GEOPHYSICAL RESEARCH LETTERS, VOL. 39, L22802, doi:10.1029/2012GL053632, 2012

Changes in polar stratospheric temperature climatology in relation to stratospheric sudden warming occurrence

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Received 23 August 2012; revised 19 October 2012; accepted 21 October 2012; published 22 November 2012.

[1] Stratospheric Sudden Warmings (SSWs) strongly affect the polar stratosphere during winter months mainly in the Northern Hemisphere. The intraseasonal distribution and type of SSWs for the 1958–1979 and 1979–2002 periods in ERA-40 and NCEP-NCAR reanalyses reveal differences. In the pre-satellite era, most events occur in January and are vortex splits. In the post-satellite era, the distribution is bimodal (peaking in December and February), and shows more displacement events. The difference in the seasonal distribution of SSWs leads to changes in the climatological state of stratospheric temperatures, with differences up to 5.9 K at 10 hPa and 3.6 K at 20 hPa in February between pre- and post-1979 periods. We find that the temperature evolution at 20 hPa is in better qualitative agreement with theoretical expectations than at 10 hPa. Hence, 10 hPa may be affected more strongly by artifacts related with satellite data assimilation, which have, however, limited impact on identification of SSWs. **Citation:** Gómez-Escolar, M., S. Fueglistaler, N. Calvo, and D. Barriopedro (2012), Changes in polar stratospheric temperature climatology in relation to stratospheric sudden warming occurrence, *Geophys. Res. Lett.*, *39*, L22802, doi:10.1029/2012GL053632.

1. Introduction

[2] Stratospheric Sudden Warmings (SSWs) are the largest sources of intraseasonal variability in the winter Northern Hemisphere polar stratosphere. These events are characterized by a dramatic increase in temperature and a decrease in zonal mean zonal wind over the polar cap region during only a few days [e.g., *Andrews et al.*, 1987]. By definition, a major SSW requires reversal of the westerlies at 60°N and 10 hPa (World Meteorological Organization). SSWs are known to be forced by the dynamical influence of upward propagating planetary Rossby waves on the stratospheric flow [e.g., *Matsuno*, 1971] along with a "pre-conditioned" stratospheric zonal flow that favors wave activity propagation towards the polar vortex [e.g., *Labitzke*, 1981; *McIntyre*, 1982]. It has been shown that the effects of SSWs are not confined to the stratosphere, but they propagate downward towards the troposphere where the circulation anomalies persist for about 2 months after the event [*Baldwin and Dunkerton*, 2001].

[3] A climatology of major SSWs for the Northern Hemisphere extended winter (November-to-March) was published by *Charlton and Polvani* [2007, hereinafter CHP07], using data from two reanalysis datasets, the 40-year European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40), and the National Center for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR), for the period 1958–2002. They reported a frequency of occurrence of about six events per decade and identified two types of SSWs: Vortex displacement, characterized by a clear shift of the polar vortex off the pole; and vortex split, when the polar vortex breaks up into two pieces of comparable size. CHP07 reported that these types should be considered dynamically distinct, but that there was little difference between vortex displacements and splits in their averaged tropospheric impact. However, recent studies have identified differences in their propagation into the troposphere [*Nakagawa and Yamazaki*, 2006], and differences in tropospheric precursors for each type of SSW [e.g., *Castanheira and Barriopedro*, 2010].

[4] CHP07 further proposed a set of diagnostics to characterize SSWs and validate numerical model simulations of SSWs. In particular, the latitudinally averaged polar cap (50–90°N) temperature anomalies at 10 hPa for the ±5 day period around the SSW central date provide a measure of the intensity of the event. CHP07 found a difference from 5.5 K to 9.2 K in the intensity of SSWs between the 1958–1978 and the 1979–2002 periods in the NCEP-NCAR reanalysis. They argued that this discrepancy may be an artifact due to the assimilation of satellite data in the reanalysis product starting in 1979. Motivated by this difference, herein we carry out a deeper analysis in order to provide further insight into the variability of occurrence of SSWs, focusing on the intraseasonal distribution and the type of SSWs for the pre- and post-1979 periods. In order to understand the observed record, and possible future changes, it is important to quantify how these intraseasonal changes in the distribution of SSWs affect the background state.

2. Data and Method

[5] Daily mean data from ERA-40 [*Uppala et al.*, 2005] and the NCEP-NCAR reanalyses [*Kistler et al.*, 2001] are analyzed here for their common period 1958–2002. Most of the results found with ERA-40 data are also observed in the NCEP-NCAR reanalysis. We show here only the former unless otherwise stated. We analyze the whole period (1958–2002) as well as pre- (1958–1978) and post-1979 (1979–2002) subperiods. We have also used Freie Universität Berlin (FUB) Stratospheric Analyses at 10 hPa to corroborate some

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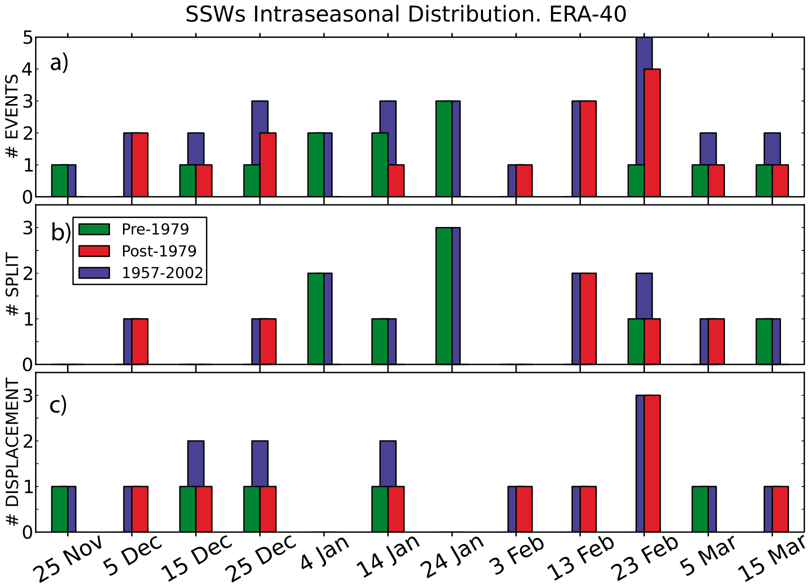

Figure 1. Subseasonal SSW frequency distribution in the ERA-40 reanalysis. Events are grouped in 10-days bins starting with the day indicated on the axis. Blue/green/red bars denote the 1957–2002/pre-1979/post-1979 period. (a) All events, (b) vortex splits, and (c) vortex displacements.

of these results with a satellite-independent data source. These daily data span from 1965 to 1997 for the September-to-March period, with only 33% of missing data for March months.

[6] We identify major mid-winter SSWs following the criteria set forth by CHP07, which require a change from westerlies to easterlies at 10 hPa and 60°N in the period November to March. The central date of the SSW is defined as the first day with easterly zonal mean zonal wind. The algorithm considers the same event if two days with easterly zonal wind are not separated by at least 20 days. The catalog excludes final warmings by demanding a return to westerlies for at least 10 consecutive days before the end of the winter season. There is a total of 29 SSWs in the ERA-40 and 26 in the NCEP-NCAR reanalysis for the period 1958–2002. The type of SSW was included in Table 1 of CHP07 and will be used here as well. A detailed description of the methodology used to classify SSWs into split and displacement events is given therein.

3. Results

[7] We first analyze the mean winter frequency of SSWs for the pre- and post-1979 periods. According to CHP07, there are not significant differences in the occurrence of SSWs: the number of events in the ERA-40 reanalysis is 13 and 16 for the pre- and post-1979 periods, respectively, and 13 and 14 for the NCEP-NCAR reanalysis. *Charlton et al.* [2007] stressed that sub-seasonal statistics give more information than winter-mean analysis in what concerns the study of extreme vortex variability. Figure 1a shows the intraseasonal distribution of SSWs in the ERA-40 reanalysis, as the total number of events in consecutive 10-day bins along the winter season for the entire period (1958–2002, blue). SSWs occurred from mid-November to mid-March, showing a bimodal distribution with two preferred timings of occurrence in late December and January and in late February. However, the corresponding histograms for the pre- (green bars) and post- (red bars) satellite periods reveal decadal changes in the intraseasonal distribution of SSWs [see also *Naujokat et al.*, 2002; *Manney et al.*, 2005]. For the pre-1979 period, a total of 7 out of 13 events occurred in January, resulting in a unimodal distribution of occurrence. Conversely, for the post-1979 period there was a total of 16 events, which clustered in December (5 events) and late February (7 events). Regarding the type of SSWs, the ratio of vortex displacements to vortex splits is 1.10 and 1.25 for the 45-year period of ERA-40 and NCEP-NCAR reanalyses, respectively (CHP07). However, these ratios change when the pre- and post-1979 periods are compared: 0.63 for ERA-40 and 0.86 for NCEP-NCAR are found during the pre-1979 period, and 1.67 and 1.8 respectively for the post-1979. Hence, although this analysis shows little changes in the total number of events, there are more displacement SSWs in the second period than in the first, with less events in mid-winter, which leads to a more bi-modal distribution.

[8] Figures 1b and 1c show the intraseasonal distribution of SSWs according to their type. For the full 1958–2002 period (blue bars), split events tend to show a peaked distribution centered in mid-winter (January) as compared to displacement events, which are more frequent in early (December) and late (February) winter. During the pre-satellite period there is a larger concentration of split events in January (green bars in Figure 1b), whereas in the post-1979 period a February peak associated to vortex displacement events is more prominent (red bars in Figure 1c). Changes in the SSW frequency distribution are concurrent with (and may be partially attributed to) changes in the type of SSWs, provided that split and displacement events exhibit distinctive seasonal distributions that match those found in the pre- and post-1979 period, respectively. These results are found in both reanalyses, but caution is warranted due to the small number of events, which prevents a robust assessment of statistical significance.

[9] One of the observable manifestations of SSWs is a generalized warming over the polar cap in the stratosphere.

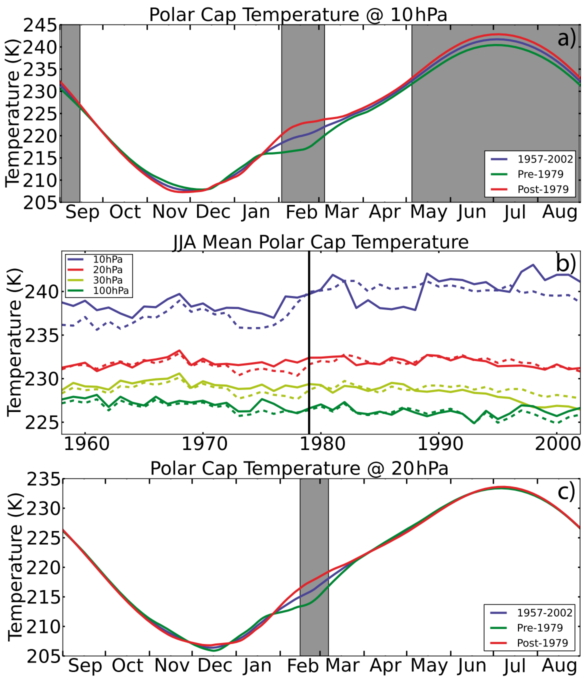

Figure 2. (a) Climatological daily evolution of the polar cap (60–90°N latitudinally averaged) temperature at 10 hPa for the entire period (1958–2002, blue) and the pre- (green) and post-1979 (red) subperiods. A 31-day running mean has been applied. Gray shading denotes periods with significant differences between the pre- and post-1979 temperatures at the 95% level after a two-tailed Student-t test; (b) Time series of summer (June–July–August) mean polar cap temperature at 10 (blue), 20 (red), 30 (yellow) and 100 hPa (green). Solid (dashed) lines are from the ERA-40 (NCEP-NCAR) reanalysis. (c) As Figure 2a but for 20 hPa.

Hence, we explore herein if the pre-/post-1979 changes in the intraseasonal distribution of SSWs have an impact in the polar cap temperatures. The 10 hPa level is frequently taken as reference for the identification and characterization of SSWs [e.g., CHP07; *Limpasuvan et al.*, 2004], and we first present results at this level. Figure 2a shows the annual cycle of the polar cap temperature (area-weighted average from 60 to 90°N) at 10 hPa (blue line), for the entire, and the two sub-periods. The stratospheric polar cap temperature evolution follows the annual cycle of radiative heating with a minimum around 207 K in November-December, and a summer maximum of about 240 K. However, the annual cycle differs between the two sub-periods in: 1) late-winter (post- minus pre-1979 temperature differences of up to +5.9 K in February); 2) higher temperatures during boreal summer (up to +2.5 K) in the post-satellite period. These pre- minus post-1979 differences are statistically significant at the 95% level with a t-student test.

[10] We would expect that, in general, temperatures should follow the long-term trend of stratospheric radiative cooling [*Ramaswamy et al.*, 2001]. While the large dynamical variability during winter may partly mask this trend, the post-1979 warming during summer months is not in agreement with expectations. Closer inspection of the time series of the mean seasonal temperature for the four seasons indicates an abrupt step in summer temperatures (June-July-August) at 10 hPa in both datasets (Figure 2b), which coincides approximately with year 1979. This is less evident in the other seasons, probably because of the larger variability (not shown). The same analysis for pressure levels below 10 hPa does not show an obvious discontinuity around the year 1979, nor a warming trend in boreal summer. Rather, they show no changes (at 20 hPa) or a cooling trend (between 30 hPa and 100 hPa), as expected. Further, we note that the largest discrepancies between reanalyses in the evolution of the seasonal mean temperature occur at 10 hPa.

[11] These results suggest that the summer shift observed in the polar cap temperature at 10 hPa is likely an artifact resulting from the assimilation of satellite data in the reanalysis products (see *Martineau and Son* [2010] and *Fueglistaler et al.* [2009] and discussion in *Simmons et al.* [2007]). In fact, when the polar cap temperature at 20 hPa is analyzed (Figure 2c), no shift in summer temperatures appears. However, the late-winter difference observed at 10 hPa between pre- and post-1979 is only slightly reduced at 20 hPa, from 5.9 K to 3.6 K, but still significant at the 95% confidence level. This post-1979 warming in late winter is well observed throughout most of the stratosphere (i.e., from 5 hPa to 50 hPa), and significant between about 7 and 20 hPa (not shown).

[12] The results from Figure 2a are corroborated using an independent dataset based on radiosondes (FUB). Warmer temperatures are found during the pre-1979 period in January (up to 4 K) and during the post-1979 period in February and March (up to 5 K) (not shown). This suggest that the aforementioned differences in winter polar cap temperatures are largely free of inhomogeneities resulting from the incorporation of satellite data to reanalysis' products.

[13] In addition to the changes in the seasonal distribution of SSWs reported here, changes in the strength of SSWs between the pre- and post-satellite period in the NCEP-NCAR reanalysis were discussed in CHP07. Table 1 shows the polar cap temperature anomaly averaged for the ±5-day period from the central date of pre- and post-satellite SSWs in ERA-40 and NCEP-NCAR. Daily anomalies were computed with respect to the seasonal cycle of the entire 45-year period and normalized by its standard deviation. Our results at 10 hPa do show an intensification of the warmings in the post-satellite SSWs in both reanalysis, in agreement with CHP07's findings. However, this intensification is not observed at 20 hPa, even when different average periods around the central date are considered to account for a possible delay in the downward propagation of the signal from 10 to 20 hPa. The difference in the strength of the SSWs at 10 hPa between the pre and post period could be in part related to the aforementioned data problems at this level. One could argue that these data problems could also affect the selection of SSW events. We have repeated the upper

Table 1. CHP07 SSW Strength Parameter Computed at 10 and 20 hPa, for the Pre-/Post-satellite Periods and the ERA-40 and NCEP-NCAR Reanalyses[a]

	ERA40			NCEP-NCAR		
	1957-2002	Pre-1979	Post-1979	1957-2002	Pre-1979	Post-1979
10 hPa	1.37	1.15	1.55	1.37	1.05	1.69
20 hPa	1.55	1.51	1.57	1.57	1.50	1.61

[a] SSW strength parameter defined as the 50–90°N averaged temperature anomalies within 5 days of the SSW central dates reported by CHP07. Anomalies were normalized dividing by the standard deviation of the 45-year climatology.

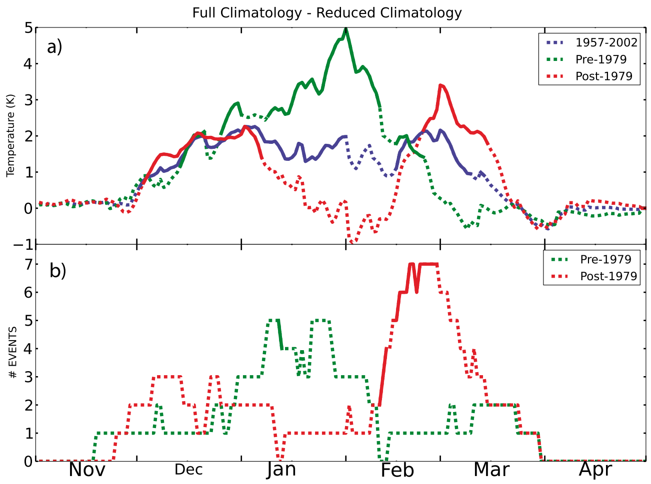

Figure 3. (a) ERA-40 difference between *full* and *reduced* polar cap temperature climatologies at 20 hPa (see text for details). (b) SSW total frequency distribution within ±10-day periods from the date displayed on the axis. Solid lines indicate differences that are statistically significant at the 90% level with a Montecarlo test of 5000 samples.

panel of Figure 1, applying the CHP07 algorithm for different thresholds of the zonal mean zonal wind (0, 2 and 5 m/s) and for different pressure levels (10 and 20 hPa) (not shown). The pre-/post-1979 difference in SSW distributions is similar for all thresholds, and for 10 hPa and 20 hPa. We conclude that our results are robust with respect to the definition of SSWs.

[14] So far we have shown differences between the pre- and post-1979 periods in both the intraseasonal distribution of SSWs and the evolution of winter temperatures. These changes can in fact be related, since a change in the preferred timings for the occurrence of SSWs may impinge on what it is perceived as a climatology. To address this question, we seek to establish a climatological mean annual cycle of temperatures without these extreme events. Considering 80 days as the life cycle of a SSW [*Limpasuvan et al.*, 2004], ±40 days of data from the central date of each SSW were removed, and the climatologies were recalculated with the so-reduced dataset. Figure 3a shows the difference at 20 hPa (which may be less affected by satellite assimilation data than 10 hPa) between the annual cycle of the mean climatology (referred as *full* since it includes all SSWs) and the climatology where SSW events were removed (referred as *reduced*). The significance of the differences between the *full* and *reduced* climatologies has been assessed with a Monte Carlo test, where 5000 trials of *reduced* climatologies were randomly created for the three periods. For each trial, we select as many events as SSWs there are, keeping the day and the month of the observed SSWs intact, but choosing the year of occurrence randomly among the available years of each analyzed period. Then, we compute the *full* and *reduced* random climatologies. Significance at the 90% level is attained when the temperature difference between the *full* and *reduced* climatology is above the 95th or below the 5th percentile of the probability distribution derived from the Monte Carlo test. For reference, Figure 3b also shows the distribution of SSW events as the total number of events within running periods of ±10 days, with solid lines denoting statistically significant differences from climatology at 90% level.

[15] As expected, the *full* climate is warmer than the *reduced* one without SSWs for the entire 45-year period (blue line). For the pre-1979 period (green line) there is a SSW-related warming peaking of +5 K in late January. In the post-1979 subset (red line), two prominent warming peaks are seen: in December of about +2 K, and in late February of +3 K. All three peaks are statistically significant at the 95% level. The warming peaks of the pre- and post-1979 (Figure 3a) are in relatively good agreement with periods of SSWs clustering in the respective frequency distribution (Figure 3b). The SSW-related temperature changes lag the occurrence of SSWs, which is in part explained by two facts: 1) the central date of the SSW corresponds to the time of zonal wind reversal rather than that of maximum temperature perturbation, 2) the timing of SSWs is based on data at 10 hPa. An additional text to show the influence of SSW on the difference in climatologies is discussed in the auxiliary material.[1]

[16] In addition to the warming peaks in Figure 3a, we note a cooling in the aftermath of these periods. For the pre-1979 data, the cooling is observed in early March, and for the post-1979 data, the cooling is observed in late January/ early February, and late March/early April. Both cooling events occur about a month after the periods of enhanced SSW occurrence, and are consistent with the SSW evolution presented by *Limpasuvan et al.* [2004, Figure 3]. During a SSW, the polar vortex weakens and the westerly winds characteristic of the winter season are temporarily replaced by easterlies. As a consequence, the tropospheric wave propagation into the stratosphere is suppressed [*Charney and Drazin*, 1961]. The lack of the wave-driven easterly momentum deposition in the polar vortex allows the vortex to recover, and after the SSW, a strong and cold polar vortex reappears in the middle atmosphere.

[17] This warming and subsequent cooling caused by the seasonal concentration of occurrence of SSWs seen in Figure 3a, can also be observed in the climatological temperature evolutions of Figure 2c. Green lines (pre-1979) in both figures peak in January and show slightly decreases afterwards, while red lines (post-1979) show peaks in late February.

[18] Finally, it is important to note that the results described above are not sensitive to the width of the window chosen for the removal of the SSW perturbation and they still appear after removing ±20-to-70 days from the central date of SSW (not shown).

4. Summary and Discussion

[19] We have reported a significant difference in the climatological temperatures of the Northern Hemisphere stratospheric polar cap between pre- and post- 1979 periods, in both reanalysis and radiosonde data, that are concurrent with simultaneous changes in the subseasonal distribution of SSWs. These differences are larger in February, and reach up to 5.9 K at 10 hPa and 3.6 K at 20 hPa. SSWs tend to occur preferentially in January in the 1958–1978 period, whereas for the period 1979–2002, they occur preferentially

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2012GL053632.

in December and end of February. These results are independent of specific thresholds or levels employed to identify SSWs, and thus they corroborate that despite being rare events, SSWs have an imprint on the seasonal march of the temperature climatology in winter.

[20] On the other hand, we found that the temperature variability associated with SSWs for the pre- and post-1979 period is in better agreement with theoretical expectations at 20 hPa than at 10 hPa, even though the 10 hPa level is frequently used for SSW identification and characterization. In addition, the increase in the temperature strength of SSWs between pre- and post-1979 reported by CHP07 at 10 hPa, does not appear at 20 hPa. While these are not definitive proofs for a systematic deficiency of the temperature data at 10 hPa, it is a strong indication that results concerning changes between the pre- and post-1979 periods and based on 10 hPa data, should be treated with caution.

[21] In this paper, we have emphasized the imprint of decadal changes in SSWs frequency on the climatology. In turn, this could have an effect on the characterization of SSWs signatures, since the anomalies are usually defined with respect to a climatology that is already perturbed by these events. This points out the necessity of being cautious when clustering SSWs events. Further work is needed to achieve an accurate representation of the impact of SSWs and to minimize the influence of satellite data assimilation on it.

[22] While a detailed analysis of possible causes to explain the results found here is out of the scope of this paper, there are a number of factors that can drive the shift in the seasonal distribution of SSWs. As described in the introduction, wave activity from the troposphere and a "pre-conditioned" polar vortex are both important in triggering SSWs. The former has been related to atmospheric blocking occurrence (among other tropospheric systems) within 10-to-20 days before the SSW [*Castanheira and Barriopedro*, 2010], while the latter could be rather determined by external factors affecting the mean polar vortex (e.g., ENSO, the QBO phase, solar activity, etc) or even by purely internal stratospheric variability. It is not even clear the specific role of each forcing in the overall winter frequency of SSWs, as there could be aliasing among factors and a non-linear response to the superposition of several forcings [e.g., *Calvo and Marsh*, 2011; *Richter et al.*, 2011]. The influence of variations of some of these forcings on the SSW and/or polar temperature shift [*Christiansen*, 2003; *Pawson et al.*, 1998], such as the change in the Holton and Tan mechanism reported by *Lu et al.* [2008] or the change in the seasonality of the phase of the QBO [*Christiansen*, 2010] will be the subject of future studies.

[23] **Acknowledgments.** We thank the Stratospheric Research Group of the FUB for preparing the stratospheric data. This research was supported by the Ministry of Economy and Competitivity of Spain under project TRODIM (CGL2007-65891-C02 and CGL2008-05968-C02-01). MGE was funded by FPI grant (BES-2008-005310). We are grateful to two referees for their helpful comments.

[24] The Editor thanks the two anonymous reviewers for their assistance in evaluating this paper.

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