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Extreme stratospheric springs and their consequences for the onset of polar mesospheric clouds

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ABSTRACT

We use data from the Aeronomy of Ice in the Mesosphere (AIM) explorer and from the NASA Modern Era Retrospective Analysis for Research and Applications (MERRA) stratospheric analysis to explore the variability in the onset of the Northern Hemisphere (NH) Polar Mesospheric Cloud (PMC) season. Consistent with recently published results, we show that the early onset of the NH PMC season in 2013 was accompanied by a warm springtime stratosphere; conversely, we show that the late onset in 2008 coincides with a very cold springtime stratosphere. Similar stratospheric temperature anomalies for 1997 and 2011 also are connected either directly, through observed temperatures, or indirectly, through an early PMC onset, to conditions near the mesopause. These 4 years, 2008, 1997, 2011, and 2013 represent the extremes of stratospheric springtime temperatures seen in the MERRA analysis and correspond to analogous extrema in planetary wave activity. The three years with enhanced planetary wave activity (1997, 2011 and 2013) are shown to coincide with the recently identified stratospheric Frozen In Anticyclone (FrIAC) phenomenon. FrIACs in 1997 and 2013 are associated with early PMC onsets; however, the dramatic FrIAC of 2011 is not. This may be because the 2011 FrIAC occurred too early in the spring. The link between NH PMC onset and stratospheric FrIAC occurrences represents a new mode of coupling between the stratosphere and mesosphere. Since FrIACs appear to be more frequent in recent years, we speculate that as a result, PMCs may occur earlier as well. Finally we compare the zonal mean zonal winds and observed gravity wave activity for the FrIACs of 2011 and 2013. We find no evidence that gravity wave activity was favored in 2013 relative to 2011, thus suggesting that direct forcing by planetary waves was the key mechanism in accelerating the cooling and moistening of the NH mesopause region in May of 2013.

1. Introduction

There has been great recent interest in Polar Mesospheric Cloud (PMC) variability as it relates to meteorological forcing originating in the lower atmosphere. Because PMCs are so sensitive to temperature and water vapor, small changes in background humidity can have large consequences for their occurrence and brightness. The meteorological forcing of PMCs is generally categorized as either inter-hemispheric (stratospheric winter weather in the opposite hemisphere) (e.g. Becker et al., 2004; Karlsson et al., 2009a and b; Siskind et al., 2011) or intra-hemispheric (coupling with late spring/early summer stratospheric conditions in the same hemisphere) (e.g., Karlsson et al., 2011). The relative roles of inter- and intra- hemispheric coupling were quantified by Gumbel and Karlsson (2011). The above studies found that intra hemispheric coupling was most effective in governing the onset of the PMC season in the Southern Hemisphere (SH) through the modulation of the gravity flux to the mesosphere by the stratospheric polar vortex. For the Northern Hemisphere (NH), Gumbel and Karlsson (2011) and Benze et al. (2012) both argued that intra-hemispheric coupling should not control the start of the season because the stratospheric winter vortex breaks down about two

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months prior to the typical start of the PMC season. However, Fiedler et al. (2014) have argued that the early onset of noctilucent clouds (NLCs) in Northern Norway in 2013 were due to the result of intra-hemispheric coupling. The overall purpose of this paper is to expand upon the Fiedler et al. (2014) analysis and place it in a more general context utilizing satellite data from multiple years. In doing so, we will identify new linkages between previously documented stratospheric variability and conditions at the springtime Northern Hemisphere mesopause region. Hereinafter we use the term "PMCs" to refer to either PMCs or NLCs.

2. Data from the Aeronomy of Ice in the Mesosphere (AIM) satellite

Many of the analyses in this paper use data from the AIM Solar Occultation for Ice Experiment (SOFIE) and Cloud Imaging and Particle Size instrument (CIPS). AIM is a sun-synchronous, polar-orbiting satellite that was launched in 2007 (Russell et al., 2009). The SOFIE instrument measures vertical profiles of temperature (Stevens et al., 2012), PMC extinction (e.g., Hervig et al., 2009), and several trace gases at polar latitudes in both hemispheres (Gordley et al., 2009). The CIPS instrument provides nadir images of the PMCs with 25 km^2 horizontal resolution; the CIPS retrieval is described by Lumpe et al. (2013) and the PMC data are validated by Benze et al. (2009; 2011).

The AIM measurements show interesting variability in the onset dates for NH PMCs, including an unusually early onset to the NH PMC season in 2013, as described by Fiedler et al. (2014). Table 1 presents the NH season onset dates as determined by the two instruments on AIM and the monthly averages of two pertinent solar flux indices, the F10.7 radio index and the Lyman alpha flux. The CIPS instrument views the clouds over a range of latitudes via nadir imaging, while SOFIE observes a narrow latitude range on the limb. To define the onset of the PMC seasons in the SOFIE record, we used the first day that showed continuous ice from one day to the next (i.e., to avoid an isolated single day anomaly). The CIPS analysis is based on the Level 3C, one-degree latitude binned data. Season start is defined as the first day when daily average CIPS cloud frequency, with an albedo threshold of $2\times10^{-6}\,\mathrm{sr}^{-1}$, exceeds 5% at any latitude. While SOFIE is more sensitive than CIPS, it typically views latitudes (65–71°) where PMCs have lower mass density than at the higher latitudes where CIPS can observe. In the end, the effects of the differing sensitivities and latitudes approximately cancel out and CIPS and SOFIE typically observe the first clouds of the season within a few days of each other. Table 1 shows that both CIPS and SOFIE observed the NH 2013 season to begin about 10–14 days earlier than in 2008. This is particularly surprising since solar activity was significantly higher in 2013 and Benze et al. (2012) found that increased solar activity, with its likely increased water vapor photodissociation and stratospheric heating, correlated with a delay in season onset; this is opposite of what is documented in Table 1.

Fig. 1 places the cloud occurrence dates in the context of SOFIE temperatures and water vapor measurements, both at 83 km (i.e. PMC altitude), for the six NH springs where both SOFIE and CIPS have consistent coverage. The figure shows generally decreasing temperatures and increasing water vapor throughout the period. The temperatures and water vapor variations also exhibit some obvious interannual differences, which closely mirror the variation in PMC onset dates given in Table 1. Most notably, 2013 was persistently colder and wetter from the end of April through May while 2008 was consistently the warmest and driest of the 6 years. In early April (days 92–100), 2011 stands out as the coldest and wettest of the 6 years; however, this did not persist. The 2011 cold anomaly will be discussed further below. The other years were intermediate between the extremes of 2013 and 2008. The cold and wet 2013 spring is consistent with the results recently presented by Fiedler et al. (2014); the fact that 2008 shows the exact opposite behavior is new to this work.

Table 1
PMC onset day numbers and solar flux values.

Year	2008	2009	2010	2011	2012	2013
CIPS onset day no	152	148	148	146	143	135
SOFIE onset day no	147	146	145	141	143	137
Mean F107[a]	68	71	74	96	121	131
Mean Ly α (x 10^{11} phcm^{-2} s^{-1})[a]	3.5	3.5	3.7	4.1	4.3	4.5

[a] F107 and Ly α values represent averages for the month of May

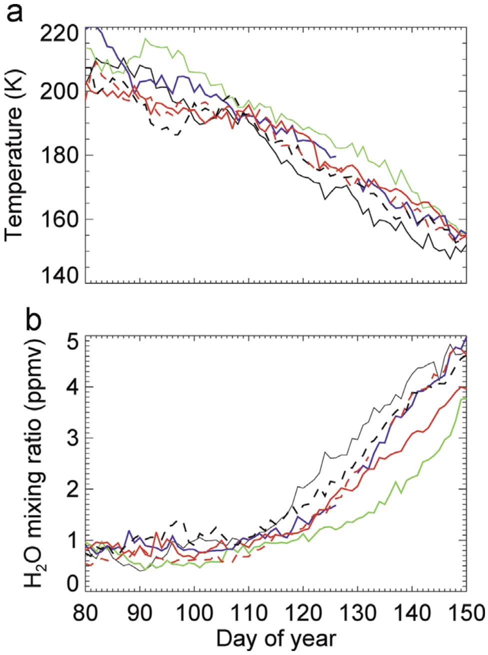

Fig. 1. Daily averaged temperatures (a) and water vapor mixing ratio (b) observed at 83 km altitude by SOFIE for 6 years for the indicated days. The solid black is 2013 (coldest and wettest), the solid green is 2008 (warmest and driest), the solid blue is 2009, the solid red is 2010, the black dashes are 2011 and the red dashes are 2012. SOFIE latitudes during this period vary smoothly between 83°N (day 90) and 68°N (day 150). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3. Stratospheric temperatures and wave activity in NH spring

Fiedler et al. (2014) attributed the 2013 early PMC onset to the occurrence of unusually late and enhanced planetary wave activity. Fig. 2 shows this by presenting time series of springtime stratospheric temperatures at 10 hPa along with the northward eddy heat flux at 60 N, which we use as an indicator of planetary wave activity. The eddy heat flux, proportional to $v'\theta'$ (cf. Andrews et al., 1987), where v is meridional wind and θ is potential temperature and primes represent deviations from the zonal mean, is derived from the MERRA data (Reinecker et al., 2011) and obtained from the web site http://acdb-ext.gsfc.nasa.gov/Data_services/met/ann_data.html. As discussed by numerous authors (Fiedler et al., 2014; Siskind et al., 2010), the divergence of this heat flux is a forcing term in the zonal momentum equation. Four specific years, to be discussed below, are highlighted along with the daily average of the MERRA dataset (solid black line) and the daily extrema (dotted lines). Taken together, these four years account for