

Indices of Pacific Walker Circulation strength: trends, correlations and uncertainty

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Key Points:

- The evolution and trends of the Pacific Walker circulation (PWC) are evaluated using ten PWC indices in ERA5 data in the 1951-2020 period.
- Trends are strongly affected by the choice of representative time period and are rarely statistically significant.
- Positive and negative trends are suggestive of the presence of a multidecadal oscillation in the PWC.

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Abstract

The strength of Pacific Walker circulation (PWC) significantly affects the global weather patterns, the distribution of mean precipitation, and modulates the rate of global warming. Different indices have been used to assess the PWC strength. Evaluated on different datasets for various study periods, the indices show large discrepancies between the reported trends. In this study, we performed sensitivity analysis of 10 PWC indices and compared them over the 1951-2020 period using the ERA5 reanalyses.

The time series of normalised indices generally agree on the annual-mean PWC strength. The highest correlations (exceeding $r = 0.9$) are between the indices that describe closely linked physical processes.

The trends of PWC strength are strongly affected by the choice of representative time period. For the commonly used 1981-2010 period, the trends show strengthening of the PWC. However, trends computed for longer period (i.e. 1951-2020) are mostly neutral, whereas the past two decades (2000-2020) display weakening of the PWC, although it is statistically not significant. The temporal evolution of trends suggests multidecadal variability of PWC strength with a period of about 35 years, implying a continued weakening of the PWC in the next decade.

Plain Language Summary

The Pacific Walker circulation (PWC) is tropical atmospheric circulation that consists of easterly winds close to the ground, westerlies aloft, upward motion in the western and downward motion over the eastern Pacific. The PWC impacts the rate of global warming and the sea-level rise. Thus, its accurate representation and prediction is an ultimate goal of climate models.

Towards this goal, the PWC strength has been described by a number of indices. Evaluated on different datasets and for various study periods, the PWC indices show large discrepancies between the reported trends. We assessed (dis)agreement among 10 PWC indices for 1951-2020 period using the ERA5 dataset, as the most reliable representation of the climate system since 1950. The indices computed from ERA5 data verify well with observations.

Indices generally agree on time series of PWC strength, with the highest correlations between the indices based on closely linked physical processes. However, we show

46 that the PWC trends are strongly affected by the choice of representative time period
47 and often not statistically significant. They overall suggest weakening of PWC in the last
48 two decades. Moreover, oscillatory structure of the trends suggest the presence of mul-
49 tidecadal oscillation of PWC.

50 **1 Introduction**

51 The Pacific Walker circulation (PWC) is the zonal part of the overturning tropi-
52 cal Pacific circulation, driven by the zonal pressure gradient and associated with the lon-
53 gitudinal gradients of sea-surface temperature. The PWC is characterized by the ascend-
54 ing motion over the warmer western Pacific east of around 150°E , and descending mo-
55 tion over the cooler eastern Pacific west of around 90°W (Peixoto & Oort, 1992; Seager
56 et al., 2019). The circulation cell is completed by the upper-tropospheric equatorial west-
57 erlies and lower-tropospheric equatorial easterlies. The magnitude of the involved hor-
58 izontal and vertical motions defines the PWC strength.

59 The strength of PWC is largely synced with the Pacific ocean circulation via the
60 Bjerknes feedback (Bjerknes, 1969). Thus, it crucially impacts the global climate; it af-
61 fects the precipitation distribution in the tropics (e.g., Barichivich et al., 2018) as well
62 as in extratropics via atmospheric teleconnections, it is coupled to the mean-sea level in
63 the tropical Pacific (e.g., Merrifield, 2011; Muis et al., 2018), impacts heat uptake (e.g.,
64 Meehl et al., 2011; England et al., 2014; McGregor et al., 2014), carbon uptake and car-
65 bon outgassing (Betts et al., 2020) and therefore also the rate of climate-change-induced
66 warming in tropics and extratropics, particularly in winter when the heat-transporting
67 stationary/transient eddies are stronger (Kosaka & Xie, 2013). Therefore, a comprehen-
68 sive description and accurate prediction of PWC is of great societal importance.

69 Several distinct metrics have been used in the literature to date to describe the PWC
70 strength and its changes in time. These metrics have been applied to distinct observa-
71 tional and reanalysis datasets for distinct time periods. For example, Sohn and Park (2010)
72 related the PWC strength to the magnitude of the water vapor transport in the lower
73 return branch of PWC. Using satellite data (from microwave imager and infrared sounder)
74 and reanalyses, they reported a PWC strengthening in the 1979-2007 period. Similar con-
75 clusions were reached by Sohn et al. (2013) for the 1979-2008 period using purely ob-
76 servational datasets and different metrics including sea-surface-temperature (SST) and

77 sea-level-pressure (SLP) differences across the equatorial Pacific. Kociuba and Power (2015)
78 applied an identical SLP index and observed significant strengthening in the 1980-2012
79 period, whereas any trend starting before 1951 and ending in 2012 is negative. Strength-
80 ening of the PWC in recent decades was suggested also by Chen et al. (2008); Luo et al.
81 (2012); Meng et al. (2012); L’Heureux et al. (2013); Bayr et al. (2014); Sandeep et al.
82 (2014); Chung et al. (2019); Zhao and Allen (2019), as well as by the isotopic analysis
83 of $\delta^{18}\text{O}$ (Falster et al., 2021). The PWC strengthening in turn lead to increased zonal
84 sea-surface temperature (SST) gradients in the equatorial Pacific (Seager et al., 2019),
85 and enhanced upwelling of the cold deep-ocean water in the Eastern Pacific, causing the
86 so-called global warming hiatus in the 2000s and early 2010s (Kosaka & Xie, 2013; Eng-
87 land et al., 2014; Watanabe et al., 2013).

88 In contrast, a number of studies reported a weakening trend of PWC, in particu-
89 lar for indices evaluated using numerical modeling. Bellomo and Clement (2015) related
90 the vertical velocity in the PWC’s ascending branch to the observed cloud cover and ar-
91 gued for a weakening PWC trend for the 1954-2008 period, consistent with the projected
92 weakening by the climate models due to anthropogenic climate change (Knutson & Man-
93 abe, 1995; Held & Soden, 2006; Vecchi et al., 2006; Vecchi & Soden, 2007; Bayr et al.,
94 2014; Wu et al., 2021; Masson-Delmotte et al., 2021). PWC weakening between 1950 and
95 2009 has been also suggested by Tokinaga et al. (2012) who analyzed the SLP gradient
96 over the tropical Pacific derived from the atmospheric general circulation model (AGCM)
97 experiments forced by the SSTs from the International Comprehensive Ocean–Atmosphere
98 Data Set (ICOADS, Woodruff et al., 2011), instead of the more commonly used HadISST1
99 data (Rayner et al., 2003). Other studies reporting a weakening trend of the Walker cir-
100 culation in the 20th century include Deser et al. (2010), Power and Kociuba (2011) and
101 DiNezio et al. (2013). This was supported by the isotopic analysis of corals in the trop-
102 ical Pacific (Liu et al., 2019).

103 The examples above reveal opposite conclusions about the trends of PWC strength
104 using different datasets and metrics of PWC strength. The PWC time series reflect a
105 combination of forced signal and multidecadal climate variability, making a direct inter-
106 comparison of various studies difficult, even for largely-overlapping periods. While a strength-
107 ening of the PWC in the period after 1979 seems firmly established (Wu et al., 2021),
108 its near-future projection is less clear. It is necessary to systematically intercompare the
109 PWC indices in use and their sensitivity to the analysis periods for the computation of

110 the trends. We carry out such a comparison in this paper. The paper complements pre-
 111 vious studies by L’Heureux et al. (2013), Plesca et al. (2018) and Chung et al. (2019)
 112 that compared the PWC trends for several PWC indices, by performing a systematic in-
 113 tercomparison of ten PWC indices used in the literature up to date on the latest gen-
 114 eration of the European reanalyses, ERA5.

115 We evaluate the ten indices using the ECMWF ERA5 dataset in the 1951-2020 pe-
 116 riod (Hersbach et al., 2020), we test their sensitivity to averaging regions and levels, and
 117 verify them with their equivalents derived directly from observations. The definitions of
 118 10 indices and details about various datasets are provided in Section 2. The time series
 119 of PWC indices, their correlations, and the sensitivity of the derived trends to different
 120 periods are compared in Section 3. Conclusions and discussions are given in Section 4.

121 **2 Pacific Walker Circulation Indices and Datasets**

122 We present ten indices, that are considered suitable given results from their recent
 123 applications and understanding of tropical east-west circulation.

124 **2.1 Definitions of Indices**

125 The following indices of Pacific Walker Circulation are compared:

- 126 1. Point-based Southern oscillation index (SOI) from Troup (1965), which is defined
 127 by the anomaly in the mean sea-level pressure difference between Tahiti and Dar-
 128 win station data standardized for each month of the year using 1950-2021 as a base
 129 period. As we compute the SOI from the reanalysis data, the closest model grid-
 130 points are used for evaluation (see Supplementary Information Fig. S1 for justi-
 131 fication).
- 132 2. Area-averaged Southern oscillation index Δ SLP from Vecchi et al. (2006), defined
 133 as a difference between anomalies in mean sea-level pressure over the eastern and
 134 western equatorial Pacific. The anomalies are averaged over two boxes, both ex-
 135 tending from 5°S to 5°N in meridional directions. In zonal direction the boxes ex-
 136 tend from 80°E to 160°E (western Pacific box) and from 80°W to 160°W (east-
 137 ern Pacific box). This index has been widely used due to the availability of long-
 138 term historical data on sea-level pressure.

- 139 3. Velocity potential index from Tanaka et al. (2004) that is computed for 2D cir-
 140 culation at a single vertical level (typically pressure p level) by solving the Pois-
 141 son equation

$$142 \quad \nabla \cdot \mathbf{V}_p = -\nabla^2 \chi_p. \quad (1)$$

143 The index was originally defined by Tanaka et al. (2004) as the yearly average of
 144 maximum deviation of velocity potential from its zonal mean over equatorial Pa-
 145 cific at 200 hPa level, χ_{200} . Here, the yearly averaging was applied as a 12-month
 146 running mean. However, as the maximum divergent outflow from a convective area
 147 over the Maritime continent is higher up in the troposphere (see Fig. S2) and varies
 148 year-to-year, we rather constructed a data-adaptive index χ_{\max} , which takes the
 149 maximal velocity potential over equatorial Pacific at each time step (see Section 3
 150 for argumentation and Fig. S3 for justification).

- 151 4. Vertical velocity index from Wang (2002) (named ω_{500}), calculated as the differ-
 152 ence in average vertical pressure velocity anomalies between eastern and western
 153 equatorial Pacific at 500 hPa. Eastern Pacific is defined as an area between 120°W
 154 and 160°W, and from 5°S to 5°N). The Western Pacific is defined between 120°E
 155 and 160°E, and from 5°S to 5°N).

- 156 5. The sea-surface temperature (SST) index defined the same way as the Δ SLP in-
 157 dex, but for the SST data. SST data are often used as a proxy/driver for PWC
 158 strength (Tokinaga et al., 2012; Meng et al., 2012; Zhang & Karneuskas, 2017).
 159

- 160 6. Effective wind for water vapor transport index following Sohn and Park (2010).
 161 The boundary layer easterlies in the lower return branch of the Walker circula-
 162 tion carry the water vapor from the eastern to the western Pacific to provide ad-
 163 ditional fuel for condensation heating, which maintains the Walker circulation. The
 164 increase and decrease of water vapor flux, normalized by the total amount of va-
 165 por in the atmospheric column, is regarded as the strengthening and weakening
 166 of circulation, respectively. The effective wind is defined as:

$$167 \quad \mathbf{V}_e = \sum_{i=1}^N \frac{PW(i)}{TPW} \mathbf{V}_D(i), \quad (2)$$

168 where $PW(i)$ is precipitable water in a vertical layer between i -th and $i + 1$ -th
 169 vertical level, TPW is the total precipitable water in a column and $\mathbf{V}_D(i)$ is di-
 170 vergent wind at i -th vertical level. The summation goes from the ground level up-
 171 wards (in our case from 1000 hPa to 850 hPa).

172 Precipitable water $PW(i)$ is calculated as

$$173 \quad PW(i) = \frac{1}{\rho_w g} \int_{p_i}^{p_{i+1}} q(p) dp, \quad (3)$$

174 where ρ_w is water density, g is gravity acceleration, $q(p)$ is specific humidity, and
 175 p_i and p_{i+1} are boundaries of specific layer ($p_{i+1} < p_i$). Total precipitable wa-
 176 ter is calculated in the same way, with $p_i = p_s$ (surface pressure) and p_{i+1} is at
 177 the top of the atmosphere.

178 As we are interested in Walker circulation, we only used the zonal component of
 179 the divergent wind (u_D) and defined the index (named V_e) as an average value of
 180 effective zonal wind for water vapor transport in the tropical Pacific area (120°E
 181 to 120°W, and 5°S to 5°N).

182 7. Stream function index, based on a mass stream function:

$$183 \quad \psi(p) = \frac{2\pi a}{g} \int_0^p u dp, \quad (4)$$

184 where a is the radius of the Earth, g is gravity acceleration, and u is the zonal com-
 185 ponent of wind averaged between 5°S and 5°N. We define the index (named ψ_{500})
 186 as maximal stream function at 500 hPa within 90°E and 80°W. Originally this
 187 index was defined using the zonal component of divergent wind (Yu & Zwiers, 2010;
 188 Bayr et al., 2014). Whereas the divergent circulation explains the majority of the
 189 meridional tropical circulation (Pikovnik et al., 2022), the zonal response to deep
 190 convective forcing over the Maritime continent projects on both the rotational and
 191 divergent flows (Gill, 1980). Thus, we opted for the zonal component of the to-
 192 tal wind instead of its divergent part (their difference is shown in Fig. S4).

193 8. Zonally-integrated (across the Pacific basin) wind stress following Clarke and Lebe-
 194 dev (1996), i.e. L_τ . It is defined as

$$195 \quad L_\tau = \int_0^L \overline{\tau_x} dx, \quad (5)$$

196 where $\overline{\tau_x}$ is meridionally averaged zonal wind stress. Zonal integration is performed
 197 between 124°E and 90°W. In the meridional direction, we choose to average be-

198 tween 5°S and 5°N, to be consistent with other indices. Following Clarke and Lebe-
 199 dev (1996), we computed wind stress as

$$200 \quad \tau_x = \rho_a c_D |\mathbf{V}| u, \quad (6)$$

201 where ρ_a is air density (with a constant value of 1.2 kg/m³ as in Clarke and Lebe-
 202 dev (1996)), c_D is drag coefficient (1.5×10^{-3}), and \mathbf{V} is horizontal surface wind
 203 vector at 10 m elevation ($\mathbf{V} = (u, v)$).

204 9. Upper tropospheric specific humidity (denoted Q_{200}). As the upper-tropospheric
 205 water vapor in the western equatorial Pacific is mainly transported by deep con-
 206 vection in the ascending branch of the PWC, a change in the upper-tropospheric
 207 humidity may indicate a change in the circulation strength (Sohn et al., 2013). To
 208 eliminate the increase of specific humidity (a general increase in humidity due to
 209 global atmospheric warming), we formulated the index as the difference in upper
 210 tropospheric humidity at the top of ascending and descending branches of Walker
 211 circulation. The humidity Walker circulation index is then defined as a difference
 212 in average specific humidity between two boxes over the eastern and western Pa-
 213 cific at 200 hPa. We used the same horizontal boxes for specific humidity as they
 214 were used for ω_{500} .

215 10. Average surface zonal winds over the central equatorial Pacific (denoted U_{ave}), af-
 216 ter Chung et al. (2019). The index is applied by averaging 10 m wind over an area
 217 from 6°S to 6°N and from 180° to 150°W.

218 The ten indices can be grouped into two categories: (a) the direct circulation in-
 219 dices (χ_{max} , ψ_{500} , L_τ , U_{ave} , \mathbf{V}_e and ω_{500}) which directly measure the velocity of the flow
 220 or associated flow function in any of the PWC branches, and (b) the indirect indices of
 221 the PWC magnitude derived from the atmospheric mass field or the lower boundary (Q_{200} ,
 222 SOI, ΔSLP and SST). The Q_{200} index measures PWC strength through the convective
 223 humidity-influx in the upper troposphere, whereas the SST index measures the PWC
 224 strength through coupled ocean-atmosphere interactions.

225 All indices are influenced also by other parts of the tropical general circulation, i.e.
 226 by the Hadley and Monsoon circulations. In particular, indices that indirectly measure
 227 PWC strength and may not only be representative of the PWC changes but also of the

228 accompanying local Hadley cells (Sohn et al., 2019; Pikovnik et al., 2022; Zaplotnik et
 229 al., 2022). The anthropogenic warming of the atmosphere and increasing water content
 230 directly affect the thermodynamic indices, whereas the SST index is also affected by the
 231 ocean processes.

232 Some of the indices attain physical units, some are made dimensionless, and they
 233 may have largely different magnitude. To make indices comparable, we standardize them,
 234 i.e. the mean value of the index is subtracted from each index and then normalized by
 235 its standard deviation within the study period. All indices are computed for 1950-2021
 236 period. As application of running mean shortens time series of χ indices for six month
 237 at each end of the interval, the comparison of indices is performed on 1951-2020 period.

238 The indices require different amounts of data for their evaluation. SOI is calculated
 239 from pressure in two particular locations and can be affected by the local microclimate,
 240 especially when computed from station measurements, whereas indices from area-averaged
 241 data (ΔSLP , ω_{500} , SST, \mathbf{V}_e , L_τ , Q_{200} , U_{ave}) should better represent large processes. Some
 242 of the indices require only one basic variable and are easily calculated (e.g. SOI, ΔSLP ,
 243 SST, Q_{200} , U_{ave}), while others require derived products (e.g. ψ_{500} , χ_{max} , L_τ , \mathbf{V}_e) and/or
 244 more complex calculation (e.g. ψ_{500} , \mathbf{V}_e). It is therefore logical that historically, the choice
 245 of the PWC index was influenced by the availability of data and computational resources.

246 **2.2 Data**

247 To intercompare a range of PWC indices, a dataset based on fully-coupled atmosphere-
 248 ocean modeling is required. The latest ERA5 reanalysis data are used for the period 1950-
 249 2021 (Hersbach et al., 2020, 2018a; Bell et al., 2020a). The indices are derived from the
 250 pressure vertical velocity ω , the zonal and meridional winds and specific humidity, which
 251 are provided on a regular latitude-longitude grid with 1° horizontal resolution and 27
 252 vertical pressure levels, extending from 100 to 1000 hPa. Sea surface temperature (SST)
 253 data and the mean-sea-level pressure (MSLP) data are at the same horizontal grid (Hersbach
 254 et al., 2018b; Bell et al., 2020b). Depending on the index, we use either monthly means,
 255 computed from either daily 00 UTC data for horizontal winds (u and v) or daily means
 256 for all other variables (MSLP, ω , specific humidity q , and sea-surface temperature SST).
 257 The mixed-use of 00 UTC and daily mean data was justified by comparison of both datasets
 258 for the ω index at 500 hPa, as the ω is one of the variables most affected by the diurnal

259 cycle. However, the choice of 00 UTC or daily mean data has negligible impact on the
260 indices (see Fig. S5).

261 We consider ERA5 sufficient for the analysis for several reasons. First, Simmons
262 (2022) has shown that ERA5 very well verifies with the upper-tropospheric wind mea-
263 surements in the tropics. The mean departure between the observations and background
264 or first-guess in data assimilation (i.e. short-range forecasts) for upper-tropospheric zonal
265 winds is trend-free and less than 1 m/s from the late 1990s onwards. In addition, the
266 supplemental material includes our verification of PWC indices based on surface winds
267 in ERA5 and the Wave- and Anemometer-based Sea surface wind product (WASWind,
268 Tokinaga & Xie, 2011) showing their close correspondence (Fig. S6). Similarly, the ERA5-
269 derived SST indices agree well with the indices derived from HadISST data (Rayner et
270 al. (2003); see Fig. S7 for comparison). The same applies to the SOI index based on ERA5
271 data verified against the index derived from raw station data (Fig. S1).

272 **3 Results**

273 In this section we first discuss temporal evolution of the ten indices (including their
274 reformulations in two cases) and correlation coefficients between various indices. This
275 is followed by the evaluation of trends and their sensitivity to the period used for the com-
276 putation of the trends.

277 **3.1 Time-series of PWC indices and their correlations**

278 Time series of the normalised annual-mean PWC indices (Fig. 1a) agree relatively
279 well on the evolution and relative strength of PWC during most of the period since 1950.
280 The majority of the indices spot strong El Niños in e.g. 1972, 1982/83, 1987, 1992, 1997/98,
281 and 2015. There is more discrepancy between the indices regarding La Niñas, as they
282 tend to be more prolonged. The two indices that deviate most from the others are the
283 stream function index based on the divergent zonal wind at 500 hPa and velocity po-
284 tential at 200 hPa. Their more poor agreement with other indices motivated their re-
285 formulation as described in the previous section and discussed below.

286 The fact that different indices describe different aspects of PWC implies that their
287 correlations will vary (Fig. 1b). Correlations are generally high between the indices de-
288 rived from physically linked processes. For example, the pair of indices with the high-

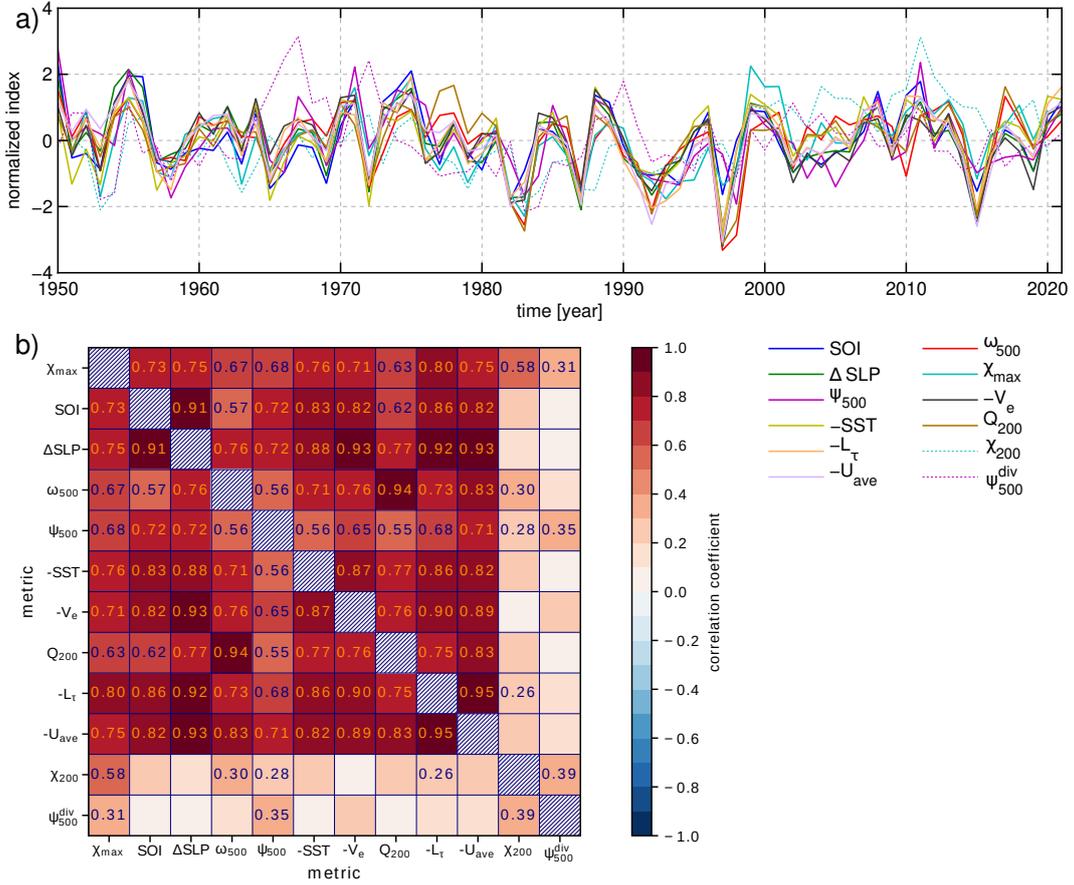


Figure 1. a) Time series of annual-mean PWC strength in ERA5 reanalysis between 1950 and 2021 for different PWC indices described in Section 2.1 as shown in the legend. b) Correlations between annual means of different PWC indices. Statistically significant (at 95 % confidence level) correlation coefficients are written in the respective fields. SST, V_e , L_τ and U_{ave} indices are multiplied by (-1) for easier comparison with other indices. χ_{200} and ψ_{500}^{div} are shown dashed in a) as they are replaced by better defined equivalent indices and not used in the continuation.

est correlation coefficient ($r = 0.95$) is U_{ave} and L_τ , which both describe surface easterlies. The ω index very highly correlates ($r = 0.94$) with the Q -index, as the amount of upper tropospheric humidity is directly related to the magnitude of vertical water vapor transport through convection. Similarly, the ΔSLP index correlates very highly ($r = 0.92$ to 0.93) with the zonal surface wind index U_{ave} , surface wind stress index L_τ , and zonal boundary-layer moisture transport (represented by the effective wind V_e). This can be expected, as the pressure difference (expressed by SOI, ΔSLP) over the Pacific drives the near-surface equatorial easterlies. The larger the pressure difference, the stronger the easterlies (U_{ave}), the wind stress (L_τ), and the water vapor transport (V_e).

The correlations are somewhat lower between indices derived from distinct processes, e.g. surface wind and upper-tropospheric humidity ($r = 0.83$). Moderate correlations are observed between ω , and SST and ΔSLP indices with $r = 0.71$ and 0.76 , respectively. This suggests, that the convective mass flux over the Maritime continent is controlled not only by the zonal SST gradient or SLP gradient but also by the local meridional gradients in the Western Pacific (Sohn et al., 2019). This is further supported by a rather moderate correlation ($r = 0.56$) between the SST and ψ indices, suggested also by He et al. (2014).

The original χ_{200} index (Tanaka et al., 2004) and stream-function index ψ_{500}^{div} (Yu & Zwiers, 2010; Bayr et al., 2014) (both indicated with dashed line in Fig. 1a) stand out from the rest and do not properly distinguish between the strongest El Niños. After the year 2000, χ_{200} -index also significantly exceeds the values of other indices. The velocity-potential index is highly susceptible to the choice of upper-tropospheric pressure level, in connection to the strong vertical profile of the divergent outflow (see Figs. S2, S3). The peak divergent outflow also occurs at different pressure levels year-to-year. Therefore an index defined at some predetermined pressure level can miss peak velocity potential. To alleviate it, we constructed a data-adaptive index, which takes the maximum of monthly-mean χ at any level within the box area. Such index correlates almost perfectly with the χ_{150} index ($r = 0.98$), meaning that the original χ_{200} index was applied too low in the troposphere. Our reformulated index χ_{max} verifies much better with other PWC indices (Fig. 1b).

Similarly, the stream-function index computed from total zonal wind instead of the zonal divergent wind verifies well with other PWC indices. The original stream-function

321 index based on the divergent wind deviates from other indices in particular in the pre-
 322 satellite era in the 1960s and 1970s (see Figs. 1a and S8). Correlations with other in-
 323 dices are small, and the only statistically significant correlations for annual means are
 324 with χ_{200} , χ_{\max} and ψ_{500} indices (r between 0.3 and 0.4).

325 PWC indices are typically defined at fixed vertical levels where the underlying phys-
 326 ical processes are on average the strongest; for example, the divergent outflow is strongest
 327 in the upper troposphere at around 150 hPa level (Fig. S2) and the stream function has
 328 largest amplitude at 500 hPa level. As the PWC strength and position oscillate on a year-
 329 to-year basis, the intercomparison of PWC indices might be skewed due to the displace-
 330 ment of maxima from vertical levels on which indices are computed. To ensure that our
 331 results are not significantly affected by such displacements, we tested the sensitivity of
 332 the indices to meaningful changes in the choice of the vertical level. The sensitivity was
 333 checked for χ , ω , ψ , and Q indices (see Figs. S3, S5, S8, and S9). We also checked the
 334 sensitivity of indices to different meridional extents of horizontal areas used in their com-
 335 putation (see Fig. S8 for ψ and Fig. S9 for Q -index). As the tropical processes are mainly
 336 centered at the ITCZ, we checked how the indices, originally defined in a narrow equa-
 337 torial belt (5°S and 5°N) change when meridional borders of the areas considered were
 338 modified (5°N and 20°N) to better align with the average position of ITCZ. This was
 339 applied to V_e , ψ , L_τ , and Q indices. In general, the indices are not very sensitive to the
 340 vertical level or horizontal area used for calculation, as long as the chosen level/area is
 341 close to the level/area used in the original definition. This is supported by high corre-
 342 lation coefficients between different variations of each index (not shown). The only ex-
 343 ception is the χ index, which varies significantly with the vertical level used for compu-
 344 tation, as already mentioned. Our sensitivity analysis confirms that the results on PWC
 345 changes, presented in this paper, are not meaningfully impacted by the mild shifts of ver-
 346 tical levels or meridional averaging.

347 **3.2 Trends in PWC and their sensitivity to the WC**

348 The PWC trends are evaluated from time series of standardized annual-mean PWC
 349 indices using linear regression. Figure 2 shows trends computed starting from various
 350 years from 1951 to 2000, with the end year of the interval fixed to 2020. This figure shows
 351 that the trends depend on the starting year. Most indices show neutral-to-negative trends
 352 for the start year between 1951 and 1970, suggesting that PWC has remained steady or

353 has been slightly weakening in the recent 70-year or 50-year time period. The exceptions
354 to this rule are the velocity-potential index and the SST index, which show strengthen-
355 ing of PWC until nearly the end of 20th century. In the 1980-2020 period, the PWC has
356 been strengthening according to most of the PWC indices. However, only χ_{\max} , ω_{500} and
357 L_{τ} indices show statistically significant strengthening at the 95% confidence level accord-
358 ing to the modified, trend free, pre-whitening Mann-Kendall test (Yue & Wang, 2002;
359 Hussain & Mahmud, 2019) (see Table S1). This applies also to the 1990-2020 period with
360 one half of the indices showing statistically significant trends. In the recent two decades
361 (2000-2020 period), the majority of the indices suggests PWC weakening, although the
362 uncertainty is relatively large.

363 Next question to ask is how the trends vary if both the end and start year for the
364 computation of the trend vary. This is shown in Fig. 3. Three distinct areas can be iden-
365 tified in the figure, although not equally clear for all ten indices: 1) trends, starting in
366 the 1950s, and ending in the 1970s are mostly positive, suggesting an increase in PWC
367 strength; 2) trends, starting approximately between 1960 and 1980, and ending around
368 2010 are mostly negative and often statistically significant, suggesting a weakening of
369 PWC; 3) trends, starting between around 1980 and mid to late 1990s are again mostly
370 positive, regardless of the end year. On the other hand, long-term trends starting be-
371 fore the mid-1970s and ending after the year 2010 are insignificant and have even dif-
372 ferent signs.

373 The right diagonal line shows 20-year running trends with start years from 1951
374 to 2000. This suggests approximately 20 years of downtrend (blue colours, start years
375 1963 to 1980) followed by 20 years of uptrend (red colours, start years 1980 to 1997). To-
376 gether, this suggests a multidecadal variability of the PWC with an approximately 35-
377 year period. If so, blue patches in the upper-right corners of Fig. 3, that indicate a PWC
378 weakening, together with recent trends in Fig. 2 suggest that a multidecadal trend re-
379 versal might be just taking place. Although a further analysis with longer dataset is needed
380 to confirm that the trends are associated with a multidecadal oscillation in PWC, our
381 expectation of a weakened PWC in the coming years agree with Wu et al. (2021) who
382 reached their conclusion by coupling the PWC with the Interdecadal Pacific Oscillation.

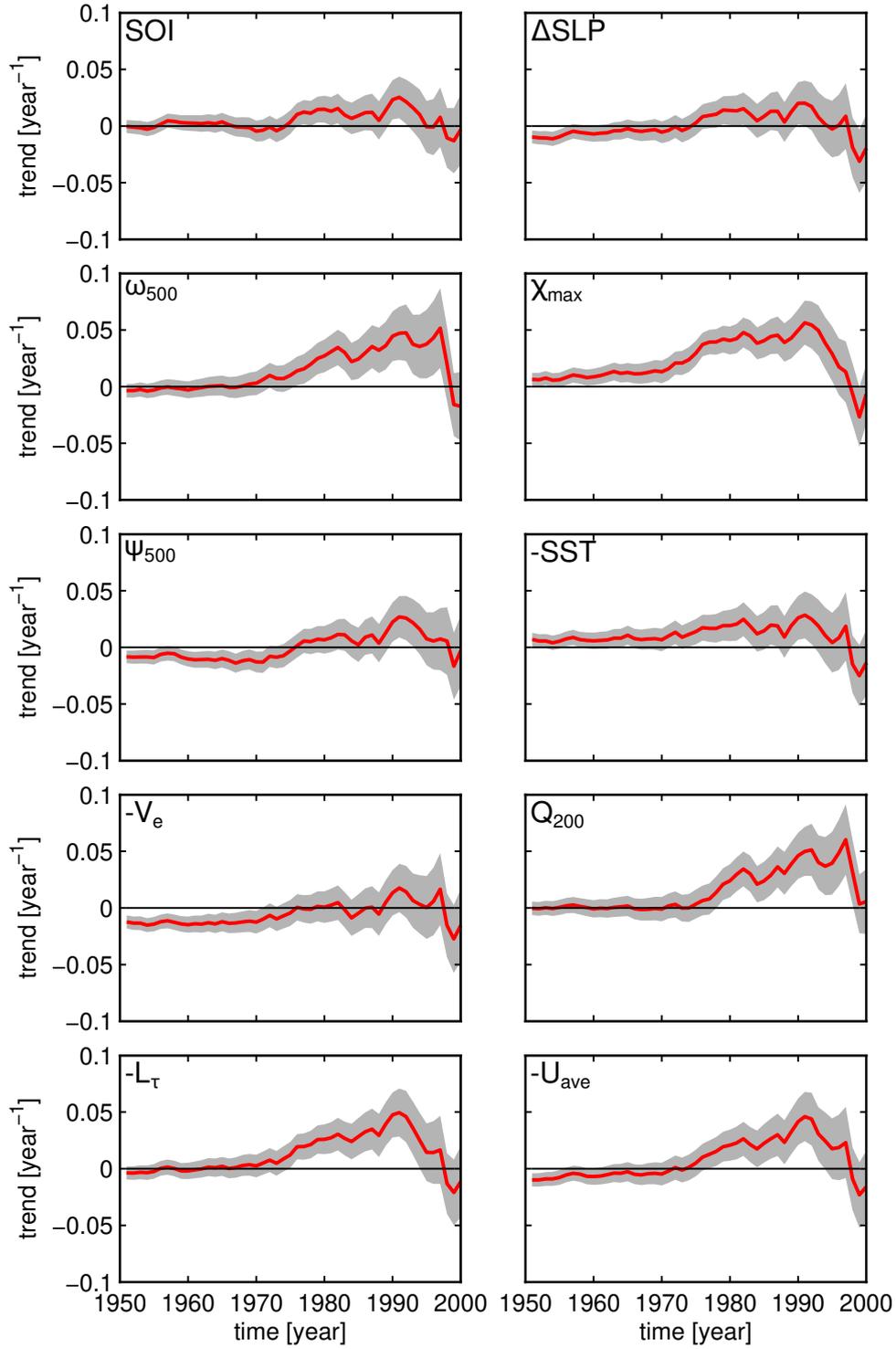


Figure 2. Trends of Pacific Walker circulation (PWC) strength as a function of the starting year of the trend for different PWC indices. The end year of all linear trends is fixed to 2020. For example, the year 1970 on the x-axis represents the PWC trend calculated for 1970-2020. PWC trends for periods shorter than 20 years are not shown. Thick red lines represent the trend value, and the gray areas represent the uncertainty (i.e. plus or minus one standard deviation) of the estimated trend. SST, V_e , L_τ and U_{ave} indices are multiplied by (-1) for easier comparison with other indices.

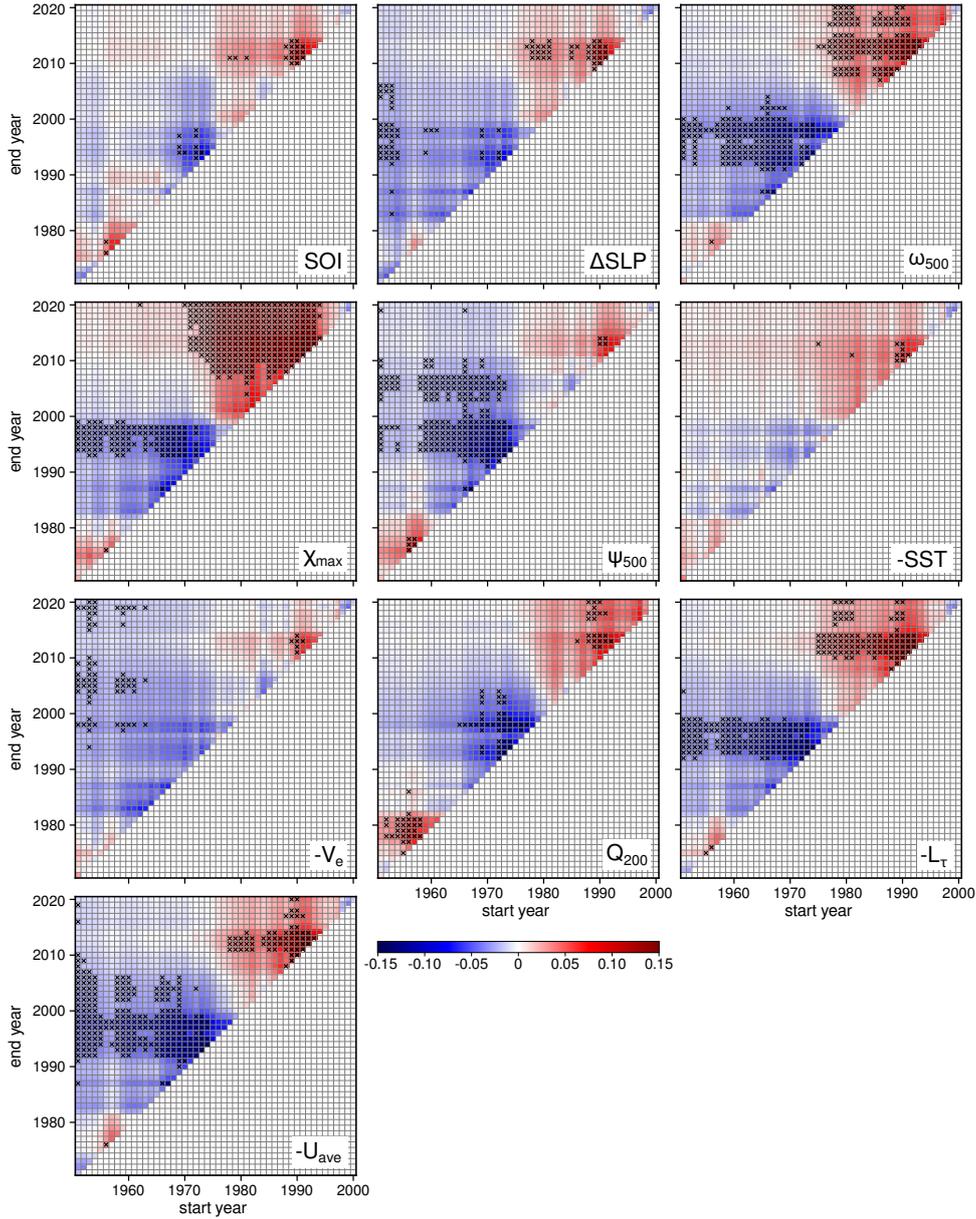


Figure 3. Trends of Pacific Walker circulation (PWC) strength as a function of the starting year (x-axis) and end year (y-axis) of the trend for different PWC indices. PWC trends for periods shorter than 20 years are not shown. Crosses represent statistically significant trends at the 95% confidence level. SST, V_e , L_τ and U_{ave} indices are multiplied by (-1) for easier comparison with other indices. The checkered pattern is a result of ENSO variability. First row in the matrix is a realisation of Fig. 2. The bottom-left top-right diagonal (0-diagonal) effectively represents a 20-year running trend (as in e.g. L’Heureux et al., 2013), whereas the k -diagonal represents a $(20 + k)$ -year running trend.

383 4 Discussion and Conclusions

384 The study compares ten different indices of the Pacific Walker circulation (PWC)
 385 strength over the 1951-2020 period using the ECMWF ERA5 reanalyses. We have shown
 386 that the indices derived from ERA5 are equivalent to indices deduced from the raw ob-
 387 servation data, as ERA5 accurately verifies with the observations of upper-tropospheric
 388 zonal winds, zonal surface winds, sea-level pressure, sea-surface temperature (see Sup-
 389 plementary information and Hersbach et al., 2020; Simmons, 2022). Some PWC indices
 390 have been refined. For example, the χ index was originally defined at 200 hPa (Tanaka
 391 et al., 2004). However, the newest state-of-the-art datasets suggest that the maximum
 392 divergent outflow associated with convection over the western Pacific is higher in the tro-
 393 posphere, at around 150 hPa. Similarly, the original definition of the stream function in-
 394 dex is based on divergent wind (Yu & Zwiers, 2010; Bayr et al., 2014) and appears to
 395 miss an important part of the zonal tropical circulation associated with the PWC. Thus,
 396 we suggest to replace χ_{200} and ψ_{500} by χ_{\max} and ψ_{500}^{tot} , respectively.

397 In general, the normalized PWC indices agree regarding the variation of annual-
 398 mean PWC strength (see Fig. 1a). The correlations are highest ($r = 0.9$ or more) be-
 399 tween the indices which describe closely linked processes, as could be expected. The in-
 400 dices are most often based on a single level. We have shown that the sensitivity of in-
 401 dices to the reasonable changes in the choice of vertical level or horizontal averaging area
 402 is negligible. One exception is the velocity potential index, which displays strong sen-
 403 sitivity to the choice of vertical level.

404 The sensitivity of the trends to the applied periods is often poorly explored in the
 405 literature. Our study shows that different indices, different lengths of the applied inter-
 406 val, and their start and end years, can largely affect the trends and their significance.
 407 In the common climatological reference period 1981-2010, the majority of indices showed
 408 PWC strengthening. On the longer time scales, i.e. 1951-2020, the trend is mostly neu-
 409 tral and insignificant. Furthermore, the majority of indices suggest that the PWC might
 410 have been weakening during the last two decades (2000-2020). A continuation of this trend
 411 implies a reversal of the PWC into an El Niño-type state with decreased ocean heat up-
 412 take and more rapid global warming. We suggest that the observed variability in the trends
 413 of the PWC indices is associated with the multidecadal variability of the PWC with a
 414 period of about 35 years. Longer data series are needed to confirm this result.

415 The recent (1981-2010) PWC strengthening has been unequivocally opposed to the
416 climate model projections (Gulev et al., 2021). Whether the source of the discrepancy
417 is multidecadal variability as seen in Fig. 3 (Meng et al., 2012; Chung et al., 2019; Wu
418 et al., 2021), forced response (Mann et al., 2021; Orihuela-Pinto et al., 2022) or biases
419 in the coupled ocean-atmosphere climate models (Durack et al., 2012; McGregor et al.,
420 2014; Seager et al., 2019; Watanabe et al., 2020; Wills et al., 2022), caution should be
421 exercised for the detection and comparison of PWC trends in the models and reanaly-
422 ses. We speculate a shift toward weakening of the PWC. If realised, it will crucially im-
423 pact the global distribution of precipitation in the tropics and extratropics, the ocean
424 heat uptake (e.g. Meehl et al., 2011), the sea-level rise and the rate of global warming.

425 **Appendix A Open Research**

426 ERA5 data (<https://doi.org/10.24381/cds.bd0915c6>, Hersbach et al., 2018) was down-
427 loaded from the Copernicus Climate Change Service (C3S) Climate Data Store (last ac-
428 cess 27 June 2022). The results contain modified Copernicus Climate Change Service
429 information 2022. Neither the European Commission nor ECMWF is responsible for any
430 use that may be made of the Copernicus information or data it contains.

431 Scripts for calculation of indices and data used to generate Figs. 1-3 and S1-S12
432 are published in Zenodo data repository: <https://doi.org/10.5281/zenodo.7359879> (Kosovelj
433 et al., 2022).

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