Institution: University of East Anglia		
Unit of Assessment: 7 - Earth Systems and Environmental Sciences		
Title of case study: More accurate weather and climate models from an improvement in surface exchange over sea ice		
Period when the underpinning research was undertaken: 2007 – 2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Ian Renfrew	Professor	2004 - to present
Period when the claimed impact occurred: 2014 – 2020		
Is this case study continued from a case study submitted in 2014? No		

1. Summary of the impact

All numerical weather and climate models need to represent the interactions between the atmosphere and the underlying surface. This is achieved through a surface exchange scheme which provides a simplified representation of the key processes, constrained by observations. We have developed a surface exchange scheme for momentum over sea ice and helped implement it into a world-leading weather and climate model, demonstrating its veracity and significance. Our research has also guided development in two of the other leading weather and climate models. The scheme became operational at the Met Office in September 2018 and contributed to one of the largest improvements in forecast accuracy in the last decade. This will benefit all forecast users both in the UK and globally. The economic value of forecasts delivered by the Met Office is estimated to be close to GBP1,500,000,000 per annum.

2. Underpinning research

All numerical weather and climate prediction models need to simulate the interaction between the atmosphere and the underlying surface, be that land, ocean or sea ice; specifically, the surface exchanges of momentum, heat and moisture. If this exchange is not accounted for, then the wind, temperature and humidity in the lower model atmosphere would be wildly inaccurate. This interaction is achieved via a *surface exchange scheme* that provides a simplified representation of the physical process – a parameterization – that is constrained by detailed observations of this process. Surface exchange over sea ice and the marginal-ice-zone (the area of fractional ice cover between the sea-ice pack and the open ocean) has often been handled very crudely, because a dearth of observations has prevented appropriate schemes from being developed and evaluated.

During the Greenland Flow Distortion Experiment, during 2005-2009 **[R1]**, we found that simulations with the Met Office Unified Model were initially inaccurate because an inappropriately large surface drag (momentum) coefficient over sea-ice was slowing down the simulated low-level winds **[R2].** We improved these particular simulations of the atmosphere by improving the sea-ice distribution and we discussed changing the parameterization of surface drag over sea ice with Met Office staff in the operational configuration of their model. But at this point in time, it was not clear how to improve the parameterization in a way that was generally appropriate. There was not a well-defined theoretical framework for a parameterization, nor any suitable observations to constrain one.

In parallel, a hierarchy of theoretical surface exchange concepts for drag over the marginal-ice-zone were being developed by scientists in Germany (e.g., Lüpkes et al. 2012, DOI:10.1029/2012JD017630). However, these were not being implemented in operational weather forecasting or climate models because too few observations were available to constrain or evaluate the schemes.

In 2013**, Renfrew** co-led an aircraft-based Arctic field campaign (ACCACIA; **R3**) that provided over 200 observations of surface drag over the marginal-ice-zone – *more than doubling the number of observations available from all previous studies* **[R4].** We used these observations to constrain and calibrate a surface exchange parameterization for drag over sea ice (that we adapted from Lüpkes et al. 2012) and then collaborated with Met Office staff to implement this scheme in the Met Office Unified Model – the atmospheric model used in all their weather forecasting and climate applications. We carried out a series of numerical model experiments to ascertain the impact of this scheme on the model atmosphere and found it to be significant. Spatial changes to the simulated surface drag were widespread, covering much of the Arctic and Antarctic and extending into the mid-latitudes, and were of the same magnitude as the mean surface drag. We also found the simulated wind, temperature and surface exchanges of momentum, heat and moisture to be much more accurate. For example, the model bias decreased from -0.51 to -0.06 m s^{-1} for wind and from 2.12 to 0.02 K for temperature, when compared to research aircraft observations **[R5].**

Ongoing research, funded by two further projects **[R6; R7]**, has corroborated our findings and is pointing the way to further improvements in heat and moisture exchange.

3. References to the research

<u>Underpinning research</u>: The underpinning research outputs have all been published in competitive, international, peer-reviewed journals and form part of a larger body of such published work. [Citations from Google Scholar]. **UEA authors** in bold. Met Office authors in blue.

[R1] The Greenland Flow Distortion experiment
Renfrew, I.A., G.W.K. Moore, J.E. Kristjánsson, H. Ólafsson, S.L. Gray, **G.N. Petersen**, K. Bovis, P.R.A. Brown, I. Føre, T. Haine, C. Hay, E.A. Irvine, A. Lawrence, T. Ohigashi, **S. Outten**, R.S. Pickart, M. Shapiro, **D. Sproson**, R. Swinbank, A. Woolley, S. Zhang
Bulletin of the American Meteorological Soctiet, **2008***,* 89, 1307-1324.
DOI: 10.1175/2008BAMS2508.1. [89 citations]
Research funded as: GFDex: The Greenland Flow Distortion experiment
PI Ian Renfrew, UEA
Funder: *NERC Discovery grant.*
Amount: GBP190,571. Dates: 2005 – 2009

[R2] An easterly tip jet off Cape Farewell, Greenland. Part II: Simulations and dynamics
Outten **S.D., I.A. Renfrew,** and **G.N. Petersen**
Quarterly Journal of the Royal Meteorological Society, **2009**, 135(645)**,** 1934-1949.
DOI:10.1002/qj.531 [36 citations]

[R3] ACCACIA: Aerosol Cloud Coupling and Climate Interactions in the Arctic (ACCACIA)
Lead PI – Ian Brooks, University of Leeds; **PI Ian Renfrew**, UEA
Funder: *NERC Arctic Research Programme grant.* Amount: Value of GBP2,057,581 overall, with GBP267,040 to UEA. Dates: 2012-2016

[R4] Observations of surface momentum exchange over the marginal-ice-zone and recommendations for its parameterization
Elvidge, A.D., I.A. Renfrew, A.I. Weiss, I.M. Brooks, T.A. Lachlan-Cope, and J.C. King
Atmospheric Chemistry and Physics, **2016***,* 16(3)**,** 1545-1563. DOI:10.5194/acp-16-1545-2016 [22 citations]

[R5] Atmospheric sensitivity to marginal-ice-zone drag: local and global responses
Renfrew, I. A., A. D. Elvidge, J. Edwards

Quarterly Journal of the Royal Meteorological Society, **2019***,* **145,** 1165-1179. DOI:10.1002/qj.3486 [11 citations]

[R6] IGP: Atmospheric Forcing of the Iceland Sea
Lead PI Ian Renfrew, UEA
Funder: *NERC Discovery grant.*
Amount: Value of GBP921,495.68 overall, with GBP342,226.98 to UEA. Dates: 2016-2021

[R7] CANDIFLOS: Characterising and Interpreting FLuxes Over Sea Ice
Lead PI – Ian Brooks, University of Leeds; **PI Ian Renfrew**, UEA
Funder: *NERC Discovery grant.*
Amount: Value of GBP784,423 overall, with GBP262,089.61 to UEA. Dates: 2019-2021

4. Details of the impact

Implementing our model parameterization

The impact of our research has been to improve a number of leading weather and climate models that are used for operational weather forecasting and for climate projections, contributing to a significant improvement in the accuracy of global weather forecasts. Our most significant relationship has been with the Met Office, but we have also worked with the European Centre for Medium-range Weather Forecasts (ECMWF; a multi-national agency primarily funded by European nations); and have recently started working with Météo-France (France's national weather and climate agency). These are three of the world's leading forecasting agencies and climate model developers. The Met Office's forecasts are the second most accurate globally – according to agreed World Meteorological Organization (WMO) statistics – while the ECMWF's forecasts are the most accurate globally (see MOSAC 2019; **S1**). The WMO is a specialized Agency of the United Nations.

We have collaborated with scientists at the Met Office from 2007-present. Between 2007-2014, this focussed on testing different settings for the existing surface exchange scheme for sea ice used in the Met Office Unified Model. From 2015, we collaborated on implementing and then testing a new surface exchange scheme based on prior theory and our observations **[R4]**. This collaboration has involved numerous visits to the Met Office, direct correspondence with key staff and the employment of **Andrew Elvidge (UEA senior research associate from 2013-2015; 2017-present)** at the Met Office from 2015-2018. Dr Elvidge worked with researchers at the Met Office to implement our surface exchange scheme in version 10.5 of the Met Office Unified Model **[S2]**.

Impact on operational weather forecast accuracy

Our surface exchange scheme became operational at the Met Office on 25th September 2018 as part of the 'Parallel Suite 41' (PS41) upgrade. From this date the Met Office's global operational weather forecasts make use of our new surface exchange parameterization. For several months prior to this date the PS41 trial forecasts were compared to the Operational Suite 40 forecasts to ascertain if the new configuration provided more accurate forecasts (e.g., Figure 1a). The PS41 configuration gave an overall improvement in the deterministic global Numerical Weather Prediction (*NWP) Index* of 1.6% (Figure 1a; **S3**). The *NWP Index* is a gross metric for forecast skill that is specified by the WMO. Note this was

> *"one of the largest improvements [in forecast skill] of the last decade"* **[S3]**.

We cannot attribute all of this forecast improvement to the new surface exchange scheme, because other changes to the forecasting system were also made during this upgrade. However separate 'paired trials' were also carried out where the only significant change to the model was to the sea-ice surface exchange scheme (Figure 1b; **S3**). In these trials there were significant improvements in several benchmark atmospheric quantities: a 1-2% improvement in mean-sea-level pressure and upper-troposphere wind in both the Southern and Northern Hemisphere extra-tropics, as well as a 5% and 1-2% improvement in mid-tropospheric geopotential height for the Southern and Northern Hemisphere extra-tropics. In total these constitute an improvement of 0.7% of the *NWP index* (Figure 1b; **[S3]**), equivalent to almost half of the PS41 improvement.

In addition to weather forecasts, the Met Office Unified Model is also a component in all of their climate models. Our new scheme was incorporated into the 'Global Land 8' (GL8) climate configuration in 2018, so will have an impact on future climate projections and predictions, including those made for future IPCC assessments.

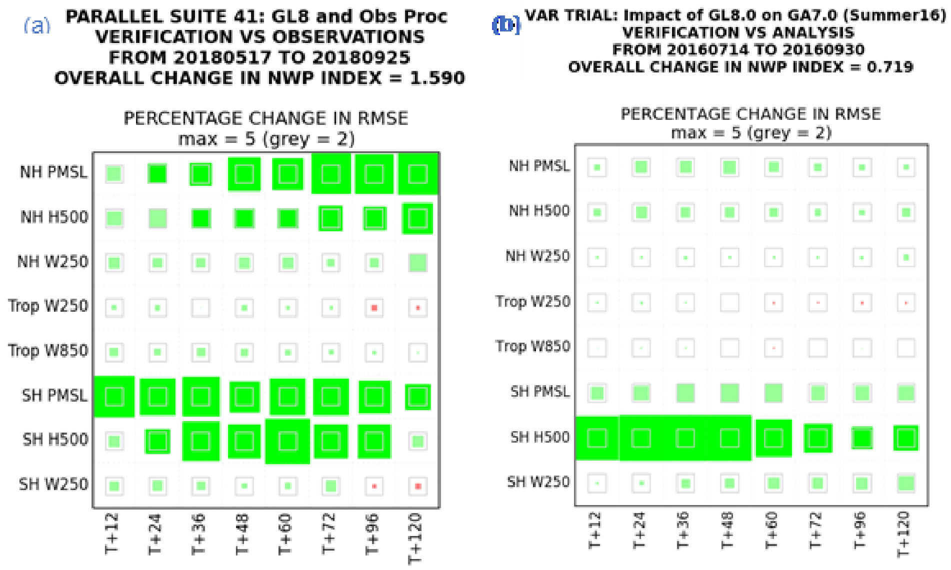

Figure 1 | Met Office model performance **[S3]** illustrating the change in RMSE (root mean square error) for several meteorological quantities at different forecast times (in hours). Here green shows an improvement and the area shaded is the magnitude of the improvement (the maximum shading is a 5% improvement). The quantities are mean-sea-level pressure (PMSL), geopotential height at the 500 hPa level (H500) and the wind at the 250 hPa or 850 hPa level for the Northern and Southern Hemispheres (NH and SH) or Tropics (Trop). A weighted combination of these quantities makes up the *'NWP index'*. Panel (a) shows the change in model performance against observations of the new forecasting set up (PS41 – Parallel Suite 41) compared to the previous operational suite (OS40); results here are for a four-month trial that had showed an overall NWP index improvement of 1.59%. This improvement included the surface exchange parameterization change, but also included other changes to the model set up. Panel (b) shows the change in model performance for a so-called paired trial experiment, where only the surface exchange parameterization is different; results here are for a two-month period and indicate an overall NWP index improvement of 0.72%. There are dramatic improvements in the winter hemisphere (SH) for H500 and also for PMSL.

The Met Office summarise in their evidence letter **[S3]**

> *"It is worth stressing that the implementation of a new surface exchange parameterization for over sea ice would not have occurred without the research led by Prof. Renfrew. Furthermore, we are pleased to confirm that this parameterization led directly to a significant improvement in our weather and climate prediction modelling systems locally and globally, making a contribution to our world-leading forecast system and climate modelling capabilities."*

Coincident with our research, staff at the ECMWF were developing a new surface exchange scheme for sea ice and our research informed this development. We presented our provisional observational results from our Arctic field campaign **[R4]** to staff at the ECMWF during a visit there in September 2014. These provided evidence that supported their proposed new sea-ice drag parameterization and consequently supported the changes they were planning to make **[S4]**. The ECMWF note

> *"The knowledge exchange with Prof Renfrew was extremely useful in making decisions. In fact, we changed the surface exchange of momentum over sea-ice parameterization for Cycle 41R1 of the IFS [Integrated Forecasting System], which became operational on 12 May 2015."* **[S4]**

Our research is now also having an impact at other leading forecasting agencies. In summer 2020 Météo-France requested our observations and, in a joint meeting, a leading Météo-France researcher, outlined their plans to us to develop a surface exchange parameterization for their suite of weather and climate models that will be guided by our research **[R4, R5]**.

Economic worth of our model improvement

It is difficult to quantify the economic value of meteorological model upgrades. Improvements in meteorological forecasts allow safer and more efficient activities throughout society. Both the Met Office and ECMWF provide hundreds of global forecast products every day to nations, businesses and the general public. It has been calculated that the economic benefits of the Public Weather Service for the UK, which is delivered by the Met Office, are

> "*very likely to exceed GBP1,000,000,000 per annum and are likely to be close to GBP1,500,000,000 per annum"* (Met Office 2016**; S5).**

Consequently, any improvement to these services contributes to this economic benefit. The forecast improvement we contributed to has been one of the largest in the last decade and so our contribution towards delivering these improved services has been significant.

5. Sources to corroborate the impact

[S1] MOSAC (2019): Met Office Science Advisory Committee Annex III: Performance metrics.

[S2] Unified Model Documentation Paper 24 (2016): The parameterization of boundary layer processes, UM version 10.5, Updated on 06/06/2016, Owner: Ian Boutle, Contributors: A. Lock, J. Edwards, I. Boutle. *[Section 8.6.2 describes surface exchange over sea ice]*

[S3] Evidence letter from the Head of Atmospheric Processes and Parametrizations Met Office, 27.07.2020

[S4] Evidence letter from the European Centre for Medium-range Weather Forecasts (ECMWF), 03.09.2020

[S5] Met Office (2016) – How valuable is the Met Office? (Last updated 20 April 2016). Based on **Public Weather Service Value for Money Review,** March 2015, by the Public Weather Service Customer Group Secretariat – Lead author Mike Gray. Accessed on 08.02.2021