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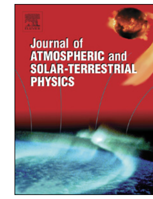

Generation of waves by jet-stream instabilities in winter polar stratosphere/mesosphere

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ABSTRACT

In the paper we investigate the manifestation of large-scale and middle-scale atmospheric irregularities observed on stratosphere/mesosphere heights. We consider typical patterns of circulation in stratosphere and lower mesosphere which are formed due to a difference of air potential energy between equatorial and polar latitudes, especially in polar night conditions. On the base of ECMWF Era Interim reanalysis data we consider the dynamics of midlatitude winter jet-streams which transfer heat from low latitudes to polar region and which develop due to equator/pole baroclinic instabilities. We consider typical patterns of general circulation in stratosphere/lower mesosphere and reasons for creation of flaky structure of polar stratosphere. Also we analyze conditions that are favorable for splitting of winter circumpolar vortex during sudden stratosphere warming events and role of phase difference tides in this process. The analysis of vertical structure of the stratosphere wind shows the presence of regions with significant shear of horizontal velocity which favors for inducing of shear-layer instability that appears as gravity wave on boundary surface. During powerful sudden stratosphere warming events the main jet-stream can amplify these gravity waves to very high amplitudes that causes wave overturning and releasing of wave energy into the heat due to the cascade breakdown and turbulence. For the dynamics observed in reanalysis data we consider physical mechanisms responsible for observed phenomena.

1. Introduction

Stratosphere/mesosphere dynamics in winter is governed by a large-scale temperature gradient which arises due to difference of solar radiation absorbed in equatorial and polar regions which especially high during polar night conditions. Cool stratospheric air in polar region lowers so that low pressure area is formed. This low pressure area is filled by the equatorial stratospheric air whose potential energy transforms to kinetic energy of pole-ward fluxes. Due to the Coriolis force the decaying air-streams turn eastward and form the structure which is similar to water whirlpool and is called as circumpolar vortex (CPV). This dynamical structure is well pronounced in autumn and winter and it transports air from warm equator to polar region where it lowers to the troposphere. This process is named the Brewer–Dobson circulation (BDC) (Brewer, 1949; Dobson, 1956). BDC affects tropospheric climate and troposphere variability with different time scales, that was found from transport of ozone (*e.g.* Thompson et al., 2011) and water vapor (*e.g.* Solomon et al., 2010). The time interval of full stratospheric circulation can be measured by decadal scales, except the cases of dynamical interactions with the jet-streams on intraseasonal time scales (*e.g.* Baldwin and Dunkerton, 2001).

Many features of winter polar circulation are well presented by various versions of General Circulation Model (GCM) (Richmond et al., 1992). The modeling shows a downward circulation in polar stratosphere, as well as adiabatic heating and upward circulation in the mesosphere (Liu and Roble, 2002). In GCM based models the Brewer–Dobson circulation is considered as a result of interaction between large scale Planetary Waves (PW) and Gravity Waves (GW) produced by different sources in the troposphere and the stratosphere. Classical mechanism (*e.g.* Charney and Drazin, 1961) suggests propagation of planetary scale waves from low to upper atmosphere. In new versions of GCM different mechanisms are used for description of downward air motion that imply for BDC both instability effects and existing of specific surf-zone where Rossby waves mix PWs (Cohen et al., 2013).

Due to restrictions in computational resources GW can be included in GCM only by using some parametrization which change actual GW sources by averaged parameters in equations used for the modeling. For that parametrization some mechanisms of generation and breaking/saturation of gravity waves remain out the consideration, and special efforts are required to make the model self-consistent (Yiğit et al., 2008). Moreover, models cannot provide a proper source of GW that gives sometimes inconsistent

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results concerning to wave propagation and interaction (Pogoreltsev et al., 2007).

We do not consider problems of GCM modeling in the present paper. Our aim here is to show what mechanisms are responsible for generation of large scale and middle scale waves in the stratosphere/mesosphere region and how it can be explained in terms of hydrodynamics. We will also try to understand why favorable conditions appear in winter stratosphere for development of Sudden Stratosphere Warming (SSW) and enhanced Brewer–Dobson circulation.

The modern version of Era Interim reanalysis from European Centre for Medium-Range Weather Forecasts (ECMWF) (Dee et al., 2011) gives a new possibility for analysis of fine structure of stratosphere dynamics. This data archive provides good latitude/longitude resolution of atmospheric parameters and can be used for investigation of stratospheric wind structures. Although direct observation of the stratosphere/mesosphere wind from ground based and satellite facilities is difficult, the reanalyze technique allows us to extract this important information and to use the reanalysis data practically as experimental material with controlled uncertainties provided by developers. As it was discussed on ECMWF site (http://www.ecmwf.int/en/research/data-assimilation) and showed in detail by (Dee et al., 2011), the reanalysis data quality is sufficiently good to reproduce the real distribution of atmospheric parameters up to heights of 10 hPa pressure level, and only some uncertainty may be at higher levels, maximum of which is 1 hPa. Keeping this in mind we will address to this data set as to experimental data, because its quality is good enough for the purpose of our study. Era Interim reanalysis has 0.75° resolution both on latitude and longitude, that is better comparing to other similar models (ECMWF Era-40, NCEP/NCAR, UKMO) and it allows us to investigate the stratosphere dynamics in more details.

The main parameters under analyzing in this study are geopotential and stratospheric wind including horizontal u and v components and vertical velocity. We also use the field of total horizontal velocity $\sqrt{u^2+v^2}$ to indicate the planetary structure of stratospheric jet-streams and vertical velocity variations for study of middle scale GWs. To investigate dynamical structures from Era Interim reanalysis data we developed special software for mapping of the data on fixed pressure levels. The software provides data scaling and possibility to do an additional processing.

All velocity fields are considered at constant pressure levels. To illustrate the different states of stratosphere dynamics we consider basically the circulation patterns in Northern hemisphere at two pressure levels 1 hPa and 10 hPa, which correspond to altitudes ~50 km and ~30 km. Using of these two levels gives us an opportunity to analyze the main altitude region of the stratosphere (10 hPa) and bottom part of the mesosphere (1 hPa). Level 1 hPa can be considered as lower mesosphere because during winter solstices the stratopause is usually located near ~50 km, and mesospheric effects well pronounce on this level.

In the paper we are focusing on jet-stream (JS) and wave-like structures, which can be studied with Era Interim reanalysis in the stratosphere/mesosphere region. For interpretation of results we use the classical approach of geostrophical hydrodynamics (Gill, 1982; Pedlosky, 1987) and some results of nonlinear fluid dynamics (Landau and Lifshitz, 1987; Kundu, 1990).

In Section 2 we consider the physical mechanism which is responsible for creating of planetary scale structures in the stratosphere and provide some theoretical estimates for characteristics of large scale jet-streams dynamics. In Section 3 we give a description of typical structures observed in global stratosphere circulation on the base of ECMWF Era Interim reanalysis and try to reconstruct the three-dimensional structure of stratospheric jet-streams. Section 4 is devoted to fine structure of winter circulation which is generated by jet streams and provides the source of irregularities and waves that propagate upward to mesosphere and lower thermosphere. In Section 5 we discuss some conclusions that can be made from results of the analysis.

2. Physical mechanism of large scale stratosphere dynamics

For illustrating the reason of jet-stream generation in the stratosphere Fig. 1 shows typical examples of Era Interim geopotential distribution for Northern hemisphere in summer and in autumn/winter seasons at two pressure levels 1 hPa (Fig. 1(a) and (b)) and 10 hPa (Fig. 1(c) and (d)). We can see that in summer the geopotential is higher above the pole and difference of geopotential heights between the pole and the equator is about ~1.3 km at 1 hPa (Fig. 1a) and ~0.5 km at 10 hPa (Fig. 1c). This difference is produced by high solar radiation flux which is absorbed by stratospheric air during polar day and initiates the rise of the atmosphere and slow equator-ward motion of air. The main part of solar flux in the stratosphere heating is the ultraviolet radiation absorbed by stratospheric ozone.

Quite different geopotential distribution is observed in autumn/winter when solar radiation flux in polar stratosphere is low or absent as it happened during the polar night conditions. During autumn in the polar region a large low pressure area is forming so that the difference of geopotential heights between equator and pole is about ~3.5 km at 1 hPa (Fig. 1b) and ~1.5 km at 10 hPa (Fig. 1d). This significant difference initiates air motion to the pole and it is realized through a complex dynamical process.

To understand the reasons why the air motion cannot be a simple pole-ward flow, let us consider a scheme of the air motion in midlatitudes. Fig. 2 shows a sketch of constant pressure surface in the presence of geopotential gradient between the equator and the pole. The surface of constant pressure in the stratosphere has a form of horn as it can be seen on Fig. 1b and Fig. 1d. Any motion when air-stream changes latitude means the changing of air potential energy which transforms to kinetic energy of stream. During a pole-ward motion air looses potential, in a motion to the equator its potential increases. Due to the Coriolis force in pole-ward motion air shifts eastward, forming a cyclonic spiral trajectory (left scheme on Fig. 2), and it shifts westward when moves southward (right scheme on Fig. 2).

The presence of significant gradient of potential energy makes the motion of air instable because of a possibility for periodic transformation of stream potential energy to kinetic energy and inversely. When air stream moves pole-ward it loses gravity potential and accelerates. If by some reason stream turns equator-ward (for example due to colliding with another stream) then it turns westward, increases gravity potential and decreases its velocity. This process can repeat periodically and it can form a periodical structure of the atmosphere. We should say that instability process can be formed only with positive equator/pole geopotential gradient (i.e. presence of polar low pressure area) in autumn/winter and it does not work in summer (in the case of polar eminence).

We can make some estimates about quantitative characteristics of instability which forms jet-streams. The stratosphere jet-stream has transverse horizontal scale L about ~1000 km. Its vertical scale D is about few kilometers and horizontal velocity U is about 70–150 m/s. We suggest that on stratospheric heights 20–50 km water vapor is absent so that pressure p, density ρ and temperature T fulfill to ideal gas equation $p=R\rho T$ (R is universal gas constant). We suggest that the temperature increases linearly $T=T_0(1+\alpha(z-z_0))$ with altitude z and has the gradient about 5 K/km ($\alpha \cong 2\cdot 10^{-5}\ \mathrm{m}^{-1}$, $T_0=250$ K, $z_0 \cong 20$ km). In static