# Trends in Ship-Reported Oceanic Precipitation Frequency from 1958 through 2014

**Grant Petty**[1]

[1]Atmospheric and Oceanic Sciences Department, University of Wisconsin-Madison

**Key Points:**

- An analysis of 57 years global shipboard observations of precipitation occurrence reveals trends of up to ∼15% per decade in oceanic precipitation frequency.
- Negative trends are observed primarily over middle- and high-latitude oceans, while large positive trends dominate throughout the tropics and subtropics.

Corresponding author: Grant W. Petty, `gwpetty@wisc.edu`

**Abstract**

57 years of qualitative ship-board weather reports are used to assess apparent trends in precipitation occurrence over the global oceans. Positive trends of up to ∼15% per decade, relative to the long term mean precipitation frequency at a location, are found over most tropical and temperate ocean areas, with negative trends of up to ∼5% per decade being found principally at higher latitudes. While it cannot be ruled out that the observed trends are an artifact of gradual changes in shipboard weather reporting habits or procedures over time, no specific candidate for such a change has been identified that could explain the existence of robust positive and negative trends and their apparent geographic coherence.

## 1 Introduction

In the era of calibrated satellite measurements of global precipitation, one that has reached its apparent zenith with the Global Precipitation Measurement (GPM) program beginning in 2014 (Skofronick-Jackson et al., 2017), we have unprecedented information about the current distribution and seasonal evolution of ocean precipitation. What remains difficult, due both to the shortness and heterogeneity of the various satellite records, is the confident assessment of multi-decadal trends in oceanic precipitation occurrence and/or amount, especially at higher latitudes, where shallower, lighter precipitation tends to escape detection by even microwave sensors (Petty, 1997; Behrangi, 2020). The most complete satellite assessment of regional trends in precipitation appears to be that of Adler et al. (2017), covering the 36-year period 1979–2014 and based on the Global Precipitation Climatology Project (GPCP) precipitation product (Huffman et al., 2009). But given the reliance of the GPCP prior to 1988 on highly indirect infrared-based estimates of precipitation amount—estimates for which there was no quantitative calibration over most ocean areas, it is difficult to know how much confidence to place in that portion of the record, especially at higher latitudes where the correlation between cloud-top temperature and surface precipitation is especially weak.

For earlier periods, the most direct information concerning oceanic precipitation existed mainly in the form of subjective and qualitative reports of precipitation occurrence and type submitted by sparsely and unevenly distributed commercial and military vessels. A number of authors derived estimates of monthly precipitation amount by assigning nominal intensities to each common present-weather code and aggregating ship reports over time (Tucker, 1961; Reed, 1979; Dorman & Bourke, 1979; Legates & Willmott, 1990).

Sidestepping the fraught problem of estimating rainfall amount, Petty (1995) derived a global climatology of ocean precipitation frequency and characteristics from 34 years of synoptic ship weather reports spanning the period 1958 to 1991. The motivation at the time was to evaluate satellite-based determinations of simple precipitation occurrence (Petty, 1997) and to elucidate regional and seasonal variations in precipitation properties likely to introduce biases into satellite retrievals of rainfall amount. The high-latitude ocean precipitation frequencies derived by by Petty (1995) were at sharply odds with the much lower microwave-derived estimates of that era (Petty, 1997) but were later largely corroborated by CloudSat (Ellis et al., 2009).

The original data set employed was the Comprehensive Ocean-Atmosphere Data Set (COADS) described by Woodruff et al. (1987). Although marine weather reports of various types are archived going back as far as 1662, the starting year for the analysis by Petty (1995) was chosen based on concerns about possibly inconsistent reporting criteria prior to that date (Reed, 1979).

With the availability today of 23 additional years of ship weather reports, this paper extends the previous analysis by examining long-term trends in the reported frequency

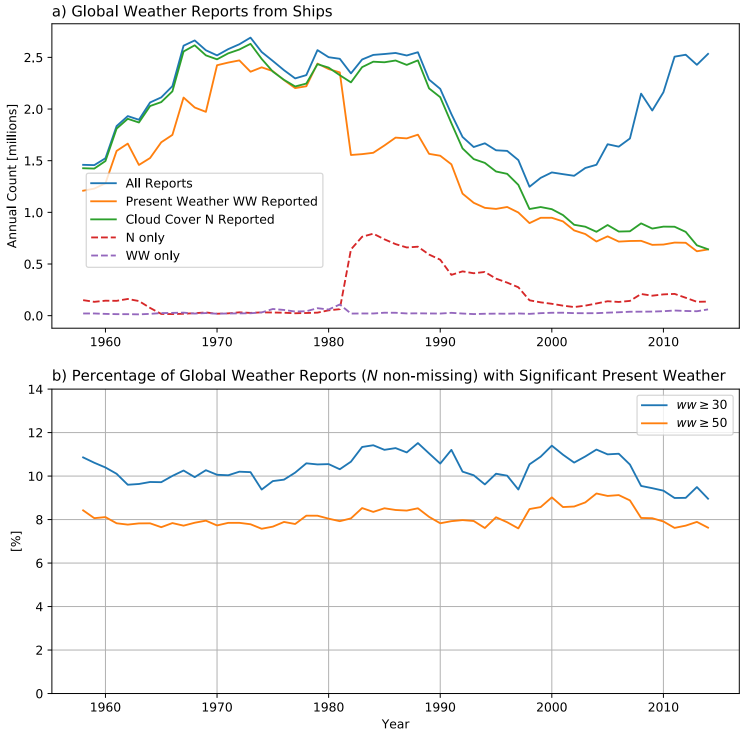


**Figure 1.** a) Gross annual counts and selected subsets of ship weather reports utilized in the analysis. b) Percentage of reports of significant present weather ($ww \geq 30$) and of precipitation ($ww \geq 50$) relative to all reports with non-missing sky cover reports $N$.

of precipitation, also known as fractional time precipitating. This effort is motivated in part by model projections of changes in precipitation frequency in response to climate change (Chou et al., 2012).

Despite significant limitations and ambiguities (see below), there is no other source of ocean precipitation data extensive enough in both time and space to permit a similar analysis covering nearly six decades. For the same reason, it may be fundamentally impossible to validate the findings herein against independent determinations of precipitation frequency far from land—such data simply do not exist. Small island weather stations believed to be representative of open-ocean conditions and found mainly in the tropics (Morrissey et al., 1995) normally report only rainfall accumulations, not precipitation occurrence.

# 2 Data

## 2.1 Source

We utilized an updated version of COADS known as the International Comprehensive Ocean-Atmosphere Data Set (ICOADS) Release 3, Individual Observations (Freeman et al., 2017; Research Data Archive, Computational and Information Systems Laboratory, National Center for Atmospheric Research, University Corporation for Atmospheric Research et al., 2016), which is available through 2014. Although this data set includes everything from manned vessels and buoys to autonomous profiling devices and tide gauges, the specific platform types associated with human observations of present weather include "U.S. Navy" (16.2 million reports, 1958–2014), "merchant/foreign ship" (2.9 million), "ocean station vessel – off station" (0.4 million), "ocean station vessel – on station" (0.6 million), "lightship" (0.7 million), and, the largest category, generic "ship" (96.6 million).

Of the above platform types, only reports from type "ship" are available without interruption throughout the period of interest. Reports identified as "U.S. Navy" are the most numerous type during the first decade of the period but abruptly disappear from the record starting in about 1978, only to reappear in moderate numbers after 2004. We elected to utilize just these two platform types in the analysis that follows, because Navy ship reports could be expected to fill in some ocean areas not well covered by commercial shipping lanes and because we suspected that Navy reports were simply being reclassified as "ship" during the period when they seemed to be missing.

The other platform types, which were generally available only very intermittently and in smaller numbers, were excluded. We did, however, consider whether reports from "ocean station vessel – on station" could be used in independent comparisons at their respective fixed locations. Of these vessels, only Ocean Weather Ship Papa, normally stationed at 50°N, 145°W, provided data up until 1980, allowing comparison over a 23-year period.

### 2.2 Interpretation and quality control

Of primary interest here is the present weather code *ww* normally included in ship synoptic reports taken every 3 or 6 hours. An overview of the meaning of the code values specifically related to precipitation is given by Petty (1995). For our purposes here, it is sufficient to note that codes 50−59 correspond to various manifestations of drizzle, codes 60−69 are continuous or intermittent rain, 70−79 are frozen precipitation, 80−89 are showery precipitation, and 90−99 are associated with thunderstorms. In short, we treat any value of 50 or higher as a human observation of precipitation in progress, while all other values are associated with other weather phenomena such as haze, fog, blowing spray, past precipitation, changing sky condition, etc. It is important to note that when precipitation is present, it generally takes priority as the phenomenon to report, so we can rule out the occurrence of precipitation whenever a *ww* code value less than 50 appears.

Figure 1a shows the variation in raw annual report counts based on the above selection. There are marked interdecadal fluctuations in the overall numbers of reports included in ICOADS; the reason for these fluctuations is unknown. As also seen, in approximately 1981, a rule change permitted synoptic reports to completely omit the *ww* present weather code if there was no significant weather to report. Unfortunately, this made it difficult to distinguish between those ships that simply omitted the code when not required and those that never reported present weather at all. We therefore used the reported sky cover code $N$ to discriminate between the two cases. The presumption was that if $N$ was non-missing, then a bona fide human (non-instrumental) environmental observation was made and that the absence of *ww* simply indicated a lack of precipitation or other significant weather. The sharp drop in the number of *ww* reports corresponded to comparable increase in the number of reports of $N$ only. Around 2000, there was an increasing tendency to always report *ww* and $N$ together if reported at all, but there was also a sharp increase in the number of of reports not accompanied by either $N$ or *ww*.

Based on the requirement for non-missing $N$, the final data set contained 95.8 million reports. This number is equivalent to an average of 575 ships reporting every 3 hours over the 57 years of the record.

The previously noted temporal inhomogeneities in the data set must be kept in mind when attaching significance to the trends reported below. Nevertheless, Fig. 1b shows that when attention is restricted to reports with non-missing $N$, the global percentage of *ww* reports with values of 30 or greater, indicating significant phenomena such as fog, blowing spray, precipitation, and related phenomena is a remarkably steady 9–11% over the entire period. The fraction of precipitation reports ($ww \geq 50$) is likewise rather constant near 8%. Interestingly, this seemingly invariant global precipitation occurrence is true only for the geographically biased sample determined by the distribution of reporting ships; regional trends will be seen to be quite different from zero.

### 2.3 Limitations

Shipboard precipitation observations are both qualitative and subjective, involving the determination by a human observer whether it is precipitating at the time of the observation and, if so, the categorical nature and intensity of the precipitation. No commercial or military vessels are routinely equipped with instrumentation to objectively detect or measure precipitation. Despite the subjectivity of the observation, and based on this author's experience as a U.S. Navy shipboard weather observer, the simple determination of whether or not it is precipitating reliable. Subjectivity is of far greater concern in the reporting of categorical intensity and type. In this study, we avoid the latter problem by focusing exclusively on the ratio of reports indicating precipitation of any type or intensity—from drizzle to heavy thundershowers— to all reports for a given time span and location.

Potentially more problematic are inconsistencies or biases in operational procedures, especially those that might change over the 57-year record. For example, there can be a fair weather bias if ships change course to avoid storms, and there can be a foul weather bias if weather reports are only submitted at all when weather is judged to be "significant." Also, practices may vary between merchant and military vessels and between crews with different training or levels of commitment to World Meteorological Organization (WMO) reporting standards. It must be kept in mind that shipboard synoptic observations have historically been taken in support of near-real-time analyses of weather systems over otherwise data-sparse ocean areas and not with long-term climatological applications in mind. With respect to the aims of this paper, the most important reporting biases would be those that change systematically over time.

Finally, the single most important data limitation is sampling. The geographic density of reports aggregated over the 57-year record varies by several orders of magnitude. There are large ocean areas far from shipping lanes and other commercial activities within which ship weather reports do not appear at all more than a few times per year. For all but the most densely sampled regions, any attempt to undertake a more fine-grained analysis, such stratifying by specific precipitation types, individual month, time of day, and/or higher-resolution geographic bins quickly runs into the limit imposed by sampling error. In the analysis below, we have attempted to achieve an optimum balance between spatial/temporal resolution and minimum acceptable sample size.

## 3 Methods and Results

Raw counts of total reports and of reports with $ww \geq 50$, indicating any form of precipitation, were aggregated by month in 5-degree latitude/longitude grid boxes. Figure 2a depicts the cumulative totals over the entire period. Counts frequently exceed $1 \times 10^5$ in heavily traveled areas of the north Pacific and Atlantic oceans, while reports are rare over most of the extratropical southern oceans. Figure 2b depicts total counts of precipitation-only reports, which is the figure most relevant to estimating precipitation frequency; in dry regions where precipitation is rare, robust determinations of trends can be difficult even if ship reports are common overall.

Figure 2c shows the ratio of the precipitation counts in Figure 2b to the report counts in Figure 2a, thus providing a gross depiction of overall precipitation frequency. The mag-

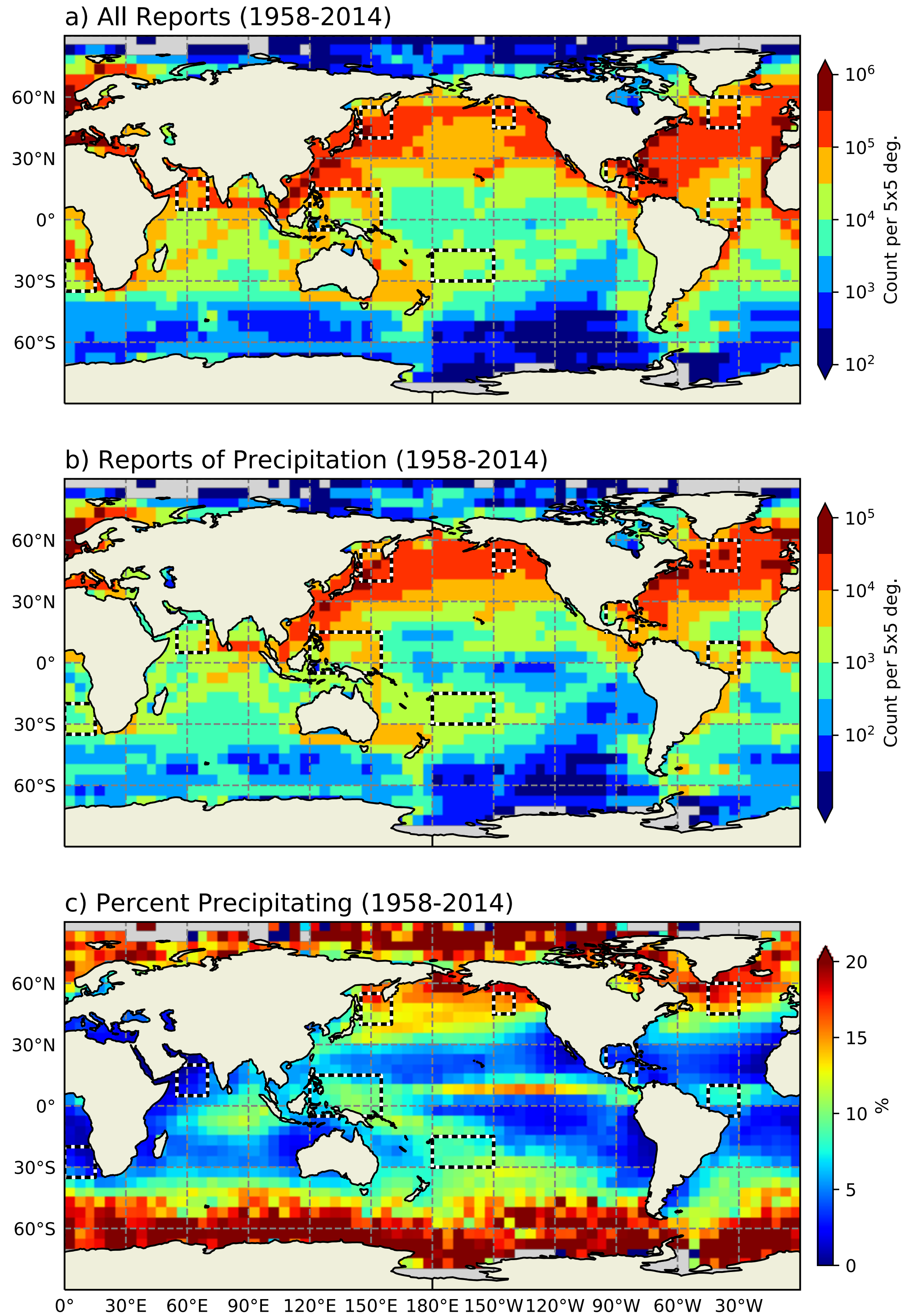


**Figure 2.** a) Total counts of included ship weather reports ("U.S. Navy" and "ship" platform types) per 5°×5° degree box over the 57-year period of interest. b) Counts of reports indicating present precipitation only. c) The ratio of precipitation reports to total reports. Nine dashed boxes depict areas selected for additional analysis.

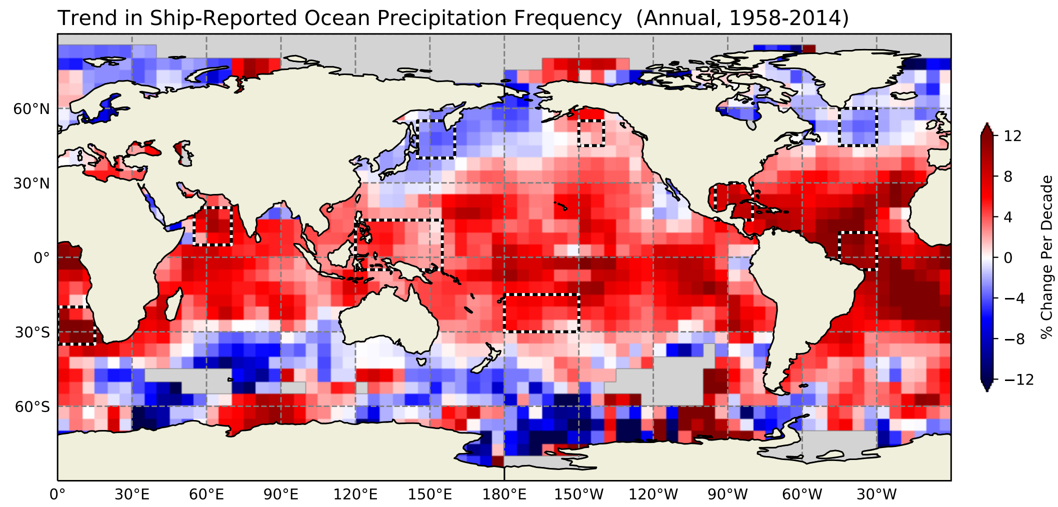


**Figure 3.** Mean trend over 57 years in precipitation frequency computed from ship reports aggregated by year and over 15°×15° boxes. Trends are expresses as percent changes (relative to the mean precipation frequency) per decade. Nine dashed boxes depict areas selected for additional analysis.

nitudes and spatial patterns are remarkably similar to those derived by Ellis et al. (2009) (their Fig. 3a) using CloudSat observations over a one-year period (August 2006 through July 2007). That such dissimilar data sources and time periods nevertheless yield nearly indistinguishable large-scale distributions of ocean precipitation frequency raises our confidence that the aforementioned data limitations do not invalidate the present analysis.

Next, we aggregated the above report counts both over entire calendar years and 15°×15° windows centered on each grid box, improving the sample density by a factor of $12 \times 9 = 108$ relative to the monthly 5° data but sacrificing both spatial and temporal resolution. Each grid point then yields a 57-year time series of precipitation frequency, from which we computed a least-squares linear fit and an associated trend, expressed in percent per decade, relative to the mean frequency over the entire period (Fig. 3).

The result of this gross trend analysis is a surprisingly consistent and spatially coherent pattern of large positive trends throughout most of the tropics and subtropics and part of the midlatitude ocean areas, especially the south Atlantic and northeast Pacific. Maximum positive trends are well in excess of 10% per decade, for example over parts of the tropical and subtropical Atlantic. Negative trends of up to $\sim -10\%$ per decade are found over the far north Atlantic, northwest Pacific, southern Indian and Pacific oceans, and in isolated pockets west of the Americas. The trend patterns over the southern oceans are noiser on account of the sparseness of ship reports. As previously noted, these raw trends could potentially be biased by temporal changes in seasonal patterns of ship traffic, but it does not seem likely that such biases, if they exist, could give rise to trends of similar sign and magnitude over such extensive contiguous areas.

Nine smaller regions were subjectively chosen for further investigation, as indicated by the dashed boxes in Figs. 2 and 3. The specific box locations were influenced in part by the existence of locally higher sample densities. One 10°×10° box centered on 50°N, 145°W in the Gulf of Alaska was chosen for comparison with with reports from OWS Papa, which were not included in the analysis and are therefore independent.

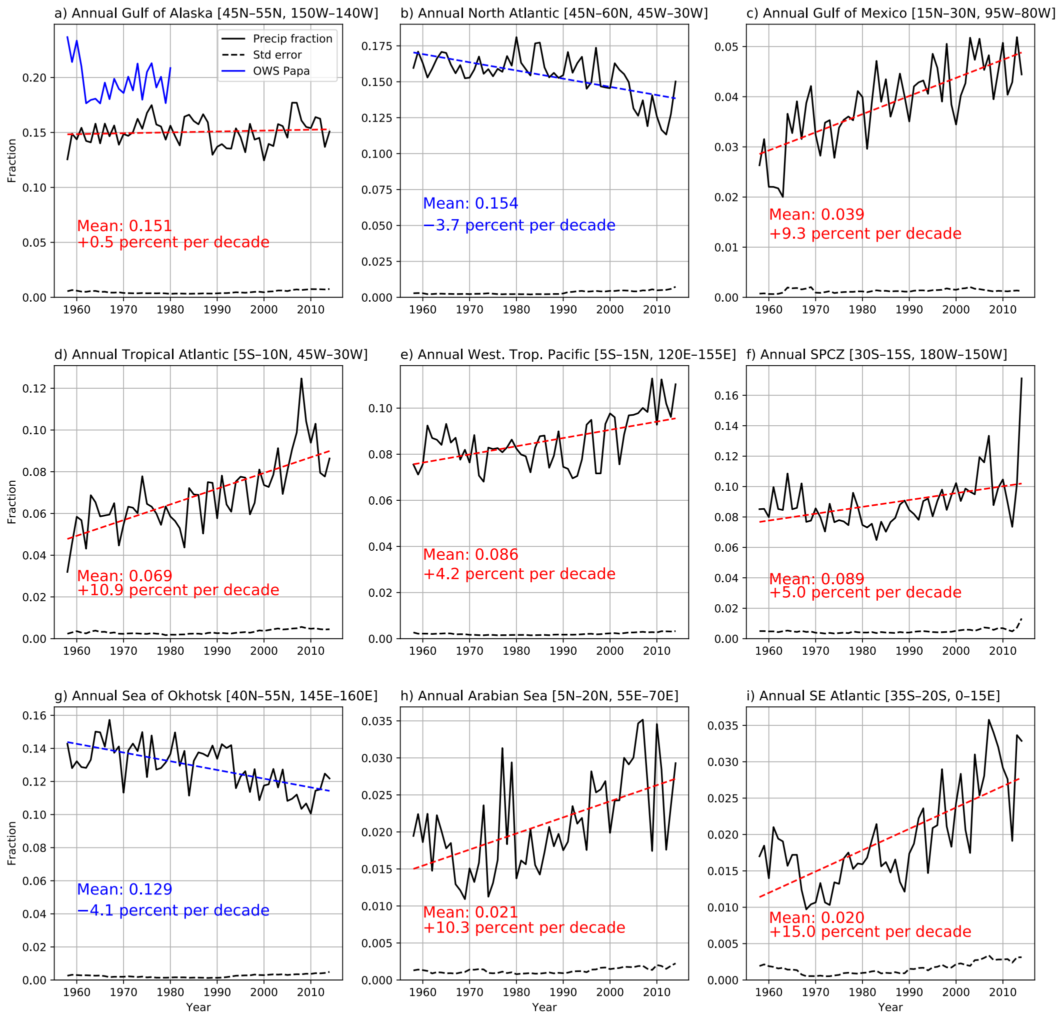


**Figure 4.** Time series of precipitation frequency computed from yearly ship reports within the indicated latitude/longitude boxes, which correspond to those depicted in Figs. 2 and 3. Dashed lines indicate the estimated random sampling error based on the number of reports (see text). Descriptive titles are for general orientation only. For the Gulf of Alaska box (a), the time series for OSW Papa is included for comparison.

**Table 1.** Trends in precipitation frequency for the indicated focus areas, expressed as the percent change per decade relative to the mean for the 57-year period. Results are given for annual pooled ship reports (same as Fig.4) and for the indicated 3-month seasons.

| Region | Latitude | Longitude | Annual | MAM | JJA | SON | DJF |
|---|---|---|---|---|---|---|---|
| Gulf of Alaska | 45N–55N | 150W–140W | +0.5 | +2.2 | −1.0 | −0.6 | +0.6 |
| North Atlantic | 45N–60N | 45W–30W | −3.7 | −5.1 | −2.5 | −4.5 | −2.6 |
| Gulf of Mexico | 15N–30N | 95W–80W | +9.3 | +5.0 | +12.2 | +9.9 | +8.1 |
| Tropical Atlantic | 5S–10N | 45W–30W | +10.9 | +9.5 | +13.7 | +11.6 | +11.1 |
| West. Trop. Pacific | 5S–15N | 120E–155E | +4.2 | +5.5 | +3.3 | +1.9 | +6.2 |
| S. Pac. Conv. Zone | 30S–15S | 180W–150W | +5.0 | +8.8 | +2.3 | +2.5 | +4.6 |
| Sea of Okhotsk | 40N–55N | 145E–160E | −4.1 | −4.7 | −6.2 | −5.6 | −3.8 |
| Arabian Sea | 5N–20N | 55E–70E | +10.3 | +5.0 | +15.6 | +10.3 | +1.3 |
| Southeast Atlantic | 35S–20S | 0–15E | +15.0 | +16.4 | +17.6 | +13.9 | +9.9 |

Time series of the annually aggregated data are depicted as solid curves in Fig. 4. For comparison, the approximate random sampling error (dashed curves) is computed as $\sigma = f N_\mathrm{p}^{-1/2}$, where $f = N_\mathrm{p}/N_\mathrm{all}$, $N_\mathrm{p}$ is the number of reports of precipitation, and $N_\mathrm{all}$ is the number of all reports.

These results reveal that the observed trends, both positive and negative, are often but not always rather linear, with the amplitude of interannual fluctuations being somewhat correlated with, but generally larger than, that expected from random sampling error alone. The largest positive trends are found in comparatively rain-free areas ($f < 0.04$), such as the Gulf of Mexico, the Arabian Sea, and the southeast Atlantic off the coast of southern Africa (Fig. 4c, h, and i, respectively). In particular, the apparent frequency of precipitation over the Gulf of Mexico increased from about 3% to almost 5% over the period in question, while in the southeast Atlantic box, it more than doubled from 1.2% to 2.7%.

In the western tropical Pacific (Fig. 4e), a linear trend is less apparent; rather, the mean frequency appears to remain relatively flat or even decrease into the 1990s before increasing fairly sharply in just the final decade. Similarly, in the Southern Pacific Convergence Zone (SPCZ; Fig. 4f), there is a general downward trend until the mid-1980s followed by a positive trend ending with a surprisingly large jump in the final year, 2014. The latter jump coincides with a much smaller-than-normal sample size for that year, so that particular feature seems suspect.

Negative trends of 4–5% per decade are seen in the north Atlantic (Fig. 4b) and near the Sea of Okhotsk (Fig. 4g). In the former case, the trend seems flat until about 2000, after which the precipitation frequency drops by about 2.5% in absolute terms or more than 15% relative to its previous average value of about 16%.

For the Gulf of Alaska case, we have the opportunity to compare the precipitation frequency from ships used in our analysis with that reported by OWS Papa at the center of the box. Recall that the ocean station vessels were excluded from the analysis, so this comparison is independent. Fig. 4a shows that the overall trend is quite flat with a mean precipitation frequency near 15%. OWS Papa, on the other hand, reports a mean frequency closer to 19%, with a significantly higher value still, near 23%, during the first three years of the period. The reasons for the discrepancies are unknown pending closer investigation but highlight, for now at least, the caveats that must be attached to climatological insights derived from the ship weather reports.

Within these boxes, ship reports were then further stratified into 3-month periods—March/April/May (MAM), June/July/August (JJA), September/October/November (SON), and December/January/February (DJF) to permit the determination of trends separately within each season. This also has the effect of reducing the potential for variable seasonal sampling biases in the determination of trends. Trends for each period are given in Table 1.

The most striking overall result is that for almost all geographic boxes, both the sign and rough magnitude of the trend is similar across seasons. The only region for which the sign changes is the Gulf of Alaska, whose overall trend is small to begin with. The general consistency of results would seem to rule out statistical sampling error alone as the source of the apparent trends. It also suggests that whatever meteorological or procedural changes may have occurred over the 57 years, they are not significantly influenced by time of year.

## 4 Conclusions

Our analysis of 57 years of shipboard synoptic reports of precipitation occurrence identifies large positive trends over most of the tropical and subtropical oceans along with negative trends over more limited areas, especially at higher latitudes. While we cannot rule out a role for long-term changes in reporting procedures, we have not yet been able to postulate a specific source of bias that could lead to the observed spatially coherent regions of positive and negative biases.

If the trends seen are correct, the positive trends seen at lower latitudes could be consistent the acceleration of the hydrological cycle and other mechanisms associated with global warming (Chou et al., 2012), while the negative trends at higher latitudes might be the result of reduced temperature contrasts and thus reduced baroclinicity and/or open-cell convective precipitation. It is notable that the largest contiguous areas of negative trend appear where wintertime frozen precipitation is the rule. It would be straightforward to extend this analysis to examine ship-based trends separately for frozen and liquid precipitation. Further analysis is also needed to assess the relationship between the trends described herein and known interannual and interdecadal climate variations, such as those represented by the El Nino/Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO), and the Atlantic Multi-decadal Oscillation (AMO), as discussed for example by Adler et al. (2017) for the shorter period 1979–2014.

With CloudSat having now operated continuously since June 2, 2006, (Stephens et al., 2008; Lebsock et al., 2020), the next step should be to directly compare CloudSat observations of precipitation frequency with our analysis for the 7.5 year period of direct overlap. Such a comparison will be most meaningful in regions where the overall occurrence of precipitation is high so as to mitigate the sampling problem. The overlap period would still be too short to identify the longer-term trends shown in Fig. 4 and Table 1, but it might be possible to validate the interannual variability in a way that could reinforce or weaken confidence in the trend. Including more recent CloudSat data might allow a general trend to be confirmed over the longer 14+ year period, though with much less confidence that this would necessarily be consistent with the earlier, longer period.

**Acknowledgments**
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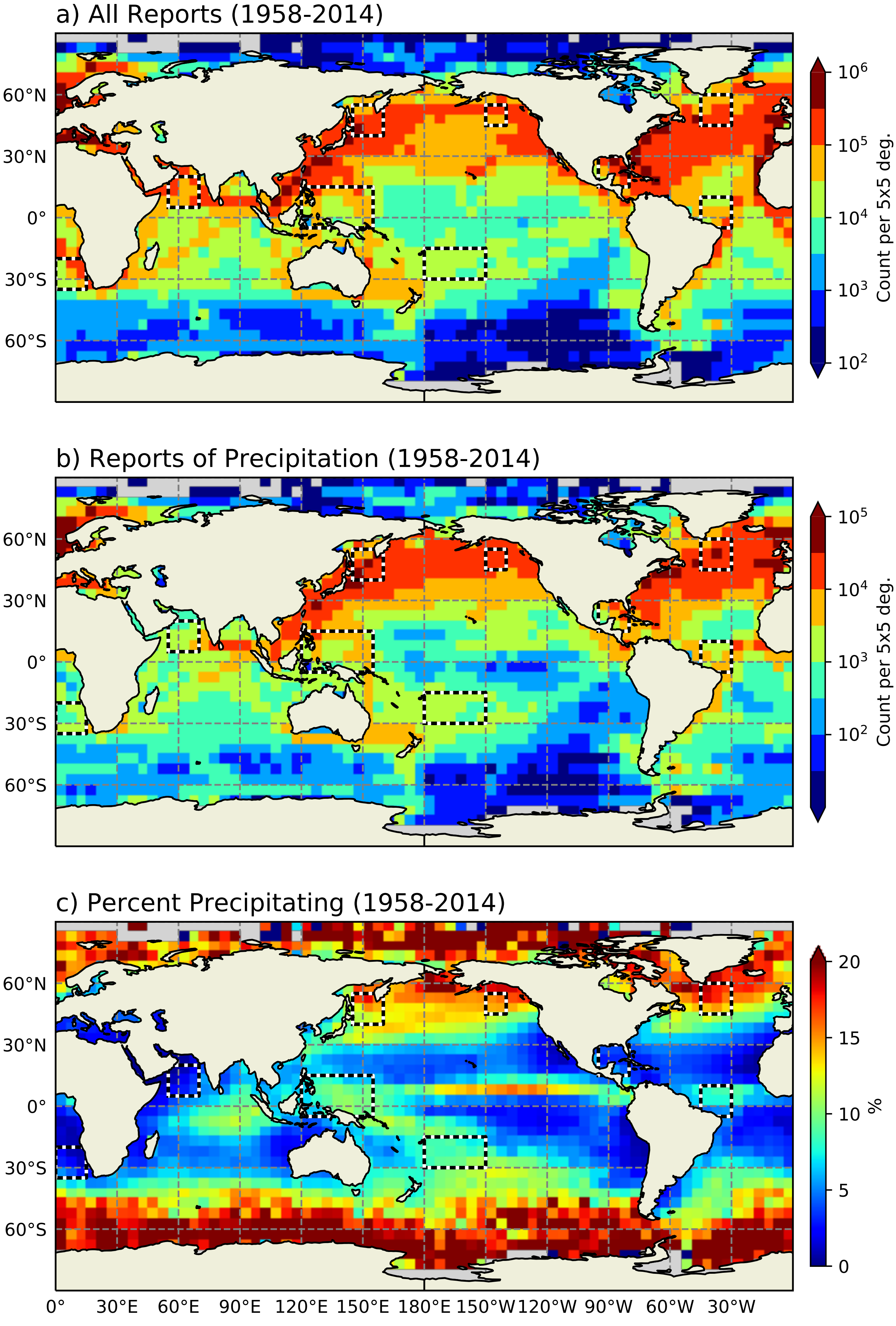
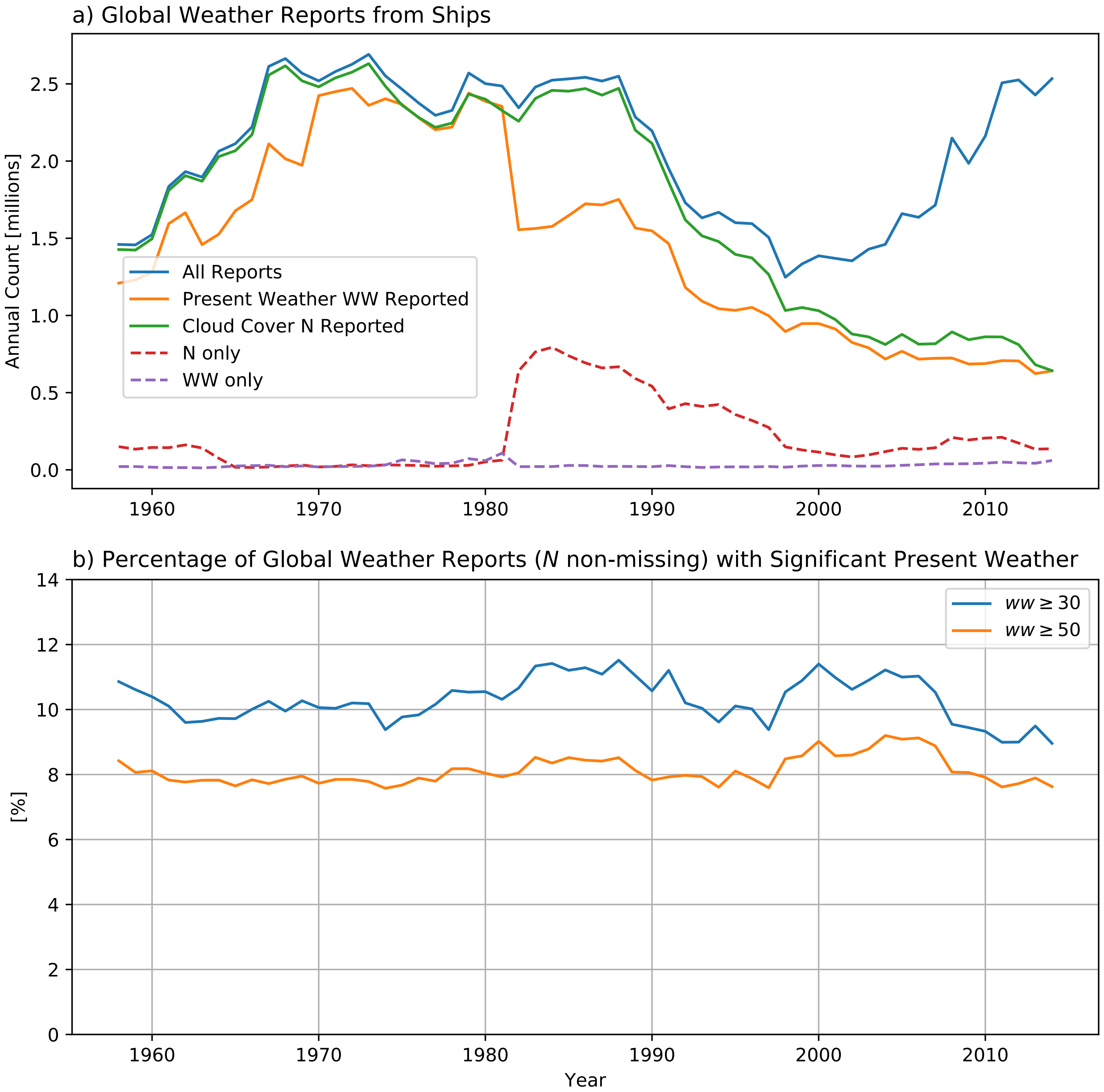
**Figure 2.**



a) All Reports (1958-2014)
b) Reports of Precipitation (1958-2014)
c) Percent Precipitating (1958-2014)
60°N
30°N
0°
30°S
60°S
0°
30°E
60°E
90°E
120°E
150°E
180°E
150°W
120°W
90°W
60°W
30°W
$10^6$
$10^5$
$10^4$
$10^3$
$10^2$
Count per 5x5 deg.
20
15
10
5
0
%

**Figure 1.**



a) Global Weather Reports from Ships
Annual Count [millions]
All Reports
Present Weather WW Reported
Cloud Cover N Reported
N only
WW only
b) Percentage of Global Weather Reports (N non-missing) with Significant Present Weather
[%]
ww ≥ 30
ww ≥ 50
Year

**Figure 3.**

Trend in Ship-Reported Ocean Precipitation Frequency (Annual, 1958-2014)

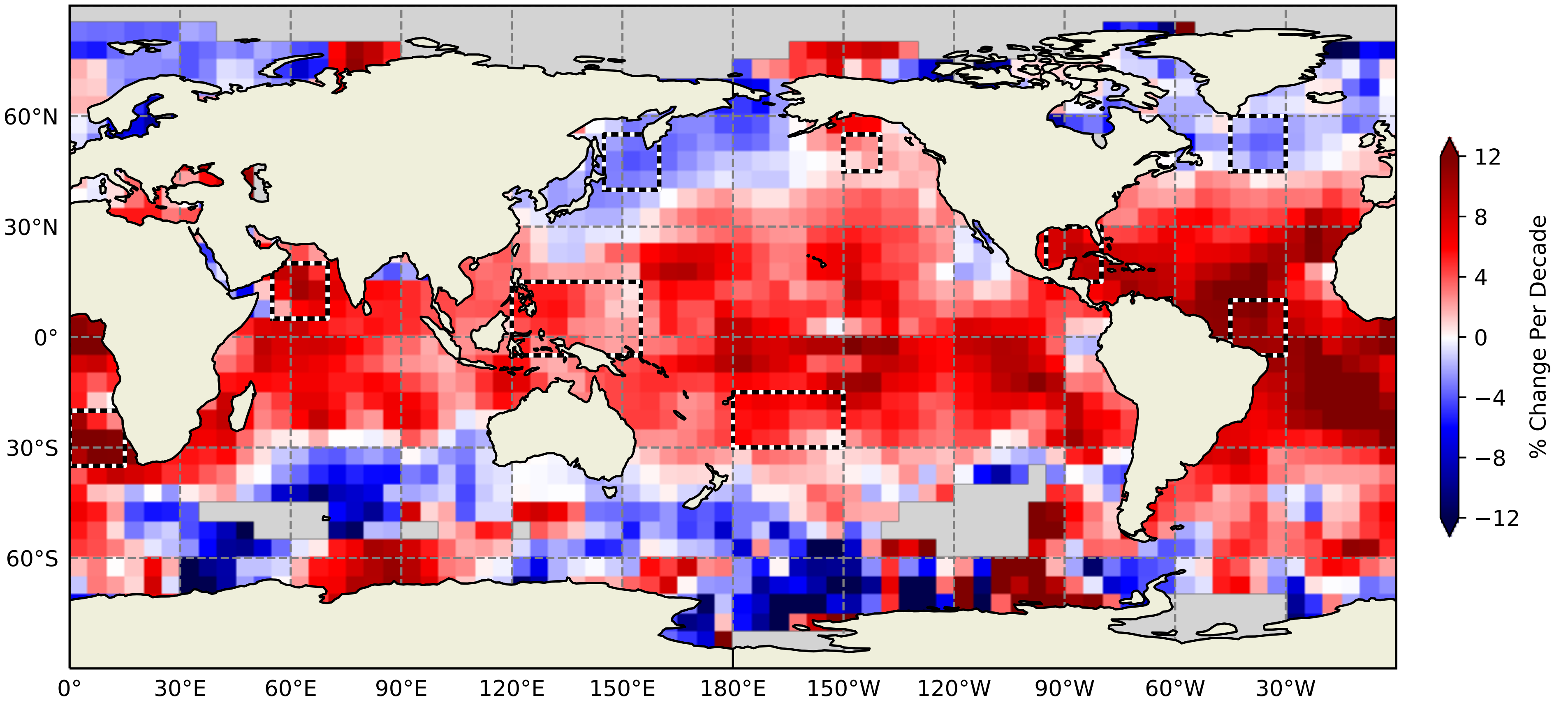
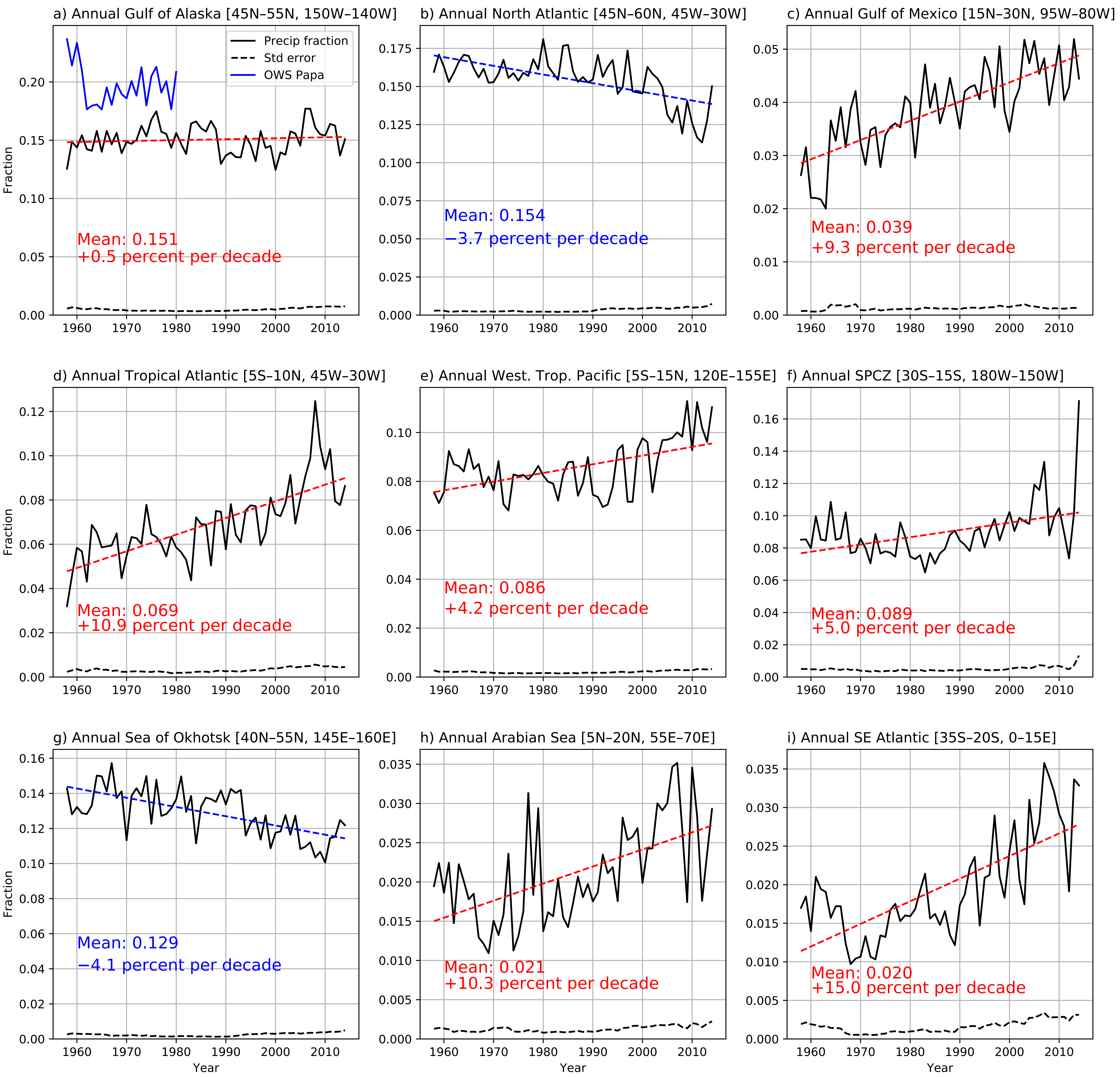


**Figure 4.**



a) Annual Gulf of Alaska [45N–55N, 150W–140W]
Precip fraction
Std error
OWS Papa
Mean: 0.151
+0.5 percent per decade
b) Annual North Atlantic [45N–60N, 45W–30W]
Mean: 0.154
−3.7 percent per decade
c) Annual Gulf of Mexico [15N–30N, 95W–80W]
Mean: 0.039
+9.3 percent per decade
d) Annual Tropical Atlantic [5S–10N, 45W–30W]
Mean: 0.069
+10.9 percent per decade
e) Annual West. Trop. Pacific [5S–15N, 120E–155E]
Mean: 0.086
+4.2 percent per decade
f) Annual SPCZ [30S–15S, 180W–150W]
Mean: 0.089
+5.0 percent per decade
g) Annual Sea of Okhotsk [40N–55N, 145E–160E]
Mean: 0.129
−4.1 percent per decade
h) Annual Arabian Sea [5N–20N, 55E–70E]
Mean: 0.021
+10.3 percent per decade
i) Annual SE Atlantic [35S–20S, 0–15E]
Mean: 0.020
+15.0 percent per decade
Fraction
Year