T. W. Fowler's measurements of sea temperature and density from merchant ships off southern Australia in 1896

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ABSTRACT

In 1896 T. W. Fowler initiated a program of twice-daily measurements of sea-surface temperature and density from merchant ships in Australasian waters. Fowler's temperatures and derived salinities south of Australia along ~35°S reveal now familiar oceanographic features: the Leeuwin Current; high-salinity waters in St. Vincent Gulf; and cold, low-salinity waters of the Southern Ocean. Fowler noted that the temperatures and densities along the ships' passages decreased during 1896, and that they continued to do so over the next three years. This appears to have been associated with one of the largest El Niños of the past 150 years that weakened the Leeuwin Current and allowed the Subtropical Front to move closer to southern Western Australia.

Keywords: T. W. Fowler, Leeuwin Current, Subtropical Front, Upwelling, Oceanography, El Niño

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INTRODUCTION

Little is known of the properties of Australia's oceans prior to the end of World War II. Thus earlier information has considerable value in reconstructing ocean conditions. In 1896, while working as a demonstrator in Engineering at the University of Melbourne, Thomas Walker Fowler (O'Neil 1981) allocated some of his spare time to initiate and run a program in which crew members on 'intercolonial steamships' plying the waters around Australia and New Zealand took seawater temperatures and samples twice daily (Fowler 1898). His work was inspired by the achievements of the 1872–76 *Challenger* expedition and he followed the method of Buchanan of that expedition in measuring densities of the seawater samples using hydrometers.

Fowler (1898) presented tables of measurements from five regions, broken into sub-tables for different seasons. The regions were Fremantle across the Great Australian Bight to Adelaide and Melbourne; Melbourne to Brisbane; the East Coast of Australia north of Brisbane; Melbourne to Bluff, New Zealand; and return to Sydney via Cook Strait. Two other tables presented his occasional seawater temperature measurements on the Bass Strait coast at Sorrento Back Beach, Victoria from early February 1895 to January 1898, probably while staying at his nearby holiday home. These were accompanied by density measurements from February 1896. Presumably it was here that he tried and tested the procedures to be used at sea and in his laboratory.

Fowler's measurements are valuable because they appear to be the first taken from ships on the Fremantle to Melbourne route over several seasons (Fig. 1), and the first to obtain measurements within the Leeuwin Current and other oceanographic features between Western Australia and Victoria. Note that the ships crossing the Great Australian Bight to and from Cape Leeuwin just south of 35°S in 1896 would have been near the shelf edge, where the Leeuwin Current flows to about 120°E, whereas farther east the shelf edge gradually angles east-northeastward. Fowler (1898) reported that the temperatures and densities south of Australia decreased during 1896, and, in an abstract published in 1901, that they continued to do so over the next three years. He attributed the decreases to strengthened southwesterly winds in the southern Indian Ocean. Unfortunately, the measurements for 1897–1899 appear to have been lost. The decreases appear to have been caused by a northward movement of the Subtropical Front associated with a strong El Niño.

The Subtropical Front (STF) was identified during a survey in late February 1976 from 110–117°E that revealed that surface salinities decreased from 35.6 to 34.8 between 38°S and 39°S, with temperatures of 16 ± 0.5°C (Cresswell *et al.* 1978). In a comprehensive study Belkin & Gordon (1996) considered the STF to lie at about 39°S, well to the south of Western Australia. Using November 1994 data from the *Franklin* voyage FR9410, Schodlok *et al.* (1997) found the STF spans 39.4 – 40°S. Using satellite imagery Kostianoy *et al.* (2004) concluded that in July 1999 there were two STFs south of Western Australia, at 38°S and 39–40°S. James *et al.* (2002, p. 145) reported that for their study area south of Australia 'salinity

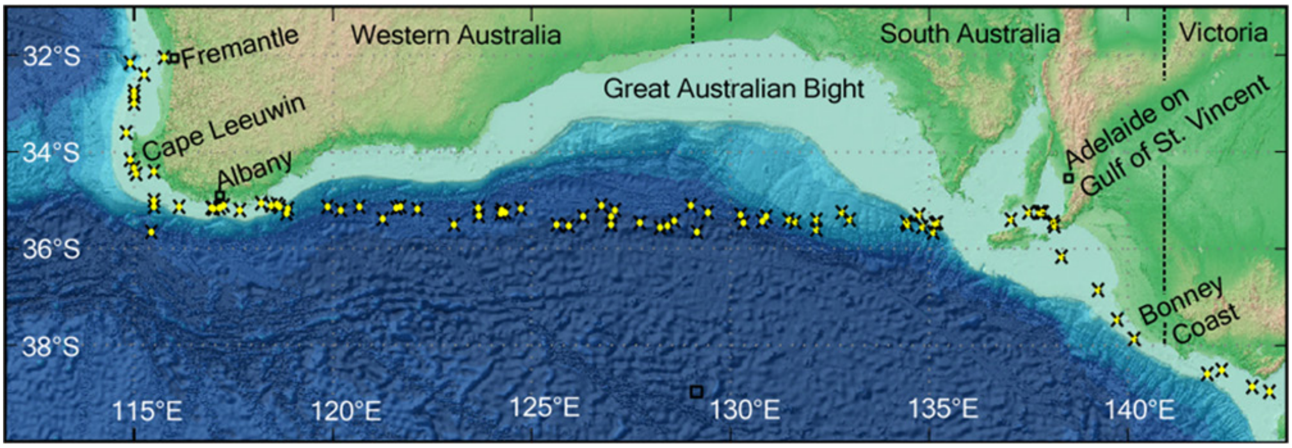

Figure 1. Chart showing all sampling points for temperature and salinity along the voyage paths between Fremantle, Adelaide and Victoria in May–June, July–August and November–December 1896. General Bathymetric Chart of the Oceans (https://www.gebco.net).

is at best weakly affected by seasonal change so that the horizontal salinity change associated with the STF usually reaches through the mixed layer'. They pointed out that the shallow (~50 m) mixed layer in summer prevents the surface expression of the characteristic 12°C isotherm. These observations show considerable ocean-current complexity south of Western Australia, as do the earliest satellite-tracked drifters and satellite sea-surface temperature measurements (Cresswell & Golding 1980; Legeckis & Cresswell 1981).

The two satellite images in Figure 2 cover a strengthening El Niño, with cold waters revealing that the STF can reach the 35°S parallel traversed by the merchant ships in 1896. The former from 18 November 1986 (Fig. 2a), with a Southern Oscillation Index (SOI) of -14, shows warm water carried southward and then eastward in the Leeuwin Current, with offshoots at 116.5°E, 118.5°E and, less obviously, at 120°E. There is a warm core eddy at 113–114°E that may have formed from a similar offshoot and drifted westward, as observed more recently (Cresswell & Griffin 2004). In the southeastern part of the image a 50-km wide band of cold water extends northwestward several hundred kilometres to 36°S, where it appears to be overrun by one of the offshoots. Features that could be identified on the edges of the cold band on this and the previous day showed movements to the northwest at 0.25 ms^{-1}. With a temperature of 13°C, this band suggests that it contains water normally found south of the STF with more cold water spreading northward to 35°S between 119°E and 121°E.

The satellite image for 6 March 1987 (Fig. 2b), with a SOI of -17 (strengthening to -24 in April), shows waters of 21°C at 32°S in the Leeuwin Current that finished near 34°S. Farther downstream to the east, ill-defined patches of 18.5°C water are possibly remnants of an earlier Leeuwin Current flow. A cool 17.5°C plume on the southern continental shelf emanating from between 116°E and 118°E was likely upwelling induced by easterly winds. The plume moved westwards to 33°S, progressively warming en route. This northward flow would later be called the Capes Current (Gersbach *et al*. 1999; Pearce & Pattiaratchi 1999). Cold water, perhaps

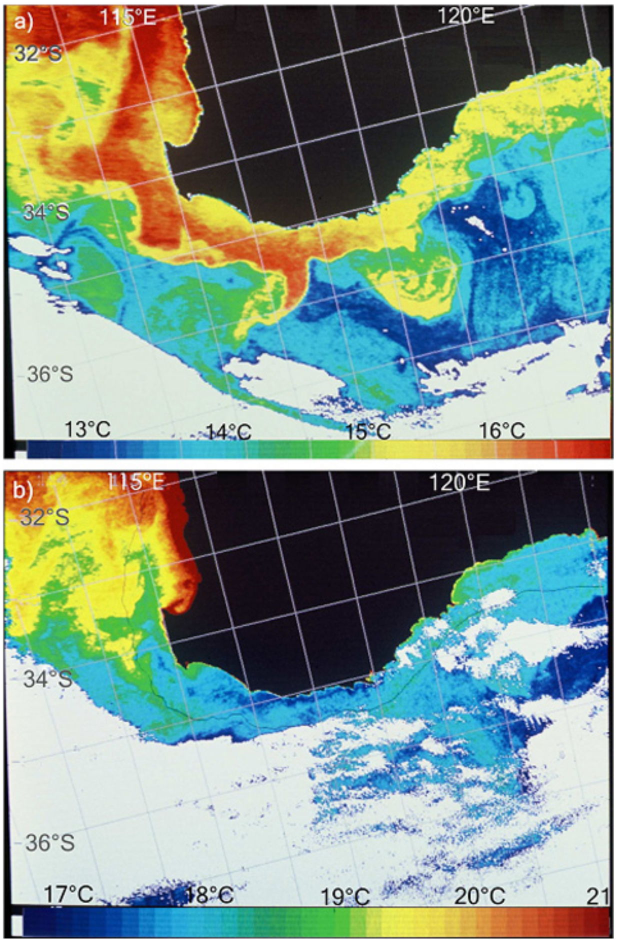

Figure 2. Satellite sea-surface temperature images from south of Western Australia: a) 18 November 1986; and b) 6 March 1987. The temperature scale is at the bottom of each image; clouds are white; a black mask has been put over the land; and there is a 1 x 1° latitude–longitude grid. Data from NOAA 9 satellite received by CSIRO in Hobart. 2b is from Cresswell & Peterson (1993, plate 1c).

related to a northward move of the STF, crossed 35°S near 122°E.

The dynamics and seasonality of the Leeuwin Current, the wind-driven upwelling current and the Flinders Current farther offshore, have been examined in detail by Akhir *et al*. (2020). The strong effects of El Niño and La Niña on the Leeuwin Current are evident in Lough *et al*. (2012, fig. 8) when compared with SOI values from the Bureau of Meteorology: La Niña drives a strong Leeuwin Current eastward along the southwestern Australian continental shelf edge whereas the Leeuwin Current is weaker during El Niño. Huang & Feng (2015) found that the extent of the Leeuwin Current's sea-surface temperature was reduced in El Niño years based on Moderate Resolution Imaging Spectroradiometer (MODIS) satellite data.

METHODS

In Melbourne Fowler (1898, p. 688) measured the densities of the water samples, 'referenced to distilled water at 39.2° Fahr. as standard', at temperatures as close as possible to 60°F (15.6°C), the design temperature of the hydrometers. He took the mean of three different readings for each water sample and reported that individual readings differed from the mean by no more than 0.0006 gram cm^{-3} (0.6 kg m^{-3}). In addition, he checked his instruments in solutions of known densities.

Sea-water density was calculated from Fofonoff & Millard (1983) to back-calculate the surface salinities from Fowler's densities (at 15.6°C). These were cross-checked with the seawater density calculator (available at https://www.mt-oceanography.info/Utilities/density.html).

Although Fowler commented that errors may have been made with some temperature measurements due to thermometers being removed from buckets too soon, or through allowing sunlight onto them, the temperatures along repeated passages (Fig. 2) were usually not overly different. However, those on the eastbound passage between 22 and 28 August 1896 deserve further comment: the temperatures were unchanged at 58°F (14.4°C) for 5° of longitude from 120°E, and then unchanged at 56°F (13.3°C) for almost 10° of longitude from 128°E. This may have been due to crewmen not completely adhering to Fowler's instructions.

Fowler's 1896 data, particularly south of Western Australia, were compared with surface data from research voyages between 1976 and 2017 accessed through the CSIRO Oceans and Atmosphere web site https://www.cmar.csiro.au/data/trawler. Until the 1980s these were from the surface Nansen bottles from hydrology casts; for later voyages a subsample of the thermosalinograph data was used. Hourly sea level data for Fremantle were accessed from gesla.org, i.e. the Global Extreme Sea Level Analysis project.

RESULTS

Fowler's temperatures and derived salinities along ~35°S between Cape Leeuwin in the west and Victoria in the east for May–June, for July–August, and for November–December 1896 are summarized in Figure 3. The temperatures for the first two periods suggest that the ships were in the warm Leeuwin Current west of about 120°E. East of there the coast and Leeuwin Current trend northward and, as would be expected, cooler Southern Ocean waters were encountered. The

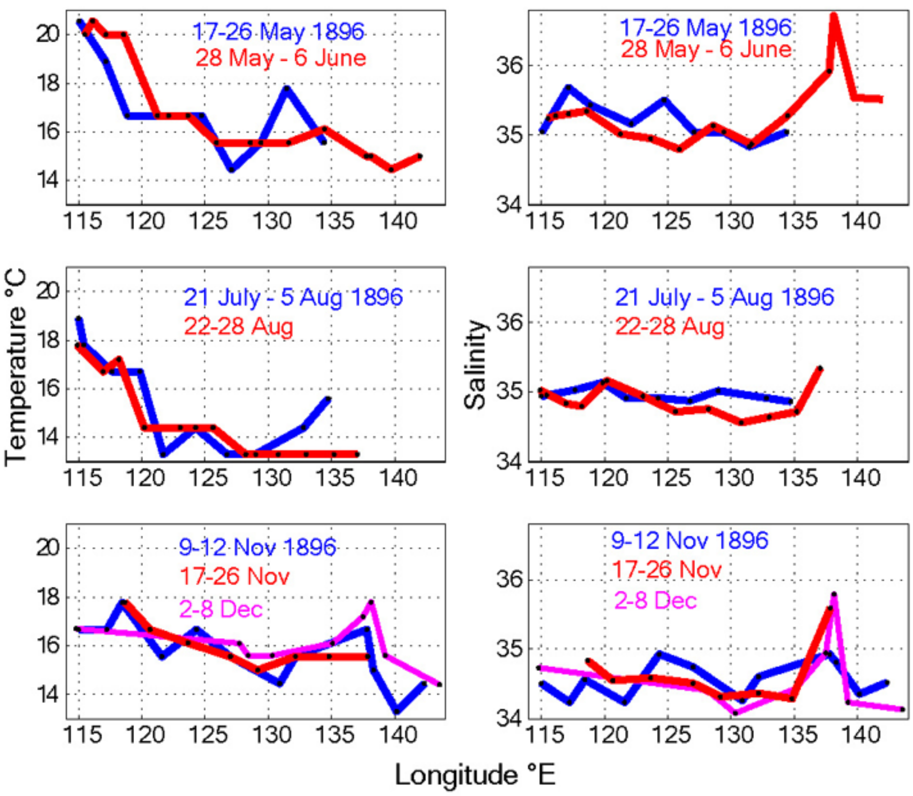

Figure 3. Temperatures (left) and derived salinities from seawater samples (right), taken on steamships in May–June, July–August, and November–December 1896. The red and magenta lines indicate eastbound passages and the blue lines for westbound. The two off-scale salinity values in St Vincent's Gulf in June (red) were 36.25 and 37.05; the off-scale salinity value in December (magenta) was 34.08.

November–December temperatures were low, <17°C in the west: possibly the result of an absence of the Leeuwin Current or wind-driven upwelling on the continental shelf immediately east of Cape Leeuwin (cf. Fig. 2b). At the same time, temperatures were as low as 13.3°C (with salinity 34.35) off the Bonney coast (140°E) of South Australia where there can be summer upwelling. The Bonney upwelling, and others that are part of the Great South Australian Coastal Upwelling System (Kämpf, 2015), occasionally take place in summer in response to coast-parallel southeasterly winds. The upwelling was first mentioned by Hynd & Robins (1967). Rochford (1977), Schahinger (1987), Kämpf *et al*. (2004) and Kämpf (2015) indicate upwellings can take place in December–March whereas Bye (1970) and Lewis (1981) suggest November–March. Whether or not there was an early upwelling in November 1896 cannot be determined with just one temperature measurement and no knowledge of the winds.

The high salinities in May–June from 115°E almost to 119°E, were probably due to the Leeuwin Current, consistent with the high temperatures there. In the shallow waters of St. Vincent's Gulf (138°E) the salinities were high, reaching 36.25 and 37.05 in May–June and a little over 36 in November–December (no data from July–August). Of particular interest is the overall decrease in salinity of roughly 0.6 over the 7-month period, in step with the decrease in density that Fowler commented upon. Note that the salinities in the west in November seem almost too low to be realistic, ranging from 35.2 to less than 34.6.

In the west in May–June (Fig. 4a, b) there is good agreement between the Fowler temperatures and those of *Franklin* in June 1987, but the Fowler salinities were lower by about 0.3. The Leeuwin Current was strong during the *Franklin* voyage (Cresswell & Peterson 1993) and was also evident in May–June 1896 (Fig. 3). The relatively high temperatures west of 120°E in both July–August 1896 and July 1994 (Fig. 4c, d) suggest the influence of the Leeuwin Current. Current measurements made during FR9407 showed the Leeuwin Current rounding Cape Leeuwin at up to 1 ms^{-1}, and that it progressively weakened eastward to end near the continental shelf edge (Cresswell & Domingues 2009). The near-shore high salinities found in the Great Australian Bight during this voyage were probably due to evaporation, which may also explain the cold salty waters in the shallow St. Vincent's Gulf.

The November 1896 measurements do not show a Leeuwin Current and the salinities were the lowest for the year (Fig. 3). In contrast, measurements from RV *Franklin* in November and December 1994 and RV *Investigator* in November 2017 (Fig. 4e, f) suggest that the warm, salty Leeuwin Current flowed eastwards after rounding Cape Leeuwin. Incidentally, the waters adjacent to the continent west of about 121°E were saltier in 1994 (*Franklin*) than in 2017 (*Investigator*). Farther south, the sub-Antarctic waters were cooler and fresher. From their analyses of data collected along 120°E on FR9410, Schodlok *et al.* (1997) concluded that the STF lay at 39.4 – 40°S with temperatures of 12.7 – 14.8°C and salinities of 34.81 – 35.48. Surface-water temperatures during the *Diamantina* voyage from 37–40°S in late February 1976 were relatively high, probably due to insolation and the formation of a mixed layer in summer, and perhaps a southward offshoot of the Leeuwin Current.

The ellipses around the Fowler temperature–salinity (T–S) values in Figure 5 show how the salinities decreased during 1896, and that the values were scattered compared with those from the more recent voyages. For the mean of the T–S values of November–December 1896 (Fig. 5c) to match those of the *Franklin* and *Investigator* voyages would require an average salinity increase from 34.6 to 35.6, or an average temperature decrease from ~16.5°C to 9.5°C. Another approach is to examine the latitude colour coding: the November–December 1896 salinities at ~35°S were found ~10° of latitude farther south during the *Franklin* and *Investigator* voyages.

The T–S data from *Diamantina* comes close to the Fowler data (Fig. 5c) and were only 2–5° of latitude south of 35°S; the surface waters would have warmed over summer. *Diamantina* reached the STF and crossed both a cyclonic eddy and a larger anticyclonic feature (Cresswell *et al.* 1977). This raises the question whether the STF moved northward to 35°S during 1896 bringing with it cool, relatively low salinity waters.

DISCUSSION

Fowler's measurements of temperature and density between southwestern Australia and Victoria yield some intriguing findings when compared with modern data, accepting that the crewmen taking the water temperatures did as good a job as conditions permitted. Fowler's density measurements on the water samples back in Melbourne with hydrometers and temperature near 60°F (15.6°C) were certainly rigorous given that he took the means of three readings and that he honed his skills with more than a year of observations at the Sorrento Back Beach. Applying the UNESCO formulae to calculate salinities from the densities, the November 1896 values at the western end of the passages were low and, in combination with their temperatures, seem unrealistic for that region. This is explored as follows:

(1) **Albany and Rottnest stations**. At the Albany 50 m hydrology station, which operated in 1978–1983, surface salinities ranged from 35.2 to 36. These values barely overlap those for November 1896 (34.55 – 35.25). Data collected from over four decades at the Rottnest Island 50 m hydrology station (near the continental shelf edge at 32°S, west of Fremantle) reveal salinities of 35.15 – 36.15 with a typical annual variation of 0.3 – 0.6, although the La Nina of 1973–75 brought the salinities down to 35.2 – 35.5.

(2) **Rainfall as a factor**. Rainfalls at Albany, Bunbury and Fremantle were not markedly different in 1896 from several years before and after (http://www.bom.gov.au/metadata/catalogue/19115/ANZCW0503900430), and so seems unlikely to explain salinity variations.

(3) **The Southern Oscillation Index and the Subtropical Front**. The strong El Niño that commenced in 1896 may have led to a weaker Leeuwin Current, thereby allowing the STF to move northward, bringing with it cooler, fresher waters towards the 35°S path of Fowler's merchant ships.

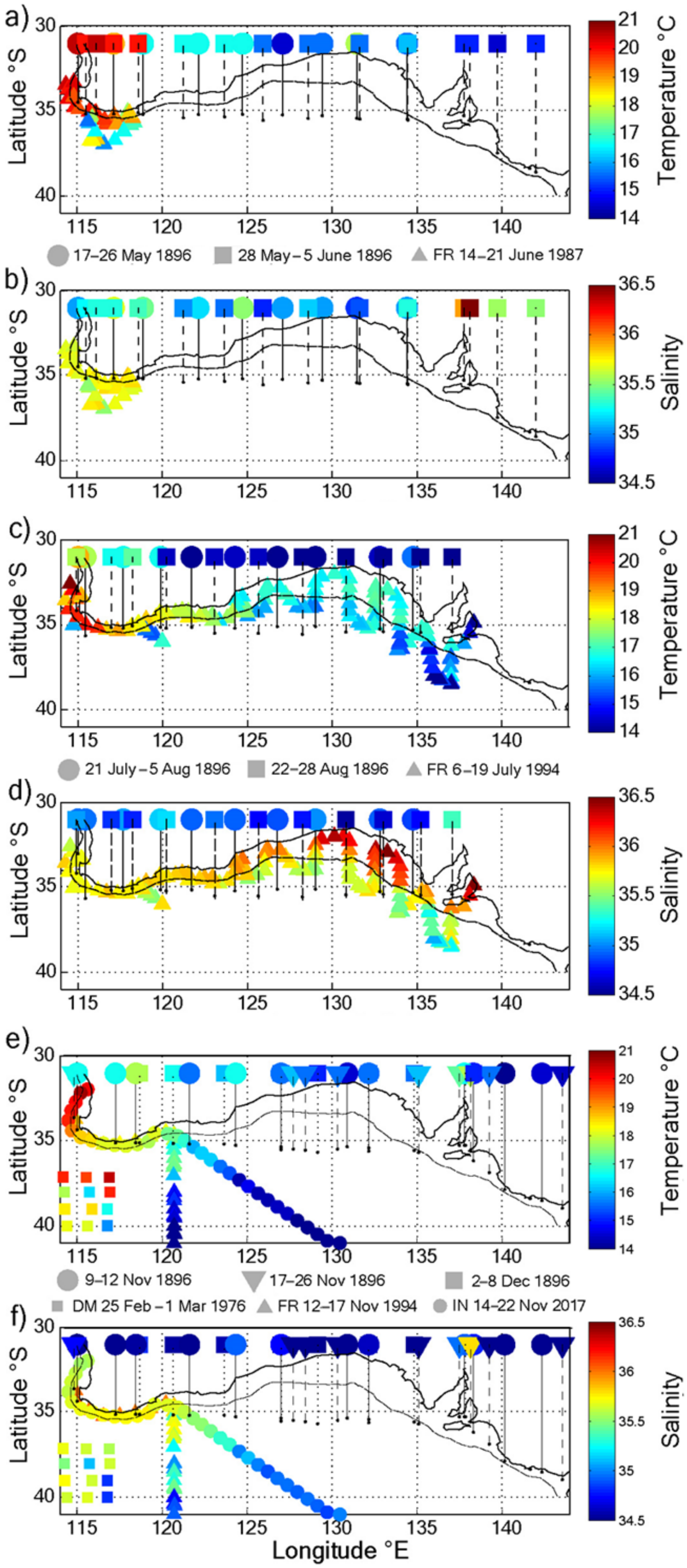

Figure 4. Fowler's 1896 temperature and salinity surface measurements colour coded as large symbols offset to 31°S compared with measurements from modern voyages: a) and b) Fowler values for May–June 1896 and modern values from RV *Franklin*; c) and d) Fowler values for July–August 1896 and modern values from RV *Franklin*; and e) and f) Fowler values for November–December 1896 and modern values from HMAS *Diamantina*, RV *Franklin*, and RV *Investigator*.

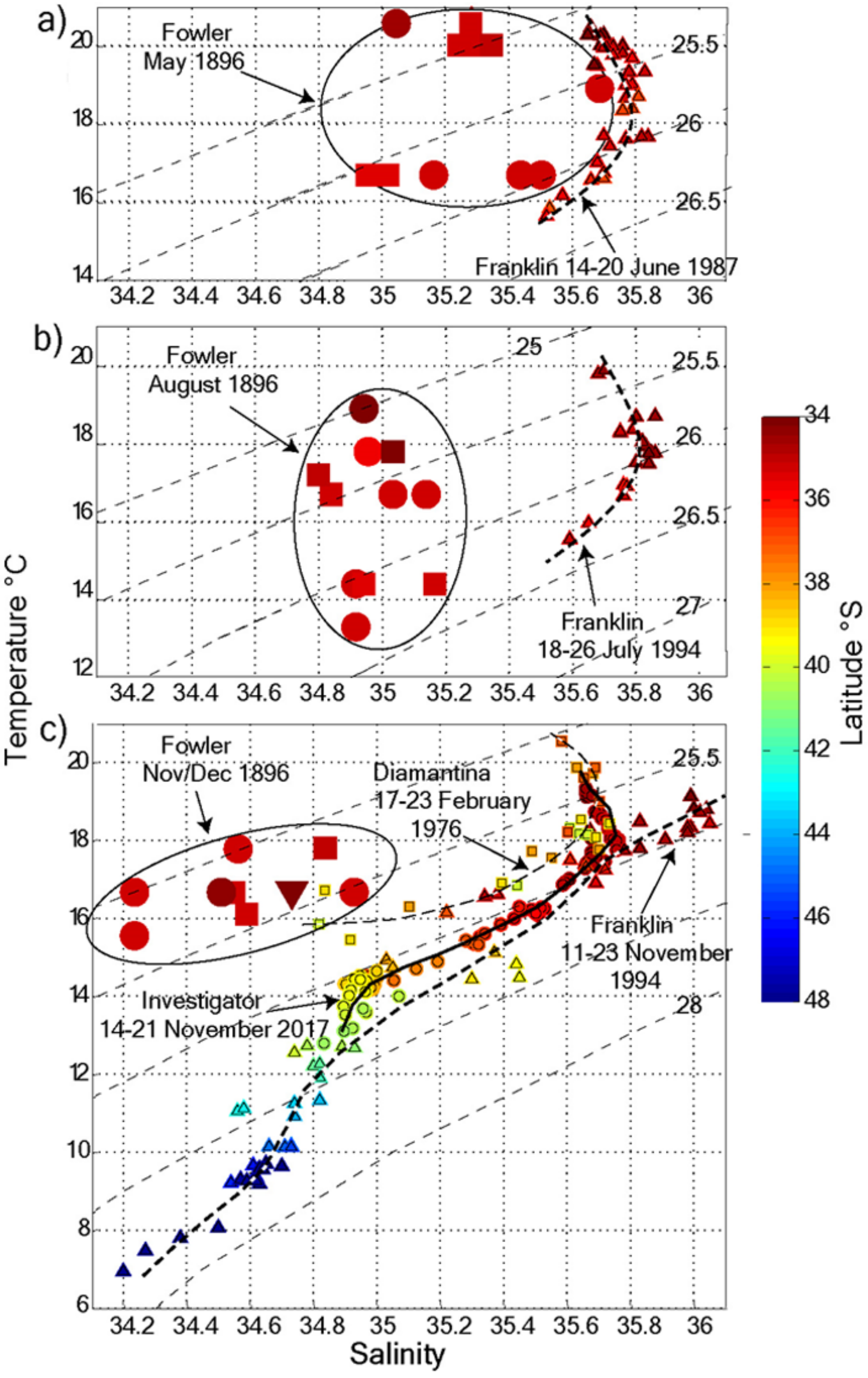

Figure 5. Temperature–salinity diagrams colour coded for latitude. The angled dashed lines are isopycnals. The Fowler data from 114–125°E have circles for westward passages and squares and a triangle for eastward ones. Small symbols mark recent surveys as follows: a) RV *Franklin* from 33–37°S, 114–119°E (triangles); b) RV *Franklin* from 32–38.5°S, 115–125°E (triangles); and c) RV *Franklin* southward from WA to 48°S (triangles); HMAS *Diamantina* from 37° to 40°S (squares); and RV *Investigator* southeastward from WA to 41°S (circles).

El Niño and La Niña events are defined by SOI values sustained at less than -7 and greater than +8, respectively. Over the past 150 years the most significant El Niño events commenced in May 1896 and May 1905 with SOI values of -42.2 and -42.6 respectively. For comparison, El Niños in 1953, 1983 and 1997 had values of -31.9, -33.3 and 24.1. The SOI associated with the 1896 El Niño (Fig. 6) took 18 months to return to zero and through to the end of 1899 only exceeded the +8 for a La Niña on seven occasions, and was not sustained. Fremantle sea level was first recorded in January 1897 and so missed the onset of El Niño in 1896; sea level was relatively low in 1897 and 1899, and high in 1898.

Fremantle sea level, when interpreted through the analyses of Feng *et al*. (2003) covering 1950–2000, suggest an El Niño was in progress in 1897 (Fig. 7), in accord with the low values of SOI. The Leeuwin Current would have been weaker, and, perhaps, almost absent south of Western Australia—as implied by the extremely low values of SOI in 1896. Zinke *et al*. (2014, fig. 4b) reconstructed Fremantle sea level from the analysis of coral core samples from the Houtman Abrolhos Islands at 28.3°S and plotted these with the observed sea level at Fremantle. Even though there are no observations before January 1897 it is likely that the reconstructed sea level was low in 1896, as would be expected from the strong El Niño.

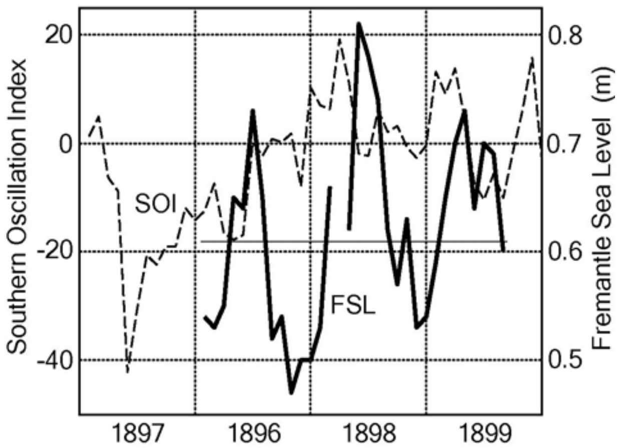

Figure 6. The Southern Oscillation Index for 1896–1899 (dashed line) and Fremantle monthly mean sea level from January 1897 (gesla.org), when recording began, to August 1899. There is a gap in the data for March 1898. The thin line at 0.61 m marks mean sea level for the late 1890s (from Pattiaratchi & Eliot 2009).

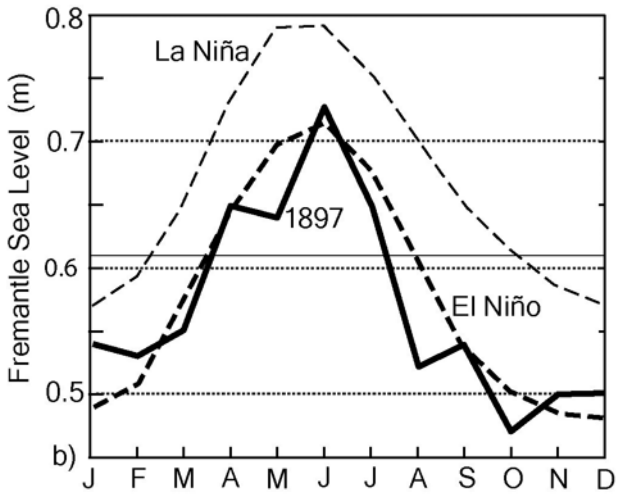

Figure 7. Monthly mean sea level at Fremantle (thick line) calculated from gesla.org for 1897 and the mean sea level of 0.61 m for the late 1890s. The dashed lines show the deviations from mean sea level for el Niño and la Niña events between 1950 and 2000 from Feng *et al*. (2003, fig. 15). Mean sea level for those years has been superimposed on the 0.61 m mean sea level for the late 1890s; the sea level scale is the same.

If the STF had moved northward in 1896 then the low salinity waters that it brought would have been largely conserved, whereas insolation may have raised the sea-surface temperatures to match those measured by Fowler. The puzzle remains and, if anything, it is made more enticing with Fowler (1901) reporting, but only in an abstract and without giving values, that water densities and temperatures off southern Australia continued to decrease through to 1899.

CONCLUSIONS

- Temperature measurements reveal the Leeuwin Current south of Western Australia in May–June and July–August 1896.
- A northward move of the Subtropical Front, linked to a very strong El Niño and a weak Leeuwin Current, is the likely cause of decreasing salinities and temperatures south of Western Australia measured during 1896 and 1898.
- All water samples from St. Vincent's Gulf were highly saline due to evaporation, in agreement with present-day knowledge.

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