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Modeling the temperature of the polar mesopause region: Part II—Intra-seasonal monthly oscillations

Hans G. Mayr [a,*], John G. Mengel [b,1], Frank T. Huang [c], Scott M. Bailey [d]

[a] Laboratory for Atmospheres, Goddard Space Flight Center, Code 613.3, 8800 Greenbelt Road, Greenbelt, MD 20771, USA
[b] Science Systems and Applications, Inc., Lanham, MD, USA
[c] University of Maryland, Baltimore, MD, USA
[d] Virginia Polytechnic Institute, Blacksburg, VA, USA

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ABSTRACT

Measurements show that the polar mesospheric clouds (PMC) can vary, in the zonal mean, with periods around 1 month [Bailey et al., 2005. Observations of polar mesospheric clouds by the Student Nitric Oxide Explorer. J. Geophys. Res. 110, D13203, doi:10.1029/2004JD005422]. This observation has been the impetus for the present paper, where we describe corresponding temperature oscillations generated by the Numerical Spectral Model (NSM). Our numerical results are taken from the 3D and 2D versions of the NSM, which produce inter-annual and long-term variations in the polar mesopause region, as discussed in the accompanying paper (Part I). In the NSM, the intra-seasonal temperature variations with periods around 2 months are generated by the meridional winds that in turn are accelerated by the momentum deposition from small-scale gravity waves (GW) propagating north/south. The wave-driven dynamical process underlying the oscillations is intrinsically non-linear like that generating the quasi-biennial oscillation (QBO). Our analysis demonstrates that the seasonal annual and semi-annual variations excite the oscillation frequencies through non-linear cascading.

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1. Introduction

The polar mesospheric clouds (PMC) observed during summer months with ground-based and spacecraft measurements reveal a rich climatology, covering a wide range of time scales as discussed in several papers (e.g., Thomas, 1984; Olivero and Thomas, 1986; Thomas and Olivero, 1989; Thomas et al., 1991; DeLand et al., 2003; Chu et al., 2003; Merkel et al., 2003). In addition to the signatures of tidal and planetary wave activity, the variations seen in the PMC have periods commensurate with the 11-year solar cycle forcing and the quasi-biennial oscillation (QBO).

The PMC also reveal zonal-mean variations with periods around 1 month, as shown by Bailey et al. (2005) based on measurements with the Student Nitric Oxide Explorer (SNOE). Such oscillations have been seen in zonal and meridional winds and in the gravity wave (GW) activity inferred from medium frequency radar observations at equatorial latitudes in the upper mesosphere and lower thermosphere (Eckermann and Vincent, 1994; Eckermann et al., 1997). Lieberman (1998), Huang and Reber (2003), and Huang et al. (2005) reported similar oscillations seen in wind measurements on the Upper Atmospheric Research Satellite (UARS), and Huang et al. (2005, 2006) inferred such variations from the temperature measurements on the UARS, and on the Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) spacecraft.

In a modeling study with the 2D and 3D versions of the Numerical Spectral Model (NSM), Mayr et al. (2003a) reported that the momentum deposition from small-scale GW, propagating north/south, generates in the meridional circulation intra-seasonal oscillations with periods between 1 and 3 months. And the meridional circulation in turn produces corresponding temperature oscillations due to adiabatic heating and cooling. Numerical experiments show that the underlying wave-driven dynamical process has the property of a non-linear auto-oscillator similar to that generating the QBO, except that the meridional, not zonal, momentum budget is involved. The oscillations are partially induced by the QBO and by the seasonal annual and semi-annual variations.

We present here the computed zonal-mean temperature oscillations with periods around 2 months, which are generated by the NSM in the polar mesopause region and would contribute to producing the corresponding variability observed in the PMC. The numerical results are taken from the 3D and 2D versions of the NSM that are discussed in the accompanying paper (Part I).

* Corresponding author. Tel.: +1 301 2867505; fax: +1 301 2862323.
E-mail address: hans.g.mayr@nasa.gov (H.G. Mayr).
[1] Deceased.

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2. 3D model results

The 3D version of the NSM employed in the present paper, and discussed in Part I, was originally applied in a modeling study of the mesospheric diurnal tide modulated by the QBO (Mayr and Mengel, 2005). Of central importance for the present application, the model incorporates the Doppler Spread Parameterization for small-scale GW developed by Hines (1997a, b). The NSM relies primarily on GW to generate the QBO and the intra-seasonal monthly oscillations discussed here. In order to resolve the sharp GW momentum source that generates these oscillations, the vertical step size needs to be small and is taken to be about 0.5 km below 120 km. At the initial height in the troposphere, the GW source peaks at the equator and is hemispherically symmetric, and it is taken to be isotropic and time independent.

For completeness, we present in Fig. 1 the computed zonal-mean temperatures variations at 85 km recorded at 7-day intervals, similar to Fig. 6 of Part I where the 14-day average is shown. In agreement with observations, the model reproduces the lower temperatures in summer and inter-annual variations that are produced by the stratospheric QBO. Of particular interest for the present paper, Fig. 1 also shows oscillations with periods around 2 months that peak in the Polar Regions, and these are referred to generically as monthly oscillations.

Analogous to Fig. 1, we present in Fig. 2a the computed variations of the meridional winds (positive (red) southward and negative (blue) northward), and in Fig. 2b the zonal winds (positive (red) eastward and negative (blue) westward). As expected, the meridional winds in Fig. 2a are largest around the equator, with the dominant component directed from summer to winter. Due to the associated adiabatic heating and cooling, which dominates the energy budget in this region of the atmosphere, the resulting temperatures are lower in summer than in winter as seen from Fig. 1. Superimposed on this annual meridional wind field, Fig. 2a also reveals sizable oscillations with periods around 2 months, which extend to high latitudes to produce, through the vertical winds primarily, the corresponding temperature variations in the Polar Regions (Fig. 1). In the zonal winds (Fig. 2b), the monthly oscillations are also pronounced, and their amplitudes are somewhat larger than those for the meridional winds (Fig. 2a).

2.1. Spectral analysis

To provide understanding, we present with Fig. 3 the power spectra of the zonal-mean temperature variations at 84°N (Gaussian point), covering the time span from 5 to 15 years in the altitude range from 70 to 100 km. In Fig. 3a, we show the component that is hemispherically symmetric (same phase), and in Fig. 3b the one that is hemispherically anti-symmetric (opposite phase). The model results are recorded in 7-day intervals to resolve periods down to half a month. To improve clarity, however, the spectral harmonics for periods shorter than 1.2 months are not shown. The spectra are presented in terms of the discrete Fourier harmonics, h. The frequencies are then given by $h/10$ (cycles per year), and the corresponding periods are $10/h$ (years). This format is perhaps unusual, but it proves to be convenient for the present purposes, where we relate the oscillations to non-linear interactions.

Considering the product of complex amplitudes, $X\exp[i\omega_X t] * Y \exp[i\omega_Y t] = Z\exp[i(\omega_X \pm \omega_Y)t]$, non-linear interactions between oscillations can be identified in the spectra simply from the additions and subtractions of integers, i.e., $\omega_X \pm \omega_Y \rightarrow h_X \pm h_Y$. Since the amplitudes for the hemispherically symmetric (S) and anti-symmetric (A) components have the same and opposite signs in the two hemispheres, respectively, their non-linear interactions produce $h_Z(S) = h_X(S) \pm h_Y(S)$ or $h_Z(S) = h_X(A) \pm h_Y(A)$, and $h_Z(A) = h_X(S) \pm h_Y(A)$. By applying these rules, one can unravel the major spectral features apparent in Fig. 3 to provide a qualitative understanding of the non-linear processes involved in generating the oscillations.

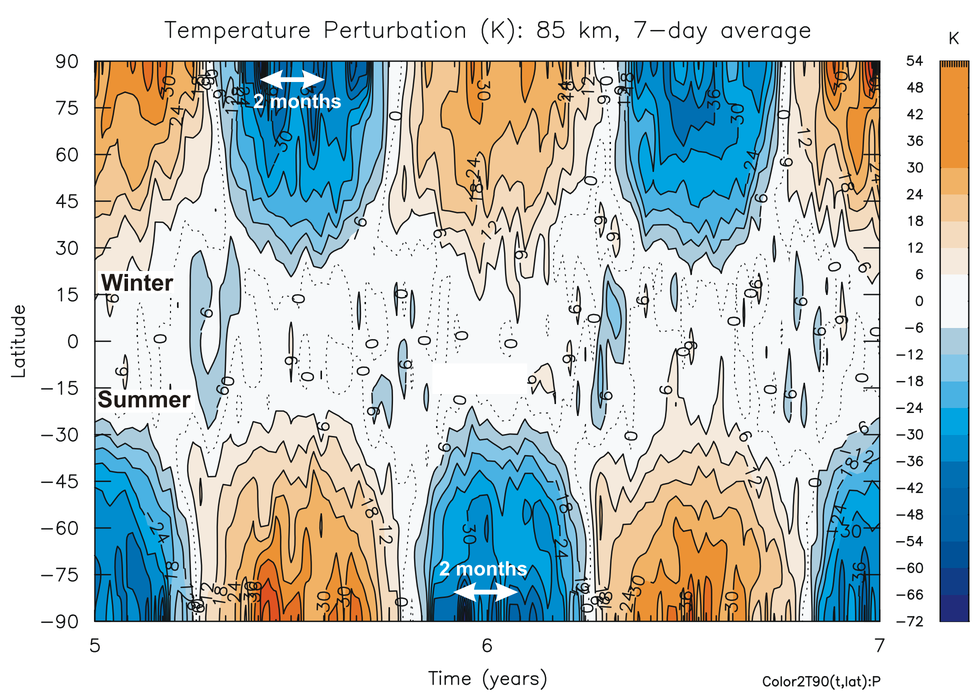

Fig. 1. Contour plot (6 K interval) of computed zonal-mean temperature perturbations at 85 km, plotted versus latitude in 7-day intervals for 5 to 7 years. In qualitative agreement with observations, the temperatures are lower (negative, blue) in summer, and higher (positive, red) in winter. Relatively large inter-annual variations are evident, which are generated primarily by the 24-month QBO, as discussed in Part I. The model also generates oscillations that have periods around 2 months. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)