Response to Reviews, CotP, Maupin et al.

Major Comments

<u>1) Comparison of Solomons vs. Vanuatu Stalagmite Records</u>

Correge states: The most disturbing fact is that no comparison is made with the speleothem record from Vanuatu published three months ago in Geology by the same authors. The two records look quite similar, and the Vanuatu record should be discussed.

***Response*: The reason that the two records were not compared in the initial CotP submission is due to the timing of the publication of the individual submissions to different journals. However, now that the Geology manuscript is published, we have the opportunity during the review process to compare the two records in this manuscript.**

We include a new figure that compares the two stalagmite records. Additionally, we have computed Singular Spectrum Analysis (SSA) to compare the timescale of variability and percent variance that the variability explains in the individual records. SSA results indicate that the top three principal components (PC; ~50 year, ~30 year, and ~17 year periods) account for >70% of the variance in both time series. Both the original $\delta^{18}O$ time series and the reconstructed $\delta^{18}O$ time series using the top 3 PC's are plotted for comparison to highlight the similarities pointed out by the reviewer.

New Text Discussing Stalagmite Comparison:

We compare our stalagmite record to a similar stalagmite record from Vanuatu (Fig. 8; Partin et al., 2013). The proxy rainfall record of Partin et al., (2013), documented decadal to multidecadal-scale rainfall changes within the SPCZ, ~1000 km to the southeast of our Solomon Islands study site. This proxy rainfall variability at Vanuatu was attributed to internal climate variability associated with the SPCZ, and not to external forcing. We performed SSA analyses on the two stalagmite records to test whether they share variance in the multidecadal band and hence record a common SPCZ signal. The first three principal components (PC) over the common interval of stalagmite growth (1557-2003 CE) are the same in both records (~50 yr, ~30 yr, ~17 yr, in descending order of variance explained) and account for over 70% of the variance in each. The percent variance explained by each PC is 40% at ~50 years, 25% at ~30 years, and 10% at ~17 years. The SSA results confirm a common signal at decadal to multidecadal time scales, which likely derives from regional scale changes in the SPCZ.

New Figure With Caption:

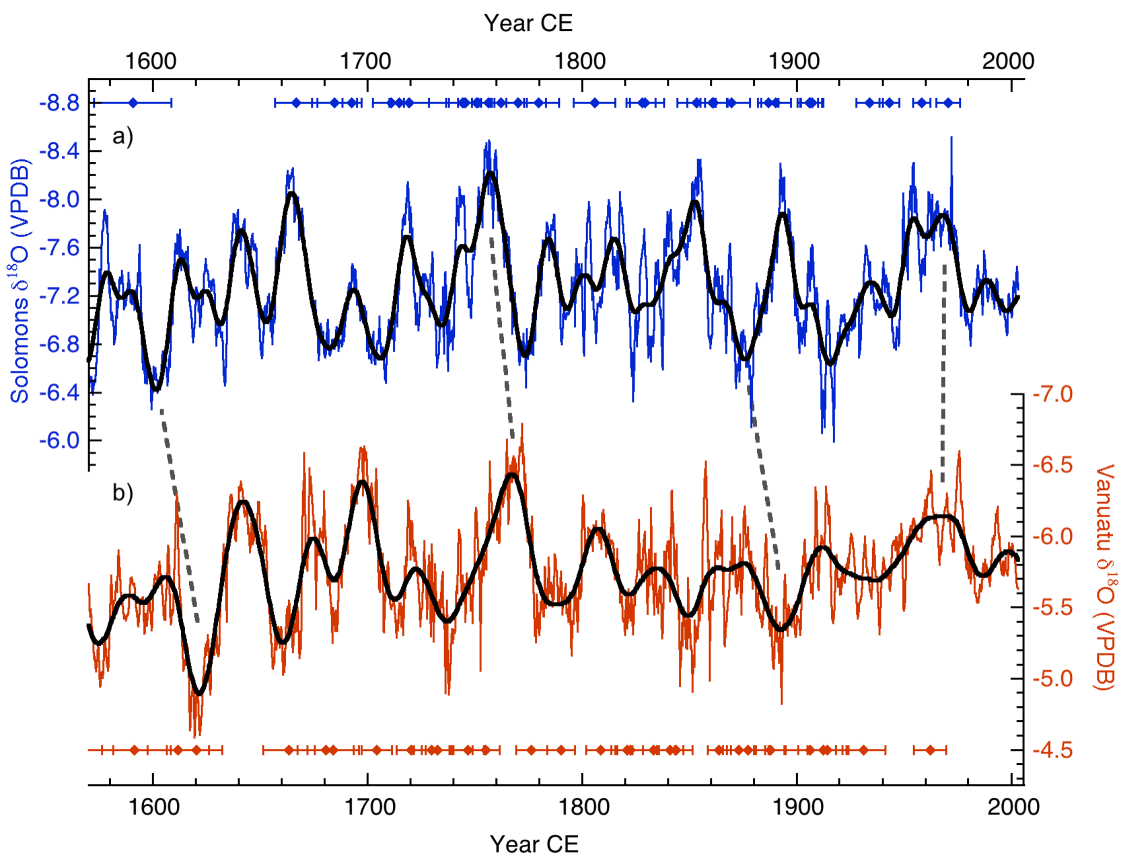

Fig. 8. Comparison of stalagmite $\delta^{18}O$ records from (a) Solomon Islands (blue) and (b) Vanuatu (red). Also plotted are the reconstructed SSA components for both records (RC, thick black line): Solomons, the first PC (35% variance at 48 years), the second PC (25% variance at 30 years), and the third PC (11% variance at 16 years); Vanuatu, the first PC (41% variance at 56 years), the second PC (25% variance at 30 years), and the third PC (9% variance at 18 years). Dashed lines highlight select periods of high and low rainfall that are coeval between the sites within age model error. The two stalagmite $\delta^{18}O$ records have similar variability in both the time and frequency domains suggesting that the multidecadal variability is regional in scale. This implies that changes in the SPCZ are the source of the observed variability in the stalagmite records. Such large-scale changes are consistent with the basin-scale nature of epoch changes and hypothesized internal forcing of variability.

2) Stalagmite Variability with Respect to Climate Variability

i) Larger-Scale Climate Dynamics

Reviewers: Both reviewers comment that there is a need to contextualize the stalagmite record of SPCZ variability in terms of larger scale climate dynamics.

***Response*:** **In the previous version, there was an emphasis on solar forcing. In the revised version, we more fully and systematically investigate additional mechanisms, in addition to solar forcing, that may explain the stalagmite $\delta^{18}O$ variability and conclude that internal climate variability is responsible for the decadal to multidecadal variability in the stalagmite record. We are including with these responses a revised introduction section where we address several mechanisms for decadal-scale variability. We have also have revised submitted Figure 8 to include a panel on volcanic forcing. Additionally, we have revised section 3.3, originally called 'External Forcing Versus Internal Variability' to 'Stalagmite Variability: External Forcing vs. Internal Variability', in the discussion that better connects the stalagmite record with larger scale climate indices, as plotted in submitted Figure 9.**

Revised Figure With Caption:

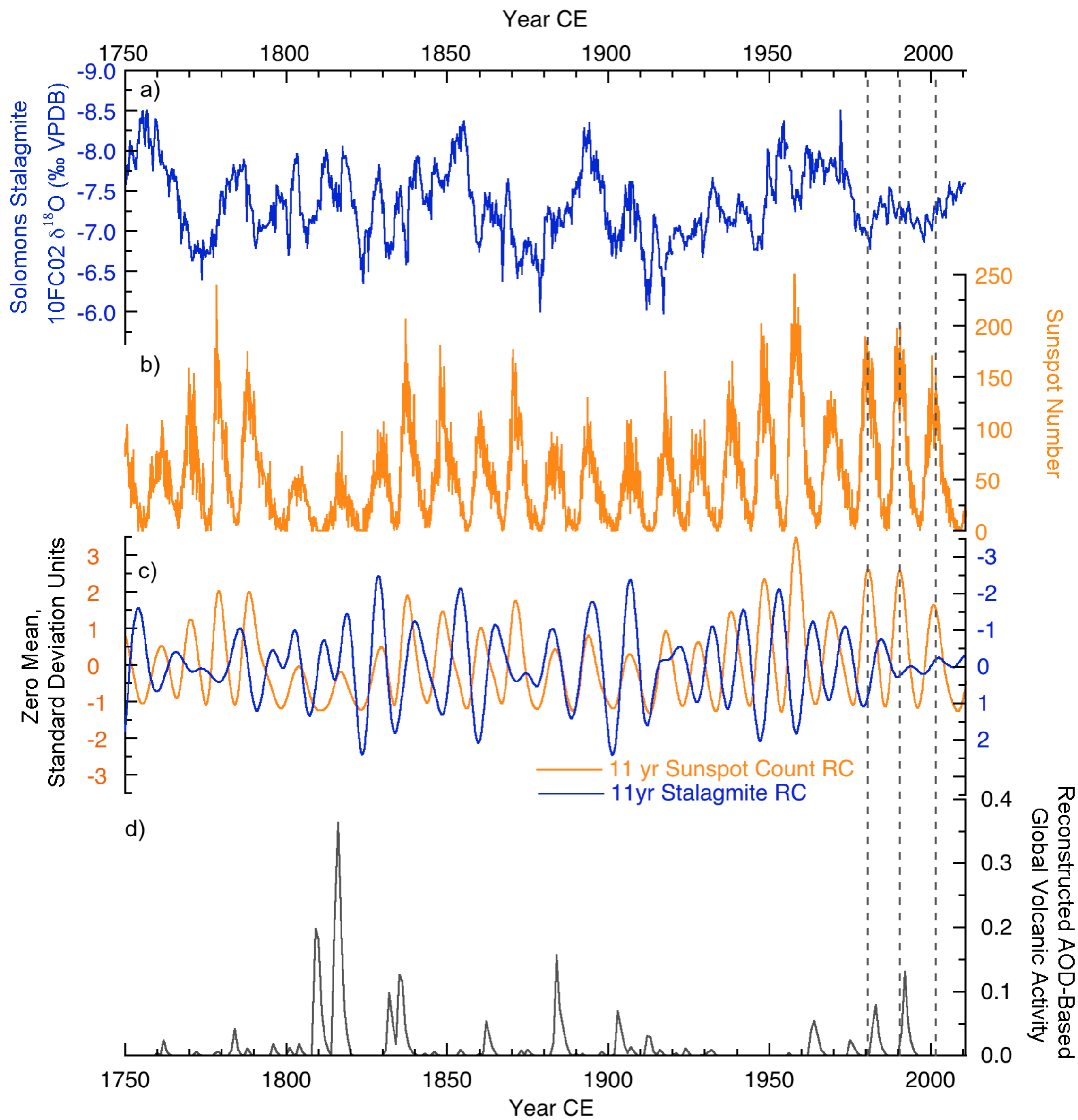

Fig. 9. Stalagmite δ^{18}O variations compared with records of solar and volcanic forcing over the period 1750-2009. Panel (a): Solomons stalagmite sample 10FCO2 δ^{18}O record. Panel (b): record of variations in sunspot number (reference). Panel (c): Reconstructed SSA components (RC) in the stalagmite and sunspot number records, selected to highlight the 11-year sunspot cycle. For the stalagmite record, the fourth PC (6% variance at 12 years) and fifth PC (4% variance at 10 years), which average to 11 years, are used to create a stalagmite RC. For the sunspot number record, the first PC (52% variance at 12 years) and second PC (33% variance at 10 years), again averaging to 11 years, are used to create a sunspot RC. The most recent three peaks of sunspot activity used by (Matthews, 2011; Meehl et al., 2009) to hypothesize a response in SPCZ precipitation to changing sunspot numbers are marked by vertical dashed lines. Panel (d) illustrates the volcanic aerosol optical depth (AOD) proxy reconstruction of global volcanic activity from Crowley

and Unterman (2012). There is no systematic relationship in phasing or amplitude modulation of the stalagmite record that supports external forcing by sunspots or volcanic activity as a driver of multidecadal SPCZ variability.

New section 1.1 here

1.1. Pacific Decadal Variability

Pacific Decadal Variability (PDV) is intimately linked with global climate variability, and is a critical factor in infrastructure and resource management planning (Cane, 2010; Dong and Lu, 2013; Goddard et al., 2012). Multiple mechanisms have been proposed to explain the source of the decadal to multidecadal-scale variability in the Pacific including: 1) solar forcing (e.g., Meehl et al., 2009), 2) volcanic forcing (e.g. Crowley, 2000; Robock, 2000), 3) oceanic integration of short-term atmospheric forcing (Newman et al., 2003; Clement et al., 2011), 4) ocean forcing via subtropical cells (Gu and Philander, 1997; McPhaden and Zhang, 2002; Zhang and McPhaden, 2006), and 5) tropical-extratropical feedbacks (Di Lorenzo et al., 2010). There is no consensus, however on the dynamical mechanism responsible for the decadal variability, which is manifest in a number of atmospheric and oceanic parameters.

A recent example of PDV occurred in 1976/1977, when multiple, basin-scale atmospheric and oceanic parameters shifted coherently to a different mean state, or epoch, that lasted for decades (Mantua, 1997; 2002). Mantua (2002) concluded that these shifts occurred primarily with 20 and 50 year periodicities in the twentieth century. The equatorial and eastern tropical Pacific became anomalously warm (Garreaud and Battisti, 1999; Zhang and McPhaden, 2006), and significantly weakened surface tradewinds and convergence just south of the equator with a span from Papua New Guinea and the Solomon Islands eastward to the South American coast were observed (Folland et al., 2002; Dong and Liu, 2013). Concurrently, there was a precipitous drop in sea level pressure (SLP) gradient across the tropical Pacific (Vecchi et al. 2006; L'Hereux 2013). Observations also support an overall weakened PWC state from 1976-1999, with a pattern of weakening easterlies aloft, mirroring the weakened surface pattern (Vecchi et al. 2006; Dong and Liu, 2013).

An important, but understudied, carrier of the atmospheric signal of PDV is the South Pacific Convergence Zone (SPCZ), which is the largest persistent rain band in the Southern Hemisphere extending from Papua New Guinea to Tahiti (e.g., Vincent, 1994). The areal extent of the SPCZ makes it the primary source of rainfall to Pacific island communities. The SPCZ consists of a equatorial portion, normally located over the western Pacific warm pool and a diagonal portion, orientated northwest–southeast (Vincent 1994), extending from near the Solomon Islands to Tahiti. On decadal time scales, the mean position of the SPCZ moves to the north and east or the south and west depending on the phase of the PDV (e.g., Deser, 2004; Dong and Lu, 2013). Two such movements in mean SPCZ position have been identified using instrumental data of rainfall (1946-1947, 1976-1977; Deser et al., 2004). Reconstructions of rainfall variability in the pre-instrumental period are needed to address whether decadal changes in mean SPCZ position are a persistent characteristic of PDV.

ii) 1976/77 Regime Shift

Anon. Reviewer states: 5595, 1 ff. It is confusing how the shift in the climate in 1976/77 is introduced. The changes in the SPCZ, PWC strength and tropical SST anomalies associated with IPO are discussed. Do these changes define these "distinct epochs"? I think you need to be clear about defining this terms, otherwise it seems like you are suggesting that a regime shift occurs during different IPO phases, but this is also an important impact of the regime shift.

***Response*: We are including with these responses a revised introduction section where we address several mechanisms for decadal-scale variability, as well as text that addresses the impact of 1976/77 regime shift. The revised discussion (Section 3.3) contains text (pasted below) that connects the stalagmite variability to larger scale climate indices during this (and other) regime shift.**

The 1976/1977 regime shift exhibits simultaneous changes that would contribute to a reduction in rainfall at the study site. Reduced surface tradewinds and easterlies aloft, and a weakening in the thermally direct Walker circulation means less latent heat flux into the atmosphere by trade-wind-driven evaporative cooling. This reduced tradewind strength has been documented by Folland et al. (2002) to allow a northeastward displacement of the SPCZ. It stands to reason that such a response mechanism to ocean-atmosphere PDV would be in operation prior to the 1976/1977 shift. Additionally, from a thermodynamic standpoint, a reduced latent heat flux into the atmosphere means that less rainfall in the tropical SPCZ and WPWP deep convection regions is required to satisfy the radiation budget.

iii) Solar Variability

5604-5605: 5605 chapter 3.3: I think the authors do not treat this part properly. They find a 11 yr cycle in their record. Sometimes, it fits the solar cycle very well, sometimes it doesn't. So their conclusion is that the speleothem 11 yr cycle is due to internal forcing of the ocean-atmosphere system. This could be true, but I think an alternative explanation can be put forward. The authors never mention the effect of volcanic eruption, although it is well-known that they will affect the climate and also cloud nucleation. It is for example quite striking to see that the in-phase relationship between the speleothem and the solar records breaks down at about the time of the Krakatoa eruption (figure 8, around 1883), to reappear after a few decades. Thus, there is the potential for volcanic eruptions to momentarily disrupt the solar- precipitation relationship (another kind of a "perturbed oscillator"), and this should be discussed in the text.

***Response*: The reviewer correctly points out a disconnect between the section title of 3.3 and the text of that section that concentrates on sunspot number. We are revising the introduction, Figure 8, and section 3.3 to address other mechanisms, including volcanic forcing, that could drive the decadal variability in the stalagmite record.**

3) Consideration of Climate Modeling Results

Reviewer: 5597 line 4-5: the Cai et al. Nature 2012 reference would be useful here to discuss the long term displacement of the SPCZ towards the Equator.

the last paragraph needs additional modelling references because global warming may also affect the record (e.g. Cai et al. 2012 and others)

5607 first sentence of chapter 4: Some models predict a more zonal SPCZ with global warming, so the increase of rain within the SPCZ might be displaced towards the Equator.

***Response*: The authors recognize that modeling studies have investigated SPCZ changes in response to anthropogenic forcing (Perkins et al., 2012; Cai et al., 2013), and the movements of the SPCZ on interannual timescales associated with ENSO. However, there is no trend in the stalagmite record associated with a long-term displacement of the SPCZ in conjunction with observed changes in Walker Circulation (Vecchi et al., 2006), and the stalagmite record cannot systematically resolve interannual variability (see wavelet analysis). Therefore, in the manuscript we revise the text (pasted below) that mentions the references to interannual changes in the SPCZ, but will not add much discussion about interannual changes due to the resolution of the proxy record.**

Given our lack of ability to consistently resolve interannual variability in the stalagmite record, we only discuss the implications briefly as they relate to the SPCZ. Interannual variability in SPCZ position is primarily mediated by ENSO phase. Warm phases cause northeast, equatorward displacement of the SPCZ, while cool phases displace the SPCZ further southwest. Recent modeling work (e.g., Cai et al. 2013) has demonstrated the possibility for warmer surface conditions to produce more extreme equatorward movement of the SPCZ during interannual variability, producing more interannual, ENSO-related drought at our study site.

4) (Lack of) Anthropogenic Trend

Reviewer: 5597 last two sentences: I agree but, as you discuss later in the ms, the wavelet analysis does not really allow you to spot changes due to global warming.

The influence of anthropogenic forcings on the regional climatology are not discussed until the final summary of the analysis. Although the anthropogenic forcings on the observed regional climatology is likely small, it would be worth discussing how relevant the modern setting (given this radiative forcing) is to reconstructing multi-century climatic records.

***Response*: While the stalagmite record does not have a long-term trend associated with the displacement of the SPCZ, there is a similarity to the published Vanuatu**

stalagmite record (Partin et al., 2013) in that the dry period during the most recent decadal shift is not as dry as previous dry phases. Text is added (pasted below) to the discussion very similar to Partin et al., 2013 that discusses the possibility of anthropogenic influences on the stalagmite record.

In the Solomon Islands stalagmite record, the most recent dry phase, beginning in the mid-1970s, is not as isotopically enriched in either location as preceding dry phases of PDV, suggesting possible anthropogenic influence. In terms of a century-long trend, the stalagmite proxy rainfall record is not unique over the 20th century in the context of the wet and dry extremes arising from the decadal to multidecadal scale variability of the previous five centuries. However, the relative wetness of the most recent dry phase is an observation consistent with the hypothesized fingerprint of anthropogenic global warming on climatological regions of high rainfall amount (Held and Soden, 2006; Perkins et al. 2012). The Solomons record is similar to the Vanuatu stalagmite record in that both show reduced amplitude of decadal variability in the past century. Hence, our finding mirrors that of Partin et al. (2013): recent wetting, in light of the extremes of PDV, is not uniquely attributable to warming.

5) Interpretation and Fidelity of Stalagmite Geochemistry

Reviewer: 5601, 4 ff. Given the acknowledged large offsets between typical stalagmite deposition temperatures in caves and temperature ranges in the laboratory, it's not clear what is being shown here. Is this a useful test? I would think the most meaningful assessment of the fidelity of calcite isotopic composition is the close match across stalagmites and across caves on these timescales.

***Response*: This is a good point. We will emphasize the fact that the reproducibility of d18O between different stalagmites from different caves.**

5602, Section 2.5. This is a fairly superficial discussion of source effects. Is this 0.3 % (line 12) or per mil? There is little discussion of variability in source through time (instead of just modern setting, and no reference to other studies explicitly addressing source effects.

***Response*: We expand our discussion of source effects (pasted below) to include the recent results of Kurita, 2013 that documents rainfall d18O composition on small tropical islands is a function of convective system type (mesoscale vs. disorganized) not the source of the rainfall. The information about the HYSPLIT trajectories included in the manuscript adds supportive evidence of the concept. The text will appropriately discuss this connection.**

Recently published analyses document that control of rainfall isotopic composition in tropical islands is by the type of convection from which the rain is falling, rather than the source from which it is derived (Kurita, 2013). Mesoscale SPCZ convection is the primary source of wet season rainfall for Forestry Cave, suggesting that this convection type dominates the isotopic composition of rainfall and by inference the stalagmite record. We further investigate how moisture source effects may complicate the relationship between rainfall amount and rainfall $\delta^{18}O$ by examining the potential pathways and sources of water vapor to the Solomons. We use model results from mid-month of the peak-dry season (August and September) and mid-month of the peak-wet season (February and March) from 2007-2009 (HYSPLIT, http://www.arl.noaa.gov/HYSPLIT.php). The resulting trajectories show possible air parcel paths and potential vapor sources ranging from the equatorial Pacific to the southeastern tropical and southern subtropical Pacific. These trajectories represent a broad range of potential water vapor sources, transit distances, mean and seasonal SST regimes, all over an interval of time where stalagmite $\delta^{18}O$ changes by only 0.3‰. This adds evidence to the notion that variability in source is not an important factor in controlling rainfall $\delta^{18}O$ in the modern setting of the SPCZ.

Section 3.1 (and 5603, line 13) I'm not sure the "Calibration" is an appropriate word to use in this section heading. Calibration implies that two measurements are being compared against each other for the purpose of adjustment. As calcite isotopic composition integrates many, complex and mutable processes, it is not a clear case of calibration against rainfall amount. Perhaps "relationship" would be more appropriate?

***Response*: The title of the section has been changed to 'Relationship between Stalagmite $\delta^{18}O$ and Rainfall Amount'.**

5602, 23 ff. This seems to be a statistical, rather than process based, understanding of the relationship between rainfall amount and calcite composition. Why is the annual rainfall amount being regressed across isotopic changes? Is this the timescale you expect to integrated into calcite signals?

***Response*: We agree that this is largely a statistical-based justification for the relationship between rainfall amount and calcite composition. However, annual rainfall total is a commonly used metric to describe rainfall variability, and we chose to use these units. The agreement with the Vanuatu stalagmite record provides additional justification for using mTAR.**

5603, 9 ff. The GNIP network is temporally and spatially sporadic, and the PNG site is located quite some distance from the Solomon Islands. Can this be discussed explicitly? Is this relevant? Can you incorporate some model-based studies in order to discuss the relationship to stalagmite composition to rainfall amount?

***Response*: Kurita, 2013 documents that the location of the site is not as important as convective system type in a tropical marine setting. As both site receive mesoscale convection during rainy events, we feel it is appropriate to compare the rainfall isotopic composition of the two sites.**

Section 3.2. It is difficult at this stage for the reader to interpret the significance of "large, abrupt" changes. I think this would be easier is figures of modern seasonal data were provided.

***Response*: As the stalagmite record cannot resolve the seasonal cycle of rainfall, we cannot address how the seasonal cycle of rainfall would change as a function of the decadal changes. Instead we focus on how many total meters of rainfall over the year are changing as a function of the decadal variability.**

<u>Other Comments:</u>

Reviewer: I do not like the title of section 1.1. "Significance" is not a very punchy term, and I think terms like "need" or "relevance" would be more appropriate 5595 line 10

***Response*: Changed the title of section 1.1 to 'Pacific Decadal Variability'**

<u>Reviewer Comments on Figure 1:</u>

5596 line 20: ...the broader tropical SPCZ domain: are you referring to the box on figure 1? This box is probably not well chosen anyway. Given the high spatial resolution of the dataset (0.25x0.25), you could have selected an inclined box encompassing the SPCZ.

I am not sure part c is needed. I am not an expert on statistics, but since part b is the spatial correlation between one point and the rest of the map, it seems that what is shown in part c is just the same as part b seen with a different parameter. Indeed, low values of p seem to correlate perfectly with high values of r.

In the caption of part b what do you mean by "rainfall anomalies in the southwestern Pacific"? Is it in the box, or is it a wider area (if so, define it).

***Response*: Revised orientation of SPCZ box in Figure 1. Deleted panel c. Clarified language in the figure caption:**

Fig. 1. Tropical rainfall patterns centered on the Indo-Pacific, based on data from Kummerow et al. (2000). White triangle denotes the Guadalcanal study site. Diagonal lines illustrate north and south boundaries of the SPCZ, after Salinger et al. (2013). a) Annual mean surface precipitation in the tropical Indo-Pacific from 1998-2011. b) Spatial correlation (*r*) between monthly rainfall anomalies at the study site and rainfall anomalies in the southwestern Pacific. Anomalies are relative to the 1998-2011 climatology.

Reviewer: 5603 line 24: "...record is decadal in nature (12 to 62 yr)": should be "decadal to multidecadal"

***Response*: Change incorporated.**

Reviewer: 5597 line 15: Not everyone is familiar with CE, define it when first used.

***Response*: We will define CE as 'Year Common Era'.**

Reviewer: 5597 line 4-5: the Cai et al. Nature 2012 reference would be useful here to discuss the long term displacement of the SPCZ towards the Equator.

***Response*: We agree that a reference is needed, and we have added Deser et al., 2004 who described these decadal-scale observations. We also discuss the Cai et al., 2012 reference in the revised section about the anthropogenic influence on interannual variability of the SPCZ.**

<u>Reviewer comment about coral records of SPCZ Variability:</u>

5606 chapter 3.4: Figure 9 you be cited in the text 5606 line 24: "Coral-based reconstructions of SSS and SST. . .": where? Under the spcz? 5606 line 25: Clement, Deser and Dong do not contain any coral data, these references are not appropriate. And it should be noted that some coral records from under the SPCZ do not show obvious decadal variability (Lebec et al., GRL 2000 or Juillet-Leclerc et al., GRL 2006 for example).

***Response*: We deleted the incorrect references of Deser and Dong and include a statement that some coral records from Fiji do not show prominent decadal variability (Lebec et al., 2000; Juillet-Leclerc et al., 2006).**

<u>Reviewer comments about stalagmite sampling and characteristics:</u>

5598 chapter 2.1: You should give the length of both speleothems 5598 line 23: "...milled from the stalagmite...": which one, you collected two

***Response*: Information added.**

5600 lines4-24: you describe the replication work, and mention the Hendy test, but where is this shown?

***Response*: The replicated records are shown in blue and red colors in Figure 4. The Hendy test is composed of a two parts: a correlation between d18O and d13C for the whole stalagmite, and the composition of d18O and d13C across a single layer. We report that the correlation between $\delta^{18}O$ and $\delta^{13}C$ is low ($R^2 = 0.11$). Furthermore, the replication of the records leaves little room for kinetic effects to have a major**

influence on stalagmite d18O composition. We did not do the second part of the Hendy test of the $\delta^{18}O$ and $\delta^{13}C$ composition across a single layer due to the low O vs. C correlation and the replication.

Figure 2: Some paths seem parallel to the growth lines, are they sampling lines for the Hendy test? Maybe show them with a different colour and mention it in the caption.

***Response*: Figure 2 is updated and the figure caption is revised.**

5601, 21. Is this correlation significant?

***Response*: This is a significant correlation, and we have added the p-value.**

Reviewer comments about stalagmite age model:

5598 line 25: delete "the" 5599 lines 20-21: you talk about knots, but they are not visible on figure 3.

Response: We greatly reduce the discussion about knots as it relates to a numerical detail about the age model calculation. Details of the age model calculation can be found in Partin et al., Geology 2013.

Figure 3: I don't really see a thin black line. It looks grey to me.

***Response*: It is grey. The figure caption has been changed accordingly.**

5599, 20. Can a citation/reference be provided for this method of age-model determination?

***Response*: Reference to Partin et al., 2013 is added.**

Reviewer: 5608 lines9-18: this paragraph is misplaced and should be deleted.

***Response*: Correct. This should go with Table 2.**

Reviewer: 5600, 4. This paragraph does not seem to readily fit in as 'Age Model', can this be contained in a new section addressing the fidelity of the record?

***Response*: Correct. This paragraph is moved to section 2.4**

Reviewer comments on Rainfall Seasonality:

5596, 22 ff. It is not clear how useful it is to describe the climatology of the area over this time period, given that you are discussing a shift occurring in 1976. Can you provide clearer comparisons of the observed climatologies before and after the shift, and perhaps figure demonstrating this?

5596, 26. Can a figure showing seasonality of rainfall be provided?

5596, 16 ff. The rainfall variability in the region is mirrored by local rainfall variability, but given that you are discussing large climatic shifts, is this necessarily always the case? You need to explicitly address potential non-stationarities over longer timescales. It seems it would be highly sensitive to boundary conditions that influence the WPWP boundary?

***Response*:** **We have added the seasonality of rainfall calculated using the Henderson Airfield rainfall record as Supplemental Figure S1. However, the stalagmite record cannot consistently resolve the annual cycle, as demonstrated by the wavelet analysis. Therefore, we cannot comment on changes in the seasonal cycle of precipitation that may or may not accompany the decadal shifts observed in the stalagmite record.**

Reviewer: Line 5606, 7. The definition of time period show ?? instead of a year.

***Response*:** **Changed ?? to 1900.**