Intra- and inter-hemispheric coupling effects on the polar summer mesosphere

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[1] The state of the mesosphere is connected to the lower atmosphere through various dynamical coupling processes. Nine years of Odin satellite observations of noctilucent clouds (NLC) have been analyzed as tracers for such processes. Inter-hemispheric coupling from the winter stratosphere and troposphere is confirmed to have a major influence on the summer mesosphere. Intra-hemispheric coupling from the spring/summer stratosphere, on the other hand, can control the onset of the NLC season. Most prominently, the southern NLC season 2010–2011 started with a delay of more than 20 days as compared to other years, which coincides with an exceptionally persistent polar vortex in the Antarctic stratosphere. Proposed mechanisms for the above teleconnections are based on the effect of lower atmospheric circulation on gravity wave filtering and, thus, on the dynamical forcing of the mesospheric circulation. Both intra- and inter-hemispheric coupling processes are needed for an understanding of the overall seasonal behavior of the summer mesosphere. **Citation:** Gumbel, J., and B. Karlsson (2011), Intra- and inter-hemispheric coupling effects on the polar summer mesosphere, *Geophys. Res. Lett.*, *38*, L14804, doi:10.1029/2011GL047968.

1. Introduction

[2] Mesospheric ice formation depends critically on the extreme thermal and dynamical conditions prevailing at the polar summer mesopause [*Rapp and Thomas*, 2006]. This makes ice phenomena like noctilucent clouds (NLCs) important tracers for the complex processes that control the state and variability of the mesosphere. Fundamental to the global coupling processes addressed in this paper are the forcing of the mesospheric circulation by gravity waves (GW) and the modification of these gravity waves by the lower atmospheric circulation. The meridional summer-to-winter flow in the mesosphere is driven by the breaking of GW and the resulting momentum transfer to the zonal mean flow [*Shepherd*, 2000; *Holton and Alexander*, 2000]. The meridional flow drives high-latitude temperatures from radiative equilibrium and results in particular in the extremely cold environment of the polar summer mesopause, with air rising and cooling above the summer pole. The magnitude and distribution of the gravity wave drag (GWD) are controlled by the zonal wind at lower altitudes that acts as a filter for gravity wave propagation. Any changes in the zonal flow thus lead to modifications of the GWD. In the summer hemisphere, the zonal flow in the middle atmosphere is relatively regular, whereas in winter it is distorted by planetary wave activity. Both seasonal and interannual variability are thus significantly larger in the winter hemisphere. In addition to this summer-winter difference, there is a hemispheric asymmetry in planetary wave activity: Caused by the more uneven land-sea distribution, the northern hemisphere (NH) is usually dynamically more active than the southern hemisphere (SH), which is reflected e.g. by frequent stratospheric warmings in the NH.

[3] Inter-hemispheric coupling denotes the dynamical control of the summer mesosphere by the winter hemisphere. The existence of such an inter-hemispheric link was first suggested by model studies [*Becker and Schmitz*, 2003; *Becker et al.*, 2004; *Becker and Fritts*, 2006], supported by local observations of mesospheric conditions. Subsequently, global observations of noctilucent clouds have confirmed this remarkable connection between the two hemispheres, both on a year-to-year basis [*Karlsson et al.*, 2007] and on an intra-seasonal basis [*Karlsson et al.*, 2009a]. A basic result is that the larger dynamical variability of NH winter causes a more variable and weaker NLC season in the SH summer mesosphere. The mechanisms behind this inter-hemispheric connection have been described in detail by *Karlsson et al.* [2009b] and *Körnich and Becker* [2010]. In short, the series of wave - mean flow interactions that couple the two hemispheres starts off in the winter troposphere and stratosphere where planetary waves modulate the westerly wind. Since GW propagation is closely tied to the zonal wind speed of the background atmosphere, modulation of the winter westerlies leads to a redistribution of the GWD and, hence, to a modulation of the meridional flow in the winter mesosphere. The response in the temperature field is such that during periods of high planetary wave activity the high latitude winter mesosphere is anomalously cold due to reduced downwelling. By continuity, the low latitude winter mesosphere is at the same time anomalously warm due to reduced upwelling. The warming response in the equatorial mesosphere changes the temperature gradient between low and high latitudes in the summer mesosphere, and thus, via the thermal wind balance, also the mesospheric zonal wind. This change in wind modulates the breaking level for the gravity waves in the summer hemisphere, hence affecting the meridional flow in the summer mesopause region so that also this part of the atmosphere is anomalously warmer. Similarly, during periods of low planetary wave activity in the winter hemisphere, the response in the summer polar mesopause region is, through the same chain of actions, an anomalous cooling.

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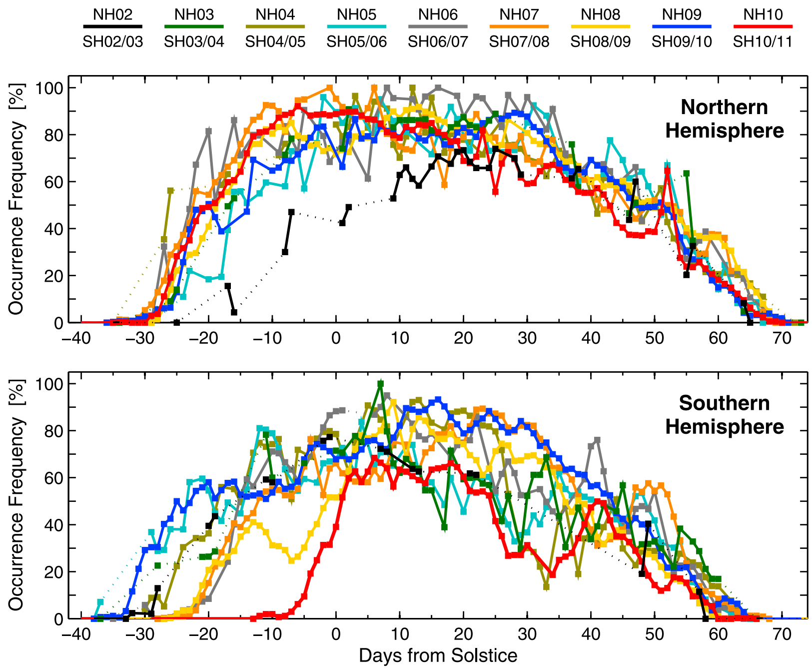

Figure 1. NLC occurrence frequency in the latitude band 60°–80° in the (top) northern hemisphere and (bottom) southern hemisphere as obtained from Odin/OSIRIS. Data are shown for the northern summers 2002–2010 and for the southern summers 2002/2003 to 2010/2011. A three-day running average has been applied. Dashed lines indicate data gaps during periods when Odin was operated in non-mesospheric modes. Time on the x-axis is given as days from summer solstice (DFS).

[4] Intra-hemispheric coupling denotes the dynamical control of the summer mesosphere from lower altitudes in the same hemisphere. Interactions of gravity waves in the stratosphere have been discussed by *Alexander and Rosenlof* [1996], who showed how differences in the zonal wind fields cause differences in the summertime GWD between the hemispheres. *Siskind et al.* [2003] have investigated the detailed effects of this on the summer mesopause region. *Kirkwood et al.* [1998] applied these ideas to discuss the seasonal behavior of polar mesosphere summer echoes in the NH. As described above, the SH winter stratosphere is less variable than the NH due to little planetary wave activity. As a consequence, the strong zonal winds that form the winter-time stratospheric polar vortex occasionally persist well into the summer in the SH. This in turn can have a major effect on the NLC environment in the summer mesosphere, as has recently been described by *Karlsson et al.* [2011]. The westerly wind that characterizes the stratospheric winter circulation filters out a significant portion of the eastward propagating GW in the lower part of the atmosphere. This prevents these GW from reaching the middle atmosphere, thus reducing the GWD in the mesosphere. If these conditions prevail into the summer season, reduced GWD leads to weaker meridional flow and thus higher temperatures in the summer mesopause region. Consequently, Karlsson et al. suggest that the onset of the NLC season is delayed during years with persistent winter flow conditions in the underlying stratosphere.

[5] In this paper, we analyze nine years of Odin satellite data. We use NLCs (also known as polar mesospheric clouds, PMCs, when observed from space) as tracers for the seasonal and interannual variability of the summer mesosphere. This is compared to stratospheric conditions obtained from the re-analysis of the European Centre for Medium-Range Weather Forecasts (ECMWF). Section 2 describes the data used for this study. Section 3 discusses signatures of intra- and inter-hemispheric coupling identified in the dataset. Section 4 concludes with a perspective on mesospheric responses to possible secular trends in stratospheric circulation.

2. Data

[6] The Swedish-led Odin satellite has been in orbit since early 2001, providing mesospheric coverage that has continuously improved during the course of the mission. In early years observation time had to be shared with astronomical and stratospheric studies, which limited regular mesospheric observations to every ninth day and occasional dedicated two-week NLC campaigns. In recent years, daily mesospheric measurements have been possible during the NLC seasons as Odin's astronomy studies ended in 2007 and the distribution between stratospheric and mesospheric observation modes has become more flexible. Basic concepts of Odin's NLC observations have been described e.g. by *Karlsson and Gumbel* [2005]. The NLC analysis is based on the Optical Spectrograph and Infra-Red Imager System (OSIRIS) that provides atmospheric limb spectra at wavelengths between 275 and 810 nm [*Llewellyn et al.*, 2004]. The results discussed here are based on NLC observations near 400 nm. Odin is in a sun-synchronous orbit providing about fifteen orbits per day with NLC observations around 6:00 and 18:00 local time.

[7] Figure 1 shows mean NLC occurrence frequencies in the latitude band 60°–80° obtained from the northern summer 2002 until the southern summer 2010/2011. Occurrence frequency is defined as the number of limb scans with identified NLCs divided by the total number of limb scans.

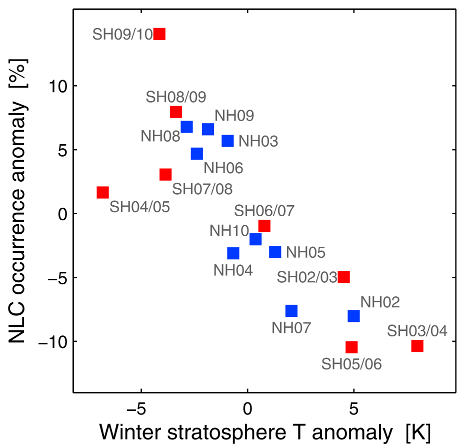

Figure 2. The relationship between summer mesosphere NLC occurrence and winter stratosphere conditions. Plotted is the anomaly in the NLC occurrence in July/January vs. the anomaly of the mid-stratosphere winter temperature field as a measure of planetary wave activity. The strong anti-correlation between both parameters is explained by inter-hemispheric coupling. See text for details.

Data points are daily means, combining both morning and evening measurements, with additional smoothing by a 3-day running average. When calculating the means, observations are weighted with the cosine of the latitude as observations at lower latitudes represent a larger latitude circle. Note that any results on NLC occurrence frequency are specific for a particular instrument and detection threshold. For OSIRIS the threshold for NLC detection is a limb backscatter ratio of ~1.3, defined as the ratio between the total signal and the molecular Rayleigh background at the NLC peak altitude.

[8] In order to investigate connections between NLC occurrence and lower atmospheric conditions, meteorological data have been used from the European Centre for Medium-Range Weather Forecasts (ECMWF) Interim Re-Analysis. This includes in particular stratospheric zonal winds and stratospheric temperature anomalies as a proxy of planetary wave activity [*Karlsson et al.*, 2007].

3. Discussion

[9] Inter-hemispheric coupling has major influences on the seasonal and interannual variability of the summer mesosphere. The Odin NLC data in Figure 1 illustrate several such influences. The NH shows less variability than the SH in both seasonal and interannual behavior. As described in section 1, this is understood in terms of the hemispheric differences in stratospheric winter planetary wave activity with substantially more wave activity in the NH than in the SH [*Karlsson et al.*, 2007]. Modulation of the zonal wind by these planetary waves is instrumental to the variability of gravity wave filtering and thus the variability of the forcing of the mesospheric circulation, which translates into the observed inter-hemispheric differences in NLC variability. An obvious exception to the low interannual variability of the NH mesosphere is the summer of 2002 in Figure 1. NLC occurrence frequencies in this season are substantially lower than during other years. This coincides with the exceptionally disturbed dynamical conditions in the SH stratosphere that led to the ozone hole split over the Antarctic in September 2002. It is this exceptional year led to the original discovery of inter-hemispheric coupling [*Becker et al.*, 2004].

[10] The inter-hemispheric coupling between stratospheric winter conditions and mesospheric summer conditions can be quantified following the ideas of *Karlsson et al.* [2007]. This results in the correlation plot shown in Figure 2. Summer mesosphere conditions (along the y-axis) are represented by the anomaly of NLC occurrence frequency. (This is in contrast to *Karlsson et al.* [2007] who used NLC particle radius as proxy for summer mesosphere conditions.) In each hemisphere, this anomaly is calculated as the deviation from the long-term average of the monthly mean NLC occurrence frequency in July (NH) or January (SH) in the latitude range 50–80°. Winter stratosphere conditions (along the x-axis) are represented by a stratospheric temperature anomaly, i.e. a deviation from the long-term temperature average, that serves as a proxy for planetary wave activity. These stratospheric temperatures are averaged over the region of largest inter-hemispheric correlation, namely the height interval 100–10 hPa and the latitude interval 60–80° and 40–60° in the NH and SH, respectively [*Karlsson et al.*, 2007, Figure 2]. The temperatures are then averaged over a 30 day period that is shifted by −7 days as compared to the averaging period for the NLC data. This shift represents a typical response time of the summer mesosphere to influences from the winter stratosphere. The underlying wave interactions and propagation times have been discussed by *Karlsson et al.* [2009a] and *Körnich and Becker* [2010].

[11] Figure 2 is an excellent confirmation of the major role of inter-hemispheric coupling for the bulk NLC season. The anticorrelation between winter stratosphere temperature (and thus planetary wave activity) and summer mesosphere NLC occurrence is here described by a correlation coefficient of −0.83. Note that the NLC occurrence frequency for SH04/05 season apparently does not follow the general anti-correlation in Figure 2. A particular feature of this season was a solar proton event (SPE) in the middle of January that caused a strong decline of NLC occurrence frequencies [*von Savigny et al.*, 2007]. In fact, in the first half of January prior to the SPE, the SH04/05 occurrence frequency was among the highest of the decennium (Figure 1). It is interesting to note that the NLC depletion following the SPE is in itself an example of a dynamical coupling process between the lower atmosphere and the mesopause region [*Becker and von Savigny*, 2010].

[12] Turning now to intra-hemispheric coupling, Figure 1 provides important information about the start and the end of the NLC season. Most notably, the start of the season in the SH is much more variable than the start of the season in the NH. A deviation from the low NH variability is the late start of the season 2002, i.e. the exceptional year of the Antarctic ozone hole split. The end of the season shows little year-to-year variability in both hemispheres, with the NH season lasting typically five days longer than the SH season. We quantify these numbers by defining the start and end of the NLC season as the first and last day, respectively, with the observed NLC occurrence frequency in Figure 1 exceeding 10%. Over the course of the Odin mission we find the NH season lasting from −26 ± 3 until 63 ± 3 days from summer

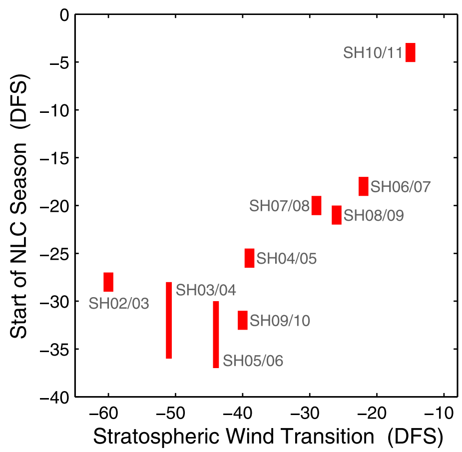

Figure 3. Relationship between the start of the southern NLC season and the end of the southern hemisphere winter polar vortex. The start of the NLC season (y-axis) is defined from Figure 1 as the first day with occurrence frequencies exceeding 10%. The date of the stratospheric wind transition (x-axis) defines the end of the winter polar vortex based the stratospheric zonal wind speed, as described in the text. Dates are plotted as days from solstice (DFS). The vertical extent of some data points represents uncertainties due to gaps in Odin's mesospheric coverage.

solstice, and the SH season lasting from −24 ± 9 until 58 ± 2 days from summer solstice.

[13] Similar to the overall variability of the SH season, the large variability of the start of the SH season may in part be explained by the variability of the NH lower atmosphere in combination with inter-hemispheric coupling. However, the intra-hemispheric coupling described in section 1 provides an explanation particularly for the occasional very late onsets of the SH season. This intra-hemispheric coupling links the delay of the NLC season to the persistency of the stratospheric winter jet. This persistency leads to GW filtering conditions that cause a delay of the onset of the mesospheric summer circulation. Indeed, the late onsets of the SH NLC seasons in 06/07, 07/08, 08/09 and 10/11 all coincide with years of long-lasting polar vortex conditions in the Antarctic stratosphere.

[14] Various measures have been defined to describe the spring breakdown of the polar vortex. *Langematz and Kunze* [2006] define this as the day when the zonal mean westerlies at 65° latitude at 50 hPa first decrease below a threshold of 10 m/s. For our purposes, we are most interested in the *final* transition of the stratospheric circulation that marks the end of the wintertime GW filtering by the westerly jet. Hence, we define a stratospheric transition date as the final day when the zonal mean westerlies at the above coordinates (65°, 50 hPa) decrease below a velocity threshold, here chosen as 30 m/s. Figure 3 plots this date of the stratospheric wind transition against the start of the SH NLC season from Figure 1. In accordance with the idea of an intra-hemispheric coupling, a strong dependence of the NLC onset on the timing of the stratospheric wind transition is indeed observed. While no obvious effect on the NLC onset is observed for early stratospheric vortex break-ups, late vortex break-ups tend to delay the NLC onset. In years with the stratospheric transition occurring later than 30–40 days before solstice, Figure 3 suggests that the NLC season starts typically 10 days after the stratospheric transition date as defined above.

[15] A similar dependence is not observed in the NH. Applying the same wind criterion as above, the stratospheric wind transition in the NH takes place typically 50–100 days before summer solstice. Hence, polar stratospheric jet conditions never last long enough to delay the onset of the polar mesospheric summer circulation, and thus the start of the NLC season.

4. Conclusions

[16] Noctilucent clouds prove to be valuable tracers for dynamical processes that involve the entire middle atmosphere. Nine years of NLC data from the Odin satellite have been analyzed with respect to coupling processes that control the polar summer mesosphere. Common to these coupling processes is the effect of lower atmospheric circulation on the filtering of gravity waves and, hence, on the forcing of the mesospheric circulation. Inter-hemispheric coupling from the winter stratosphere is confirmed to play a decisive role for the seasonal, interannual, and hemispheric variability of NLCs. Intra-hemispheric coupling from the stratosphere, on the other hand, opens an upward pathway for polar vortex conditions to affect the summer mesosphere. In particular, the strong SH stratospheric jet can delay the start of the SH NLC season in years when the jet is persistent beyond 30–40 days before summer solstice.

[17] The persistency of the Antarctic stratospheric vortex and its effect on the onset of the SH polar mesospheric summer circulation are important in the light of long-term trends in the stratosphere. *Waugh and Polvani* [2010] point out a significant positive trend of the vortex persistency over recent decades. Through the intra-hemispheric coupling described above such a stratospheric trend would make very late onsets of the SH NLC season as observed in 2010/2011 more common in future. However, as various trends may affect stratospheric dynamics, the future development of vortex conditions remain an open question [*Son et al.*, 2008].

[18] In conclusion, both intra- and inter-hemispheric coupling processes need to be addressed for an understanding of the overall seasonal behavior of the summer mesosphere. Future observational and model studies should include the interplay of both mechanisms. The current paper has focused on signatures of inter- and intra-hemispheric coupling in NLC occurrence data. An upcoming paper will address a more detailed analysis of global coupling processes based on Odin results on NLC properties, water vapor and temperature.

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