South Pacific Convergence Zone dynamics, variability and impacts in a changing climate

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Abstract

The South Pacific Convergence Zone (SPCZ) is a band of intense rainfall and deep atmospheric convection extending from the equator to the subtropical South Pacific. Displacement of the SPCZ causes variability in rainfall, tropical cyclone activity and sea level that affects South Pacific Island populations and the surrounding ecosystems. In this Review, we synthesize recent advances in understanding the physical mechanisms responsible for the SPCZ location and orientation, its interactions with the principal drivers of tropical climate variability, regional and global effects of the SPCZ and its response to anthropogenic climate change. Emerging insight is beginning to provide a coherent description of the character and variability of the SPCZ over synoptic, intraseasonal, interannual and longer timescales. However, persistent biases in, and deficiencies of, existing models limit confidence in future projections. Improved climate models and new methods for regional modelling might better constraint

future SPCZ projections, aiding climate change adaptation and planning among vulnerable South Pacific communities.

[H1] Introduction

The South Pacific is the principal region in which persistent deep convection of tropical origin often merges with the highly fluctuating mid-latitude storm track. These interactions result in a band of heavy convection, known as the South Pacific Convergence Zone (SPCZ), arising from low-level convergence between northeasterly trade winds and weaker westerly winds (Fig. 1). The SPCZ extends southeastward from the maritime continent across the tropical and subtropical Pacific Ocean[1-4], and owing to deep tropical convection, can be identified as a region of maximum rainfall (Fig. 1a) and minimum outgoing longwave radiation, with the largest amplitude observed during the austral summer (December to February).

The SPCZ is often considered to have two components: a zonally oriented tropical rainfall band located over the West Pacific Warm Pool, and a diagonally oriented (northwest to southeast) subtropical rainfall band that extends to approximately 30°S, 120°W. The tropical component is located where sea surface temperatures (SSTs) >26°C (Fig. 1b) permit deep convection[11]. The diagonal (subtropical) component, by contrast, is located over somewhat cooler SSTs, with convection instead governed by interactions with troughs in the mid-latitude circulation[1,8].

With substantial contributions to total precipitation in the South Pacific, any variability in the location and intensity of the SPCZ has the potential to greatly affect Pacific Island Communities and Territories (PICTs), a region reliant on rainfall for drinking water and agriculture; extreme rainfall can promote flooding and landslides, while an absence of rainfall can lead to drought. Moreover, changes in the location of the SPCZ also drive variability in tropical cyclogenesis, in some cases permitting cyclones to track far eastward of their usual position, posing considerable risk to already-vulnerable communities (as observed during tropical cyclone Martin in 1997, for example). Thus, there is key need to understand the mechanisms, variability and impacts of the SPCZ, especially against a background of anthropogenic warming anticipated to modify tropical climate dynamics.

In the 25 years since the last comprehensive Review of the SPCZ[1], investigations have benefited from a diverse array of new and updated climate observations, including satellite retrievals[7,20,21], atmosphere and ocean reanalyses[21-23], and paleoclimate reconstructions of ocean temperature, salinity and rainfall derived from coral and speleothem records[24-27]. Accordingly, knowledge of the mechanisms determining the SPCZ's diagonal orientation[6,28-

[31] and its eastern boundary[9,32,33], as well as responses to phenomena such as the Madden-Julian Oscillation (MJO), El Niño–Southern Oscillation (ENSO) and Interdecadal Pacific Oscillation (IPO) have considerably improved[12,16,28,34,35]. Similarly, global ocean–atmosphere coupled models[13,18,19,36-38], regional atmospheric models[39,40] and idealized or process-based models of the atmosphere[30,31,33] have enabled in-depth assessment of SPCZ mechanisms and projected change under anthropogenic warming. These advances have collectively developed coherent perspective of the SPCZ spanning synoptic, intraseasonal, interannual and longer timescales.

In this Review, we synthesize these latest developments in the causes and consequences of the SPCZ. We outline the mechanisms thought to account for the SPCZ and its diagonal orientation, and describe its natural variability on synoptic to multi-decadal timescales. The impacts of this variability are subsequently discussed, followed by the projected changes in response to anthropogenic warming are subsequently discussed. We end with outstanding research questions intended to drive the field forward.

The South Pacific is the principal region in which persistent deep convection of tropical origin often merges with the highly fluctuating mid-latitude storm track. These interactions result in a band of heavy rainfall, known as the South Pacific Convergence Zone (SPCZ), which extends southeastward from the maritime continent across the tropical and subtropical Pacific Ocean[1-4]. In observations, the SPCZ can be identified as a region of maximum rainfall (Fig. 1a) and minimum outgoing longwave radiation due to the presence of deep tropical convective clouds, with greatest extent during the austral summer (December to February). This zone of intense convective activity results from low-level convergence between northeasterly trade winds (Fig. 1a) generated via anticyclonic flow around high pressure in the southeastern Pacific (Fig. 1b) and much weaker westerly winds[4,5].

The SPCZ is often considered to have two components: a zonally oriented tropical rainfall band located over the western Pacific warm pool, and a diagonally oriented (northwest to southeast) subtropical rainfall band that extends to approximately 30°S, 120°W. The tropical component is located where sea surface temperatures (SSTs) >26°C (Fig. 1b) permit deep convection[11]. The diagonal (subtropical) component, by contrast, is located over somewhat cooler SSTs, with convection instead governed by interactions with troughs in the mid-latitude circulation[1,8]. Alternatively, some studies identify equatorial, tropical and subtropical components of the SPCZ[6] or break the diagonal portion of the SPCZ into two parts, with a steeper slope in the eastern part[7].

Fluctuations in both atmospheric and oceanic circulations can cause large changes in the location, intensity and extent of the SPCZ[12,13]. Within the SPCZ, rainfall varies over daily to weekly (synoptic) timescales as well as intraseasonal timescales such as the 30–60-day fluctuations associated with the Madden–Julian oscillation (MJO)[14,15]. The SPCZ also varies over interannual, decadal and longer timescales in response to the El Niño–Southern oscillation (ENSO)[1,4,12] and the interdecadal Pacific oscillation (IPO)[16,17]. As the Earth's climate warms, changes in the mean state of the tropical Pacific ocean might shift the position or intensity of the SPCZ[18,19]. A warmer climate could also lead to changes in ENSO, such as an increase in the frequency of extreme El Niño events, which drive a large northward displacement of the SPCZ[13]. Variability of the SPCZ is linked to changes in regional rainfall, tropical cyclone activity and sea level, which affect the numerous and diverse island communities of the South Pacific. SPCZ variability also influences the global climate through the redistribution of convection and associated changes in atmospheric circulation patterns.

Investigations of the SPCZ have benefited from a diverse array of updated climate observations and models. Data sources include several decades of satellite observations[7,20,21], reanalyses of atmospheric and oceanic datasets that provide retrospective descriptions over much of the twentieth century[21-23] and paleoclimate reconstructions of ocean temperature, salinity and rainfall derived from coral and speleothem records[24-27]. As a result, knowledge of the mechanisms determining the SPCZ's diagonal orientation[6,28-31] and its eastern boundary[9,32,33], as well as the SPCZ's response to phenomena such as the MJO, ENSO and IPO have considerably improved[12,16,28,34,35]. Studies of the mechanisms that cause the SPCZ and how it is projected to change under anthropogenic warming in the future now utilize a multiplicity of climate models, including global ocean–atmosphere coupled models[13,18,19,36-38], regional atmospheric models[39,40] and idealized or process-based models of the atmosphere[30,31,33]. These advances have enabled the development of a coherent perspective of the SPCZ spanning synoptic, intraseasonal, interannual and longer timescales.

In this Review, we synthesize these latest developments in the causes and consequences of the SPCZ. We outline the mechanisms thought to account for the SPCZ and describe its natural variability on synoptic to multi-decadal timescales. The impacts of this variability are subsequently discussed, , followed by the projected changes in response to anthropogenic warming. We end with outstanding research questions intended to drive the field forward.

[H1] Physical mechanisms driving the SPCZ

The existence of persistent regions of large-scale organized convection in the southern hemisphere was first identified in early satellite images as distinct bands of persistent cloudiness in each of the major ocean basins[2,3] that are associated with widespread convection, rainfall and low-level wind convergence. The SPCZ is the most intense and extensive of these bands[4], though less intense features are also found in the Atlantic and Indian Oceans - the South Atlantic Convergence Zone (SACZ)[3,41,42] and the South Indian Convergence Zone (SICZ)[43].

One of the most intriguing questions about the SPCZ (and the other southern hemisphere convergence zones) is why these bands of convection are oriented diagonally to the southeast from the equatorial region to the subtropics. Numerous modelling studies have investigated the boundary conditions necessary to support a diagonal SPCZ. In general, the South American continent and the orography of the Andes have only a modest direct effect[6,31,8,48]. In contrast, the zonal SST gradient is thought to be central to driving the diagonal alignment, reaching its seasonal maximum during the austral summer. The resulting strong South Pacific High transports moist air from the equator into the SPCZ. Of course, the anticyclonic circulation contributes to the development of the zonal SST gradient, indicating continental land mass configurations and orography indirectly support the SPCZ through their role in setting the boundary conditions for the zonal SST gradient[9].

Related to these boundary conditions, three mechanisms have been proposed to support the diagonal SPCZ formation: transient bursts of diagonally oriented convection triggered by Rossby waves[6,28,29]; direct forcing by tropical convection[34,44]; and southwestward moisture advection from the eastern Pacific dry zone[9,32]. While these mechanisms are likely to act in concert to produce observed SPCZ behavior, how they affect a given SPCZ state may differ.

[H2] Transient Rossby wave forcing

The SPCZ has long been recognized as a 'frontal graveyard'[4] — that is, a region within which weather fronts or synoptic disturbances moving from the southwest dissipate. This aspect of the SPCZ can be explained by the strong zonal SST gradient in the subtropical Pacific (Fig. 1b) and the associated trade wind and convergence patterns, both of which generate a background atmospheric flow that slows the passage of synoptic disturbances originating from the mid-latitudes and accumulates Rossby wave energy[6]. It is this accumulation of Rossby wave energy that has been used to explain the diagonal orientation of the SPCZ[28,29] (**Fig. 2a**). During austral summer, Rossby waves from the southern hemisphere subtropical jet are refracted towards the equator near New Zealand owing to vorticity gradients in the background flow. The subtropical jet is a bountiful source of wave trains originating from baroclinic waves (typical mid-latitude synoptic weather systems) and extratropical responses to remote tropical convection. Once refracted, the Rossby waves transit into the 'westerly duct', describing the region in which westerly upper-level tropospheric winds facilitates wave propagation[46]. Owing to the combined effects of meridional shear of the zonal flow and refraction, these waves acquire a diagonal orientation[29]. Subsequent disturbances trigger deep convection and low level convergence along the SPCZ, related to favorable thermodynamic conditions and a supply of moisture from the subtropical high[28]. Negative feedback between latent heat release from deep convection and the associated vortex stretching consequently leads to dissipation of the Rossby waves in the SPCZ[28-30], typically within a day of convection triggering. The timescale for such a chain of events, from the initial wave train in the subtropical jet to the burst of convection, is approximately 5 days, the seasonal average of which explains the diagonal orientation of the eastern part of the SPCZ.

[H2] Direct forcing by tropical convection

While most of convective activity in the SPCZ is linked to refraction of transient Rossby waves[28], localized steady tropical convective heating over the maritime continent is also an important mechanism[34,44] (**Fig. 2b**). Indeed, the direct wave response to maritime continental heating accounts for the existence of the westerly duct, a necessary condition for the refraction of mid-latitude transient waves towards the equator and the SPCZ.

[H2] Advection from the east Pacific dry zone

The SPCZ lies in a region with a pronounced west-to-east moisture gradient. The area to the east of the SPCZ, for example, is referred to as the southeast Pacific dry zone because it is persistently free of deep convective rainfall, believed to be linked to orographic forcing from the Andes via feedbacks involving subsidence, low clouds and cooler SSTs[9]. The extent of this dry zone – linked to the orientation of the southeasterly trade wind flow - influences the maintenance of the eastern edge of the SPCZ, and thus its diagonal tilt[32,33].

For instance, on short (1–5 day) timescales, periods of anomalous westerly winds (reduced trade wind strength over the southeast Pacific can shift the eastern margin of the SPCZ towards South America[33]. In terms of large-scale moisture transport, trade wind inflow into the SPCZ is associated with a change from low to high mean moisture values, which corresponds to a drying term in the atmospheric moisture budget. Conversely, a reduction in trade wind strength is associated with an anomalous moistening term in the atmospheric moisture budget.

As deep convection is thought to be precipitated at a critical moisture threshold[47], reduced trade wind strength leads to increases in deep convection and rainfall, which can be interpreted as a shift in the eastern SPCZ margin[33].

[H1] Natural variability of the SPCZ

The SPCZ can be viewed as the sum of discrete pulses of convective activity lasting several days. Low-frequency variability of the background state can modify the characteristics of such convective events[6,28] resulting in SPCZ variability on intraseasonal to interdecadal timescales. The available evidence of such SPCZ natural variability and its proposed mechanisms are summarized in the following sections.

[H2] Synoptic and intraseasonal timescales

The MJO is an eastward-propagating equatorial mode of planetary-scale convective anomalies, nominally occurring every 30–60 days[14,15], and is known to influence the SPCZ[1].Analysis of satellite records, for example, reveal the propagation of MJO signals within the SPCZ, driving both enhanced and suppressed convection during different phases of the MJO (as defined by the standard Wheeler and Hendon MJO phase index[49]). Specifically, as the MJO propagates eastward, the region of enhanced SPCZ convective activity also moves eastward; during MJO phases 4 and 5, for instance, convection over the Maritime Continent extends SPCZ anomalies from north of Australia to as far as 30°S, and during phases 6 and 7, the SPCZ extends eastward and poleward from its climatological position[7]. Analysis of a single MJO event similarly reveals the poleward and eastward progression of intraseasonal anomalies along the SPCZ[34.]

Dynamical models indicate that the MJO primarily influences the SPCZ through its modulation of the transient, short-timescale (about 5 days) interactions between extra-tropical and tropical wave events. For instance, when MJO convection is enhanced over the eastern Indian Ocean and Maritime Continent (phases 3–6 of the MJO), an equatorial Kelvin wave response produces westerly anomalies in the upper troposphere over the equatorial western Pacific, extending the westerly wind duct toward the western Pacific. Consequently, extra-tropical wave trains propagating eastward along the southern hemisphere subtropical jet refract towards the equator at westward longitudes, thereby generating diagonally oriented convective events west of the mean SPCZ position. When these changes are averaged over a period of several days, the mean position of the SPCZ is observed to shift westward[28].

[H2] Seasonal timescales

The seasonal cycle of insolation and SSTs drives the most prominent variations in the SPCZ. The SPCZ is most fully developed (in terms of having the greatest accumulated rainfall and largest spatial extent) in the austral summer, when the oceanic heat content and the zonal SST gradient are at their maximum. Other ingredients essential for the formation of the SPCZ are also only consistently present during the austral summer: namely, the westerly wind duct, which enables equatorward propagation of Rossby waves, and high SSTs in the southwest Pacific that fuel convection[30,32].

The seasonal cycle of the SPCZ also differs along its length. The subtropical portion of the SPCZ is most active around November to December, whereas the tropical portion is most active in January and February[7]. Moreover, the tropical and subtropical portions of the SPCZ are not always connected on either subseasonal or seasonal timescales, but during December to February — the period of most intense SPCZ activity — the two portions align in a continuous region of convection[7].

[H2] Interannual timescales

[H3] Observed interannual variability

Other than the seasonal cycle, the largest variability of the SPCZ is associated with ENSO, occurring on timescales of 2–7 years[4]. For example, early studies identified a displacement of the SPCZ from its climatological position during different phases of the ENSO cycle: during La Niña events the SPCZ moves south and west by ~1-3°, whereas during El Niño events, it moves north and east by similar amounts[4,52,53] (**Figs. 3a, b, c**). However, it is now appreciated that the response of the SPCZ to ENSO is more complex than a simple south-west (La Niña) or north-east (El Niño) spatial displacement. Indeed, during particularly strong El Niño's, such as those of 1982–1983, 1991–1992, 1997–1998[12] and 2015–2016 (Ref [54]), the SPCZ shifts much closer to the equator (moving northwards by up to 10° latitude) and loses its diagonal orientation[12,13] (**Fig. 3d**). These so-called zonal SPCZ events are associated with a weak meridional (north–south) temperature gradient between the eastern equatorial Pacific cold tongue and the climatological location of the SPCZ[12,13,55].

Similar to the MJO, ENSO influences SPCZ variability through perturbations to the westerly wind duct and subsequent impacts on Rossby wave refraction. Specifically, during La Niña events convection is enhanced over the eastern Indian Ocean and Maritime Continent, expanding the westerly duct, wave refraction and SPCZ position westward[28]. Moreover, positive SST anomalies in the vicinity of the SPCZ provide additional thermodynamic forcing. During El Niño events, by contrast, the westerly duct is retracted[28]. Anomalous ocean temperatures associated with ENSO also modify the Walker and Hadley Cells, influencing the organization of the SPCZ.

Consideration of large-scale atmospheric divergent moist static energy (MSE) transport further offers mechanistic insight into ENSO and the SPCZ. Under El Niño conditions, the central and eastern equatorial Pacific is an anomalous source of MSE, since oceanic warming supplies energy to the atmosphere in the form of increased surface turbulent fluxes, particularly latent heating[59]. Thus, low-level MSE supports deep convection in a region that is typically unfavorable for such processes, that is, northeast of the SPCZ. Moreover, weakened trades winds suppress the advection of low MSE air into the SPCZ from the southeastern tropical Pacific, encouraging convection eastward of its climatological location. On the basis that rainfall in the SPCZ shifts spatially by an amount equal to the displacement of the zero line of the divergent MSE flux (the so-called energy flux equator), the observed northeastward and equatorward SPCZ displacements experienced during El Niño are comparable to the shifts obtained from the 2D energetics framework, i.e., via the latter, it is possible to relate quantitatively the amount by which the SPCZ shifts to a given anomalous MSE source. The 2D energetics framework further allows for diagnosis of component processes associated with SPCZ displacements during El Niño; for example, it appears that cloud-radiative feedback contributes a positive feedback to these displacements[35].

[H3] Paleoclimate records of interannual variability

The limited availability of climate observations in the South Pacific before the mid-twentieth century means that paleoclimate reconstructions from natural archives, such as corals and speleothems, offer valuable tools to reconstruct past variability of the SPCZ. A key aspect of relevance to paleoclimate analysis is the southwestern Pacific ‘salinity front’, where highly saline subtropical waters meet the low-salinity waters beneath the SPCZ[60,61]. Hence, ^{18}O:^{16}O isotope ratios (expressed as $\delta^{18}O$) from coral records in the southwestern Pacific can be used to understand displacement of the SPCZ in response to ENSO[24,62-67].

For instance, a coral $\delta^{18}O$ series from Ta’u Island in American Samoa provides a record of SST and salinity extending back nearly 500 years (1521–2011 CE) in a location close to the SPCZ central rainfall axis[63,68]. This coral series records an interannual phase shift in the late 1920s, revealing that the current relationship whereby El Niño events lead to increased salinity(and thereby eastward shift) in this region holds true only after this shift[68]. Ta’u Island is situated in the current ENSO ‘null’ zone where, on average, interannual SST anomalies show no correlation with those on the equator. The Ta'u coral record provides evidence that this ENSO null zone in the central SPCZ rainfall axis is not stationary but instead has shifted northeast and southwest in the past[63].

Coral records also provide information about the sensitivity of SPCZ responses to different types of El Niño events[26,62,63]. For example, analysis of a 262-year (1742–2004 CE) coral record of sea surface salinity from the Makassar Strait, the main channel of the Indonesian Throughflow, shows that interannual changes in surface salinity are intermittently related to zonal SPCZ events,[26]. During these events, stronger South Pacific boundary currents force high salinity water through the Makassar Strait and truncate the normal seasonal freshening. Accordingly, Makassar Strait coral $\delta^{18}O$ data provide a first estimation of the frequency of zonal SPCZ events before 1979 and suggest that these events have occurred on a semi-regular basis since at least the mid-1700s[26].

[H2] Interdecadal timescales

[H3] Observed interdecadal variability

Decadal-scale climate variability in the tropical Pacific is dominated by the IPO[69] and the closely related Pacific Decadal Oscillation[70]. The spatial pattern of SST anomalies associated with the IPO resemble those of ENSO, but with larger anomalies in the subtropics, which cause large decadal to multi-decadal variations of SPCZ location[16,17,71]. Indeed, the SPCZ tends to move northeastward during positive IPO phases, as it does during El Niño events, and southwestward during negative IPO phases, as it does during La Niña events. Although shifts in the position of the SPCZ due to ENSO and the IPO have comparable magnitude, they operate quasi-independently[16]. IPO modulation of SPCZ position has occurred since the early twentieth century[23] and is evident in atmospheric reanalyses [72].

[H3] Paleoclimate records of interdecadal variability

Similar to interannual timescales, paleoclimate records are invaluable for reconstructing SPCZ variability on interdecadal timescales. For instance, an index of South Pacific surface ocean salinity developed from $\delta^{18}O$ series from *Porites* corals in Fiji and Tonga suggests that interdecadal SPCZ variability has remained relative stable for the last 400 years, with a mean period of ~20 years[25], related to the IPO. However, another study that assessed two centuries of $\delta^{18}O$ data from *Diploastrea* corals in Fiji suggests that interdecadal fluctuations are not static, becoming more variable from ~1880 to 1950 (Ref [73]).

Trends in SPCZ position evaluated using Fiji and Rarotonga coral $\delta^{18}O$ data and Sr:Ca ratios (which are sensitive to changes in ocean temperature) show that the eastern border of the SPCZ has shifted in a westerly direction by 10–20° of longitude three times since the early 1600s[24]. The largest shift began in the mid-1800s as the salinity front moved progressively eastward, indicating a gradual change to La Niña-like mean conditions[24]. A subsequent re-evaluation of coral $\delta^{18}O$ series from Fiji, Tonga and Rarotonga revealed that freshening began in the mid-1800s in Fiji, but occurred later in Tonga and Rarotonga[62]. The temporal difference between these sites suggests that this freshening does not simply reflect changes in the SPCZ character but instead is primarily the result of changes in ocean circulation.

Speleothem records of the SPCZ have also been obtained from a number of Pacific Islands, including Vanuatu[27], Solomon Islands[74] and Niue[75]. In Vanuatu, for instance, a 446-year record shows evidence of large-scale, quasi-periodic multi-decadal variability of the SPCZ, with lower amplitude variability in the instrumental era compared to the previous 350 years[27]. A 600-year speleothem record from the Solomon Islands[74] also captures movements of the SPCZ in response to Pacific decadal variability that persist over the entire record. The large natural interdecadal variability of SPCZ rainfall observed in paleoclimate records implies that the South Pacific region is highly vulnerable to future changes in decadal SPCZ variability[27].

[H1] Regional effects of SPCZ variability

The variability of the SPCZ on the timescales described above produces a wide range of effects on the climate of the South Pacific region, which in turn have socioeconomic and environmental consequences for South Pacific island communities. SPCZ-mediated climatic effects in the South Pacific include changes in mean seasonal rainfall and rainfall extremes, changes in the starting location and tracks of tropical cyclones and sea level anomalies. In addition, SPCZ variability is associated with effects on regional and global climate via atmospheric teleconnections.

[H2] Rainfall

Many South Pacific island communities rely on rainfall for both drinking water and agriculture, and are therefore vulnerable to changes in rainfall related to the position and intensity of the SPCZ[76]. Fluctuations of the SPCZ on interannual and decadal timescales can substantially increase or decrease seasonal mean and total rainfall for these islands[60,76,77], as well as rainfall extremes linked to floods and droughts[77-79].

Given ENSO's influence on SPCZ location, it too substantially influences total rainfall and rainfall extremes in the South Pacific[79] (**Fig. 3**). Islands located near the equator (for example, Nauru and Kiribati) and those east of the mean SPCZ position (for example, Tahiti) generally experience increases in mean and extreme rainfall during El Niño events, whereas islands located in the southwest Pacific, south of the SPCZ mean location (for example, Vanuatu, Fiji, Tonga and New Caledonia), experience drier conditions. For example, satellite records of rainfall reveal large-scale interannual anomalies of over $\pm$50%, particularly for the region around Tahiti[80], which is especially vulnerable to heavy rainfall during strong El Niño (zonal SPCZ) events and droughts during La Niña (diagonal SPCZ) periods.

Different foci of El Niño events have distinct effects on rainfall in the South Pacific[76]. For instance, El Niño events centered in the eastern Pacific typically produce marked drying over southwest Pacific islands, whereas such drying is weaker during El Niño events occurring in the central Pacific. This disparity stems from the fact that northward excursions of the SPCZ are larger during eastern Pacific El Niño events than during central Pacific El Niño events. Thus, during the strong El Niño events of 1982–1983 and 1997–1998, Nauru and Tarawa (Kiribati) experienced dry conditions, whereas these islands typically experience wetter than average conditions during El Niño years[76].

[H2] Tropical cyclones

Tropical cyclones account for three-quarters of reported natural disasters within the Pacific[81] and have substantial socioeconomic and ecological consequences for the island communities of the Southwest Pacific[82]. In general, tropical cyclones develop in regions where four essential atmospheric conditions exist[85]: sufficient thermodynamic energy; abundant moisture; low-level cyclonic vorticity; and minimal vertical wind shear. The environment along and up to 10° poleward of the main axis of the SPCZ exhibits these requirements during the austral summer, which is also the peak of the regional tropical cyclone season[12,83,84].

The importance of the SPCZ in generating the large-scale atmospheric conditions that favour tropical cyclone genesis is also illustrated by considering the effect of interannual variations of the SPCZ during El Niño and La Niña events[12,86-88] (Fig. 4a). Specifically, a northeastward (El Niño) shift of the SPCZ induces a ~25% decrease in tropical cyclone genesis in the Coral Sea and near Fiji, whereas a southwestward (La Niña) shift of the SPCZ results in a ~75% decrease in tropical cyclogenesis in the Tuvalu region anda ~30% increase in the Fiji region[12]. Whether the SPCZ is zonal (as found during strong El Niño events) also influences tropical cyclone characteristics in the South Pacific. Tahiti, for example, is generally threatened only during such zonal events (**Fig. 4a).** For instance, during the extreme El Niño event of 1982–1983, Polynesia experienced 6 tropical storms, including the Category 4 Severe Tropical Cyclone Veena[90] (the most every recorded), while during the 1997-1998 event allowed cyclones to track far eastward of their normal position to Tahiti[12], including Category 3 Severe Tropical Cyclone Martin, which caused 28 deaths[91].

[H2] Sea level

The South Pacific experiences substantial sea level variations owing to wind-stress anomalies related to the position and intensity of the SPCZ[80]. These changes expose shallow reefs and can cause severe damage to associated coral ecosystems[95] and intertidal zones such as mangrove forests[96]. As for the other climate impacts discussed, ENSO explains most of the interannual sea level variability in the SPCZ region.

During El Niño events, the reduced strength of Pacific trade winds and negative wind-stress curl associated with a northeastward shift in SPCZ position induce a shoaling of the thermocline in the southwestern Pacific. This shoaling causes a concurrent drop sea surface height (Fig. 4b), which can lower sea levels by more than 30cm during strong El Niño events[80,93,94.] The zonal character and equatorward shift of the weakened SPCZ during strong El Niño events also induces an asymmetry in the sea level signature between the North and South Pacific, which prolongs below-normal sea levels (and their associated ecological impacts) in the southwestern Pacific for several months after El Niño has ended[80]. By contrast, during La Niña events, the SPCZ shifts southwest, the thermocline deepens in the southwestern Pacific and the regional sea level rises (Fig. 4b). Above-normal sea levels during La Niña (typically around 10 cm higher than the long-term average[80]) can exacerbate the coastal flooding associated with storms and the ongoing rise in global sea level, as well as the local land subsidence[97] occurring in parts of the SPCZ region such as that around the Samoan Islands[98,99].

[H2] Remote teleconnections

SPCZ variability not only exerts a local influence over the southwest Pacific, but also remote regions, in the tropics and elsewhere, through atmospheric teleconnections. For instance, shifts in SPCZ location modulate rainfall over South America at both interannual[100-102] and intraseasonal[103] timescales. Over 30–60 day (MJO) timescales, anomalous convective activity in the SACZ and SPCZ regions is dynamically connected via Rossby wave propagation[104,105]. Differences in the effects of ENSO in South America in the boreal spring have also been attributed to SPCZ variability and the propagation of stationary Rossby waves from the South Pacific into South America[106].

The SPCZ also influences the climate of southern hemisphere high latitudes via atmospheric teleconnections. For example, the variability of the SPCZ in early austral spring is an important contributor to atmospheric circulation and surface temperature trends across the South Pacific, South Atlantic, Antarctic Peninsula and West Antarctica. Increased deep convection along the poleward margin of the SPCZ in September, driven by increased low-level wind convergence, produces a Rossby wave train that propagates across the South Pacific to the South Atlantic[107]. In addition, many of the climate shifts across West Antarctica during 2000–2014, when the IPO was negative, can be explained by teleconnection of the SPCZ and the Amundsen Sea low[108].

[H1] Climate change impacts on the SPCZ

In addition to the effects of natural variability on the SPCZ, anthropogenic warming can potentially alter SPCZ location and intensity and variability, with corresponding impacts on the climate of the South Pacific.

[H2] Historical observations

In general, a warming climate is expected to increase mean rainfall in tropical convergence zones such as the SPCZ[109,110]. Similarly, warming is anticipated to alter rainfall patterns associated with SST gradients[111,112]. With observed warming of x°C in the South Pacific, some changes in the characteristics of the SPCZ may already have been observed. For example, analysis of historical rainfall records from South Pacific islands over 1961–2000 indicate trends towards wetter conditions to the northeast of the SPCZ but drier conditions to the southwest SPCZ[77]. These changes have been attributed to an abrupt displacement of the diagonal section of the SPCZ in the late 1970s or early 1980s. However, trends calculated over 1951-2015 reveal statistically insignificant rainfall changes, except in southwestern French Polynesia and the southern subtropics where reductions of 53.4mm and 33.6 mm/decade have been observed, respectively[115]. These contrasts can be explained by a shift of the IPO from a positive to negative phase around 1999. Such minimal trends in precipitation are also consistent with a sea level pressure-based index of the SPCZ, which reveals limited century-scale changes from 1910-2012, insignificant compared with the interannual and interdecadal variability in SPCZ position[116]. Thus, the detection and attribution of observed changes in the SPCZ – including its location and rainfall - is hampered by the large natural multi-decadal variability, which at present, likely dominates any responses associated with anthropogenic warming[71].

[H2] Projections from climate models

Assessment of the SPCZ response to global warming relies heavily on climate projections performed with coupled models, including those from the Coupled Model Intercomparison Projects (CMIP)[117-119]. Prior to discussing these projections, it must be acknowledged that simulations of the SPCZ are limited. While representations of tropical Pacific climate[120,121] and the SPCZ[19] have improved from CMIP3 to CMIP6, long-standing biases persist, including an excessively cold equatorial cold tongue that extends too far into the western Pacific[122], and a tendency for the SPCZ to be too zonal and extend too far eastward[19,36], sometimes referred to as the ‘double ITCZ’ bias. Since the simulation of tropical rainfall and circulation is highly sensitive to the mean state of the tropical Pacific in climate models[111,112,123,124], the existence of model SST biases in this region limits the reliability of future projections. However, despite these limitations, many CMIP5 models are able to produce a realistic north-east and south-west displacement of the SPCZ in response to El Niño and La Niña events[19]; capture zonal SPCZ events[13,55,40]; and reasonably simulate underlying dynamic and thermodynamic processes[136].

CMIP simulations generally indicate no consistent shift in SPCZ position (slope or mean latitude) in a warmer climate; while some models simulate shifts northward, others predict shifts southward[19,37] As a result, projections of SPCZ-related precipitation in the core region are also uncertain, attributed to two competing mechanisms[18]: warmer tropical SSTs lead to increased atmospheric moisture and rainfall (the thermodynamic or ‘wet gets wetter’ response; Fig. 5b), whereas weaker SST gradients reduce moisture convergence in the SPCZ leading to drying (the dynamic or ‘warmest gets wetter’ response; Fig. 5c). The amount of future warming, as well as the projected SST pattern, therefore largely determines which mechanism dominates; a drier SPCZ more likely for moderate warming and a wetter SPCZ more likely for warming exceeding 3°C by the end of the century[18]. Most models, however, do exhibit a robust drying of up to 30% along the southeastern margin of the SPCZ (**Fig. 6a**), attributed to anomalous transport of dry subtropical air into the SPCZ region associated with increased meridional SST gradients to the east[18].

Recognition of systematic biases in global coupled models has motivated a range of alternative approaches for simulating future changes in the SPCZ. Several studies have used atmospheric models forced with some form of bias-corrected SSTs[18,39,40,123] or explored the use of regional models[39,40]. For example, unlike projections from coupled models (**Fig. 6a**), atmosphere-only model simulations (forced with SSTs consisting of the mean warming pattern from CMIP models added to the present-day observed climatology) indicate that future drying of the SPCZ is a foreseeable possibility[18,40]. Similarly, a set of regional atmospheric models forced at their boundaries with outputs from global CMIP models exhibited some agreement on future drying of the SPCZ[39].

Another focus of research on future SPCZ projections is the possibility of changes in interannual variability, especially the occurrence of zonal SPCZ events. Despite an absence of consensus on how ENSO-driven SST variability may change in the future[114,125,126], a large ensemble of climate model experiments report a near doubling of zonal SPCZ event occurrence in the period 1991-2090 compared with 1891-1990 (Ref[13]). The increased occurrence of zonal SPCZ stems from reduction of the South Pacific meridional SST gradient[13,129], which facilitates equatorward displacement of the SPCZ. The increase in zonal SPCZ events also drives a similar enhancement in El Niño–related sea level extremes in the tropical southwestern Pacific[94]. In contrast with results based on CMIP models[13], however, bias-corrected models do not predict any increase in zonal SPCZ events in the future, even with weakened meridional SST gradients[39,40,130].

[H1] Summary and future perspectives

Studies published over the past 25 years have facilitated the construction of a comprehensive description of the SPCZ that links its behavior over daily timescales to its interannual and interdecadal variability and long-term trends. For example, the diagonal orientation of the SPCZ can now largely be linked to Rossby wave energy accumulate and the westerly duct. However, the respective contributions of the different mechanisms remain to be adequately quantified.

New or refined datasets might open additional avenues for research. For example, atmospheric and oceanic reanalyses beginning in the early twentieth century could be used to evaluate SPCZ variability prior to the satellite era[23]. As much of the SPCZ region remains poorly observed, both in the atmosphere and ocean, targeted field studies are needed. New observations could shed light on the interplay of dynamical mechanisms and thermodynamic processes affecting the SPCZ. Specific aspects of the SPCZ, such as the vertical distribution of diabatic heating, cloud radiative interactions, and air–sea interactions, would benefit from careful observation. One important focus is to clearly identify the main sources of moisture for the SPCZ and how air masses are modified as they flow into and sustain rainfall in the SPCZ.

The unexpected complexity of the natural variability of the SPCZ over interannual timescales indicates that further work is needed to fully characterize the effects of different types of El Niño events (those centered in the eastern Pacific versus the central Pacific)[131] on the SPCZ, and to develop improved models of possible future changes in the pattern or frequency of such events[134]. New paleoclimate records from corals and speleothems could also help to extend our understanding of SPCZ variability over interannual, interdecadal and longer timescales. Promising multi-proxy datasets are being developed in this regard. These include the Past Global Changes (PAGES) 2K Network (PAGES2K)[132] and related Iso2K and CoralHyro2K databases, along with other marine and continental initiatives such as Speleothem Isotope Synthesis and Analysis (SISAL) and Marine Annually Resolved Proxy Archives (MARPA). Paleoclimate records of rainfall, salinity and other relevant variables might enable reconstructions of SPCZ responses to cold glacial conditions or changes in zonal or meridional temperature gradients. If the effects of past climates on the SPCZ can be reconstructed with sufficient confidence, they can similarly provide targets for climate model simulations[133].

In that regard, reliable projections of future changes in the SPCZ are necessary to support climate adaptation in the South Pacific islands. Coupled climate models have long struggled to accurately simulate the SPCZ and future projections of rainfall changes remain highly uncertain (Fig. 5a). Thus, there is a need for long-term efforts to improve climate model representation of the Pacific oceanic and atmospheric mean state and ENSO variability[134]. Such improvements are a necessary condition for an improved simulation of the SPCZ, although model resolution, sophistication of model convection schemes, and representation of atmosphere-ocean feedbacks may also play important roles. When robust regional projections are urgently required, some form of model bias correction (atmospheric experiments forced with corrected SST or flux-adjusted climate simulations) may improve model projections in the shorter term[40].

Although much progress has been made towards understanding the SPCZ, some areas of uncertainty remain. Topics for future work include improved understanding of the relationship between the SPCZ and SST patterns; further investigation of the similarities and differences between the SPCZ and other diagonal convergence zones such as the SACZ; and improved description of the impact of the SPCZ on regional and global weather and climate. The development of improved climate forecasting capabilities has emerged as a critical global need, and reliable projections of the future of the SPCZ will be essential to both build resilience to climate variability and support climate adaptation in the South Pacific islands.

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Author contributions

J.R.B, M.L., B.R.L., M.J.W. and K.v.d.W. researched data for the article, wrote the manuscript, contributed to discussions of its content and participated in review and/or editing of the manuscript before submission. C.D., B.K.L., A.J.M. and J.R. also wrote the manuscript and participated in review and/or editing of the manuscript before submission. C.D. additionally researched data for the article.

Competing interests

The authors declare no competing interests.

Peer review information

Publisher's note

Key points

- The South Pacific Convergence Zone (SPCZ) is a major region of low-level wind convergence, convection and rainfall extending from the equator towards the southeast in the South Pacific
- Variability of the SPCZ has a large effect on Pacific Island communities
- The location and intensity of the SPCZ vary on timescales ranging from days to decades, as the SPCZ interacts with regional climate drivers such as the El Niño–Southern Oscillation.
- Climate models disagree on whether the SPCZ will become wetter or drier in the future, highlighting the need to improve the reliability of climate models

Figure 1: Climatology of the South Pacific. a | Mean December to February precipitation[137] (shaded contours; mm/day) and 925hPa winds[138] (vectors; m/s), and **b |** sea surface temperature[139] (shaded contours; °C) and sea level pressure[138] (contours; hPa) averaged over 1980–2005.

Figure 2: Formation of the diagonal SPCZ. a | extratropical-tropical interaction: The zonally asymmetric distribution of sea surface temperatures generates a subtropical anticyclone over the southeast Pacific ('H'), guiding moisture transport into the SPCZ region (dashed blue arrow). Dynamical forcing from equatorward propagating Rossby waves (blue arrow) triggers deep convection along a band oriented in a northwest-southeast direction. Upper-level easterly winds (hatching) prevent cross-equatorial Rossby wave propagation, which can only occur in the westerly duct . **b |** Direct forcing: Convection over the maritime continent (grey oval) forces an equatorial Rossby wave response, establishing an upper-tropospheric anticyclone (blue arrow) that advects potential vorticity equatorward on the eastern flank. The PV anomaly destabilises the atmosphere, resulting in deep convection along the SPCZ. Panel **a** adapted, with permission, from refs[31]. Panel **b** adapted, with permission, from refs[34].

Figure 3: ENSO influence on SPCZ orientation. Composites of December–February precipitation[137] (shading) for all years (panel **a**), La Niña years (panel **b**), weak to moderate El Niño years (panel **c**) and strong El Niño years (panel **d**). La Niña years are defined as those in which the NINO3 index (derived using ERSSTv5[139]) is <-0.5 standard deviations; weak-moderate El Niño as those as 0.5-1.5 standard deviations; and strong El Niño as those > 1.5 standard deviations. Yellow lines represent the position of the SPCZ, expressed as the latitude of maximum precipitation over 155°E–150°W and 0–30°S. The SPCZ position in **a** is replicated in **b**-**d** as red dashed lines. Contours in **b**–**d** indicate anomalous rainfall relative to **a**, drawn at thresholds of –4, –2, –1, 1, 2 and 4 mm/day; negative values are shown as dashed lines.

Figure 4: ENSO-modulated SPCZ climate variability.
a | Normalized November-April tropical cyclone track density[140] regressed onto the November-April Oceanic Niño Index (ONI) during 1979–2016. Purple lines indicate cyclone tracks during extreme El Niño seasons (corresponding to zonal SPCZ events: 1982/83, 1991/92, 1997/98, and 2015/16). **b |** as in **a**, but for satellite[141] (shading) and tidal-gauge[142] (filled circles) sea

level. Blue and red contours indicate the -10cm and 10cm sea level anomalies associated with the 1997/98 and 2015/16 El Niño events.

Figure 5: Climate model simulation of the SPCZ. December–February seasonal mean precipitation in observations[137] (part **a**), CMIP3[117] multi-model mean (part **b**), CMIP5[118] multi-model mean (part **c**) and CMIP6[119] multi-model mean (part **d**). Yellow lines represent the position of the SPCZ, expressed as the latitude of maximum precipitation over 155°E–150°W and 0–30°S. 24, 26 and 27 models are used for the multi-mode mean in panel b, c and d, respectively. s = slope (S/°E); lat = mean latitude of the SPCZ

Figure 6: Effects of climate change on the SPCZ. **a|** Projected change in December–February precipitation from 2075-2100 relative to 1980-2005, as derived from the multi-model mean of 36 CMIP5 models forced by RCP 8.5 (shading). Stippling indicates regions where less than two-thirds of models agree on the direction of change (larger circles) or the predicted future change is minimal (below ±1 mm per day; smaller diamonds). Blue and magenta contours indicate observed[143] and CMIP5-simulated rainfall reaching 5mm/day over 1980-2005. **b |** the thermodynamic ('wet gets wetter') response of SPCZ rainfall to anthropogenic warming. **c |** the dynamic ('warmest gets wetter') response of SPCZ rainfall to anthropogenic warming. In **b** and **c**, brown and blue contours indicate, respectively, and green and brown arrows tendencies for increased or decreased rainfall, respectively. ITCZ, intertropical convergence zone. **b** and **c** adapted, with permission, from ref.[18].

Glossary

Rossby waves

Kelvin wave

Online ToC

The South Pacific Convergence Zone (SPCZ) describes a band of heavy precipitation extending southeastward from the Solomon Islands to French Polynesia. This Review discusses the mechanisms explaining the diagonal orientation of the SPCZ, its variability, and projected changes under anthropogenic warming.