Chapter 9
Comparing Earth and Venus

Hauke Schmidt

9.1 Introduction

For obvious reasons the atmosphere of Venus has received much less attention in the natural sciences than the atmosphere of Earth. The same is true for numerical modeling efforts concerning the two atmospheres. The circulation of Venus' atmosphere can be described by the same set of basic equations valid for the other planetary atmospheres: the Navier-Stokes equations describing the temporal evolution of momentum plus equations of continuity and the conservation of thermodynamic energy (see Chap. 5). These equations are discretized in the so-called dynamical cores of numerical models, and it is not surprising that Venus models, in general, use dynamical cores originally built for Earth modeling (see Chap. 6). Parameterizations needed in complex planetary models to describe subgrid-scale processes are more difficult to exchange because parameters may differ considerably among planets. Nevertheless, many parameterizations used in Venus models are based on developments made for other planets.

The Venus model presented by Lebonnois et al. (2010), for instance, see also Chaps. 6 and 8, uses several parameterizations applied originally to Earth, but also used for modeling of Mars and Titan. But there may be more to learn for Venus modeling from more or less recent successes in Earth modeling. Consequently, the purpose of this chapter is to describe features of the Earth atmosphere and their numerical simulation that may help in the understanding phenomena of the Venus' atmosphere. The focus will be on the zonally averaged circulation both in the tropics and extra-tropics. Atmospheric dynamics on Earth and Venus exhibit some significant differences. Due to the fast rotation of the Earth, e.g., wind patterns over

---

H. Schmidt (✉)
Max Planck Institute for Meteorology, Hamburg, Germany
e-mail: hauke.schmidt@zmaw.de

L. Bengtsson et al. (eds.), *Towards Understanding the Climate of Venus*, ISSI Scientific Report Series 11, DOI 10.1007/978-1-4614-5064-1_9,

a large range of scales can be understood assuming geostrophic equilibrium, while cyclostrophic equilibrium is a useful concept for the atmosphere of the slow rotating Venus (see Chap. 5).

However, there are also important similarities that will be the subject of the following sections. For a start, it may be useful to remind the reader of the mean circulation in Earth's atmosphere. Figure 9.1a shows the annual and zonal mean zonal wind as simulated by the Hamburg Model of the Neutral and Ionized Atmosphere (HAMMONIA Schmidt et al. 2006). HAMMONIA is a general circulation and chemistry model covering the atmosphere from the surface to the lower thermosphere. While the observational coverage of the troposphere and lower stratosphere, that are accessible to balloon soundings and remote sensing from satellites, is excellent, the knowledge on the circulation of mesosphere and lower thermosphere is much less complete and except for sparse rocket soundings based on remote sensing from satellite or the surface. Similar to the situation on Venus, modeling is therefore necessary not only to understand the observations but also to fill their gaps. Figure 9.1a shows the westerly jets in the subtropical upper troposphere. Stratosphere and lower mesosphere are dominated by easterlies in the tropics and westerlies in the extra tropics, a picture that reverses in the upper mesosphere. While in the case of Venus the obliquity is close to zero, the relatively high obliquity of the Earth axis leads to a strong seasonality of the circulation. This is indicated by Fig. 9.1b that shows zonal mean winds for July. It is clear from this figure that the annual mean extra-tropical westerlies in the stratosphere are resulting from the strong polar night jets in the respective winter hemispheres. However, even seasonal wind fields provide only limited insight in the actual circulation as strong variability exists on many other (shorter and longer) timescales.

Although this chapter mainly deals with phenomena of the zonally averaged circulation, the importance of eddies or waves (i.e. deviations from a zonally averaged state) for the general circulation on both Venus and Earth can hardly be overestimated. Waves may influence the mean flow by depositing their momentum and depend on the atmospheric background state that defines propagation conditions. Such wave-mean flow interactions play an important role for the phenomena described below. An overview and a theoretical description of important wave modes on Venus (and Earth) are given in Sect. 6.6. Further comprehensive information on waves in the terrestrial atmosphere is provided e.g. in the textbooks from Holton (2004) and Andrews et al. (1987).

9.2 Super-Rotation and the Qbo: The Role of Eddy Momentum Transfer

The strong super-rotation of the Venus atmosphere is arguably one of the most challenging scientific issues in planetary atmospheric studies. Theoretical considerations have shown that momentum transport by eddies and the transfer of their momentum

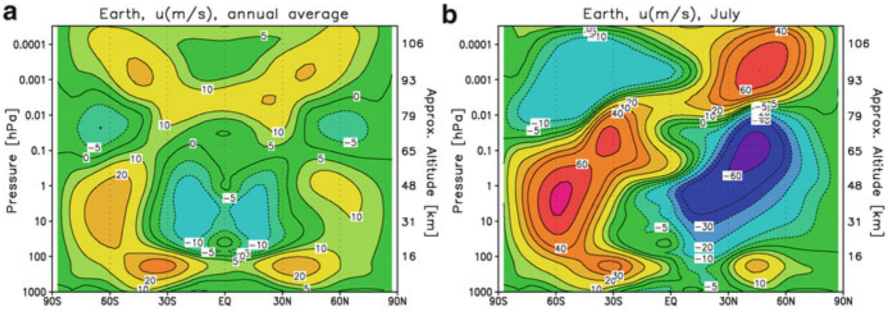

Fig. 9.1 (**a**): Annual and zonal mean zonal wind (m/s) of the Earth atmosphere averaged from a multi-year simulation with the HAMMONIA model. (**b**): same as (**a**) but as an average over all simulated months of July

to the zonal mean flow are necessary to sustain a super-rotation (Chap. 5). Although today's Venus models are able to produce super-rotating atmospheres it is still not completely clear, which role different types of waves may play. Planetary scale waves, but also small scale gravity waves and thermal tides may all have an influence (Chaps. 6 and 8). Zonal winds with westerly speeds up to about 100 m/s in large parts of the Venus atmosphere extend by far the rotational speed of Venus that is of about 2 m/s at the equator. Absolute zonally averaged wind speeds observed in the Earth atmosphere are in general below 100 m/s everywhere (see Fig. 9.1) and thus largely exceeded by the equatorial rotational speed of about 460 m/s. Such high wind speeds have only occasionally and locally been observed on Earth in the high latitude lower thermosphere (Tsuda et al. 2009).

But as on Venus, the momentum transfer through eddies plays an important role in determining the zonally averaged circulation on Earth, as well. In this section, we focus on equatorial zonal winds, and specifically on the phenomenon known as QBO: the quasi-biennial oscillation of stratospheric zonal winds. As shown in Fig. 9.2, the winds change their direction with an observed average period of about 28 months from easterly (of up to about –35 m/s in the middle stratosphere) to westerly (of up to about 15 m/s) and back. Like the super-rotation on Venus the occurrence of the QBO had remained unexplained for a long time and is still subject of scientific research. Periods of one year or harmonics of it are observable in many atmospheric quantities but a period of about 28 months had presented a puzzle over decades. More detailed historical surveys on the discovery of the QBO and a review of the current scientific understanding are given e.g. by Hamilton (1998); Labitzke and van Loon (1999), and Baldwin et al. (2001). Here we want to give only a relatively brief overview.

After the eruption of the tropical volcano Krakatoa in August 1883 a westward transport of the volcanic cloud around the globe at about 25 km of altitude was observed. Based on these global sightings of the cloud, Russell (1888) estimated an easterly wind velocity of slightly more than 30 m/s for the cloud altitude. This fitted nicely to the expectation of having easterly winds in the equatorial region.

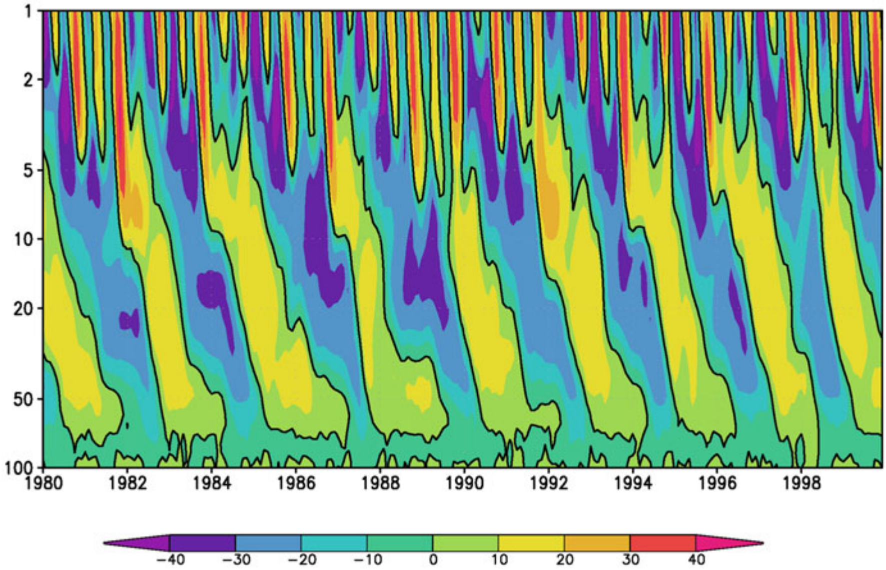

Fig. 9.2 Zonal mean zonal winds (m/s) at the equator for the stratosphere. Pressure levels of 100 and 1 hPa correspond to altitudes of approximately 16 and 48 km, respectively. Winds are simulated by the HAMMONIA model but nudged to radio soundings from Singapore (2°N) in the lower to middle stratosphere

Today we know that if Krakatoa had erupted a year earlier or later, the cloud would likely have moved in the opposite direction. In 1908, the German Meteorologist A. Berson launched balloons in equatorial Africa, and discovered westerly winds in altitudes between about 18 and 20 km. In the first half of the twentieth century it was then assumed that narrow bands of westerly winds (called "Berson westerlies") were embedded in the prevailing easterlies. Only after more regular balloon soundings in the tropics had started in the 1950s the alternation of prevailing easterly and westerly winds, the QBO, was discovered (e.g. Reed et al. 1961). So in the early 1960s, the phenomenon was observed but waited to be understood. Early assumptions that the QBO might be a harmonic of the 11-year solar cycle proved inconclusive. Two main QBO features were difficult to explain: First, why did the structure propagate downward without any change of amplitude over a fairly large part of the stratosphere, and second, why would winds turn westerly at all. They do not represent a super-rotation in the Venusian sense of a zonal wind faster than the rotation, but in the opposite direction. It was shown that the necessary momentum transfer could neither be explained by meridional advection nor by meridional eddy momentum transport (Wallace and Holton 1968). Rather transport of zonal momentum by vertically propagating equatorial waves had to be involved, but by which type of waves? Lindzen and Holton (1968) and Holton and Lindzen (1972) developed conceptual models that explained the QBO with wave-mean flow interactions resulting from a combination of eastward and westward travelling waves. While in the first paper internal gravity waves were assumed to provide the momentum transport, in the second paper Holton and Lindzen (1972) presented a revised theory based on equatorial planetary waves (Kelvin and mixed Rossby-gravity waves). It took until the turn of the century before the main features of the QBO were successfully simulated in Earth GCMs (e.g. Takahashi 1999; Scaife et al. 2000).

Today it is assumed that momentum deposition from a broad spectrum of small scale gravity waves (that need to be parameterized in standard GCMs) and from planetary waves drives the QBO. Simulations by Giorgetta et al. (2006) indicate that gravity waves provide the dominant forcing for the QBO east phase while planetary waves have a larger contribution to the west phase. Still today, many GCMs do not succeed in reproducing a QBO, although it has become clear that two major requirements have to be met: First, an appropriate parameterization of convective processes that provide energy for planetary waves and second, a high vertical resolution of the model capable of resolving the waves that carry the momentum. Observational confirmation of the mechanism assumed to drive the QBO seems difficult. This is in particular related to the difficulty in quantifying gravity wave parameters on a global scale due to their small spatial scale and inappropriate resolution of satellite observations. Similarly, one can expect for Venus that a conclusive theory of the super-rotation will have to rely heavily on numerical simulations.

The QBO is not the only interesting feature in the equatorial Earth atmosphere. As can be seen from Fig. 9.2, the equatorial stratopause region is dominated by a semi-annuals oscillation (SAO), and also in the upper mesosphere a strong SAO is present. The semi-annual period appears much less mysterious than the 28-month period of the QBO. Many GCMs have successfully simulated the stratopause SAO and it is generally assumed that the east phase of the SAO is forced by a combination of the effect of quasi-stationary planetary waves and by momentum advection by the meridional winds directed from the winter to the summer hemisphere at the stratopause (thus causing the locking to the seasonal cycle). The westerly acceleration is less clearly understood, but several studies point to the importance of gravity waves. This is also supported by the fact that different phases of the SAOs in the different altitudes are modulated by the QBO, which is probably due to the filtering effects of the QBO on gravity waves (see e.g. Pena-Ortiz et al. 2010). To complete the picture it should be noted that also momentum deposition by tidal waves is supposed to play a role in equatorial dynamics, specifically in the mesopause region as discussed e.g. by Lieberman et al. (2011).

9.3 Polar Vortices on Venus and Earth

Polar vortices exist on both Earth and Venus and it is tempting to compare them, and to learn from the better observed Earth vortices about the Venus vortices where the major source of information is the tracking of cloud features at the upper cloud surface close to 70 km of altitude. However, it is suggested by Limaye et al. (2009)

that differences between the planetary vortices are large, and dynamically the Venus vortices may have more similarities with another feature of the Earth atmosphere, namely tropical cyclones.

So what are the obvious similarities and differences? Earth vortices are seasonal features observed to occur in both winter hemispheres. As mentioned earlier, due to an almost vertical obliquity, Venus shows no distinct seasons. Its vortices are observed on both hemispheres and assumed to be of permanent nature. Wind fields of both planets, including their polar vortices, can largely be deduced from the temperature fields via thermal wind equations but while a geostrophic thermal wind is observed on Earth, the Venus equilibrium is of cyclostrophic nature (Chap. 5). The Earth vortices extend in the winter hemisphere over a large vertical range from the upper troposphere to the lower mesosphere (see Fig. 9.1b). Maximum wind speeds are in general obtained close to or slightly above the stratopause near the polar night terminator (hence the name "polar night jet"). They can easily be explained by the meridional gradient in solar heating by ozone absorption. Solar heating in the Venus atmosphere that may be relevant for the vortices occurs mainly at the top of the cloud layer. So the existence of the Venus vortices is likely less related to heating gradients but to the momentum transfer processes mentioned in connection with the super-rotation. Figure 6.4 shows a plausible zonal wind field consistent with angular momentum and momentum transfers that would explain super-rotation. The wind field shows jets in both hemispheres with zonal wind maxima close to 50 degrees of latitude. Many present-day Venus models simulate polar vortices. This can be inferred e.g. from the zonal wind fields from a variety of models presented in Fig. 8.2. Strength and location of high-latitude jet maxima differ however strongly among the models. Further work is required to understand these differences and the role of the high latitudes for the global circulation on Venus in general (see Chaps. 6 and 8). An observed feature in the center of the Venus vortices is a deviation from zonal symmetry occurring as an S-shape (sometimes also referred to as a dipole). Elson (1982) found that the Venus vortex is barotropically unstable. Limaye et al. (2009) confirmed this in a two-dimensional model simulation initialized with a latitudinal vorticity field from Venus observations (see Fig. 6.17). In their model, wave-2 patterns occur that resemble very much the S-shape structure observed on Venus. Figure 9.3 shows the vortex as observed during October 2006 by the VIRTIS instrument on Venus Express. Occasionally, Earth vortices produce similar wave-2 patterns as can be seen in Fig. 9.4. Such events in general belong to the category of "sudden stratospheric warmings" (SSW) that still are an important topic of middle atmosphere research. These events were discovered by R. Scherhag in 1952. His balloon soundings revealed a temperature increase in the middle stratosphere of about 40 K within two days. Today, it is known that the high latitude temperature increase is always accompanied by a reversal (or strong weakening) of the wintertime westerly zonal winds, i.e. it is a signal of an intermediate breakdown of the polar vortex. "Major" stratospheric warmings are defined using as criterion the reversal of the zonal mean zonal wind at 60 degrees latitude and 10 hPa plus a reversal of the usually negative poleward temperature gradient. Such events are relatively frequent in the Northern hemisphere, occurring in about two out of three

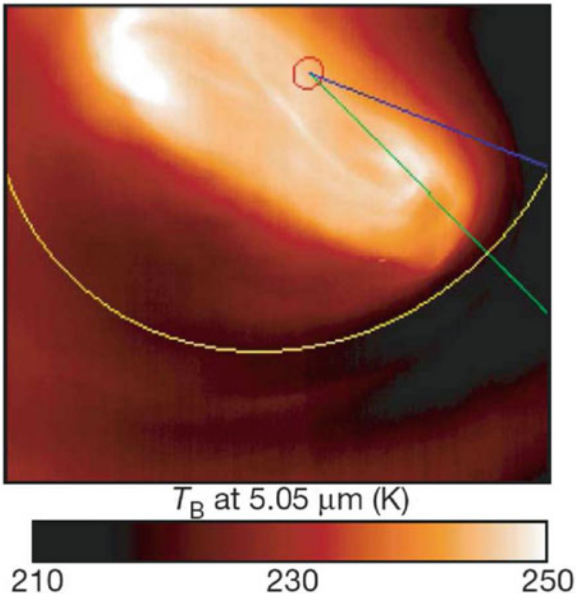

Fig. 9.3 False color image at a wavelength of 5.05 mm of the Venus south polar vortex acquired on 28 May 2006 by the VIRTIS instrument on Venus Express. Color shading indicates the brightness temperature in K. The *blue* and the *green lines* mark the meridians at 330° and 350° of longitude, respectively. The red circle indicates the south pole. The *yellow curve* is the parallel at –70° of latitude. Figure reprinted by permission from Macmillan Publishers Ltd, Piccioni et al. (2007), ©(2007)

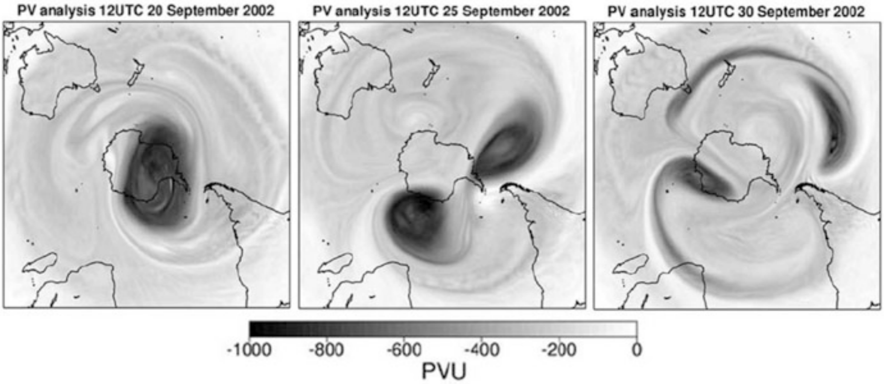

Fig. 9.4 ECMWF analyses of potential vorticity in units of 10^{-6} m^2 s^{-1} K kg^{-1} on the 850 K isentropic surface (≈30 km altitude) for 1200 UTC on 20, 25, and 30 September 2002. While the vortex on 20 September has a fairly typical shape, the split vortex at 25 September is indicative of the, so far, unique observed event of a major sudden stratospheric warming in the southern hemisphere. Major warmings characterized by a vortex split occur on average about each three years in the northern hemisphere winter. Figure adapted from Simmons et al. (2005). ©American Meteorological Society. Reprinted with permission

years (Charlton and Polvani 2007), but have been observed only once (in 2002) in the Southern hemispheric winter. In the Northern hemisphere, SSWs can be characterized either as wave 1-events, called "vortex displacements", where the vortex center is significantly displaced from the pole, or as "vortex splits" with a wave 2-structure as in the middle panel of Fig. 9.4. The occurrence of these events can, however, not be explained with barotropic instability as it seems to be the case on Venus. According to Andrews et al. (1987), early attempts to explain sudden warmings investigated the possibility of barotropic instability of the large scale polar vortex as well as of baroclinic instability of the polar night jet, but the developing instabilities were too small to explain the observed characteristics of warmings. Today, it is generally assumed that SSWs are the result of upward propagating Rossby waves that originate in the troposphere and interact with the stratospheric mean flow. This conceptual idea was first brought up by Matsuni (1971). Many Earth GCMs are able to simulate more or less satisfactorily the polar vortices and their occasional breakdown in the form of an SSW. It is however still a challenge to simulate the correct occurrence frequency of SSWs and its seasonal cycle (Charlton et al. 2007).

As stated in the beginning the dynamical origin of polar vortex instabilities on Venus and Earth is likely to be very different. Limaye et al. (2009) suggested that dynamical similarities rather exist with tropical cyclones on Earth although these have a much smaller scale. They show that S-shaped structures occur also in the eye of cyclones, and mention the occurrence of small scale transverse waves extending radially from the centres of both terrestrial cyclones and the Venus polar vortices. Accordingly, earlier theoretical studies have shown that barotropic instability is of importance in the inner core of tropical cyclones (Schubert et al. 1999). However, it can not be excluded that studies of Venus polar vortices may benefit from comparisons with their terrestrial counterparts. Relatively recently, vertical coupling processes during SSWs have been discussed that reach far beyond the stratosphere. It is observed that stratospheric warmings are in general accompanied by mesospheric coolings and possibly also by thermospheric warmings (e.g. Funke et al. 2010). This is explained by changes in the filtering of upward propagating waves (in particular small scale gravity waves) during SSWs and subsequent changes in wave-mean flow interactions in the upper atmosphere. Hence, SSWs can be seen as a manifestation of dynamical coupling between atmospheric layers from the surface to the thermosphere. It would be interesting to investigate if similar coupling processes occur also on Venus.

9.4 Conclusions and Outlook

What can be learned from the comparison of Earth and Venus phenomena as done above and where could future Venus modeling benefit from current developments in Earth modeling? All phenomena described above, super-rotation and S-shaped vortex instabilities on Venus, the quasi-biennial oscillation and sudden stratospheric warmings on Earth have been observed, first, and then scientists have tried to understand them with the help of numerical models. This is not an unusual sequence in atmospheric science. Labitzke and van Loon (1999) in their book on the stratosphere cite the German-Russian climatologist and meteorologist Wladimir Köppen (1846–1940). In general, theory has to follow the experience ("die Theorie muss der Erfahrung folgen"). In the above cases, one reason for this is probably that the phenomena can not be simulated from first principles alone. In all cases parameterizations are needed, for instance of the radiative effect of clouds in the case of the Venus circulation and of subgrid-scale gravity waves in the cases of the QBO and of coupling effects during SSWs. The transfer of parameterizations from Earth to Venus models is not generally feasible, because parameter ranges may be very different. A candidate for transfer are parameterizations of subgrid-scale gravity wave effects. A parameterization for non-orographic gravity waves has already been used for Venus and shown to affect super-rotation (Ikeda et al. 2007), but the standard approach in Venus modeling is to parameterize the damping effect of gravity waves on horizontal winds via a Rayleigh friction approach (see Chap. 8).

In Earth models this technique has been largely replaced by more physically based gravity wave parameterizations. But also these parameterizations have severe limitations, as they in general assume a strict vertical and instantaneous propagation of the waves and are poorly coupled to actual sources. Current development efforts try to overcome these deficiencies (e.g. Song and Chun 2008; Richter et al. 2010). Another approach is to eliminate parameterizations completely by strongly increasing the model resolution and actually resolving large parts of the gravity wave spectrum. This was done in a simulation by Kawatani et al. (2009) that successfully reproduced a QBO-like structure albeit with a too short period. These developments might be perspectives for Venus modeling, too. Future transfer of parameterizations and knowledge from Earth to Venus may also be useful in case of the cloud layer. Because of the large uncertainty clouds introduce with respect to climate change on Earth, they are a topic of intensive research. Numerical efforts concentrate on both, improved parameterizations of cloud effects in global climate models and process studies with limited area high resolution models. In most Venus models of today, the cloud layer has been represented only by a simple parameterization of their effect on radiation (see Chap. 8). Obviously, the sulfuric acid clouds on Venus differ strongly from the water clouds on Earth. A link to sulfate aerosol modeling, another important topic in current Earth atmosphere research, may be more promising. A comparison of clouds and cloud modeling for Venus and other terrestrial planets is presented e.g. by Montmessin (2010).

As stated in the beginning, it seems obvious that Venus modeling should exploit efforts made for Earth. But the transfer of code, knowledge, and understanding is not likely to be straightforward. A growing number of terrestrial atmosphere or climate models are applied to extreme cases, such as very different climates in the geological history of Earth. This is done not only to understand these historical climates but also to possibly eliminate parameterizations developed with too narrow a scope. Thereby confidence is gained for the applicability of the models to a broad spectrum of climate states, and in particular confidence in the ability to project future climate change. Venus is an excellent example for such an extreme climate.

References

D.G. Andrews, J.R. Holton, C.B. Leovy, *Middle Atmosphere Dynamics* (Academy, Orlando, Florida, 1987)

M.P. Baldwin, L.J. Gray, T.J. Dunkerton, K. Hamilton, P.H. Haynes, W.J. Randel, J.R. Holton, M.J. Alexander, I. Hirota, T. Horinouchi, D.B.A. Jones, J.S. Kinnersley, C. Marquardt, K. Sato, M. Takahashi, The quasi-biennial oscillation. Rev. Geophys. **39**, 179–229 (2001)

A.J. Charlton, L.M. Polvani, A new look at stratospheric sudden warmings. part I: Climatology and modeling benchmarks. J. Climate **20**, 449–469 (2007)

A.J. Charlton, L.M. Polvani, J. Perlwitz, F. Sassi, E. Manzini, K. Shibata, S. Pawson, J.E. Nielsen, D. Rind, A new look at stratospheric sudden warmings. part II: Evaluation of numerical model simulations. J. Climate **20**, 470–488 (2007)

L.S. Elson, Wave instability in the polar-region of Venus. J. Atmos. Sci. **39**, 2356–2362 (1982)

B. Funke, M. Lopez-Puertas, D. Bermejo-Pantaleon, M. Garcia-Comas, G.P. Stiller, T. von Clarmann, M. Kiefer, A. Linden, Evidence for dynamical coupling from the lower atmosphere to the thermosphere during a major stratospheric warming. Geophys. Res. Lett. **37**, L13803 (2010)

M.A. Giorgetta, E. Manzini, E. Roeckner, M. Esch, L. Bengtsson, Climatology and forcing of the quasi-biennial oscillation in the MAECHAM5 model. J. Climate **19**, 3882–3901 (2006)

K. Hamilton, Dynamics of the tropical middle atmosphere: A tutorial review. Atmos.-Ocean **36**, 319–354 (1998)

J.R. Holton, *Introduction to Dynamic Meteorology*, 4th edn. (Academic, New York, 2004)

J.R. Holton, R.S. Lindzen, Updated theory for quasi-biennial cycle of tropical stratosphere. J. Atmos. Sci. **29**, 1076–1080 (1972)

K. Ikeda, M. Yamamoto, M. Takahashi, Superrotation of the Venus atmosphere simulated by an atmospheric general circulation model. IUGG/IAMAS Meeting, Perugia, Italy (2007)

Y. Kawatani, M. Takahashi, K. Sato, S.P. Alexander, T. Tsuda, Global distribution of atmospheric waves in the equatorial upper troposphere and lower stratosphere: AGCM simulation of sources and propagation. J. Geophys. Res.-Atmos. **114**, D01102 (2009)

G.K. Labitzke, H. van Loon, *The Stratosphere: Phenomena, History, and Relevance* (Springer, Berlin, 1999)

S. Lebonnois, F. Hourdin, V. Eymet, A. Crespin, R. Fournier, F. Forget, Superrotation of Venus' atmosphere analyzed with a full general circulation model. J. Geophys. Res.-Planets **115**, 6006 (2010), doi:10.1029/2009JE003458

R.S. Lieberman, D.A. Ortland, D.M. Riggin, Q. Wu, C. Jacobi, Momentum budget of the migrating diurnal tide in the mesosphere and lower thermosphere. J. Geophys. Res.-Atmos. **116**, D07110 (2011)

S.S. Limaye, J.P. Kossin, C. Rozoff, G. Piccioni, D.V. Titov, W.J. Markiewicz, Vortex circulation on Venus: Dynamical similarities with terrestrial hurricanes. Geophys. Res. Lett. **36**, L04204 (2009), doi:10.1029/2008GL036093

R.S. Lindzen, J.R. Holton, A theory of Quasi-Biennial Oscillation. J. Atmos. Sci. **25**, p. 1095–1107 (1968)

T. Matsuno, Dynamical model of stratospheric sudden warming. J. Atmos. Sci. **28**, 1479–1494 (1971)

F. Montmessin, Clouds of Venus: comparison with other terrestrial planets. In VEXAG2010 workshop abstract, Madison, WI, USA (2010)

C. Pena-Ortiz, H. Schmidt, M.A. Giorgetta, M. Keller, QBO modulation of the semiannual oscillation in MAECHAM5 and HAMMONIA. J. Geophys. Res.-Atmos. **115**, D21106 (2010)

G. Piccioni, P. Drossart, A. Sanchez-Lavega, R. Hueso, F.W. Taylor, C.F. Wilson, D. Grassi, L. Zasova, M. Moriconi, A. Adriani, S. Lebonnois, A. Coradini, B. Bezard, F. Angrilli, G. Arnold, K.H. Baines, G. Bellucci, J. Benkhoff, J.P. Bibring, A. Blanco, M.I. Blecka, R.W. Carlson, A. Di Lellis, T. Encrenaz, S. Erard, S. Fonti, V. Formisano, T. Fouchet, R. Garcia, R. Haus, J. Helbert, N.I. Ignatiev, P.G.J. Irwin, Y. Langevin, M.A. Lopez-Valverde, D. Luz, L.

Marinangeli, V. Orofino, A.V. Rodin, M.C. Roos-Serote, B. Saggin, D.M. Stam, D. Titov, G. Visconti, M. Zambelli, South-polar features on venus similar to those near the North Pole. Nature **450**, 637–640 (2007)

R.J. Reed, L.A. Rasmussen, W.J. Campbell, D.G. Rogers, Evidence of a downward-propagating,annual wind reversal in equatorial stratosphere. J. Geophys. Res. **66**, 813–818 (1961)

J.H. Richter, F. Sassi, R.R. Garcia, Toward a physically based gravity wave source parameterization in a General Circulation Model. J. Atmos. Sci. **67**, 136–156 (2010)

F.A.R Russell, Spread of the phenomena round the world. *The Eruption of Krakatoa and Subsequent Phenomena* (Trübner & co, London, 1888)

A.A. Scaife, N. Butchart, C.D. Warner, D. Stainforth, W. Norton, J. Austin, Realistic quasi-biennial oscillations in a simulation of the global climate. Geophys. Res. Lett. **27**, 3481–3484 (2000)

H. Schmidt, G.P. Brasseur, M. Charron, E. Manzini, M.A. Giorgetta, T. Diehl, V.I. Fomichev, D. Kinnison, D. Marsh, S. Walters, The HAMMONIA chemistry climate model: Sensitivity of the mesopause region to the 11-year solar cycle and CO2 doubling. J. Climate **19**, 3903–3931 (2006)

W.H. Schubert, M.T. Montgomery, R.K. Taft, T.A. Guinn, S.R. Fulton, J.P. Kossin, J.P. Edwards, Polygonal eyewalls, asymmetric eye contraction, and potential vorticity mixing in hurricanes. J. Atmos. Sci. **56**, 1197–1223 (1999)

A. Simmons, M. Hortal, G. Kelly, A. McNally, A. Untch, S. Uppala, ECMWF analyses and forecasts of stratospheric winter polar vortex breakup: September 2002 in the Southern Hemisphere and related events. J. Atmos. Sci. **62**, 668–689 (2005)

I.-S. Song, H.-Y. Chun, A Lagrangian spectral parameterization of gravity wave drag induced by cumulus convection. J. Atmos. Sci. **65**, 1204–1224 (2008)

M. Takahashi, Simulation of the quasi-biennial oscillation in a general circulation model. Geophys. Res. Lett. **26**, 1307–1310 (1999)

T.T Tsuda, S. Nozawa, S. Oyama, T. Motoba, Y. Ogawa, H. Shinagawa, N. Nishitani, K. Hosokawa, N. Sato, M. Lester, R. Fujii, Acceleration mechanism of high-speed neutral wind observed in the polar lower thermosphere. J. Geophys. Res.-Space Phys. **114**, A04322 (2009)

J.M. Wallace, J.R. Holton, A diagnostic numerical model of the Quasi-Biennial Oscillation. J. Atmos. Sci. **25**, 280–292 (1968)