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SOUTH PACIFIC QUASI-STATIONARY WAVES AND ANOMALOUSLY COLD SUMMERS IN THE NORTHERNMOST ANTARCTIC PENINSULA

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ABSTRACT

The present work aims to analyze the tropospheric circulation in the Southern Hemisphere (SH) associated with anomalously cold summers (ACS, Dec-Feb) in the period 1981-2010 over northernmost Antarctic Peninsula (AP). A quartile criterion is used to identify ACSs, and a wave-activity flux for stationary quasi-geostrophic (QG) eddies on a zonally varying basic flow is used as a diagnostic tool to study wave-train propagation from the Pacific Ocean. It is shown that the summer of 2010 was singularly cold, so this summer is studied separately from the ACS composites previous to 2010.

The ACSs prior to 2010 are characterized by a Pacific-South American (PSA)-like quasi-stationary wave (QSW) train that extends barotropically through the troposphere up to the lower stratosphere. It is emanated from a region of anomalous convection in New Zealand and it is directed towards the South Pacific. The wave train leads to an anomalous stationary cyclone that is located to the northwest of the AP. The easterly wind anomalies induced by this local anomalous stationary cyclone together with higher cloudiness anomalies are found to be associated with ACS events over the northern AP.

The 2010 cold summer not only shows an anomalous stationary cyclone to the northwest of the AP, but singularly also shows a mid-latitude anomalous anticyclone over the south-eastern South Pacific. From there, a shorter QSW regionally propagates towards southern South America. In this case there is no PSA-like wave structure crossing the South Pacific. The short regional QSW seems to emanate from a region of positive sea surface temperature (SST) anomalies in the middle of the southern South Pacific. The SST anomalies can be related to the generation of locally increased mean-flow baroclinicity. Hence, this QSW propagation is related to anomalous transient activity. In turn, these SST anomalies could be induced by a PSA-like QSW propagation during the previous spring (Sep-Nov) of 2009.

Keywords: Anomalously Cold Summers; Quasi-stationary waves; Northernmost Antarctic Peninsula; South Pacific.

ONDAS CUASI-ESTACIONARIAS EN EL PACIFICO SUR Y VERANOS FRIOS ANOMALOS EN EL EXTREMO NORTE DE LA PENINSULA ANTARTICA

RESUMEN

El presente trabajo tiene como objetivo analizar la circulación troposférica en el Hemisferio Sur (HS) asociada a veranos (Dic-Feb) anómalamente fríos (VAF) en el período 1981-2010 sobre el extremo norte de la Península Antártica (PA) mostrando que el verano de 2010 es singularmente frío, razón por la cual este verano es estudiado por separado. De ahí que el verano de 2010 es comparado con la composición de los VAFs previos a 2010. Se utiliza el criterio del cuartil para identificar VAFs y un flujo de actividad de onda para perturbaciones estacionarias cuasi-geostróficas (CG) embebidas en un flujo básico que varía zonalmente como herramienta de diagnóstico para estudiar la propagación de trenes de ondas desde el Pacífico.

Los VAFs previos a 2010 se caracterizan por un tren de ondas cuasi-estacionarias (OCE) - del tipo patrón PSA (Pacífico-Sudamericano) - extendido barotrópicamente en tropósfera hasta baja estratósfera, propagándose sobre el Pacífico Sur desde una región de convección anómala sobre Nueva Zelanda. Este tren de ondas da lugar a un centro ciclónico estacionario anómalo al noroeste de la PA. La componente anómala inducida de viento del Este junto a anomalías de alta nubosidad se encuentran asociadas a los VAFs sobre el norte de la PA.

El singular verano de 2010 no sólo muestra un centro ciclónico estacionario anómalo al noroeste de la PA sino que también muestra uno anticiclónico en latitudes medias sobre el sudeste del Pacífico Sur. Desde ahí, hay propagación de OCE, localizada regionalmente, atravesando el sur de Sudamérica ya que no se observa una estructura de onda del tipo PSA sobre el Pacífico Sur. La propagación emana desde una zona de anomalías positivas de la temperatura de superficie del mar (TSM) en el Pacífico Sur a través de la generación local de baroclinicidad del flujo medio. De ahí que esta propagación de OCE está asociada a actividad transiente anómala. A su vez, estas anomalías en la TSM podrían estar inducidas por propagación de OCE del tipo PSA durante la primavera (Sep-Nov) de 2009.

Palabras claves: Veranos Anómalamente Fríos; Ondas cuasi-estacionarias; Extremo norte de la Península Antártica; Pacífico Sur.

INTRODUCTION

In a context of climatic change and variability, the Antarctic Peninsula (AP) has received much attention as being the region with the largest warming in the world during the last 50 years (IPCC, 2007). According to Monaghan et al. (2008), trends in annual near-surface temperature are increasingly and significantly positive within the AP. The highest significant warming over some of the northernmost AP stations is observed during the austral summer (Dec-Feb) for the period 1971-2000 (Turner et al., 2005).

Seasonal and annual trend changes by early 1990s have been found by some authors for the whole Antarctic region (Monaghan et al., 2008). Most of the Antarctic observed trends have been attributed to the Southern Hemisphere annular mode (SAM) variability, which has undergone a trend towards its positive phase since the early 1960s (Marshall, 2003). Particularly, the positive summer temperature trends in the northernmost AP are associated with increased circumpolar westerlies related to the SAM positive trend, advecting relatively warm air over the orographic barrier of the AP, because of the föhn effect on the lee side (Marshall et al., 2006; van Lipzig et al., 2008). Likewise, there is some evidence that the El Niño-Southern Oscillation (ENSO) is influencing the Antarctic ice records through the Pacific-South American (PSA) mode and its interactions with the SAM (Mo and Häkkinen, 2001; Turner, 2004).

In recent years there has been some evidence of teleconnections between the tropical Indo-Pacific basin and mid-to-high latitude climates of South America and Antarctica that can be explained by propagation of Rossby waves. For example, recent winter warming in continental West Antarctica is related to sea surface temperature (SST) changes in the tropical Pacific (Ding et al., 2011). Likewise, Rossby wave propagation provides a strong relation between anomalous convection in the tropical Pacific and the occurrence of blocking over the southeast Pacific Ocean (Renwick and Revell, 1999). On a submonthly scale, the South Atlantic Convergence Zone (SACZ) is affected by a Rossby wave train propagating from the midlatitudes of the Southern Hemisphere (SH; Liebmann et al., 1999). On an interannual scale, the summer season over southern South America and adjacent areas could be modulated by quasi-stationary wave (QSW) propagation from the southern Indian Ocean and the South Pacific, as seen in the precipitation variability in central-west Argentina (Agosta and Compagnucci, 2011) and the Mendoza grapevine yield (Agosta et al., 2012). The frequency of frost occurrence during winter in the wet Pampas, in central Argentina, is also related to propagation of Rossby waves (Müller and Ambrizzi, 2010).

In the context of summer warming over the AP, the present work studies summer temperature interannual variability over the area. This work attempts to determine the dynamical forcings associated with anomalously cold summer (ACS) events during the period 1981-2010 over northernmost AP as well as the diverse features associated with the singularly cold summer of 2010.

DATA AND METHODOLOGY

The data consist of monthly mean time series of daily temperature (ºC) and daily sunshine duration (hours) from the Servicio Meteorológico Nacional for the Argentine Antarctic stations of Jubany (62ºS 58ºW), Esperanza (63ºS 56ºW) and Marambio (64ºS 56ºW), which are located in northernmost AP. The summer season is considered as the three-monthly average from December to February for both temperature and sunshine duration time series at each station. The year corresponding to each summer is indicated by the year containing February. Since correlation of the summer temperature time series amongst the stations is over 0.8 (significant at the 99 per cent confidence level), it is decided to devise a summer temperature index (STI) as their average. Hence the STI time series well represents the interannual variability of the areal summer temperature in northernmost AP. ACS events are identified using a quartile criterion for the detrended STI time series distribution in the period 1981-2010. Because of gaps in the sunshine duration time series at Jubany and Marambio stations, only the Esperanza station sunshine duration time series is used. Fisher's F-test is used to analyse changes in STI time series interannual variability.

Monthly outgoing longwave radiation (OLR, in W/m^2), 300 and 850hPa air temperature (T, in ºC), zonal and meridional wind components (U,V, in m/s), and geopotential height (GPH, in m) data from NCEP/NCAR reanalysis are used to study tropospheric circulation composite anomalies associated with ACSs. Monthly extended SST (ºC) data are provided by NOAA (available at www.esrl.noaa.gov/psd).

QSWs embedded in the mean flow are identified by estimating zonal asymmetries of the GPH anomalies composite field, that is to say, the difference between local composite anomalies and the zonal average of composite anomalies. The significances of the asymmetries in the dynamical fields are tested by means of the unequal variance 2-tailed Student's t-test for sample means (Moser et al., 1989; Moser and Stevens, 1992).

A wave-activity flux (W) for stationary quasi-geostrophic (QG) eddies on a zonally varying basic flow, derived by Takaya and Nakamura (2001), is used as a diagnostic tool to study the propagation of QSWs over the Pacific Ocean. W-fluxes are calculated using the zonal asymmetries. Generally, wave activity for small-amplitude disturbances superimposed on a basic flow satisfies a conservation law, that is,

$$\frac{\partial A}{\partial t} + \nabla . F = D \tag{1}$$

Here A and F are the density of wave activity and its flux, respectively. The term D vanishes when the wave and basic flow are both conservative. The divergence and convergence of F indicate where the wave packet is emitted and decaying, respectively. Identifying these wave "sources" or "sinks" is important in understanding the dynamics behind various atmospheric phenomena. It is convenient for this purpose if F and A are independent of the wave phase so as to represent phase-averaged statistics (Takaya and Nakamura, 2001). Plumb (1985) was the first to derive a conservation law for small-amplitude stationary eddies on a zonally uniform basic flow representing three-dimensional wave propagation with a wave-activity flux that is free of any oscillatory component. Takaya and Nakamura (2001) attempted to generalize the flux and conservation law of Plumb so as to be applicable to small-amplitude QG disturbances, either stationary or migratory, that are superimposed on a zonally varying basic flow. They derive an approximate conservation relation showing that a linear combination of quantities A (proportional to wave enstrophy) and E (proportional to wave energy), that is, (A+E)/2, is a conservative quantity that can be interpreted as a wave-activity density for QG eddies. Hence, their W-flux of wave-activity density is phase-independent and parallel to the local group velocity (Cg) of Rossby waves. Therefore, when derived without any averaging, W can depict instantaneous three-dimensional wave-packet propagation. Thus, W may be a useful diagnostic tool for a snapshot analysis of both migratory and stationary disturbances propagating through a zonally varying basic flow, which is its greatest advantage compared to Plumb's flux.

Summer extratropical Rossby Wave Source (RWS) and OLR anomalies are calculated in order to identify source regions of QSW propagation associated with deep convection. A main RWS anomaly is associated with planetary-vorticity divergence and with the divergent wind components of the vorticity anomaly budget, following the equation from Rasmusson and Mo (1993):

$$RWSa \approx f * Da + \beta * V_{\chi} a \tag{2}$$

where f is the planetary vorticity, Da is the divergence anomaly, β is the meridional planetary vorticity gradient and $V_{\chi}a$ is the anomalous divergent wind component. The subindex *a* denotes seasonal departure from climatology.

RESULTS

ACS events in northernmost AP

In order to evaluate the interannual variability of summer temperature over the northernmost AP, the STI time series is shown in Figure 1. An overall trend of 0.3ºC/decade is computed with a correlation of 0.39 significantly different from zero at a 95% confidence level (Fig. 1a). ACS events are identified using a quartile criterion for the detrended STI time series distribution in the period 1981-2010 (Fig. 1b). Index values below the first quartile (-0.35ºC) corresponds to ACSs of 1983, 1984, 1986, 1991, 1992, 2001, 2004 and 2010. It can be observed that the summer of 2010 is singularly cold, with the lowest detrended STI value (Fig. 1b). The coldest 2010 summer is further analysed in comparison with the composite of the remaining ACSs.

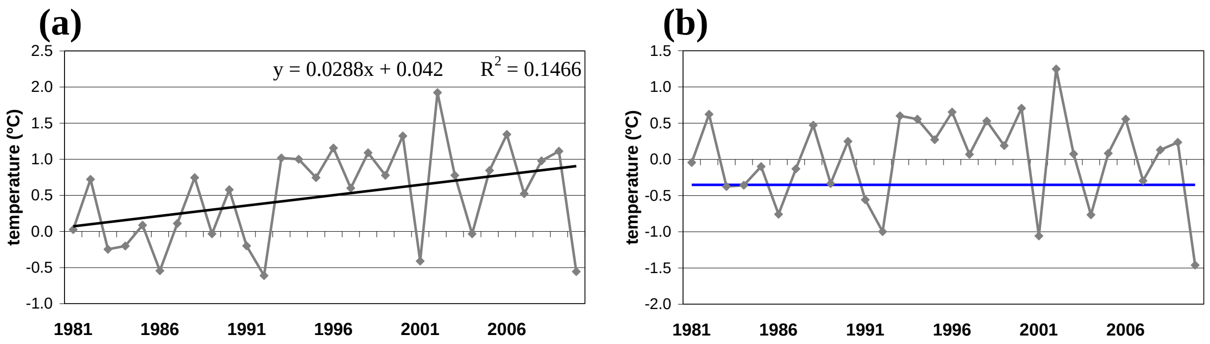

Figure 1: **(a)** STI (ºC) time series from 1981 to 2010 and significant positive trend (straight line). **(b)** Detrended STI time series and a threshold at -0.35 ºC according to the first quartile (blue line).

Note that the interannual STI variability appears to change between the early 1990s and the early 2000s (Fig. 1b). To evaluate the significance in variance change, the variances sampled in the subperiods 1981-1993, 1993-2000 and 2000-2010 are tested using the Fisher's F-test (Table 1). The 1981-1993 variance (S_1^2) and the 2000-2010 variance (S_3^2) are not significantly different at a 95% confidence level, whereas the 1993-2000 variance (S_2^2) is significantly different. The change in variance indicates a change in the interannual STI variability. It is noteworthy that a change in variance is also observed by the early 1990s in the SAM interannual variability, as suggested by Barrucand et al. (2008) and Agosta and Canziani (2011).

Subperiods	Observed F Statistic	Confidence Level
S_1 & S_2	4.54	97.3 %
S_1 & S_3	2.29	91.2 %
S_2 & S_3	10.41	99.7 %

Table 1: Observed F Statistic ($F=S_A^2/S_B^2$) with $S_A^2 \geq S_B^2$ where S_1^2 is the variance for the first subperiod 1981-93, S_2^2 for 1993-2000 and S_3^2 for 2000-2010 and Confidence Level ((1-α)*100) necessary for rejecting null hypothesis of equal variabilities between subperiods.

A dispersion diagram for the summer mean sunshine duration and summer mean temperature at the Esperanza station is shown in Figure 2 for the period 1981-2010. There is an overall linear-fit behaviour showing correlation of 0.65, significant at a 95% confidence level. Thus colder (warmer) summers are associated with less (more) daily sunshine duration which in turn can be linked to higher (lower) cloudiness anomalies at high-to-polar Antarctic latitudes (Dutton et al., 1991; Matuszko, 2012).

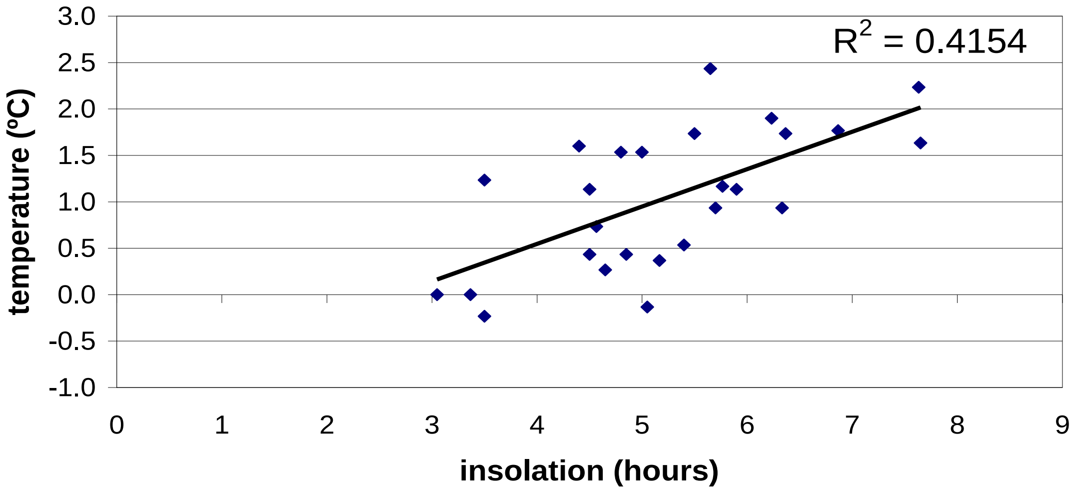

Figure 2: Dispersion diagram for Esperanza station between summer mean temperature (ºC) and summer mean daily sunshine duration (hours) from 1981 to 2010. Correlation coefficient is 0.65, significant at 95% of confidence.

The tropospheric circulation for ACSs

GPH zonal asymmetries composite for all ACSs is shown at 300 hPa (Fig. 3a) and 850 hPa (Fig. 3b). The composite is made without the inclusion of the coldest 2010 summer. The analysis of the coldest summer of 2010 is shown further below. It can be observed from the figures that wave-train-like anomalies extend from the mid-latitude South Indian toward the South Pacific, going across New Zealand eastward. The W-flux shows a main source of stationary wave-activity near New Zealand, from where QSW activity emanates toward the mid-latitude South Pacific. The QSW propagation reaches southern South America and the AP region. There, the QSW generates an anomalous stationary cyclone, zonally extended over the northern AP, which could be responsible for the occurrence of the cold events. Hence, the local cyclonic anomalies, extended from lower to upper troposphere, dynamically favour enhanced cloudiness anomalies. This is consistent with the direct relationship found between STI and sunshine duration in the AP, shown in the previous section. Therefore, ACSs appear to be associated with an anomalous cyclonic circulation generating decreased sunshine duration due to dynamically enhanced cloudiness. Likewise, these cyclonic anomalies generate easterly wind anomalies over the northern AP. According to King and Turner (1997), the mountainous spine along the AP acts as a dividing barrier between the relatively warmer climate of the west and much colder climate of the east coast that is affected by cold continental air masses. Therefore, the anomalous easterly wind component during the summer further favours cold temperature anomalies over the area.

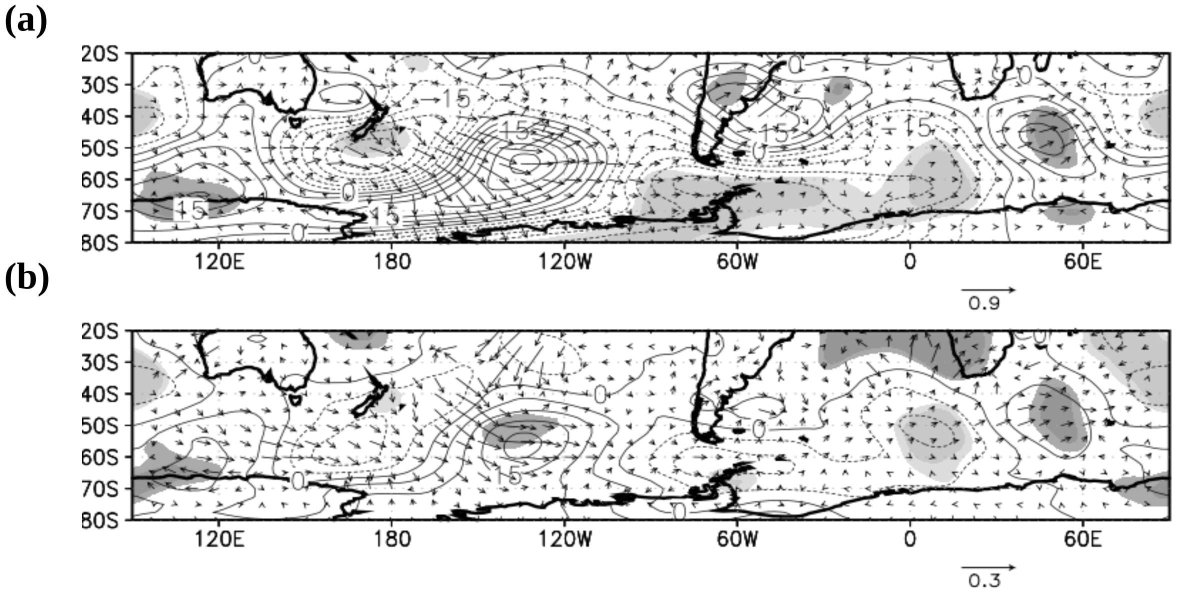

Figure 3: GPH zonal asymmetries composite for ACS events at **(a)** 300hPa and **(b)** 850hPa (contours) and associated horizontal component of the wave-activity flux (vectors). Dashed contours correspond to negative values. The contour interval is 5 m. Vector units are m^2 s^{-2}. Grey scale shaded indicates 90-95% significance levels for negative *(lighter grey)* and positive *(darker grey)* asymmetries.

The phase coincidence between wave anomalies at lower and upper levels of the troposphere (Fig. 3) reveals a barotropic nature of the QSWs, which suggests a barotropic Rossby wave origin. From eq. (2), at mid-latitudes, a main RWS is associated with the components of the planetary vorticity-divergence and of the divergent wind. That is to say, in a seasonal average the local divergence of anomalous deep convection is candidate of RWS under strong meridional planetary vorticity gradient. Figure 4a shows the anomalous RWS associated with these terms. The wave activity flux seems to emanate from large RWS anomalies zonally extended to the south of New Zealand. The RWS anomalies are co-located with significant negative OLR anomalies in the region, that could be linked to deep convection at the mid-latitudes (Fig. 4b). Hence the quasi-stationary cyclonic perturbation to the south of New Zealand (Fig. 3) would favour the occurrence of summer enhanced convection that can be related with variations in the mid-latitude stormtrack activity. In turn, this cyclonic perturbation appears in association with wave-activity flux convergence from another wave-train propagating eastward from the South Indian Ocean, between 60ºE and 120ºE (Fig. 3). This QSW train is strongly associated with positive RWS anomalies over the tropical-subtropical South Indian, to the east of Madagascar (Fig. 4a), which are clearly related to significant negative OLR anomalies over there (Fig. 4b). Furthermore the OLR anomalies are co-located over positive SST anomalies in the tropical South Indian between 60ºE and 80ºE (figure not shown). Chan et al. (2008) pointed out that this oceanic area is candidate for QSWs propagation from the South Indian toward the South Pacific, reaching South America and affecting precipitation. This oceanic area could be associated with pure Indian Ocean Dipole (IOD) events, that is to say, IOD events without ENSO occurrence. Likewise the QSWs propagation observed over the South Pacific could be a particular expression of the two well-known PSA modes in association with ENSO, which are principal patterns of the SH low-frequency circulation variability (Mo, 2000). Understanding how the SH low-frequency atmosphere-ocean processes are affecting the summer temperature variability over the AP is beyond the scope of this work. Further analysis is required.

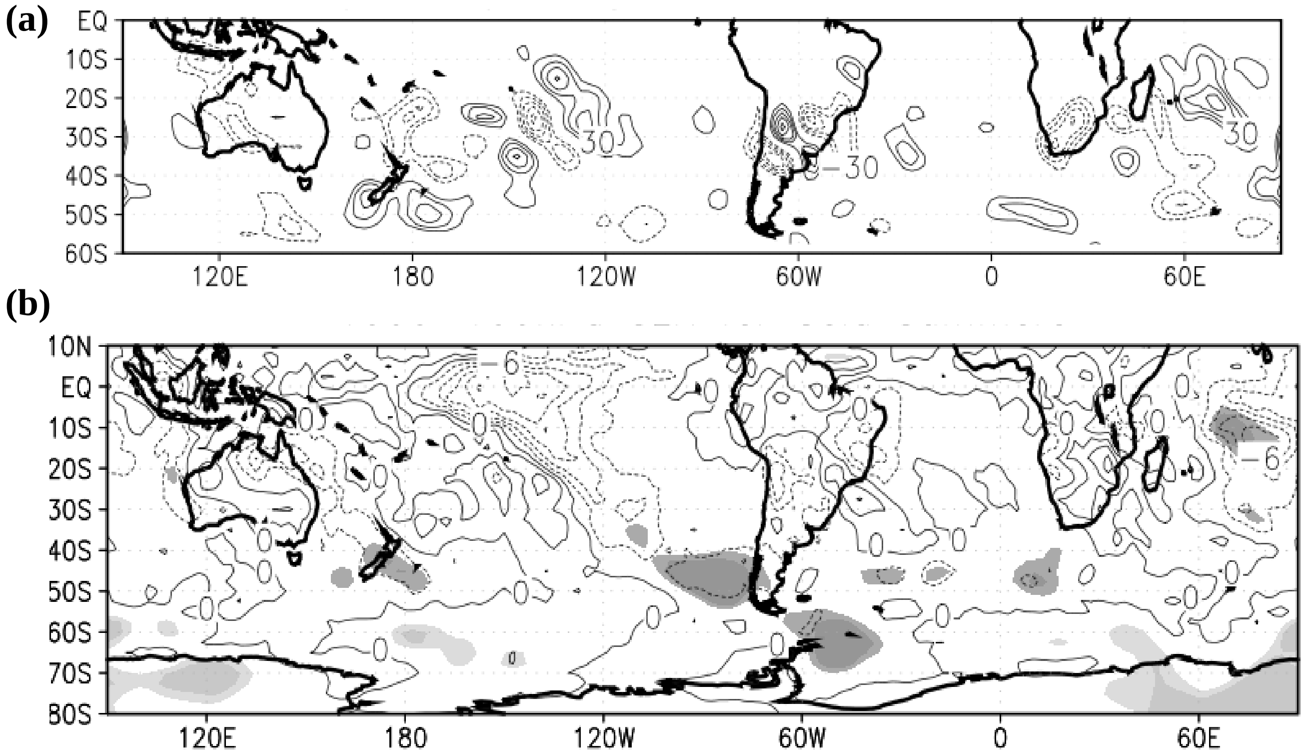

Figure 4: (a) 200hPa Rossby Wave Source (s^{-2}) anomalies due to planetary vorticity-divergence and wind divergence components of the vorticity anomaly budget and **(b)** 1000-100hPa OLR (W/m^2) anomalies and 90-95% significance level *(grey shaded)*, for ACS events. Dashed contours correspond to negative values.

The cold summer of 2010

The tropospheric features related with the coldest 2010 summer are analysed by comparison with the tropospheric circulation anomalies obtained from the ACS composites previous to 2010. For the 2010 summer, the GPH asymmetric anomalies in the upper (300hPa, Fig. 5a) and lower (850hPa, Fig. 5b) troposphere show the typical zonally extended anomalous stationary cyclone to the south of South America, over the Drake Passage, slightly northward displaced with respect to the previous ACSs composite. Unlike previous ACSs, the anomalous stationary cyclone is not generated by a QSW propagating over the South Pacific (resembling a PSA-like pattern), but to a shorter regional QSW propagation going through southern South America from the southeastern South Pacific and being redirected to the northeast over the South Atlantic (Fig. 5a).

The upper-level wave activity flux (W) shows an eastward wave-activity emanation from a source region over the South Pacific, as noticed by diverging W-fluxes. Extratropical transient eddies can indirectly interact with stationary wave activity through latent heat release and can directly interact through convergence/divergence of eddies vorticity fluxes (Plumb, 1985). Notably, the localized QSW cannot be associated with latent heat release by anomalous deep convection since neither relevant OLR nor RWS anomalies are observed in the area (figures not shown). Nonetheless the source region is located over positive 2010 summer SST anomalies, estimated with respect to previous ACSs composite, as can be seen in Figure 6a. Meridional SST gradients due to positive SST anomalies could be involved in the generation of locally increased mean-flow baroclinicity, which in turn induces positive wind shear anomalies over the area due to the thermal wind relationship. A measure of this baroclinicity is provided by the Eady Growth Rate (EGR) maximum (Hoskins and Valdes, 1990), according to the following equation:

$$EGR = 0.31 * f * \left|\frac{\partial u}{\partial z}\right| * N^{-1} \tag{3}$$

where f is the Coriolis parameter, $\frac{\partial u}{\partial z}$ is the vertical wind shear and N is the Brunt-Vaisala frequency.

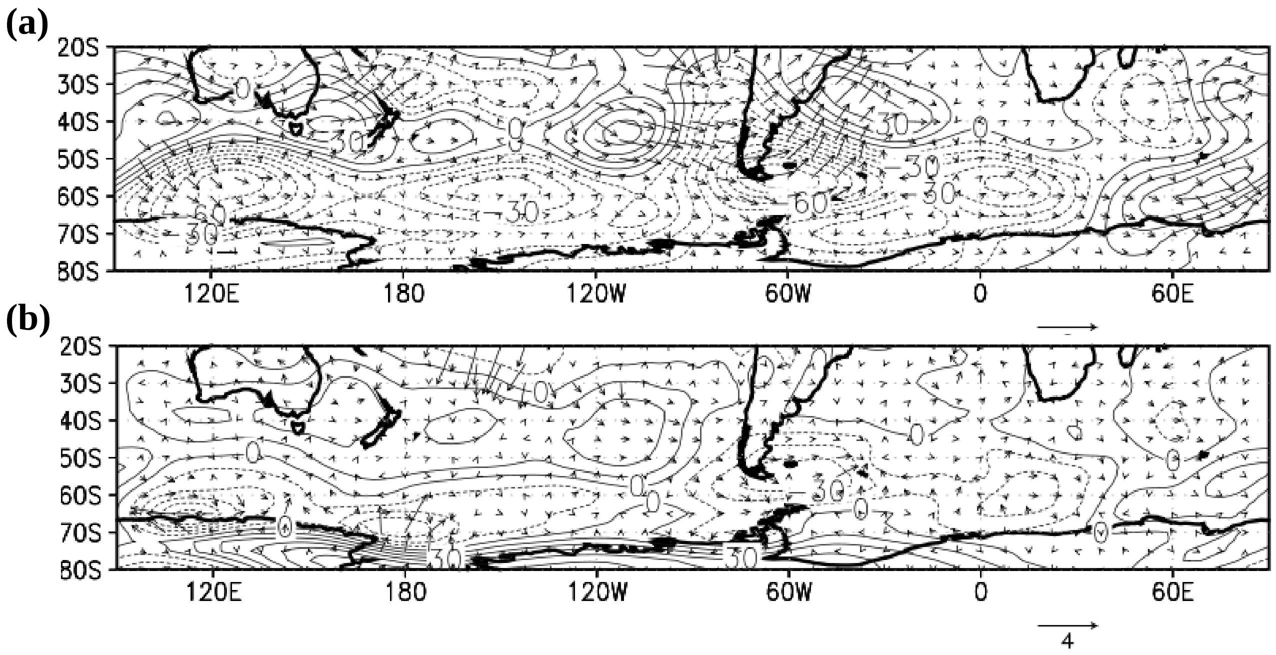

Figure 5: GPH zonal asymmetries composite for the coldest summer of 2010 at **(a)** 300hPa and **(b)** 850hPa (contours) and associated horizontal component of the wave-activity flux (vectors). Dashed contours correspond to negative values. The contour interval is 10 m. Vector units are $m^2 s^{-2}$.

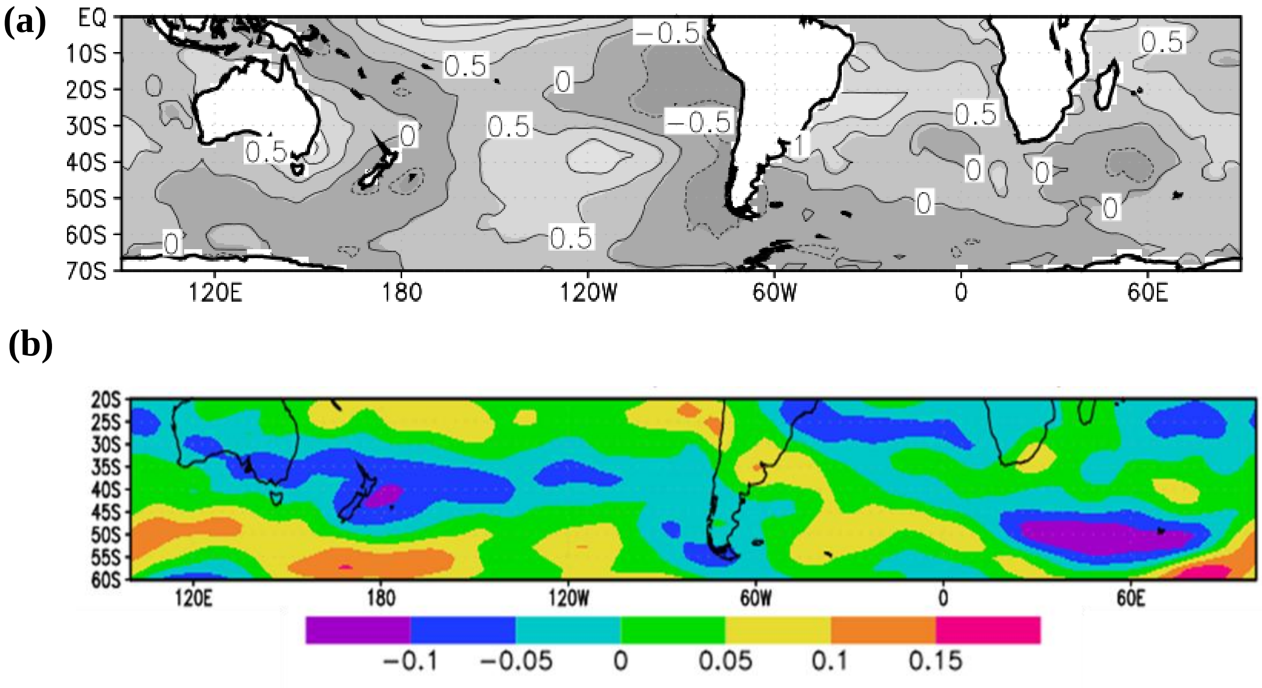

Figure 6: **(a)** Extended SST (ºC) anomalies and **(b)** Maximum Eady Growth Rate (day^{-1}) anomalies, for summer of 2010 with respect to previous ACSs composite.

The EGR maximum anomalies for the summer of 2010 with respect to previous ACSs composite are displayed in Figure 6b. Negative anomalies are observed to the north of the maximum positive SST anomalies in the South Pacific, where ta strong meridional SST gradient is evident. Therefore, the mean-flow potential energy generated by the locally increased baroclinicity is available to be converted into kinetic energy for transient eddies. Hence, the localized QSW propagation seems to be maintained by (or related with) the anomalous transient activity. According to Lee et al. (2010), the positive SST anomalies over the mid-latitude South Pacific correspond to an extreme warming event during the late 2009 and early 2010 associated with the 2009-10 El Niño event. The authors suggest that these anomalies are induced by strong anticyclonic circulation anomalies over the central South Pacific during the previous spring (Sep-Nov) of 2009, as can be seen in Figure 7, where the spring 300 and

850hPa GPH asymmetric anomalies are shown. A prominent mid-latitude South Pacific QSW propagation, similar to a PSA-like pattern, is observed extending eastward from New Zealand. The wave propagation is probably related with El Niño seasonal modulation during spring.

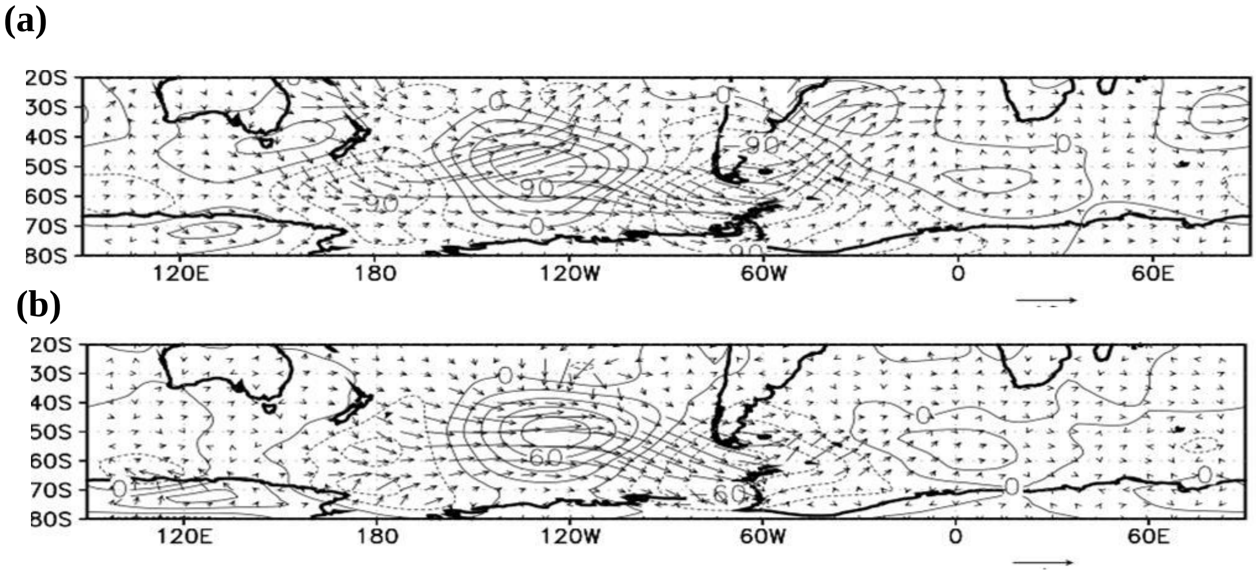

Figure 7: GPH zonal asymmetries composite for the previous spring of 2009 at **(a)** 300hPa and **(b)** 850hPa (contours) and associated horizontal component of the wave-activity flux (vectors). Dashed contours correspond to negative values. The contour interval is for **(a)** 30 m and for **(b)** 20 m. Vector units are $m^2 s^{-2}$.

DISCUSSION AND CONCLUSIONS

In this paper it has been analysed the occurrence of ACS events over northernmost AP and its association with SH tropospheric circulation in the period 1981-2010. The summer of 2010 is the coldest one in the 30-year detrended STI timeseries and shows distinct tropospheric circulation anomalies with respect to the previous ACS events.

ACSs previous to 2010 over the northernmost AP are characterized by a PSA-like QSW propagation over the South Pacific that emanate from a region of anomalous convection near New Zealand. The source region is evidenced by significant negative OLR anomalies that are located there. The wave-train generates a significant anomalous cyclonic circulation to the northwest of the AP, which extends throughout the troposphere. This stationary anomalous cyclone generates easterly wind anomalies and dynamic conditions favourable to positive anomalous cloudiness, leading to near surface lower temperatures. The anomalous convection area near New Zealand seems to be enhanced by an stationary anomalous cyclone, that is related with wave-activity flux convergence from another wave-train propagating eastward from the Indian Ocean and modulating the mid-latitude eddies' storminess activity. In turn, this second wave train can be associated with a region of anomalous convection to the northeast of Madagascar as evidenced by the significant negative OLR anomalies over the area.

The exceptionally cold summer of 2010 shows the anomalous stationary cyclone to the north of the AP that is typical in the ACS composite and responsible for lower temperatures, though it is slightly northward displaced. Unlike previous-ACSs, this cyclonic anomaly is not generated by a PSA-like QSW propagation, but it is related to a shorter regional QSW propagation going across southern South America. Furthermore, these QSWs cannot be associated with anomalous deep convection since relevant OLR anomalies are not observed there. Instead, they are associated with SSTs anomalies in the mid-latitude South Pacific through the generation of locally increased mean-flow baroclinicity. Hence this regionally localized QSW propagation is related with anomalous transient activity. Moreover, a strong PSA-like QSW propagation over the South Pacific is also observed in the previous spring of 2009. The spring QSW, that is closely related to the strong El Niño event of 2009-10, is probably acting as a preconditioning for the downstream activation of QSW propagation in the following summer due to changes in SSTs anomalies over the mid-latitude South Pacific.

Finally, it is noteworthy that changes in the interannual variability of the northernmost AP summer temperature by the early 1990s are coincident with variability changes in the SAM (Barrucand et al.,2008). Since the SAM clearly influences on the AP summer temperature variability, further analysis including anomalously warm summers is needed to elucidate such a relationship.

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