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Long Term and Recent Changes in Sea Level in the Falkland Islands

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Abstract

Mean sea level measurements made at Port Louis in the Falkland Islands in 1981-2, 1984 and 2009, together with values from the nearby permanent tide gauge at Port Stanley, have been compared to measurements made at Port Louis in 1842 by James Clark Ross. The long-term rate of change of sea level is estimated to have been +0.75 ± 0.35 mm/year between 1842 and the early 1980s, after correction for air pressure effects and for vertical land movement due to Glacial Isostatic Adjustment (GIA). The 2009 Port Louis data set is of particular importance due to the availability of simultaneous information from Port Stanley. The data set has been employed in two ways, by providing a short recent estimate of mean sea level itself, and by enabling the effective combination of measurements at the two sites. The rate of sea level rise observed since 1992, when the modern Stanley gauge was installed, has been larger at 2.51 ± 0.58 mm/year, after correction for air pressure and GIA. This rate compares to a value of 2.79 ± 0.42 mm/year obtained from satellite altimetry in the region over the same period. Such a relatively recent acceleration in the rate of sea level rise is consistent with findings from other locations in the southern hemisphere and globally.

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1. Introduction

In 1839 James Clark Ross set out on a voyage of discovery and research in the Southern Ocean which was to last until 1843 (Ross, 1847). In April 1842, his ships *Erebus* and *Terror* arrived at Port Louis in East Falkland having suffered major damage from ice-bergs and collision. Ross set up a winter base there, repairing his ships, establishing a magnetic observatory, and making astronomical, oceanographic and meteorological measurements.

Sea level measurements were made every half an hour, and more frequently around the times of high and low water, from 10 May to 15 December 1842, although with major gaps between September and December when Ross took the two ships to Tierra del Fuego in order to make simultaneous measurements of the magnetic field in South America and the Falklands. As a result, only the sea level data up to the end of August are useful. The mean level of the sea at Port Louis between May and August 1842 was calculated by Ross as being 5 feet 8 inches below two benchmarks cut into the rock of the adjacent cliffs and marked with brass plaques (Ross, 1847, volume 2 and Figure 1). The marks have survived in good condition and afford the possibility, as was Ross's intention, of estimating changes in sea level between 1842 and points in the future.

This paper describes how a new set of measurements undertaken at exactly the same spot in February-March 2009 has been combined with the 1842 and other measurements at Port Louis and with those from Port Stanley (or Stanley), 25 km to the south-east (Figure 2). The combined data set enables the determination of a long term rate of sea level change in the region, and an investigation of whether a relatively recent acceleration in the rate of sea level rise has occurred , as has been reported elsewhere in the southern hemisphere and globally.

2. Sea Level and GPS Data Sets

Ross's original journal, listing the entire set of half-hourly measurements at Port Louis, is believed to have been destroyed accidentally by the UK Hydrographic Office (UKHO) at some point during the 1990s. Fortunately, the journal was inspected in some detail by William Whewell and co-workers at Trinity College, Cambridge during the nineteenth century, and a record of the heights and times of each high and low water was kept in Whewell's research notes which are preserved in the Wren Library.

Our 2009 Port Louis data set, which covers the period from 24 February to 11 March, was acquired with the use of three sub-surface pressure transducers. Two of the sensors were located adjacent to the Ross benchmarks (indicated by 'JCR' in Figure 2c,d). These sensors were Richard Brancker Research (RBR) XR-420 strain gauges which sampled sea pressure every six minutes and were corrected for air pressure changes with the use of an additional, nearby RBR sensor which functioned as a barometer. The third instrument, located at a jetty in Port Louis harbour (Figure 2c,d), was constructed by the Proudman Oceanographic Laboratory (POL) and consisted of a 'differential' transducer attached to a vented cable, such that air pressure corrections were applied automatically. Measurements were recorded by an OTT Hydrometry data logger using one minute sampling. This third gauge was used to provide a backup to, and validation of, data sets from the two sensors at the relatively open-sea benchmark location. The findings discussed below are identical at the millimetre level with the use of data from any of the three instruments. Datum control for the pressure-based time series was provided by means of two tide boards located near to Ross's benchmarks, the heights of which were related to the marks by geodetic levelling. Although this modern data set is short, it has the great benefit of simultaneous recording at the nearby Stanley tide gauge, as will be described below.

In between the 1842 and 2009 measurements, two other important sea level data sets were acquired at or near to Port Louis. The first was a set of half-hourly data from a tide gauge installed by the UKHO at Green Patch, 2 km across Berkeley Sound from Port Louis (Figure 2). This data set spanned December 1981 to March 1982, measurements having been curtailed by the Falklands War. The datum of the gauge was later connected to Ross's benchmarks by means of Global Positioning System (GPS) measurements undertaken in 1996 by a surveying team from HMS *Endurance*. The second was a set of half-hourly sea level measurements obtained from a bubbler tide gauge at the harbour jetty, approximately 1 km from the benchmarks (Figure 2). This instrument was installed by the Institute of Oceanographic Sciences (as POL was then called) and its data set spans May to September 1984. The datum of this time series was related to Ross's benchmarks by levelling conducted by a surveying team from HMS *Herald*.

In 2003, we undertook two sets of sub-surface pressure measurements at Port Louis and Green Patch. These data sets, both of several months duration, were obtained with RBR instruments. These records had no datum control and hence are not useful for study of mean sea level change.

However, they are valuable in providing an estimate of the magnitude of variability in sea level difference between Berkeley Sound and Stanley.

Sea level measurements using conventional float and stilling well gauges were made by the UKHO at Government Jetty in Stanley during the 1960s and 1970s, although only the data from the 1960s are of acceptable quality. Modern pressure-based tide gauges have been deployed by POL at the Falkland Interim Port And Storage System (FIPASS) floating warehouses in Stanley since the early 1990s as part of the Global Sea Level Observing System (GLOSS, see Woodworth et al., 2003). These gauges provide accurate measurements of sea level in addition to sub-surface and air pressures (Woodworth et al., 1996). Since 2005, an OTT Kalesto radar tide gauge has been added to the station to provide data for comparison to and validation of the pressure-based information. Data from these gauges have been described by Woodworth et al. (2005) and are available from http://www.pol.ac.uk/ntlsf/.

Sea surface heights from the TOPEX/Poseidon and Jason-1 satellite radar altimeters were obtained from the University of Colorado global sea level change web site (http://sealevel.colorado.edu). These data are available in the form of gridded fields and have all environmental and instrumental corrections applied (Leuliette et al., 2004).

During the 2009 campaign, simultaneous GPS measurements using Ashtech Micro-Z receivers were made near to the benchmarks at Port Louis and at the Stanley FIPASS tide gauge. These data sets were analysed in combination with those from two long-term GPS installations in Stanley owned by Ohio State University and the Jet Propulsion Laboratory (JPL), USA. GPS coordinates of the benchmarks were computed relative to those given for the JPL station by the International Global Navigation Satellite System (GNSS) Service (IGS) (http://igscb.jpl.nasa.gov/network/site/falk.html). When combined with a suitable geoid model (e.g. Earth Gravitational Model (EGM) 08, Pavlis et al., 2008), and with an assumption of little oceanographic sea surface gradient between Port Louis and Stanley, then the use of GPS in this way should allow sea level data from both sites to be treated as being from the same location. (We return to the issue of quality of geoid models and the accuracy of this method below.) GPS measurements were also undertaken near to the main geodetic control points in Stanley and at other points of interest (e.g. Ross's magnetic observatory marker).

A separate report on the tide gauge and GPS fieldwork undertaken at Port Louis and Stanley in 2009 is available from the authors. The work included the installation of additional benchmarks at both locations, as a safeguard in case of loss or damage to the original marks, and in order to comply with GLOSS standards for sea level stations (IOC, 2006).

3. Tests of the Quality of Ross's Data

Although Ross refers to 'tide gauges' several times in the two volumes of his 1847 book, it is not clear what sort they were. It is most likely that they were simple tide boards (or 'tide poles') with a vertical graduated scale as recommended to captains of Royal Navy ships at that time (e.g. see the Hydrography section of Herschel, 1849). However, it is conceivable that they could have comprised an upright tube for filtering out wave action, in which a float was attached to an upright rod for indicating water level (see the Tides section of Herschel, 1849). Such a float and stilling well gauge would have been potentially more accurate but somewhat more difficult to install and operate. Ross (1847) makes no mention of tubes or floats.

It will be seen that the conclusions of this paper depend as much upon the quality of Ross's measurements as upon that of our more modern data. Although Ross is known to have been an excellent scientific observer in general, it has to be kept in mind that the sea level measurements were not his priority. Therefore, it is necessary to design some tests of their accuracy which can provide confidence in their use in the present study.

Figure 3 presents a time series of daily mean tide level (MTL) from 11 May to the end of August 1842. Daily MTL is defined as the average of the average high waters and average low waters recorded each day. Also shown is a time series of daily mean air pressure recorded on board the *Erebus,* with an allowance for the height of the barometer above sea level (six feet). These barometer measurements are known to have been corrected rigorously for temperature and instrumental biases (Ross, 1847, volume 1) although it is not known how many times a day and at what times measurements were made.

The correspondence between daily MTL and air pressure can be clearly seen in Figure 3, with part of the difference between the two likely to be due to the steric component of the sea level seasonal cycle. The correspondence is also demonstrated in Figure 4(a). In this case, the MTL values have been corrected for occasional spikes in the daily record which can arise due to aliasing by the semi-diurnal and diurnal components of the tide (primarily the diurnal tides) and both records have been smoothed with a 3 day boxcar filter. A regression fit between the two yields a slope of -0.968 ±

0.049 cm/mbar, consistent with known values of ‘inverse barometer (IB) coefficient’ in this part of the world (Mathers and Woodworth, 2001; Woodworth et al., 2005). The daily mean sea level (MSL) data set acquired from almost the same location in 1984 (i.e. at the Port Louis harbour jetty instead of near to the benchmarks, Figure 2), covering a similar part of the year, yields a similar coefficient (-0.935 ± 0.048 cm/mbar, Figure 4b, a boxcar filter not being necessary in this case).

Determination of the IB coefficient from Ross’s data is not only an interesting finding in itself, but provides a sensitive test of the quality of both the sea level and air pressure information. If the quality of either one, or both, of the records had been poor, then the correlation observed would have been less evident. Such checks on the quality of historical data, where information for both parameters exists, have been successfully used previously at other locations (e.g. for 18th century Liverpool data, Woodworth, 2006).

Many years later, Ross was to make measurements at Port Leopold in Canada which would lead to his being recognized as one of the discoverers of the ‘IB effect’ (Ross, 1854). However, it is unlikely that, at the time of his stay at Port Louis, he would have had a particular insight into the IB, and he would certainly not have known the precise value of the coefficient. It is inconceivable that the sea levels and air pressures are other than independent data sets. Therefore, their comparison provides a first test of their quality.

A second test is to check if the high and low water values provide the same information with regard to mean sea level variability. Figure 5 shows values of each quantity, with the astronomical tide removed from each high or low value and with a 3 day boxcar filter applied. In this case, the astronomical tidal heights were calculated from a full set of tidal constants determined from analysis of the 1984 data. Of course, the highs and lows on each day (minus the tide) need not always be identical, as sub-daily sea level variability such as short-duration surges or seiches can affect high and low levels differently. However, the low frequency character of the two time series should be similar if ‘mean sea level’ variation in the data set is to be meaningful. One can see that the two series do indeed correspond closely, although the low waters present a negative bias relative to the high waters of 3.28 cm. Closer inspection shows that the bias originates primarily from daytime low waters, the series for night-time lows presenting little bias relative to either daytime or night-time high waters. The source of this bias almost certainly stems from some peculiarity in the way that the original half-hourly data were acquired during different parts of the day, although it is possible that it could have been introduced in the later Cambridge extraction of the highs and lows. The resulting possible bias in mean level of 1.64 (= 3.28/2) cm is included in the overall uncertainty in Ross’s mean level discussed below.

A final test is of the timings of Ross’s individual high and low waters, compared to predictions for 1842 based on tidal constants computed from the 1984 data set. This test is less important with regard to our application of Ross’s measurements, which is focused on levels. However, it does provide further insight into general quality. This comparison requires two assumptions: that Ross’s clock employed local mean time (from inspection of the Trinity records it seems that Whewell made the same assumption), and that the character of the local tides has not changed significantly in the last one and a half centuries.

The times of the 1842 high waters were found to be on average 5 minutes later than those predicted, the difference between the two sets of times increasing slightly from near zero at the start of the record to 15 minutes by the end of August, with a standard deviation in time-difference of 31 minutes. Inspection of the short sections of data after August shows that the time-difference was maintained on average at 2 minutes until the end of the year. For the low waters, the average time-difference was larger at 12 minutes, being near zero at the start of the record and increasing to about 35 minutes at the end of August, and with a standard deviation of time-difference of 34 minutes. The time-difference was smaller at around 13 minutes in the short sections of data after August and up to the end of the year.

We consider these to be satisfactory checks of timings, given that the recorded times were in most cases provided only in multiples of 5 minutes, and that times of high waters are more difficult to determine than levels, even given half-hourly sampling. Nevertheless, the 15 and 35 minute drifts in the time-differences for high and low waters respectively are not understood. The fact that the time-differences returned to smaller values in the later sections of data suggests that the variations in time-difference must have been due to some kind of alterations in observational practice.

The standard deviations in time-difference of over half an hour are a consequence of the original half-hourly sampling, the fact that Whewell probably defined high (and low) heights and times from the individual highest (and lowest) samples around each tide, rather than perform some kind of interpolation, and that non-tidal variability at Port Louis has a standard deviation of 11 cm (based on the 1984 data set) compared to an average tidal amplitude of half a metre. A simulation of the time-differences to be anticipated in Ross's high and water values was made using the 1984 data set, with standard deviations of 28 minutes obtained for both high and low waters.

Although Ross's high and low waters are of good quality, they are in fact not used directly in the following analysis. That is because the datum of the measurements, which was presumably the zero of the gauge, was not recorded in terms of the heights of his benchmarks in either Ross's surviving records or Whewell's research notes. Therefore, although we can infer what that datum was, there is no explicit confirmation of it. Consequently, for a mean sea level estimate we have to rely on the height of the 'Ross' benchmark with its engraved brass plaque (Figure 1), and on the 'mean level of the sea 5 feet 8 inches below the benchmark' statement in Ross (1847, volume 2). This is admittedly not an ideal situation, but is an inevitable consequence of the loss of Ross's tidal journal which must have contained more detailed information on the measurements. However, given that he had what must have been good half-hourly data to make that mean sea level calculation, we have confidence in using it.

4. Methods of Analysis of Sea Level Data

There were three main steps in the analysis of the 1842, 1981-2 and 1984 sea level data sets:

(1) As explained above, sea level in this area is known to have an approximate 'inverse barometer' response to air pressure changes, which can be large. Consequently, all sea levels have been adjusted using surface air pressures. Ross's 1842 mean sea level was corrected using the air pressure recorded on the *Erebus*. For the 20th and 21st century data, daily values of sea level,

obtained by application to the sea level data of an appropriate digital filter (Pugh, 1987), were adjusted using daily means of surface air pressure obtained from National Centers for Environmental Prediction – National Center for Atmospheric Research (NCEP-NCAR) reanalyses (Kistler et al., 2001). Woodworth et al. (2005) concluded that these reanalysis values provide a good representation of air pressure variations in this area. In addition, they have been validated by comparison to an observational data set derived from several locations around the islands (Jones et al., 1999). The comparison indicated no significant long term trend but differences of order 1 mbar for some extended periods. Appendix 1 describes how the air pressure adjustments resulted in values of ‘corrected sea level’ (SLC).

(2) As each data set was acquired at a different time of year, it was necessary to apply a further correction to the SLC for the period of measurement as compared to the annual average. This correction was calculated by averaging the corresponding daily means of SLC from the same parts of 13 near-complete years of data from the modern Stanley gauge, and by comparing that average to mean SLC over the 13 years. This procedure requires the reasonable assumption that the seasonal cycles in Berkeley Sound and at Stanley are the same. Figure 6 displays the seasonal cycle of SLC for the 13 years of data, which indicates the magnitude of the correction at different times of the year.

(3) Each SLC record can then be expressed relative to the height of Ross’s benchmarks with an uncertainty that will be due primarily to the interannual variability in the SLC for the same times of year as the measurements. This uncertainty was calculated from the 13 years of near-complete data from Stanley to be 2.3 cm for each of the 1842, 1981-2 and 1984 measurements. The uncertainty

computed this way includes any sea level variability due to the nodal (18.6 year) tide in SLC: that is estimated to be only several mm in magnitude in each case if the long period nodal tide has an amplitude expected from equilibrium theory (Pugh, 1987).

The uncertainty for 1842 was increased further for the following reasons. Half an inch (1.27 cm) was considered as the standard error of Ross's mean level due to it being quoted in inches; it is not clear how the quoted value was rounded into an integer number of inches. This standard error also includes an uncertainty due to the small difference in height between the two Ross benchmarks (the 'James' mark being approximately 1 cm higher than and approximately 60 m to the east of the larger and better preserved 'Ross' mark shown in Figure 1. Both marks are stated in Ross (1847, volume 2) as being 5 feet 8 inches above sea level). The probable bias in daytime low waters (1.64 cm) was also taken into account, as was an uncertainty in SLC due to that in sea surface temperature (SST) at the time discussed below (2.8 cm). Therefore, the overall uncertainty becomes 4.2 cm when uncertainties are added in quadrature.

The uncertainties for 1981-2 and 1984 were increased to account for possible errors in geodetic connections to the Ross benchmarks. In the 1981-2 case, a connection was made between the Green Patch tide gauge and the Port Louis benchmarks with the use of GPS measurements made by HMS *Endurance* in 1996, together with a geoid-difference estimate from EGM08 (the latter being only 1.1 cm for the 2 km separation across Berkeley Sound). In the 1984 case, a levelling connection was necessary between the Port Louis harbour jetty tide gauge and the benchmarks. That connection was made at the time of gauge installation by the HMS *Herald* survey team and required levelling over almost 1 km of soft and hilly ground. We have assessed the errors in such short distance GPS/geoid and levelling connections to be around 2 cm. The addition of this term in quadrature raises the overall uncertainties for 1981-2 and 1984 to 3.0 cm. We have not included uncertainties due to SST in these calculations, the influence of SST on the 1981-2 and 1984 SLC values being discussed further below.

Other uncertainties are more difficult to estimate. For example, what systematic uncertainty should be attached to the tide board or tide gauge values averaged over their measurement periods? What errors should be attached to any local levelling which Ross must have made? We assume that such errors are at ~1 cm level and, therefore, are less important than the overall uncertainties determined above. The mean values of SLC estimated this way for the 1842, 1981-2 and 1984 measurement periods are shown in Figure 7(a) expressed relative to the height of the 'Ross' benchmark (Figure 1). The 'Ross' benchmark height was defined as the average of the heights of 4 brass screws at each corner of the plaque, consistent with previous practice by HMS *Endurance* (details of individual heights may be found in the authors' fieldwork report).

Thereafter, two different analysis methods were applied which combine the measurements from Berkeley Sound with those from Stanley. Both methods require assumptions that the spectra of variability in SLC, including the seasonal cycle, are similar at the two locations, and that there are no major differences in rates of vertical land movement. Both methods also have the prerequisites of accurate local levelling during our 2009 fieldwork, between the major and auxiliary benchmarks at Port Louis and Stanley, including of course the Ross benchmarks. Local levellings were made at least twice at each location with repeatability typically at the several mm level.

The first analysis method makes use of the fact that our 2009 Port Louis sea level data set was acquired at the same time as data were available from the tide gauge at Stanley. The second method ignores the 2009 Port Louis sea level information and relies on the GPS connections between Port Louis and Stanley to combine the various SLC data sets.

Analysis Method 1

In the first method, the average SLC was computed at the two locations for the 14 day measurement period (25 February – 10 March 2009), and then an offset was applied to the Stanley data such that the two sets of SLC have the same values in that period. Any systematic error is estimated to be 1 cm or less, based on a comparison of the Port Louis measurements with both the pressure- and radar-derived data from Stanley. The root-mean-square (rms) of daily SLC-difference between the two sites, obtained by comparison of Stanley values to those obtained in 2003 and 2009 from Green Patch and Port Louis, was also found to be 1 cm. We regard the uncertainties in SLC due to errors in the offset to be negligible. When the offset is applied to the entire Stanley record, including data from both Government Jetty and FIPASS, we obtain the time series of monthly means included in Figure 7(a).

It is important to realise that the SLC connection between Port Louis and Stanley, which makes use of the short 2009 Port Louis data set, has centimetric accuracy. That is because any common sea level variability at the two sites cancels in the computation of the offset. However, if the fortnight of Port Louis data were to be added to Figure 7(a) in its own right, in the same way as we have included the 1842, 1981-2 and 1984 data, then an uncertainty would have to be attached to its average SLC, after seasonal correction, as for the other measurement periods. In this case, the uncertainty due to interannual variability has a larger value of 3.4 cm. However, local levelling and other errors considered are smaller than for the earlier periods. The star in Figure 7(a) represents the 2009 Port Louis SLC computed in this way and, while it is based on only a short record, it provides an important test of consistency with the SLC connection method, as will be discussed further below.

The importance of using SLC values in this exercise instead of measured sea levels is demonstrated by Figure 7(b), in which measured MSL values at Port Louis and Green Patch have been included, and monthly means of sea level at Stanley have been referred to those at Port Louis with the use of the 2009 daily sea level, as opposed to SLC, information. It can be seen that, while the essence of findings with regard to long term sea level change and possible recent acceleration (to be discussed in detail below) is also represented in this figure, it contains a considerably noisier set of information. In particular, the 1984 measurement appears low (due to high air pressure at the time), the Stanley monthly means exhibit considerably higher variability, and a larger standard error applies to the 2009 Port Louis measurement shown by a star (the latter with a seasonal correction applied as discussed above for the corresponding SLC value).

Analysis Method 2

The second analysis method, which relies on the accuracy of the GPS connection between the two sites and on an assumption of little gradient in sea surface topography (mean sea surface minus geoid), results in the data distribution shown in Figure 8. It can be seen that Figures 7(a) and 8 are similar but that the Stanley SLC data transferred by GPS to Port Louis in Figure 8 differ from those in Figure 7(a) by approximately 5 cm. Given the accuracy of the first method, we believe that this difference is primarily a consequence of errors in geoid-difference, as calculated by EGM08, together with possible centimetric sea surface topography differences. EGM08 formal errors at Port Louis and Stanley are approximately 10 cm. Consequently, one would expect that errors in EGM08 geoid-difference must be at least of the order of several cm, even without regard for omission errors. We expect that this second method will be repeated using the same sea level data when more accurate geoid models, which take into account more copious local gravity information, become available. Meanwhile, all findings discussed below are based on the first method.

It will be noted that a similar GPS-based method was used to make a geodetic connection between the 1981-82 Green Patch tide gauge data and the Port Louis benchmarks. However, in that case the distances involved were so short that errors in GPS relative height and geoid-difference are likely to have been at the ~1 cm level.

5. Relationships between SLC and Sea Surface Temperature

An important question, prior to a discussion of long term trends in sea level, is whether any of the SLC values in Figure 7(a) might have been affected by anomalous meteorological or oceanographic conditions. Although extreme sea level events can occur during storms and due to the high-frequency seiching which occurs around the Falklands coast (Woodworth et al., 2005 discuss effects of wind forcing and seiches on Stanley sea level), Figure 4(a,b) has demonstrated that the adjustment of sea level to SLC is likely to have been an adequate one with regard to meteorological influences, when averaged over the several months of each of the historical sets of measurements. However, the present study has also indicated the possibly greater importance of oceanographic (steric) variability to a discussion of SLC variations.

Figure 9 demonstrates that the variability of Stanley SLC is very similar to that observed in deeper water around the islands by satellite altimetry, and so must be representative of variability over an extended area. This suggests that oceanographic conditions determine the variability in SLC rather than coastal wind or wave setup. The only period of disagreement at the ~5 cm level is for August to October 2008. However, the monthly mean sea levels obtained from the pressure and radar gauges at Stanley agree to ~1 cm in this period, and the close agreement in SLC between tide gauge and altimetry is restored thereafter. The most likely interpretation is that the area of negative SLC anomaly on the Patagonian shelf in this period was of different magnitude at the *in situ* tide gauge location and off-shore.

Figure 10(a) shows the same monthly mean SLC values together with those for SST obtained from the National Oceanic and Atmospheric Administration (NOAA) Optimum Interpolation (OI) SST Version 2 (V2) data set (http://www.cdc.noaa.gov/data/gridded/data.noaa.oisst.v2.html). The SST analysis is produced weekly on a one-degree grid using *in situ* and satellite SSTs, with the satellite data adjusted for biases using the method of Reynolds (1988) and Reynolds and Marsico (1993). The data set commences at the end of 1981. Figure 10(a) shows that both SST and SLC at Stanley have a seasonal cycle, with that for SST leading SLC by approximately 1.5 months, while the two deseasonalised time series (Figure 10b) are similar with a correlation coefficient between them of

0.466 at zero lag (0.425 and 0.424 at lags of 1 and 2 months respectively). The corresponding coefficient for annual mean values is 0.767.

The Southern Annular Mode (SAM) is an oscillation in sea level pressure between a node centred over Antarctica and an annulus encircling the Southern Ocean, and is quantified by the SAM, or Antarctic Oscillation, Index (e.g. Thompson and Wallace, 2000). Meredith et al. (2008) demonstrated a relationship between SST and the SAM in a large area around South Georgia, in the Scotia Sea and on the continental shelf around the Falklands, using values of SAM index from the Climate Prediction Center of NCEP (http://www.cpc.ncep.noaa.gov). Their Figure 3 shows modest correlation (~0.3) between SST and SAM in the Stanley area, and the present analysis has obtained a similar correlation between Stanley SLC and SAM (coefficient of 0.459 using annual means detrended over the measurement period). Therefore, Stanley SLC is affected in a positive sense by the strength of the Southern Ocean atmospheric circulation, represented by the SAM index, in contrast to SLC for stations in Antarctica which are related to the SAM in a negative sense (Hughes et al., 2003; Meredith et al., 2004).

Stanley SLC is simulated satisfactorily by the Ocean Circulation and Climate Advanced Modelling Project (OCCAM) ocean circulation model (Webb et al., 1997) forced by wind fields up to 2004, with a correlation coefficient of 0.690 between measured and modelled annual mean SLC (both time series detrended over their years in common). On the other hand, our attempts to simulate Stanley SLC satisfactorily with a barotropic (depth averaged) version of OCCAM have been unsuccessful so far, although limited model resolution and other technical factors remain to be improved upon. Therefore, for present purposes, we have concluded that Stanley SLC variability could well contain contributions from steric processes related to the wind field and SAM, as well as from processes which do not depend upon stratification. Such steric variability could consist of halo-steric as well as thermosteric fluctuations, with the observed variations in SST being an approximate proxy for both in combination. Hydrographic data, such as those used to derive time series of global steric changes (cf. Domingues et al., 2008), do not exist in sufficient quantity to enable local steric time series to be computed.

Temperature-dependent contributions to the earlier SLC data sets must also be considered, if a relationship between SLC and SST exists. A comparison of rms values of the time series in Figure 10(b) suggests that a SST anomaly of 1° C corresponds to an SLC anomaly of approximately 5.6 cm. Consequently, we can to some extent further explain the low data point for the 1984 measurements in Figure 7(a). SST anomaly in that period (May-September) averaged -0.4° C (Figure 11), which suggests a lower SLC than normal of approximately 2.2 cm. Similar periods of negative SST anomaly, for which we have corresponding SLC information, occurred during 1995-1996, 2000-2002 and 2007-2008 (Figures 9, 10b and 11). The SST anomaly during the 1981-2 measurements (December-March) was approximately zero.

One might ask what values of SST occurred during Ross's stay at Port Louis. The average of his daily values of 'mean temperature of sea at surface' from 11 May to the end of August 1842 was 4.1° C, which corresponds to an anomaly of -1.6° C with respect to the seasonal average SST derived from 27 complete years (1982-2008) of NOAA OI SST data. At face value, this suggests that the Ross SLC value of Figure 7(a) was lower than normal by as much as 9 cm. However, while the biases in SST measurements, averaged over many ships and for extended periods, tend to be of the order of 0.1° C, even for the Southern Ocean during the middle of the 19th century (cf. Figure 18 of Folland and Parker, 1995), the uncertainty in (probably bucket) measurements by any one vessel, even in more recent times, could be of the order of 1° C (Kent and Berry, 2008). Consequently, Ross's SST value has to be treated with caution, especially as it is not known at what time of day the measurements were made and by what method. There is even the possibility that, as the ships were careened for at least part of this period, the SST measurements were made from the beach, which would in the winter have biased them low.

Ross also measured the daily mean 'temperature of the air in the shade' which averaged 2.1° C during May-August 1842, compared to average values of 2.7 and 3.0° C (standard deviations 0.4 and 0.8° C respectively) for the same parts of the year measured by the Met Office at Stanley (1959-1980) and at Mount Pleasant airport 44 km SW of Stanley (1989-2008). This is likely to be a more robust estimate of temperature and suggests that, while the winter of 1842 was probably colder than normal, it was not exceptionally so (Ross, 1847, volume 2 includes no mention of harsh winter conditions). Variability in winter air temperatures in the Falklands is similar to that in SST (Figure 12) with a correlation coefficient between May-August average values of 0.719 and with a ratio of 0.56 for the standard deviation of SST compared to that of air temperature. Consequently, an air temperature anomaly of -0.9° C in the Ross period is likely to have corresponded to an SST anomaly of approximately -0.5° C and an SLC anomaly of -2.8 cm. While we have not applied this correction to Ross's sea level measurement shown in Figure 7(a), as we have no reliable direct measure of SST (and such a procedure would involve an assumption that the regional mean climate during the mid-19th century was similar to that of recent decades), we have included it within the overall SLC error assessment, as mentioned above.

6. Long Term Changes in Sea Level

Based on Figure 7(a), it is possible to compute an average rate of rise of sea level (SLC) from the 1842, 1981-2 and 1984 data. These values were obtained from measurements at Port Louis and Green Patch in Berkeley Sound only, and not by transfer from Stanley. The lower trend line in Figure 7(a) is constrained to pass between the 1842 and 1984 values, yielding a rate of 0.23 ± 0.35 mm/year. The standard error of the trend was estimated by combining a standard error for mean levels in the 1980s, defined by half of the difference between the 1981-2 and 1984 values (an amount which is similar to the individual standard errors), with the uncertainty in 1842. If we adopt an estimate of -0.52 mm/year for the rate of present-day sea level change expected due to Glacial Isostatic Adjustment (GIA, see below), then we obtain 0.75 ± 0.35 mm/year for the average rate of sea level rise in the region corrected for vertical land movement.

It is also possible to compute a rate in terms of change from Ross's measurement to those obtained over the last two decades at Stanley. That produces a value of 0.54 ± 0.26 mm/year for the period from 1842 to the mid-point of the recent data (upper trend line in Figure 7(a)) or 1.06 ± 0.26 mm/year after GIA correction. In this case, the standard error is assumed to be dominated by the uncertainty in 1842 alone. An important question is whether the two estimates are compatible. It can be seen that the 1981-2 value is within one standard error of the upper trend line in Figure 7(a), while that for 1984 falls about 7 cm below it. However, it will be recalled that there is reason to believe that the 1984 value is biased low by ~2 cm due to the lower SST at the time, while the 1981-2 value is relatively unbiased by SST. Consequently, the 1984 value can also be claimed to be only one standard error away from the long-term trend shown by the upper line. The Government Jetty data from Stanley from the late 1960s are broadly consistent with both trend lines.

The GIA correction applied above is derived from predictions of the ICE-5G v1.2 ice model combined with either the VM2 or VM4 earth models of Peltier (2004), which are available from the Permanent Service for Mean Sea Level (PSMSL) web site (http://www.psmsl.org/train_and_info/geo_signals/gia/peltier). It is an update to the correction of -0.59 mm/year used by Woodworth et al. (2005) which was based on the earlier ICE-4G (VM2) model of Peltier (2001, 2004). Both of these models pay particular attention to the role of rotational feedback and 'broad shelf effect' (Peltier and Drummond, 2002). The rotational feedback component is particularly important in reproducing the highstands of sea level observed along the South American coast (Rostami et al., 2000; Peltier, 2004, 2007; Peltier and Luthcke, 2009) and is as important within discussion of Falklands sea levels.

Few geological measurements have been made in the Falkland Islands themselves which might confirm or disprove such a long-term rate of uplift. As discussed in Woodworth et al. (2005), the only relevant study known to us is that of Roberts (1984), summarised by Clapperton and Roberts (1986) and reviewed by Aldiss and Edwards (1999). These reports present evidence for high stands of sea level in the geological past, of which two sets several metres above present sea level almost certainly formed after 5000 BP, including one particularly important data point from a raised beach 6 km east of Stanley and 6 to 8 m above present sea level. These high stands are comparable in amplitude to those found along the coast of Patagonia, where Rostami et al. (2000) estimated a longer-term tectonic uplift value of 0.09 mm/year, additional to Holocene GIA rates, which should also be representative of the Falkland Islands. This area of the Patagonian shelf experiences few large earthquakes that might result in abrupt vertical land movement (see for example Figure 6.1 of Aldiss and Edwards, 1999).

In principle, confirmation of an uplift of the order of 0.5-0.6 mm/year should be possible by means of continuous GPS measurements. Ohio State University has operated a GPS station on Lookout Hill above Stanley since 1999, the vertical motion of which has been analysed within a reference frame defined by over 200 GPS stations distributed worldwide (the 'VREF' set of Bevis et al., 2009). This reference frame is similar to the International Terrestrial Reference Frame 2005 (Altamimi et al., 2007). Within that frame, the Stanley GPS has an upward velocity of 0.2 ± 0.2 mm/year (95% standard error) (private communication, Prof. Mike Bevis, Ohio State University). This rate is lower than expected from the GIA model (Peltier, 2004) but invites further comparison as the Stanley GPS record length increases and as GIA models continue to develop.

If we now turn to the recent sea level information, the rate of change of SLC at Stanley from November 1992 to the end of 2008 was 1.99 ± 0.58 mm/year (Figures 7(a) and 9), or 2.51 mm/year when corrected for GIA. Since the start of this period, precise measurements of sea surface height from space by the TOPEX/Poseidon and Jason satellite radar altimeters have become available. The altimetric trend in sea surface height adjusted for the ‘inverse barometer’ in the area of ocean around the Falklands was 2.79 ± 0.42 mm/year over almost the same period (Figure 9), comparable to the rate observed by the Stanley gauge. The two recent values are considerably in excess of the long-term rate and indicate a relatively recent acceleration in the rate of sea level rise. (We have not applied a GIA correction to the quoted altimeter rate (i.e. in effect a correction for the local rate of change of the geoid) as that correction is expected to be considerably smaller than the ‘statistical’ error, cf. Figure 8d of Peltier, 2004.)

7. Discussion

Port Louis was not the only sea level measurement location with which Ross was associated. Pugh et al. (2002) and Hunter et al. (2003) have discussed measurements made at Port Arthur, Tasmania by T.J. Lemprière from mid-1837 to at least the end of 1842. The scientific value of these measurements was increased greatly in July 1841 by the addition of a benchmark in order to provide a datum reference to the sea level data. This installation was made at the suggestion of Ross, after having been encouraged to install marks wherever sea level measurements were made in a letter from Alexander von Humboldt. Ross received von Humboldt’s letter via the Admiralty after he had arrived to over-winter in Tasmania (Ross, 1847, volume 2).

Hunter et al. (2003) concluded from the historical and modern Port Arthur measurements that sea level had risen at an average rate of 1.0 ± 0.3 mm/year since 1842, after a small correction for vertical land movement. This rate is consistent with our own long-term estimates, providing further evidence from data sparse regions of the southern hemisphere that sea level has been rising during the 19th and 20th centuries at a rate comparable to that in the northern hemisphere (Bindoff et al., 2007).

However, which of our 0.75 mm/year (Berkeley Sound data only up to the 1980s) or 1.06 mm/year (Ross’s 1842 measurement combined with the last two decades of data from Stanley) is to be preferred as a long term rate? At first, it seems unreasonable to, in effect, give greater weight to less than 4 months of measurements in 1984 at Port Louis, and choose the lower trend line, than to prefer over 16 years of data at Stanley, thereby selecting the upper trend line. However, it can be seen from Figure 7(a) that, if the rate of approximately 2 mm/year observed at Stanley during the 1990s and 2000s is representative of the last quarter-century, then a ‘two stick’ trend model becomes more plausible, with a long term trend represented by the lower line together with a recent acceleration.

The joining of Stanley data to those from Port Louis and Green Patch, thereby appearing to produce a recent acceleration, does look odd. However, a similar conclusion would have been drawn from the Berkeley Sound data alone without the benefit of the long Stanley record (other than in the provision of a seasonal cycle correction). As described above, the star in Figure 7(a) shows the SLC over our 14 days of measurements in 2009, corrected for air pressure and seasonal cycle in SLC in the same way as for 1842, 1981-2 and 1984. Although the measurement period was short, one might have concluded on the basis of this single point that a recent acceleration had occurred.

The star lies a little above the earlier monthly mean SLC values from Stanley. SST in February to March 2009 was high for that time of year, with an anomaly of approximately 0.5°C (Figure 11) which suggests that SLC was higher than normal by about 2.8 cm. When all the Berkeley Sound and Stanley data are considered together, then it can be seen that the Stanley monthly mean SLC record provides a plausible interpolation between the Berkeley Sound data of the 1980s and 2009.

While it might be the case that the rate of SLC change in recent decades has been larger than the long term value, the lack of data between 1842 and 1981-2 allows other interpretations of Figure 7(a). For example, there could have been a negative trend during most of the 19th century, an acceleration at the end of the 19th and early 20th centuries, and a higher rate during the 20th century as a whole. Such behaviour would have been similar to that observed in long sea level records from the northern hemisphere (e.g. at Brest, France see Wöppelmann et al., 2006). In this case the higher rates seen between 1981-2 and 2009 would not necessarily be describable as a 'recent acceleration'. Nevertheless, in the absence of a continuous record, then the simplest interpretation remains a 'long term' trend with a value, after GIA correction, similar to that at Port Arthur.

If we focus on the recent decades, then the consistency between tide gauge measurements, GIA correction and altimetric data provides reassurance with regard to the evidence for an increased rate of sea level rise. However, there is no corresponding increase in levels on the neighbouring continental coastline. As the Argentine tide gauge information is fragmented, two composite SLC records were made by combining records from Buenos Aires and Palermo, and Mar del Plata and Quequen, using annual mean sea levels from the PSMSL (http://www.psmsl.org) and inverse barometer air pressure corrections using the HadSLP2 air pressure data set (http://hadobs.metoffice.com/hadslp2/). The latter has coarser spatial resolution than the NCEP-NCAR product but extends back to the 19th century. Rates of vertical land movement were assumed to be the same for each pair of nearby stations. The composite records (not shown) suggest no acceleration during the last few decades. However, they are from lower latitudes than Stanley (34 and 38° S respectively compared to 51° S), time series from stations further south along the Argentine coast being of little use in this application. In addition, one notes that records from stations near to the River Plate estuary are affected considerably by river runoff connected to El Niño – Southern Oscillation events (Douglas, 2001).

Most regions worldwide are known to have experienced higher rates of sea level rise in the 1990s (e.g. Holgate and Woodworth, 2004), although whether that rate of rise was unprecedented in the instrumental record is a matter of debate. Merrifield et al. (2009) have suggested that the 1990s acceleration was indeed unusual in that it took place in most ocean basins, with particular contributions from the tropics and from higher southern latitudes. The Falklands data would appear to be consistent with that picture.

8. Conclusions

Sea level measurements at Port Louis in East Falkland in 1981-82 and 1984 have been compared to those made by James Clark Ross in 1842, with each set of measurements made with respect to the original benchmarks installed by Ross. This comparison has provided an estimate of how sea level has changed in the area over approximately one and a half centuries. The long-term rate of 0.75 mm/year between 1842 and the early-1980s, after correction for air pressure effects and for vertical land movement due to GIA, is similar to that obtained over a similar period, and using similar methods, at Port Arthur in Tasmania (Pugh et al., 2002; Hunter et al., 2003). This long-term rate is also similar to those observed in the northern hemisphere during the 19th and early 20th centuries (Church et al., 2001; Wöppelmann et al., 2008).

During February and March 2009, a further set of sea level measurements was undertaken at Port Louis with respect to the same benchmarks. Although the measurement period was short, the value of mean sea level obtained was an accurate one and infers that a relatively recent acceleration in the rate of sea level rise has taken place.

However, the 2009 data set has proved to be of greatest value as a means of combining the historical data from Port Louis with those from the permanent tide gauge station at Stanley, 25 km to the south-east, using the Method 1 described above. The Stanley SLC data have been shown to provide an effective interpolation between the Port Louis measurements during the early-1980s and those in 2009. The Stanley data suggest that the rate of change of sea level in East Falkland since 1992 has been approximately 2.5 mm/year, a rate supported by information from satellite altimetry. Altogether, these data sets provide evidence for a recent acceleration in the rate of sea level rise that is consistent with accelerations reported for other locations in the southern hemisphere and globally. Whether the high recent rate is some kind of decadal fluctuation, or is the start of an accelerated climate change (cf. Rahmstorf et al., 2007), remains to be seen.

A relationship between Stanley SLC, SST around the islands and the SAM index has been identified, providing more understanding of the differences in SLC observed between sets of historical sea level measurements. The study of such relationships may prove to be of wider interest in understanding the atmosphere and ocean dynamics of the region and thereby the sources of variability in sea level in East Falkland and the SW Atlantic in general.

The geodetic benchmarks established by Ross at Port Louis in 1842, relative to which all sea level measurements at that location have been made, have survived in good condition and have been complemented by a set of ancillary marks established in 2009. These marks offer the possibility for further studies of long term sea level change to be undertaken at the site in the future.

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Appendix 1:

Method of Computation of Corrected Sea Level (SLC) from Mean Sea Level (MSL) Values Obtained at Port Louis and Green Patch in Berkeley Sound

James Clark Ross had been encouraged by Alexander von Humboldt to install benchmarks wherever extended sea level measurements were made. Consequently, Ross would have been aware that it was likely that his measurements at Port Louis would be repeated at some point in the future. Similarly, we hope that other researchers will make measurements with respect to the same benchmarks at Port Louis at some point later in this century. Port Louis is an environmentally pristine location, the benchmarks (both Ross's original marks and our newly installed ones) are likely to survive for many years to come, and the likelihood is that future measurements will be both feasible and scientifically interesting.

A first concern relates to the preservation of historical information. In order to guard against further disasters, such as the loss of Ross's original journal of half-hourly sea level measurements, copies of all sea level and GPS data sets, and relevant documents in electronic form, will be lodged with the British Oceanographic Data Centre (BODC, www.bodc.ac.uk) and the Falkland Islands Government Archives. (Copies of the logs of several of Ross's officers, some of which contain meteorological information, have recently been made available in electronic form via the British Atmospheric Data Centre (BADC), www.badc.ac.uk.)

A second concern stems from the fact that our analyses have been based upon the use of SLC which is quantity derived from the measured MSL. Therefore, it is important to explain how SLC was computed, and the likely errors involved, so that future researchers can reproduce and extend our results.

All SLC values given in this paper were derived from the relationship:

$$\mathrm{SLC} = \mathrm{MSL} + (\mathrm{AP} - \mathrm{AP}_{\mathrm{ref}}) * 0.9948 \qquad (1)$$

where SLC and MSL are measured in cm, surface air pressure (AP) is given in mbar, a reference air pressure ($\mathrm{AP}_{\mathrm{ref}}$) of 1001.98 mbar chosen, that being the average surface air pressure at Stanley for the period January 1948 – March 2009 from NCEP-NCAR, and the factor of 0.9948 represents a typical IB response.

Table 1 lists the measurement periods at Port Louis and Green Patch in 1842, 1981-2, 1984 and 2009 and the measured MSL values in these periods. As explained above, the MSL for 1842 is taken simply from the information in Ross (1847, volume 2), while the MSL values for the other periods could if required be recomputed from the original sea level data files lodged with BODC.

The Port Louis measurements in 1842 will have been made close to the Ross benchmarks in Berkeley Sound (Figure 2) while those for 1984 were made at the harbour jetty. Measurements in 2009 were made near to the benchmarks (two sensors) and at the jetty; results presented in Table 1 are based on the former. Also provided to BODC will be measurements of sub-surface pressure with 3 minute sampling obtained at Green Patch and Port Louis harbour jetty between 20 April and 22 September 2003; these data have no corresponding barometer information or datum control.

Table 1 also shows the air pressure correction applied to the MSL information (equation 1), the 1842 air pressures having been extracted from Ross (1847, volume 2) and those in later periods from NCEP-NCAR. The correction can be seen to be only a small number of cm in each case, with the exception of 1984 which was a period of high air pressure. The penultimate column of Table 1 gives the additional correction applied to allow for the seasonal cycle in SLC on the east coast of the Falkland Islands. The final column presents the SLC values given in Figure 7(a).

Several variations could be made in the method of determining SLC from MSL. For example, we have employed a typical IB factor in equation (1) (Aviso, 1994). This produces a form of SLC akin to sub-surface pressure. However, we have demonstrated above that the effective 'IB coefficient' at Port Louis is closer to 0.95 than 0.9948, on daily timescales at least, while Woodworth et al. (2005) showed with the use of monthly mean values from the Government Jetty and FIPASS gauges that a similar factor applies at monthly and longer timescales. It can be seen from Table 1 that the choice of a factor ~5% different from that employed results in only a 3 mm change in air pressure correction for the case when the correction was largest in 1984.

Equation (1) was also used to convert monthly mean MSL values from the Stanley tide gauge to the SLC values displayed in Figure 7(a). For most of the monthly means, a 5% variation in the factor results in SLC values differing from those shown by only millimetres and, in the most extreme cases, differences of 4 and 7 mm for odd months of Government Jetty and FIPASS data respectively when air pressure variations were largest.

A second issue with equation (1) is that, instead of AP_{ref}, a reference air pressure could have been chosen representative of average air pressure over the global ocean, as is standard practice in altimeter data processing (AVISO, 1994). Global-ocean average air pressure has an rms variation of approximately 0.54 mbar, and has a large annual component which peaks in southern hemisphere winter (e.g. Figure 3a of Wunsch and Stammer, 1997). Given that two of the measurement periods in Table 1 were in summer (1981-2 and 2009) and two were largely in winter (1842 and 1984), but noting that, with the exception of 2009, measurements took place over several months, an error in air pressure correction of the order of 0.5 mbar could remain from the simpler parameterisation of equation (1). A less quantifiable issue concerns interannual variations and secular trends in global-ocean average air pressure, especially with regard to the use of the chosen value of AP_{ref} for adjustment of the 1842 data.

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Figure Captions

1. (a) A ledge cut into a rock outcrop on the beach at Port Louis which James Clark Ross used as the 'Ross' benchmark for sea level measurements. On the ledge is a commemorative brass plaque. The official benchmark height is the average of the heights of the tops of four small screws at each corner of the plaque. (b) The brass plaque fixed to the ledge of the 'Ross' benchmark.

2. Maps of the Falkland Islands showing locations mentioned in the text. PL = Port Louis; PS = Port Stanley; GJ = Government Jetty tide gauge location; FIPASS = Falkland Interim Port And Storage System tide gauge location; JCR = James Clark Ross benchmark. The Port Louis harbour shown in (c) and (d) is roughly circular with a narrow entrance to Berkeley Sound. Its jetty is located at the south-west of the harbour.

3. Daily values of mean tide level (MTL) in 1842 (blue) together with daily values of air pressure (red). Air pressure values are shown inverted and their average adjusted to equal that in MTL. The MTL daily values are defined as the average of the average of high waters and average of low waters recorded each day.

4. (a) Daily MTL and air pressure in 1842 indicating an 'IB regression slope' of -0.968 cm/mbar. (b) Daily mean sea level, derived from filtering of half-hourly values, and air pressures in 1984 indicating a slope of -0.935 cm/mbar.

5. Individual high (red) and low (blue) water levels for 1842, each with an astronomical tidal prediction subtracted.

6. Average seasonal cycle of SLC at Stanley derived from 13 recent and near-complete years of tide gauge data. The error bars indicate standard errors of the monthly mean values.

7 (a). Values of corrected sea level (SLC) in Berkeley Sound averaged over each period of measurement in 1842 (Port Louis), 1981-2 (Green Patch) and 1984 (Port Louis) (dots). Values are shown relative to the height of the 'Ross' benchmark and are adjusted for the average seasonal cycle in SLC. The star indicates SLC during a fortnight measurement period at Port Louis in February-March 2009. Also shown are monthly mean values of SLC from tide gauges at Stanley. Stanley data have been aligned with those from Port Louis using the first method described in the text. The lower dash-dotted trend line connects the 1842 value to the 1981-2 and 1984 values, while the upper line connects the 1842 value to the average of the Stanley SLC data since 1992. The solid line is a linear fit to the Stanley SLC data since 1992 extrapolated back to the early 1980s. (b). A compilation of values similar to those shown in (a) except using measured instead of corrected sea levels.

8. As for Figure 7(a), except that Stanley and Port Louis data have been combined using GPS minus geoid levelling between the two sites.

9. Monthly mean values of SLC from Stanley compared to satellite radar altimeter information from TOPEX/Poseidon and Jason-1. The black and red trend lines for Stanley SLC and altimetry

have gradients of 1.99 and 2.79 mm/year respectively (see text). (The SLC values in this figure are to be regarded as having an arbitrary datum.)

10. (a) Monthly mean values of SLC from Stanley compared to monthly SST values averaged over 8 one-degree square boxes of ocean centred on Stanley (i.e. 3x3 boxes with one mostly over land not included). For presentation purposes, SST values in °C have been multiplied by 2.41 so as to have the same standard deviation as SLC measured in cm during the period 1993-2008. (b) As for (a) but with the average seasonal cycle of each parameter removed. In this case, SST values have been multiplied by 5.61. The temperatures shown on the right-hand side of each figure are relative to the average SST over the period while the SLC values are to be regarded as having an arbitrary datum.

11. Monthly mean anomalies of SST from the NOAA SST-OI-V2 data set since the end of 1981. Anomalies are defined with respect to the average seasonal cycle during 1982-2008. The periods of sea level measurements at Port Louis and Green Patch in 1981-2, 1984 and 2009 are indicated beneath the time series.

12. Average SST during May-August in the waters around the Falklands compared to average May-August air temperature recorded at Mount Pleasant airport.

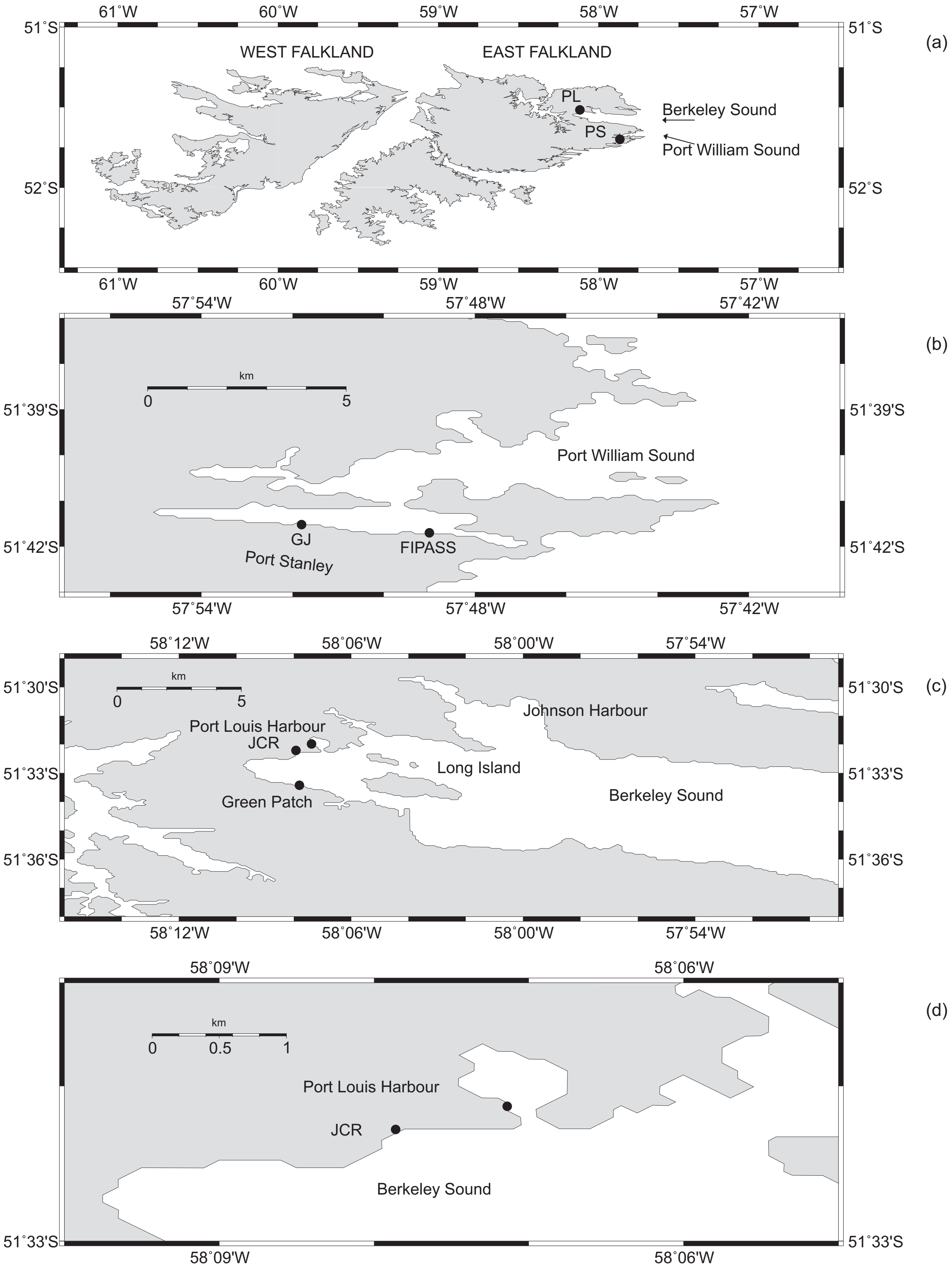
Table 1: Sea Level Measurements in Berkeley Sound

Location	Year	Dates Corresponding to MSL Measurements	MSL relative to the height of the 'Ross' benchmark (cm)	Air Pressure Correction according to Equation 1 (cm)	Seasonal Cycle of SLC Correction (cm)	SLC relative to the height of the 'Ross benchmark' (cm)
Port Louis	1842	10 May-31 Aug	-172.7	-2.4	-0.2	-175.3
Green Patch	1981-2	6 Dec-27 Mar	-167.5	-0.3	-1.8	-169.6
Port Louis	1984	23 May – 7 Sep	-181.5	+6.4	+0.6	-174.5
Port Louis	2009	25 Feb -10 Mar	-162.8	+2.7	-2.2	-162.3

Figure 1(a)

Figure 1 (b)

Figure 2 on next page


(a)
61˚W
60˚W
59˚W
58˚W
57˚W
51˚S
52˚S
WEST FALKLAND
EAST FALKLAND
PL
PS
Berkeley Sound
Port William Sound
(b)
57˚54'W
57˚48'W
57˚42'W
51˚39'S
51˚42'S
km
0
5
Port William Sound
GJ
FIPASS
Port Stanley
(c)
58˚12'W
58˚06'W
58˚00'W
57˚54'W
51˚30'S
51˚33'S
51˚36'S
km
0
5
Johnson Harbour
Port Louis Harbour
JCR
Long Island
Berkeley Sound
Green Patch
(d)
58˚09'W
58˚06'W
51˚33'S
km
0
0.5
1
Port Louis Harbour
JCR
Berkeley Sound

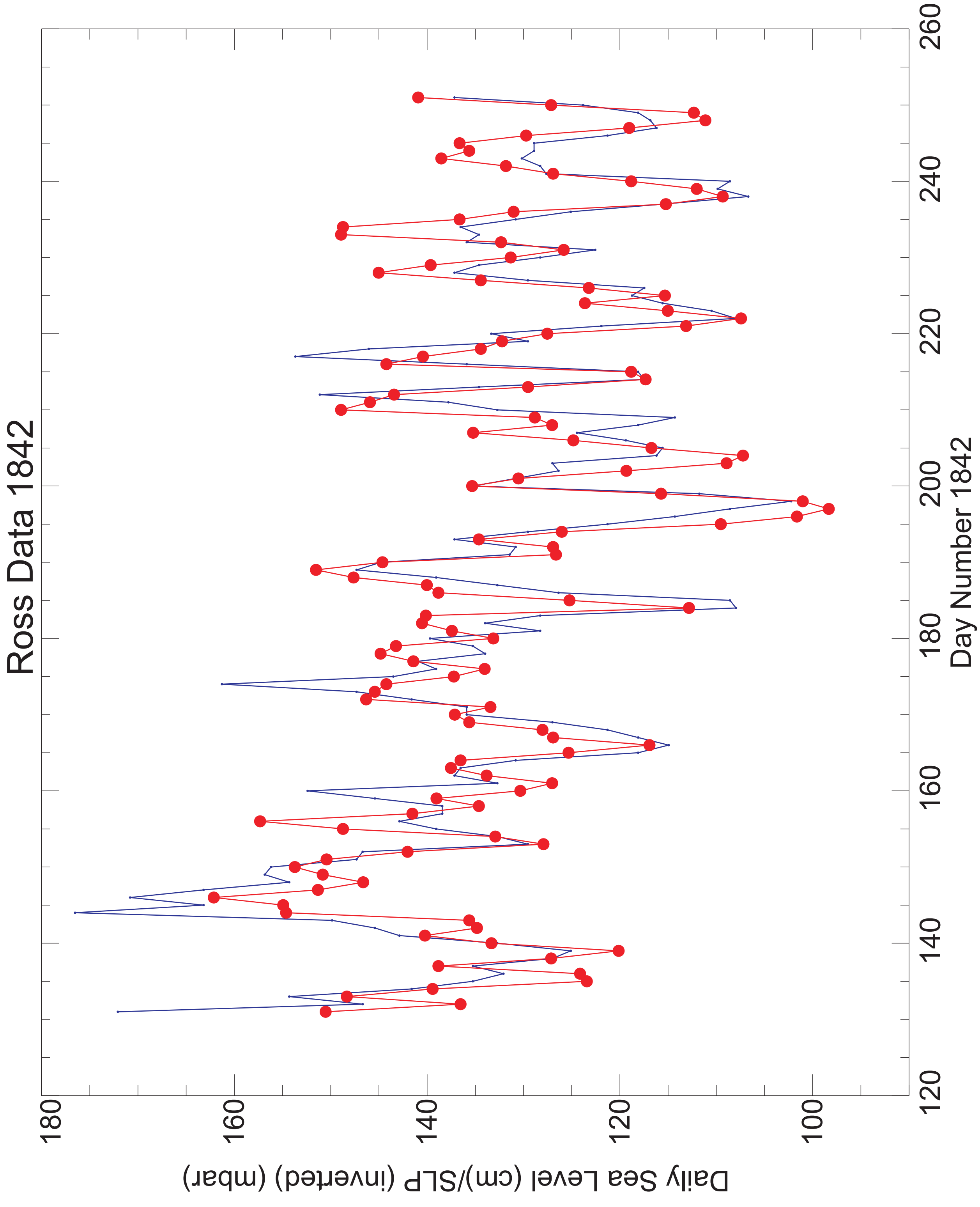

Ross Data 1842
Daily Sea Level (cm)/SLP (inverted) (mbar)
180
160
140
120
100
Day Number 1842
120
140
160
180
200
220
240
260

Figure 3

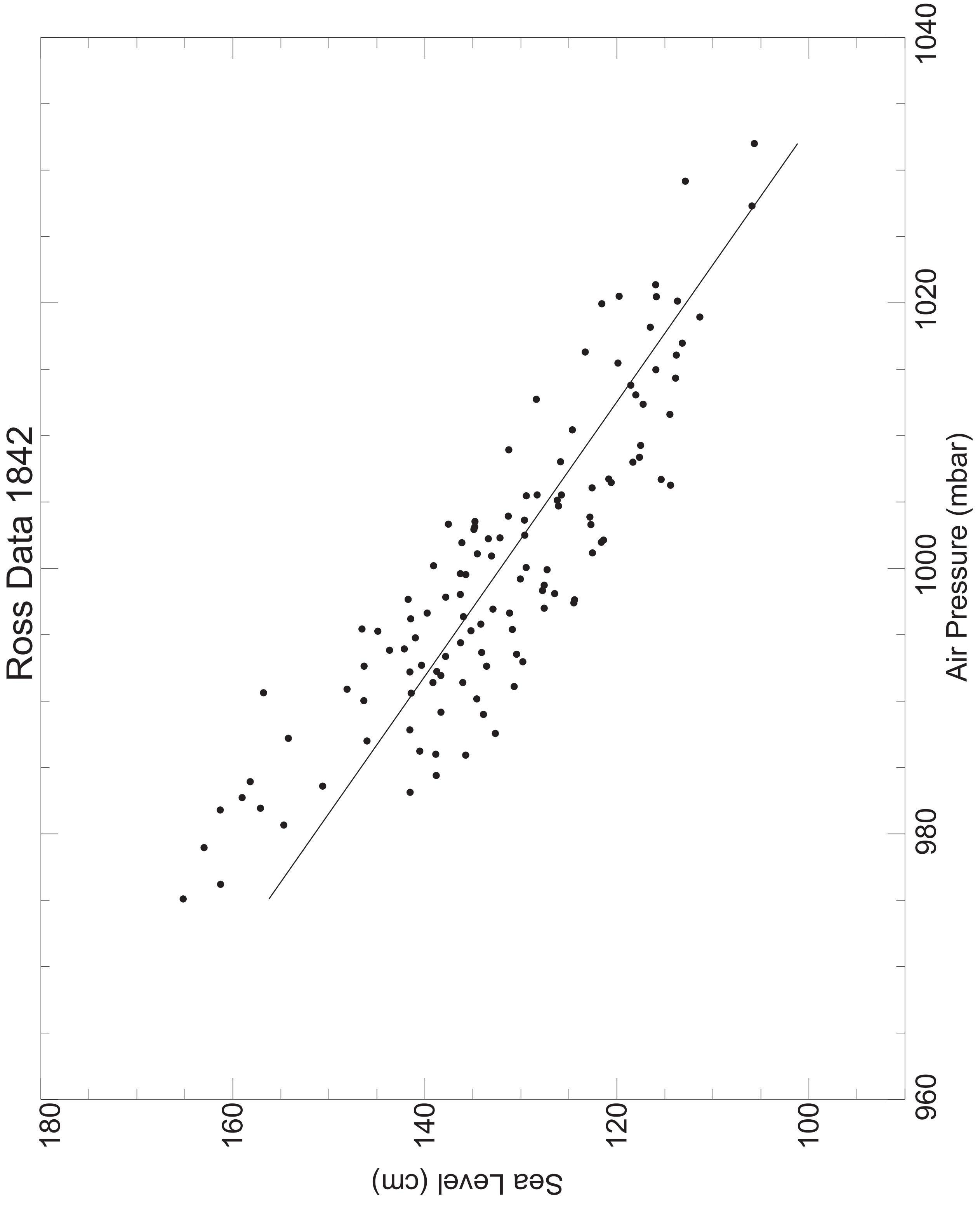

Ross Data 1842
Sea Level (cm)
180
160
140
120
100
Air Pressure (mbar)
960
980
1000
1020
1040

Figure 4a

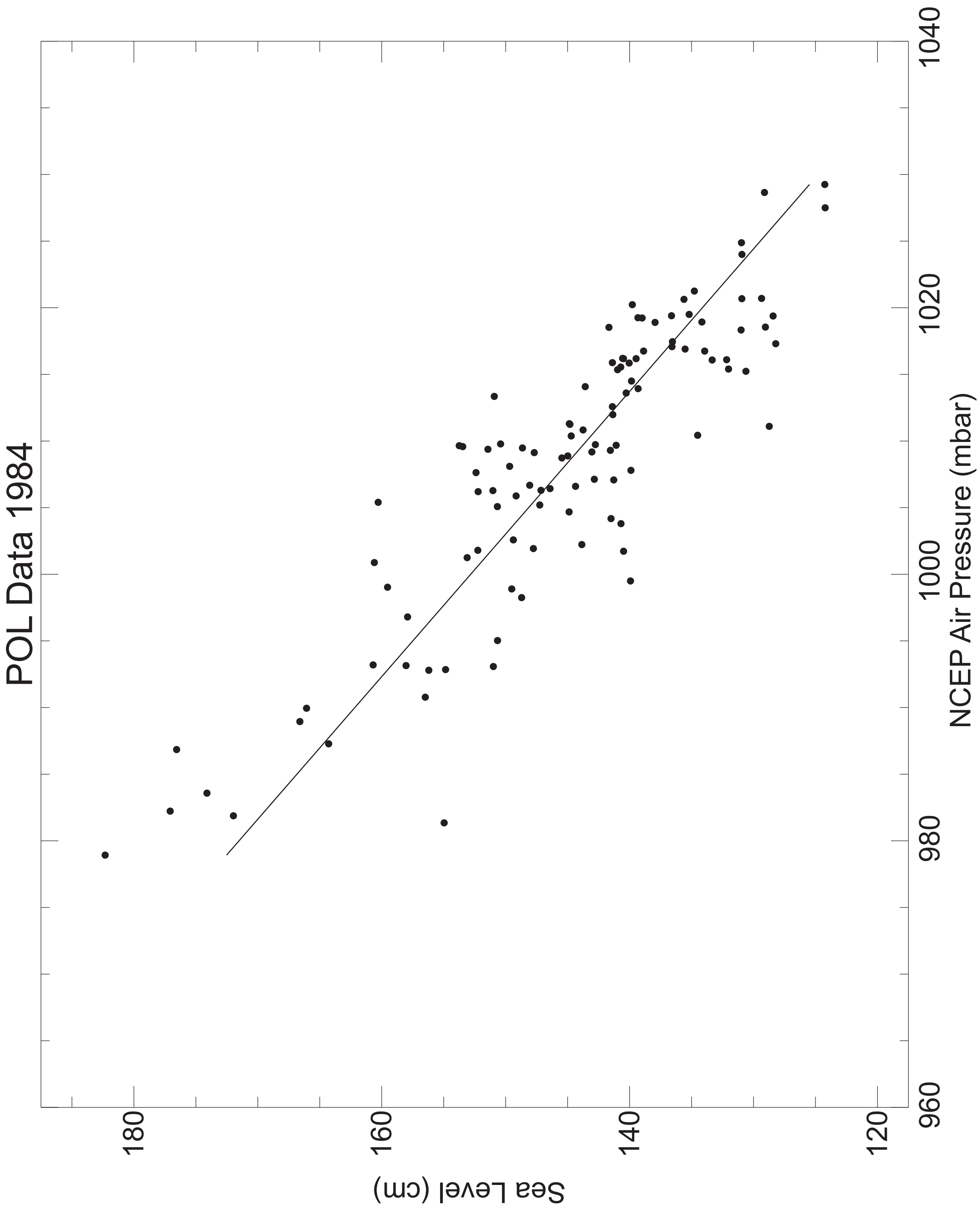

POL Data 1984
NCEP Air Pressure (mbar)
960
980
1000
1020
1040
Sea Level (cm)
180
160
140
120

Figure 4b

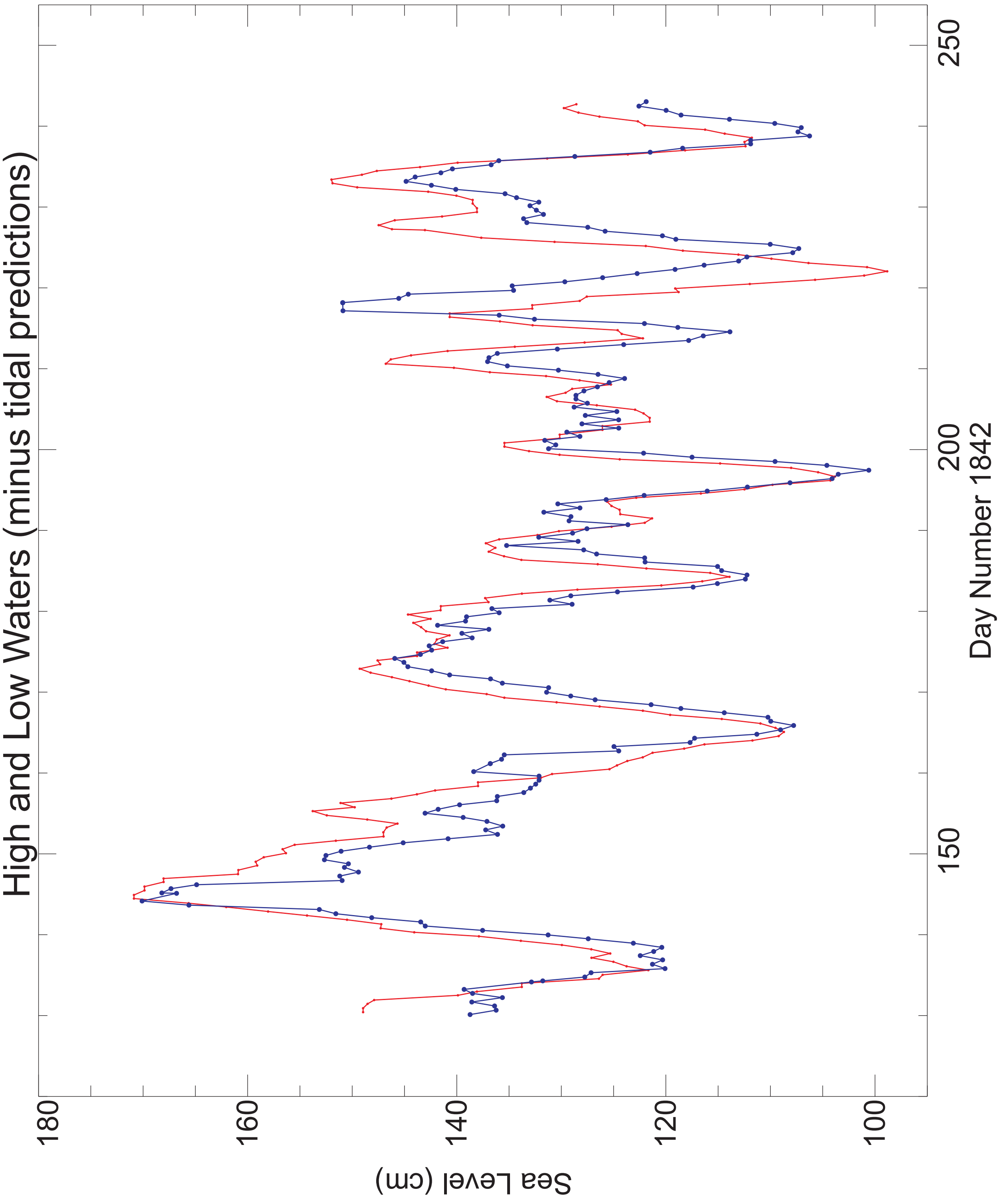

High and Low Waters (minus tidal predictions)
Sea Level (cm)
180
160
140
120
100
Day Number 1842
150
200
250

Figure 5

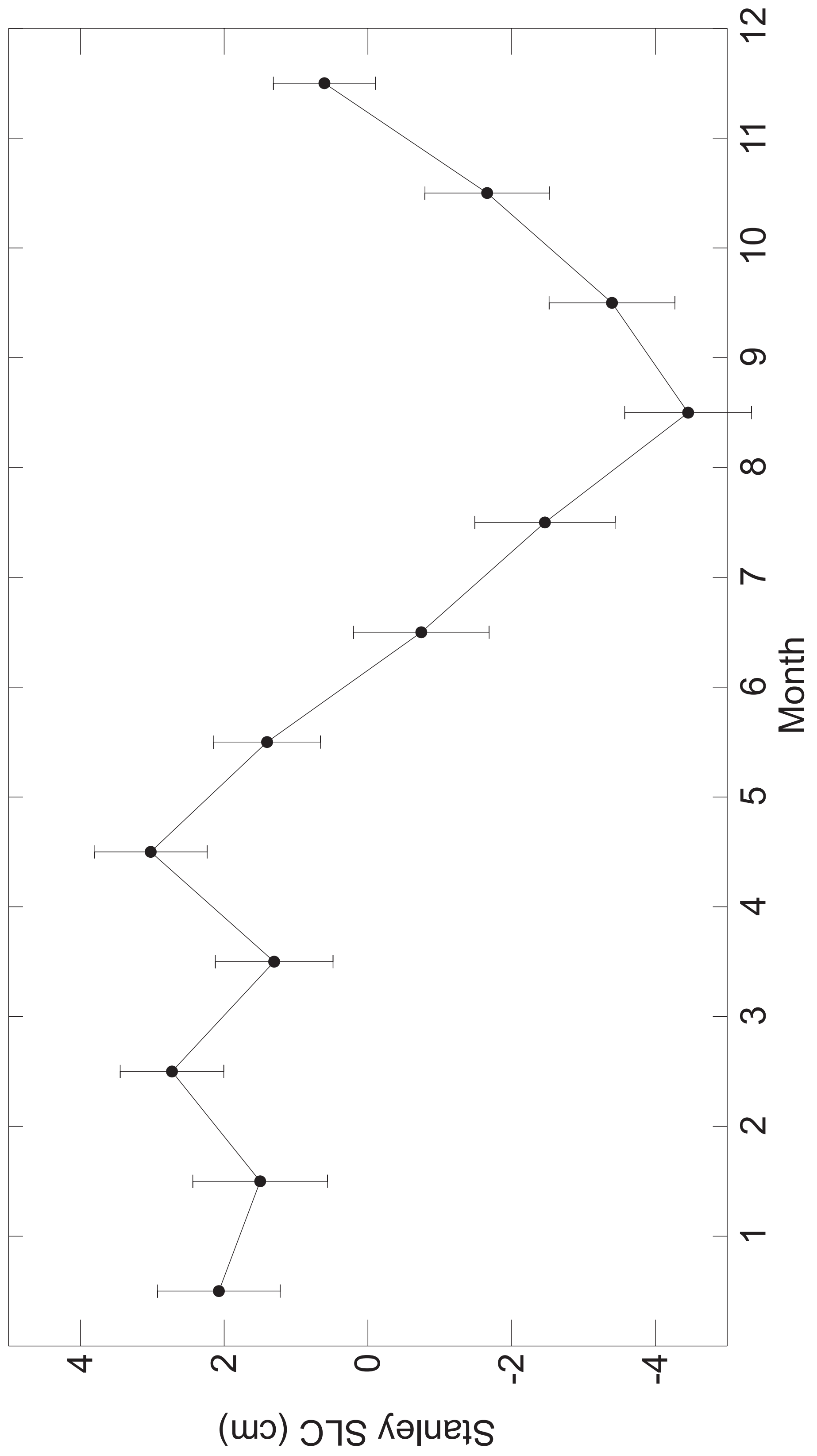


Figure 6

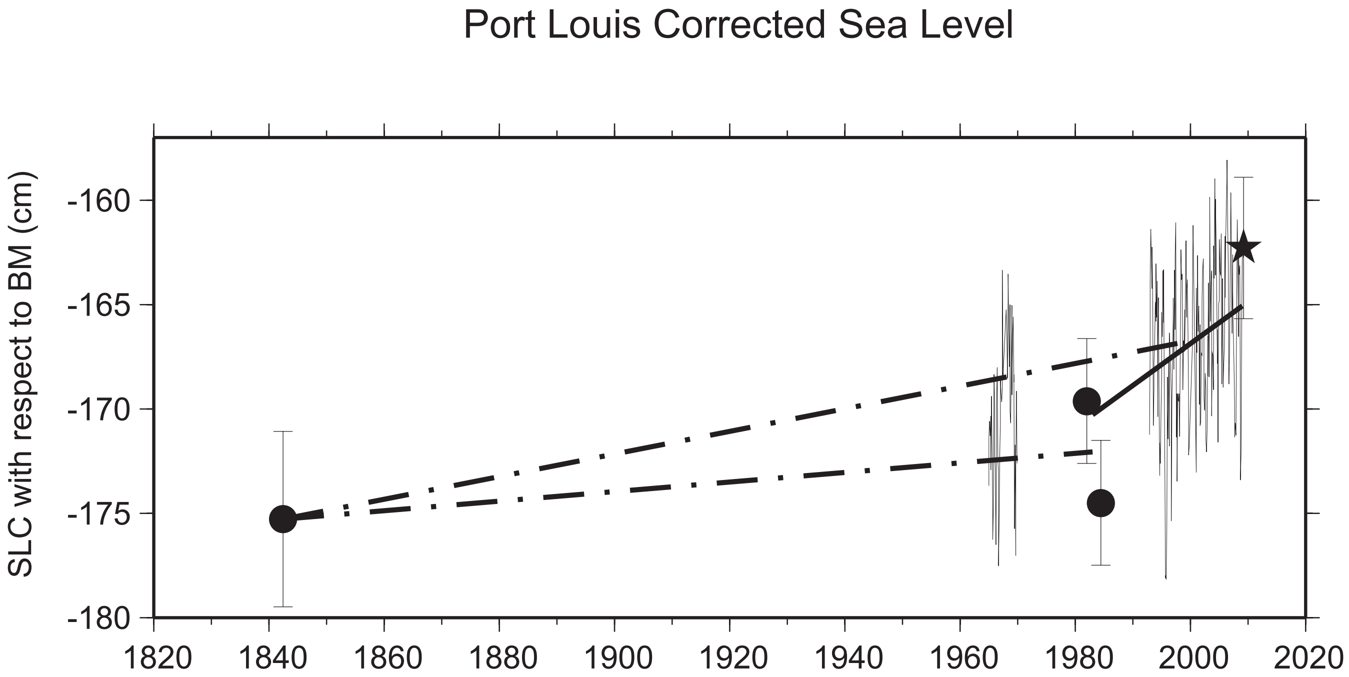


Figure 7(a)

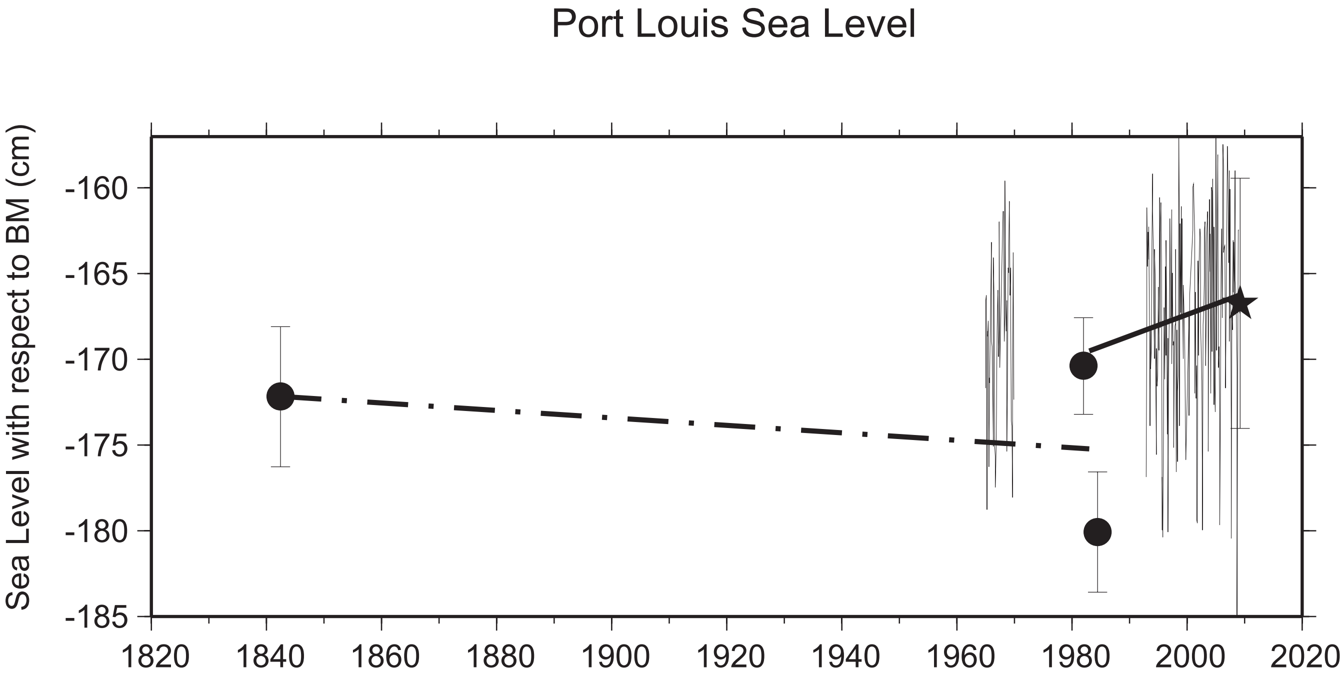


Figure 7(b)

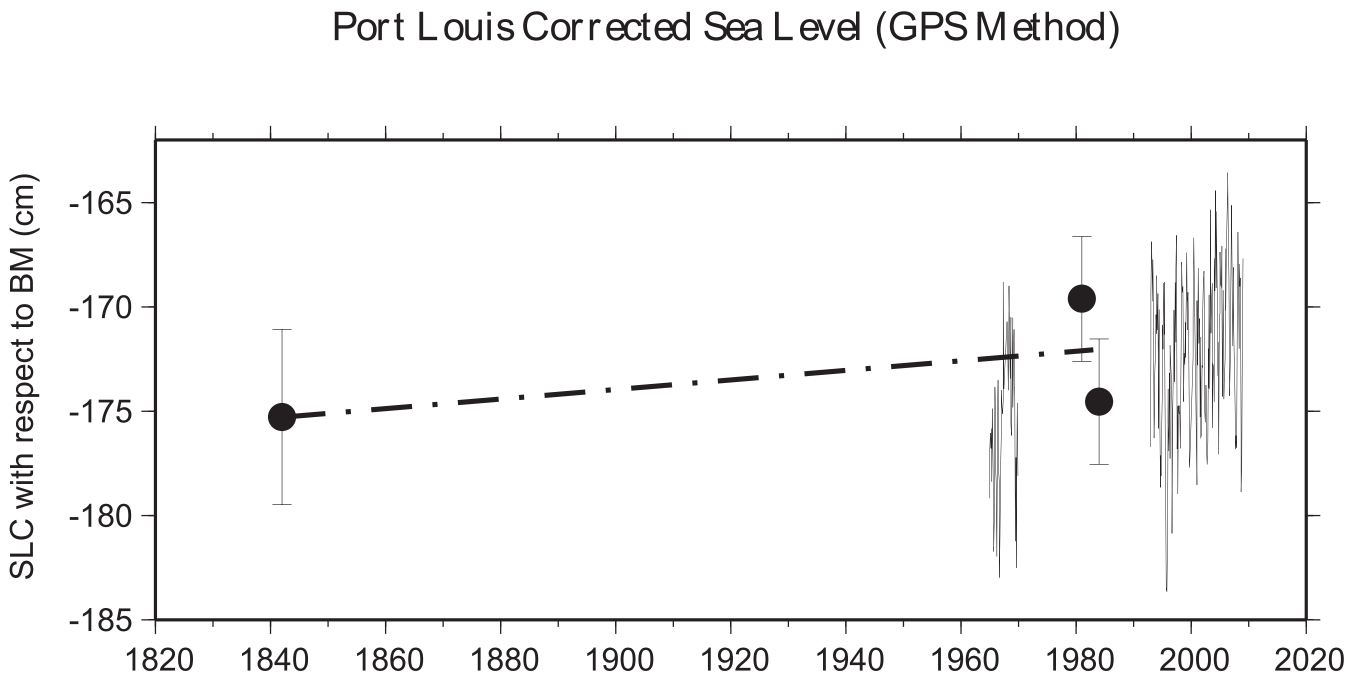

Port Louis Corrected Sea Level (GPS Method)
SLC with respect to BM (cm)
-165
-170
-175
-180
-185
1820
1840
1860
1880
1900
1920
1940
1960
1980
2000
2020

Figure 8

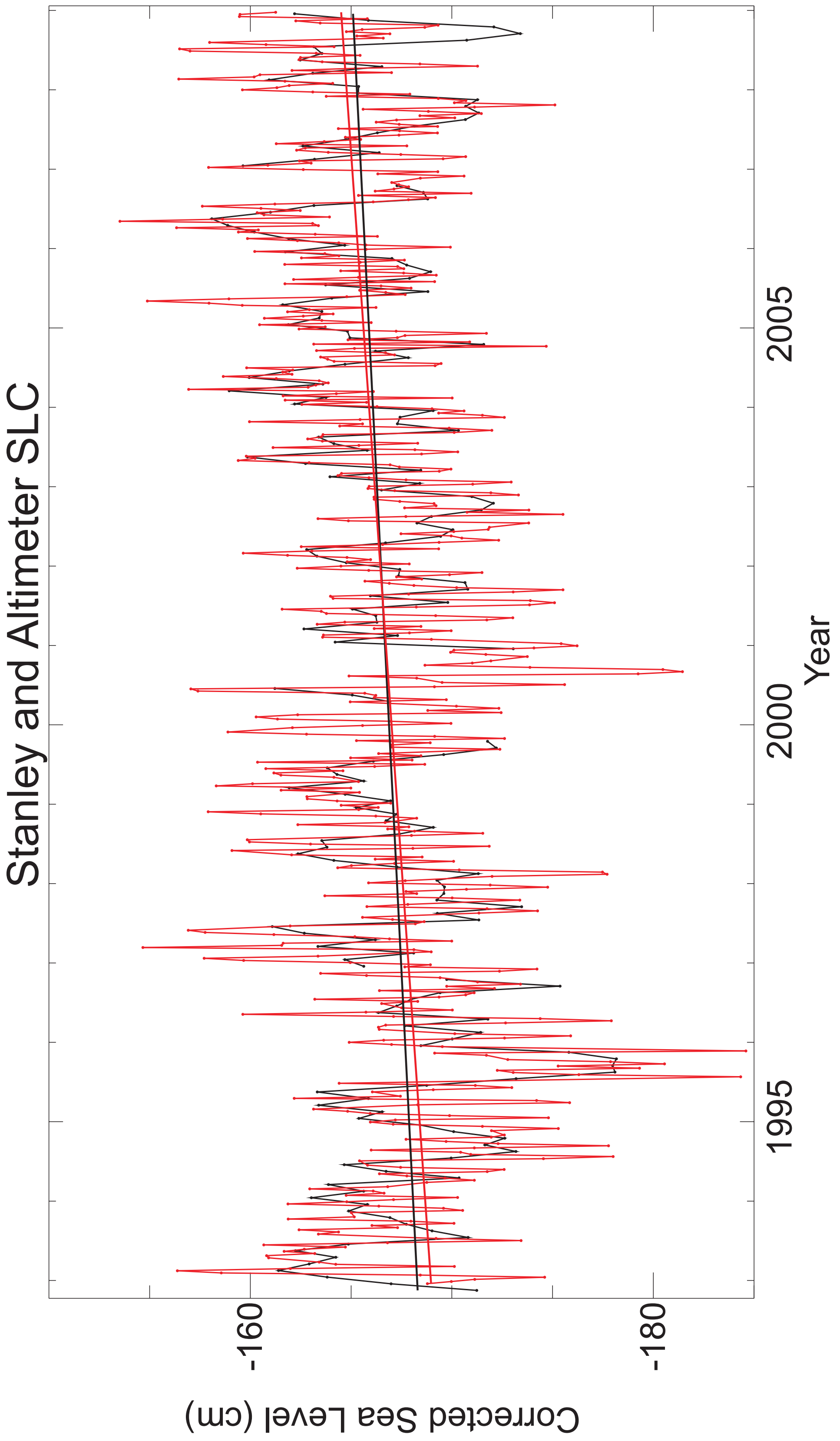

Stanley and Altimeter SLC
Corrected Sea Level (cm)
-160
-180
Year
1995
2000
2005

Figure 9

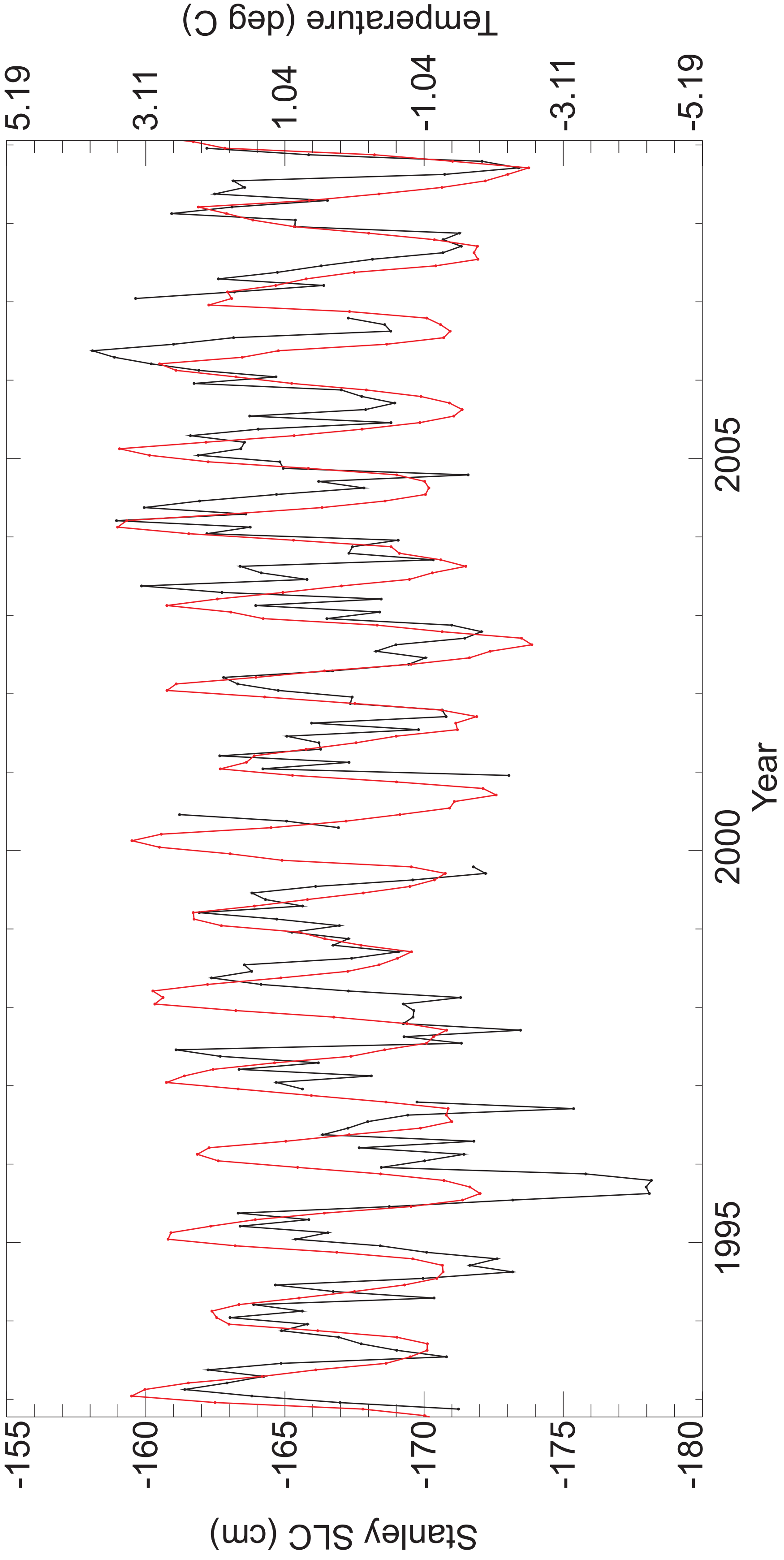

Temperature (deg C)
5.19
3.11
1.04
-1.04
-3.11
-5.19
Stanley SLC (cm)
-155
-160
-165
-170
-175
-180
Year
1995
2000
2005

Figure 10a

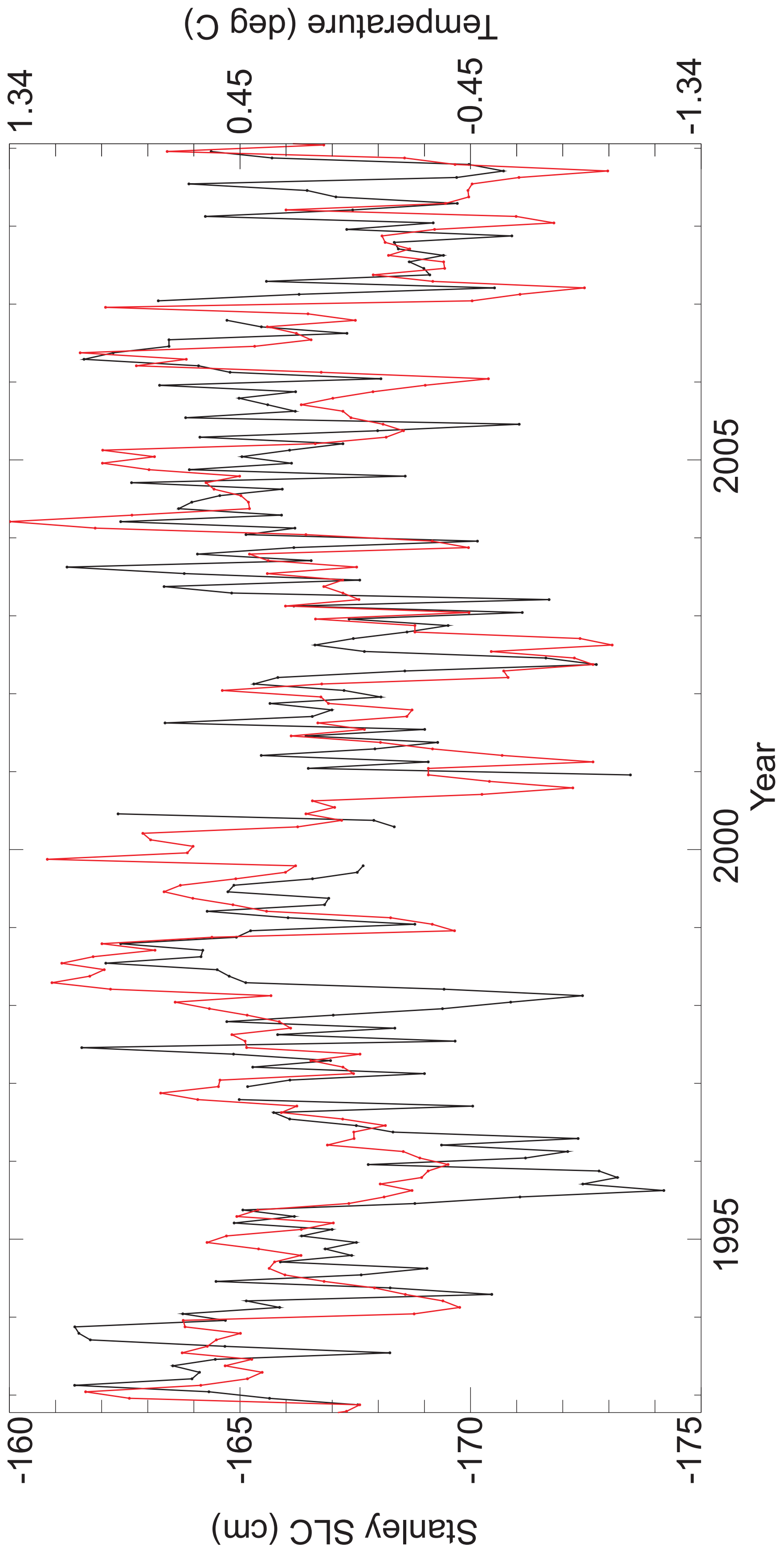

Stanley SLC (cm)
-160
-165
-170
-175
Year
1995
2000
2005
Temperature (deg C)
1.34
0.45
-0.45
-1.34

Figure 10b

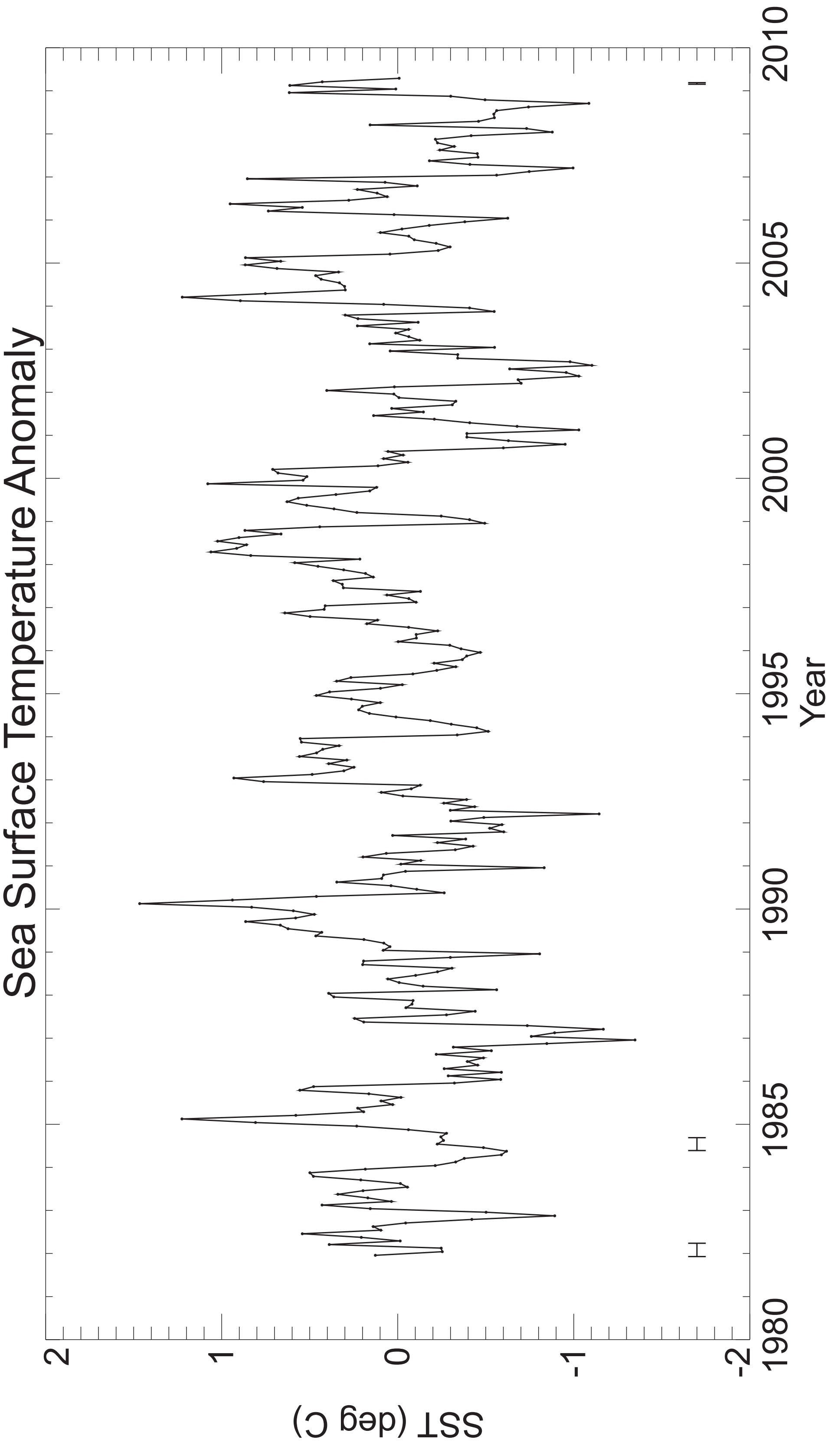

Sea Surface Temperature Anomaly
SST (deg C)
2
1
0
-1
-2
Year
1980
1985
1990
1995
2000
2005
2010

Figure 11

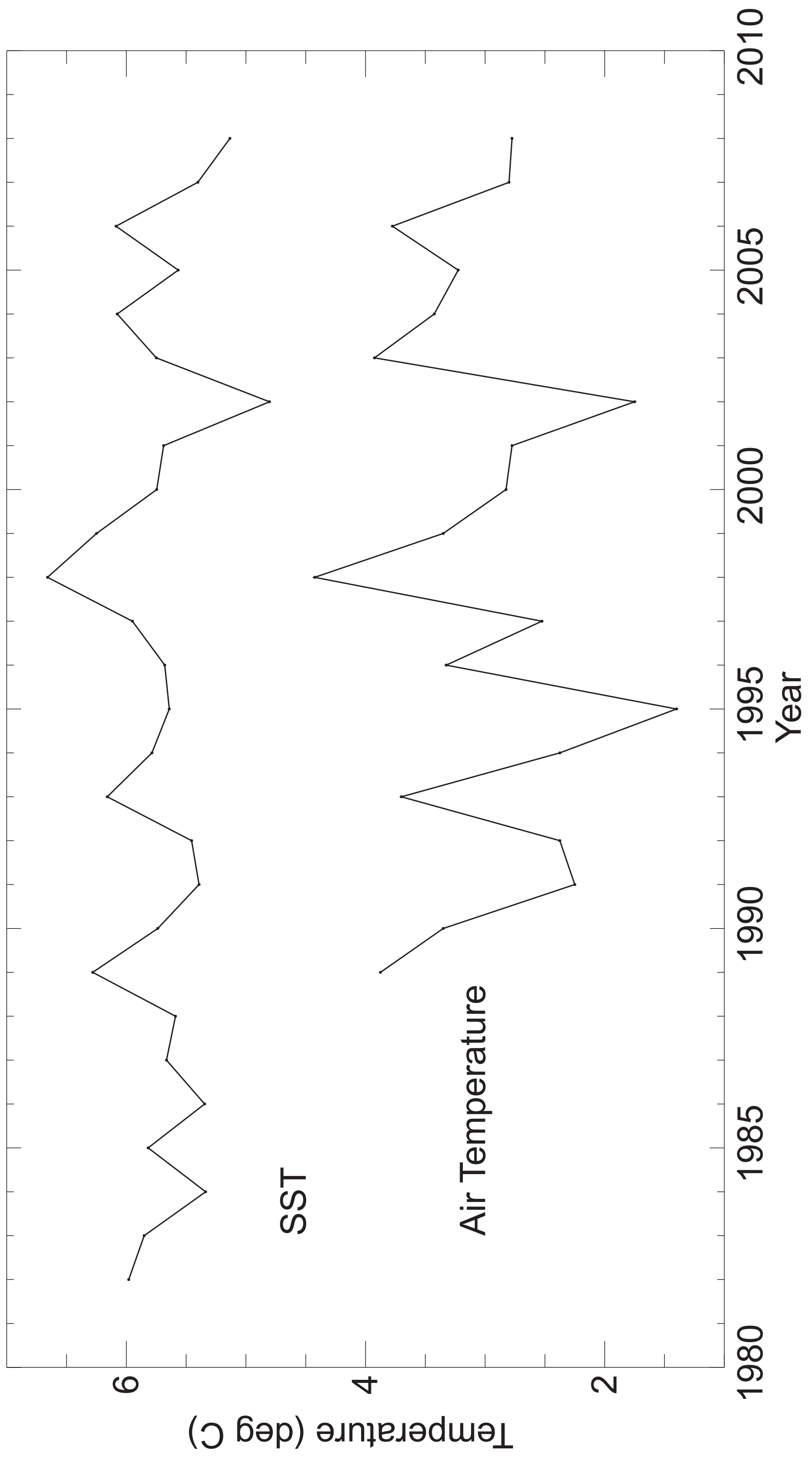

SST
Air Temperature
Temperature (deg C)
6
4
2
Year
1980
1985
1990
1995
2000
2005
2010

Figure 12