Trends in oceanic precipitation characteristics inferred from shipboard present-weather reports, 1950-2019

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Trends in oceanic precipitation characteristics inferred from shipboard present-weather reports, 1950–2019

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Key Points:

• Drizzle-intensity precipitation accounts for an increasing fraction of ship-reported precipitation occurrence in the tropics since 1950.
• Precipitation trends tend to be coherent across both geographic regions and seasons for most regions.
• The fraction of precipitation that is frozen has decreased along the southern extent of the subpolar Northern Hemisphere.

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Abstract

Manual shipboard present weather reports from 1950 to 2019 are aggregated and composited yearly and seasonally on a $1^\circ \times 1^\circ$ grid to characterize the global climatology and long-term trends in the relative frequency of four categories of oceanic precipitation: drizzle, moderate and heavy non-drizzle, precipitation associated with thunderstorms and deep convection, and frozen-phase precipitation. Although ship reports are susceptible to subjective interpretation, the inferred distributions of these phenomena are consistent with datasets derived from other platforms. These distributions highlight widespread 70-year trends that are often consistent across both annual and seasonal frequencies, with statistical significance at 95% confidence. The relative frequency of ship-reported drizzle has largely increased in the tropics annually and seasonally, with linear best-fit relative increases by as much as 15% per decade. Decreased relative frequencies have been observed in parts of the subtropics and at higher latitudes. Heavier precipitation has encompassed a growing fraction of non-drizzle precipitation reports over the subtropical North Pacific and Mediterranean. The relative frequency of thunderstorm reports has declined over the open Atlantic but show positive trends over the Mediterranean and the western Atlantic. The trends in relative frozen precipitation occurrence suggest a poleward retreat of areas receiving frozen precipitation in the Northern Hemisphere. Possible mechanisms for these ship-observed trends are discussed and placed in the context of the modeled effects of climate change on global precipitation.

Plain Language Summary

Climate change is expected to cause changes to precipitation worldwide. These include changes to the intensity, frequency, and type of precipitation. While most precipitation reports are taken from land, ships have long reported weather conditions worldwide. Their reports include information on the nature and character of precipitation when it occurs. An analysis of these ship reports collected during the 70 years spanning 1950–2019 from throughout the world’s oceans shows broad trends in the character and intensity of oceanic precipitation. Drizzle has accounted for a growing fraction of precipitation reports over most of the ocean, especially in the tropics. Heavier precipitation and thunderstorms have been reported more frequently in parts of the subtropics, including along the North American and Mediterranean coasts. The ship reports also provide evidence that the area receiving snowfall in the oceanic Northern Hemisphere is shrinking.

1 Introduction

Accurate assessment of the state of, and changes in, the hydrologic cycle is vital for understanding global climate, ecosystem health, agricultural productivity, and water resource management (Chahine, 1992; Huntington, 2010; Bernacchi & VanLoocke, 2015; D. Yang et al., 2021). Oceanic precipitation forms a critical component of the global hydrologic cycle, vastly dwarfing land-based hydrologic fluxes with an average transport of approximately $424 \times 10^3$ km$^3$ of water annually (Douville et al., 2021).

Climate change is expected to modify the global hydrologic cycle and impact global precipitation characteristics, with an increase in global surface air temperatures raising saturation vapor pressure, enhancing moisture transport, and thus supporting an increase in global mean precipitation (Pendergrass & Hartmann, 2014a; Allan et al., 2020; Douville et al., 2021). Over the ocean, simple energetic constraints and scaling show that the intensification of the hydrologic cycle reflected in these changes should broadly manifest as an increase in mean precipitation over the wetter tropics and higher latitudes paired with a decrease in mean precipitation over the drier subtropics (Allan et al., 2020; Trenberth, 2011; Yu et al., 2020). Simulations of global precipitation by climate models in Phase 5 (CMIP5, Taylor et al., 2012) and Phase 6 (CMIP6, Eyring et al., 2016) of the
Coupled Model Intercomparison Project (CMIP, Meehl et al., 2000) capture these expected trends in both historical and projected runs (e.g. Ren et al., 2013; Sarojini et al., 2012; Douville et al., 2021). Climate change also implies an increase in the frequency of heavier precipitation relative to light precipitation (Chou et al., 2012) and a decrease in the relative frequency of snow (Trenberth, 2011). Consistent with an increase in moisture convergence (Trenberth, 1999), CMIP5 simulations point to an increase in precipitation occurrence at all intensities with a relative shift towards more intense precipitation events (e.g. Pendergrass & Hartmann, 2014b). Simulations and observations also suggest a decrease in snowfall extremes, extent, and the snow-rain event ratio (e.g. O’Gorman, 2014; Kunkel et al., 2016; Mudryk et al., 2020; Shi & Liu, 2021), though analysis of these trends has been primarily focused over land. The impact of anthropogenic influences on lightning occurrence, including the sign of trends in global activity, remain unclear (e.g. Price & Rind, 1994; Albercht et al., 2011; Singh et al., 2017; Thornton et al., 2017; Finney et al., 2018).

Although oceans cover around 70% of the Earth’s surface area and receive 74–82% of global precipitation, quantitative in-situ measurements of oceanic precipitation are virtually non-existent apart from extremely sparsely and unevenly distributed atolls, islands, buoys, and research vessels (Kidd et al., 2022; Levizzani & Cattani, 2019). Only around 4% of the ocean falls within 100 km of a rain gauge, as compared to 23% of land between 60°S–60°N falling within just 10 km of a rain gauge (Kidd et al., 2017). Almost all of the ocean coverage is due to land-based gauges, which not only provide no insight into precipitation patterns or trends outside of coastal regions but are also potentially unrepresentative of even nearby ocean areas due to orographic and other effects.

In recent decades, the dearth of direct observations has been mitigated primarily by satellite-derived ocean precipitation estimates, using visible, infrared (IR), and microwave radiometers and with spaceborne precipitation radars (available since 1997 over the tropics and since 2014 near-globally) serving as calibration standards (Prigent, 2010; Draper et al., 2015; Levizzani & Cattani, 2019; Kummerow, 2020). Satellite-based ocean precipitation datasets generally show an increase in mean tropical ocean precipitation amount (Dore, 2005). The Global Precipitation Climatology Project (GPCP, Adler et al., 2018) gridded monthly precipitation product, with one of the longest periods of record among satellite-based precipitation datasets (Sun et al., 2018), suggests no statistically significant trend in global mean precipitation over the period 1979–2020 but indicates trends consistent with a narrowing of the Intertropical Convergence Zone (ITCZ) and drying over parts of the subtropical ocean (Gu & Adler, 2022).

Nonetheless, the complete satellite-based record of oceanic precipitation remains relatively short, spanning only around five decades. Moreover, only since 1987 have satellite passive microwave observations contributed significantly to these estimates, with prior periods being based entirely on far less reliable visible and IR-based estimates. Additionally, the record incorporating the more physically direct satellite radar determinations of precipitation rate only covers around two decades in the tropics and a decade at higher latitudes.

Analyses relying on such short records cannot reliably distinguish between natural multidecadal variability and true long-term trends. Satellite microwave precipitation algorithms are also less reliable with respect to the detection and measurement of shallow and/or light precipitation characteristic of the higher latitudes (Tapiador et al., 2017). Additionally, spaceborne precipitation estimates are susceptible to large changes arising from algorithm or calibration adjustments (e.g. Z. Liu, 2016), changes in the available satellite sensors, and difficulties in distinguishing virga from true surface precipitation (e.g. Y. Wang et al., 2018; Tan et al., 2018).

Aside from satellite-based methods, reconstructions of oceanic precipitation over a comparable or longer period of record have been attempted by exploiting correlations
with other observed fields (e.g. Smith, 2013) or from model reanalyses that infer precipitation as a byproduct of dynamical processes (e.g. C. Li et al., 2021). However, these alternatives do not represent directly observed oceanic precipitation, and errors cannot be readily characterized owing to the lack of reliable validation data.

While quantitative measurements of precipitation are almost never available from ships, qualitative reports of precipitation type and intensity by shipboard weather observers offer a more extensive historical record that is suitable for evaluating some aspects of climate distributions and trends. Particularly in the post-war half of the 20th century and beyond, numerous ships around the world regularly reported weather and oceanographic observations through the Voluntary Observing Ships (VOS) Program, a global data collection effort coordinated by the World Meteorological Organization (WMO).

The focus of this paper is on the \textit{ww} code for reporting present weather, which is part of the WMO-defined synoptic code system used in meteorological observations, including those from ships and land stations. This code is a two-digit number that represents specific weather conditions at the time of observation, ranging from clear or cloudless skies to various precipitation types, thunderstorms, fog, dust, and other phenomena. Codes 50–99 are specific to precipitation occurring at the location and time of the observation, and different values distinguish precipitation by intensity, phase, and character (Petty, 1995).

Prior to the availability of satellite precipitation estimates, attempts were made to determine climatological distributions of ocean precipitation amount either by way of empirical relationships between \textit{ww} codes and precipitation intensity at land-based stations (e.g. Tucker, 1961; Reed & Elliott, 1973) or assuming a relationship between precipitation frequency and quantitative amount (e.g. Reed, 1979; Elliott & Reed, 1984). These methods were essentially the sole foundation of our understanding of oceanic precipitation distributions prior to remotely sensed precipitation retrievals (e.g. Sharova, 1990; da Silva et al., 1994).

The determination of precipitation amount from reported \textit{ww} codes is fraught with challenges, but shipboard present weather reports have been used to identify other characteristics of oceanic precipitation, such as the frequency of occurrence of any kind of precipitation and/or of specific precipitation classes (e.g. Petty, 1995; Dai, 2001; Petty & Tran, 2023) and properties of the rain–snow transition (e.g. Sims & Liu, 2015; Shi & Liu, 2021). Despite the qualitative, sparse, and subjective nature of \textit{ww} observations, as well as the potential for fair-weather bias (Berry & Kent, 2011), analyses using such data have been partly validated by more sophisticated instrumentation (Ellis et al., 2009).

Petty and Tran (2023) showed that statistically significant trends in the reported overall occurrence of precipitation exist over large parts of the global oceans during the 70-year period 1950–2019, with positive trends in frequency being found throughout much of the tropics and subtropics and negative trends being found mainly at higher latitudes. This paper extends that analysis by undertaking a more detailed examination of annual and seasonal trends for various subtypes of precipitation.

2 Data and Methods

2.1 Data

Shipboard observations were extracted from the International Comprehensive Ocean-Atmosphere Data Set (ICOADS), which is composed of both Release 3.0 (R3.0.0, Freeman et al., 2016), including marine observations from 1667–2014, and Near Real Time Release 3.0.2 (R3.0.2, C. Liu et al., 2022), a preliminary near-realtime dataset of marine observations from 2015–present. The analysis period covers the 70-year period from 1950 to 2019 and thus draws upon both releases of ICOADS. Both datasets were retrieved with
“enhanced” filtering as described by ICOADS (2016). Key observational variables used for this analysis include the present weather code $ww$ (valued 00–99, corresponding to World Meteorological Organization [WMO] code table 4677), the total observed cloud cover $N$ (in oktas, corresponding to WMO code table 2700), and the measured air temperature $AT$. The subsequent filtering of reports to arrive at a more consistent and homogeneous collection of maritime observations, described below, follows the procedure outlined in Petty and Tran (2023) except where noted.

Only observations associated with a platform type ($PT$) of 0 (U.S. Navy, “deck” log, or unknown), 1 (merchant ship or foreign military), and 5 (ship) were used; observations with missing $PT$ were excluded. On 1 January 1982, a WMO rule change went into effect that permitted a $ww$ value of “/” (encoded as a blank $ww$ value) if there was no significant present weather observed by a human observer (Dai, 2001). A new station/weather indicator ($ix$) was introduced by the rule change to clarify whether or not omission of $ww$ was due to the lack of significant weather or the lack of data availability. Ship observations quickly adopted the practice of $ww$ during insignificant weather but did not reliably use $ix$ until 1985 (Hahn et al., 1992).

To address cases where $ix$ could not be used to determine the availability of $ww$, the accompanying presence of non-missing $N$ was used as a proxy for establishing that a human observer was present and omitted $ww$. Thus, ship observations providing either $N$ or $ww$ were kept, with an absence of $ww$ accompanying extant $N$ presumed to indicate no precipitation. All present weather observations tagged as automated ($ix \geq 4$) were excluded. The procedure using $N$ has also been employed in previous analyses of present weather in ICOADS ship reports (e.g. da Silva et al., 1994; Petty, 1995; Petty & Tran, 2023).

Due to clearly spurious temporal and spatial inhomogeneities resulting from their inclusion in the analyzed dataset, observations associated with the Inter-American Tuna Commission (IATTC, deck number [DCK] 667) and the Russian Marine Meteorological Data Set (MORMET, DCK= 732) were excluded. Some prior analyses of ICOADS have also excluded these datasets for the same reason (Woodruff, 1995).

The ICOADS dataset includes some $ww$ reports of frozen precipitation at unrealistically warm temperatures, though collectively these are a small fraction of the overall dataset ($\sim 0.001\%$). To avoid spurious depictions of non-zero frozen precipitation fraction over warm ocean areas, only reports with non-missing air temperature ($AT$) were retained, and frozen precipitation observations accompanied by $AT > 10^\circ C$ were discarded. This additional filter differs from Petty and Tran (2023).

Altogether, the fully filtered dataset, covering the 70 years from 1950 through 2019, contains 99.7 million shipboard observations. In addition to the ship reports, we used gridded sea surface temperature (SST) from the Kaplan Extended SST V2 dataset (A. Kaplan et al., 1998).

2.2 Methods

The present weather code $ww$ encompasses a wide array of observable meteorological phenomena. Observations coded with $ww \geq 50$ are associated with the occurrence of precipitation at the time and location of observation. Within this range, there are several subcategories, with codes 50–59 indicating continuous or intermittent drizzle of various intensities, 60–69 non-showery rain, 70–79 non-showery frozen precipitation, 80–90 showers (liquid or frozen), and 90–99 precipitation associated with a thunderstorm (Petty, 1995). The occurrence of precipitation takes precedence over other phenomena in determining $ww$, and thus a report indicating $ww < 50$ rules out precipitation occurring at the time of observation (Petty & Tran, 2023). The precipitating present weather codes can be further subdivided based on the intensity, phase, and character of the precipita-
Table 1. Selected $ww$ groupings pertaining to precipitation intensity, character, and phase. See Table 1 in Petty (1995) for interpretations of individual $ww$ codes.

<table>
<thead>
<tr>
<th>Category</th>
<th>$ww$ codes</th>
</tr>
</thead>
<tbody>
<tr>
<td>All precipitation</td>
<td>$ww \geq 50$</td>
</tr>
<tr>
<td>Drizzle-intensity precipitation</td>
<td>50, 51, 52, 53, 54, 55, 57, 65, 77, 78</td>
</tr>
<tr>
<td>Moderate/heavy precipitation</td>
<td>59, 62, 63, 64, 65, 67, 69, 72, 73, 74, 75, 81, 82, 84, 86, 88, 90, 94, 95, 96, 97, 98, 99</td>
</tr>
<tr>
<td>Strong convection and thunderstorms</td>
<td>82, 89, 90, 91, 92, 93, 94, 95, 96, 97, 98, 99</td>
</tr>
<tr>
<td>Frozen precipitation</td>
<td>70, 71, 72, 73, 74, 75, 76, 77, 78, 85, 86</td>
</tr>
</tbody>
</table>

As with Petty and Tran (2023), ship reports were mapped to a $1^\circ \times 1^\circ$ resolution grid at monthly resolution, producing a total number of reports $n$ and $m$ observations of the desired subset of precipitation. The resulting grids were then aggregated both annually and over 3-month seasons and coarser spatial resolutions of $3^\circ$, $5^\circ$, $7^\circ$, $9^\circ$, and $11^\circ$ latitude and longitude, as well as a coarsest spatial resolution of $13^\circ$ latitude by $26^\circ$ longitude.

For sufficiently large sample size $n$, $m/n$ provides a good estimate of the unknown true fraction of occurrence $f$. For small $m$ and/or $n$, however, this ratio significantly underestimates the expected value of $f$. This is especially apparent when $m = 0$, since a significant range of non-zero $f$ can be statistically consistent with this outcome. Unbiased estimates $\hat{f}$ of $f$ and associated sampling uncertainty $\hat{\sigma}$ are therefore calculated as follows:

$$\hat{f} = \frac{m + 1}{n + 2}$$

$$\hat{\sigma} = \left[ \frac{(m + 1)(n - m + 1)}{(n + 3)(n + 2)^2} \right]^{1/2}$$

These equations correspond to a Bayesian determination of the expected value of $f$, assuming a uniform distribution on the interval [0,1] as a non-informative prior. Equation (1) is appropriate when $m$ and/or $\hat{f}$ are small (e.g. Basu et al., 1996) and reduces to $m/n$, as expected, for large $n$ and $m$. When $n < 5$ and $m = 0$, the uncertainty is considered too large to be useful, and $\hat{f}$ is treated as indeterminate.

$\hat{f}$ and $\hat{\sigma}$ are initially computed at the coarsest spatial resolution and progressively replaced by repeated computation at finer resolutions at each $1^\circ \times 1^\circ$ gridbox only if the finer sampling did not markedly increase the relative uncertainty $\hat{\sigma}/\hat{f}$. This procedure results in composite maps of frequency and trends that reflect coarser geographic aggregations of reports in data-sparse regions and finer resolution in data-rich regions such as near shipping lanes and coastal areas. This procedure was performed independently for each seasonal period.

Trends in frequency were computed using ordinary least-squares regression, with the significance of those trends relative to the null hypothesis of zero trend evaluated using a two-tailed Student’s $t$-test at the 95% confidence level. Though the length of the time series at each gridbox $S = 70$ years, a reduced effective independent sample size...
S′ = S(1 − ρ)/(1 + ρ), where ρ is the lag-1 autocorrelation, was used for significance testing of both trends and correlations (Box et al., 2015).

Trends and frequencies were not computed for grid cells where more than 5 years of aggregate data were missing or where ˆσ/ˆf ≥ 0.4. As this determination varies depending on the number of relevant ship observations, the data coverage presented below differs between w.e groupings.

To compare data from the 1°×1° resolution gridded shipboard data with the 5°×5° resolution SST data, the latter were interpolated to a 1°×1° grid. To assess the correlation between the two datasets, each dataset was detrended by subtracting the least-squares regression from 1950 to 2019 before computing the Pearson correlation coefficient r between the yearly relative precipitation frequencies and the yearly mean Kaplan SST anomaly. A two-tailed Student’s t-test utilizing the reduced sample size S′ was used to evaluate significance relative to the null hypothesis of r = 0 at the 95% confidence level.

3 Results

In the following, results are presented for four categories of precipitation: 1) drizzle-intensity, 2) moderate or heavy intensity, 3) deep convection and thunderstorms, and 4) ice-phase. In groups 1 and 4, the statistics considered are the fraction of these reports relative to the occurrence of precipitation of any type, while groups 2 and 3 are characterized relative to the occurrence of non-drizzle precipitation. Where trends are discussed below, we confine our attention to trends identified as significant at the 95% level, as indicated by a lack of stippling in the associated maps, unless otherwise noted.

3.1 Drizzle-intensity fraction

As a fraction of all reports of precipitation in progress, drizzle-intensity reports are most prevalent in the mid-latitudes, particularly over the eastern halves of oceanic basins within the summer hemisphere and along the western coast of South America (Figure 1). The annual zonal mean fraction of shipboard precipitation with drizzle intensity peaks at roughly ±45° latitude, reaching approximately 0.39±0.09 and 0.33±0.01 in the Southern and Northern Hemispheres, respectively.

The annual fraction of ship-reported drizzle is generally negatively correlated with SST over the eastern Pacific and positively correlated over the western Pacific (Figure 2a). Positive correlation coefficients are highest in the mid-latitudes of the northwestern Pacific and North Atlantic while negative correlations are strongest in the equatorial East Pacific and off the Pacific coasts of Canada and the United States.

From 1950 through 2019, an increase in the proportion of drizzle-intensity precipitation is broadly observed over the tropics, with weakly negative trends in the mid- to high-latitudes (Figure 3). Positive trends in drizzle proportion are statistically significant over much of the lower latitudes (30°S–30°N) within all oceanic basins. The fractional zonal mean increase in the proportion of precipitation reports with drizzle intensity are broadly on the order of 5% per decade equatorward of 30°, equivalent to roughly a 1 percentage point increase in the absolute drizzle proportion per decade. The observed drizzle fraction trend is positive across all of the oceanic tropics except for marginal decreases in parts of the eastern Pacific and Western Caribbean.

Absolute and relative trends are most strongly positive within the East China Sea, off the eastern coast of Brazil, across the subtropical South Pacific, and in the equatorial Indian Ocean. These trends are generally consistent between seasons and in the annual aggregate. The positive trend in drizzle fraction off the eastern coast of Brazil appears to be influenced by abnormally frequent reporting of drizzle in 2016 and 2018 (Fig-
ure 4b), though a long-term increasing trend is still evident outside of those years. Other regional variations in drizzle proportion reflect consistent gradual trends over the 70-year period.

A possible signal of multidecadal variability is observed over the western Pacific and equatorial Indian Ocean, with minima in drizzle frequency occurring around 1960, 1980, and 2005 in both regions. The Pacific and eastern Atlantic north of 30°N show a weak but statistically significant decrease in drizzle proportion, particularly in JJA (Figure 3d).

### 3.2 Moderate/heavy non-drizzle fraction

Moderate and heavy precipitation accounts for a larger fraction of non-drizzle precipitation reports over the tropical and equatorial regions, with lower frequencies over parts of the eastern North Pacific and eastern South Atlantic (Figure 5). More frequent heavier precipitation is observed over the equatorial Indian Ocean and around the Maritime Continent.

The zonal mean annual fraction peaks at 0.44±0.04 near 5°N and exhibits minima of 0.39±0.06 at 25°S and 0.37±0.03 at 25°N. Over much of the Northern Hemisphere, the annual relative fraction of moderate to heavy non-drizzle precipitation is negatively correlated with SST and somewhat positively correlated throughout the Southern Hemisphere (Figure 2b).

The zonal mean trend in moderate and heavy intensity non-drizzle precipitation reports exhibits a broad maximum in the subtropical Northern Hemisphere and a broad minimum in the subtropical Southern Hemisphere both annually and seasonally. The broader zonal pattern differs between the Northern and Southern Hemisphere, with the tropical Southern Hemisphere lacking the broad positive trends observed in the North Pacific.

A prominent region of statistically significant increase is observed over the central and eastern Pacific between 15–30°N for the annual fraction, with increases in seasonal fractions throughout the same areas and along the Pacific coasts of the United States and Canada (Figure 6). Most of this positive trend appears to be associated with a fractional increase in reports of moderate and heavy precipitation from about 1950 to 1970, with little trend evident during 1970–2019 for those areas. The fractional positive trends in these regions are on the order of 5–10% per decade, corresponding to a roughly 2–4% increase in the fraction both annually and seasonally. Statistically significant positive trends are also observed over the Mediterranean Sea. The regions of negative 70-year trends are smaller and exhibit lower magnitude than positive-trending areas globally.

### 3.3 Deep convection/thunderstorms fraction

Shipboard precipitation reports associated with thunderstorms or otherwise deep convection are most prevalent in the equatorial Atlantic, western tropical Atlantic, off the Pacific coast of Mexico, and within the Mediterranean Sea (Figure 8). In these areas, the annual fraction is on the order of 0.15. For areas with sufficiently low uncertainty, the zonal mean fraction of ship-reported thunderstorm or deep convection broadly peaks at roughly 0.10 ± 0.02 at 15°N and declines poleward.

Shipboard reports of deep convection or thunderstorms within the frequency hotspots in the Western Hemisphere peak during boreal summer and peak in the Mediterranean during boreal autumn. Over the equatorial Indian Ocean and western Pacific, thunderstorm and deep convection-related precipitation reports are most prevalent during boreal spring. The annual relative fraction of these reports are generally negatively correlated with SST over the subtropical North Pacific and North Atlantic, but show pos-
Figure 1. Annual and seasonal fraction of shipboard precipitation reports with drizzle-intensity precipitation, regardless of phase. Gray shading denotes areas with more than 5 years of missing values or excess uncertainty (see text) after the compositing procedure is performed.
Figure 2. Correlation coefficients between shipboard precipitation fractions and Kaplan Extended SST V2 for the period 1950–2019. Non-stippled regions are statistically significant at the 95% confidence level. Gray shading denotes areas with more than 5 years of missing values or excess uncertainty (see text) after the compositing procedure is performed.

itive correlations in the tropical East Pacific and the higher latitudes of the West Pacific and North Atlantic (Figure 2c).

Statistically significant negative 70-year annual trends cover much of the open north and equatorial Atlantic, as well as within the Indian Ocean off of South India. Significant positive trends are observed along the United States East Coast and in the East China Sea in the annual fraction and in all four seasonal fractions. Positive seasonal trends have also been observed within the Sea of Japan and along the eastern and southern coasts of Japan. However, statistically significant positive trends cover a much smaller area than statistically significant negative trends.

3.4 Frozen precipitation fraction

As a fraction of overall precipitation reports, frozen precipitation is most prevalent within the Antarctic and Arctic circles, accounting for the majority of annual ship-reported precipitation occurrence. Within the Northern Hemisphere, where cold-season ship observations are more numerous, higher frozen precipitation fractions extend southward into the Sea of Okhotsk and south of the Labrador Sea offshore Atlantic Canada and the northeastern United States. These fractions are highest in boreal winter and lowest in boreal summer, when frozen precipitation reports are largely absent. The mean annual fraction in the Northern Hemisphere is below 1% equatorward of 35°N. Frozen precipitation shows statistically significant negative correlations with SST throughout most of the Northern Hemisphere for which fractions were computed (Figure 2d).

Along the southern fringes of the Northern Hemisphere regions with a mean frozen precipitation fraction ≥ 1%, the fraction of observed frozen precipitation has tended to
Figure 3. Relative linear best-fit trend (in percent per decade) of the annual and seasonal fractions of shipboard precipitation reports with drizzle intensity precipitation, regardless of phase. Non-stippled regions are statistically significant at the 95% confidence level. Gray shading denotes areas with more than 5 years of missing values or excess uncertainty within the ship data after the compositing procedure is performed.
Figure 4. Regionally-aggregated area-weighted time series of year-to-year annual and seasonal fractions of shipboard precipitation reports with drizzle intensity precipitation (left) over the selected region outlined by the rectangular region (right). Gray shading denotes areas with more than 5 years of missing values or excess uncertainty (see text).
Figure 5. As in Figure 1, but for shipboard precipitating non-drizzle reports associated with moderate or heavy intensities.
Figure 6. As in Figure 3, but for shipboard precipitating non-drizzle reports associated with moderate or heavy intensities.
Figure 7. As in Figure 4, but for shipboard precipitating non-drizzle reports.
Figure 8. As in Figure 1, but for shipboard precipitation reports associated with deep convection or thunderstorms.
Figure 9. As in Figure 3, but for shipboard precipitation reports associated with deep convection or thunderstorms.
Figure 10. As in Figure 4, but for shipboard precipitation reports associated with deep convection or thunderstorms.
decrease (Figure 12). Trends in these areas have been especially apparent since the 1990s (Figure 13). Statistically significant decreases in the annual occurrence with relative trends on the order of 10–15% per decade are prominent over the Norwegian Sea, and over the central North Pacific south of Alaska between roughly 40–50°N.

Increasing trends are observed over an area of the North Atlantic south of Greenland and east of Newfoundland, approximately in the region bounded by 40–52°W, 35–55°W. Varying trends are apparent over the Southern Ocean, particularly during DJF, including statistically significant negative trends within the Drake Passage and significant positive trends in the Cooperation Sea south of the Indian Ocean.

4 Discussion

4.1 Drizzle fraction

The general features of the global oceanic drizzle distribution as a proportion of precipitation occurrences are broadly similar to results obtained by Petty (1995) and Dai (2001) for the period 1958-1991 and 1975-1997, respectively, with the greatest proportion of drizzle occurring over areas with greater subsidence. Among the precipitation classes analyzed, trends associated with drizzle were the most widespread and highest in magnitude. The often consistent trend in drizzle fraction suggests that the underlying physical mechanisms supporting the trend are not strictly seasonal. Increased anthropogenic aerosol production has been associated with decreased drizzle production via direct modification of cloud condensation nuclei (CCN) distributions (Ferek et al., 2000; Fu & Dan, 2014) or increased CCN concentrations overall (Mann et al., 2014). Ships themselves may locally suppress drizzle via aerosol emission (Ferek et al., 2000), though the distribution of drizzle frequencies and trends shows little difference between heavily and lightly traversed waters.

Statistically significant trends in ship-observed drizzle frequency are less widespread when restricted to the much shorter satellite-based record of aerosol optical depth (AOD). Increasing trends in annual AOD were highlighted by Mehta et al. (2016) around the Arabian Peninsula and the Indian subcontinent using data from the Moderate Resolution Imaging Spectroradiometer (MODIS) and Multiangle Imaging Spectroradiometer (MISR) for the period 2001–2014. The trends in annual ship-reported drizzle fraction in these areas were negative during this period, consistent with suppression of drizzle production by aerosols. The negative trends in AOD observed by MODIS throughout much of the tropics are broadly coincident with the widespread increase in drizzle fraction over the larger 70-year period, though drizzle trends are less consistent when limiting the ship record to 2001-2014.

Drizzle is especially ubiquitous in marine boundary layer stratocumulus clouds, which occur throughout much of the global ocean but are most frequent across the North Pacific north of 35°N, in the eastern subtropical North Pacific, across the North Atlantic north of 40°N, and in the eastern subtropical South Atlantic (Klein & Hartmann, 1993; vanZanten et al., 2005; Brient et al., 2019). Except for some regions in the North Atlantic, there has been a slight decrease in the proportion of shipboard precipitation observations reporting drizzle across these areas over the past 70 years. These regions are among the few where decreases in the fraction of drizzle observed by ships are statistically significant. Consequently, zones that typically experience the most frequent drizzle have observed a general decline in reported drizzle occurrences, whereas areas with historically less frequent drizzle have noted increases in such reports. The downward trends in high-drizzle areas might suggest a reduction in marine stratocumulus occurrences or a decline in the efficiency of these clouds to produce drizzle. Conversely, there could be an increase in stratocumulus cloud coverage or an improvement in drizzle production efficiency in tropical regions.
Figure 11. As in Figure 1, but for shipboard precipitation reports associated with frozen hydrometeors. Additionally, areas with less than 1% annual or seasonal fraction are also omitted (shaded in gray) along with areas with excess uncertainty.
Figure 12. As in Figure 3, but for shipboard precipitation reports associated with frozen hydrometeors. Additionally, areas with less than 1% annual or seasonal fraction are also omitted (shaded in gray) along with areas with excess uncertainty.
Figure 13. As in Figure 4, but for shipboard precipitation reports associated with frozen hydrometeors. Additionally, areas with less than 1% annual or seasonal fraction are also omitted (shaded in gray) along with areas with excess uncertainty.
The microphysical properties of these clouds and their behavior are substantially influenced by the properties of aerosols in the local environment (Lu et al., 2018; Christensen et al., 2020). Increased aerosol concentrations are associated with increased cloud cover in the stable atmospheric conditions characteristic of stratocumuli (Christensen et al., 2020). However, satellite-derived cloud cover trends since the 1980s differ between these stratocumulus-rich regions (Norris et al., 2016), suggesting that changes in the coverage of marine stratocumuli alone are an insufficient indicator for a possible mechanism producing the observed trends in drizzle in those locations. Satellite-derived trends in the occurrence of low clouds (Marchand, 2013) are also geographically inconsistent with the geographic distribution of ship-based drizzle trends in both regions of increasing and decreasing ship-reported drizzle frequency.

Changes in drizzle frequency within marine stratocumuli might also be associated with changes in cloud depth. Thicker clouds more readily produce drizzle (Yamaguchi et al., 2017) and exhibit greater virga depth (F. Yang et al., 2018), with thicker stratocumuli increasing the likelihood of drizzle registering as surface precipitation. Additionally, the effect of drizzle suppression by aerosols is more efficient for thinner clouds (L’Ecuyer et al., 2009; Terai et al., 2012). A decrease in drizzle occurrence over the eastern oceanic basins could thus be produced by long-term decreases in the thickness of marine stratocumuli, with increases elsewhere associated with the thickening of stratocumuli. Within the Pacific, recent intensification of the Walker circulation (L’Heureux et al., 2013) may provide a mechanism for this thinning. However, consistent trends in cloud thickness have not been clearly observed over stratocumulus-rich regions (Kishcha et al., 2007; Lelli et al., 2014).

Alternatively, changes in vertical wind shear may influence drizzle production in some marine stratocumulus clouds by modifying the generation of turbulent kinetic energy and entrainment of dry air (Wu et al., 2017). In particular, an increase in shear may promote greater drizzle production in marine stratocumulus clouds while also reducing their cloud fraction and depth, as suggested by Jeong et al. (2023). Considering the shallow nature of marine boundary layer clouds, any such trends in wind shear could be confined to low altitudes.

The apparent low-frequency sinusoidal variability of the drizzle fraction in at least part of the Indian Ocean and West Pacific, with similarly timed extrema in drizzle frequency, suggests a possible influence of a large-scale mode affecting both regions. Within the Indian Ocean, the leading modes of variability for monthly-resolved SST are the El Nino-Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD; Saji et al., 1999). However, these modes have much shorter timescales than the observed decadal to multi-decadal variation in drizzle (Dommengen, 2010). Ummenhofer et al. (2017) identified a low-frequency variation in the thermocline depth of the eastern Indian Ocean with strong forcing on the behavior of IOD events and similar periodicity to the drizzle variability. This variability may be associated with the Pacific decadal oscillation (PDO; Mantua & Hare, 2002), which modulates regional precipitation behavior (e.g. Krishnan & Sugi, 2003; S. Wang et al., 2014; Wei et al., 2021), providing a possible cross-basin influence on drizzle frequency.

4.2 Heavier and/or convective precipitation fraction

Though limited in coverage, the frequency of deep convection and thunderstorms as reported by ships matches the general global distribution inferred by radio lightning sensors (J. O. Kaplan & Lau, 2021). Improvements in the prediction and monitoring of oceanic storms, potentially improving storm avoidance, could manifest as a fractional decrease in ship-reported lightning or heavier precipitation. However, the 70-year waver trends indicate this is not globally evident.
The broad spatial patterns of trends are similar between the two groupings of shipboard weather reports. Increases in the relative frequency of moderate or heavy non-drizzle intensity precipitation and in the frequency of deep convection are most prevalent near western boundary currents in the Northern Hemisphere and near the Tropic of Cancer across the Central Pacific.

The increase in the fraction of heavier precipitation in the North Pacific, particularly around 15°N, may be an indicator of the poleward expansion of the Hadley cell due to climate change (Hu et al., 2010), decreasing in large-scale subsidence equatorward of the expanding subtropical dry zone. However, the region of ship-observed increases extends poleward into areas with satellite-derived decreasing trends in precipitation amount (R. Liu et al., 2015).

Simultaneous increasing trends in both heavier precipitation and drizzle, such as over the Mediterranean Sea, Yellow Sea, and Central North Pacific, may be a signal of a shift towards precipitation extremes. The ship-based trends in the Mediterranean are consistent with a shift towards more extreme precipitation events in the Mediterranean observed on land-based data (Norant & Dougdroit, 2005). Regional climate model simulations of the Mediterranean suggest a future increase in extreme daily precipitation over land in the northern part of the Mediterranean and a decrease in the southern part of the basin (Tramblay & Somot, 2018). The ship-observed trends in the relative frequency of heavier precipitation or thunderstorms are more strongly positive in the northern part of the basin but have not indicated a decrease along the North African coast.

The ship-observed increases in the proportion of heavier precipitation in the Yellow Sea have also been observed on land-based stations along the western coast (H. Wang et al., 2017). An increase in convective available potential energy (CAPE) under warming conditions may lead to a corresponding increase in lightning activity (Romps et al., 2014). Many of the areas with ship-observed increases in deep convection and thunderstorms correspond with areas with increasing reanalysis-inferred trends in the 95th percentile of CAPE since the late-20th century (Taszarek et al., 2021). Changes in aerosol concentrations may also play a role in enhancing or suppressing cold-rain processes and lightning production (Tao et al., 2012), though satellite-observed changes in AOD are not closely aligned with the ship-observed trends in heavier precipitation and thunderstorms.

### 4.3 Frozen precipitation fraction

The decreasing trend in the annual relative frequency of frozen precipitation reports along the southern periphery of the area in the Northern Hemisphere receiving frozen precipitation provides possible evidence for a poleward retreat of the Arctic area receiving frozen precipitation. A decrease in snowfall amount along this transition zone is depicted in climate projections (Krasting et al., 2013) and was also reflected in a similar analysis of the snow event to precipitation event ratio undertaken by Shi and Liu (2021), though a corresponding increase in snowfall amount farther poleward is not distinctly apparent using shipboard frozen precipitation frequencies.

The transition from decreasing frozen precipitation frequencies in southern Japan to increasing frequencies in northern Japan is consistent with trends observed by land-based stations (Takahashi, 2020). The significant increase in the reporting of frozen-phase precipitation over the North Atlantic over a region east of Newfoundland and south of Greenland is located near a “warming hole” (Drijfhout et al., 2012; L. Li et al., 2021) where SSTs have decreased over the last century in stark contrast to the rest of the global ocean. The relative frequency of ship-reported frozen precipitation in this region appears sensitive to SST and may be capable of capturing more transient SST anomalies. For instance, the spike in the relative fraction in 2015 observed in parts of the subpolar North
Atlantic may be linked to an anomalous patch of cooler SSTs that emerged that year (Maroon et al., 2021).

The inverse relationship between SST and relative snowfall frequency is consistent with SSTs locally affecting the temperature characteristics of the lower troposphere and thus precipitation phase. Similarly, the long-term negative frozen precipitation trends in the Drake Passage appear to correspond with observed long-term negative trends in sea ice over the nearby Bellingshausen and Amundsen seas, while positive frozen precipitation trends over the southern Indian Ocean align with long-term positive trends in sea ice over the region (Parkinson & Cavalieri, 2012). These sea ice trends are also partly reflected in sea ice extent reconstructions (Fogt et al., 2022). An assessment of reanalyses by Boisvert et al. (2020) found little change in annual snowfall frequency in the period 2000-2016 within the Southern Ocean, consistent with ship-based results. However, ship-observed frozen precipitation frequencies may potentially be influenced by the navigability of the Southern Ocean.

5 Conclusions

The spatial and seasonal coherence of both magnitudes and trends in precipitation occurrence of various types, independent of variations in sampling density, lends some confidence in the reality of both. Unfortunately, corroborating data from other sources is virtually non-existent apart from satellite observations of ocean precipitation, and even the satellite record is quite short if one limits attention to the most direct indicators of precipitation occurrence, namely active microwave measurements from spaceborne Ku-band and W-band radars carried by the TRMM (1997–2015), GPM (2014–present), and CloudSat satellites (2006–2023, with reduced capabilities after 2011). In short, direct validation of the long-term trends described herein is probably impossible. However, some observed trends are broadly consistent with modeled or observed trends of precipitation and related environmental parameters.

A pronounced increase in drizzle frequency is seen annually and seasonally across the tropics, with relative trends exceeding 10% per decade in several regions. Areas with observed decreases in drizzle proportion have tended to be drizzle-rich regions. These trends may result from long-term trends in the coverage of drizzle-producing clouds, such as marine stratocumulus, or the efficiency of drizzle production, which is partly controlled by aerosol concentrations. However, the ship-observed spatial patterns of trends in oceanic drizzle are not necessarily consistent with the observed spatial patterns of changes in aerosols, and there may not be a dominant contributor to these trends globally. While there has been ample research concerning the variability of drizzle over land, further investigation of oceanic drizzle is needed to more clearly delineate possible mechanisms for the observed increase in tropical drizzle frequency.

The ship-based record captures statistically significant fractional increases in the relative proportion of moderate- and heavy-intensity non-drizzle precipitation or thunderstorms in some areas. Many areas with positive trends in relative thunderstorm frequency are consistent with reanalysis-derived positive trends in the occurrence of favorable thunderstorm environments. Shipboard observations of thunderstorms have mostly decreased over the open ocean but have shown relative increases in the western North Atlantic and western North Pacific.

Trends in the reporting of frozen precipitation in the Northern Hemisphere are consistent with a poleward retreat of oceanic areas receiving frozen precipitation, with a decrease in frozen precipitation frequency observed over the North Pacific and North Atlantic near 40°N. Over the North Atlantic, the relative proportion of frozen precipitation is well-correlated with SSTs, with an increase in frozen precipitation frequency ob-
served near a region with secular cooling SST trends. Over the Southern Ocean, ship-observed trends in frozen precipitation are consistent with sea ice extent.

This study has primarily examined trends in precipitation occurrence. The next phase will involve using the modern satellite PMW-based precipitation records to calibrate qualitative ship reports with the help of machine learning techniques during the period of overlap. If successful, this approach could enable the reconstruction of more accurate distributions and trends in ocean precipitation amounts from the pre-satellite era, dating back to as early as 1950.

6 Open Research

ICOADS R3.0.0 and R3.0.2 (Research Data Archive, Computational and Information Systems Laboratory, National Center for Atmospheric Research, University Corporation for Atmospheric Research et al., 2016) data were obtained from dataset ds548.0 in the National Center for Atmospheric Research (NCAR) Research Data Archive at https://rda.ucar.edu/datasets/ds548.0. Kaplan Extended SST V2 data were provided by the NOAA Physical Sciences Laboratory (NOAA PSL) at https://psl.noaa.gov/data/gridded/data.kaplan_sst.html. Jupyter/Python notebooks used to obtain numerical and graphical results herein are available at Zenodo as gpetty/JGR-2024 via https://doi.org/10.5281/zenodo.8140237 and are released under GNU General Public License version 2 (GPLv2).

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References


Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., &
Taylor, K. E. (2016, May). Overview of the Coupled Model Intercomparison
Project Phase 6 (CMIP6) experimental design and organization. Geoscientific

the Atmospheric Sciences, 57(16), 2707–2728. doi: 10.1175/1520-0469(2000)
057(2707:dsist)2.0.co;2

under climate change. Nature Climate Change, 8(3), 210–213. doi:
10.1038/s41558-018-0072-6

A regime shift in seasonal total Antarctic sea ice extent in the twentieth cen-

Freeman, E., Woodruff, S. D., Worley, S. J., Lubker, S. J., Kent, E. C., Angel,
to the historical marine climate record. International Journal of Climatology,
37(5), 2211–2232. doi: 10.1002/joc.4775

Fu, C., & Dan, L. (2014, February). Trends in the different grades of precipita-
tion over South China during 1960–2010 and the possible link with anthro-
pogenic aerosols. Advances in Atmospheric Sciences, 31(2), 480–491. doi:
10.1007/s00376-013-2102-7

Gu, G., & Adler, R. F. (2022, November). Observed variability and trends in global
.1007/s00382-022-06567-9

Ship Observations in Cloud Climatologies. In H. F. Diaz, K. Wolter, &
S. D. Woodruff (Eds.), Proceedings of the International COADS Workshop
(pp. 267–276). NOAA Environmental Research Laboratories. Retrieved from

expansion of the Hadley circulation. Advances in Atmospheric Sciences, 28(1),
33–44. doi: 10.1007/s00376-010-0032-1

Huntington, T. G. (2010). Climate Warming-Induced Intensification of the Hydro-
logic Cycle. In Advances in Agronomy (pp. 1–53). Elsevier. doi: 10.1016/b978
-0-12-385040-9.00001-3

ICOADS. (2016). International Comprehensive Ocean-Atmosphere Data Set
(ICOADS) Release 3.0 Quality Control (QC) and Related Processing (Tech.
Rep.). National Atmospheric and Oceanic Administration. Retrieved from

and Aerosol Conditions on the Organization of Precipitating Marine Stratocu-
10.1029/2023jd039081

Kaplan, A., Cane, M. A., Kushnir, Y., Clement, A. C., Blumenthal, M. B., & Ra-
doi: 10.1029/97jc01736

climatology and time series. Earth System Science Data, 13(7), 3219–3237.
doi: 10.5194/essd-13-3219-2021

satellite precipitation data records. In Precipitation Science (pp. 177–199). El-
sevier. doi: 10.1016/b978-0-12-822973-6.00004-4


Manuscript submitted to JGR: Atmospheres


Research Data Archive, Computational and Information Systems Laboratory, National Center for Atmospheric Research, University Corporation for Atmospheric Research, Physical Sciences Laboratory, Earth System Research Laboratory, OAR, NOAA, U.S. Department of Commerce, Cooperative Institute for Research in Environmental Sciences, University of Colorado, National Oceanography Centre, University of Southampton, Met Office, Ministry of Defence, United Kingdom, Deutscher Wetterdienst (German Meteorological Service), Germany, ... National Centers for Environmental Information, NESDIS, NOAA, U.S. Department of Commerce (2016). International comprehensive ocean-atmosphere data set (icoads) release 3, individual observations [dataset]. Boulder CO: Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. Retrieved from https://doi.org/10.5065/D6ZS2TR3


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Trends in oceanic precipitation characteristics inferred from shipboard present-weather reports, 1950–2019

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Key Points:

- Drizzle-intensity precipitation accounts for an increasing fraction of ship-reported precipitation occurrence in the tropics since 1950.
- Precipitation trends tend to be coherent across both geographic regions and seasons for most regions.
- The fraction of precipitation that is frozen has decreased along the southern extent of the subpolar Northern Hemisphere.

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Abstract

Manual shipboard present weather reports from 1950 to 2019 are aggregated and com-
posed yearly and seasonally on a $1^\circ \times 1^\circ$ grid to characterize the global climatology
and long-term trends in the relative frequency of four categories of oceanic precipitation:
drizzle, moderate and heavy non-drizzle, precipitation associated with thunderstorms and
deep convection, and frozen-phase precipitation. Although ship reports are susceptible
to subjective interpretation, the inferred distributions of these phenomena are consis-
tent with datasets derived from other platforms. These distributions highlight widespread
70-year trends that are often consistent across both annual and seasonal frequencies, with
statistical significance at 95% confidence. The relative frequency of ship-reported driz-
ze has largely increased in the tropics annually and seasonally, with linear best-fit rel-
ative increases by as much as 15% per decade. Decreased relative frequencies have been
observed in parts of the subtropics and at higher latitudes. Heavier precipitation has en-
compassed a growing fraction of non-drizzle precipitation reports over the subtropical
North Pacific and Mediterranean. The relative frequency of thunderstorm reports has
dropped over the open Atlantic but show positive trends over the Mediterranean and the
western Atlantic. The trends in relative frozen precipitation occurrence suggest a pole-
ward retreat of areas receiving frozen precipitation in the Northern Hemisphere. Pos-
sible mechanisms for these ship-observed trends are discussed and placed in the context
of the modeled effects of climate change on global precipitation.

Plain Language Summary

Climate change is expected to cause changes to precipitation worldwide. These in-
cludes changes to the intensity, frequency, and type of precipitation. While most pre-
cipitation reports are taken from land, ships have long reported weather conditions world-
wide. Their reports include information on the nature and character of precipitation when
it occurs. An analysis of these ship reports collected during the 70 years spanning 1950–
2019 from throughout the world’s oceans shows broad trends in the character and in-
tensity of oceanic precipitation. Drizzle has accounted for a growing fraction of precip-
itation reports over most of the ocean, especially in the tropics. Heavier precipitation
and thunderstorms have been reported more frequently in parts of the subtropics, in-
cluding along the North American and Mediterranean coasts. The ship reports also pro-
vide evidence that the area receiving snowfall in the oceanic Northern Hemisphere is shrin-
ging.

1 Introduction

Accurate assessment of the state of, and changes in, the hydrologic cycle is vital
for understanding global climate, ecosystem health, agricultural productivity, and wa-
ter resource management (Chahine, 1992; Huntington, 2010; Bernacchi & VanLoocke,
2015; D. Yang et al., 2021). Oceanic precipitation forms a critical component of the global
hydrologic cycle, vastly dwarfing land-based hydrologic fluxes with an average transport
of approximately $424 \times 10^3$ km$^3$ of water annually (Douville et al., 2021).

Climate change is expected to modify the global hydrologic cycle and impact global
precipitation characteristics, with an increase in global surface air temperatures raising
saturation vapor pressure, enhancing moisture transport, and thus supporting an increase
in global mean precipitation (Pendergrass & Hartmann, 2014a; Allan et al., 2020; Dou-
ville et al., 2021). Over the ocean, simple energetic constraints and scaling show that the
intensification of the hydrologic cycle reflected in these changes should broadly manifest
as an increase in mean precipitation over the wetter tropics and higher latitudes paired
with a decrease in mean precipitation over the drier subtropics (Allan et al., 2020; Tren-
berth, 2011; Yu et al., 2020). Simulations of global precipitation by climate models in
Phase 5 (CMIP5, Taylor et al., 2012) and Phase 6 (CMIP6, Eyring et al., 2016) of the
Coupled Model Intercomparison Project (CMIP, Meehl et al., 2000) capture these expected trends in both historical and projected runs (e.g. Ren et al., 2013; Sarojini et al., 2012; Douville et al., 2021). Climate change also implies an increase in the frequency of heavier precipitation relative to light precipitation (Chou et al., 2012) and a decrease in the relative frequency of snow (Trenberth, 2011). Consistent with an increase in moisture convergence (Trenberth, 1999), CMIP5 simulations point to an increase in precipitation occurrence at all intensities with a relative shift towards more intense precipitation events (e.g. Pendergrass & Hartmann, 2014b). Simulations and observations also suggest a decrease in snowfall extremes, extent, and the snow-rain event ratio (e.g. O’Gorman, 2014; Kunkel et al., 2016; Mudryk et al., 2020; Shi & Liu, 2021), though analysis of these trends has been primarily focused over land. The impact of anthropogenic influences on lightning occurrence, including the sign of trends in global activity, remain unclear (e.g. Price & Rind, 1994; Albercht et al., 2011; Singh et al., 2017; Thornton et al., 2017; Finney et al., 2018).

Although oceans cover around 70% of the Earth’s surface area and receive 74–82% of global precipitation, quantitative in-situ measurements of oceanic precipitation are virtually non-existent apart from extremely sparsely and unevenly distributed atolls, islands, buoys, and research vessels (Kidd et al., 2022; Levizzani & Cattani, 2019). Only around 4% of the ocean falls within 100 km of a rain gauge, as compared to 23% of land between 60°S–60°N falling within just 10 km of a rain gauge (Kidd et al., 2017). Almost all of the ocean coverage is due to land-based gauges, which not only provide no insight into precipitation patterns or trends outside of coastal regions but are also potentially unrepresentative of even nearby ocean areas due to orographic and other effects.

In recent decades, the dearth of direct observations has been mitigated primarily by satellite-derived ocean precipitation estimates, using visible, infrared (IR), and microwave radiometers and with spaceborne precipitation radars (available since 1997 over the tropics and since 2014 near-globally) serving as calibration standards (Prigent, 2010; Draper et al., 2015; Levizzani & Cattani, 2019; Kummerow, 2020). Satellite-based ocean precipitation datasets generally show an increase in mean tropical ocean precipitation amount (Dore, 2005). The Global Precipitation Climatology Project (GPCP, Adler et al., 2018) gridded monthly precipitation product, with one of the longest periods of record among satellite-based precipitation datasets (Sun et al., 2018), suggests no statistically significant trend in global mean precipitation over the period 1979–2020 but indicates trends consistent with a narrowing of the Intertropical Convergence Zone (ITCZ) and drying over parts of the subtropical ocean (Gu & Adler, 2022).

Nonetheless, the complete satellite-based record of oceanic precipitation remains relatively short, spanning only around five decades. Moreover, only since 1987 have satellite passive microwave observations contributed significantly to these estimates, with prior periods being based entirely on far less reliable visible and IR-based estimates. Additionally, the record incorporating the more physically direct satellite radar determinations of precipitation rate only covers around two decades in the tropics and a decade at higher latitudes.

Analyses relying on such short records cannot reliably distinguish between natural multidecadal variability and true long-term trends. Satellite microwave precipitation algorithms are also less reliable with respect to the detection and measurement of shallow and/or light precipitation characteristic of the higher latitudes (Tapiador et al., 2017). Additionally, spaceborne precipitation estimates are susceptible to large changes arising from algorithm or calibration adjustments (e.g. Z. Liu, 2016), changes in the available satellite sensors, and difficulties in distinguishing virga from true surface precipitation (e.g. Y. Wang et al., 2018; Tan et al., 2018).

Aside from satellite-based methods, reconstructions of oceanic precipitation over a comparable or longer period of record have been attempted by exploiting correlations...
with other observed fields (e.g. Smith, 2013) or from model reanalyses that infer precipitation as a byproduct of dynamical processes (e.g. C. Li et al., 2021). However, these alternatives do not represent directly observed oceanic precipitation, and errors cannot be readily characterized owing to the lack of reliable validation data.

While quantitative measurements of precipitation are almost never available from ships, qualitative reports of precipitation type and intensity by shipboard weather observers offer a more extensive historical record that is suitable for evaluating some aspects of climate distributions and trends. Particularly in the post-war half of the 20th century and beyond, numerous ships around the world regularly reported weather and oceanographic observations through the Voluntary Observing Ships (VOS) Program, a global data collection effort coordinated by the World Meteorological Organization (WMO).

The focus of this paper is on the \textit{ww} code for reporting present weather, which is part of the WMO-defined synoptic code system used in meteorological observations, including those from ships and land stations. This code is a two-digit number that represents specific weather conditions at the time of observation, ranging from clear or cloudless skies to various precipitation types, thunderstorms, fog, dust, and other phenomena. Codes 50–99 are specific to precipitation occurring at the location and time of the observation, and different values distinguish precipitation by intensity, phase, and character (Petty, 1995).

Prior to the availability of satellite precipitation estimates, attempts were made to determine climatological distributions of ocean precipitation amount either by way of empirical relationships between \textit{ww} codes and precipitation intensity at land-based stations (e.g. Tucker, 1961; Reed & Elliott, 1973) or assuming a relationship between precipitation frequency and quantitative amount (e.g. Reed, 1979; Elliott & Reed, 1984). These methods were essentially the sole foundation of our understanding of oceanic precipitation distributions prior to remotely sensed precipitation retrievals (e.g. Sharova, 1990; da Silva et al., 1994).

The determination of precipitation amount from reported \textit{ww} codes is fraught with challenges, but shipboard present weather reports have been used to identify other characteristics of oceanic precipitation, such as the frequency of occurrence of any kind of precipitation and/or of specific precipitation classes (e.g. Petty, 1995; Dai, 2001; Petty & Tran, 2023) and properties of the rain-snow transition (e.g. Sims & Liu, 2015; Shi & Liu, 2021). Despite the qualitative, sparse, and subjective nature of \textit{ww} observations, as well as the potential for fair-weather bias (Berry & Kent, 2011), analyses using such data have been partly validated by more sophisticated instrumentation (Ellis et al., 2009).

Petty and Tran (2023) showed that statistically significant trends in the reported overall occurrence of precipitation exist over large parts of the global oceans during the 70-year period 1950–2019, with positive trends in frequency being found throughout much of the tropics and subtropics and negative trends being found mainly at higher latitudes. This paper extends that analysis by undertaking a more detailed examination of annual and seasonal trends for various subtypes of precipitation.

2 Data and Methods

2.1 Data

Shipboard observations were extracted from the International Comprehensive Ocean-Atmosphere Data Set (ICOADS), which is composed of both Release 3.0 (R3.0.0, Freeman et al., 2016), including marine observations from 1667–2014, and Near Real Time Release 3.0.2 (R3.0.2, C. Liu et al., 2022), a preliminary near-realtime dataset of marine observations from 2015–present. The analysis period covers the 70-year period from 1950 to 2019 and thus draws upon both releases of ICOADS. Both datasets were retrieved with
“enhanced” filtering as described by ICOADS (2016). Key observational variables used for this analysis include the present weather code $ww$ (valued 00–99, corresponding to World Meteorological Organization [WMO] code table 4677), the total observed cloud cover $N$ (in oktas, corresponding to WMO code table 2700), and the measured air temperature $AT$. The subsequent filtering of reports to arrive at a more consistent and homogeneous collection of maritime observations, described below, follows the procedure outlined in Petty and Tran (2023) except where noted.

Only observations associated with a platform type ($PT$) of 0 (U.S. Navy, “deck” log, or unknown), 1 (merchant ship or foreign military), and 5 (ship) were used; observations with missing $PT$ were excluded. On 1 January 1982, a WMO rule change went into effect that permitted a $ww$ value of “/” (encoded as a blank $ww$ value) if there was no significant present weather observed by a human observer (Dai, 2001). A new station/weather indicator ($ix$) was introduced by the rule change to clarify whether or not omission of $ww$ was due to the lack of significant weather or the lack of data availability. Ship observations quickly adopted the practice of $ww$ during insignificant weather but did not reliably use $ix$ until 1985 (Hahn et al., 1992).

To address cases where $ix$ could not be used to determine the availability of $ww$, the accompanying presence of non-missing $N$ was used as a proxy for establishing that a human observer was present and omitted $ww$. Thus, ship observations providing either $N$ or $ww$ were kept, with an absence of $ww$ accompanying extant $N$ presumed to indicate no precipitation. All present weather observations tagged as automated ($ix \geq 4$) were excluded. The procedure using $N$ has also been employed in previous analyses of present weather in ICOADS ship reports (e.g. da Silva et al., 1994; Petty, 1995; Petty & Tran, 2023).

Due to clearly spurious temporal and spatial inhomogeneities resulting from their inclusion in the analyzed dataset, observations associated with the Inter-American Tuna Commission (IATTC, deck number [DCK] 667) and the Russian Marine Meteorological Data Set (MORMET, DCK= 732) were excluded. Some prior analyses of ICOADS have also excluded these datasets for the same reason (Woodruff, 1995).

The ICOADS dataset includes some $ww$ reports of frozen precipitation at unrealistically warm temperatures, though collectively these are a small fraction of the overall dataset (~0.001%). To avoid spurious depictions of non-zero frozen precipitation fraction over warm ocean areas, only reports with non-missing air temperature ($AT$) were retained, and frozen precipitation observations accompanied by $AT > 10\degree C$ were discarded. This additional filter differs from Petty and Tran (2023).

Altogether, the fully filtered dataset, covering the 70 years from 1950 through 2019, contains 99.7 million shipboard observations. In addition to the ship reports, we used gridded sea surface temperature (SST) from the Kaplan Extended SST V2 dataset (A. Kaplan et al., 1998).

2.2 Methods

The present weather code $ww$ encompasses a wide array of observable meteorological phenomena. Observations coded with $ww \geq 50$ are associated with the occurrence of precipitation at the time and location of observation. Within this range, there are several subcategories, with codes 50–59 indicating continuous or intermittent drizzle of various intensities, 60–69 non-showery rain, 70–79 non-showery frozen precipitation, 80–90 showers (liquid or frozen), and 90–99 precipitation associated with a thunderstorm (Petty, 1995). The occurrence of precipitation takes precedence over other phenomena in determining $ww$, and thus a report indicating $ww < 50$ rules out precipitation occurring at the time of observation (Petty & Tran, 2023). The precipitating present weather codes can be further subdivided based on the intensity, phase, and character of the precipita-
Table 1. Selected *ww* groupings pertaining to precipitation intensity, character, and phase. See Table 1 in Petty (1995) for interpretations of individual *ww* codes.

<table>
<thead>
<tr>
<th>Category</th>
<th><em>ww</em> codes</th>
</tr>
</thead>
<tbody>
<tr>
<td>All precipitation</td>
<td><em>ww</em> ≥ 50</td>
</tr>
<tr>
<td>Drizzle-intensity precipitation</td>
<td>50, 51, 52, 53, 54, 55, 57, 65, 77, 78</td>
</tr>
<tr>
<td>Moderate/heavy precipitation</td>
<td>59, 62, 63, 64, 65, 67, 69, 72, 73, 74, 75, 81, 82, 84, 86, 88, 90, 94, 95, 96, 97, 98, 99</td>
</tr>
<tr>
<td>Strong convection and thunderstorms</td>
<td>82, 89, 90, 91, 92, 93, 94, 95, 96, 97, 98, 99</td>
</tr>
<tr>
<td>Frozen precipitation</td>
<td>70, 71, 72, 73, 74, 75, 76, 77, 78, 85, 86</td>
</tr>
</tbody>
</table>

As with Petty and Tran (2023), ship reports were mapped to a $1^\circ \times 1^\circ$ resolution grid at monthly resolution, producing a total number of reports $n$ and $m$ observations of the desired subset of precipitation. The resulting grids were then aggregated both annually and over 3-month seasons and coarser spatial resolutions of $3^\circ$, $5^\circ$, $7^\circ$, $9^\circ$, and $11^\circ$ latitude and longitude, as well as a coarsest spatial resolution of $13^\circ$ latitude by $26^\circ$ longitude.

For sufficiently large sample size $n$, $m/n$ provides a good estimate of the unknown true fraction of occurrence $f$. For small $m$ and/or $n$, however, this ratio significantly underestimates the expected value of $f$. This is especially apparent when $m = 0$, since a significant range of non-zero $f$ can be statistically consistent with this outcome. Unbiased estimates $\hat{f}$ of $f$ and associated sampling uncertainty $\hat{\sigma}$ are therefore calculated as follows:

\[
\hat{f} = \frac{m + 1}{n + 2} \quad (1)
\]
\[
\hat{\sigma} = \left[ \frac{(m + 1)(n - m + 1)}{(n + 3)(n + 2)^2} \right]^{1/2} \quad (2)
\]

These equations correspond to a Bayesian determination of the expected value of $f$, assuming a uniform distribution on the interval [0,1] as a non-informative prior. Equation (1) is appropriate when $m$ and/or $f$ are small (e.g. Basu et al., 1996) and reduces to $m/n$, as expected, for large $n$ and $m$. When $n < 5$ and $m = 0$, the uncertainty is considered too large to be useful, and $\hat{f}$ is treated as indeterminate.

$\hat{f}$ and $\hat{\sigma}$ are initially computed at the coarsest spatial resolution and progressively replaced by repeated computation at finer resolutions at each $1^\circ \times 1^\circ$ gridbox only if the finer sampling did not markedly increase the relative uncertainty $\hat{\sigma}/\hat{f}$. This procedure results in composite maps of frequency and trends that reflect coarser geographic aggregations of reports in data-sparse regions and finer resolution in data-rich regions such as near shipping lanes and coastal areas. This procedure was performed independently for each seasonal period.

Trends in frequency were computed using ordinary least-squares regression, with the significance of those trends relative to the null hypothesis of zero trend evaluated using a two-tailed Student’s $t$-test at the 95% confidence level. Though the length of the time series at each gridbox $S = 70$ years, a reduced effective independent sample size...
\[ S' = S(1 - \rho)/(1 + \rho) \], where \( \rho \) is the lag-1 autocorrelation, was used for significance testing of both trends and correlations (Box et al., 2015).

Trends and frequencies were not computed for grid cells where more than 5 years of aggregate data were missing or where \( \hat{\sigma}/\hat{f} \geq 0.4 \). As this determination varies depending on the number of relevant ship observations, the data coverage presented below differs between \( \text{ww} \) groupings.

To compare data from the 1°×1° resolution gridded shipboard data with the 5°×5° resolution SST data, the latter were interpolated to a 1°×1° grid. To assess the correlation between the two datasets, each dataset was detrended by subtracting the least-squares regression from 1950 to 2019 before computing the Pearson correlation coefficient \( r \) between the yearly relative precipitation frequencies and the yearly mean Kaplan SST anomaly. A two-tailed Student’s \( t \)-test utilizing the reduced sample size \( S' \) was used to evaluate significance relative to the null hypothesis of \( r = 0 \) at the 95% confidence level.

3 Results

In the following, results are presented for four categories of precipitation: 1) drizzle-intensity, 2) moderate or heavy intensity, 3) deep convection and thunderstorms, and 4) ice-phase. In groups 1 and 4, the statistics considered are the fraction of these reports relative to the occurrence of precipitation of any type, while groups 2 and 3 are characterized relative to the occurrence of non-drizzle precipitation. Where trends are discussed below, we confine our attention to trends identified as significant at the 95% level, as indicated by a lack of stippling in the associated maps, unless otherwise noted.

3.1 Drizzle-intensity fraction

As a fraction of all reports of precipitation in progress, drizzle-intensity reports are most prevalent in the mid-latitudes, particularly over the eastern halves of oceanic basins within the summer hemisphere and along the western coast of South America (Figure 1). The annual zonal mean fraction of shipboard precipitation with drizzle intensity peaks at roughly \( \pm 45^\circ \) latitude, reaching approximately 0.39±0.09 and 0.33±0.01 in the Southern and Northern Hemispheres, respectively.

The annual fraction of ship-reported drizzle is generally negatively correlated with SST over the eastern Pacific and positively correlated over the western Pacific (Figure 2a). Positive correlation coefficients are highest in the mid-latitudes of the northwestern Pacific and North Atlantic while negative correlations are strongest in the equatorial East Pacific and off the Pacific coasts of Canada and the United States.

From 1950 through 2019, an increase in the proportion of drizzle-intensity precipitation is broadly observed over the tropics, with weakly negative trends in the mid- to high-latitudes (Figure 3). Positive trends in drizzle proportion are statistically significant over much of the lower latitudes (30°S–30°N) within all oceanic basins. The fractional zonal mean increase in the proportion of precipitation reports with drizzle intensity are broadly on the order of 5% per decade equatorward of 30°, equivalent to roughly a 1 percentage point increase in the absolute drizzle proportion per decade. The observed drizzle fraction trend is positive across all of the oceanic tropics except for marginal decreases in parts of the eastern Pacific and Western Caribbean.

Absolute and relative trends are most strongly positive within the East China Sea, off the eastern coast of Brazil, across the subtropical South Pacific, and in the equatorial Indian Ocean. These trends are generally consistent between seasons and in the annual aggregate. The positive trend in drizzle fraction off the eastern coast of Brazil appears to be influenced by abnormally frequent reporting of drizzle in 2016 and 2018 (Fig-
ure 4b), though a long-term increasing trend is still evident outside of those years. Other regional variations in drizzle proportion reflect consistent gradual trends over the 70-year period.

A possible signal of multidecadal variability is observed over the western Pacific and equatorial Indian Ocean, with minima in drizzle frequency occurring around 1960, 1980, and 2005 in both regions. The Pacific and eastern Atlantic north of 30°N show a weak but statistically significant decrease in drizzle proportion, particularly in JJA (Figure 3d).

### 3.2 Moderate/heavy non-drizzle fraction

Moderate and heavy precipitation accounts for a larger fraction of non-drizzle precipitation reports over the tropical and equatorial regions, with lower frequencies over parts of the eastern North Pacific and eastern South Atlantic (Figure 5). More frequent heavier precipitation is observed over the equatorial Indian Ocean and around the Maritime Continent.

The zonal mean annual fraction peaks at $0.44 \pm 0.04$ near 5°N and exhibits minima of $0.39 \pm 0.06$ at 25°S and $0.37 \pm 0.03$ at 25°N. Over much of the Northern Hemisphere, the annual relative fraction of moderate to heavy non-drizzle precipitation is negatively correlated with SST and somewhat positively correlated throughout the Southern Hemisphere (Figure 2b).

The zonal mean trend in moderate and heavy intensity non-drizzle precipitation reports exhibits a broad maximum in the subtropical Northern Hemisphere and a broad minimum in the subtropical Southern Hemisphere both annually and seasonally. The broader zonal pattern differs between the Northern and Southern Hemisphere, with the tropical Southern Hemisphere lacking the broad positive trends observed in the North Pacific.

A prominent region of statistically significant increase is observed over the central and eastern Pacific between 15–30°N for the annual fraction, with increases in seasonal fractions throughout the same areas and along the Pacific coasts of the United States and Canada (Figure 6). Most of this positive trend appears to be associated with a fractional increase in reports of moderate and heavy precipitation from about 1950 to 1970, with little trend evident during 1970–2019 for those areas. The fractional positive trends in these regions are on the order of 5–10% per decade, corresponding to a roughly 2–4% increase in the fraction both annually and seasonally. Statistically significant positive trends are also observed over the Mediterranean Sea. The regions of negative 70-year trends are smaller and exhibit lower magnitude than positive-trending areas globally.

### 3.3 Deep convection/thunderstorms fraction

Shipboard precipitation reports associated with thunderstorms or otherwise deep convection are most prevalent in the equatorial Atlantic, western tropical Atlantic, off the Pacific coast of Mexico, and within the Mediterranean Sea (Figure 8). In these areas, the annual fraction is on the order of 0.15. For areas with sufficiently low uncertainty, the zonal mean fraction of ship-reported thunderstorm or deep convection broadly peaks at roughly $0.10 \pm 0.02$ at 15°N and declines poleward.

Shipboard reports of deep convection or thunderstorms within the frequency hotspots in the Western Hemisphere peak during boreal summer and peak in the Mediterranean during boreal autumn. Over the equatorial Indian Ocean and western Pacific, thunderstorm and deep convection-related precipitation reports are most prevalent during boreal spring. The annual relative fraction of these reports are generally negatively correlated with SST over the subtropical North Pacific and North Atlantic, but show pos-
Figure 1. Annual and seasonal fraction of shipboard precipitation reports with drizzle-intensity precipitation, regardless of phase. Gray shading denotes areas with more than 5 years of missing values or excess uncertainty (see text) after the compositing procedure is performed.
Figure 2. Correlation coefficients between shipboard precipitation fractions and Kaplan Extended SST V2 for the period 1950–2019. Non-stippled regions are statistically significant at the 95% confidence level. Gray shading denotes areas with more than 5 years of missing values or excess uncertainty (see text) after the compositing procedure is performed.

Statistically significant negative 70-year annual trends cover much of the open northern and equatorial Atlantic, as well as within the Indian Ocean off of South India. Significant positive trends are observed along the United States East Coast and in the East China Sea in the annual fraction and in all four seasonal fractions. Positive seasonal trends have also been observed within the Sea of Japan and along the eastern and southern coasts of Japan. However, statistically significant positive trends cover a much smaller area than statistically significant negative trends.

3.4 Frozen precipitation fraction

As a fraction of overall precipitation reports, frozen precipitation is most prevalent within the Antarctic and Arctic circles, accounting for the majority of annual ship-reported precipitation occurrence. Within the Northern Hemisphere, where cold-season ship observations are more numerous, higher frozen precipitation fractions extend southward into the Sea of Okhotsk and south of the Labrador Sea offshore Atlantic Canada and the northeastern United States. These fractions are highest in boreal winter and lowest in boreal summer, when frozen precipitation reports are largely absent. The mean annual fraction in the Northern Hemisphere is below 1% equatorward of 35°N. Frozen precipitation shows statistically significant negative correlations with SST throughout most of the Northern Hemisphere for which fractions were computed (Figure 2d).

Along the southern fringes of the Northern Hemisphere regions with a mean frozen precipitation fraction ≥ 1%, the fraction of observed frozen precipitation has tended to
Relative Trend in Fraction of Precipitation with Drizzle Intensity
(Unstippled: Significant at 95% Confidence Level)

Figure 3. Relative linear best-fit trend (in percent per decade) of the annual and seasonal fractions of shipboard precipitation reports with drizzle intensity precipitation, regardless of phase. Non-stippled regions are statistically significant at the 95% confidence level. Gray shading denotes areas with more than 5 years of missing values or excess uncertainty within the ship data after the compositing procedure is performed.
Figure 4. Regionally-aggregated area-weighted time series of year-to-year annual and seasonal fractions of shipboard precipitation reports with drizzle intensity precipitation (left) over the selected region outlined by the rectangular region (right). Gray shading denotes areas with more than 5 years of missing values or excess uncertainty (see text).
Figure 5. As in Figure 1, but for shipboard precipitating non-drizzle reports associated with moderate or heavy intensities.
Figure 6. As in Figure 3, but for shipboard precipitating non-drizzle reports associated with moderate or heavy intensities.
Figure 7. As in Figure 4, but for shipboard precipitating non-drizzle reports.
Figure 8. As in Figure 1, but for shipboard precipitation reports associated with deep convection or thunderstorms.
Figure 9. As in Figure 3, but for shipboard precipitation reports associated with deep convection or thunderstorms.
Figure 10. As in Figure 4, but for shipboard precipitation reports associated with deep convection or thunderstorms.
decrease (Figure 12). Trends in these areas have been especially apparent since the 1990s (Figure 13). Statistically significant decreases in the annual occurrence with relative trends on the order of 10–15% per decade are prominent over the Norwegian Sea, and over the central North Pacific south of Alaska between roughly 40–50°N.

Increasing trends are observed over an area of the North Atlantic south of Greenland and east of Newfoundland, approximately in the region bounded by 40–52°W, 35–55°W. Varying trends are apparent over the Southern Ocean, particularly during DJF, including statistically significant negative trends within the Drake Passage and significant positive trends in the Cooperation Sea south of the Indian Ocean.

4 Discussion

4.1 Drizzle fraction

The general features of the global oceanic drizzle distribution as a proportion of precipitation occurrences are broadly similar to results obtained by Petty (1995) and Dai (2001) for the period 1958-1991 and 1975-1997, respectively, with the greatest proportion of drizzle occurring over areas with greater subsidence. Among the precipitation classes analyzed, trends associated with drizzle were the most widespread and highest in magnitude. The often consistent trend in drizzle fraction suggests that the underlying physical mechanisms supporting the trend are not strictly seasonal. Increased anthropogenic aerosol production has been associated with decreased drizzle production via direct modification of cloud condensation nuclei (CCN) distributions (Ferek et al., 2000; Fu & Dan, 2014) or increased CCN concentrations overall (Mann et al., 2014). Ships themselves may locally suppress drizzle via aerosol emission (Ferek et al., 2000), though the distribution of drizzle frequencies and trends shows little difference between heavily and lightly traversed waters.

Statistically significant trends in ship-observed drizzle frequency are less widespread when restricted to the much shorter satellite-based record of aerosol optical depth (AOD). Increasing trends in annual AOD were highlighted by Mehta et al. (2016) around the Arabian Peninsula and the Indian subcontinent using data from the Moderate Resolution Imaging Spectroradiometer (MODIS) and Multiangle Imaging Spectroradiometer (MISR) for the period 2001–2014. The trends in annual ship-reported drizzle fraction in these areas were negative during this period, consistent with suppression of drizzle production by aerosols. The negative trends in AOD observed by MODIS throughout much of the tropics are broadly coincident with the widespread increase in drizzle fraction over the larger 70-year period, though drizzle trends are less consistent when limiting the ship record to 2001-2014.

Drizzle is especially ubiquitous in marine boundary layer stratocumulus clouds, which occur throughout much of the global ocean but are most frequent across the North Pacific north of 35°N, in the eastern subtropical North Pacific, across the North Atlantic north of 40°N, and in the eastern subtropical South Atlantic (Klein & Hartmann, 1993; vanZanten et al., 2005; Briet et al., 2019). Except for some regions in the North Atlantic, there has been a slight decrease in the proportion of shipboard precipitation observations reporting drizzle across these areas over the past 70 years. These regions are among the few where decreases in the fraction of drizzle observed by ships are statistically significant. Consequently, zones that typically experience the most frequent drizzle have observed a general decline in reported drizzle occurrences, whereas areas with historically less frequent drizzle have noted increases in such reports. The downward trends in high-drizzle areas might suggest a reduction in marine stratocumulus occurrences or a decline in the efficiency of these clouds to produce drizzle. Conversely, there could be an increase in stratocumulus cloud coverage or an improvement in drizzle production efficiency in tropical regions.
Figure 11. As in Figure 1, but for shipboard precipitation reports associated with frozen hydrometeors. Additionally, areas with less than 1% annual or seasonal fraction are also omitted (shaded in gray) along with areas with excess uncertainty.
Relative Trend in Fraction of Precipitation with Frozen Phase
(Unstippled: Significant at 95% Confidence Level)

Figure 12. As in Figure 3, but for shipboard precipitation reports associated with frozen hydrometeors. Additionally, areas with less than 1% annual or seasonal fraction are also omitted (shaded in gray) along with areas with excess uncertainty.
Figure 13. As in Figure 4, but for shipboard precipitation reports associated with frozen hydrometeors. Additionally, areas with less than 1% annual or seasonal fraction are also omitted (shaded in gray) along with areas with excess uncertainty.
The microphysical properties of these clouds and their behavior are substantially influenced by the properties of aerosols in the local environment (Lu et al., 2018; Christensen et al., 2020). Increased aerosol concentrations are associated with increased cloud cover in the stable atmospheric conditions characteristic of stratocumuli (Christensen et al., 2020). However, satellite-derived cloud cover trends since the 1980s differ between these stratocumulus-rich regions (Norris et al., 2016), suggesting that changes in the coverage of marine stratocumuli alone are an insufficient indicator for a possible mechanism producing the observed trends in drizzle in those locations. Satellite-derived trends in the occurrence of low clouds (Marchand, 2013) are also geographically inconsistent with the geographic distribution of ship-based drizzle trends in both regions of increasing and decreasing ship-reported drizzle frequency.

Changes in drizzle frequency within marine stratocumuli might also be associated with changes in cloud depth. Thicker clouds more readily produce drizzle (Yamaguchi et al., 2017) and exhibit greater virga depth (F. Yang et al., 2018), with thicker stratocumuli increasing the likelihood of drizzle registering as surface precipitation. Additionally, the effect of drizzle suppression by aerosols is more efficient for thinner clouds (L’Ecuyer et al., 2009; Terai et al., 2012). A decrease in drizzle occurrence over the eastern oceanic basins could thus be produced by long-term decreases in the thickness of marine stratocumuli, with increases elsewhere associated with the thickening of stratocumuli. Within the Pacific, recent intensification of the Walker circulation (L’Heureux et al., 2013) may provide a mechanism for this thinning. However, consistent trends in cloud thickness have not been clearly observed over stratocumulus-rich regions (Kishcha et al., 2007; Lelli et al., 2014).

Alternatively, changes in vertical wind shear may influence drizzle production in some marine stratocumulus clouds by modifying the generation of turbulent kinetic energy and entrainment of dry air (Wu et al., 2017). In particular, an increase in shear may promote greater drizzle production in marine stratocumulus clouds while also reducing their cloud fraction and depth, as suggested by Jeong et al. (2023). Considering the shallow nature of marine boundary layer clouds, any such trends in wind shear could be confined to low altitudes.

The apparent low-frequency sinusoidal variability of the drizzle fraction in at least part of the Indian Ocean and West Pacific, with similarly timed extrema in drizzle frequency, suggests a possible influence of a large-scale mode affecting both regions. Within the Indian Ocean, the leading modes of variability for monthly-resolved SST are the El Niño-Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD; Saji et al., 1999). However, these modes have much shorter timescales than the observed decadal to multi-decadal variation in drizzle (Dommenget, 2010). Ummenhofer et al. (2017) identified a low-frequency variation in the thermocline depth of the eastern Indian Ocean with strong forcing on the behavior of IOD events and similar periodicity to the drizzle variability. This variability may be associated with the Pacific decadal oscillation (PDO; Mantua & Hare, 2002), which modulates regional precipitation behavior (e.g. Krishnan & Sugi, 2003; S. Wang et al., 2014; Wei et al., 2021), providing a possible cross-basin influence on drizzle frequency.

4.2 Heavier and/or convective precipitation fraction

Though limited in coverage, the frequency of deep convection and thunderstorms as reported by ships matches the general global distribution inferred by radio lightning sensors (J. O. Kaplan & Lau, 2021). Improvements in the prediction and monitoring of oceanic storms, potentially improving storm avoidance, could manifest as a fractional decrease in ship-reported lightning or heavier precipitation. However, the 70-year \( \Delta w \) trends indicate this is not globally evident.
The broad spatial patterns of trends are similar between the two groupings of shipboard weather reports. Increases in the relative frequency of moderate or heavy non-drizzle intensity precipitation and in the frequency of deep convection are most prevalent near western boundary currents in the Northern Hemisphere and near the Tropic of Cancer across the Central Pacific.

The increase in the fraction of heavier precipitation in the North Pacific, particularly around 15°N, may be an indicator of the poleward expansion of the Hadley cell due to climate change (Hu et al., 2010), decreasing in large-scale subsidence equatorward of the expanding subtropical dry zone. However, the region of ship-observed increases extends poleward into areas with satellite-derived decreasing trends in precipitation amount (R. Liu et al., 2015).

Simultaneous increasing trends in both heavier precipitation and drizzle, such as over the Mediterranean Sea, Yellow Sea, and Central North Pacific, may be a signal of a shift towards precipitation extremes. The ship-based trends in the Mediterranean are consistent with a shift towards more extreme precipitation events in the Mediterranean observed on land-based data (Norraert & Douguédroit, 2005). Regional climate model simulations of the Mediterranean suggest a future increase in extreme daily precipitation over land in the northern part of the Mediterranean and a decrease in the southern part of the basin (Tramblay & Somot, 2018). The ship-observed trends in the relative frequency of heavier precipitation or thunderstorms are more strongly positive in the northern part of the basin but have not indicated a decrease along the North African coast.

The ship-observed increases in the proportion of heavier precipitation in the Yellow Sea have also been observed on land-based stations along the western coast (H. Wang et al., 2017). An increase in convective available potential energy (CAPE) under warming conditions may lead to a corresponding increase in lightning activity (Romps et al., 2014). Many of the areas with ship-observed increases in deep convection and thunderstorms correspond with areas with increasing reanalysis-inferred trends in the 95th percentile of CAPE since the late-20th century (Taszarek et al., 2021). Changes in aerosol concentrations may also play a role in enhancing or suppressing cold-rain processes and lightning production (Tao et al., 2012), though satellite-observed changes in AOD are not closely aligned with the ship-observed trends in heavier precipitation and thunderstorms.

### 4.3 Frozen precipitation fraction

The decreasing trend in the annual relative frequency of frozen precipitation reports along the southern periphery of the area in the Northern Hemisphere receiving frozen precipitation provides possible evidence for a poleward retreat of the Arctic area receiving frozen precipitation. A decrease in snowfall amount along this transition zone is depicted in climate projections (Krusting et al., 2013) and was also reflected in a similar analysis of the snow event to precipitation event ratio undertaken by Shi and Liu (2021), though a corresponding increase in snowfall amount farther poleward is not distinctly apparent using shipboard frozen precipitation frequencies.

The transition from decreasing frozen precipitation frequencies in southern Japan to increasing frequencies in northern Japan is consistent with trends observed by land-based stations (Takahashi, 2020). The significant increase in the reporting of frozen-phase precipitation over the North Atlantic over a region east of Newfoundland and south of Greenland is located near a “warming hole” (Drijfhout et al., 2012; L. Li et al., 2021) where SSTs have decreased over the last century in stark contrast to the rest of the global ocean. The relative frequency of ship-reported frozen precipitation in this region appears sensitive to SST and may be capable of capturing more transient SST anomalies. For instance, the spike in the relative fraction in 2015 observed in parts of the subpolar North
Atlantic may be linked to an anomalous patch of cooler SSTs that emerged that year (Maroon et al., 2021).

The inverse relationship between SST and relative snowfall frequency is consistent with SSTs locally affecting the temperature characteristics of the lower troposphere and thus precipitation phase. Similarly, the long-term negative frozen precipitation trends in the Drake Passage appear to correspond with observed long-term negative trends in sea ice over the nearby Bellingshausen and Amundsen seas, while positive frozen precipitation trends over the southern Indian Ocean align with long-term positive trends in sea ice over the region (Parkinson & Cavalieri, 2012). These sea ice trends are also partly reflected in sea ice extent reconstructions (Fogt et al., 2022). An assessment of reanalyses by Boisvert et al. (2020) found little change in annual snowfall frequency in the period 2000-2016 within the Southern Ocean, consistent with ship-based results. However, ship-observed frozen precipitation frequencies may potentially be influenced by the navigability of the Southern Ocean.

5 Conclusions

The spatial and seasonal coherence of both magnitudes and trends in precipitation occurrence of various types, independent of variations in sampling density, lends some confidence in the reality of both. Unfortunately, corroborating data from other sources is virtually non-existent apart from satellite observations of ocean precipitation, and even the satellite record is quite short if one limits attention to the most direct indicators of precipitation occurrence, namely active microwave measurements from spaceborne Ku-band and W-band radars carried by the TRMM (1997–2015), GPM (2014–present), and CloudSat satellites (2006–2023, with reduced capabilities after 2011). In short, direct validation of the long-term trends described herein is probably impossible. However, some observed trends are broadly consistent with modeled or observed trends of precipitation and related environmental parameters.

A pronounced increase in drizzle frequency is seen annually and seasonally across the tropics, with relative trends exceeding 10% per decade in several regions. Areas with observed decreases in drizzle proportion have tended to be drizzle-rich regions. These trends may result from long-term trends in the coverage of drizzle-producing clouds, such as marine stratocumulus, or the efficiency of drizzle production, which is partly controlled by aerosol concentrations. However, the ship-observed spatial patterns of trends in oceanic drizzle are not necessarily consistent with the observed spatial patterns of changes in aerosols, and there may not be a dominant contributor to these trends globally. While there has been ample research concerning the variability of drizzle over land, further investigation of oceanic drizzle is needed to more clearly delineate possible mechanisms for the observed increase in tropical drizzle frequency.

The ship-based record captures statistically significant fractional increases in the relative proportion of moderate- and heavy-intensity non-drizzle precipitation or thunderstorms in some areas. Many areas with positive trends in relative thunderstorm frequency are consistent with reanalysis-derived positive trends in the occurrence of favorable thunderstorm environments. Shipboard observations of thunderstorms have mostly decreased over the open ocean but have shown relative increases in the western North Atlantic and western North Pacific.

Trends in the reporting of frozen precipitation in the Northern Hemisphere are consistent with a poleward retreat of oceanic areas receiving frozen precipitation, with a decrease in frozen precipitation frequency observed over the North Pacific and North Atlantic near 40°N. Over the North Atlantic, the relative proportion of frozen precipitation is well-correlated with SSTs, with an increase in frozen precipitation frequency ob-
served near a region with secular cooling SST trends. Over the Southern Ocean, ship-
observed trends in frozen precipitation are consistent with sea ice extent.

This study has primarily examined trends in precipitation occurrence. The next
phase will involve using the modern satellite PMW-based precipitation records to cal-
ibrate qualitative ship reports with the help of machine learning techniques during the
period of overlap. If successful, this approach could enable the reconstruction of more
accurate distributions and trends in ocean precipitation amounts from the pre-satellite
era, dating back to as early as 1950.

6 Open Research

ICOADS R3.0.0 and R3.0.2 (Research Data Archive, Computational and Informa-
tion Systems Laboratory, National Center for Atmospheric Research, University Corpor-
ation for Atmospheric Research et al., 2016) data were obtained from dataset ds548.0
in the National Center for Atmospheric Research (NCAR) Research Data Archive at https://
rdas.ucar.edu/datasets/ds548.0/. Kaplan Extended SST V2 data were provided by
the NOAA Physical Sciences Laboratory (NOAA PSL) at https://psl.noaa.gov/data/
gridded/data.kaplan_sst.html. Jupyter/Python notebooks used to obtain numeri-
cal and graphical results herein are available at Zenodo as gpetty/JGR-2024 via https://
doi.org/10.5281/zenodo.8140237 and are released under GNU General Public License
version 2 (GPLv2).

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References

Adler, R., Sapiano, M., Huffman, G., Wang, J.-J., Gu, G., Bolvin, D., . . . Shin,
Monthly Analysis (New Version 2.3) and a Review of 2017 Global Precipita-
Albercht, R. I., Goodman, S. J., Petersen, W. A., Buechler, D. E., Bruning, E. C.,
Blakeslee, R. J., & Christian, H. J. (2011, August). The 13 years of TRMM
Lightning Imaging Sensor: From individual flash characteristics to decadal
tendencies. In XIV ICAE: International Conference on Atmospheric Electric-
ity. Retrieved from https://ntrs.nasa.gov/api/citations/20110015779/
downloads/20110015779.pdf
Zolina, O. (2020, April). Advances in understanding large-scale responses
of the water cycle to climate change. Annals of the New York Academy of
Sciences, 1472(1), 49–75. doi: 10.1111/nyas.14337
ability of Occurrence of Tumor for a Rare Cancer with Zero Occurrence in
a Sample. Regulatory Toxicology and Pharmacology, 23(2), 139–144. doi:
10.1006/rtp.1996.0035
Bernacchi, C. J., & VanLoocke, A. (2015, April). Terrestrial ecosystems in a chang-
ing environment: a dominant role for water. Annual Review of Plant Biology,
Berry, D. I., & Kent, E. C. (2011, December). Air-Sea fluxes from ICOADS: the con-
struction of a new gridded dataset with uncertainty estimates. International


Research Data Archive, Computational and Information Systems Laboratory, National Center for Atmospheric Research, University Corporation for Atmospheric Research, Physical Sciences Laboratory, Earth System Research Laboratory, OAR, NOAA, U.S. Department of Commerce, Cooperative Institute for Research in Environmental Sciences, University of Colorado, National Oceanography Centre, University of Southampton, Met Office, Ministry of Defence, United Kingdom, Deutscher Wetterdienst (German Meteorological Service), Germany, ... National Centers for Environmental Information, NESDIS, NOAA, U.S. Department of Commerce (2016). *International comprehensive ocean-atmosphere data set (icoads) release 3, individual observations [dataset]. Boulder CO: Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. Retrieved from https://doi.org/10.5065/D6ZS2TR3


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