ARCTIC OZONE EVOLUTION AROUND THE STRATOSPHERIC FINAL WARMING

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1.- INTRODUCTION

The stratospheric dynamic is determined by a strong temperature gradient established between the pole and equator during the solstices, due to the different latitudinal solar warming which exists between these regions. This thermal gradient generates a zonal wind profile from west in the winter hemisphere and from east in the summer hemisphere. The westerlies are more intense so they originate a zonal wind belt at high latitudes in winter which isolates the inside air to the rest of the atmosphere. This cyclonic system is called Stratospheric Polar Vortex, and although it is maintained during the whole winter, it is also sensitive to be affected by the vertical wave propagation from the troposphere.

Apart from the dynamic effects, chemicals processes take place in the stratosphere also; among them, ozone production and destruction stand out. The stratospheric ozone production is a natural process that occurs basically in the equator and involves ultraviolet sunlight and oxygen molecules. Meanwhile the destruction is located fundamentally in poles and promoted by reactive gases that contain bromine and chlorine, such as chlorofluorocarbons (CFCs). To make the ozone destruction possible the molecules of these reactive halogen gases must be actived by the ultraviolet sunlight and chemical reactions with other molecules, like those contained in the Stratospheric Polar Clouds (SPC) (Fahey 2007).

Both types of processes, dynamic and chemical, are not independent between each other, since the destruction suffered by the ozone in the stratospheric polar region is related to the dynamic activity presents there. The isolation of air inside the stratospheric polar vortex avoids the mixing with warmer air masses coming from mid-latitudes, which favours the cooling in the polar region. In turn, the cooling can lead the formation of PSCs, which contributes to the stratospheric ozone destruction.

To sum up, the connexion between the polar vortex and the ozone content in the high-latitude stratosphere is a relevant topic in climate studies, with an important role in the climate models improving. The present study, focused on the northern hemisphere, analyses this relation during one month around the occurrence of the breakdown of the polar vortex observed every spring, associated with the annual change in the stratosphere wind regime, from the winter westerlies to the summer easterlies. This phenomenon, accompanied by a rapid increase in the stratospheric polar temperature, is called Stratospheric Final Warming (hereafter, SFW; Andrews et al. 1987).

2.- DATA AND METHODOLOGY

This study has been performed using daily data from ERA-40 reanalysis, with a horizontal resolution of 2.5ºx2.5º. The dataset corresponds to 50hPa, level where the stratospheric vortex breakdown is reported (Black et al. 2006) and covers the polar band region, 60ºN-90ºN-180ºW-180ºE, where generally the vortex core is found. The period analysed is March-April-May from 1979 to 2002, that is, the ERA-40 period including satellite data, essential in the realistic stratospheric representation (http://data.ecmwf.int/data).

The variables used to define the polar vortex activity are the zonal wind velocity at 50hPa and the potential vorticity at the equivalent isentropic level 475K (u50 and PV475, respectively), being the meridional gradient of PV especially useful to delimit the vortex edge (Baldwin and Holton 1987). To assess the stratospheric ozone content in the study region, its mixing ratio at 50hPa (q50) has been used. Also temperature at the same pressure level (T50) has been considered. The spatial characterization for each variable in the period of ± 30 days around the date of the SFW has been done plotting the mean (μ) and the standard deviation (σ) corresponding to the study period 1979-2002. To identify how the different variables evolve over time in de polar stratospheric region, the time series of the respective spatial mean has been plotted.

3.- RESULTS

To understand the stratospheric conditions around the annual SFW occurrence, this work starts with a summary of the mean characteristics over the Arctic stratosphere and its evolution during March, April and May. Next, we focus on the polar stratospheric situation surrounding the date of the SFW.

3.1.- Mean conditions and evolution in springtime

In order to know the mean conditions during the spring months in the Arctic stratosphere, the spatial average for the different variables has been calculated for each month. It can be seen in Figure 1 how the spatial distribution of the analysed variables evolves along the season, with a progressive decrease in their values. It is outstanding the change in the zonal wind, from westerlies to easterlies, and the decrease of the PV475 meridional gradient. The values of the standard deviation over the analysed region gradually decrease with time as well (Fig. 2). This indicates that the interannual variability in March is greater than in May, that is, March months are less similar among them than May months.

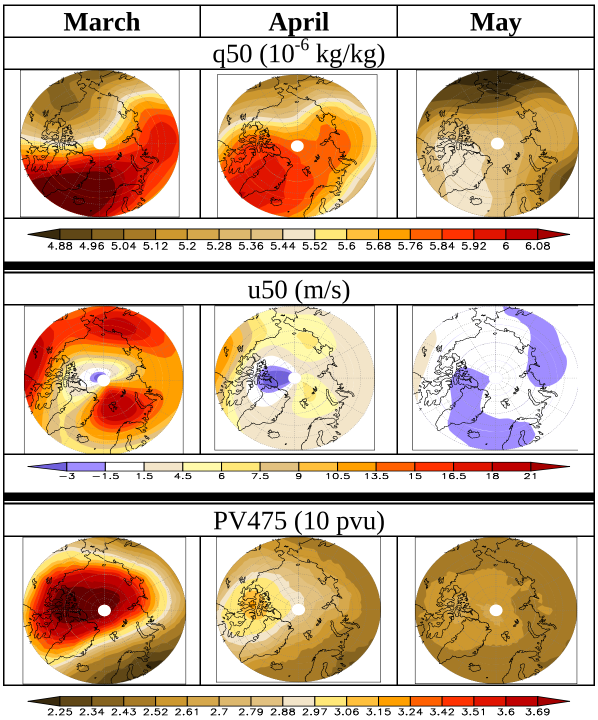

Fig. 1.- Monthly mean spatial distribution, over 60ºN-90ºN at 50hPa, of ozone mixing ratio (q50, in 10^{-6} kg/kg), zonal wind (u50, in m/s) and potential vorticity (PV475, in 10 pvu) for each spring month in the 1979-2002 period.

With the aim of studying the mean evolution of a variable in the Arctic during the spring, the spatial average has been calculated over the 60ºN-90ºN band. We use square brackets to denote the spatial-average variables, e.g. [u50] in the case of the zonal wind velocity at 50hPa. Figure 3 shows the set of the 24 spring evolutions of [q50] in the period 1979-2002, along with the corresponding mean evolution (red solid line). A little increment of the 50hPa ozone concentration during March can be observed, whereas [q50] decreases progressively during April and May. This overall behaviour can be understood because in March is when the solar light reaches the Arctic region, which leads to a warming in the region with the consequent polar vortex weakening. This allows that the transport of stratospheric ozone from tropical latitudes reaches the pole by the Brewer-Dobson circulation, and thus the ozone content in the Arctic stratosphere increases. As the spring advances, the solar radiation increases favouring the ozone destruction by photochemical processes. Although nearly all years in 1979-2002 present this common behaviour in the evolution of [q50], Figure 3 shows that 1996 and 1997 do not, with extremely high and low values, respectively.

Finally, from Figure 3 we can see also how the interannual variability of the springtime evolution of [q50] decreases along the season.

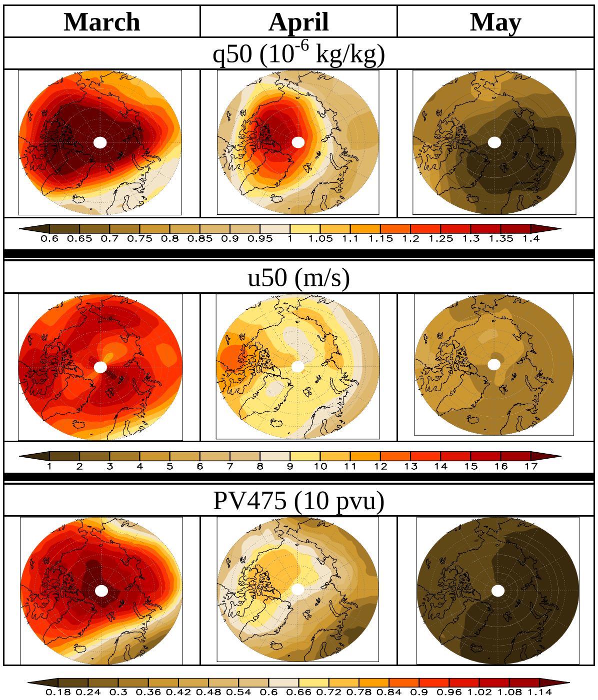

Fig. 2.- Standard deviation spatial distribution, over 60ºN-90ºN at 50hPa, of ozone mixing ratio (q50, in 10^{-6} kg/kg), zonal wind (u50, in m/s) and potential vorticity (PV475, in 10 pvu) for each spring month in the 1979-2002 period.

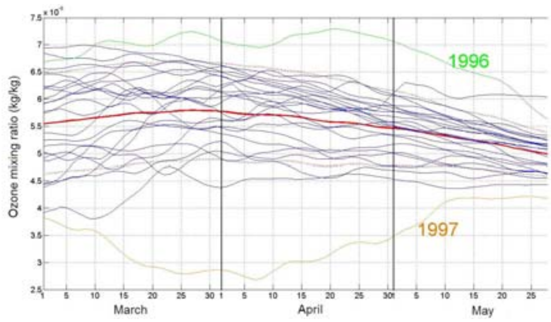

Fig. 3.- Set of 24 time evolutions of the Arctic 50hPa ozone mixing ratio during spring (1979-2002). Evolutions have been smoothed by a five-day running average. The red solid line represents the 24-yr mean evolution (μ) and the dashed lines display the evolutions μ ± σ.

As expected, the 50hPa zonal wind and temperature in the Arctic spring have opposite evolutions (Fig. 4). The former decreases gradually during the whole spring until finishing the season with values around zero, the vortex has broken and the winds become easterlies. Meanwhile the polar T50 tends to increase due to the solar radiation increases in the region.

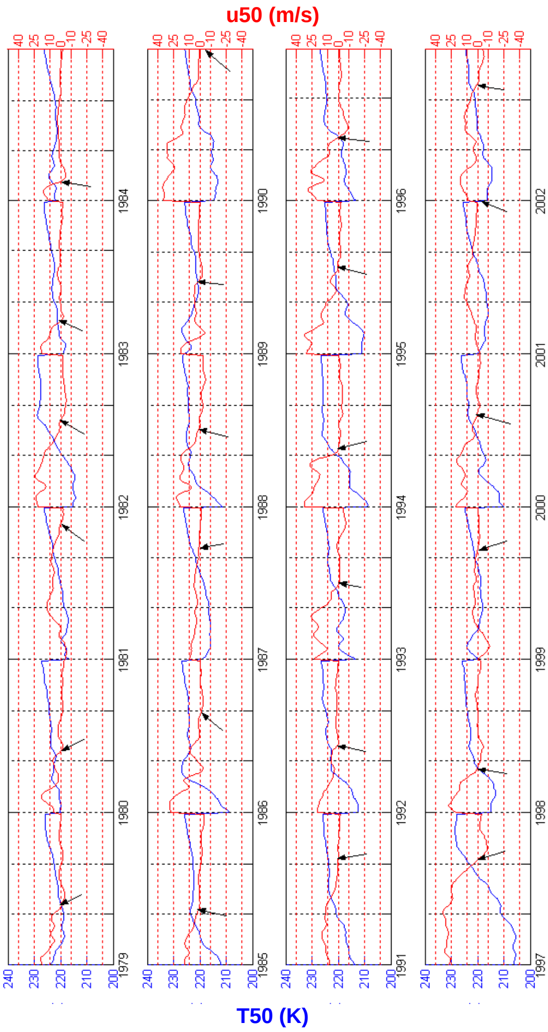

Fig.4.- Daily time series of temperature (blue line) and zonal wind (red line) over the Arctic at 50hPa during March-Apr-May 1979-2002. Rows indicate the date of the SFW for each year.

The date of the SFW for each year is indicated by an arrow in Figure 4 (information taken from Ayarzagüena and Serrano 2009). Notice the extreme low T50 and high u50 registered before the SFW in 1997, year with very low 50hPa ozone along this spring, especially in March and April. The low stratospheric ozone registered in 1997 can be understood because of the very strong polar vortex observed before its breakdown on 3rd May. This feature means isolation of the air inside the vortex from the warmer air coming from mid-latitudes during long time in the spring. Consequently, the air inside the vortex remains cold, which favours the formation of the PSCs that, in turn, promotes the destruction processes of ozone.

	February	early-March	
	Temperature	ozone mixing ratio	vortex intensity
1979	WARM		
1980	COLD		
1981	WARM		WEAK
1982			
1983		LOW	
1984	COLD	LOW	
1985		LOW	WEAK
1986	COLD	LOW	STRONG
1987	WARM		WEAK
1988	COLD	LOW	
1989	WARM	HIGH	
1990		HIGH	STRONG
1991	WARM		
1992			
1993			
1994			STRONG
1995		HIGH	STRONG
1996	COLD	HIGH	STRONG
1997	COLD	LOW	STRONG
1998		LOW	STRONG
1999		LOW	WEAK
2000	COLD	LOW	
2001	WARM	LOW	WEAK
2002		LOW	

Table 1.- Classification of Februaries in cold or warm according to T50 averaged in the Arctic, and characterization of the early-Marches, in basis of the 50-hPa ozone concentration and zonal wind averaged in the region (see text for more details).

As it has been mentioned, the polar stratosphere interannual variability, in both ozone content and zonal wind, decreases during the spring (Fig. 2). Related to this feature, it has been tested if the major variability between Marches observed in the stratosphere is associated with the thermal conditions in the previous late-winter. To do this, the Arctic-average monthly T50 in February has been analyzed along with [q50] and [u50] for the first 10 days of March for each year in 1979-2002 period.

Temperature has been chosen as the representative variable of the stratospheric polar conditions at late-winter because it affects both the dynamic and chemical processes influencing the polar vortex. In basis of the mentioned variables, the first step in this analysis has been to identify each February as warm or cold, and the values of [q50] and [u50] as high or low.

For these classifications, percentiles have been calculated using the whole ERA-40 dataset period (1958-2002). We have considered high values in [T50], [q50] or [u50] those greater than the 75^{th} percentile, and low values those less than 25^{th} percentile.

After analysing the results summarized in Table 1 about the relation between [T50] in February and the stratospheric conditions (ozone and polar vortex) at the beginning of March in the Arctic, the following scores are extracted:
- Only one out of the six years with warm February had low ozone at the beginning of March (i.e. 2001), that is, lower ozone than the corresponding 25^{th} percentile ($5.35.10^{-6}$ vs. $6.79.10^{-6}$).
- None year with warm February and strong polar at the beginning of March.
- None year with cold February and weak polar vortex at the beginning of March.

These results confirm the relation that exists in the stratospheric polar region between the temperature, the zonal wind intensity and the quantity of ozone. As it has been mentioned before, low temperatures are associated with strong polar vortex, because intense zonal wind avoids the polar air mixing with warm air coming from mid-latitudes. Also, low temperatures favour the formation of PSC, which in turn increments the ozone destruction.

3.2 Conditions surrounding the date of the Stratospheric Final Warming.

In this part of the work, we focus on the occurrence of the annual Stratospheric Final Warming (SFW).

As was mentioned in the Introduction, this phenomenon is associated with the reversal of the stratospheric circulation, from the winter westerlies to the summer easterlies, and thus with the breakdown of the polar vortex. The date of the SFW for each year in 1979-2002 is taken from a recent paper by Ayarzagüena and Serrano (2009; see Table 2).

To see the spatial evolution of different variables surrounding the breakdown of the stratospheric polar vortex, the 30 days before and after its occurrence have been analysed. Each 30-day period has been divided in three consecutive 10-day sets, whose time means in 1979-2002 have been calculated. Four cases were not included in this computation: 1984, 1988, 1990 and 2001. The two latter SFW occurred out of Mach-April-May period, i.e. on 3^{rd} June 1990 and 2^{nd} June 2001, respectively. As regards 1984 and 1988, a *stratospheric sudden warming* (SSW, event that occurs occasionally in wintertime) was observed nearly 30 days before the SFW (i.e. on 24^{th} February and 14^{th} March, respectively), and thus, the stratospheric conditions prior to the respective SFW might have been perturbed by the previous late SSW.

1979	1980	1981	1982	1983
04-apr	07-apr	22-may	23-apr	21-mar
1984	1985	1986	1987	1988
13-mar	04-apr	29-apr	08-may	19-apr
1989	1990	1991	1992	1993
15-apr	03-jun	05-may	12-apr	14-apr
1994	1995	1996	1997	1998
3-apr	26-apr	08-apr	03-may	26-mar
1999	2000	2001	2002	
06-may	24-apr	02-jun	10-may	

Table 2.- Date of the SFW, calculated with Black et al. (2006) criteria (from Ayarzagüena and Serrano (2009)

As expected, the westerlies at 50 hPa reduce velocity over the whole Arctic region as the SFW occurrence is getting closer (Fig. 5). As regards PV475, Figure 6 shows its highest values located over the Canadian Arctic Archipelago, with progressive decrease during the period prior to the SFW event. Also, it is noticeable the weakening in the meridional gradient of PV475. This spatial and time behavior of PV475 explains the evolution of the three 10-day structures of the 50-hPa ozone displayed in Figure 7. These structures of q50 show a similar pattern with two extensive centres, one with higher ozone content (over Greenland Sea) than the other, which is located where PV475 is high. Notice that the contrast in values between the two centres of q50 is getting progressively smaller as the SFW event is getting closer, that is, the high q50 values decrease and the low q50 increase slightly.

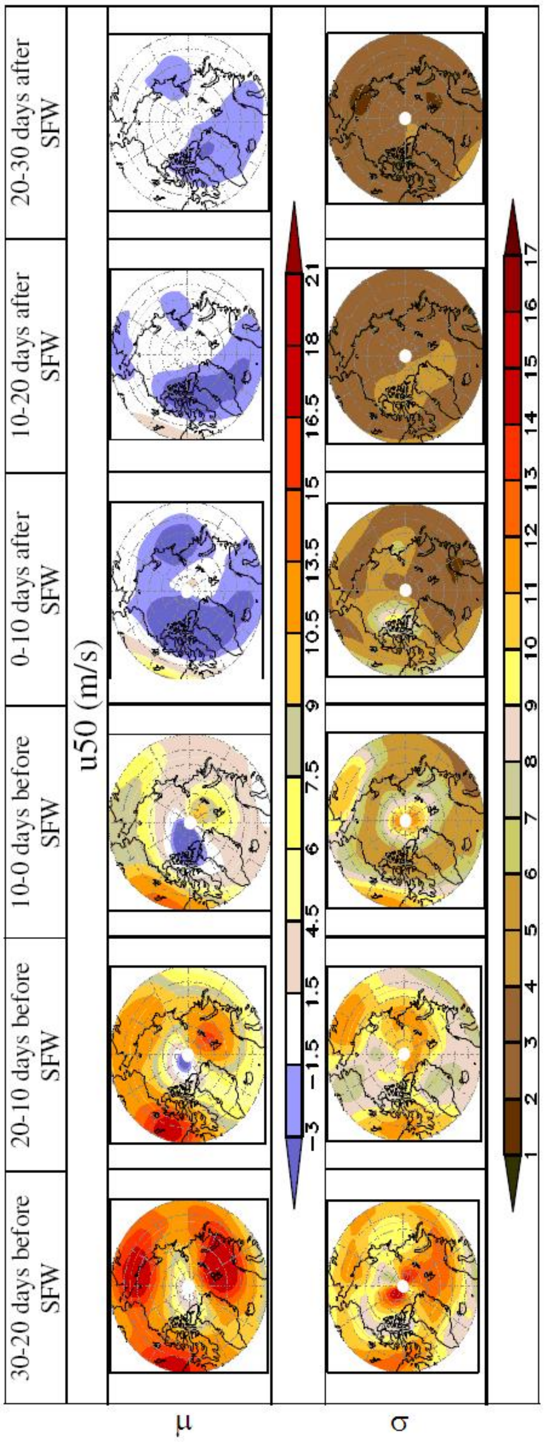

Fig. 5.- Ten-day mean (μ) and standard deviation (σ) spatial distributions of 50-hPa zonal wind (m/s) over the Arctic along the sequence of ± 30 days surrounding the date of the SFW. Period: 1979-2002.

The interannual variability of the three variables, u50, PV475 and q50, also decreases gradually prior to the SFW event (bottom panels in Figs. 5, 6 and 7).

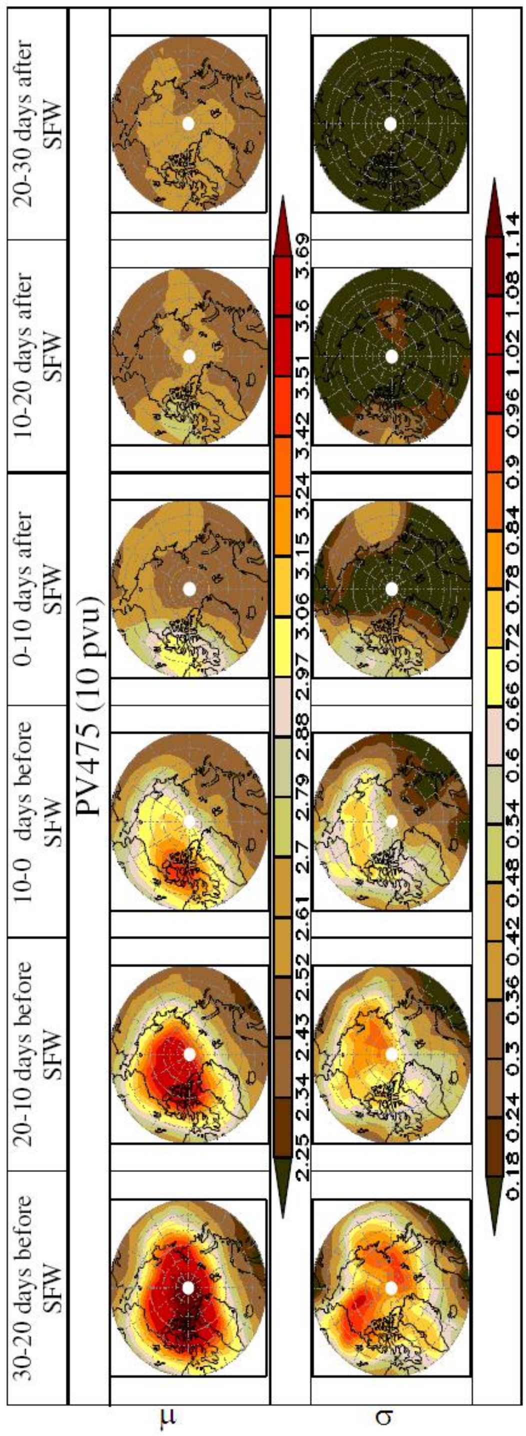

Fig. 6.- As in Fig. 5 but for the potential vorticity at the isentropic level 475 K (in 10 pvu).

After the occurrence of the SFW the 50-hPa zonal wind, with expected negative values in almost the whole Arctic region (i.e. easterly winds), reaches its highest mean velocity in the first days after the SFW (around 4.5 m/s) and takes values closer to zero as the date of the SFW is getting far. This result is very similar between years, and even more as the time advances, as we can see in Figure 5 (bottom panel). The PV475 values are lower as the breakdown of the polar vortex is getting far, in such a way that its meridional gradient is practically null after the SFW event. As for u50, the interannual variability of PV475 decreases gradually after the SFW occurrence, reaching a homogeneous low value over the whole polar region 30 days later (bottom panel in Fig. 6).

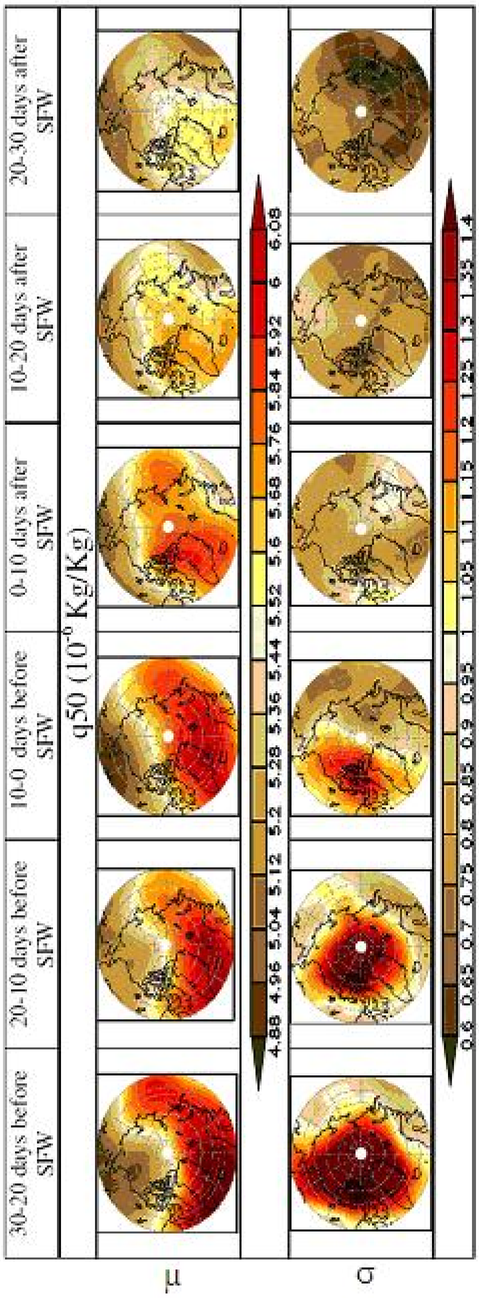

Fig. 7.- As in Fig. 5 but for 50-hPa ozone mixing ratio (10^{-6} kg/kg).

As regards the ozone content after the SFW event, Figure 7 shows how q50 decreases gradually over the whole Arctic region, reaching very low values (about 5×10^{-6} kg/kg).

Figure 8 displays the time evolutions of 50-hPa zonal wind averaged over the Arctic region (i.e., 60ºN-90ºN), centred on the date of the SFW, for each year. It can be seen clearly how [u50] values decreases as the SFW is getting closer and how the highest easterlies values, even though low, are reported just after the SFW occurrence. While the interannual variability of the time evolution of [u50] prior to the breakdown of the polar vortex is large, the weak easterlies after the SFW event are quite common between years.

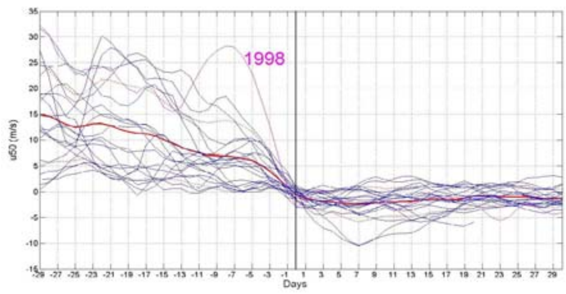

Fig. 8.- Set of twenty time evolutions (in 1979-2002) of the Arctic zonal wind at 50 hPa (m/s) during ±30 days surrounding the date of the SFW. Evolutions have been smoothed by a five-day running average. The red solid line represents the 20-yr mean evolution (μ) and the dashed lines display the evolutions μ ± σ. The SFW of 1984, 1988, 1990 and 2001 are not included (see text for more details).

In the case of 50-hPa ozone, the average concentration over the Arctic during a month before the SFW is almost constant (Fig. 9), but we should keep in mind that there are notable differences between two large zones in the region as the upper panel in Figure 7 shows. Once the SFW has occurred, a very slight decrease in [q50] is observed during the 30 days after. Once more, 1996 and 1997 stand out as years with the highest and the lowest values of [q50], respectively, in the 1979-2002 period.

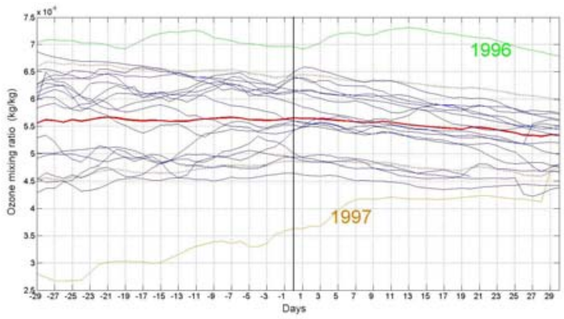

Fig.9.- As in Fig. 8 but for 50-hPa ozone mixing ratio (10^{-6} kg/kg).

4.- SUMMARY AND CONCLUSIONS

Stratospheric ozone content and vortex conditions over the Arctic region during the springtime have been analysed. In particular, we have focused on the evolution of the ozone during a month before and after the date of the SFW, i.e. the breakdown of the polar vortex. Daily data from ERA-40 for the period including satellite data (i.e. 1979-2002) and the 60ºN-90ºN domain have been used. Ozone mixing ratio and zonal wind at 50hPa along with potential vorticity at 475K have been analysed (q50, u50, and PV475, respectively). The main conclusions of the work are summarized as follows:

- Springtime in the Arctic stratosphere presents a large variability, both intraseasonal and interannual.

- The intensity of the stratospheric polar vortex and the ozone content at the beginning of March are related to the temperature in February. A warm February does not go with strong polar vortex in the first ten days of March, neither usually with low ozone; a cold February is not followed by weak polar vortex at early-March. This result is in agreement with that low stratospheric temperatures are associated with a strong polar vortex, which avoids the polar air mixing with warm air coming from mid-latitudes. Besides, low stratospheric temperatures favour the formation of PSC, which in turn increments the ozone destruction.

- During the previous month of the SFW occurrence the spatial distribution of 50-hPa ozone mixing ratio over the Arctic does not change much. The pattern is formed by two extensive centres: one with much higher ozone content (over Greenland Sea) than the other, which is located where PV475 is high. The difference in values between the two centres of q50 is getting smaller as the SFW event is getting closer, that is, the high q50 values decrease and the low q50 increase slightly. This behavior explains the almost constant value of the 50-hPa ozone averaged over the polar region during the 30 days prior to the date of the SFW.

- After the breakdown of the polar vortex, the ozone concentration at 50hPa decreases gradually in the Arctic, reaching very low values over the whole polar region at the end of the 30-day period. After the date of the SFW, the easterlies keep a low intensity during the whole post-SFW period analysed, being the highest values reported just after the SFW event.

- The interannual variability of 50-hPa ozone content over the Arctic reduces gradually from 30 days prior to SFW occurrence until 30 days after. For u50 and PV475, differences between years decrease progressively as the date of the SFW is getting closer, and become very small once the polar vortex has broken down.

ACKNOWLEDGEMENTS

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