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Dynamically induced hemispheric differences in the seasonal cycle of the summer polar mesopause

Erich Becker*, Rahel Knöpfel, Franz-Josef Lübken

Leibniz Institute of Atmospheric Physics at the University of Rostock, Schlossstr. 6, 18225 Kühlungsborn, Germany

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ABSTRACT

A mechanistic atmospheric general circulation model from the surface up to the mesopause region with explicit representations of radiation and the tropospheric moisture cycle is employed to study hemispheric differences during the summer season with focus on dynamical coupling processes in the middle atmosphere. Hemispheric differences are imposed in the model by the geographical distributions of surface parameters. Consistent with reanalyses, we find that prior to summer solstice, the polar troposphere and lower stratosphere are significantly colder in the southern hemisphere than in the northern hemisphere. This induces vertically altering wind and temperature differences between the two hemispheres that are consistent with the recently detected Intrahemispheric Coupling mechanism. In particular, in the southern hemisphere the model yields a high mesopause around solstice which propagates downward over the season. Such a behavior has recently been observed by lidar measurements in Antarctica and is different from the northern hemisphere where the polar mesopause stays at approximately the same altitude over the summer season. After summer solstice, the mesopause is significantly warmer in the southern hemisphere, which is in accordance with Interhemispheric Coupling, i.e., the hemispheric differences after summer solstice are influenced by the strong planetary Rossby-wave activity in the northern stratosphere during boreal winter. Also enhanced filtering of eastward GWs in the southern troposphere contributes to the behavior after solstice. Orbital eccentricity is found to enhance the importance of Intrahemispheric Coupling. A more quantitative description of the hemispheric differences in the stratosphere and lower mesosphere as seen in reanalyses is obtained by adding an additional westward gravity drag in the southern stratosphere. The vertical coupling mechanisms responsible for hemispheric differences apply also in this case.

1. Introduction

Hemispheric differences of the large-scale atmospheric circulation are mainly caused by the different land–sea distributions in the two hemispheres. This is obvious for the troposphere where the planetary Rossby-wave activity during the winter season is usually much stronger in the northern hemisphere (NH) than in the southern hemisphere (SH). The corresponding wave generation is caused by the large mountain ranges (Himalayas and Rocky Mountains) and by the zonally asymmetric latent and sensible heating induced by the North Pacific and North Atlantic Oceans. In the SH we have instead the circumpolar ocean at middle latitudes, with only a weak generation of planetary Rossby waves. Some relevant consequences for the middle atmosphere that result from these surface asymmetries are well known. First, the wintertime polar vortex is much weaker and more variable in the NH than in the SH, which on average is accompanied by a warmer stratosphere and a colder stratopause and lower mesosphere aloft (e.g., Rosenlof, 1995; Becker and Schmitz, 2003). Second, variations of the Rossby-wave drag in the winter stratosphere cause Interhemispheric Coupling: Intra-seasonal or inter-annual variations of the circulation and temperature in the summer polar mesopause region can be induced by variations of the polar night jet in the winter hemisphere. The validity of this mechanism has been confirmed in general circulation models (GCMs) of the middle atmosphere (Becker et al., 2004; Becker and Fritts, 2006; Karlsson et al., 2009a; Körnich and Becker, 2010) and in various observational studies (Goldberg et al., 2004; Karlsson et al., 2009b; Espy et al., 2011; Tan et al., 2012), including hemispheric differences in polar mesospheric summer echoes (e.g., Latteck et al., 2008). In a more general sense, Interhemispheric Coupling may be interpreted as an extension of the wintertime Annular Modes

* Corresponding author. Fax: +49 382936850.
E-mail addresses: becker@iap-kborn.de (E. Becker), knoepfel@iap-kborn.de (R. Knöpfel), luebken@iap-kborn.de (F.-J. Lübken).

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(e.g., Wallace, 2000; Körnich et al., 2006) into the mesosphere/lower thermosphere (MLT) on a global scale via modulating the propagation conditions for gravity waves (GWs) in either hemisphere.

The overall eastward wave drag in the summer mesopause region is largely dominated by GWs, but is nevertheless significantly less than the GW drag. The reason is on opposing drag induced by westward traveling planetary waves such as the quasi 2-day and 5-day waves. These waves exist in the summer mesopause region because of the baroclinicity maintained by the GW-driven residual circulation (e.g., Norton and Thuburn, 1996; McLandress et al., 2006; Pendlebury, 2012). Hence, one would expect that the westward planetary wave drag is closely related to the GW drag and should not give rise to some independent modulation of the summer mesopause. As recently shown by Siskind and McCormack (2014), this is not necessarily the case. Episodes of enhanced westward planetary waves in the summer mesosphere may well occur along with reduced eastward GW drag. For certain events this may suggest a much stronger influence of Interhemispheric Coupling than is actually the case. Other complications are possibly related to the influence of equatorial waves on the cross-equatorial flow, and to the modulation of GW propagation by thermal tides at middle latitudes (Becker, 2012).

Another mode of internal variability has recently been shown to affect the southern extratropical middle atmosphere during late spring and early summer. Smith et al. (2010) analyzed a simulation of trends in the second half of the twentieth century using the Whole Atmosphere Community Climate Model (WACCM). They found that the stratospheric temperature trend caused by the ozone hole induces vertically alternating wind and temperature signals up to the lower thermosphere during December over the polar cap in the SH. Karlsson et al. (2011), Gumbel and Karlsson (2011), and Benze et al. (2014) showed that the year-to-year variations in the onset of the polar mesospheric cloud (PMC) season are closely related to the timing of the breakdown of the wintertime polar vortex in the stratosphere, which in the SH can prevail until early summer. They identified similar vertically alternating temperature and wind signals as in the study of Smith et al. (2010). The underlying dynamical mechanism has been named Intrahemispheric Coupling and explains the variations in the occurrence of polar mesospheric summer echoes (PMSE) and noctilucent clouds (NLC) in the SH. A similar vertical coupling mechanism originating in the lower polar mesosphere may be induced by solar proton events and does possibly lead to anomalously high temperatures in the vicinity of the summer polar mesopause (von Savigny et al., 2007; Becker and von Savigny, 2010). Also Intrahemispheric Coupling is likely subject to modulations by variations in the westward drag due to traveling planetary waves (Siskind and McCormack, 2014).

The question addressed in the present study is whether and how Interhemispheric and Intrahemispheric Coupling explain observed hemispheric differences in the seasonal cycle of the summer polar mesopause. This topic is inspired by Fe-lidar temperature measurements performed at the station of Davis at Antarctica (69°S) during the 2011/2012 austral summer season. These measurements have been published by Morris et al. (2012) and Lübken et al. (2014) and results are reprinted in Fig. 1a. The most striking feature is the onset of a cold mesopause at extraordinary high altitudes in early December 2011. About 10 days before summer solstice, the mesopause was located at an altitude of about 92 km and it was colder than 130 K for a few days (see also Fig. 2 in Lübken et al., 2014). As the season progressed, the temperature minimum propagated downward and warmed significantly. This behavior is quite different from that typical for the NH. According to falling sphere measurements by Lübken (1999, his Plate 1), the NH summer mesopause does not notably change its altitude during the season and is coldest during the first 20 days after solstice (see Fig. 1b). Summarizing these findings, the summer mesopause appears to be somewhat colder and higher before and around solstice in the SH, and colder after solstice in the NH.

The behavior after solstice is also confirmed by temperature retrievals from the SABER instrument on-board the TIMED satellite (see review of Smith, 2012, her Fig. 1). On the other hand, comprehensive climate models that extend into the thermosphere show either no clear hemispheric difference of the summer polar mesopause after solstice (Smith, 2012, her Fig. 1), or simulate an opposite behavior (Karlsson et al., 2009a, their Fig. 12). An idealized model study by Siskind et al. (2003) suggests that the warmer summer mesopause in January can be explained by a stronger filtering of eastward propagating GWs in the troposphere and lower stratosphere, thus highlighting the importance of vertical coupling within the summer hemisphere. In this context it is important to note that the summer polar stratosphere is warmer in the SH than in the NH (Rosenlof, 1995). The fact that the solar insolation is stronger by about 7% during austral summer than boreal summer due to orbital eccentricity is only partly responsible for this asymmetry. As shown by Rosenlof (1996) and Alexander and Rosenlof (1996), a significant westward drag by non-orographic GWs in the SH is required for a quantitative explanation, particularly with respect to the mid and lower stratosphere. Evidently, the hemispheric differences in the stratosphere are relevant for hemispheric differences in the mesopause region.

To the best of our knowledge, the temporal evolution of the summer polar mesopause and related hemispheric differences

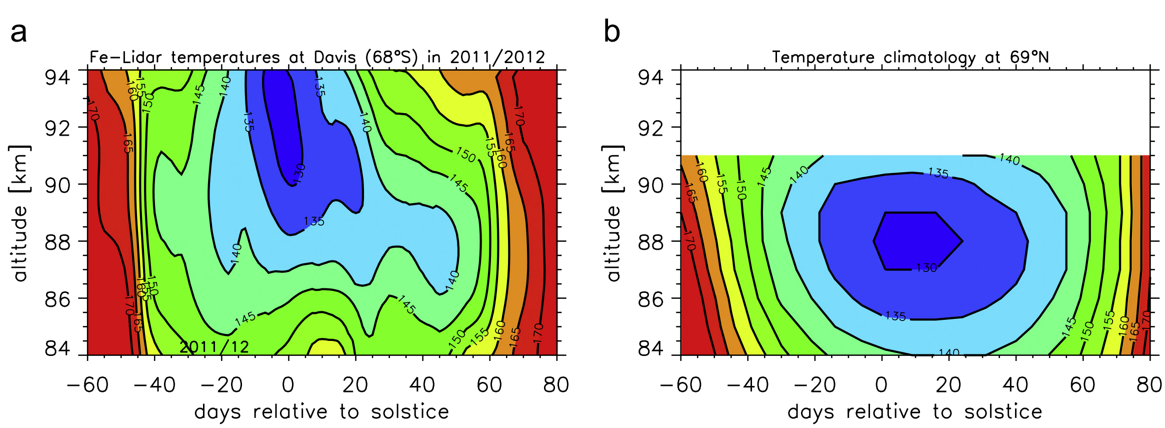

Fig. 1. Annual cycle of the summer polar mesopause (temperature in K) according to available local measurements. (a) Southern hemisphere at the site of Davis (69°S), data adapted from Lübken et al. (2014) and based on lidar soundings for the 2011–2012 season. (b) Northern hemisphere at the site of Andenes (69°N), data adapted from Lübken (1999) and based on falling-sphere measurements between 1987 and 1997.