

The influence of ocean variations on the climate of Ireland

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Introduction

That the temperature of small islands downwind of large oceans reflects that of the neighbouring ocean is a basic principle of a maritime climate. Such is the case with Ireland, where prevailing southwesterly winds bring warm, moist air onshore in winter, maintaining the relatively mild climate there. The climate of Ireland – and indeed northwestern Europe in general – is sometimes contrasted with locations on the other side of the Atlantic. St John's in Newfoundland is at a similar latitude, but average wintertime (annual) temperatures are over 9 degC (5 degC) lower than those of Dublin in Ireland (Figure 1). However, this comparison is not valid when discussing the impact of the ocean on the climate of Ireland. Newfoundland, although an island subject to maritime influences, does not have a maritime climate. In winter, Newfoundland is subject to prevailing winds arriving over the frigid North American continent (with the only maritime influence coming from the cold Labrador Current flowing offshore).

It is more valid to contrast a maritime climate such as Seattle with that of Dublin. Seattle is located a similar distance from the Pacific as Dublin is to the Atlantic, yet mean winter (annual) temperatures are 4.3 degC (1.5 degC) lower than those of Dublin, in spite of Seattle being 6° of latitude closer to the equator (Figure 1). This remaining temperature differential is generally ascribed to larger ocean heat transport in the Atlantic than in the Pacific. Originally, as popularised by Maury (1855), the picture was of the Gulf Stream carrying warm water in the direction of northwestern Europe. The nomenclature of Maury (1855) has been updated to more accurately describe the current as the North Atlantic Current (Sweeney, 2014), which describes the continuation of the Gulf Stream on leaving the coast of the United States at Cape Hatteras.

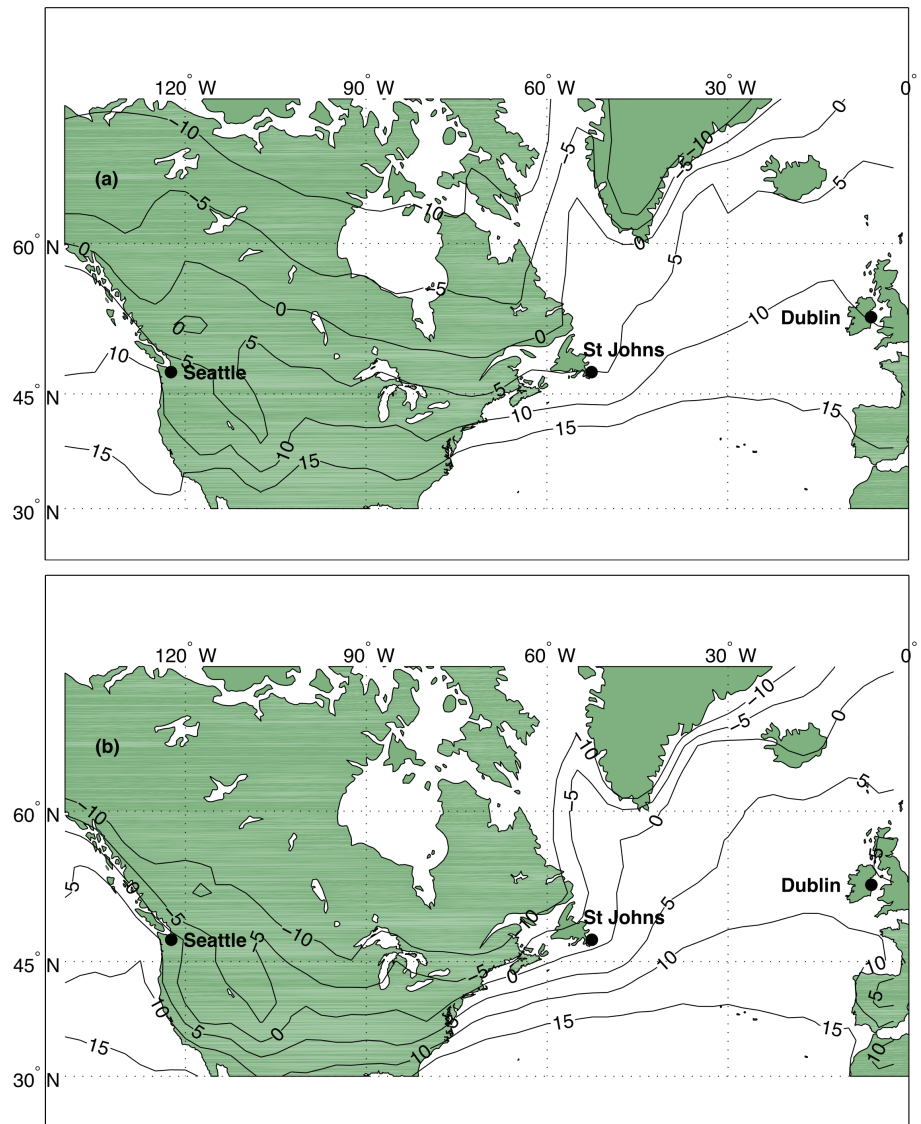


Figure 1. (a) Annual mean surface air temperatures (°C), from the NCEP reanalysis (Kalnay et al., 1996), 1948–2013. The 10°C contour borders the maritime climates of Dublin and Seattle in spite of Dublin being 6° farther north. By contrast St. John's is 5 degC cooler than Seattle in spite of having practically identical latitudes. (b) The pattern is even more pronounced in winter (Dec–Feb) when the 5°C isotherm is south of Seattle, whereas the 5°C isotherm is closer to Iceland than Ireland during the same period.

However, the idea of an ocean current transporting warm water in this manner is an overly simplistic way of considering ocean heat transport. A true heat transport requires zero mass transport (Montgomery, 1974). This framework can be pictured by considering the latitude of 26°N. At this

latitude, a relatively constant Gulf Stream in the Florida Straits carries 32Sv (1Sv = $10^6\text{m}^3\text{s}^{-1}$) of warm, shallow (<1000m) water northwards. Just over half of this (18Sv) is recirculated southwards in the almost equally warm, shallow waters of the subtropical gyre, the rest returning in the cold,

deep waters of the Atlantic overturning circulation, primarily as North Atlantic Deep Water formed in the Nordic and Labrador Seas. If all the Gulf Stream waters were recirculated in the gyre, then little heat would be transported northwards. Therefore, the majority (90%) of the 1.3PW (1PW = 10^{15} W) of heat transport at 26°N is carried in the overturning circulation (Johns *et al.*, 2011; McCarthy *et al.*, 2015b). While the proportion of heat transported in the overturning circulation changes moving northwards, with more heat carried in the horizontal circulation (Grist *et al.*, 2010), the key idea is not just where warm water is going but also where cooler water is returning. Most of the 1.3PW transported by the ocean at 26°N is released to the atmosphere over the North Atlantic such that only 0.3PW of heat is transported by the ocean across the Greenland-Scotland ridge (Østerhus *et al.*, 2005). It is this heat, released by the Atlantic over the mid- to high-latitudes, that is the key to the maintenance of warmer temperatures in Dublin than in Seattle.

But even this framework has been challenged. Seager *et al.* (2002) (and a number of popular publications, e.g. Seager (2006)) challenged the view that ocean heat transport was important to the maintenance of the relatively mild northwestern European temperatures. They claimed that atmospheric patterns of prevailing winds induced by orographic forcing from the Rocky Mountains leading to the prevailing southwesterlies in Ireland render the importance of ocean heat transport in the maintenance of mild temperatures negligible. They suggest that the ocean's role could be reproduced by a static slab ocean, which merely acted as a seasonal heat storage device, storing summer heat and releasing it in winter. Unsurprisingly, the Seager *et al.* (2002) paper provoked some reaction in defence of the importance of the ocean circulation and ocean heat transport in the climate system. Rhines *et al.* (2008), for one, maintained the importance of ocean heat transport and emphasised a key missing element of the work of Seager *et al.* (2002): the crucial role of latent heat fluxes and moisture transfer between the atmosphere and the ocean (i.e. that it not only mattered that the ocean was warm but also that it was wet). Also, surface conditions in the Atlantic – in particular sea-surface temperature gradient set by the location of ocean current – also influence the prevailing atmospheric circulation (Brayshaw *et al.*, 2011). In a coupled system, like the atmosphere–ocean, it is not possible to entirely separate the effects of orographically forced winds from the role of ocean heat transport. The wind pattern induced by the Rocky Mountains is undoubtedly important for Europe's mild climate. Indeed, the pattern of winds may even be important in maintaining vigorous Atlantic heat

transport (Sinha *et al.*, 2012). Nonetheless, ocean heat transport does play an important role in the maintenance of a relatively mild climate in northwestern Europe.

A simple thought experiment to consider the influence of ocean heat transport on the climate of northwestern Europe is to ask: what happens when it is turned off? Studies have shown that a collapsed overturning circulation would reduce the temperature over the North Atlantic by, in one example, 6 degC (Rahmstorf, 2002). Evidence for shutdowns in the overturning circulation has been found in ice core records (Dansgaard *et al.*, 1993), but similar evidence is not present in the contemporary instrumental record. Shutdowns are thought to be highly unlikely (<5% probability) in the present day, according to the latest Intergovernmental Panel for Climate Change report (Stocker *et al.*, 2013). What does exist in contemporary temperature records is evidence of significant multi-decadal variability, dating back to the late nineteenth century.

A prominent mode of multi-decadal variability is the Atlantic multi-decadal oscillation (AMO), which consists of spatially coherent changes in North Atlantic sea-surface temperature (SST) with a peak-to-trough amplitude of 0.5 degC and with a timescale of around 60 years for the twentieth century, though the record is too short to know if 60 years is a fundamental mode. The AMO used in this study (<http://www.esrl.noaa.gov/psd/data/timeseries/AMO/>) is calculated by averaging the SSTs over the whole North Atlantic and removing a linear trend. It is sometimes taken that the linear trend removed is representative of forced variability, especially anthropogenic warming, and that the AMO is solely an internal oscillation. However, removing a linear trend does not necessarily remove the forced variability, even when it is known a priori (Mann *et al.*, 2014). Nonetheless, an accepted AMO index that represents solely internal variability does not yet exist, so we use the standard, linearly-detrended AMO for this study. Positive periods of the AMO are associated with warm SSTs such as occurred during the 1940s and the 1990s. Negative periods are associated with cold SSTs such as occurred during the 1970s. Recently, it has been suggested that we are entering a negative AMO phase again (Klowner *et al.*, 2014). Fluctuations in North Atlantic heat transport are commonly found to be the cause of these SST oscillations in numerical models (Schmith *et al.*, 2014). Direct observations of ocean heat transport of sufficient length to support the ocean control of the AMO do not exist. Recently, new analysis of tide gauge data used as a proxy for ocean circulation has provided the first observational support for the role of ocean circulation in this multi-decadal oscillation

(McCarthy *et al.*, 2015a). Observational support for ocean control of the AMO had previously been found indirectly in air-sea fluxes (Gulev *et al.*, 2013).

Interpretation of Irish climate records in the context of a dynamic ocean

Here, we emphasise the role of ocean circulation on the climate of Ireland by focusing on the impact of these ocean circulation driven multidecadal oscillations. We focus on the analysis of the annual mean temperature of Ireland based on five long-term stations since the beginning of the twentieth century (Figure 2(a), Dwyer, 2012). This station-based record shows good agreement with the NCEP surface air temperature but is an independent record when comparing with SST (SST data are considered in the NCEP reanalysis (Kalnay *et al.*, 1996)). The temperatures show an overall upward trend in line with global warming. However, significant multi-decadal variability is evident in the 20-year running average. A significant feature is the cooling of 0.1 degC/decade that occurred from the mid-1940s to the mid-1970s. This feature is more pronounced in Irish temperatures than it is in the global temperature record (McElwain and Sweeney, 2003, their Fig. 2). This cooling occurred quickly. To contrast, the cooling in Irish temperatures during these three decades is almost twice as large as the mean global surface temperature increase of 0.6 degC/century (Stocker *et al.*, 2013) since the late nineteenth century (although warming in recent decades is larger than this century-length estimate). Figure 2(b) shows the linearly detrended Irish temperature record with the AMO overlaid. Practically all of the multi-decadal variability in Irish temperature is captured in the AMO. The 20-year filtered time series have a correlation of 0.9. Using a long filter length limits the degrees of freedom, and the real degrees of freedom could be even less than that set by the filter length, so, to determine the significance of this correlation, we use scrambled tests (Ebisuzaki (1997)), which estimate the significance level as 93%. The high degree of correlation in itself is not surprising: as we stated, the temperature of small islands downwind of large oceans reflects that of those oceans. The influence of the AMO on decadal temperature fluctuations in the whole northern hemisphere has been highlighted previously (Muller *et al.*, 2013), but the degree of similarity in the Irish record is striking. An immediate conclusion is that fluctuations in the circulation of the Atlantic are the likely cause of the cooling from the 1940s to the 1970s. Once these ocean oscillations are accounted for and removed (Figure 2(c)), a rise in temperatures since the beginning of the record is more evident.

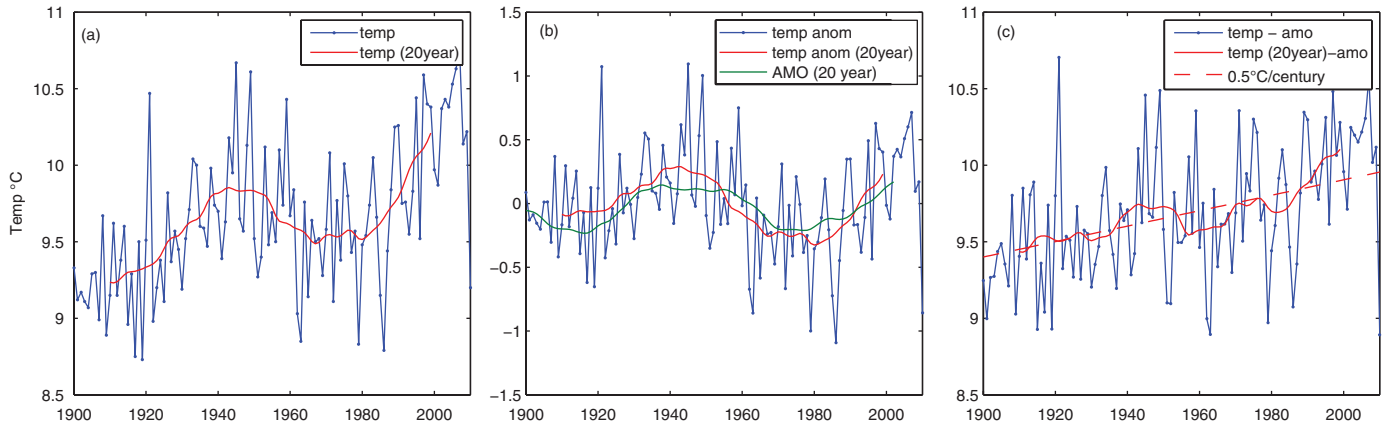


Figure 2. (a) Annual (blue) and 20-year low-pass filtered (red) Irish land temperatures. (b) Detrended annual (blue), 20-year low-pass filtered (red) Irish land temperature anomalies (relative to the full period) and the AMO based on the Kaplan SST dataset (green). (c) Annual (blue) and 20-year low-pass filtered (red) Irish land temperatures with the AMO subtracted and a linear trend fitted to these data (red, dashed).

The 0.5 degC/century warming signal that remains following the removal of the AMO is consistent with the global warming signal reported by Stocker *et al.* (2013) including a suggestion of increased warming in recent decades.

Further support for the dynamic ocean's role in the multi-decadal variability in the temperature of Ireland can be found in analysing the pattern of the SST changes during the warm (1935–1948, Figure 3(a)) and the cool (1971–1984, Figure 3(b)) periods of the AMO and the Irish temperature record. Figure 3 includes contours of satellite derived mean dynamic topography that can be interpreted as mean ocean circulation streamlines (for the period 1993–present). The intensified warming and cooling that occurs near 45°N, 45°W overlies the zero line of dynamic topography (i.e. approximately the mean path of the Gulf Stream and its extension). This line also marks the boundary between the subtropical gyre and subpolar gyre. It is no coincidence that the

largest changes in SST overlie this intergyre region, as the patterns of circulation in this region have been linked to changes in the AMO (McCarthy *et al.*, 2015a). Indeed, the region around 45°N, 45°W is just upwind of the so-called 'warming hole' in surface air temperatures that has been linked to a declining Atlantic overturning circulation (Drijfhout *et al.*, 2012).

The ocean circulation not only affects temperature but also the precipitation patterns. Sutton and Dong (2012) have shown that summer precipitation patterns in north-western Europe are related to AMO induced changes in atmospheric circulation with drier (wetter) summers being associated with a negative (positive) AMO. This is certainly consistent with long-term (1941–present) rainfall records in Ireland (Figure 4, Dwyer, 2012), though the relative brevity of these precipitation records poses a problem when drawing concrete conclusions. During the cold phase of the AMO in the 1970s there was less summer precipitation in Ireland. The

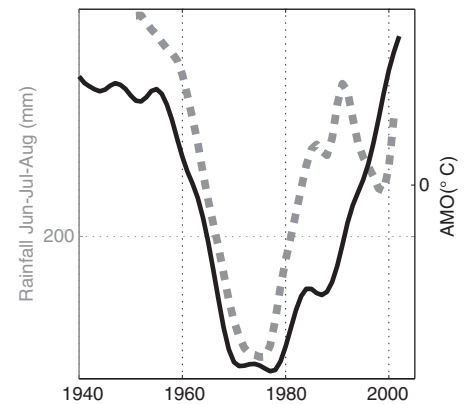


Figure 4. 20-year low-pass filtered Irish summertime (JJA) rainfall records from the 1940s (grey, dashed) show a similar pattern of variability to the AMO (black).

average precipitation for the Irish summer (June, July, August (JJA)) during the 1970s saw 183mm of rainfall in comparison with 234mm for the 1940s and 236mm for the 2000s. While this is a relatively large percentage change (the 1970s were 22% drier relative to either the 1940s or 2000s), due to the highly variable nature of precipitation, only the change between the 1970s and the 2000s is significant at the 95% level. No such relationship with the AMO exists with winter precipitation, which has been related to the winter North Atlantic Oscillation (Sweeney *et al.*, 2002).

Conclusions

In this paper, we have analysed long climate records from Ireland to assess the role of the ocean circulation on long-term trends in temperature and precipitation. Ireland is particularly influenced by the ocean as it is a small land mass bordering a large ocean. How the ocean influences the climate is perhaps a more subtle question than what is held in the popular conscience. Original concepts of an ocean river of warm water flowing towards Ireland have been replaced with the ideas of ocean heat transport, car-

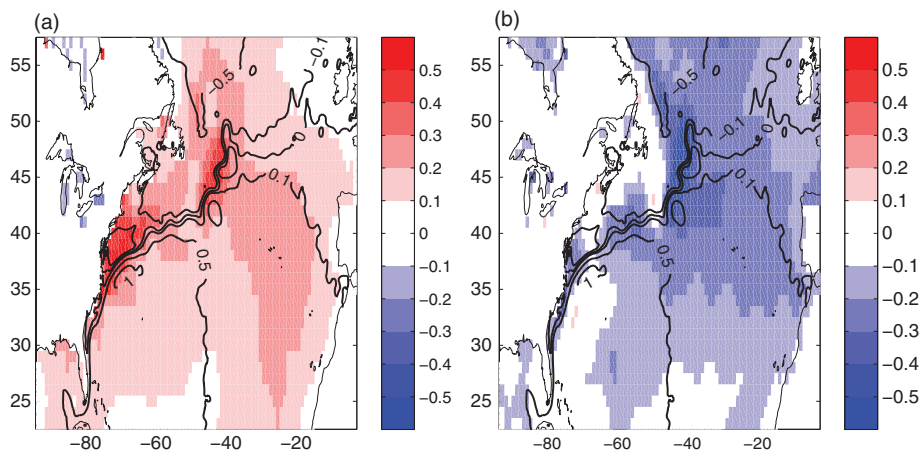


Figure 3. SST anomalies (HadISST dataset, Rayner *et al.*, 2003) from (a) 1935–1948 and (b) 1971–1984, relative to 1900–2010. Contours of mean dynamic topography in metres (1993–2004) are overlaid in black and can be interpreted as mean streamlines. Anti-cyclonic (negative) contours describe the subtropical circulation and cyclonic (positive) contours describe subpolar circulation. The zero contour nominally depicts the mean path of the Gulf Stream and its extension. The intensified warming/cooling around 45°N, 45°W occurs close to the warming 'hole' of Drijfhout *et al.* (2012).

ried primarily in the Atlantic overturning circulation, converging and diverging to release greater or lesser amounts of heat to the atmosphere. Even this picture has been challenged, with some suggesting that the patterns of prevailing winds largely induced by the Rocky Mountains are more important than ocean heat transport. We sidestep this debate by focusing on the influence of multi-decadal variability on the climate of Ireland – as important as the Rockies may be, they cannot contribute to multi-decadal variability. Through its influence on SSTs, ocean circulation has a major influence on the mean annual temperature and summertime precipitation. This multidecadal variability can be twice as large as background global warming. It is crucial when interpreting long climate records that such variability is understood. Otherwise, decades of cooling can be seen as a contradiction to increased surface temperature trends (in response to continually increasing greenhouse gas emission) when natural ocean variability may be the cause. The ocean has generally been implicated as the likely heat sink in the current global warming ‘hiatus’. Most studies highlight the cooling of surface waters in the tropical Pacific (e.g. Kosaka and Xie (2013)) as a source of the missing heat. However, the Atlantic has recently been highlighted (Chen and Tung, 2014) as a location for this missing heat. Such ocean variability needs to be borne in mind when interpreting slowdowns or surges in global warming.

The patterns of SST warming and cooling can be related to the imprint of changes in the Atlantic overturning circulation (Drijfhout *et al.*, 2012). In a warming climate, the overturning circulation is predicted to slow by around 0.5 Sv/decade (Stocker *et al.*, 2013). Observations of the overturning circulation have seen a rapid decline of 0.5 Sv/year over the first 10 years (Smeed *et al.*, 2014). This could contribute to a decline in the AMO (Klower *et al.*, 2014). Consequently, cooler temperatures (and drier summers) in Ireland relative to a background of increasing global temperatures may well be expected.

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