



Excessive 21st century North Pacific solar absorption attributed to poleward storm track shift, sea surface warming, and aerosol decreases

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Abstract. This study analyzes the trend in Absorbed Shortwave Radiation (ASR) in the North Pacific, where an increasing
10 ASR trend of 3.31 W/m²/dec is observed, constituting the dominant regional contributor to the global ASR increase. Multiple regression analysis shows that 1.57 W/m²/dec (47.5%) of that trend is explained by changes in cloud fraction, 1.08 W/m²/dec (32.7%) by changes in cloud optical thickness, and 0.61 W/m²/dec (18.3%) by changes in aerosol optical depth indicative of the aerosol direct effect. The pattern of cloud fraction change shows two distinct regimes: one dominated by decreases in high and middle clouds and a second dominated by decreases in low clouds. The cloud fraction contribution to
15 the ASR trend can be broken then into a 0.88 W/m²/dec contribution from high and middle cloud fraction changes and a 0.73 W/m²/dec contribution from low cloud fraction changes. Analysis incorporating cloud controlling factors shows that the high/middle cloud fraction changes are driven by atmospheric dynamics and thermodynamics, while the low cloud fraction and optical thickness changes are driven by sea surface warming and aerosol indirect effects. High/middle cloud fraction decreases correlate with a poleward shift in the N. Pacific midlatitude storm track, pointing to a potential positive cloud
20 feedback loop between Sea Surface Temperature increase and a poleward shift of the midlatitude storm track, mediated by the reduction in high/middle cloud fraction.

1 Introduction

Satellite retrievals of the Earth's energy budget components from the Clouds and the Earth's Radiant Energy System
25 (CERES) instrument over the past 25 years show a large increasing trend of the Earth's Energy Imbalance (EEI), explained primarily by an increase in the Absorbed Shortwave Radiation (ASR) of about 0.8 W/m²/decade since the beginning of the 21st century (e.g. Loeb et al. 2021, 2024). There have been several modeling and observational studies that examine a range of processes that contribute to the increasing ASR trend, with the focus placed mostly on the forcing from changes in aerosol emissions and on cloud changes either due to natural variability or due to feedbacks related to climate warming. Studies
30 investigating the contribution of decreases in aerosol emissions to the ASR trend, either through a direct decrease in aerosol



sunlight reflection or through an indirect aerosol effect on cloud cover and reflectivity, derive a range of estimates depending on the methods, models, and datasets used. Modeling studies using aerosol-only experiments to derive the radiative forcing from global aerosol emission declines, estimate aerosol contributions to the 21st century ASR trend of about 0.2 W/m²/decade, but the estimates are model-dependent and not tightly constrained (Hodnebrog et al. 2024, Raghuraman et al. 2023). The observational study by Park and Soden (2025) finds a globally negligible aerosol indirect effect trend for the same time period, due to a cancellation of positive and negative trends in the Northern and Southern hemispheres, respectively, while von Salzen et al. (2025) find that in the combined N. Atlantic and Northeast Pacific region aerosol decreases contribute 69% of a 2.8% per decade decrease in marine cloud reflectivity. Modeling and observational studies of the radiative effect of aerosol decreases caused by ship emission regulations imposed in 2020 estimate the effect to be between 0.12 - 0.2 W/m² (Gettelman et al. 2024, Yuan et al. 2024), while Hansen et al. (2025) uses modeling and observational arguments and estimates that effect to be around 0.5 W/m².

The increase in ASR is driven primarily by a decrease in the reflection of SW radiation by clouds, occurring at a rate of 0.37 to 0.45 W/m²/decade depending on the period analyzed (Loeb et al. 2024, Tselioudis et al. 2025). Loeb et al. (2024) find that in the Northern Hemisphere the increasing ASR trend is primarily driven by decreases in stratocumulus and mid-level clouds over the subtropics and decreases in low and mid-level clouds in the midlatitudes, while in the Southern Hemisphere the trend is driven by decreases in mid-level clouds. The study of Goessling et al. (2025), using CERES radiative components and cloud fraction and reanalysis cloud types, attributes the decreased planetary albedo primarily to a reduction of low cloud cover. Modeling studies using AMIP simulations (Raghuraman et al. 2021, Hodnebrog et al. 2024) suggest that the large ASR increases during the CERES period can only be explained as the additive contributions of effective radiative forcing and climate response to the warming. The recent study of Ceppi et al. (2026) finds that the low cloud radiative contribution to the 21st century ASR trend is about 0.22 W/m²/decade globally, while Zelinka et al. (2026) find this contribution to be around 0.85 W/m²/decade in the N. Pacific region.

In a recent analysis of multiple satellite datasets, Tselioudis et al. (2024) examined the zonal mean trends of cloud and radiation properties during the satellite era. They found a poleward shift of the midlatitude storm clouds, similar to that found in the earlier study of Bender et al. (2012), a poleward expansion of the subtropical low cloud fraction region, and a narrowing of the Intertropical Convergence Zone (ITCZ). In a follow up paper (Tselioudis et al. 2025), an analysis of CERES SW Cloud Radiative Effect (SWCRE) trends in the 21st century found that the poleward shift and the contraction of the Earth's storm cloud zones can explain the majority of the positive trend in solar absorption through a significant decrease in the area coverage of highly reflective storm clouds.

The studies conducted so far attempt to resolve the processes responsible for the ASR trend for the global domain, and for the most part concentrate on the effect on ASR of a single factor and process. However, to derive an understanding of the



65 global ASR trend, one must take into account the combined influences on ASR of several competing processes that apply
 contrasting effects at different regional scales and climate regimes. In the present study, we concentrate the analysis of the
 ASR trend to the N. Pacific region, which constitutes the dominant regional contributor to the global ASR increase, and we
 examine the effects on ASR of all the main cloud and aerosol related radiation controlling factors. The objective is to
 quantify the contribution of aerosol effects and cloud changes to the ASR trend in that region, and to understand the
 70 mechanisms responsible for the aerosol and cloud changes.

2 Datasets

All observational datasets are analyzed between August 2002 and December 2025. We used top of atmosphere (TOA) SW
 radiative fluxes from the NASA CERES Energy Balanced and Filled Edition 4.2 (CERES EBAF-TOA_Ed4.2) monthly
 global fluxes on a $1^\circ \times 1^\circ$ grid (Loeb et al. 2018). This product is derived from SW radiative fluxes from CERES
 75 measurements, which are adjusted within observational uncertainty to ensure consistency with in-situ estimates of the
 Earth's energy imbalance. We calculate the ASR or clear-sky ASR (ASR_{cs}) by taking the difference between incoming TOA
 SW radiation and outgoing TOA SW radiation or outgoing TOA clear-sky SW radiation, respectively.

Monthly cloud property observations were derived from the NASA Aqua Moderate-resolution Imaging Spectroradiometer
 80 (MODIS) and Suomi National Polar-Orbiting Partnership (SNPP) Visible Infrared Imaging Radiometer Suite (VIIRS)
 climate data record continuity cloud properties products (CLDPROP), which is averaged on a $1^\circ \times 1^\circ$ grid at monthly
 resolution (Platnick et al., 2020). This product provides monthly cloud observations from MODIS Aqua and VIIRS SNPP
 using only channels shared between the two instruments. As the two satellites share the same equator-crossing time, these
 products allow continuity to across their respective datasets. The MODIS Aqua data products extend from August 2002 to
 85 the present, but in early 2021, Aqua performed its last orbital correction and entered a free drift mode, where it has been
 drifting towards earlier equator crossing times and lower altitudes (Parkinson, 2022). By affecting solar zenith angles,
 viewing geometries, and spatial resolution, this drift impacts the retrieval algorithms and has been found to introduce
 systemic biases into MODIS products in recent years (e.g. Liu et al., 2026). The VIIRS SNPP product extends from March
 2012 to present. To combine the two datasets, for each cloud property we use, we first calculate mean monthly deviations in
 90 the region being analyzed. A linear regression is calculated between the MODIS- and VIIRS-derived time series in the
 overlapping pre-MODIS drift time period (March 2012 to February 2021), and the VIIRS-derived product is “corrected” to
 match the MODIS-derived product. Then, the MODIS values are used from 08/2002 to 02/2012, a mean of the MODIS and
 corrected VIIRS values are used between 03/2012 and 02/2021, and the corrected VIIRS values are used from 03/2021 to
 12/2025. We use this method to calculate monthly deviations for the following cloud properties: total cloud fraction (TCF),
 95 low cloud fraction (LCF), high + middle cloud fraction (HMCF), total cloud optical thickness (COT), liquid cloud optical
 thickness (COT_{liq}), and ice cloud optical thickness (COT_{ice}). We also use liquid cloud effective radius (r_e) to derive liquid
 water path (LWP) and liquid cloud droplet number concentration (N_d) using equation 11 in Grosvenor et al. (2018). Running

means of the monthly deviations for these cloud variables, the corrected VIIRS values, and the combined values are shown in Fig. S1 (a-l, q-t) for the analysis region. For these variables, agreement in the overlapping pre-orbital drift is found to be high, with r^2 values between 0.85 and 0.95. For maps of trends in monthly deviations, the correction is applied for each pixel to account for the bias between MODIS and VIIRS retrievals changing with latitude.

For aerosol properties used in this study, we apply the same method to combine retrievals from MODIS Aqua and VIIRS SNPP. We use monthly aerosol optical depth (AOD) retrievals at 550 nm over ocean from MODIS Level 3 monthly mean $1^\circ \times 1^\circ$ gridded product from the Aqua satellite (MYD08_M3, Collection 6.1) using the Dark Target retrieval algorithm (Levy et al., 2013) and the VIIRS Deep Blue Level 3 AOD product at 550 nm (AERDB_M3_VIIRS_SNPP) (VIIRS Atmosphere Science Team, 2023). As a proxy for cloud condensation nuclei, we use the fine-mode AOD at 550 nm from both of these products. These aerosol products are only derived over what MODIS and VIIRS determine as clear sky scenes, and their combination is shown in Fig S1 (m-p). Fine-mode AOD is derived by partitioning total AOD into the fine mode fraction, which is estimated over ocean by fitting the spectral AOD into a combination of fine- and coarse-mode models. Fine-mode AOD has been found to better approximate cloud-condensation nuclei than AOD (Jia et al., 2021). Cross contamination of AOD retrievals by cloud fraction has been found not to be a dominant problem for Level 3 MODIS ocean products, as aggressive cloud masking removes most cloudy pixels and the residual cirrus cloud bias (which constitutes the main contamination source) is only 0.015 ± 0.003 at 550 nm. While AOD retrievals are systematically higher in situations with very high cloud fraction, much of this is driven by aerosol humidification rather than algorithm bias (Kaufman et al. 2005). Moreover, these high cloud fraction retrievals constitute only 2% of scenes over ocean and therefore have a small effect on large-scale aerosol analyses (Remer et al. 2008).

For atmospheric dynamics and thermodynamics parameters we use monthly wind, sea surface temperature, relative humidity, atmospheric temperature, and geopotential height data from ERA5 reanalysis (Hersbach et al. 2020). ERA5 is an hourly global atmospheric reanalysis dataset from the European Centre for Medium-Range Weather Forecasts (ECMWF). The data is provided on a 30 km grid with 137 vertical levels. We also use data from the Centre for Earth Observation Science (CEOS)/National Snow and Ice Data Center (NSIDC) Extratropical Cyclone Tracking (CNECT) project (Crawford et al., 2021). This project inputs sea level pressure data at 3-hourly, 25-km resolution from ERA5 into a Lagrangian cyclone detection and tracking algorithm and reports individual extratropical cyclone tracks, sizes, and strengths in the Northern Hemisphere. We compiled the storm center of those individual tracks into a $1^\circ \times 1^\circ$ monthly gridded dataset to create an extratropical cyclone (ETC) density variable.

3 Methods

To attribute the observed trend in ASR to physical drivers, we employed a multiple regression-based trend decomposition method. After computing the domain-average time series for all variables, we first subtract ASR_{cs} from ASR to calculate the



shortwave cloud radiative effect (SWCRE), which separates processes affecting ASR through cloud property changes from the direct aerosol effect. Using annual means for each variable in each region of interest, we fit the following ordinary least squares regression models:

$$ASR_{CS}(t) = \beta_0 + \beta_{AOD}AOD(t) + \varepsilon_1(t), \quad (1)$$

$$SWCRE(t) = \beta_1 + \beta_{TCF}TCF(t) + \beta_{COT_{liq}}COT(t) + \varepsilon_2(t), \quad (2)$$

where β_i is the estimated regression coefficient and ε is the model residual. In decompositions in which total cloud fraction changes are separated into high/middle and low cloud fraction changes and cloud optical thickness changes are separated into ice and liquid optical thickness, in Eq. 2, TCF is replaced by HMCF and LCF and COT is replaced by COT_{ice} and COT_{liq} as separate predictors with separate regression coefficients.

The trend in ASR, ΔASR , and each predictor, ΔX_i , is calculated via a linear regression of monthly deviations against time. The contribution of each predictor to the trend in ASR is then

$$\Delta ASR_{X_i} = \beta_i \Delta X_i, \quad (3)$$

so that $\Delta ASR_{AOD} = \beta_{AOD} \Delta AOD$, $\Delta ASR_{TCF} = \beta_{TCF} \Delta TCF$, and so on. The fractional contribution of each predictor to the trend in ASR is $\Delta ASR_{X_i} / \Delta ASR$. Uncertainties in each contribution or set of contributions are estimated as $\sqrt{\Delta X^T \mathbf{C} \Delta X}$, where $\mathbf{C}$ is the covariance matrix. Thus, due to multicollinearities between predictors, the uncertainty of some summed contributions is less than individual contributions.

The same decomposition method is applied to LCF, HMCF, and COT_{liq} , attributing their trends into changes in aerosol and meteorological cloud controlling factors (CCF), taken as proxies for the processes determining cloud cover and cloud radiative properties:

$$C(t) = \beta_0 + \sum_i \beta_i CCF_i(t) + \varepsilon(t), \quad (4)$$

where C is the cloud property of interest (LCF, HMCF, or COT_{liq}). The contribution of each cloud controlling factor to the cloud property trend is computed as $\beta_i \Delta CCF_i$.

Prior studies have used multiple regression to estimate sensitivities (β) of properties like SW radiation, cloud radiative effect, and cloud fraction to aerosol and/or meteorological variables (e.g. Myers et al. 2021, Andersen et al. 2023, Grise & Tselioudis 2024, Ceppi et al. 2026, Zelinka et al. 2026). The recent studies of Zelinka et al. 2026, and Ceppi et al. 2026 focus on low cloud radiative effects on ASR trends and detrend the predictors and predictand to evaluate whether interannual



sensitivities generalize out-of-sample to long-term trends. Our analysis is a detection and attribution study, seeking to attribute the observed long-term trends in ASR and cloud properties to the changes in their physical drivers at all time scales. Therefore, removing the long-term trends prior to regression would eliminate the primary signal we are trying to explain. To test the validity of regressing on non-detrended trend-stationary series we performed several diagnostics. The autocorrelation functions of our regression residuals fall within the 95% confidence interval at all lags, consistent with white noise. Moreover, for all but one regression, the residuals are unit-root stationary ($p < 0.05$). These diagnostics indicate that spurious regression and systematic omitted structure are unlikely. Finally, the predictors used here are well established as the primary physical mechanisms controlling the predictand, making the omission of a significant unaccounted driver unlikely.

4 Results

4.1 Trend attribution analysis

The map of the 21st century monthly-deviation trend in CERES ASR is shown in Figure 1a, where the black contour represents the 1.75 W/m²/decade isoline and captures the entirety of the areas with statistically significant, positive ASR trends. The figure indicates that a dominant signal of the 21st century global ASR increasing trend comes from the North Pacific region, where an extensive, statistically significant area of increasing ASR is observed. Other large areas of statistically significant increasing ASR trends include the subtropical northeast Pacific and the Pacific ITCZ regions, the N. Atlantic, the tropical Indian Ocean, the Namibia stratocumulus region, the South Atlantic, and sections of the two polar oceans. The mechanisms involved in creating the regions of positive ASR trends in those widely different climate regimes in all probability involve different atmospheric properties and processes in each regime. The signal contributed by the N. Pacific region to the global, positive ASR trend is 3.31 W/m²/dec and accounts for 40.3% of that trend, making it by far the greatest single contributor, so it is crucial to investigate and understand the factors that are responsible for the N. Pacific increasing ASR pattern. A detailed depiction of the N. Pacific ASR increasing trend region (Fig. 1b) shows that it extends throughout the Pacific basin covering the area between 25°N and 55°N, and includes two centers of intense ASR increases (defined by the 3.7 W/m²/dec isoline): a small center located in the Sea of Japan at the western edge of the basin, and a second extensive center that covers most of the central part and western parts of the N. Pacific basin. The region of strong and statistically significant N. Pacific ASR increase bounded by the 1.75 W/m²/decade isoline is the region that will be the focus of the analysis performed in this study.

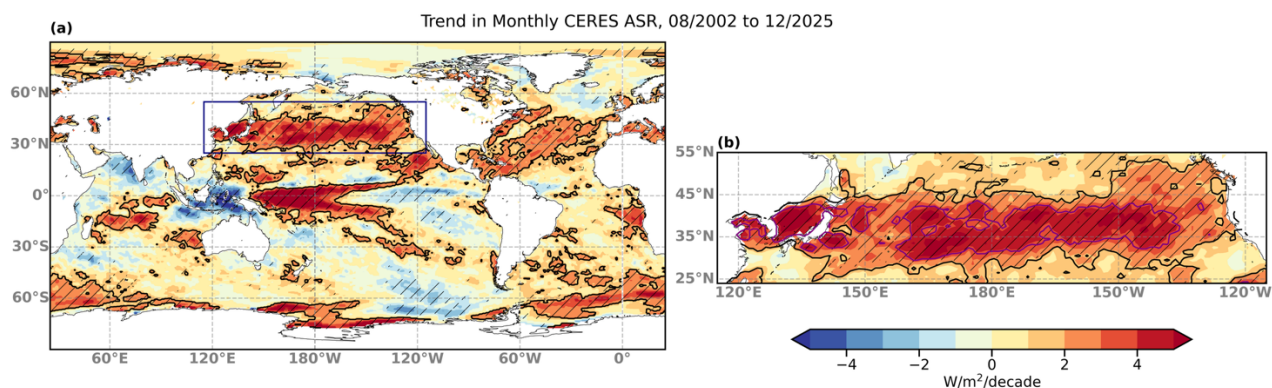
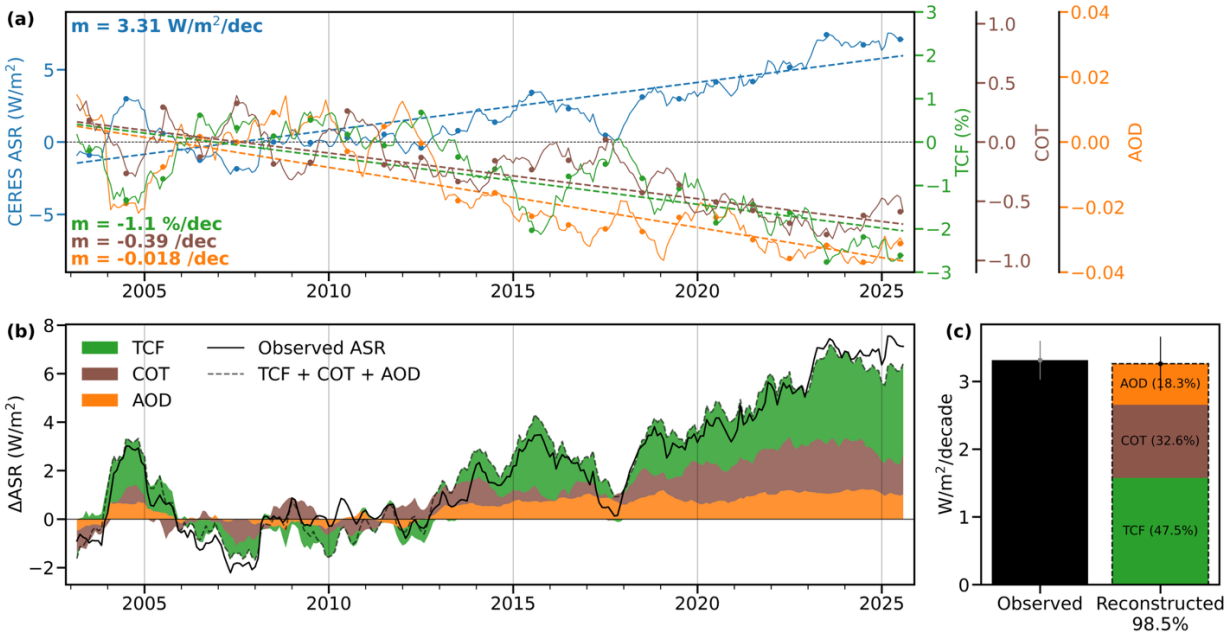


Figure 1: a) Trend in monthly anomaly values of CERES ASR for the 8/2002 – 12/2025 period. Black contour delineates the 1.75 W/m²/decade isoline, purple contour delineates the 3.7 W/m²/decade isoline. Hatching indicates statistically significant trends ($p < .05$). b) Detail of Fig.1a for the N. Pacific Ocean region.

The primary processes controlling the ASR trend, namely changes in cloud fraction and reflectivity and changes in the direct aerosol effect, are examined in this study through analysis of the Total Cloud Fraction (TCF), Cloud Optical Thickness (COT), and Aerosol Optical Depth (AOD). The regional mean ASR time series for the region bounded by the 1.75 W/m²/dec isoline is shown in Figure 2a, along with the time series of TCF, COT and AOD from MODIS/VIIRS, and the values of the linear trend slopes of the time series are noted on the plot. The figure shows that while ASR is increasing by 3.31 W/m² per decade in the past 25 years, TCF is decreasing by 1.1% per decade, COT is decreasing by 0.39 per decade, and AOD is decreasing by 0.018 per decade. The negative trends in TCF, COT, and AOD all contribute to the increasing trend in ASR through decreases in cloud area coverage and cloud reflectivity and decreases in clear-sky aerosol scattering that is indicative of the aerosol direct effect. To quantify these contributions, a multiple regression analysis is performed (Eqs. 1 and 2) and the parts of the ASR trend attributed to each parameter are calculated (Eq. 3). Figure 2b illustrates the relative contributions to the ASR trend by the three radiation-controlling components, and the multiple regression results of the three contributions along with the associated uncertainty ranges are presented in Table 1. The analysis shows that of the 3.31 W/m²/dec ASR trend, 1.57 W/m²/dec (or 47.5%) is explained by TCF, 1.08 W/m²/dec (32.7%) is explained by COT, and 0.61 W/m²/dec (18.3%) is explained by AOD, for a total reconstructed trend of 3.26 W/m²/dec and a residual of 0.05 W/m²/dec (1.5%). Note that throughout the time period, the additive contribution of those three parameters explains nearly the full magnitude of the ASR trend. Note also that the uncertainty ranges for the three ASR contributions are relatively small and the value differences large enough that those contributions are for the most part separated beyond analysis uncertainty. Finally, the seasonal variability of the attribution results was examined and showed that the cloud contributions are dominant in all seasons but strongest in the summer and fall, even when adjusting for the difference in solar insolation, while the aerosol contribution is strongest in the winter and spring months.



215 **Figure 2:** a) 12-month running mean time series relative to the 2002-2012 mean for the N. Pacific region bounded by the 1.75 $\text{W/m}^2/\text{dec}$ isoline for CERES ASR (blue line), MODIS/VIIRS TCF (green line), MODIS/VIIRS COT (brown line), and MODIS/VIIRS AOD (orange line). b) Contribution to the N. Pacific ASR trend from AOD (orange), COT (brown) and TCF (green). The black line shows the ASR trend and the dotted line the sum of the contribution of the three factors.

	Trend (W/m^2)	Contribution(%)
Total ASR	3.31 ± 0.29	
TCF	1.57 ± 0.19	47.5 ± 7.0
COT	1.08 ± 0.22	32.7 ± 7.1
AOD	0.61 ± 0.07	18.3 ± 2.6
TCF+COT+AOD	3.26 ± 0.17	98.5 ± 9.9

220 **Table 1.** Trends in ASR broken into cloud parameter (TCF, COT) and aerosol parameter (AOD) contributions for the N. Pacific region bounded by the 1.75 $\text{W/m}^2/\text{dec}$ isoline.

In order to examine the spatial distribution of the N. Pacific cloud and aerosol property changes, Figure 3 shows the trend maps of TCF, COT, and AOD, superimposed on the 1.75 and 3.7 $\text{W/m}^2/\text{dec}$ isolines. Cloud fraction decreases throughout the region of ASR increase, with a spatial structure that shows strong TCF decreases collocated with the two centers of intense ASR increase, emphasizing the strong interdependence between ASR and TCF trends. Cloud optical depth also decreases significantly throughout the region of ASR increase, with stronger signals in the eastern and western ends of the basin. Aerosol optical depth shows an overall decreasing signal but with a strong longitudinal gradient and the strongest significant decreases concentrated in the western part of the basin, particularly over the Sea of Japan and the Yellow Sea.

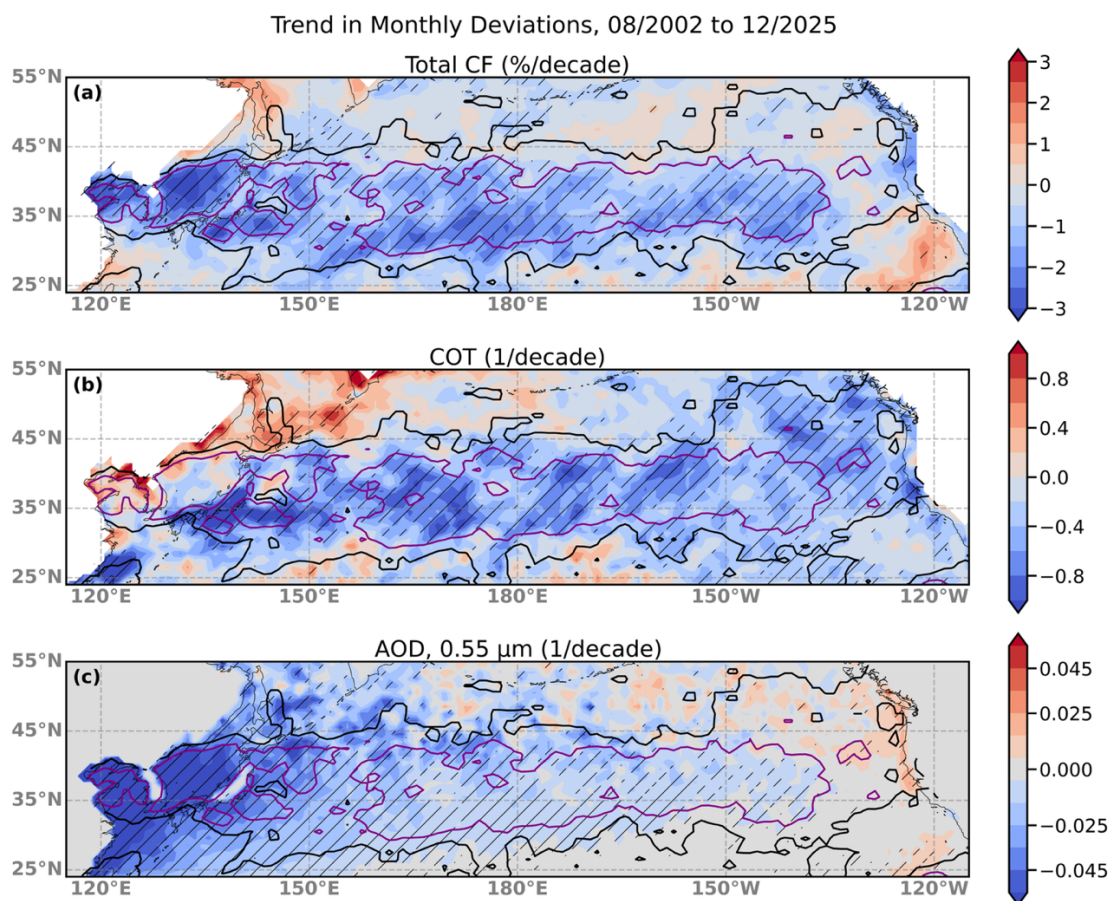
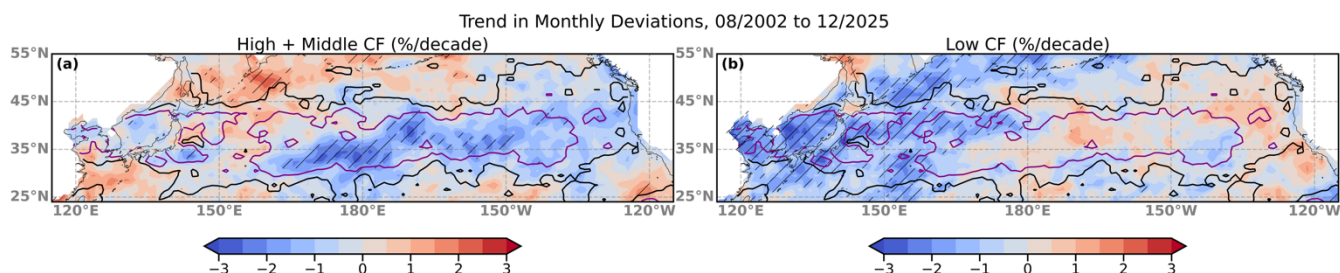


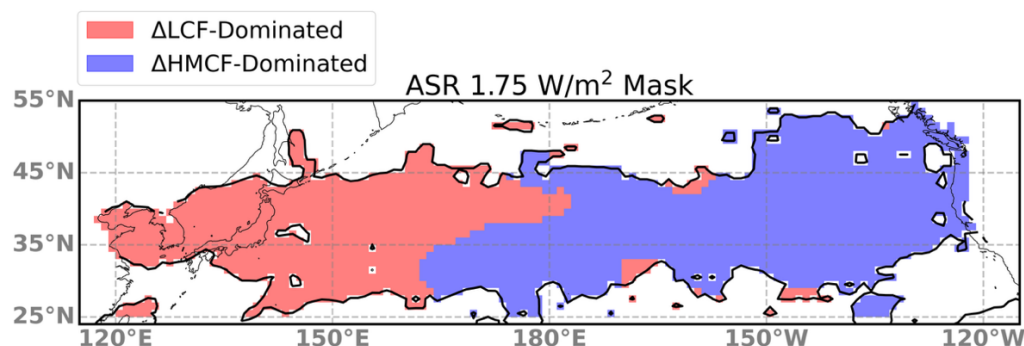
Figure 3. Maps of trends in monthly anomalies of a) TCF, b) COT, and c) AOD, for the N. Pacific region, superimposed on the 1.75 and 3.7 $\text{W}/\text{m}^2/\text{dec}$ ASR trend isolines. Hatching indicates statistically significant trends ($p < .05$).

Previous work has shown the important effects of low-top cloud changes in the 21st century ASR trends (Loeb et al. 2024, Goessling et al. 2024, Zelinka et al. 2026), while the work of Tselioudis et al. (2025) found that in the midlatitude regions the contraction of highly reflective storm clouds, which have mostly middle- and high-tops, can produce large increases in absorbed sunlight. To examine the cloud-type structure of the TCF trend we plot separately the cloud fraction trends of high-plus-middle-top clouds (Fig. 4a) and low-top clouds (Fig. 4b) from the MODIS/VIIRS dataset. The high-plus-middle cloud field, associated in those latitudes with extratropical storms (e.g. Tselioudis et al 2021), shows significant decreases in the middle and eastern parts of the basin and increases in the western part, forming a difference pattern that is reminiscent of a poleward shift of the midlatitude jet (Bender et al. 2012, Tselioudis et al. 2016). The low cloud field shows strong and significant decreases in the western part of the region, including the Sea of Japan and Yellow Sea basins, and smaller decreases in the southern and eastern parts of the basin.



245 **Figure 4. As in Fig.3 for a) High plus Middle CF, and b) Low CF.**

The patterns in Figure 4 indicate the presence of two regimes in the region of increasing ASR: one regime dominated by decreases in high and middle clouds potentially related to shifts in atmospheric dynamics, and one regime dominated by decreases in low clouds potentially related to changes in cloud controlling factors including atmospheric aerosol concentrations. To distinguish and quantify the effects of atmospheric dynamics and cloud controlling factors on the cloud and radiation fields, we apply a masking process in the region bounded by the $1.75 \text{ W/m}^2/\text{dec}$ isoline. After applying 2° Gaussian smoothing to the trend maps of HMCF and LMCF, we define one region where high and middle cloud decreases dominate the TCF trend (ΔHMCF -dominated) and one region where low cloud decreases dominate the TCF trend (ΔLCF -dominated, Fig. 5), and perform analysis separately for the two regions representing the two cloud change regimes. The two regimes have comparable area coverage of the $1.75 \text{ W/m}^2/\text{dec}$ bounded region (58.9% for the ΔHMCF -dominated vs 41.1% for the ΔLCF -dominated) and similar ASR trends (3.35 vs $3.27 \text{ W/m}^2/\text{dec}$), thus implying that the ΔHMCF regime contributes $1.91 \text{ W/m}^2/\text{dec}$ (or 58%) and the ΔLCF regime contributes $1.41 \text{ W/m}^2/\text{dec}$ (or 42%) to the regional mean ASR trend of $3.31 \text{ W/m}^2/\text{decade}$.



260 **Figure 5. Mask showing the $1.75 \text{ W/m}^2/\text{dec}$ ASR isoline regions dominated by Low CF changes (red region) and High plus Middle CF changes (blue region).**

Multiple regression analysis is used next to quantify the contribution to the ASR trend of the radiation controlling parameters separately in the two regimes. Figure 6 shows the time series of ASR and the contributions of HMCF, LCF, COT_{ice} , COT_{liq} ,



and AOD for the regime dominated by high and middle cloud fraction changes (Δ HMCF Regime – Fig. 6a) and the regime dominated by low cloud fraction changes (Δ LCF Regime – Fig. 6b). The values for the trend contributions of each parameter along with the associated uncertainty ranges are listed in Table 2. In the Δ HMCF-dominated regime, the change in middle and high cloud fraction is, as expected, the dominant contributor to the ASR increasing trend, accounting for 1.63 W/m²/dec (48.9%), while COT_{liq} contributes another 1.33 W/m²/dec (39.8%). AOD has a small contribution of 0.25 W/m²/dec (7.4%) while COT_{ice} and LCF have very small contributions of 0.08 and -0.02 W/m²/dec respectively. Thus, the reconstructed trend matches the observed trend at 3.28 W/m²/dec. In contrast, in the Δ LCF-dominated regime, LCF is the dominant factor, contributing 1.53 W/m²/dec (46.9%) of the ASR increasing trend. In the same region, AOD shows a significant contribution of 1.02 W/m²/dec (31.2%) and COT_{liq} has a noticeable contribution of 0.58 W/m²/dec (17.9%), while HMCF and COT_{ice} have small contributions of 0.13 and 0.15 W/m²/dec respectively. The reconstructed trend is 3.41 W/m²/dec, with a residual of 0.14 W/m²/dec. This trend attribution analysis shows that in the Δ HMCF-dominated regime, the increase in ASR primarily happens due to the decrease in middle and high clouds and despite the slight increase in low clouds, while in the Δ LCF-dominated regime, the ASR increase happens primarily because of a decrease in low cloud amounts. In both regimes, the increase in COT_{liq} contributes significantly to the increase in ASR while COT_{ice} has very small contributions. It is noticeable that the COT_{liq} contribution is greater in the Δ HMCF-dominated than in the Δ LCF-dominated regime. This may be happening for two reasons. First, regimes are defined based on cloud fraction *changes* rather than cloud amounts and mean low cloud fraction is greater in the Δ HMCF-dominated (44.4%) than in the Δ LCF-dominated (39.5%) regime, implying more available warm clouds to turn ‘darker’ in that region. Second, in the eastern Pacific location of the Δ HMCF-dominated regime, mean COT_{liq} values are overall climatologically lower than in the western Pacific, which implies that they produce larger radiative effects for similar changes in cloud optical thickness. On the other hand, AOD decreases contribute significantly mainly in the Δ LCF regime, which is consistent with the fact that AOD decreases are primarily happening in the western part of the Pacific basin (Fig. 3b), indicating an aerosol direct effect potentially related to decreases in aerosol emissions from China and neighboring countries in East Asia.

The results of our trend decomposition analysis can be compared with those of Zelinka et al. (2026), who examined the low-cloud SW radiative effect in a region over the N. Pacific Ocean using boundaries that are shifted southward by 5 degrees compared to the ones in the present study. In their region, which has an ASR trend of 1.94 W/m²/dec, the low-cloud SW radiative effect contribution, which includes cloud fraction and optical thickness changes, is around 0.95 W/m²/dec or 49% of the total. In our region, with an ASR trend of 3.31 W/m²/dec within the 1.75 W/m²/dec isoline, the cumulative low-cloud fraction and optical thickness contribution is 1.65 W/m²/dec or 50% of the total, a remarkable similarity given the different analysis domains in the two studies.

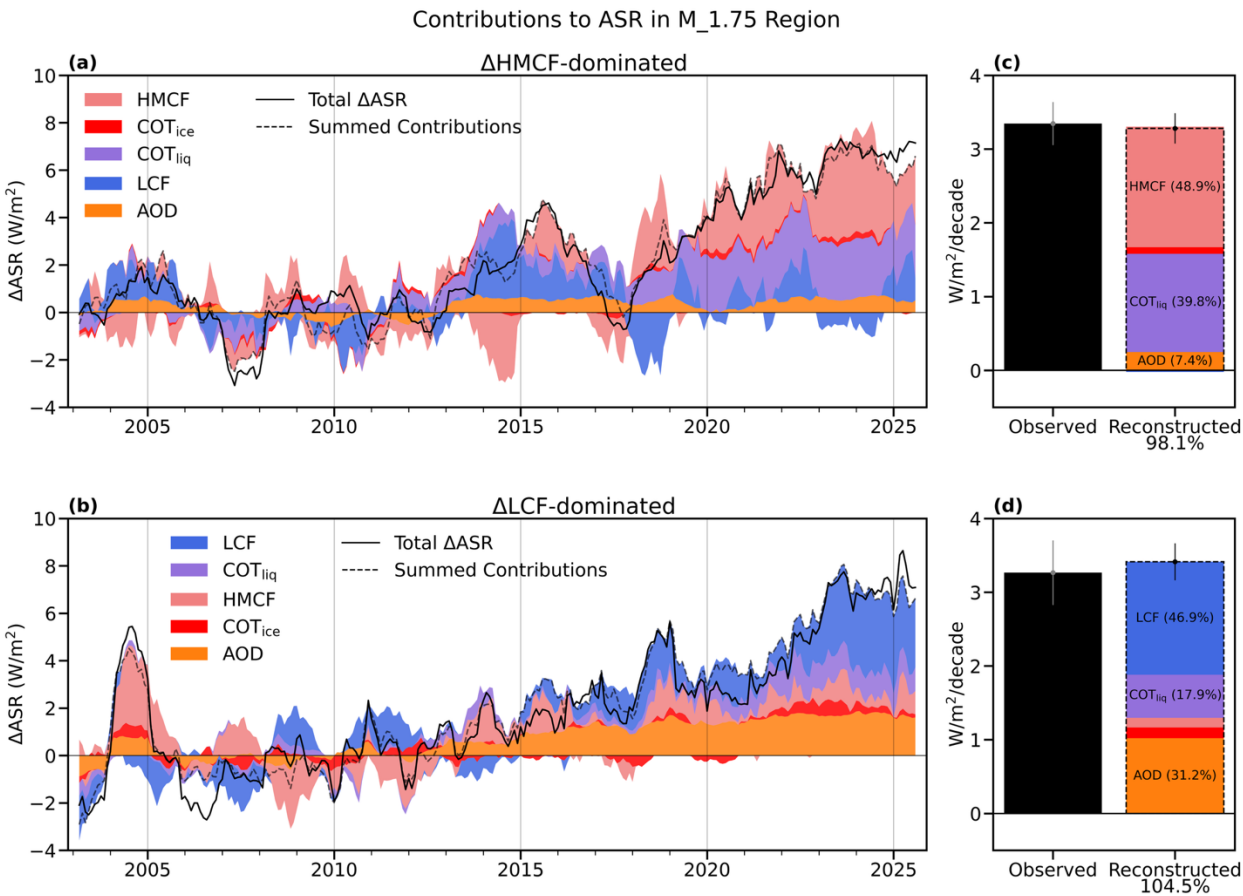


Figure 6. Contribution to the ASR trend from AOD (orange), COT_{liq} (purple), LCF (blue), COT_{ice} (red) and HMCf (salmon), for a) the $\Delta HMCf$ -dominated regime, and b) the ΔLCF -dominated regime. The black line shows the ASR trend and the dotted line the sum of the contribution of the three factors.

	Total Region	$\Delta HMCf$ -Dom	ΔLCF -Dom
Total ASR	3.31 ± 0.29	3.35 ± 0.29	3.27 ± 0.44
TCF	1.57 ± 0.19	—	—
HMCf	0.88 ± 0.12	1.63 ± 0.21	0.13 ± 0.02
LCF	0.73 ± 0.12	-0.02 ± 0.004	1.53 ± 0.29
COT	1.08 ± 0.22	—	—
COT _{ice}	0.15 ± 0.10	0.08 ± 0.13	0.15 ± 0.09
COT _{liq}	0.92 ± 0.32	1.33 ± 0.33	0.58 ± 0.35
AOD	0.25 ± 0.06	0.25 ± 0.06	1.02 ± 0.10
Sum	3.26 ± 0.17	3.28 ± 0.21	3.41 ± 0.25

Table 2. Trends in ASR broken into cloud parameter (TCF, HMCf, LCF, COT, COT_{ice}, COT_{liq}) and aerosol parameter (AOD) contributions for the whole N. Pacific region (first column) and the $\Delta HMCf$ -dominated (second column) and ΔLCF -dominated (third column) regions.



4.2 Cloud controlling factor analysis

The results in Table 2 quantify the contributions of low-cloud and high/middle-cloud fraction changes, low-cloud optical thickness, and aerosol optical depth to the N. Pacific ASR trend in the two cloud-defined regimes. The table shows that the main contributions to the ASR trend come from the high/middle cloud fraction changes in the ΔHMCF -dominated regime, the low cloud fraction changes in the ΔLCF -dominated regime, and the low cloud optical thickness changes in both regimes. Changes in clear-sky aerosol optical depth also contribute to the ASR trend, particularly in the ΔLCF -dominated regime, and can be considered as the aerosol direct effect resulting from aerosol emission decreases. To explore the mechanisms responsible for the cloud fraction and optical thickness trends, a Cloud Controlling Factor (CCF) analysis is performed that can disentangle the contributions of different processes to the cloud property trends (e.g. Klein et al. 2017, Grise and Tselioudis 2024, Zelinka et al. 2026). Using the same set of CCFs as Zelinka et al. (2026), we use multiple regression analysis to quantify the contributions of seven CCF fields to the changes in low and high/middle cloud fraction and liquid-cloud optical thickness for the two cloud-defined regimes (Eq. 4). Those CCF fields are Sea Surface Temperature (SST), Estimated Inversion Strength (EIS), temperature advection (T_{adv}), 700mb relative humidity (RH_{700}), 500mb vertical velocity (ω_{500}), near-surface wind speed (WS), and the natural logarithm of fine-mode AOD at 550 nm (AOD_{fine}). The first six CCFs represent meteorological contributions to the cloud fraction and optical thickness changes while the seventh one represents the availability of cloud condensation nuclei in the atmosphere and can be considered the aerosol contribution to the cloud property changes.

Figure 7, with a format adopted from Zelinka et al. (2026) to facilitate comparisons, shows the observed cloud property changes (black bars), the cumulative contributions of the meteorological and aerosol changes (light and dark grey bars), and the individual contributions of all CCF changes (colored bars) for the two regimes. A first observation is that the reconstructed contribution of the selected CCF changes explains almost the totality of the cloud property changes in both regimes. In the ΔHMCF -dominated regime the meteorological CCFs explain almost the total variance of the cloud property changes with minimal aerosol contribution, with SST and vertical velocity determining to a large extent the high/middle cloud fraction change (Fig. 7a) and SST determining the low cloud optical thickness change (Fig. 7b). Closer analysis (Fig. S2) shows that ω_{500} covaries with the high frequency variability of the HMCF field while SST introduces a longer-term decreasing trend. In the ΔLCF -dominated regime, the decrease in fine mode AOD is the dominant contributor to the low-cloud optical thickness decrease (Fig. 7d), pointing to a mechanism of reductions in cloud reflectivity caused by decreases in cloud condensation nuclei and thus increases in cloud particle size as explained by the Twomey effect (Twomey 1977). In that same regime, the low-cloud fraction changes (Fig. 7c) are affected primarily by increases in SST pointing to the action of atmospheric thermodynamical processes, but also by decreases in fine-mode AOD pointing to a mechanism of reductions

in cloud cover caused by increases in cloud particle size and thus increases in precipitation rate as explained by the Albrecht effect (Albrecht 1989).

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The results of our CCF analysis are in qualitative agreement with those of Zelinka et al. (2026), who show (their Fig.3b) that in their N. Pacific domain, meteorological factors explain about 62% of the low-cloud radiative effect and aerosol changes explain the rest. In our analysis, a weighted average of the low cloud fraction and optical depth contributions in Fig.7 show that, for our domain, the effects of the meteorological factors constitute about 65% of the combined low cloud fraction and

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low cloud optical depth changes.

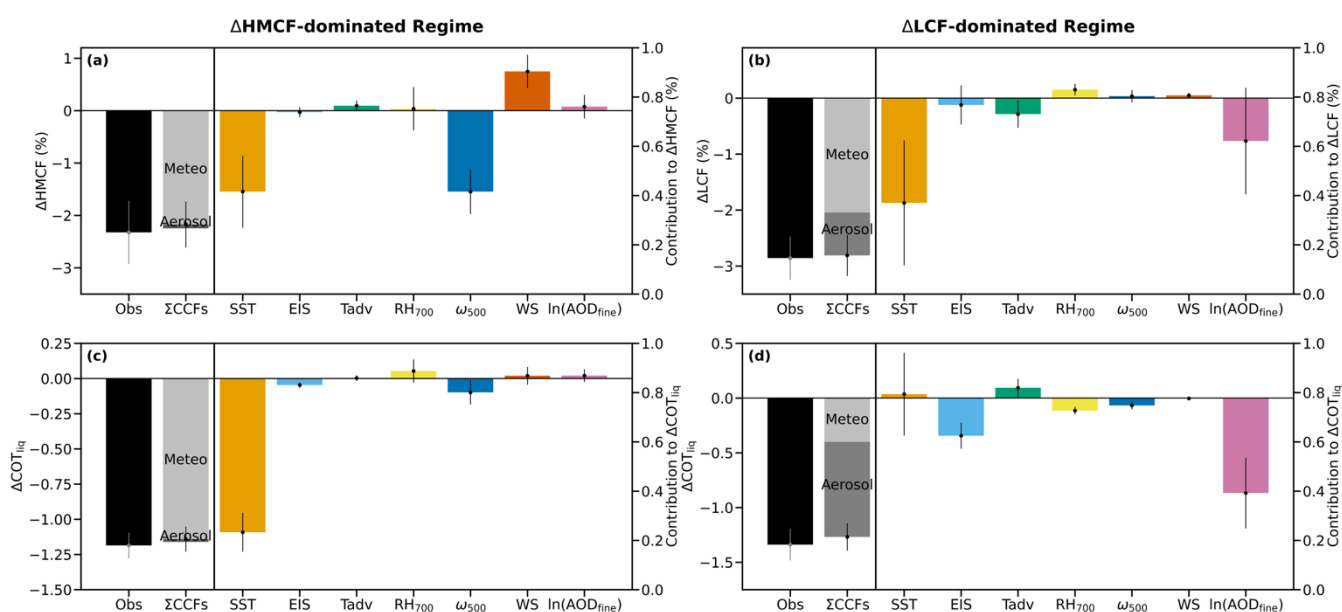


Figure 7. Contribution of CCFs to the a) HLCF trend in the ΔHLCF -dominated regime, b) LCF trend in the ΔLCF -dominated regime, c) COT_{liq} trend in the ΔHLCF -dominated regime, and d) COT_{liq} trend in the ΔLCF -dominated regime. The observed (“Obs”) and reconstructed (“ΣCCFs”) trends are on the left of each panel, and the individual contributions are on the right of each panel in different colors.

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Summary and discussion

The N. Pacific basin shows an ASR increasing trend of $3.31 \text{ W/m}^2/\text{dec}$, which is globally the most pronounced regional trend and accounts for 40.3% of the positive global ASR trend. The analysis presented in this work aims to quantify and understand the role of cloud fraction and optical thickness changes and aerosol effects in determining this increasing ASR trend. A multiple regression analysis shows that $1.57 \text{ W/m}^2/\text{dec}$ (or 47.5%) of that trend is explained by decreases in cloud fraction, $1.08 \text{ W/m}^2/\text{dec}$ (32.7%) is explained by decreases in low-cloud optical depth, and $0.61 \text{ W/m}^2/\text{dec}$ (18.3%) is

355



explained by changes in aerosol optical depth. An analysis of the pattern of cloud fraction change shows two distinct regimes: one regime dominated by decreases in high and middle clouds and contributing $1.97 \text{ W/m}^2/\text{dec}$ to the overall regional trend, and one regime dominated by decreases in low clouds and contributing $1.34 \text{ W/m}^2/\text{dec}$ to that trend. Taking into account the relative coverage and trend strength of the two regimes, the cloud fraction contribution to the overall ASR trend can be broken into a $0.88 \text{ W/m}^2/\text{dec}$ contribution from high and middle cloud fraction changes and a $0.73 \text{ W/m}^2/\text{dec}$ contribution from low cloud fraction changes. Further multiple regression analysis incorporating cloud controlling factors indicates that the high and middle cloud fraction decreases are driven mostly by changes in atmospheric dynamics and thermodynamics, as expressed by increases in SST and in mid-tropospheric subsidence, low-cloud fraction decreases are driven by combined increases in SST and decreases in cloud condensation nuclei, while low-cloud optical thickness decreases are driven in the western part of the N. Pacific basin by decreases in condensation nuclei and in the eastern part by increases in SST.

The aerosol effects on the N. Pacific ASR trend, both in the direct and the indirect forms, are the result of aerosol forcing that could be attributed to decreases in aerosol emissions, both through pollution regulations in East Asia countries and through emission regulations in shipping that originally took effect in 2015 and in a stricter form in 2020 (e.g. Hansen et al. 2023, 2025). The analysis of MODIS/VIIRS aerosol retrievals presented in this study shows that the decreases in aerosol optical depth, which increase ASR through decreases in atmospheric scattering and absorption in clear sky conditions (Yu et al. 2006), happen primarily in the western end of the basin, indicating a connection with changes in aerosol emissions upstream of the basin, in an area covered by China and neighbouring countries. However, smaller but statistically significant AOD decreases extent throughout the N. Pacific basin indicate a role of the restrictions in ship emissions. The CCF analysis (Fig. 7b, d) shows that changes in low-cloud optical thickness have different dependencies in the western and eastern parts of the basin. In the western part, low-cloud optical thickness changes are dependent primarily on changes in fine mode AOD, indicating that the darkening of the clouds is due to aerosol indirect effects, while in the eastern part they are depending primarily on changes in SST, indicating the potential for a positive low cloud optical thickness feedback. When the liquid cloud optical thickness trend is broken into contributions from cloud Liquid Water Path (LWP) and cloud particle number density (N_d) (Fig. S3), it is found that in the ΔHMCf -dominated regime, low cloud-optical thickness decreases are primarily due to a decrease in LWP, supporting the presence of a positive low-cloud optical thickness feedback, while in the ΔLCF regime, low cloud-optical thickness decreases are due to decreases in N_d , supporting the presence of the first indirect effect (Twomey 1977).

The cloud fraction effects on the N. Pacific ASR trend can be attributed to changes in cloud controlling factors that are the result of either cycles of natural variability or cloud feedbacks related to climate warming. In the case of high and middle cloud fraction changes, which constitute the dominant factor of the cloud fraction trend, Fig. 7a shows that atmospheric thermodynamics and dynamics are the primary contributor to the HMCf decreases. In addition, the map of high and middle



cloud changes shown in Fig. 4a reveals a poleward cloud shift indicative of a shift in the midlatitude jet (e.g. Bender et al. 2012, Tselioudis et al. 2016). To explore further the role of atmospheric dynamics changes and circulation shifts to the N. Pacific HMCF trend, Figure 8a shows the 21st century trend in 500mb zonal wind (U_{500}) from ERA5, together with the location of the U_{500} maximum in the 2000-2005 (red line) and 2020-2025 (green line) periods to depict the change in the position of the midlatitude jet core. The plot shows a weakening of the zonal wind on the subtropical side and a strengthening on the polar side of the basin, indicating a poleward shift in the midlatitude jet. The jet shift is also illustrated by the change in the position of the jet core, which is greatest in the central and eastern parts of the basin where it reaches values of 3 to 4 degrees of latitude. Note that the decrease in U_{500} shown here is strongly correlated with the decrease in ω_{500} (result not shown), which is shown to be a main contributor to the HMCF trend (Fig. 7a). Figure 8b shows the 21st century trend in extratropical cyclone density (ETC), a quantity that is derived using a storm-tracking algorithm applied to the ERA5 sea level pressure field. The map shows a clear poleward shift of the storm track that includes a westward tilt, indicative of the pattern of change of both the midlatitude jet (Fig. 8a) and the high/middle cloud field (Fig. 4a). The relationship between the position of the midlatitude jet and the change in the high/middle cloud fraction for the Δ HMCF-dominated region is quantified in Fig. S4 which shows a statistically significant relation of 0.73% decrease in HMCF per degree of poleward shift of the midlatitude jet. Note that the effect of El Niño variability on both the jet latitude and the high/middle cloud trends was examined, and no significant effect was found.

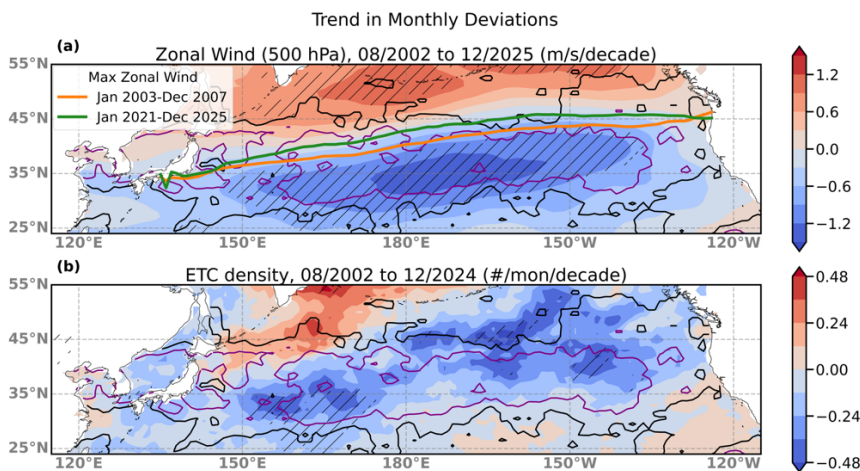


Figure 8. a) Trend in 500mb zonal wind (U_{500}) from ERA5, and location of the U_{500} maximum in the 2003-2007 (red line) and 2021-2025 (green line) periods. b) Trend in extratropical cyclone density (ETC) from ERA5 superimposed on the $1.75 \text{ W/m}^2/\text{dec}$ ASR isoline. Hatching indicates statistically significant trends ($p < .05$).

Correlative trend analysis with atmospheric dynamics parameters presented here shows that the N. Pacific high and middle cloud decreases can be attributed to a poleward shift in the midlatitude jet and storm track. Similar connections between midlatitude storm track and high cloud shifts have been shown in Bender et al. (2012) and Tselioudis et al. (2016). One critical question is the extent to which the documented shift in the N. Pacific storm track, which causes the cloud change with the largest contribution to the ASR trend, is a component of natural variability or a feedback caused by mechanisms



related to climate warming. The recent study of Chemke and Yuval (2026), analyzed the location trend of the N. Pacific storm track since 1979 and used modeling runs to define the width of storm track internal variability in the basin. They show that, especially after 2015, the poleward shift of the storm track emerges from internal variability and can be attributed to external forcing. Theoretical explanations for poleward jet shifts in response to greenhouse forcing have been proposed and include increases in extratropical dry static stability and tropopause height (see Shaw (2019) for a thorough review). Furthermore, the modeling study of Grise and Polvani (2014) showed that in increased CO₂ simulations, the poleward jet shift is driven far more strongly by the indirect SST increases than by the direct CO₂ radiative forcing. The results presented in our analysis show that the N. Pacific poleward shift causes a decrease in the high and middle cloud fraction (Fig. 7a) which in turn increases absorbed solar radiation at the surface (Fig. 6a) and thus increases SST. This indicates the potential for a positive feedback loop, where SST increase triggers a poleward shift of the midlatitude storm track and thus a reduction in high/middle cloud fraction, which increases the amount of absorbed SW radiation and thus SST. Note that a poleward shift of the midlatitude storm track also decreases the surface winds in the lower midlatitude part of the basin (Fig. S5), which can further increase SST by both decreasing evaporative cooling and increasing ocean mixed layer stratification, thus decreasing downward ocean heat transport. The potential for a positive feedback loop, involving increasing SST and the poleward shift of the midlatitude jet, need to be further explored through sensitivity analyses with coupled models that capture correctly the mechanisms in cloud-dynamics interactions and in ocean-atmosphere energy exchanges.

This study analyzed, to the length and detail allowed by the available satellite datasets, the 21st century ASR trend in the region of the globe where that trend is the most pronounced and found that it can be attributed to a suite of parameters and processes ranging from large scale dynamical changes to cloud microphysical processes. The N. Pacific basin is shown to be an area of strong aerosol direct and indirect forcing, caused by both emission reductions in SE Asia and ship emission regulations, and an area of strong cloud radiative effects resulting from a poleward shift of the Pacific storm track. The convergence of all of these factors can explain the reason for the prominence of the N. Pacific ASR trend signal in the global domain. It is almost certain that a similar analysis of the other regions of strong ASR increases shown in Figure 1 will produce different dependencies of the ASR trend on radiation-controlling properties and processes, and that globally valid conclusions for the mechanisms causing the strong 21st century ASR trend can be structured only as a synthesis of the mechanisms operating in the different regions and climate regimes.



Code and Data Availability

The analysis in the paper does not produce any new data. The code for the analysis will be made available once it is finalized at the time of the final publication.

450 **Supplement link**

The link to the supplement will be included by Copernicus, if applicable.

Author contributions

GT designed the analysis steps and took the lead in writing the paper. JK co-designed the analysis work, performed the analysis steps, and assisted in writing the paper.

455 **Competing interests**

There are no competing interests to report.

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