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Air-Sea Fluxes of Heat and Freshwater

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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. However, these changes are likely to be small and very difficult to detect with currently available surface flux datasets. Several studies have analysed the increase in observed ocean heat content over the past 50 years and place a limit of about 0.5 W m^{-2} on the increase in surface heat flux to the ocean over this time period both globally and for the North Atlantic. Given the high level of uncertainty in available flux datasets no formal attempt has yet been made to detect this signal. A similar situation holds for the surface freshwater flux, for which there are additional problems arising from the difficulty in obtaining reliable long term estimates of precipitation. Some progress towards detecting changes in the hydrological cycle has been made using salinity as an integral measure of variations in the net evaporation.

Obtaining reliable predictions of future changes in the air-sea heat and freshwater fluxes in the UK marine environment is difficult as the anthropogenic signal is small and may be strongly influenced by changes due to natural variability in the climate system.

FULL REVIEW

1. What is already happening?

Introduction

The transfers of heat and freshwater between the ocean and atmosphere are key components of the climate system. Anthropogenic climate change is widely expected to lead to changes in these fluxes as a result of global warming and strengthening of the hydrological cycle. There is compelling evidence that an increase in the global ocean heat content has already happened (e. g. Levitus *et al.*, 2009) and this implies an increase in the net heat flux into the ocean. However, the expected change in global mean net heat flux is small, only about 0.5 W m^{-2}. This signal is too small to be detectable given the accuracy of currently available heat flux datasets and this situation is unlikely to change in the near future.

A strengthening of the hydrological cycle will influence the exchange of freshwater (evaporation – precipitation) between the ocean and the atmosphere and potentially leave an imprint in ocean salinity. Due to problems with obtaining reliable measurements of precipitation over the ocean, the level of uncertainty in freshwater flux datasets is greater than that for heat flux and it is again not possible to currently detect anthropogenic climate change in this variable. However, there is some evidence that changes in the hydrological cycle have modified ocean salinity (Stott *et al.*, 2008) as this acts as an integrator of variations in the surface freshwater exchange.

These points are expanded on in the following sections which detail the heat and freshwater flux separately. A further section describes how these two fields combine to form the air-sea density flux and recent work which uses the density flux to obtain estimates of variability in the North Atlantic overturning circulation at mid-high latitudes including the latitude of the UK.

Air-Sea Heat Flux

The net air-sea heat flux is the sum of four components: these comprise two turbulent heat flux terms (the latent and sensible heat fluxes) and two radiative terms (the shortwave and longwave fluxes). The latent and sensible heat fluxes are proportional to the products of the near surface wind speed with the sea-air humidity and sea-air temperature difference respectively. However, the detailed form of these relationships remains poorly known under certain conditions, in particular at high wind speeds and this provides a significant source of uncertainty in estimates of these fluxes. The shortwave flux is primarily a function of solar elevation and cloud amount with an additional dependence on ocean albedo. The net surface longwave (infrared) flux is the difference between large upward and downward terms from the ocean and atmosphere. The ocean term depends on sea surface temperature and the atmosphere term on air temperature and humidity in addition to cloud amount.

The processes controlling these exchange terms and methods for their estimation are discussed in detail in WGASF (2000). Surface flux datasets have been determined in a number of studies and a recent overview is provided in Gulev *et al.* (2009). The three primary sources for generation of flux products are surface meteorology reports (mainly from Voluntary Observing Ships), satellite observations and atmospheric model reanalyses which assimilate various data types. All three sources use similar empirical (bulk) formulae to estimate the latent and sensible heat fluxes.

Individual estimates of the surface heat flux components may be obtained from surface meteorology reports using the appropriate formulae and combined using various averaging and interpolation techniques to form gridded fields. A number of studies have adopted this approach over the years including the National Oceanography Centre 1.1 (NOC1.1) flux dataset (Josey *et al.*, 1999). The major development over the last 2 years has been the release of the new NOC2 flux dataset which for the first time has error estimates for all of the basic meteorological and derived flux fields (Berry, 2009; Berry and Kent, 2009a,b). The new dataset has been constructed using optimal interpolation of International Comprehensive Ocean-Atmosphere Data Set (ICOADS) Release 2.4 ship data and spans the period 1973-2006. It is presented as a time series of monthly mean values on a 1 degree area grid. The monthly means were derived from daily estimates of each variable and the standard deviation of these daily values is also available. 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.

Satellite gridded surface flux datasets are also available from various sources, a recent example being the Hamburg Ocean-Atmosphere Parameters and Fluxes from Satellite Data version 3 (HOAPS3, Andersson *et al.*, 2007). However, satellite estimates suffer because it is not possible to measure near surface air temperature and humidity directly from space. Indirect techniques must be used instead and this leads to a major source of uncertainty in the turbulent heat flux terms. Atmospheric model reanalyses also provide surface heat flux fields - the two major products being those from the National Centres for Environmental Prediction and the National Centre for Atmospheric Research (NCEP/NCAR) and the European Centre for Medium-Range Weather Forecasts (ECMWF). For the reanalyses, the turbulent flux terms are again estimated from the model surface meteorology fields while the shortwave and longwave flux are output from a radiative transfer model. A further type of flux product seeks to combine data from various sources, the leading example being the Objectively Analyzed air-sea Fluxes (OAFLUX) dataset (Yu and Weller, 2007) which blends reanalysis and satellite surface meteorology fields prior to estimation of the fluxes. Each of these classes of flux product has its own advantages and disadvantages (see Gulev *et al.*, 2009 and the earlier WGASF, 2000 review for details).

The annual mean net air-sea heat flux field for the mid-latitude North Atlantic, including the UK marine sector, is shown in Figure 1 for four of the flux datasets discussed above. The same broad scale pattern is observed for each dataset with strong heat loss over the Gulf Stream and a transition towards ocean heat gain from west to east. The NCEP/NCAR fields tend to have stronger heat loss than the other three datasets considered but this is partly due to an artificially high choice for the transfer coefficients which determine the strength of the turbulent heat loss terms; this choice is not supported by observational analyses. NOC1.1, NOC2 and OAFLUX all show similar results for the location of the zero net heat flux line which extends from south-west to north-east across the basin. The UK marine environment region lies at the north-eastern end of this line and experiences close to zero annual mean net heat flux. However, it is likely that variations in the intense heat loss over the Gulf Stream and their subsequent influence on the atmosphere via cyclogenesis are more important for UK climate than variations within UK waters.

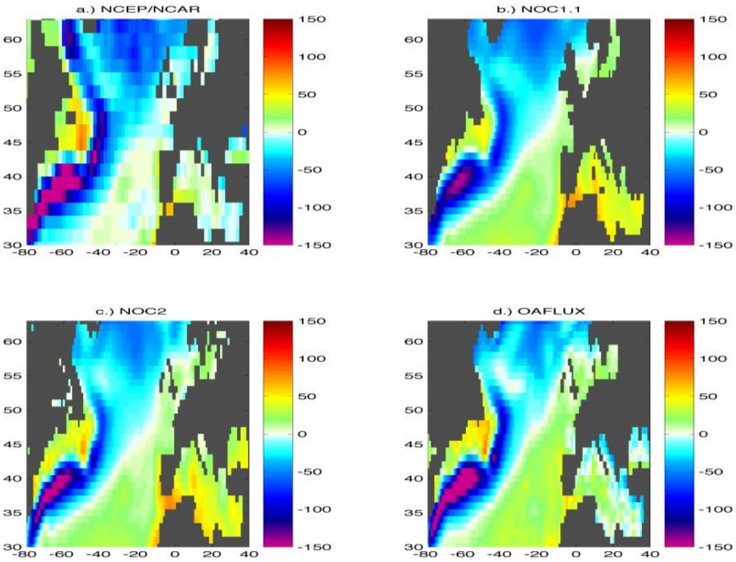


Figure 1. *Annual mean net air-sea heat flux from a.) NCEP/NCAR, b.) NOC1.1, c.) NOC2 and d.) OAFLUX for the common period 1984-2004, units W m^{-2}. Blue colours : ocean heat loss to the atmosphere, red ocean heat gain.*

The net heat flux field exhibits a strong seasonal cycle (not shown) primarily as a result of intensification of the shortwave flux from winter to summer and an increase in the strength of the turbulent heat loss terms in winter. In addition to the seasonal cycle there may be significant anomalies in the heat loss for a given month as a result of extreme conditions. This is illustrated in Figure 2 which shows a time series of the monthly net heat flux anomaly (i.e. with seasonal cycle removed) averaged over an example box (40-55 ^{o}N, 20-40 ^{o}W) in the mid-latitude North Atlantic for each of the four flux datasets. Strong month to month variability is evident in the figure with box averaged anomalies often exceeding 50 W m^{-2}. Similar variations are observed in each of the datasets for the periods in which they overlap. To some extent this is to be expected as, despite major differences in analysis methods, observations from Voluntary Observing Ships are a primary source of data for each of the flux products considered.

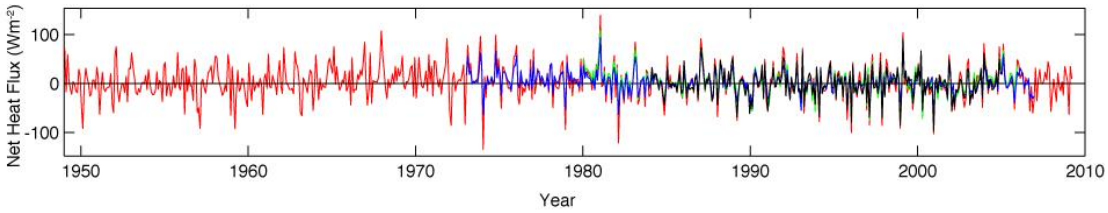


***Figure 2**. Monthly mean net air-sea heat flux anomaly for the box (40-55 °N, 20-40 °W) from NCEP/NCAR (red), NOC1.1 (green), NOC2 (blue) and OAFLUX (black), units W m^{-2}.*

Both observation and model based analyses of changes in the surface air-sea heat flux associated with increasing global ocean heat content have revealed that the anthropogenic climate signal 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 W m^{-2} with corresponding changes in the individual heat flux components of less than 2 W m^{-2}. Lozier *et al.* (2008) have examined the spatial pattern of heat-content change in the North Atlantic using historical hydrographic station data from the National Oceanic Data Center World Ocean Database from 1950 to 2000. They found that the total heat gained by the North Atlantic Ocean is equivalent to a basin wide increase in the flux of heat across the ocean surface of 0.4 W m^{-2}. However, they note that it is not possible to say whether this gain is due to anthropogenic warming because natural variability may be masking this signal. A trend of +4 W m^{-2} decade^{-1} in the global mean latent heat flux was obtained from an analysis of OAFLUX by Yu and Weller (2007). However, as has been noted by Berry (2009), this seems unrealistically large given the constraints arising from changes in ocean heat content and the climate model analyses.

Air-Sea Freshwater Flux

The air-sea freshwater flux is simply the difference between evaporation from the ocean surface and precipitation from the atmosphere, often written E-P (i.e. evaporation - precipitation). It is linked to the net heat flux as the evaporation term corresponds to the latent heat flux component of the net heat exchange discussed above.

Estimates of the evaporation are available from the same sources noted above for the heat flux i.e. ship-based flux datasets, atmospheric model reanalyses and satellite measurements. Various precipitation products are available from satellites (Gulev *et al.*, 2009), for example from the Global Precipitation Climatology Project Version 2 (GPCPv2, Adler *et al.* 2003). Atmospheric model reanalyses also provide precipitation but here care must be taken as unphysical trends have been observed in some areas, particularly for the ECMWF reanalysis in the Tropics. Precipitation is difficult to measure directly at sea (Weller *et al.*, 2008) but may be estimated from present weather codes in voluntary observing ship meteorological reports and was included in the NOC1.1 flux dataset (Josey *et al.*, 1999). However, further work is needed before this method can be reliably used for climate studies and at present precipitation is probably the least well determined of the surface exchange fields.

The climatological annual mean freshwater flux field for 1980-2005 from NCEP/NCAR is shown in Figure 3 together with the near surface wind field. The UK marine environment region experiences a progressive transition from west to east between weak freshwater gain by the ocean from the atmosphere to weak freshwater loss. However, the UK climate is more likely to be affected by the integrated effects of freshwater loss from the ocean further to the south-west in the Atlantic - note the strong losses over the Gulf Stream region and direction of the air flow.

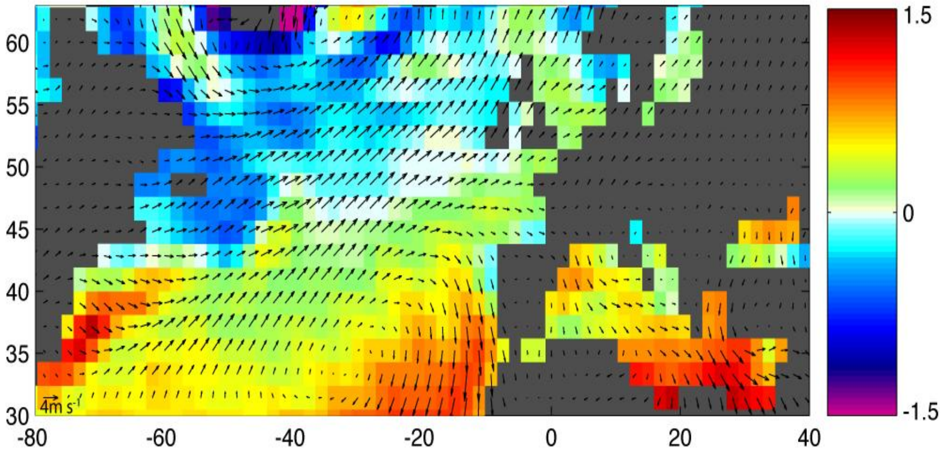


Figure 3. *Climatological annual mean freshwater flux (E-P) from the NCEP/NCAR reanalysis for the period 1980-2005, units m yr^{-1}. Blue colours: net precipitation (i.e. freshwater gain by the ocean), red colours: net evaporation (i.e. freshwater loss from the ocean). Arrows show the corresponding NCEP/NCAR 10 m wind speed, reference value of 4 m s^{-1} in lower left corner.*

Variations in the freshwater flux to the mid-high latitude North Atlantic are driven in part by changes in the strength of the two major modes of atmospheric variability - the North Atlantic Oscillation (NAO) and the East Atlantic Pattern (EAP). The eastern half of the subpolar North Atlantic freshened from the 1960s to the 1990s. A study using the NCEP reanalysis and coastal rain gauge data has attributed about two-thirds of the freshening in this region to an increase in precipitation associated with the EAP (Josey and Marsh, 2005), with the NAO playing a secondary role. Since the mid 1990s, there has been a return to more saline, warmer waters in this region (Holliday *et al.*, 2008) and it is likely that advective rather than surface exchanges processes are responsible for these recent changes.

Identification of a signal in the freshwater flux associated with anthropogenic climate change is made difficult by the high level of uncertainty in the available datasets and the strong influence of natural variations in the major modes of atmospheric variability. Ocean salinity fields are likely to provide a better indication of changes in the hydrological cycle as to some extent they act as an integrator of freshwater flux anomalies. Stott *et al.* (2008) have recently analysed observed and modelled salinity changes and find that changes of salinity as a result of human influence are beginning to emerge. In particular, they find a significant increase in observed salinity in recent decades in the 20 – 50 ^{o}N latitude band of the Atlantic ocean, although changes at sub-polar latitudes of the Atlantic, and in other ocean basins, are not significant compared to modelled internal variability (Pardaens *et al.,* 2008; Wu and Wood, 2008).

Impacts of Heat and Freshwater Fluxes on the North Atlantic Circulation

The surface fluxes of heat and freshwater each act to modify the density of the ocean surface layer via their impact on temperature and salinity. Cooling of the ocean surface and net freshwater loss serve to increase the density as they result in a reduction in temperature and increase of salinity (the converse holds for ocean warming and freshwater gain). The combined effect of the heat and freshwater exchanges can be expressed in terms of the surface density flux (also referred to as the buoyancy flux). Variations in the density flux at high latitudes have potentially significant implications for UK climate as they modify the amount of dense water formed in deep convection regions (Grist *et al.*, 2007; 2008) and consequently the overturning circulation of the North Atlantic.

The impact of the air-sea density flux on the amount of water formed in different density classes can be determined using water mass transformation theory. A modification of this method has been recently used to estimate surface forced variability in the North Atlantic overturning circulation (Grist *et al.*, 2009; Josey *et al.*, 2009). The method has been shown to provide useful estimates of the overturning circulation variability in the range 35 – 65 ^{o}N with the HadCM3 coupled climate model and has been applied using NCEP/NCAR reanalysis flux fields to estimate variability in the mid-high latitude North Atlantic for the past 45 years. The variability in the circulation at latitude 55 ^{o}N, which is approximately the mid-latitude of the UK, is shown in Figure 4.

The figure reveals a tendency for an anomalously high overturning circulation, by about 1-2Sv, from the late 1970s to the late 1990s. This period coincides with the prolonged positive phase of the North Atlantic Oscillation and may indicate that surface forcing associated with this mode plays a significant role in determining the strength of the circulation at the latitude of the UK. From 2000 onwards, there is some indication of weakening of the transport which probably reflects natural variability. Further work is planned to refine the method which has the potential to provide valuable complementary information on circulation variability at mid-high latitudes to that obtained from the Rapid array at 26 ^{o}N.

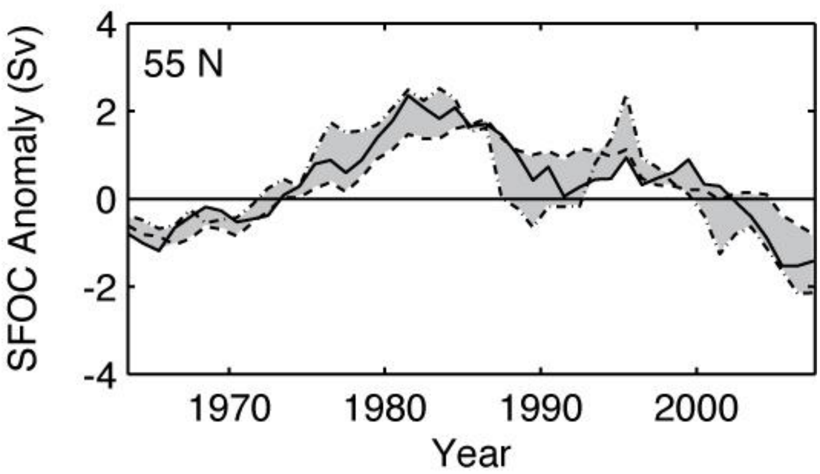


Figure 4. *Reconstruction of the maximum surface forced North Atlantic overturning circulation anomaly (Sv) at 55 ^{o}N using density fluxes determined from the NCEP/NCAR reanalysis. Details of the method are given in Josey et al. (2009), the different lines are estimates based on surface flux fields integrated over 6 years (dash-dot line), 10 years (solid line) and 15 years (dashed line).*

2. What could happen in the future?

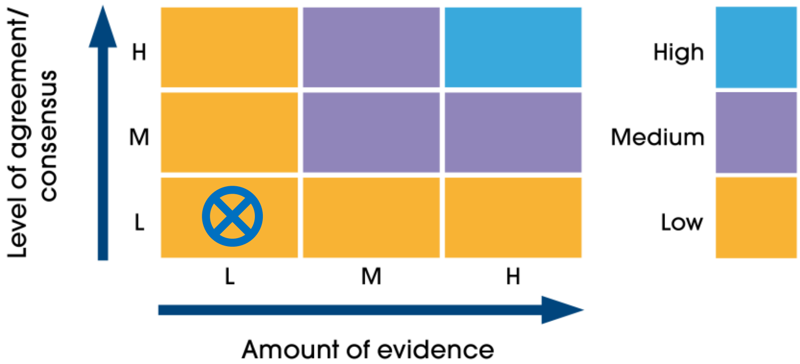
Obtaining reliable predictions of future changes in the air-sea heat and freshwater fluxes in the UK marine environment is difficult as the anthropogenic signal is small and may be strongly influenced by changes due to natural variability in the climate system. Furthermore, at larger scales there is considerable disagreement between the predictions of climate models regarding changes in the components of the energy balance. Andrews (2009) assessed such changes in eight different climate models and found major variations in the model predictions of changes in the different heat flux components. Nevertheless, there are fairly consistent projections on the increase of ocean heat uptake and hydrological cycle intensification under increasing greenhouse gas concentrations. The reduction in sensible heat flux due to decreasing air-sea temperature difference and the increase in evaporation and latent heat flux seem to be robust in the AR4 models (Lu and Cai, 2009).

In addition to the direct global warming signal, anthropogenic climate change may cause the centres of action of the major modes of atmospheric climate variability to shift. In particular, it has been suggested that the low pressure pole of the North Atlantic Oscillation may move north-eastward as a result of climate change (e.g. Ulbrich and Christoph, 1999) and this has potentially significant consequences for air-sea interaction in the UK marine environment and precipitation over the UK. Thus 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.

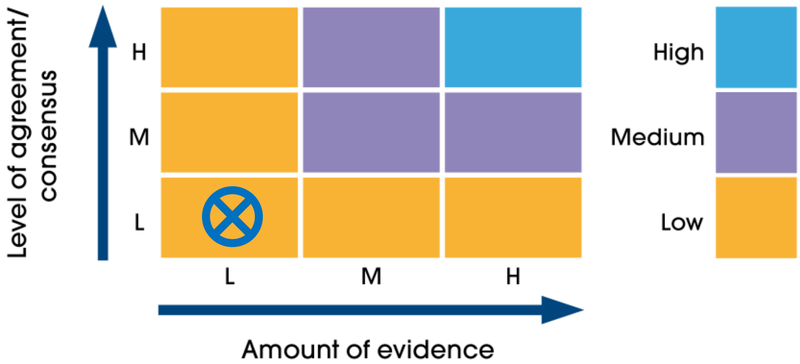
In addition, it is also possible that variations in freshening of surface waters associated with an intensification of the hydrological cycle could impact on dense water formation with consequences for UK climate. However, at present, research in this area is insufficiently developed to allow any firm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

3. Confidence in the science

***What is already happening:* Low**



***What could happen:* Low**



4. Knowledge gaps

The top priority knowledge gaps that need to be addressed in the short term to provide better advice to be given to policy makers are:

1. 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?
2. What impacts have such changes had on a.) the ocean circulation in the UK marine environment and b.) the UK climate?
3. 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?

5. Socio-economic impacts

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

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