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Geophysical Research Letters

RESEARCH LETTER
10.1029/2021GL095774

Trends in Global Tropical Cyclone Activity: 1990–2021

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Key Points:

- Global hurricane counts and Accumulated Cyclone Energy (ACE) have significantly decreased since 1990 likely due to a trend toward La Niña
- Short-lived named storms, extreme rapid intensification events (50+ kt day^{-1}) and global damage have increased significantly from 1990 to 2021
- Decreasing trend in global hurricanes and ACE is primarily driven by downturn in western North Pacific activity

Supporting Information:

Supporting Information may be found in the online version of this article.

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Citation:

Klotzbach, P. J., Wood, K. M., Schreck III, C. J., Bowen, S. G., Patricola, C. M., & Bell, M. M. (2022). Trends in global tropical cyclone activity: 1990–2021. *Geophysical Research Letters*, *49*, e2021GL095774. https://doi.org/10.1029/2021GL095774

Received 26 AUG 2021
Accepted 3 MAR 2022

Abstract This study investigates global tropical cyclone (TC) activity trends from 1990 to 2021, a period marked by largely consistent observational platforms. Several global TC metrics have decreased during this period, with significant decreases in hurricane numbers and Accumulated Cyclone Energy (ACE). Most of this decrease has been driven by significant downward trends in the western North Pacific. Globally, short-lived named storms, 24-hr intensification events of ≥50 kt day^{-1}, and TC-related damage have increased significantly. The increase in short-lived named storms is likely due to technological improvements, while rapidly intensifying TC increases may be fueled by higher potential intensity. Damage increases are largely due to increased coastal assets. The significant decrease in hurricane numbers and global ACE are likely due to the trend toward a more La Niña-like base state from 1990 to 2021, favoring North Atlantic TC activity and suppressing North and South Pacific TC activity.

Plain Language Summary This study investigates 1990–2021 global tropical cyclone (TC) activity trends, a period characterized by consistent satellite observing platforms. We find that fewer hurricanes are occurring globally and that the tropics are producing less Accumulated Cyclone Energy—a metric accounting for hurricane frequency, intensity, and duration. This decreasing trend has primarily been driven by a significant downturn in western North Pacific TC activity—the tropical basin that typically is the most active. Short-lived named storms (TCs lasting ≤2 days) and the number of times that TCs quickly strengthen (≥50 kt in 24 hr) have increased significantly since 1990. Identifying more short-lived named storms is likely due to improved sensors, while increases in rapidly intensifying storms may be driven by more favorable conditions. Global damage from TCs has significantly increased as well, likely largely due to population growth and increased value of coastal assets (physical structures and non-physical risk exposure). The trend during the past 32 years toward a more La Niña-like environment has favored North Atlantic TC activity and suppressed North and South Pacific activity. Since the Pacific Ocean normally generates much more activity than the Atlantic, global TC activity has generally trended downward.

1. Introduction

Tropical cyclones (TCs) are one of the most damaging natural catastrophes, causing hundreds of fatalities and billions of US dollars in damage globally each year (Klotzbach et al., 2018; Mendelsohn et al., 2012). Consequently, scientists have explored the potential impacts of human-induced climate change on TC frequency, intensity, and associated metrics. These impacts have been recently summarized in a pair of papers that examined observed trends for several TC metrics (Knutson et al., 2019) as well as projected future TC activity using climate models (Knutson et al., 2020). Though future projections of TC activity are an important research topic, this manuscript focuses on recent observed TC activity trends.

Several studies have examined global TC activity trends. Webster et al. (2005) noted a near-doubling of global Category 4–5 hurricanes on the Saffir-Simpson Hurricane Wind Scale (SSHWS; ≥113 kt) during 1970–2004. However, subsequent studies argued that observational network changes (e.g., improved satellite capability) in the 1970 and 1980s likely contributed to those increases (Landsea et al., 2006). Klotzbach and Landsea (2015) explored the 1970–2014 period and found that 1990–2014 was marked by a slight insignificant downward trend in Category 4–5 hurricane frequency and a slight insignificant upward trend in the percentage of hurricanes reaching Category 4–5 intensity. Consequently, they argued that most of the increase noted by Webster et al. (2005) was due to observational platform changes, primarily in the 1970 and 1980s. Recently, Kossin et al. (2020) found a significant increasing trend in the ratio of major (Category 3+ on the SSHWS; ≥96 kt) hurricane observations to all hurricane observations using ADT-HURSAT, a satellite-derived TC intensity data set, from 1979 to 2017.

Global Accumulated Cyclone Energy (ACE; Bell et al., 2000) – an integrated metric that accounts for frequency, intensity, and duration of TCs – showed no significant long-term trend during 1970–2011, with global ACE in 2010/11 at its lowest levels since the late 1970s (Maue, 2011). He attributed the ACE downturn to the Pacific decadal oscillation transition (Mantua & Hare, 2002) to its negative phase and several strong La Niña events that generally suppress ACE in the climatologically active Pacific.

Other studies have examined TC rapid intensification (RI) trends in addition to the aforementioned TC metrics. Various RI thresholds exist, but the canonical definition, ≥30 kt day^{-1}, represents approximately the 95th percentile of 24 hr over-water North Atlantic TC intensification rates (Kaplan & DeMaria, 2003). Balaguru et al. (2018) found a significant increasing trend of the 95th percentile of 24 hr intensity changes in the eastern and central tropical Atlantic from 1986 to 2015. Bhatia et al. (2019) examined observational data and ADT-HURSAT from 1982 to 2009 and found significant increasing trends for global TCs as well as North Atlantic TCs, specifically at the highest intensity change quantiles in both data sets.

Several studies have highlighted increases in TC-related damage for both the United States (Grinsted et al., 2019; Klotzbach et al., 2018; Weinkle et al., 2018) and globally (Weinkle et al., 2012). These increases have been largely attributed to growth in population and the increased value of coastal assets, but increases in TC intensity may also play a role (Grinsted et al., 2019).

Prior to 1990, data issues likely precluded an accurate estimate of global TC intensities. No direct geostationary satellite data over the North and South Indian Oceans were available until *Meteosat-5* was launched in 1989 (Knapp & Kossin, 2007). In the eastern North Pacific, the responsibility transfer from the Weather Service Forecast Office, Redwood City, California, to the National Hurricane Center following the 1987 hurricane season may have caused a jump in analyzed intensities (Klotzbach & Landsea, 2015). Consequently, this study examines trends for several TC metrics using 1990–2021 observational data. We also examine large-scale atmospheric and oceanic patterns that may contribute to these trends. We note that TC trends and atmospheric/oceanic pattern trends over the past 32 years may not be representative of longer-term variability.

2. Data and Methodology

Data for the 1990–2020 TC seasons are obtained from US warning agency best tracks: the National Hurricane Center/Central Pacific Hurricane Center (e.g., HURDAT2; Landsea & Franklin, 2013) for the North Atlantic and eastern North Pacific and the Joint Typhoon Warning Center (Chu et al., 2002) for all remaining TC basins as hosted by the International Best Track Archive for Climate Stewardship version 4 (IBTrACSv4; Knapp et al., 2010). Operational best track data from IBTrACSv4 are used for the 2021 Northern Hemisphere TC season and for the July–December 2021 portion of the 2021–2022 Southern Hemisphere TC season.

We define TC basins following Knapp et al. (2010) and Klotzbach and Landsea (2015), dividing the eastern North Pacific and western North Pacific basins at the International Date Line and the South Indian and South Pacific basins at 135°E. Though Southern Hemisphere TC seasons are typically defined to cover 1 July–30 June, in this study, we examine calendar year TC activity trends. A storm is counted based on the year that it reached a particular threshold: If a TC reached tropical storm intensity on 30 December and hurricane intensity on 2 January, it would count as a named storm in the first year and a hurricane in the second year. If a TC extends from one calendar year to the next, it only counted for the calendar year in which it formed. Though various names are used for TCs depending on ocean basin (e.g., typhoon, cyclone), we use the term "hurricane" to refer to all TCs reaching hurricane strength (≥64 kt) regardless of formation location.

We evaluate 24 hr RI events at two thresholds: 30 kt and 50 kt. If a TC intensified by a given threshold for adjacent 24 hr periods, it counted as multiple RI events. Given uncertainties in estimating tropical depression intensity (Klotzbach & Landsea, 2015), we calculate RI events for TCs that were at least tropical-storm strength (≥34 kt) at the onset of RI. We also evaluate over-ocean rapid weakening (RW; Wood & Ritchie, 2015) at thresholds of −30 kt and −50 kt in 24 hr. To be included as RW events, the TC center must remain ≥100 km from land and the TC intensity ≥34 kt throughout the 24 hr period.

The ENSO Longitude Index (ELI; Williams & Patricola, 2018) estimates the average longitude of deep convection associated with the Walker Circulation and is consequently preferred to classify the ENSO state over the canonical Nino 3.4 index (Barnston et al., 1997) due to its improved ability at capturing ENSO spatial characteristics. ELI is calculated from the monthly Extended Reconstructed Sea Surface Temperature version 5 data set (Huang et al., 2017).

Global damage is obtained from EM-DAT (EM-DAT, 2021) with additional damage provided by Aon in public annual catastrophe reports and their proprietary Catastrophe Insight Database.

We use the European Centre for Medium Range Weather Forecasts fifth-generation reanalysis (ERA5; Hersbach et al., 2020) for all other atmospheric and oceanic calculations. In this study, we evaluate monthly fields derived from the 0.25°, hourly ERA5 reanalysis.

We calculate correlation statistical significance and least squares linear trends using a two-tailed Student's *t*-test and treating each year as independent of the preceding year given the low autocorrelation between year-to-year global TC activity. For environmental fields, significance of trends is calculated using a two-tailed Wald test via *SciPy*. Statistical significance is reported at the 10% level.

3. Trends in Tropical Cyclone Activity

Figure 1 highlights trends for several 1990–2021 global TC activity metrics. Table S1 in Supporting Information S1 provides average global TC activity for these and additional TC metrics and the percentage contribution of each basin and hemisphere to the global total. Table S2 in Supporting Information S1 states the numerical values of linear trends for each index in Figure 1 as well as several additional indices. Category 4–5 percentage trends in Figure 1 and Table S2 in Supporting Information S1 are displayed in percentage increase/decrease decade^{-1}; that is, if a basin's Category 4–5 percentage increased from 36% to 42% over the 32-year period, it corresponds to a ∼2% increase decade^{-1}. North Indian Ocean Category 4–5 hurricane percentage linear trends are not displayed due to limited per-year hurricane formations.

The western North Pacific generates the most TC activity for each investigated parameter except for RW events, producing a higher percentage of the global total for more intense TC metrics (e.g., Category 4–5 hurricanes vs. named storms; Table S1 in Supporting Information S1). While contributing 11% of global Category 4–5 hurricanes and 16% of global ACE, North Atlantic TCs caused 62% of global damage.

Figure 2a displays 1990–2021 global named storms (maximum sustained winds ≥34 kt). The 32 year period exhibits a weak, insignificant upward trend in global named storm activity, with a significant increasing trend in North Atlantic TC activity and a significant decreasing trend in western North Pacific TC activity (Figure 1a).

Landsea et al. (2010) noted a significant increase in short-lived named storms (≤2 days) in the North Atlantic that began around 2000 associated with improved microwave sensors, scatterometry, and application of the cyclone phase space diagram (Hart, 2003). Both the North Atlantic and eastern North Pacific basins have shown significant increases in short-lived named storms during the 32 year period (Figures 1b and 2b), likely due to improved technology. Other basins show insignificant trends in short-lived named storms.

Named storms lasting >2 days is likely a more robust metric of longer-term variability in global named storm activity. Globally, these storms have decreased by 2 storms decade^{-1}, although this decreasing trend is insignificant (Figures 1c and 2c). While not significant for 1990–2021, a decrease in global named storm activity is generally expected by most climate models with continued anthropogenic climate change (Knutson et al., 2020). Throughout the 32 year period, named storms lasting >2 days have significantly increased in the North Atlantic and significantly decreased in the western North Pacific (Figure 1c).

Figure 3 displays global hurricane, major hurricane, and Category 4–5 hurricane numbers, as well as the percentage of hurricanes reaching Category 4–5 intensity from 1990 to 2021. Consistent with Figure 1d, we find a significant decreasing trend in global hurricane activity, with a significant decrease in western North Pacific hurricane activity being the primary driver (Figure 3a). North Atlantic hurricane activity has increased by 0.6 hurricanes decade^{-1}, but this increase is not significant. All other basins exhibit relatively small insignificant trends.

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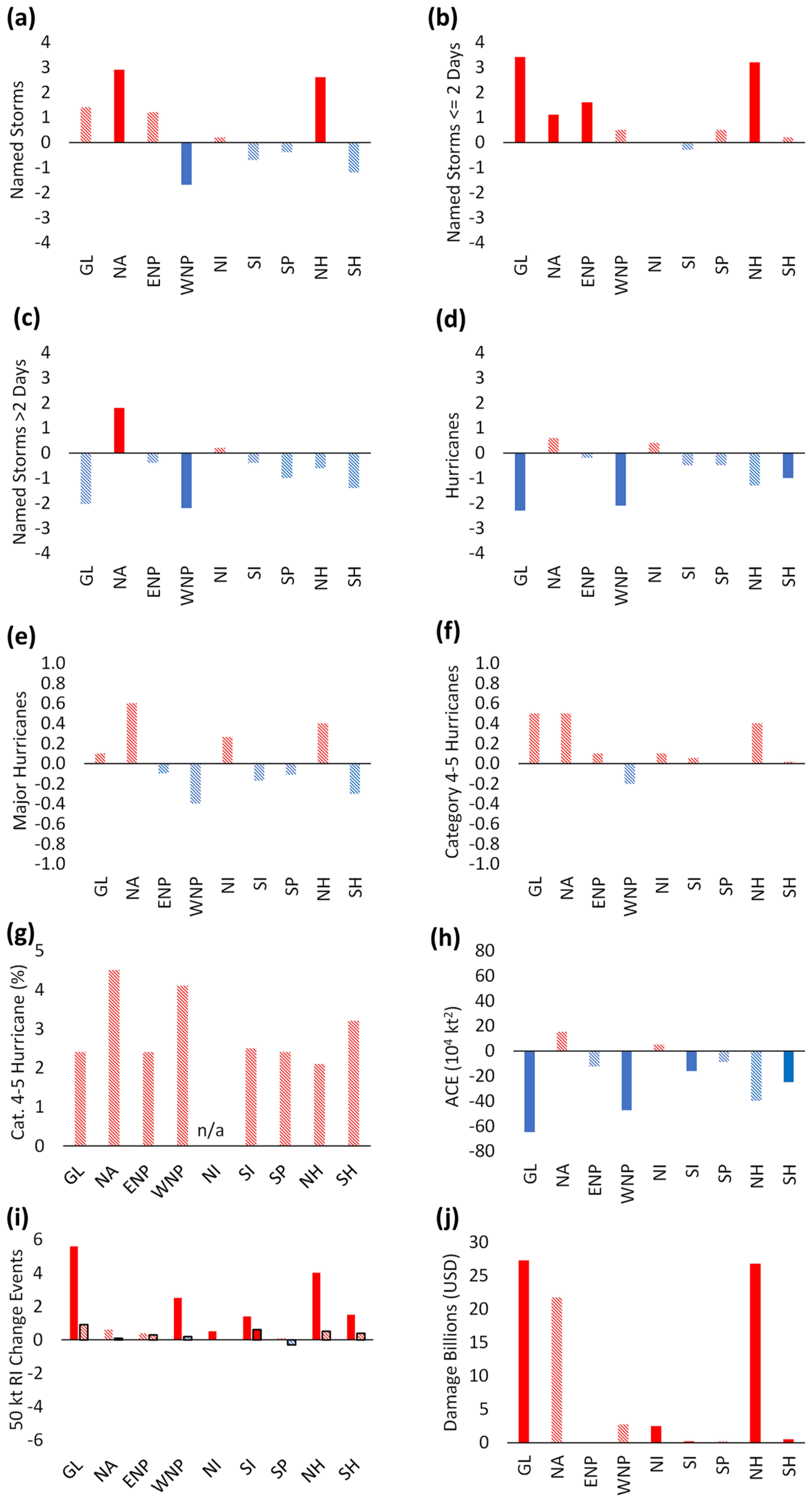

Figure 1. Per-decade linear trends for (a) named storms, (b) named storms lasting ≤2 days, (c) named storms lasting >2 days, (d) hurricanes, (e) major hurricanes, (f) Category 4–5 hurricanes, (g) Category 4–5 hurricane percentage, (h) Accumulated Cyclone Energy, (i) 50 kt rapid intensification and rapid weakening episodes (highlighted with black borders) and (j) damage (billions USD). Significant trends are displayed with solid bars; insignificant trends are lighter in color and hashed. Regions displayed are: global (GL), North Atlantic (NA), eastern North Pacific (ENP), western North Pacific (WNP), North Indian (NI), South Indian (SI), South Pacific (SP), Northern Hemisphere (NH) and Southern Hemisphere (SH).

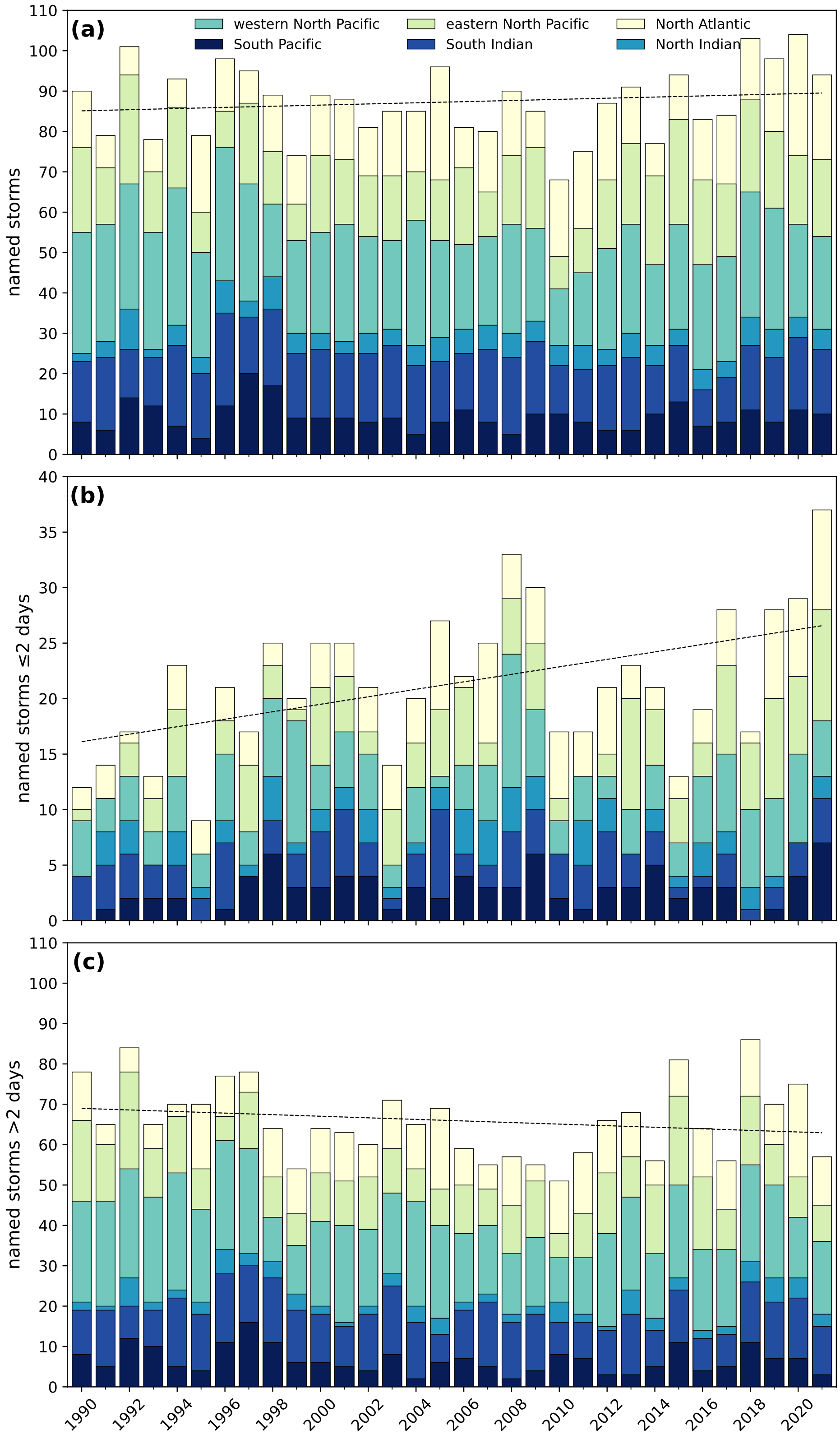

Figure 2. Global named storm formations during 1990–2021. (a) Named storm formations in six tropical cyclone basins. (b) As in (a) but for named storms lasting ≤2 days (c) As in (a) but for named storms lasting >2 days. Dashed lines in each panel represent 1990–2021 linear trends.

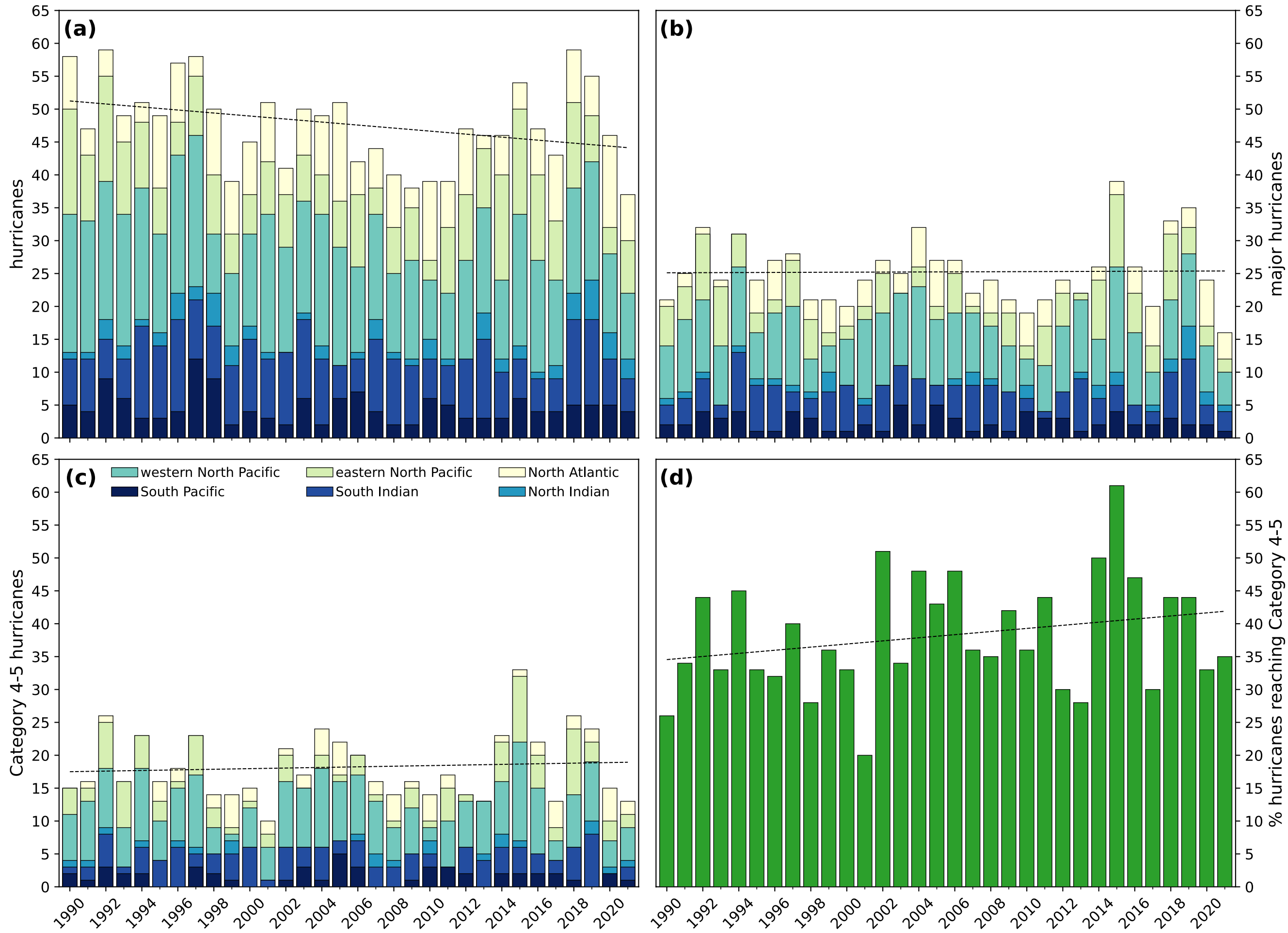

Figure 3. As in Figure 2 but for (a) hurricanes, (b) major hurricanes, and (c) Category 4–5 hurricanes. (d) Global percentage of hurricanes reaching Category 4–5 intensity.

While there has been a decreasing trend in hurricane activity, major hurricane activity has shown little trend and Category 4–5 hurricane activity has increased (although insignificantly) since 1990 (Figures 1e, 1f, 3b and 3c). The overall increasing trend in Category 4–5 hurricanes accompanied by a decreasing trend in all hurricanes indicates a shift toward more intense global hurricane activity and a higher Category 4–5 percentage (Figure 3d), as also noted by Elsner et al. (2008) and Kossin et al. (2020).

Global ACE has significantly decreased since 1990 (Figures 1h and 4a), indicating that decreases in frequency and duration of TCs currently dominate over increases in hurricane intensity (Figure 3d). Western North Pacific ACE has significantly decreased since 1990, and South Indian Ocean ACE also decreased significantly. The North Atlantic shows the largest overall increasing trend, although it is insignificant given large year-to-year volatility.

The 30 kt day^{-1} RI criterion has been frequently investigated (e.g., Kaplan & DeMaria, 2003; and many others), but this metric shows relatively small changes in most basins (Table S2 in Supporting Information S1). Global trends for 30 kt day^{-1} RI are not significant (Figure S1 in Supporting Information S1); however, the global trend in 24 hr intensification periods at the higher 50 kt day^{-1} RI threshold are significant (Figures 1i and 4b), corroborating Bhatia et al. (2019). All six basins show an increasing trend, with significant increasing trends in the western North Pacific, North Indian, and South Indian basins as well as combined RI events in both the Northern and Southern Hemisphere. The number of -50 kt day^{-1} RW events is also trending upward, though the global total has not increased significantly (Figures 1i and 4b). Global increases in -30 kt day^{-1} RW events are insignificant (Figure S1 in Supporting Information S1).

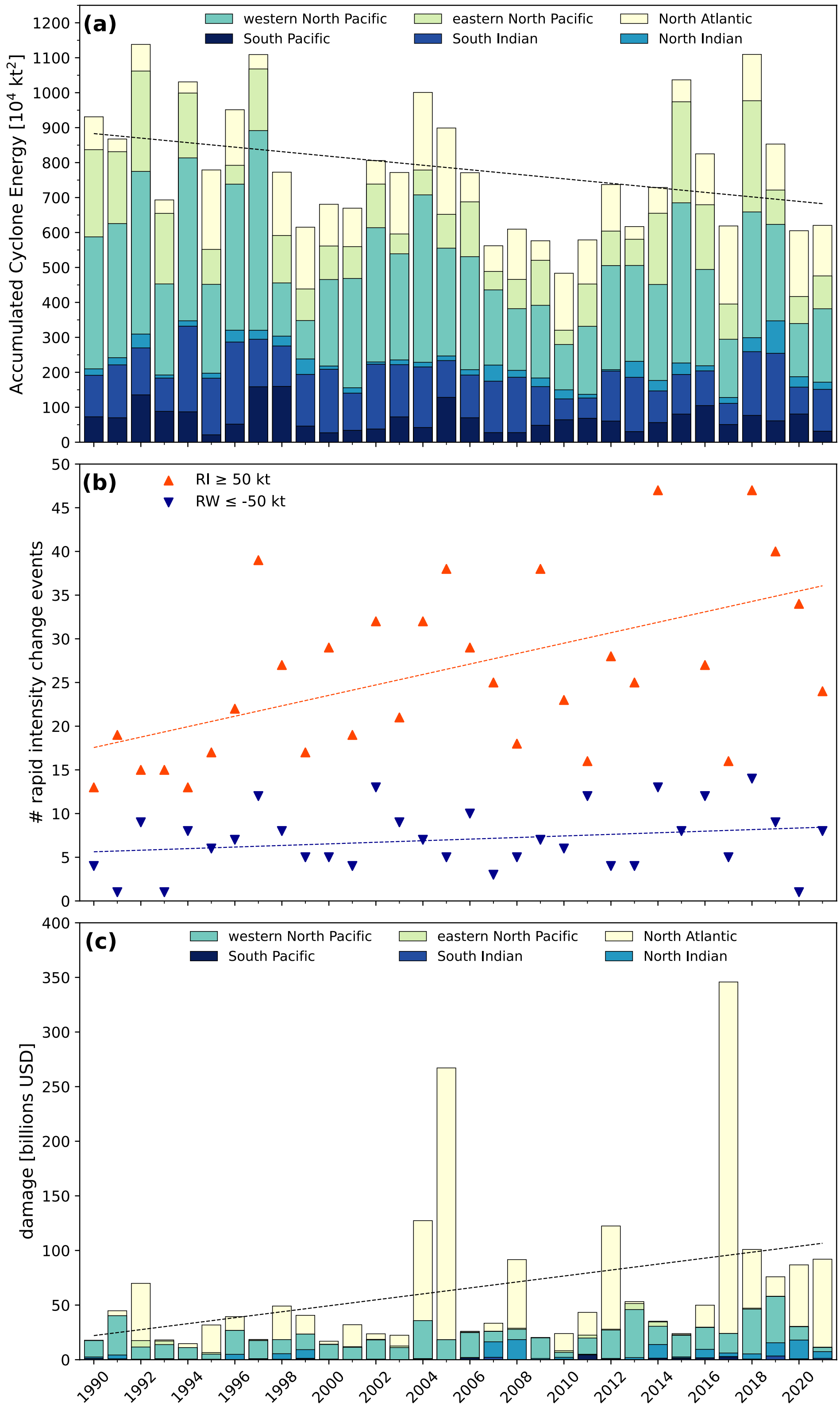

Figure 4. (a) As in Figure 2 but for Accumulated Cyclone Energy (10^4 kt^2). (b) Global rapid intensity change events for 50 kt rapid intensification and −50 kt rapid weakening thresholds. (c) As in Figure 2 but for damage (billions USD).

Corroborating Weinkle et al. (2012), we find a significant increase in global damage (Figures 1j and 4c) as well as significant increases for the North Indian and South Indian basins and in the Northern and Southern Hemisphere more broadly. The linear trend in North Atlantic damage is sizable; however, given the large year-to-year volatility in damage, the increase does not reach statistical significance. These increases in physical damage are generally the result of rising coastal populations and increasing value of physical structures or non-physical risk exposure (Klotzbach et al., 2018; Weinkle et al., 2018). However, we note that a growing portion of observed damage may reflect storm severity increases (Grinsted et al., 2019) and increases in tertiary storm impacts such as greater rainfall and background sea level rise (Knutson et al., 2020). These storm impacts highlight coastal exposure vulnerabilities that require expenditures to modernize and/or retrofit local infrastructure as well as regional residential and commercial exposure. We also stress the importance of strengthening local building codes.

4. Large-Scale Drivers of Observed Trends

We now turn our attention to the large-scale atmospheric/oceanic drivers of these observed TC trends by exploring spatial patterns of 1990–2021 annually averaged trends (Figure 5). Notable TC signals in the past ~30 years include significant decreasing trends in western North Pacific hurricane numbers and ACE as well as increasing trends in the percentage of Category 4–5 hurricanes and 50 kt RI events. Increasing shear has occurred across much of the central Pacific (Figure 5a), though these trends are near zero for the most TC-active portion of the Northern Hemisphere. Mid-level moisture has decreased over portions of the Pacific, but moisture has increased over the Maritime Continent and parts of the Indian Ocean with some regions achieving statistical significance (Figure 5b). Notably, potential intensity (PI) has increased across most tropical basins (Figure 5c), largely co-located with rising SSTs (Figure 5d), that are statistically significant. The increasing SST and especially PI may be responsible for the observed 50 kt RI event increase. We find similar patterns in difference maps between the 2006–2020 and 1990–2005 averages (not shown).

Increasing upper-level temperatures help explain the more moderate trends in PI compared with SST (Figure 5e). When examining annual averages computed within 30° longitude bins between 10–20°N and 10–20°S, 200 hPa temperature always exhibited a positive trend. These trends were statistically significant for all Northern Hemisphere bins and all Southern Hemisphere bins between 180° and 0°. Similar trends are observed for all five large-scale fields if we separately examine January–March and August–October trends (Figures S2 and S3 in Supporting Information S1) to highlight the peak of the Southern Hemisphere and Northern Hemisphere TC season, respectively.

We finally examine trends in the ELI (Figure 5f), as prior studies have shown that ENSO is a significant driver of global TC activity (e.g., Camargo et al., 2007). The 1990–2021 period exhibited a statistically significant westward shift in the annually averaged ELI, indicating a stronger and westward-shifted Walker Circulation, as recently noted by Seager et al. (2019) and Zhao and Allen (2019). This trend toward a more La Niña-like base state is consistent with observed atmospheric/oceanic pattern changes as well as the observed decreasing trend in western North Pacific ACE and increasing trend in North Atlantic ACE since 1990.

As shown in Table S3 in Supporting Information S1, the August–October ELI significantly positively correlates with eastern North Pacific ACE ($r = 0.47$) and western North Pacific ACE ($r = 0.76$) and significantly negatively correlates with North Atlantic ACE ($r = -0.51$). January–March-averaged ELI significantly positively correlates with South Pacific ACE ($r = 0.66$). Given that the Pacific climatologically generates much more ACE than the Atlantic, global ACE has significantly trended downwards since 1990.

Because ENSO may also affect the frequency of rapid intensity change, we also evaluate the relationship between ELI and 50 kt RI events (Table S4 in Supporting Information S1). Eastern North Pacific 50 kt RI events significantly positively correlate with the August–October ELI ($r = 0.72$), while the North Atlantic significantly negatively correlates ($r = -0.48$). While not reaching statistical significance, the western North Pacific also positively correlates with the ELI ($r = 0.30$). Given that ~60% of global 50-kt RI events occur in the North Pacific, global 50-kt RI events positively correlate with the ELI ($r = 0.44$). The current trend toward a La Niña-like base state may be muting the longer-term climate change-induced trend toward more high-end RI events.

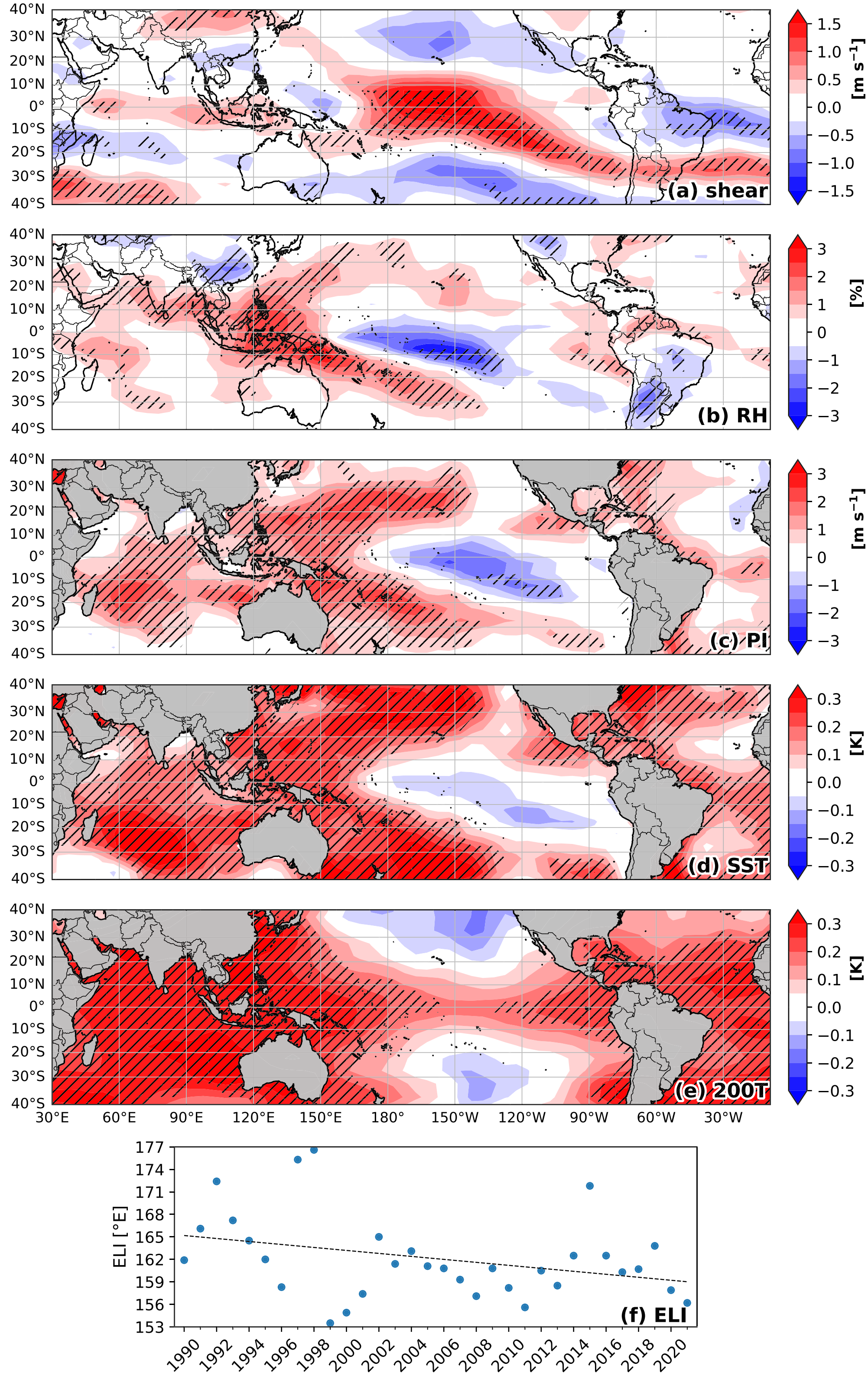

Figure 5. Maps of 1990–2021 per-decade trend values (shaded) and annual trend p-values ≤0.10 (hatching) for ERA5 annually averaged (a) 200–850 hPa vertical wind shear (m s^{-1}), (b) 500–700 hPa relative humidity (%), (c) potential intensity (m s^{-1}), (d) sea surface temperature (K) and (e) 200 hPa temperature (K). ERA5 data are averaged over 5° × 5° boxes prior to computing trends. (f) Annually averaged ELI (°E, dots) and the 32-year trend (dashed line).

5. Conclusions

By investigating global TC activity from 1990 to 2021, we find significant decreasing trends in global hurricane numbers and ACE, primarily due to a significant decreasing trend in the western North Pacific. Corroborating prior research, we have shown that El Niño favors Pacific Ocean TCs while La Niña favors North Atlantic TCs. Since the Pacific climatologically generates much more TC activity than the Atlantic, the observed decreasing trend is likely linked to a trend toward a more La Niña-like base state. Short-lived named storms ($\leq$2 days) have increased globally with most of this increase coming from the North Atlantic and eastern North Pacific basins. We find significant global increases in $\geq$50 kt day^{-1} RI events and global TC damage costs.

The increase in short-lived named storms is primarily attributed to improvements in observational technology, including microwave sensors and scatterometry (Landsea et al., 2010). The increase in high-end RI events is likely due to higher SSTs and especially increased PI, while global damage increases are largely tied to increasing population and wealth in coastal regions (Weinkle et al., 2012; Klotzbach et al., 2018).

Data Availability Statement

Tropical cyclone data were taken from the International Best Track Archive for Climate Stewardship version 4: https://www.ncdc.noaa.gov/ibtracs/index.php?name=ib-v4-access. All atmospheric and oceanic data were obtained from the European Centre for Medium Range Weather Forecasts Reanalysis 5: https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5. The ENSO Longitude Index was taken from: https://portal.nersc.gov/archive/home/projects/cascade/www/ELI. EM-DAT is available at: https://public.emdat.be/.

Acknowledgments

We thank the reviewers for helpful comments that improved the manuscript. P. Klotzbach acknowledges a grant from the G. Unger Vetlesen Foundation. K. Wood was supported by National Science Foundation award AGS-2011812 and Mississippi State University's Office of Research and Economic Development. C. Patricola acknowledges support from the U.S. Department of Energy, Office of Science, Office of Biological and Environmental Research, Earth and Environmental Systems Modeling Program, under Early Career Research Program Award Number DE-SC0021109. C. Schreck was supported by NOAA through the Cooperative Institute for Satellite Earth System Studies under Cooperative Agreement NA19NES4320002. M. Bell was supported by Office of Naval Research award N000142012069.

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