Published in the Scottish Geographical Journal in 2024
10.1080/14702541.2024.2374373

A Study of Ten Tide Gauge Records from the Clyde in Western Scotland

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Abstract

Sea level information, and its understanding, are essential for research in oceanography and coastal engineering. This paper describes sea level variability in the Clyde using data from 10 tide gauges. High coherence of sea level variability is found between the Firth of Clyde and estuary of the River Clyde, and between the Firth and estuary and the upstream part of the river. Consequently, if gaps exist in any of the records, missing information can be inferred from others. This applies to timescales of typically hours and longer, appropriate for storm surge or mean sea level change studies.

No evidence exists for 'see-saw' oscillations of the river on subtidal timescales, as reported for the River Thames. However, higher-frequency variability (typical period 45 minutes), is found with equal, or opposite, phase at different river locations. Such a standing wave behaviour would be one of the few reported examples of 'river seiches'.

Data from several agencies are used: 2 gauges of the UK National Network of the Environment Agency, 5 from the Scottish Environment Protection Agency, and 3 from Peel Ports. Only the former tend to be used in academic studies, but the present paper has demonstrated how useful complementary sources can be.

Keywords: Tide gauge data; Ocean tides; Non-tidal sea level variations; River oscillations; Seiches

Word count: 6500

1. Introduction

The Clyde is a fascinating area for studying many different aspects of physical oceanography and marine biology (e.g. Matthews et al., 1999; SMFC, 2021). The complex bathymetry and indented nature of the coastline play important roles in the former, including in internal tide generation (e.g. Midgley, 1998; Jackson and Elliot, 2002; Elliot et al., 2003; Cottier et al., 2004; Robins and Elliot, 2009). Essential to most oceanographic studies is good sea level information, and one aim of the present paper is to point out that the Clyde is as well equipped with sea level stations as most points on the British coast. A second aim is to provide an overview of its present tides and its non-tidal changes in sea level.

We define 'the Clyde' to include collectively the River Clyde, Firth of Clyde and the Clyde Sea (Figure 1). The separation between the River Clyde and the Firth of Clyde is defined in different ways in the literature. When we mention the 'river' in this paper, we will mean the narrow section of the River Clyde upstream of Bowling Harbour. This section contains three of the tide gauges shown in Figure 1. Beyond Bowling, the river discharges into the Upper Firth of Clyde, then the Lower Firth, which contain four and one gauges respectively. The Upper Firth is also known as the Outer Estuary, while the Lower Firth is also called the Clyde Sea. One gauge is located further west on the Kintyre Peninsula. There is a shallow glacial sill at the mouth of the Lower Firth called the Great Plateau, stretching southeast from the Mull of Kintyre to Corsewall Point in Galloway. Water over the sill has a depth of approximately 40-50 m and separates the Lower Firth from the North Channel of the Irish Sea. The Portpatrick tide gauge is located on the North Channel coast beyond the sill.

The astronomical tide of this region is predominantly semi-diurnal, with the amplitude of the main lunar constituent, called M2, exceeding a metre. However, the river in particular has changed enormously during the past two centuries, following the demands of the industry that used to occupy both banks, changing from a shallow and wide river to a deeper navigable channel (Bateman et al., 1873; Macalister, 1889; Wheeler, 1893; Blyth et al., 1915; Allen, 1966). This has affected the tidal propagation in the river. For example, Bateman et al. (1873) reported "the tide, which occupied 3 hrs. between Greenock and Glasgow, now accomplished the same distance in 1 hr. 5 mins., those results must be regarded as of a most gratifying character." The physical models that used to be employed to simulate the tides (Thom, 1948; Thomson, 1969) have since been replaced by numerical computer models (Sabatino, 2017).

The Clyde also experiences non-tidal changes in sea level such as the storm surge that resulted in major flooding in January 1991 (Kaya et al., 2005). These changes can also be modelled, and predicted to a great extent, with the use of numerical models (e.g. Crowther and Chen (2001); Bekic et al. (2006); Townson and Donald, 1985; Flather, 2000; Sabatino et al., 2016a,b).

Time series of these non-astronomical changes can also be obtained from tide gauge records from which the astronomical tide has been subtracted. Figure 1 shows the collection of tide gauges in the Clyde that we know of with recent data. They are operated by three separate agencies (Table 1). The Environment Agency (EA) operates Portpatrick and Millport, which are two of the 44 in the UK National (or 'A Class') Network. These stations have been established for many years. However, they have recently not been maintained to as high a standard as one would wish, with the result that their records contain frequent gaps and/or data that is flagged as suspect. As for all 'A Class' stations, they provide 15-min averages of sea level. The Scottish Environment Protection Agency (SEPA) operates five of the stations in Figure 1 (Gourock ceased operation in 2020), using radar and pressure gauges that provide 15-min average values. The three stations of Peel Ports are radar gauges providing 1-min sea levels.

This study started from a long-standing interest in seiches, quasi-resonant oscillations in sea level with a frequency determined by the water depth and shape of coastal inlets (Pugh et al., 2020). The Firth of Clyde, the largest fjordic system in Scotland, at first sight seemed to be a suitable candidate for such research. To study seiches properly, one needs as many monitoring stations as possible. Again, the Clyde was a good candidate, having a coverage of more operational tide gauge stations than most British estuaries.

As things have worked out, our investigation has digressed into several other aspects of sea level variability in the Clyde. Consequently, an overview is presented of the main sea level processes in the area. The only other estuary in the UK which contains a number of tide gauges and has been studied to any great extent is the Thames. Such research over many years has included studies of tides, storm surges (a term coined by Arthur Doodson as part of his study of the Thames floods of 1928), extreme water levels and oscillations of sea level within the river (e.g. Amin, 1983; Doodson, 1929; Inayatillah et al., 2022; Thompson, 1982). The present work on the Clyde, therefore, provides some kind of complement to that body of work on a different estuary.

First, we describe how the Clyde tide gauge data sets were processed. This is followed by a brief review of the main characteristics of the astronomical tide in this area. Then, we consider the extent to which 'non-tidal residual variability' (the difference between the measured record and the astronomical tide) at low frequencies is the same at each station. A practical objective is to decide whether one can use information from one record to fill gaps, or test for errors, in others.

This leads to a discussion of time series of residuals at the three river stations. The extent that their low-frequency variability is the same as that for stations outside the river has also been tested. In addition, it became apparent that there was coherent higher-frequency variability within the river itself, akin to a see-saw, and somewhat similar to high-frequency seiche-like oscillations observed previously in many lakes, bays and harbours, but not observed previously in many rivers. The only UK study along these lines is that of subtidal oscillations of the River Thames by Thompson (1982). This investigation employed only two months of data but that was enough to identify a see-saw between Greenwich and Southend at subtidal frequencies, that is to say, using time series of non-tidal residuals that had been low-pass filtered and then sampled every 12 hours. The oscillations had a magnitude of ±10 or 15 cm, and Thompson (1982) concluded that they were generated by local wind forcing and fluctuations of sea level at the mouth of the Thames. Elsewhere, Long et al. (2020) reported oscillations of ±0.1 m in the Xiangxi River in China with a period around 2 hours caused by operations at the Three Gorges Dam. Oscillations with a period of about 2 hours on the Buffalo River in New York have been reported at several conferences (e.g. Singer et al., 2011; Willard et al., 2019) but their generation mechanism is not clear. Cooper and Ebel (2020) reported model studies of possible seiches on the Delaware and Housatonic Rivers of the kind observed after the New York City earthquake of 1884.

The paper concludes with mention of an unsuccessful search for seiches in the data set, which was the original motivation for the present study. There then follow some overall conclusions.

2. Tide gauge data and data processing

The Portpatrick and Millport records from the 'A Class' network, available from the British Oceanographic Data Centre (BODC), commence in 1968 and 1978 respectively. They contain time series of hourly values of sea level up to 1992, after which they are 15-minute averages. The SEPA records commence in the late 1990s, while those of Peel Ports (Port of Glasgow) start after 2017. The fact that data became available from all ten stations only recently, and that there are data gaps in some, mean that we have focused in this paper on data from 2021. In this year, data are available from 9 of the 10 stations (Gourock not operational from 2020). Information from 2019 was also used for confirmation of 2021 findings.

First, the Peel records were converted to 15-min average sea levels by averaging the 1-min values centred on 0, 15, 30 and 45 minutes past the hour, to be consistent with the 'A Class' and SEPA records, so that they could be analysed together. Then, each year of data was subjected to a tidal analysis to separate the astronomical tide from the non-tidal residuals. The TASK-2000 package of the National Oceanography Centre (Bell et al. 1999) was used to make these analyses. The tide was defined as the sum of 63 harmonic components, including the seasonal components (Ssa and Sa with periods of 6 and 12 months respectively) which we consider here as part of the 'astronomical tide' although they are not completely astronomical in origin (Pugh and Woodworth, 2014). As is common in such tidal analyses, the power spectra of the residuals contain small remaining spikes at tidal frequencies due to the imperfect separation; this is almost certainly due to interaction between tide and surge throughout the year. Each residual time series was 'buddy checked' with its neighbours to identify datum shifts or other problems with the data; only those mentioned below were considered serious enough to affect the analyses.

The tidal analyses can work satisfactorily with time series that contain gaps. However, the work with non-tidal residuals discussed below, including spectral analysis, requires continuous records. Therefore, given that the residual records were similar at each station (see below), any gaps in them were filled using the average of the residual values at that time in all other available records. We realise the dangers of such gap-filling, but it was considered to be a reasonable approach when gaps are small.

In 2021, five of the 9 available residual time series had less than 3% gaps. Stations 1, 2, 4 and 5 had 5, 16, 25 and 10% gaps respectively. The gaps in the Millport record (station 4) were particularly frequent, but the record was considered to be just about acceptable for inclusion in the following analysis. Another reason to keep it was that Millport is located in the centre of our area of interest, on Great Cumbrae island in the Firth of Clyde. In 2019, Millport's record had 42% gaps, which is why it was decided to use 2019 data only as confirmation of 2021 findings. Otherwise, the first 21 days in 2021 of Rothesay Dock (station 8) residuals were replaced by those of adjacent Renfrew, to correct for an obvious datum shift, while Rothesay (station 5) appeared to have datum shifts that could not be easily corrected and so has not always been used below.

3. Results

3.1 The astronomical tide

The ocean tide results from the gravitational forces exerted by the Moon, and to a lesser extent by the Sun. If one imagines a simplified situation in which the Moon were to have a circular orbit in the Equatorial plane, and the Earth was a perfect sphere with an ocean of uniform depth and with no land, and there were to be no dissipative processes in that ocean, then one would have a tide with two high and low waters in each lunar day of 24 hours and 50 minutes. (The lunar day is longer than the solar day as the Moon revolves around the Earth in the same direction as the Earth rotates and the extra 50 minutes is the time taken for a point on the Earth to reoccupy its same position relative to the Moon). Therefore, each tidal cycle would be perfectly sinusoidal with a period of 12 hours 25 minutes. Tidal scientists denote this cycle as M2 ('M' for Moon and '2' for approximately 2 cycles per day). However, the Moon's real orbit is ellipsoidal rather than circular, and is at a varying angle to the Equator, and in the real ocean there is tidal friction and other physical processes. As a result, there are many cycles other than M2 to be considered when accounting for the overall tide. Similar arguments apply to the components of the tide due to the Sun's gravity (i.e. there are components called S2 etc.) Cartwright and Tayler (1971) have explained how what is known as the 'tidal potential' (the gravitational forcings of the Moon and Sun which generate the tide) can be parameterised as a sum of such harmonic terms. They showed that the tidal potential contains many hundreds of such additional components, each with its unique frequency. However, the set of 63, as used in the present analysis (section 2), is known to be a reasonable, practical one for parameterising the tide in semi-diurnal regimes such as around the UK and indeed for most parts of the world coastline. (The full list of 63 components can be found in the Appendix of Woodworth, 2017).

In the real ocean, the relative proportion and the phase of each component at a particular location will not be the same as in the tidal potential, and need to be determined by tidal analysis fitting as described in section 2. M2, with a period of half a lunar day (or a frequency of 0.0805 cycles per hour, cph), is again the main tidal component in the Clyde. However, other components are of particular interest. For example, M4 and M6 are harmonics of M2, with frequencies twice and three times that of M2 respectively. These harmonics do occur in the tidal potential, and so are a partial consequence of forcing by the Moon's gravity. However, their amplitudes near to the coast, and especially up rivers, are much larger than one would expect from the tidal potential alone, and are primarily a consequence of shallow water processes (see below and Pugh and Woodworth, 2014 or Gerkema, 2019). When the M4 amplitude is larger than 1/4 of the M2 amplitude, or the M6 amplitude is larger than 1/9 of the M2 amplitude, as is the case for the latter for the upper part of the river Clyde, then the tidal curve becomes significantly non-sinusoidal. This manifests itself in the case of Glasgow (for example) as a double maximum on the rising part of the curve (Pugh and Woodworth, 2014 and see also Crowther and Chen, 2001 who attempted to model this feature in the Clyde).

Table 2 lists the amplitudes and phase lags for M2 obtained from the 2019 and 2021 Clyde data, together with the amplitudes for M4 and M6. Figure 2(a) shows the same information but with the M4 and M6 amplitudes given as a proportion of those of M2. Table 2 also includes the amplitudes and phase lags for M2 in the Admiralty Tide Tables (1995); it is not known from which years of data the ATT values were derived. The 2019, 2021 and ATT values are slightly different. However, such 'tidal constants' are never found to be truly constant from year to year, again due to tide-surge interaction and other processes that are different in different years (Doodson and Warburg, 1941; Pugh and Woodworth, 2014).

Leaving aside Portpatrick (station 1), which is at the seaward boundary of our area of interest (Figure 1), the M2 amplitude can be seen to increase as one enters the Clyde Sea and the Firth of Clyde from 105 cm at Girvan (station 2) to 119 cm at Greenock (station 7). Meanwhile, its phase lag varies by only a few degrees throughout the whole area (Figure 2b). These values are consistent with the numerical tidal model of Sabatino (2017), see Figure 3. They are known to be a consequence of a semi-diurnal amphidromic system centred to the north-west near to the Isle of Mull (Figure 3, and see also Figure 5 of Davies et al., 2004). More locally within the Clyde, however, one might also characterise the M2 tide as a standing wave with amplitude increasing towards the head of the Firth due to conservation of energy within the narrowing and shallowing inlet. This is partly a consequence of what is called Green's Law (Pugh and Woodworth, 2014).

Figure 2 (a) shows that, as one enters the river (stations 8-10), the amplitude of M2 increases by ~20% and the phase lag increases by ~12°. Amplitudes and phase lags of M2 are essentially the same for all three river stations (Figure 2b). At the same time, the magnitude of M6 increases in proportion to M2, rather than M4. The relative importance of M6 rather than M4 has been known for many years, both from inspection of tide gauge charts and physical modelling (Thom, 1948). Thom (1948) suggested that the natural period of oscillation of the Clyde was about one-third that of M2. However, quadratic frictional energy losses and dissipation near the river mouth could explain things just as well. Energy is lost from M2 by the product of quadratic friction and velocity, hence velocity-cubed. The fact that M2 amplitude is almost the same at all three river stations further suggests that any dissipation occurs near to the river mouth.

3.2 Non-tidal residuals

Figure 4 shows that the 15-minute non-tidal residuals for all stations are similar, whether stations are in the outer part of the Clyde or in the river. They are larger as one progresses from ocean to river, with standard deviation of 17.9 cm at Portpatrick increasing to 23.8 cm at Glasgow. The large negative spike at 26-27 November was due to the storm surge of Storm Arwen which resulted in large negative residuals along the entire west coast of Great Britain.

The similarity of the residuals can be investigated in other ways. Figure 5 (a) shows the magnitude-squared coherence of residuals at Millport and Greenock in the outer part of the Clyde, indicating high coherence at low frequencies from 0.0 cph to approximately 0.3 cph, and low coherence at higher frequencies. (The negative spikes in coherence at M2 frequency appear to be due to imperfect separation of total sea level into 'tide' and 'residual'). Figure 5 (b) shows that within this low-frequency band the phase difference between stations is close to zero, while the transfer function magnitude is almost 1.0 at zero frequency and increases to approximately 1.2 at 0.3 cph (Figure 5c). (These figures were made using the Matlab (Version 9.11, R2021b) functions pwelch, mscohere and tfestimate.) Choosing any pair of stations in the outer Clyde results in similar figures.

One can also perform a Principal Components Analysis (PCA) of residuals of stations 1-4 in the outer Clyde (Portpatrick, Girvan, Tarbert and Millport) using the Matlab function pca. Analyses have been made using either the original 15-min residuals, or hourly ones which we choose to show in Table 3, or low-pass filtered with a 12-hour filter as used in the following section. Findings for all choices are essentially the same. Table 3 (a) shows that 96% of the overall variance can be explained by the first component, demonstrating coherence in the residual time series. Table 3 (b) gives the principal component coefficients (or loadings) for each component (column) and station (row). Values in the first column are all around 0.5 as expected for 4 stations in the analysis (4 times 0.5-squared summing to 1.0), while there is an anomalous entry for station 4 (Millport) in component 2, which is probably an artefact of the gaps in, and the quality of, its record. As explained above, Millport was included in this study, in spite of its gaps, because of its importance in the national network. If one takes the first 3 stations only, omitting Millport, then the 96% described by the first component increases to 97.5%.

Therefore, the definite conclusion is that the variability in the residual records is so similar at each station that any gaps in one can safely be used to fill gaps in others. Such a procedure for a data analyst would involve computing the tide in the gap, making use of data from the part of that record which does have useful data, to which an inferred residual could be added from another station.

Turning now to consideration of the river, Figure 6 (a) shows the magnitude-squared coherence of the residuals at Greenock, which is the nearest station to the river in the outer Clyde, and Glasgow at almost the upstream limit of the river. This indicates once again high coherence at low frequencies from 0.0 cph to approximately 0.3 cph, and low coherence at higher frequencies. The phase difference in Figure 6(b) increases with frequency, as might be expected from the time taken for any wave (tidal or non-tidal) to travel from Greenock and up the river to Glasgow. Such an argument implies a linear relationship between frequency and phase difference, while that of Figure 6(b) suggests phase difference increasing faster with frequency. This is almost certainly an artefact of non-linear river dynamics. Figure 6(b) indicates that there is a phase difference in the non-tidal residuals around M2 frequency (about 0.1 cph), similar to that in the astronomical tide (i.e. the approximately 11° difference in Table 2a), while the absolute transfer function (Figure 6c) is approximately unity. Therefore, the tide and the non-tide function as similar sorts of waves around this frequency.

A progressive wave would take a time L/sqrt(gh) to travel a distance L in water with depth h, g being acceleration due to gravity. Therefore, assuming h = 10 m on average, a wave would take 58 minutes to travel the 35 km between Greenock and Glasgow, corresponding to a phase difference of 35° at 0.1 cph, rather than the ~11° observed for both tide and non-tide. This suggests that, rather than a progressive wave, the estuary and the river can be better considered as being parts of the same standing wave system of the Clyde as a whole.[1]

In spite of the phase difference differing from zero as frequency increases, the river station records can be taken as useful ones for sea level research after filtering (e.g. for studies of changes in mean sea level or even storm surges). Table 4 (a) shows the results of a PCA using all 8 available stations in 2021 (i.e. the 10 of Table 1 less Gourock and Rothesay, see above), once again using hourly values. 93% of the overall variance is described by the first component, while the loadings for the first component (Table 4b) are all around 0.35 as expected for a PCA with 8 stations. Therefore, the 3 river stations can be considered as coherent with the others at low frequencies for practical purposes. Any differences become apparent in the second component (column) where the values for the 3 river stations are larger than, and have opposite sign to, the others.

3.3 River oscillations

Figure 7 (a,b) shows magnitude-squared coherence and phase difference between Rothesay Dock, roughly half way between Glasgow and the end of the narrow part of the river, and Glasgow itself. The latter station is located near to the Millennium Bridge, only 3 km from the upstream tidal limit, at the weir at Glasgow Green. The modern version of this weir dates from 1949 (Secret Scotland, 2023). Figure 7(a) shows high coherence between 0.0 and 0.3 cph, as observed between other pairs of stations. There is near-zero phase difference between them in this low-frequency band. However, there is also a wide band of moderately high coherence between 0.7-1.8 cph, centred on 1.3 cph. The time series in this band are only a few centimetres in magnitude, having a standard deviation over the whole year of 0.60 and 0.83 cm on average at Rothesay Dock and Glasgow respectively (see below). They have opposite phase (Figure 7c), and a correlation coefficient between them of -0.494, demonstrating a see-saw. (Figures 7 (b) and (c) are the same but with the latter's y-axis centred at 180°.) The absolute transfer function in Figure 7(d) has a value of about 0.8 at 1.3 cph, suggesting Glasgow has a slightly smaller amplitude than Rothesay Dock, the opposite way round as indicated by the standard deviations; that is a result of the coherence and correlation not being perfectly 1.0 and -1.0 respectively.

The central frequency is consistent with the Merion Formula period T = 2L/sqrt(gh) for an oscillation with an anti-node at the weir boundary and another nearer to the river mouth, taking a length of river (L) and depth (h) (Pugh and Woodworth, 2014). Allen (1966) states that the river has at least 28 feet depth at Low Water Spring Tides nearly all the way up to Glasgow. Therefore, taking h = 10 m for

[1] The Clyde bathymetry contains a deep area (~68 m depth) called 'The Hole' approximately 1.5 km offshore of Greenock (at which gauge 7 is located), landward of which is an anchorage called the 'Tail of the Bank'. Upstream of these features are shallow sandbanks which mark the transition between the river and the Outer Firth. Otherwise, the channel from Greenock to Glasgow throughout the estuary and river can be estimated as having a depth of ~10 m (Allen, 1966; Bekic et al., 2006; EMODnet, 2023).

simplicity as above, and T = 47 minutes, one concludes that the oscillation occurs over a length (L) of 14 km. This is roughly the distance between Rothesay Dock and Glasgow tide gauges, suggesting that this approach is on the right lines, with the two stations on opposite sides of the node. Unfortunately, the wide 0.7-1.8 cph frequency range does not lend itself to testing whether the frequency varies with the tide, as was possible for narrower-band resonances (Woodworth et al., 2005; Pugh et al., 2020).

Figure 8(a) shows standard deviations of band-pass filtered sea level for each day for Rothesay Dock (red) and Glasgow (black). (In calculating these standard deviations, anomalous spikes in the band-pass filtered residuals larger than 5 cm were excluded.) As mentioned above, the band-pass filtered residuals are only centimetric, but the various times when their variability is larger or smaller can be seen to be similar in each record. Variability is greater in winter months, but there is a suggestion of association with times of spring tides in the quieter summer months, as indicated by the red circles.

There are some clues as to what causes the variability in winter. Figure 8(b) shows river flow measured at Blairston located about 20 km, as the river flows, above the weir. Such river data are available from the National River Flow Archive (NRFA, https://nrfa.ceh.ac.uk). The y-axis of this plot is shown with a logarithmic scale as conventional in hydrology. The various peaks can be seen to largely coincide with those in Figure 8(a). In addition, Figure 8(c) shows daily mean sea level at the three stations in the river. The three records are almost identical and, as discussed above, are essentially the same as records from the outer Clyde. Their peaks coincide, approximately at least, with those in Figures 8 (a) and (b). Altogether this suggests that the high-frequency see-saw coincides with times of higher river flow and higher sea level (or surge), suggesting that the see-saw happens during times of meteorological activity. However, inspection of local winds and air pressures from Bishopton near Glasgow, processed by the UK Met Office, and available via the Centre for Environmental Data Analysis (https://www.ceda.ac.uk/), failed to show a stronger relationship with the peaks.

When something such as this is identified in a tide gauge record, then consideration must be given to whether it is an instrumental artefact. However, that is unlikely in this case. For example, a common problem with tide gauges is error in the timing of their data. But a timing error in one or both gauge records would not produce the constant 180° phase difference in Figure 7(c); a phase difference that varied linearly with frequency would result.

One way to validate the Rothesay Dock information is by comparison to data from the Renfrew tide gauge located on the opposite (south) bank of the river and 1.4 km further upstream. Table 1 shows that the two gauges employ different technologies and are operated by different agencies; both of these aspects add value to an independent validation. Their residual records show high coherence, similar to Figure 7(a). Their phase difference shows a linear dependence on frequency across all frequencies (Supplementary Figure 1), suggestive of a systematic timing difference of about 3.3 minutes. This difference can be accounted for by either an error in the clock of one of the gauge data loggers and/or in the way the 15-min SEPA averages were computed. If one allows for such a linear affect, then the phase difference at 1.3 cph would be consistent with zero, validating the Rothesay Dock data.

Similar subtidal oscillations to those reported in the Thames by Thompson (1982) do not occur in the Clyde. Supplementary Figure 2 (a) shows time series for Greenock, Rothesay Dock and Glasgow, low-pass filtered to a similar extent as those of Thompson (1982). The three time series are essentially the same, with differences between them of only ~2 cm (Supplementary Figure 2b). Of course, the Clyde is a shorter river than the Thames, so any wind forcing has a shorter distance over which to act. In addition, the absence of any difference between the time series suggests that any large-scale forcing affecting levels in the Firth is not able to generate subtidal oscillations in the river.

3.4 Seiches

As mentioned above, an initial motivation for this investigation was to search for evidence of seiches in the Clyde, given that we know seiches are present in Shetland and probably in most inlets along the Scottish coast (Pugh et al., 2020). The usual way to identify seiches is by observing peaks in power spectra of the sea level records. At first sight, the dimensions of the Clyde seemed favourable for seiches. Therefore, it was somewhat surprising that no convincing peaks could be identified in the 10 records, at least with the 15-min sampling we have used in this paper. The spectra of the three 1-minute records of Peel Ports were also inspected without obvious peaks being found. Of course, the 10 gauges might not be in optimum positions and the 15-min sampling is not ideal. Higher-frequency (1-min) data from other locations in the Clyde would be interesting. The river oscillations, if we have interpreted them correctly, would be a type of seiche so perhaps our original aim was partially successful.

4. Conclusions

This paper has been concerned primarily with the astronomical tides and the non-tidal variability observed in the sea level records at the 10 Clyde stations during 2019 and 2021. The tidal constituents determined in these years are consistent with those calculated previously and with the model of Sabatino (2017). However, one notes that the river tides have changed considerably over the years, and so those presented here will be a sort of snapshot. Undoubtedly, the Clyde tides will change again as the area adapts to rising sea levels and climate change (Trewhella et al., 2022).

The non-tidal variability shown by the residuals in Figure 4 indicate modest storm surges during 2021 (e.g. a maximum of 148.5 cm at Glasgow on 23 February) and an unusual negative surge (-130.7 cm at Glasgow on 27 November) associated with Storm Arwen. These events have been catalogued in a review of UK storm surges for that year (Dr. Jo Williams, National Oceanography Centre, private communication). The changes in amplitude and phase lag between the outer Clyde and the river for the non-tidal residuals at a frequency of ~0.1 cph is almost the same as for the astronomical tide.

The non-tidal residuals are similar at all stations at low frequencies (less than about 0.3 cph), as demonstrated by cross-spectral and principal component analyses. The similarity means that information from one station can be used to check, or fill gaps, in time series from other stations. This is especially important for the two ‘A Class’ stations which have experienced variable data quality in recent years; the additional information from the two other agencies could prove to be very useful in this regard.

At frequencies higher than ~0.3 cph, there is general low coherence between pairs of stations, with one exception. That concerned the unexpected finding of a see-saw sea level oscillation in the river centred at a frequency of approximately 1.3 cph. The best explanation for this see-saw is an apparent connection with large surges and river flow, both associated with high winds and rainfall. If correct, this would demonstrate that river flow has a role, albeit a small one, in sea level variability in the river. Otherwise, river flow has previously been thought to have only centimetric contribution to surges in the Clyde (Sabatino et al., 2016a).

The only way to confirm the see-saw theory is to have simultaneous data from further down-river, in addition to data from the three stations used here. Suitable locations for new installations might be Bowling Harbour, Dumbarton and Port Glasgow, and preferably all three. Unfortunately, such data are not available at present. Another approach is to digitise tide gauge paper charts and handwritten ledgers from a number of stations in the river, including Bowling Harbour, Rothesay Dock and Glasgow. These charts and ledgers span the late 19th and early 20th centuries and are presently being scanned and converted to usable computer form by SEPA in cooperation with BODC (BODC, 2016). Simultaneous charts would have to be selected from several sites and then digitised with, for example, 10-minute resolution in order to resolve the 47-min (1.3 cph) fluctuations. Greater temporal resolution might not be practical for scanning, and any oscillations of even higher frequency might anyway have been damped by the stilling wells of the float gauges then in operation.

The study of a high-frequency see-saw in the river might appear to be a somewhat esoteric one, and this paper has probably made more of them than the present data justifies. However, they are of potential interest to the dynamics of rivers and estuaries. In addition, even if they are small, such oscillations will contribute to the extreme sea levels which can ultimately result in flooding (e.g. Woodworth et al., 2021). Therefore, understanding such contributions is of some importance.

Acknowledgements

Grant Kennedy (SEPA Hydrometry) and Niall Mason (Peel Ports) are thanked for details about their tide gauges. Steve Turner (NRFA) helped with access to river flow data from the Clyde. Jo Williams (NOC) provided information on major UK storm surges during 2021 and Andy Matthews (NOC) supplied a listing of BODC holdings of historical Clyde data. I am grateful to Alessandro Sabatino and the University of Strathclyde for permission to reproduce Figure 3, and to Jill Singer of SUNY-Buffalo State University who provided information on water level variability in the Buffalo River. Some figures in this paper were generated using the Generic Mapping Tools (Wessel and Smith, 1998).

Disclosure statement

No potential conflict of interest was reported by the author.

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Table 1. Operational tide gauges in the Clyde as of June 2023.

Operator	Stations	Gauge Types and Available Data	Data Source
Environment Agency (EA)	Portpatrick, Millport	Bubbler pressure gauges providing 15-min average sea levels	https://www.bodc.ac.uk
Scottish Environment Protection Agency (SEPA)	Girvan, Tarbert, Rothesay, Renfrew	Radar at Girvan and Tarbert, radar and pressure sensors at Rothesay, and pressure sensor at Renfrew. 15-min average sea levels	https://timeseriesdoc.sepa.org.uk
Peel Ports	Greenock, Rothesay Dock, Glasgow	Radar gauges providing 1-min average sea levels, filtered to 15-min for the present paper	https://peelports.port-log.net/

Table 2. (a) Amplitudes (H, cm) and Greenwich phase lags (G, deg) of M2 obtained from data for 2019 and 2021 at each station. For three of the stations, the amplitudes and phase lags of M2 given in the Admiralty Tide Tables (ATT) are also shown. The ATT claims that there are seasonal variations in M2 amplitude at Greenock and the 116 cm shown here is an average of the ATT's listed seasonal values. (b) Amplitudes (cm) for M4 and M6 from 2019 and 2021 data.

(a)

		2019 Data		2021 Data		ATT Values	
		H	G	H	G	H	G
1	Portpatrick	133.2	332.0	133.9	332.1		
2	Girvan	103.5	341.8	104.6	340.9		
3	Tarbert	111.3	344.2	111.8	345.3		
4	Millport	108.0	342.3	113.4	342.2	112	341
5	Rothesay	116.5	343.9	112.9	339.9		
6	Gourock	118.0	344.2	-	-		
7	Greenock	118.4	343.1	119.1	343.0	116	346
8	Rothesay Dock	135.8	353.6	130.1	353.4		
9	Renfrew	137.5	354.3	139.3	355.5		
10	Glasgow	138.8	354.4	139.9	354.2	140	357

(b)

		M4		M6	
		2019	2021	2019	2021
1	Portpatrick	0.4	0.4	0.5	0.4
2	Girvan	6.0	6.1	0.6	0.5
3	Tarbert	9.4	9.6	2.5	2.6
4	Millport	8.8	9.1	2.3	2.5
5	Rothesay	10.5	9.8	3.1	3.1
6	Gourock	11.6	-	4.0	-
7	Greenock	11.7	11.9	4.1	4.3
8	Rothesay Dock	15.9	15.7	12.4	12.4
9	Renfrew	16.5	17.0	13.5	14.0
10	Glasgow	17.4	17.9	15.3	16.0

Table 3. Results of a Principal Components Analysis of hourly residuals for stations 1-4 in 2021. (a) Percentage variance explained by each component. (b) PCA coefficients (loadings) for each component (column) and station (row).

(a)

1	96.26
2	1.90
3	1.13
4	0.71

(b)

0.5008	-0.4242	-0.5229	-0.5439
0.5009	-0.1702	0.8249	-0.1993
0.5033	-0.2485	-0.1608	0.8118
0.4950	0.8540	-0.1422	-0.0737

Table 4. Results of a Principal Components Analysis of hourly residuals for stations 1-4 and 7-10 in 2021. (a) Percentage variance explained by each component. (b) PCA coefficients (loadings) for each component (column) and station (row).

(a)

1	92.86
2	4.71
3	0.91
4	0.62
5	0.55
6	0.15
7	0.11
8	0.09

(b)

0.3507	-0.3700	-0.3299	-0.4617	-0.5884	-0.2108	0.1087	0.1249
0.3551	-0.2614	-0.1828	-0.3919	0.7864	-0.0033	0.0049	-0.0083
0.3574	-0.2960	-0.2308	0.3904	-0.1170	0.6400	-0.2972	-0.2597
0.3531	-0.1954	0.8929	-0.1497	-0.0913	0.0891	-0.0180	-0.0288
0.3587	-0.2161	-0.0057	0.6719	0.0997	-0.4582	0.2325	0.3150
0.3553	0.3825	-0.0366	0.0109	-0.0401	-0.4815	-0.5241	-0.4668
0.3518	0.4439	-0.0609	-0.0052	-0.0355	0.1757	0.7210	-0.3514
0.3461	0.5281	-0.0453	-0.0826	-0.0226	0.2558	-0.2259	0.6895

Figure Captions

1. The white box in the upper panel shows the Clyde study area in western Scotland. The lower panel shows tide gauge locations in the area: Portpatrick (PP), Girvan (GI), Tarbert (T), Millport (M), Rothesay (RO), Gourock (GO), Greenock (GR), Rothesay Dock (RD), Renfrew (R) and Glasgow (G).

2. (a) Amplitudes of M2 at the 10 stations in the Clyde using data for 2019 and 2021 (black and red large dots respectively), and ratios of the amplitudes of M4 and M6 to those of M2 (black and red small dots and solid and dashed connecting lines respectively). (b) Greenwich phase lags of M2 at the 10 stations. See Table 2 for the actual values.

3. Cotidal chart for the M2 harmonic component in the Clyde Sea from a recent numerical model. Solid lines are amplitudes (cm) and the dashed lines are Greenwich phase lags (deg). Copied from Figure 5.5 of Sabatino (2017) with permission.

4. Time series of residuals at each station in 2021 with each record offset by 100cm for presentational purposes. Gaps in each record have been filled using the average values of other available stations.

5. (a) Magnitude-squared coherence between non-tidal residuals at Millport and Greenock in 2021. (b) Phase difference, negative values mean that Greenock lags Millport. (c) Transfer function magnitude (Greenock/Millport).

6. (a) Magnitude-squared coherence between non-tidal residuals at Greenock and Glasgow in 2021. (b) Phase difference, negative values mean that Glasgow lags Greenock. (c) Transfer function magnitude (Glasgow/Greenock).

7. (a) Magnitude-squared coherence between non-tidal residuals at Rothesay Dock and Glasgow in 2021. (b) Phase difference, negative values mean that Glasgow lags Rothesay Dock. (c) As (b) but y-axis centred on 180°. (d) Transfer function magnitude (Glasgow/Rothesay Dock).

8. (a) Time series of standard deviation of high-frequency variability between 0.7-1.8 cph each day at Rothesay Dock (red) and Glasgow (black) in 2021. Red circles indicate times of summertime spring tides. (b) Daily river flow at Blairston on the River Clyde located about 20 km above the weir at Glasgow Green. (c) Daily mean sea level in 2021 at the three river stations: Rothesay Dock (blue), Renfrew (red) and Glasgow (black). The average sea level during the year has been subtracted from each record.

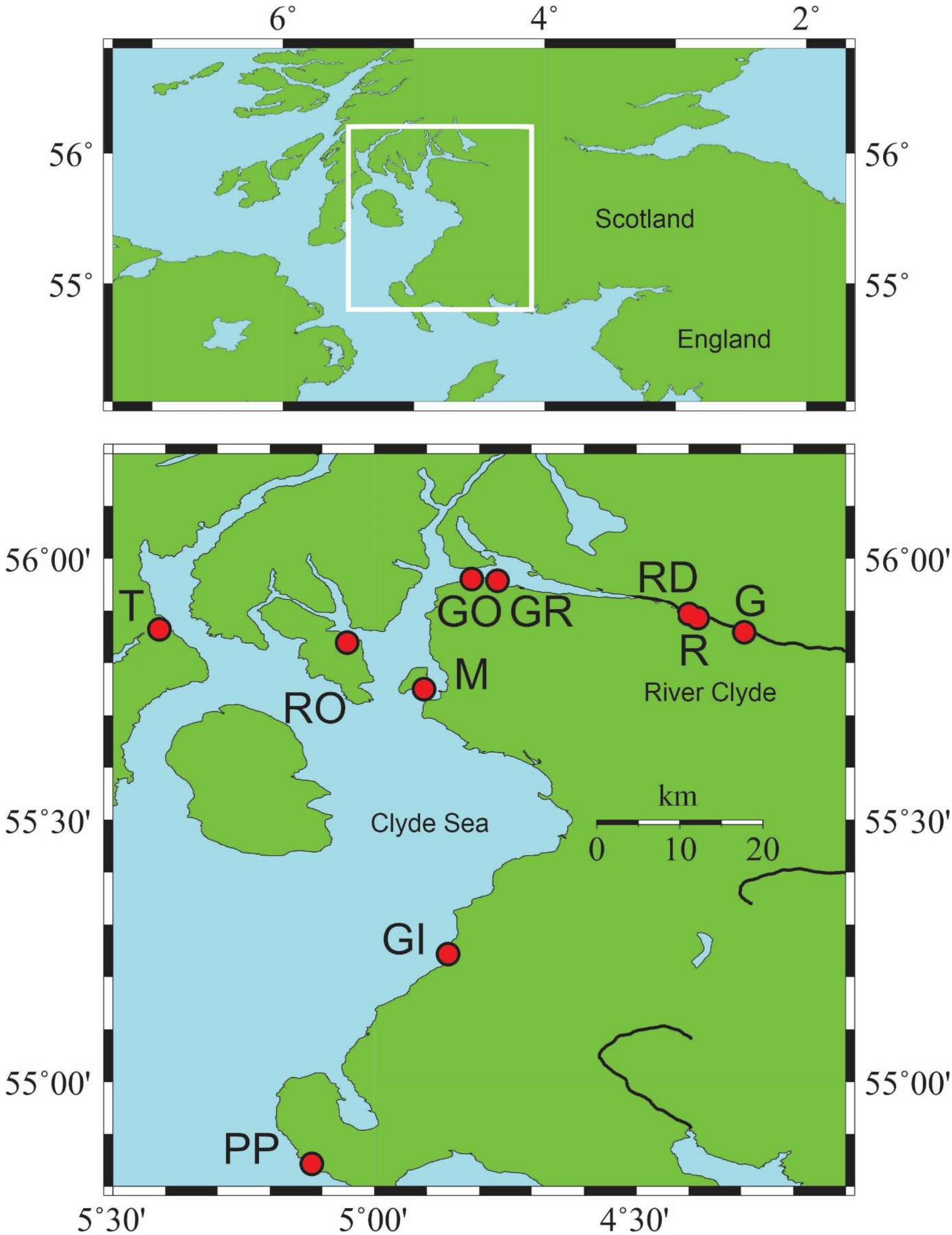

6°
4°
2°
56°
55°
Scotland
England
56°00'
55°30'
55°00'
5°30'
5°00'
4°30'
T
RO
M
GO
GR
RD
G
R
River Clyde
Clyde Sea
km
0
10
20
GI
PP

Figure 1

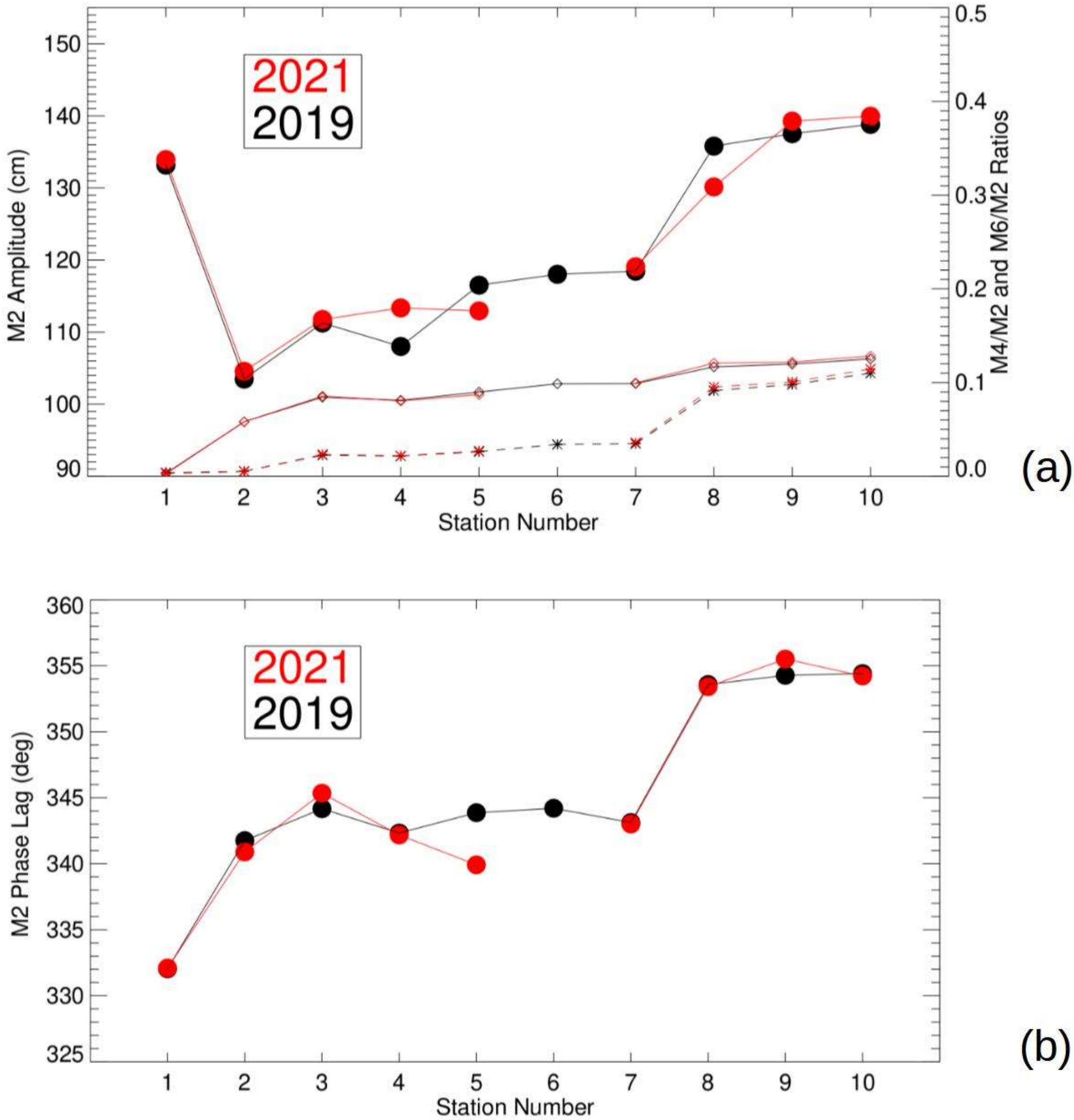

2021
2019
M2 Amplitude (cm)
M4/M2 and M6/M2 Ratios
Station Number
(a)
2021
2019
M2 Phase Lag (deg)
Station Number
(b)

Figure 2

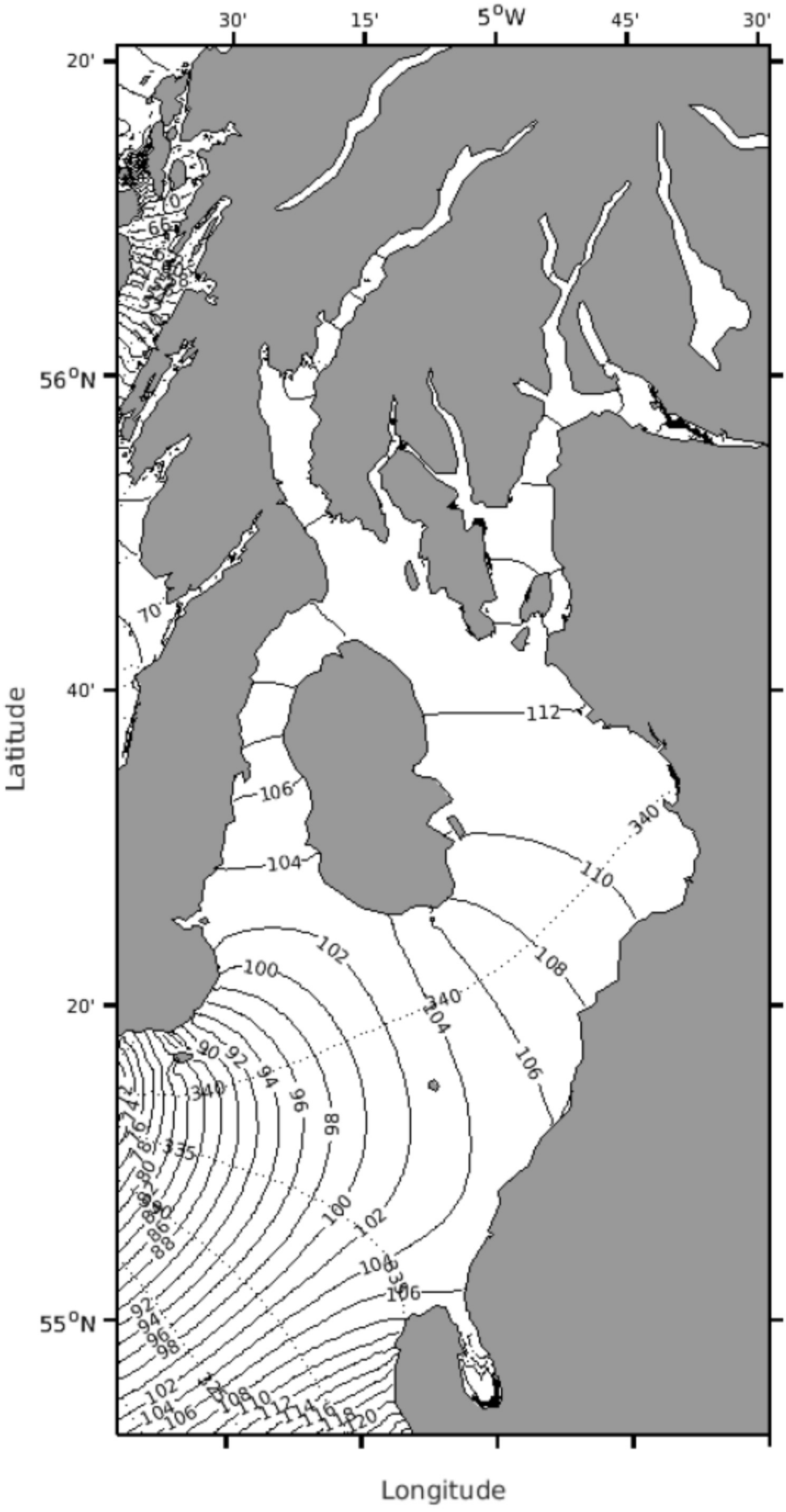
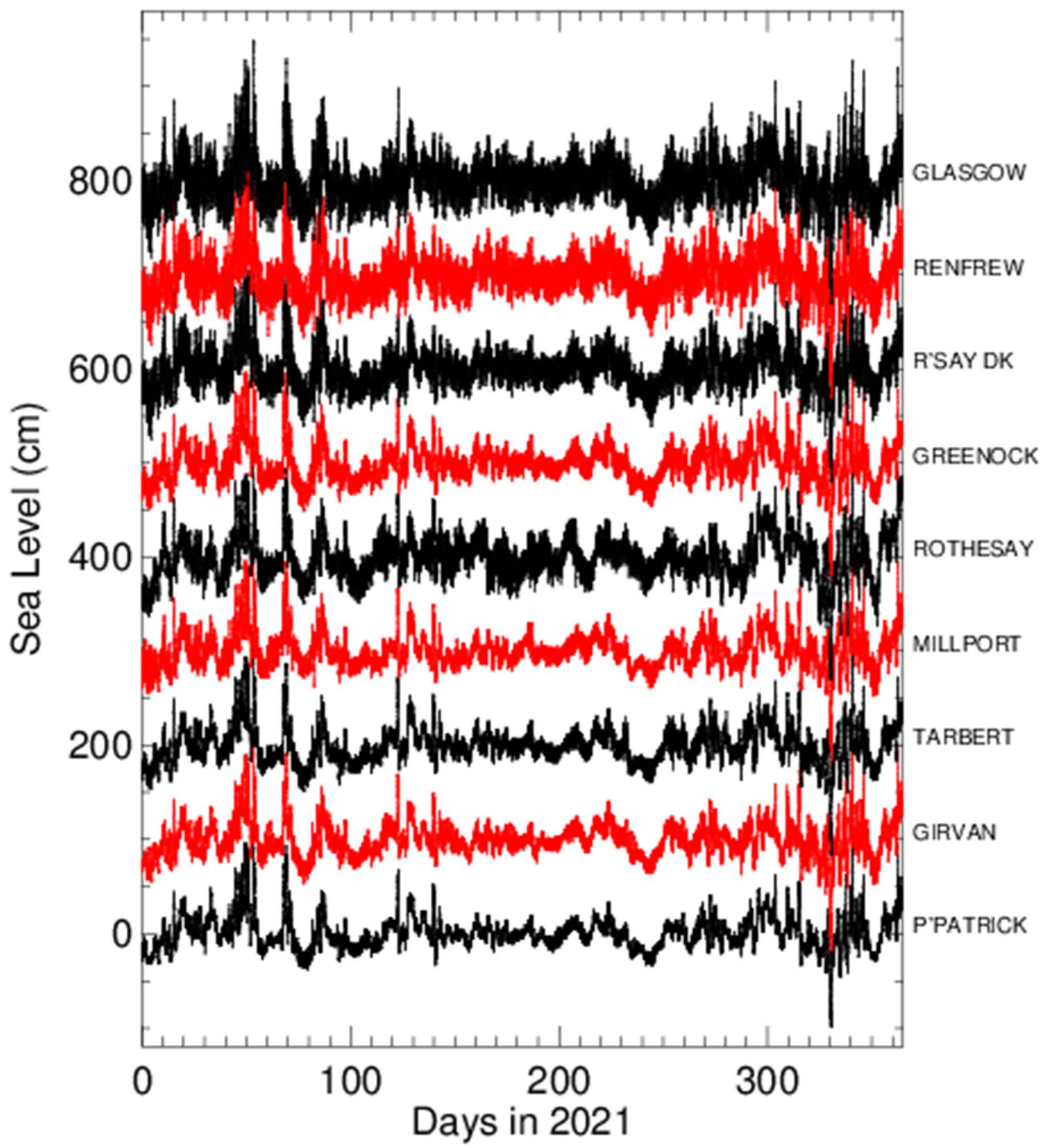

30'
15'
5°W
45'
30'
20'
56°N
40'
20'
55°N
Latitude
Longitude
112
106
104
340
110
108
102
100
104
106
90
92
94
96
98
335
100
102
106
70

Figure 3



Sea Level (cm)
800
600
400
200
0
0
100
200
300
Days in 2021
GLASGOW
RENFREW
R'SAY DK
GREENOCK
ROTHESAY
MILLPORT
TARBERT
GIRVAN
P'PATRICK

Figure 4

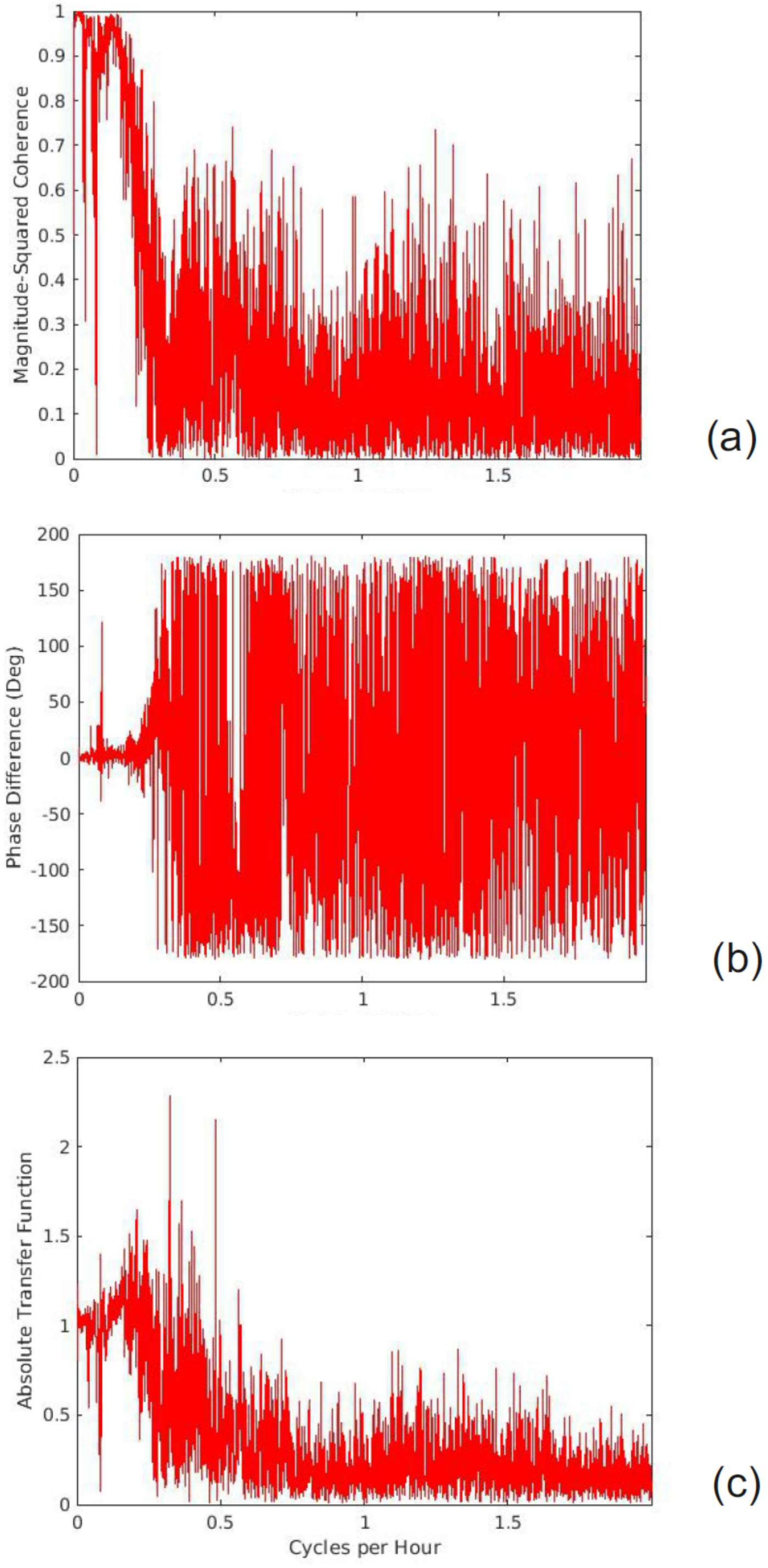

Magnitude-Squared Coherence
(a)
Phase Difference (Deg)
(b)
Absolute Transfer Function
(c)
Cycles per Hour

Figure 5

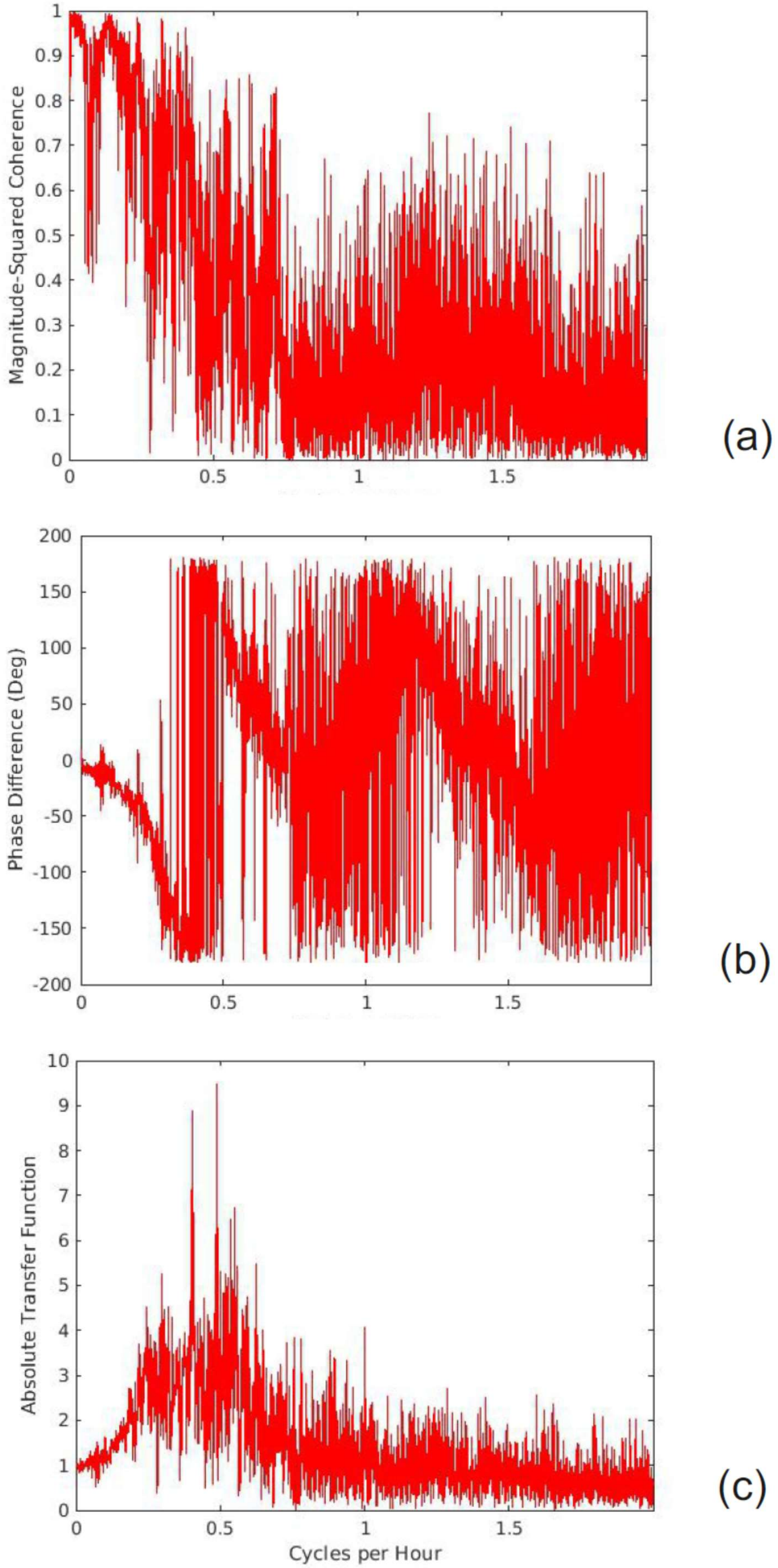
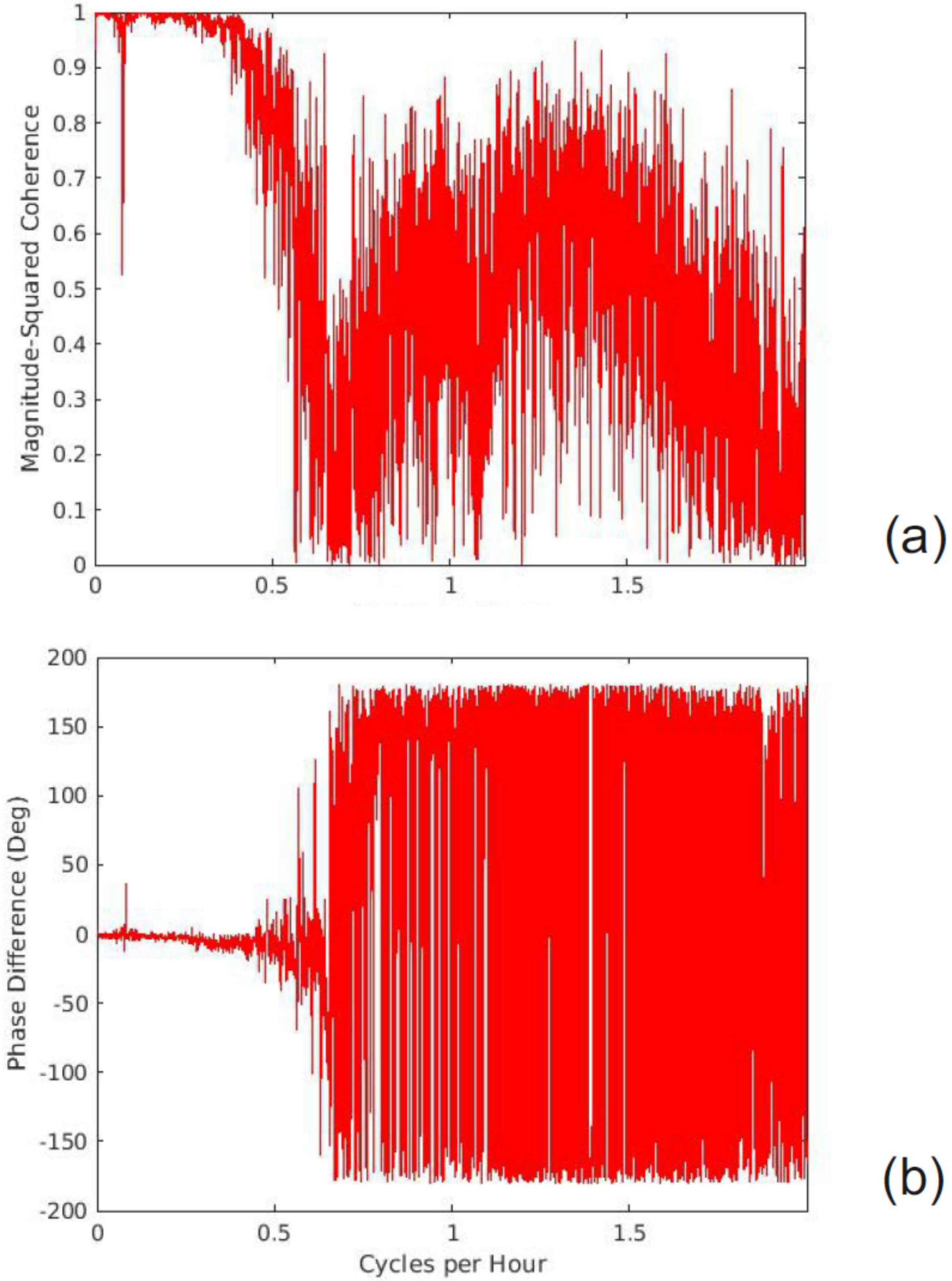
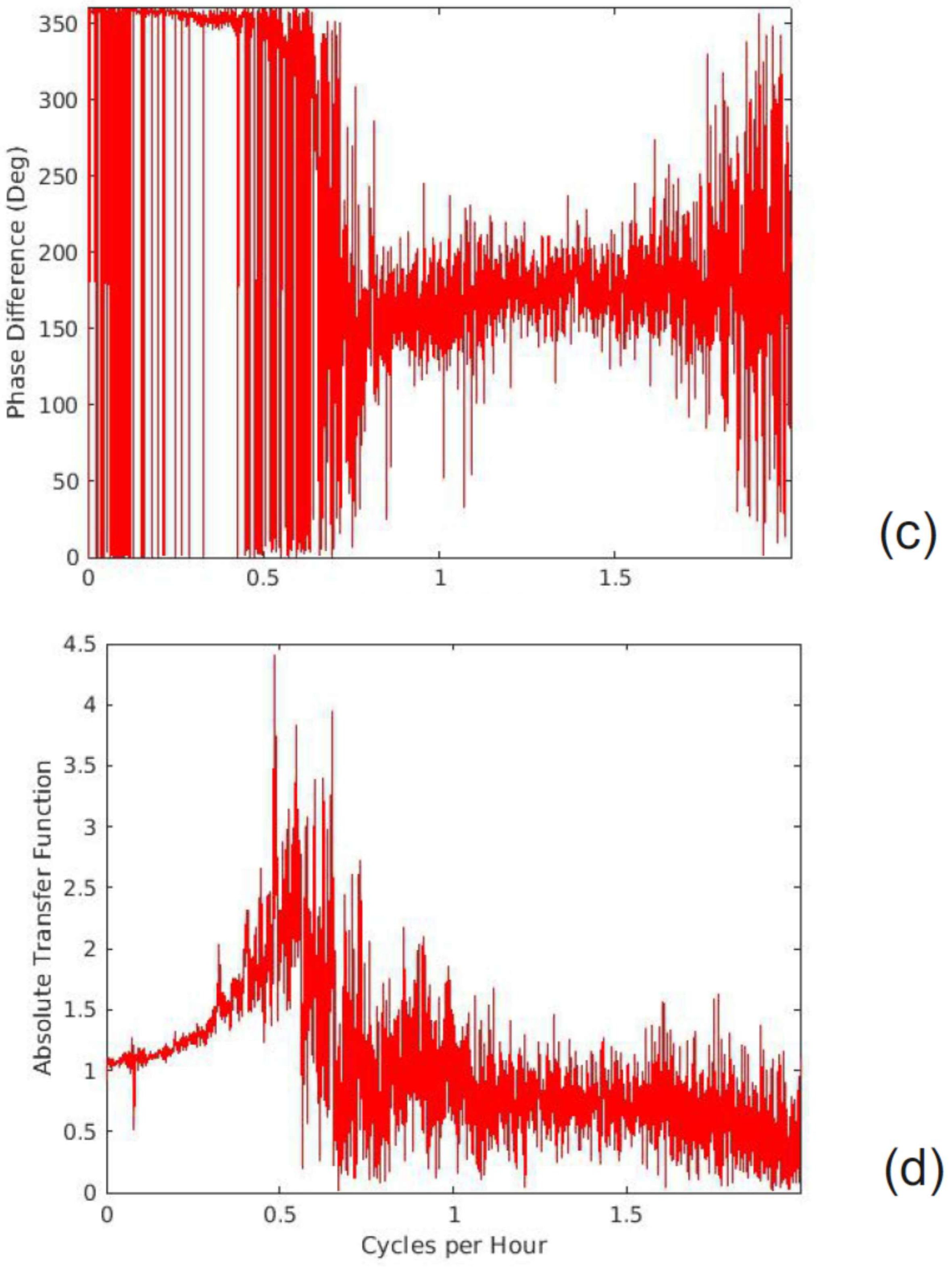

Magnitude-Squared Coherence
(a)
Phase Difference (Deg)
(b)
Absolute Transfer Function
(c)
Cycles per Hour

Figure 6

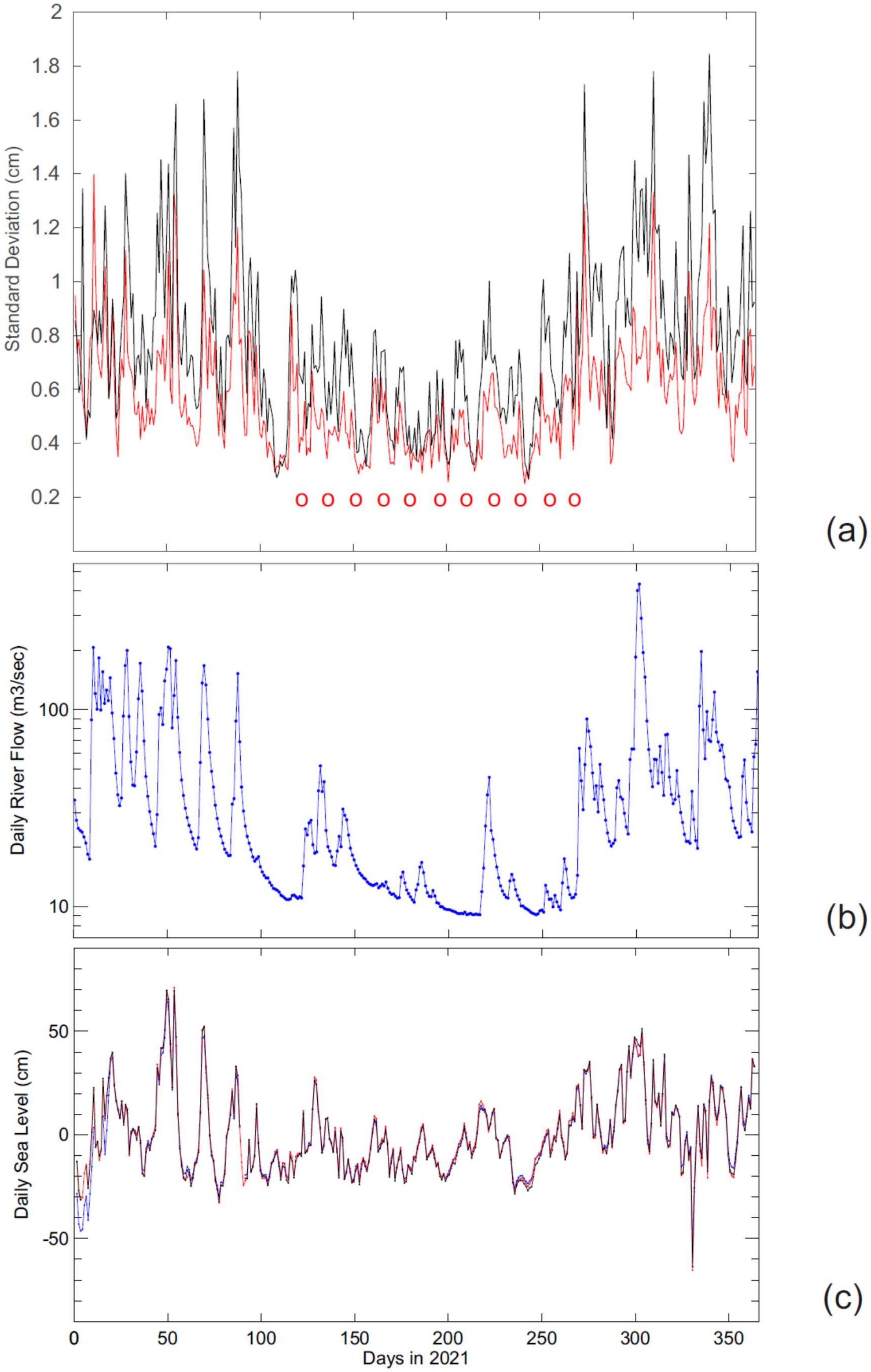


Magnitude-Squared Coherence
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.5
1
1.5
(a)
Phase Difference (Deg)
200
150
100
50
0
-50
-100
-150
-200
0
0.5
1
1.5
Cycles per Hour
(b)



Phase Difference (Deg)
350
300
250
200
150
100
50
0
0
0.5
1
1.5
(c)
Absolute Transfer Function
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0
0.5
1
1.5
Cycles per Hour
(d)

Figure 7



Standard Deviation (cm)
(a)
Daily River Flow (m3/sec)
(b)
Daily Sea Level (cm)
(c)
Days in 2021

Figure8