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Published in:
Progress in Oceanography
Publication date:
2018

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Jones, S., Cottier, F., Inall, M., & Griffiths, C. (2018). Decadal variability on the Northwest European continental shelf. Progress in Oceanography, 161, 131-151. https://doi.org/10.1016/j.pocean.2018.01.012

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Download date: 06. Jun. 2021
Decadal variability on the Northwest European continental shelf

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Abstract

Decadal scale time series of the shelf seas are important for understanding both climate and process studies. Despite numerous investigations of long-term temperature variability in the shelf seas, studies of salinity variability are few. Salt is a more conservative tracer than temperature in shallow seas, and it can reveal changes in local hydrographic conditions as well as transmitted basin-scale changes. Here, new inter-annual salinity time series on the northwest European shelf are developed and a 13 year high resolution salinity record from a coastal mooring in western Scotland is presented and analysed. We find strong temporal variability in coastal salinity on timescales ranging from tidal to inter-annual, with the magnitude of variability greatest during winter months. There is little seasonality and no significant decadal trend in the coastal time series of salinity. We propose 4 hydrographic states to explain salinity variance in the shelf area west of Scotland based on the interaction between a baroclinic coastal current and wind-forced barotropic flow: while wind forcing is important, we find that changes in the buoyancy-driven flow are more likely to influence long-term salinity observations. We calculate that during prevailing westerly wind conditions, surface waters in the Sea of the Hebrides receive a mix of 62 % Atlantic origin water to 38 % coastal sources. This contrasts with easterly wind conditions, during which the mix is 6 % Atlantic to 94 % coastal sources on average. This ‘switching’ between hydrographic states is expected to impact nutrient transport and therefore modify the level of primary productivity on the shelf. This strong local variability in salinity is roughly an order of magnitude greater than changes in the adjacent ocean basin, and we infer from this that Scottish coastal waters are likely to be resilient to decadal changes in ocean climate.

Keywords
European, Scottish, salinity, variability, wind, shelf

Abbreviations: SPG: Subpolar Gyre, SS: Surface Salinity, SCC: Scottish Coastal Current, SoH: Sea of the Hebrides, TPM: Tiree Passage Mooring, SAMS: Scottish Association for Marine Science, ROFI: Region of Freshwater Influence, TPC: Tiree Passage Composite time series, ESS: Ellett Line Surface Salinity time series, NAO: North Atlantic Oscillation
1. Introduction

The exchange of water between the ocean and the shelf, and the behaviour of water on the shelf is important to numerous fields of study: while they account for only 0.5% of the oceans by volume, shallow seas are disproportionately important for the growth of phytoplankton and are thought to contribute around 16% of the primary production in the oceans (Chen et al., 2013; Jahnke, 2010; Simpson and Sharples, 2012). In turn, this results in a supply of food for higher trophic levels, so that as much as 90% of the world’s commercial fish catches occur on the continental margin (Pauly et al., 2002). Physical oceanographic processes at the shelf break mediate this productivity (Painter et al., 2016) as oceanic water imported onto the shelf is a key source of nutrients (Proctor et al., 2003). The proximity of the coastline means that the majority of human interaction with the ocean takes place in these regions.

Physical oceanographic variability in the shelf seas therefore impacts the biology, biogeochemistry and economy of coastal regions. This variability may be split into 3 categories: short term; encompassing forcings such as discharge of fresh water, meteorological and instabilities in prevailing currents, seasonal changes such as solar heating and air-sea energy exchange and long-term (inter-annual and decadal) (Mork, 1981). However many shelf sea studies cite wind and buoyancy as the key drivers of change, the latter largely supplied by land runoff and in the high latitudes, snow and ice melt (e.g. Simpson (1997), Sutherland and Pickart (2008), Souza and Simpson (1997)). Due to the short timescales of influence of these forcings coupled with the typically rapid flushing of shelf sea regions, shallow seas often feature strong, short period variability (Brooks and Townsend, 1989; Hill and Simpson, 1988; Münchow and Garvine, 1993a).

The relative importance of shelf processes is dependent on local hydrography and meteorology, and here we highlight examples in the literature which illustrate the different structures of hierarchy which can emerge. Studies of the freshwater plumes generated by riverine discharge onto the (saline) continental shelf are numerous, notable examples being Chesapeake Bay (Lentz et al., 2006), the continental shelf off Delaware Bay (Münchow and Garvine, 1993b; Wong and Munchow, 1995), the Louisiana coastal current (Wiseman et al., 1997) and the Rhine outflow into the North Sea (Simpson et al., 1993; Souza and Simpson, 1997). These regions all feature a coastal current driven by the differing density between the saline shelf water and the freshwater outflow. In the northern hemisphere the current turns to flow with the land on its right (the direction of Kelvin wave propagation) due to Coriolis. These relatively small buoyancy currents can be strongly influenced by winds, either in the direction of flow (downwelling) or against it (upwelling). Downwelling winds
result in a narrowing and strengthening of the current, whereas upwelling winds result in a spreading of surface layers and a slowing of the current, even flow reversal (Simpson, 1997).

A somewhat different system emerges on shelves featuring high freshwater input, such as those bordering fjordic or high latitude coastlines where the sources of runoff merge into a large, coherent coastal current. In these cases, the buoyancy-driven flow is not significantly impacted by wind events, most likely due to the short timescales typical of wind forcing (and the currents generated) not being long enough for the overall spatial extent of the flow to be impacted. Examples of such systems can be found on the East Greenland Shelf (Bacon et al., 2002; Sutherland and Pickart, 2008), the Alaskan coastal current (Whitney and Garvine, 2005) and the Norwegian coastal current (Mork, 1981). Oceanic processes can sometimes intrude onto the continental shelves and affect the coastline, with the on-shelf propagation of eddies and meanders in boundary currents being key culprits in this regard. The latter process is thought to be responsible for sporadic warming on the West Spitzbergen Shelf off Svalbard (Cottier et al., 2007).

While physical processes on the continental shelves and slopes are well described over short periods, typically using moored current meters, boat surveys or langrangian drifters, there are few studies investigating how these short-term changes may be extrapolated to inter-annual and longer timescales. Where long time series do exist, they can prove valuable for linking short-term processes to longer-term trends. For example, pulses of oceanic incursion superimposed on a decadal temperature trend were linked by Reid et al., (2001) to changes in phytoplankton density in the North Sea. Similarly, a study of decadal salinity and dissolved organic phosphate on the European shelf by Laane et al., (1996) utilised 4 observational time series to investigate inter-annual variability in nutrient availability across the shelf. In the Pacific, the 43-year time series of the California Current System reported by Roemmich and McGowan (1995) demonstrated an upper ocean warming of 1.5 °C combined with an 80 % reduction in zooplankton biomass. The authors suggested that increased thermal stratification resulting from surface warming decreased nutrient input to the upper ocean, which resulted in the observed decline in the zooplankton population. Subsequent studies have also noted a clear El Niño signal in these temperature observations (Kim et al., 2007) which indicates that the shallow seas off California track inter-annual changes in the adjacent ocean.

Here, we present an analysis of salinity variability on the NW European Shelf on timescales ranging from tidal to decadal, and extending between the coast and the shelf break. Salinity is an effective
tracer of shelf behaviour because it is more conservative than temperature, it is easy to distinguish coastal from oceanic origins and its use in observational campaigns has been routine for decades, enabling long time series to be constructed. The sensitivity of salt to advection in particular can make it a more critical measure of model skill in semi-confined basins than temperature, e.g. Young and Holt (2007). This work complements the analyses of coastal current physics by investigating their implications over inter-annual time scales.

1.1 Regional setting
The shallow waters west of Scotland are subject to both coastal and oceanic influences (Burrows et al., 1999; Hill et al., 1997; Inall et al., 2009; McKay et al., 1986). The region is of a greater complexity than many shelf sea areas, as it features numerous influences on the physical oceanography combined with a convoluted coastline. The offshore Atlantic water displays well documented inter-annual variability in temperature, salinity and nutrient content (Holliday, 2003a; Holliday et al., 2000; Johnson et al., 2013; Reid et al., 2001) and it is speculated that the coastal waters exhibit similar variability (Inall et al., 2009; Laane et al., 1996). Ecosystems in this region have been shown to be sensitive to changing water properties (Gowen et al., 1998; MacLeod et al., 2005; Reid et al., 2001) and flow pathways (Adams et al., 2014; Miller, 2013).

Inshore, the islands and fjord-like sea lochs (a term used to describe a lake or sea inlet) of the Scottish west coast (Figure 1) present a complex route for transiting water masses, with numerous bathymetric constrictions resulting in powerful tides between islands and over shallow reefs. The inner Malin Shelf is flushed by the Scottish Coastal Current (SCC), a persistent northward flow of relatively fresh water, much of it originating from the Irish Sea (Ellett et al., 1984; McCubbin et al., 2002; McKay and Baxter, 1985; Simpson and Hill, 1986). Further offshore, the island chain of the Outer Hebrides forms a partial barrier between the north-west Scottish coastline and the North Atlantic. The resultant tapering south-north oriented channel is known as the Minch.
1.2 Oceanographic setting

Basin-scale variability and climate

The waters at the shelf edge and in the slope current are regularly mixed with the upper layers of the eastern Rockall Trough so may be considered to have the same origins (Ellett et al., 1986). The primary mode of inter-annual variability influencing the upper waters (<1000 m) of the Rockall Trough results from the changing strength of the Subpolar Gyre (SPG). A strong SPG expands eastwards into the Rockall Trough, resulting in the admission of fresher and cooler water, whereas a weak SPG is associated with an increased warm, saline Atlantic flow (Hátún et al., 2005; Holliday, 2003b). The state of the SPG can be tracked by an index developed by Hátún et al. (2005), which compares the relative strengths of the Atlantic Subpolar and Subtropical gyres using satellite altimetry.
Between 2000 and 2010 the SPG weakened resulting in high temperatures and salinities in the upper waters of the Rockall Trough (Holliday and Gary, 2014; Holliday, 2003b). The weak SPG was also linked to lower nutrient levels in these waters (Johnson et al., 2013). The status of the SPG in 2010 appears to be weaker than at any time since 1960 (Hátún et al., 2005; Lohmann et al., 2008), though in recent years its strength has increased marginally (Holliday et al., 2015). The primary mode of atmospheric variability over the Northeast Atlantic is the North Atlantic Oscillation (NAO). The NAO index developed by Hurrell (1995) tracks the relative positions of the Icelandic low and Azores high pressure systems by comparing the pressure differential between the two locations. A high NAO (in which air pressure over Iceland is much lower than that over the Azores) is characterised by a westerly airflow and enhanced storm activity over the Northeastern Atlantic, resulting in mild winters and increased precipitation over much of Western Europe. During a low NAO phase, winds over the UK are generally lighter, winters are cooler and precipitation is lower than average.

**The slope current**

At the shelf edge, a bathymetrically-controlled slope current of 10-30 cm s\(^{-1}\) typically occupies the region between the 200 m and 900 m isobaths (Hill and Mitchelson-Jacob, 1993; Huthnance and Gould, 1989; Huthnance, 1986; Pingree et al., 1999). Current meter observations at 56.5 °N during the Shelf Edge Study (SES) campaign showed a strong tendency for water to flow parallel to the local shelf edge throughout the water column, so the presence of the slope current may limit the free exchange of waters between the Rockall Trough and the continental shelf (Burrows et al., 1999; Souza et al., 2001). There is some evidence that the slope current flow becomes stronger but is less spatially coherent during periods dominated by the passage of low pressure systems (Pingree et al., 1999; Souza et al., 2001).

**Incursion of oceanic water onto the Malin Shelf**

Despite the bathymetric constraints on ocean-shelf exchange, there is strong evidence from multiple tracers, most notably salinity time series over several decades, for the incursion of Atlantic water onto the Malin shelf. Hydrographic surveys record the persistent presence of high salinity Atlantic water (S > 35) which is easily distinguished from coastal sources (S < 34.5) over a hundred kilometres inshore of the shelf-edge (Economides et al., 1985; Ellett, 1978, 1979; Hill et al., 1997; Inall et al., 2009). In addition a substantial portion of drifters released at the shelf edge move onto the shelf, ultimately passing close to the Scottish coastline (Burrows and Thorpe, 1999; Burrows et al., 1999). However it is not clear what drives this on-shelf incursion and to what extent it influences the water properties at the coast.
The Scottish Coastal Current (SCC)

The SCC is a persistent northward current on the inner Malin Shelf. Its density is typically 0.5-1 kg m\(^{-3}\) lower than that of other water masses on the Malin Shelf (Hill et al., 1997; Simpson and Hill, 1986) which is primarily due to the lower salinity at its origin in the Irish Sea (Lee, 1960), although freshwater input is also contributed by the many sea lochs and rivers on the west coast of Scotland, dominated by the Clyde Sea and Firth of Lorne systems (Barnes and Goodley, 1958). Many of the characteristics of the SCC are consistent with those of a buoyancy-controlled region of freshwater influence (ROFI, Simpson (1997)), and this model has been used by Hill et al. (1997) to make predictions of its behaviour.

The western boundary of the SCC is partially fixed by the Islay Front for approximately 100 km north of the Irish coast; its position largely maintained by a balance between tidal mixing and solar heating (Hill and Simpson, 1989; Simpson et al., 1979, 1981). North of the Islay Front, tidal constraints weaken and other processes controlling the width of the SCC take over. This segment of the SCC may be regarded as a large-scale buoyant outflow since its observed width (20–40 km) is greater than the internal Rossby radius of deformation (R), which is approximately 7 km on the inner Malin shelf. Other time-dependent factors appear to mediate the width of the SCC north of the Islay Front and these are poorly understood, but westerly winds leading to the encroachment of Atlantic water (Xing and Davies, 2001a) and flushing events in the Irish Sea resulting in a pulse of fresher water being expelled onto the Malin shelf (McKay and Baxter, 1985) have been posited as narrowing and widening influences respectively.

The export of water from the Irish Sea onto the Malin Shelf is consistent with a general anti-cyclonic flow around the UK coastline (Hill et al., 2008). Whilst the rate of outflow from the North Channel is undoubtedly modified by wind (Brown and Gmitrowicz, 1995; Davies and Xing, 2003; Knight and Howarth, 1999), it is generally accepted that the permanent density gradient between the Irish Sea and the Malin Shelf is sufficient to drive an underlying buoyancy flow northwards (Howarth, 1982). Estimates of the average volume flux of water exported from the Irish Sea through the North Channel lie between 0.03 Sv (Sverdrup = \(10^6\) m\(^3\) s\(^{-1}\), Bowden and Hughes (1961)) and 0.12 Sv (Brown and Gmitrowicz, 1995); 1 to 2 orders of magnitude greater than the buoyancy contribution from runoff, which is principally from the Clyde Sea and Firth of Lorne (Barnes and Goodley, 1958).

The Tiree Passage Mooring (TPM) and the Ellett Line

Since 1981 the Scottish Association for Marine Science (SAMS) has maintained a mooring in Tiree Passage in the Inner Hebrides (hereafter TPM). Tiree Passage separates the islands of Tiree and Coll from Mull, and is roughly 10 km wide at its narrowest point. As with much of the Malin Shelf, sub-
Tidal currents are typically northward, with a mean velocity of 10.8 cm s\(^{-1}\) (Inall et al., 2009). Whilst model studies capture some of the main oceanographic features in the region (Adams et al., 2014; Davies and Xing, 2003; Gillibrand et al., 2003; Holt et al., 2009; Xing and Davies, 1996), much of the observed variability in water properties remains unexplained.

The Ellett Line is a multi-decadal hydrographic transect between Scotland and Iceland, its easternmost stations sampling within 10 km of the TPM. It has been occupied at intervals between 1975 and present, typically 1-2 times per year (Holliday and Cunningham, 2013). The present transect builds on earlier observations by ocean weather ships and bisects the route by which Atlantic water is transported north towards the Nordic Seas and Arctic Ocean.

Inall et al. (2009) demonstrated a strong correlation between local wind forcing and sub-tidal currents within Tiree Passage, and found that temperatures showed greater correlation with the Irish Sea than the adjacent Rockall Trough. No attempt was made by the authors to analyse the salinity at the mooring due to the short duration of reliable data. The salinity of the nearby Ellett Line repeat transect was examined, but no explanation for the observed variability could be found.

This unexplained coastal variability forms the basis for our investigation. The remainder of the paper is structured as follows: in Section 2 the data sources are introduced. Section 3 presents new measures of coastal variability covering tidal to multi-decadal periods, and Section 4 extends the analysis from the Scottish coastline to the continental shelf edge, presenting a multi-decadal time series of hydrographic transects spanning the 120 km Malin shelf. Section 5 investigates the relationship between the observed variability and likely oceanographic and meteorological drivers, and Section 6 discusses the physical origins of the variability.

## 2. Data sources

### 2.1 Tiree Passage Mooring (TPM)

The TPM is situated in northern Tiree Passage at 56.62° N, 6.4° W in roughly 45 m deep water. It is serviced at intervals of 3-5 months and the data presented here were prepared and concatenated by staff at SAMS. Hourly current meter and temperature measurements were made at the TPM using Anderaa recording current meters (RCMs) between June 1981 and present (Figure 2) at a nominal depth of 20 m.
Figure 2: [In colour] Hourly data from the Tiree Passage Mooring. (a) along channel velocity time series (grey) following Inall et al. (2009). Black crosses show mean along-channel velocity calculated for each calendar month. (b) 20 m temperature time series (grey); black crosses show month mean temperature with seasonal cycle removed (c) 20 m salinity time series (black points). Winter months (DJFM) are indicated by grey bands. Note the reduced temporal extent of the salinity time series, delineated by black boxes in (a) and (b). Overlaid are supplementary salinity observations from Tiree Passage, which are introduced in Section 3.3. Legend as per Figure 4.

While the RCMs were capable of measuring salinity these data were found to be prone to sensor drift and were not considered to be of scientific value. In August 2002 a Seabird Microcat salinity sensor was added to the standard array, and this installation forms the salinity time series analysed here. Temperature and current meter data from the TPM were presented and analysed by Inall et al. (2009), and a full description of the mooring deployments to 2006 may be found therein. CTD casts were conducted at the beginning and end of most deployments to aid calibration of temperature and salinity. Further information on quality control of the TPM dataset may be found in Appendix A.

2.2 The Ellett Line: stations on the Malin Shelf

The Ellett Line is managed by staff at SAMS, Oban and NOC (National Oceanography Centre), Southampton. Of primary interest to this study are the 17 CTD stations regularly occupied on or
near the Malin Shelf. Significant temporal gaps exist in these records, so to achieve a seasonal data resolution across the shelf, historical data from the International Council for the Exploration of the Sea (ICES) were used to supplement the core Ellett Line dataset (see Appendix C for more details).

2.3 ICES CTD and surface data

ICES maintains a large database of historical CTD and bottle data which has been assembled from numerous sources and subjected to basic quality control (Berx and Hughes, 2009). Data from the near-surface (<10 m) are maintained separately; these are typically sourced from underway observations from ships of opportunity such as cargo ships, ferries and research vessels between 1877 and present. Both datasets were obtained from the ICES online data repository (ICES.dk).

2.4 Port Erin salinity observations

Observations at Port Erin on the Isle of Man are used as a measure of Irish Sea water properties in this study, following Inall et al. (2009). Salinity measurements were taken from near-surface waters at the end of the Port Erin breakwater (54.08 °N, 4.77 °W) from 1965 to 2008. The Port Erin datasets were maintained by the Isle of Man Government and formed part of the Irish Sea Coastal Observatory. For this study, the dataset was provided by the British Oceanographic Data Centre (www.bodc.ac.uk). Temperature and salinity data from this location are available from 1966 to 2008 when sampling ceased.

2.5 ECMWF wind data

Daily 10 m wind data were acquired from two reanalysis models maintained by ECMWF (www.ecmwf.int). The ERA-interim model covers the period between 1979 and present, however as this study required data from 1975 onwards, the output of the ERA-20C model was used to provide data for this interval. A comparison of the two models over a common time-frame showed virtually no discrepancy between the two, so the transition between models was deemed to be valid. Data were downloaded on a 1° x 1° grid, from which a time series on the central Malin Shelf (56° N, 7° W) was extracted. Wind stress was calculated from the velocity data using:

$$
\tau_{\text{wind}} = C_D \rho_{\text{air}} U^2
$$

(1)

Where \( \rho_{\text{air}} \) is the density of air in kg m\(^{-3}\) and \( U \) the 10 m wind speed in m s\(^{-1}\) at a height of 10 m. \( C_D \) is the coefficient of drag, given by the approximation suggested by Large and Pond (1981):

$$
C_D = (0.63 + 0.066U) \times 10^{-3}
$$

(2)
The use of ECMWF reanalysis wind data on the European Shelf is commonplace (Holt and Proctor, 2003; Huthnance et al., 2009; Pingree et al., 1999) and its accuracy on inter-annual time-scales is considered to be sufficient for the statistical analyses presented here.

2.6 The Sub-Polar Gyre (SPG) index

The index of SPG strengths used in this study was constructed from altimetry observations (Häkkinen and Rhines, 2004) and was provided by Sirpa Häkkinen. Due to the limited availability of satellite altimetry from which this index is derived, this dataset covers the period from 1993 to 2015. A description of the impacts of the SPG state on the upper waters of the NE Atlantic is given in Section 1.2.

2.7 Precipitation data

Precipitation on the Scottish west coast is amongst the highest in the UK (Barnes and Goodley, 1958). Monthly precipitation totals (in mm) at Dunstaffnage Marine Station (DMS, Figure 1) were downloaded from the UK Met Office website (http://www.metoffice.gov.uk/public/weather/climate-historic). This location was chosen as being most representative of the western Scottish climate: mean annual precipitation at Dunstaffnage is 1681 mm, which is close to the average for western Scotland (1787 mm). Despite the high precipitation for the region, the watersheds which feed the rivers and sea-lochs of the Scottish west coast are generally confined to within 30 km of the coastline due to the steep terrain on the western side of the country (Edwards and Sharples, 1986). While the Dunstaffnage station is coastal it features a similar climate to more inland stations due to the mountainous island of Mull situated 20 km to the west.

3. Salinity variability near the Scottish coastline

3.1 Description of the Tiree Passage Mooring (TPM) salinity time series

The 20 m salinity time series derived from Microcats on the TPM (Figure 2c) features both gradual changes (for instance the decrease of 0.9 units during the spring/summer of 2004) and rapid, high amplitude fluctuations such as the subsequent rapid increase of 1 unit during winter 2004-5, and the decrease of 1.1 units during winter 2013-14. The mean 20 m salinity is 34.40 with a standard deviation of 0.22. There is no significant salinity trend over the 12 years of observations.

3.2 Harmonic analysis of the Tiree Passage Mooring (TPM) salinity time series

Following Inall et al. (2009) the Lomb-Scargle method (Press et al., 1992) was used to analyse TPM salinity due to the presence of unevenly spaced data (Figure 3). In common with many geophysical time series, the power spectrum of salinity resembles a red-noise spectrum (Torrence and Compo,
1998), which is typified by a tendency towards higher energy at long periods. The length of the available data restricts the analysis to periods up to 2 annual cycles, but there is no clear power maximum at a period of 1 year and hence no evidence of a defined seasonal cycle. The lack of a seasonal cycle is in contrast to the analyses of temperature and current by Inall et al. (2009) which found clear seasonality in both. There are peaks in the semi-diurnal and higher harmonic tidal species, possibly caused by the periodic advection of fronts or property gradients past the fixed mooring.

Figure 3: Power spectrum of TPM salinity time series, for the period of near-continuous records between 2002 and 2005. SA = Solar Annual (1 year). Periods of M2, S2, M4 and S4 tidal components are shown.

3.3 The Tiree Passage Composite (TPC) time series

To provide a decadal context for the salinity observations at the TPM to date, historical data within the confines of Tiree Passage were assembled into a composite 40 year time series. The source data comprised the ICES CTD and surface datasets, monthly means of the hourly TPM observations, and Ellett Line station 2G which is situated at the northern end of the passage. The resultant composite time series of salinity is shown in Figure 4a, and depictions of data availability are given in Figure 4b and c. More information on estimation of errors associated with the observations is given in Appendix B.
Figure 4: [In colour] Composite salinity time series in Tiree Passage. (a) Salinity observations and their source datasets. Surface data are averaged into 5 day bins, CTD data are sampled at 20 m depth, TPM mooring data are month means. Vertical lines show error estimate associated with each observation. Explanation of error estimates is given in Appendix B. (b) Seasonal and temporal distribution of observations. (c) Coverage of winter (DJFM) and summer (JJAS) observations. The standard deviations of these subsets are indicated by the shaded regions.

Figure 5 depicts the TPC time series compared with observations from 20 m depth at Station Q on the Ellett Line representing salinity at the shelf-edge, and observations from Port Erin on the Isle of Man representing the salinity in the central Irish Sea, following Inall et al. (2009). Between 1976 and 2014, the salinity in Tiree Passage has a mean of 34.42 and a standard deviation of 0.22. This may be compared to values of 34.15 +/- 0.26 at Port Erin, and 35.37 +/- 0.05 at station Q.
Figure 5: a) Comparison of salinity time series. Black dashed line shows observations from 20 m depth at station Q at the shelf edge (note expanded scale); solid black line shows month-mean salinity observations at Port Erin in the Irish Sea; shaded region shows the TPC time series (seasonal means +/- 1 standard deviation). b) Comparison of seasonality in salinity time series; shaded regions indicate month means +/- 1 standard deviation. c) Comparison of seasonality in temperature time series; shaded regions indicate month means +/- 1 standard deviation.

We follow the approach of Inall et al. (2009) (table 5 therein) by performing correlations between time series from Tiree Passage, the Rockall Trough and Port Erin (Table 1). This enables a comparison between long-term temperature variability in the region (Inall et al., 2009) and salinity variability (present study). Statistical comparisons between time series are expressed using the $R^2$ statistic (the square of the correlation coefficient, $r$), giving the amount of variance explained by each time series comparison. Hence, an $R^2$ of 1 indicates a perfect match while a value of 0 shows no statistical relationship between the time series. The p-value is also given as a qualitative measure of significance, taking into account the effect size, sample size and variability of the data (a low p-value indicates higher confidence in the correlation). In contrast to the comparison between Port Erin and TPM temperature time series by Inall et al. (2009) ($R^2 = 0.505$), there is very little relationship between the salinities of Tiree Passage and Port Erin (Table 1, $R^2 = 0.015$). However there are periods when the time series are somewhat coherent; for instance between 1976 and 1982, and between 1994 and 2003. The relationship in salinity between Tiree Passage and Station Q on the shelf-edge ($R^2 = 0.154$) is of similar magnitude to the temperature comparison of Inall et al. (2009) ($R^2 = 0.167$), though the authors instead employed a temperature anomaly product by
Holliday (2003b) as a proxy for upper ocean temperatures. There is a moderate relationship ($R^2 = 0.129$) between inter-annual temperature and salinity anomalies in Tiree Passage.

While temperature has a clear seasonal cycle (Figure 5c), salinity does not (Figure 5b). However, the highest and lowest salinities typically occur in winter, and consequently the standard deviation of the Tiree Passage time series varies seasonally, rising from 0.14 in August to 0.30 in January.

Table 1: Correlations between time series. Tiree is lagged by one season in the Port Erin correlation to acknowledge the estimated 3-6 month transit time (McKay and Baxter, 1985). A range of lags were tested to ensure that the correlation was not sensitive to this choice.

| Time series                  | $R^2$ | p-value |
|------------------------------|-------|---------|
| Tiree 20 m sal and Port Erin SS | 0.023 | 0.142   |
| Tiree 20 m sal and Station Q 20 m sal | 0.154 | 0.002   |
| Port Erin SS and Station Q 20 m sal | 0.004 | 0.627   |
| Tiree 20 m temp. and Tiree 20 m sal. | 0.129 | 0.001   |

4. Salinity variability in the Ellett Line Surface Salinity (ESS) dataset

The regular occupations of the Ellett Line form an excellent resource for charting the variability in water properties across the Malin Shelf. Between 1976 and 1996 several CTD transects per year were conducted, but the frequency of cruises decreased markedly after this date. Therefore temporal gaps on the continental shelf were filled using data extracted from the ICES CTD and surface datasets (Section 2.3). The methods used to merge the data are described in Appendix C.

From the shelf edge to the southern tip of the Hebrides, the mean surface salinity (SS) decreases continuously from 35.4 to 34.75 (Figure 6a, d). There is a minor increase to 34.85 at station 9G (7.4°W) and a further decline east of here, with the salinity gradient strongest between Stations 2G (Tiree Passage) and 1G (Sound of Mull). The strongest variability in salinity is seen in the stations which sample the Sea of the Hebrides (hereafter SoH, 11G-4G, $\sigma = 0.24$).

Episodic high salinity anomalies occur at the inner shelf stations in the early 1990s and the late 2000s, and clusters of negative salinity anomalies are present in the late 1970s - early 1980s and in the early 2000s (Figure 6c). There is little zonal correspondence in the time series; i.e. positive and negative anomalies in the Rockall Trough are not necessarily coincident with those near the coast.
Figure 6: (In colour) (a) Hovmöller plot of surface salinity of Ellett Line shelf stations, supplemented by ICES CTD dataset and ICES surface dataset. Significant shelf features are marked; SE: Shelf Edge, Heb: southern tip of the Hebrides, TPM: location of the Tiree Passage Mooring. The date and longitude of observations are shown as black points with a white outline. Contours are at 0.2 unit intervals. (b) Zonal mean salinity anomaly between 7° W and 9° W. c) as for a) but depicting surface salinity anomaly (calculated by subtracting the time-mean salinity for each station). d) Mean salinity of Ellett Line stations (solid black line) by longitude. Grey region shows +/- 1 standard deviation for each station.

5. Origins of salinity variability in the ESS dataset

This section examines the potential drivers of variability in the ESS dataset. While Whitney and Garvine (2005) used an analytical model to decompose wind and buoyancy and thus characterise local variability, their assumption of independence between wind forcing and the baroclinic transport may not be true on the Malin Shelf, for reasons discussed in Section 6. Here, we instead use an empirical statistical approach based on existing hypotheses of the behaviour of the shelf in the literature. The rationale behind each correlation study is described in the following subsections.

5.1 Influence of the Rockall Trough through advection

Whilst the shelf edge presents a partial barrier to the exchange of water, it is clear that ocean-shelf exchange does occur (Burrows et al., 1999; Huthnance, 1995; Huthnance et al., 2009; White and
Bowyer, 1997). However it is not known to what extent signals propagate across the shelf. To test the likelihood of an oceanic salinity anomaly propagating eastwards, the SS time series at station Q (from the ESS dataset, located at the shelf edge) was utilised. Correlating station Q with each Ellett Line station in turn (e.g. Q with Q, Q with R, etc.) provides a measure of the de-correlation scale on the shelf and thus informs on the likelihood of upper ocean changes being detectable at the coast.

5.2 Influence of the Sub Polar Gyre (SPG) state through advection

An alternate measure of the propagation of oceanic anomalies was examined by correlating each ESS time series with the SPG index. The strength of the SPG has been shown to be the dominant mode of variability in temperature, salinity and nutrient content in the upper Rockall Trough (Holliday and Gary, 2014) and the resultant decadal salinity changes may be detectable on the shelf. As a stronger SPG results in lower salinity water being admitted into the Rockall Trough, an inverse relationship might be expected between the SPG and the ESS time series.

5.3 Influence of the Irish Sea through advection

The Port Erin salinity time-series was compared to each Ellett Line station as there is much evidence to suggest that Irish Sea water contributes to the coastal water mix on the inner shelf (Ellett et al., 1984; McCubbin et al., 2002; McKay and Baxter, 1985; Simpson and Hill, 1986), and it is possible that variability in the Irish Sea could be transmitted through advection. The Port Erin salinity time series was binned into seasonal means for this study. McKay and Baxter (1985) estimate a transit time of 3-6 months from the Eastern Irish Sea to Loch Etive in the Inner Hebrides, so a lag of 1 season was applied to account for this interval.

5.4 The effect of wind on shelf salinity

Wind is known to be a major influence on smaller coastal current systems in other regions (Lentz et al., 2006; Münchow and Garvine, 1993b; Simpson et al., 1993; Wiseman et al., 1997; Wong and Munchow, 1995) and several studies have qualitatively cited wind forcing as a potential driver of change on the Malin shelf and at the shelf break (Burrows et al., 1999; Hill and Simpson, 1988; Huthnance et al., 2009; Souza et al., 2001).

The effect of wind on flow pathways on the Malin shelf was investigated in a series of model studies by Davies and Xing (2003) and Xing and Davies (2001a). Their findings indicated that winds with a westerly component intensify the import of water from the outer Malin Shelf towards the coastline, so it might be expected that westerly winds would be correlated to periods of higher salinity on the inner shelf. Similarly, there is a clear relationship between the passage of weather systems and the strength of currents on the shelf (Hill and Simpson, 1988; Inall et al., 2009). However there is likely
to be a disconnect between the dynamic response time of the shelf to wind (on the order of hours) and the physical advection of a tracer resulting from a wind-driven flow. If we consider salt to be a tracer on the shelf, then its concentration during an instantaneous sample depends not only on the processes which drive advection, but also on the flushing time of the shelf. The average flushing time of the Malin shelf is suggested by radioisotope studies to be of order 2 months (McCubbin et al., 2002; McKay and Baxter, 1985). However a simple estimate can also be made using a conservation of volume argument, assuming the Malin shelf to be a semi-enclosed body of water with exchange mediated by channel flow and shelf edge processes. If the inflow to the Malin shelf \( V_{in} \) is given by

\[
V_{in} = V_{nc} + V_{cs+} + V_r + V_p
\]  

where \( V_{nc} \) is the input from the North Channel, \( V_{cs+} \) is the on-shelf component of cross-shelf flow, \( V_r \) is the contribution from runoff, and \( V_p \) from precipitation. The outflow is:

\[
V_{out} = V_{heb} + V_{cs-} + V_e
\]  

Where \( V_{heb} \) is the flow past the Hebrides towards the North Sea, \( V_{cs-} \) the off-shelf component of cross-shelf flow, and \( V_e \) the evaporation. As \( V_r, V_p \) and \( V_e \) are all less than \( 10^3 \) m\(^3\) s\(^{-1}\) (Jones, 2016) they are discounted for this approximation leaving:

\[
V_{nc} + V_{cs+} = V_{heb} + V_{cs-}
\]  

Using values of \( V_{nc} = 7.7 \times 10^4 \) m\(^3\) s\(^{-1}\) (Knight and Howarth, 1999), \( V_{cs+} = 6.2 \times 10^5 \) m\(^3\) s\(^{-1}\) and \( V_{cs-} = 1.3 \times 10^5 \) m\(^3\) s\(^{-1}\) (Holt et al., 2009), \( V_{heb} \) is deduced to be \( 5.7 \times 10^5 \) m\(^3\) s\(^{-1}\). The flushing time \( T_f \) is simply the shelf volume (3 x 10\(^{12}\) m\(^3\)) divided by the total flow rate through the region (7.0 x 10\(^5\) m\(^3\) s\(^{-1}\)) = 50 days. However given the various assumptions used for this estimate, here we employ the value of 60 days obtained using radiocaesium tracer studies (McCubbin et al., 2002; McKay and Baxter, 1985). Thus each observation in the ESS time series was compared to the cumulative wind stress for the preceding 60 days for the westerly, easterly, southerly and northerly wind components.

### 5.5 The effect of precipitation on shelf salinity

The salinity on the shelf may be influenced by trends in precipitation, both through direct freshwater input and through runoff from the watersheds in western Scotland. To test this theory, each observation in the ESS time series was compared to precipitation totals at Dunstaffnage Meteorological Station for the preceding 2 months (again assuming the Malin shelf to be semi-enclosed by land and shelf edge processes). As precipitation increases the freshwater contribution
to the shelf, an inverse correlation would be expected between the ESS time series and precipitation trends.

5.6 Correlation results

Figures 7a and b show the SS variance accounted for by salinity variability at the shelf edge and changes in SPG strength respectively. Variance explained by SS at the shelf break decreases rapidly with distance from the shelf edge: while 55% of the variance at station R and 34% at station S is shared with station Q, between 13G and the coastline there is very little correspondence with shelf edge variability. Variance accounted for by the SPG index is low both on the Malin Shelf and perhaps surprisingly in the surface waters of the Rockall Trough. Similarly, the Port Erin SS time series (Figure 7c) shares very little variance with any of the ESS stations.

In contrast, there is a weak to moderate relationship ($R^2 = 0.17$) between cumulative westerly wind stress and SS at stations 6G and 4G in the SoH (Figure 7d). The opposite is true between cumulative easterly wind stress and stations 7G-4G (Figure 7e); the SS at these stations shows a moderate negative relationship ($R^2 = 0.22$) with easterly winds. Neither southerly nor northerly wind stress (Figures 7f and 7g) have a significant relationship with SS with the exception of the negative correlation at Station 1G in the Sound of Mull.

The precipitation study (Figure 7h) exhibits a similar shelf-wide pattern to westerly wind stress; some variance is shared with inner shelf stations, but this switches to a negative relationship at Station 1G in the sound of Mull. None of the test variables showed a significant relationship with station 2G in Tiree Passage.
Figure 7: [In colour] Results of correlation studies. Note that all studies except (a) feature the same axis scales. Solid black line shows $R^2$ (variance in ESS time series accounted for by test variable, 0-1). Black crosses show positive correlations, red circles show negative correlations. Dashed grey line gives p-value for each correlation. Ellett Line stations used in the study are labelled and their locations marked with black ticks (14G and 10G omitted for clarity). Plots show correlations between ESS time series and: (a) Station Q (shelf edge) surface salinity, (b) The SPG index, (c) Port Erin (Irish Sea) surface salinity, (d) 60 day cumulative westerly wind stress, (e) 60 day cumulative easterly wind stress, (f) 60 day cumulative southerly wind stress, (g) 60 day cumulative northerly wind stress, and (h) Dunstaffnage (Scottish west coast) precipitation.

6. Discussion

A new high resolution time series of salinity in a dynamic coastal environment is presented. To aid interpretation, two new data products are constructed from historical observations in the region; a 40 year time series of salinity in Tiree Passage (the TPC time series) and the same duration of surface salinity transects between Tiree Passage and the shelf edge (the ESS time series). This work complements the analysis of temperature and current meter data obtained from the TPM by Inall et al. (2009) and adds to the small network of coastal time series on the European shelf capable of resolving climatic cycles and trends (Allen et al., 1998; Holt et al., 2012; Laane et al., 1996).
The analysis focusses on time-scales of seasonal and longer, though as with temperature (Inall et al., 2009) salinity variability in Tiree Passage can be observed down to tidal periods. It is clear from the TPM salinity observations that rapid, high amplitude changes in salinity in Tiree Passage are commonplace, though with a 12 year record no trend is apparent (Figure 2). The 40 year TPC time series shows that variability during the winter months (DJFM) dominates the inter-annual salinity signal, whereas during the summer (JJAS) the salinity remains relatively stable at 34-34.5 (Figure 4c). The winter months often feature very high or very low salinities, but these extremes largely cancel out between years, so on average there is little seasonality in Tiree Passage salinity.

While a linear temperature increase of 0.57 °C per decade between 1981 and 2006 was observed by Inall et al. (2009) this study shows that since the late 2000s the temperature anomaly has decreased by approximately 0.5 °C (Figure 2). This pattern is consistent with the recent (post-2010) marginal increase in SPG strength (Holliday et al., 2015; Johnson et al., 2013) and the associated input of cooler, fresher water into the Rockall Trough. Given the apparent tracking of inter-annual oceanic temperature anomalies by coastal waters, it is therefore surprising that neither the TPC salinity time series nor the inner stations of the ESS time series show any significant correlation with the salinity of the Rockall Trough or the SPG index. However, the rapid de-correlation of SS with eastward progress across the shelf (Figure 7a) is an indicator that changes in Atlantic salinity are unlikely to be detectable at the Scottish coastline. This de-correlation may be exacerbated because the Ellett Line transect bisects the SCC as it recirculates around the southern tip of the Outer Hebrides, which may limit the eastward influence of Atlantic water more at this latitude than if the experiment was repeated further south. However it is probable that oceanic signals are largely masked by energetic shelf processes, which will be examined in more detail in Section 6.1.

Despite substantial evidence that Irish Sea water exists on the inner Malin Shelf (Jefferies et al., 1973; McKay et al., 1986; McKinley et al., 1981), no significant relationship between Irish Sea SS and Malin Shelf SS is present (Figure 7c). Whilst it might be speculated that this lack of shared variance is because the SCC has its origins in the eastern, rather than central Irish Sea (where Port Erin is located), we suspect that this is not the case. Allen et al., (1998) found Port Erin to be representative of variability in the wider Irish Sea area, particularly in winter. In addition, Jones (2016, pp. 84–87) compared the Port Erin SS time series to SS samples obtained by the Stranraer-Larne ferry in the North Channel between 1971 and 1986 and found that the SS of the North Channel largely tracked the inter-annual changes observed at Port Erin. Therefore the SS signal observed at Port Erin is detectable at least as far north as the Clyde Sea. It is unlikely that Irish Sea water remains undiluted below the surface mixed layer on Malin shelf during summer months: attempting the correlations for winter data only, or using near-bed salinity observations gives similar
results to the findings presented. Similarly, we tested a range of lags for the correlation but these did not result in significant changes to the overall finding.

The lack of correlation between the SPG index and SS in the Rockall Trough (Figure 7b) may be surprising given the asserted significance of the SPG signal on inter-annual changes in the Rockall Trough (Holliday and Gary, 2014; Holliday, 2003a). However taking into account the known seasonal variability in surface waters (Holliday et al., 2000) this result is consistent with current hydrographic understanding. If we instead compare the SPG index and, for example, Station Q salinity at a depth of 150 m, 43 % of the shelf edge salinity variance is explained.

If long-term salinity signals are advected towards the inner Malin Shelf from elsewhere, they appear to be largely masked by local processes. Summers feature lower average SS than winters, and seasons dominated by westerly (easterly) winds are associated with higher (lower) than average SS on the inner Malin Shelf. The proposed drivers of this effect are discussed in the next section.

6.1 The competition between buoyancy and wind on Malin shelf: the definition of four states

We propose that the complex hydrography of the Malin Shelf can be largely characterised by four states, and that the strong variability observed on the inner shelf can be explained in part by a switching between these states.

State1: Buoyancy only; thermally stratified

If it is accepted that the underlying driver of the SCC is the salinity differential between the Irish Sea and the Malin Shelf (Hill et al., 2008) this infers a permanent mechanism for buoyancy forcing for the SCC regardless of season. This process occurs because of the tendency for fresher Irish Sea water to spread out on top of denser Atlantic water as they meet on the southern Malin shelf. However due to the Earth’s rotation the lighter Irish Sea water is deflected to the right of its direction of travel, and the system can therefore reach equilibrium with Irish Sea water forming a wedge against the west Scottish coastline and flowing with the land on its right (a ROFI system, Simpson (1997)). The theoretical structure is shown in Figure 8d, and the path of the buoyant plume, which becomes the SCC (Hill, 1983; Hill et al., 1997; McKay and Baxter, 1985; McKay et al., 1986; Simpson and Hill, 1986) is shown in Figure 8e. In its buoyancy-driven state, the SCC has many similarities with the coastal current systems highlighted in other regions. Its typical flow rate of $10^4 – 10^5$ m$^3$ s$^{-1}$ is somewhat larger than many river plume systems (Münchow and Garvine, 1993b; Souza and Simpson, 1997; Wiseman et al., 1997) but is substantially smaller scale than, for instance the large coastal currents off Greenland and Alaska (Bacon et al., 2002; Whitney and Garvine, 2005).
Water depth is typically 40-70 m, and tidal stirring is an important control of the offshore current boundary in the Islay Front vicinity (see Section 1). North of the breakdown of the Islay Front, there is no clear topographic control on current width. Note that both Tiree Passage and the Minch are thought to represent partial barriers to the through-flow of the SCC, with the result that it bifurcates in these regions and a portion flows around the outside of the channels (Hill, 1983).

Figure 8: (In colour) Typical hydrographic conditions for state 1 (see text): thermally stratified, no significant easterly or westerly wind stress. (a) Ellett Line transect of the Malin shelf showing potential energy anomaly, (b) salinity overlaid with potential density contours; inset shows temperature, also with potential density contours. CTD stations occupied are labelled and indicated with black ticks. (c) Quiver plot of 10 m wind speed and direction on Malin shelf for the 60 days preceding the Ellett Line occupation. Date of shelf occupation shown by grey bar. (d) The ROFI ‘wedge’ structure (modified from Simpson and Sharples 2012). (e) The expected flow pathway of the buoyant portion of the SCC.

We propose that this condition is the default state on the Malin shelf in the absence of significant forcing by wind or pressure gradients. In summer months, the westward slumping of surface waters is further facilitated by the onset of thermal stratification. An Ellett Line transect during such conditions (Figure 8a-c) has strong vertical and horizontal gradients in salinity, temperature and
density. The influence of coastal waters (indicated by lower salinities) extends virtually to the shelf edge and a pool of dense salty water is trapped below 50-70 m in the SoH. The potential energy anomaly $\phi$ (Figure 8a) represents the amount of work required to fully mix the water column and provides a quantitative measure of the level of stratification (Simpson et al., 1990). Here we have evaluated $\phi$ for the top 200 m of the water column to enable comparison with other shelf states.

State 2: Buoyancy only; mixed

With the onset of autumn, thermal stratification is eroded by storms and convective instabilities, but the constant input of freshwater from the Irish Sea and coastal runoff reduces the density of shallow waters which tend to relax away from the coast. Consequently, while long periods of light winds are rare in the NE Atlantic during winter, weak haline stratification is expected to develop during calmer periods. The Ellett Line transect in Figure 9 shows the Malin shelf during a brief calm period following a month of strong winds, predominately from the south. The shelf is close to fully mixed and temperature is uniform with depth. Vertical density gradients are low, as evidenced by the potential energy anomaly $\phi$ in Figure 9a, however horizontal density gradients are moderate. Salinity in the eastern Minch is relatively high at 34.8, but still significantly lower than the oceanic water to the west (35.4). Note that an Ellett Line section with a more pronounced haline stratification (an example of the ROFI structure) is shown in Figure 10, but it is used to illustrate a separate wind-driven process.
While baroclinicity may be the underlying driver of flow on the Malin shelf, we argue that flow due to wind stress can easily override this mechanism. Here, a simple order of magnitude comparison between wind and buoyancy suggested by (Hill, 1983) is informative.

To estimate the poleward flow $V_B$ due to density differential on the Malin Shelf, a thermal wind balance is assumed so that vertical density gradients are neglected:

$$V_B = \int_{-H}^{0} \nu dz = g H^2 \frac{\delta \rho}{\delta x} / 2f \rho$$

Where $g$ is acceleration due to gravity, $\rho$ density, $\frac{\delta \rho}{\delta x}$ the change in density per unit distance offshore and $f$ the Coriolis parameter. Substituting values of $\rho = 1027$ kg m$^{-3}$ and $\frac{\delta \rho}{\delta x} = 1$ kg m$^{-3}$ per 40 km, the density-driven transport $V_B$ is estimated to be 5 m$^2$ s$^{-1}$.
A contrasting approximation is used to estimate wind-driven flow. In this scenario the sea surface moves with a wind-driven friction velocity $U_*$ in a shallow sea of depth $H$, with linearised bottom friction $B_x = C_d(V_w/H)^2$ in which $C_d$ is the drag coefficient and $V_w$ the resultant northward transport. In this case the balance between transport and bottom friction is

$$V_w = \frac{U_* H}{\sqrt{C_d}}$$  \hspace{1cm} (7)

Using a value of $U_* = 1$ cm s$^{-1}$ (roughly corresponding to a 10 m wind speed of 10 m s$^{-1}$, (Csanady, 1981)) $H = 70$ m and $C_d = 10^{-3}$, the wind-driven transport $V_w$ is 22 m$^2$s$^{-1}$. Thus even moderate wind forcing would be expected to temporarily replace buoyancy as the dominant driver of flow on the shelf. In the above approximations, the wind speed required to balance the density-driven transport is roughly 7 m s$^{-1}$; a value which is regularly exceeded throughout the winter months in the NE Atlantic. To gauge the short-lived but substantial influence of winter storms, we can use the approximate linear relationship between wind and current speed in shallow seas suggested by Whitney and Garvine (2005):

$$u_{\text{wind}} \approx 2.65 \times 10^{-2} U$$  \hspace{1cm} (8)

Where $U$ is the wind speed and $u_{\text{wind}}$ is the approximate resultant current flow. A daily mean wind speed of 18 m s$^{-1}$ for example (exceeded 1-2 times per year) allows us to compute a depth-averaged current of 47 cm s$^{-1}$, while the speed implied for the buoyancy driven flow (Equation 6) in 70 m deep water is only 7 cm s$^{-1}$.

The important wind directions for a buoyant current are predicted by theory to be aligned with the axis as the current; i.e. for a south-north flow southerly winds should result in a narrowing and intensification whereas northerly winds should drive a weakening of flow and spreading of surface layers (Simpson, 1997). Winds perpendicular to current flow should not have a net effect on the current. However we find the opposite: Figures 7f and g (southerly and northerly wind stress) do not have a significant relationship with SS. Conversely Figures 7d and e (westerly and easterly wind stress) show positive and negative relationships between SS and wind stress respectively. This finding is in agreement with the current flows predicted by the model studies of Davies and Xing (2003) and Xing and Davies (2001a). We discuss the processes which may contribute to this effect in the following sections.

State 3: easterly wind stress

Numerous observational studies have correlated transport through the North Channel with winds parallel to the channel (Brown and Gmitrowicz, 1995; Davies and Xing, 2003; Howarth, 1982; Knight and Howarth, 1999). Here we propose that sustained easterly winds (which have a component
parallel to the poleward outflow of the North Channel) drive a pulse of Irish Sea water onto the Malin shelf, and that it may reside on the shelf until it is diluted or advected out of the region. Thus the supply of the majority of freshwater onto Malin Shelf (≈ 90 %, Barnes and Goodley (1958), Edwards and Sharples (1986)) would be dependent on local wind patterns. Figure 10 shows the Ellett Line transect after a period of strong easterly winds, and shows coastal water (S < 34.4) extending across the SoH. Temperature is homogeneous with depth on the shelf, and about 1 °C colder than the adjacent ocean. Density is determined by salinity, and exhibits moderate vertical and horizontal gradients.

Figure 10: [In colour] Typical hydrographic conditions for state 3 (see text): easterly wind stress. (a) Ellett Line transect of the Malin shelf showing potential energy anomaly, (b) salinity overlaid with potential density contours; inset shows temperature, also with potential density contours. (c) Quiver plot of 10 m wind speed and direction on Malin shelf for the 60 days preceding the Ellett Line occupation. Date of shelf occupation shown by grey bar. (d) Progressive vector diagram for 10 m wind on Malin Shelf, for the 60 days preceding the occupation. Circle shows start, red bar denotes cruise period. (e) Expected flow pathways during these conditions, from Xing & Davies 1996.
State 4: westerly wind stress

Westerly winds are often associated with stormy conditions in the NE Atlantic, and tend to be strongest during the winter. The model studies of Davies and Xing (2003) and Xing and Davies (2001b) indicate that westerly winds result in an intensified inflow from the outer shelf along the north coast of Ireland and a blocking surface slope which limits or prevents the buoyancy-driven outflow from the Irish Sea. This would have the effect of increasing salinity at the inner stations by replacing the SCC with water from the outer shelf. Figure 11 shows an Ellett Line transect occupied after a sustained period of strong westerly winds. In contrast to the other examples discussed, temperature, salinity and density are nearly homogeneous across the shelf with only stations inshore of 4G experiencing fresher coastal water. Note the coastal stratification apparent at Station 1G, which is presumably due to enhanced coastal runoff (Figure 11a). SS in the SoH is 35.2, which suggests a recent oceanic source with little dilution.

Figure 11: [In colour] Typical hydrographic conditions for state 4 (see text): westerly wind stress. (a) Ellett Line transect of the Malin shelf showing potential energy anomaly, (b) salinity overlaid with potential density contours; inset shows temperature, also with potential density contours. (c) Quiver plot of 10 m wind speed and direction on Malin shelf for the 60 days preceding the Ellett Line occupation. Date of shelf occupation shown by grey bar. (d) Progressive vector diagram for 10 m wind on Malin Shelf, for the 60 days preceding the occupation. Circle shows start, red bar denotes cruise period. (e) Expected flow pathways during these conditions, from Xing & Davies 1996.
Short-lived pulses of high salinity water can also be seen in the TPM 20 m time series, and these are nearly always associated with very strong westerly wind events which typically occur 1-2 times per winter (daily mean >18 m s\(^{-1}\), Figure 12a). Two such events are shown in detail: in January 2004-5 (Figure 12b,c,d) and December 2013-14 (Figure 12 e,f,g). On both occasions salinity in Tiree Passage was already above average (S = 34.6-34.7) prior to the wind events. In each case, poleward current speeds through Tiree Passage increased shortly after the wind event, an observation which supports the link between wind and current flow found by Hill and Simpson (1988) and Inall et al. (2009). An increase in salinity occurred 5-10 days after the initial wind event, and salinity remained very high for 10-15 days before decreasing. An interesting feature in Figures 12b and e is the dramatic increase in short-period variability associated with the high salinity pulses: a frequency analysis of these events (not shown) displays a peak in energy at inertial frequencies (1-2 days) which is not present in the spectral analysis of a continuous 2 year record (Figure 3). This suggests that the passage of storms result in a state of disequilibrium on the inner shelf, and this provides some dynamical context to the westerly observations. The peak flow speeds of 50 cm s\(^{-1}\) are close to those predicted by the approximation of Whitney and Garvine (2005) for winds of 18 m s\(^{-1}\) (see Equation 8) which implies that the barotropic assumptions based on the Delaware coastline also hold for the Malin shelf.
Figure 12: (In colour) (a) TPM 20 m salinity. Overlaid green lines show instances of daily mean westerly winds on Malin Shelf exceeding 18 m s\(^{-1}\). There are 17 occurrences between 2002 and 2015. Grey bars indicate DJFM for each year, pink bars show periods enlarged in (b-g). (b) Comparison between TPM 20 m salinity, (c) along-channel (poleward) low-pass filtered current speed and (d) 10 m wind speed on Malin Shelf for winter 2004-5. Green vectors show daily mean westerly winds exceeding 18 m s\(^{-1}\). (e) Comparison between TPM 20 m salinity, (f) along-channel (poleward) low-pass filtered current speed and (g) 10 m wind speed on Malin Shelf for winter 2013-14. Green vectors show daily mean westerly winds exceeding 18 m s\(^{-1}\).

6.2 Comparison between the ‘4 state’ model and observed variability

The previous section proposed four states which broadly describe the hydrography of the Malin shelf under different seasons and atmospheric conditions. Here we examine the extent to which these states are able to capture the observed variability on the Malin Shelf.

To achieve this, the ESS observation dates were first divided into summer (April-September, state 1) and winter (October-March, state 2) to broadly characterise the thermally stratified and thermally mixed seasons. To define observations made after a period of unusual wind stress, a 60 day flushing time was assumed as in previous sections. Note that as inferred by Figure 12, the shelf may be flushed more rapidly during storm events but a more advanced modelling study would be required to estimate how this may affect advection of salt and freshwater. Integrating over a reduced period
for westerly winds does not significantly improve correlations, and the possible reasons for this are subsequently discussed.

The standard deviation of 60 day cumulative easterly and westerly stress on Malin shelf was calculated for the full duration of the ECMWF record (1940-present). These were found to be 2.16 N m\(^{-2}\) and 5.00 N m\(^{-2}\) respectively. Observations in the ESS time series which were preceded by easterly or westerly winds exceeding 1.5 standard deviations from the mean were defined as state 3 or state 4 respectively. For easterly winds, this additive stress is approximately equivalent to 10 days during a 2 month period with average wind speeds of more than 12 m s\(^{-1}\), or 20 days exceeding 9 m s\(^{-1}\). For westerly winds, the threshold value is equivalent to 10 days which exceed 17 m s\(^{-1}\) (a statistically unlikely scenario) or 20 days greater than 13 m s\(^{-1}\). Where these criteria are fulfilled, they override states 1 and 2. In the event that the criteria for both states 3 and 4 are met, state 4 takes priority due to the greater energy associated with westerly wind stress.

The time-mean of ESS observations assigned to each state is shown in Figure 13. The SS difference between stratified (state 1) and mixed (state 2) is relatively small at 0.25 units in the SoH. The only notable difference between SS for westerly wind stress (state 4) and ‘typical’ winter conditions is the greater freshening present at Station 1G (Sound of Mull) and Station 10 G (east of Hebrides). Easterly wind stress (state 3) is associated with much lower SS across most of the Malin shelf.

![Figure 13: Time-mean of ESS observations, grouped by their hydrographic / meteorological state (as described in Figures 8-11). SE: Shelf edge, Heb: southern tip of the Hebrides, TPM: location of Tiree Passage Mooring.](image)

The mean potential energy anomaly \(\varphi\) of each station grouped by state is shown in Figure 14. Note that these averages are comprised of fewer observations than SS as \(\varphi\) is an integral value necessitating a full-depth CTD measurement. States 1 and 2 (stratified and mixed, Figure 14a) exhibit a similar cross-shelf pattern which is due to the regions of shallow and deep bathymetry bisected by the Ellett Line. States 3 and 4 (wind-driven) are shown separately due to the much lower values of \(\varphi\) in the absence thermal stratification (Figure 14b). Easterly wind stress (state 3) is associated with higher stratification in the eastern SoH and west of the Hebrides, which is consistent
with the presence of a ROFI-type structure adjacent to the land. Westerly wind stress is associated with greater stratification in the Sound of Mull (Station 1G) which, in accord with other measures in this study, we take as evidence of local freshwater runoff residing at the surface, as the passage of Atlantic storms also results in higher precipitation. The higher stratification and lower SS east of the Hebrides (Station 10G) is noteworthy as to reach this station, freshwater must be advected southwards along the eastern coast of the Hebrides (see inset in Figure 1). This suggests that a more localised coastal current containing (though not necessarily driven by) freshwater runoff is active during stormy periods when the SCC (in its buoyancy-driven form) is largely inactive.

Figure 14: [In colour] Time-mean of Ellett Line potential energy anomaly observations grouped by their hydrographic / meteorological state (as described in Figures 8-11). SE: Shelf edge, Heb: southern tip of the Hebrides, TPM: location of Tiree Passage Mooring. (a) compares mixed and stratified conditions; wind-forced states are shown in (b) for clarity. Note different y axis.

We can gain some insight on the implications of these states for discrete observations by examining time series of SS and $\varphi$ at Station 7G (Figure 15). This station exhibits some of the highest variance on the shelf, and is better sampled than other stations in the SoH (Figure 6a shows ESS sample frequency).

In this location both summer and winter observations feature high variability (Figure 15a), though on average SS is slightly higher in the winter (e.g. Figure 12). Easterly wind stress has the clearest effect on SS, as all instances are associated with very low salinities. While the availability of full-depth CTD profiles is limited, 3 of the 4 observations made following easterly wind stress show above average levels of stratification for winter (Figure 15b). There is not a clear relationship between SS and westerly wind stress at this location; while some of the high SS observations in the 1990s were preceded by westerly winds, many high SS events are not linked to westerly wind stress. However
strong westerly winds are associated with levels of stratification below the winter average (Figure 15b).

![Station 7G](image)  

**Figure 15**: [In colour] (a) ESS time series at station 7G on the Ellett Line. Observations are coloured by the hydrographic / meteorological state which preceded them (as described in Figures 8-11). (b) Potential energy anomaly (ϕ) observations at station 7G. For clarity, only winter observations are shown.

There is substantial evidence in the literature that wind stress enhances residual flow on Malin Shelf, and that westerly winds produce favourable conditions for the import of oceanic water to the coastline (Burrows et al., 1999; Hill and Simpson, 1988; Inall et al., 2009; Xing and Davies, 1996). It is therefore surprising that this pattern of wind stress does not show a strong relationship with SS observations. We suggest several factors which may contribute to this finding. The pulses of high salinity recorded by the TPM (and occasionally by the Ellett Line) are short-lived and are often followed by an unusually fresh episode, presumably due to the enhanced contribution from freshwater runoff associated with winter storms. The discrete observations of the ESS time series (with irregular sampling averaging 3 times per year) are likely to under-sample or alias this mode of variability which occurs on timescales of days or weeks.

As indicated by the TPM current meter observations in Figures 12 c and f, poleward residual flow on the inner shelf during and following a wind event can exceed 25 cm s⁻¹ for 10 days, which would equate to a tracer transport of over 200 km. For comparison the distance between the shelf edge and Tiree Passage via the accepted flow pathway for oceanic water is 130 km (Figure 1), so it seems probable that water can be advected rapidly from the shelf edge during storms. The assumption implicit in the 4-state model is that this process will be additive, with the impacts of individual wind events being summed over time. However the events examined in Figure 12 suggest that the inner
shelf tends to quickly return to its ‘pre-forced’ state (states 1 or 2), and that it may require multiple
wind events in quick succession to maintain a flow long enough to import oceanic water to the inner
shelf. In addition, the high flow speeds recorded in Tiree Passage during storms imply a faster
turnover of shelf water. Consequently, the assumption of ‘additive’ wind forcing, and the flushing
time estimate of 60 days for Malin shelf, are probably inappropriate for this scenario. However the
4-state model does appear to predict when shelf-wide SS will be lower due to easterly wind stress. If
this effect was simply a form of ‘plume broadening’, we might expect it to quickly return to its pre-
forced state in the absence of wind as for the westerly scenario. The implied longevity of the
easterly events (such that they can be captured by the ESS time series) supports the hypothesis of
McKay and Baxter (1985): that a pulse of Irish Sea water is propelled onto the southern Malin shelf,
which results in reduced SS and a well-defined baroclinic coastal current for several months, until it
is mixed or advected off the shelf. The Ellett Line section in Figure 10 provides some evidence for
this theory, as a pronounced haline structure exists on the shelf despite the fact that easterly wind
stress ceased 20 days prior to sampling, and strong westerly winds prevail. This effect would be
additive, with successive pulses of Irish Sea water contributing to the mix on the shelf, and we
suggest that this is why it is more successfully predicted by the 4-state model.

6.3 Application for other regional studies
This work demonstrates that the multiple drivers in a shelf system can mask coherent signals in
variability, but that knowledge of these drivers can allow a level of determination of how a system
can respond to (or be resilient to) climate variability. As we have discussed, the hierarchy of
processes observed on the Malin shelf are somewhat anomalous when compared to literature on
buoyancy-driven flows in other regions. Here, a wind-driven process is the main source of buoyancy
on this region of shelf, which means that the contributions from wind and buoyancy cannot easily be
decomposed. In addition the east-west geometry of the north coast of Ireland enables a set-up of
downwelling flow along this coastline during westerly winds, which both advects oceanic water
towards Scotland and blocks the outflow from the Irish Sea.

In other respects our findings regarding wind-driven barotropic flow and its impacts on tracer
advection are compatible with the hydrography in other shelf locations. Despite the capacity of
wind to exert a powerful influence on the shelf, the recurring themes of time and space scales
appear to dictate the overall importance of wind vs. buoyancy for long-term changes. The ratio of
buoyancy-driven flow to wind-driven flow for the SCC appears to be roughly analogous to smaller
river outflow systems (Münchow and Garvine, 1993b; Souza and Simpson, 1997; Wiseman et al.,
1997). While there is a high volume flux from the Irish Sea feeding the SCC (3–12 x 10$^{4}$ m$^{3}$ s$^{-1}$,
Bowden and Hughes (1961), Brown and Gmitrowicz (1995)) it is only 1.5 units fresher than the
ambient shelf water so does not contribute buoyancy as effectively as a direct riverine or estuarine
outflow. The relatively weak buoyancy-driven flow of the SCC can therefore be easily overpowered
by wind-forced currents.

Nevertheless, long-term observations of salinity suggest that buoyancy is the process most likely to
be captured by the inter-annual record. We speculate that this finding is due to the typical brevity of
wind events: low pressure systems transit the area rapidly and their effects rarely last more than 1-2
days. A wind speed of 20 m s$^{-1}$ may set up a current which can advect material a distance of 10-20
km in a matter of hours (Whitney and Garvine, 2005) but this situation is rarely sustained, and it
seems that complete displacements or reversals of the SCC are dependent on near-continuous
storm-level wind forcing for at least 5-10 days. By combining a long-term shelf transect with a high-
resolution coastal mooring, we have also illustrated the nature and temporal scale of processes
which are likely to be missed by sporadic transect occupations. Based on this study, to satisfactorily
capture the short-term physical variability would require a sampling frequency less than the
estimated shelf flushing time of 2 months. However given the limitations of budget and
infrastructure, the minimum sampling schedule to characterise the shelf would include at least one
mid-summer and one mid-winter occupation, in addition to the high resolution coastal data
provided by the TPM.

6.4 Basin-scale influences on the Malin shelf

While water temperatures are not the primary focus of this work, we have found some evidence to
support the assertion of Inall et al. (2009) that the inter-annual temperature anomaly recorded by
the TPM may be influenced by basin-scale temperature fluctuations (Figure 2b). Accordingly, the
trend in recent years for a return to a stronger SPG (Holliday and Gary, 2014) may result in a minor
decrease (-0.5 °C) in temperature anomalies and increase in the availability of nitrate (+ 0.5-1 µM)
and phosphate (+ 0.05-0.1 µM) on the shelf as the Rockall Trough receives a greater contribution
from distant sub-polar waters (Johnson et al., 2013). An interesting continuation to this work would
be to examine the Ellett Line nutrient observations for evidence of this effect. We find the winter
NAO index to have only an indirect relationship with the salinity time series developed in this work.
Examining Figure 16, the Atlantic (Irish Sea) dominated state is more likely during high (low) NAO
winters, but many exceptions exist. Due to the suspected faster flushing time of Malin shelf during
the winter months, the origin of water on the shelf or near the coast is likely to be mediated by more
local trends in storm track and distribution than can be captured by the NAO index. While longer
period fluctuations such as the Atlantic Multidecadal Oscillation have been observed to impact
coastal temperatures on long timescales on Malin shelf (Cannaby and Husrevoglu, 2009), the
present salinity time series is too short to determine whether this mode of variability underlies the
stronger year-to-year changes.

Figure 16: [In colour] (a) DJFM NAO index, (b) Malin wind index aggregated by month and year. A coloured month indicates that the previous 60 days fulfilled the criteria for either easterly or westerly wind stress. While the index is calculated on a daily basis, months are aggregated using the mode (most common) state for that month.

6.5 Impact of local meteorological forcing on biology and biogeochemistry

The shorter-term switching between hydrographic states on the shelf probably has greater
consequence for local biology. The distribution of zooplankton species for example has been found
to clearly track the position of fronts which separate Irish Sea and Atlantic water (Gowen et al.,
1998; Miller, 2013). Taking a mean salinity of 34.15 for the Irish Sea and 35.37 for the Rockall
trough, state 4 (forced by westerly winds) represents a mix of 62 % Atlantic water to 38 % Irish Sea
water at in the SoH. Meanwhile state 3 (forced by easterly winds) results in only a 6 % contribution
from Atlantic water and the remaining 94 % supplied by the Irish Sea. Note that as inferred by
Figure 12, during very strong westerly wind events the Atlantic contribution may briefly be much
higher than these averages suggest.

This wind-driven process represents an episodic but important alteration to flow pathways to the
SoH and by continuation through the Minch into the North Sea, which has clear consequences for
the supply of heat and nutrients to the coast, and the transport of organisms and pollutants along
the shelf. The main source of nutrients to the Malin Shelf is the open ocean (Proctor et al., 2003)
and the presence or absence of nitrate is identified as the limiting factor in productivity by Smith et
al. (2014). A modification in the ingress of oceanic water onto the shelf, and particularly its access to
the coastline, could therefore significantly impact phytoplankton bloom timing and dynamics.

Coastal blooms of harmful phytoplankton are known to impact fishing and aquaculture industries, and harm human health (Berdalet et al., 2016). In particular, blooms of the destructive ‘red tide’ dinoflagellate *Alexandrium fundyense* are thought to be mediated by water mass positioning and front strength in the western Gulf of Maine (Luerssen et al., 2005). Red tides have been observed in Scottish waters (Jones et al., 1982) but the nutrient supply is typically from land runoff. Few biological studies have been conducted on the Malin shelf during the westerly wind-forced periods highlighted here, as they represent extremely stormy episodes and typically preclude fieldwork. However winter sampling of the European shelf has improved in recent years with the regular deployment of autonomous gliders with biological sensors.

**Acknowledgments**

This work was funded by UK NERC through the Fluxes Across Sloping Topography of the North East Atlantic (FASTNET) campaign (NE/I030151/1). The Tiree Passage Mooring was funded by UK NERC through the Oceans 2025 programme and national capability funding. We would like to thank Sirpa Häkkinen, (NASA Goddard Space Flight Centre) for supplying the altimetry-derived Subpolar Gyre index.

**Appendix A: Quality control of the Tiree Passage Mooring salinity time series**

Sustained salinity sampling in Tiree Passage is challenging due to the exceptionally high levels of marine life present in the channel during the summer months, and the susceptibility of instrument conductivity sensors to fouling. The conductivity data from Andera RCMs (used routinely between 1981 and 2002) were found to be highly prone to sensor drift when deployed for more than 30 days, and calibration CTD samples were rarely collected. Due to low confidence in these data, salinity data acquired from the TPM prior to the redeployment of the mooring in 2002 were treated as unrecoverable.

This study instead focuses on salinity data obtained from Sea-bird Microcat sensors which were added to the standard mooring array post-2002. Even on these more reliable sensors, certain models were found to be prone to drift. In general, it was found that devices fitted with an anti-fouling plug were more resistant to fouling-related sensor drift. CTD profiles were often undertaken at the beginning and end of mooring deployments, and these provide a means to validate the mooring salinity data. A CTD profile was typically carried out within 2 hours of deployment and in the vicinity of the mooring.
In Figure A.1, the salinity measured by TPM at 20 m depth is compared to independent observations. The maximum, minimum and mean salinities measured by each calibration CTD are shown in red. In addition, the other datasets comprising the TPC time series are included to provide improved temporal coverage.

![Figure A.1: Comparison between salinity measured at Tiree Passage Mooring (black points) and supplementary data from within Tiree Passage (the TPC time series). Description of the construction of the TPC time series in Section 3.3. (a) shows the period between 2002 and 2007; (b) the period between 2007 and 2014. Period shaded in grey shows the TPM data rejected due to sensor drift. Dashed black lines indicate the affected mooring deployment dates.](image)

In general, the Microcats were found to perform well with most salinity data falling within the error bars of the independent observations. The only period of concern was between 2005 and 2007 which appeared to show a systematic decline in the salinity reported by the mooring, which is not corroborated by any other datasets. Whilst this decline spans multiple mooring deployments, it was found that the same instrument was redeployed repeatedly during this period due to a lack of alternatives. Therefore it is suspected that this salinity decline was a systematic sampling error due to sensor drift. Due to the severity of the drift (reaching 0.6 units), no attempt at correction was made and the salinity data returned by deployments 398, 399, 400, 403 and 407 (between 25/02/2005 and 08/11/2006) were rejected. A full list of mooring deployments and instrument numbers is available in Jones (2016).
Appendix B: Estimating uncertainty in the Tiree Passage Composite salinity dataset

The TPC salinity time series is comprised of 5 discrete datasets: 20 m observations from Microcats on the TPM, calibration CTD data obtained at the beginning and end of most TPM occupations, CTD data from Station 2G on the Ellett Line, CTD data obtained from ICES and surface underway data obtained from ICES. The following describes the approach used to minimise the chance of aliasing the TPC time series through data type or sample location.

CTD data were subsampled at 20 m depth (in accordance with the TPM sensor depth), and the basic error estimated using the maximum and minimum salinity recorded by the CTD. The ICES surface underway dataset cannot be sampled at 20 m: observation depths vary between 0 and 10 m due to the range of vessels and techniques contributing to the data set, and in a ROFI regime the inclusion of this dataset may result in a small fresh bias resulting from the regularly salt-driven density structure. The magnitude of this potential error can be estimated using the available CTD data in Tiree Passage, as the mean of 5 m CTD salinity subtracted from 20 m CTD salinity for all observations. A mean salinity difference of 0.04 between 5 m and 20 m is found to be present in Tiree Passage, but with a standard deviation of 0.07. Given the high variance associated with the estimated error, no correction was attempted but the estimated error ascribed to the ICES surface underway dataset was enlarged accordingly.

Tiree Passage is semi-enclosed, relatively well mixed vertically (Gillibrand et al., 2003; Inall et al., 2009) and is subject to little modification throughout its length, so offers a level of spatial homogeneity in an otherwise complex region. However, there is a tendency for fresher water to inhabit the landward (eastern) side of the channel (Gillibrand et al., 2003) so there is the risk of spatial salinity biases arising from sampling inshore or offshore of the TPM location.

In an attempt to account for these spatial biases, an error was estimated as a function of the across channel distance of data from the TPM location (56.625 °N, 6.4 °W). A linear regression was fitted using the R statistical package, using the across channel distance as a predictor, and the composite salinity observations as the response variable. A significant relationship between salinity and across channel distance was found, but the magnitude of the computed spatial error was deemed to be minor (0.03 units/km). However estimated errors associated with each observation were enlarged according to their across-channel displacement from the TPM.
Appendix C: Constructing the Ellett Line Surface Salinity (ESS) time series

To merge historical data with the Ellett Line time series, each Ellett Line station was assigned a search radius around its nominal location. In recognition of the increasing hydrographic complexity towards the coast, the search radii were decreased in size from +/- 0.1° at the shelf-edge to +/- 0.05° at station 1G: the regions associated with each station are illustrated by the rectangular boxes in Figure 1. All observations were binned into four seasons (DJF, MAM, JJA, SON). SS anomalies (Figure 6c) were calculated by subtracting the time-mean SS for each station from its time series.

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