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Sea Surface Salinity Measurements in the Historical Database

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[1] We have examined historical distributions of sea surface salinity (SSS) observations in a data set consisting of a combination of the World Ocean Database 1998 (WOD98) and a thermosalinograph and bucket salinity database collected from volunteer observing ships. It is well known that SSS in much of the world's ocean is measured infrequently or not at all. We find that 27% of one-degree squares in the world ocean (open and coastal, excluding the Arctic Ocean) had no observations of SSS in the historical database, and 70% had 10 or fewer. Systematic sampling of SSS (more than 10,000 observations per year globally) did not start until after 1960. Most SSS observations in the WOD98 are concentrated in the North Sea and coast of northern Europe, the east and west coasts of North America, and around Japan. About 28% of SSS measurements are in coastal waters. We plotted frequency histograms of SSS for some selected well-sampled one-degree squares in the North Atlantic and tropical Pacific. We found most frequency histograms to be non-Gaussian. The main departure from normal distribution is due to anomalous low-salinity measurements creating a negative skewness. This conclusion is verified as a global phenomenon by examining statistics of mean-median SSS difference within one-degree squares. This quantity is found to be predominantly negative over the global ocean. These anomalous low-salinity values may be due to rainfall events, but there are other plausible physical mechanisms, like frontal movement and eddy activity. There were also areas where the distributions were bimodal due to the presence of meandering fronts with little cross-frontal mixing. Examples are shown where the non-Gaussian nature of the distributions in the areas examined is both a short-term and a long-term phenomenon. That is, the distributions are skewed on a nearly instantaneous (~1 month) basis and averaged over long time periods (1 + years). This has important implications for climatologies because the differences between mean and modal SSS, for the analyzed one-degree squares, is of order 0.1. Furthermore, the implication for validation studies for remote sensing missions is that the studies must make enough measurements of SSS to determine the extent to which the probability density is not Gaussian. *INDEX TERMS:* 4532 Oceanography: Physical: General circulation; 4572 Oceanography: Physical: Upper ocean processes; 4283 Oceanography: General: Water masses; *KEYWORDS:* Sea surface salinity, historical data, frequency histogram, probability density, world ocean database, skewness

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1. Introduction

[2] Sea surface salinity (SSS) has long been known to be an important, though difficult to monitor, state variable in the coastal regime. However, only relatively recently has the measurement of SSS taken on much interest among large-scale physical oceanographers and climate scientists. Indeed, an emphasis on the need for global salinity data to improve coupled climate prediction models is being made by the Climate Variability Program (CLIVAR) of the World Climate Research Program and the Global Ocean Data Assimilation Experiment (GODAE). The Salinity and Sea Ice Working Group (http://www.esr.org/lagerloef/ssiwg/ssiwgrep1.v2.html) has documented some of the scientific importance of accurate determination of SSS. Global maps

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of average SSS and standard deviation have been published (*Levitus* [1982], *Newell et al.* [1992], http://www.nodc.noaa.gov/OC5/WOA98F/woaf_cd/search.html, *Boyer et al.* [1998a, 1998b, 1998c]); so we have some idea of the distribution of mean SSS on the largest global scale. The main features of the mean SSS include large high-salinity areas in the middle of the subtropical gyres of each ocean and lower salinities in high latitudes and in the tropics [*Boyer et al.*, 1998a, 1998b, 1998c]. Such descriptions are formulated by using sparsely distributed data mapped with a large-scale (550 km [*Boyer et al.*, 1998a, 1998b, 1998c]) spatial filter. With a few exceptions based on ship-of-opportunity measurements [e.g., *Delcroix et al.*, 1998; *Hénin et al.*, 1998; *Poulos et al.*, 1997], we have almost no information about the variability of SSS on monthly, seasonal, or interannual timescales.

[3] SSS variations are important for a range of processes in the coupled ocean-atmospheric system. Salinity, along with temperature, controls the buoyancy of the mixed layer. Changes in buoyancy of the mixed layer affects its dynamics and thermodynamics and hence affects both the exchange of heat and salt with the underlying ocean and the sensible and latent heat with the overlying atmosphere. The net gain of fresh water by the atmosphere from the ocean (evaporation minus precipitation, or $E - P$) is a poorly measured, but important, forcing for SSS. However, where time series of sufficient length are available, the relationship between E-P and SSS is not always straightforward and illustrates the necessity of including many of the terms in the salinity budget of the mixed layer to understand the relationship. For example, in the tropical Pacific, SSS minima have been found 4°–6° poleward of the mean maximum precipitation axes associated with the Intertropical Convergence Zone and the South Pacific Convergence Zone [*Delcroix and Hénin*, 1991]. The first step beyond looking at seasonal and annual means and standard deviations is examining probability density. There are processes such as rainfall, frontal meandering and mixing, and eddy activity that may cause the probability density of SSS to be non-Gaussian.

[4] In the coastal regime, where the dynamic range of salinity variability is high, remote sensing of SSS using L band radiometers on aircraft has demonstrated the ability to retrieve useful data at a precision of about 1 [e.g., *Miller et al.*, 1998]. There have been recent developments in the technology of measuring SSS remotely, either from space or from an aircraft [*Lagerloef et al.*, 1995] which promises retrieval precision of about 0.1 at weekly to monthly timescales and 100 km length scales. At this level of precision, remotely measured SSS would be useful for open ocean measurements where the dynamic range is about 0.5 (though at any given location the temporal dynamic range is usually much smaller). Over the past year, several NASA-funded field campaigns have been conducted to demonstrate the ability to retrieve open ocean SSS variability [*Le Vine et al.*, 2000; *Wilson et al.*, 2000]. As of this writing, there are plans to prepare and launch missions which will remotely measure SSS from space (http://www.cesbio.ups-tlse.fr/indexsmos.html).

[5] Before launching new missions to space, however, we need to understand what the current state of knowledge is regarding SSS. How well has it been measured in the past? What areas of the ocean are well measured and what areas are not? Are there areas in which we have any sort of time history of SSS variability? What are typical probability densities of SSS in given areas of the ocean? In addition, we need to begin to formulate plans for validation experiments that will test the accuracy of remote measurement of SSS. What kind of validation experiments will be necessary, and where are the optimal regions? Various potential platforms for validation experiments are or will become available: volunteer observing ships, ARGO floats [*ARGO Science Team*, 1999], and surface drifters with conductivity sensors, to name a few. Which of these platforms could provide the accuracy and coverage required to test remote sensing SSS retrieval algorithms?

[6] In this paper we will try to address some of these questions, using a database of historical SSS observations. As we will see, the current database of SSS observations is only barely adequate to characterize the gross features of the salinity over most of the ocean and, except for a few locations, completely inadequate to characterize the variability. In contrast, the sea surface temperature (SST) has been measured much longer and is better understood. Moreover, since the first NOAA satellites were launched in the late 1970s, we have had continuous and comprehensive remote measurement of SST. There has been great interest in low-frequency regime shifts of SST [e.g., *Trenberth*, 1990; *Tanimoto et al.*, 1993] and their role in the planet's changing climate. Could SSS play a similar role or have similar regime shifts?

2. Data Processing

[7] Part of the SSS data set we used in this analysis was extracted from the World Ocean Database 1998 (WOD98 [*Levitus et al.*, 1998]). The WOD98 is a historical database, containing measurements of SSS going back to 1874. We extracted a subset of the database with SSS observations, using salinities measured at 5 m or less in depth which passed the WOD98 criteria for data quality. The creators of the WOD98 put the data through a number of quality control checks, checks for duplicates, standard deviation checks, density inversion checks, etc. [*Conkright et al.*, 1999]. The extracted data set consists of approximately 1.1 million measurements of SSS, about half of which are from the North Atlantic. Some discussion of the WOD98 salinities can be found in the work of *Boyer et al.* [1998a, 1998b, 1998c]. This discussion includes smoothed maps of surface mean and seasonal data distributions.

[8] The remainder of the SSS data set was taken from a recently released CD-ROM issued by the Etudes Climatiques de l'Océan Pacifique Tropicale (ECOP) project [*Delcroix et al.*, 2000] containing thousands of measurements of SSS taken over 30 years, mainly from volunteer observing ships. The data set consists of two parts, a set of 154,000 bucket measurements from 1969 to 1999 and a set of thermosalinograph (TSG) measurements collected from 1990 to 2000 (they are still actively being collected). These data were collected almost entirely in the tropical Pacific, between 30°N and 30°S. *Delcroix et al.* [1996] have plotted the distribution of observations from an earlier version of this database (see their Figure 1).

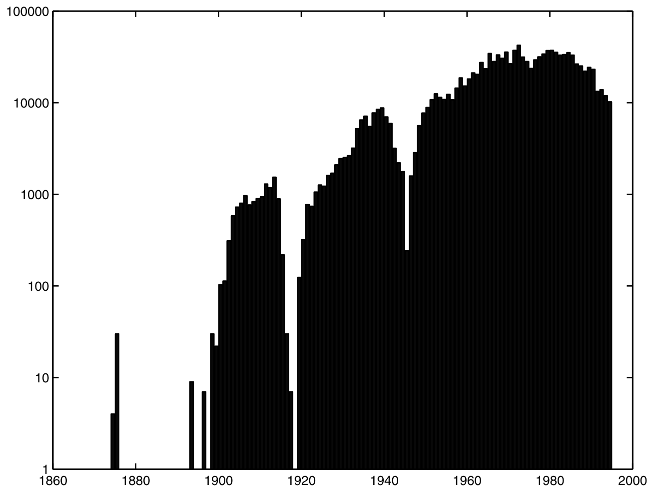

Figure 1. Distribution of SSS observations by year. Note logarithmic scale of vertical axis.

[9] There are approximately 1.45 million observations in the TSG database. The data are collected by using continuous instruments and reported typically every 5 min along a particular ship track. Because of the high rate of sampling, not all 1.45 million observations are independent. The 5-min along-track observations were filtered by using a 2-hour median filter, reducing the spatial resolution of the sampling to approximately 0.5°. This procedure reduced the size of the TSG database to about 86,000 observations.

[10] The bucket and reduced TSG data were combined, and a few duplicate stations between the two data sets were discarded. The combined ECOP data set was compared with the WOD98 database. Any observation taken within 1° latitude and longitude and 10 days in time of a comparable observation in the WOD98 database was considered duplicate and was discarded. The resulting TSG/bucket database provided approximately 200,000 nonduplicate observations which were added to the WOD98. The combined WOD98 and ECOP data set contains close to 1.3 million observations.

[11] In order to distinguish between land, coastal ocean, and open sea, we used the ETOPO5 global bathymetry data set [*National Geophysical Data Center*, 1988]. ETOPO5 contains estimates of elevation every 5 min, 169 estimates per 1° square (including the edges), throughout the globe. One-degree squares where all 169 of the elevations were positive, or above sea level, were characterized as land. Squares where some of the elevations were negative and some positive were characterized as coastal ocean, and squares where all of the elevations were negative were open sea. By these criteria, 361,000, or about 28%, of the 1.3 million SSS observations were coastal.

[12] We plotted frequency histograms of SSS in some 1° squares using the WOD98 data. A frequency histogram is an estimator of the probability density function of a random variable from a finite data set [*Bendat and Piersol*, 1971].

3. Results

[13] Sampling of SSS did not commence in earnest until after 1900 (Figure 1). The number of SSS samples taken per year in the global ocean rose exponentially between 1900 and 1970, with pauses for World Wars I and II, and then held steady throughout the 1970s and 1980s. The dip in number of observations after the early 1990s is likely due to institutions not submitting their data to their countries' oceanographic data centers in a timely manner. An animation of this is available[1], or a nonanimated version using an older data set can be found in the work of *Levitus and Gelfeld* [1992]. A few major features can be pointed out, though. SSS was sampled primarily in the North Atlantic until the mid-1920s, when systematic observations of SSS began to be carried out in the western North Pacific. Any sort of global coverage, with measurements taken outside of coastal areas, did not occur until the 1930s, with a few exceptions. In the mid-1970s volunteer observing ship lines began routine measurement of SSS along regular routes across the open ocean, particularly in the and tropical Pacific. It was not until after about 1960 that the number of SSS measurements per year in the entire world's oceans exceeded 10,000.

[14] There are approximately 43,000 1° squares in the world's oceans (open and coastal, excluding the Arctic Ocean, defined as being north of 80°N); so even a data collection rate of 10,000 per year translates to less than 1 measurement per 2° × 2° box per year. Additionally, those measurements that have been made are concentrated in a few small areas: the east and west coasts of the United States, the North Sea and coastal areas of Europe, near Japan, and a few other areas (Figure 2). There are many other areas of the ocean that are badly undersampled; 27% of the oceans' 1° squares have never been sampled for SSS (Table 1), or the SSS measurements have not made it into our database; 70% of 1° squares have less than 10 observations. Many of these undersampled areas are, as expected, remote regions: the subtropical South Pacific and high-latitude Southern Hemisphere oceans. However, there are even large areas of the central North Atlantic with less than 10 observations per 1° square throughout history (Figure 2). An analysis (not shown) of the zonally averaged number of observations underscores a severe Northern Hemisphere bias in the distribution. Zonally averaged around the globe, there are 20–30 measurements per 1° square between 80°S and 20°N. Between 20°N and 60°N, one finds a zonal average of over 100 observations per 1° square.

[15] In order to understand probability density of 1° square SSS, we concentrated on a few well-sampled 1° squares in the North Atlantic (Figures 3 and 4, Table 2) and tropical Pacific (Figures 5 and 6, Table 3). Future satellite missions are projected to estimate SSS over a 100 km × 100 km area over a time period of 1 month. One-degree squares have approximately the same area as a 100-km square, depending on latitude. We use 1° squares in this paper for convenience.

[16] One such square in the Sargasso Sea (Figures 4a and 7) shows the poor distribution of the sampling. Most of the sampling was done during a 5-year period around 1970 with only a few scattered measurements before or after. These observations were taken by the U.S. Coast Guard and come

[1] Supporting material is available via Web browser or via Anonymous FTP from ftp://ftp.agu.org, directory "apend" (Username = "anonymous", Password = "guest"); subdirectories in the ftp site are arranged by paper number. Information on searching and submitting electronic supplements is found at http://www.agu.org/pubs/esupp_about.html.

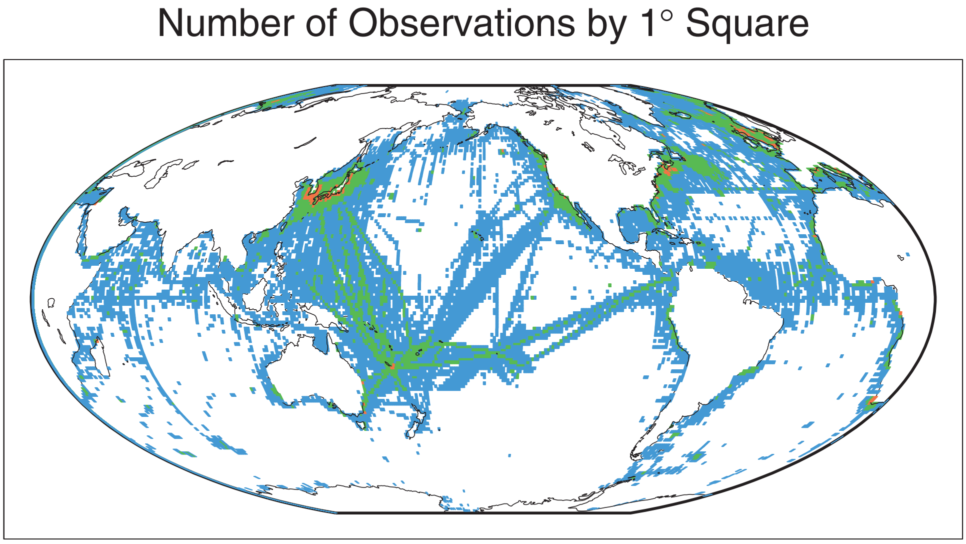

Figure 2. Number of historical SSS observations per 1° square. Blue, >10 observations; green, >100 observations; and red, >1000 observations. No color means less than 10 observations.

from what is known as Ocean Weather Station "E" [*Dinsmore*, 1996; *T. Boyer, personal communication*, 2000]. The distribution of SSS in this square (Figure 4a) is typical of many mid-ocean areas in that it is strongly skewed toward low salinity by a relatively small number of low outliers. Examination of the record in this square shows that these outliers are the signature of a small number of discrete low-salinity events. One particularly strong event occurred in July–November of 1970, with salinity between 35.2 and 36. We calculated the skewness for this distribution [*Press et al.*, 1986] and found it to be significantly different from zero. A useful indicator of the skewed nature of the distribution is the difference between the mean and median values of SSS, ~0.03. This is a significant fraction of the contemplated accuracy of satellite-based SSS platforms (~0.1). More important, the difference between the mode (most likely value) and the mean is 0.093, which is almost 1/2 the standard deviation. The skewness of the histogram is possibly a result of local rainfall events temporarily lowering the surface salinity. Another possibility is that the Gulf Stream front separates relatively constant and high Sargasso Sea salinities from relatively more variable and lower-salinity slope waters. That means that eddies that make it across the Gulf Stream front could have a range of salinities (all lower than the Sargasso Sea waters), and so eddies could also create a salinity distribution that is negatively skewed rather than strictly bimodal.

[17] A square in the Gulf Stream (Figures 3, 4b) was sampled over a 10-year period during the 1970s. Most of these data were collected for the purpose of studying Gulf Stream meanders [*Robinson et al.*, 1974]. This square has a SSS distribution that is somewhat bimodal owing to the presence of the Gulf Stream front that meanders back and forth across the square. It still shows a strong negative skewness, with a significant number of observations at very

Table 1. Number of 1° Squares With Given Number of Observations[a]

Number of Observations	Number of 1° Squares
0	11,768[b]
1	5,074
2–10	13,304
11–100	10,090
101–1000	2,350
1001–10,000	144
>10,000	1

[a]For example, there are 5,074 1° squares that have only one observation of SSS. The total number of 1° squares on Earth is 64,800. The total number of squares that are either open ocean or coastal and are not in the Arctic Ocean is approximately 43,000.

[b]Not including land areas.

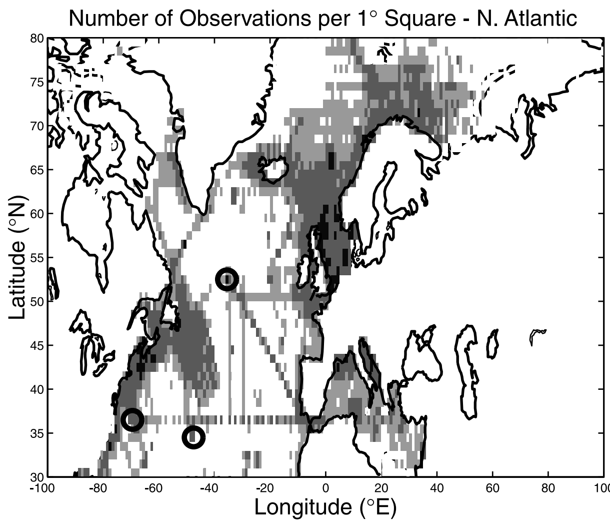

Figure 3. Number of historical SSS observations per 1° square in the North Atlantic. Note slightly different scale from Figure 2. Light gray, ≥30 observations; dark gray, ≥100 observations; and black, ≥1000 observations. No fill means less than 30 observations. Dark circles at (35.5°W, 52.5°N), (69.5°W, 36.5°N), and (47.5°W, 34.5°N) are squares listed in Table 2 and have details of data distribution shown in Figures 4a–4c.

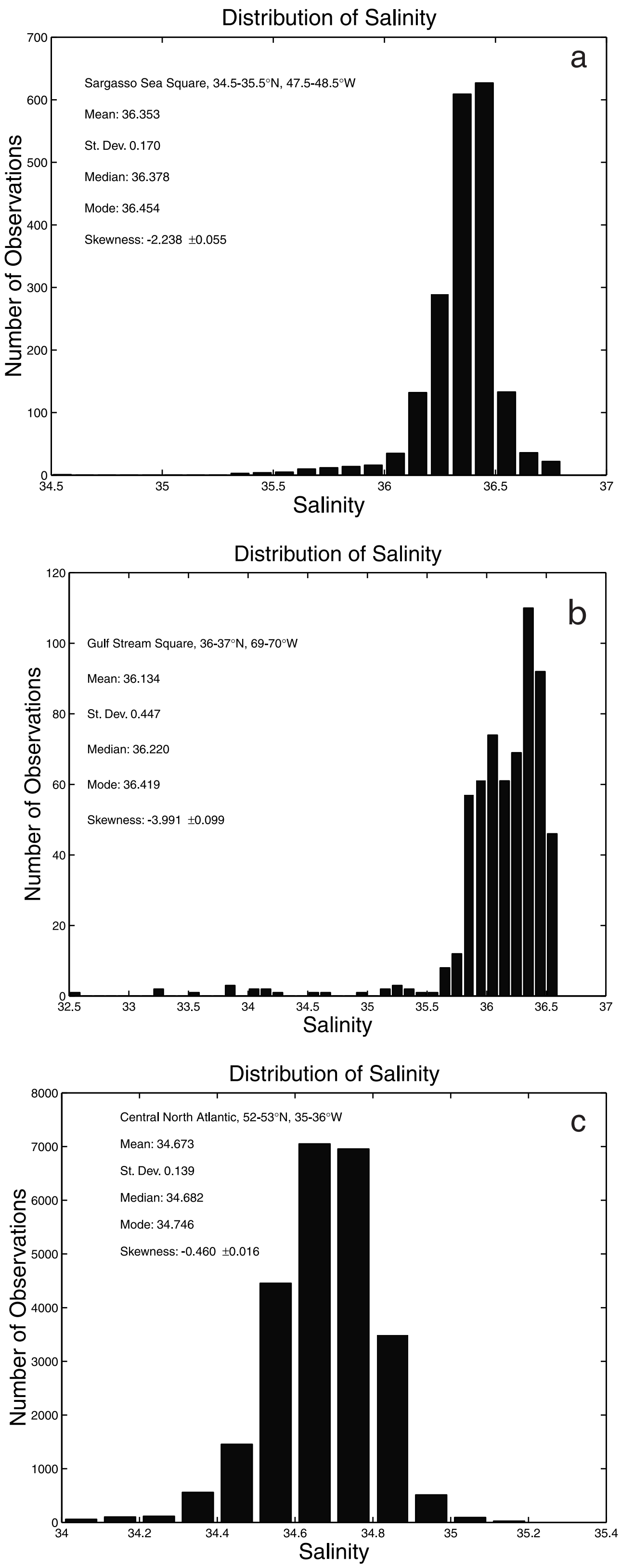

Figure 4. Frequency histograms of SSS in selected 1° squares in the North Atlantic. See Table 2 for square locations.

Table 2. Individual 1° Squares in the North Atlantic

Latitude	Longitude	Description	Figure	Number of Observations
34.5°–35.5°N	47.5°–48.5°W	Sargasso Sea	4a	1,948
36°–37°N	69°–70°W	Gulf Stream	4b	614
52°–53°N	35°–36°W	central N. Atlantic	4c	25,267

low salinity. The example of this square shows another type of SSS distribution that may be common in the ocean, that is, a bimodal distribution. One would expect to find this type of distribution near salinity fronts and especially in coastal areas. Again, the difference between the mode and the mean is large, being over 1/2 the standard deviation.

[18] A square in the central North Atlantic (Figures 3, 4c) has an enormous number of observations (Table 2). Thousands of samples per year were taken here from the mid-1960s to the late 1980s. This is the site of Ocean Weather Station "C". It was occupied by the U.S. Coast Guard from 1948 to 1973 (who made temperature measurements only) and by the Soviet Hydrometeorological Service from 1975 to 1989 [*Levitus et al.*, 1994]. The total number of observations at this square is over 25,000, or about 3% of all open ocean observations in the WOD98 database. There is again a small but significant number of observations at low salinity; the difference between the mean and median is ~0.06, and the difference between the mode and mean is 0.73, which is over 1/2 the standard deviation. Two further analyses of the data from this square are done. First, we calculated the frequency histogram of temperature anomaly from the monthly mean (Figure 8). This histogram is quite different from the SSS distribution. It has relatively few outliers and appears normally distributed. The skewness is

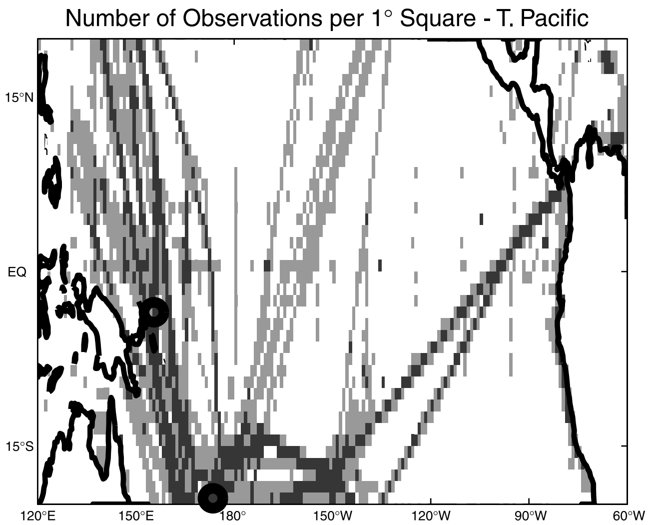

Figure 5. Number of historical SSS observations per 1° square in the western tropical Pacific. Light gray, >30 observations; dark gray, >100 observations. There are no squares with more than 1000 observations in this region. No fill means less than 30 observations. Dark circles at (4°S, 156°E) and (19.5°S, 173.5°E) are squares listed in Table 3 and have details of data distribution shown in Figures 6a and 6b.

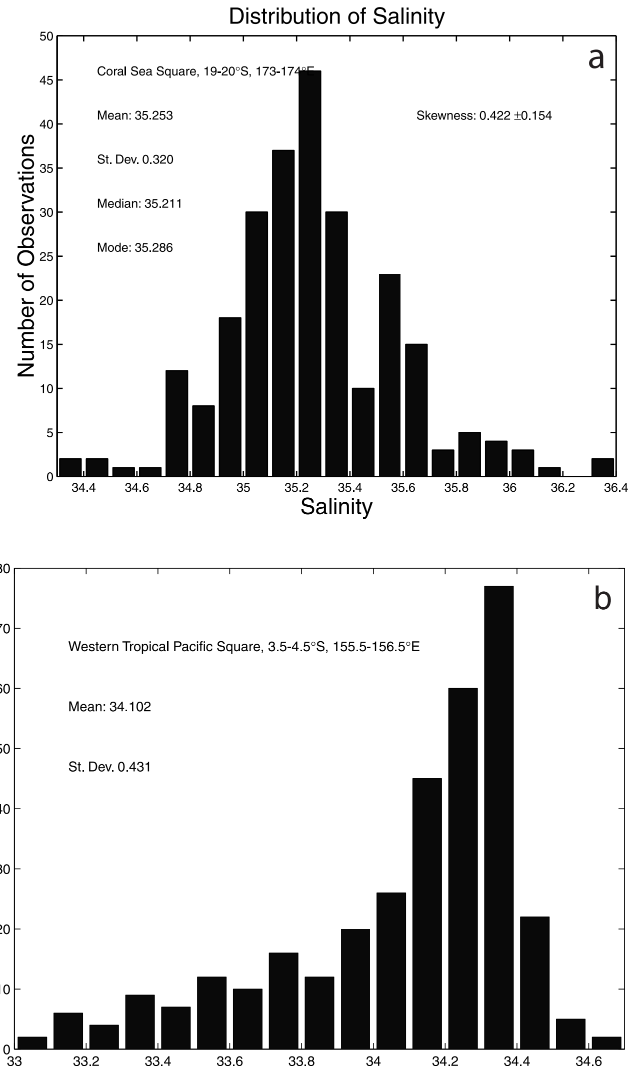

Figure 6. Frequency histograms of SSS in 1° squares in tropical Pacific centered at (a) (19.5°S, 173.5°E) and (b) (4°S, 156°E). In Figure 6b, Note all observations were collected in a 2-month period, December 1992–February 1993, as part of the TOGA-COARE experiment.

nonzero but much smaller than the standard deviation, unlike many of the SSS distributions examined. The mean, median, and mode are all very close to each other. The nonskewed nature of the SST has allowed comparison of remotely sensed and in situ SST to be carried out successfully for many years. Second, we calculated a time history of the SSS frequency histogram as a function of year from 1975 to 1990 (Figure 9). This figure shows the changing shape of the frequency histogram over the years and some fascinating interannual variability in the yearly mean. Most

Table 3. Individual 1° Squares in the Western Tropical Pacific

Latitude	Longitude	Description	Figure	Number of Observations
3.5°–4.5°S	155.5°–156.5°E	western Pacific	6a	335
19°–20°S	173°–174°E	Coral Sea	6b	253

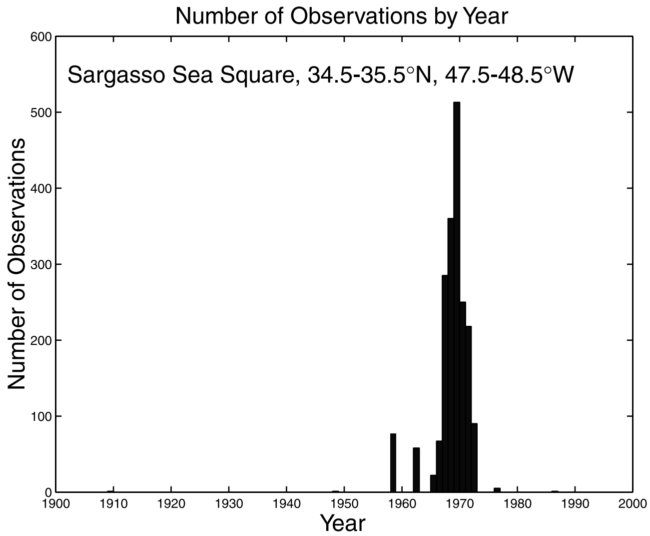

Figure 7. Time history of sampling in the 1° square at (35.5°W, 52.5°N) (Figures 3 and 4c).

individual yearly distributions are negatively skewed, although some years are more so than others. In most years the mean salinity is different from the mode by at least 0.1.

[19] As we have seen, frequency histograms of SSS for various squares vary, and the temporal sampling varies, but for most areas of the ocean the skewness of the data distribution is apparent. Most oceanic SSS data are not normally distributed with the data tailing off toward the negative end of the distribution. This is not always the case, though. An example from the Coral Sea [*Hénin et al.*, 1980, 1982] shows a 1° square where the distribution has a positive skewness (Figures 5, 6a). (An area such as this, where the distribution of SSS is not skewed, would be a good candidate for validation study for a SSS mission. This area is relatively warm and fresh. Salinity variability in

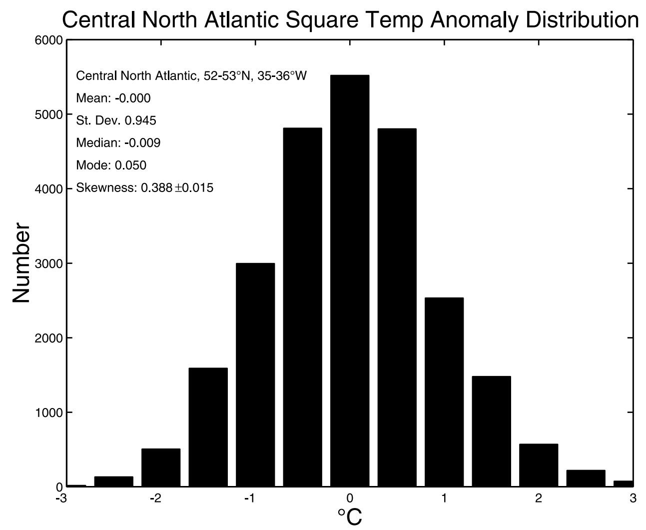

Figure 8. Frequency histogram of surface temperature anomaly for the central North Atlantic 1° square (Figures 3 and 4c). Temperature anomaly was calculated by computing a monthly mean for all observations in the square and taking anomalies from that monthly mean.

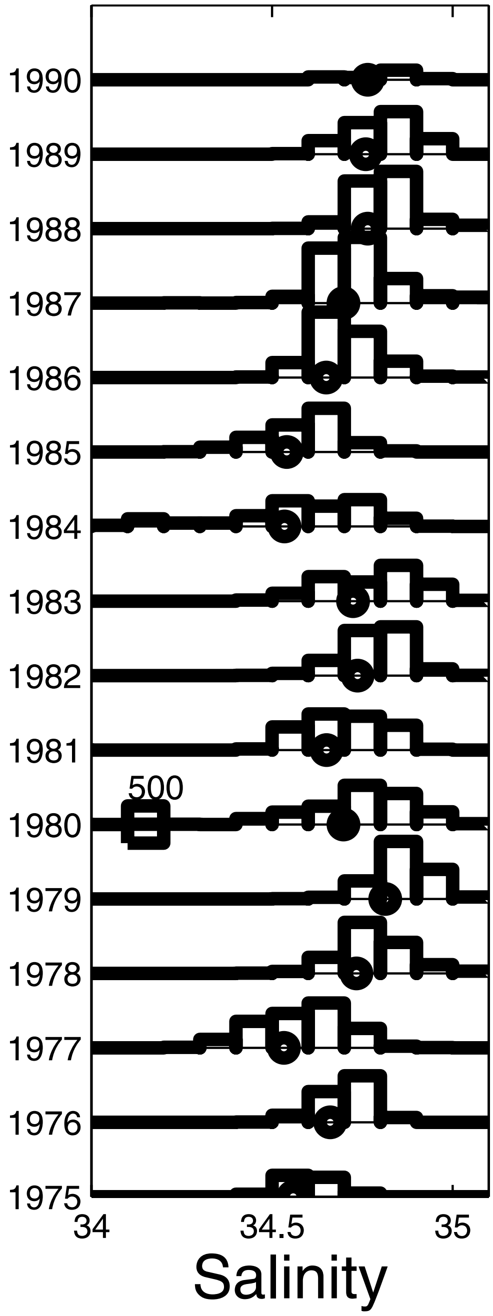

Figure 9. Frequency histograms of SSS for 15 years of intensive observations in the central North Atlantic 1° square (Figures 3 and 4c). A scale is indicated in the histogram for the year 1980. The box offset from the line shows the scale for 500 observations. Heavy circles in each year are mean SSS values.

warm and fresh waters has a relatively larger effect on brightness temperature than it does in colder waters [*Lagerloef et al.*, 1995].) This area is one where there is a network of SSS observations currently being carried out at a high intensity [*Delcroix et al.*, 2000].

[20] A final example is from the western equatorial Pacific. This region is the site of the TOGA-COARE experiment during 1992 and 1993 [*Webster and Lukas*, 1992]. The only measurements of SSS here are from Tropical Ocean–Global Atmosphere/Coupled Ocean-Atmosphere Response Experiment (TOGA-COARE), in an area centered at 4°S, 156°W during an approximately 2-month period, December 1992–February 1993. As in the other squares, the SSS distribution is skewed (Figures 5, 6b) with the mode 0.27 above the mean. The mode is again over 1/2 of the standard deviation of 0.430.

[21] Negative skewness in the salinity frequency histogram is a common feature throughout the ocean. To show this, we have calculated the difference between mean and median SSS for all 1° squares in the world ocean with more than 10 observations. A histogram of this quantity shows it to be negative for most 1° squares (Figure 10). When the distribution of SSS is negatively skewed, we would expect this quantity to be negative. The ensemble mean SSS is offset low in relation to the ensemble median as a result of low outliers. Maps of the mean-median difference over the globe were examined but are not reproduced here. If our conjecture about this negative skewness being a result of rainfall is correct, we would expect the mean-median difference to be correlated with areas of documented high rainfall [*Baumgartner and Reichel*, 1975; *Spencer*, 1993; *Huffman et al.*, 1997]. They showed some slight correlation but were somewhat noisy and inconclusive. With the present data set we were not able to detect a clear pattern.

[22] Although the global ocean average precipitation (P) and evaporation (E) are in near balance, P occurs in a more episodic fashion than *E*, and during these episodes the volume flux of fresh water across the surface is greater than for P than for E. For example, *Johnson et al.* [1996] show daily averaged P and *E* values from the TOGA-COARE intensive flux array over a 3-month period. Over the time period, P rates are highly variable with peaks of about 20 mm/d. *E* rates are more stable, hovering in the range 3–5 mm/d. Given that *E* is a slower but steadier process and is destabilizing (cooling and increased salinity), it is likely that negative skewness would occur. Even at a location where P and *E* are in balance, salinity anomalies

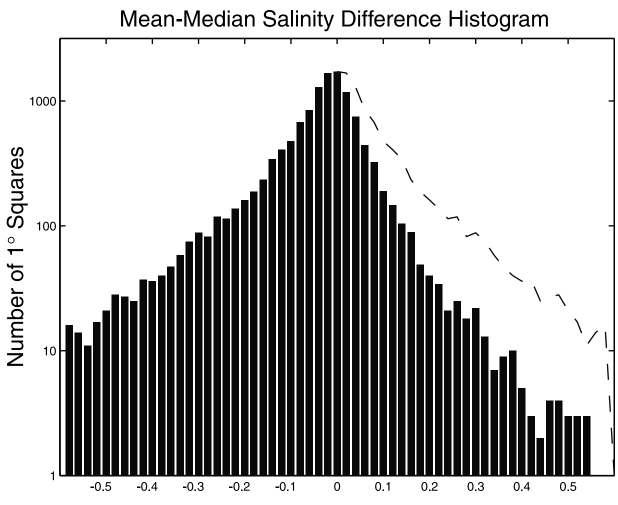

Figure 10. Histogram of the mean-median SSS difference for all 1° squares with more than 10 observations over the globe. Note logarithmic scale on the vertical axis. For comparison, bar heights from the negative axis are reflected onto the positive axis by a dashed line.

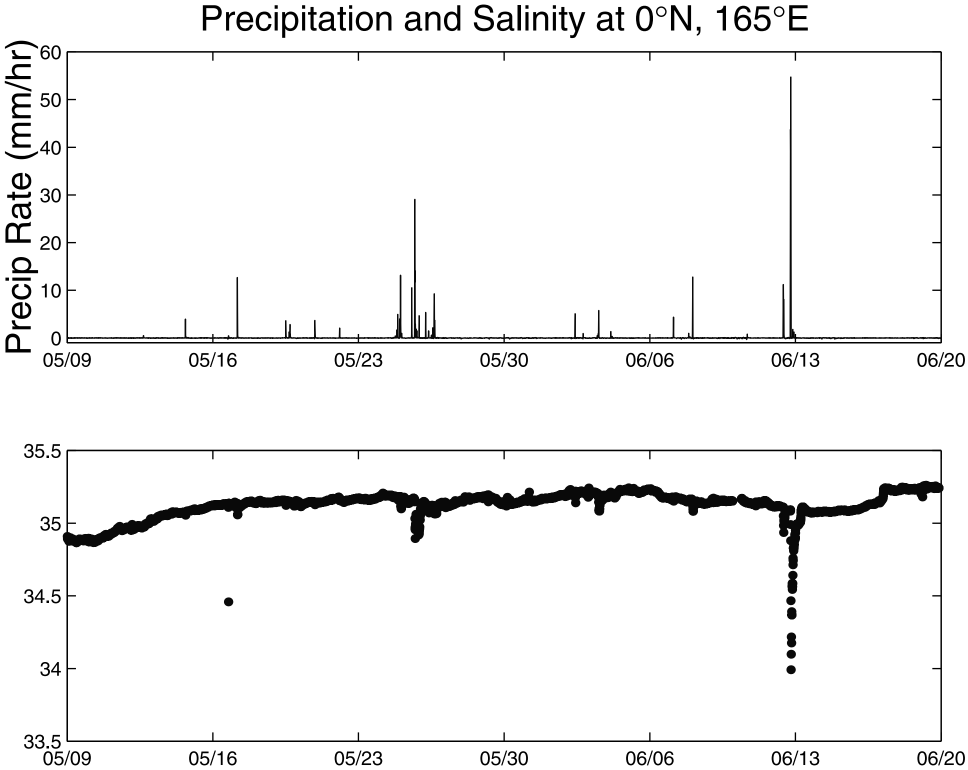

Figure 11. (top) Precipitation rate and (bottom) SSS from TOGA TAO mooring at 0°, 165°E, May–June 1999 [*McPhaden et al.*, 1998]. The record shown is a piece of a longer record of length approximately 1 year.

due to P would be longer lived, and those due to *E* would mix away more quickly with the underlying water. To show a small example of how rainfall events influence the SSS, we have extracted SSS and precipitation data (Figure 11) from a mooring at 0°, 165°E from the TOGA Tropical Atmosphere-Ocean (TAO) array [*McPhaden et al.*, 1998]. This 1-month piece of record is typical in that it shows the strong and short-term nature of the influence of rainfall on the surface layer. Low-salinity events occur in association with precipitation. The frequency histogram of the entire record of SSS at this location (not shown) is skewed very much like that at the western tropical Pacific area described earlier (Figure 6b). It is easy to see why from this part of the time series.

4. Discussion

[23] Salinity is a notoriously difficult quantity to measure accurately, and thus there are many possibilities for errors. It is important to address the question of whether the negative skewness results could be due to measurement errors. TSG intakes on fast-moving ships can become contaminated by bubbles and give low readings. Conductivity and associated temperature sensors can have timing mismatches, leading to salinity spiking. Conductivity cells are subject to calibration drift. Bucket measurements can be contaminated by rain-water or excessive evaporation before being run through a salinometer. The relevant question is whether any of these types of errors can result in the overwhelmingly negative bias shown in this paper. We cannot make any definitive conclusion on this question here; however, we can make some statements. Most of the examples studied in Figures 4 and 6 are derived from bucket measurements, making these examples exempt from problems associated with TSGs. Indeed, except for the data from the tropical Pacific, bucket measurements dominate our database. Even the TSG data we used were processed with a median filter, which is specifically designed to reduce the number of outliers. It is difficult to imagine a process by which bucket salinities could have an overwhelmingly negative bias. *Reverdin et al.* [1994] specifically note the main problem with bucket measurements collected in the North Atlantic is the presence of salt crystals in the buckets before collection and evaporation from samples during storage. Both of these problems would tend to lead to salinity measurements biased high rather than low. Thus although measurement error cannot be ruled out as the source of the negative skewness, it seems unlikely.

[24] We have found negative skewness in the SSS distribution over decadal scales (e.g., Ocean Weather Station C) to monthly scales (e.g., the TOGA-COARE site). Satellite systems will most likely measure some weighted average of the SSS over the footprint of the spacecraft. Validation experiments designed to test satellite algorithms must take the basic skewness of the SSS field into account. What a satellite measures may be very different from what is measured by one-point measurement, even one repeated over the course of a month. One of the main ways of validating the remotely sensed SSS may be through comparison with ARGO floats. Since ARGO floats pop up in random times and at random places, the value of SSS measured by an ARGO float will be closest to the mode

of the SSS distribution, the most likely value. We will likely find that the satellite measurement, since it is close to the average SSS as opposed to the mode, is biased low as compared with the floats. The amount of bias will depend on the probability density of SSS at the time of comparison and may be between 0 and 0.1. A better type of validation study for the satellite mission would be one where the measurements were intensive enough in one area to adequately measure SSS to get values for the mean, median, and mode of the field. This type of information might best be collected by volunteer ships that frequently cross a particular area or by a seeding of an area with surface drifters equipped with conductivity cells (assuming their calibration drift could be corrected). Another option is to find areas of the ocean where the SSS is normally distributed. We speculate that such an area would be one of very low rainfall. We found one such square in the Coral Sea, but a further search of the historical database may reveal other areas.

[25] A caveat to the above analysis is that the importance of the skewed SSS distribution for calibrating and validating measurements from space will depend upon the relative contributions of skewness due to temporal and spatial variability and the length scales of those variations. For example, if the skewness is due to temporal variations with longer timescales than the separation between in situ and remote measurements and the length scales of variability are larger than the satellite footprint, then there is not a problem in comparing the measurements. Skewness in regions of large-scale organized convection may be coherent over a satellite footprint. In these regions a more fundamental problem may be temporary fresher rain lenses riding on top of the mixed layer.

[26] The conclusions reached here also have implications for published climatologies like the climatology of *Boyer et al.* [1998a, 1998b, 1998c]. The algorithm used to calculate such climatological values is a weighted average of historical measurements over some area. What values the algorithm calculates in a given area is a function of how the weighting works and what influence radius is chosen. If there is a significant skewness in the observations, the climatology will be biased low in comparison with what would be typically observed. How much bias depends on the probability density of SSS in the area but, from the results shown here, may be up to 0.1. Because subsurface waters are not as directly affected by rainfall events, frequency histograms of subsurface salinity away from frontal regions may not be negatively skewed like the surface distributions. Whether this effect is present or significant in climatological profiles is a subject for future research.

5. Conclusions

[27] We have examined historical distributions of SSS observations in the WOD98 database. Figures 1 and 2 and Table 1 give a good indication of how poorly sampled SSS is in the ocean. This is especially true given that about 28% of the measurements in the database are in coastal waters. If we believe that SSS is an important variable for understanding ocean circulation, this analysis gives strong justification for increased efforts to measure it. The analysis points out that a significant benefit from satellite measurements of SSS will be in the discovery process when SSS data are collected from the 27% of the (non-Arctic) 1° squares in the world ocean that have no SSS measurements and the 70% that have 10 or fewer measurements.

[28] We plotted frequency histograms of SSS for some selected 1° squares in the North Atlantic and tropical Pacific. We found most frequency histograms to be non-Gaussian. The main departure from normal distribution is due to anomalous low-salinity measurements creating a negative skewness. Fronts such as the Gulf Stream are locations of non-Gaussian, bimodal distributions. The non-Gaussian nature of the distributions in the areas examined may be both a short-term and a long-term phenomenon. We have seen examples of histograms skewed on a nearly instantaneous ($\sim$1 month) basis and averaged over long time periods (1 + years). The implication for validation studies for remote sensing missions is that the studies must make enough measurements of SSS to determine the extent to which the probability density is not Gaussian. A region (Coral Sea) was identified where SSS is normally distributed which would make calibration/validation studies simpler. Future work will focus on finding similar regions.

[29] There are three basic sources of data for calibration/validation studies of a future satellite mission: ARGO floats and surface drifter data, TSG-equipped ships of opportunity, and dedicated measurements. The former two types are the most economical from the standpoint of mission funding. While ARGO floats will prove to be invaluable, care must be taken in the comparison with satellite data where the SSS statistics are not well known. Volunteer observing ships provide very good SSS statistics on a regional basis and have the important property that the measurements are repeated. However, funding is tenuous for many of these measurements. Currently, NOAA has no funding committed for replacing TSGs should any of the systems become unrepairable on the vessels in its program (*G. Thomas*, personal communication, 2000). Future work will identify which areas and vessels are most suitable for calibration/validation efforts so that suggestions can be made of where to set priorities for funding in the event of TSG system failures.

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