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South Pacific Split Jet, ITCZ shifts, and atmospheric North–South linkages during abrupt climate changes of the last glacial period

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ABSTRACT

A number of key paleoclimate records in the Southern Hemisphere midlatitudes exhibit climate changes synchronous with abrupt climate changes in the North Atlantic. We advance a hypothesis – argued from consideration of model evidence, observational climate diagnostics, and atmospheric dynamics – that attributes said climate changes in the Southern Hemisphere to a modulation in the strength of the South Pacific Split Jet, a pronounced zonally asymmetric feature of the wintertime Southern Hemisphere westerlies. North Atlantic cooling is associated with a weaker Split Jet, characterized by weaker South Pacific subtropical and subpolar jets and a strengthened midlatitude jet. It leads to climate impacts over the South Pacific sector that coincides with regions with observed paleoclimate changes timed to the North Atlantic. These circulation changes are envisioned to operate in addition to the climate impacts resulting from the oceanic bipolar seesaw.

A proposed global atmospheric teleconnection links North Atlantic cooling to the weakening of the Split Jet. North Atlantic cooling induces a southward shift of the marine Intertropical Convergence Zone and weakening of the Asian monsoon. The resulting Hadley circulation change weakens the wintertime South Pacific subtropical jet, and which in turn leads to a weaker South Pacific Split Jet. A weaker Split Jet leads to a southward shift of the zero wind-stress curl line, implying a shift in the same sense for the South Pacific subtropical front. Over land, it leads to winter warming over New Zealand, winter cooling over subtropical South America, drying over Western Patagonia, and winter warming and wetting of southernmost Patagonia. Our hypothesis also predicts reduced storminess over West Antarctica. Similar changes but of opposite sign occur in the Northern Hemisphere, where a stronger wintertime North Pacific subtropical jet increases precipitation over the Western United States.

1. Introduction

The transition from the Last Glacial Maximum (LGM) to the Holocene was punctuated by abrupt climate changes over the high latitude North Atlantic, namely the Heinrich Stadial 1 cold, Bølling–Allerød (B/A) warm and Younger Dryas (YD) cold events. They have been tied to global climate changes, most prominently the Intertropical Convergence Zone (ITCZ) (Peterson et al., 2000; Wang et al., 2004), Asian monsoon (Wang et al., 2001), and midlatitude climates in both hemispheres (Broecker et al., 2009; Kaplan et al., 2010; Moreno et al., 2001).

Interpretations of Southern Hemisphere midlatitude paleoclimate changes typically invoke a wholesale meridional shift of the westerlies (Toggweiler, 2009), paralleling recent developments in dynamical meteorology examining poleward shifts of the westerlies under global warming (Yin, 2005), and the Annular Mode-type interannual variations in the midlatitudes (Thompson and Wallace, 2000). Variations to the interpretation include (i) intensification of the westerlies (Moreno et al., 2010; Lee et al., 2011); and (ii) meridional contraction/expansion of the westerly belt (Lamy et al., 2010).

Our paper advances an alternative hypothesis for these changes, namely the modulation of the South Pacific Split Jet during austral winter. The Southern Hemisphere westerlies are largely perceived

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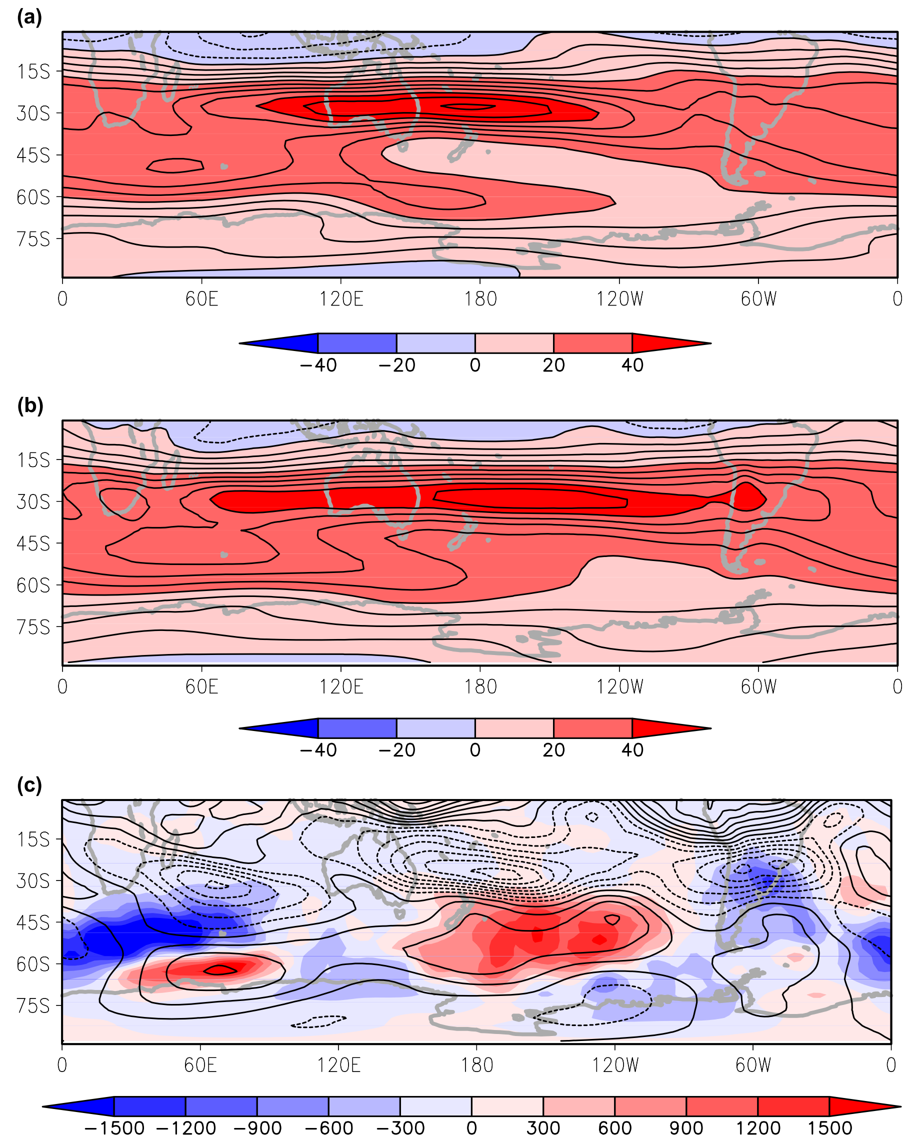

Fig. 1. (a) June–August (JJA) 250 mb zonal wind climatology from NCEP reanalyses (Kalnay et al., 1996) averaged over 1979–2009, showing the presence of the Split Jet in the South Pacific. Contour interval is 5 m/s. Negative values are stippled. (b) Simulation of 250 mb climatological JJA zonal wind (contour interval 5 m/s). (c) JJA 250 mb zonal wind anomalies (contour interval 2 m/s) and anomalies in the JJA 2–8 day bandpassed variance in 500 mb geopotential height, a measure of transient eddy activity (shading; units are m^2) in response to North Atlantic cooling. In (b) and (c) the climatology is the BASE simulation in Lee et al. (2011), and the anomaly the difference between the HE and BASE simulations respectively. The anomaly shows the weakening of the South Pacific Split Jet in response to North Atlantic cooling. The strengthening zonal wind in the midlatitude South Pacific is associated with a strengthening of transient eddy activity.

to be zonally symmetric, but in fact exhibit a pronounced zonal asymmetry in the austral winter where the core of the upper-level westerlies splits into a subtropical and subpolar branch just south of Australia (Fig. 1a). This 'Split Jet' is a well-documented feature in the dynamical meteorology literature (e.g. Inatsu and Hoskins, 2004; Nakamura and Shimpo, 2004), and exhibits strong interannual variability (e.g. Bals-Elsholz et al., 2001). While the Southern Annular Mode is thought to be the leading mode of atmospheric variations in the Southern Hemisphere extratropics, this is strictly true only for the austral summer; in the other seasons, variations to the Southern Hemisphere westerlies exhibit strong zonal asymmetries (Ding et al., 2012).

We advance the hypothesis that the South Pacific Split Jet *weakens* during North Atlantic stadials. Initial motivation for this hypothesis comes from our previous modeling study (Lee et al., 2011) that showed a Southern Hemisphere westerly intensification to imposed North Atlantic cooling, in particular over the South Pacific sector. Since then, we have more specifically identified these changes as a South Pacific Split Jet response.

We briefly clarify the meaning of North Atlantic 'stadials/interstadials' (or 'cold/warm' phases) used here. Virtually all paleoproxy evidence cited for Southern Hemisphere climate changes (excluding Antarctica) tied to the North Atlantic occurs during the deglacial Heinrich Stadial 1 – Bølling–Allerød – Younger Dryas sequence. There is yet no convincing evidence for changes coincident with Dansgaard–Oeschger (D/O) cold/warm phases, although this may reflect a lack of long-term high-resolution records rather than an absence of signal. On the other hand, the modeling evidence used in this paper mimics North Atlantic cooling as occurring during a slowdown scenario of the Atlantic Meridional Overturning circulation (AMOC). While AMOC variations are thought to play a central role in D/O variations (e.g. see Alley, 2007), this view is not universal (for example, see a recent hypothesis by Dokken et al., 2013). Our hypothesis only cares that the North Atlantic cools or warms; as such, we simply pose our

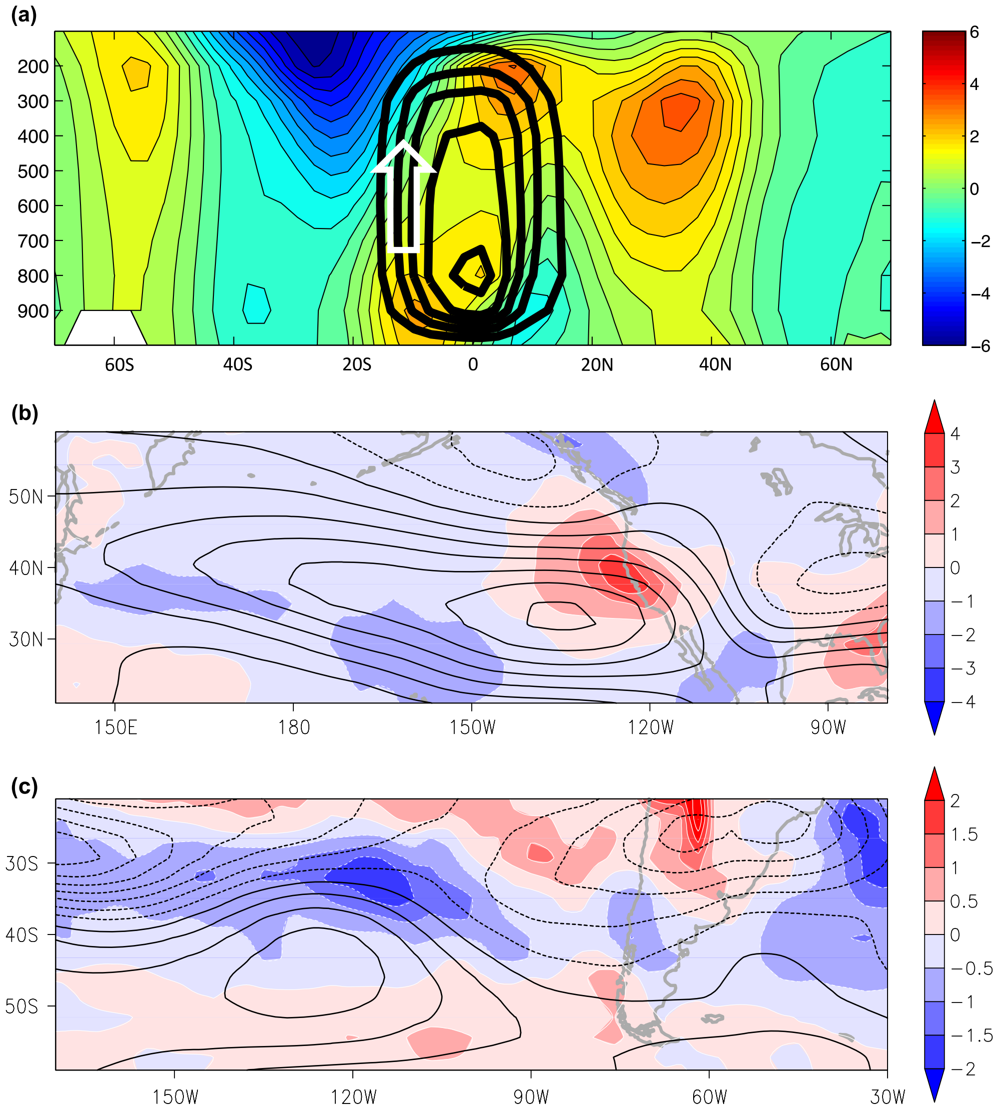

Fig. 2. Simulated changes to North Atlantic cooling in the simulations of Lee et al. (2011), HE minus BASE. (a) Annual mean change to the mean meridional streamfunction (contour interval 2×10^{10} kg/s, zero contour not shown) and zonal mean zonal winds (shaded, units are m/s). (b) DJF 250 mb zonal wind (contour interval 3 m/s) and rainfall (shaded, mm/d) anomalies, showing an increased subtropical jet and rainfall anomalies over the Western United States. (c) Same as (b) but for JJA anomalies, with decreased subtropical jet and rainfall over Western Patagonia. Contour interval is 2 m/s.

hypothesis as applicable to a 'canonical' North Atlantic cold/warm phase.

We first describe the data used in this study in Section 2, and then present our argument. Starting from the premise that the ITCZ shifted southwards during North Atlantic stadials, we show how that in turn affects the subtropical westerlies of each hemisphere and associated precipitation (Section 3). We then link the subtropical westerly changes to the observed South Pacific Split Jet, and present our 'Split Jet' hypothesis in Section 4. Using today's modulation of the Split Jet as an analog, we make predictions in Section 5 for the climate impacts in the South Pacific sector associated with a weaker Split Jet. For completeness, in Section 6 we briefly discuss another potential mechanism for Southern Hemisphere westerly changes via the bipolar seesaw.

2. Data used

We use National Centers for Environmental Prediction reanalyses (NCEP; Kalnay et al., 1996) fields to show the climatological structure of the westerlies, as well as various climate impacts associated with interannual modulation of the Split Jet. Only data since 1979 are used as satellite information was incorporated into the assimilation at that time. For precipitation we use the Climate Prediction Center Merged Analysis of Precipitation (CMAP; Xie and Arkin, 1996).

Simulations of the Community Climate Model version 3 (Kiehl et al., 1998) coupled to a reduced gravity ocean (CCM3-RGO), originally used in Lee et al. (2011), are also used here to show the modeled impacts of North Atlantic cooling. The reader is referred to Lee et al. (2011) for details. The two main simulations are used from that study – a control simulation (BASE) is representative of glacial conditions, and another (HE) which is the same as BASE except for the imposition of cooling over the North Atlantic north of 25°N, representative of stadial conditions.

Finally, we use simulations archived in the Paleoclimate Model Intercomparison Project phase 2 (PMIP2; Braconnot et al., 2007) in Section 4 to show the simulated mean structure of the Southern Hemisphere westerlies (see Supplementary Fig. 1 for a list of the models used). 100 yr each of the preindustrial control and LGM simulations are averaged to form the climatology, except for CCSM3 where we used 50 yr of each.

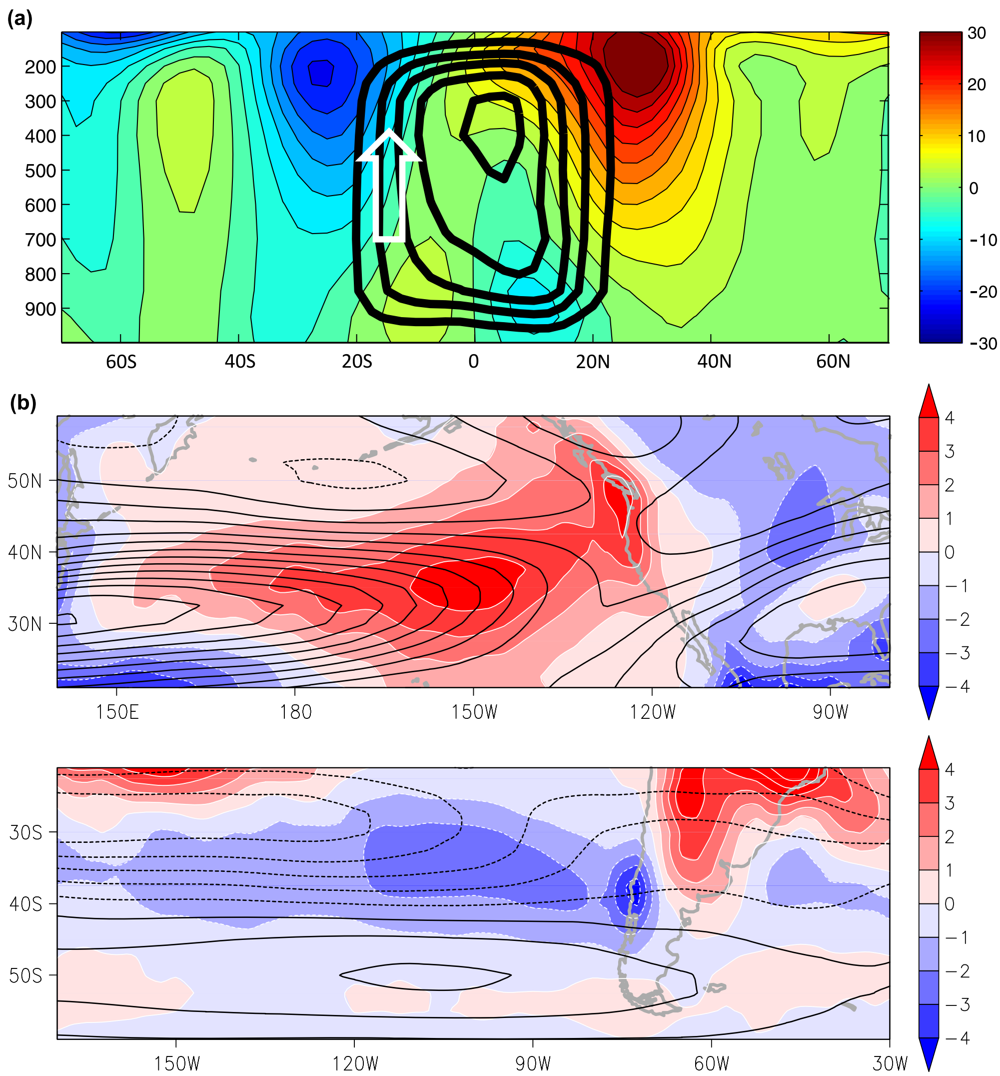

Fig. 3. Subtropical jet and rainfall changes over the seasonal cycle. (a) seasonal deviations (DJF minus JJA) of the zonal mean meridional circulation (contour interval 5×10^{10} kg/s, zero contour not shown) and zonal mean zonal winds (shaded, units m/s). Note the significantly larger magnitude of the subtropical jet changes in comparison to the more muted southern midlatitude and polar westerlies, despite the much steeper equator-to-pole temperature gradient. (b) Seasonal (DJF minus JJA) 250 mb zonal wind (contour interval 5 m/s) and rainfall (shaded, units mm/d) changes. Data from NCEP reanalyses (Kalnay et al., 1996) averaged over 1979–2009, except for precipitation from CMAP (Xie and Arkin, 1996) averaged over 1979–2009.

3. ITCZ shift and the subtropical jets

We begin by asking: what happens to the large-scale circulation and the westerlies when the latitudinal position of the tropical rainfall shifts southwards? The southward ITCZ shift and weakened NH summer monsoons are now established features of North Atlantic cold events, supported by both paleoproxy and modeling evidence (see Chiang and Friedman, 2012 for a review). A southward displacement in the rising branch of the Hadley circulation reduces the strength of the southern Hadley cell and increases the strength of the northern cell (Lindzen and Hou, 1988). In turn, there should be a commensurate effect on the wintertime subtropical jets in each hemisphere, which exist as a result of angular momentum transport by the thermally-direct Hadley circulation (Held and Hou, 1980).

Indeed, the southward ITCZ shift and associated circulation changes are precisely seen in our previous study (Lee et al., 2011). An applied cooling over the extratropical North Atlantic results in a simulated cooling over the entire Northern Hemisphere and southward displacement of the tropical rainband (see Fig. 1 of Lee et al., 2011). The southern Hadley cell weakens and northern Hadley cell strengthens (Fig. 2a); as a result, the southern wintertime subtropical jet weakens and northern wintertime subtropical jet strengthens (Fig. 2b and c). The subtropical jet changes have a pronounced impact on the wintertime rainfall. In Western Patagonia, precipitation is dominated by wintertime rainfall from storm systems steered by the subtropical jets (Fig. 2c), so a weakened jet leads to less rainfall. A similar but opposite situation exists for the Western United States during boreal winter.

A similar Hadley circulation response and changes to the subtropical jets also occurs in a fully-coupled climate model North Atlantic 'hosing' simulation using the CCSM3, where a large freshwater pulse was applied to the high-latitude North Atlantic to induce a sudden slowdown of the AMOC (results not shown here, but see Fig. 9 of Lee et al., 2011 and associated text).

The seasonal transition in today's climate shows a very similar behavior in the Hadley cells, subtropical jets, and precipitation. We plot the seasonal differences (Dec–Feb minus Jun–Aug) of the mean meridional streamfunction and zonal winds (Fig. 3a). Here, the region of uplift is in the Southern Hemisphere, and there is a strong winter Hadley cell straddling the equator. The associated seasonal variation of the subtropical jets exceeds 30 m/s in core region, and there is pronounced impact on wintertime rainfall, both over Western Patagonia and the Western United States (Fig. 3b).

Thus drawing from model evidences and the seasonal cycle analog, we expect a southward displacement in the ITCZ during North Atlantic stadials to strengthen the wintertime North Pacific subtropical jet and weaken the wintertime South Pacific subtropical jet, with commensurate impact on Western United States and Western Patagonian rainfall respectively. We explore the Patagonian situation in the next section, but the pattern of hydrological changes seen over the Western United States during North Atlantic stadials is broadly consistent with what is suggested here. The Great Basin in the western US features a dry climate today. However, ancient lake shorelines have been well observed to stand high in the region, which suggests that substantially elevated precipitation and runoff prevailed in the past (e.g. Broecker, 2010; Hostetler and Benson, 1990; Munroe and Laabs, 2013). Geomorphological and geochronological studies on the sediments both from ancient highstands and lake beds showed that during the Heinrich Stadial 1, massive lakes dominated in the vast hydrologically closed and semi-closed basins, stretching from Lake Lahontan (Adams et al., 2008; Benson et al., 1990) and Lake Bonneville (McGee et al., 2012; Oviatt et al., 1992) as far north as ∼42°N, to Lake Russell at ∼38°N (Benson et al., 1990), and even further south to Lake Estancia at ∼35°N (Allen and Anderson, 2000). These lakes ubiquitously endured a dramatic lake level drop or even completely dry-out during the Bølling–Allerød period when the North Atlantic was warm. Most lakes then underwent a brief transgression in the Younger Dryas before turning back to the long journey of desiccation through the Holocene (Broecker, 2010). Winter precipitation changes in the same sense were registered in the isotopic composition of stalagmites from the southwestern US (Asmerom et al., 2010).

4. South Pacific Split Jet

We now focus our attention on the Southern Hemisphere westerlies, where during austral winter they exhibit a pronounced zonal asymmetry whereby the core of the westerlies splits into a subtropical branch and a subpolar branch just south of Australia (Fig. 1a). These westerly jets act as waveguides, such that transient eddies from the Indian Ocean sector enters the South Pacific either along the subtropical or subpolar branch (Nakamura and Shimpo, 2004). The zonal asymmetry in the Southern Hemisphere westerlies and resulting storm track has been attributed to the zonal asymmetry in the tropical SST and its resulting effect on tropical convection (Inatsu and Hoskins, 2004)

We posit that this austral winter split jet structure weakened during extreme cold events in the high latitude North Atlantic as a direct consequence of the weakened southern subtropical jet. With a weaker South Pacific subtropical jet, transient eddies propagating eastwards from the South Indian sector would increasingly propagate zonally, rather than being swept up into the subtropical jet. The transient eddies in the South Pacific would then act to reinforce the midlatitude westerlies through the eddy convergence of zonal momentum. The signature of such changes is a weakened subtropical jet coupled to a stronger midlatitude jet, and with more transient eddy activity within this latter jet. These indeed occur in the North Atlantic cooling simulations of Lee et al. (2011) (Fig. 1c); in particular, the increased westerlies in the South Pacific midlatitudes exhibit the features of an eddy-driven jet, with an associated increased transient eddy activity and barotropic vertical structure.

Modulation of the split jet strength is also observed in the interannual variability – in fact, it is statistically the dominant mode of interannual variation in the South Pacific westerlies, and resembles the westerly changes seen in Lee et al. (2011). Previous work (e.g. Bals-Elsholz et al., 2001) has shown that the modulation of the winter South Pacific split jet is a leading mode of interannual variation of the zonal jets in that region. We compute the EOF of the 3-dimensional zonal wind field over the South Pacific from 120°E to 270°E, 90°S to 0°S, and 1000 mb to 100 mb, using June–August (JJA) averaged NCEP reanalyses (Kalnay et al., 1996) fields from 1979 to 2009. The data was interpolated to 100 mb thickness intervals and weighted by the square root of the cosine of latitude prior to computing the covariance matrix.

The results are shown in Fig. 4 as regressions on the normalized first principal component of the EOF analysis. EOF1 dominates the explained variance (27%) and is characterized by a reduction to the subtropical jet and increase to the midlatitude jet (Fig. 4a). This is similar to the South Pacific zonal wind response in Lee et al. (2011) (compare Fig. 4a with Fig. 2b of Lee et al., 2011). The similarity between the EOF pattern and the anomalies seen in Lee et al. (2011) extend to various other fields, including the surface westerlies (not shown), and changes to the upper tropospheric zonal wind and transient eddies (Fig. 4b, compare to Fig. 1c).

Moreover, the interannual weakening of the split jet is tied to a weakening of the cross-equatorial branch of the austral winter Hadley circulation (Fig. 4c), similar to the argument presented in Lee et al. (2011). In this case however, the weakening is driven by La Niña conditions in the tropical Pacific that act to reduce the convection in the North Pacific ITCZ region (Fig. 4d). Thus, the interannual variation is a modern-day analog to the westerly wind changes seen in Lee et al. (2011), including the weakening of the subtropical and subpolar jets, strengthening of the midlatitude jet and associated storminess, and weakening of the Hadley cell.

It could be argued that the split jet did not occur during glacial times because the Southern Hemisphere circulation could have been vastly different. However, coupled model simulations of the LGM suggest otherwise. Rojas et al. (2009) assessed the Southern Hemisphere westerlies in several Paleoclimate Modeling Intercomparison Project phase 2 (PMIP2; Braconnot et al., 2007) models for the LGM, concluding that the Southern Hemisphere westerlies did not change appreciably from those of the preindustrial control simulation. We also examined the Southern Hemisphere winter westerlies in the PMIP2 simulations of the LGM, specifically focusing on the Split Jet. Fig. S1 shows that all the models considered simulate the zonal asymmetry of the Southern Hemisphere winter westerlies, specifically the strengthened subtropical jet in the Australia–South Pacific sector. In the LGM simulations, the subtropical jet appears to weaken slightly in all models, but the basic zonally asymmetric structure of the zonal westerlies remains intact. Thus, the PMIP2 simulations suggest that the split jet structure remained intact during the LGM.

5. Predictions of the hypothesis and comparison to paleoproxies

As a test of our hypothesis, we use the observed climate changes associated with a weakening of the Split Jet structure to compare against past climate changes. First, we infer changes to the oceanic South Pacific Subtropical Front, as a prelude to comparing against climate changes registered by climate-sensitive mountain glacier systems in the New Zealand Southern Alps and Patagonian Andes. We show that the atmospheric and (inferred) oceanic circulation changes appear consistent with the prevailing evidence. We also make predictions for West Antarctica, which has (as yet) no published evidence for an immediate response to North Atlantic stadials.

5.1. South Pacific subtropical front

A prominent sea surface temperature record from ODP core site 1233 (41°S, 74°27′W) off the coast of the Chilean Lake District indicates a clear and distinct abrupt warming during the Younger Dryas and Heinrich Stadial 1 (Lamy et al., 2004). The warming is

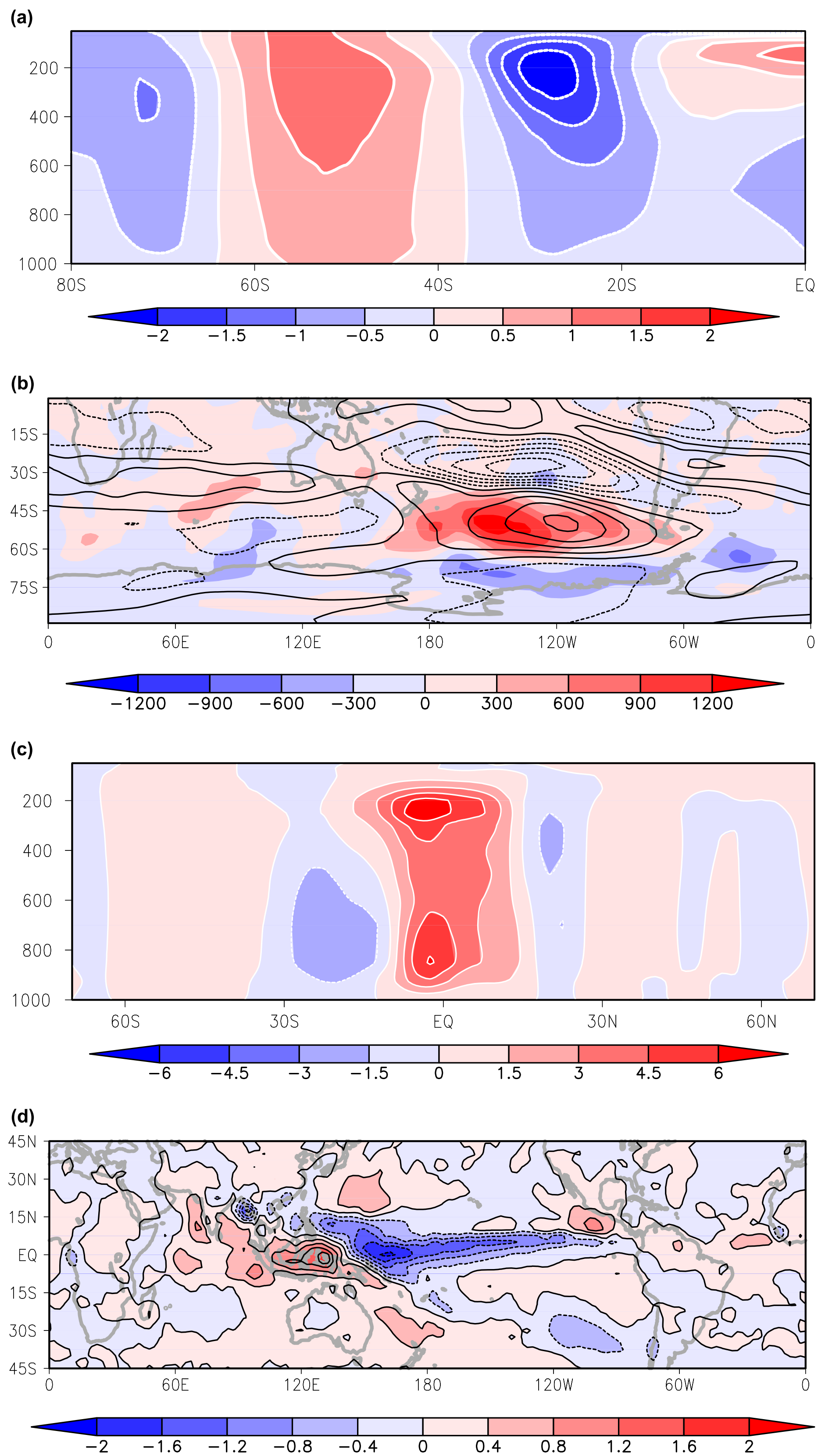

Fig. 4. Regression on the normalized PC1 of South Pacific JJA zonal winds. Units are expressed in terms of per standard deviation of PC1. (a) Regression onto the JJA zonal mean winds; shown is the regression zonally averaged over 120°E to 300°E. Units are m/s. (b) Regression onto 250 mb JJA zonal winds (contour interval 1 m/s) and JJA 2–8 day bandpassed variance in 500 mb geopotential height (colors, units m^2), a measure of midlatitude transient eddy activity. (c) Regression onto the JJA mean meridional streamfunction (units are $\times 10^9$ kg/s per unit standard deviation). (d) Regression onto JJA precipitation (units mm/d per unit standard deviation). The sense of these regressions is for a weakened Split Jet, corresponding to the hypothesized situation during North Atlantic cold events. Data are from NCEP reanalyses (Kalnay et al., 1996) 1979–2009 except for precipitation, which is from CMAP (Xie and Arkin, 1996) 1979–2009.

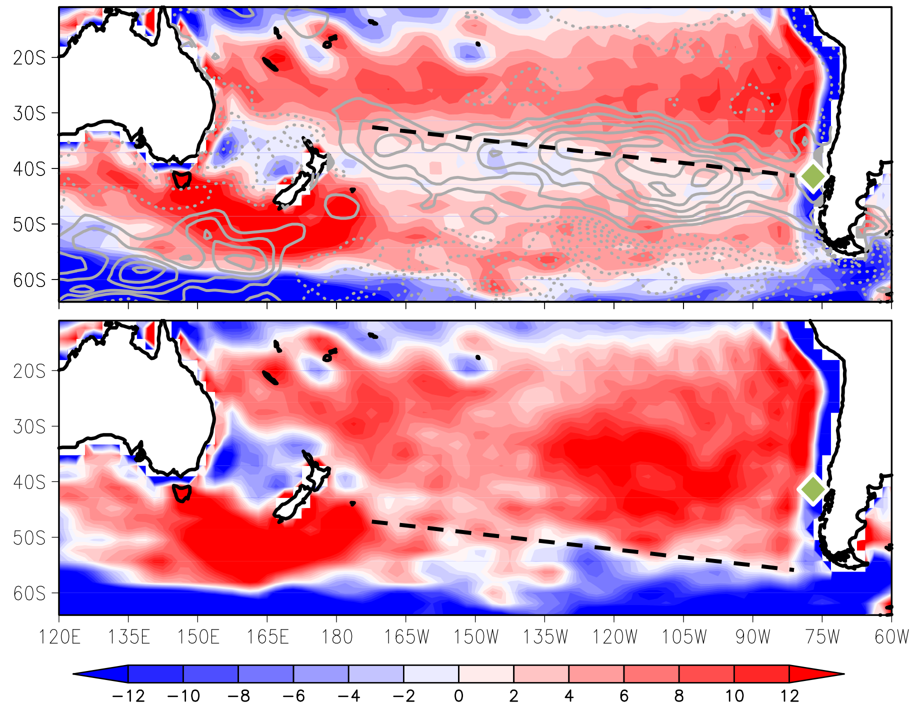

Fig. 5. Effect of a weaker South Pacific Split Jet on wind stress curl. (a) Shading shows the JJA mean surface wind stress curl (units are $\times 10^{-8}$ Pa/m), and contours show the regression onto the normalized PC1 index of the Split Jet modulation on JJA surface wind stress 1979–2009 (contour interval is 1×10^{-8} Pa/m, and negative values are dashed). Regression is signed to indicate a weaker Split Jet representing Greenland stadial conditions, and the contour values shown are per unit standard deviation of the index. The diamond shows the location of site ODP1233, and the dashed line indicates the approximate zero wind stress curl line. (b) Same as (a), but with the anomalies (multiplied by 2) added to the climatological wind stress. The zero wind stress curl line shifts south as a consequence of the anomalies. Wind stress data are from NCEP reanalyses (Kalnay et al., 1996) 1979–2009.

in phase with Antarctica but occurred more rapidly, indicating that the transfer of signal from the Atlantic to the Southeastern Pacific must somehow bypass the thermal inertia of the Southern Ocean that is thought to regulate the pace of Antarctica temperature rise (Lamy et al., 2007). Lamy et al. (2007) postulated that this rapid transfer involves changes to the Antarctic circumpolar current – westerlies coupled system, induced by the oceanic bipolar seesaw.

We infer the effect of a Split Jet weakening on the wind-driven ocean circulation through computing the wind stress curl (Fig. 5). Typically, the midlatitude zero wind-stress curl line coincides with the southern boundary of the subtropical gyre. In the JJA climatology (Fig. 5a, shaded), this line is ill-defined and there is a region around 35°S–45°S where the wind-stress curl is close to zero, but with no clear transition. This is consistent with the observation that the South Pacific subtropical front is displaced far northwards and is not well defined (Tomczak and Godfrey, 2003, p. 134). When the Split Jet weakens, this region changes to positive wind-stress curl, whereas south of ~50°S the wind-stress curl becomes more negative (Fig. 5b). With a sufficient weakening of the Split Jet, the zero wind-stress curl line would thus shift southwards, as indicated by the dashed lines in Fig. 5a (mean position) and 5b (weaker Split Jet conditions).

We infer that with a weaker Split Jet (corresponding to North Atlantic stadial conditions), the subtropical front will become more well-defined and move southwards. This implies that sea surface temperatures at ODP site 1233 – which is today in a region with sharp meridional temperature gradients – would warm abruptly, consistent with the observations of Lamy et al. (2007). Note that we do not show this warming explicitly; more detailed ocean dynamical study is needed to confirm such an effect, but this is beyond the scope of our current study (we are in the process of testing this idea with an ocean general circulation model). This southward shift of the subtropical front, were it to occur, would have exerted a powerful influence on atmospheric temperatures driving the melt of southern middle latitude glacier systems.

5.2. New Zealand

Past glacier fluctuations in the New Zealand Southern Alps have been robustly anticorrelated with North Atlantic stadials during the last glacial termination. Mountain glacier fluctuations there are tightly linked to changes in atmospheric temperature as modulated by offshore sea-surface temperature and regional wind direction (Anderson and Mackintosh, 2006, 2012; Fitzharris et al., 1997b). Chronologies of past glacier advances have been reconstructed in detail on the basis of glacial geomorphology (Barrell et al., 2011) and precise ^{10}Be surface-exposure chronologies, and when combined with glaciological modeling and snowline reconstruction, afford a quantitative and purely physical record of past atmospheric temperatures.

Glacial landforms of the central Southern Alps document extensive ice recession and atmospheric warming from LGM moraines concomitant with Heinrich Stadial 1 in the North Atlantic region (Putnam et al., 2013a, 2013b). This ice recession was interrupted by widespread glacier resurgence during the North Atlantic Bølling–Allerød interstadial (Kaplan et al., 2013; Putnam et al., 2010b). At 13,000 years ago, the final pulse of ice recession and warming occurred in concert with Younger Dryas cooling in the North Atlantic region (Kaplan et al., 2010).

Fig. 6a shows the JJA regression onto 700 mb winds and temperatures over New Zealand, indicative of the circulation influence on New Zealand at ~3 km glacier elevation. The circulation is dominated by an anomalous northerly flow that bring warm and dry subtropical air to New Zealand. Thus, a weaker Split Jet leads to stronger northerlies and northeasterlies impinging over New Zealand during the accumulation season. According to

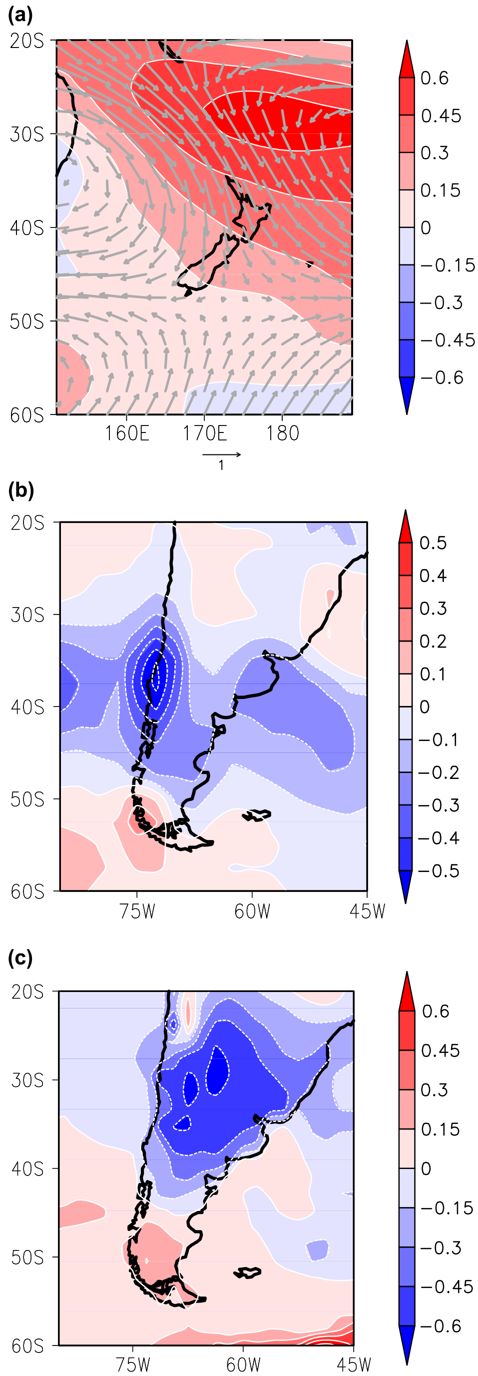

Fig. 6. Climate impacts of a weaker South Pacific Split Jet over New Zealand and Southern South America. Regression of the normalized PC1 index of the Split Jet modulation (1979–2009) on various fields, signed to indicate a weaker Split Jet representing stadial conditions. Values shown are per unit standard deviation of the index. (a) JJA 700 mb air temperatures (shaded, units are K) and winds (reference vector is 1 m/s) over New Zealand. (b) JJA rainfall (units mm/d) and (c) surface temperature (units in K) over Southern South America. Data are from NCEP reanalyses (Kalnay et al., 1996) 1979–2009 except for precipitation, which is from CMAP (Xie and Arkin, 1996) 1979–2009.

Fitzharris et al. (1997a), regional wind direction exerts strong control over the interannual variability in glacier mass balance: years with negative mass balance for glaciers in the Southern Alps are associated with anomalous northerlies and northeasterlies during the accumulation (winter) season, as they bring warmer and drier airmasses from the subtropics to New Zealand. Such an increase in the proportion of subtropical air masses flowing over the Southern Alps during the winter season would have the effect of lengthening the summer ablation season.

The inferred southward shift of the South Pacific subtropical front from Split Jet weakening (Section 5.1) will also affect the glacier mass balance. A southward shift in the position of the Subtropical Front will warm atmospheric temperatures over the Southern Alps, and initiate recession of mountain glaciers (Harrington, 1952; Putnam et al., 2010a). These relationships are consistent with our hypothesis of a weakened Split Jet during North Atlantic cold events, when Southern Alps glaciers underwent decisive recession.

5.3. Western Patagonia

The observed interannual relationship shows that a weaker Split Jet leads to reduced rainfall over most of Western Patagonia (30°S–50°S), and wetter conditions over the southernmost tip of South America (polewards of 50°S) (Fig. 6b). There is also a temperature response with austral winter cooling over subtropical South America roughly between 20°S to 43°S, and a mild warming over the southernmost South America south of this cooling region (Fig. 6c). In the paleoclimate situation, this southern South American warming will be additionally augmented by the southward shift of the oceanic Subtropical Front, at least south of 41°S (the latitude of ODP 1233) (note that the interannual observed relationship would not show the inferred southward shift of the subtropical front as there is insufficient time for the ocean dynamics to adjust).

Dynamically, storms are preferentially steered by the midlatitude jet rather than the subtropical jet, leading to wetter conditions in the south, and cooler and drier conditions further north. The subtropical latitudes become colder presumably because less advection of warmer subtropical air to that region. Thus, our hypothesis predicts a dipole-like response in the hydrology with a colder North Atlantic, with drier conditions over most of western Patagonia except for southern tip of South America. At the nodal point around ∼50°S, there is no significant change in rainfall.

There are a number of paleoclimate records now existing over Western Patagonia that collectively indicate a strong linkage to the North Atlantic. The clearest impacts of the Split Jet modulation are hydrological, but unfortunately the proxies most able to capture pure hydrological changes – closed-basin lake levels and speleothems – are not readily available for that region (Quade and Broecker, 2009).

Nevertheless, records of glacier fluctuations over Patagonia from the Chilean Lake District (∼41°S) and to the south exhibit a signature nearly identical to glacier reconstructions from the Southern Alps of New Zealand. Records from the Chilean Lake District imply ice recession during Heinrich Stadial 1 (Denton, 1999; Denton et al., 2010). Further south, outlet glaciers of the South Patagonian icefield at Lago Argentino (50°S) and Cordillera Darwin (54°S) underwent extensive recession during Heinrich Stadial 1 in the North Atlantic region (Hall et al., 2013; Menounos et al., 2013; Strelin et al., 2011). This ice recession was subsequently interrupted by glacier resurgence during the North Atlantic Bølling–Allerød interstadial by outlet glaciers of the South Patagonian icefield at Lago Argentino (Kaplan et al., 2011; Strelin et al., 2011), Torres del Paine (Garcia et al., 2012), and Cordillera Darwin (Menounos et al., 2013). Renewed glacier recession and atmospheric warming in southern Patagonia attended cooling during Younger Dryas stadial conditions in the northern Atlantic (Kaplan et al., 2011; Strelin et al., 2011).

These glacier changes are largely consistent with our hypothesized climate impacts from Split Jet modulation. From the Chilean Lake District latitude (∼41°S) and southwards, austral winter

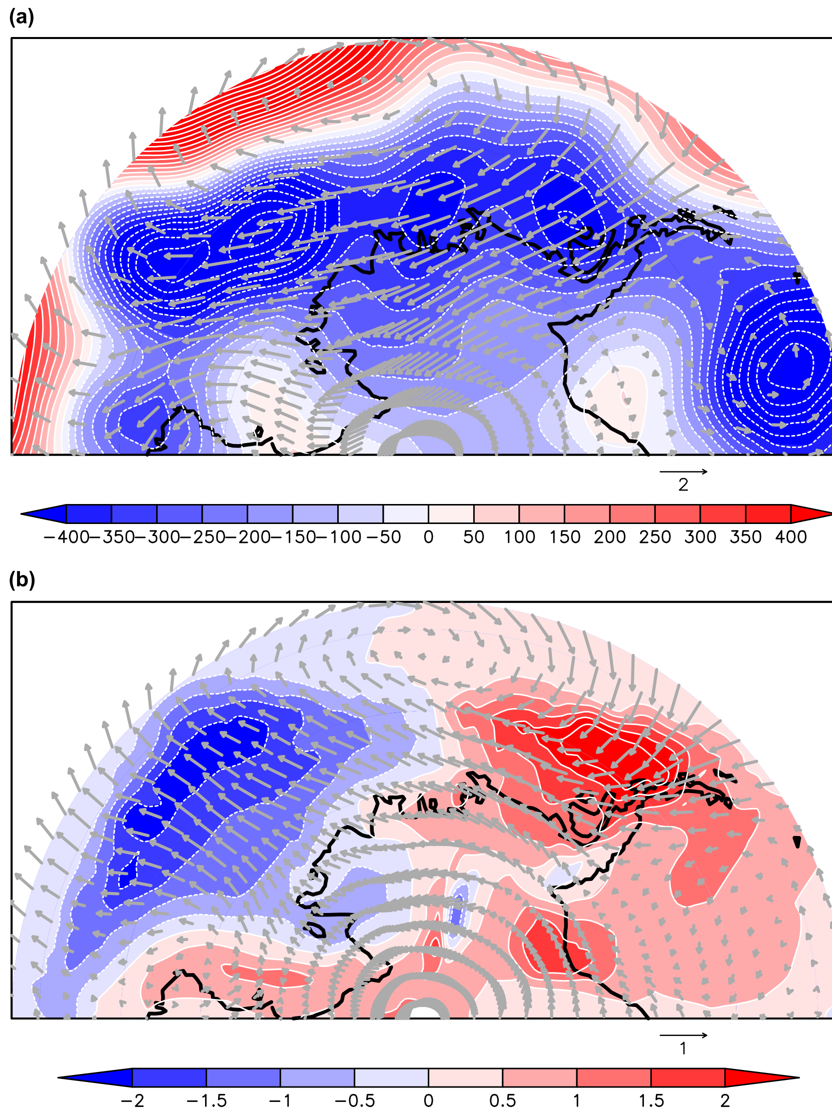

Fig. 7. Climate impacts of a weaker South Pacific Split Jet over Antarctica. Regression of the normalized PC1 index of the Split Jet modulation (1979–2009) on various fields, signed to indicate a weaker Split Jet representing stadial conditions. Values shown are per unit standard deviation of the index. (a) JJA 500 mb 2–8 day bandpassed geopotential height variance (shaded, units are m^2) and JJA 500 mb winds (arrows, reference vector is 2 m/s); and (b) JJA surface temperature (shaded, units are K) and JJA 10 m winds (arrows, reference vector is 1 m/s) over the western sector (160°E–340°E) of Antarctica. Data are from NCEP reanalyses (Kalnay et al., 1996) 1979–2009.

rainfall will be reduced (Fig. 6b) and temperatures warmed with a weakened Split Jet, both conducive to glacier retreat. The temperature increase come from the southward shift of the South Pacific subtropical front which warmed downstream air temperatures, as well as from a contribution by the Split Jet circulation change from about 45°S and southwards. One potential complication is that the rainfall increases over the southernmost South America polewards of 50°S (Fig. 6b); this may grow rather than shrink glaciers. We however note that the rainfall increase is small relative to the decreased rainfall over Western Patagonia, and that this region experiences warming from both the oceanic changes and the direct influence of the weakened Split Jet (Fig. 6c). Maritime glaciers such as these tend to be more sensitive to temperature changes than to precipitation changes (Anderson and Mackintosh, 2012; Oerlemans, 1997). Thus the influence of temperature warming on glacier recession is thought to outweigh any effects of precipitation increase.

Finally, in a Holocene study of Patagonian climate changes, Lamy et al. (2010) infer changes to the Southern Hemisphere westerlies over the Holocene and find a "distinct anti-phasing of wind strength between the core and northern margin over multi-millennial timescale"; they furthermore point to the seasonal cycle as an analog of such behavior. We note that this modulation between the core and northern margin is readily explained by the modulation of the Split Jet; in fact, the dominant seasonal cycle difference in the South Pacific westerlies is the presence of a Split Jet in austral winter, but a single midlatitude jet in the summer.

5.4. West Antarctica

Our hypothesis makes a specific prediction for West Antarctic climate response to North Atlantic cooling. A weaker Split Jet makes West Antarctic circulation more isolated from the Southern Hemisphere midlatitudes, because of the weakening of the subpolar branch that is directed towards Antarctica. Specifically, over the West Antarctic Ice Sheet there will be less advection from the North and fewer transient eddies, making that region less stormy (Fig. 7a). Studies suggest that less cyclonic activity leads to lower accumulation rates (e.g. Bromwich, 1988; Kaspari et al., 2004), and this linkage has been used to infer changes to storm track directions in the past given spatial changes to accumulation rates (e.g. Morse et al., 1998).

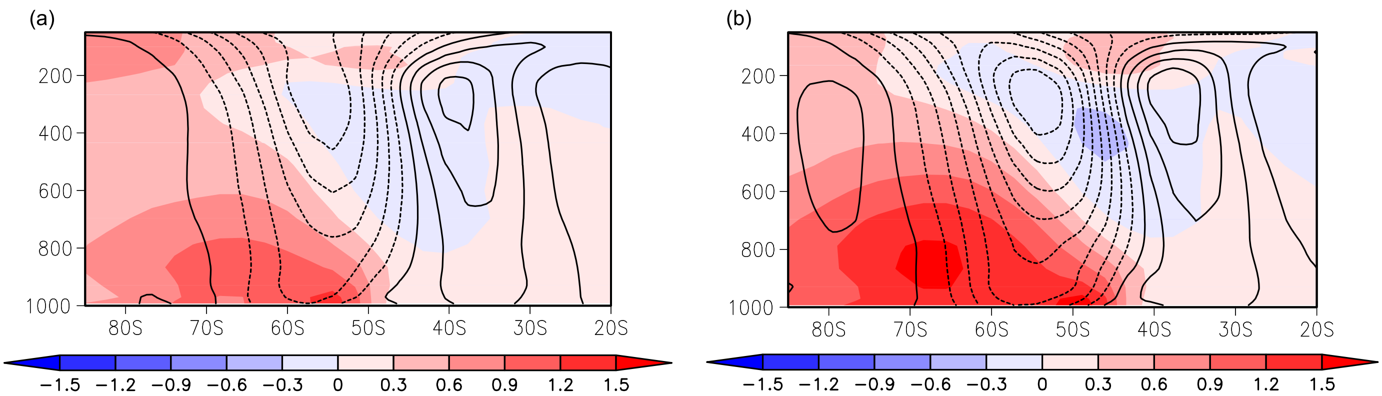

Fig. 8. Annual and zonal mean temperature (shaded, units are K) and zonal wind (contour interval 0.3 m/s, dashed contours are negative) anomalies in the CAM3 perturbation simulations with Southern Ocean SST warming. (a) With +2 K SST anomalies imposed up to 50°S. (b) With +2 K anomalies imposed up to 45°S. In both instances, the meridional temperature gradient between the polar and subtropical regions is reduced, as are the zonal winds over the Southern Ocean in particular over the Drake Passage latitudes.

The accumulation rate changes suggest a test for the hypothesis using ice core data, but accumulation rates are also dependent on air temperature, with the increased moisture-carrying capacity of warmer air leading to greater accumulation rates. In this respect, the resulting reduced advection of warmer midlatitude air towards West Antarctica creates a 'dipole' in temperature and sea ice cover over the Southern Ocean with colder temperatures upstream and warmer temperature downstream of West Antarctica (Fig. 7b; note that this response is similar to what is seen during El Nino events; Yuan and Martinson, 2000). The colder upstream temperatures thus reinforce the sense of lower accumulation rates over Antarctica with a weaker Split Jet. Note that the predicted temperature change directly over West Antarctica is relatively small.

In short, we posit a fast and direct atmospheric influence on West Antarctic climate timed with North Atlantic abrupt events, in addition to the established influence by the oceanic bipolar seesaw which has an out of phase relationship with the North Atlantic. West Antarctic ice core records do not (as yet) show evidence for a fast response to North Atlantic cooling, and in particular the recent record from the WAIS Divide (WAIS Divide Project Members, 2013) shows consistent results with other Antarctic records – warming during cold events in the North Atlantic and cooling following rapid warming events.

That being said, the Split Jet weakening has little impact on West Antarctic temperatures itself (see Fig. 7b); rather, we predict reduced wintertime storminess. Furthermore, colder temperatures over the Southern Ocean upstream of West Antarctica (i.e. north of the Ross sea) might suggest more sea ice coverage in that region, and moisture sources for West Antarctica would be further removed; this should have an effect on the deuterium excess of precipitation. Recent (and yet unpublished) deuterium excess results from the WAIS ice core suggest that there is indeed a signal showing an immediate response to North Atlantic warming (B. Markle and E. Steig, pers. communication, 2014).

6. The effect of Southern Ocean warming on the Southern Hemisphere Westerlies

A feature of equilibrated coupled model AMOC-slowdown simulations is the warming of the Southern Ocean (e.g. Kageyama et al., 2010; Knutti et al., 2004). This warming alters the meridional temperature gradient over the southern midlatitudes and presumably the westerlies (through altering baroclinicity and thermal wind balance). As such, it provides another potential pathway for AMOC-driven North Atlantic cooling to affect the Southern Hemisphere winds. In this section, we briefly contrast this effect to the Split Jet hypothesis proposed here using a climate model simulation.

We use the Community Atmosphere Model 3 (CAM3 – Collins et al., 2006), with a basic state climate to be that for the LGM: orbital conditions to 21,000 BP, solar constant at 1365 W/m^2, methane concentrations at 350 ppbv, CO_2 at 185 ppmv, and N_2O at 200 ppbv. We imposed monthly mean climatological SSTs and sea ice boundaries in our simulation, derived from a fully-coupled CCSM3 simulation of the LGM climate by Li and Battisti (2008) (the CAM3 is the atmospheric component of the CCSM3, for consistency). We ran this configuration for 40 model years, and took the last 20 model years to compute the monthly climatology. Using this CAM3 LGM simulation as our control climate, we then imposed a 2 °C SST warming at all ocean points south of 50°S, and for all months of the year. We kept the sea ice cover the same in this experiment, even though it is likely that the AMOC-induced warming over the Southern Ocean would reduce sea ice cover and thus augment the warming. We ran this also for 40 model years, taking the last 20 model years to compute the climatology.

Results (Fig. 8a) show that the Southern Hemisphere westerlies *weaken* between 50°S and 65°S with a magnitude of ∼1.5 m/s in the upper tropospheric jet and ∼0.6 m/s at the surface; notably, the maximum weakening occurs over the latitudes of the Drake Passage. This weakening occurs throughout the year, though it is strongest in the austral summer months (not shown). A less-pronounced strengthening of the westerlies occurs towards the northern edge of the jet stream around 38°S, away from the Southern Ocean latitudes. We also tested the sensitivity of the response to the latitude boundary of the warming by applying warming up to 45°S (Fig. 8b); qualitatively the results are similar, although the weakening of the midlatitude westerlies is more pronounced, and they shifted further equatorwards consistent with the more equatorward-shifted warming.

The weakened midlatitude westerlies are dynamically consistent with the changes in the air temperatures through the thermal wind relationship. The air temperature warming induced by the SST is almost entirely south of 50°S, and restricted to the lower-mid troposphere; this produces a weakened meridional temperature gradient at those latitudes, and the zonal wind changes are largest where the temperature gradient changes maximize. Note that the warming over Antarctica is around ∼0.5–0.8 K, and is consistent magnitude-wise with the observed peak warming over Antarctica during North Atlantic stadials. This suggests that our applied Southern Ocean warming is of reasonable magnitude.

With respect to our hypothesis, the response here would act to oppose the strengthening of the midlatitude eddy-driven jet by the atmospheric teleconnection during North Atlantic stadials. However, the timing would be different: whereas the Split Jet effect would respond relatively instantaneously with North Atlantic

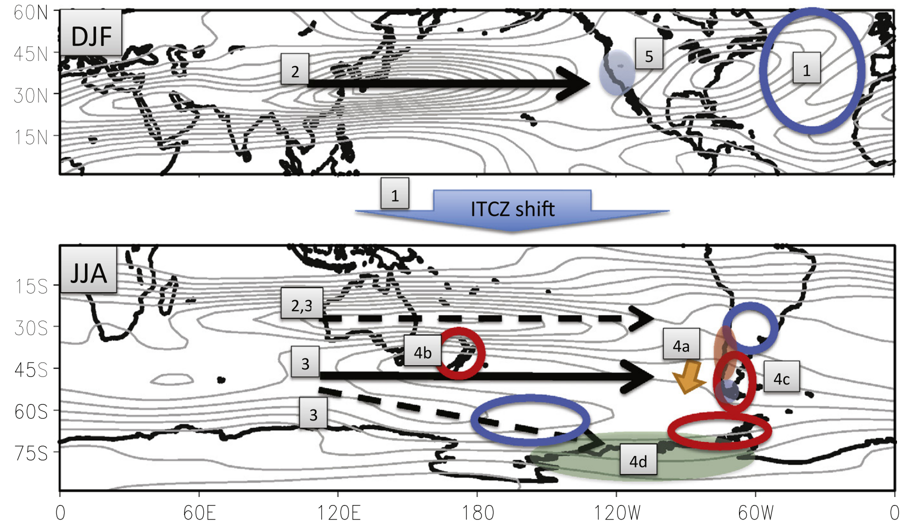

Fig. 9. Schematic of the Split Jet mechanism for Southern Hemisphere westerly wind changes. Blue circle *borders* represent cold surface temperature anomalies, and red circle borders for warm. Blue circle *shading* represent wetter conditions, and red circle shading for drier. Black solid arrows represent strengthening of the respective jet (and dashed arrows for weaker jets). The orange arrow represents the southward shift of the Subtropical Front, and the green oval represents reduced transient eddy activity over West Antarctica. See text for details of the sequence of associations 1 through 5. For reference, the 250 mb zonal winds for the represented months are shown in the gray contours.

changes, the westerly response to the Southern Ocean warming would be delayed in accordance with the lag in the oceanic bipolar seesaw. Using the Antarctic temperature response as an indicator of Southern Ocean warming, it suggests that at the onset of an abrupt northern interstadial *warming*, midlatitude westerlies over the South Pacific sector would abruptly decrease but then slowly strengthen with the Southern Ocean cooling. Over New Zealand however, gradual cooling of the Southern Ocean from the bipolar seesaw would augment the abrupt atmospheric cooling by the stronger Split Jet response. On the other hand, the transition from interstadial to stadial is more gradual (compared to bipolar seesaw timescales), so the different timescales of atmospheric and ocean teleconnections may not have as much of a contrasting effect on the southern hemisphere westerlies.

7. Summary and discussion

7.1. Summary

In closing, we elucidate the specific dynamics of a global reorganization of the tropical and midlatitude climate to high latitude North Atlantic cooling, mediated by the atmosphere. Previous works (Broccoli et al., 2006; Chiang and Bitz, 2005; Kang et al., 2009) have detailed the first step in this atmospheric teleconnection, namely the influence of extratropical cooling to the ITCZ. The 'Split Jet' hypothesis constitutes the next step in this teleconnection hypothesis. Our schematic (Fig. 9 – the numbering below corresponds directly to those in the figure) summarizes the mechanism:

1. North Atlantic cooling weakens the Northern Hemisphere monsoons and shifts the marine ITCZ southwards
2. Consequently, the northern Hadley cell strengthens, with consequent strengthening of that hemisphere's winter subtropical jet. A similar but opposite response occurs for the southern hemisphere
3. As a result, the South Pacific Split Jet weakens and Southern Hemisphere westerlies become more zonally symmetric
4. The weakened Split Jet
   a. shifts the zero wind-stress curl line southwards, implying the same for the South Pacific Subtropical Front; this leads to atmospheric warming over the latitudes that the front has shifted across;
   b. warms New Zealand by allowing tropical airmasses to penetrate further southwards;
   c. creates a dipole hydrological response with drier conditions over most of Western Patagonia except for the southernmost South America which becomes slightly wetter;
   d. reduces the steering of storms into West Antarctica, and creates a dipole in surface temperatures over the Southern Ocean with colder conditions upstream of West Antarctica, and warmer conditions downstream
5. Over the North Pacific, a strengthened boreal winter subtropical jet leads to wetter conditions over the Western US.

We think that the compelling aspects of our teleconnection hypothesis are that:

(i) The weakening Split Jet is a dynamical consequence of the southward ITCZ shift and Asian summer monsoon weakening, the latter which has been established to occur during North Atlantic stadials
(ii) The Split Jet is highly susceptible to change: it is a leading mode of interannual variation of the Southern Hemisphere westerlies during austral winter
(iii) It connects paleoclimate changes over disparate locations over the South Pacific sector, all with strong paleoclimate signals linked to abrupt events registered in Greenland ice cores
(iv) Our hypothesis produces testable predictions for climate changes during North Atlantic stadials, in particular over West Antarctica and western United States.

7.2. Discussion

An underlying motivation for this study is to highlight that paleoclimate changes to the southern hemisphere westerlies need not be viewed as annular mode-like, as implicitly assumed in most paleoclimate studies. However, interannual variability in the Split Jet is significantly negatively correlated to southern annular-mode variability (Bals-Elsholz et al., 2001), suggesting that the Split Jet modulation may project strongly onto the zonal mean. This begs the question of how distinguishable our proposed circulation changes are from the zonally-symmetric picture.

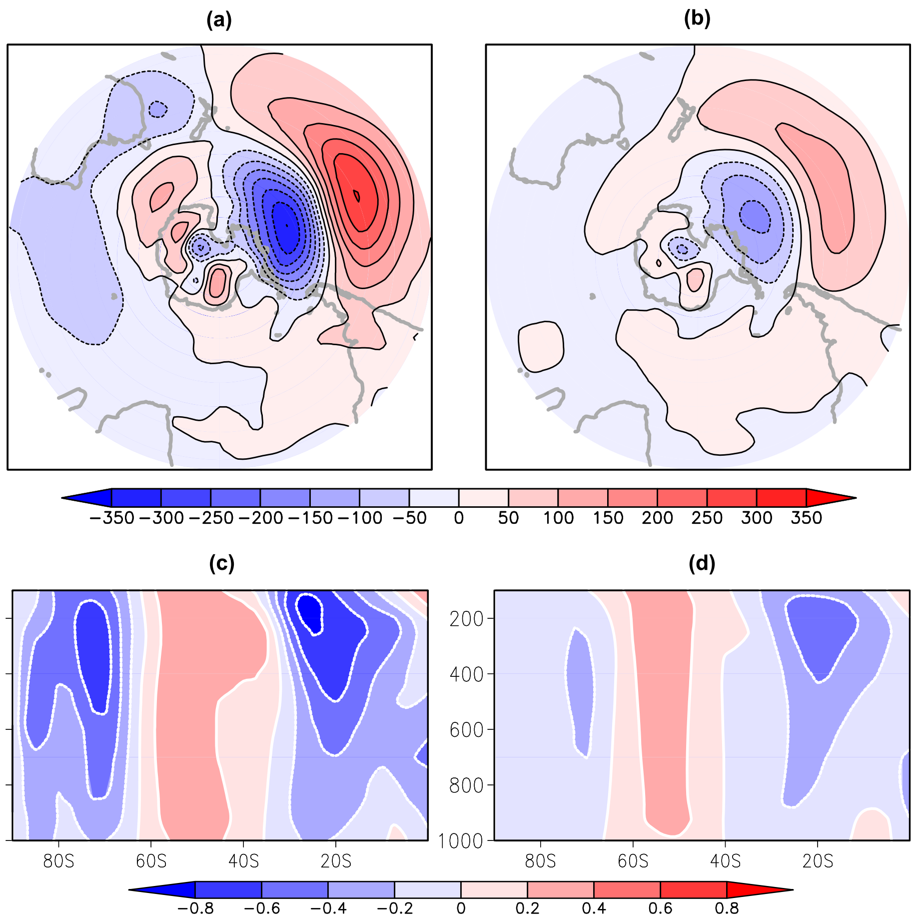

Fig. 10. Regression of the Split Jet index onto (a) JJA sea level pressure anomalies, and (b) annual mean sea level pressure anomalies (both contour interval 50 Pa per standard deviation); (c) JJA zonal mean zonal wind, and (d) annual mean zonal mean zonal wind (both contour interval 0.2 m/s per standard deviation). Data are from NCEP reanalyses (Kalnay et al., 1996) 1979–2009.

To assess this, we regressed the Split Jet index onto JJA sea-level pressure (Fig. 10a). The structure of the sea-level pressure anomalies is far from zonally symmetric, instead having a strong local projection on the South Pacific. This remains true even if the index is regressed onto the annual mean sea-level pressure anomaly (Fig. 10b), indicating that there is relatively little spatial overlap between the Split Jet variability and the southern annular mode. The Split Jet index does project on the JJA zonal mean zonal winds changes (Fig. 10c), with a stronger midlatitude jet and weaker jets in the subtropics and subpolar regions; however, the changes are quite weak (on the order of 0.5–1 m/s for 1 standard deviation of the index). The contributions are even weaker if annual mean winds are considered (Fig. 10d). Thus, our hypothesized changes are distinctly different from the zonally-symmetric view.

An outstanding issue with our hypothesis is the effect of a weakened Split Jet on upwelling over the Southern Ocean. Lee et al. (2011) found – by applying the wind changes in their climate model simulations to the Minnesota Earth System Model for Ocean Biogeochemistry (MESMO) – that both upwelling and oceanic carbon fluxes to the atmosphere increased over the Southern Ocean (see Fig. 3 of Lee et al., 2011). However, the ocean component of MESMO is coarse-resolution (36×36 equal-area grid), and the winds applied possess spatial biases (as with any model simulation). As such, a detailed study with a high-resolution ocean model is needed to properly understand how our weakened Split Jet hypothesis matches up against the results of Anderson et al. (2009). We are currently in the process of exploring this issue.

While our Split Jet hypothesis is testable, we point out potential complications in doing so. First, the atmospheric circulation changes are restricted to the winter season; on the other hand, the majority of paleoproxies are at most annually resolvable. Second, our mechanism will be competing with the oceanic bipolar seesaw effect and it is yet unclear what the relative effectiveness of each influence is. Finally, there is an assumption that the Split Jet configuration is present in the glacial climate – while we think this is true (as informed by our analysis of PMIP2 simulations), there may be a spatial offset in the mean jet configuration that may complicate our prediction of impacts.

There are several other midlatitude locations with strong climate change signals coincident with North Atlantic abrupt climate changes, and it remains to be seen if our hypothesis could be made consistent with them. Lake Lisan, a closed-basin lake in the Jordan Rift Valley of the Near East, is thought to behave similarly to the Western US closed basin lakes for the late-glacial millennial events (Broecker, 2010). The Near East has a Mediterranean rainfall climate similar to the Western US, and rainfall changes seen there could be plausibly explained by the strengthening of the North Atlantic subtropical jet. This will however be complicated by the effect of the Laurentide ice sheet on the North Atlantic westerlies. The Altiplano region of the Andes is another location with strong signals (Baker et al., 2001; Blard et al., 2011), with cold North Atlantic conditions coeval with wet conditions over the Altiplano.

We think that the South Pacific Split Jet may be sensitive to climate forcings other than North Atlantic cooling. In particular, precessional influences may have a big effect, as stronger Northern Hemisphere summer insolation would strengthen the northern hemisphere monsoons. This would in turn strengthen the southern Hadley cell and strengthen the southern subtropical jet. Following the dynamical arguments we made in Section 3, this leads to a strengthening of the South Pacific Split Jet. Thus, we may predict a stronger austral winter South Pacific Split Jet in the early-mid Holocene.

Finally, we emphasize that the hypothesized changes proposed here are not at the exclusion of the climate impacts resulting from the oceanic bipolar seesaw; rather, our view is that ***both*** have to operate at some level. As highlighted in Section 6, the characteristics and timing of the oceanic bipolar influence on the Southern Hemisphere westerlies are different from those predicted by the Split Jet hypothesis; also, our hypothesis only applies to the austral winter season. Future studies will need to incorporate both the atmospheric and ocean-mediated North–South teleconnections in understanding the Southern Hemisphere westerlies.

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Appendix A. Supplementary material

Supplementary material related to this article can be found online at http://dx.doi.org/10.1016/j.epsl.2014.09.012.

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