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Impacts of climate change on air-sea exchanges of heat and water

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EXECUTIVE SUMMARY

Changes in the air-sea fluxes of heat and freshwater are expected as a result of anthropogenic climate change. Studies of increasing observed ocean heat content place a limit of about 0.5 W m^{-2} on the increase in the global ocean mean net surface heat flux. Given the high level of uncertainty in available flux datasets this signal is likely to be very difficult to detect. A similar situation holds for the surface freshwater flux, for which there are additional problems associated with obtaining reliable long-term estimates of precipitation. Observations of changing ocean salinity suggest a strengthening of the hydrological cycle but further research is required to link this to changing freshwater flux. Variations in freshwater exchanges in the UK marine environment may also occur as a result of shifts in the spatial patterns of the major modes of atmospheric variability.

1. WHAT IS ALREADY HAPPENING?

The air-sea fluxes of heat and freshwater form two key elements of the climate system. The underlying processes determining these fluxes have been discussed in the previous scorecard (MCCIP 2009) and here we give an update that focuses on subsequent developments. As previously noted, both the heat and freshwater flux are expected to change in response to global warming and a stronger hydrological cycle. Since MCCIP 2009, there is further observation-based evidence for an increase in global ocean heat content (e. g. Levitus *et al*., 2012). These observations imply an increase in the global mean net heat flux into the ocean at the same small level stated in MCCIP 2009, to about 0.4 - 0.5 W m^{-2}. It remains the case that this signal is too small to be detected with currently available heat flux datasets and this situation is unlikely to change in the near future.

Ocean salinity is expected to change in response to a strengthening of the hydrological cycle as a result of variations in the air-sea freshwater (evaporation – precipitation) flux. New observation based analyses have revealed significant changes in ocean salinity which strengthen earlier results suggesting that high salinity regions have become more salty and low salinity regions have become fresher over the past 40 years (Hosoda *et al*., 2009; Durack and Wijffels, 2010).

The heat and freshwater fluxes are discussed in detail below. We also update a section from MCCIP 2009 which described how these two fields are used to determine the air-sea density flux and research into using the density flux to obtain estimates of North Atlantic overturning circulation variability at mid-high latitudes including UK waters.

Air-sea heat flux

The net air-sea heat flux is the sum of two turbulent heat flux terms (the latent and sensible heat fluxes) and two radiative terms (the shortwave and longwave fluxes; see MCCIP 2009 for full discussion). Surface flux datasets have been determined in a wide range of studies using three primary sources a.) surface meteorology reports (mainly from Voluntary Observing Ships), b.)satellite observations and c.) atmospheric model reanalyses which assimilate various data types (see Josey, 2011 for a recent review).

Surface meteorology report based flux datasets have been produced at the National Oceanography Centre (NOC1.1, Josey *et al*., 1999; NOC1.1a, Grist and Josey 2003; NOC2, Berry, 2009; Berry and Kent, 2009; Berry and Kent, 2011). NOC2 is the only flux dataset to have error estimates for all of the basic meteorological and derived flux fields. Since MCCIP 2009, NOC2 has been updated to cover the period 1973-2011 using the International Comprehensive Ocean-Atmosphere Data Set (ICOADS) release 2.5 for the additional period 2007-2011. As before, users of this dataset are advised to take account of the uncertainty estimates provided, and to note that in very poorly sampled regions, such as the Southern Ocean, the uncertainty estimates themselves may be unreliable.

Air-sea flux datasets have been derived from remote sensing observations in a variety of studies. A leading example is the Hamburg Ocean-Atmosphere Parameters and Fluxes from Satellite Data described in MCCIP 2009 which has now been updated to version 3.2 covering the period July 1987 – Dec 2008 (HOAPS3.2, Fennig *et al*. 2012). It remains the case that satellite estimates are limited by difficulties in measuring near surface air temperature and humidity from space which lead to major uncertainties in satellite turbulent heat flux estimates.

Since MCCIP 2009, several new atmospheric model reanalyses have become available, for example the NASA Modern Era Retrospective Reanalysis (MERRA) and the NOAA-CIRES 20th Century Reanalysis V2 (20CRv2). In addition, the first coupled ocean-atmosphere reanalysis has been undertaken at NCEP, termed the Climate Forecast System Reanalysis (CFSR). Full details of these and other products are available at https://reanalyses.org/atmosphere/overview-current-reanalyses. This new generation of reanalyses have in most cases been carried out on higher resolution grids than their predecessors but it remains to be determined whether this has led to significant improvements in the accuracy of the surface exchanges. Large differences in the hydrological cycle between many of the available reanalyses have recently been noted by Trenberth *et al.* (2011) and this is a source of concern.

Blended flux products make use of data from different sources, principally reanalysis and satellite based fields. The Objectively Analyzed air-sea Fluxes (OAFlux) dataset (Yu and Weller, 2007) blends reanalysis and satellite surface meteorology fields prior to estimation of the fluxes and since MCCIP 2009 this product has been updated through to Feb 2012. Large and Yeager (2009) developed the Coordinated Ocean Research Experiments version 2 (COREv2, spanning 1948-2006) turbulent fluxes by adjusting NCEP/NCAR reanalysis state variables prior to flux calculation. They combined these fields with satellite based radiative flux estimates to produce a globally balanced net heat flux field for forcing ocean models. However, the adjustments were based on limited period analyses and it is not clear to what extent COREv2 can be used to study interdecadal variability.

In MCCIP 2009, we discussed the mid-latitude North Atlantic net air-sea heat flux field for four products (NCEP/NCAR, NOC1.1, NOC2 and OAFlux), including the UK marine sector (MCCIP 2009, Figure 1). Here we show the corresponding fields for the four new flux products discussed above (CFSR, COREv2, MERRA and 20CRv2). Similar broad scale patterns to those noted in MCCIP 2009 are observed in each case with strong Gulf Stream heat loss and a west to east transition from ocean heat loss to ocean heat gain. The UK marine environment experiences close to zero annual mean net heat flux and it remains likely that Gulf Stream heat loss variations and their subsequent influence on the atmosphere are more important for UK climate than variations within UK waters.

The 20CRv2 reanalysis spans 1870-2008 (in contrast to other available flux products which all start at some point after 1948) and thus opens up the possibility for studies of flux variability at centennial timescales. However, it is difficult to assess its reliability given the lack of evaluation datasets over the early period. A time series of monthly net heat flux anomaly averaged over the box (40-55 °N, 20-40 °W) in the mid-latitude North Atlantic for the period since the mid-1940s when 20CRv2 can be compared with other datasets is

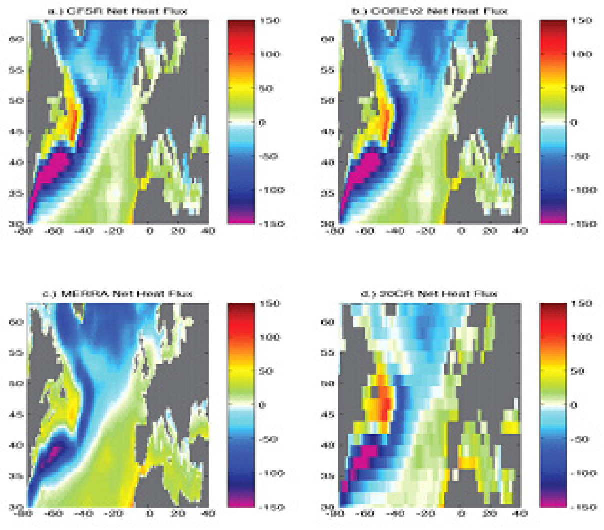


Figure 1: Annual mean net air-sea heat flux from a.) CFSR, b.) COREv2, c.) MERRA and d.) 20CRv2, units W m^{-2}. Blue colours : ocean heat loss to the atmosphere, red ocean heat gain.

shown in Figure 2 (a version of this figure without 20CRv2 appeared in MCCIP 2009). The month-to-month variability obtained with 20CRv2 is similar to that seen in other datasets with box-averaged anomalies often exceeding 50 Wm^{-2}.

As discussed in MCCIP 2009, observation and model based analyses both show that the changing air-sea heat flux signal associated with increasing global ocean heat content is small (Pierce *et al.*, 2006; Levitus *et al.*, 2009). Changes in the net surface heat flux over the past 50 years at global and basin scales are expected to be about 0.5 Wm-2 with corresponding individual heat flux component changes of less than 2 W m^{-2}. More recent analyses of changing ocean heat content support the small magnitude for the implied change in global mean net heat flux (e.g. Levitus *et al.*, 2012). It is still the case that currently available heat flux datasets are not sufficiently accurate to allow this change to be detected and this situation is unlikely to change in the near future.

Air-sea freshwater flux

The air-sea freshwater flux is given by the difference of evaporation from the ocean surface (E) and precipitation from the atmosphere (P.). Sources of data for E and P are discussed in MCCIP 2009. The main change in the intervening period is a revision of the satellite observation based Global Precipitation Climatology Project product which now spans October 1996 - June 2011 (http://precip.gsfc.nasa.gov/). Atmospheric model reanalyses also provide precipitation but caution is required due to inconsistencies in this field across a range of reanalyses (Trenberth *et al.*, 2011).

An update of the climatological annual mean freshwater flux field for 2006-2010 from NCEP/NCAR is shown in Figure 3 (the corresponding field for 1980-2005 was shown in MCCIP 2009) together with the near surface wind field. The main features of the updated field are similar to those shown previously, specifically a shift from west to east across the basin between weak ocean freshwater gain to weak ocean

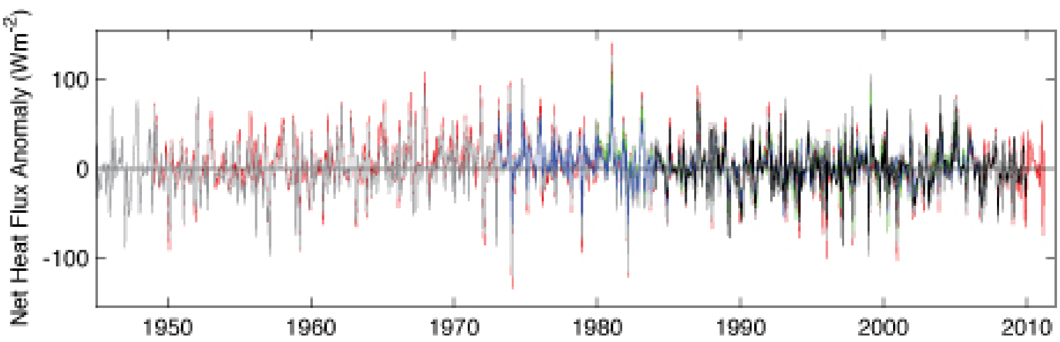


Figure 2: Monthly mean net air-sea heat flux anomaly for the box (40-55 oN, 20-40 oW) for the period 1870-2010 from NCEP/NCAR (red), NCEP 20CRv2 (grey), NOC1.1 (green), NOC2 (blue) and OAFLUX (black), units W m^{-2}.

freshwater loss in the UK marine environment. As before, the UK climate is likely to be affected by integrated ocean freshwater loss to the south-west in the Atlantic - note the strong Gulf Stream losses and north-eastwards direction of the air flow.

As noted in MCCIP 2009, variations in mid-high latitude North Atlantic freshwater flux are influenced by the two major modes of atmospheric variability - the North Atlantic Oscillation (NAO) and the East Atlantic Pattern (EAP), see Josey and Marsh (2005). Since 2010, the EAP has shown no tendency for a prolonged period in either state while the NAO has been predominantly negative which is expected to result in reduced net freshwater flux (precipitation - evaporation) to the ocean north-west of the UK.

It remains the case that ocean salinity fields may provide a useful indication of changes in the hydrological cycle through integration of freshwater flux anomalies. Since MCCIP 2009, observation based analyses by Hosoda *et al.* (2009) and Durack and Wijffels (2010) have revealed an increase (reduction) in salinity in high (low) salinity regions over the past 40 years. The pattern of ocean salinity change is similar

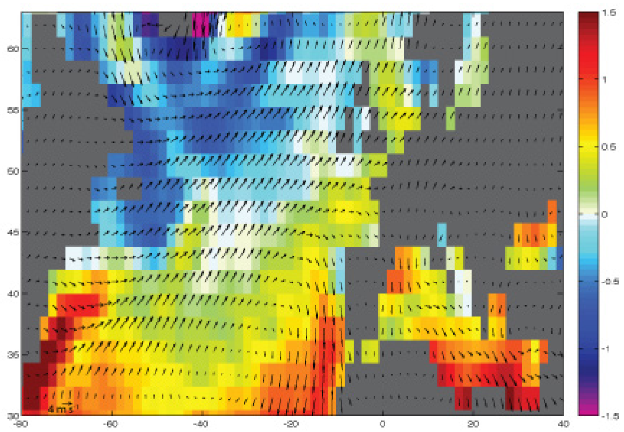


Figure 3: Climatological annual mean freshwater flux (E-P) from the NCEP/NCAR reanalysis for the period 2006-2010, units m yr^{-1}. Blue colours: net precipitation (i.e. freshwater gain by the ocean), red colours : net evaporation (i.e. freshwater loss from the ocean). Arrows show the corresponding NCEP/NCAR 10 m wind speed, reference value of 4 m s^{-1} in lower left corner.

to the mean E-P field suggesting a relationship between the two although further work is required in this area (Durack and Wijffels, 2010).

Impacts of heat and freshwater fluxes on the North Atlantic circulation

The combined effect of the heat and freshwater exchanges can be expressed in terms of a surface density flux. High latitude variations in the density flux have potentially significant implications for UK climate and their potential impact on variability of the overturning circulation of the North Atlantic has been investigated using water mass transformation theory (Grist *et al.*, 2009; Josey *et al.*, 2009; see MCCIP 2009 for details). Since MCCIP 2009, further research has been directed at refining the method using an alternative choice for the vertical coordinate. The new research has led to improvements in the accuracy of the method in the mid-high latitude North Atlantic (Grist *et al.*, 2012). The analysis reveals increased variability in the surface forced overturning circulation by about 1-2Sv from the late 1970s to the early 2000s but no evidence for a long term trend.

2. WHAT COULD HAPPEN?

As reported in MCCIP 2009, it is still the case that obtaining reliable predictions of future air-sea heat and freshwater fluxes changes in the in the UK marine environment is difficult as the anthropogenic signal is small and may be strongly influenced by natural variability. In particular, the influence of anthropogenic climate change on the major modes of atmospheric climate variability remains an open question. Variations in the location and strength of the poles of the North Atlantic Oscillation would have potentially significant consequences for air-sea interaction in the UK marine environment and precipitation over the UK. Thus, as noted previously, the major source of future change may prove to be a shift in the spatial patterns of atmospheric variability rather than warming induced changes in air-sea heat exchange.

In addition, it remains possible that variations in freshening of surface waters associated with an intensification of the hydrological cycle could impact on dense water formation with consequences for UK climate. Research in this area is still insufficiently developed to allow any firm conclusions to be drawn on the likelihood of this occurring.

3. KNOWLEDGE GAPS

These remain the same as in MCCIP 2009:

a. What influence has anthropogenic climate change had on air-sea heat and freshwater fluxes in the UK marine environment and wider North Atlantic over the past 50 years?

b. What impacts have such changes had on a.) the ocean circulation in the UK marine environment and b.) the UK climate?

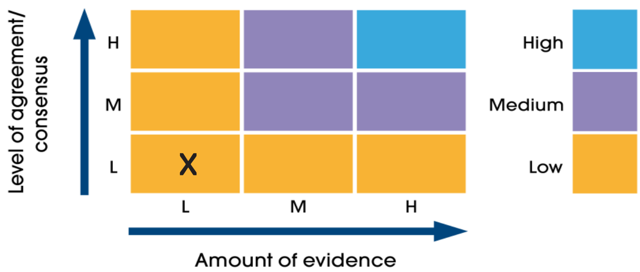
c. How will air-sea heat and freshwater fluxes in the UK marine environment and wider North Atlantic vary over the next 50 years and what impacts will this have?

4. SOCIO-ECONOMIC IMPACTS

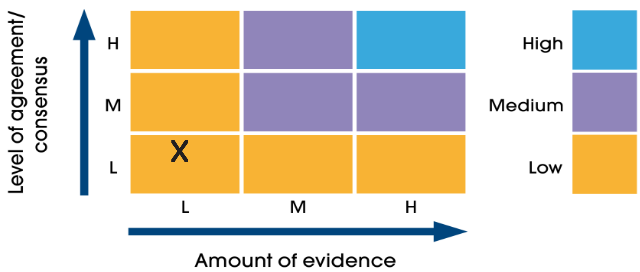
Not possible to comment on this given Knowledge Gaps identified above.

5. CONFIDENCE ASSESSMENT

What is already happening?



What could happen?



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