Why was the 2023 jump in global temperature so extreme?

J. Mex[1,2], C. Cassou[1], A. Jézéquel[1,3], S. Bony[4], C. Deser[5]

[1]LMD/IPSL, École Normale Supérieure, PSL Université Paris, Paris, France

[2]Leipzig Institute for Meteorology, Leipzig University, Leipzig, Germany

[3]École Nationale des Ponts et Chaussées, Champs sur Marne, France

[4]LMD/IPSL, Sorbonne University, CNRS, Paris, France

[5]National Center for Atmospheric Research, Boulder, CO, USA.

Corresponding author: Julius Mex (julius.mex@uni-leipzig.de)

Abstract

Global surface air temperature reached unprecedented heights in early boreal fall of 2023, surpassing the previous record for the largest year-to-year temperature increase by a significant margin. Here we attribute the majority of the temperature jump to the physical specificities observed in the onset and maturing stages of the 2023 El Niño event. Using a process-based approach applied on a combination of observational datasets, we show that the uniqueness of the 2023 event can be largely related to the La Niña-like ocean-atmosphere background state upon which it developed. The effects of the background state have been further reinforced at interannual timescale by a preceding intense La Niña event in 2022. This resulted in (1) a record-breaking change in the radiative budget over the Indo-Pacific basin due to a steep year-to-year increase of SSTs, particularly in mean subsidence regions, which reduced low cloud cover at the onset of the 2023 event; and (2) an extreme and unusually early increase in tropical tropospheric temperature in boreal fall relative to past strong El Niños, due to unusual diabatic heating fueled by abnormally sustained precipitation over regions of high SSTs. The latter have been at record level for more than three years over the western Pacific and remained very high in 2023, impeding the canonical cooling effect over the warm pool during El Niños, as well as inhibiting the reduction/displacement of the Walker Cell.

The influence of the record-high SSTs in the Atlantic in modulating these mechanisms are briefly discussed. Our study contributes to a better understanding of the interactions between interannual internally-driven processes and a changing background state, which is crucial to isolate the fingerprint of anthropological forcing in ongoing trends.

1 Introduction

In the context of continuing greenhouse gas emissions and resultant long-term global warming, new temperature records and experiencing extreme heat waves has, as expected, become more and more frequent (Coumou et al., 2013). The year 2023, however, has set a range of new records from daily to annual timescale, both globally and regionally, that were so extreme and widespread that concerns of possible and unanticipated accelerated global warming have been put forward (Kuhlbrodt et al. 2024).

While anthropogenic forcing undoubtedly plays a large role in 2023 observed temperature anomalies (Min 2024), several natural external forcing mechanisms have been proposed to explain the temperature spike, such as the maximum of the 11-year solar cycle in a rising phase (Camp and Tung 2007) or the January 2022 Hunga Tonga eruption (Schoeberl et al. 2023). Beyond greenhouse gases, it has been proposed that the reduction of sulphur emissions resulting from the 2020 regulation on fuel qualities in marine shipping (Quaglia and Visioni 2024; Gettelman et al. 2024; Yoshioka et al. 2024) amay have also contributed to the warming by reducing the aerosol cooling effect. The relative importance of these factors is still a matter of debate; together they are insufficient to explain the global temperature spike in the annual, seasonal or monthly values of global surface air temperature (GSAT) observed in 2023 (Rantanen and Laaksonen 2024; Schmidt 2024; Rantanen and Laaksonen 2024; Forster et al. 2025).

Anthropogenically-forced global warming can be temporarily amplified (or attenuated) by internal climate variability, whose extreme cases can be seen as foreshadowing impacts and risks of near-future global warming levels. El Niño Southern Oscillation (ENSO) is the main interannual mode of internal variability and modelling studies suggest that it has played a major role in setting the 2023 global annual temperature record based on model outcomes (Raghuraman et al. 2024; Gyuleva et al., 2025; Jiang et al. 2025; Samset et al. 2024). On a monthly timescale, the use of large ensembles of the most recent generation of climate models tends to suggest that the observed jump in the September GSAT record can be regarded as an exceptional event with very low probability of occurrence, even at the current global warming level (Rantanen and Laaksonen 2024; Terhaar et al. 2025). Alternatively, the rarity of these types of events in models could be due to model biases, including for instance the underestimation of intraseasonal internal variability in climate models or the deficiencies in capturing diversity of ENSO dynamics (temporality, spatiality etc.) and related global teleconnection (Planton et al. 2021). It also raises the question of possible changes in the mechanisms and dynamics of internal variability in a non-stationary climate.

After a multi-year La Niña event in 2020-2022, the year 2023 saw the build-up to a moderate-to-strong El Niño event. An increase in global temperature was thus expected, but not as early as the August-to-October (ASO) late summer season considering the canonical lagged relationship between ENSO and GSAT (Schmidt 2024). Using methods of non-stationary normals, (Cattiaux et al., 2024) confirm the singularity of the timing while also providing evidence that the jump of annual temperature in 2023 is comparable to other El Niño episodes (eg. 1997-1998) when accounting for anthropogenically-forced global warming trends (Forster et al. 2024).

In this study, we investigate the specific characteristics of the 2023 El Nino in producing the late summer GSAT extreme based on a process-based approach using observations only. In section 3.1, we first analyse the contributions of the various ocean basins to the global temperature jump and quantify the importance of the Indo-Pacific Ocean. Section 3.2 and 3.3 then unravel two physical mechanisms to explain both the magnitude of the jump and the extreme level of the observed warming in the early fall of 2023. The implications of these findings are discussed in Section 4.

2 Materials and Methods

2.1 Data

Analyses are carried out on monthly mean ERA5 (Hersbach et al. 2020) data at 0.25° resolution for SST, air temperature (at the surface, 1000mb, 700mb and 500mb), vertical air velocity at 500mb, net radiation at the top of the atmosphere (TOA) and cloud cover. For precipitation, the Global Precipitation Climatology Project (GPCP, Adler et al. 2003) data at a resolution of 2.5° is used. For consistency, we reduce our analysis to the time period over which GPCP precipitation data is available, i.e. 1979-2024. Where required, the ERA5 data is linearly interpolated onto the GPCP grid. For radiation, the Clouds and Earth's Radiation Energy Systems Energy Balanced and Filled (CERES-EBAF) (Loeb et al. 2018), available from 2000 onwards is used to evaluate the ERA5 radiation data. All anomalies are computed with respect to the 1991-2020 climatology. Detrending of data, where applicable, is done using a LOESS detrending with a bandwidth of 0.6 on the 45 years of data (Cleveland, Cleveland, and Terpenning 1990). The Oceanic Niño Index (ONI, computed as a 3-month running SST average anomaly with respect to a 30-year climatology updated every five years, over the region 5°S-5°N, 170°W-120°W from ERA5) and the Southern Oscillation Index (SOI, computed as the standardized difference of standardized sea level pressure between Tahiti and Darwin, NOAA, https://www.ncei.noaa.gov/access/monitoring/enso/soi) are used to monitor ENSO. Except for the tropospheric temperature, which is assumed to be homogenous under the weak gradient approximation (Sobel and Bretherton 2000), all spatial averages are computed over ocean grid points only. The term "tropical averages" refers to the 20°S-20°N domain, except when focusing on the ASO season, where we consider 15°S-25°N to account for the northward seasonal shift of the deep atmospheric convection zone.

2.2 Composites

To make comparisons between the 2023 El Niño and past events, we constructed composite fields for strong El Niños available in the data period. Those are defined by ONI values greater than 1.5 K following the National Oceanic and Atmospheric Administration (NOAA, 2019) criteria. This includes the 1982-83, 1987-88, 1991-92, 1997-98, 2009-10 and 2015-16 ENSO episodes (See SI Fig.1).

3. Results

3.1 Characterisation of the early fall temperature jump in 2023

The change of global sea surface air temperature between two consecutive years in ASO seasons is record high between 2022 and 2023 (Fig.1a). The onset of El Niño generally produces the strongest year-to-year global temperature jumps like in 1987, 1997 and 2015 but the margin by which the early fall temperature change record is broken in 2023 is remarkable. Note that cooling occurred in 1982 and 1991 despite developing El Niño because of the dominating influence of the volcanic eruptions of El Chichon and Pinatubo, respectively, The contribution of the various ocean basins to the ASO global marine surface air temperature (GMSAT) anomaly is assessed by considering their respective area-weighted anomalies (Fig.1b). The Austral and North Atlantic Oceans, which have been warming in recent years due to the combination of pronounced decadal variability and human influence (Purich and Doddridge 2023; Guinaldo et al. 2025) have both contributed significantly to the 2023 ASO temperature anomaly (0.13ºC and 0.12ºC, respectively, out of 0.65ºC). The contribution for the temperature jump, however, results overwhelmingly from the Indo-Pacific Ocean (+0.35ºC between 2022 and 2023). Despite the Indo-Pacific Ocean having the strongest variance at interannual timescale, no comparable temperature jump is observed for any of the other strong-to-moderate El Niño events since 1979 (Fig.S2). Regarding the temporal progression, the onset of the 2023 El-Niño event follows a seasonal evolution that is comparable to those of other strong El-Niño events according to the ONI (Figure 1c), with a progressive build-up in boreal spring and maximum intensity in early winter. There is a diversity in El Niño history with events starting in all possible phases of ENSO in the year before. The specificity of the 2023 event lies in the strong La Niña state present in 2022, with the 2009 event being the closest analog based on ONI.

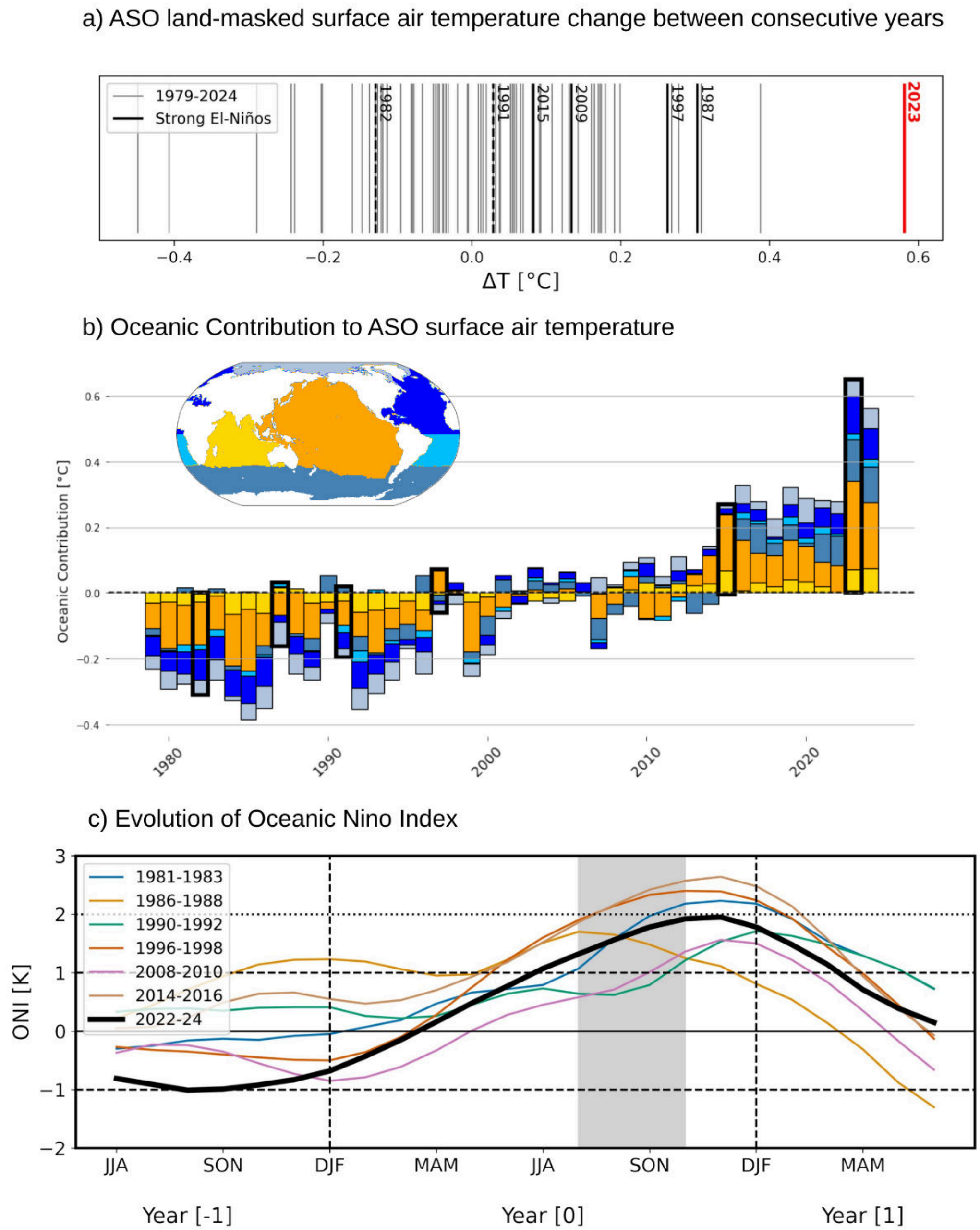

Figure 1. **Observed record-breaking jump of Global Marine Surface Air Temperature** a) Change of ASO GMSAT between two consecutive years for the years 1979-2024 (grey), with strong El-Niño years highlighted in black and 2023 in red, all in °C (ERA5). b) Area-weighted oceanic contributions to land-masked global air temperature at 2m anomalies for the ASO season relative to 1991-2020 in °C (ERA5). The built up years of strong El Niño years are highlighted in black. The

oceanic basins represented in different colours (upper-left map) are defined from Fay and McKinley (2014). c) The ENSO cycle (from JJA Year [-1] to JJA Year [+1]) assessed from ONI for the El Niño composite years (light coloured solid lines) and the 2022-24 event (thick black), The ASO season Year [0] is highlighted in grey.

3.2 Extreme jump in radiative forcing

To understand how the preconditioning of the Indo-Pacific in 2022 impacted the evolution of SST, cloud cover and radiative anomalies, and contributed to the observed sudden increase of GMSAT in ASO 2023, we consider the change in SST (ΔSST) between those two years based on April-to-September (AMJJAS) means. This extended period is chosen to capture the radiative forcing contribution in the build-up of SST anomalies in ENSO events (Ceppi and Fueglistaler 2021).

The change in AMJJAS SST between 2022 and 2023 is characterized by a warming in the Eastern and Central Pacific (Fig.2a) that was both stronger in magnitude and more widespread compared to canonical El Niños (Fig.2b-c). This specificity is attributable to the rapid switch to El Niño from a triple-dip La Niña and related strong cold anomalies along the South American coast and more broadly over the Southeastern tropical Pacific basin that were present in 2022 (Jiang et al. 2025). In the central basin, the Pacific system flipped from an intense seasonal cold tongue penetrating westward at the equator around the dateline in 2022, that is typical for La Niña events (Trascasa-Castro et al. 2019), to a retracted one in 2023. When ΔSST is assessed as a function of climatological mean ascending and descending motion in the mid troposphere (at 500hPa, ω_{500}) over the Indo-Pacific domain, results show a much larger increase of SST in subsidence zones in 2022-2023 than in the other El Niños, particularly in the regions of strongest mean subsidence (i.e. the southeastern tropical Pacific) (Fig.2g).

The changes of SST have an impact on the TOA energy budget by influencing the lower tropospheric stability, defined as LTS = $\Theta_{700}-\Theta_{1000}$, where Θ is the potential temperature (Klein and Hartmann, 1993). While the free tropospheric temperature follows a moist temperature adiabat, primarily set by deep convection over the warmest SSTs and is uniformly distributed throughout the tropics on a timescale of a few days to weeks (Emanuel, David Neelin, and

Bretherton 1994), the temperature in the boundary layer is set by local SSTs (Sobel and Bretherton 2000). Therefore, warming of SSTs (particularly in regions of subsidence) increases the local Θ_{BL} and decreases LTS and consequently the inversion strength, favoring a decrease of low cloud cover (Klein and Hartmann 1993) (Fig.S3a) This results reduces the albedo and leads to a positive radiative budget anomaly at the top of the atmosphere. This so-called pattern effect (Stevens et al. 2016; Bloch-Johnson, Rugenstein, and Abbot 2020; Dong et al. 2019; Zhang, Zhao, and Tan 2023) has been applied to the build-up of an El Niño event to explain why the warming in the Niño3.4 region is preceded by a several-months-long positive radiative budget anomaly in subsidence regions (Fueglistaler 2019).

Through this mechanism, the steep change of SSTs in subsidence regions from 2022 to 2023, strongly impacts the change in TOA radiation budget (ΔN) between the two years (Fig.2d), which spatially overlaps with the jump in SST (Fig.2a). The robustness of ERA5 anomalies shown is verified by comparison to CERES (Fig.S4). Maximum radiative excess is located (i) in the central Pacific, (ii) along the southern flank of the climatological ITCZ at 5ºN of latitude with reinforced anomalies in the easternmost part of the basin closer to the Equator and (iii) over the mean subsiding areas to a lesser extent in absolute value. The 2022-2023 jump in ΔN is much more pronounced in the latter two domains with respect to canonical El Niños (Fig.2e-f). This is consistent with the ΔSST pattern and related increase of Θ_{BL} leading to lower local tropospheric stability and a stronger reduction in 2022-2023 of low-level cloud cover (Fig.S3a-c). This is especially pronounced over the regions where subsidence mean background is the largest (Fig.2h), matching the SST behavior (Fig.2g). Low-level clouds also control the radiative budget over the marginal zones of the subsidence areas that are subject to variations in the sign of ω, like in the central basin and south of the ITCZ. The strongest jump in SST (Fig.2c) and low cloud cover (Fig.S3c) along the coast of America is associated with the onset of the very extreme coastal El Niño (Peng et al. 2024). At the western extremity of the equatorial cold tongue, low-level clouds decreased more strongly between 2022 and 2023 than for canonical El Niño shifts, consistent with stronger ΔSST at the west of the dateline.

While an El Niño is developing, convection shifts eastward from the warm pool, which causes increased high-cloud cover in the central Pacific and locally affects ΔN. The specificity of the

2022-2023 event lies in the persistence and reinforcement of convection and related high-level cloud over the western Pacific basin (west of 170º West), which usually diminishes in canonical El Niños (Fig.S3d-f). When stratified in ω_{500} deciles over the entire Indo-Pacific basins, 2022-2023 changes in high-level clouds differ from other El Niños in the deepest convective regions (first decile, where ascendance is the largest) but not in subsidence zones which undergo canonical changes (Fig.2i). Consistently, the upward branch of the Walker Circulation as delineated by the $\omega_{500} = 0$ contour (Fig.2c,f) exhibits a smaller shift towards the central Pacific in 2022-2023 than is typically seen for previous El Nino events. The latitudinal dipole in ΔN located off Australia-New Guinea (Fig.2d,f) features an equatorward shift of the South Pacific Convergence Zone evidenced by reduced high-level clouds (Fig.S4d-f) replaced by increased low-level ones (Fig.S4a-c), whose combined radiative effects lead to strong but confined loss in radiative budget centered at 15ºS-160ºW.

As a result of all these features, the jump in radiative budget between 2022 and 2023 when averaged over the entire tropical Indo-Pacific domain, turns out to be the second largest since 1979 behind 2011-2012 (Fig.2j). The positive ΔN is accompanied by a drop of about 2.5 standard deviations in low-level clouds. Such a link is consistent with the linear relationship between the two quantities but the amplitude of the loss is the largest (Fig.S2g); the closest ENSO analog to 2022-2023 is 1996-1997 according to this metric. By contrast, the huge drop in low-cloud cover is not associated with a large change in low tropospheric stability (LTS) when averaged over the entire Indo-Pacific basin (Fig.S3h) as opposed to 1996-1997. This is due to the fact that Θ_{Tropo} and Θ_{BL} warms simultaneously in the 2022-2023 event (not shown). The specificity of the anomalous convection and related Walker cell, which is much less reduced in the developing stage of ENSO in 2023 compared to other events as confirmed by weak Southern Oscillation Index (SOI, Fig.S5) and as discussed in detail by Peng et al., 2025, is investigated in depth in the following section.

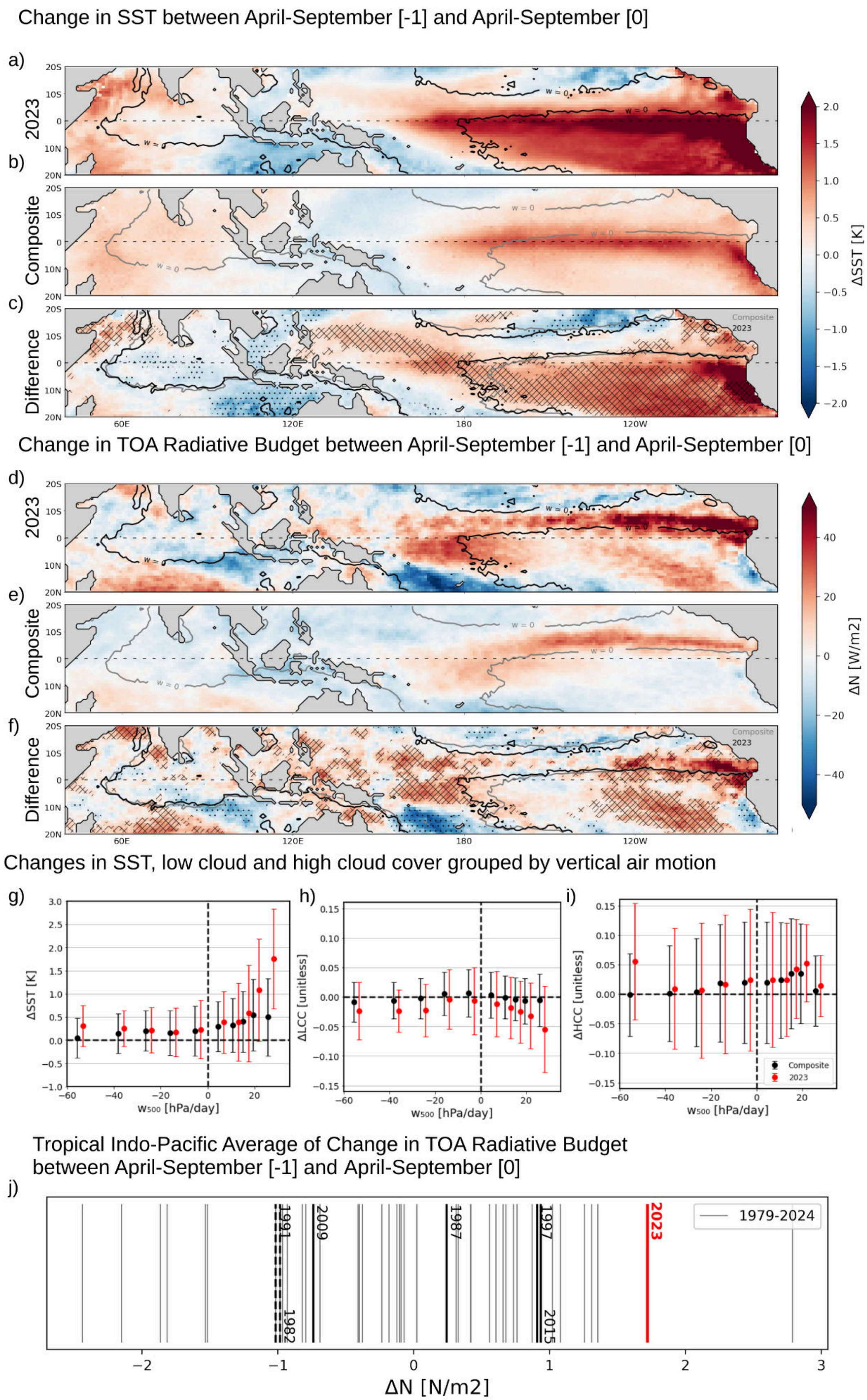
Change in SST between April-September [-1] and April-September [0]
a)
2023
b)
Composite
c)
Difference
20S
10S
0
10N
20N
60E
120E
180
120W
w = 0
Composite
2023
ΔSST [K]
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
Change in TOA Radiative Budget between April-September [-1] and April-September [0]
d)
2023
e)
Composite
f)
Difference
ΔN [W/m2]
40
20
0
−20
−40
Changes in SST, low cloud and high cloud cover grouped by vertical air motion
g)
h)
i)
ΔSST [K]
ΔLCC [unitless]
ΔHCC [unitless]
w500 [hPa/day]
Composite
2023
Tropical Indo-Pacific Average of Change in TOA Radiative Budget
between April-September [-1] and April-September [0]
j)
1979-2024
1991
1982
2009
1987
1997
2015
2023
ΔN [N/m2]

Figure 2. **Changes in SST and Net radiation for the 2023 El Nino built-up and the composite El-Nino.** Changes in SST leading up to ASO season, calculated as the April-to-September (AMJJAS) average anomalies of ERA5 SST for (**a**) 2023-2022 , (**b**) Year[0] – Year[-1] for the composite year (1982, 1987, 1991, 1997, 2009 and 2015) and (**c**)the difference between 2023 and the composite event. **d-f)** Same but for net radiation. In **a)** and **f)**, cross hatching is used where the 2023 anomaly is higher than all years of the composite event, and stippling where it is lower than all. The $w_{500} = 0$ contour is shown for 2023 (**a)** and **d)**), the composite (**b)** and **e)**) and both (**c)** and **f)**). **g-i)** The collocation of changes in tropical (S20-N20) indo-pacific **g)** SST, **h)** low cloud cover (LCC) and **i)** high cloud cover (HCC) , defined as the AMJJAS change between Year [-1] and Year [0], binned into deciles of the climatological w_{500} AMJJAS distribution. The error bars denote the spread as ±1σ for the composite (black) and 2023 (red). **j)** Change of tropical (S20-N20), indo-pacific average of TOA radiative Budget between AMJJAS [-1] and AMJJAS [0] for the years 1979-2024 (grey), strong El-Niños (black) and 2023 (red) in N/m-2 from ERA5.

3.3 Extreme jump in tropospheric heating

The spatio-temporal evolution of precipitation anomalies is assessed from 2022 to 2024 as a function of climatological SSTs ranked in percentiles (Fig.3a-c). During an El Niño, reduction of precipitation usually occurs over the Indo-Pacific warm pool where the climatological background state for atmospheric deep convection is located (Dai and Wigley 2000). By contrast, rainfall increases over the lower SST deciles from early fall onwards (Fig.3b); this see-saw reaches its maximum amplitude in boreal winter and following early spring in parallel with the SST anomalies (Fig.3e). However, the 2022-2023 event significantly differs from canonical ENSO (Fig.3c,f). Enhanced precipitation over middle-to-low climatological SST occurred but was considerably less pronounced and widespread in 2022-2023 compared to canonical El Ninos. Over regions of climatologically high SSTs, rainfall increased from summer 2023 instead of decreasing as in canonical El Niños, as also evidenced by the high cloud cover anomalies documented earlier (Fig.S3d). Illustratively, the meridional profile of the ASO tropical rainfall anomalies shows precipitation excess along the equator which remained confined to Western Pacific in 2023 whereas it is usually shifted to the Central basin for canonical El Niños (Fig.3g). This pattern persisted, which over time until 2024, is a clear specificity of the 2023-2024 event with respect to its strong historical counterparts (Fig.3c).

Concurrently, SSTs cooled significantly less over the climatologically highest SSTs (Fig.3d,f) and warmed less over the coldest ones, except at the early stage of the event associated with the development of a strong coastal El Niño (Peng et al 2024). In ASO 2023, SST anomalies remained warmer than average over the warm pool (Fig.3h and Fig.S6d). Maximum positive SST anomalies were found at the easternmost part of the basin but the seasonal background ocean cooling that started in May, precluded deep convection (Fig.3g), consistent with Peng et al. 2024. At the same time, the Eastern Pacific SST warming considerably reduced low-level cloud cover and perturbed the radiative budget as documented in the previous section. Note that the gradient of tropical SST anomalies in ASO is located around 110°W in 2023, a position that is well eastward displaced compared to 180° for canonical El Niños. Such a longitudinal position is too far east to efficiently reduce the Walker cell, which is consistent with the overall weak response in SOI mentioned earlier (Fig.S5). The specificity of the 2023 El Niño event to have followed La Niña years (Fig.3h, dotted line) is well captured in Fig.3f with positive (negative) SST anomalies over the warmer (colder) climatological SSTs. Interestingly, this pattern remained nearly unchanged in geographical structure and amplitude across the change in ENSO phases between 2022 and 2023, as also measured in SOI (SIFig.5) with a persistently more intense Walker and more convective rainfall over the Western Pacific across the entire ENSO cycle (Fig.3g).

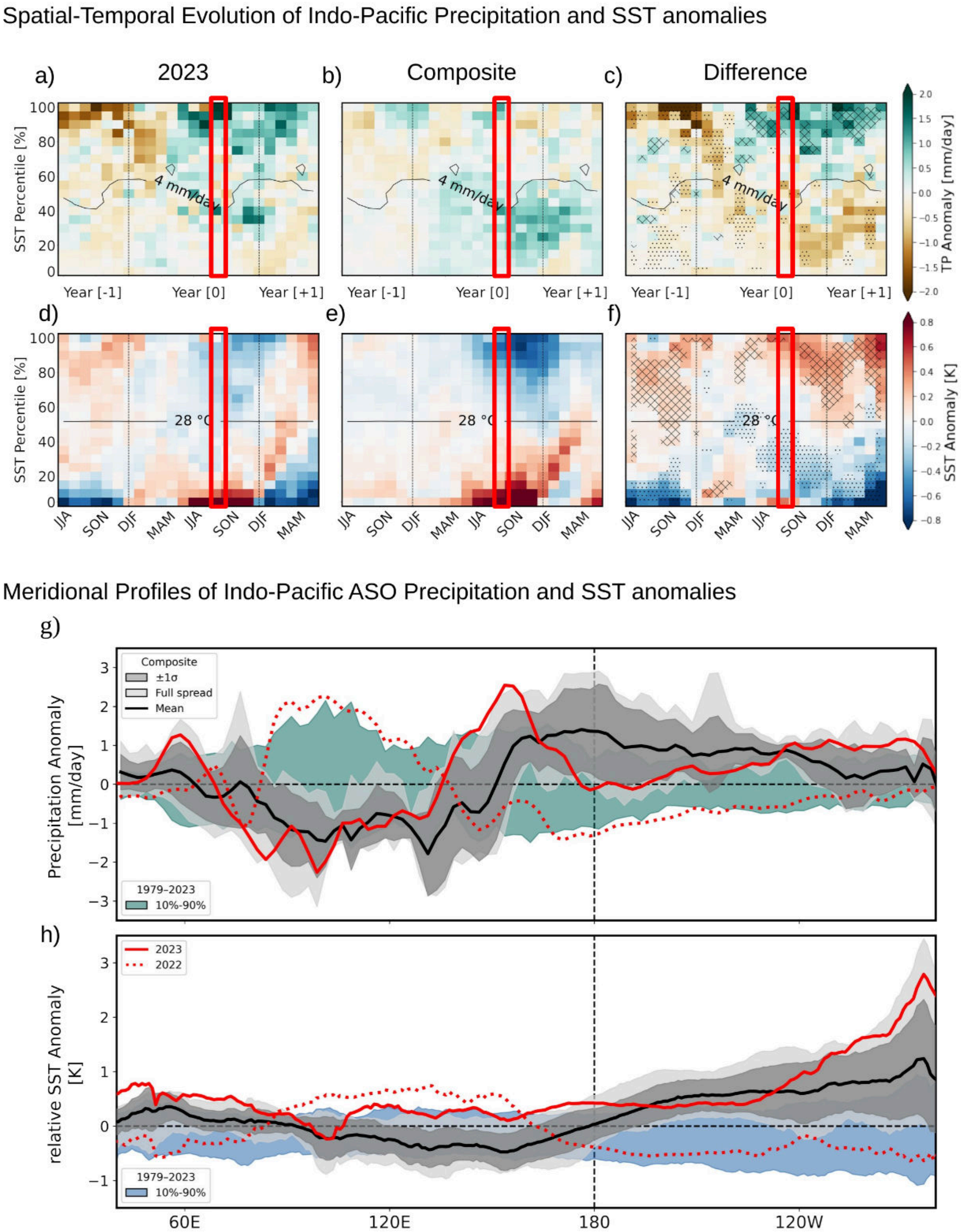

Figure 3. Evolution of Precipitation and SST anomalies grouped by the climatological SST distribution. Tropical (15-25N), Indo-Pacific 3-month running mean precipitation anomalies (in mm/day) binned in equal area percentiles of the

SST 1991-2020 climatological distribution, from coldest to warmest as in Fueglistaler 2019, using 20 bins for **a)** July 2022 to June 2024. **b)** composites July [year -1] to June [year 1] (1982, 1987, 1991, 1997, 2009, 2015) and **c)** the difference between 2023 and the composite. **d) - f)** As a)-c) but for relative SST (mean tropical SST removed) anomalies (in Kelvin). Hatching (stippling) highlights regions where the 2023 anomalies are larger (smaller) than all of the composites. The ASO season is highlighted by the red boxes. **g)** Meridional Profile of the tropical (S15-N25), land-masked ASO anomalies of precipitation (in mm/day). Green shading shows the variability (10th to 90th percentile) for the years 1979-2024. The solid black line corresponds to the composite, with the grey (lightgrey) shading for the $\pm 1\sigma$ (full) spread. The solid red line indicates ASO 2023, the dotted red line 2022. **h)** As in g) for SST anomalies (in K).

As argued above, it is the SST in regions of deep convection, that control a large fraction of variance in tropospheric temperature through injection of anomalous diabetic heating into the atmospheric column (Fueglistaler 2019; Sobel, Held, and Bretherton 2002; Bony et al. 2020), from where it influences GSAT through teleconnections. In 2023, the tropical atmospheric warming started earlier in boreal summer with respect to other El Niños as assessed from potential temperature at 500mb, $\bar{\Theta}_{500}$ (Fig.4a).

During a canonical El Niño, atmospheric tropical heating through anomalous convection occurs late in the course of the year, from late boreal fall to the following early spring, being phase-locked with the seasonal cycle of the SST (Fig.3b), especially at the equator along the cold tongue. Specifically during the boreal summer and fall seasons, positive SST anomalies occur preferentially in areas of low mean SST (non-convective), and are not associated with a significant heat source for the troposphere until late fall when SSTs are warm enough to trigger convection (Fueglistaler 2019). This explains the lag between the tropospheric temperature warming and the ONI SST anomalies. In 2023, reinforced deep convection over the warmest climatological SSTs that were even warmer than during other El Niños (Fig.3 and Fig.S6) is hypothesized here to have produced an efficient heat source to the tropical troposphere as early as late summer; this feature persisted until the end of the event.

The relationship between tropospheric heating and precipitation-weighted SSTs (PWS) (Flannaghan et al. 2014) is investigated to further illustrate the specificity of the 2023 El Niño and related jump in ocean surface air temperature and GSAT as early as ASO (Fig.1a). PWS is defined at each grid-point as the product of raw SST and precipitation rate, normalised by the tropical mean precipitation rate at the corresponding time, so that

$$PWS = \frac{\overline{\mathrm{SST} \cdot \mathrm{tp}}}{\overline{\mathrm{tp}}},$$

where overbars denote the average over the tropical Indo-Pacific basins. All data are detrended and we focus again on the ASO season.

PWS is very well correlated with $\bar{\Theta}_{500}$, with R=0.81 ($R^2 = 0.67$). The largest values of PWS are obtained for the strong El-Niño Years [0] used in the composite (Fig.4b); 2023 ranked 2nd in $\bar{\Theta}_{500}$ but does not significantly depart from the other ones in terms of PWS. However it has the third largest residual in PWS with respect to the linear relationship between the two quantities when assessed over the 1979-2024 period, larger than any of the other strong El-Niño events. In order to extract which oceanic configuration acts as a “booster” for tropospheric warming beyond the linear relationship with Indo-Pacific PWS, we calculate the correlation map of the $\bar{\Theta}_{500}$/PWS residuals on the observed SST anomalies (Fig.4c). First, the tropical north Atlantic clearly stands out with warmer SST, providing an additional source of diabatic heating. Re-evaluating the $\bar{\Theta}_{500}$/PWS relationship accounting for all tropical basins, thus including the Atlantic, improves the relationship (R=0.86 and $R^2 = 0.75$, SI-Fig.7b) between the two variables and confirms the second-order but not neglectable role of the tropical Atlantic Ocean. Evidence is provided in Fig.S7b) that the exceptional state of the Atlantic in 2023 has clearly boosted the Indo-Pacific induced tropospheric warming and has contributed to the record jump in $\bar{\Theta}_{500}$ in early fall. Second, positive SST anomalies over the Indo-Pacific warm-pool where most of the deep convection occurs also reinforce the tropospheric warming. The SST correlation map overall exhibits a Niña-like pattern with large-scale teleconnection in the subtropics. This pattern largely overlaps with the regions of atypical high SSTs observed in ASO 2023, as detailed through this paper (SI Fig.6f).

Finally it is essential to mention that both PWS and $\bar{\Theta}_{500}$ were at the lower end of their distributions in 2022, notably lower than any preceding years for the other strong El Niños (Fig.4b) over 1979-2024. This mainly explains why the jump in tropospheric temperature between two consecutive years has been the strongest in 2022-2023 (Fig.S7a).

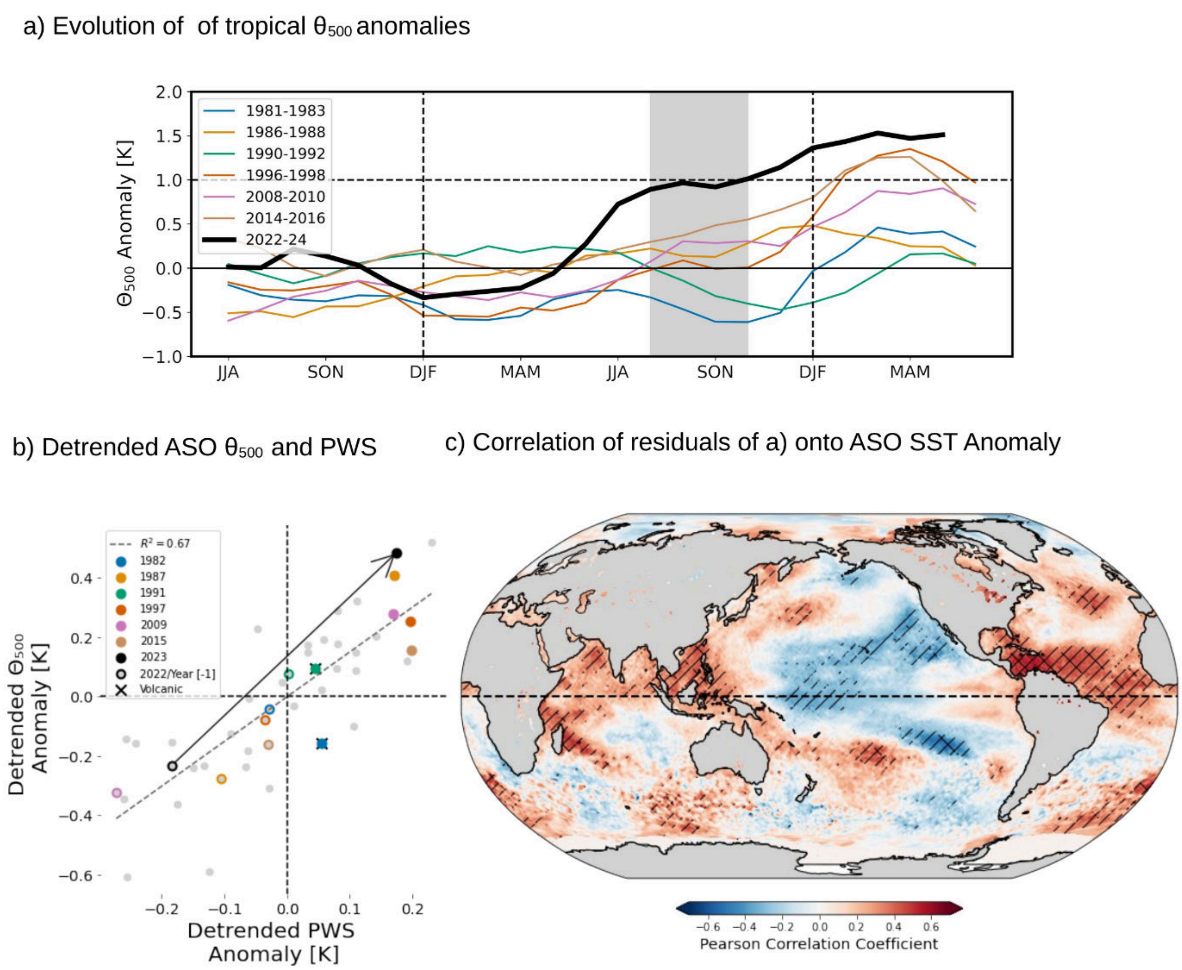

Figure 4. The Evolution of tropospheric warming and SSTs in deep convective regions. a) The evolution of tropical (15S-25N) $\bar{\Theta}_{500}$ anomalies (from JJA Year [-1] to JJA Year [+1]) for the El Niño composite years (light coloured solid lines) and the 2022-24 event (thick black). The ASO season Year [0] is highlighted in grey. **b)** Anomaly of tropical (15S-25N), tropospheric (500mb) potential temperature for the

ASO season, LOWESS-detrended, against tropical Indo-Pacific SST, LOWESS-detrended, precipitation-weighted sea surface temperature (PWS) for the years 1979-2023. The linear regression ($R^2 = 0.67$) is shown (dotted line), ENSO composite years [0] are marked in filled colour dots, year [-1] in empty dots. Crossed dots stand for El Niño years affected by volcanic eruptions. 2023 is marked in black and the arrow stands for the jump between 2022 and 2023. **c)** Map of pearson correlation coefficient of the residuals of **a)** and ASO SST anomalies. Diagonal hatching corresponds to areas significant at the 95th percentile, and cross-hatching for the 99th percentile based on t-statistics.

4 Discussion and Conclusion

This work aims to analyse the role of ENSO, and more broadly the role of internally-driven processes, in producing the extreme jump in global surface temperature observed in 2023. We have highlighted the boreal early fall season (hereafter ASO) which is the most atypical aspect of the 2023 El Nino lifetime when compared to other strong El Niños of the 1979-2024 period. We here provide multiple lines of evidence that the exceptional 2023 jump in ASO temperature (Fig.1) can be explained by the rare confluence of several physical processes in a warming climate.

The overarching factor setting the ground for their combined, strong effect lies in the preconditioning of the Indo-Pacific into a Niña-like state. This is a specificity of the 2023-2024 El Niño with respect to the onset of other strong El Niños in recent history and results in:

1. A record year-to-year warming over the Eastern Pacific, more specifically over regions of mean subsidence during the build-up phase of ENSO events in boreal spring and summer (Fig.2g). This is accompanied by a steep warming of boundary layer temperature there, decreasing the lower tropospheric stability and the inversion strength, therefore resulting in a sharp and widespread loss of low clouds (Fig.5b, Fig.2h). Altogether, this led to an upsurge in the Indo-Pacific averaged radiative budget between 2022 and 2023, which was the strongest recorded for the onset months of El Niños (Fig.2j). The emergence of an extreme coastal El Niño in spring is likely to have contributed to such a record (Peng et

al. 2024). This is coherent with the record low planetary albedo observed in 2023 as documented in Goessling et al. (2024) and the atypical large Earth Energy Imbalance discussed by Minobe et al. (2025), to which we here provide a mechanistic explanation.

2. An atypical climate response to the El Niño build-up over the Western Pacific both in terms of temperature, precipitation and related Walker circulation (Fig.3). SST cooled significantly less over the warm pool (Fig.3f) in 2023 with respect to other El Niños, while precipitation increased there instead of decreasing (Fig.5d, Fig.3c) SOI, used as a proxy for Walker cell displacement/strength, consistently remained relatively high despite strong warming over the Eastern Pacific (SI-Fig.5). As shown by Peng et al. (2025), the preceding, prolonged La Niña acted as a strong preconditioning factor for such specificities because of the accumulation of a large amount of warm water in the western Pacific basin by the boreal winter of 2022. Ocean heat content is record high (Lian et al. 2023), ensuring the stronger persistence of surface temperature anomalies over the warmest waters. Consequently, the anomalous SST gradient is located too far east in 2023 (Fig.3h) to efficiently displace or weaken the Walker cell. Accordingly, precipitation shifted only slightly eastward between 2022 and 2023 (Fig.3g) but remained high and was even reinforced over the warmest water of the Pacific warm pool (Fig.3c, Fig.S6a). This also contributed to the strong radiative gain over the western Pacific basin through an atypical high cloud response (Fig.S3d).
3. An exceptional surge in tropospheric warming as early as late-summer/early-fall (Fig.5d). We show that SST variations over regions of deep convection control about 70% of the variance in tropical atmospheric heating through its control of the tropical moist adiabat (Fig.4b). 2023 is atypical compared to other El Niños as (i) it is characterized by the strongest tropospheric warming for anomalies of similar amplitude in precipitation-weighted SST and (ii) it transitioned from a cold tropical atmosphere in 2022 set by the preceding La Niña (Fig.4b), leading to record-high jump in temperature of the tropical troposphere (Fig.S7a).

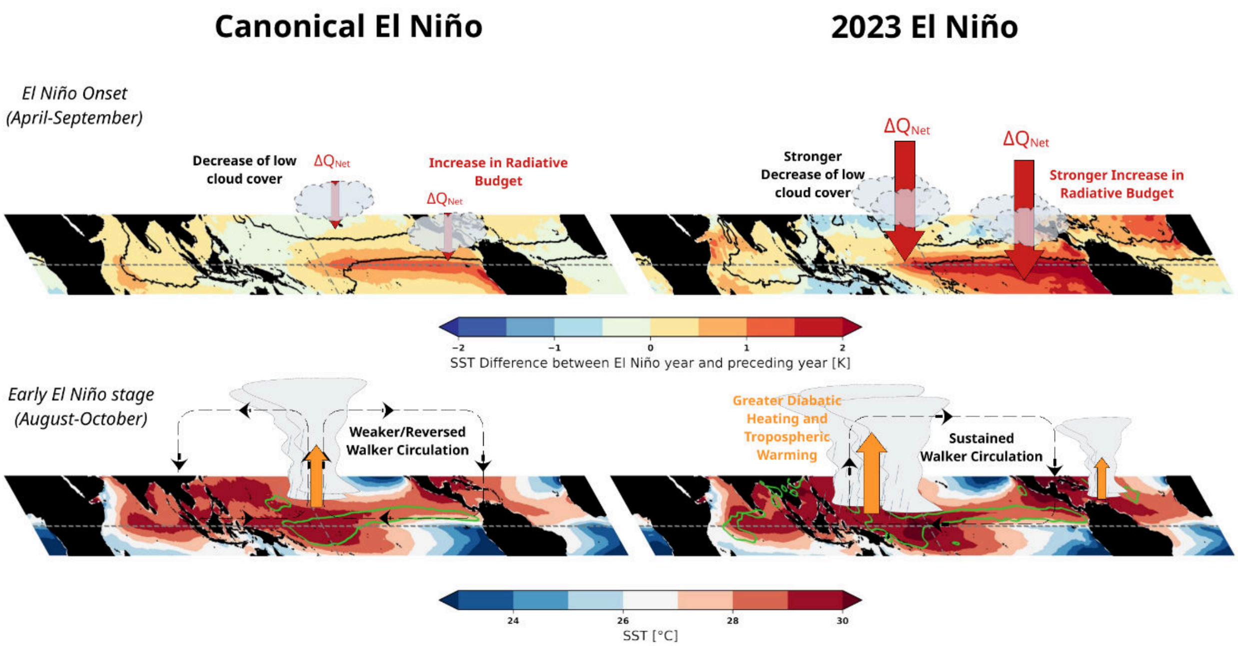

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Figure 5. Summary of the physical processes contributing to the year-to-year jump in Global Temperature in 2023. Schematic overlay of the coupled ocean-atmosphere state during the Onset (top row) and early stage (bottom row) for canonical El Nino (left column) and the 2023 El Nino (right column). *Top row*: colored shading shows the change of SST in AMJJAS between two consecutive years when ENSO develops, with the black line being the w_{500} equal to 0hPa/s contour to differentiate between convective and subsidence areas. *Bottom row*: colored shading shows the raw SST in ASO with the green contour being the anomaly of precipitation equal to 1.5mm/day to highlight the source of anomalous diabatic heating.

All of these mechanisms, affecting the heat budget through either radiation or diabatic heating, have individually manifested during other years to a comparable extent. We argue that their temporal synchronicity significantly contributed to the observed jump in early-fall global temperature.

Therefore, the large-scale background state of the Indo-Pacific is hypothesized here to be crucial in setting the timing and extent of these mechanisms; this raises questions about the respective roles of the interannual-to-multidecadal internal modes of variability and the anthropogenically-forced trend in the preconditioning.

1. At interannual timescale, the preceding, rare triple-dip La Niña amplified the Pacific SST zonal gradient and set the stage for the jump to occur at the onset of an El Niño. Out observational analysis thus supports the importance of a preceding La Niña suggested by modelling studies (Raghuraman et al. 2024; Gyuleva, Knutti, and Sippel, 2025), which supports our results from a process-based approach based on observations only. In fact, it may not be the year 2023 that was exceptional but rather the year 2022.
2. At decadal timescale, upper-ocean heat accumulated, as a response to ever-increasing human-caused Earth Energy Imbalance, but with a large-scale regional fingerprint (Lian et al. 2023; Minobe et al. 2025). Ocean heat content has risen considerably in the Western Pacific as opposed to the East; concurrently, the zonal SST gradient and the Walker cell have strengthened and low cloud cover has increased over the Eastern Pacific basin over the past decades. This again has set an atmospheric background stage for a stronger jump in radiation with low cloud amount being initially high, close to record, and then disappearing at the onset of this El Niño, as also mentioned in (Goessling, Rackow, and Jung 2024). We have shown that the large-scale SST pattern boosting the tropospheric warming, which is strongly governed by ENSO at interannual scales, projects on a La Niña-like state. It is spatially correlated at 0.42 ($p<0.01$) to the Interdecadal Pacific mode of Variability (IPV) as defined in the 6th IPCC report (Cassou et al., 2023) and reproduced in Fig.S8b). It is worth noting that the Pacific Decadal Oscillation, which is very well correlated with IPV, remains significantly negative across the full La Niña–El Niño 2022-2024 cycle as part of a long-lasting multidecadal negative phase initiated in early 2000s and still ongoing (NOAA, https://www.ncei.noaa.gov/access/monitoring/pdo/). We argue here that part of the sustained precipitation in the western Pacific during the 2023 El Niño event could have been driven by the low-frequency modes of variability in the Pacific.
3. On a longer timescale, the observed Pacific SST trend is also showing a 'Niña-like' pattern (Fig.S8c). The causes of this observed trend pattern are still debated as it is

difficult to disentangle multi-decadal internally-driven variations from actual anthropogenically-driven trends over too short periods. In addition, climate models generally underestimate Pacific Decadal Variability (PDV) (Zhao et al. 2023) and the anthropogenically-forced response pattern over the Pacific is still a matter of debate (Watanabe et al. 2024).

All together, low-frequency processes (multiyear La Niña, PDV and trends) are poorly simulated in models (Wills et al. 2022; Zhao et al. 2023b; Lee et al. 2022). In addition, our results highlighted the importance of cloud-radiative response to SSTs and it has been shown that CMIP-class models show a large spread in the relation between low clouds and tropospheric stability while underestimating stratocumulus clouds sensitivity to local SSTs (Myers et al. 2021; Yuan et al. 2018). Therefore, both the model-observation discrepancy in the Pacific SST low-frequency variations, forced and/or internally-driven trends, and the underestimation of stratocumulus sensitivity, could explain why climate models struggle to reproduce the observed temperature jump in 2023 (Terhaar et al. 2025).

Finally, we have provided some evidence that the tropical North Atlantic also played a role in the early-fall jump of global temperature: (i) at interannual time scale through its contribution to direct heating of the tropical troposphere, associated with an extreme phase of internal variability evaluated to be a centennial-type event (Guinaldo et al. 2025). Note that the Atlantic hurricane season has been ranked 4th despite El Niño, that typically results in less activity, suggesting reversed-signed teleconnection between the Pacific and Atlantic in Summer-Fall 2023 (Klotzbach et al. 2024); (ii) through its decadal influence upon the Pacific dynamics modulating the Walker circulation and favoring a background climate projecting on negative IPV/La Niña like dynamics, characterized by sustained precipitation in the western Pacific and a reduced surface wind response over the tropical Pacific (Trascasa-Castro et al. 2021). Analyses of preindustrial control simulations and dedicated model sensitivity experiments to isolate and quantify the role of the different processes documented here will help to deepen our understanding of the observed 2023 jump in global temperature.

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Supporting Information for

Why was the 2023 jump in global temperature so extreme?

J. Mex[1,2], C. Cassou[1], A. Jézéquel[1,3], S. Bony[4], C. Deser[5]

[1]LMD/IPSL, École Normale Supérieure, PSL Université Paris, Paris, France

[2]Leipzig Institute for Meteorology, Leipzig University, Leipzig, Germany

[3]École Nationale des Ponts et Chaussées, Champs sur Marne, France

[4]LMD/IPSL, Sorbonne University, CNRS, Paris, France

[5]National Center for Atmospheric Research, Boulder, CO, USA.

Contents of this file

Oceanic Nino Index

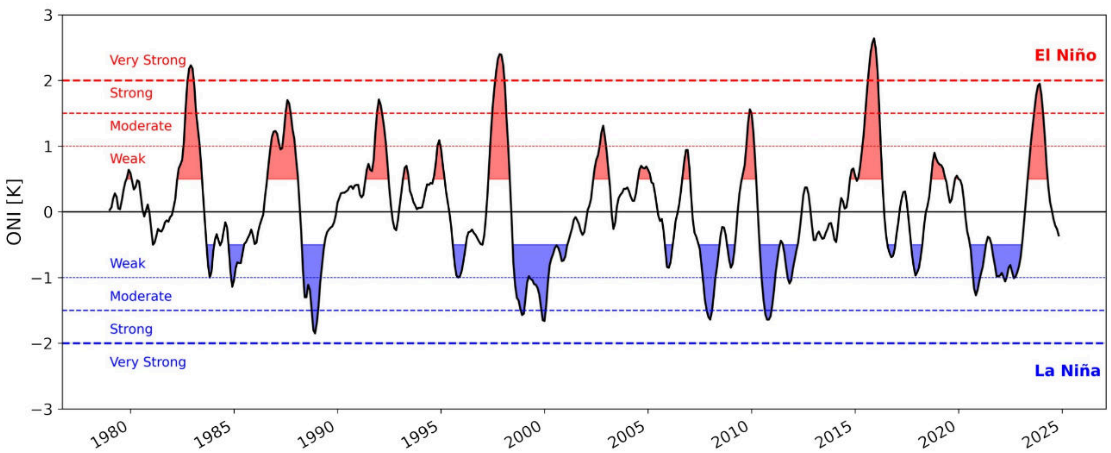


Figure S1. The Oceanic Nino Index. ONI index from 1979 to 2024 with El Niño (La Niña) episodes shaded in red (blue).

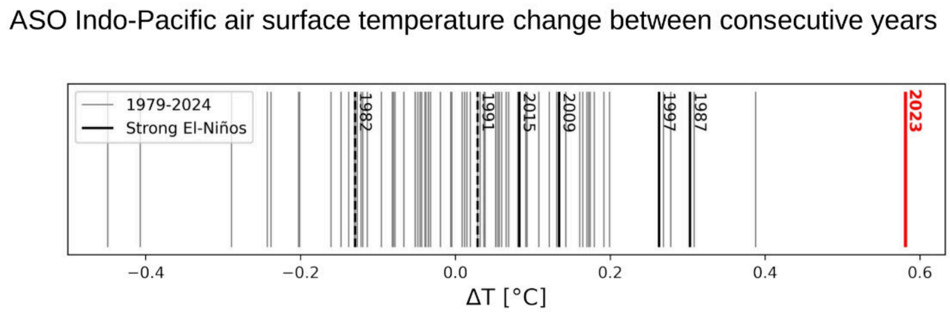
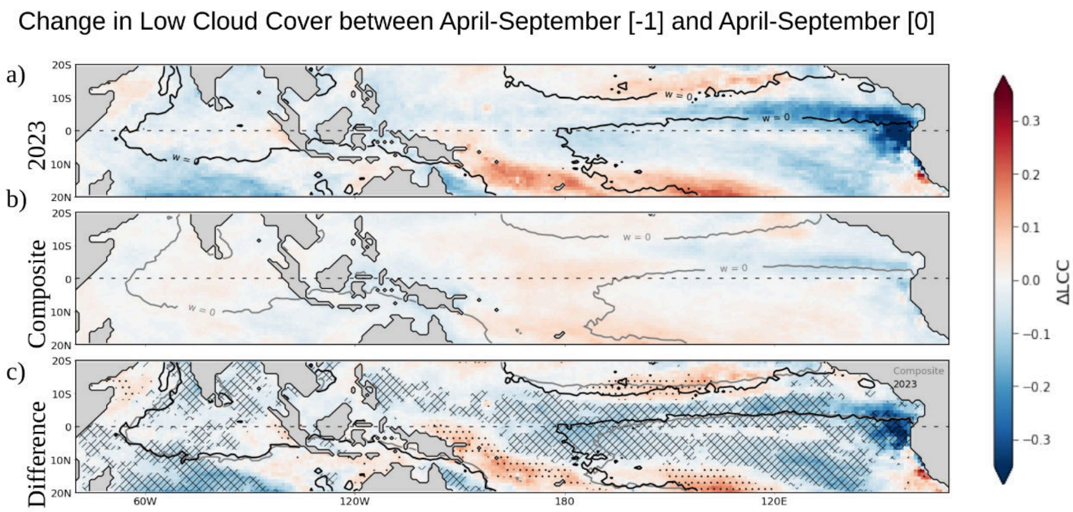
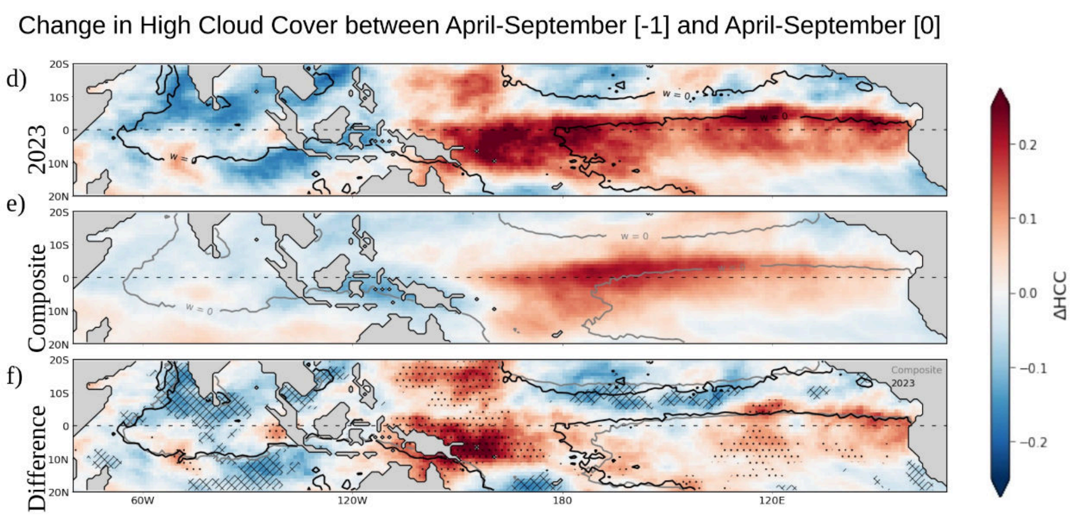


Figure S2. The year-to-year jump in Indo-Pacific Surface Air Temperature. As Figure 1a) for the Indo-Pacific surface air temperature.


Change in Low Cloud Cover between April-September [-1] and April-September [0]
a)
2023
b)
Composite
c)
Difference
20S
10S
0
10N
20N
60W
120W
180
120E
w = 0
Composite
2023
ΔLCC
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3


Change in High Cloud Cover between April-September [-1] and April-September [0]
d)
2023
e)
Composite
f)
Difference
20S
10S
0
10N
20N
60W
120W
180
120E
w = 0
Composite
2023
ΔHCC
0.2
0.1
0.0
−0.1
−0.2

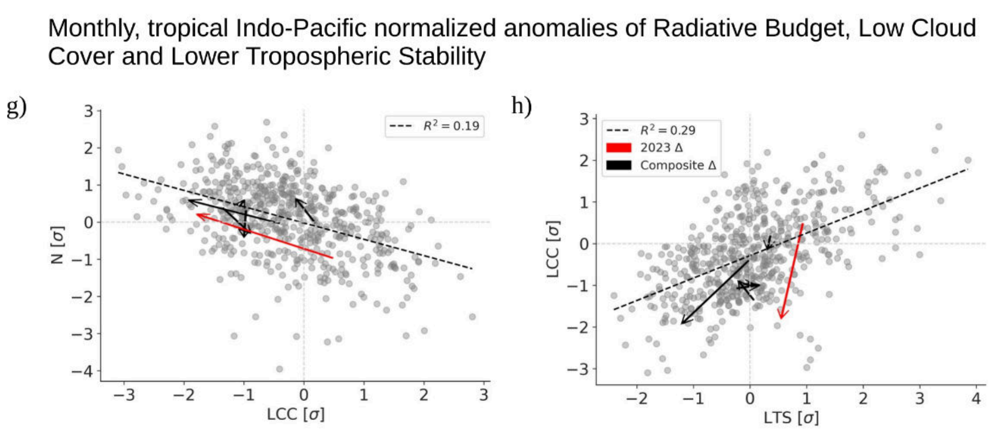

Monthly, tropical Indo-Pacific normalized anomalies of Radiative Budget, Low Cloud Cover and Lower Tropospheric Stability
g)
h)
$R^2 = 0.19$
$R^2 = 0.29$
2023 Δ
Composite Δ
N [σ]
LCC [σ]
LTS [σ]

Figure S3. Changes in cloud cover for the 2023 El Nino built-up Changes in Cloud Cover prior to ASO, between AMJJAS [0] and AMJJAS [-1] for 2023 (a, d), the composite (b, e) and the difference between the two (c, f) for the low cloud cover (LCC, a-c) and high cloud cover (HCC, d-f) . Cross shading is used in regions where 2022- 2023 is lower than all of the composite years, stippling in regions where it is higher. **g)** Monthly normalized anomalies of tropical, indo-pacific TOA radiative budget against low cloud cover along with its linear regression line (dotted) and R-squared value. Arrows indicate the change between two consecutive years: the arrow points from the AMJJAS [-1] average to the AMJJAS [0] average for all the strong El Niños (black) in the composite and 2023 (red). **h)** as in **g)** but for low cloud cover against low tropospheric stability (LTS).

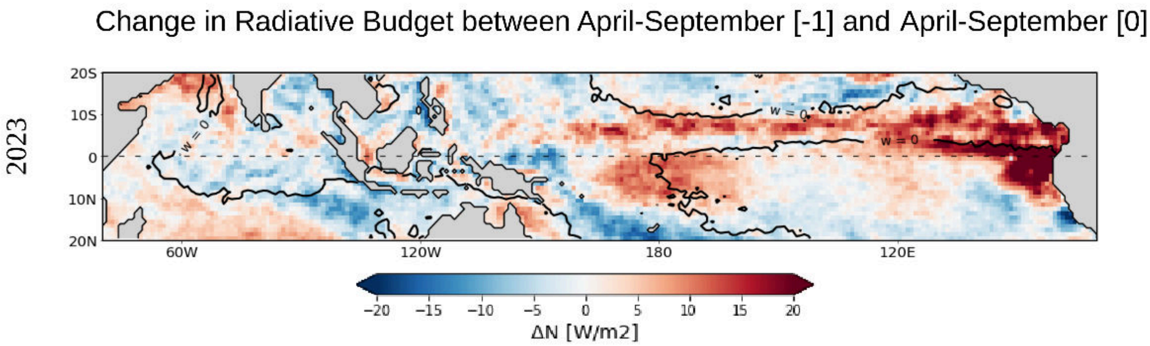


Figure S4. CERES top of atmosphere net radiation changes. As Figure 2 b) but with CERES-EBAF data.

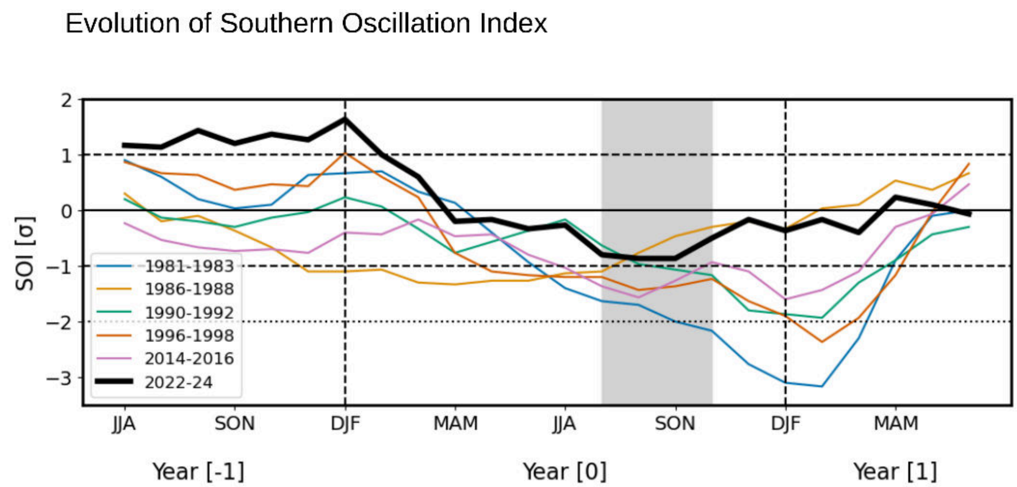


Figure S5. Evolution of the Walker Cell during an El-Nino event. ENSO cycle (from JJA Year [-1] to JJA Year [+1]) assessed from the Southern Oscillation Index (NOAA, https://psl.noaa.gov/data/timeseries/monthly/Niño34/) for the El Niño composite years (light coloured solid lines) and the 2022-24 event (thick black), The ASO season Year [0] is highlighted in grey.

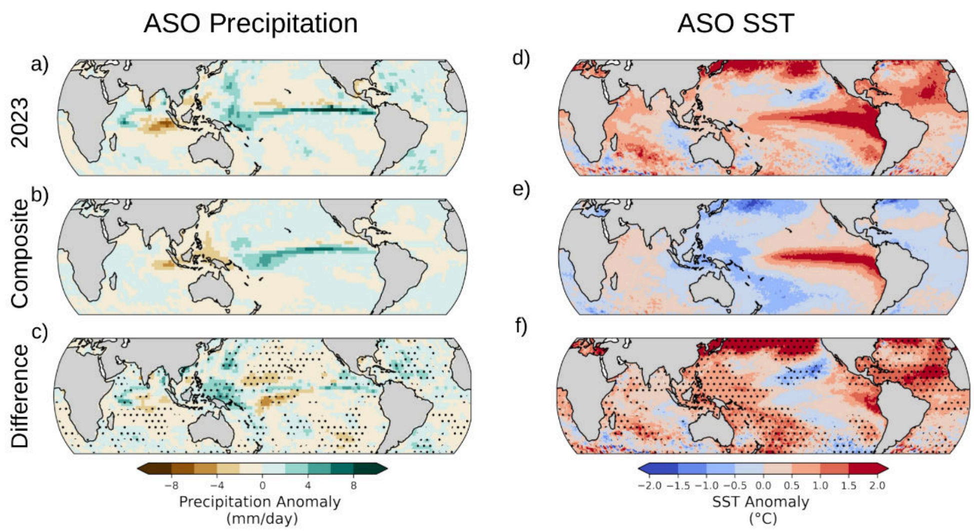


Figure S6. Specificity of the 20023 ENSO event in ASO. Precipitation (left) and SST (right) anomalies for 2023 (top row) with respect to the 1991-2020 climatology, for ENSO composite of strong El-Niño years (1987, 1991, 1982, 1997, 2009, 2015) (middle row) and the difference between the two (bottom row). Stippling indicates that the 2023 anomalies are the largest of any ENSO events used for compositing.

a) ASO θ_{500} changes between consecutive years

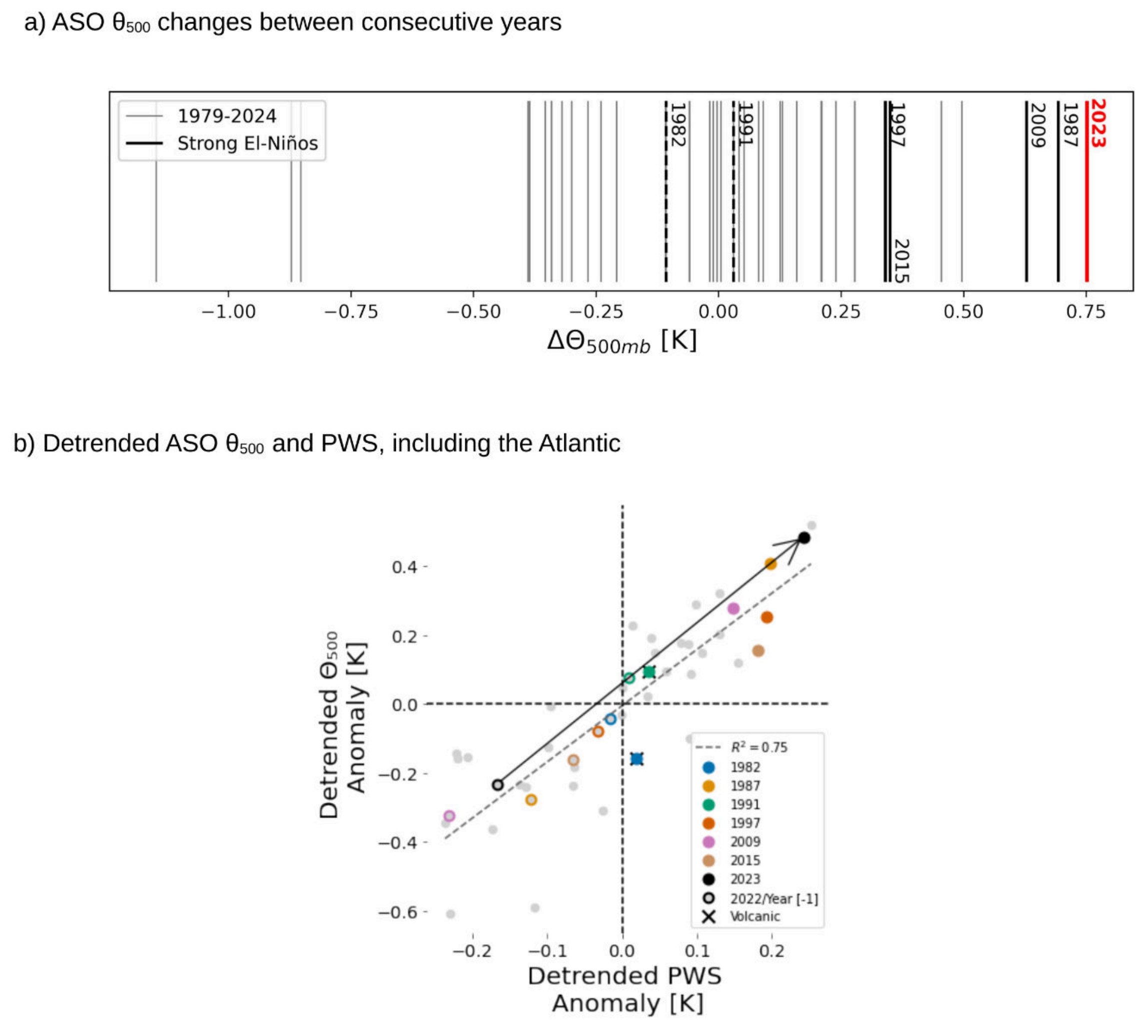


Figure S7. The record-breaking jump in tropospheric temperature and SST in deep convective regions. a) Change of tropical (S15-N25) average of ASO Θ_{500mb} between two consecutive years over 1979-2024 (grey), with strong El-Niños and 2023 highlighted in black and red, respectively. Dotted lines stand for El Niño years perturbed by strong volcanic eruptions. **b)** As Figure 3 b) including all tropical oceans for the calculation of PWS.

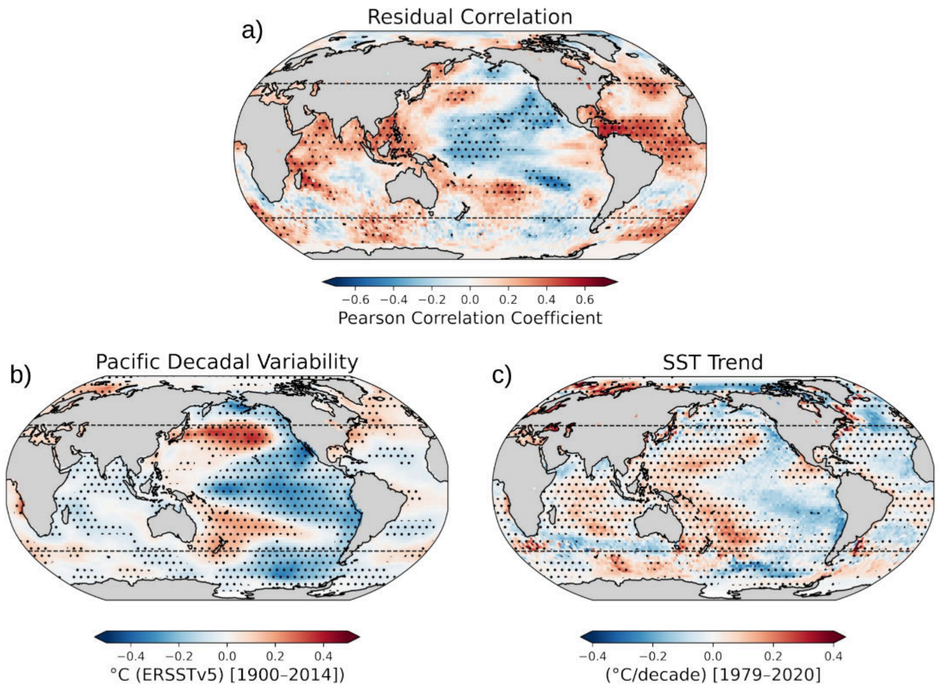


Figure S8. a) Oceanic regions of importance in the modulation of interannual tropospheric warming and the observed patterns of low-frequency SST changes. Correlation of residuals of ASO Θ_{500mb} onto SST as in Fig 4 c). **b)** Loading Pattern of Interdecadal Pacific Variability (negative phase) as defined by the IPCC AR6 (Cassou et al. 2021). **b)** ASO SST trend over the period 1979-2020. The pattern correlation coefficient is 0.42 between a) and b) and 0.17 and between a) and c). Dots indicate significance at the 10% level.