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Increased Summer Monsoon Rainfall over Northwest India caused by Hadley Cell Expansion and Indian Ocean Warming.

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Key Points:

- Large increase in summer monsoon precipitation over Northwest India
- The strengthening of the monsoon winds and the Indian Ocean warming drives increasing evaporation.
- Poleward shift and expansion of high-pressure belts and the Indian Ocean warming are responsible for the strengthening of winds.

20 **Abstract**

21 The Indian summer monsoon precipitation trend from 1979 to 2022 shows a substantial 40%
22 increase over Northwest India, which is in agreement with the future projections of the Coupled
23 Model Intercomparison Project 6 (CMIP6). The observationally constrained reanalysis dataset
24 reveals that a prominent sea surface warming in the western equatorial Indian Ocean and the
25 Arabian Sea might be responsible for the rainfall enhancement through strengthening the cross-
26 equatorial monsoonal flow and associated evaporation. We show that the cross-equatorial
27 monsoon winds over the Indian Ocean are strengthening due to the merging of Pacific Ocean
28 trade winds and rapid Indian Ocean warming. These winds also enhance the latent heat flux
29 (evaporation), and in combination, this results in increased moisture transport from the ocean
30 toward the land.

31 **Plain Language Summary**

32 The Indian summer monsoon rainfall has increased by 40% over Northwest India from 1979-
33 2022. The analysis suggests that a noticeable warming of the sea surface in the western
34 equatorial Indian Ocean and the Arabian Sea could be causing this increase in rainfall. This
35 warming strengthens the winds crossing the equator in the Indian Ocean and increases
36 evaporation. The study also shows that these monsoon winds are getting stronger because of the
37 merging of winds from the Pacific Ocean and the warming of the Indian Ocean. These stronger
38 winds cause more evaporation, which means more moisture is carried from the ocean to the land,
39 leading to increased monsoon rainfall.

40 **1 Introduction**

41 India receives approximately 80% of its total rainfall during the Indian Summer Monsoon
42 (ISM) season from June through September (JJAS). Billions of people depend on monsoon
43 rainfall for food, water security, and electricity. The timing and intensity of ISM rainfall play a
44 significant role in shaping the country's economy (Gadgil & Gadgil, 2006; Prasanna, 2014; Saha
45 et al., 1979). Extreme rainfall events have tripled in India since 1950, resulting in devastating
46 flooding events that cost the country about 3 billion dollars annually (Roxy et al., 2017).
47 Therefore, projecting and forecasting the ISM rainfall variability in a warming climate is crucial
48 for sustainable development, water resource management, and policymaking. However, ISM
49 rainfall exhibits temporal variability spanning intra-seasonal to multi-decadal time scales (See
50 Hrudya et al., 2021 for a recent review), and it involves complex interactions between different
51 factors (Rao et al., 2019).

52 The differential heating between the land and the sea and the northward migration of the
53 Inter Tropical Convergence Zone (ITCZ) drive the south-westerly winds, which carry moisture
54 from the ocean toward the land, resulting in ISM rainfall (Gadgil, 2018; Roxy et al., 2015).
55 Evaporation over the central and south Indian Ocean is the major contributor to the ISM rainfall,
56 followed by contributions from local recycling, the Arabian Sea, remote sources, and the Bay of
57 Bengal (Dey & Döös, 2021). The Indian Ocean is warming rapidly compared to other tropical
58 oceanic regions. Observations indicate a basin-scale warming of the Indian Ocean that is more
59 prominent in the west equatorial region and the Arabian Sea (Rao et al., 2012; Roxy et al., 2014;
60 Sharma et al., 2023; Swapna et al., 2014). This sea surface warming has the potential to increase
61 evaporation, making more moisture available in the atmosphere along the typical moisture

62 transport pathway over the Indian Ocean, which feeds ISM rainfall (Dey & Döös, 2021; Skliris
63 et al., 2022).

64 According to the Clausius-Clapeyron (CC) relationship, the water-holding capacity of air
65 is expected to increase by 7% per degree of global warming. If the atmospheric circulation
66 remains constant, the global water cycle is expected to amplify following the CC rate (Held &
67 Soden, 2006). Salinity observations over the last few decades indicate an amplification of the
68 global water cycle, with wet (net precipitation) regions becoming wetter and dry (net
69 evaporation) regions becoming drier, but at a significantly lower rate of 2–4% per degree of
70 global warming (Skliris et al., 2016). Several studies have shown that the frequency and intensity
71 of ISM rainfall are increasing in a warming climate (Bhowmick et al., 2021; Hari et al., 2020;
72 Katzenberger et al., 2021; Rai & Raveh-Rubin, 2023; B. Wang et al., 2013). For instance,
73 Katzenberger et al. (2021) projected an increase of 5% in ISM rainfall per degree of global
74 warming in the late 21st Century, and Wang et al. (2013) showed that the northern hemisphere
75 summer monsoon is intensifying due to mega-El Niño/Southern Oscillation and a hemispherical
76 asymmetric response to global warming. Furthermore, the climate model simulations of Coupled
77 Model Intercomparison Project 6 (CMIP6) robustly indicate a strengthening of the ISM rainfall
78 in a warming climate. However, some studies have shown that, on the contrary, the ISM is
79 weakening due to the reduced land-sea thermal gradient caused by the rapid Indian Ocean
80 warming (Roxy et al., 2014, 2015; Swapna et al., 2014; Wang et al., 2022; Yadav & Roxy,
81 2019).

82 Considering these contrasting results, further analysis of the recent changes in ISM
83 rainfall is needed. Furthermore, most ISM research is focused on central and northeast India,
84 whereas only a few recent studies have focused on the monsoon trends in the western region.
85 Rajesh & Goswami (2023) showed that the mean rainfall over northwest India and Pakistan has
86 increased by 10%-50% during 1901-2015 and is expected to increase by 50%-200% under the
87 moderate greenhouse gas scenarios. Li et al. (2023) showed that the springtime warming in the
88 Middle East enhances the summer monsoon over northwestern India and Pakistan by
89 strengthening the meridional sea level pressure gradient between the Middle East and the
90 southern Arabian Sea, and driving the changes in the low-level jet. Mahendra et al. (2024)
91 showed ISM rainfall over northwestern India is increasing and it is associated with the Silk Road
92 Pattern phase change in the 1990s. Yadav (2024) showed that the ISM rainfall has shifted
93 westward due to south-central equatorial Indian Ocean warming which increases the in-situ
94 convection and Hadley cell subsidence branches over South Africa and eastern Europe. Yadav
95 (2024) further showed that the anomalous subsidence over east Europe increases the adiabatic
96 warming, which excites a Rossby wave towards central Asia, redirecting the migratory mid-
97 latitude troughs to penetrate northwest India, shifting ISM rainfall westward. Based on these
98 studies, it is clear that the ISM precipitation over the northwest Indian region is increasing
99 significantly; however, the effect of the large-scale wind circulation changes on the moisture
100 transport and precipitation trend is still unexplored.

101 The objectives of this study are thus to investigate the precipitation trend over Northwest
102 India using state-of-the-art reanalysis and observational datasets, focusing on the possible role
103 played by large-scale changes in wind patterns. This paper is organized as follows. The dataset
104 and the methods used in this study are described in section 2. In section 3, the main results are
105 documented. The final section summarizes the results of the present work and provides
106 concluding remarks.

107

108 **2 Data and Methods**

109 2.1 Observational and Reanalysis Datasets

110 The datasets used in this study include in-situ, remote sensing, and atmospheric
 111 reanalysis data. The precipitation dataset is obtained from the Indian Meteorological Department
 112 (IMD), which is a high spatial resolution daily gridded dataset (0.25 x 0.25 degrees) (Pai et al.,
 113 2014). The monthly datasets for winds, specific humidity, Mean Sea Level Pressure (MSLP),
 114 land evaporation, and vertically integrated water vapor flux (vertically integrated moisture
 115 transport hereafter) are obtained from ERA5 reanalysis (Hersbach et al., 2020). Monthly Sea
 116 Surface Temperature (SST) data are obtained from the HadISST1 dataset provided by the Met
 117 Office Hadley Centre (Rayner et al., 2003). The oceanic evaporation data are obtained from
 118 OAflux (Yu & Weller, 2007). The time series of Niño 3.4 and the Southern Annular Mode
 119 (SAM) index are obtained from the Physical Sciences Laboratory (PSL), and the Climate Data
 120 Guide (CDG). All analyses are conducted from 1979 to 2022. The data file for CMIP6 analysis is
 121 downloaded from the IPCC WGI Interactive Atlas (Iturbide et al., 2021).

122 2.2 Hadley cell extent and removing ENSO effect

123 The poleward extent of the Hadley cell is calculated as the latitude at which the zonal
 124 mean of the zonal wind at 850 hPa is closest to zero. Similar results can be derived using a time
 125 series of the latitude at which the 500 hPa mean meridional stream function crosses zero
 126 poleward of its tropical extremum in the southern hemisphere (Schmidt & Grise, 2017).

127 Numerous studies have documented the impact of El Niño-Southern Oscillation (ENSO)
 128 on the Hadley circulation and have shown that the circulation expands during La Niña and
 129 contracts during El Niño (Lyon & Barnston, 2005). The effect of ENSO can be removed from an
 130 observed field ($A(x, t)$) using the approach defined by (Schmidt & Grise, 2017). At each
 131 location x , let $R(x)$ be the slope of the linear regression of $A(x, t)$ to the Niño 3.4 index ($N(t)$).
 132 Then, the ENSO-congruent time series at each location is $R(x)N(t)$, and the residual time series,
 133 after ENSO removal, is as follows:

$$B(x, t) = A(x, t) - R(x)N(t)$$

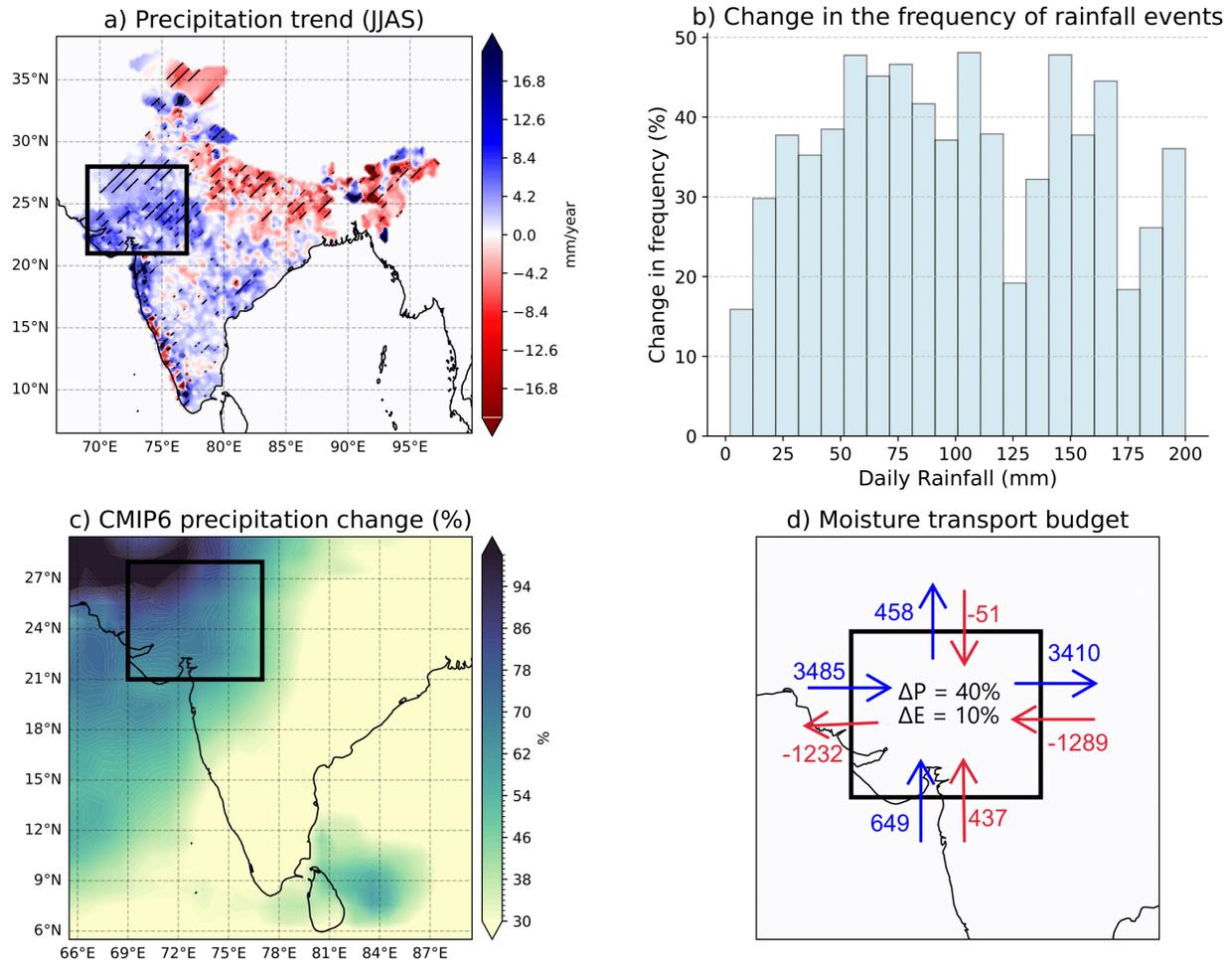
134

Equation 1

135 The fields are detrended before computing the regression analysis.

136 2.3 Statistical significance test

137 The trend is calculated using the ordinary least square (OLS) linear regression method.
 138 The statistical significance test is performed using the two-tailed t-test.



139
 140 **Figure 1:** a) Trend in JJAS precipitation (mm/year) from IMD dataset during 1979-2022. The
 141 hashed regions show values that are significant at the 95% confidence level. b) The percentage
 142 change (2013-2022 compared to 1979-1988) in the frequency of daily rainfall (mm) in JJAS
 143 over Northwest India (black box; 21°N-28°N; 69°E-77°E). c) JJAS precipitation long-term
 144 (2081-2100) change relative to 1850-1900 in SSP5-8.5 emissions scenario from the CMIP6
 145 ensemble (%). d) JJAS vertically integrated moisture transport trend budget analysis over 1979-
 146 2022 from ERA5. The direction and value of the mean over 1979-1989 ($\text{kg m}^{-1} \text{s}$) are shown in
 147 blue, and trends ($\text{kg m}^{-1} \text{s}/44 \text{ years}$) are shown in red. More information regarding Figure 1d is
 148 given in the supplementary materials.

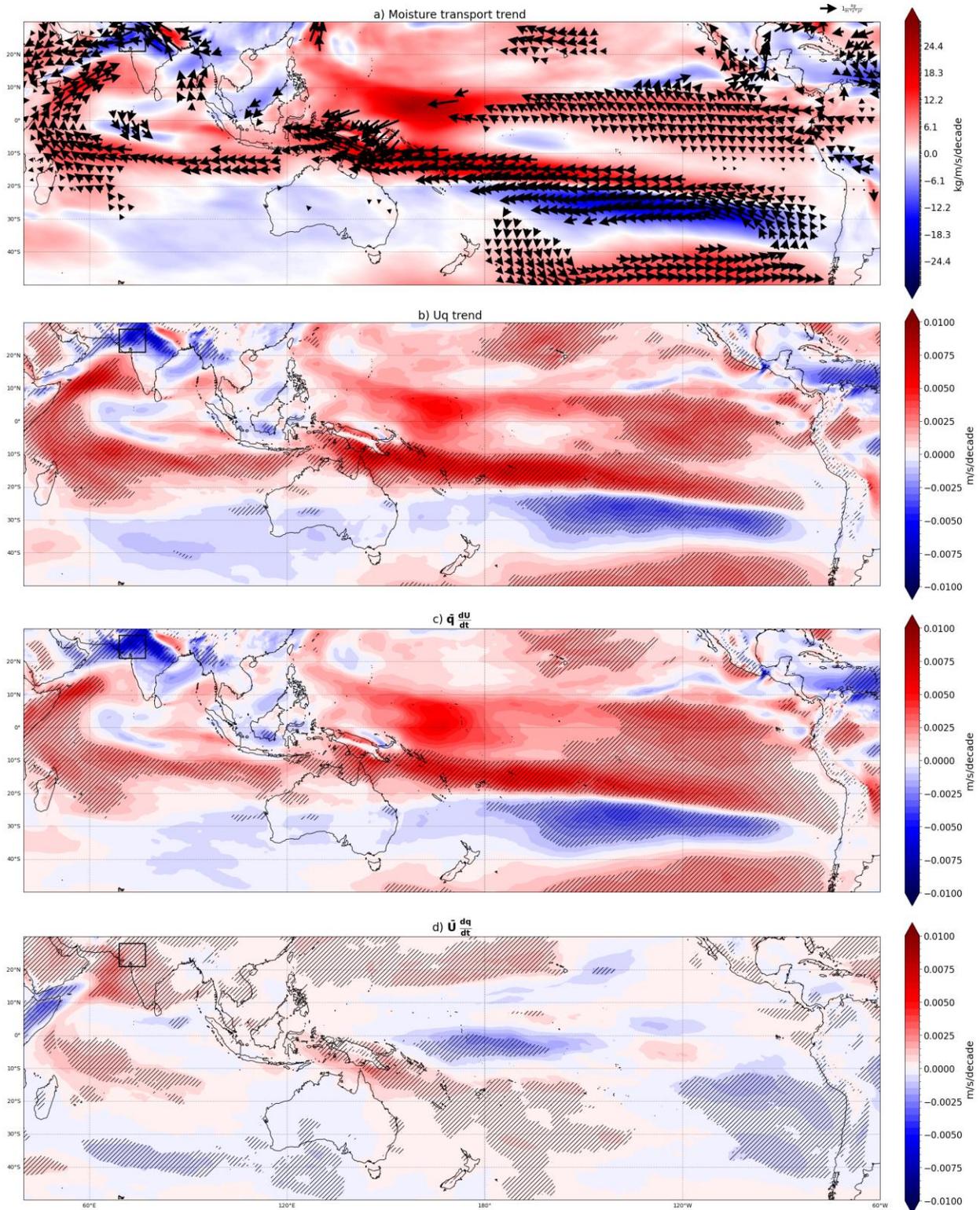
149 3 Results

150 In Sect. 3.1, we first examine trends in regional precipitation and the associated atmospheric
 151 moisture transport, partitioning this between trends in winds and specific humidity. In Sect. 3.2,
 152 we further link these ISM changes to atmospheric circulation across the Indo-Pacific region,
 153 evident in 850-hPa wind trends, and attribute the drivers of these trends to evolving patterns of
 154 sea level pressure.

155 3.1 Trends in Precipitation and Moisture Transport

156 The ISM rainfall is characterized by large regional differences with maximum JJAS mean
157 precipitation over northeast India and Western Ghats and minimum over northwest India
158 (supplementary Figure S1). The ISM precipitation trend during 1979–2022 shows increased
159 precipitation over northwest India, modest increases in central and southern parts of the country
160 and decreasing precipitation in northeast India (Figure 1a). The northwest Indian region (NWI;
161 black box in Figure 1a; 21°N–28°N; 69°E–77°E) typically receives a mean rainfall of 455 mm
162 during the summer monsoon period. However, in the recent decade, the region experienced a
163 precipitation increase of ~40% compared to the 1979–1988 period. The percentage change in the
164 frequency of daily rainfall during JJAS in the last decade (2013–2022) compared to the first
165 decade (1979–1988) over NWI is shown in Figure 1b (actual values of frequency for the
166 mentioned time periods are shown in supplementary Figure S3). The frequency of rainfall events
167 has increased notably throughout the distribution, suggesting that both the mean state and the
168 number of extreme events have increased over this region.

169 If we assume that the observed precipitation trend over NWI is linked to global warming,
170 then we should expect to note the same trend in the CMIP6 model projections. To test this, the
171 percentage change in rainfall between 2081 - 2100 and 1850 - 1900 is plotted in Figure 1c. The
172 CMIP6 projections show a substantial increase in JJAS precipitation with a pronounced rise over
173 the NWI under the highest greenhouse gas emission scenario (SSP5-8.5) (Figure 1c), suggesting
174 a possible role of anthropogenic warming in the wet trend. A moisture budget trend analysis
175 revealed an overall moisture convergence, which is driven by ~68% increased moisture entering
176 from the Arabian Sea concomitant with strongly reduced outgoing moisture transport through the
177 eastern (~38%) and northern (~12%) boundaries (Figure 1d). Therefore, moisture entering
178 through the Arabian Sea is vital in driving the rainfall variability over NWI.



179

180 **Figure 2:** a) Trend in JJAS vertically integrated moisture transport (colors – magnitude; kg m^{-1}
 181 s/decade). The arrows are plotted only if at least a component of the transport is statistically
 182 significant at the 95% confidence level. b) Trend in JJAS moisture transport at 850 hPa (m s^{-1}
 183 /decade). c) JJAS mean of the specific humidity multiplied by the wind speed trend at 850 hPa

184 (m s⁻¹/decade). This map highlights the contribution of the wind change to moisture transport
 185 change. d) JJAS mean wind speed multiplied by the trend in specific humidity at 850 hPa (m s⁻¹
 186 ⁻¹/decade). This map highlights the contribution of the specific humidity change to the moisture
 187 transport change. The hashed regions indicate values that are significant at the 95% confidence
 188 level. All datasets used here are from ERA5.

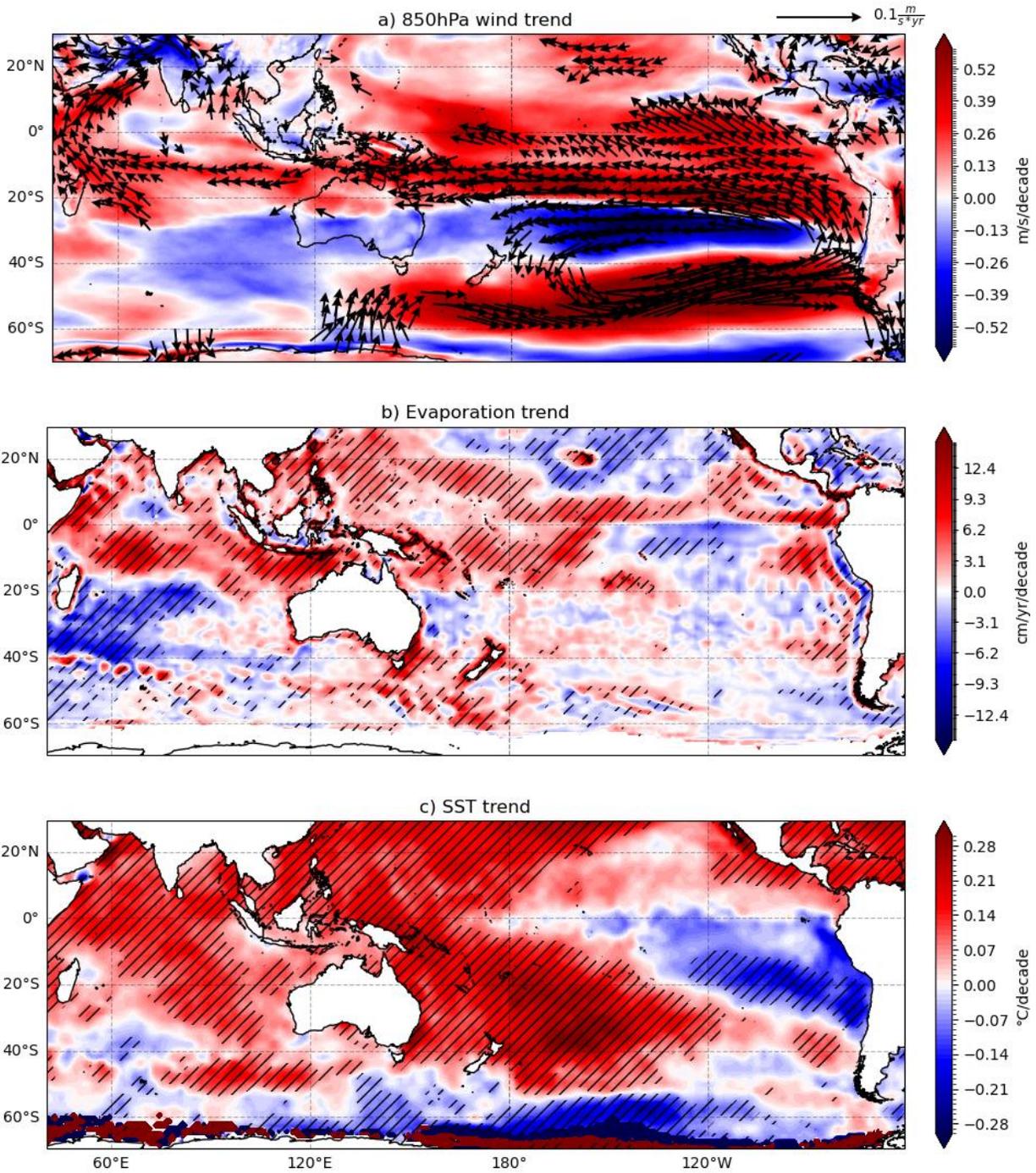
189 The spatial trend of JJAS vertically integrated moisture transport is shown in Figure 2a,
 190 which confirms that more moisture is transported from the ocean toward the NWI landmass. It
 191 further shows an extensive increase in moisture transport along the tropical Indian and Pacific
 192 Oceans. The increasing trend can occur due to increased wind speed and/or increased moisture in
 193 the atmosphere. It is well documented in the literature that most of the moisture available in the
 194 atmosphere is concentrated at lower levels (Dey & Döös, 2019). Further, the 850-hPa level, which is
 195 at an altitude of about 1.5 km, is often used to study the monsoon circulation (Gadgil, 2018).
 196 Therefore, we calculated the moisture transport at 850 hPa and its trend is shown in Figure 2b.
 197 To analyze the relative contribution of wind and specific humidity to the trend in moisture
 198 transport at 850 hPa, the following approximate decomposition is used:

$$\frac{d(Uq)}{dt} = \bar{U} \frac{dq}{dt} + \bar{q} \frac{dU}{dt} + Residual$$

199 Equation 2

200 here \bar{U} and \bar{q} are the means and $\frac{dU}{dt}$ and $\frac{dq}{dt}$ are the trends of wind speed and specific humidity at
 201 850 hPa. The terms $\bar{q} \frac{dU}{dt}$ and $\bar{U} \frac{dq}{dt}$ are the contributions of wind speed change and specific
 202 humidity change, respectively, which drive the moisture transport trend.

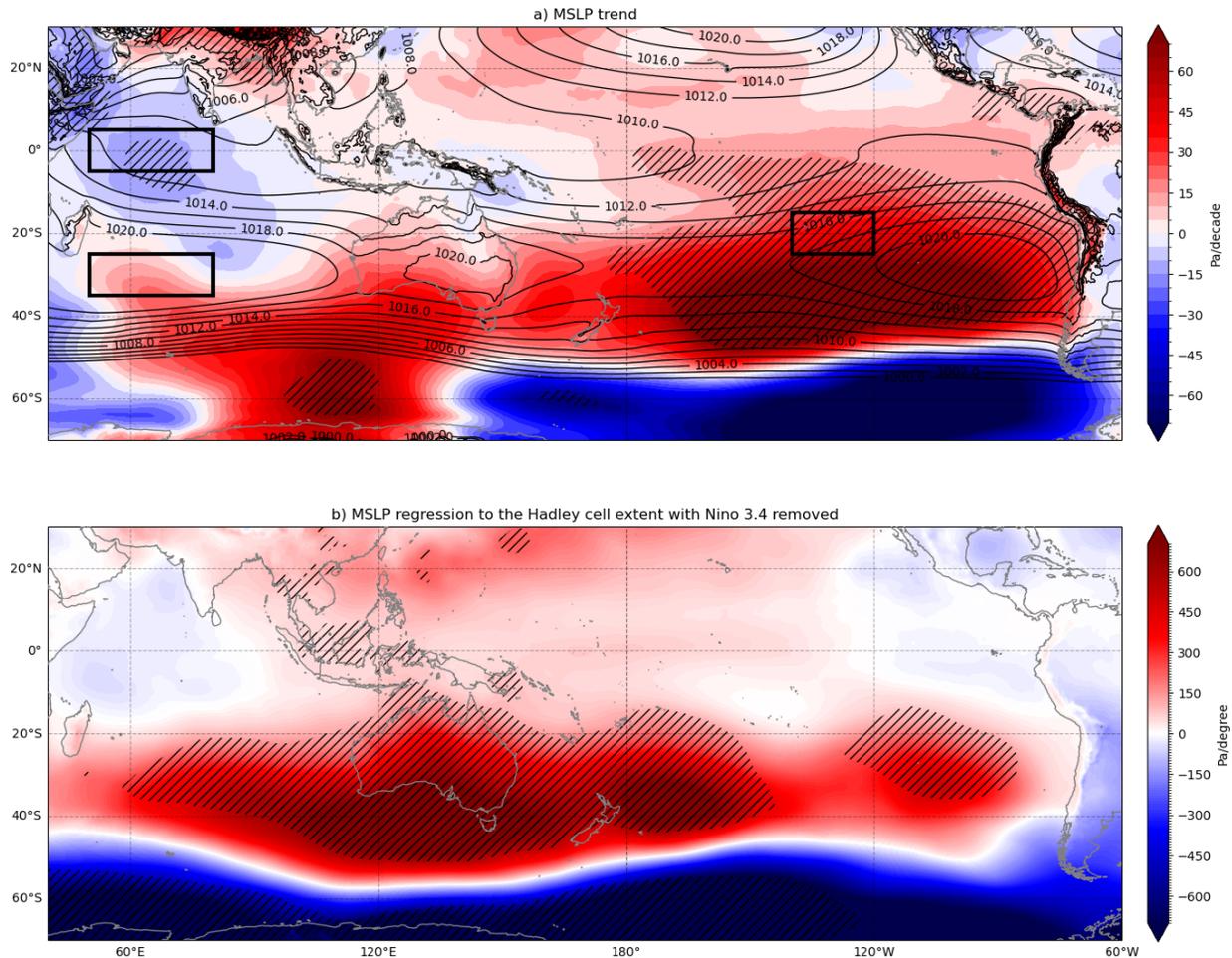
203 The spatial plots of $\bar{q} \frac{dU}{dt}$ and $\bar{U} \frac{dq}{dt}$ are shown in Figures 2c and 2d which reveal that the moisture
 204 transport trend is attributed to changes in the wind pattern with a lower but significant
 205 contribution from the changes in specific humidity, particularly over the Arabian Sea. The
 206 increased moisture transport trend across the southern boundary of NWI is found to be associated
 207 with the broad-scale wind trends over the Indian Ocean and humidity trends over the Arabian
 208 Sea (Figure 2 c,d). Therefore, it is essential to analyze the changes in the wind pattern.



209
 210 **Figure 3:** a) Trend in JJAS 850 hPa wind (colors –speed ($\text{m s}^{-1}/\text{decade}$)) from ERA5. The arrows
 211 are plotted only if at least a component of the wind is statistically significant at the 95%
 212 confidence level. b) Trend in JJAS oceanic evaporation rate ($\text{cm ann}^{-1}/\text{dec}$) from OAflux. c)
 213 Trend in JJAS SST ($^{\circ}\text{C}/\text{decade}$) from HadISST1. The hashed regions indicate values that are
 214 significant at the 95% confidence level.

215 3.2 850 hPa wind trends and drivers

216 The low-level 850-hPa wind trend suggests an overall strengthening of the cross-
 217 equatorial monsoon winds and the Pacific Ocean trade winds (Figure 3a). The strengthening of
 218 the wind drives an increase in oceanic evaporation which results in more moisture being
 219 available in the atmosphere (Figure 3b). Apart from the wind speed, the SST can also impact
 220 evaporation by modifying the moisture gradient. The SST trend pattern indicates a basin-scale
 221 warming of the Indian Ocean that is more prominent in the west equatorial region and the
 222 Arabian Sea (Figure 3c). It is expected that the evaporation increases with an increase in SST as
 223 a thermodynamic response; however, the close similarity between the wind speed (Figure 3a)
 224 and the evaporation rate (Figure 3b) trends over the Indian Ocean reveals that the dynamical
 225 process (wind speed) is also vital in driving the evaporation over this region. Furthermore, the
 226 strengthened monsoon winds will transport more moisture from the ocean toward the NWI
 227 landmass, and the weakening of the wind over north India will reduce the moisture outflow,
 228 resulting in an overall convergence of moisture over this region. Therefore, it is essential to study
 229 the physical mechanisms driving these wind trend patterns.



230

231 **Figure 4:** a) Trend in JJAS MSLP (Pa/decade) from ERA5. JJAS mean of MSLP is plotted as
 232 green contours (hPa). b) Regression of detrended and ENSO removed JJAS MSLP onto the

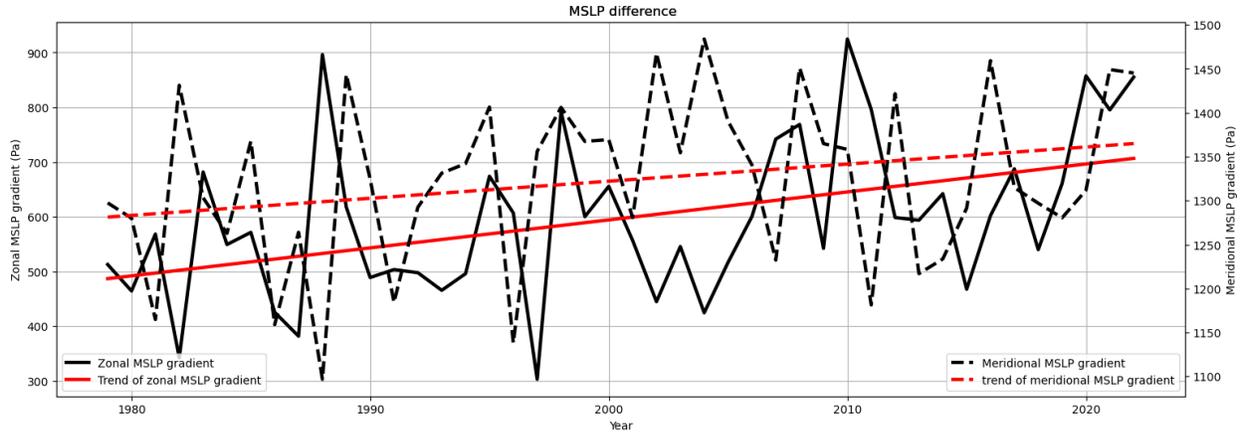
233 Hadley cell extent in the southern hemisphere (see section 2.3). The hashed regions indicate
234 values that are significant at the 95% confidence level.

235 The trend analysis of MSLP shows that the major high-pressure belts over the Indian and Pacific
236 Oceans in the southern hemisphere have expanded and shifted poleward (Figure 4a). Previous
237 studies have shown that the expansion and shift of high-pressure zones are attributed to Hadley
238 cell expansion (Schmidt & Grise, 2017). To filter out the MSLP trends associated with the
239 Hadley cell expansion, the ENSO effect from the MSLP is removed and then regressed onto the
240 southern hemisphere Hadley cell extent time series (section 2.3) (Figure 4b). The high significant
241 positive regression coefficient over the Pacific Ocean signifies that the expansion of the Hadley
242 cell resulted in an increased MSLP over this region, and this expansion is independent of ENSO.

243 This result agrees with numerous observational studies that show that the Hadley cell has
244 been expanding poleward over the last few decades (Birner et al., 2014; Lu et al., 2007; Lucas et
245 al., 2014; Schmidt & Grise, 2017; Xian et al., 2021). Multiple factors are responsible for this
246 expansion, including increasing greenhouse gases, stratospheric ozone depletion, and
247 anthropogenic aerosols (Lucas et al., 2014). Lu et al. (2007) showed that this expansion is
248 caused by an increase in the subtropical static stability, pushing the baroclinic instability zone
249 poleward and, hence, the outer boundary of the Hadley cell. Numerous climate models have
250 projected this poleward shift and expansion, with a 2-3 times more pronounced change in the
251 southern hemisphere (Grise & Davis, 2020).

252 The poleward shift in the high-pressure zone over the southeast Pacific strengthens the
253 trade winds, creating an anticyclonic motion around the increased MSLP over this region. This
254 strengthening of the easterlies might result in the cooling of SST along the west coast of South
255 America and far into the eastern Pacific through Ekman pumping and latent heat loss (Figure 3c),
256 which can further increase the MSLP (Figure 4a) and acts as positive feedback in strengthening
257 the southern hemisphere trade winds. Furthermore, a broad-scale decrease of MSLP is observed
258 over the Indian Ocean (Figure 4a), with a significant decline in the west equatorial region, which
259 is attributed to rapid Indian Ocean warming.

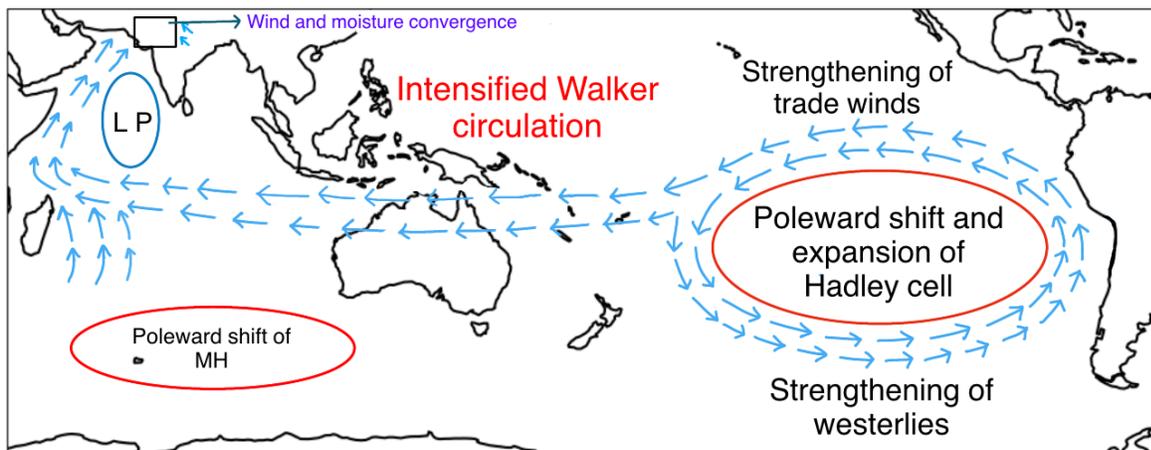
260 These MSLP trends induce a zonal pressure gradient with increased MSLP over the
261 eastern Pacific and reduced MSLP over the Indian Ocean, resulting in an intensification of
262 Walker circulation, which extends the strengthened trade winds from the Pacific towards the
263 Indian Ocean. Further, the poleward shift and expansion of high pressure over the Mascarene
264 High, along with the decrease in MSLP over the equatorial Indian Ocean, induces a meridional
265 pressure gradient, which further strengthens the cross-equatorial monsoon winds. To confirm
266 this, the time series of the zonal ($25^{\circ}\text{S}-15^{\circ}\text{S}; 140^{\circ}\text{W}-120^{\circ}\text{W}$ minus $5^{\circ}\text{S}-5^{\circ}\text{N}; 50^{\circ}\text{E}-80^{\circ}\text{E}$) and
267 meridional ($35^{\circ}\text{S}-25^{\circ}\text{S}; 50^{\circ}\text{E}-80^{\circ}\text{E}$ minus $5^{\circ}\text{S}-5^{\circ}\text{N}; 50^{\circ}\text{E}-80^{\circ}\text{E}$) MSLP gradient is shown in
268 Figure 5. The increasing trends in the time series confirm the intensification of the zonal and
269 meridional pressure gradients, which results in an overall strengthening of the monsoon winds.
270 Therefore, these wind trend patterns result in an overall strengthening of moisture convergence
271 over the NWI, hence substantially increasing rainfall (i.e. by ~40%) over this region during
272 1979-2022.



273
 274 **Figure 5:** The time series of the zonal (25°S - 15°S ; 140°W - 120°W minus 5°S - 5°N ; 50°E - 80°E)
 275 and meridional (35°S - 25°S ; 50°E - 80°E minus 5°S - 5°N ; 50°E - 80°E) MSLP gradient from ERA5.
 276 The locations are marked as black boxes in Figure 4a. The trends are statistically significant at
 277 the 90% confidence level.

278 **4 Discussion and Concluding Remarks**

279 This study shows that the ISM rainfall over the NWI has increased by ~40% during
 280 1979-2022. This precipitation increase is found to be driven by an enhancement of cross-
 281 equatorial monsoon winds, which increases evaporation over the Indian Ocean and transports
 282 more moisture from the Arabian Sea to NWI. It is further shown that the monsoon winds are
 283 strengthened by the merging of Pacific Ocean trade winds and rapid Indian Ocean warming. The
 284 strengthening of the southern hemisphere trade winds over the eastern Pacific is attributed to the
 285 shift and poleward expansion of the Hadley cell, whereas the strengthening along the western
 286 Pacific and Indian Ocean is due to the Indian Ocean warming. These wind patterns result in
 287 overall moisture convergence over Northwest India, with more moisture imported from the
 288 ocean and less exported, resulting in increased rainfall. A schematic summary is shown in Figure
 289 6.
 290
 291



292

293 **Figure 6:** A schematic summary of the study. LP stands for Low-Prssure.

294 The MSLP trend pattern in the Pacific resembles the positive phase of the Southern
295 Annular Mode (SAM) (Fogt & Marshall, 2020). It is well documented in the literature that the
296 positive SAM is associated with stronger than average westerlies over the mid-high latitudes
297 (50S-70S) and weaker westerlies in the mid-latitudes (30S-50S) (Fogt & Marshall, 2020). The
298 time series of the SAM index for JJAS calculated as the zonal pressure difference between the
299 latitudes of 40S and 65S is shown in Figure S4. The frequency of positive SAM events has
300 increased during the last decade. Therefore, it is plausible that these trends have an impact on the
301 MSLP and 850-hPa wind trends. However, the regression of the SAM index onto the ENSO-
302 removed MSLP could not explain the significant positive MSLP trend seen over the eastern
303 Pacific (Figure S5). The poleward shift in the Hadley cell might explain the increasing frequency
304 of positive SAM events; however, more research needs to be done to confirm this.

305 Furthermore, the strengthened trade winds have the potential to lower SST along the
306 southeastern Pacific Ocean via Ekman pumping and latent heat loss, further intensifying the
307 MSLP gradient and acting as possible positive feedback. Surface cooling across the tropical
308 eastern Pacific is indicative of a La-Nina-type SST pattern. During the last decade, there were
309 more prolonged La Nina than El-Niño events, which may account for some of the SST trend
310 patterns (supplementary Figure S6) (Skirris et al., 2022). However, plotting the SST and MSLP
311 trends after removing the ENSO effects shows similar results, and hence, it confirms that these
312 trends are largely independent of ENSO.

313 Although the moisture availability in the atmosphere is expected to increase under global
314 warming, future changes in the precipitation pattern over India will be strongly dependent on the
315 changing monsoon atmospheric circulation, as evidenced in our results for the recent historical
316 period. The wind pattern, in particular, will strongly control how much of the increased moisture
317 originating from the ocean in the future will be transported toward the Indian landmass to feed
318 local precipitation. Recent and future warming of the Indian Ocean is complicit in the changing
319 ISM. The CMIP6 model projections show continued warming of the Indian Ocean and expansion
320 of the Hadley cell in all future scenarios. This has the potential to intensify the MSLP gradient
321 and, hence, can strengthen the trade winds further with strong implications for ISM rainfall.

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331 summary (Figure 6).

332

333 **Open Research**

334 The IMD dataset used in the study is available at <https://imdpune.gov.in/lrfindex.php>. The ERA5
 335 dataset is available at <https://cds.climate.copernicus.eu>. The CMIP 6 data file used to generate
 336 Figure 1c is available at <https://interactive-atlas.ipcc.ch/>. The OAflux dataset is available at
 337 http://apdrc.soest.hawaii.edu/datadoc/whoi_oaflux.php. The Niño 3.4 index and SAM index are
 338 downloaded from https://psl.noaa.gov/gcos_wgsp/Timeseries/Nino34/ and
 339 [https://climatedataguide.ucar.edu/climate-data/marshall-southern-annular-mode-sam-index-](https://climatedataguide.ucar.edu/climate-data/marshall-southern-annular-mode-sam-index-station-based)
 340 [station-based](https://climatedataguide.ucar.edu/climate-data/marshall-southern-annular-mode-sam-index-station-based) respectively.

341

342 The analyses are performed using Python 3.10.0.

343

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