

Anthropogenic influence on 2022 extreme January–February precipitation in Southern China

Article

Accepted Version

Hu, Y., Dong, B. ORCID: https://orcid.org/0000-0003-0809-7911, Xie, J., Tan, H., Zhou, B., Lin, S., He, J. and Zhao, L. (2023) Anthropogenic influence on 2022 extreme January–February precipitation in Southern China. Bulletin of the American Meteorological Society, 104 (11). E1935-E1940. ISSN 1520-0477 doi: 10.1175/BAMS-D-23-0136.1 Available at https://centaur.reading.ac.uk/113953/

It is advisable to refer to the publisher's version if you intend to cite from the work. See <u>Guidance on citing</u>. Published version at: https://journals.ametsoc.org/view/journals/bams/104/11/BAMS-D-23-0136.1.xml To link to this article DOI: http://dx.doi.org/10.1175/BAMS-D-23-0136.1

Publisher: American Meteorological Society

All outputs in CentAUR are protected by Intellectual Property Rights law, including copyright law. Copyright and IPR is retained by the creators or other copyright holders. Terms and conditions for use of this material are defined in the <u>End User Agreement</u>.

www.reading.ac.uk/centaur



CentAUR

Central Archive at the University of Reading

Reading's research outputs online

2	Anthropogenic Influence on 2022 Extreme January–February
3	Precipitation in Southern China
4	
5	Yamin Hu, ^a Buwen Dong, ^b Jiehong Xie, ^c Haobo Tan, ^d Baiquan Zhou, ^e Shuheng Lin, ^f
6	Jian He, ^a and Liang Zhao ^g
7	^a Guangdong Climate Center, CMA, Guangzhou, China
8	^b National Centre for Atmospheric Science, Department of Meteorology, University of Reading,
9	Reading, United Kingdom
10	^c Jieyang Meteorological Bureau, CMA, Jieyang, China
11	^d Guangdong Meteorological Service, CMA, Guangzhou, China
12	^e State Key Laboratory of Severe Weather, Chinese Academy of Meteorological Sciences, CMA, Beijing,
13	China
14	^f School of Atmospheric Sciences, Sun Yat-sen University, Guangzhou, China
15	⁸ State Key Laboratory of Numerical Modeling for Atmosphere Sciences and Geophysical Fluid
16	Dynamics (LASG), Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing China
17	
18	Corresponding Author: Yamin Hu, huym@gd121.cn
19	Corresponding Author: Jiehong Xie, jiehongx@foxmail.com

CAPSULE

The precipitation in January–February 2022 in Southern China was the second largest since 1961. Anthropogenic influence reduced the likelihood of extreme events like 2022 by about 50% (55%) in HadGEM3 (CMIP6).

24 **1. Introduction**

From January to February (J-F) 2022, Southern China (SC) experienced 25 abnormally heavy precipitation, with the regionally averaged total precipitation 26 27 reaching 248 mm, making it the second-largest value since 1961. This extreme event resulted in significant damage to transportation, power supply, and crop production. 28 About 6.092 million people and 422,300 hectares of crop area were affected, leading to 29 a direct economic loss of 7.89 billion CNY. As a result, it was identified as one of the 30 top ten natural disasters in 2022 by the Department of Emergency Management in 31 32 China (https://www.mem.gov.cn/xw/yjglbgzdt/202301/t20230112_440396.shtml). This extreme precipitation event was attributed to the internal atmospheric dynamics 33 (Ma et al. 2022). In this study, we assess how anthropogenic activity has changed the 34 35 likelihood of extreme precipitation events similar to the J-F 2022 event over SC.

Previous studies have focused on summer extreme precipitation (Zhang et al. 2020; Li et al. 2021) and showed that anthropogenic warming has affected extreme precipitation over East Asia (Ma et al. 2017), intensifying the probability of short-term extreme precipitation events (Westra et al. 2014; Dong et al. 2020, 2021; Sun et al. 2022), while less attention was given to winter counterparts over SC (Hu et al. 2021). The objective of this study is to investigate whether anthropogenic influence has altered the likelihood of unusual precipitation in the 2022 J–F.

43 **2. Data and methods**

Daily gauge precipitation observations from approximately 2400 stations across China were obtained from the China Meteorological Administration (CMA) for the period 1961–2022. Monthly wind and sea level pressure fields from the ERA5

47 reanalysis provided by the European Centre for Medium-Range Weather Forecasts
48 (ECMWF) (Hersbach et al. 2020) were used to analyze circulation characteristics.

To assess anthropogenic and natural factors' influences on the probability of the 49 50 exceptional precipitation event in SC during J-F 2022, we used the Met Office 51 HadGEM3-GA6-N216 model (referred to as HadGEM3 hereafter) simulations at a horizontal resolution of $0.56^{\circ} \times 0.83^{\circ}$ and 85 vertical levels (Ciavarella et al. 2018). The 52 HadGEM3 model simulations are forced by observed sea surface temperature 53 (SST)/sea ice extent (SIE) and therefore attribution of events is conditioned to SST/SIE. 54 Both natural and anthropogenic forcing (ALL) and natural forcing (NAT) experiments 55 were used. The details of the model can be found in Christidis et al. (2013). The 56 ensemble simulations consisted of 15 members for 1960-2013 with ALL forcings, and 57 525 members for 2022 with ALL and NAT forcings (ALL₂₀₂₂ and NAT₂₀₂₂). 58

Meanwhile, we utilized simulations from climate models that participated in the 59 Coupled Model Intercomparison Project Phase 6 (CMIP6) and Detection and 60 Attribution Model Intercomparison Project (DAMIP) (Eyring et al. 2016; Gillett et al. 61 2016) under all anthropogenic and natural forcing combined (ALL), well-mixed 62 greenhouse gas forcing (GHG), anthropogenic aerosol forcing (AA), and natural 63 forcing (NAT) to assess the anthropogenic influence on the likelihood of the 2022 event 64 (more details of model information are listed in Table ES1). CMIP6 model simulations 65 are coupled model simulations and therefore we cannot use a specific year to represent 66 2022. We specify a period around our target year to represent 2022. Since historical 67 68 simulations stopped in 2014 in CMIP6 and therefore we need to merge historical simulations with SSP2-4.5 future scenario simulations for 2015 to 2026. But the NAT 69 simulations (DAMIP) stopped in 2020 and therefore are no NAT future scenario 70 simulations. Therefore, in order to have enough samples to give a robust estimate of 71 PDFs, we used a 15-year window of 2006-2020 in ALL, GHG, AA, and NAT as 72 ALL₂₀₂₂, GHG₂₀₂₂, AA₂₀₂₂, NAT₂₀₂₂ in CMIP6/DAMIP simulations with a total 405 73 74 sample points (see details in SI).

75 In the 2022 J–F, the excessive precipitation was mainly concentrated over the region of $(20.5^{\circ} - 27^{\circ}N, 106^{\circ} - 119^{\circ}E)$ (Fig.1a). To evaluate the model performance, 76 we calculated the SC precipitation index (SCPI), defined as the normalized regional-77 averaged precipitation anomaly in J-F with respect to the climatological period of 78 1961–2005. Except for Quantile-Quantile (QQ) and Kernel Density Estimation (KDE) 79 plot, a two-sample Kolmogorov-Smirnoff (K-S) test with a significance level of 0.05 80 was used to test whether the observed and simulated SCPI during 1961-2013 were from 81 82 the same distribution.

83 The generalized extreme value (GEV) distribution was used to fit the precipitation indices and estimate the occurrence probability and return periods for both observations 84 and simulations. The probability of an event, which is equivalent to or heavier than the 85 J-F 2022 event, was defined as PALL and PNAT for ALL and NAT, forcing experiments, 86 87 respectively. The probability ratio ($PR_{ALL} = P_{ALL}/P_{NAT}$) is calculated to quantify the anthropogenic influences. Similarly, we used PR_{GHG}= P_{GHG}/P_{NAT} and PR_{AA}=P_{AA}/P_{NAT} 88 to denote the GHG or AA forcing influences. The 90% confidence interval (90% CI) 89 was obtained by using 1000 bootstrap resampling. 90

91 **3. Results**

The J-F time-averaged precipitation for 1961-2005 was about 117 mm in SC. 92 However, during the J-F in 2022, the regional mean precipitation was about 248mm 93 over SC and it was the second highest value since 1961 with the anomaly being about 94 2.3 standard deviations (2.3o, using as the threshold for the 2022 event) above the 95 96 climatology in the period of 1961-2005 (Figs. 1a-b). There are two dynamical drivers for this precipitation anomaly. One is the wave train propagating along the South Asian 97 jet that intensifies the India-Burma trough. It enhances the SCP through exciting 98 anomalous strong moisture transport from the Bay of Bengal and ascending motion. 99 The other is the positive geopotential height anomaly over eastern Siberia that prompts 100 southward cold air intrusion and convergence over the SC region (Fig. 1c) (Ma et al. 101

2022). The observed SCPI in 2022 J–F corresponds to a 1-in-31-year (18-143 year)
event (Fig. 1d).



104

Fig. 1. (a) Percentage anomalies of observed precipitation in 2022 J–F relative to the 1961–2005 climatology. (b) Observed SCPI in each J–F for 1961–2022. (c) Spatial distribution of sea level pressure anomaly (shading, unit: hPa) and 850hPa wind anomaly (vector, unit: m/s). (d) GEV fit (blue solid line) of observed SCPI with 90% CI. The crosses are estimated from the empirical distributions of the observed precipitation index with the red square denoting the 2022 event.

Both the HadGEM3 and CMIP6 simulations reasonably well capture the variability 111 of observed SCPI for the period 1961–2013, as shown in Figs. 2a-b, and probability 112 density functions (PDFs) in simulations are comparable to that observed (Figs. 2c-d). 113 Moreover, the observed precipitation indices fall within the range of those simulated 114 by the models. We applied the QQ and KDE plots to test the distribution between the 115 simulations and observations. Results show the simulations of HadGEM3 and CMIP6 116 follow the same distribution as observations (not shown). PDFs of SCPI exhibit similar 117 distributions between model simulations and observations (Figs. 2c-d) with p-values 118 of 0.50 and 0.33, respectively, according to the two-sample K-S test. These results 119 suggest that both HadGEM3 and CMIP6 models can be considered reliable for the 120

121 attribution of the 2022 J–F extreme precipitation event over SC.

Figures 2e-f show the GEV-fitted PDFs for the 2022-like event under different 122 external forcings. In both two sets of model simulations, PDFs of SCPI exhibit a drying 123 shift from NAT to ALL. This shift indicates that the observed extreme precipitation 124 event like 2022 is less likely to occur with anthropogenic influence (Table 1). The 125 estimated occurrence probability decreased from 1.3% (1.3%-1.7%) in NAT to 0.7% 126 (0.6%-0.9%) in ALL, with a PRALL of 0.50 (0.41-0.60) in HadGEM3 simulations. The 127 return period is significantly increased from ~77 years in NAT to ~143 years in ALL 128 129 (Fig. 2g). Similarly, in CMIP6 simulations, the estimated occurrence probability decreased from 3.8% (2.6%-4.8%) in NAT to 1.7% (1.0%-2.4%) in ALL, with a PR_{ALL} 130 of 0.45 (0.38–0.53) and the return period increased from ~26 years in NAT to ~59 years 131 in ALL (Fig. 2h). These results suggest that anthropogenic influence reduced the 132 133 likelihood of extreme event like 2022 by about 50% (55%) in HadGEM3 (CMIP6).

Furthermore, the GHG forcing leads to a rightward shift of PDFs to a wetter climate relative to NAT(Fig.2f), while the AA forcing shifts to a drier world. The estimated P_{GHG} and P_{AA} indicate that a ~26 years event becomes a ~15 years event with PR_{GHG}=1.75(1.60–2.00) in GHG and a ~83 years event in AA with PR_{AA}=0.31 (0.24– 0.37).

Table 1. Attribution results for the 2022 J–F event with probability ratio (PR $_{ALL}$, PR $_{GHG}$ and PR $_{AA}$), exceedance probability from ALL (P $_{ALL}$), GHG (P $_{GHG}$), AA (P $_{AA}$) and NAT (P $_{NAT}$), and the 90% confidence intervals (CI) in the bracket in HadGEM3 and CMIP6 simulations.

	HadGEM3	CMIP6
PR _{ALL}	0.50(0.41~0.60)	0.45(0.38~0.53)
PR _{GHG}		1.75(1.60~2.00)
PR _{AA}		0.31(0.24~0.37)
P _{ALL} (%)	0.7(0.6~0.9)	1.7(1.0~2.4)

$P_{GHG}(\%)$		6.7(5.1~7.9)
P _{AA} (%)		1.2(0.5~1.9)
P _{NAT} (%)	1.3(1.3~1.7)	3.8(2.6~4.8)

How does anthropogenic influence reduce the likelihood of extreme events like
2022? The J–F differences of ensemble mean precipitation and atmospheric circulations
between ALL and NAT experiments are analyzed (Fig. ES1). Decreases in precipitation
occur in both HadGEM3 and CMIP6 simulations over SC (Figs. ES1a–b), accompanied
by anomalous positive sea level pressure (SLP) and an anomalous anticyclonic
circulation over SC (Figs. ES1c–d).

The two most important anthropogenic forcings are greenhouse gases and 149 150 atmospheric aerosols and they can have different effects on SC J-F precipitation. According to the CMIP6 results, compared to the NAT, the GHG simulation is shifting 151 rightward to a wetter climate, while the AA distribution is marked by a flatter 152 distribution with shifting to a drier region (Fig. 2f). A further comparison of AA and 153 154 GHG with the NAT experiments reveals the impact of different anthropogenic forcings. Through aerosol radiation and cloud interactions, there is a positive SLP anomaly in 155 most of the mid-high latitudes of East Asia, with an anomalously strong Siberian High 156 together with changes in the Walker circulation over the eastern Indian Ocean, Maritime 157 158 Continent and western Pacific Ocean (Takahashi et al. 2018) and with a weakening of anomalous anticyclonic circulation over the western North Pacific(WNP), which leads 159 to anti-cyclone anomaly over the SC, so a reduction in J-F precipitation happened in 160 161 SC (Fig. ES2a). On the other hand, over SC, the effect of non-absorbing aerosols is dominant. The solar flux at the surface is significantly reduced directly by the scattering 162 of non-absorbing aerosols and indirectly by the intensification of short-wave cloud 163 forcing. Accordingly, the surface air temperature in SC is reduced, which leads to the 164 moisture transport decreasing, so the precipitation is also significantly reduced in South 165 166 China (Huang et al. 2007; Jiang et al. 2017) (Fig. ES2c).

167

On the other hand, GHG contributes to an increase in precipitation over SC (Fig.

ES2b). This is partly related to GHG induced increase of moisture in the atmosphere 168 associated with warming (Guo et al. 2023) and is also associated with an anomalous 169 negative SLP in the mid-latitudes, where the Baikal trough deepens and favors the cold 170 air to SC. The anomalous anticyclonic circulation in the WNP subtropical region, 171 caused the convergence of warm and moist air from the southern flank of the Philippine 172 high, contributing to SC precipitation increase (Fig. ES2d). The impacts from aerosols 173 overwhelm the impacts from GHG changes, leading to a decrease of precipitation from 174 175 NAT to ALL in CMIP6/DAMIP simulations.



Fig. 2. (a–b) Time series of observed (black) and simulated ensemble mean (blue)
SCPI for 1961–2022, with 15-member (a) and 27-member (b) spread shown as light
blue shading in HadGEM3 and CMIP6 simulations, respectively. (c–d) SCPI original

(bar) and GEV fitted PDFs (solid line) of observations (yellow bar and black line) and
historical ALL simulations (blue bar and blue line) for 1961–2013 in HadGEM3 (c) and
CMIP6 (d). The p-value for the K-S test is on the top right. (e–f) GEV fitted PDFs of
SCPI in 2022 based on ALL (blue) and NAT (red) ensembles in HadGEM3, and ALL
(blue), NAT (red), GHG (purple) and AA (yellow) in CMIP6 simulations. The dashed
green line denotes the observed 2022 event. (g–h) As in (e–f) but for return periods.

186 **4.** Conclusions

187 We conducted an assessment of the anthropogenic influence on the likelihood of the 2022 extreme wet J–F in SC using two sets of model simulations. The analysis 188 reveals that anthropogenic activities have reduced the likelihood of extreme events like 189 2022 by about 50% (55%) in HadGEM3 (CMIP6) simulations. Analyses of single 190 forcing experiments using CMIP6 model ensembles demonstrate different roles of 191 changes in GHG and AA in J-F precipitation over SC with GHG forcing inducing an 192 increase and AA forcing inducing a decrease, similar to previous studies in warm 193 194 season (Sun et al. 2022; Guo et al. 2023; Hu et al. 2023). However, the magnitude of AA-induced precipitation decrease is larger than that of GHG-induced increase (Cao et 195 al.2022), leading to the reduced likelihood of the J–F precipitation event similar to that 196 of 2022 in SC by the combined effect of anthropogenic forcing. 197

198

199 Acknowledgements.

This study was funded by the National Natural Science Foundation of China (U2142205 and 42075040); Guangdong Major Project of Basic and Applied Basic Research (2020B0301030004); Special Fund of China Meteorological Administration for Innovation and Development (CXFZ2023J027); and Special Fund for Forecasters of China Meteorological Administration (CMAYBY2020-094).

205

206 Data Availability Statement.

The following data are available online: the CMIP6 GCM simulations (https://esgfnode.llnl.gov/projects/cmip6/), and the homogenized station data in China (http://data.cma.cn/).

- 210
- 211

REFERENCES

- Cao, J., Wang, H., Wang, B., Zhao, H., Wang, C., and Zhu, X., 2022: Higher sensitivity
 of Northern Hemisphere monsoon to anthropogenic aerosol than greenhouse gases. *Geophysical Research Letters*, 49, e2022GL100270.
 https://doi.org/10.1029/2022GL100270
- 216 Christidis, Nikolaos., P. A. Stott, A. A. Scaife, A. Arribas, G. S. Jones, D. Copsey, J. R.
- Knight, and W. J. Tennant, 2013: A new HadGEM3-A-based system for attribution
 of weather- and climate-related extreme events. *J. Clim.*, 26, 2756–2783,
 https://doi.org/10.1175/JCLI-D-12-00169.1
- Ciavarella, A., and Coauthors, 2018: Upgrade of the HadGEM3-A based attribution
 system to high resolution and a new validation framework for probabilistic event
 attribution. *Wea. Climate Extremes*,20,9–32,

223 <u>https://doi.org/10.1016/j.wace.2018.03.003.</u>

- Dong, S., Y. Sun, and C. Li, 2020: Detection of human influence on precipitation
 extremes in Asia. J. Clim., 33, 5293–5304, <u>https://doi.org/10.1175/JCLI-D-19-</u>
 0371.1.
- 227 Dong, S., Sun, Y., Li, C., Zhang, X., Min, S.-K., and Kim, Y.-H., 2021: Attribution of
- Extreme Precipitation with Updated Observations and CMIP6 Simulations. J. Clim.,
- 229 34, 871–881. <u>https://doi.org/10.1175/JCLI-D-19-1017.1.</u>
- Eyring, V. and Coauthors, 2016: Overview of the coupled model intercomparison
 project phase 6 (CMIP6) experimental design and organization. *Geosci. Model Dev.*9, 1937–1958, https://doi.org/10.5194/gmd-9-1937-2016.
- 233 Gillett, N. P., and Coauthors, 2016: The detection and attribution model

intercomparison project DAMIP v1.0) contribution to CMIP6. *Geosci. Model Dev.*

235 9, 3685–3697, https://doi.org/10.5194/gmd-9-3685-2016.

- Guo, Y., Dong, B. and Zhu, J. 2023: Anthropogenic impacts on changes in summer
 extreme precipitation over China during 1961–2014: roles of greenhouse gases and
 anthropogenic aerosols. *Clim. Dyn.*, 60, 2633–2643,
 https://doi.org/10.1007/s00382-022-06453-4.
- Hersbach, H., Bell, B., Berrisford, P., et al. 2020: The ERA5 global reanalysis. Q J R
 Meteorol Soc. 146: 1999–2049. <u>https://doi.org/10.1002/qj.3803</u>
- Hu, Z., and Coauthors, 2021: Was the Extended Rainy Winter 2018/19 over the Middle
 and Lower Reaches of the Yangtze River Driven by Anthropogenic Forcing? *Bull.*
- 244 Amer. Meteor. Soc., 102, S67–S73, <u>https://doi.org/10.1175/BAMS-D-20-0127.1.</u>
- Hu, T., and Coauthors, 2023: Anthropogenic Influence on the 2021 Wettest September
 in Northern China. *Bull. Amer. Meteor. Soc.*, 104, E243–248,
 <u>https://doi.org/10.1175/BAMS-D-22-0156.1.</u>
- Huang, Y., W. L. Chameides, and R. E. Dickinson, 2007: Direct and indirect effects of
 anthropogenic aerosols on regional precipitation over East Asia, *J. Geophys. Res.*,
 112, D03212, https://doi:10.1029/2006JD007114.
- Jiang, Y., and Coauthors, 2017: Anthropogenic aerosol effects on East Asian winter
 monsoon: The role of black carbon-induced Tibetan Plateau warming, J. Geophys.
 Res. Atmos., 122, 5883– 5902, https://doi:10.1002/2016JD026237.
- Li, R., and Coauthors, 2021: Anthropogenic Influences on heavy precipitation during the 2019 extremely wet rainy season in Southern China. *Bull. Amer. Meteor. Soc.*,
- 256 102, S103–S109, <u>https://doi.org/10.1175/BAMS-D-20-0135.1.</u>
- Ma, H., Wang, R., Li, X., Lai, A., Yang, H., and Li, X., 2022: Why was South China
 extremely wet during January–February 2022 despite La Niña? *Front. Earth Sci.*,
 10, 982225, https://doi.org/10.3389/feart.2022.982225.
- 260 Ma, S., and Coauthors, 2017: Detectable Anthropogenic Shift toward Heavy

- Precipitation over Eastern China. J. Clim., 30, 1381–1396,
 <u>https://doi.org/10.1175/JCLI-D-16-0311.1.</u>
- Sun, Y., and Coauthors, 2022: Understanding human influence on climate change in
 China. *Natl. Sci. Rev.*, 9, 3, <u>https://doi.org/10.1093/nsr/nwab113.</u>
- Takahashi, H.G., Watanabe, S., Nakata, M. et al., 2018: Response of the atmospheric 265 hydrological cycle over the tropical Asian monsoon regions to anthropogenic 266 267 aerosols and its seasonality. Prog. Earth. Planet. Sci., 5. 44. https://doi.org/10.1186/s40645-018-0197-2. 268
- Westra, S., and Coauthors, 2014: Future changes to the intensity and frequency of shortduration extreme rainfall. *Rev. Geophys.*, 52,522–555,
 https://doi.org/10.1002/2014RG000464
- 272 Wu, R., Hu, Z. and Kirtman, B., 2003: Evolution of ENSO-related rainfall anomalies
- in East Asia. J. Clim., 16, 3742–3758, <u>https://doi.org/10.1175/1520-</u>
 0442(2003)016<3742:EOERAI>2.0.CO;2.
- Z75 Zhang, W., and Coauthors. 2020: Anthropogenic influence on 2018 summer persistent
- heavy rainfall in central Western China. Bull. Amer. Meteor. Soc., 101, S65-S70.
- 277 <u>https://www.jstor.org/journal/bullamermetesoci.</u>