Propagación vertical de la señal de ENSO hacia la estratosfera: Una Síntesis

The upward propagation of the ENSO signal towards the stratosphere: An Overview

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RESUMEN

Hasta esta ultima década, el estudio del fenómeno ENSO (El Niño-Oscilación del Sur) en la estratosfera no ha sido muy exhaustivo, debido principalmente a la falta de observaciones globales en altura y a la presencia de otras fuentes de variabilidad en la estratosfera cuyas señales se solapan con la generada por ENSO. Los últimos estudios con modelos de circulación general, capaces de aislar la señal de ENSO, han mostrado su impacto en la estratosfera. En este trabajo, utilizamos el Modelo Climático Comunitario de Atmósfera Completa (WACCM) para ilustrar su propagación y los mecanismos por los que ENSO se manifiesta en la estratosfera. Los resultados muestran que la señal de ENSO se propaga hasta aproximadamente 40 km de altura en latitudes medias del Hemisferio Norte durante el invierno boreal, a través de ondas de Rossby ultra largas. La señal de ENSO también se identifica en latitudes tropicales en forma de enfriamiento zonal homogéneo durante su fase cálida o El Niño y en latitudes polares como un calentamiento zonal acompañado por vientos más débiles durante episodios extremos de El Niño en los meses del invierno boreal. Esta señal es el resultado de la intensificación de la circulación meridiana estratosférica forzado por la propagación y disipación anómalas de ondas de Rossby en latitudes medias durante episodios El Niño intensos.

Palabras clave: ENSO; dinámica de la estratosfera; circulación meridiana media estratosférica; ondas de Rossby; interacción ondas-flujo de fondo.

ABSTRACT

The study of El Niño-Southern Oscillation (ENSO) phenomenon above the troposphere has traditionally been difficult because of the lack of global observations at high altitudes and also because of the presence of other sources of variability whose signals are difficult to disentangle from ENSO effects. Recent works with general circulation models that isolate the ENSO signal have demonstrated its upward propagation into the stratosphere. Here we use a recent version of the Whole Atmosphere Community Climate Model to illustrate the propagation and mechanisms whereby the signal manifests itself in the stratosphere. The ENSO signal propagates upwards to about 40 km at middle latitudes in Northern Hemisphere boreal winter months by means of

large-scale Rossby waves. The ENSO signal is also identified at tropical latitudes in the form of a zonally homogeneous cooling during strong El Niño events and at polar latitudes in the Northern Hemisphere winter as a zonally homogeneous warming accompanied by weaker winds during a strong El Niño event and winter boreal months. This signal is the result of the intensification of the stratospheric meridional circulation forced by anomalous propagation and dissipation of Rossby waves at middle latitudes during strong El Niño events.
Key words: ENSO; stratospheric dynamics; stratospheric mean meridional circulation; Rossby waves; wave-mean flow interaction.

1. INTRODUCTION

El Niño-Southern Oscillation (ENSO) is a coupled phenomenon of the ocean and the atmosphere. Its warm phase or El Niño refers to the ocean component of the system, an anomalous warming in the Eastern Tropical Pacific which usually peaks in boreal winter. The atmospheric component, known as the Southern Oscillation, refers to the sea level pressure variation between the eastern Pacific and the Indian Ocean. The effects of El Niño-Southern Oscillation (ENSO) on atmospheric temperatures have been widely investigated in the troposphere where ENSO is known to be one of the main sources of variability.

Several studies have presented evidence that ENSO propagates and also has an effect in the stratosphere. The first works dealt with observations (van Loon and Labitzke 1987, Hamilton 1993, Baldwin and O'Sullivan 1995) but their results were not uniformly consistent. Some of them did find a relationship between ENSO and the polar vortex in the Northern Hemisphere stratosphere whereas others did not find statistically significant signal and pointed out the difficulty in isolating the ENSO signal from other sources of variability that affect the stratosphere. In the tropical stratosphere, ENSO signal was also found in radiosonde and satellite observations (Reid et al. 1989; Yulaeva and Wallace, 1994; Calvo Fernandez et al., 2004) with opposite sign to that in the tropical troposphere.

The lack of global and well resolved observational datasets together with the difficulties in disentangling the ENSO signal from those generated by other sources of variability as the Quasi-Biennial Oscillation (QBO), the volcanic eruptions, climate change related to the greenhouse gases and solar variability have complicated the analysis of the ENSO signal in the stratosphere. Very recently, several studies have pointed out that the combined effects of two of these forcings as ENSO and QBO (Calvo et al., 2009) or ENSO and solar signal (Kryjov and Park, 2007; Kuroda, 2007) are very different from those obtained when they operate independently, which highly confuse the whole picture.

This is why in the last years general circulation models (GCMs) with high vertical and horizontal resolution and coverage and able to isolate the ENSO signal have become one of the few tools available to investigate this phenomenon in the middle atmosphere. Some works specifically focused on ENSO effects in this type of GCMs are those of Sassi et al. (2004), who used the Whole Atmosphere Community Climate Model, version 1 (WACCM1), developed at the National Center for Atmospheric Research (NCAR); Manzini et al. (2006) , using the Middle Atmosphere European Center Hamburg Model MAECHAM5; and Garcia-Herrera et al. (2006), who compared in detail results from these two models and the European Center for Medium-Range Weather Forecasts (ECMWF) reanalysis of atmospheric observations (ERA40).

In this paper, we present an overview of the current knowledge on ENSO signal in the middle atmosphere. We make use of model ouput from the recent version 3 of WACCM to illustrate the upward propagation of the ENSO signal and to show the mechanisms by which the signal reaches the stratosphere.

2. MODEL AND MEHOD

WACCM3 is a fully chemistry coupled GCM based on the U.S. National Center for Atmospheric Research's Community Atmosphere Model (CAM3). WACCM3 includes all of the physical parameterizations of CAM3 and most of the physical and chemical processes that are important for describing the dynamics and chemistry of the atmosphere above the troposphere and up to about 140 km. It has 66 vertical levels from surface up to about 140 km and its vertical coordinate is purely isobaric above 100 hPa (~16 km) but hybrid below that level. The vertical resolution is variable, ranging from 1.1 km in the troposphere, above the planetary boundary layer, to about 3.5 km in the upper atmosphere.

The simulation used for this study spans from 1950 to 2004. Sea surface temperatures (SSTs) are prescribed as boundary conditions. The model does not produce a QBO which has the advantage that it allows analysis of model results without this additional source of variability. Chemical effects of volcanic aerosols are included but not their radiative effects. The 11-yr solar cycle irradiance variability is parameterized in terms of the observed f10.7 radio flux. Detailed information about the model, processes and parameterizations can be found in Garcia et al. (2007).

The results presented here are based upon three realizations of WACCM3 run at horizontal resolution of 4° x 5° (latitude x longitude). The ensemble average of the three realizations was computed for the period 1979-2000 in order to better compare with previous results that used the same period of analysis. To characterize the timing and intensity of ENSO, we have used the Niño3.4 index (N3.4) which is computed using SST anomalies for the region between 120°W and 170°W longitude and 5°S to 5°N latitude. Warm and cold ENSO events have been chosen whenever this index exceeds 1.2 standard deviations (Table 1). All of the ENSO events peak in late fall-early winter except the strong warm ENSO event in August 1988, which has not been considered in this study to avoid misleading interpretation of the mechanisms involved since the stratosphere dynamics is strongly modulated by the seasonal cycle. Composites for the strongest El Niño and La Niña events were constructed and then the differences (El Niño minus La

Niña averages) were analyzed. In the composite analysis, month 0 indicates the month in which all the ENSO events reach their maximum N3.4 index value. The significance of the ENSO anomalies with respect to the internal variability of the model has been tested by a Monte Carlo method following the methodology in Garcia-Herrera et al., (2006). In the figures, the shadowed areas denote anomalies significant at the 95% confidence level.

WARM ENSO EVENTS		COLD ENSO EVENTS	
January 1983	2.74	December 1984	-1.21
January 1992	1.82	November 1988	-1.91
December 1994	1.32	December 1988	-1.51
November 1997	2.76		

Table 1. Central month and its corresponding N3.4 value for the warmest and coldest ENSO events considered in the study.

3. RESULTS

3.1 Wave-like ENSO signal

Composite differences (El Niño minus La Niña events) for atmospheric temperature anomalies obtained from WACCM3 are shown in Fig. 1 in a longitude height domain at 42ºN from month 0 to month 5. This latitude has been chosen as representative of middle latitudes in the Northern Hemisphere (NH). Most of the significant anomalies are located in the troposphere and stratosphere over the Pacific Ocean. Some of the significant areas correspond to some of the regions of the PNA pattern which is known to be related to ENSO (e.g. Horel and Wallace, 1981; Ribera and Mann, 2002). The negative anomalies observed in the troposphere and the positive ones in the stratosphere are characteristic of ultralong Rossby waves. These patterns tilt westward with height as expected for upward propagating Rossby waves. Significant anomalies are observed up to about 40 km and maximize in months 0 and 1 with largest values about 4 K. These values are in very good agreement with those from WACCM1 and MAECHAM5 models shown in Garcia-Herrera et al. (2006), but with slightly smaller anomalies reaching higher altitudes than for the ERA40 observational data set. Five months after the maximum of N3.4 (month 5), the anomalies have almost disappeared.

In the Southern Hemisphere (SH, figure not shown), the ENSO related anomalies also have the shape of wave patterns but propagation into the stratosphere seems far less effective. The anomalies are weaker and the significant regions smaller, located at lower heights. This different propagation between NH and SH might be related to phasing of ENSO events with respect to the seasonal cycle. There is a strong relationship between vertical propagation of Rossby waves and zonal wind regimes. The Charney and Drazin (hereafter, CD) criterion

(Charney and Drazin, 1961) indicates that quasi stationary Rossby waves propagate into the stratosphere mainly during winter since vertical propagation requires that the zonal wind be westerly (from west to east) and lower than a certain critical threshold which depends on the total horizontal wave number.

Thus, only ultralong Rossby waves are able to propagate into the stratosphere in the climatological westerly winds that prevail in the winter stratosphere. Figure 2 shows the climatology of zonal mean zonal winds for December, January, February climatology (DJF) for the analyzed period. Taking into account the CD criterion, it follows that in the NH westerlies help propagate the ENSO signal towards the middle atmosphere while in the SH easterlies inhibit wave propagation above 20 km in agreement with WACCM3 results in temperature shown before.

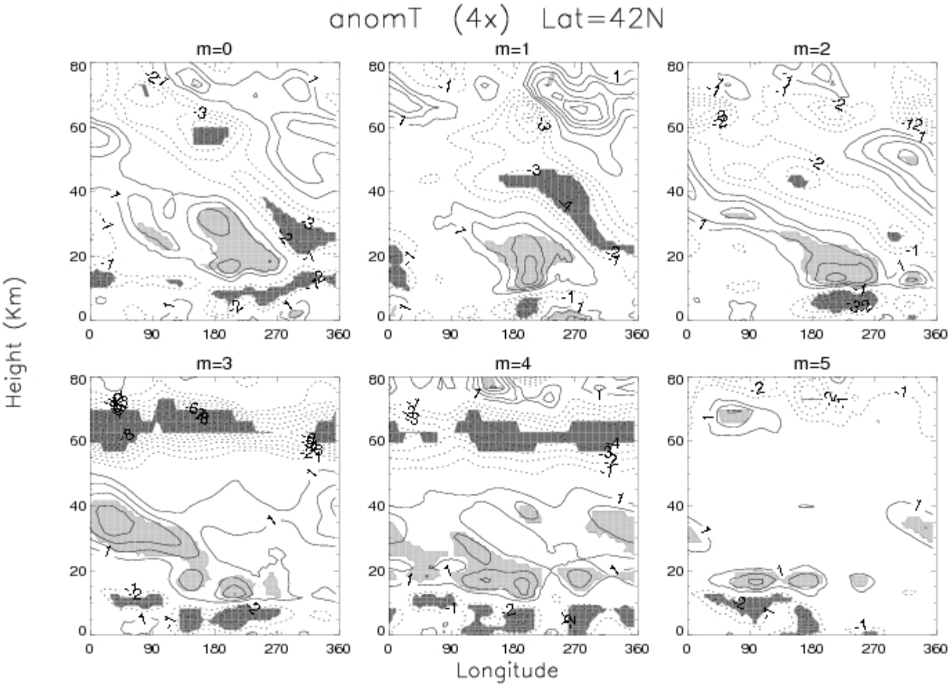

Figure 1. Composite difference (El Niño minus La Niña) of the temperature anomalies at lat 42ºN from the WACCM3 ensemble simulation for months 0 to 5 after and El Niño event. Solid (dashed) lines denote positive (negative) anomalies. Light (dark) shadowed regions indicate positive (negative) statistically significant anomalies at the 95% confidence level. Contours are drawn every 1K (zero line has not been displayed).

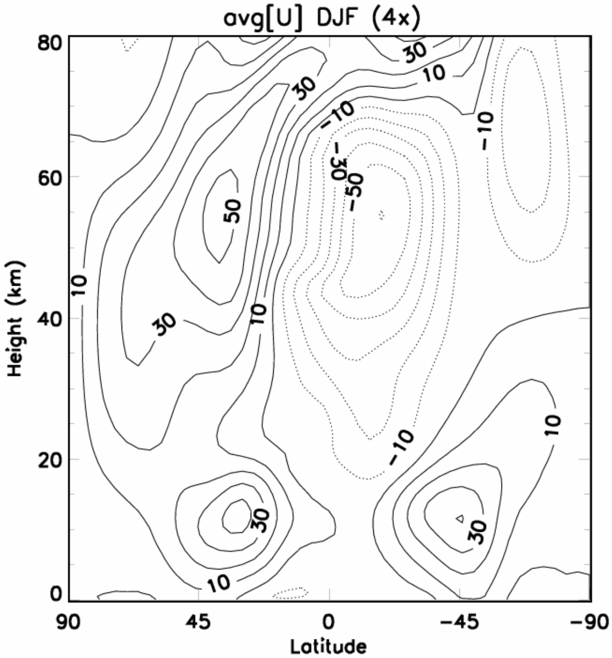

Figure 2. Winter climatology (December, January, February) of the zonal mean zonal winds for the period 1979-2000. Contours are drawn every 10 m·s^{-1}; solid (dashed) contours for westerly (easterly) winds.

The Rossby wave propagation may be further visualized by means of the Eliassen Palm (hereafter, EP) flux. Figure 3 represents the composite difference El Niño-La Niña for EP flux anomalies. The EP flux vectors can be considered as a measure of the wave propagation from one latitude and height to another (Edmon et al., 1980). Thus, at middle latitudes, WACCM3 shows clear evidence of enhanced upward propagation in the NH and reduced propagation in the SH in month 0 (referred to climatology), the former being much more intense. This is consistent with the temperature pattern observed in Fig. 1.

At tropical latitudes, the ENSO signal looks quite different from the one in extratropics. Figure 4 shows the composite differences at 2ºN although similar results are obtained at any tropical latitude (not shown). A wave-like ENSO signal is confined to the troposphere and lower stratosphere with opposite signs in troposphere and lower stratosphere in agreement with observational results from satellite data (Calvo Fernandez et al., 2004; Yulaeva and Wallace, 1994). The upward propagation of the wave signal is inhibited in this region because of the small vertical group velocity of tropical Rossby waves and the easterly winds above 20 km (Fig. 2). Beyond the lower stratosphere, the signal acquires a zonal symmetric behavior with the largest negative anomalies in month 3, which is known to be related to the mean meridional circulation as will be explained next.

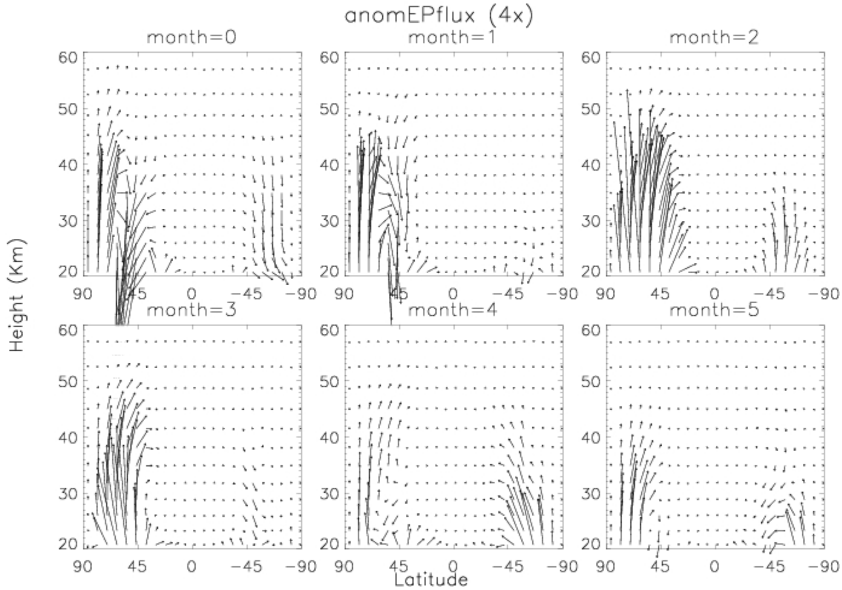

Figure 3. As Fig. 1 for Eliassen Palm flux anomalies. Arrow scale is arbitrary.

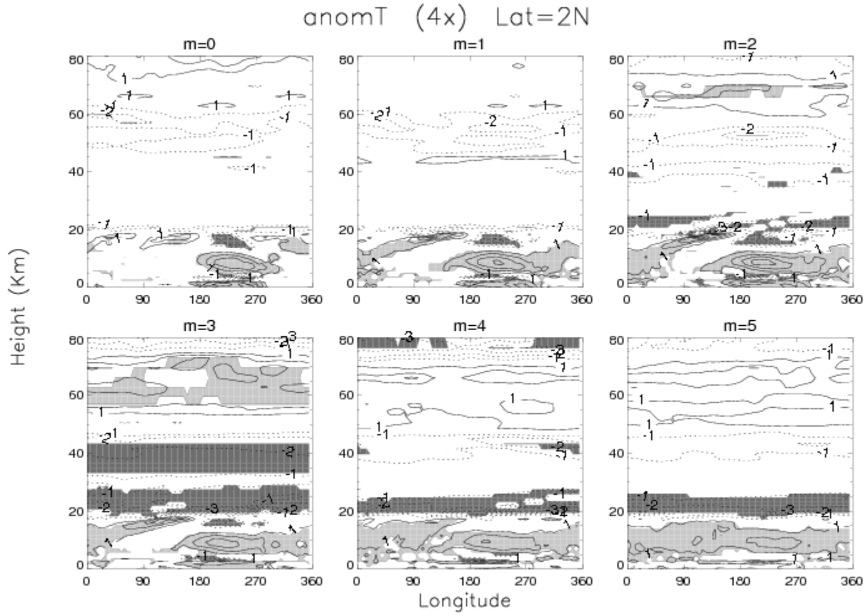

Figure 4. As Figure 1 at latitude 2ºN.

3.2 Zonal mean ENSO signal and wave mean flow interaction

In addition to the wavelike signal, ENSO also generates anomalies in zonal mean fields. Composite differences (El Niño minus La Niña) for zonal mean temperature are shown in Fig. 5. In the tropics, the anomalous warming observed in the troposphere corresponds to the well known zonally symmetric warming that develops during the mature phase of a warm ENSO event. (e.g. Yulaeva and Wallace, 1994; Calvo Fernandez et al., 2004). In the polar regions of the NH, WACCM3 shows a significant anomalous warming in the polar middle stratosphere accompanied by a cooling above it. This dipole structure propagates downwards as time progresses, in good agreement with results shown in MAECHAM5 by Manzini et al. (2006). The largest significant anomalies in WACCM3, both in the tropical and polar regions, are observed in month 3, with values up to 7K at high latitudes. Weaker zonal mean zonal winds are also observed at high latitudes in the winter hemisphere during strong El Niño events (not shown) accompanied by the warm anomalies, as expected from geostrophic balance.

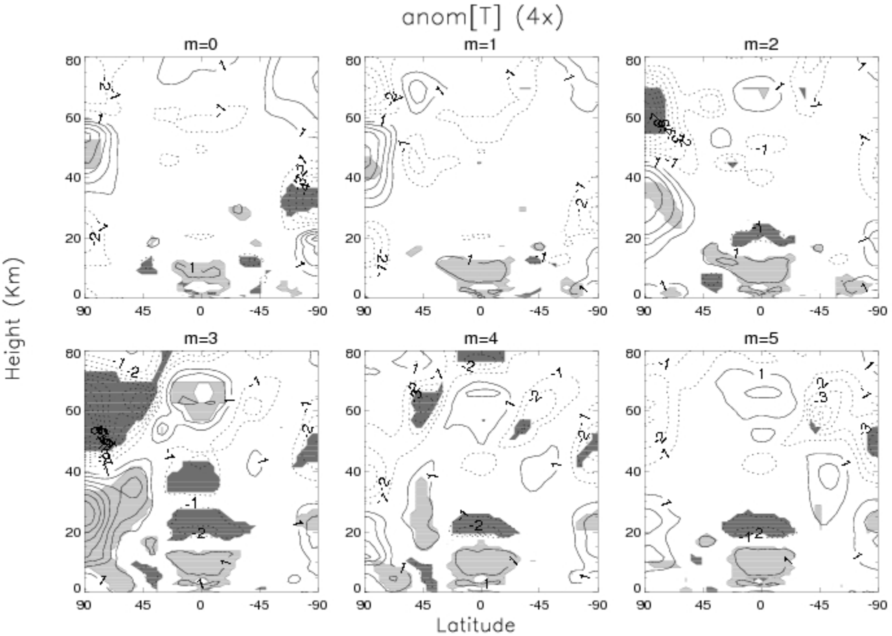

Figure 5. As Figure 1 for zonal mean temperature anomalies.

These anomalous patterns in zonal mean temperature and zonal wind point out the modulation of the stratospheric branch of the mean meridional circulation during extreme ENSO events. This circulation, also known as Brewer Dobson circulation (hereafter, BD), moves air from the tropical lower stratosphere to the polar regions in the winter hemisphere and is forced by the dissipation of atmospheric waves. Fig.6 shows the composite differences El Niño – La Niña of residual circulation anomalies (arrows) and EP flux divergence (contours). The divergence of the EP flux indicate the regions where Rossby waves dissipate and transfer momentum to the zonal mean flow. The arrows in Fig.6 show that from month 1 to month 5, the stratospheric circulation is intensified towards the North Pole as a result of the anomalous wave dissipation indicated by the negative values in the EP flux divergence anomalies.

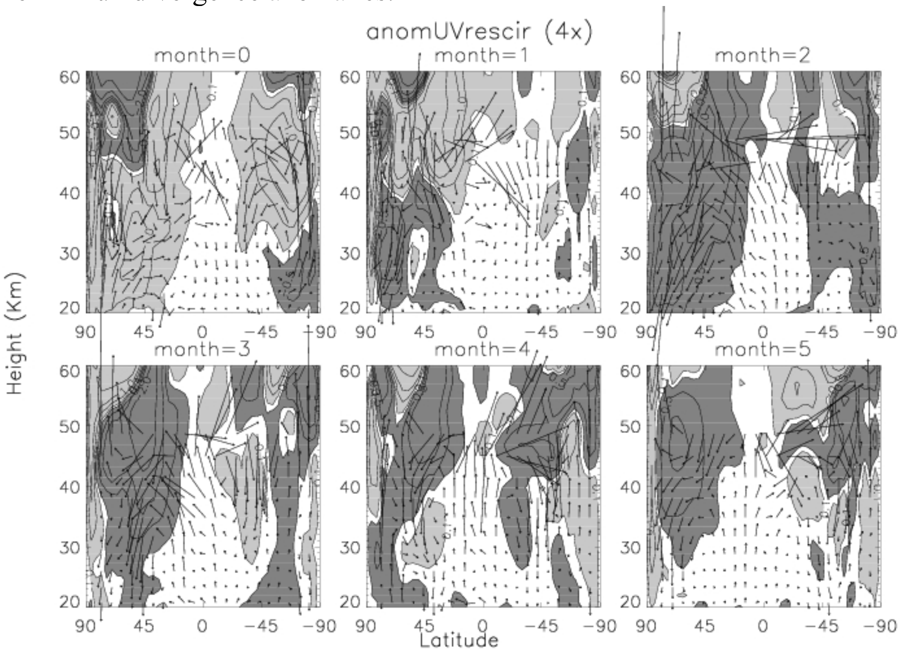

Figure 6. As Figure 1 for the meridional mean circulation velocity anomalies (arrows) and the EP flux divergence (contours) anomalies. Values of the meridional circulation are shown in 0.1 m·s^{-1}. Contours of the EP flux divergence are drawn at ± 0.1, 0.5, 1, 2, 4 m·s^{-1}·day^{-1}. Shadow regions are for EP flux divergence anomalies larger than ± 0.1 m·s^{-1}·day^{-1}.

Therefore, during a warm ENSO event, a more intense Rossby wave propagation and dissipation occurs at middle and high latitudes in the NH. As the waves dissipate, they deposit easterly momentum, which decelerates the mean westerly flow in the NH stratosphere. The wave dissipation also alters the extratropical angular momentum balance and forces a stronger mean meridional circulation which in turn gives rise to tropical cooling and high-latitude warming at high latitudes as has been shown in Fig.5. A summary chart showing all these processes and interactions is depicted in Fig. 7.

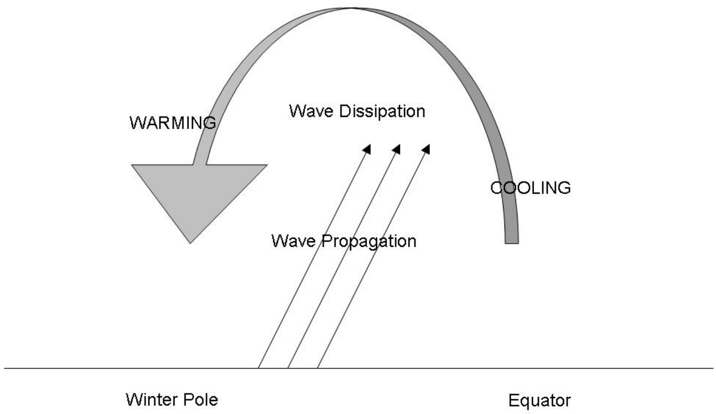

Figure 7. Main mechanism involved in the propagation of the ENSO signal in the stratosphere. The thin arrows indicate the anomalous wave propagation and point to the wave dissipation region. The gray arrows indicate the air movement by the intensification of the stratospheric mean meridional circulation from anomalous wave dissipation. As a result, the air cools down in the tropical stratosphere and warms up at polar latitudes in the Northern Hemisphere.

4. CONCLUSIONS

We have analyzed the propagation of the ENSO signal on atmospheric temperatures from the troposphere to the stratosphere using results from the Whole Atmosphere Community Climate Model, version 3. The main findings are two fold:

- The ENSO signal propagates towards the middle atmosphere by means of ultralong Rossby waves. This propagation is more effective at middle latitudes in the NH during the winter months mainly because ENSO tends to peak in the northern winter when stratospheric winds are westerly in that hemisphere and allow vertical propagation of Rossby waves. The wave-like ENSO signal is observed in this region up to 40 km.
- The anomalous increase in upward propagation and dissipation of Rossby waves at middle latitudes in the NH stratosphere forces an enhancement of the winter stratospheric branch of the BD circulation, which gives rise to an anomalous polar warming in the NH in boreal winter months and anomalous cooling in the tropics a few months after the maximum of the N3.4 index.

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