Global-scale patterns of observed sea surface salinity intensified since the 1870s

W. John Gould & Stuart A. Cunningham

Sea surface salinity patterns have intensified between the mid-20th century and present day, with saline areas becoming saltier and fresher areas fresher. This change has been linked to a human-induced strengthening of the global hydrological cycle as global mean surface temperatures rose. Here we analyse salinity observations from the round-the-world voyages of HMS Challenger and SMS Gazelle in the 1870s, early in the industrial era, to reconstruct surface salinity changes since that decade. We find that the amplification of the salinity change pattern between the 1870s and the 1950s was at a rate that was 54 ± 10% lower than the post-1950s rate. The acceleration in salinity pattern amplification over almost 150 years implies that the hydrological cycle would have similarly accelerated over this period.
The scientific definition of salinity started in the 1890s and only in the Atlantic has it been possible to document salinity changes into the 19th century. For the voyages of HMS Challenger (1872–1876) and SMS Gazelle (1874–1876), which took place early in the industrial era, we have derived absolute salinity from the specific gravity measurements at the almost 400 stations occupied (Fig. 1a). The process of converting specific gravity observations to salinity and the assessment of the data quality are described in the “Methods” section. When combined with 20th century reconstructions of the global salinity field, the data allow us to assess changes in surface salinity globally over almost 150 years.

We focus the analysis on three periods, the 1870s and the decades centred on 1954 and 2014. This allows comparisons with other analyses describing salinity change between the latter two periods. The 1870s data are compared with the 5 m salinity values in the EN4 (Version 4.2.1) data set. We chose the EN4 data set because it is based solely on observational data. We also repeated the analysis using the newer Cheng et al. data set, which relies on CMIP5 output.

Results and discussion

Patterns of salinity change since the 1870s. We noted that the regional patterns of change between the 1950s and 2008 reported showed saline areas becoming more saline and the fresh areas fresher, an amplification (defined as the amplitude of the change between saline and fresh regions) believed to be indicative of strengthening of the global hydrological cycle since the mid-20th century and summarised in.

In order to reveal whether the patterns of change between the 1870s and the 1950s might have been similar to those since the 1950s we identified regional groups of Challenger and Gazelle stations, the positions of which lay in distinct areas of post-1950s freshening or salinification revealed by the EN4 5 m fields representing the salinity difference from the decadal averages, 1950 to 1959 and 2010 to 2019.

Figure 1a shows the Challenger and Gazelle station positions in relation to the mean EN4 5 m surface salinity field (1950–2019). The regionally grouped 1870s stations are shown in Fig. 1b and 1c. The stations in each regional group are listed in Supplementary Table S1.

The areas traversed by Challenger and Gazelle were marked by salinification in the subtropical gyres of the North and South Atlantic and South Indian Oceans (Gazelle only). Freshening is seen in the low-latitude western Pacific, the equatorial Atlantic and the Southern Ocean. The patterns of change from the EN4 data are similar to those reported by between the 1950s and 2012.

For each of these station groups we computed mean rates of salinity change from the 1870s to the mean decadal average EN4 salinity field.
5 m salinity (1950–59) and compared these with the changes from the 1950s to 2010–19. These comparisons are in Fig. 2.

The plots show a stronger correlation for **Challenger** than for **Gazelle**. This reflects the wider regional distribution and larger number of **Challenger** stations (285 after 15 rejected) than Gazelle (101 after 9 rejected) stations in the regional analysis. The areas of strongest and most consistent change since the 1870s are freshening of the Pacific Warm Pool (**Challenger** and **Gazelle**) and salinification in the North and South Atlantic subtropical gyres (**Challenger**) and equatorial Atlantic (**Gazelle**).

The ratio of the regional salinity rate of change in these two periods is a measure of the salinity amplification. For the **Challenger** data there is a clear linear relationship between the rates of change (slope 0.6 ± 0.2, correlation coefficient 0.64). The equivalent figures for Gazelle are, slope 0.4 ± 0.3, correlation coefficient 0.36. The slopes are statistically inseparable. We also computed the equivalent relationships using the Cheng (CZ16) data set for which the corresponding slopes and correlation coefficients were **Challenger** (0.51 ± 0.31, 0.33) and Gazelle (0.66 ± 0.46, 0.43).

In these analyses all regions were given equal statistical weight even though they contained differing numbers of stations. We chose this simple approach because the stations are not equally spaced and thus the number of stations cannot be seen as representative of the track length (area) in which changes occur.
To convert the rate of change in the salinity amplification to a salinity anomaly in the 1870s we first computed the global salinity change in the EN4 data sets between the decades centred on 1954 and 2014. (We excluded sea ice influenced areas north of 65°N from this analysis where EN4 salinities appeared anomalous and high latitude areas were not sampled in the 1870s). From EN4 we calculated the global mean salinity change in areas where salinity increased and in those where salinity decreased between 1955 and 2015. These values are respectively +0.0940 g kg\(^{-1}\) and -0.0897 g kg\(^{-1}\), giving a global amplitude of salinity amplification of 0.184 g kg\(^{-1}\) over 60 years. This implies that the rate of salinity amplification since 1955 is 0.306 g kg\(^{-1}\) century\(^{-1}\) (Table 1).

We then used the ratio of regional salinity changes, as represented by the slopes of Fig. 2, to project back to the 1870s. This calculation implies a mean salinity change between the 1870s and 1950s (based on analyses of Challenger and Gazelle and using EN4 and CZ16 data sets) of 0.133 ± 0.041 g kg\(^{-1}\), a rate of 0.166 ± 0.052 g kg\(^{-1}\) century\(^{-1}\) (Table 1).

The ratio of pre-1950s rate of SSS change to post-1950s is 1:1.84 ± 0.44 (Table 1). Thus, we find that the rate of salinity pattern amplification before the 1950s was 54 ± 10% lower than the rate since the 1950s.

Implications for global hydrology. In order to investigate the insights that our estimates of salinity change might give into the global hydrological cycle we plot the salinity changes since the 1870s against changes in surface air temperature from the HadCRUT.5.0.1.0\(^{12}\) data set and sea surface temperature from HadSST.4.0.0.0\(^{12}\) in Fig. 3. These plots show that our salinity change results are consistent with the link described in\(^\text{12}\) between the rate of amplification, (fresh gets fresher - saline gets saltier) and temperature.

The statistics in Table 1 summarise the changes and rates of change of SST, SAT and SSS (from this study) plotted in Fig. 3 for the periods before and after the 1950s. While previous analyses of the relationship between salinity change and the global hydrological cycle have focussed on the relatively well-observed period since the 1950s during which changes in SAT and SST have been close to linear, this analysis includes the pre-1950s period which exhibited slower changes in SAT and SST. Figure 3 and the statistics in Table 1 suggest a closer relationship between SSS pattern amplification and SST changes than with changes in SAT over the 145 years of this study. The model-based analysis by Zika et al.\(^{14}\) of the post-1950s salinity pattern amplification (5–8%) attribute approximately half of that amplification to ocean surface warming (SST) with the remainder being linked to strengthening of the hydrological cycle.

Conclusions

The conversion of the Challenger and Gazelle specific gravity observations from the 1870s to equivalent absolute salinities produces values that are consistent with the large-scale surface salinity structure as defined by the EN4 data set. This holds good for the areas sampled by both expeditions covering all the major ocean basins. Furthermore, the salinity values are of high enough quality to permit meaningful estimates of the changes in salinity since the 1870s in areas of persistent freshening and salinification.

The 1870s data, being from a time-window before the rapid 20th century changes, allow us to study changes during a time span in which the rates of increase in both surface air temperature and sea surface temperature accelerated. The regional Challenger and Gazelle data when combined with the post-1950s EN4 and CZ16 products show that the pattern of salinity amplification (fresh areas becoming fresher, saline areas more salty) is consistent with the post-1950s pattern amplification reported by

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Table 1 Summary of SST, SAT and SSS changes, 1870s to 1950s and 1950s to present.

| Years Time span years | SST change rate °C century\(^{-1}\) | SAT change rate °C century\(^{-1}\) | SSS change g kg\(^{-1}\) | SAT change rate °C century\(^{-1}\) | SSS change g kg\(^{-1}\) | CH/EN4 | GZ/CZ16 | CH/CZ16 | Mean |
|-----------------------|----------------------------------|----------------------------------|--------------------------|----------------------------------|--------------------------|--------|--------|--------|-------|
| (1870–1879) to (1950–1959) | 0.208 ± 0.005 | 0.166 ± 0.058 | 0.208 ± 0.05 | 0.028 ± 0.005 | 0.184 ± 0.001 | 0.166 ± 0.058 | 0.184 ± 0.001 | 0.166 ± 0.058 | 0.400 ± 0.002 |
| (1950–1959) to (2010–2019) | 0.208 ± 0.005 | 0.166 ± 0.058 | 0.208 ± 0.05 | 0.028 ± 0.005 | 0.184 ± 0.001 | 0.166 ± 0.058 | 0.184 ± 0.001 | 0.166 ± 0.058 | 0.400 ± 0.002 |

Changes and rates of change of Sea Surface Temperature (SST), Surface Air Temperature (SAT) and Sea Surface Salinity (SSS) over the periods 1870–1879, 1873 for SSS, 1950–59 and 1950–2010 to 2019. The errors for SST and SSA are computed from the root-sum-square of the standard deviation divided by the square root of the sample size. The errors for SAT are standard errors of the mean. The means for the periods 1870–1879, 1950–59 and 1950–2010 to 2019. These errors for SSA are computed from the root-sum-square of the standard deviation divided by the square root of the sample size. The errors for SAT are standard errors of the mean. The means for the periods 1870–1879, 1950–59 and 1950–2010 to 2019.
Assessing the quality of the 1870s data. The geographical coverage of the Challenger and Gazelle stations at which specific gravity was measured are shown in Fig. 1a which shows the tracks superimposed on the present-day near-surface salinity field from the EN4 data set representing conditions from 1950 to 2019 inclusive. In this paper we do not analyse the subsurface values, the distribution of which is shown in Supplementary Information Fig. S1.

Though the Challenger and Gazelle tracks are not ideal for sampling the major features of the global salinity field, they did cross the northern and southern subtropical gyres of the Pacific and Atlantic oceans. Challenger made a single excursion across the Antarctic circumpolar current and Gazelle surveyed the south Indian Ocean. Unfortunately, specific gravity sampling on Gazelle did not start until the vessel had crossed the equator on its outward voyage.

For comparisons between the 1870s surface bucket sampled data and modern values we use the shallowest EN4 level (5 m) and CZ16 (1 m) as being representative of surface values. The post-1990 EN4 data have smaller uncertainties since they include data from the World Ocean Circulation Experiment (1990–1997) and from the Argo profiling float programme (2000 onwards and covering the uppermost 2000 m).

We removed outlying salinity values from the 1870s data based on two passes of a standard deviation filter from the corresponding value in the EN4 reference set. The first pass is three standard deviations, effectively removing egregious data, the second pass is two standard deviations (95% confidence limit). The EN4 and CZ16 reference sets were determined by computing the monthly mean 5 m depth salinity (1 m for CZ16) for the month of the Challenger or Gazelle observation. The standard deviation of this monthly mean is computed from 10 monthly values from the same month as the Challenger/Gazelle observation.

The first test of the value of the 1870s data is the extent to which they reproduce the present-day variations along ships’ tracks. The comparisons to EN4 are shown in Fig. 4. From the upper panel it is clear that both the Challenger and Gazelle observations follow the structures in the EN4 data. The close match is seen even for the Challenger excursions into the low salinity region off Nova Scotia (around

Fig. 3 Surface salinity changes since the 1870s compared with Surface Air Temperature (SAT) and Sea Surface Temperature (SST). Surface salinity (SSS) changes compared with changes in a, HadCRUT Surface Air Temperature (SAT) and b, HadSST Sea Surface Temperature (SST). Both data sets have been adjusted so that the average temperature anomaly for the period (1950–1959) is zero. The solid black line from 1954 to 2014 is the mean EN4 salinity change (2010–2019)–(1950–1959) between positive and negative salinity anomaly regions of 0.184 g kg⁻¹. The salinity change pre-1950s is determined from the comparison of the Challenger and Gazelle data to both EN4 and CZ16 data. The error bars are derived from the 95% confidence limits. Magenta solid CH(EN4), magenta dashed GZ(EN4), green solid CH(CZ16) and green dashed GZ(CZ16). The solid red is the mean of the slope and error from the four analyses.
We also investigated whether there were large ENSO events in the 1870s that might have created significant large-scale perturbations in surface conditions. The classification of ENSO events by Gergis and Fowler suggests that there were no such events during the mid 1870s. The longer (1990–2019) EN4 window period did contain several ENSO events but we have assumed that these would have been averaged and so exerted minimal regional bias to EN4.

### Data availability

The original specific gravity observations are published in references. The transcribed values have been submitted to the US National Centres for Environmental Information (https://doi.org/10.25921/jcca-e972).

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Author contributions

W.J.G. conceived the study and transcribed the Challenger and Gazelle information from the original printed reports. S.A.C. carried out all computations and statistical analysis. The interpretation and manuscript preparation were carried our jointly.

Competing interests

The authors declare no competing interests.

Additional information

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Correspondence and requests for materials should be addressed to W.J.G.

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