Studies of planetary waves in ozone and temperature fields as observed by the Odin satellite in 2002-2007

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Studier av planetära vågor i ozon och temperatur från mätningar med satelliten Odin 2002-2007

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Cover picture:
Schematic illustration of planetary waves around the globe,
created by Peter Dalin using MATLAB software.

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DOKTORSAVHANDLING VID INSTITUTET FÖR RYMDFYSIK
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Sammanfattning

Resultaten som presenteras i den här doktorsavhandlingen baseras huvudsakligen på mätningar gjorda med den avancerade sub-mm radiometern (SMR) på Odin satelliten under åren 2002-2007. Huvudsakliga data är serier av temperatur- och ozonprofiler i mellanatmosfären upp till 68 km höjd. Dessa data används för att uppskatta globala egenskaper för fortplantningen av planetära vågor i både horisontell och vertikal riktning. Eftersom det inte finns data av hög kvalitet från Odin över 68 km höjd har dessa kompletterats med mätningar av parametrar väsentliga för studiet av planetära vågor från andra källor till ett större höjdintervall. Dessa källor är temperaturmätningar för 85-90 km från markbaserade meteorradaranläggningar på norra halvklotet (NH), i Skandinavien vid Esrange och i Andenes, och i Kanada vid Resolute Bay och Yellowknife. Ozonprofiler från den markbaserade mm-vågsradiometern KIMRA i Kiruna används också för att jämföra vågegenskaper genom mätningar av ozonkoncentrationen globalt av Odin och lokalt av KIMRA.

Den huvudsakliga uppgiften i den här doktorsavhandlingen är att studera karakteristika för 5-dagars planetära vågor i jordens atmosfär. Atmosfärens cirkulation påverkas av vågor till exempel genom att det uppstår betydande lokala avvikelser från strålningsjämvikt som observerats i stratosfären under vintern och i närheten av mesopausen under sommaren. Årstidsvariationer hos 5-dagars planetära vågor och fysikaliska fenomen relaterade till dessa variationer studeras också i avhandlingen.

Under vintern fortplantas vågor fritt i vertikal riktning och de största vågamplituderna hittas i stratosfären utanför det tropiska området. Vinterperioderna på NH för åren 2002-2003 och 2005 har studerats och jämförelser mellan variationer i temperatur och ozonkoncentration med avseende på planetära vågor har gjorts. Generellt visar resultaten som väntat att temperatur och ozonkoncentration varierar i fas i den lägre stratosfären (av dynamiska orsaker) och ur fas i den övre stratosfären (vilket är en förväntad effekt av fotokemiska processer).

Tidigare teoretiska och experimentella studier har visat att trots ofördelaktiga vindförhållanden under sommaren kan 5-dagars planetära vågor registreras såväl i övre stratosfären som på högre höjd i mesosfären. NHs somrar 2003-2005 och 2007 har undersökts och resultaten har konfirmerat förekomsten av 5-dagars planetära vågor upp till mesopausens höjd (85-90 km). Resultaten visar att för olika perioder kan ursprunget för de observerade vågorna återfinnas på lägre höjd på båda hemisfärerna så att de successivt fortplantas till mesosfären eller att de genereras där de observeras som ett resultat av baroklinisk instabilitet i sommarens ostliga jetström.

Nyckelord: mellanatmosfärens dynamik, planetära vågor, 5-dagars planetär våg, samband mellan temperatur och ozon i atmosfären, satelliten Odin

Abstract

The results presented in this PhD thesis are mainly based on measurements collected by the advanced sub-mm radiometer (SMR) aboard the Odin satellite in 2002-2007. The primary data are series of temperature and ozone profiles in the middle atmosphere up to 68 km. These data are used to estimate global properties of planetary wave propagation in both horizontal and vertical directions. As good-quality retrievals from Odin are not available above 68 km, additional data sources have been considered in order to extend coverage of planetary wave properties to higher levels. These sources are temperature observations at 85-90 km obtained by the ground-based meteor radars located in the polar region in the Northern Hemisphere in Scandinavia at Esrange and at Andenes, and in Canada at Resolute Bay and at Yellowknife. Also, the series of ozone profiles from the ground-based Kiruna mm-wave radiometer, KIMRA, are used in order to compare the wave properties in ozone fields measured globally by Odin and locally by KIMRA.

The main task of this PhD thesis is to study the 5-day planetary wave characteristics in the Earth's atmosphere. The influence of waves on the atmospheric circulation causes, for example, substantial local departures from radiative equilibrium, observed in the winter stratosphere and close to the summer mesopause. Seasonal variations of the 5-day planetary wave properties and physical phenomena related to these variations are also studied in this thesis.

During winter, planetary waves propagate freely in the vertical direction, and maximal wave amplitudes are found in the extratropical stratosphere. The Northern Hemisphere (NH) winter periods of 2002-2003 and 2005 have been examined and a comparison has been carried out between the planetary wave properties in temperature and ozone variations. In general, the results show an expected in-phase behavior between the temperature and ozone fields in the lower stratosphere (due to dynamic effects) and an out-of-phase pattern in the upper stratosphere (which is expected as a result of photochemical effects).

Earlier theoretical and experimental studies have shown that, despite unfavourable summertime wind conditions, 5-day planetary waves can be registered not only in the stratosphere but also at higher altitudes in the mesosphere. The NH summers of 2003-2005 and 2007 have been considered and results have confirmed the existence of 5-day planetary waves up to the mesopause level (85-90 km). The results demonstrate that, for different periods, the possible source of the observed waves could be located at lower altitudes in both hemispheres with successive propagation into the summer mesosphere, or the waves could be generated in-situ as a result of the baroclinic instability of summer easterly jet.

Keywords: middle atmosphere dynamics, planetary waves, 5-day planetary wave, temperature-ozone relationship, Odin satellite

Contents

List of included papers

This thesis is based on the work reported in the following papers:

Paper I. Belova, A., Kirkwood, S., Raffalski, U., Kopp, G., Hochschild G., and Urban J.: Five-day planetary waves as seen by Odin satellite and the ground-based Kiruna millimeter wave radiometer in January-March 2005, Can. J. of Phys., 86, 459-466, 2008.

Paper II. Belova, A., Kirkwood, S., Murtagh, D., Mitchell, N., Singer, W., and Hocking, W.: Five-day planetary waves in the middle atmosphere from Odin satellite data and ground-based instruments in Northern Hemisphere summer 2003, 2004, 2005 and 2007, submitted to Annales Geophysicae.

Paper III. Belova, A., Kirkwood, S., and Murtagh, D.: Planetary waves in ozone and temperature in the Northern hemisphere winter of 2002-2003 by Odin satellite data, submitted to Annales Geophysicae.

Paper IV. Kopp, G., Belova, A., Diez y Riega V E., Groß, J., Hochschild, G., Hoffmann, P., Murtagh, D., Raffalski, U., and Urban J.: Intercomparison of Odin–SMR ozone profiles with ground-based millimetre-wave observations in the Arctic, the mid-latitudes, and the tropics, Can. J. Phys., 85, 1097-1110, 2007.

Paper V. Kirkwood, S., Belova, A., Murtagh, D., Réchou, A., Goldberg, D., and Schmidlin, F.: Polar mesocyclones and their extension to the UTLS - a case study using ESRAD, Odin and MaCWAVE radiosondes, Proceedings of the 18th ESA Symposium on European Rocket and Balloon Programmes and Related research, Visby, Sweden, June 2007, ESA SP-647, 585-588, 2007.

The papers have been reprinted with permission from the publishers, and are included as appendices to this thesis.

1. Introduction

The main purpose of this PhD thesis is to study the characteristics of 5-day planetary waves in the Earth's atmosphere. Planetary, or Rossby, waves are large-scale (thousands of kilometers in the horizontal direction) atmospheric disturbances which are possible to observe in changes of the atmospheric parameters such as temperature, pressure, wind, and in the concentration of some atmospheric species. These waves were first identified in the atmosphere by Swedish-American meteorologist Carl-Gustaf Rossby who established their connection to weather phenomena (Rossby et al., 1939). Interaction between waves and atmospheric circulation leads to, for example, the substantial local departures from radiative equilibrium observed in the winter stratosphere and close to the summer mesopause. Seasonal variations of the planetary wave properties and related physical phenomena are studied in this thesis.

A prominent mode of free traveling planetary waves is the 5-day wave, a westward propagating Rossby mode with period of about five days, which is approximately sinusoidal around latitude circles and symmetric relative to the equator.

Studies of the 5-day planetary wave have a long history that began with several theoretical investigations, for example, by Geisler and Dickinson (1976) and Salby (1981a,b). The theoretical predictions have since been confirmed by both ground-based and satellite observations (Hirooka, 2000; Lawrence and Jarvis, 2003; Riggin et al., 2006).

One of the main features of planetary wave propagation is its westward phase speed relative to the mean flow. The conditions for the wave propagation alter from favourable during wintertime to unfavourable during summertime due to the atmospheric circulation which undergoes seasonal modifications resulting in westerly zonal winds in the winter stratosphere and easterly winds in the summer one.

In Paper I, the Northern Hemisphere (NH) winter period of 2005 has been examined and a comparison has been carried out between the 5-day planetary wave properties in the middle atmosphere obtained from global satellite measurements and from local ground-based observations.

One of the well-known phenomena observed in the winter stratosphere is a stratospheric warming and current theories suggest that tropospherically-forced planetary waves play a crucial role in this event. A case study of a relationship between the stratospheric warming and planetary wave occurrence is presented in Paper III for the NH winter of 2002-2003.

Earlier theoretical and experimental studies have shown that despite unfavourable wind conditions in summertime, 5-day planetary waves have been registered not only throughout the stratosphere but also at higher altitudes, in the mesosphere. In Paper II, several events are considered for the NH summers of 2003-2005 and 2007, confirming the existence of 5-day planetary waves up to the mesopause level.

Section 2 introduces fundamentals of the atmospheric phenomena considered in this PhD thesis such as seasonal variations in the atmospheric circulation, physical properties of the planetary wave propagation and its influence on the relationship between ozone and temperature. In Section 3, a description of the main data sources is presented: the global satellite data from the Odin SMR instrument and additional local ground-based measurements. The procedure for the extraction of planetary waves and estimation of their properties is included in Section 4. The final Section 5 describes the main results of this thesis, characterizing the planetary wave properties for different seasonal conditions (Paper I-III).

2. Background

2.1 Seasonal distribution of temperature and meridional drift in the middle atmosphere

The Earth's atmosphere is the gaseous envelope surrounding our planet, retained by gravity. The atmosphere plays an important role in the transfer of energy between the Sun and the planet's surface and from one region of the globe to another. These energy transfers maintain radiative equilibrium and determine the Earth's climate.

The global temperature in the middle atmosphere, in the absence of eddy or wave motions (departures from zonal symmetry), would be near to radiative equilibrium at all latitudes. The most substantial local deviations from the equilibrium, induced by eddy motions, are observed in the summer mesosphere and polar winter stratosphere. It is generally believed that the breaking of gravity and planetary waves is the main reason for these deviations from radiative equilibrium.

Figure 1 represents the zonal mean temperature in the presence of eddy motions for solstice conditions.

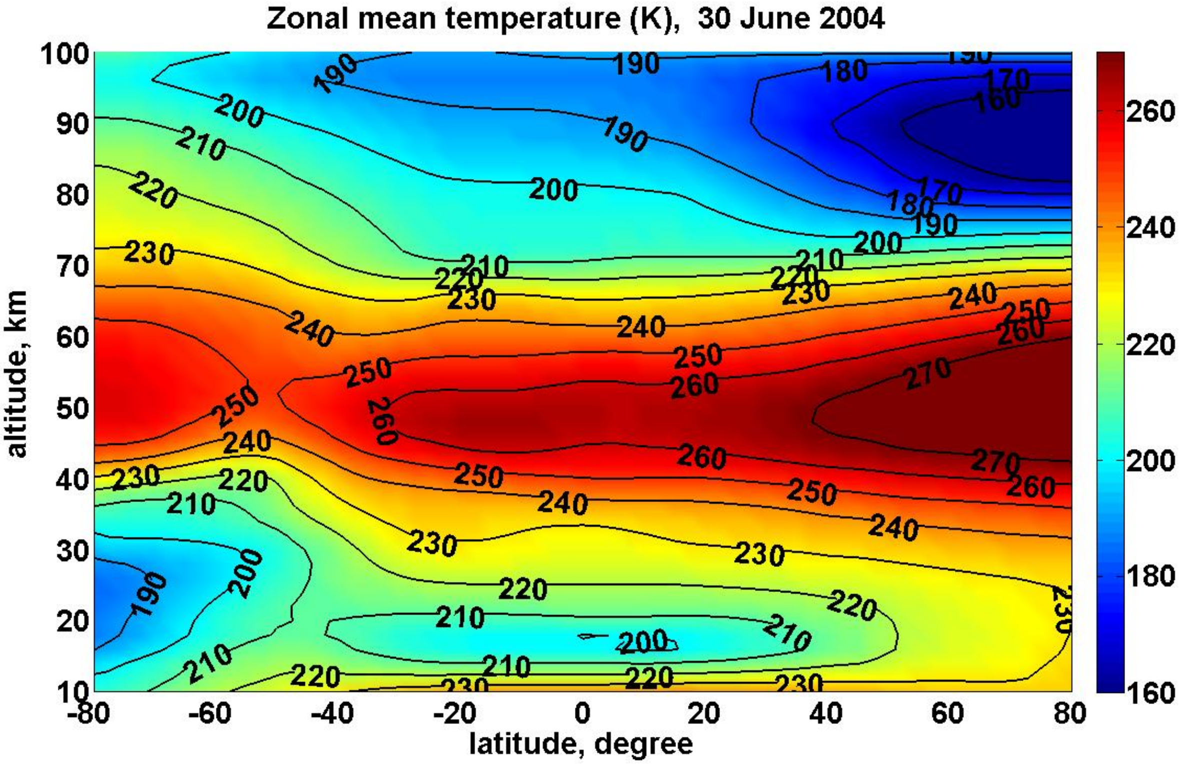

Figure 1. Latitude-height section of the zonal mean temperature (K) distribution for solstice conditions (30 June 2004) using a combination of data from Odin SMR measurements in the middle atmosphere, meteorological data in the lower atmosphere (ECMWF) and model data in the upper atmosphere (MSIS).

The net radiative heating distribution in the stratosphere has a strong seasonal dependence, with maximum heating at the summer polar region and maximum cooling at the winter polar region. At the equinoxes the maximum heating is at the equator and cooling occurs at both poles. The meridional circulation balances dynamically this difference in heating. This requires a circulation primarily driven by wave motion, not by radiative heating directly. In the middle atmosphere the meridional circulation at the solstices begins with rising motions near the summer pole, then air drifts in the meridional plane into the winter hemisphere and sinks near the winter pole.

The latitudinal temperature gradient in each hemisphere creates a latitudinal pressure gradient. The main wind systems depend on these gradients and on the Coriolis force, which is a result of the influence of the Earth's rotation on a moving object, and leads to deflecting a moving portion of air to the right of its motion in the Northern Hemisphere (NH) and to the left in the Southern Hemisphere (SH). Coriolis torque tends to generate zonal mean westerlies (from west to east) in the winter hemisphere and easterlies (from east to west) in the summer hemisphere that are in an approximate geostrophic balance with the meridional pressure gradient force. Figure 2 illustrates schematically the geostrophic balance.

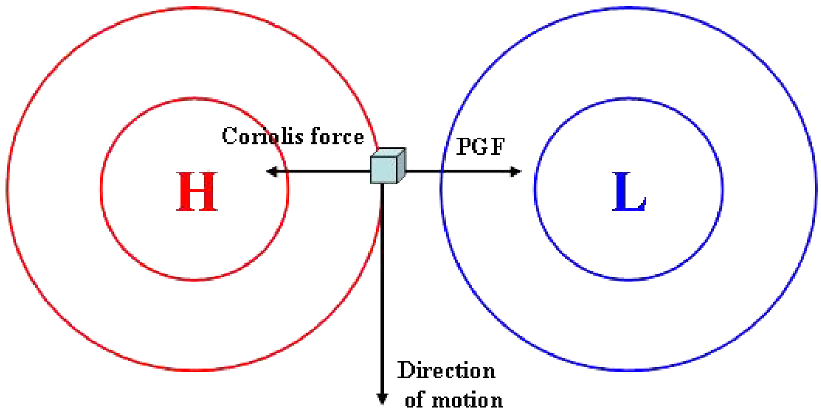

Figure 2. Schematic plot of geostrophic balance. In the upper atmosphere, above the friction layer, the friction force acting on an air parcel is practically negligible. Therefore, only two forces act on the parcel, Coriolis and Pressure Gradient Force (PGF). When these two forces balance each other, the situation is called the *geostrophic balance*. This balance leads to wind motions that circulate along isobars (surfaces of constant pressure) at a given height.

Figure 3 presents schematically the circulation in the middle atmosphere at solstice conditions. In the stratosphere at solstice, the horizontal temperature and pressure differences between the warm summer hemisphere and the cold winter hemisphere result in pole-to-pole gradients. The main winds then blow westward in the summer hemisphere and eastward in the winter hemisphere.

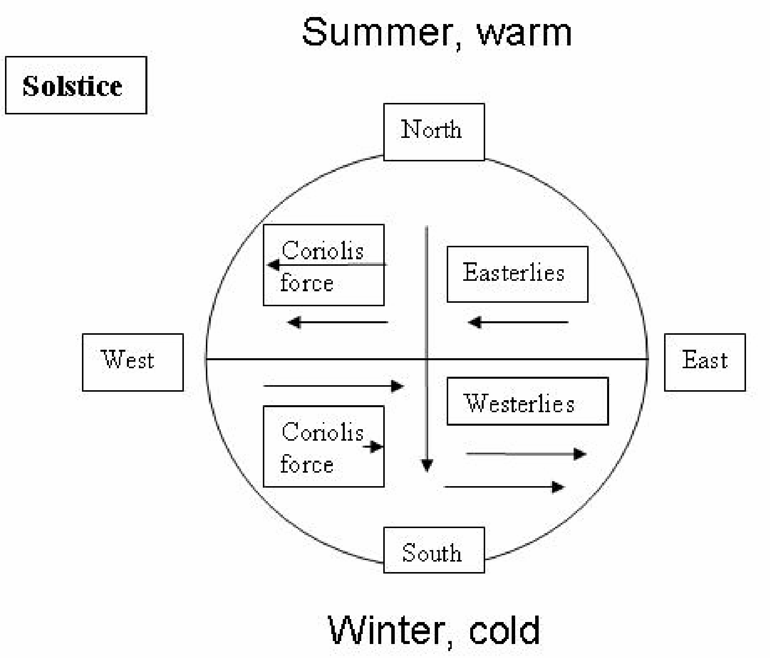

Figure 3. Schematic picture of the circulation in the stratosphere for solstice conditions, NH summer. Coriolis force deflects air flow to the right (west) in the NH and to the left (east) in the SH.

In spring and autumn the equatorial area is warmer than both poles, and the pressure gradient together with the Coriolis torque generate mean zonal westerlies in both hemispheres. Figure 4 demonstrates circulation in the middle atmosphere for equinox conditions.

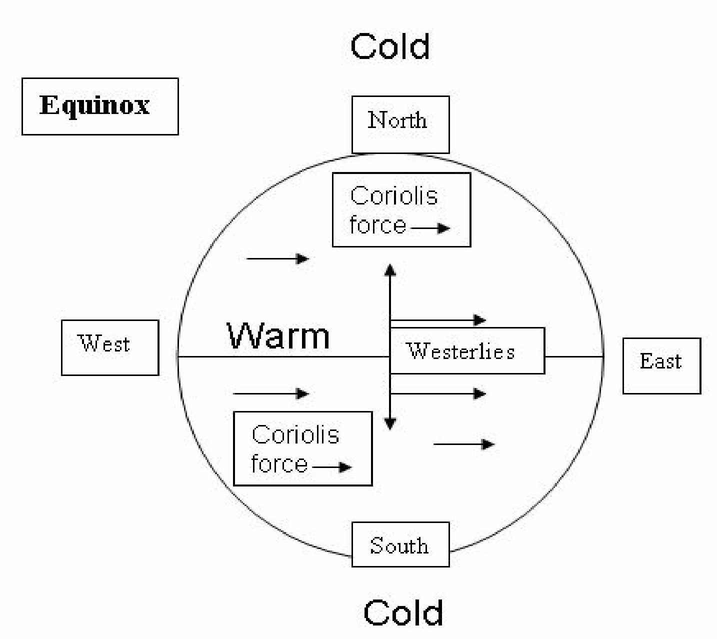

Figure 4. Schematic picture of the circulation in the middle atmosphere for equinox conditions. The pressure gradient is from the warm equator region to both the colder poles, and the winds are westerly in both hemispheres.

2.2 Planetary wave propagation in the Earth's atmosphere

Waves in the Earth's atmosphere are excited when air is disturbed from equilibrium (e.g., mechanically when air is displaced over elevated terrain or thermally when air is heated inside convection). The wave motions transfer the energy from one region to another. Such motions are possible in the presence of a positive restoring force, which, by opposing disturbances from equilibrium, supports local oscillations in a field of atmospheric variables (like pressure, temperature or wind velocity). Variation of the Coriolis force with latitude provides such a restoring force which supports large-scale (thousands of kilometers in the horizontal direction) atmospheric disturbances that are known as *Rossby waves*.

These waves were first identified in the atmosphere by Swedish–American meteorologist Carl-Gustaf Arvid Rossby who established their connection to weather phenomena (Rossby et al., 1939). These waves are also referred to as rotational and, on the gravest dimensions, as planetary waves. Rossby found that much of the character of atmospheric flows could be explained by conservation of the absolute vorticity in a barotropic nondivergent fluid. This conservation is represented by Equation (1):

$$\frac{d\eta}{dt} = \frac{d(\xi + f)}{dt} = 0 \qquad (1)$$

where η is the absolute vorticity that is a sum of the relative (local) vorticity ξ and planetary vorticity f. *(A barotropic fluid is one in which the pressure and density are related by an equation of state that does not contain the temperature as a dependent variable. Mathematically, the equation of state can be expressed as* $p = p(\rho)$ *or* $\rho = \rho(p)$*.)*

From (1) follows that the absolute vorticity η is conserved for an individual air parcel and under barotropic nondivergent conditions; it behaves as a tracer of horizontal air motion and is transformed by the Earth's rotation. In the Northern hemisphere, a movement of air from north to south must compensate for decreasing f by spinning up anticlockwise. Air moving from south to north must rotate in the opposite direction, i.e., clockwise to compensate for increasing f.

Rossby explained the planetary wave motion and showed that its restoring force originates from the meridional gradient of the Coriolis parameter (also called the *Rossby parameter*):

$$\beta = \frac{2\omega \cos\varphi}{a} \quad (2)$$

where φ is the latitude, ω is the angular speed of the Earth's rotation, and a is the mean radius of the Earth.

The main properties of Rossby waves can be obtained using the β-plane approximation:

$$f(y) = f_0 + \beta y \quad (3)$$

where f is the planetary vorticity, which varies linearly with northward distance y; $f_0 = 2\omega \sin\varphi$ is the Coriolis parameter.

For the barotropically stratified uniform nondivergent motion (where the vertical motion vanishes) the zonal phase speed for Rossby waves is equal to:

$$c_x = \bar{u} - \frac{\beta}{k^2 + l^2} \quad (4)$$

where c_x is the zonal wave phase speed, $\bar{u}$ is the zonal mean flow, β is the Rossby parameter, k and l are horizontal zonal and meridional wavenumbers respectively ($wavenumber = \frac{2\pi}{\lambda}$, λ is a wavelength).

The Coriolis parameter $\beta > 0$, then from (4) always satisfies:

$$\bar{u} - c_x > 0 \quad (5)$$

which means that the wave crests and troughs (which move with the phase speed) move westward with respect to the background flow. The Rossby wave phase speed depends inversely on the square of the horizontal wavenumbers (l and k) and therefore, the wave's phase speeds increase rapidly with increasing wavelength. The variation of the phase speed with λ implies that these waves are strongly dispersive: an initial disturbance composed of a number of different wavelengths will tend to break down in time because the various λ-components propagate with different phase speeds.

Large-scale disturbances (several tens of thousands of kilometers) with a high phase speed move westward while small-scale ones with lower phase speed will be swept eastward by westerly zonal flow during the winter season (for example, synoptic disturbance with horizontal length scale of the order of 1000 kilometers or more).

The group velocity (at which the observable disturbance, i.e. energy of the wave, moves with time) for the barotropic nondivergent case on β-plane is equal to:

$$c_g = (c_{gx}, c_{gy}) = (\bar{u} + \frac{\beta(k^2 - l^2)}{(k^2 + l^2)^2}, \frac{\beta k l}{(k^2 + l^2)^2}) \quad (6)$$

While the Rossby wave phase speed is always westward relative to the mean flow, the group velocity may be either east or westward relative to the main flow, depending on the ratio of the zonal and meridional wavenumbers (k and l).

Charney and Drazin (1961) explained the main features of the Rossby wave propagation using observations from the International Geophysical Year taken in 1958. They found that only planetary-scale components of the wave spectrum can propagate into the strong westerlies of the winter stratosphere. The smaller-scale disturbances encounter turning levels close to the tropopause where they are reflected down. During the summer, the easterlies in the stratosphere prevent vertical propagation of Rossby waves with all horizontal scales because the waves reach critical levels, where $c_x = \bar{u}$ and the wave activity is absorbed.
The criterion for the vertical wave propagation is represented by

$$0 < \bar{u} - c_x < \bar{u}_c \qquad (7)$$

where $\bar{u}_c$ is the critical velocity defined as:

$$\bar{u}_c \equiv \frac{\beta}{k^2 + l^2} \qquad (8)$$

For the stationary waves ($c_x = 0$), the Charney-Drazin criterion is

$$0 < \bar{u} < \bar{u}_c \qquad (9)$$

This criterion means that stationary waves propagate vertically only in eastward background flow ($\bar{u} > 0$) that is not too strong ($\bar{u} < \bar{u}_c$). Since the critical velocity $\bar{u}_c$ grows with increasing horizontal wavelength, large-scale waves propagate vertically under a wider range of eastward flows than small-scale waves do. The observations show that large-scale stationary waves propagate in the eastward stratospheric flow in the NH winter time but these waves are absent in the westward flow in summer time.

Rossby waves can be divided into forced and free (resonant) traveling waves. Forced stationary waves are very important for understanding the planetary scale circulation pattern in the low and middle atmosphere. Rossby waves can be forced by topography, for example, stationary modes are forced by flow over the large-scale features such as the Rocky Mountain range of North America and the Himalaya-Tibet complex. They are also forced by land-ocean heating contrasts or may be induced by instabilities arising from horizontal and/or vertical gradients in the temperature and wind distributions.

Free propagating Rossby waves are rather weakly excited in the atmosphere compared to forced waves. But they are clearly detected in the middle atmosphere and reported by many authors, for example, Madden and Labitzke (1981), Venne (1985), Hirota and Hirooka (1984), Hirota and Hirooka (1985), Prata (1989), Hirooka (2000). Free waves are global normal modes and are not maintained by forcing effects.

2.3 Five-day planetary waves in the Earth's atmosphere

A prominent mode of free waves is the 5-day wave, a westward traveling Rossby mode with a period close to 5 days, which is approximately sinusoidal around latitude circles with zonal wavenumber s=1 (i.e., has one maximum and one minimum at a latitude circle) (Andrews et al., 1987).

Studies of the 5-day planetary wave have a long history that began with several theoretical investigations, for example, by Geisler and Dickinson (1976) and Salby (1981a,b). The theoretical predictions have since been confirmed by both ground-based and satellite observations (Hirooka, 2000; Lawrence and Jarvis, 2003; Riggin et al., 2006).

In the Earth's atmosphere, the disturbance associated with this wave peaks at midlatitudes and is symmetric about the equator at all heights during equinoxes. The 5-day wave amplitude increases with height and the wave also has a slightly westward phase slope. However, the wave sometimes departs from this normal mode character. For example, Geisler and Dickinson (1976) and Salby (1981a,b) examined theoretically the behavior of normal mode Rossby waves under realistic wind fields. According to their results, the overall structure of the 5-day wave is somewhat affected by non-uniformities of zonal wind fields throughout the middle atmosphere. During solstice conditions, the wave is not symmetric about the equator in the mesosphere and wave amplitudes are greater in the summer mesosphere than in the winter one.

Observations reported by Wu (1994) demonstrated that this wave sometimes occurs in bursts of activity and exhibits significant phase tilt with height in the middle atmosphere. Analysis of the UK Met Office stratospheric assimilated data of 1992-2001 by Fedulina et al. (2004) has shown a substantial variation of the 5-day wave properties from season to season and from year to year, with a long-period modulation of the wave amplitude with period of about 30 days. The period of 5-day planetary waves varies with season as well (Salby, 1981a,b). Results based on the space observations from Nimbus-6 (Prata, 1989) indicate a period closer to 6 days in spring and autumn (equinox conditions) and about 5.2 days in summer and winter (solstice conditions).

2.4 Ozone in the Earth's atmosphere

About 90% of the ozone in our atmosphere is contained in the stratosphere (where it plays an important role in regulating solar UV radiation) and the rest is in the troposphere. Ozone is a relatively unstable molecule that is made up of three atoms of oxygen. The ozone maximum in the lower stratosphere is known as the *ozone layer*. Chapman (1930) was the first who attempted to explain this maximum of ozone concentration. He considered a set of only oxygen reactions, beginning with the photolysis of molecular oxygen by UV photons with $\lambda \leq 240$ nm:

$$O_2 + h\nu \rightarrow 2O \qquad (10a)$$

Next two reactions interconvert O and O_3:

$$O + O_2 + M \rightarrow O_3 + M \qquad (10b)$$

Photolysis of ozone is caused by photons with $\lambda \leq 1140$ nm:

$$O_3 + h\nu \rightarrow O + O_2 \qquad (10c)$$

Finally, ozone is destroyed by the reaction:

$$O + O_3 \rightarrow 2O_2 \qquad (10d)$$

While the net effect of reactions (10a) and (10b) is to produce ozone from molecular oxygen ($3O_2 \rightarrow 2O_3$), the net effect of reactions (10c) and (10d) is to destroy ozone ($2O_3 \rightarrow 3O_2$).

The Chapman theory predicted too much ozone in the lower stratosphere due to neglecting the effects of ozone-destroying catalytic cycles. A common catalytic cycle consists of the following reactions:

$$X + O_3 \rightarrow XO + O_2 \qquad (10e)$$

$$XO + O \rightarrow X + O_2 \qquad (10f)$$

The net effect of this reaction is

$$O + O_3 \rightarrow 2O_2 \qquad (10g)$$

which destroys ozone according to the Chapman reaction (10d). The molecule *X* is a catalyst (for example, *OH*, *NO*, *Cl*) that only takes part in reactions (10e) and (10f) but is itself not consumed. A single molecule *X* is "recycled" and is able to destroy many ozone molecules.

Figure 5 shows a latitude-height cross-section of the zonal-mean ozone volume mixing ratio (ppmv, *parts per million by volume*) obtained from the Odin SMR data for solstice conditions (30 June 2004). The ozone maximum (>7.5 ppmv) is observed near 35 km in the tropical region, where the insolation is maximal and, therefore, photodissociation of O_2 and production of ozone are largest compared with other regions. Also, slightly lower ozone mixing ratio values (4-6 ppmv) are found in the summer hemisphere, even in the polar area, since the sun is above the horizon and illuminates the atmosphere 24-hours a day. In the winter extratropical stratosphere, where the insolation is minimal, the ozone concentration reaches also significant values (3-4 ppmv) due to the meridional transport to this region from the summer hemisphere and winter tropical regions.

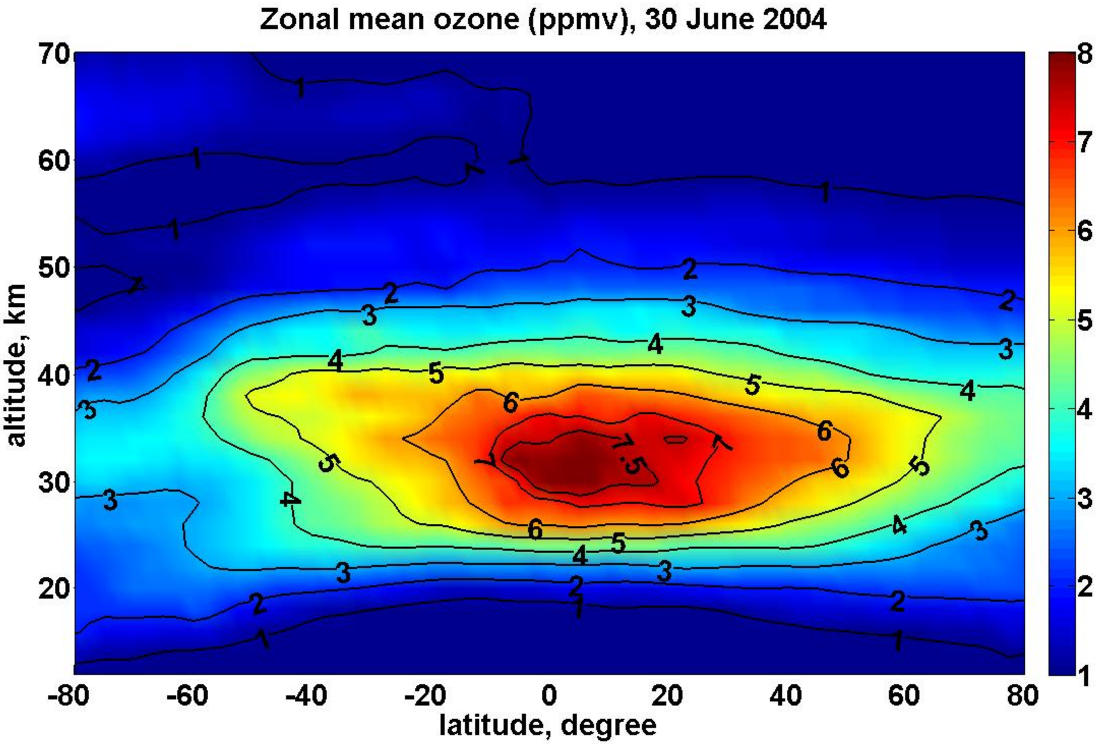

Figure 5. Latitude-height cross-section of the zonal-mean ozone volume mixing ratio (ppmv) obtained from the Odin SMR data for solstice conditions (30 June 2004).

2.5 Temperature-ozone relationship in the Earth's atmosphere

The study of the relationship between ozone and temperature in the Earth's atmosphere has been the topic of many theoretical and experimental investigations. This relationship is complicated by its dependence on the interaction between radiative, dynamical and photochemical processes in the atmosphere. In the upper stratosphere, the ozone molecule has a very short lifetime (~ 1 day) when compared to the timescale of the dynamic effects and ozone is approximately in photochemical equilibrium. Consequently, at these heights, ozone is controlled by photochemical effects. Hence, in the upper stratosphere, an increase in temperature will increase the rate at which ozone is destroyed and therefore will tend to induce a change in ozone of the opposite sign, that is temperature and ozone fields anticorrelate. Below 30 km the photochemical lifetime of ozone becomes much longer (of the order of several weeks) and near the tropopause the time associated with transport becomes much shorter than the photochemical lifetime. Therefore, in the lower stratosphere, ozone is controlled by dynamic effects and correlates with temperature (Brasseur and Solomon, 1986).

An example illustrating the relationship between temperature and ozone concentration is shown in Figure 6. This shows zonal means from the Odin data in the lower (28 km) and upper (42 km) polar stratosphere in the NH winter of 2002-2003. This example demonstrates that temperature and ozone variations tend to be in phase in the lower stratosphere and out of phase in the upper stratosphere, as expected.

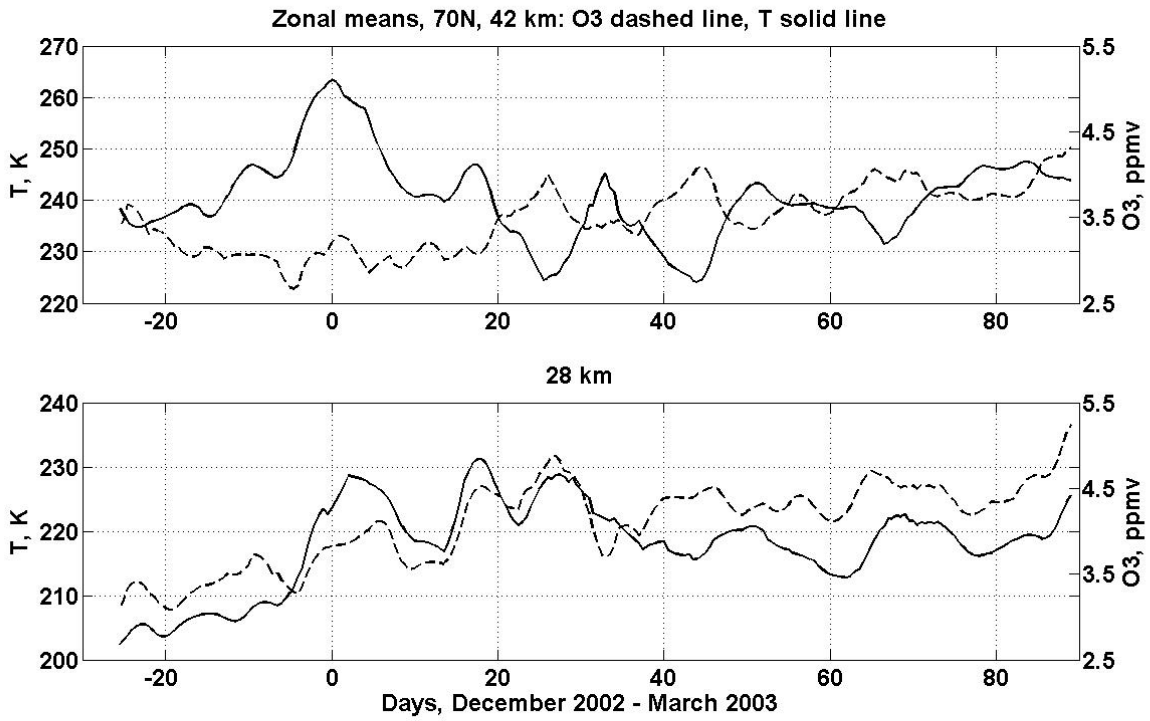

Figure 6. Zonal means from the Odin data for temperature (left scale, K, solid line) and ozone (right scale, ppmv, dashed line) at 70°N; upper panel is for the 42 km level, lower panel is for the 28 km level (Figure 3 from Paper III).

Several theoretical and experimental studies (Hartman and Garcia, 1979; Wang et al., 1983; Randel, 1994; Wirth, 1993; Sabitus et al., 1997) have shown that upward-propagating planetary waves, which are generated in the troposphere, play a very important role for vertical transport of ozone into the stratosphere, either directly or through their influence on the mean circulation.

Hartman and Garcia (1979) have analyzed the coupling between chemistry and dynamics based on the linearized, eddy continuity equation on a β-plane:

$$\left(\frac{\partial}{\partial t}+\bar{u}\frac{\partial}{\partial x}\right)\mu' + v'\frac{\partial\bar{\mu}}{\partial y} + w'\frac{\partial\bar{\mu}}{\partial z} = -\alpha\mu' - \theta T' \tag{11}$$

where t is time, x, y, z are coordinates in the zonal, meridional and vertical directions, $\bar{u}$ is the zonal mean wind, v' and w' are the eddy meridional and vertical velocity, $\bar{\mu}$ is the zonal mean ozone mixing ratio, μ' is the eddy ozone mixing ratio, and T' is the eddy temperature. The eddy terms are deviations from the zonal mean. The parameters α and θ describe the response of ozone concentration to the dynamically-induced perturbations in ozone and temperature. These parameters are derived from the Chapman scheme.

Regions where the terms on the left side of (11) are much smaller than those on the right, and where dynamic effects are unimportant, describe photochemically-controlled areas. When the parameter α is large, local photochemical equilibrium is maintained and the ozone perturbations μ' are out of phase with the temperature perturbations T':

$$\mu' = -\frac{\theta}{\alpha} T' \quad (12)$$

An anticorrelation between the ozone and temperature fields in the upper stratosphere was explained by photochemical effects in several papers (Gille et al., 1981; Wang et al., 1983; Rood and Douglas, 1985; Froidevaux et al., 1989; Randel and Cobb, 1994). A region where photochemical and dynamical effects are both important is termed the *transition region*. In this region, the phase relation of the temperature and ozone perturbations shifts from in-phase to out-of-phase. Hartman and Garcia (1979) have showed that, for the long-period (stationary) wave with zonal wavenumber one, the transition region is situated at a 33-48 km height under winter mid-latitude conditions. Gille (1981) and Wang (1983) have observed similar phase shifts in the transition region between ozone and temperature perturbations to as those shown in the Hartman and Garcia (1979) calculations.

Theoretical considerations by Rood and Douglas (1985) and Douglas et al. (1985) have confirmed these results, however, they indicated that it is necessary to take strong precaution in analyzing the influence of the dynamic terms on the ozone transport before the correlations between ozone and temperature can be attributed to any specific process.

The correlation pattern in the lower atmosphere and anticorrelation pattern in the upper atmosphere, between temperature and ozone, has been found not only for long period stationary waves but also for travelling waves. For example, in the experimental work by Ward et al. (2000), wavenumber two signatures have been observed with a period of ~12.5 days in temperature and ozone measurements from the CRISTA instrument (during the second CRISTA 2 mission, 7-17 August 1997). The results demonstrate that the relative phase of waves in temperature and ozone varies with height and shows in-phase behaviour below 30 km and 180 degrees out-of-phase above 40 km.

In other experimental work by Azeem et al. (2001), the 2-day wave properties have been analyzed using ozone and temperature data obtained by the Microwave Limb Sounder (MLS) on board the Upper Atmosphere Research Satellite (UARS). Analysis of phases of the 2-day wave observed in ozone and temperature measurements in the mesosphere shows that the perturbations are out-of-phase. At the same time, the amplitudes of the perturbations in temperature and ozone are found to be positively correlated. The results suggest that the variations in ozone are photochemically driven in the mesosphere region via changes in reaction rates that are strongly temperature dependent.

The Canadian Middle Atmosphere Model (CMAM, a general circulation model of the troposphere-stratosphere-mesosphere system with fully interactive chemistry) has been applied by Pendlebury et al. (2007) to investigate the role of the dynamic variability due to normal mode Rossby waves and the impact of this variability on fluctuations between the temperature and chemical species. They have considered the first three gravest modes of wavenumber one (5-day, 10-day and 16-day westward travelling waves) in the NH summer at 52˚N and have calculated time-lagged correlations between the fields of several chemical species (nitrous oxide, methane and ozone) and temperature. The presence of 5-day, 10-day and 16-day waves has been found in all fields with clear correlation between the temperature, nitrous oxide, methane and ozone, both in space and time when the correlations for each wave are considered. In particular for ozone, the results show that a positive correlation with an approximately two-day lead for temperature between 28 and 33 km (an increase in temperature corresponds to an increase in ozone approximately two days later) which corresponds to the region where the chemical lifetime of ozone (~ 1 month) is longer than the transport time scale. Above these altitudes, where the ozone chemical lifetime is shorter (~1 day), ozone anti-correlates with temperature, suggesting that it adjusts almost simultaneously to the temperature and an increase in temperature produces a simultaneous decrease in ozone due to an increase in ozone destruction.

3. Data sources

3.1 The Odin satellite and the SMR data

The main data source for this PhD thesis is a set of ozone and temperature profiles from the advanced sub-mm radiometer which is installed on the Odin satellite (Murtagh et al., 2002). The Odin satellite was lunched on 20 February 2001 from Svobodny, in the Russian Far East, and placed into a 600 km sun-synchronous, terminator orbit. As of the summer of 2008, the satellite is still in operation. Odin is a Swedish mini-satellite in cooperation with the space agencies of France, Canada and Finland. This satellite combines two scientific disciplines on a single spacecraft for studies of star formation (astronomy) and of the mechanisms behind the depletion of the ozone layer in the Earth atmosphere (aeronomy) by observation of molecular spectral lines (H_2O, O_2, O_3, CO). The payload is composed of two main instruments: 1) Sub-Millimeter Radiometer (SMR, is used for both astronomy and aeronomy missions) from which data are analysed in Sweden and France, 2) Odin Spectrometer and InfraRed Imager System (OSIRIS, is used for the aeronomy mission) which is developed in Canada, where the data are also analysed.

As Odin has a joint astronomy and atmospheric mission, the observation time has been equally divided between the disciplines. To ensure continuous coverage and to provide for campaign-oriented observational periods, the atmosphere is observed every third day with an additional day in each third cycle. Periods of 1-2 weeks of uninterrupted atmospheric operations are scheduled in accordance with geophysical conditions.

The Odin SMR data for the period 2002-2007 have been examined with the purpose of finding continuous time intervals without large data gaps, in order to be able to extract 5-day planetary waves. As a result, several such time intervals have been found and analyzed in Papers I-III.

The ozone and temperature retrieved profiles (level-2 version 2.0), which have been examined in this work, are produced at the Chalmers University of Technology (Gothenburg) from measurements of the SMR at 544.6GHz (Frisk et al., 2003; Olberg et al., 2003; Urban et al., 2005). The temperature (K) estimates and ozone mixing ratio (ppmv), which are used in this study, came from the retrieved profiles with measurement response > 75% (i.e. the retrieved value is less than 25% dependent on the initial profile used in the retrieval). For the time intervals considered in Papers I-III, profiles with a good quality are found mostly between 24 and 56 km for temperature, and between 18 and 68 km for the ozone retrievals. The vertical resolution is about 2 km for both parameters. The estimated uncertainty in absolute values in Odin SMR profiles for temperature is about 0.5–1% between 24 and 40 km and about 1-3% between 40 and 56 km. For ozone is about 5-10% between 18 and 50 km and about 10-30% between 50 and 68 km. The retrieved fields of temperature and ozone mixing ratio are available between 82˚N and 82˚S on a grid of about 7˚ in latitude and 30˚ in longitude at mid-latitudes and 15˚-20˚ at high latitudes. These data have been linearly interpolated to a 2.5˚x 3.75˚ latitude-longitude grid for the analysis described below. Missing orbits and short data gaps in time have also been linearly interpolated. The fraction of missing orbits is about 5% of all available data.

3.2 Additional ground-based data

For additional information on planetary wave properties, ground-based measurements have been considered in Papers I and II. In Paper I, ozone measurements obtained with the millimetre wave radiometer (KIMRA, Kiruna millimetre wave radiometer) installed in Kiruna (67˚N50', 20˚E24', 420 m above sea level) have been applied. The technique of deriving ozone profiles can be found in (Rodgers, 1976; Krupa et al., 1998; Kopp, 2001). KIMRA provides measurements of ozone content at a height between 15 and 55 km. The height resolution of the retrievals varies between about 6 and 20 km, with the best resolution (6 km) at about 24 km altitude, increasing to 20 km resolution by 50 km altitude. The absolute accuracy in the retrieved ozone amounts is estimated to be about 1 ppmv. Uncertainties and changes in local tropospheric and stratospheric weather from day to day can lead to random errors up to 12-15%. Results of the comparison between the ozone profiles by KIMRA and Odin are presented in Paper IV.

Besides the ozone data, temperature measurements around the mesopause obtained with several meteor radars have been used and the results are described in Paper II. The meteor radars are located in the polar region in Sweden at Esrange (67˚N56', 21˚E04'), in Norway at Andenes (69˚N17', 16˚E00'), in Canada at Resolute Bay (74˚N30', 95˚W00') and at Yellowknife (62˚N30, 114˚W32'). The decay time of meteor trails is used to provide estimates of temperature at a height between 85 and 90 km. The technique of deriving temperature from meteor echoes can be found in Hocking et al. (2004) and references there-in. The resulting data consist of time series of daily average temperatures.

4. Data analysis

4.1 Evaluation of planetary wave properties from the temperature and ozone fields

The motion in the atmosphere can be explained, at least in part, in terms of linear wave theory. One of the usual starting points for such analysis is to subtract the zonal average from the flow field, thus isolating wave components. These wave components can be further subdivided into different zonal Fourier modes (for example, wave with zonal number 1, 2, 3…). A subsequent subdivision can be performed by subtracting the time average over a specific period from the flow field, thus isolating the transient components. Finally, these transient components can be separated into different frequency components by a Fourier transform in time. This common procedure, which includes all of the above mentioned divisions, is called *space-time spectral analysis*.

Hayashi (1971) has applied the basic mathematical technique to obtain the field variation over longitude and time in terms of a Fourier expansion in a set of functions with particular wavenumber-frequency pairs. Any function of longitude (λ) and tine (t) can be described as a double Fourier expansion:

$$X(\lambda,t) = \sum_k \sum_{\pm\omega} W_{k,\pm\omega} \cos(k\lambda \pm \omega t + \phi_{k,\pm\omega}) \qquad (13)$$

where k is the zonal wavenumber, ω the central frequency, φ a phase, and plus and minus signs correspond to westward and eastward moving components, respectively.

For the zonal spatial Fourier transform the coefficients $W_{k,\pm\omega}$ and phases $\phi_{k,\pm\omega}$ are obtained as follows:

$$X(\lambda,t) = \sum_k C_k(t)\cos k\lambda + S_k(t)\sin k\lambda \qquad (14)$$

Then a time Fourier transform applies to the cosine $C_k(t)$ and sine $S_k(t)$ coefficients of the spatial Fourier transform:

$$C_k(t) = \sum_\omega A_{k,\omega}\cos\omega t + B_{k,\omega}\sin\omega t \qquad (15)$$

$$S_k(t) = \sum_\omega a_{k,\omega}\cos\omega t + b_{k,\omega}\sin\omega t \qquad (16)$$

The coefficients *A, B, a* and *b* are related to the coefficients $W_{k,\pm\omega}$ and phases $\phi_{k,\pm\omega}$ (a detailed description is given in a paper by Hayashi, 1971).

All calculations in this PhD thesis have been performed using MATLAB software. The results of the analysis of temperature and ozone fields are the zonal means, wavenumber one and 5-day planetary wave variations. A standard signal processing technique is applied in this work for the Odin SMR measurements and consists of two steps: the first step is spatial filtering and the second is time filtering.

The Odin satellite provides data with a complete coverage of all longitudes each 12 hours using both ascending and descending nodes. A spatial Fourier transform is applied to the ozone and temperature fields around a latitude circle to extract the zonal means and the lowest harmonic spatial component, which is a wavenumber one, separately at each latitude and altitude for each 12-hour interval of Odin measurements. Odin's observing schedule is usually such that it makes atmospheric observations in two consecutive 12-hour periods, followed by a 24 or 48-hour gap (depending on measurement schedule), thereafter continuing with next two 12-hour observations. This time gap has been linearly interpolated. For the wavenumber one, the interpolation has been applied separately to real and imaginary parts of complex amplitude.

In order to find the 5-day temporal component, the time series of amplitude and phase (expressed as a complex amplitude for wavenumber one) for each latitude and altitude is filtered by a bi-directional 4-6 day band-pass filter. By applying a bi-directional filter, one can avoid introducing artificial phase shifts and, by using a filter with complex coefficients, it is possible to separate the westward and eastward travelling waves. As a result, time series of the characteristics of the westward propagating 5-day planetary wave, as a function of height and latitude, are derived for both ozone and temperature fields, and comparison between these two data sets can be made.

To test the significance of the extracted 5-day waves, a random permutation technique has been used. For the Odin data, 10 000 random permutations have been applied to the complex amplitudes of the wavenumber one in ozone and temperature. Then, the filtering procedure has been performed to extract 5-day waves from the each obtained random series of wavenumber one complex amplitudes. The obtained 10 000 random 5-day waves are statistically independent with respect to the original 5-day wave calculated from non-permutated wavenumber one. Finally, a comparison between random 5-day waves and the original 5-day wave has been made on the basis of the maximal wave amplitude (i.e., if the amplitude of the original wave is higher than 80% of the wave amplitudes resulting from random permutation of the data, we say it is of 80% significance). The significance of the 5-day temperature waves from the meteor radar data has been tested in the same way by applying the same random permutation technique but to the temperature estimates, and then, amplitude comparison between the original and random 5-day waves has been done as well. In Papers I-III, if it is not specially mentioned, only 5-day waves with significance more than 80% have been considered.

In Paper III, an additional test on significance of the calculated 5-day wave is performed using the well-known physical property of this wave that it should be coherent relative to the equator at middle latitudes. Latitude bands between 40˚- 60˚N and 40˚- 60˚S have been considered for all heights and for each available time period to select a coherent 5-day wave pattern for the whole latitude band. As a result, one or two short time intervals with convincing 5-day waves have been found in each observation period.

Figure 7 demonstrates an example for such a time interval (considered in Paper II) when the 5-day temperature perturbations tend to be in phase in latitude bands 40˚- 60˚N and 40˚- 60˚S at the 42 km level. These coherence patterns within a wide latitude band in each hemisphere demonstrate that, indeed, we observe large-scale harmonic oscillations due to the 5-day wave.

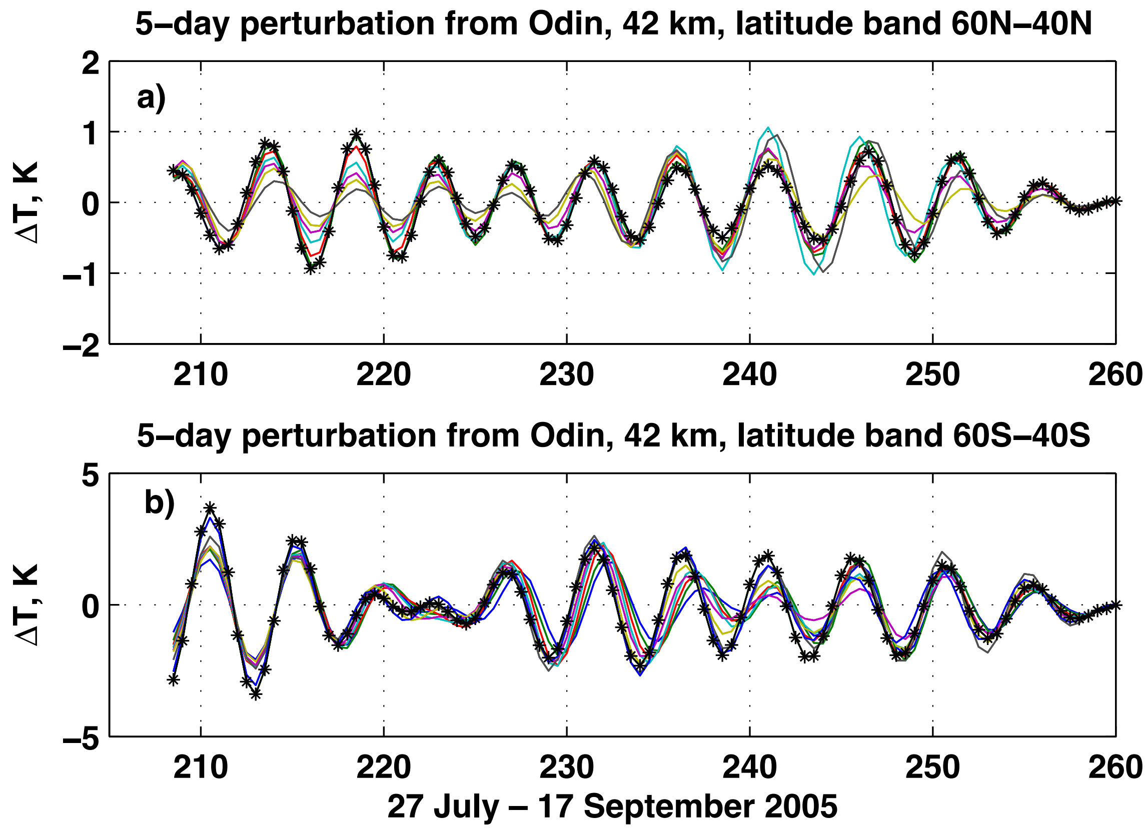

Figure 7. Comparison between 5-day temperature perturbations for 27 July – 17 September 2005 from the Odin data at the 42 km level, at longitude=21˚E and at latitude band 40˚-60˚N (***a***) and 40˚-60˚S (***b***), black curves with star are for 60˚N and 60˚S.

Another example is shown in Figure 8 for the 5-day ozone perturbations in the NH summer of 2004 (regarded in Paper II). One can see, that on the upper panel (***a***), the perturbations are coherent over the latitude band 40˚- 60˚N for almost the entire time interval. This is similar to Figure 7 and indicates that a coherent pattern over a wide latitude band is observed due to the presence of the 5-day wave.

The 5-day oscillations in the opposite hemisphere at 40˚- 60˚S (lower panel ***b***) during days 189-210 do not show the clear coherent pattern that is expected for the 5-day wave, therefore, this time interval (at this particular height) is rejected from further study. Thus, only the intervals for days 166-188 and 211-224, when the perturbations tend to be in phase due to the 5-day wave, are considered.

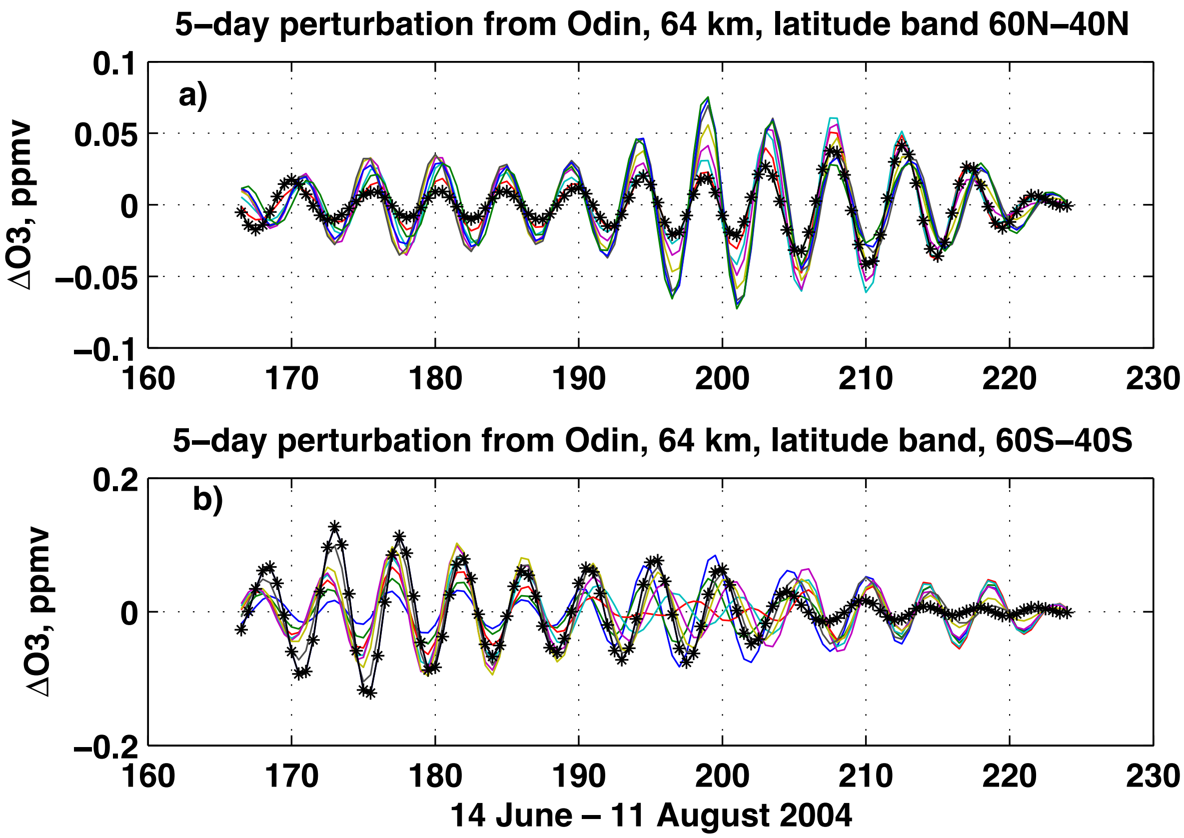

Figure 8. Comparison between the 5-day ozone perturbations for 14 June – 11 August 2004 from Odin data at the 64 km level, at longitude=21˚E and at latitude band 40˚-60˚N (***a***) and 40˚-60˚S (***b***), black curves with star are for 60˚N and 60˚S.

4.2 Validation of the Odin SMR data and extracted planetary waves

Validation of the ozone data was performed in the experimental work by Kopp et al. (2007) (Paper IV). In the latter paper, an intercomparison of the Odin-SMR ozone profiles with ground-based ozone observations has been performed. The results showed that the Odin measurements taken at 544.9 GHz yielded a systematic bias of 20-30% lower ozone mixing ratios in the middle stratosphere compared to the ground-based measurements. The results presented in this thesis are based mainly on the perturbations in ozone concentration and any systematic bias in the absolute values of ozone mixing ratio should not affect our results.

A check on the Odin temperature retrievals (from the 544.9 GHz channel) has been performed by comparing with temperature data obtained by the Microwave Limb Sounder (MLS) experiment during the Aura mission (Schwartz et al., 2008). We use MLS analysis version 2.2, level 2 data. The period 27 July – 16 September 2005 has been considered. Figure 9 shows a comparison between zonal means from the Odin and Aura temperature retrievals for the period 27 July – 6 August 2005. One can see that, between 24 and 43 km, the temperature profiles are quite similar according to both data sets with differences of about 3 K at the most, for the summer hemisphere (at 40˚N and 60˚N) and for middle latitudes (40˚S) in the winter hemisphere. The greatest discrepancy (~ 10 K) between two data sets is observed at 60˚S, which is at high latitude in winter. This result can be compared with results from the paper by Schwartz et al. (2008) in which the MLS temperature version 2.2 has been validated by extensive comparison between MLS and other experimental and assimilated data sets. In particular, the validation shows a difference up to 12 K between MLS temperatures and GEOS-5 and ECMWF assimilated data sets at altitude about 1 hPa (~ 48 km) for the latitude band 50˚-90˚S and for time period of June - August.

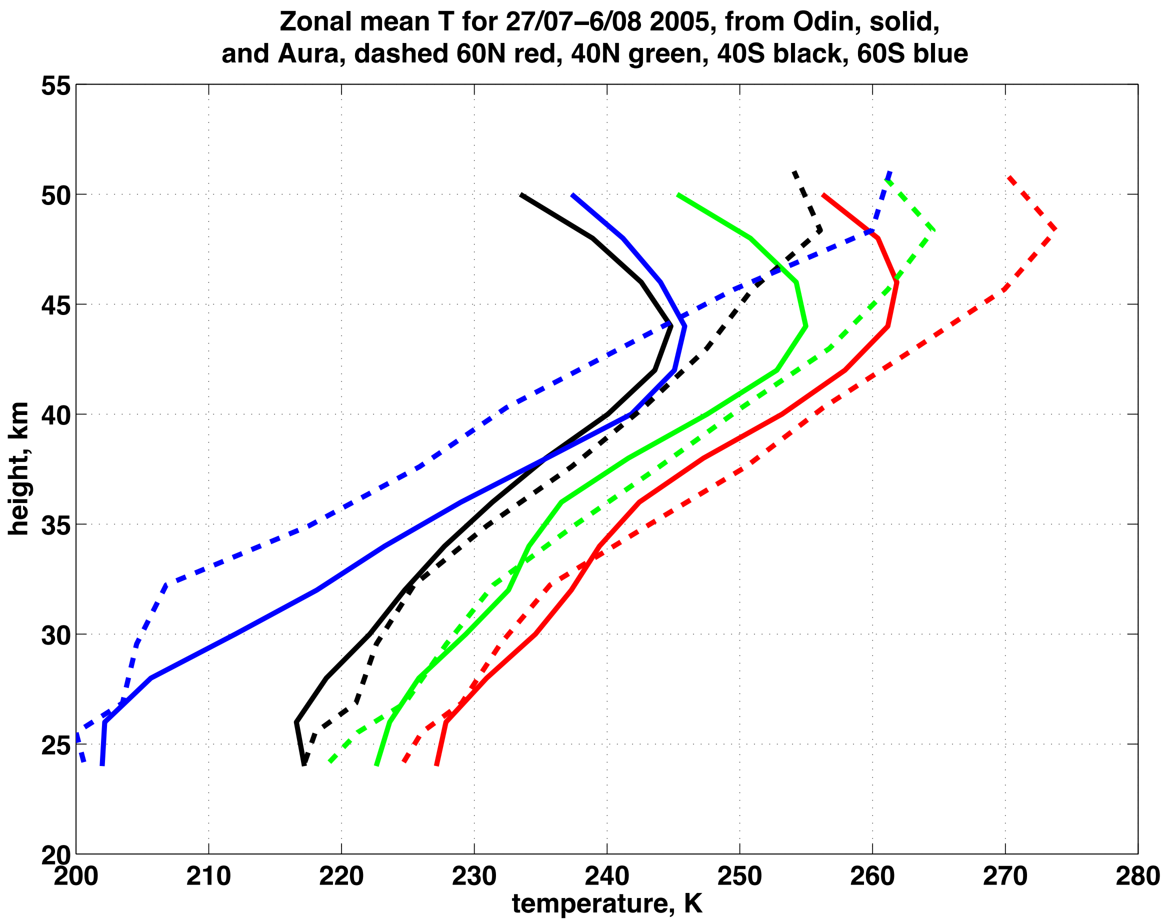

Figure 9. Comparison between zonal mean temperatures from Odin and Aura data for the period 27 July – 6 August 2005. Solid lines are for Odin and dashed lines are for Aura: at 60˚N (red line), at 40˚N (green line), at 40˚S (black line) and at 60˚S (blue line).

Also, a comparison between the 5-day temperature perturbations extracted from the Odin and Aura data has been performed. Dynamic conditions for 5-day planetary wave propagation are more favourable in the winter stratosphere than in summer one, therefore the wave amplitudes reach larger values in the winter stratosphere. Figure 10 illustrates an example of comparison between the 5-day temperature perturbations observed by the Odin and Aura-MLS satellite in the winter stratosphere at 38 km in the latitude band 40˚- 60˚N. One can see that the perturbation amplitudes have almost the same magnitude (1-4 K from Odin, 1-5 K from Aura) and the perturbation patterns are quite similar in both data sets. Figure 10 also shows that the 5-day perturbations in both the Odin (***a***) and the Aura (***b***) data tend to be in phase over the latitude band 40˚- 60˚S for days 208-220 and 243-260 (during days 221-242 the 5-day oscillation is quite noisy in both data sets and it is not used for further analysis). The coherence of the perturbations over the latitude band 40˚- 60˚S indicates clearly the presence of a 5-day wave, observed simultaneously in both data sets, which are completely independent.

Panel ***c***) of Figure 10 presents a comparison between the perturbations obtained from Odin (solid lines) and Aura (dotted lines) data at 40˚S and 60˚S. It is evident that, for days when the perturbations are coherent (days 208-220 and 243-260) in each data set (Odin – panel ***a*** and Aura – panel ***b***), they also tend to be in phase relative to each other (panel ***c***). The perturbation amplitudes are sometimes larger from the Aura data set at 60˚S (black line). Discrepancy of the amplitude values at 60˚S could be due to differences for the Odin and Aura satellite in data collection (time and space resolution: Odin scans each 90 s and makes 40 scans per orbit, Aura scans each 25 s and makes 240 scans per orbit, so that Odin might miss the maximum amplitudes). It is also possible that the discrepancy in the wave amplitudes from Odin and Aura data at 60˚S has the same (unknown) cause as the substantial difference between the zonal mean temperatures (demonstrated in Figure 9). It seems that the wave amplitudes from Odin are underestimated, but on the other hand, the amplitudes by Aura are perhaps overestimated because a magnitude of 5 K is indeed very large even in the case of a strong 5-day wave in the winter stratosphere. Further investigations are required to clarify these discrepancies.

Despite the difference in the perturbation amplitudes at 60˚S, the Odin and Aura measurements demonstrate almost the same magnitudes ~ 1-2 K at 40˚S (blue line in Figure 10) and the perturbations tend to be in phase relative to each other. Then, one can see that quite similar perturbations are observed due to the 5-day wave in both independent satellite data sources from Odin and from Aura. Thus, the Odin data are sufficiently reliable to estimate the properties of the 5-day planetary waves, at least for the locations and time intervals with high wave amplitude.

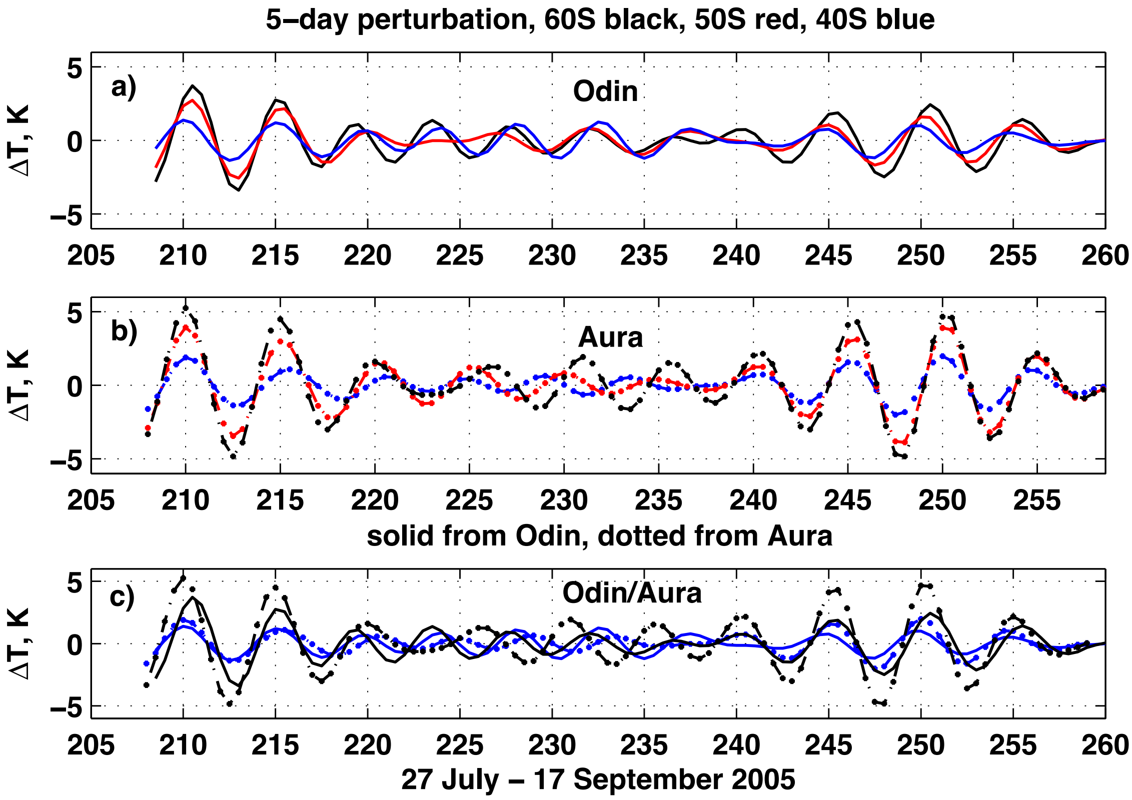

Figure 10. Comparison between 5-day temperature perturbations from Odin and Aura data at the 38 km level, at longitude=21˚E and latitude 40˚S (blue line), 50˚S (red line) and 60˚S (black line), for 27 July – 17 September 2005.

Figure 11 demonstrates the result of an analysis on simulated data including signals with different periods, subjected to sampling at intervals as available for Odin data. This allows for an examination of the limitations of our sampling/interpolation/filtering procedure when it is applied to real data. This figure shows the amplitude of the 5-day wave that is obtained after applying a 4-6-day filter to a simulated wave of unit amplitude. Wave period is shown on the x-axis and sampling was as follows: blue: sampled at 12 h intervals; green: sampled at 2 consecutive 12 h intervals each 2 days; red: sampled at 2 consecutive 12 h intervals each 3 days (with linear interpolation over the gaps in the last two cases).

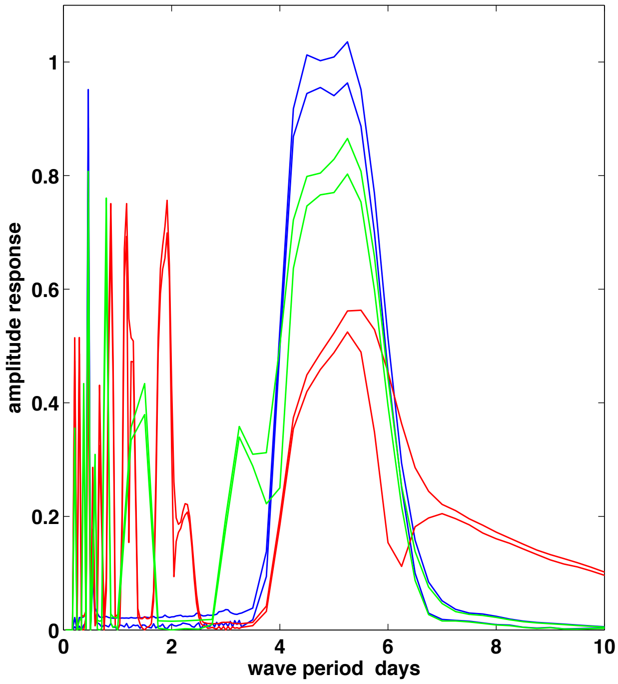

Figure 11. Amplitude response for the 5-day wave that has been obtained from simulated time series for waves with unit amplitude and different sampling schemes: blue: sampled at 12 h intervals; green: sampled at 2 consecutive 12 h intervals each 2 days; red: sampled at 2 consecutive 12 h intervals each 3 days.

The exact response depends on the phase of the wave relative to the sampling, so the curves are generated using 100 random phases for each period. Maximum and minimum responses are plotted. Figure 11 illustrates that the technique should be valid as long as there are no waves with periods less than 3 days. It is also seen that the amplitudes of real 5-day waves will be underestimated by about a factor 0.5 (red) or 0.8 (green).

5. Main results

5.1 Planetary wave propagation in the Northern Hemisphere in the winters of 2002-2003 and 2005

The most favorable background wind conditions for the planetary wave propagation occur in the winter stratosphere. One of the prominent modes observed in the winter extratropical region is a wavenumber one mode which includes several components with different time periods. Usually, a stationary wave is the dominant one with the highest amplitude. Other components of wavenumber one are freely traveling around the globe with periods of about 5 days, 10 days and 16 days.

One can observe the planetary wave characteristics in changes of properties of the atmospheric parameters such as temperature, pressure, wind velocity and in the concentration of atmospheric species.

Characteristics of the 5-day wave observed in the NH winter of 2005 are presented in Paper I. The wave is detected in the global satellite data in both temperature and ozone fields (Figure 1 of Paper I) and they tend to be out of phase in the upper stratosphere (Figure 3 of Paper I), as expected, as a result of photochemical effects (see Section 1.4). Besides the planetary waves observed in global data from the Odin satellite, local 5-day perturbations in the ozone concentration are registered (in the polar region in Scandinavia above Kiruna) using KIMRA measurements. Detailed comparison demonstrates a good correlation between the global and local ozone time series (Figure 5 of Paper I) in terms of both phase and amplitude of the perturbations during January-February of 2005.

Another case study of planetary waves including the NH winter period of 2002-2003 is described in Paper III. For this winter, the planetary waves are observed in both temperature and ozone fields as in the case of 2005. The results shown in Paper III are presented for the wavenumber one and for the 5-day wave variations. Several stratospheric warming events have been observed during this winter season. One of the sources of stratospheric warming is the orography and land-sea temperature contrast that are responsible for the generation of long-wavelength (wavenumber 1 or 2) planetary waves in the troposphere. These waves travel upward into the stratosphere and dissipate there, producing the warming by decelerating the mean flow. As a result of the stratospheric warming event, the polar vortex of westerly winds abruptly (i.e. in a few days) slows down or even reverses direction, accompanied by an increase of stratospheric temperature by several tens of degrees.

Along with the warming events observed in the NH winter of 2002-2003, amplification of the amplitude in wavenumber one (Figs. 4, 5 of Paper III) and partly in the 5-day perturbation (Figs. 8, 9 of Paper III) has been detected in both temperature and ozone fields. In general, the results show an expected in-phase behavior between temperature and ozone in the lower stratosphere due to dynamic effects and an out-of-phase pattern in the upper stratosphere which is expected as a result of photochemical effects (see Section 1.4). However, during the strongest stratospheric warming event, when the wave amplitude changes dramatically, the phase relationship between ozone and temperature varies, so that the perturbations sometimes tend to be in phase even in the upper stratosphere.

5.2 Five-day planetary wave propagation in the Northern Hemisphere summers of 2003-2005 and 2007

In summer, zonal winds are westerly in the troposphere and change direction to easterly in the lower stratosphere. Zonal wind velocities grow with altitude and reach maximum values at about 60-70 km. Around the summer mesopause, the wind alters direction again to westerly. Planetary waves propagate vertically provided that their phase speeds are westward relative to the mean flow. This means that, is in summer time in the stratosphere, the planetary waves propagate in the same direction as the background wind blows. The waves are able to travel vertically until they reach a height where the wind speed in the direction of their phase propagation equals the wave phase speed (known as a critical level, see Eq. 7). The wave then dissipates and its energy is absorbed in the background flow.

Despite the unfavorable background wind conditions in the summer hemisphere, vertical planetary wave propagation into the mesosphere has been observed using global satellite measurements (Prata, 1989; Hirooka, 2000; Garcia et al., 2005; Riggin et al., 2006). This possibility has also been earlier discussed in several theoretical studies (Geisler and Dickinson, 1976; Salby, 1981a,b; Miyoshi, 1999).

In Paper II, several occurrences of 5-day waves are demonstrated for the NH summers of 2003-2005 and 2007, confirming the existence of 5-day planetary waves up to the mesopause level. One of the interesting features of the 5-day planetary wave properties in summertime is their large amplitude during the solstice condition in the extratropical upper mesosphere with maximal magnitudes appearing in the polar region.

The results of Paper II show that the 5-day planetary wave has been observed in temperature variations derived from meteor radar measurements around the summer polar mesopause during several NH summers. Three possible sources of this wave have been considered. One possibility is vertical wave propagation from lower to upper altitudes in the summer hemisphere. The second possibility is the same process but in the winter hemisphere, with subsequent horizontal travel of the wave at mesospheric heights into the opposite, summer, hemisphere. A planetary wave originating in the troposphere may not be able to propagate through the stratosphere without being partly absorbed and, thus, some of the waves observed in the mesosphere may be excited in-situ when the dynamic conditions there are suitable. This is the third possible origin of the 5-day planetary wave in the summer mesosphere.

From the theoretical consideration by Plumb (1983) it follows that a possible origin for the quasi-two-day planetary wave in the summer mesosphere is the baroclinic instability of the easterly jet in the summer time. Plumb pointed out that, around the solstices, the stratospheric easterlies in the summer hemisphere intensify because of heating of the atmosphere in the high-latitudes regions. Almost at the same time, a strong westerly shear develops in the upper mesosphere driven by the gravity wave breaking (Holton, 1982; Matsuno, 1982). Eventually, such shear may become so strong that the jet becomes baroclinically unstable, a process that could be manifested by the appearance of the two-day planetary wave. These theoretical considerations on the influence of the baroclinic instability on wave amplitude growth in the summer mesosphere have been supported by several experimental works, and not only for the 2-day wave, but also for a spectrum of waves that cluster along a line of constant westward phase velocity (Garcia et al., 2005; Riggin et al., 2006). The observed structure of these waves, and the fact they have high amplitudes only close to the solstices, are consistent with excitation of a spectrum of atmospheric normal modes by the baroclinic instability of the easterly summer jet in the mesosphere. In other experimental work by Riggin et al. (2006), based on the SABER measurements, it was found that the 5-day wave in the summer high-latitude mesosphere was amplified by the baroclinic instability, although its source seemed to be in the winter stratosphere.

In Paper II the three possible sources outlined above have been examined to find out whether northern-hemisphere or southern-hemisphere planetary waves at lower altitudes, or in-situ excited, are the more likely source of the fluctuations at the summer mesopause.

The results demonstrate that in one case, far from solstice, the baroclinic instability is unlikely to be involved. In an additional case, close to solstice, upward propagation in the same hemisphere seems to be ruled out. In all other cases, all or any of the three proposed mechanisms are consistent with the observations.

Summary of the included papers

Paper I. Belova, A., Kirkwood, S., Raffalski, U., Kopp, G., Hochschild G., and Urban J.: Five-day planetary waves as seen by Odin satellite and the ground-based Kiruna millimeter wave radiometer in January-March 2005, Can. J. of Phys., 86, 459-466 (2008).

Characteristics of 5-day planetary waves observed in temperature and ozone mixing ratio are examined in Paper I for the Northern Hemisphere (NH) winter in January-March 2005. The wave is detected in the global data from the Odin satellite in both temperature and ozone fields and the highest wave amplitudes are found in the winter hemisphere in the latitude band 60˚-70˚N. The relative phase between ozone and temperature perturbations shows the expected anti-phase behaviour in the upper stratosphere as a result of photochemical effects. The global 5-day planetary wave properties from Odin have been compared with local 5-day perturbations in ozone mixing ratio measured by the millimeter wave radiometer (KIMRA) located in the polar region in Scandinavia above Kiruna. Detailed comparison demonstrates a good correlation between the global and local ozone time series in terms of both phase and amplitude of the perturbations during the middle winter in January-February of 2005.

Paper II. Belova, A., Kirkwood, S., Murtagh, D., Mitchell, N., Singer, W., and Hocking, W.: Five-day planetary waves in the middle atmosphere from Odin satellite data and ground-based instruments in Northern Hemisphere summer 2003, 2004, 2005 and 2007, submitted to Annales Geophysicae.

Results presented in Paper II demonstrate the existence of 5-day waves between the lower stratosphere and upper mesosphere in the NH summers of 2003-2005 and 2007. The 5-day planetary wave characteristics have been extracted and analyzed on a global scale using temperature and ozone measurements by the Odin satellite. The satellite data show the presence of 5-day planetary waves in temperature at 24-54 km height range. These waves have the expected higher amplitudes in the winter hemisphere and (usually) inter-hemispheric symmetry in phase. Wave amplitudes are typically about 2 K (maximum ~ 4 K) in the winter stratosphere and about 0.5 K (maximum ~ 1 K) in the summer stratosphere. Five-day waves in ozone concentration are detected at 24-68 km height range. In general, the wave amplitude in ozone is about 0.0025-0.05 ppmv in the summer hemisphere and about 0.05-0.1 ppmv in the winter one. Local 5-day temperature fluctuations are examined at the summer mesopause (85-90 km) as obtained by several ground-based meteor radars located in northern Scandinavia and in northern Canada. These 5-day temperature perturbations show high amplitudes (up to 15 K) and 1-2.5 day phase shifts between Scandinavia and Canada, consistent with the expected westward propagation of 5-day planetary waves. Three possible sources of the detected waves around the summer polar mesopause have been considered: upward propagation from the stratosphere in the summer-hemisphere, horizontal propagation from the winter-hemisphere or in-situ excitation as a result of the baroclinic instability. The results demonstrate that in one case, which is far from solstice, the baroclinic instability is unlikely to be involved. In one further case, close to solstice, upward propagation of the 5-day planetary wave in the same hemisphere seems to be ruled out. In all other cases, all or any of the three proposed mechanisms are consistent with the observations.

Paper III. Belova, A., Kirkwood, S., and Murtagh, D.: Planetary waves in ozone and temperature in the Northern hemisphere winter of 2002-2003 by Odin satellite data, submitted to Annales Geophysicae.

Paper III studies the relationship between temperature and ozone concentration in the lower and upper stratosphere (between 24-46 km) in the NH for the period of December 2002 – March 2003 using Odin satellite data from the advanced sub-millimetre radiometer. Comparison between the ozone mixing ratio and temperature fields has been performed for the middle and high winter latitudes (40˚-70˚N) for zonal means, for wave number one variations and for 5-day planetary waves. Several stratospheric warming events were observed during this winter season. Along with these warming events, amplification of the amplitude in wave number one and partly in the 5-day perturbation has been detected, in both temperature and ozone fields. In general, the results show the expected in-phase behavior between the temperature and ozone fields in the lower stratosphere due to dynamic effects, and an out-of-phase pattern in the upper stratosphere which is expected as a result of photochemical effects. However, during the strongest stratospheric warming event, when the wave amplitude changes dramatically, the phase relationship between ozone and temperature varies in such way that the perturbations sometimes tend to be in phase even in the upper stratosphere.

Paper IV. Kopp, G., Belova, A., Diez y Riega V E., Groß, J., Hochschild, G., Hoffmann, P., Murtagh, D., Raffalski, U., and Urban J.: Intercomparison of Odin–SMR ozone profiles with ground-based millimetre-wave observations in the Arctic, the mid-latitudes, and the tropics, Can. J. Phys., 85, 1097-1110, 2007.

Paper IV presents the results of comparison between the ozone profiles measured by Odin sub-millimetre radiometer (SMR) and measurements taken by ground-based millimetre wave radiometers in the Arctic; at Kiruna, Sweden; in the mid-latitudes on the Zugspitze, Germany; and in the tropics at Mérida, Venezuela. The Odin data used for these comparisons are level-2 data of version 2.1 for the 501.8 GHz band and of version 2.0 for the 544.6 GHz band. The Kiruna Microwave Radiometer (KIMRA) covers the frequency range 195-224 GHz, and the Millimeter Wave Radiometer MIRA 2, which has been operated on the Zugspitze and at Mérida, measures in the frequency band 268-281 GHz. The ground-based measurements have a lower vertical resolution than those of Odin and the latter have been interpolated to the grid of the ground-based measurements and degraded to the vertical resolution of the corresponding measurements using the averaging kernels of the ground-based retrievals. The comparison of the resulting profiles with the ground-based data enables the identification of biases in the Odin measurements and their possible latitudinal variation. In general, a good agreement between satellite and ground-based measurements for the 501.8 GHz band was found in the stratosphere except for a negative bias in the Odin data of about 10–15% in the tropics. The Odin measurements taken at 544.9 GHz yielded systematically 20–30% lower ozone mixing ratios in the middle stratosphere than the ground-based measurements at all sites. The reasons for the systematically lower ozone concentrations of the Odin-SMR measurements in the 544.9 GHz band are unknown so far. In principal, the measurements at the strong ozone line at 544.9 GHz are better situated for measurements at altitudes with low ozone concentrations than those measured at the weaker line in the 501.8 GHz band. However, the Odin ozone data taken in the 544.9 GHz band must be handled with caution if one is interested in absolute values. Nevertheless relative changes like the seasonal variation of ozone can be studied using this data.

Papper V. Kirkwood, S., Belova, A., Murtagh, D., Réchou, A., Goldberg, D., and Schmidlin, F.: Polar mesocyclones and their extension to the UTLS - a case study using ESRAD, Odin and MaCWAVE radiosondes, Proceedings of the 18th ESA Symposium on European Rocket and Balloon Programmes and Related research, Visby, Sweden, June 2007, ESA SP-647, 585-588, 2007.

Many studies have been made of the importance of UTLS (upper-troposphere, lower stratosphere) processes, such as Rossby Wave Breaking (RWB), for the growth of tropical storms and cyclones. While weather systems associated with these processes are large scale, and can be effectively studied using synoptic meteorological assimilations, the corresponding systems at high latitudes (mesocyclones or polar lows) are much smaller and are often unresolved by synoptic data fields. The RWB is important not only for its effects on storms, but also on the mixing of air between the stratosphere and troposphere. In this paper ESRAD MST radar has been used to study small scale structures in wind and potential vorticity (associated with features such as polar mesocyclones) from the middle troposphere up to ~15 km altitude. In the case study the radiosondes launched from Esrange during MaCWAVE campaign in January 2003 have been used to provide the necessary calibration of the ESRAD scattered signal power. However, since this calibration is needed only occasionally, it will be possible to use the regular radiosondes from the international meteorological network, using periods when a fairly uniform air-mass is located over the region. Results from the

MaCWAVE radiosondes, and from the Odin satellite, allow validation of estimates of static stability and potential vorticity derived from ESRAD. Results from both ESRAD and Odin are shown to be better than a standard meteorological assimilation in indicating the presence of a mesoscale potential vorticity structure over northern Scandinavia.

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List of Acronyms

CMAM	Canadian Middle Atmosphere Model
CRISTA	CRyogenic Infrared Spectrometers and Telescopes for the Atmosphere
ECMWF	European Centre for Medium-Range Weather Forecasts
ESRAD	ESrange RADdar
GEOS-5	Goddard Earth Observing System Model
KIMRA	Kiruna millimetre wave radiometer
MATLAB	MATrix LABoratory
MLS	Microwave Limb Sounder
MSIS	Mass Spectrometer - Incoherent Scatter (model of the upper atmosphere)
MST	Mesosphere-Stratosphere-Troposphere
NH	Northern Hemisphere
PGF	Pressure Gradient Force
SABER	Sounding of the Atmosphere using Broadband Emission Radiometry (instrument aboard the TIMED satellite)
SH	Southern Hemisphere
SMR	sub-mm radiometer (instrument aboard the Odin satellite)
TIMED	Thermosphere Ionosphere Mesosphere Energetics and Dynamics
UARS	Upper Atmosphere Research Satellite