PRELIMINARY ANALYSIS OF AIR AND SEA TEMPERATURES AT MILLPORT FIELD CENTRE, GREAT CUMBRAE, SCOTLAND

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A monthly record of mean sea surface temperature at Millport, Great Cumbrae, Firth of Clyde, derived from daily records of sea water temperature taken from the Field Centre's Keppel pier, is available for the following years: 1909-1914; 1916-1926; 1949 to present. This record is compared to meteorological data from the local region, most notably those from the Field Centre itself (from 1st January 1951), and with climate drivers such as the North Atlantic Oscillation. The ameliorating effect of the sea is clearly evident at Millport compared to the mainland. Just like the land surface temperature record, the long-term record of sea surface temperature at Millport shows a general warming trend, but with greater differences between warmer and cooler years compared to the air temperature record: temperatures match closely in the cooler years but sea surface temperatures are noticeably higher in the warm years.

INTRODUCTION

The temperature regime is one of the most distinctive features of the climate of the British Isles (Manley, 1952; Tout, 1976; Kington, 2010). Given the relatively northern location, winters are mild but summers never hot or humid. Locations on the north-west coast (and more widely along the west coast) experience 'oceanic' air temperatures that parallel the temperature of the surrounding ocean, whereas away from the coast and especially towards south-east England, the temperature range is larger, more akin to conditions found on the continental mainland. We may start with the premise therefore that the thermal climate at Millport will demonstrate oceanicity, conditions in the north-east Atlantic Ocean providing the dominant climatic driver.

Given increasing concern about climate change, it is critical to provide information on current and future climate dynamics over large spatial domains (Hannah *et al*., 2011). In particular, it is important to conduct research that seeks to elucidate patterns and drivers of widespread climatic response and to identify those regions and time periods most susceptible to climate change and anthropogenic influence. Important themes to emerge recently in the study of large-scale climatology include quantification of large-scale variations (in both time and space) and the need for better understanding of large-scale climate-hydrology interactions (Cloke and Hannah, 2011). In both these cases, the quality of data being used to underpin analysis is paramount, but a combination of short records, poor data quality, non-stationarity and other methodological constraints is a major obstacle to the attribution of change (Burt *et al*., 2016).

At a global scale, there has been considerable effort recently to relate air temperature to sea surface temperature, perhaps the most important driver of climate change (O'Reilly *et al*., 2016). The deep ocean around the UK is influenced strongly by changes in ocean circulation, which in turn is affected by large-scale atmospheric conditions (Holliday, 2003). The surface layer of the ocean (the top 100 m) is influenced most heavily by the atmosphere and is more variable than the deep ocean temperature. The upper layer of the deep ocean (0-600 m) around the UK is presently becoming warmer (Dye *et al*., 2013). Time series for shallow coastal waters are noisier than those in mid-ocean with large-scale, long-term patterns overlain by higher variability related to locally important processes such as changing positions of fronts, passing of eddies, river flow, the changing inflow of sea water of different origins, and the exchange of heat with the atmosphere (Holliday *et al*., 2008). Surface waters in the north Atlantic were relatively cool from 1900 and 1930, warmer from 1930 to 1960, cooler again between the late 1960s and 1990 and then warm to present. The warming observed in the last three decades has been particularly strong in parts of the north-east Atlantic, the sea surface around the UK and Ireland warming at rates up to six times greater than the global average. Notwithstanding the long-term warming trends, sea temperature change at a given location has not been linear or smooth with some short periods of rapid change over a few years and others of little change. It remains difficult to fully distinguish the natural variations in temperature from those due to anthropogenic influence (Dye *et al*., 2013).

Coastal habitats are vulnerable to a wide range of impacts. Local changes in sea surface temperature can be expected to be a major driver of ecological change. Healthy and biologically diverse seas rely on maintaining the balance between a wide range of biological, chemical and physical factors. Given slow and subtle response of individual organisms and ecosystems to climate change, a major challenge is to collect sufficient data over a long enough period of time to establish meaningful trends (Burt, 1994; MCCIP, 2013). Nearshore waters tend to have better available data, compared to deeper-water situations, but the variety of influences, terrestrial as well as marine, can complicate interpretation. The focus of this paper is the air and sea surface temperature records for Millport Field

Centre. Its situation in the north-west British Isles, on an island in the Firth of Clyde (Latitude 55° 44′ 56′′ N, 4° 54′ 31′′ W, National Grid Reference NS 175544), means that the North Atlantic must inevitably be the main driver of climate change. Nevertheless, hydrological influences from the mainland to the east, the River Clyde in particular, together with the influence of tides and storms in the Firth, mean that the sea temperature time series may prove more variable than records from the deeper ocean. By the same token, marine air temperature records from more remote, oceanic locations may be more straightforward to interpret than those even from coastal locations like Millport.

DATA SOURCES

Daily weather data are available for the Millport Marine Biological Station (now FSC Millport Field Centre) from 1/1/1951. The record from 1/1/1959 to 18/2/2010 was supplied to the field centre by the UK Meteorological Office (UKMO). Data from 1/1/1951 to 31/12/1958 were transcribed from ledgers held at the UKMO Edinburgh office. Some gaps in the record from 1/9/2008 could be infilled from the pocket register (the original data recording book) held at the Centre. From 19/2/2010, data are from the UKMO automatic weather station. Gaps in the record were infilled from Hunterston (located straight across the channel from Millport): 1969-1973, plus occasional gaps. May 1972 plus 11 days in January 1972 were infilled from Prestwick. Note that the daily maximum record at Millport only begins on 1/2/1954; daily maximum temperature (MPmax) data for Millport from 1/1/51 to 31/1/54 were based on Tiree (MPmax = (TIRmax*1.2) – 1.52; r = 0.989; n = 429).

A monthly record of mean sea surface temperature at Millport is held by the field centre for the following years: 1909-1914; 1916-1926; 1949 to present. This monthly record is derived from daily records of sea water temperature taken from the field centre's Keppel pier using the standard "bucket" approach, where a sample of water is drawn from the sea surface using a bucket tied to the end of a rope. There can be potential deficiencies in this technique. A bucket exposed to warm air and sun or to cold air during cold winter conditions prior to sampling may affect the subsequent temperature of the water samples slightly. If the bucket lands on its base in the water, it has to be pulled on its side with the rope and then tends to sip the surface water layer, which may be important during calm conditions in summer when the warm sun heats up the water surface. On the other hand, if the bucket lands more or less upside down, it will take water from deeper, cooler levels as well as the surface. It is not easy to read a thermometer held in the bucket, especially during severe weather conditions at the end of the pier. The thermometer always has to be held at an angle, which means parallax errors are inevitable. These can only be eliminated by the use of a viewing telescope, but this has never been done at Millport and indeed probably never anywhere else. Although these deficiencies in the bucket technique have now been eliminated in recent years by the use of modern, very accurate electronic loggers, bucket data are all we have for the long time series and so are used here with the proviso that some inaccuracies must exist.

Climate drivers employed in the statistical analysis were the North Atlantic Oscillation (NAO) index and the Atlantic Multidecadal Oscillation (AMO) index. The NAO is traditionally defined as the normalized pressure difference between a station on the Azores and one on Iceland; NAO data were obtained from the Climatic Research Unit (http://www.cru.uea.ac.uk/). The AMO is derived from detrended SST data from the North Atlantic and is used to characterise decadal-scale variability (Enfield *et al.*, 2001; O'Reilly *et al.*, 2016). Monthly AMO data are available from the NOAA Earth System Research Laboratory:
http://www.esrl.noaa.gov/psd/data/correlation/amon.sm.long.data

RESULTS

Annual means

Annual means of sea surface temperature (SST) and mean air temperature (MAT) at Millport fluctuate within a narrow range. The mean annual SST temperature at Millport is higher than the mean annual MAT, given that air temperature is driven by ground surface temperature (Table 1); this may be an island microclimate effect. It is surprising that the range is slightly greater for SST (2.6°C) than MAT (2.3°C). The MAT range at Millport is greater than those quoted by Tout (1976) for three contrasting locations across the UK (two of which are relatively close to Millport) for the period 1941-70: Plymouth (2.2 °C), Aldergrove (Belfast airport, 1.8 °C) and Eskdalemuir (Southern Uplands of Scotland, 1.7 °C). For comparison, MAT data from Oxford indicate a more continental climate with a slightly greater range (3.0°C); similar minima reflect the relatively mild, oceanic climate for both regions, even for an inland location like Oxford, given the location of the British Isles on the edge of the Atlantic Ocean.

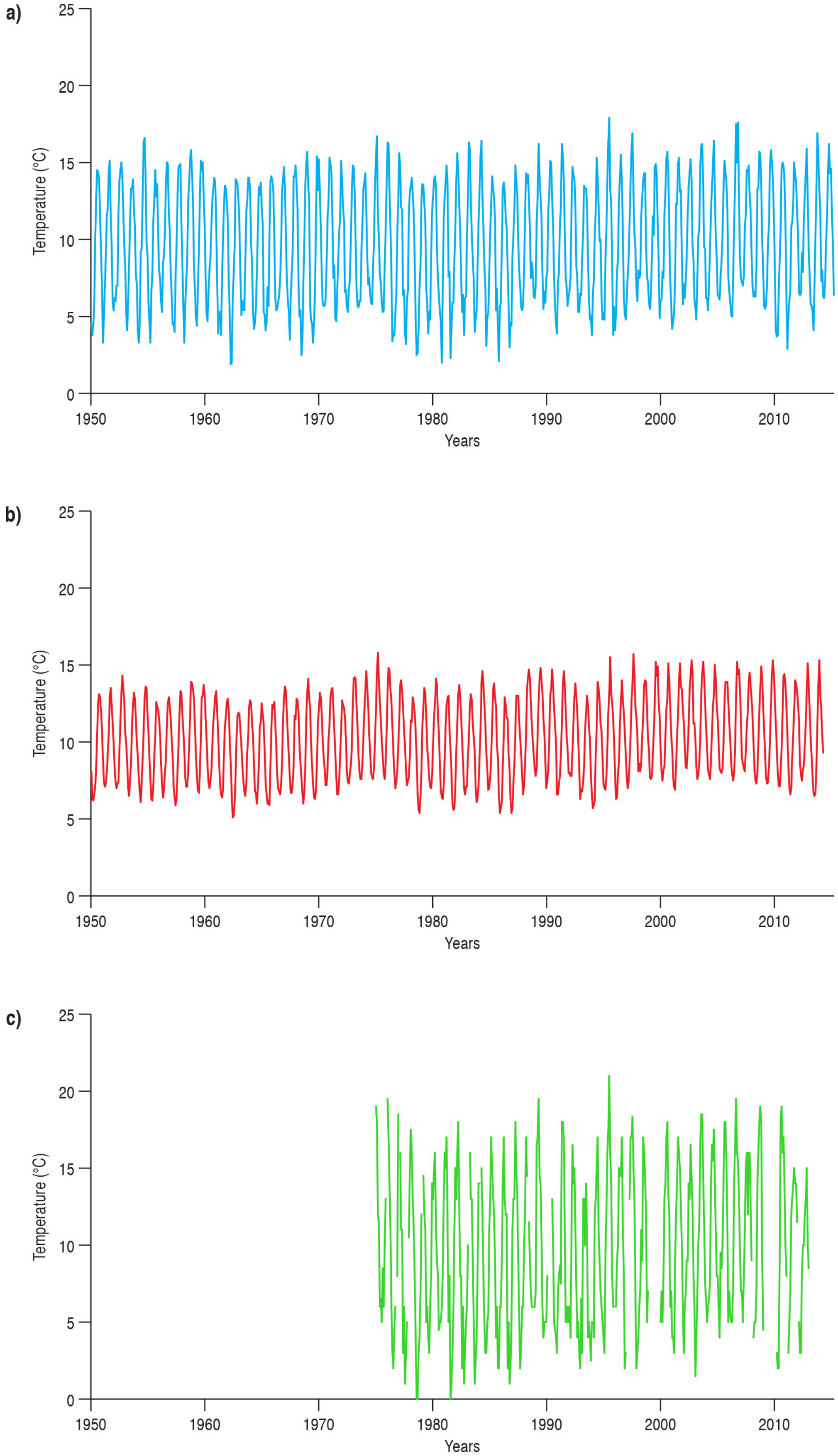

FIGURE 1. Monthly mean temperatures (°C) since 1951: (a) Millport air temperature; (b) sea surface temperature at the Keppel pier, Millport Field Centre; (c) river water temperature for River Clyde at Glasgow Green.

TABLE 1. Mean annual temperature (°C) and the range of mean annual temperature (°C) at Millport and Oxford, 1951 to present. (SST, surface sea temperature; MAT, mean air temperature).

Annual Temperature (°C)	**Location**			
	Millport SST	Millport MAT	Oxford MAT	River Clyde
Maximum	11.4	10.7	11.5	11.2
Mean	10.2	9.6	10.1	9.7
Minimum	8.8	8.4	8.5	7.4
Range	2.6	2.3	3.0	3.8

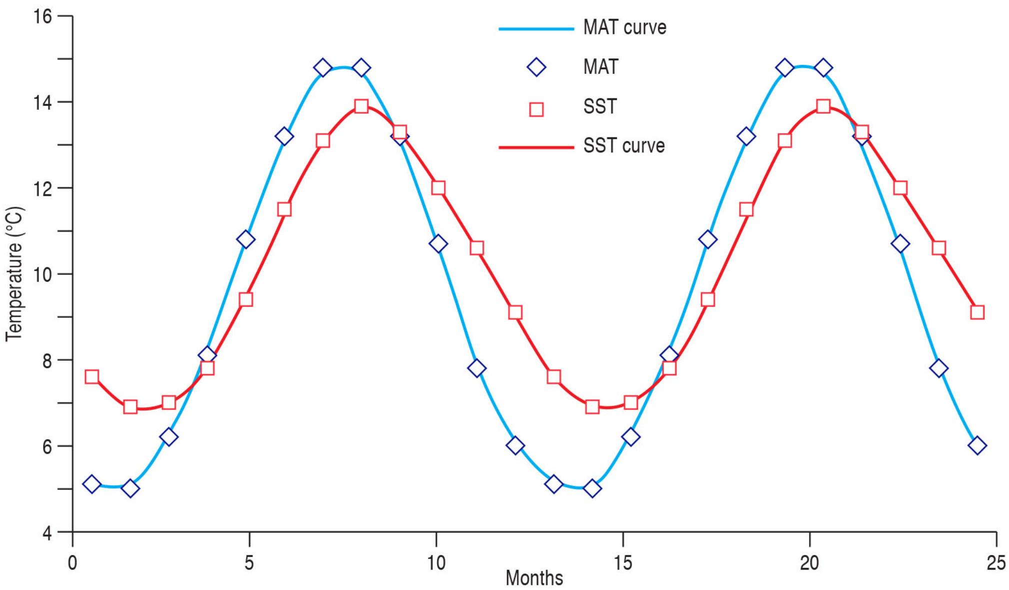

FIGURE 2. Mean monthly temperatures (°C) for MAT and SST at Millport with sine curves fitted.
MAT = 9.8 + 5.0 * sin (π * (MAT_x – 4.5) / 6) where MAT_x are monthly MAT means.
SST = 10.0 + 3.8 * sin (π * (SST_x – 5.2) / 6) where SST_x are monthly SST means.
(MAT, mean air temperature; SST, surface sea temperature).

TABLE 2. Average range of seasonal temperature (°C) in coastal locations in the north and south of the British Isles compared to Millport (Based on Smith, 1976). (SST, surface sea temperature; MAT, mean air temperature). Paisley data updated using UKMO historic data from 1959. http://www.metoffice.gov.uk/public/weather/climate-historic/

Station		**MAT** (°C)			**SST** (°C)	
	February	**July**	**Range**	**February**	**July**	**Range**
St Helier (Jersey)	6.0	17.1	11.1	8.5	15.6	7.1
Millport	5.0	14.8	9.8	6.9	13.1	6.2
Lerwick (Shetland)	3.2	12.0	8.8	7.8	11.5	3.7
Paisley (Glasgow)	4.3	15.5	11.2	-	-	-

Monthly means

Monthly means of SST and MAT at Millport since 1951 are shown on Figures 1a and 1b, respectively. The annual temperature range for the SST record is smaller than for the MAT record. Note that the temperature axis on both graphs is the same, to allow simple comparison. Figure 2 shows the mean monthly pattern of SST and MAT at Millport, repeated so that the full cycle can be easily appreciated. SST warms and cools more slowly than MAT, indicating the influence of the high thermal heat capacity of water in slowing any change of temperature compared to air temperature which is more influenced by the more rapid warming and cooling of the land surface and through the influence of different air masses from the Atlantic. Air masses tend to be more "tropical" in the summer half of the year and more "polar" in the winter, but there is a good deal of within-season variability too. When these monthly patterns are approximated by sinusoidal curves, it is clear that the seasonal MAT follows this pattern closely throughout the year, whereas the SST remains slightly warmer than the modelled curve during the winter period. The phase-difference between these fitted curves suggests SST peaks around 21 days after the peak in MAT; this lag reflects the specific heat of water.

'Thermal modification' is one of the most publicised aspects of coastal climates and there is ample evidence to show that coastal areas experience a more equable temperature regime than equivalent locations inland (Smith, 1976). Smith goes on to conjecture that the effect might increase with latitude due in part to stronger advection associated with higher wind speeds in the north and in part to the influence of comparatively high sea surface temperatures. Table 2 shows that the range of seasonal temperature is lower in Shetland than in Jersey and that this is largely due to the relatively high winter values in Shetland. In turn, this may be related to the warming effect exerted by the winter ocean surface temperatures off Scotland (Smith, 1976). Millport fits neatly in between the other two stations, noting that the Millport data include more recent decades than the other two stations.

By way of comparison with a nearby inland station, Table 2 shows that Paisley has a greater range than Millport, a lower February MAT and a higher July MAT, both reflecting a more inland location away from the ameliorating effect of the sea. The MAT at Paisley is 9.4°C, with a mean maximum of 12.7 °C and a mean minimum of 6.1°C. At Millport the range is narrower: MAT is 9.6 °C with a mean maximum of 12.3 °C and a mean minimum of 6.9 °C. Smith (1976) notes that a substantially higher mean minimum is very often the case for a coastal location compared to inland.

Long-term trends

The long-term record of sea surface temperature around the British Isles shows a general, warming trend. On a decade-to decade basis, however, this overall picture is complicated by short-term natural variability. For example, within the last decade, the average UK coastal sea-surface temperature was actually lower in 2008-2012 than in 2003-2007 (Dye *et al.*, 2013). In general terms, relative to the underlying warming trend during the 20th century, the surface waters averaged over the North Atlantic were warm from 1930 to 1960, cool between the late 1960s and 1990 and then warm to present (Dye *et al.*, 2013). Locally, there has been more variability in SST in the Firth of Clyde. Figure 3 shows the long-term pattern of warming for both SST and MAT at Millport since 1951. SST and MAT match closely in the cooler years but SSTs are noticeably higher in the warm years. Thus, from the cool 1960s, the upward trend for SST is more marked overall. At Millport, it is too simplistic to describe the period 1960 to 1990 as "cool"; there were clearly some much warmer years: 1975-76 and 1989-1990, warm years across the British Isles in general (Burt *et al.*, 2016); but cooler periods too, the late 1970s - early 1980s and the early 1990s. After peaking in the mid 2000s, temperatures have fallen somewhat since then.

Statistically, we need to be cautious about fitting trends to the time series data. There is significant serial autocorrelation in the annual SST record, as shown by the Durbin-Watson statistic (U = 0.957, $p < 0.0001$, n = 65). This reflects a sluggish response of a deep water body to climatic forcing. The Durbin-Watson statistic for the MAT record is not significant (U = 1.68, p = 0.053). The non-parametric Spearman Rank test shows highly significant annual trends forboth SST ($r_s = 0.516$, $p< 0.00005$) and for MAT ($r_s = 0.445$, $p < 0.0005$). All seasons show a significant upward trend for SST and all seasons except spring for MAT. Fitting a linear trend (noting the caveat of serious serial autocorrelation) through both data sets indicates a regression coefficient for SST of 0.021 and 0.014 for MAT, implying that overall it would take 47 years for a 1°C rise in SST and 70 years for a 1°C rise in MAT. The River Clyde too has a significant upward trend in autumn ($r_s = 0.551$, p = 0.009, n = 34) and for the year as a whole ($r_s = 0.631$, $p < 0.01$, n = 18)).

Notwithstanding the shorter-term variability at both inter-annual and inter-decadal timescales, these are notably strong upward trends, indicating substantial change in both the marine and terrestrial environments at Millport since the middle of the last century (and in the fluvial environment since the mid-1970s). Note that there is a highly significant correlation between annual values of MAT and SST at Millport ($r_s = 0.771$, $p < 0.0001$), confirming the close association depicted in Figure 3; all seasons also have highly significant correlations between SST and MAT at Millport.

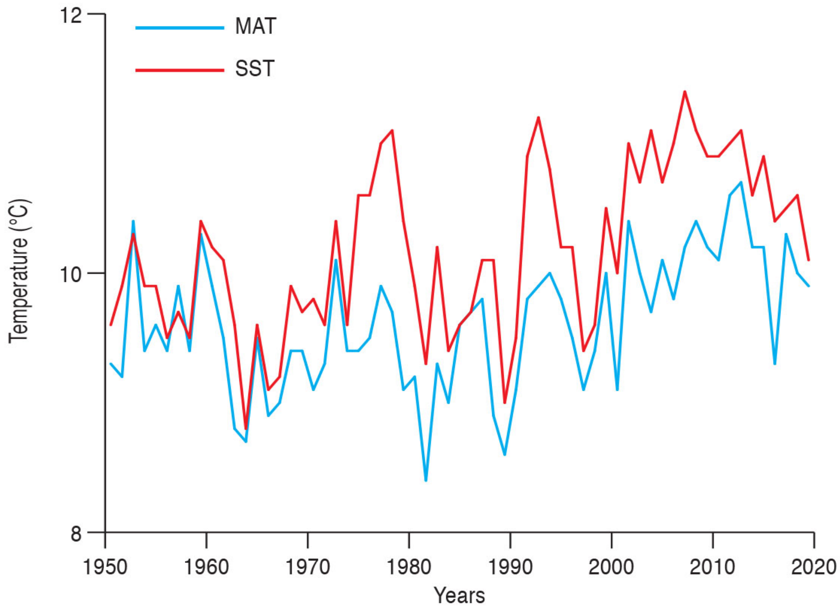

FIGURE 3. Long-term pattern of warming: annual mean temperatures (°C) at Millport for MAT and SST since 1951. (MAT, mean air temperature; SST, surface sea temperature

Drivers of climate

The NAO is often described as the most important driver of climatic variability in the northern hemisphere. It controls the strength of westerly winds between the 'Azores high' and the 'Icelandic low' that bring a succession of weather systems to Western Europe (Rodwell *et al.*, 1999; Burt and Howden, 2013). European climate exhibits a dipolar signal due to changes in the NAO: northern and southern Europe experience opposite effects (Hurrell and Van Loon, 1997; Folland *et al.*, 2011). At Millport, the only significant correlation between seasonal or annual temperature and NAO is for MAT in winter ($r = 0.700$, $p < 0.0001$; Figure 4). There is no significant wintertime correlation between NAO and SST.

The AMO index (defined above) has been used to describe inter-decadal variation in North Atlantic climate. AMO correlates seasonally at Millport with MAT ($r = 0.325$, $p < 0.01$; $r = 0.402$, $p < 0.001$) and SST ($r = 0.434$, $p < 0.0005$; r Fig 4 wasn'= 0.421, $p < 0.001$) for summer and autumn respectively. Taken together, these results suggest that winter weather is driven by the strength of the pressure gradient across the polar front in the North Atlantic whereas summer and autumn temperatures at Millport, for both MAT and SST, reflect more general patterns of inter-decadal SST variability across the North Atlantic. There is as yet no accepted mechanism for explain this quasi-cycle, which seems to have a periodicity of roughly 70 years: whilst ocean temperature will be primarily driven by direct turbulent heat exchange with the atmosphere, ocean currents and atmospheric circulation (bringing different air masses across a region) will also be important, and the nature of these heat exchanges and related feedback mechanisms are not yet fully understood (O'Reilly *et al.*, 2016).

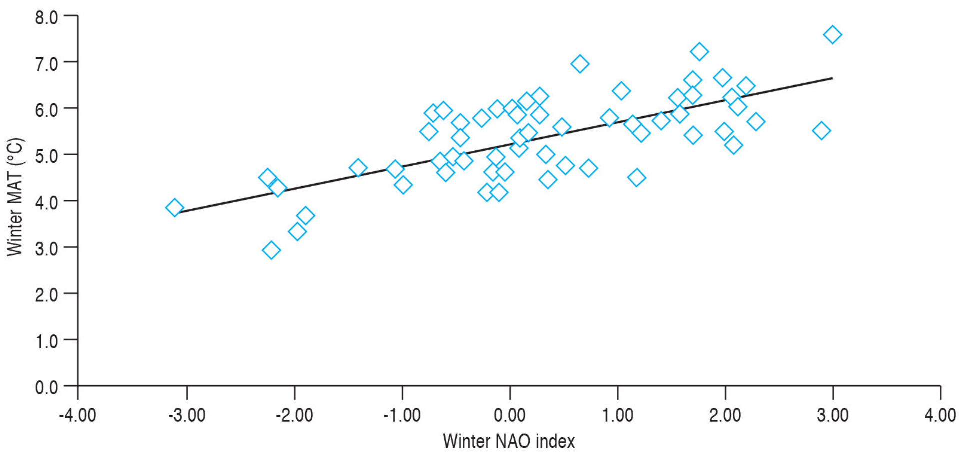

FIGURE 4. The relationship between winter MAT (°C) and winter NAO index (NAOI) at Millport. MAT = 5.21 + 0.47 * NAOI; $R^2 = 0.49$. (MAT, mean air temperature; NAO, North Atlantic Oscillation).

Extremes of air temperature

Air temperatures at Millport have varied between -8.5°C (20/1/2001) and 28.5 °C (28/6/1995, 18/7/2006), an absolute range of 37 °C, relatively low compared to other stations across the British Isles (Tout, 1976). Again, the maritime influence predominates. The annual number of air frosts across the British Isles varies from less than 5 in the Scilly Isles to over 100 in the Highlands of Scotland (Tout, 1976). Millport averages 14 air frosts each year, a typically low number for a coastal location, ranging from a maximum of 38 in 1969 to none at all in 2014. No air frosts have been recorded in the period May through September. Note that Paisley, being inland, averages 38 air frosts per year (range from11 to 75).

In complete contrast, the period May through September is the only time at Millport in which maximum temperatures above 20°C have been recorded. The range is from 45 days in 1998 to none in the period 1954-56 (although there must be some doubt about the veracity of the measurements at that time since a maximum thermometer, according to the UKMO ledger, had only been used from 1954). Ignoring the early period, the lowest annual total of days above 20°C is 2 in 1981.

DISCUSSION

The ameliorating effect of the sea is clearly evident at Millport in comparison to Paisley, because of the latter's urban situation and distance inland, some 40 km. Air temperature fluctuates within a narrow range at Millport, with few air frosts and not many days where the maximum exceeds 20°C. Advection of air from the adjacent sea is an important part of the temperature regime at Millport, mitigating against both the higher maxima and lower minima experienced inland. The annual temperature range for the SST record is smaller than for MAT (Figure 1), a reflection of Millport's island location. The sea warms and cools more slowly than the air (Figure 2), a reflection of both the thermal inertia of the water and the influence of air mass advection providing a more variable air temperature record. The fact that the MAT range at Millport is greater than those quoted by Tout (1976) may indicate a period of greater climatic variability recently within the context of a generally warming climate.

Just like the land surface temperature record, the long-term record of sea surface temperature around the British Isles shows a general warming trend. The experience at Millport is no different and the long-term upward trends are clear to see. Nevertheless, there is an interesting contrast between SST and MAT at Millport: SST and MAT match closely in the cooler years but SSTs are notably higher in the warm years (Figure 3). Thus, since the cooler early 1960s, the rate of increase has been greater for SST than for MAT at Millport. The larger difference between SST and MAT in warmer years is worthy of further study, to establish whether this is a general pattern or whether such differences are confined to situations like Millport. It would also be helpful to compile a more complete record of river flow temperature in the future, in order to gauge better the influence of river flow on estuarine temperature.

Past behaviour can never be a fully reliable guide to the future, but there is plenty of independent evidence based o ocean-atmosphere modelling to predict that MAT and SST will continue to rise in the future (Lowe *et al.*, 2009). Over the 21st century, warming in the shelf seas around the UK and Ireland and the upper layers of the North Atlantic is predicted to continue, although perhaps at a lesser average rate to that observed in the last 30 years. Natural variability, driven by atmospheric and oceanic processes, introduces a level of uncertainty that makes it difficult to predict the direction of temperature change over the next decade (Dye *et al.*, 2013). Since 1995, the annual mean SST at Millport has been higher every year than the 1971-2000 mean (10.2°C) until 2014. It is clear from Figure 3 that annual mean SSTs at Millport have been falling since the 2002 peak, with the annual mean SST in 2014 falling below the 1971-2000 mean for the first time in 20 years.

In the long-term, significant warming is very likely during all seasons and in all coastal waters around the British Isles: annual temperature rises of ~1.5–2.5 °C are projected (Lowe *et al.*, 2009). For shorter-term predictions (up to a decade), natural internal variability cannot currently be predicted with any confidence and it is, therefore, difficult to determine if natural variability will enhance or oppose the long term warming trend over the next decade (Dye *et al.*, 2013). Given the relatively sheltered position of Millport, it would be fascinating to contrast the sea and land station temperatures along an increasingly oceanic axis, perhaps taking in Arran, Colonsay, Tiree, Barra and even Lerwick.

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SUPPLEMENTARY INFORMATION

The file Millport data for Field Studies.xlsx provides monthly air and sea temperatures for Millport from 1951 to 2013 inclusive. Readers are welcome to use these data for their own purposes. Please quote this paper as the source reference in any publication. The file can be downloaded from here.

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