Sea level trends at Townsville, Great Barrier Reef, Queensland

Dr. Bill Johnston[1]

http://www.bomwatch.com.au/
(scientist@bomwatch.com.au)

Abstract

Mean monthly sea level (MSL) measured at Cape Ferguson near Townsville, Queensland since October 1991 was analysed using an innovative covariate approach to distinguish between variables that caused variation ***IN*** the data (covariables) from those that impacted ***ON*** the data-stream (impact variables). Except for the Southern Oscillation Index (SOI_{3pt}), which lacked a seasonal cycle, data were deseasoned beforehand.

In order of importance, SOI_{3pt}; barometric pressure (hPa); lag1 solar exposure (MJ/m^2); Lag2 rainfall (mm), and current rainfall explained 31.9% of variation in MSL. Due to a step-change in 2009 related to a change in calculating 10-minute values from 1-second samples, residuals were not homogeneous. Accounting for the step-change and a residual 18.06-year cycle, increased R^2_{adj} to 0.645 (64.5%). Having removed variation ***IN*** the data and the effect of the inhomogeneity ***ON*** the data-stream, no trend or change was attributable to any other factor, including sea level rise.

The dataset for Townsville Harbour from January 1959, was nosier than Cape Ferguson, partly because data before 1984 were digitized manually from tide gauge charts and also because water levels in the harbour, which lies at the entrance to Ross Creek are greatly influenced by hydrological processes within the catchment, including urban development, irrigation, leakage etc. Thus, while SOI_{3pt} was less influential, components of the water-balance (rainfall, evaporation and seasonality) were more so.

With effects due to significant covariables accounted for, inhomogeneities in residuals aligned with construction of the Ross River Dam in 1971 and its enlargement 2007. A third inhomogeneity in 1987 may have been associated with harbour developments or a change related to the gauge.

If the melting of glaciers in Greenland significantly influenced MSL it would be detectable in the data. However, with significant effects accounted for, there was no evidence that climate change or warming unduly affected sea-levels at Cape Ferguson or Townsville or were likely to affect the central Great Barrier Reef.

Data measured by tide gauges are coarse, poorly documented and inadequately understood by climate scientists and oceanographers who routinely conflate variables that cause variation ***IN*** data and those that impact ***ON*** the data-stream, as being due to the climate. Peer-review does not work. Scores of papers published at great expense in elite scientific journals, by multiple authors supported by long reference lists are biased by lack of attention to detail and poor science. The covariate approach outlined in the study sets a benchmark for undertaking due diligence on data, and findings of papers that failed to assess the fitness of data they used to determine trend and change should be disregarded.

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[1] Former NSW Department of Natural Resources research scientist.

Introduction

The Australian Baseline Sea Level Monitoring Program (ABSLMP) aims to identify long-period sea level changes with particular emphasis on the enhanced greenhouse effect. The project commenced in 1993 under the auspices of the National Tide Centre (NTC), now a unit within the National Operations Centre, in Australia's Bureau of Meteorology (BoM). Although NTC maintain a metadata database it is more than a decade out of date.

Peer-reviewed papers on mean sea level and sea-surface temperature trends around Australia, have neglected the effect of the local environment and other factors on data for individual gauges. There is a need therefore, to adopt a scheme for ensuring that tide gauge data are not compromised by extraneous effects i.e., that data reflect the waterbody alone. The NTC gauge at Cape Ferguson near Townsville, Queensland, is presented as a case study to guide climate scientists exploring and analysing trend and change in tide-gauge data. The study is replicated using data for the nearby gauge in Townsville Harbour.

1.1 The underlying problem

Sea-level change is naïvely evaluated using linear regression of the form: MSL ~ time, mostly without regard to parallel inhomogeneities that may affect trend. While comparisons of independent random variables using linear correlation assumes no functional association; linear regression assumes the independent variable, *x*, predicts the dependent variable *y*; i.e., that x is deterministic on y. It falls to the experimenter to justify the basis of that hypothesis. For instance, to posit a reasoned case that MSL (y) measured at Cape Ferguson would be physically dependent on *time* (x).

Referred to as the NULL hypothesis, the statistical F-test, evaluates the probability that the slope coefficient describing the relationship equals zero; i.e., that trend = zero. If the result *P* is less than threshold values of F (typically $P < 0.05$), the NULL is rejected and the slope coefficient is declared significant. Thus, the larger the F-value, the smaller the probability that trend = 0 and the more significant is the relationship. However, there are traps that are often overlooked, mainly those that relate to co-variation that is unexplained by trend alone.

Since September 1991 deseasoned MSL at Cape Ferguson ($MSL_{anomaly}$) appears to be increasing at the rate of 0.049 m/decade (about 5 cm/decade; Figure 1(a)); but how would we know if that was true? The rate coefficient is highly significant ($P < 0.001$), but quantitatively how could time alone explain 44.9% of the variation in MSL? Does MSL inherently increase with age for instance; is it a sign of decay? If trend explained all systematic variation in MSL data, residuals (data minus the trend) would be zero-centred and time-random with no discernible systematic time-related variation. However, as this is not the case (Figure 1(b)), something is wrong; explanatory variables are missing and the trend-alone hypothesis cannot be rational nor physically based.

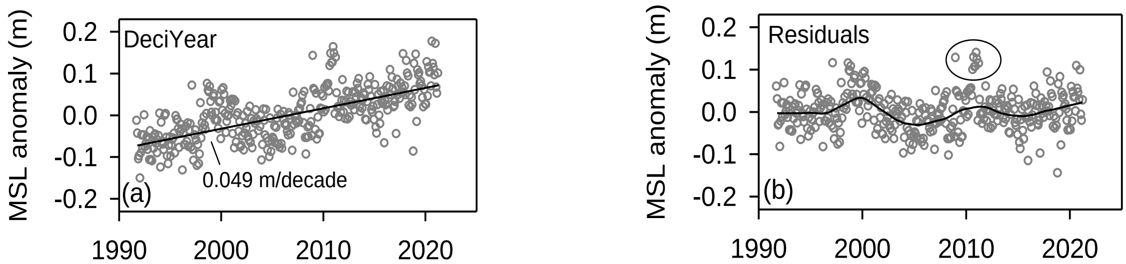


Figure 1, (a): - the naïve linear regression relationship (MSL ~ DeciYear) was highly significant (*P* <0.001) and explained 44.9% of variation in MSL. However, tracked by the LOWESS curve (b) and verified by statistical tests, zero-centred residuals (data minus trend) were neither random nor independent. Some data in 2009/2010 (circled) appear to be outliers. Trend was not a pure signal thus the naïve relationship in (a) was spurious.

This Report investigates the question:

- Is mean monthly sea level (MSL) increasing, and if so, at what rate.

Set out in detail, analysis is undertaken in three stages:

i. Although data are time-ordered, variables that cause variation in MSL are firstly identified and investigated and their effects accounted for in the covariate-domain (i.e., NOT as time series).

ii. Having accounted for variables that impact on MSL data, underlying residual signals (inhomogeneities), which are indicative of one or more missing variables are investigated in the time-domain. Inhomogeneities in residuals may be caused by a site-change (e.g., the sensor may have moved or changed), a change in the way data were acquired (a data processing change); or some other extraneous factor. Detected changepoints are cross-referenced where possible with metadata, other documentation, aerial photographs etc.

iii. Specified as factor or attribute variables, final-round analysis verifies the significance of underlying impacts on the datastream.

At each step variables that are not significant are discarded. Residuals from final-round analysis are examined for unexplained trend, changes or cycles that could be due to the climate or something else.

The three-stage approach outlined in the following sections, distinguishes between variables that cause variation ***IN*** the data (covariables), from those that impact ***ON*** the data-stream (impact variables). Thus, while the tide gauge may record data continuously and faultlessly, an event such as bump to the wharf or an abrupt change in equipment may result in a change that is unrelated to the waterbody. A single dataset describing two or more parallel processes is referred to as confounded and the methodology aims to de-couple such signals using replicable, objective, statistical methods, which are key elements of the scientific method.

2. Data and methods

Data were downloaded from the Bureau of Meteorology website at http://www.bom.gov.au /oceanography/projects/abslmp/ data/monthly.shtml and the BoM's climate data online facility (http://www.bom.gov.au/climate/data/). Daily data for the nearest SILO grid-cells (Latitude -19.30, Longitude 147.05 for Cape Ferguson; and -19.45 and 146.74 for the catchment above the Townsville gauge) were obtained (https://www.longpaddock.qld.gov.au/silo/) and summarised as month by year averages.

Time was expressed as month-centred DeciYears (Year + (month$_{(1\ \text{to}\ 12)}$ - 0.5)/12). Predictor variables used for Cape Ferguson, which is the case study, were monthly rainfall (mm) and average maximum temperature (Tmax, ^{o}C); average daily solar exposure (MJ/m^2); mean monthly barometric pressure (hPa); monthly BoM Southern Oscillation Index seasonally smoothed by a 3-point running mean (SOI_{3pt}); mean SST (^{o}C) in the case of MSL, and mean MSL (m) in the case of SST. While some variables are surrogates of others (solar exposure and possibly rainfall, for cloudiness, for example), research is limited to those readily available. In addition, all variables were lagged; that is, data for up to three previous months were bought forward and analysed as separate variables.

Using R[1] and the *Rcmdr*[2] package, relationships between dependent (MSL) and independent (predictor) variables were examined using multiple linear regression (MLR). Residuals - the portion of total variation not explained by predictors (covariates) were examined graphically. Timewise homogeneity was evaluated using sequential t-test analysis of regime shifts (STARS), more recently updated as the SRSD method

[1] R Core Team (2021). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

[2] https://cran.r-project.org/web/packages/Rcmdr/index.html

(Sequential Regime Shift Detection; see https://sites.google.com /view/regime-shift-test)). Some additional analysis was undertaken using the desk-top application PAST from the University of Oslo (https://www.nhm.uio.no/english/research/infrastructure/past/).

The usual statistical rules apply: should MLR residuals be normally distributed, independent and homoscedastic (having random variance) in the covariate-domain; and homogeneous in the time-domain, variation in the dependent variable is fully explained.

3. Results

3.1 Sea-level at Cape Ferguson

The Cape Ferguson ABSLMP gauge is located on the wharf used by the Australian Institute of Marine Science (AIMS), a Commonwealth government agency which is part of a vast conglomerate of research institutions and non-research bodies including the Great Barrier Reef Marine Park Authority, the Great Barrier Reef Foundation, the Climate Council and WWF that claim that the Reef is imperiled and that its survival is threatened by sea-level rise, global warming and anthropogenic climate change.

As illustrated in Figure 1, with the exception of SOI_{3pt}, variables were dominated by seasonal cycles. Seasonality ($Month_{factor}$) explained 57.6% of variation in MSL; 93.0% in SST; 86.1% in barometric pressure; 75.9% in solar exposure; 87.7% in Tmax; and 37.8% in rainfall. Seasonality causes residuals to be autocorrelated and as cycles may not be in-phase, their combined effect may not be well-described by cosine/sine functions of time, or $Month_{1-12}$ as a factor variable. As cycles also exhibit no trend and may inflate variation explained (R^2_{adj}); all data with the exception of SOI_{3pt} were made seasonally stationary by deducting monthly grand means from respective months data. Transformed values are referred to as anomalies.

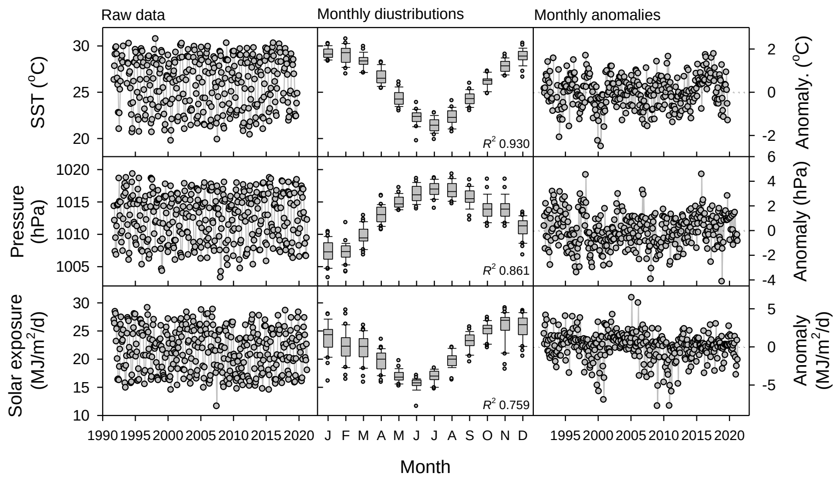


Figure 1. Examples of variables (left-hand panels) that with the exception of the SOI embed seasonal cycles (middle panels) that obstruct a clear-view of underlying patterns and possible trends. While properties of original data are preserved, deducting monthly grand-means reduces the range, exposes possible outliers and results in comparable seasonally stationary series (right panels).

3.1.1 Factors affecting sea level at Cape Ferguson

Significance of potential predictors (and lags thereof) of $MSL_{anomaly}$ was evaluated in the first instance using all-variables MLR and sequential analysis of variance (aov). Variables were ranked on the basis of their significance and proportional contribution (%) to the total sum of squares (Table 1). SOI, anomalies of barometric pressure and previous and current month's average daily solar exposure were the most influential (P <0.001), followed by current and lagged maximum temperature (P <0.01), and lagged and current month's rainfall (*P* <=0.05). It follows that contamination of tide gauge measurements by the combined effect of significant covariables may mask the 'true' behaviour of the oceanic waterbody.

All-variables MLR explained 39.1% of variation in MSL. Although not analysed as time-series, cases were nevertheless time-ordered. Also, although they were normally distributed with equal variance, residuals were not independent. In addition, a possible step-change in 2009 showed residuals were not homogeneous, indicating an influential variable is missing from the analysis.

Table 1. Response of monthly MSL anomalies to independent predictors and lags thereof (L_N), fitted sequentially ranked by F-test values. Total sum of squares estimates total variation in $MSE_{anomaly}$; percent total sum of squares is the proportion of that explained by respective terms.

Source of variation	Sum of squares	Percent of Total SS	Df	F-value	Pr(>F)
SOI_{3Pt}	0.22	19.46	1	104.23	<0.001
$hPa_{Anomaly}$	0.05	4.68	1	25.06	<0.001
$Solar_{AnomalyL1}$	0.06	5.18	1	27.75	<0.001
$Solar_{Anomaly}$	0.07	5.70	1	30.53	<0.001
$Tmax_{Anomaly}$	0.03	2.26	1	12.11	<0.001
$Rain_{AnomalyL2}$	0.02	1.39	1	7.44	0.007
$Tmax_{AnomalyL1}$	0.01	1.14	1	6.11	0.014
$MeanSST_{Anomaly}$	0.01	0.76	1	4.08	0.057
$Ra_{Anomaly}$	0.01	0.50	1	2.67	0.092
$Ra_{AnomalyL1}$	0.00	0.10	1	0.53	0.459
$Tmax_{AnomalyL2}$	0.00	0.03	1	0.18	0.676
Residual	0.67	58.80	315		
Total SS	1.147				

As they were not significant, $Tmax_{AnomalyL2}$, $Rain_{AnomL1}$ and $MeanSST_{Anomaly}$ were omitted and the dataset was re-analysed (Table 2). Twenty-seven cases of missing SST data (used as a potential predictor of MSL), including from November 2019 to the end of the record in April 2021 caused R^2_{adj} to change slightly from 0.391 (all-variables) to 0.382 (Table 2). Also, inclusion of additional cases increased degrees of freedom (Df) from 315 to 345 and the total sums of squares from 1.147 to 1.364.

Table 2. Response of monthly MSL anomalies to independent predictors and lags (L_N) thereof, fitted sequentially ranked by F-value.

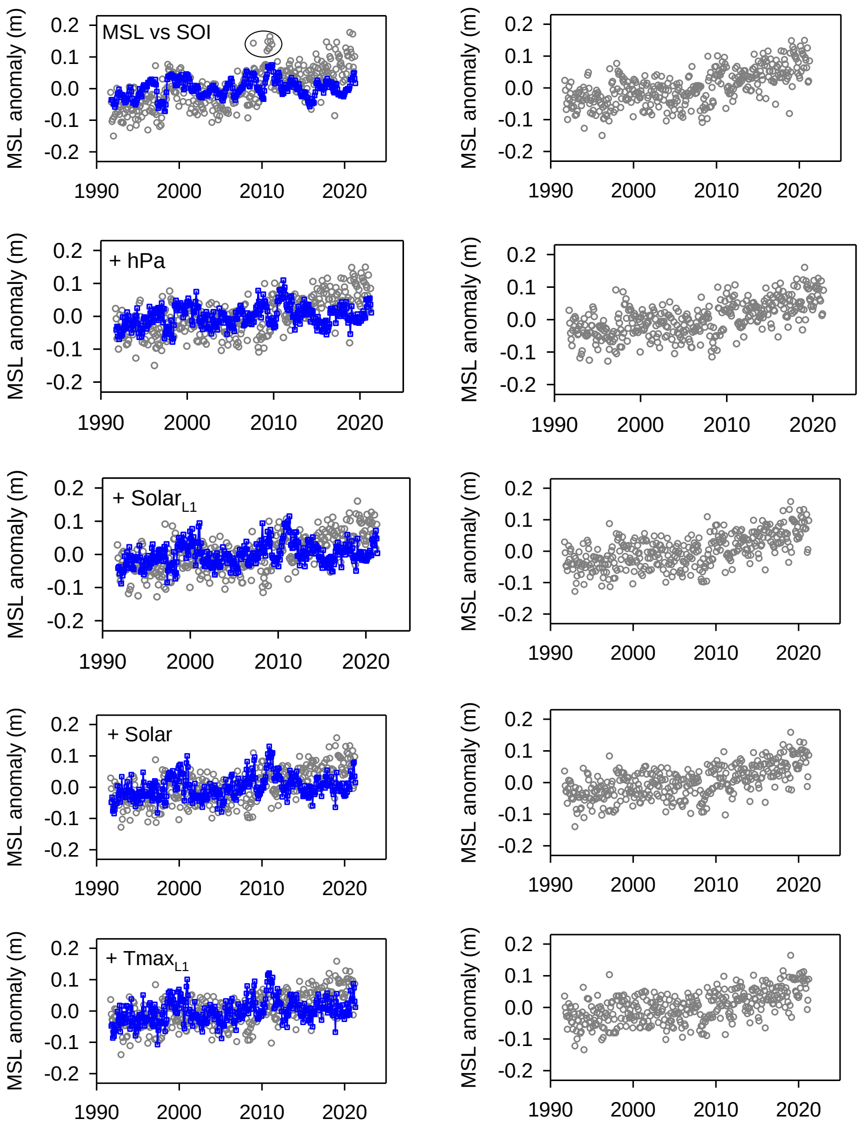
Source of variation	Sum of squares	Percent of Total SS	Df	F-value	Pr(>F)
SOI_{3Pt}	0.28	20.85	1	119.02	< 0.001
$hPa_{Anomaly}$	0.07	5.24	1	29.89	< 0.001
$Solar\_MJ_{AnomalyL1}$	0.05	3.50	1	19.97	< 0.001
$Solar\_MJ_{Anomaly}$	0.06	4.38	1	24.98	<0.001
$Tmax_{AnomalyL1}$	0.04	2.81	1	16.01	<0.001
$Rain_{AnomalyL2}$	0.02	1.27	1	7.23	0.008
$Tmax_{Anomaly}$	0.01	0.86	1	4.91	0.027
$Rain_{Anomaly}$	0.01	0.66	1	3.78	0.053
Residual	0.82	60.44	345		
Total sum of squares	1.364				

Reiterating that exploratory analysis aimed only to identify influential predictors; sequential aov of the all-predictors model (Table 1) ranked all contenders that *might* be influential by their effect on MSL. Second-round analysis (Table 2) excluded those that were not significant, re-partitioned the total sum of squares, which estimated overall variation in $MSL_{anomaly}$ and proportional contributions were recalculated. For example, SOI_{3pt} accounted for 20.9% of Total SS, with the proportions for additional terms diminishing rapidly. As the Residual SS (the unexplained portion) is 60.44%, influential variables are either missing or MSL data was inadequately explained by covariables.

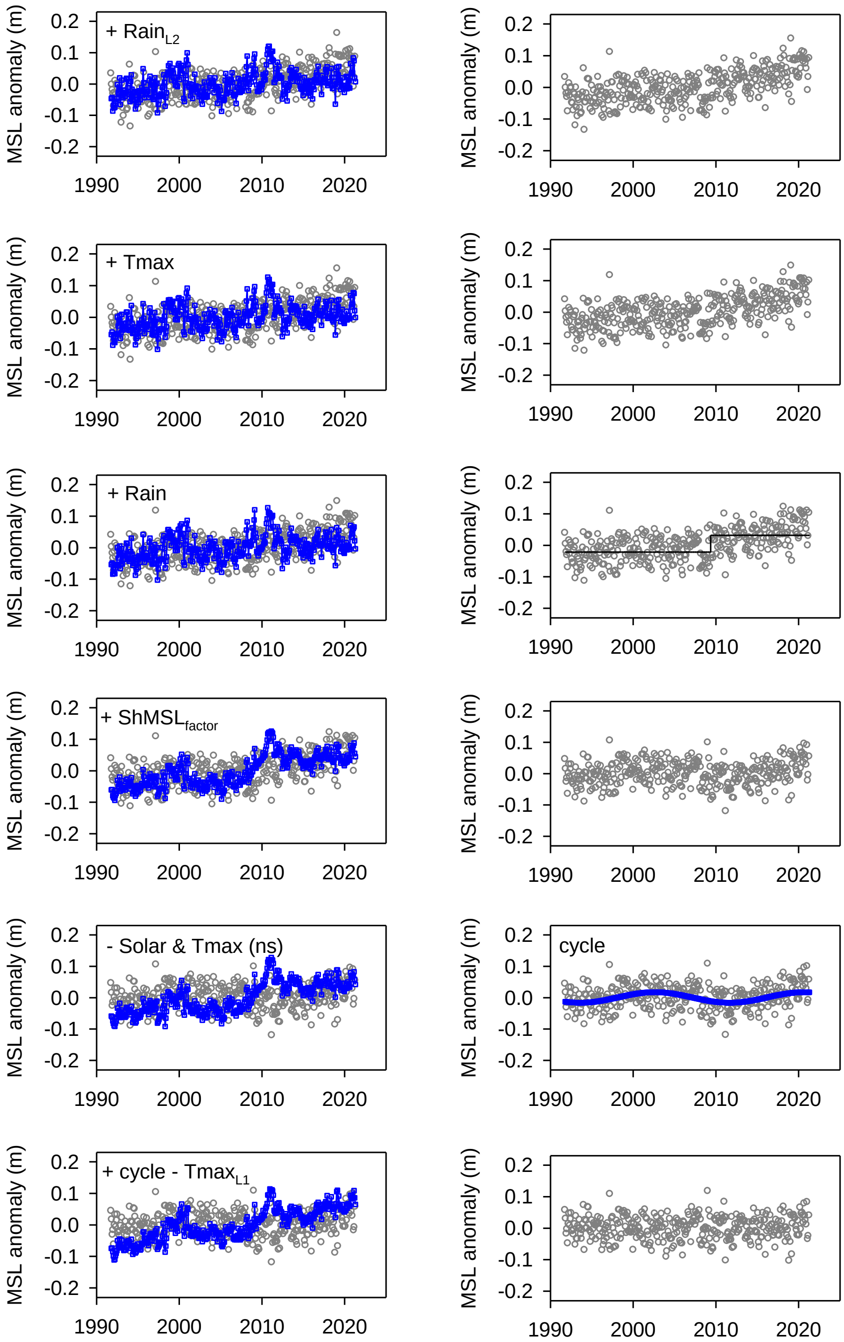
To expand on the process of investigating the effect of variables listed in Table 2 on $MSL_{anomaly}$, data are analysed in ranked order, sequentially in Table 3. At each step, variables that ceased to be significant (P >0.05) were dropped and the case re-analysed. As the effect of covariables is additive and to avoid the possibility of inhomogeneities being confounded with, or mistaken for abrupt environmental changes, step-change analysis of residuals was undertaken after the effect of all other significant variables $MSL_{anomaly}$ had been accounted for.

Table 3. Sequential MLR analysis of the effect of variables listed in Table 2, on MSL anomalies at Cape Ferguson. Effects are additive and for each iteration residuals from the previous fit are shown overlaid by the current fit. F-test probability values (*P*) refer to the significance of the last-added term; Sh refers to a shift (categorical) variable.

Fitted model (blue) | Residual variation | Regression statistics



1. MSL ~ SOI_{3pt}; P <0.001; R^2_{adj} 0.206; RSS = 1.079. Note that apparent outliers highlighted in Case 1 were accounted for by the SOI.
2. MSL ~ SOI_{3pt} + hPa_{anom}; P <0.001; R^2_{adj} 0.257; RSS = 1.008.
3. MSL ~ SOI_{3pt} + hPa_{anom} + $Solar_{anomL1}$; P <0.001; R^2_{adj} 0.290; RSS = 0.961
4. MSL ~ SOI_{3pt} + hPa_{anom} + $Solar_{anomL1}$ + $Solar_{anom}$; P <0.001; R^2_{adj} 0.332; RSS = 0.901
5. MSL ~ SOI_{3pt} + hPa_{anom} + $Solar_{anomL1}$ + $Solar_{anom}$ + $Tmax_{anomL1}$; P <0.001; R^2_{adj} 0.359; RSS = 0.863



6. MSL ~ SOI_{3pt} + hPa_{anom} + $Solar_{anomL1}$ + $Solar_{anom}$ + $Tmax_{anomL1}$ + $Rain_{anomL2}$; *P* =0.008; R^2_{adj} 0.370; RSS = 0.845
7. MSL ~ SOI_{3pt} + hPa_{anom} + $Solar_{anomL1}$ + $Solar_{anom}$ + $Tmax_{anomL1}$ + $Rain_{anomL2}$ + $Tmax_{anom}$; *P* =0.027; R^2_{adj} 0.377; RSS = 0.845
8. MSL ~ SOI_{3pt} + hPa_{anom} + $Solar_{anomL1}$ + $Solar_{anom}$ + $Tmax_{anomL1}$ + $Rain_{anomL2}$ + $Tmax_{anom}$ + $Rain_{anom}$; *P* =0.053; R^2_{adj} 0.382; RSS = 0.825. Step change 0.053 m in May 2009; *P* <0.000.
9. MSL ~ SOI_{3pt} + hPa_{anom} + $Solar_{anomL1}$ + $Solar_{anom}$ + $Tmax_{anomL1}$ + $Rain_{anomL2}$ + $Tmax_{anom}$ + $Rain_{anom}$ + $ShMSL_{factor}$; *P* <0.001; R^2_{adj} 0.603; RSS = 0.529
10. Non-significant variables removed: MSL ~ SOI_{3pt} + hPa_{anom} + $Solar_{anomL1}$ + $Tmax_{anomL1}$ + $Rain_{anomL2}$ + $Rain_{anom}$ + $ShMSL_{factor}$; R^2_{adj} 0.602; RSS = 0.532. (18.06 yr. cycle determined using PAST.)
11. Remove $Tmax_{anomL1}$: MSL ~ SOI_{3pt} + hPa_{anom} + $Solar_{anomL1}$ + $Rain_{anomL2}$ + $Rain_{anom}$ + $ShMSL_{factor}$ + cycle; R^2_{adj} 0.645; RSS = 0.475.

Accounting for (removing) the effect of nominated variables as a step-wise sequence of additive terms shows the mechanics associated with reducing variation in residuals. Case 1 residuals show subtraction of the SOI signal from raw $MSL_{anomaly}$ data has the largest effect and accounted for high sea-levels associated with the deep 2009/10 La Niña event, which caused widespread flooding. While the analysis sequence (Case 1 to Case 8), accounted for all significant co-variables their effect on residuals diminished, thus illustrating the difference between *significance* and *importance*. Step-change analysis detected a significant inhomogeneity in Case 8 residuals in May 2009 that aligned closely with replacing the former Sutron datalogger with a Telmet 320 that used a different averaging algorithm.

Case 10 residuals were analysed for the possible existence of a significant cycle using sinusoidal regression in PAST. The 'Fit Periods' option optimised the period of the cycle using a 'matching pursuit' algorithm[1]. The

[1] https://www.nhm.uio.no/english/research/infrastructure/past/downloads/past4manual.pdf p. 163

18.06-year cycle, which closely matched the 18.61-year lunar nodal cycle[1] was highly significant (P <0.001) and explained 12.0% of additional variation that was not explained by Case 10: (partial R^2 = ($RSS_{Case\ 10}$ – $RSS_{Case\ 11}$)/ $RSS_{Case\ 10}$ = 0.120). Case 11 residuals were independent, randomly distributed with equal variance and there was no evidence that sea-level was increasing nor any evidence of climate change.

Comparing the original data with values fitted by Case 11 showed all the apparent trend in $MSL_{anomaly}$ was embedded in the fit i.e., trend was due to the combination of co-variables and the step-change; possibly confounded by the cycle. The step-change showed data were not homogeneous, which is a key assumption of trend analysis. Also, as Case 11 residuals were random and untrending, it is clear that climate scientists claiming sea levels were increasing in the vicinity of the Great Barrier Reef had not thoroughly investigated datasets they used.

For its part the BoM potentially hid problems relating to continuity of the record by not updating ABSLMP metadata since 2010. It is unsatisfactory that the most useful metadata was discovered at the University of Hawaii, Joint Archive for Sea Level, but not in Australia. Together with maintaining an up-to-date record; providing a link to the UHSLC metadata which must have been provided by the NTC, would temporarily remedy the situation (http://uhslc.soest.hawaii.edu/rqds/pacific/doc/qa343a.dmt). A search of the UHSLC database found other ABSLMP tide gauges that were also possibly affected by changed dataloggers and averaging algorithms include Rosslyn Bay, Darwin, Broome, Port Stanvac, Thevenard, Spring Bay, Burnie and Port Kembla.

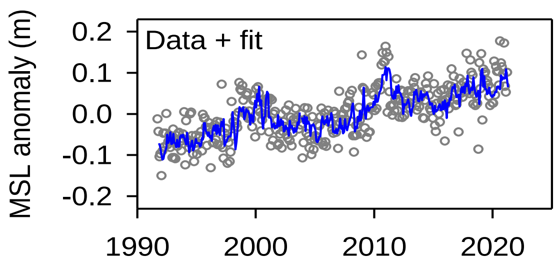


Figure 3. From a trend perspective, as seasonal cycles were removed, de-seasoned MSL data (grey circles) reflect variation in the signal, not the seasonal cycle. The effect of significant factors that cause variation in MSL, accumulated by Case 11 (blue line) were confounded with, but were unrelated to MSL *per se*.

Table 4 shows sequential sums of squares for Case 11 in Table 3 in order of fitting. Based on their proportional contribution, the $shift_{factor}$ variable (Sh) was the most influential followed by SOI_{3pt}, solar exposure for the previous month (L1) and the lunar nodal cycle. Although significant, the influence of current and previous month's rainfall was trifling.

Table 4. Sequential aov for Table 3, Case 11. (Sh refers to the $shift_{factor}$ variable.)

Source of variation	Sum of squares	Percent of total SS	Df	F-value	Pr(>F)
SOI_{3Pt}	0.28	20.85	1	207.17	<0.001
$hPa_{anomaly}$	0.07	5.24	1	52.04	<0.001
$Solar_{anomalyL1}$	0.05	3.50	1	34.76	<0.001
$Rain_{anomalyL2}$	0.01	0.64	1	6.34	0.012
$Rain_{anomaly}$	0.04	2.61	1	25.89	<0.001
$ShMSL_{residuals}$	0.37	27.47	1	272.90	<0.001
Cycle	0.07	4.88	1	48.48	<0.001
Residual	0.475	34.82	346		
TOTAL SS	1.364				

[1] See Haig et al. 2011. doi:10.1029/2010JC006645

3.2. Sea level in Townsville Harbour

The Townsville tide gauge is located on a wharf in Townsville Harbour, about 24 km directly west of Cape Ferguson but on the northern side of Cape Cleveland. The harbour is also the mouth of Ross Creek, possibly the historic bed or overflow channel of the Ross River, which drains a rugged catchment south-west of the city. The coastal delta consists of coarse sediments and because the harbour is confined, tide-gauge measurements can be expected to be influenced by hydrological processes operating across the catchment, interacting with tidal elements, possibly superimposed by issues relating to operation of the harbour and the gauge. Thus, there are three potential sources of MSL variation – oceanic, catchment-wide and harbourside effects.

According to Modra (2013)[1]: (Quote) *The Townsville record consists of four campaigns in two locations within the port of Townsville, with overlapping records.*

Gauging began on the No.6 wharf on the eastern side of the harbour on 19 November 1948, using an Amsler chart recorder. This continued until 31 December 1993.

A second gauge was installed on the western side of the harbour at the Roll On-Roll Off wharf with a Leupold and Stephens recorder. This gauge was upgraded on 15 June 1984 with a Mace digital recorder and encoder attached to the chart recorder. The chart recorder was removed from the system in 2002. Recording at this site ended in September 2011, and the gauge is currently located at the original site on No. 6 wharf.

Due to changes in locations and equipment, it should not be assumed that gauge-changes have not affected continuity of the MSL-record.

Via weirs, bores and pipelines, Ross River has always been the source of potable water for Townsville. The Ross River Dam, constructed in 1971 for flood mitigation and water storage was enlarged in 2007. Since 1988 the water supply to the dam has also been augmented by pumping water released from the Burdekin Dam via weirs and a pumping station on the Haughton River; thus, the river is not a closed catchment.

As the catchment is relatively short (49 km in length) and the dam is on the outskirts of the city, building and enlarging the dam and its operation may also affect tide-gauge measurements down-stream at the mouth of Ross Creek, even though aerial photographs show the creek was cut-off from the River between 1958 and 1961.

3.2.1 Factors affecting Townsville MSL

An expanded dataset that included some likely influential variables, including monthly evaporation, and water balance components calculated for the aforementioned closest SILO grid-cell was prepared, with variables except for SIO_{3pt} expressed as anomalies. Several rounds of exploratory analysis showed multicollinearity was a problem for derived water balance estimates so they were dropped from the predictor dataset. MSL data were obtained from http://www.bom.gov.au/oceanography/projects/abslmp/data/monthly.shtml; while metadata was sourced from NTC and UHSLC (http://uhslc.soest.hawaii.edu/rqds/pacific/doc/qa334a.dmt).

Varying the approach outlined previously for Cape Ferguson, following an initial all-variables analysis, forward/backward stepwise model selection and the Akaike information criterion (AIC), was used to short-list variables that were influential, without over-fitting (the trade-off between the goodness of fit and the simplicity of the model) (Table 5).

[1] Tide Gauge Histories. Metadata for National and NSW Tide Gauges. Report MHL2179. NSW Department of Public Works, Manly Hydraulics Laboratory; October 2013. NSW Office of Environment and Heritage.

Table 5. Sequential aov of variables identified using forwards/backwards model selection, as influencing tide-gauge measurements in Townsville Harbour. (R^2_{adj} 0.253).

Response: $MSL_{anomaly}$

Source of variation	Sum of squares	Percent of Total SS	Df	F-value	Pr(>F)
SOI_{3Pt}	0.21	6.83	1	68.30	<0.001
$Tmin_{anomaly}$	0.14	4.48	1	44.80	<0.001
$Rain_{anomalyL1}$	0.12	3.90	1	39.06	<0.001
$Epan_{anomaly}$	0.08	2.48	1	24.79	<0.001
$Rain_{anomaly}$	0.13	4.09	1	40.92	<0.001
$Tmax_{anomaly\ (neg)}$	0.08	2.47	1	24.70	<0.001
$Rain_{anomalyL2}$	0.04	1.37	1	13.71	<0.001
$Epan_{anomalyL2}$	0.02	0.49	1	4.90	0.027
Residual	2.289	73.89	739		
Total sum of squares	3.098				

While the SOI_{3pt} again accounted for the highest proportion of the Total SS, variables related to plant growth (Tmax and Tmin) and the evaporation component of the water balance (evaporation (0.8 * Epan) and lags thereof) as well as rainfall, were significant. (While other coefficients were positive the tide gauge response was negatively related to $Tmax_{anomaly}$.) Nevertheless, relative to that for Cape Ferguson (Table 2) the proportion of unexplained variation (residual SS, 73.9%) was high. Analysis indicates the tide-gauge is strongly influenced by landscape-wide hydrological processes in the Ross River catchment. Unknowns include volumes of water drawn from the Burdekin Dam, urban irrigation, leakage etc. from infrastructure and changed water use as a result of replacing open space with houses and roads, and deep-rooted, summer-growing grasses, shrubs and trees with shallow rooted plants and lawn. Changed hydrology may result in a sub-surface 'water-mound', which ultimately must drain to waterways or directly to the Reef lagoon.

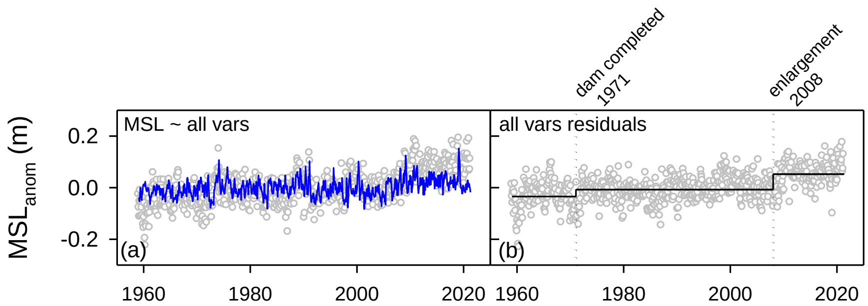


Figure 4. MSL_{anomay} (grey circles) overlaid by the combined effect of the variables summarised In Table 5 (a). Effects are additive; step-changes in $MSL_{anomaly}$ residuals related to the construction and enlargement of the Ross River dam are overlaid in (b).

Of a range of scenarios based on changes noted in metadata and further statistical tests using STARS, AIC for the scenario that best described the data were step-changes associated with construction of the Ross River Dam, which was completed in 1971 and its enlargement in 2007 (Table 6). While other variables were significant, changed hydrology, including urban water use due to population increase, was indicated as having the greatest impact. In summary, reduced peak-flows in summer and increased base-flow across non-summer months increased the average volume of water draining to the delta and Ross Creek. The negative coefficient for $Tmax_{anomaly}$, signalled that the change in base-flow was greatest during the summer wet season when water was withheld by the dam.

Table 6. Sequential aov of variables influencing tide-gauge measurements in Townsville Harbour, including the categorical step-change variable. Note that while the Total SS was the same and variation explained by other variables was little changed, the shift variable reduced the unexplained (residual) SS from 73.89% (Table 5) to 46.97%. (R^2_{adj} 0.524).

Response: $MSL_{anomaly}$

Source of variation	Sum of squares	Percent of Total SS	Df	F-value	Pr(>F)
SOI_{3Pt}	0.21	6.83	1	107.15	<0.001
$Min_{anomaly}$	0.14	4.48	1	70.29	<0.001
$Rain_{anomalyL1}$	0.12	3.90	1	61.27	<0.001
$Epan_{anomaly}$	0.08	2.48	1	38.90	<0.001
$Rain_{anomaly}$	0.13	4.09	1	64.19	<0.001
$Tmax_{anomaly\ (neg)}$	0.08	2.47	1	38.75	<0.001
$Rain_{anomaly}$	0.04	1.37	1	21.51	<0.001
$Ep_{anomalyL2\ (neg)}$	0.02	0.49	1	7.69	0.006
$Sh_{RossRDam}$	0.83	26.91	2	211.15	<0.001
Residuals	1.455	46.97	737		
Total sum of squares	3.098				

Residuals resulting from analysis in Table 6, were fitted directly with the 18.61-year lunar nodal cycle using PAST (Figure 5). However, being a noisy dataset, the cycle was less evident than was the case for Cape Ferguson.

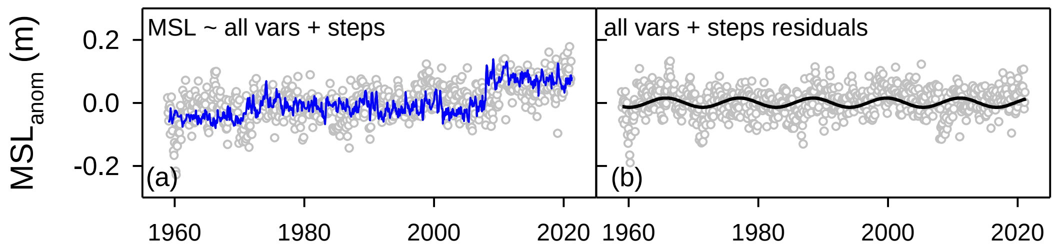


Figure 5. MSL_{anomay} (grey circles) overlaid by the combined effect of the variables summarised In Table 6 (a). Effects are additive and with step-changes accounted-for (blue line in (a)), residuals were fitted with the 18.61-year lunar nodal cycle using PAST in (b).

Final-round analysis, which included the lunar nodal cycle (Table 7) explained 54.4% of variation in $MSL_{anomaly}$. Variables and factors were highly significant; construction and enlargement of the Ross River Dam were the most influential factors, followed by SOI_{3pt} then variables accounting for interaction between tide-gage measurements and the wider environment, including lagged (or delayed) responses. Overlaid on the raw $MSL_{anomaly}$ dataset the combined fit and residuals are shown in Figure 6.

A cumulative sum (CuSum) plot of residuals suggested that due to strong inflections in 1969, 1987 and 2004 residuals in Figure 6, may still not be homogeneous. Aerial photographs show an area within the harbour was in-filled for a new wharf and facilities between 1965 and 1974 (which is now used by the Royal Australian Navy and Cruise liners). Also, as the tide gauge moved from one wharf to another, instrumentation changed and that overlap data were possibly used to make adjustments, other potential sources of inhomogeneities could not be specifically attributed.

Table 7. Sequential aov of variables influencing tide-gauge measurements in Townsville Harbour, including the 18.61-year lunar nodal cycle, which was fitted to previous residuals using PAST. (R^2_{adj} 0.544)

Response: $MSL_{anomaly}$

Source of variation	Sum of squares	Percent of Total SS	Df	F-value	Pr(>F)
SOI_{3Pt}	0.21	6.83	1	111.75	<0.001
$Tmin_{anomaly}$	0.14	4.48	1	73.30	<0.001
$Rain_{anomalyL1}$	0.12	3.90	1	63.90	<0.001
$Epan_{anomaly}$	0.08	2.48	1	40.56	<0.001
$Rain_{anomaly (neg)}$	0.13	4.09	1	66.95	<0.001
$Tmax_{anomaly}$	0.08	2.47	1	40.41	<0.001
$Rain_{anomalyL2}$	0.04	1.37	1	22.43	<0.001
$Epan_{anomalyL2 (neg)}$	0.02	0.49	1	8.01	<0.001
$Sh_{RossRdam}$	0.83	26.91	2	220.21	<0.001
18.61-yr cycle	0.06	1.99	1	32.62	<0.001
Residuals	1.393	44.98	736		
Total sum of squares	3.098				

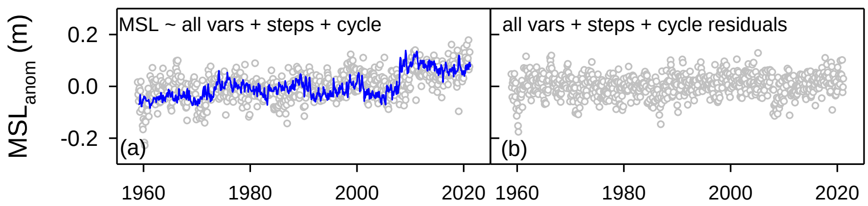


Figure 6. Variation explained by final-round analysis shown in Table 7 i.e., the fitted data, overlaid on the original $MSL_{anomaly}$ series (a); and residuals (original data minus fitted values) in (b).

3.2.2 Verification of changepoints using covariate analysis

Covariate analysis requires that the outcome variable (MSL) be dependent on the covariate. Of the variables in Table 7, SOI_{3pt} was significantly (positively) related to $MSL_{anomaly}$ (β= 1.87E-03, P <0.001; R^2_{adj} = 0.067; Figure 7) and was therefore chosen as the single covariate to the exclusion of others.

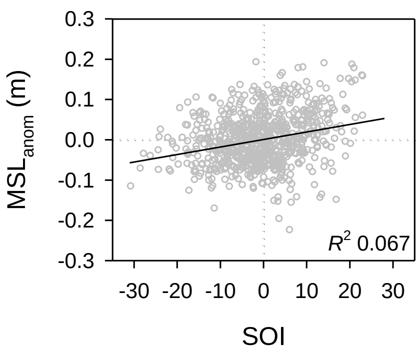


Figure 7. The relationship between $MSL_{anomaly}$ and SOI_{3pt} was highly significant (P <0.001), but only explained 6.7% of $MSL_{anomaly}$ variation.

Covariance analysis required that:

i. SOI_{3pt} -adjusted $Scenario_{factor}$ means were significantly different (i.e., segmented regressions were not coincident, thus, individual relationships were offset);
ii. $Scenario_{factor}$ by SOI_{3pt} interaction was not significant (lines were parallel, meaning slopes were homogeneous); and,
iii. R^2_{adj} was highest and AIC was least, for the most parsimonious model.

Where differences between adjusted scenario means in (i) were the same (lines were coincident), they were combined into a single category. The aim of covariance analysis was to further verify that that the final model best explained the data.

3.2.2.1 Background

MSL data are potentially affected by compounded site changes, and analysis thus far has not evaluated their quality or fitness for determining trend. Data was acquired from manually-digitised charts until December 1993 and a digital recorder and encoder from June 1984. CuSum analysis of residuals identified changepoints in addition to those identified previously, in 1969, 1987 and 2004. In addition, the site moved from No. 6 wharf to the roll-on roll-off wharf and back again, and overlap data may have been used to adjust location changes. The No. 6 wharf was demolished in 2016 and dredging and other major infrastructure changes have happened as well. Furthermore, 10-minute data for the Townsville Storm Surge Gauge (H055003A), which commenced 1 January 1996 were merged with the current gauge (No. H100447) from 26 September 2011, but no coordinates for the current gauge were provided with the record. Lack of comprehensive metadata is a significant problem and metadata that exists may not be accurate.

Based on what was known, and timing of construction of the dam, a range of scenarios was devised and tested iteratively for their effect on $MSL_{anomaly}$ using SOI as the covariate (or control variable). Assisted by the Akaike information criterion (AIC), the hypothesis: $MSL_{anomaly} \sim Scenario_{factor} + SOI_{3pt}$ was investigated iteratively, statistically, and graphically by comparing fits and residuals.

First-round analysis of a scenario that included changepoints nominating construction and enlargement of the dam; and potential shifts in $MSL_{anomaly}$ in 1969, 1987 and 2004 found the possible shift in 1969 was coincident with that in 1971 (Table 8); the dam may have partially filled for example. Segments were thus merged and the number of potential changepoints reduced from five to four. Reanalysis confirmed that data before 1971 formed a single segment, and also that the $MSL_{anomaly}$ mean from 2004 to 2007 was not significantly different to that from 2008 to 2012. With those segments combined changepoints reduced from four to three and the dataset was reanalysed. The final iteration identified three changepoints subtending four data-segments whose segmented means were not the same (Figure 8).

While the changepoint in 1986/87 was not confidently identified previously, and neither could it be attributed to specific changes at the Port, associated documentation or metadata or be cross-referenced by available aerial photographs, covariate analysis confirmed the changepoint was significant. Lack of association between $MSL_{anomaly}$ and SOI_{3pt} prior construction of the dam in 1971 was striking; however, that was during the period of manual digitisation of chart-recorder charts, which continued until June 1984. (Charts were apparently digitised at 10-minute intervals.) Furthermore the relationship with SOI_{3pt} was not significant until after 1974. Fits and residuals for the final model (Iteration 3), which explained 49.2% of variation in MSL are shown in Figure 9.

4. Discussion

In order to draw valid conclusions from datasets they use, it is imperative that climate scientists implement a quality assurance process that distinguishes between variables that cause variation ***IN*** the data (covariables), from those that impact ***ON*** the data-stream (impact variables). The three-stage approach used in the Cape Ferguson study, and replicated using data for Townsville Harbour was objective, insightful of the range of factors operating at the sites and able to discriminate between causal co-variables and changes that cause underlying inhomogeneities that may otherwise be mistaken as part of the signal. In both cases, accounting for variables and factors left no trend or change that could be attributed to the climate, CO_2 or anything else.

Table 8. Iterative analysis of scenarios based on residual CuSum changepoints combined with inhomogeneities related to construction and enlargement of the Ross River Dam, completed in 1971 and 2008. Ninety-five percent confidence limits and significances of differences between groups are shown.

Iteration 1	Seg. mean (m)	lower.CL	upper.CL	Sig.	
1959 to 1968	-0.049	-0.057	-0.041	a	
1969 to 1970	-0.049	-0.068	-0.031	ab	
1971 to 1986	-0.024	-0.031	-0.018	bc	
1987 to 2003	0.001	-0.006	0.007	d	
2004 to 2007	-0.005	-0.018	0.008	cd	
2008 to 2021	0.074	0.067	0.081	e	
Iteration 2					
1959 to 1970	-0.049	-0.057	-0.042	a	
1971 to 1986	-0.024	-0.030	-0.018	b	
1987 to 2003	0.001	-0.006	0.007	c	
2004 to 2007	-0.005	-0.018	0.008	bc	
2008 to 2021	0.074	0.067	0.081	d	
Iteration 3					Slope
1959 to 1970	-0.049	-0.057	-0.042	a	P >0.05 (ns)
1971 to 1986	-0.024	-0.030	-0.018	b	P <0.05; R^2_{adj} 0.061
1987 to 2007	0.000	-0.006	0.005	c	P <0.001; R^2_{adj} 0.215
2008 to 2020	0.074	0.067	0.081	d	P <0.001; R^2_{adj} 0.075

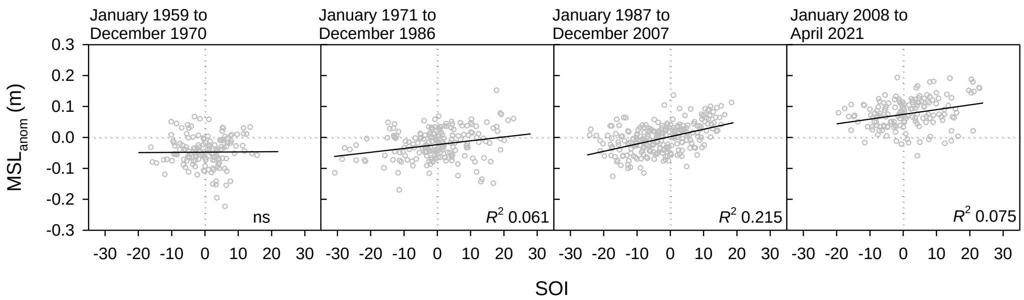


Figure 8. Free-fit relationships between $MSL_{anlomay}$ and SOI_{3pt} for data segments defined by step-changes in 1971, 1987 and 2008. As $MSL_{anomaly}$ is zero-centred and SOI_{3pt} is time-stationary, offsets relative to the data centroid (dotted lines) are attributable to differences between segments; meaning that $MSL_{anomaly}$ is not homogeneous.

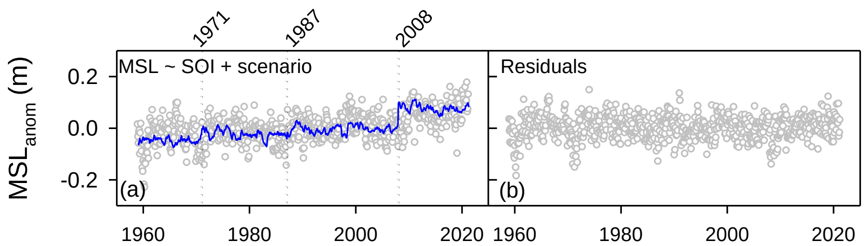


Figure 9. (a) original $MSL_{anomaly}$ data (grey circles) overlaid by the fitted Iteration 3, SOI_{3pt} + scenario model; and (b), residuals resulting from the fit. Compared to Figure 6, the slight step-change in 1987 has been removed by the fitted signal. While residuals may be further decomposed by removing irregular cycles there appears to be too much interference for an overarching cycle to be extracted from the data.

The Cape Ferguson case-study presented a detailed variable-by-variable decomposition the MSL dataset, commencing with the most influential (SOI_{3pt}), including in order of relative importance (Table 2), all covariables that were significant (Table 3). Although not precisely aligned, step-change analysis detected a latent inhomogeneity in 2009 attributable to replacing the Sutron datalogger with a Telmet T320 and a change in the method of deriving 6-minute means. Metadata from UHSLC, which is not available from the NTC, showed many if not all ABSLMP sites were up-graded around that time, thus resulting in parallel inhomogeneities across the network.

If MSL was truly increasing as an inherent property of the waterbody, it would do-so with the effect of influential variables and factors removed. As their effects are additive, multiple linear regression is the tool of choice for decomposing their effect on the total signal. It is also emphasised, that although data are time-ordered the approach is an application of covariance analysis, not time-series analysis *per se*, which would be unlikely to detect inhomogeneities in raw data. Only after influential co-variables are accounted for, is analysis in the time-domain likely to be unbiased by non-oceanic factors.

Like many others around Australia including our longest continuous datasets for Newcastle and Sydney harbours, NSW, and Freemantle, WA; the tide gauge at Townsville is located near the mouth of an active waterway where runoff and subsurface flow from local and possibly regional aquifers as well as landscape-wide hydrological processes that determine flow in the Ross River, can be expected to influence water level in the harbour. Despite the high likelihood of hydrological connections, scientists have consistently conflated variation and structural breaks in data, with 'the climate', climate change or melting glaciers; often using complex statistical methods that average-out or otherwise side-step influential processes

In addition to the SOI, rainfall and evaporation, and Tmax and Tmin, which although affecting the growth of plants, more likely index the seasonality of changed hydrological regimes, completion of the Ross River Dam in 1971 and its enlargement in 2007 affected MSL. Dams store water during rainy seasons for use during the dry, and rainfall and evaporation regimes at Townsville are strongly seasonal. While discharge is an impulse variable that recedes rapidly; in a confined waterway, increased baseflow would be sufficient to cause a consistent increase in the volume of water draining to the riverine delta and Ross Creek during low-rainfall months. Lagged responses are consistent with a time delay in those responses.

Tide gauge measurements integrate the balance between inputs to the water-body (rainfall minus evaporation, expressed as components of the water balance – runoff, discharge, deep drainage etc.), and oceanic processes, not ocean processes alone. It is apparent from the study that tide gauge data are coarse (imprecise), poorly documented and inadequately understood by climate scientists eager to show that ocean levels are increasing relative to the land.

Although transitions to instruments that are similar may be seamless, compared to chart recorders with floats dampened by stilling-wells, high-frequency data acquired by transponders and more recently radar and sonic sensors have increased the 'noise' component of the signal (variance) indivisibly from the signal itself. Also, for high-frequency samples, methods of averaging may also influence apparent trend. Relative to digitised chart recorders, digital instruments sampling 1-pulse/second may confound increased boating activity on a waterway with the signal. As metadata is neither comprehensive nor current, inferences can only be drawn using objective statistical methods, cross-referenced to other information *post hoc*, which is the main strength of the approach outlined here.

If the melting of glaciers in Greenland significantly influenced MSL at Cape Ferguson or Townsville it would be detectable either by the analysis or in the residuals of Case 11 in Table 3 or Figures 4, 6 and 9. Adjusted for extraneous effects, no evidence was found that sea-levels have increased in the vicinity of Cape Ferguson and Townsville Harbour. The claim that sea-level rise threatens survival of the Great Barrier Reef cannot be substantiated.

Dr. Bill Johnston
05 August, 2021

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Author's note: Although this draft paper has been carefully researched and uses statistical tools, data and other evidence that is available in the public domain, no responsibility is accepted for errors of fact arising from the scarcity of information or photographs etc.

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