than in valleys of the solar cycle, between 30 degrees S and 70 degrees S they were lower in the peaks, and above Antarctica they were higher. This meridional pattern of differences and the fact that they decrease with decreasing elevation suggest that the solar signal observed below 10 hPa is imposed from above as an indirect, dynamic effect. The pattern of the temperature and height differences indicates that the solar cycle affects the southern winter and northern summer stratospheric vortices. At the earth's surface an 11-year solar signal is not obvious in the zonally averaged temperatures and pressures in July-August.

Authors   M Salby, P Callaghan
Title   **Connection between the solar cycle and the QBO: The missing link**
Full source   Journal of Climate, 2000, Vol 13, Iss 14, pp 2652-2662
Address   Salby M, Univ Colorado, Campus Box 311, Boulder,CO 80309 USA
Abstract   Evidence of the solar cycle in stratospheric polar temperature rests on a connection to the quasi-biennial oscillation (QBO) of equatorial wind. New evidence reported here establishes a mechanism for how the solar signature in polar temperature follows from the QBO, which itself is shown to vary with the solar cycle. Equatorial westerlies below 30 hPa vary systematically with solar activity, as do equatorial easterlies above 30 hPa. Changes in their duration introduce a systematic drift into the QBO's phase relative to winter months, when the polar vortex is sensitive to equatorial wind. Corresponding changes in the polar-night vortex are consistent with the solar signature observed in wintertime records of polar temperature that have been stratified according to the QBO.

Authors   K Labitzke, H vanLoon
Title   **The QBO effect on the solar signal in the global stratosphere in the winter of the Northern Hemisphere**
Full source   Journal of Atmospheric and Solar - Terrestrial Physics, 2000, Vol 62, Iss 8, pp 621-628
Address   Labitzke K, Free Univ Berlin, Inst Meteorol, CH Beckerweg 6-10, D-12165 Berlin, GERMANY
Abstract   This paper contains correlations between the NCEP/NCAR global stratospheric data below 10 hPa and the 11-year solar cycle. In the north summer the correlations between the stratospheric geopotential heights and the 11-year solar cycle are strong and positive on the Northern Hemisphere and as far south as 30 degrees S, whereas they are weak in the north winter all over the globe. If the global stratospheric heights and temperatures in the north winter are stratified according to the phase of the QBO in the lower stratosphere, their correlations with the solar cycle are large and positive in the Arctic in the west years of the QBO but insignificantly small over the rest of the earth, as far as the South Pole. In the east years, however, the arctic correlations with the solar cycle are negative, but to the south they are positive and strong in the tropical and temperate regions of both hemispheres, similar to the correlations with the full series of stratospheric data in the other seasons. The influence of the solar cycle in the Arctic is stronger in the latter half of the winter. The global difference, in the northern winter, in the sign and strength of the correlations between the stratospheric heights and temperatures and the solar cycle in east and west years of the QBO can be ascribed to the fact that the dominant stratospheric teleconnection and the solar influence work in the same direction in the east years, but oppose each other in the west years.

Authors   M Bittner, D Offermann, HH Graef
Title   Mesopause temperature variability above a midlatitude station in Europe

Address   Bittner M, Deutsch Fernerkundungsdatenzentrum, Deutsch Zentrum Luft & Raumfahrt, D-82234 Wessling, GERMANY
Abstract   More than 2000 mean night temperatures (1987-1995) were derived from OH* near-infrared emissions in the upper mesosphere (around 87 km) above Wuppertal (51 degrees N, 7 degrees E) from ground-based measurements. Variations of 4-50 days' period were analyzed using maximum entropy and wavelet methods. A climatology showing the seasonal dependence of occurrence and long-term evolution of the strength of these variations is presented. While longer period oscillations (greater than similar to 10 days' period) are observed to be more frequent during local winter and almost absent during local summer. There is an opposite behavior for the shorter period oscillations. **Temperature oscillation amplitudes are found to be modulated with a quasi 2 year oscillation. It is believed that the quasi-biennal oscillation is responsible for these modulations.** A long-term trend showing an increase of about 16% per decade is found in the temperature variability. Furthermore, positive and negative long-term trends are found in the temporal evolution of temperature oscillation amplitudes. A possible relationship to solar activity is investigated. Evidence is found that shorter period oscillations (smaller than similar to 20-25 days) are anticorrelated while longer period oscillations are correlated with solar activity.

Author   B Soukharev
Title   **On the solar/QBO effect on the interannual variability of total ozone and the stratospheric circulation over Northern Europe**
Address   Soukharev B, St Petersburg State Univ, Dept Climatol, 10 Linia 33, St Petersburg 199171, RUSSIA
Abstract   Based on total ozone data from the World Ozone Data Center and stratospheric geopotential height data from the Meteorological Institute of Berlin Free University for the months of January through March for the time period of 1958-1996, the influence of the 11-year solar cycle and the equatorial quasi-biennial oscillation (QBO) on total ozone and the stratospheric circulation at 30 hPa over Northern Europe is investigated. The analysis is performed for different levels of solar activity. The relationship of the equatorial QBO with ozone and the stratospheric circulation over the study region exhibits unique features attributed to strong opposite connections between the equatorial zonal wind and ozone/stratospheric dynamics during periods of solar minimum and maximum. Using the Solar/QBO effect, a statistical extraction of the interannual variations of total ozone and stratospheric circulation over Northern Europe has been attempted. The variations extracted and observed for late winter show very good correspondence, The solar/QBO effect in total ozone and stratospheric dynamics over Northern Europe appears to be related to planetary wave activity.

Authors   AA Scaife, IN James
Title   **Response of the stratosphere to interannual variability of tropospheric planetary waves**
Address   Scaife AA, Meteorol Off, Bracknell RG12 2SZ, Berks, ENGLAND
Abstract   A primitive-equation global model of the middle atmosphere is used to investigate the response of the extratropical stratosphere to different levels of wave forcing from steady perturbations of the geopotential height near the tropopause. The response of the stratosphere is compared to that in quasi-geostrophic beta-plane models used in previous studies. The primitive-equation model exhibits three flow regimes under perpetual-January conditions: strong westerly, steady flow for small wave-amplitude forcing, strong westerly but

unsteady flow for moderate wave-amplitude forcing and oscillations between easterly and westerly flow for large wave-amplitude forcing. The regimes for low and high forcing are analogous to solutions of the simpler Holton-Mass (HM) quasi-geostrophic model. The moderate-forcing regime does not occur in the HM model and it is attributed to instability of the strongly sheared flow generated by planetary waves in the upper stratosphere. We also show how the observed patterns of interannual variability in the winter stratosphere can be explained in terms of these three flow regimes: in the northern hemisphere the flow often enters the high-forcing regime, where variations in conditions in the early-winter how or quasi-steady upper-tropospheric planetary-wave amplitudes make similar contributions to the interannual variability in the stratospheric circulation. For the southern hemisphere, we suggest that the flow alternates between the low- and moderate-forcing regimes through year-to-year changes in the amplitude of quasisteady waves near the tropopause. This mechanism produces large enough changes to explain the interannual variability in the southern stratosphere.

Authors   NK Balachandran, D Rind, P Lonergan, DT Shindell
Title   Effects of solar cycle variability on the lower stratosphere and the troposphere
Full source   Journal of Geophysical Research - Atmospheres, 1999, Vol 104, Iss D22, pp 27321-27339
Address   Balachandran NK, NASA, Goddard Inst Space Studies, 2880 Broadway, New York, NY 10025 USA

Abstract   The effects of solar irradiance variability on the lower stratosphere and the troposphere are investigated **using observed and general circulation model (GCM) generated 30 and 100 hPa geopotential heights**. The GCM includes changes in UV input (+ or -5% at wavelengths below 0.3 micron and no ozone photochemistry and transport) to roughly approximate the combined effects of UV and ozone changes associated with the solar variability. The annual and seasonal averages of the height differences between solar maximum and solar minimum conditions are evaluated. In the subtropics, observations indicate statistically highly significant increased geopotential heights during solar maximum, compared to solar minimum, in composite annual and seasonal averages. The model simulates this feature reasonably well, although the magnitude and statistical significance of the differences are often weaker than in observations, especially in summer. Both the observations and the model results show a strong dipole pattern of height differences when the data are partitioned according to the phase of the quasi-biennial oscillation (QBO), with the pattern reversing itself with the change in the phase of the QBO. The connection between solar variability and lower atmospheric charges are interpreted as follows: The solar changes directly affect the stratosphere by changing the vertical gradients of temperature and zonal wind. This leads to changes in propagation conditions for planetary waves resulting in changes of E-P flux divergence and then by the downward control principle, affecting the circulation in the lower stratosphere and the troposphere.

Authors   JS Kinnersley, KK Tung
Title   **Mechanisms for the extratropical QBO in circulation and ozone**
Source   Journal of the Atmospheric Sciences 56: 12 (JUN 15 1999)
Page(s)   1942-1962
Address   JS Kinnersley, Univ Washington, Dept Appl Math, Box 352420, Seattle, WA 98195 USA

Abstract A two-and-a-half-dimensional interactive stratospheric model(i.e., a zonally averaged dynamical-chemical model combined with a truncated spectral dynamical model), whose equatorial zonal wind was relaxed toward the observed Singapore zonal wind, was able to reproduce much of the observed quasi-biennial oscillation (QBO) variability in the column ozone, in its vertical distribution in the low and middle latitudes, and also in the high southern polar latitudes. To reveal the mechanisms responsible for producing the modelled QBO signal over the globe, several control runs were also performed. The authors find that the ozone

variability in the lower stratosphere - and hence also in the column - is determined mainly by two dynamical mechanisms. In the low to midlatitudes it is created by a "direct QBO circulation." Unlike the classic picture of a nonseasonal two-cell QBO circulation symmetric about the equator, a more correct picture is a direct QBO circulation that is strongly seasonal, driven by the seasonality in diabatic heating, which is very weak in the summer hemisphere and strong in the winter hemisphere at low and midlatitudes. This anomalous circulation is what is responsible for creating the ozone anomaly at low and midlatitudes. Transport by the climatological circulation and diffusion is found to be ineffective. At high latitudes, there is again a circulation anomaly, but here it is induced by the modulation of the planetary wave potential vorticity Aux by the QBO. This so-called Holton-Tan mechanism is responsible for most of the QBO ozone signal poleward of 60 degrees During spring in the modeled northern polar region, chaotic behavior is another important source of interannual variability, in addition to the interannual variability of planetary wave sources in the troposphere previously studied by the authors.

Authors   D Shindell, D Rind, N Balachandran, J Lean, P Lonergan
Title   **Solar cycle variability, ozone, and climate**
Source   **Science** 284: 5412 (APR 9 1999)
Page(s)   305-308
Address   D Shindell, NASA, Goddard Inst Space Studies, 2880 Broadway, New York, NY 10025 USA
Abstract Results from a global climate model including an interactive parameterization of stratospheric chemistry show how upper stratospheric ozone changes may amplify observed, 11-year solar cycle irradiance changes to affect climate. In the model, circulation changes initially induced in the stratosphere subsequently penetrate into the troposphere, demonstrating the importance of the dynamical coupling between the stratosphere and troposphere. The model reproduces many observed 11-year oscillations, including the relatively long record of geopotential height variations; hence, it implies that these oscillations are likely driven, at least in part, by solar variability.

Authors   H Vanloon, K Labitzke
Title   **The signal of the 11-year solar cycle in the global stratosphere**
Source   Journal of Atmospheric and Solar - Terrestrial Physics 61: 1-2 (JAN 1999)
Page(s)   53-61
Address   H Vanloon, NCAR, Boulder, CO 80307 USA
Abstract The search for a signal of the 11-year sunspot cycle in the heights and temperatures of the lower stratosphere was previously successfully conducted for the northern hemisphere with a data set from the Freie Universitat Berlin, covering four solar cycles. This work has been extended to the whole globe by means of the NCEP/NCAR reanalyses for the period 1968-1996. The re-analyses show that the signal exists in the southern hemisphere too, and that it is of nearly the same size and shape as on the northern hemisphere. The NCEP/NCAR reanalyses yield higher correlations with the solar cycle than do the Berlin analyses for the same period, because the interannual variability is lower in the NCEP/NCAR data.
The correlations between the solar cycle and the zonally averaged temperatures at the standard levels between 200 and 10 hPa are largest between the tropopause and the 25 km level, that is, in the ozone layer. This may be partly a direct effect in this layer? because of more absorber (ozone) and more ultraviolet radiation from the sun in the peaks of the 11-year solar cycle. However, it is more likely to be mainly an indirect dynamical consequence of UV absorption by ozone in the middle and upper stratosphere.
 The largest temperature correlations move with the sun from one summer hemisphere to the other, and the largest height correlations move poleward from winter to summer.

Authors   MP Baldwin, TJ Dunkerton

Title   Quasi-biennial modulation of the southern hemisphere stratospheric polar vortex
Source   Geophysical Research Letters 25: 17 (SEP 1 1998)
Page(s)   3343-3346
Address   MP Baldwin, NW Res Associates Inc, POB 3027, Bellevue, WA 98009 USA

Abstract Observations reveal that the wintertime southern hemisphere stratospheric polar vortex is modulated by the phase of the equatorial quasi-biennial oscillation (QBO). The high-latitude southern stratosphere is shown to be slightly colder throughout the winter, and the final warming occurs later, when the QBO is in its west phase. During May-October, the modulation of winds by the QBO is confined to midlatitudes, at the edge of the polar vortex. The difference between west and east phase composites of zonal mean wind during November, at the time of the final warming in the southern hemisphere, exceeded 14 ms(-1). This difference is very similar to that in January in the northern hemisphere. While northern hemisphere QBO effects are optimized using equatorial winds near 40 hPa, southern hemisphere effects are best seen using similar to 25 hPa winds.

Authors   KK Tung, H Yang
Title   Global QBO in Circulation and Ozone .2. A Simple Mechanistic Model
Source   Journal of the Atmospheric Sciences 51: 19 (OCT 1 1994)
Page(s)   2708-2721
Address   KK Tung, Univ Washington, Dept Appl Math FS20, Seattle, WA 98195 USA

Abstract **Although the phenomenon of equatorial quasi-biennial oscillation is relatively well understood, the problem of how the equatorially confined QBO wave forcing can induce a signal in the extratropics of comparable or larger magnitude remains unsolved**. A simple mechanistic model is constructed to provide a quantitative test of the hypothesis that the phenomenon of extratropical QBO is mainly caused by an anomalous seasonal circulation induced by an anomalous Eliassen-Palm flux divergence. The anomaly in E-P flux divergence may be caused in turn by the relative poleward and downward shift of the region of irreversible mixing (breaking) of the extratropical planetary waves during the easterly phase of the equatorial QBO as compared to its westerly phase. The hemispheric nature of the anomaly wave forcing in solstice seasons (viz., no wave breaking in the summer hemisphere) induces a global circulation anomaly that projects predominantly into the first few zonal Hough modes of Plumb. Such a global QBO circulation pattern, although difficult to measure directly, is reflected in the distribution of stratospheric tracers transported by it. Our model produces a global pattern of QBO anomaly in column ozone that appears to account for much of the unfiltered interannual variability in the column ozone observed by the TOMS instrument aboard the Nimbus satellite. Furthermore, the model produces the characteristic spectrum of the observation with peaks at periods of 20 and 30 months.

Author   B Soukharev
Title   The sunspot cycle, the QBO, and the total ozone over northeastern Europe: a connection through the dynamics of stratospheric circulation
Source   Annales Geophysicae - Atmospheres Hydrospheres and Space Sciences 15: 12 (DEC 1997)
Page(s)   1595-1603
Address   B Soukharev, St Petersburg State Univ, Dept Climatol, 10 Linia, St Petersburg 199178, Russia

Abstract **The interaction between the factors of the quasi-biennial oscillation (QBO) and the 11-year solar cycle is considered as an separate factor influencing the interannual January-March variations of total ozone over Northeastern Europe**. Linear correlation analysis and the running correlation method are used to examine possible connections between ozone and solar activity at simultaneous moment the QBO phase. Statistically significant correlations between the variations of total ozone in February and, partially, in March, and the sunspot numbers during the different phases of QBO are found. The running correlation

method between the ozone and the equatorial zonal wind demonstrates a clear modulation of 11-y solar signal for February and March. Modulation is clearer if the QBO phases are defined at the level of 50 hPa rather than at 30 hPa. The same statistical analyses are conducted also for possible connections between the index of stratospheric circulation C-1 and sunspot numbers considering the QBO phase. Statistically significant connections are found for February. The running correlations between the index C-1 and the equatorial zonal wind show the clear modulation of 11-y solar signal for February and March. Based on the obtained correlations between the interannual variations of ozone and index C-1, it may be concluded that a connection between solar cycle QBO - ozone occurs through the dynamics of stratospheric circulation.

Author   BE Soukharev
Title   **The interannual variability of temperature in the polar stratosphere during the winter: The influence of the QBO phase and an 11-yr solar cycle**
Address   BE Soukharev, St Petersburg State Univ, Fac Geog & Geoecol, Dept Climatol, 10 Linia, St Petersburg 199178, Russia
Abstract The relation between the temperature of polar stratosphere in winter (from November until March), the phase of the QBO, and the activity of the 11-yr sunspot cycle is investigated. The results obtained by defining the QBO phase separately at 30 and 50 hPa are compared. It is shown that the large distinction in the distribution of major warming cases at various QBO phases exists depending on how the QBO phase is defined (at 30 or 50 hPa). A correlation analysis of the relation of the stratospheric temperature during different QBO phases and the activity of the 11-yr solar cycle has shown that there is significant (99%) correlation only in the westerly phase of QBO, and in February. Comparisons of cases of major winter stratospheric warmings during different phases of QBO with periods of high and low activity of 11-yr sunspot cycle do not result in such a simple conclusion. If warmings not only in January and February are considered, then during westerly and easterly phases of QBO the warmings are observed both in periods of high and low solar activity.

Author   MJ Jarvis
Title   Quasi-biennial oscillation effects in the semidiurnal tide of the Antarctic lower thermosphere
Address   MJ Jarvis, British Antarctic Survey, NERC, Madingley Rd, Cambridge CB3 0ET, England
Abstract **A continuous 37-year record of the geomagnetic field from Argentine Islands Geomagnetic Observatory at Faraday research station (65 degrees S, 64 degrees W), Antarctica, has been analysed to reveal a 27-month periodicity in the amplitude of the semidiurnal Sq variation in the II-component significant at the 98% level**. This indicates the presence of a periodicity in the strength of the semidiurnal tide at dynamo region altitudes matching that of the quasi-biennial oscillation (QBO) classically observed in the zonal stratospheric winds at equatorial latitudes. It adds to similar observations (Olsen, 1994) which demonstrated such an effect in the diurnal Sq range at near-equatorial latitudes but which showed no evidence for its presence at mid-latitudes. Faraday research station is in a uniquely advantageous geophysical location for such geographically high-latitude observations.

Authors   **K Labitzke, H Vanloon**
Title   **Connection between the troposphere and stratosphere on a decadal scale**

Address   H Vanloon, Free Univ Berlin, Inst Meteorol, CH Becker Weg 6-10, D-12165 Berlin, Germany

Abstract A decadal oscillation of the geopotential heights in the lower stratosphere, which is well-correlated with the 11-year solar cycle, is closely linked to changes of the temperature on the same time scale in the middle and upper troposphere, the temperature being higher on an average in the maxima than in the minima of the 11-year solar cycle. It appears likely that these changes in the tropospheric temperature are associated with changes in the Hadley circulation. It is well established that the decadal oscillation in the stratosphere is modulated by the Quasi-Biennial Oscillation in winter. We point out that the QBO also modulates the decadal oscillation at other times of the year, but that the effect of the modulation is then weaker because of the different wind regime in the stratosphere.

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