Response to Referees

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A New Index For The Wintertime Southern Hemispheric Split Jet

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For a better readability all reviewers' comments are written in italics. The associated responses are written in roman style and are blue colored. New paragraphs, which were added to the manuscript are also written in roman style (black).

1 Response to Referee #1

This manuscript introduces a new index for the Southern Hemisphere (SH) winter split jet. The split jet is an important feature of SH winter climate which requires greater understanding due to its importance in understanding a globally-relevant part of the climate. Winter (July-September) monthly zonal wind data from a reanalysis dataset (ERA-Interim) is used to define an index based on principal component analysis. The rationale is that there is some disagreement between previous locally-defined split jet indices in terms of conclusions on links between split jet variability and large-scale modes of climate variability. The creation of a new hemispheric-scale index is motivated by the need to understand these disagreements. With regard to the manuscript itself. I found it difficult to follow and have a number of concerns about the methodology and rationale which are crucial the main conclusions. These are listed below and represent major comments that would need to be addressed for publication in ACP.

Major comments:
I'll start with a recommendation in light of the below comments. My feeling is that this work would be easier to interpret and present clearly if the methodology and questions were reversed. By reversed I mean that the present approach of developing an EOF-based index that correlates with previous split jet indices could be reversed and instead the EOF analysis could be used to investigate in detail the linkages between existing split jet indices and large-scale patterns of atmospheric circulation variability. This could help to solve a number of issues listed below relating to the methodology and interpretation. In fact, in light of the major points below I find it difficult to see another option for raising the manuscript to the necessary standard.

Thanks for this recommendation. It shows that we had not sufficiently explained our line of arguments. To remedy this weakness, we revised the introduction of our manuscript and added the following paragraph:

Additionally, the literature lacks a description of whether the split jet variability is related to the Pacific South American (PSA) patterns, although these were found to be associated with both teleconnection indices, ENSO and the AAO. The PSA patterns are conventionally seen as Rossby wave trains emanating in quadrature to each other from the tropical Pacific towards Argentina and serve simultaneous as waveguide for eddies moving south. On interannual time scales the

PSA-1 mode is tied to ENSO, while the PSA-2 pattern is associated with the quasi-biennial component of ENSO (e.g., Mo, 2000). Furthermore, although called an "annular" mode, the AAO contains asymmetries, which are most pronounced in Austral winter and over the Pacific sector. This (tropically forced) component of the AAO is related to a fixed active Rossby wave source and resembles the spacial structure of the PSA patterns (Ding et al., 2012). The lack of knowledge about the relationship between the split variability and the PSA patterns and the inconsistencies among earlier studies concerning the connections to ENSO and the AAO motivate the development of an improved SH split jet index.

The underlying idea of our work is the analysis of the SH split jet variability and its links to the large-scale modes of climate variability. To archive this aim the established split jet indices were calculated. We found that they have large discrepancies among each other. The inconsistency among the three split indices stems from their rigid definitions in different meteorological fields, areas and levels and results in varying relationships to the known modes of climate variability. The authors' approach was therefore to abandon these rigid definitions and to apply the (in the climate community more common) EOF analysis for the whole SH instead in order to describe the SH split jet variability. Therefore, the EOF analysis of the 200 hPa zonal wind field is the most central aspect to define the new index. For better readability we added a paragraph at the beginning of section 3, introducing our motivation:

As mentioned previously, the wintertime split jet is the most prominent asymmetric feature of the mid-latitude SH circulation centered over the Pacific sector although it bears as well hemispheric signatures (Yang and Chang, 2006). In order to design a PC based split jet index, three earlier defined split jet indices (Section 2.4) were reproduced and their statistical relationships to the leading modes of the SH wintertime circulation (as depicted by zonal wind anomalies at 200 hPa) have been investigated. The EOF modes showing the largest coherence with the split jet indices (as defined by the respective studies) are assumed to contain the main signals associated with the split variability.

1a) The rationale for the precise combination of PCs used for the PSI index is not explained and seems arbitrary (equation 5 on line 25 of page 8). Why was this specific linear combination chosen?

PC2 and PC3 were chosen with respect to the correlation analysis between the earlier split indices and the leading 5 PCs of the zonal wind field (table 2 in the manuscript), which confirms that the split variability is contained in particular these components. The fact, that all three very different indices correlate significantly with these PCs, indicates that our method is consistent and that it is appropriate to linearly combine these into a new split index. Adding PC1 to the linear combination failed to improve the correlative relations.

1b) The actual EOF patterns are not shown, which makes it very difficult to judge the relevance of these patterns for the split jet region and possible variability with other aspects of the SH climate system.

The negative and positive index phases of PC2 and PC3 do not mirror each other, i.e. the spatial patterns look different for positive/negative PC index composites. Since we are interested in the spatial pattern of the positive composite of PC2 and the negative of PC3, the authors decided for composite instead of regression plots. Nevertheless, we added the regression plots here (Fig.1) for comparison to the composite plots.

1c) The vertical pressure level seems to be chosen on the basis of highest correlation with previous split jet indices rather than a specific dynamical reason. It is important to explain why 150 hPa is more appropriate than the lower 200/300 hPa levels used previously.

The PSI was previously calculated for several vertical levels from the surface to the stratosphere, but the correlation to the mean of all earlier split indices maximizes in the 150 hPa level. Thus, and due to the mechanisms associated with the jet(s) variability, which have their

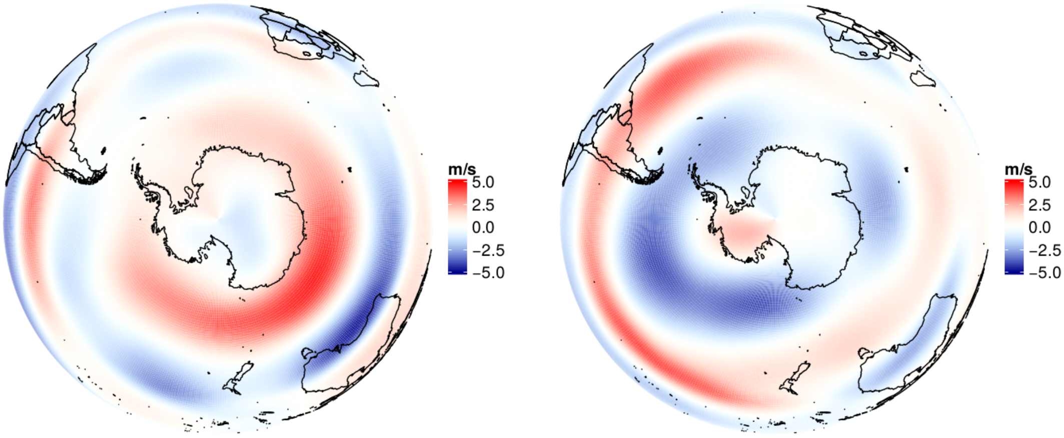

Figure 1: Regressions of the 200 hPa zonal wind on PC2 (left) and PC3 (right) in the anomalous zonal wind field.

maximum at that level (Akahori and Yoden, 1997), the 150 hPa level was chosen for the split definition. Fig.2 displays the correlation values between the PSI (defined in several vertical levels) and the mean of all three earlier split indices and shows that primarly the tropopause level is associated to the split variability. Since the correlation value of the PSI in the 200 hPa level of the zonal wind is as well highly significant and in order to facilitate the comparison to the older split indices (which are defined in 200 and 300 hPa levels), the authors thank for the constructive advise and change the level of PSI definition from 150 hPa to 200 hPa.

1d) I'm not an expert on EOF analysis, but it seems problematic to me to just perform this on winter months since presumably large jumps can occur between the end of one winter and the beginning of another that could introduce artefacts into the analysis of month-to-month variability. An explanation of why this approach is acceptable or what was done to avoid this is important.

Indeed, using subsets of yearly time series instead of all months of the year can lead to jumps in the PC time series. This should be taken into account for considerations concerning e.g. frequency analysis. In awareness of this fact, the authors selected methods (composite and correlation analysis), which are not sensitive to these jumps. A similar procedure is applied by NOAA for monthly and seasonal EOF analysis[1]. Several authors are calculating the seasonal EOFs in the same manner as we did (e.g., Wallace et al., 1993; Baba and Renwick, 2017).

2) The use of a combination of PC2 and PC3 used in the PSI index are potentially problematic in discussion of links with ENSO (section 4.2). The context for this is that in tropospheric geopotential height, the 2nd and 3rd PCs are associated with two variants of the so-called Pacific South American (PSA) pattern (e.g. see Cai and Watterson, 2002), which are often interpreted as representing Rossby wave trains from the tropics (e.g. Karoly (1989)).

The calculation of the PCs which are used to define the PSI, is performed with zonal wind in 200 hPa, the PSA patterns are associated with PCs of the geopotential height in 500 hPa. An EOF mode to EOF mode connection cannot be expected for two physical related fields (Ambaum

[1] See `(https://www.esrl.noaa.gov/psd/enso/mei.ext/)` and references therein.

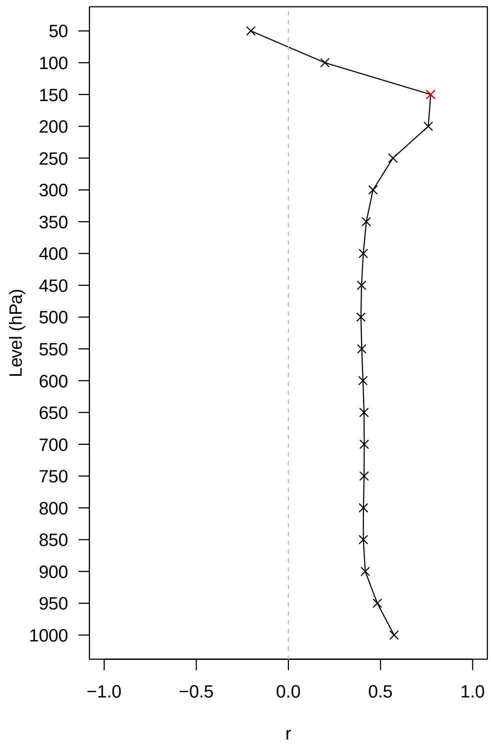

Figure 2: Pearson's correlation coefficients for the PSI (defined in different vertical levels) and the mean of all three earlier split jet indices. The red cross marks the maximum value.

et al., 2001) and therefore no connection between PSA (in geopotential height) and PSI (in zonal wind) was expected. Nevertheless, the authors agree that the links between the leading modes of the geopotential height field and the EOF modes of the zonal wind are worthwhile (especially in context of the nonlinear linkage between split events and ENSO). To summarize, our new result indicates that the PSA-1 mode is associated with the PC3 component of the PSI (r = 0.55). However, while the correlation to the PC3 component is significant, the PSI shows weak correlation to both PSA modes ($r_{PSA-1} = 0.2$ and $r_{PSA-2} = 0.1$, respectively) – consistent with the earlier split indices. The low correlation values between PSI and PSA modes (as defined in (Mo, 2000)) were added to table 3 in the manuscript and the dynamical mechanisms are discussed and added to the last section. We thank for this comment and mention this aspect now in section 4.2.:

Fig. 9 in the manuscript shows the time series of both PSA modes and the PSI. Although the correlation between PSI and the PSA indices is low ($r_{PSA-1} = 0.19$ and $r_{PSA-2} = 0.06$), the PSA-1 mode is significantly correlated to the individual PCs of the SH zonal circulation variability (Tab. 1). Both PSI components (i.e. PC2 and PC3) are associated to the PSA-1 pattern. The spacial pattern of EOF2 was previously identified to resemble the dominant part of the split jet structure (Section 3.1) marked by an intensified PFJ over the eastern hemisphere. Since the PSA-1 pattern is primary associated with the variability over the central and western Pacific sectors, it can be concluded that PC2 describes less PSA-1 variability but contains a considerable part of the wind response associated with the AAO. PC3 accounts for the "non-annular" component of the PSI and contains most variability over the Pacific sector. It is argued, that PC3 contains remarkable PSA-1 variability. However, only 3 cases were identified where both indices, PSI and PSA-1, exceeded the threshold of one standard deviation during the analysis period (not shown).

3) The relatively low correlation between the PSI index and previous split jet indices is a concern (Table 2). Correlations of around 0.7 only explain 50% of the variance and to me this indicates that the new index could be mixing up a number of other correlated dynamical features that exist on the hemispheric scale. In particular see the above point about PSA-1 and PSA-2. It seems possible that the PSI captures some sort of PSA-related patterns, which we know are highly correlated with the split jet region (Figure 1 of Cai and Watterson).

As mentioned previously, it is not straightforward to connect EOF modes of two physical related fields to each other (see previous answer). By definition, the leading mode of the SH 500 hPa geopotential height field is the AAO (Mo, 2000, e.g.). Since the corresponding PCs are by definition uncorrelated to each other, it is not surprising that the PSI (which is significantly correlated (r= 0.81) to the AAO) does not show a statistical relationship to the PSA modes (i.e. the second and third modes of the ZG field under investigation). Nevertheless, the relationships between the earlier split indices, PSI and the PSA modes were re-examined (previous answer).

2c) Statistical significance should be included on the composite anomaly maps shown in Figures 5 and 6, otherwise it is difficult to judge which aspects of the maps to focus on.

Significances are now included.

2d) The manuscript needs to be reviewed by a fluent English speaker (or alternatively one of the many available English review services) since it is not currently of a publishable standard.

The manuscript will be reviewed by a professional native English speaker before the publication.

	PSI	PC2	PC3	BE	YC	IH	Mean
	JAS – correlation values						
AAO	**0.81**	**0.65**	**-0.50**	**0.45**	**0.66**	**0.58**	**0.64**
MEI	-0.09	0.07	0.20	0.20	0.12	**0.34**	**0.25**
PSA-1	0.19	**-0.26**	**-0.55**	0.14	0.16	-0.17	0.05
PSA-2	0.06	0.20	0.13	0.22	0.20	-0.12	0.11

Table 1: Monthly (JAS) Pearson correlation coefficients of the three split indices introduced in the methods section, as well as the PSI with three major SH climate mode indices for the Antarctic Oscillation (AAO), ENSO (Multivariate ENSO Index) and the Pacific South American (PSA) patterns (PSA-1 and PSA-2 indices as defined in Mo (2000)). Bold values are significant at the $\alpha = 1\%$ level.

Minor (textual) comments:
Page 1, line 1: I suggest mentioning explicitly that the split jet is evident in mid-latitude westerly/zonal winds.
The mid-latitude westerlies are explicitly mentioned now.
Page 1, line 9: Similarly, it should be mentioned here that the principle component is defined from the zonal wind field.
The sentence was changed to: Our index is based on the principal components (PC) of the zonal wind field for the SH wintertime.
Page 1, line 15: "relation" → relationship.
The "relation" was reworded to relationship.
Page 1, line 19: "an SH" → a SH.
The "an SH" was changed to "a SH".
Page 2, line 2: "minimum wind speeds in the westerlies of the upper level flow" → weak upper-level westerly winds.
The rewording was adopted.
Page 2, line 9: Mention somewhere here that the AAO is now more commonly referred to as the Southern Annular Mode (SAM), since many (most?) readers will be most familiar with the SAM terminology.
The authors thank for the advice and added the SAM terminology.
Page 2, line 26: The meaning of "which confines with the relationships between" is not clear to me. This needs to be re-worded.
The question has been changed to: Can an index be defined which clarifies the relationships between the SH split jet and the large-scale teleconnection indices ENSO and AAO?.
Page 2, lines 34-35: I disagree that inconsistent relationships indicates deficiencies. I would prefer to say that these differences need to be understood and motivate the development of an alternative index to help in this understanding. Also, the concept of a more hemispheric definition than the previous regionally-defined indices represents a key novelty in the authors' proposed index.
The authors agree, that inconsistencies do not equal deficiencies. The sentence has thus been changed to: These inconsistencies motivate the development of an improved SH split jet index.
Page 3, lines 1-5: I'm not sure what the main point being made here is. This should either be made clearer or possibly the paragraph could be removed. Also, it important to note that the impact of stratospheric ozone depletion in the lower-troposphere is highly seasonal (mainly summer) and not significant in austral winter.

The authors agree and deleted the paragraph.
Page 3, line 10: Note that the AAO/SAM is not specifically a low-frequency mode of variability, although it will contain a component of externally-driven low-frequency variability and trends.
The authors agree that the categorization of the AAO/SAM as low-frequency mode is mistakable in that case and decided for the terminology "large-scale" mode of the SH variability.
Page 4, line 1: "dissolved" → resolved.
The rewording has been adopted.
Page 4, Section 2.2: The use of different terminology in the title (EOF analysis) and main text (principal component analysis) is confusing and should be clarified.
The authors agree and changed the sentence to: Analysis of atmospheric circulation patterns can be done by means of an Empirical Orthogonal Functions Analysis (EOF), which is also referred to as Principal Component Analysis (PCA) (Jolliffe, 2002; Hannachi et al., 2007).
Page 4, line 12: I'm not an expert on EOF analysis, but it seems odd to me to just perform this on winter months since presumably large jumps can occur between the end of one winter and the beginning of another that could introduce artefacts into the analysis of month-to-month variability. An explanation of why this approach is acceptable is important.
As mentioned in the answer to the point 1d) of the discussion, an EOF analysis is not sensible to jumps in the time series. There is a number of references, executing monthly and seasonal EOFs in the same manner.
Page 4, line 18: I don't understand what is being described in the sentence starting "Afterward, the monthly ...". Maybe this needs clarification and/or re-wording.
The sentence was deleted since the authors decided to show the composite mean instead of the composite anomalies w.r.t. the 1979–2015 mean.
Page 4, line 19: "the relationship" → the linear relationship
The word linear has been added.
Page 6, line 23: "isobar" → "pressure level"
"isobar" has been changed to "pressure level".
Page 8,line 1: It seems odd to mention the PSI here before it is defined in the next section. I would prefer to keep the focus on the individual PCs in this section.
The authors agree and discuss the PSI in section 3.2 only.
Page 8, lines 18-19. I would remove "This gives rise to the assumption" and simply state that splits are less correlated to PC1 than PC2 and 3.
The suggestion was adopted and the sentence has been changed to: Altogether, the splits in the westerlies are less correlated to PC1, but are rather associated with the higher order PCs in the 200 hPa zonal wind field.
Page 8, line 22: Further explanation of what is meant by a "dynamical PC based index" is needed.
"Dynamical" equals here "not static", i.e. the PSI disclaims fixed geographical definitions in contrast to the earlier split jet indices. Nevertheless, the authors agree, that the word "dynamical" is confusing in that case and was thus deleted.
Page 8, line 23: It's not clear how this particular linear combination was decided on. This needs to be explained.
As stated earlier, the linear combination was chosen, due to the significant correlation values between these PCs and the earlier split indices. This fact has been highlighted now: In order to develop a PC based split jet index, these PCs, correlating well with the earlier split jet indices, are coupled to a linear combination.
Page 8, line 29: How well correlated are the various indices with each other? A correlation of around 0.7 between the PSI and these indices explains only half of the variance and therefore could potentially capture quite different aspects of variability.

PCs are by construction linear combinations of the physical field under investigation and it is therefore not excluded that these PCs capture different aspects of the tropospheric variability. However, the correlation analysis bears, that the relationships between the large-scale variability patterns (AAO, PSA, ENSO) and the older split indices are consistent with the relationships to the PSI and can thus been seen as potential modulators of the split variability, rather than being a disturbing factor it is assumed, that the split variability is a constructive combination of certain phases of different low-frequency modes. The correlation value of 0.76 between the mean of the earlier indices and the PSI captures around 60% of the variance. Differences between the PSI and the "static" earlier indices are indicative of different input variables, levels and regional definitions.

Page 9, first paragraph of section 4.1. It is important to add statistical significance to the composite difference plots. Also, it would be useful for the reader to see what these composites look like for the split jet indices rather than not show them.

The authors thank for the advice and added significances to all composite plots. The composite analysis for the earlier split jet indices has been added here for comparison (see figure 3). The interested reader is referred to the composite plots of Bals-Elsholz et al. (2001), Yang and Chang (2006), Inatsu and Hoskins (2006), respectively, where composites of the earlier split jet indices have already been published. The authors thus disclaim to add these plots to the manuscript, since they do not add a new information to our work.

Page 10, main text discussion on individual PC2 and PC3 composites: Given that these show rather different composite patterns, it would be useful to give an explanation of how the combination of the two provides an appropriate PSI.

The authors assume that the individual contribution to the spatial structure of the PSI is questioned here. It seems that we have not well described the particular portions of EOF2 and EOF3 patterns, therefore we added the following sentence to the appropriate paragraph (p.10, l.3 ff.) to clarify this issue: In summary, the positive PSI composite benefits from the combination of the double jet structure with a pronounced minimum between the jets associated with PC2+ and the strong PFJ over the South Pacific Ocean associated with the "non-annular" component of PC3-.

Page 12, Section 4.2: As mentioned above, I doesn't seem appropriate to categorise the AAO/SAM as a low-frequency climate mode due to the importance of jet vacillations in its existence.

As already mentioned, the authors agree that the categorization of the AAO/ SAM as low-frequency mode is mistakable in that case and decided for the terminology "large-scale" mode of the SH variability.

Page 14, discussion of ENSO links in main text: In the lower troposphere the 2nd EOF of monthly geopotential height often shows a pattern referred to as the eastern Pacific South American Pattern (PSA). I would encourage the authors to comment on how this might relate to their results and also PC2 in zonal winds at 150 hPa.

The authors re-examined the relationships between split indices and the PSA patterns, defined as EOF modes (Mo, 2000). The results are summarized in table 1. It seems, that especially PC3 is associated with the PSA-1 mode of the ZG field in 500 hPa (r = 0.55). Since EOF3 bears strong variability over the South Pacific sector, where the PFJ shows large variance, the authors conclude that the split jet resembles parts of the spatial structure of the PSA-1 mode. The re-examined table 1 was therefore added to the manuscript in Section 4.2. as well as to the discussion in section 5:

The traditional perception suggests that the PSA patterns are part of a stationary Rossby wave train extending from the central Pacific to Argentina (e.g., Mo and Higgins, 1998). The PSA patterns, typically defined as 2^{nd} and 3^{rd} modes of tropospheric geopotential height variability over the SH (e.g., Mo, 2000), have been attributed to ENSO (PSA-1) on interannual time

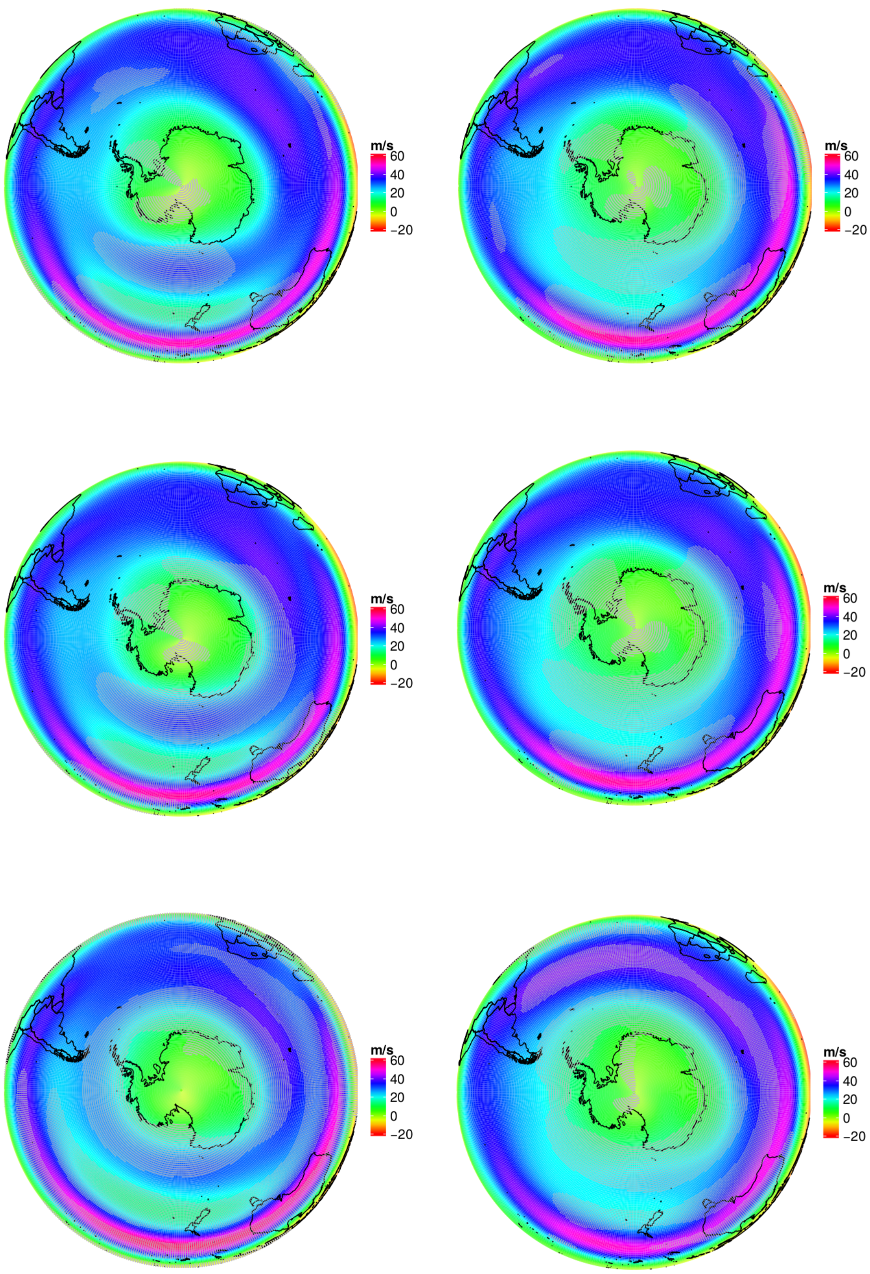

Figure 3: Positive (left) and negative (right) composites of the earlier split jet indices as defined in Bals-Elsholz et al. (2001), Yang and Chang (2006), Inatsu and Hoskins (2006), respectively, in the 200 hPa zonal wind field. Gray dotted areas are significant at the $\alpha = 1\%$ level.

scales and to the quasi-biennial component of ENSO and the Madden-Julian-Oscillation (PSA-2), respectively (Mo and Paegle, 2001). The relationship between the PSA indices and the PSI revealed a low relationship to both indices ($r_{PSA-1} \approx 0.2$ and $r_{PSA-2} = 0.06$). In contrast, the individual PCs of the zonal circulation in 200 hPa correlate significantly to the PSA-1 index. Positive PSA phases are associated with a strong PFJ over the western Pacific sector (not shown) and the PSA-1 mode is consistently significantly correlated to the PC3(-) component, which is (by definition) related to split events. Negative PSA events are associated with an enhanced PFJ over the eastern hemisphere, which represents the partly EOF2 variability. It is reasoned that PC3 represents both, AAO as well as PSA variability. However, the connection between the PSA-1 mode and the PSI is canceled out by the PC2 component, which is (as well as the PC3 component) negatively correlated to the PSA-1 mode.

2 Response to Referee #2

This manuscript proposed a new index for the wintertime Southern Hemispheric split jet based on the principal components. Compared with the existing split indexes, this new one considers the split jet as hemispheric rather than a regional feature. Further analysis indicated that the newly defined index has a strong coherence with the Antarctic Oscillation (AAO), but the split jet variability is less dependent on the phases of ENSO. This paper is well written, and the proposed index could be used as an extra index for understanding the mechanism of the wintertime Southern Hemispheric split jet. I have major concerns regarding the ENSO modulation of the split jet variability as detailed below. At this point I cannot recommend publication of this paper.

Major comment:
The modulation of ENSO on the split jet index has not been investigated in great detail in this study, since the time scale studied here for the split jet index is the sub-seasonal, while the ENSO varies on seasonal to inter-annual time scales. The proposed index is highly correlated with AAO, which has a strong month to month variability, so it is not surprising to see that there is no correlation between the index and ENSO on the monthly time series. I would recommend investigating the relationship between the seasonal mean split jet index and the seasonal mean ENSO index.

The relationship between the split jet variability and ENSO is very complex and changing in time. The missing correlation between PSI and MEI stems from the fact, that both La Niña as well as El Niño events are associated with a strengthening of one of the jets (PFJ or STJ). This asymmetric response to the ENSO leads thus to a low and insignificant correlation to the MEI. The positive correlation during strong La Niña phases cancels the negative correlation during El Niño events out. Thus, the time series do not correlate on a significant level. Fig.4 shows further that the relationship is changing in time as well. That does not mean that there is no relationship between the split jet variability and ENSO, rather the true interdependency between both is hidden.

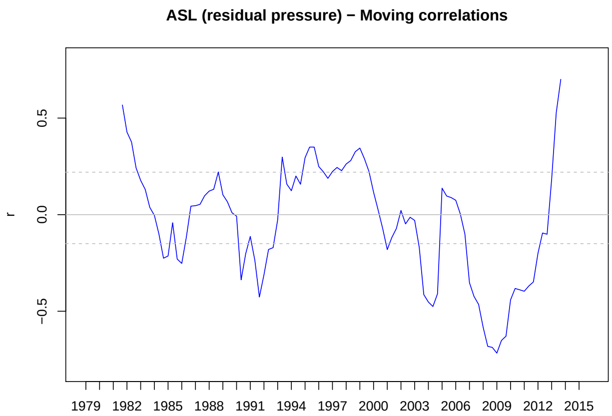

Figure 4: Running correlation (15-month) coefficients between the PSI and MEI indices for the period 1979–2015. Dotted gray lines indicate statistical confidence intervals using a two-tailed Student's t test.

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A New Index For The Wintertime Southern Hemispheric Split Jet

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Abstract. One of the most prominent asymmetric features of the southern hemispheric (SH) circulation is the split jet over Australia and New Zealand in Austral winter. Earlier studies developed indices to detect to which degree the upper-level mid-latitude westerlies are split and investigated the relationship between split events and the low-frequency teleconnection patterns Antarctic Oscillation (AAO) and El Niño-Southern Oscillation (ENSO). These different studies produced inconsistent results so that the relationships between the wintertime SH split jet and these climate variability indices remain unclear and are thus the scope of this study.

Up to now, all split indices are based on a definition, which focuses on a specific region where the jet split is recognizable. We consider the split jet as hemispheric rather than a regional feature and propose a new, hemispherical defined index: Our index is based on the principal components (PC) of the zonal wind field for the SH wintertime. A linear combination of PC2 and PC3 of the anomalous monthly (JAS) zonal wind is used to identify the split jet condition.

In a subsequent correlation analysis, our newly defined index (PSI) indicates a strong coherence with the Antarctic Oscillation (AAO). However, the significant relationship is unstable over the analysis period: During the 1980s the AAO amplitude was higher than the PSI and vice versa in the 1990s. It is supposed that the PSI, as well as the AAO, underlie low-frequency variability on the decadal to centennial time scales, but the analysis period is too short to draw these conclusions. A regression analysis with the Multivariate ENSO index points to a nonlinear relationship between PSI and ENSO, i.e. split jets occur during strong positive and negative phases of ENSO, but hardly under "normal" conditions. [new: The PSA patterns, defined as the 2^{nd} and 3^{rd} mode of the geopotential height variability in 500 hPa, correlate poorly to the PSI ($r_{PSA-1} \approx 0.2$ and $r_{PSA-2} = 0.06$), but significantly to the individual components (PCs) of the PSI, uncovering an indirect influence on the SH split jet variability.]

Our study suggests that the wintertime SH split jet is strongly associated with the AAO, while ENSO is to a lesser extent connected to the PSI. It is concluded that a positive AAO phase, as well as both flavors of ENSO and the PSA-1 pattern, produce favorable conditions for a SH split event.

1 Introduction

The circulation of the Southern Hemisphere (SH) is generally more zonally symmetric than its Northern Hemisphere counterpart, but there are still significant zonal variations in the upper-tropospheric time-mean flow. A unique asymmetric feature of the SH winter circulation is the climatological split jet over the longitudes of Australia and New Zealand (Fig. 1).

The split is composed of two well distinguishable branches: The northern branch, the subtropical jet (STJ) is located over the South Indian Ocean expanding to the South Pacific Ocean between the latitudes of 25° and 30° S. The STJ is paralleled by a weaker jet, the Polar Front Jet (PFJ), which is also concentrated in the south of Australia and over the South Pacific Ocean, but further poleward, near 60° S. A distinct feature of the split structure is a pronounced "gap" between these two branches, characterizing a zone of weak upper-level westerly winds over New Zealand (Bals-Elsholz et al., 2001).

Several past studies addressed the existence, location and variability of the wintertime SH split jet. An early study of Taljaard (1972) connected the existence and strength of the split jet to the outflow from the Asiatic monsoon anticyclone of the Northern Hemisphere. Further studies suggested that the split jet is associated with: Cold air outbreaks (Mo et al., 1987); the breakdown of the Antarctic polar vortex in late spring (Mechoso et al., 1988) or the phase of the El Niño-Southern Oscillation (ENSO) (Karoly, 1989; Chen et al., 1996) and the Antarctic Oscillation (AAO) (Yang and Chang, 2006).

The AAO, which is in literature also referred to as Southern Annular Mode (SAM), is the dominant climate mode of the extra-tropical SH circulation variability and describes the out-of-phase pressure anomalies in polar and mid-latitude regions (e.g. Lorenz and Hartmann (2001), Thompson and Wallace (2000)). Positive (negative) phases of the AAO are linked to a poleward (equatorward) shift and strengthening (weakening) of the PFJ. The AAO was found to be the main modulator of the PFJ strength and location (Limpasuvan and Hartmann, 1999) and is thus expected to play a major role in the split jet formation. The ENSO has an impact on both, STJ and PFJ by directly acting on the Hadley circulation: While El Niño events are connected to increased (equatorial) convection and a stronger Hadley cell, which in turn enhances the STJ and simultaneously weakens the PFJ, La Niña phases are marked by a stronger (weaker) PFJ (STJ) (Karoly, 1989; Chen et al., 1996; Kitoh, 1994). Gallego et al. (2005) affirmed that the ENSO impact on attributes of the PFJ (strength, wavenumber, average latitude) is mainly confined to the Pacific sector, where the split jet is located.

Bals-Elsholz et al. (2001) developed a vorticity based split index and investigated the relation to both, ENSO and the AAO. Their study reveals that the existence of the split jet depends highly on the presence of the PFJ part, given that the STJ is a quasi-permanent feature of the SH winter circulation. The PFJ part of the split index is indeed correlated to the AAO, while the STJ part shows no correlation. Thus, in total their index correlates weakly to the AAO. A later study (Inatsu and Hoskins, 2006) suggested a split index based on zonal mean zonal wind variations. It correlates low ($r = 0.43$), although significant to the AAO. Both studies also investigated the relation to ENSO: Neither the index from Bals-Elsholz et al. (2001) nor the one developed by Inatsu and Hoskins (2006) correlated on a significant level to the Southern Oscillation Index (SOI).

The controversy about the relations between AAO, ENSO and the SH split jet among these studies led to the question: Can an index be defined which clarifies the relationships between the SH split jet and the large-scale teleconnection indices ENSO and AAO?

In both formerly studies (Bals-Elsholz et al. (2001) (hereafter BE), Inatsu and Hoskins (2006) (IH)) and in the work of Yang and Chang (2006) (YC) indices were developed to detect the characteristics of the SH climatological split in Austral winter. These indices represent the split structure in several meteorological variables and in different but comparable levels: 200 hPa vorticity (BE), 300 hPa zonal wind anomalies (YC), 200 – 300 hPa difference in the zonal mean zonal wind (IH). The mutuality in the construction of all these split indices is a definition based on the regions accounting for the two branches of the split

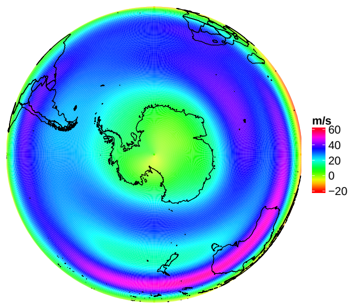

Figure 1. Climatological zonal wind (m/s) in 200 hPa in Austral winter (JAS) averaged for the period 1979–2015.

jet (STJ, PFJ) and the gap between those over the Australian / New Zealand region. Although these indices are constructed similarly, the respective studies revealed inconsistent relations to the AAO and ENSO.

[new: Additionally, the literature lacks a description of whether the split jet variability is related to the Pacific South American (PSA) patterns, although these were found to be associated with both teleconnection indices, ENSO and the AAO. The PSA patterns are conventionally seen as Rossby wave trains emanating in quadrature to each other from the tropical Pacific towards Argentina and serve simultaneous as waveguide for eddies moving south. On interannual time scales the PSA-1 mode is tied to ENSO, while the PSA-2 pattern is associated with the quasi-biennial component of ENSO (e.g., Mo, 2000). Furthermore, although called an “annular” mode, the AAO contains asymmetries, which are most pronounced in Austral winter and over the Pacific sector. This (tropically forced) component of the AAO is related to a fixed active Rossby wave source and resembles the spacial structure of the PSA patterns (Ding et al., 2012).]

[new: The lack of knowledge about the relationship between the split variability and the PSA patterns and the inconsistencies among earlier studies concerning the connections to ENSO and the AAO motivate the development of an improved SH split jet index.] The split jet is one of the most important features of the interannual variability in the SH winter circulation and its pattern is not only centered over the Australian / New Zealand region but bears also hemispheric signatures (Yang and Chang, 2006). Consequently, we assume that the split jet variability is already intrinsically contained in one or several leading modes of the SH winter zonal wind field.

In this study, we provide a PC based methodology to describe the SH wintertime split jet in order to clarify the relations between the SH split jet and the large-scale teleconnection indices ENSO and AAO. This paper is organized as follows: The data set and methodology used for the reconstruction of the split jet indices and for the calculation of the new PC based split index (PSI) are introduced in the data and methods Section 2. The definition of the new index is proposed in Section 3. We will use the PSI to examine the relations between split phases to the known large-scale variability modes (ENSO, AAO and PSA) in Section 4. Finally, the main results are summarized and discussed in Section 5.

2 Data and methods

2.1 Data

This study makes use of the ERA-Interim (Dee et al., 2011) reanalysis data sets from the European Centre for Medium Range Weather Forecast (ECMWF). ERA-Interim was selected because ECMWF products (e.g. MSLP and geopotential height in 500 hPa from ERA-Interim) were found to be the most reliable data, in particular over the Antarctic continent (Bracegirdle and Marshall, 2012).

We use monthly zonal wind an geopotential height data covering the winter seasons, defined here for the months from July to September (JAS) in accordance with the three studies mentioned above. All fields were used on a 0.75° grid and were analyzed for the period from 1979–2015.

The monthly resolved teleconnection indices used in this study, namely the Antarctic Oscillation Index and the Multivariate ENSO Index, are both freely available from NOAA's website (http://www.noaa.gov/).

All time series used in this study are standardized so that they have a mean of zero and a standard deviation of one.

2.2 Empirical Orthogonal Function (EOF) Analysis

Analysis of atmospheric circulation patterns can be done by means of an Empirical Orthogonal Functions Analysis (EOF), which is also referred to as Principal Component Analysis (PCA) (Jolliffe, 2002; Hannachi et al., 2007). By definition, an EOF analysis reduces a data set containing a large number of variables to a data set containing fewer new variables, which are linear combinations of the original ones (Wilks, 2011). The first principal component (PC) is the linear combination with the largest variance.

To analyze the variability of the SH zonal wind we first removed the seasonal cycle by taking the anomalies with respect to a mean annual cycle which was obtained by an average of the individual winter months of the year. The individual grid cells are then centered and scaled with the square-root of their latitude to account for different grid cell sizes. We then performed an EOF analysis of the 111 winter months from the period 1979–2015. The associated PC gives the respective time series.

[new: By definition, the PSA modes are the 2^{nd} and 3^{rd} EOF of the 500 hPa geopotential height anomalies over the SH (Mo, 2000). The associated PCs give the PSA-1 (2^{nd} PC) and PSA-2 (3^{rd} PC) time series.]

2.3 Composite and Correlation Analysis

Composites of months with an anomalous high or low split index are the basis for investigating the potential mechanisms associated with splits in the time-mean SH winter circulation. Monthly values exceeding (undercutting) the respective normalized index mean (1979–2015) about plus (minus) one standard deviation (Hendon et al., 2007) were averaged and defined as positive (negative) composite. To quantify the linear relationship between the split jet time series and several indices of the known large-scale oscillations (i.e. AAO and ENSO) the Pearson's correlation coefficient is evaluated (Wilks, 2011).

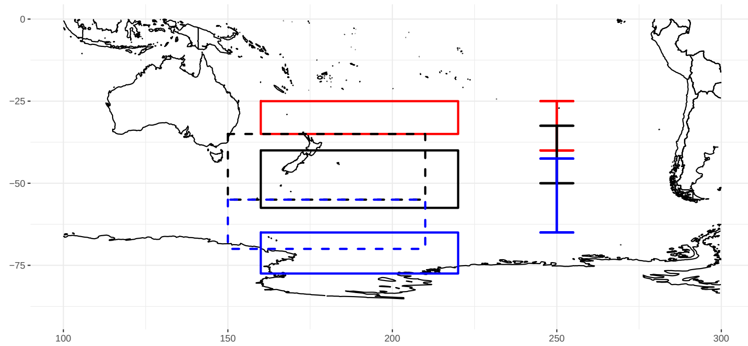

Figure 2. Area definitions of three earlier studies. Red lines show the STJ part, blue lines the PFJ part and the black lines the gap between the two branches defined by the different studies. Continuous lines refer to the SFI of Bals-Elsholz et al. (2001) and dashed lines mark the two regions defined in Yang and Chang (2006). The right side shows the meridional boundaries used in the split index defined by Inatsu and Hoskins (2006).

2.4 Split Jet Index Definitions

Fig. 1 shows the 200 hPa climatological SH winter (JAS) zonal mean wind and the typical time-mean split jet, composed of a subtropical (at 30° S) and a polar branch (roughly at 60° S) as well as the characteristic zonal wind minimum in between.

The three split jet indices which were introduced in the introduction are based on flow characteristics for the specific regions of Australia and New Zealand (see Fig. 2). Each index is based on a Subtropical Jet (STJ) and a Polar Front Jet (PFJ) component and a gap between these two branches, except the YC index, which lacks the subtropical part. Table 1 provides information about these areas and gives an overview of the particular data sets used in the split jet references.

2.4.1 Split-flow Index (SFI)

Bals-Elsholz et al. (2001) developed the very first split index to evaluate the structure and evolution of the SH split jet structure. A Split-Flow Index (SFI) based on the relative vorticity (ζ) in 200 hPa in three neighboring regions (Fig. 2) was designed as follows:

$$SFI = \zeta_{PFJ} + \zeta_{STJ} - \zeta_{GAP} \quad (1)$$

The normalized monthly index gives large negative (positive) values for split (non-split) years. Split flow regimes similar to the climatological mean have normalized SFI values near zero.

	SFI (BE)	STJ (YC)	STJ (IH)	PSI
Reference	Bals-Elsholz et al. (2001)	Yang and Chang (2006)	Inatsu and Hoskins (2006)	Defined within this study (Sec. 3.2)
Data sets				
Variable	relative vorticity	zonal wind	zonal mean wind	zonal wind
Level	200 hPa	300 hPa	mean of 200 and 300 hPa	200 hPa
Data Source	NCEP NCAR	ERA15	ERA40	ERA-Interim
Period	1958 – 2000	1979 – 1993	1979 – 2001	1979–2015
Regions used for definitions				
STJ	25 – 35° S	–	25 – 40° S	
GAP	40 – 57.5° S	35 – 55° S	32.5 – 50° S	SH
PFJ	65 – 77.5° S	55 – 70° S	42.5 – 65° S	

Table 1. List of split jet definition constraints as suggested in three earlier studies. The indices resemble specific areas depicting the equatorward branch of the split (STJ), the gap between the jets (GAP) and the Polar Front Jet part (PFJ).

2.4.2 Normalized Monthly Split-Jet Index (NMSJI)

The Yang and Chang (2006) Split Jet Index (SJI) is based on the difference in 300 hPa time-mean zonal wind anomalies (U) in two adjoining areas (PFJ, GAP). The index is normalized then by subtracting the climatological mean and by dividing its standard deviation.

$$SJI = \overline{U}_a^{PFJ} - \overline{U}_a^{GAP} \tag{2}$$

$$NMSJI = \frac{MSJI - \overline{MSJI}}{\sigma} \tag{3}$$

2.4.3 Split Jet Index (SJI)

The Split Jet Index published by Inatsu and Hoskins (2006) was defined as the difference of the 200 hPa and 300 hPa zonal mean zonal wind (U) between the (overlapping) latitudinal boundaries given in Tab. 1 and illustrated in Fig. 2.

$$SJI = U_{STJ} - 2 \cdot U_{GAP} + U_{PFJ} \tag{4}$$

In agreement with the weighting of the wind minimum between the jets by 2, the index values rise for both, a strong STJ and/or PFJ and reduce or even reverse if there is a strong single jet centered in the (gap) region between the two jets.

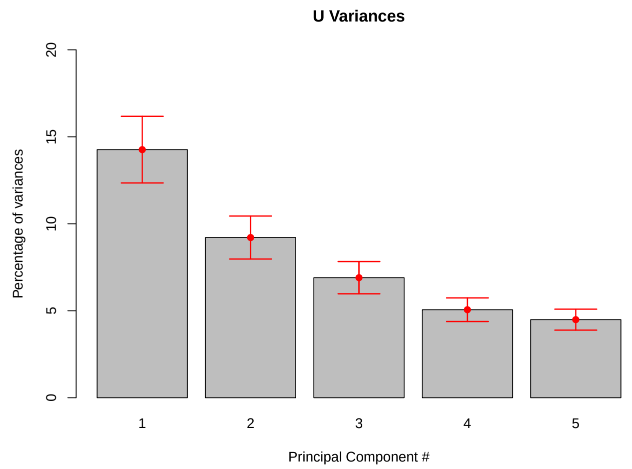

Figure 3. Proportions of the total variance [%] associated with the leading 5 EOFs for the 200 hPa zonal wind field of ERA-Interim reanalysis. Error bars are estimates of sampling errors in EOF computation according to "North's rule of thumb" (North et al., 1982).

3 A new index for the wintertime SH split jet

[new: As mentioned previously, the wintertime split jet is the most prominent asymmetric feature of the mid-latitude SH circulation centered over the Pacific sector although it bears as well hemispheric signatures (Yang and Chang, 2006). In order to design a PC based split jet index, three earlier defined split jet indices (Section 2.4) were reproduced and their respective statistical relationships to the leading modes of the SH wintertime circulation (as depicted by zonal wind anomalies at 200 hPa) have been investigated in this section. The EOF modes showing the largest coherence with the split jet indices (as defined by the respective studies) are assumed to contain the main signals associated with the split variability.]

3.1 EOFs in SH zonal wind

The three leading spatial patterns of variability (EOFs) for [new: U 200 hPa] anomalies on the SH (0–90° S) account for roughly 14%, 9% and 7% of the total variability of the 200 hPa zonal wind field (Fig. 3). The 200 hPa pressure level was chosen due to the mechanisms associated with the jet(s) variability, which have their maximum at that level (e.g., Galvin, 2007). The subsequent EOFs (higher than the 3^{rd}) represent about 5% and less of the total variability and are not distinguishable from each other after "North's rule of thumb" (North et al., 1982).

The correlation between the leading 5 PCs and the split indices introduced earlier is shown in Tab. 2. PC1 correlates significantly (r = -0.49) with the zonal mean zonal wind based index developed by Inatsu and Hoskins (2006) and weakly although significant to the relative vorticity based index designed by Bals-Elsholz et al. (2001). The weaker correlation to the Yang and Chang (2006) index, which is also defined in zonal wind accounts from the fact, that this SJI lacks the STJ part.

	PC1	**PC2**	**PC3**	**PC4**	**PC5**	**PSI**
			JAS – correlation values			
-BE	**-0.28**	**0.44**	**-0.36**	-0.09	-0.15	**0.56**
YC	-0.24	**0.56**	**-0.48**	-0.13	-0.09	**0.73**
IH	**-0.49**	**0.57**	**-0.43**	**0.26**	0.09	**0.71**
Mean	**-0.38**	**0.59**	**-0.48**	0.02	-0.05	**0.76**

Table 2. Monthly (JAS) Pearson correlation coefficients of individual leading 5 PCs in the 200 hPa zonal wind as well as the PSI with the split jet indices introduced in the methods section (Sec. 2). By construction, the Bals-Elsholz et al. (2001) index becomes negative during split events and its sign is therefore reversed. Bold values are significant at the α = 1% level.

Whereas the 4^{th} and 5^{th} PC correlate poorly with any of the indices, the 2^{nd} and 3^{rd} PC show robust relations to split events. While PC2 is strongly positively correlated to the split indices with coefficient values ranging from r = 0.44 (BE) to r = 0.57 (IH), PC3 is negatively related to the split regimes: Pearson's correlation values of PC3 raise from r = -0.36 (BE) to r = -0.48 (YC). Generally, the correlation values associated with the relative vorticity based index designed by Bals-Elsholz et al. (2001) show the weakest links to PC2 and PC3 of the zonal wind field, but are however significant at the α = 1% level.

The two zonal wind-based indices (IH and YC) produce the strongest correlations to PC2 and PC3, which is excelled only by the mean of all three earlier split indices for PC2 (r = 0.59). Altogether, the splits in the westerlies are less correlated to PC1, but are rather associated with the higher order PCs in the 200 hPa zonal wind field.

3.2 Definition of the PC based Split Index (PSI)

From the correlation analysis with three discussed split indices it is apparent, that PC2 and PC3 are associated with the SH wintertime split jet events and resemble the partly split variability. In order to develop a PC based split jet index, these PCs, correlating well with the earlier split jet indices, are coupled to a linear combination. Consequently, the monthly wintertime (JAS) PC based SH Split Jet Index (PSI) is defined as follows:

$$PSI = PC2_{U_{200hPa}} - PC3_{U_{200hPa}} \quad (5)$$

The PSI is based on the 2^{nd} and 3^{rd} PC of the anomalous 200 hPa zonal wind field over the whole SH during Austral winter (JAS). The PSI time series, as well as the split indices of the previous studies, are displayed in Fig. 4.

The correlation values between these indices and the PSI in 200 hPa are shown in the last column of Tab. 2. All indices are well correlated to the PSI with coefficients ranging from 0.56 (BE) to 0.73 (YC) and the mean of all the three earlier split indices raises Pearson's correlation coefficient to r = 0.76. This relationship is significant at the α = 1% level and shows that the linear combination of PC2 and PC3 exceeds the relation compared to the performance of the individual PCs (Tab. 2).

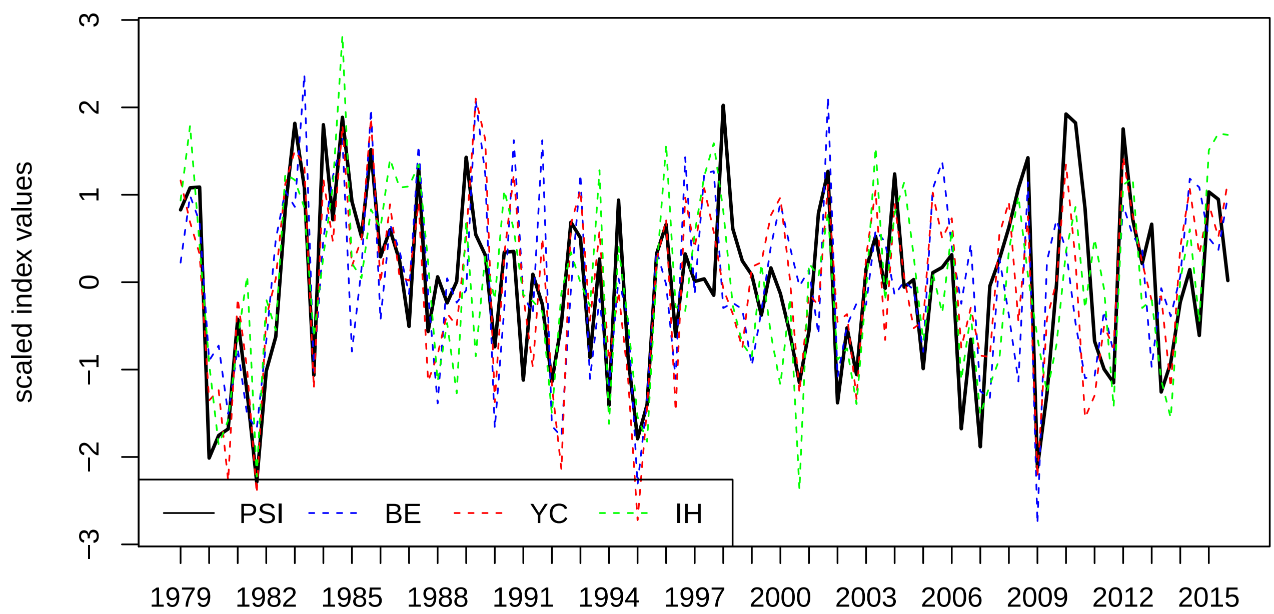

Figure 4. PSI (PC2-PC3) index in 200 hPa zonal wind and three earlier split jet indices defined by Bals-Elsholz et al. (2001) (BE), Yang and Chang (2006) (YC) and Inatsu and Hoskins (2006) (IH). All time series were scaled for illustration purposes.

4 Results

4.1 Composite Analysis of U 200 hPa with PSI

Fig. 5 shows the spatial patterns of U in 200 hPa for high (18 cases) and low (19 cases) PSI index phases. The positive composite affirms the characteristic split structure with an existing, but weak STJ, a pronounced PFJ and a well-defined minimum of zonal wind strength in between. The split composite shows that the PFJ strength is not limited to the Australian sector of the east Pacific, but is enhanced from the Indian Ocean over the full width of the South Pacific Ocean. The low index composite displays a clear non-split or "merged" jet state with a strong STJ over the Australian continent and a missing PFJ. The spatial patterns of the split and non-split cases are well captured by the PSI and show similar results to the composites of the indices defined in Section 2.4 (not shown).

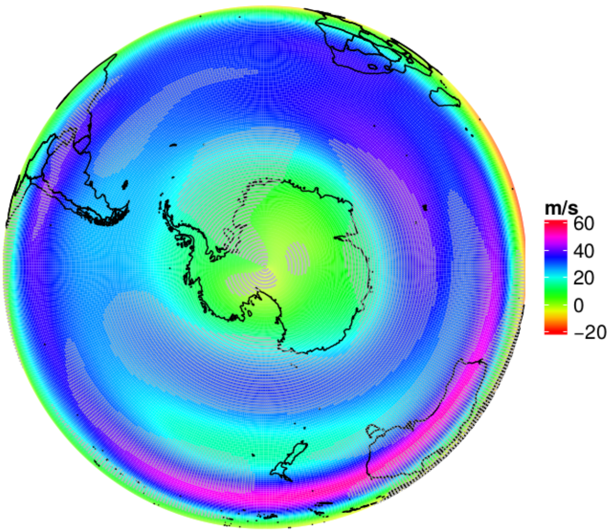

Figure 5. Positive (left) and negative (right) composite of the PSI (PC2-PC3) index in 200 hPa zonal wind. Gray dotted areas are significant at the α = 1% level.

To understand the contribution of both components of PSI, i.e. PC2 and PC3, a composite study of both PCs was also done separately. Fig. 6 shows the appropriate composites of the 2^{nd} and 3^{rd} EOF in U 200 hPa. Please note that the plots in Fig. 6 are arranged in such a way, that the left column refers to the split condition and the right column to the non-split phase. The positive composite of PC2 shows the typical split, which was developed over the Indian Ocean and strengthened in the western Pacific sector where a clear double jet structure with a pronounced minimum in U 200 hPa between the two jets is visible. Crosswise, the negative composite of PC2 displays a single jet formation (right column).

The bottom row of Fig. 6 gives the equivalent composites of PC3. The most striking difference in the split composites (Fig. 6, top left) is the PFJ strength over the western Pacific Ocean and the Drake Passage, which lacks in the PC2 composite. Compared to PC2, where the PFJ blends over the central Pacific, the PFJ reinforces and establishes a double jet structure over the Atlantic Ocean, which breaks down south of South Africa and results in a strong STJ again (Fig. 6, bottom left). A further feature of the positive composite is the lack of annular structure compared to PC2. In literature, this known zonal wave number 3 pattern is often referred to as a modulator of e.g. Blocking events in the New Zealand region and Australian rainfall (Trenberth and Mo, 1985; Pook et al., 2013).

The negative composite (Fig. 6, bottom right) of the second term of Eq. 5, i.e. -PC3 (non-split / single jet regime) bears resemblance to the appropriate composite of PC2 but describes a stronger STJ over the central and east South Pacific Ocean

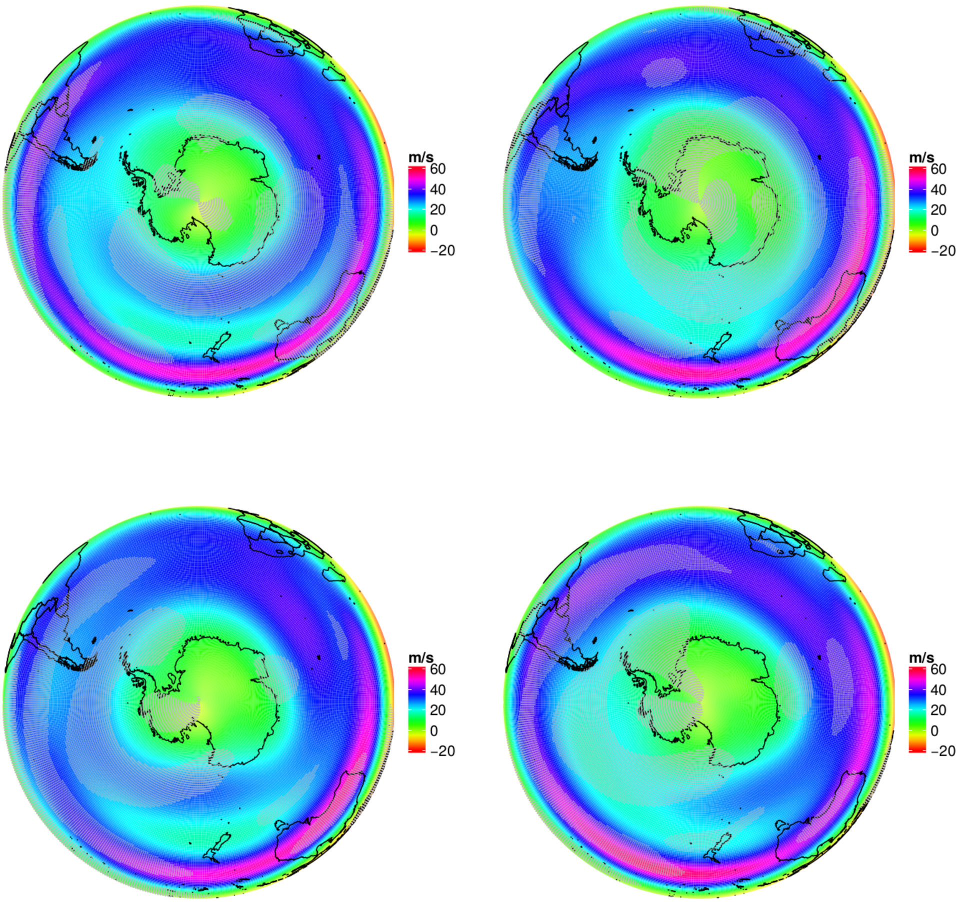

Figure 6. Composites of positive (left) and negative (right) phases of PC2 (first summand of Eq. 5; top row) and -PC3 (second summand of Eq. 5; bottom row) time series of the SH zonal wind in 200 hPa. Gray dotted areas are significant at the α = 1% level.

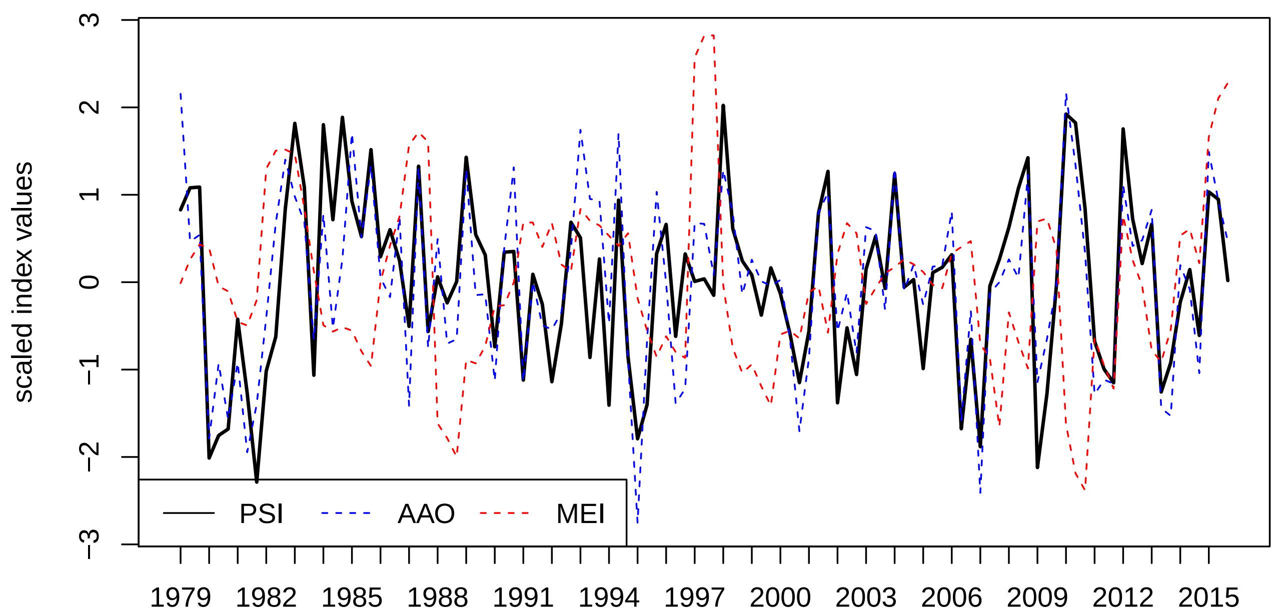

Figure 7. Time series of PSI (black solid line), NOAA's AAO (blue dotted line) and NOAA's MEI (red dotted line) from 1979 to 2015.

and South America. Additionally, the PFJ is weakened in the non-split composite, but south of the Australian / New Zealand region there are still traces of a PFJ.

In summary, the positive PSI composite (Fig. 5 left) benefits from the combination of the double jet structure with a pronounced minimum between the jets associated with PC2(+) and the strong PFJ over the South Pacific Ocean associated with the "non-annular" component localized over the South Pacific Ocean of PC3(-).

4.2 Links between PSI and large-scale climate modes (AAO, ENSO and PSA)

In order to determine whether the PSI is modulated by large-scale phenomena, i.e. the Antarctic Oscillation (AAO) and the El Niño-Southern Oscillation (ENSO), correlations between the PSI and the teleconnection indices are computed. The respective time series are illustrated in Fig. 7 and Pearson's correlation coefficients, based on 111 winter months, are summarized in Tab. 3.

	PSI	PC2	PC3	BE	YC	IH	Mean
JAS – correlation values							
AAO	**0.81**	**0.65**	**-0.50**	**0.45**	**0.66**	**0.58**	**0.64**
MEI	-0.09	0.07	0.20	0.20	0.12	**0.34**	**0.25**
PSA-1	0.19	**-0.26**	**-0.55**	0.14	0.16	-0.17	0.05
PSA-2	0.06	0.20	0.13	0.22	0.20	-0.12	0.11

Table 3. Monthly (JAS) Pearson correlation coefficients of the three split indices introduced in the methods section, as well as the PSI with three major SH climate mode indices for the Antarctic Oscillation (AAO), ENSO (Multivariate ENSO Index) [new: and the Pacific South American (PSA) patterns (PSA indices as defined in Mo (2000) for PSA-1 and PSA-2).] Bold values are significant at the α = 1% level.

The Antarctic Oscillation (AAO), in literature also referred to as the Southern Annular Mode (SAM), is defined here as the anomalous geopotential height in 700 hPa (NOAA's AAO) and describes the out-of-phase pressure anomalies in polar and mid-latitude regions (e.g. Lorenz and Hartmann (2001), Thompson and Wallace (2000)). The correlation analysis reveals a powerful connection (r = 0.81) between the PSI (defined in 200 hPa) and the AAO. The highly significant correlation value accounts for the large influence of the AAO to the PFJ variability, which in turn is associated with the regime of the jets (Fyfe (2003), Gallego et al. (2005)).

Although there is a significant correlation to the AAO proposing a strong link to the PSI variability, there is no such relation to the Multivariate ENSO Index (MEI). Fig. 8 shows a regression of the monthly MEI values in dependence on the respect PSI value. The correlation value between the PSI and MEI is low (r = 0.04), but by comparing the top left and the top right quadrant of the scatter plot (Fig. 8) to the respective bottom quadrants it is evident that warm (red dots) and cold (red dots) ENSO events are both associated with positive (or neutral) values of the PSI. Altogether, from 24 warm and cold ENSO events as occurred in 111 winter months, there was no month with a negative PSI value. This asymmetric and nonlinear behavior damps the correlative relation.

Tab. 4 gives counts of positive (first column), negative (second column) and neutral (last column) PSI months and the corresponding predominant AAO and ENSO states. The box, which emerges when concentrating on the first six lines and columns of the same table, contains all possible AAO^+/PSI^+ and AAO^-/PSI^- cases during the analysis period. Although the AAO index is well correlated to the PSI, the last column of the same table bears that 5 AAO^+ months are marked as neutral PSI months, while there are 5 months of PSI^+ and neutral AAO conditions. Consequently, the jet is able to split under neutral AAO conditions and not every AAO^+ month leads compulsorily to a split event. The negative phases of the AAO nearly mirror the conditions of its positive counterpart. Altogether 7 events occurred under AAO^-/PSI^0, likewise, 6 months were counted as AAO^0/PSI^- cases.

By revisiting these points in the investigated period from 1979 to 2015 it turns out that 3 months of the first case (AAO^+/PSI^0) occurred in a period during the 1980s and 3 of the latter cases (AAO^0/PSI^+) build a sequence in the 1990s (not shown). A spectral analysis of the time series of the differences between PSI and AAO index shows multiple frequencies over the 37 year

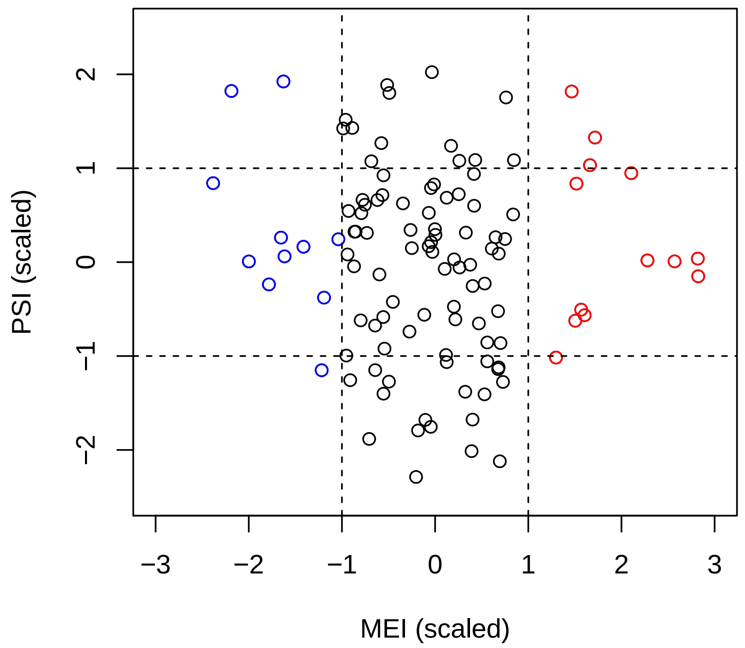

Figure 8. Scatter plot of the new split index (PSI) and MEI, the Multivariate ENSO Index (each normalized to unit variance). Dashed lines give (minus) one standard deviation of MEI and PSI indices, respectively. Red (blue) dots mark warm (cold) ENSO events.

Combination	**PSI$^+$**	**PSI$^-$**	**PSI^0**
AAO$^+$ MEI$^+$	3	–	–
AAO$^+$ MEI$^-$	2	–	–
AAO$^+$ MEI^0	8	–	5
AAO$^-$ MEI$^+$	–	–	1
AAO$^-$ MEI$^-$	–	1	–
AAO$^-$ MEI^0	–	12	6
AAO^0 MEI$^+$	2	–	7
AAO^0 MEI$^-$	–	–	8
AAO^0 MEI^0	3	6	47

Table 4. The predominant jet regimes (PSI$^+$ = split jet, PSI$^-$ = single jet, PSI^0 = mixed jet regime) as counted during the 111 winter months of the 1979–2015 period, separated by occurred combinations of AAO and ENSO states.

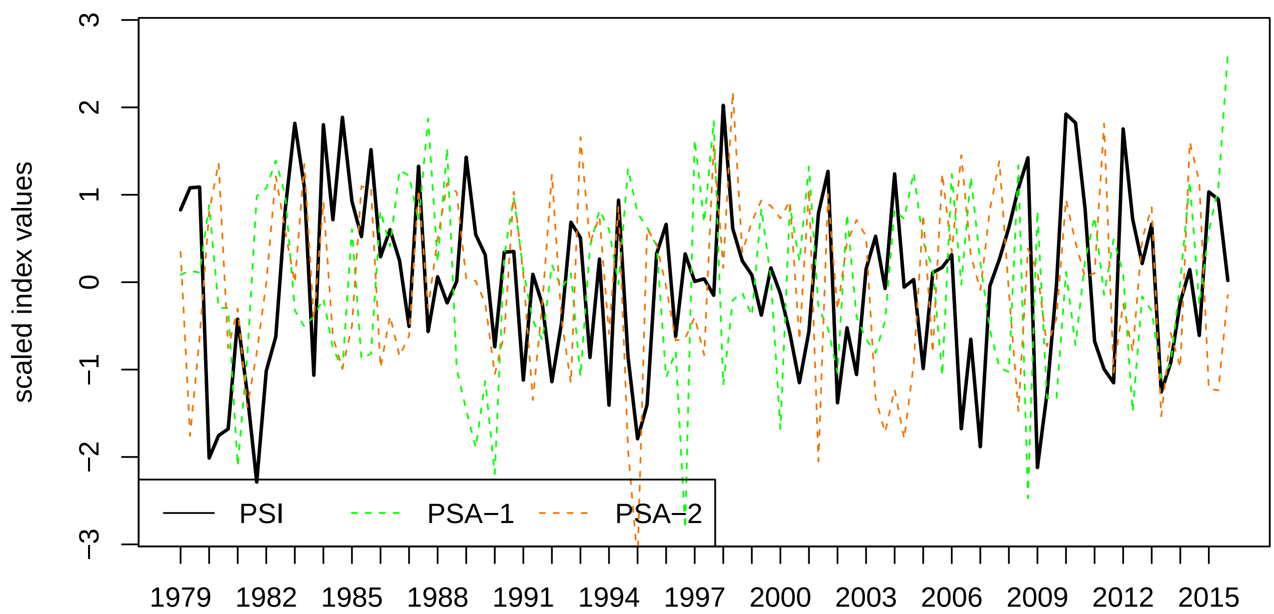

Figure 9. [new: Time series of PSI (black solid line), PSA-1 index (green dotted line) and PSA-2 index (orange dotted line) from 1979 to 2015.]

long period (not shown). Unfortunately, the time series is too short to draw meaningful conclusions about decadal to centennial variabilities. Furthermore, the time series of differences is neither correlated to ENSO nor to the well known Pacific Decadal Oscillation (NOAA's PDO index, not shown).

The low correlative relationship between MEI and PSI mentioned above arises from the fact, that 8 out of 18 split events occurred during any flavor of ENSO phases, while only one cold ENSO event occurred in a negative PSI phase. The last three rows of Tab. 4 reveal that there are 7 (8) ENSO warm (cold) events, thereof the extreme La Niña event in 1988 and the severe El Niño event from 1997, where a mixed jet (PSI^0) regime predominated.

[new: Fig. 9 shows the time series of both PSA modes and the PSI. Although the correlation between PSI and the PSA indices is low (r_{PSA-1} = 0.19 and r_{PSA-2} = 0.06), the PSA-1 mode is significantly correlated to the individual PCs of the SH zonal circulation variability (Tab. 3). Both PSI components (i.e. PC2 and PC3) are associated to the PSA-1 pattern. The spacial pattern of EOF2 was previously identified to resemble the dominant part of the split jet structure (Section 3.1) marked by an intensified PFJ over the eastern hemisphere. Since the PSA-1 pattern is primary associated with the variability over the central and western Pacific sectors, it can be concluded that PC2 describes less PSA-1 variability but contains a considerable part of the wind response associated with the AAO. PC3 accounts for the “non-annular” component of the PSI and contains most variability over the Pacific sector. It is argued, that PC3 contains remarkable PSA-1 variability. However, only 3 cases were identified where both indices, PSI and PSA-1, exceeded the threshold of one standard deviation during the analysis period (not shown).]

5 Summary and discussion

While many previous studies of the SH winter circulation examined the presence, origin and structure of the climatological time-mean SH split jet, which establishes over the western South Pacific Ocean in the vicinity the South Australia / New Zealand region, only a few studies developed indices capturing the SH split variability to quantify the relations to the large-scale variabilities, i.e. the Antarctic Oscillation (AAO) and the El Niño-Southern Oscillation (ENSO).

According to our literature review, up to now there are three (past) studies suggesting a SH split jet index. All indices use a region based definition, which contradicts the assumption, that the SH split jet is a hemispheric feature rather than a regional effect. The most important advantage and the novelty of our new PC based split index (PSI) compared to the existing indices, is its independence from regional definitions: The PSI is defined by linearly combining the SH 2^{nd} and 3^{rd} principal component of the monthly (JAS) anomalous zonal wind in 200 hPa.

The PSI correlates well to the individual split indices and the mean of all gives a significant correlation coefficient of 0.76 to the PSI. An analysis of Bals-Elsholz et al. (2001) showed, that their SFI agreed favorably with a subjective classification of the split regime, with the exception of 1998. This year was affected by a strong La Niña event and an anomalously weak STJ. While the three earlier split indices failed to agree with the (subjective) split regime, the PSI value for July 1998 was high and thus marked as one of 18 split events. From this fact, from the correlation analysis and the investigation of PSI composites in the 200 hPa zonal wind field it is evident, that our PC based split index is able to reproduce the SH wintertime split jet structure.

Separate composites of PC2 and PC3 reveal that both PCs are essential for the split representation. PC2 is associated with the jet strength (Lorenz and Hartmann, 2001) over the eastern hemisphere, whereas PC3 exhibits a “non-annular” component in both composites. It is reasoned that split events are connected to PC2 because it represents the jet strength and to PC3, as it adds a “non-annular” component to the jet variability. Thus, the PC based split jet index (PSI) is a qualitative measure of the spatio-temporal variability of the split jet and can efficiently be used to investigate the relationships to the known climate variability modes, i.e. AAO, ENSO and PSA patterns.

Although not demonstrated in earlier studies concerning the SH circulation (jet) variability (e.g. Gallego et al. (2005)) it was expected that the SH split jet exhibits a solid connection to the AAO. The new PSI shows a highly significant correlation to the leading mode in a near-surface level of the geopotential height anomalies (NOAA’s AAO in 700 hPa) with r = 0.81. This highly significant relation of the PSI to the leading mode in geopotential reiterates the importance of the AAO to the PFJ variability (Fyfe (2003), Gallego et al. (2005)). The PFJ strength is enhanced under AAO^{+} conditions in accordance with the negative pressure anomalies over the polar region occurring under AAO^{+}. Since the PFJ variability is more important for the representation of split events (Bals-Elsholz et al., 2001) than its subtropical counterpart, the AAO has a high correlation with the PSI (0.81). Nevertheless, there are 5 out of 18 split events occurring in the analysis period of 1979–2015, where the AAO index had a neutral value. It can be concluded that a positive AAO phase is a preferred condition for the SH split jet, however, the split jet is also able to arise in neutral AAO months.

The correlation between the Multivariate ENSO Index (MEI) to the PSI is low, but 7 out of 18 split events occurred during a warm (5) or cold (2) ENSO month. The occurrence of both, warm and cold ENSO events damps indeed the correlation value to the PSI, but the relative frequency of ENSO events is still 30%. It seems likely that any kind of ENSO flavor is favorable for split events, which results in a nonlinear relation between PSI and ENSO, i.e. that positive (negative) PSI values mainly occurred during warm or cold (neutral) ENSO states. From earlier studies it is well known, that El Niño (La Niña) phases enhance (reduce) the STJ strength over the South Pacific Ocean via advection of mean flow momentum flux (e.g. Chen et al. (1996)). This is consistent with our finding that 5 out of 18 split events occurred during a warm ENSO phase, which enhances the STJ (PFJ) strength. Otherwise, there are strong ENSO events (El Niño of 1997 and La Niña in 1988) during the analysis period, which did not lead to a pronounced split event. Thus, an ENSO event alone is not able to reproduce the SH split jet variability. Worth mentioning, in literature it is well known that ENSO and AAO are in turn not independent from each other. There are hints that cold ENSO events are favored by positive phases of the AAO (e.g. Carvalho et al. (2005)). As these are in turn associated with split events, we expected La Niña phases to occur more often than El Niño events during PSI^+ phases. Contrastingly, the ENSO warm phase coincided more frequent (5 months) with the high PSI (split jet) phases than its cold counterpart (2 months), although both flavors of ENSO appeared roughly equally during the considered time period of 111 winter months. It is reasoned that the ENSO induced Rossby wave dynamics are beneficial for the SH split jet modulation, regardless of the sign of that oscillation. However, further work is needed here to clarify the complex relationship between ENSO and the SH split jet.

[new: The traditional perception suggests that the PSA patterns are part of a stationary Rossby wave train extending from the central Pacific to Argentina (e.g., Mo and Higgins, 1998). The PSA patterns, typically defined as 2^{nd} and 3^{rd} modes of tropospheric geopotential height variability over the SH (e.g., Mo, 2000), have been attributed to ENSO (PSA-1) on interannual time scales and to the quasi-biennial component of ENSO and the Madden-Julian-Oscillation (PSA-2), respectively (Mo and Paegle, 2001). The relationship between the PSA indices and the PSI revealed a low relationship to both indices ($r_{PSA-1} \approx 0.2$ and $r_{PSA-2} = 0.06$). In contrast, the individual PCs of the zonal circulation in 200 hPa correlate significantly to the PSA-1 index. Positive PSA phases are associated with a strong PFJ over the western Pacific sector (not shown) and the PSA-1 mode is consistently significantly correlated to the PC3(-) component, which is (by definition) related to split events. Negative PSA events are associated with an enhanced PFJ over the eastern hemisphere, which represents the partly EOF2 variability. It is reasoned that PC3 represents both, AAO as well as PSA variability. However, the connection between the PSA-1 mode and the PSI is canceled out by the PC2 component, which is (as well as the PC3 component) negatively correlated to the PSA-1 mode.]

The authors concluded that the strength of the relations between the new PC based SH split jet index and the large-scale modes AAO and ENSO are nonlinear. The highly significant relationship to the AAO highlights the importance of the PFJ variability, which is a determining factor for the split jet formation, while the ENSO and PSA effects are complex and relatively less important.

Interestingly, the SH split jet representation is poor in the Earth System Model (not shown) of the Max-Planck-Institute of Meteorology (MPI-ESM) in the Medium resolution (Giorgetta et al., 2013). A possible reason for this deficiency could be a too strong modeled low-pressure system over the Amundsen Sea (Jungclaus et al., 2013), i.e. the prominent (surface) Amundsen Sea Low (ASL). The underestimated variability in that model leads to significant differences in the representation of the leading EOF patterns in the 700 hPa geopotential height (and thus zonal wind) fields in the MPI-ESM model compared to the ERA-Interim reanalysis (Babian et al., 2016).

An extension of the current work is the investigation of seasonal variations in the PSI. In the context of a positive summertime trend in the AAO due to ozone depletion, it is likely that the PSI exhibits significant trends at least on seasonal time scales. Furthermore, the potential of a higher temporal resolved index will be explored. A daily index would be desirable to describe the processes connected to Blocking activity over the Australia / New Zealand sector. These options are currently being investigated and the results will be published in a follow-up study.

Data availability. The ERA-Interim reanalysis data used in this article are freely available from the ECMWF (https://www.ecmwf.int/en/research/climate-reanalysis/era-interim). The climate indices are available from NOAA (http://www.noaa.gov/).

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