Literature review: Enhancing and evaluating weather and climate information

Sammy Petch- 24/06/2024 – Final version

1.Introduction

Enhancing weather and climate information encompasses the multifaceted efforts aimed at refining the accuracy, reliability and overall effectiveness of weather, climate, and Earth system models. Evaluation of these models is necessary to assess limitations and identify areas for improvements. These models are vital tools for understanding and predicting the complex behaviour of weather and climate systems, ranging from data-driven to physical models, and from conceptual to quantitative models. From a societal perspective, models serve a variety of purposes and cater to a diverse range of users, aiding decision-making processes. Improving models narrows the gap between the model world and reality, with the potential to facilitate more informed decisions, thereby fostering resilience in the face of environmental challenges, and mitigating the impacts of a dynamically evolving climate.

The University of Reading (UoR) has made notable contributions to this field. Here, we aim to showcase the current expertise of UoR's staff, exploring their contributions across several key topics including data assimilation, ensembles, high resolution modelling, high resolution climate modelling, and Earth system model development.

2.Ensembles

2.1 Introduction

Ensemble simulations serve as a valuable tool for representing uncertainty in climate simulations. Uncertainties arise from various sources such as internal variability, model structure, and external forcings. Ensembles explore these uncertainties by running simulations multiple times while perturbing these factors to generate a range of possible outcomes.

2.2 SMILE

A single model initial-condition large ensemble (SMILE) is a set of model simulations starting from different initial conditions but produced with a single climate model and identical external forcings. A SMILE offers robust estimates of a model's internal variability, while multiple SMILEs can provide a measure of model structural uncertainty (Holland et al., 2020). Lehner et al. (2020) leverages a number of SMILES to separate uncertainty in climate projections into contributions from different sources, revisiting the framework proposed by Hawkins and Sutton (2009). The study demonstrated the added value of SMILEs for quantifying and diagnosing uncertainty in climate projections, particularly in situations where internal variability and forced changes are important. Holland et al. (2021) used data from seven SMILEs to assess the time of emergence of Arctic amplification, a defining feature of global warming. Given that the Arctic is home to large internal variability, detection of a forced climate response can be difficult. However, the use of SMILEs allowed Holland et al. (2021) to assess the influence of both internal variability and forced model response, albeit with relatively few models.

2.2 LESFMIP

On multi-annual to decadal timescales climate can be influenced by several external factors such as volcanic aerosols, greenhouse gas concentrations, and solar irradiance, as well as internal variability. Relying solely on observations for attribution leads to challenges in distinguishing between various external drivers and internal variability. To address this challenge, Smith et al. (2022) introduced the Large Ensemble Single Forcing Model Intercomparison Project (LESFMIP) which involves a set of coordinated model experiments to isolate and assess the impacts of different factors influencing multi-annual to decadal changes in climates.

2.3 PPE / MME

Perturbed physics ensembles (PPE) sample model uncertainty by using an ensemble generated with a single model and different settings of the physics. For instance, Anugerahanti et al. (2020) explored uncertainties in marine biogeochemical models by perturbing the biogeochemistry equations and physical input (e.g. vertical velocity, temperature, mixed layer depth, and vertical diffusivity). Hermoso et al. (2020) explored convective scale probabilistic forecasts, evaluating fifty ensembles based on multi-physics and different stochastic methods. The study looked at how different parameters affect the ensemble spread. Additionally, Mulholland et al. (2017) explored a new use of PPE by employing them to deduce regional process errors that are present in the HadCM3 coupled atmosphere-ocean model which cause the model to drift at early stages in the projection.

Multi model ensembles (MME) are another way model structure can be explored and are sometimes required to establish confidence when projected changes are uncertain (Baker et al., 2022). It is found that MMEs can lead to more skilful forecasts than deterministic models. For instance, Titley et al. (2020) highlighted the advantages of transitioning operational tropical cyclone forecasting from deterministic approaches to incorporating probabilistic uncertainty information from dynamic multi-model ensembles. Additionally, Storer et al. (2020) exploited the benefits of MMEs for improving turbulence forecasts. Additionally, Zhao et al. (2023) used MME projections of near-term precipitation changes over east China, employing clustering techniques which are required when large model uncertainty exists.

2.4 Initial conditions and other uncertainties

Ensembles can be useful in various other contexts. For instance, they can often be necessary to identify statistically significant signals when studying the forced variability of atmospheric circulation regimes. This is because observed data is often affected by the noise associated with sampling uncertainty (Falkena et al., 2021). Falkena et al. (2021) employed a regularised k-means clustering algorithm to better identify the signal in a model ensemble, ultimately identifying six distinct circulation regimes, enhancing understanding of regime dynamics and their connection to ENSO. Additionally, Flack et al. (2020) compared the uncertainty due to initial and boundary condition perturbations and boundary-layer turbulence using a superensemble framework. These findings suggest that statistical post-processing can be used instead of running larger ensembles, potentially leading to more reliable probabilistic forecasts of convective events and their associated hazards. Gentile et al. (2022) examined the effects of atmosphere-ocean-wave coupling in convective-scale ensemble prediction systems for extratropical cyclone forecasting. The study found that the dynamical coupling to ocean and sea state were particularly important aspects of model uncertainty.

3. Data assimilation

3.1 Introduction

Improvements in predictive skill go hand in hand with a growing network of observations. However, it is important to acknowledge that both models and observations contain errors. Data assimilation (DA) is a process that addresses this challenge by balancing observations and models according to their relative uncertainties. This process is used either to estimate the current state of a system, which is required to initialise new model forecasts and for producing reanalysis products, or to estimate model parameters. There is a wide range of DA research taking place at UoR, encompassing efforts to improve methodologies, refine error quantification, and explore new types of observations that can be used through the DA process.

3.2 DA Methods:

Data assimilation methods can typically be classified into three main categories': variational methods, ensemble DA, based on the ensemble Kalman filter, and Monte-Carlo methods which relax the Gaussian assumption of the distribution of the state variables, such as particle filters (Bannister, 2017). Each method is subject to its own advantages and limitations which determine its suitability for specific applications. Variational DA, for instance, is commonly used in Numerical Weather Prediction (NWP) and implements an algorithm to minimise a cost function, such as gradient descent methods or Quasi-Newton methods. Bannister et al. (2020) introduced a variational DA system linked with the convective scale toy model 'ABC model', facilitating cost-effective research into DA methods for convective scale systems. Zhu and Bannister (2023) extended this model to include mixing ratios of vapour and condensate phases of water, called 'Hydro-ABC'. Furthermore, Cheng et al. (2023) proposed an ensemble based Kalman filter for a Lagrangian sea ice model to enhance its Arctic sea ice forecast skill, while Dong et al. (2023) presented a simplification of Kalman smoother to enhance ocean reanalyses.

Di Mauro et al. (2022) discussed the capability of methods like particle filters in dealing with nonlinear systems, and proposed a new approach based on a tempered particle filter (TPF) to improve the assimilation of synthetic aperture radar sensor (SAR) derived flood extent maps into a flood forecasting model. In particle filters, the prior PDF is drawn from an ensemble of model states, called particles. At each time step the particles are weighted according to their likelihood. However, overtime the particles tend to degenerate, resulting in a poorly approximated posterior distribution. To address this, the TPF introduces a tempering coefficient to inflate the posterior variance, mitigating degeneracy and enables long-lasting forecast improvements (Di Mauro et al., 2022). Hybrid methods combine variational and ensemble DA techniques to maximise the benefits of both methods and limit the inadequacies (Bannister, 2016). For instance, Lee et al. (2022) focused on the hybrid covariance ensemble variational approach which is introduced to the existing ABC-DA framework, while Shataer et al. (2023) established a set of theories for the conditioning of hybrid 4D-Var.

3.3: DA using new observations

Large amounts of new satellite data are now available, which require DA systems to fuse observations and models into meaningful information for end users (De Lannoy et al., 2022). Amezcua et al. (2021) is one of several studies paving the way to the assimilation of atmospheric infrasound data into NWP models. Additionally, Hooker et al. (2023) used satellite SAR-derived observations of flooding extent to assess the spatial spread-skill of ensemble flood maps, demonstrating the value of these observations for model validation.

De Lannoy et al. (2022) discussed new opportunities to estimate components of the water cycle via satellite-based land DA. Moreover, Pinnington et al. (2018) showed that satellite derived estimates of shallow soil moisture can be used to calibrate a land surface model at the regional scale using DA techniques.

Beyond satellite data, other types of innovative datasets are emerging. For example, Bell et al. (2022) explored the possibility of using crowdsourced vehicle-based observations of air temperature for kilometre-scale data assimilation to improve forecast skill in convection permitting NWP. Data assimilation techniques can also be used to fill spatial and temporal gaps in observations, as demonstrated by Williams et al. (2023), who presented the first results of a new sea ice data assimilation system.

3.4 Assimilating into different types of models:

Data assimilation techniques extend beyond NWP, encompassing various other types of models. For instance, Pinnington et al. (2020) developed a generic DA technique for JULES and other land surface models using 4DEnVar techniques (LAVENDAR). The technique was tested for maize crop in Nebraska, U.S. and was found to improve modelled estimates of yield by 74%. Fowler et al. (2023) focused on an operational marine coupled physical-biogeochemical model, aiming to improve uncertainty assumptions made during the assimilation of ocean-colour-derived chlorophyll. There is also strong motivation for the development of DA methods within coupled models, as discussed by Fowler and Lawless (2016). The level of coupling can range from weakly coupled, (e.g., used in Leung et al. 2022), to strongly coupled (e.g., Smith et al., 2020a). Coupled DA requires establishing a link between errors across different components of the Earth system, as explored by Wright et al. (2024) regarding cross correlations between atmosphere and ocean fields. Additionally, Smith et al. (2022b) looks at the role of cross-domain error correlations in strongly coupled 4D-Var atmosphere-ocean DA.

3.5 Errors:

Dealing with uncertainty is at the heart of DA. Both the prior information – often known as 'background', and observations contain errors, and knowledge of these errors needs to be specified for the DA scheme to work well. However, estimating error covariance matrices can be challenging, especially when correlated in time and space. Amezcua et al. (2023) investigated the possibility of including the estimation of time-related model error parameters in the DA processes, while Hu and Dance (2021) discussed spatially correlated observation error covariances. Additionally, Leung et al. (2022) focused on the covariance structure of background errors, and Tabeart et al. (2020) focused on observation errors, presenting new theory aimed to improve the DA process in high dimensional problems such as NWP.

4.High resolution modelling:

4.1 Introduction

In recent years, there has been a rapid growth in the development and use of convective scale numerical weather prediction systems (Clarke et al., 2016). Unlike traditional GCMs, which rely on parameterisation schemes to represent the average effects of convection, these systems operate at kilometre and sub-kilometre scales, enabling the explicit representation of small-scale weather phenomena and atmospheric processes such as convection. While this advancement presents opportunities, it also introduces new challenges for physical parameterisations, necessitating the development of novel evaluation methods. Despite considerable progress in convective-permitting models, several key challenges persist.

4.2 ParaCon

The University of Reading is actively engaged in addressing these challenges, particularly through their participation in ParaCon, a five-year collaborative program between the Met Office and several UK universities. ParaCon aims to significantly enhance the representation of convection across various model scales. Within ParaCon, three convective parameterisation frameworks have been developed: CoMorph, a flexible mass-flux scheme (e.g., Daleu et al., 2023; Lavendar et al., 2024); a new turbulence scheme for kilometre and sub-kilometre scales (e.g. Hanley et al., 2019); and a multifluid framework, which partitions the air into two or more fluids and allows for the net mass transport by convection (e.g., Thuburn et al., 2018; Weller & McIntyre, 2019; McIntyre et al., 2020; Weller et al., 2020; Shipley et al., 2021).

Research within ParaCon has also focused on the development and exploration of stochastic convection schemes, which introduce randomness or variability to help capture some of the uncertainty associated with convection (e.g. Hagos et al., 2018). Additionally, Harvey et al. (2022) have made strides in capturing the phase and amplitude of the daily precipitation cycle in parameterised convection, while Hagos et al. (2022) have integrated a machine learning-assisted stochastic cloud population model with the Weather Research and Forecasting model. Gu et al. (2020) evaluated approximations for turbulent fluxes for deep convection, and Daleu et al. (2020) looked at memory effects which identify the effects of previous convection in modifying current convection, all as part of ParaCon efforts.

4.3 Radiation

Radiation schemes pose a significant challenge in high-resolution modelling, particularly when accounting for 3D cloud effects, which are often ignored in favour of more computationally affordable 1D schemes. Meyer et al. (2022) proposed leveraging machine learning techniques to efficiently incorporate 3D effects. Hogan and Bozzo (2018) introduced a new software package capable of representing 3D radiative cloud effects, operational in the ECMWF forecast model. Additionally, Ukkonen and Hogan (2024) employed code optimisation techniques to accelerate computations, enabling the implementation of radiation schemes that account for 3D effects to be practical for operational use.

4.4 Radar and stochastic boundary layer scheme

Further advancements in high-resolution modelling include Stein et al. (2015) who took a new approach to evaluate and improve convection permitting models through the DYMECS project (Dynamical and Microphysical Evolution of Convective Storms), gathering a large database of 3D storm structures on several convective days and comparing to storm life cycles derived from the UK radar network. Stein et al. (2020) further explored the use of radar to evaluate the representation of convective storms. Additionally, Clark et al. (2021) presented a stochastic boundary layer perturbation scheme implemented in the Met Office’s Unified model (UM). Subsequently, Flack et al (2021) used this scheme to investigate uncertainties stemming from both initial and boundary layer condition perturbations, as well as boundary layer turbulence, using a superensemble framework, which is a large ensemble consisting of several subensembles.

4.5. Urban modelling

High resolution modelling in urban areas also presents new challenges, requiring new modelling approaches and extensive evaluation techniques (Hall et al., 2024). To capture the impact of cities on surface-atmosphere interactions urban land-surface models are used within NWP and climate models (Hertwig et al., 2020). The heterogeneous nature of urban surfaces complicates representation, often leading to oversimplified assumptions in urban schemes, such as infinite street canyons with constant dimensions (Stretton et al., 2023). Addressing this, Stretton et al. (2023) characterises the vertical structure of buildings in cities for use in atmospheric models at a 2km grid scale. Lean et al. (2019) addressed another key issue of how to handle the representation of partially resolved turbulence in 100m scale NWPs over cities, by looking at the representation of a clear, convective boundary layer over London with 100m and 50m models. Lean et al. (2022) followed on from this, using urban scale models to clarify reasons for the discrepancies between different measures of mixing height. Hall et al. (2024) focused on evaluating NWP in urban setting, exploiting land surface temperature data to assess 100m resolution NWP for London.

5. High resolution climate modelling

5.1 Introduction

High resolution global climate modelling encompasses a hierarchy of model resolutions ranging from 130 km to 25 km in the atmosphere, and 1 degree to 0.25 degree in the ocean. These high-resolution models allow for improved representation of small-scale processes, such as weather phenomena including mid-latitude storms, tropical cyclone, ocean eddies and atmospheric blocking. Despite their potential, the computational demands of high-resolution simulations had previously limited their widespread application. However, recent advances in high-performance computing resources, coupled with initiatives like CMIP6, have facilitated detailed investigation of the impact of increased resolution on climate simulations through the High-Resolution Model Intercomparison Project (HighResMIP) (Haarsma et al., 2016). The University of Reading has made substantial contributions to the field of high-resolution climate modelling, particularly through their involvement in projects such as PRIMAVERA, EERIE, and nextGEMS.

5.2 Tropical cyclones

Tropical cyclones (TC) can have extremely high socioeconomic impacts, yet their simulation in traditional climate models remains a challenge. TCs are often underestimated in both the number of TCs and their intensity, likely related to coarse model resolution (Befort et al., 2022). Increasing the horizontal model resolution has been demonstrated to improve the representation of TCs in climate models (Vidale et al., 2021). However, general circulation models (GCMs), including those in CMIP6 HighResMIP, exhibit biases in TC simulation regarding storm structure, spatial distribution as well as frequency and intensity, particularly in the West Northern Pacific (Roberts et al., 2020, Hodges et al., 2019). Feng et al. (2020) speculated this bias to be be related to deficiencies in representing large scale wind circulations. Moreover, Feng et al. (2024) proposed a new approach to understand model bias of tropical cyclogenesis. Akhter et al. (2023) assessed the performance of six HighResMIP multi-ensemble GCMs in simulating tropical cyclones in the Bay of Bengal. Additionally, Baker et al. (2022) conducted a systematic multi-model study on the extratropical transition of tropical cyclones and the impact of increasing model resolution. Vanniere et al. (2020) explored the sensitivity of tropical cyclone precipitation and moisture budget to changes in resolution, while Zhang et al. (2022) evaluated how spatial resolution affects the representation of TC rainfall using CMIP6 HighResMIP runs of PRIMAVERA. Vidale et al. (2021) discussed how stochastic physics may act as an alternative to increasing resolution to improve the simulation of TCs, providing some benefits at a fraction of the cost. The study presented a systematic comparison of the role of model resolution and stochastic physics in the simulation of TCs, finding that stochastic physics can increase TC frequency in a strikingly similar way to the use of higher resolution.

5.3 Ocean Mesoscale

Climate models can be highly sensitive to the choice of horizontal resolution in the ocean component (Hewitt et al., 2020). As climate models move towards higher resolution their ocean components are now able to resolve mesoscale features, such as eddies and boundary currents, which have a major influence on the large-scale circulation (Moreton et al., 2020). Moreton et al. (2020) compared the strengths and limitations of two typical high-resolution categorisations for ocean models: eddy-present and eddy-rich resolutions.

UoR, along with 16 other partners, are participating in the EERIE (European Eddy Rich Earth System Models) project, which aims to reveal and quantify the role of ocean mesoscale processes in shaping the climate trajectory over seasonal to centennial timescales (EERIE, 2023). This project began January 2023 and will run until December 2026. EERIE will develop a new generation of Earth System models that are capable of explicitly representing the ocean mesoscale.

Studies assessing simulations under the HighResMIP protocol reveal the benefits of increased ocean resolution. For instance, Athanasiadis et al. (2022) showed that increasing model resolution led to significant reduction in a typical wintertime cold SST bias at the beginning of the North Atlantic current. Roberts et al. (2020b) found that higher-resolution models performed better in simulating key aspects of the Atlantic Meridional Overturning Circulation. Bellucci et al. (2021) found that increased model resolution led to more realistic SST-turbulent heat flux covariance, as well as several other key benefits. Schiemann et al. (2020) found that higher resolution PRIMAVERA models represent the mean blocking frequency better than the low-resolution models for the Euro-Atlantic region during winter and summer and for the Pacific in summer, with no resolution sensitivity seen in winter.

5.4 Analysis

The analysis of high-resolution models presents significant challenges due to the large volumes of data involved. However, tools such as the PRIMAVERA data management tool, described by Seddon et al. (2023), have enabled collaborative analysis of multi-model high-resolution climate simulations, essential for project success. Furthermore, the EERIE initiative is exploring machine learning techniques to streamline data output and accelerate scientific discovery in climate modelling (EERIE, 2023).

6. Earth System Model development and Evaluation

6.1 Introduction

Earth system models (ESM) integrate various components of the Earth system, including the atmosphere, oceans, land surface, cryosphere, and biosphere. They capture the interactions and feedbacks between these components, allowing the simulation of complex Earth system processes and the projections of future climate scenarios. The UKESM1 model is the UKs first community Earth system model, developed by the Met Office and the Natural Environment Research Council (NERC), with significant contributions from UK universities, including the University of Reading (Senior et al., 2020).

6.2 Component models

UKESM1 is built upon several component models (Sellar et al., 2019), with its land surface component coming from the Joint UK Land Environment Simulator (JULES). Ongoing research at UoR focuses on advancing JULES. For instance, Oliver et al. (2022) concentrates on enhancing the representation of plant physiology, while Vidale et al. (2021) implements new treatments of soil water, and Harper et al. (2021) contributes to improving the modelling of plant responses to low soil moisture.

The physical core of UKESM is based on the coupled climate model HadGEM3-GC3, which encompasses atmosphere, land, ocean, and sea ice components (Kuhlbrodt et al., 2018). Mulcahy et al. (2018) worked on improving the aerosol in HadGEM3, which is key uncertainty in estimating anthropogenic radiative forcing of climate. Additionally, UoR has played a key role in the progress in coupling ice sheets to UKESM. The physical interactions between ice sheets and their surroundings are a major factor in determining the state of the climate system, yet many earth system models omit them entirely or approximate them in a heavily parameterised way (Smith et al., 2021a). Smith et al. (2021b) looks at how models of the Greenland and Antarctic ice sheets have been incorporated into the global UKESM1.

UoR is also involved in the work targeting the ocean component. Yool et al. (2021) conducted a comprehensive evaluation of ocean components within UKESM. Additionally, Kuhlbrodt (2023) addressed ocean heat content with two pairs of CMIP6 models, including UKESM1 and HadGEM3-GC3, and Hewitt et al. (2020) worked on resolving and parameterising the ocean mesoscale in earth system models.

6.3 Evaluating Earth system models

A range of research has gone into evaluating UKESM and other Earth system models. Andrews et al. (2019) evaluated climate forcing, sensitivity and feedback metrics in HadGEM3-GC3.1 and UKESM1.1, while Robson et al. (2020) evaluates the ability of UKESM1 to simulate the North Atlantic climate system. Mulachy et al. (2021) evaluates the aerosol schemes implemented in HadGEM3-GC3.1 and UKESM1. Mulcahy et al. (2023) discusses the development and evaluation of an updated configuration of the UKESM1.1, which aimed to reduce the historical cold vias in the model. Swaminathan et al. (2023) explores machine learning approaches to evaluate vegetation modelling in Earth System models, focusing on the estimation of GPP.

6.4 Evaluation tools

Eyring et al. (2016) introduces ESMvalTool, a community diagnostics and performance metrics tool for the evaluation of ESMs that allows for routine comparison of single or multiple models, either against predecessor versions or against observations. This versatile tool facilitates climate data analysis, efficient data processing, and supports multiple programming languages and operating systems. This tool was employed by Bock et al. (2020) to assess performance of the CMIP6 ensemble compared to previous generations. Since the first release, substantial technical improvements have been made by a continuously growing developer community and additional diagnostics have been added (Eyring et al., 2020) . Lauer et al. (2017) presents an enhanced version of the ESMValTool that exploits a subset of Essential Climate Variables from the European space agency's climate change Initiative, while Eyring et al. (2020) presents an updated version ESMValToolv2.0.

7. Conclusion

In conclusion, the University of Reading has consistently been at the forefront of advancing our understanding and prediction of weather and climate. Through ongoing innovation, such as developing new research in high-resolution modelling and convective scale data assimilation, and ground-based remote sensing, UoR continues to lead advancements in the field. Collaborations with leading meteorological organisations, including the Met Office, European Centre for Medium Range Weather Forecasting (ECMWF), and National Centre for Atmospheric Science (NCAS), have been a large part in helping UoR further their research. Key collaborative efforts have included the development of JULES and UKESM, among various other projects. The university possesses a diverse range of expertise that continues to grow, with recent expansion seen in areas of environmental prediction, including hydrology and flooding, urban meteorology, and energy meteorology. While we have focused on several key topics here, it's important to note that UoR has made significant contributions across various other important areas. Overall, UoR's research extends beyond its academic contribution, helping to address societal concerns and shape policy by informing how governments, organisations, industries, and communities respond to complex issues such as climate change and extreme weather events.

References

Akhter, S., Holloway, C. E. , Hodges, K. and Vanniere, B. (2023) How well do high-resolution Global Climate Models (GCMs) simulate tropical cyclones in the Bay of Bengal? Climate Dynamics, 61 (7-8). pp. 3581-3604. ISSN 1432-0894 doi: https://doi.org/10.1007/s00382-023-06745-3

Amezcua, Javier , Ren, Haonan and Van Leeuwen, Peter Jan (2023) Using the (iterative) ensemble Kalman smoother to estimate the time correlation in model error. Tellus A: Dynamic Meteorology and Oceanography, 75 (1). pp. 108-128. ISSN 1600-0870 doi: https://doi.org/10.16993/tellusa.55

Amezcua, Javier and Barton, Zak (2021) Assimilating atmospheric infrasound data to constrain atmospheric winds in a two-dimensional grid. Quarterly Journal of the Royal

Meteorological Society, 147 (740). pp. 3530-3554. ISSN 1477-870X doi: https://doi.org/10.1002/qj.4141

Andrews, T., Andrews, M. B., Bodas-Salcedo, A., Jones, G. S., Kuhlbrodt, T., Manners, J., et al. (2019). Forcings, feedbacks, and climate sensitivity in HadGEM3-GC3.1 and UKESM1. *Journal of Advances in Modeling Earth Systems*, 11, 4377–4394. https://doi.org/10.1029/2019MS001866

Anugerahanti, Prima, Roy, Shovonlal and Haines, Keith (2020) *Perturbed biology and physics signatures in a 1-D ocean biogeochemical model ensemble.* Frontiers in Marine Science, 7. 549. ISSN 2296-7745 doi: https://doi.org/10.3389/fmars.2020.00549

Athanasiadis, P. J., Ogawa, F., Omrani, N.-E., Keenlyside, N., Schiemann, R. , Baker, A. J. , Vidale, P. L., Bellucci, A., Ruggieri, P., Haarsma, R., Roberts, M., Roberts, C., Novak, L. and Gualdi, S. (2022) Mitigating climate biases in the mid-latitude North Atlantic by increasing model resolution: SST gradients and their relation to blocking and the jet. Journal of Climate, 35 (21). pp. 3379-3400. ISSN 1520-0442

Baker, A. J. , Roberts, M. J., Vidale, P. L., Hodges, K. I., Seddon, J., Vanniere, B. , Haarsma, R. J., Schiemann, R. , Kapetanakis, D., Tourigny, E., Lohmann, K., Roberts, C. D. and Terray, L. (2022) Extratropical transition of tropical cyclones in a multiresolution ensemble of atmosphere-only and fully coupled global climate models. Journal of Climate, 35 (16). pp. 5283-5306. ISSN 1520-0442 doi: https://doi.org/10.1175/JCLI-D-21-0801.1

Baker, Alexander J. , Roberts, Malcolm J., Vidale, Pier Luigi, Hodges, Kevin I., Seddon, Jon, Vanniere, Benoit , Haarsma, Rein J., Schiemann, Reinhard , Kapetanakis, Dimitris, Tourigny, Etienne, Lohmann, Katja, Roberts, Christopher D. and Terray, Laurent (2022) Extratropical transition of tropical cyclones in a multiresolution ensemble of atmosphere-only and fully coupled global climate models. Journal of Climate, 35 (16). pp. 5283-5306. ISSN 1520-0442 doi: https://doi.org/10.1175/JCLI-D-21-0801.1
Bannister, R.N. (2017), A review of operational methods of variational and ensemble-variational data assimilation. Q.J.R. Meteorol. Soc, 143: 607-633. https://doi.org/10.1002/qj.2982

Bannister, Ross N. (2020) The ABC-DA system (v1.4): a variational data assimilation system for convective-scale assimilation research with a study of the impact of a balance constraint. Geoscientific Model Development, 13 (8). pp. 3789-3816. ISSN 1991-9603 doi: https://doi.org/10.5194/gmd-13-3789-2020

Bannister, Ross N., Chipilski, Hristo and Martinez-Alvarado, Oscar (2020) Techniques and challenges in the assimilation of atmospheric water observations for numerical weather prediction towards convective scales. Quarterly Journal of the Royal Meteorological Society, 146 (726). pp. 1-48. ISSN 1477-870X doi: https://doi.org/10.1002/qj.3652

Befort, D. J., Hodges, K. I. and Weisheimer, A. (2022) Seasonal prediction of tropical cyclones over the North Atlantic and Western North Pacific: dependence on model, resolution and stochastic physics. Journal of Climate, 35 (5). pp. 1385-1397. ISSN 1520-0442 doi: https://doi.org/10.1175/JCLI-D-21-0041.1

Bell, Zackary, Dance, Sarah L. and Waller, Joanne A. (2020) Accounting for observation uncertainty and bias due to unresolved scales with the Schmidt-Kalman filter. Tellus A: Dynamic Meteorology and Oceanography, 72 (1). pp. 1-21. ISSN 1600-0870 doi: https://doi.org/10.1080/16000870.2020.1831830

Bellucci, A. , Athanasiadis, P. J., Scoccimarro, E., Ruggieri, P., Gualdi, S., Fedele, G., Haarsma, R. J., Garcia-Serrano, J., Castrillo, M., Putrahasan, D., Sanchez-Gomez, E., Moine, M.-P., Roberts, C. D., Roberts, M. J., Seddon, J. and Vidale, P. L. (2021) Air-Sea interaction over the Gulf Stream in an ensemble of HighResMIP present climate simulations. Climate Dynamics, 56 (7-8). pp. 2093-2111. ISSN 1432-0894 doi: https://doi.org/10.1007/s00382-020-05573-z

Bock, L., Lauer, A., Schlund, M., Barreiro, M., Bellouin, N., Jones, C., et al. (2020). Quantifying progress across different CMIP phases with the ESMValTool. Journal of Geophysical Research: Atmospheres, 125, e2019JD032321. https://doi.org/10.1029/2019JD032321

Cheng, Sukun, Chen, Yumeng , Aydoğdu, Ali, Bertino, Laurent, Carrassi, Alberto , Rampal, Pierre and Jones, Christopher K. R. T. (2023) Arctic sea ice data assimilation combining an ensemble Kalman filter with a novel Lagrangian sea ice model for the winter 2019–2020. The Cryosphere, 17 (4). pp. 1735-1754. ISSN 1994-0424 doi: https://doi.org/10.5194/tc-17-1735-2023

Clark, P. , Halliwell, C. and Flack, D. (2021) A physically-based stochastic boundary-layer perturbation scheme. Part I: formulation and evaluation in a convection-permitting model. Journal of the Atmospheric Sciences, 78 (3). pp. 727-746. ISSN 1520-0469 doi: https://doi.org/10.1175/JAS-D-19-0291.1

Clark, P., Roberts, N., Lean, H., Ballard, S.P. and Charlton-Perez, C. (2016), Convection-permitting models: a step-change in rainfall forecasting. Met. Apps, 23: 165-181. https://doi.org/10.1002/met.1538

Daleu, C. L., Plant, R. S., Woolnough, S. J., Stirling, A. J., & Harvey, N. J. (2020). Memory properties in cloud-resolving simulations of the diurnal cycle of deep convection. Journal of Advances in Modeling Earth Systems, 12, e2019MS001897. https://doi.org/10.1029/2019MS001897

Daleu, C.L., Plant, R.S., Stirling, A.J. & Whitall, M.(2023) Evaluating the CoMorph-A parametrization using idealized simulations of the two-way coupling between convection and large-scale dynamics. *Quarterly Journal of the Royal Meteorological Society*, 149(757), 3087–3109. Available from: https://doi.org/10.1002/qj.4547

De Lannoy, Gabriëlle J. M., Bechtold, Michel, Albergel, Clément, Brocca, Luca, Calvet, Jean-Christophe, Carrassi, Alberto , Crow, Wade T., de Rosnay, Patricia, Durand, Michael, Forman, Barton, Geppert, Gernot, Girotto, Manuela, Hendricks Franssen, Harrie-Jan, Jonas, Tobias, Kumar, Sujay, Lievens, Hans, Lu, Yang, Massari, Christian, Pauwels, Valentijn R. N., Reichle, Rolf H. and Steele-Dunne, Susan (2022) Perspective on satellite-based land data assimilation to estimate water cycle components in an era of advanced data availability and model sophistication. Frontiers in Water, 4. ISSN 2624-9375 doi: https://doi.org/10.3389/frwa.2022.981745

Di Mauro, Concetta Di, Hostache, Renaud, Matgen, Patrick, Pelich, Ramona, Chini, Marco, Van Leeuwen, Peter Jan, Nichols, Nancy and Blöschl, Gunter (2022) A tempered particle filter to enhance the assimilation of SAR-derived flood extent maps into flood forecasting models. Water Resources Research, 58 (8). e2022WR031940. ISSN 1944-7973 doi: https://doi.org/10.1029/2022WR031940

Dong, Bo, Bannister, Ross, Chen, Yumeng, Fowler, Alison and Haines, Keith (2023) Simplified Kalman smoother and ensemble Kalman smoother for improving reanalyses. Geoscientific Model Development, 16. pp. 4233-4247. ISSN 1991-9603 doi: https://doi.org/10.5194/gmd-16-4233-2023

EERIE. (2023). European Eddy Rich ESMs. Retrieved March 28, 2024, from https://eerie-project.eu/

Eyring, V., Bock, L., Lauer, A., Righi, M., Schlund, M., Andela, B., Arnone, E., Bellprat, O., Brötz, B., Caron, L.-P., Carvalhais, N., Cionni, I., Cortesi, N., Crezee, B., Davin, E., Davini, P., Debeire, K., de Mora, L., Deser, C., Docquier, D., Earnshaw, P., Ehbrecht, C., Gier, B. K., Gonzalez-Reviriego, N., Goodman, P., Hagemann, S., Hardiman, S., Hassler, B., Hunter, A., Kadow, C., Kindermann, S., Koirala, S., Koldunov, N. V., Lejeune, Q., Lembo, V., Lovato, T., Lucarini, V. , Massonnet, F., Müller, B., Pandde, A., Pérez-Zanón, N., Phillips, A., Predoi, V., Russell, J., Sellar, A., Serva, F., Stacke, T., Swaminathan, R. , Torralba, V., Vegas-Regidor, J., von Hardenberg, J., Weigel, K. and Zimmermann, K. (2020) Earth System Model Evaluation Tool (ESMValTool) v2.0 – an extended set of large-scale diagnostics for quasi-operational and comprehensive evaluation of Earth system models in CMIP. Geoscientific Model Development Discussions, 13 (7). pp. 3383-3438. ISSN 1991-962X doi: https://doi.org/10.5194/gmd-13-3383-2020

Eyring, V., Righi, M., Lauer, A., Evaldsson, M., Wenzel, S., Jones, C., Anav, A., Andrews, O., Cionni, I., Davin, E. L., Deser, C., Ehbrecht, C., Friedlingstein, P., Gleckler, P., Gottschaldt, K.-D., Hagemann, S., Juckes, M., Kindermann, S., Krasting, J., Kunert, D. et al (2016) ESMValTool (v1.0) – a community diagnostic and performance metrics tool for routine evaluation of Earth system models in CMIP. Geoscientific Model Development, 9 (5). pp. 1747-1802. ISSN 1991-9603

Falkena, Swinda K. J., de Wiljes, Jana, Weisheimer, Antje and Shepherd, Theodore G. (2022) *Detection of interannual ensemble forecast signals over the North Atlantic and Europe using atmospheric circulation regimes.* Quarterly Journal of the Royal Meteorological Society, 148 (742). pp. 434-453. ISSN 1477-870X doi: https://doi.org/10.1002/qj.4213

Feng, X., Klingaman, N. P., Hodges, K. I., & Guo, Y. P. (2020). Western North Pacific tropical cyclones in the Met office global seasonal forecast system: Performance and ENSO teleconnections. Journal of Climate, 33(24), 10489–10504. https://doi.org/10.1175/jcli-d-20-0255.1

Feng, X., Toumi, R., Roberts, M., Hodges, K. I., & Vidale, P. L. (2023). An approach to link climate model tropical cyclogenesis bias to large-scale wind circulation modes. *Geophysical Research Letters*, 50, e2023GL103838. https://doi.org/10.1029/2023GL103838

Flack, D., Clark, P. , Halliwell, C., Roberts, N., Gray, S. , Plant, B. and Lean, H. (2021) A physically-based stochastic boundary-layer perturbation scheme. Part II: perturbation growth within a super ensemble framework. Journal of the Atmospheric Sciences, 78 (3). pp. 747-761. ISSN 1520-0469

Flack, David, Clark, Peter , Halliwell, Carol, Roberts, Nigel, Gray, Suzanne , Plant, Bob and Lean, Humphrey (2021) A physically-based stochastic boundary-layer perturbation scheme. Part II: perturbation growth within a super ensemble framework. Journal of the Atmospheric Sciences, 78 (3). pp. 747-761. ISSN 1520-0469 doi: https://doi.org/10.1175/JAS-D-19-0292.1

Fowler, A. M., and A. S. Lawless, 2016: An Idealized Study of Coupled Atmosphere–Ocean 4D-Var in the Presence of Model Error. Mon. Wea. Rev., 144, 4007–4030, https://doi.org/10.1175/MWR-D-15-0420.1.

Fowler, A.M., Skákala, J. & Ford, D.(2023) Validating and improving the uncertainty assumptions for the assimilation of ocean-colour-derived chlorophyll *a* into a marine biogeochemistry model of the Northwest European Shelf Seas. *Quarterly Journal of the Royal Meteorological Society*, 149(750), 300–324. Available from: https://doi.org/10.1002/qj.4408

Gentile, Emanuele S. , Gray, Suzanne L. and Lewis, Huw W. (2022) *The sensitivity of probabilistic convective-scale forecasts of an extratropical cyclone to atmosphere–ocean–wave coupling.* Quarterly Journal of the Royal Meteorological Society, 148 (743). pp. 685-710. ISSN 0035-9009 doi: https://doi.org/10.1002/qj.4225

Haarsma, R. J., Roberts, M. J., Vidale, P. L., Senior, C. A., Bellucci, A., Bao, Q., Chang, P., Corti, S., Fučkar, N. S., Guemas, V., von Hardenberg, J., Hazeleger, W., Kodama, C., Koenigk, T., Leung, L. R., Lu, J., Luo, J.-J., Mao, J., Mizielinski, M. S., Mizuta, R., Nobre, P., Satoh, M., Scoccimarro, E., Semmler, T., Small, J., and von Storch, J.-S.: High Resolution Model Intercomparison Project (HighResMIP v1.0) for CMIP6, Geosci. Model Dev., 9, 4185–4208, https://doi.org/10.5194/gmd-9-4185-2016, 2016.

Hagos, S., Chen, J., Barber, K., Sakaguchi, K., Plant, R. S., Feng, Z., & Xiao, H. (2022). A machinelearning-assisted stochastic cloud population model as a parameterization of cumulus convection. Journal of Advances in Modeling Earth Systems, 14, e2021MS002808. https://doi. org/10.1029/2021MS002808

Hagos, S., Feng, Z., Plant, R. S., Houze, R. A., & Xiao, H. (2018). A stochastic framework for modeling the population dynamics of convective clouds. Journal of Advances in Modeling Earth Systems, 10, 448–465. https://doi. org/10.1002/2017MS001214

Hall, T., Blunn, L., Grimmond, S. , McCarroll, N., Merchant, C. , Morrison, W., Shonk, J., Lean, H. and Best, M. (2024) Utility of thermal remote sensing for evaluation of a high-resolution weather model in a city. Quarterly Journal of the Royal Meteorological Society. ISSN 1477-870X (In Press)

Hanley, K., Whitall, M., Stirling, A. and Clark, P. (2019) Modifications to the representation of subgrid mixing in kilometre-scale versions of the Unified Model. Quarterly Journal of the Royal Meteorological Society, 145 (725). pp. 3361-3375. ISSN 1477-870X doi: https://doi.org/10.1002/qj.3624

Harper, A. B., Williams, K. E., McGuire, P. C., Duran Rojas, M. C., Hemming, D., Verhoef, A., Huntingford, C., Rowland, L., Marthews, T., Breder Eller, C., Mathison, C., Nobrega, R. L. B., Gedney, N., Vidale, P. L., Otu-Larbi, F., Pandey, D., Garrigues, S., Wright, A., Slevin, D., De Kauwe, M. G., Blyth, E., Ardö, J., Black, A., Bonal, D., Buchmann, N., Burban, B., Fuchs, K., de Grandcourt, A., Mammarella, I., Merbold, L., Montagnani, L., Nouvellon, Y., Restrepo-Coupe, N., and Wohlfahrt, G.: Improvement of modeling plant responses to low soil moisture in JULESvn4.9 and evaluation against flux tower measurements, Geosci. Model Dev., 14, 3269–3294, https://doi.org/10.5194/gmd-14-3269

Harvey, N.J., Daleu, C.L., Stratton, R.A., Plant, R.S., Woolnough, S.J. & Stirling, A.J.(2022) The impact of surface heterogeneity on the diurnal cycle of deep convection. *Quarterly Journal of the Royal Meteorological Society*, 148(749), 3509–3527. Available from: https://doi.org/10.1002/qj.4371

Hawkins, E. and Sutton, R.: The potential to narrow uncertainty in regional climate predictions, B. Am. Meteorol. Soc., 90, 1095–1107, https://doi.org/10.1175/2009BAMS2607.1, 2009.

Hermoso, A., Homar, V. and Plant, R. S. (2021) Potential of stochastic methods for improving convection-permitting ensemble forecasts of extreme events over the western Mediterranean. Atmospheric Research, 257. 105571. ISSN 0169-8059 doi: https://doi.org/10.1016/j.atmosres.2021.105571

Hertwig, D. , Grimmond, S. , Hendry, M. A. , Saunders, B. , Wang, Z. , Jeoffrion, M., Vidale, P. L. , McGuire, P. C. , Bohnenstengel, S. I. , Ward, H. C. and Kotthaus, S. (2020) Urban signals in high-resolution weather and climate simulations: role of urban land-surface characterisation. Theoretical and Applied Climatology, 142. pp. 701-728. ISSN 0177-798X

Hewitt, H. T. , Roberts, M., Mathiot, P., Biastoch, A., Blockley, E., Chassignet, E. P., Fox-Kemper, B., Hyder, P., Marshall, D. P., Popova, E., Treguier, A.-M., Zanna, L., Yool, A., Yu, Y., Beadling, R., Bell, M., Kuhlbrodt, T. , Arsouze, T., Bellucci, A., Castruccio, F., Gan, B., Putrasahan, D., Roberts, C. D., Van Roekel, L. and Zhang, Q. (2020) Resolving and parameterising the ocean mesoscale in earth system models. Current Climate Change

Reports, 6. pp. 137-152. ISSN 2198-6061 doi: https://doi.org/10.1007/s40641-020-00164-w

Hodges, K. I. and Klingaman, N. P. (2019) Prediction errors of tropical cyclones in the western north Pacific in the Met Office global forecast model. Weather and Forecasting, 34 (5). pp. 1189-1209. ISSN 0882-8156

Hogan, R. J., & Bozzo, A. (2018). A flexible and efficient radiation scheme for the ECMWF model. Journal of Advances in Modeling Earth Systems, 10, 1990-2008. https://doi.org/10.1029/2018MS001364

Holland MM and Landrum L (2021) The Emergence and Transient Nature of Arctic Amplification in Coupled Climate Models. Front. Earth Sci. 9:719024. doi: 10.3389/feart.2021.719024

Hooker, H., Dance, S. L., Mason, D. C., Bevington, J., and Shelton, K.: Assessing the spatial spread–skill of ensemble flood maps with remote-sensing observations, Nat. Hazards Earth Syst. Sci., 23, 2769–2785, https://doi.org/10.5194/nhess-23-2769-2023, 2023.

Hu, Guannan and Dance, Sarah (2021) Efficient computation of matrix-vector products with full observation weighting matrices in data assimilation. Quarterly Journal of the Royal Meteorological Society, 147 (741). pp. 4101-4121. ISSN 1477-870X doi: https://doi.org/10.1002/qj.4170

Kuhlbrodt, T. , Voldoire, A., Palmer, M. D., Geoffroy, O. and Killick, R. E. (2023) Historical ocean heat uptake in two pairs of CMIP6 models: global and regional perspectives. Journal of Climate, 36 (7). pp. 2183-2203. ISSN 1520-0442 doi: https://doi.org/10.1175/JCLI-D-22-0468.1

Kuhlbrodt, T., Jones, C. G., Sellar, A., Storkey, D., Blockley, E., Stringer, M., et al. (2018). The low-resolution version of HadGEM3 GC3.1: Development and evaluation for global climate. Journal of Advances in Modeling Earth Systems, 10. https://doi.org/10.1029/2018MS001370

Lauer, A., Eyring, V., Righi, M., Buchwitz, M., Defourny, P., Evaldsson, M., Friedlingstein, P., de Jeu, R., de Leeuw, G., Loew, A., Merchant, C. J. , Müller, B., Popp, T., Reuter, M., Sandven, S., Senftleben, D., Stengel, M., van Roozendael, M., Wenzel, S. and Willen, U. (2017) Benchmarking CMIP5 models with a subset of ESA CCI Phase 2 data using the ESMValTool. Remote Sensing of Environment, 203. pp. 9-39. ISSN 0034-4257 doi: https://doi.org/10.1016/j.rse.2017.01.007

Lean HW, Barlow JF, Halios CH. The impact of spin-up and resolution on the representation of a clear convective boundary layer over London in order 100 m grid-length versions of the Met Office Unified Model. *Q J R Meteorol Soc* 2019; 145: 1674–1689.https://doi.org/10.1002/qj.3519

Lean, H.W., Barlow, J.F. & Clark, P.A.(2022) The use of 100 m scale NWP models to understand differences between different measures of mixing height in a morning growing clear convective boundary layer over London. *Quarterly Journal of the Royal Meteorological Society*, 148(745), 1983–1995. Available from: https://doi.org/10.1002/qj.4291

Lee, Joshua Chun Kwang, Amezcua, Javier and Bannister, Ross Noel (2022) Hybrid ensemble-variational data assimilation in ABC-DA within a tropical framework. Geoscientific Model Development, 15 (15). pp. 6197-6219. ISSN 1991-9603 doi: https://doi.org/10.5194/gmd-2022-3

Lehner, F., Deser, C. Maher, N., Marotzke, J.,m Fischer, E. M., Brunner, L., Knutti, R. and Hawkins, E. Partioning climate projection uncertainty with multiple large ensembles Earth Syst. Dynam., 11, 491–508, 2020 https://doi.org/10.5194/esd-11-491-2020

Leung, Tsz Yan , Lawless, Amos S., Nichols, Nancy K. , Lea, Daniel J. and Martin, Matthew J. (2022) The impact of hybrid oceanic data assimilation in a coupled model: a case study of a tropical cyclone. Quarterly Journal of the Royal Meteorological Society, 148 (746). pp. 2410-2430. ISSN 0035-9009 doi: https://doi.org/10.1002/qj.4309

McIntyre, W. A., Weller, H. and Holloway, C. E. (2020) Numerical methods for entrainment and detrainment in the multi-fluid Euler equations for convection. Quarterly Journal of the Royal Meteorological Society, 146 (728). pp. 1106-1120. ISSN 1477-870X doi: https://doi.org/10.1002/qj.3728]

Meyer, D., Hogan, R. J., Dueben, P. D., & Mason, S. L. (2022). Machine learning emulation of 3D cloud radiative effects. Journal of Advances in Modeling Earth Systems, 14, e2021MS002550. https://doi. org/10.1029/2021MS002550

Moreton, S. M., Ferreira, D. , Roberts, M. J. and Hewitt, H. T. (2020) Evaluating surface eddy properties in coupled climate simulations with 'eddy-present' and 'eddy-rich' ocean resolution. Ocean Modelling, 147. 101567. ISSN 1463-5003

Mulholland, D. P., Haines, K. , Sparrow, S. N. and Wallom, D. (2017) Climate model forecast biases assessed with a perturbed physics ensemble. Climate Dynamics, 49 (5-6). pp. 1729-1746. ISSN 0930-7575

Mulcahy, J. P., Jones, C. G., Rumbold, S. T., Kuhlbrodt, T., Dittus, A. J., Blockley, E. W., Yool, A., Walton, J., Hardacre, C., Andrews, T., Bodas-Salcedo, A., Stringer, M., de Mora, L., Harris, P., Hill, R., Kelley, D., Robertson, E., and Tang, Y.: UKESM1.1: development and evaluation of an updated configuration of the UK Earth System Model, Geosci. Model Dev., 16, 1569–1600, https://doi.org/10.5194/gmd-16-1569-2023, 2023.

Mulcahy, J. P., Jones, C., Sellar, A., Johnson, B., Boutle, I. A., Jones, A., Andrews, T., Rumbold, S. T. , Mollard, J., Bellouin, N. , Johnson, C. E., Williams, K. D., Grosvenor, D. P. and McCoy, D. T. (2018) Improved aerosol processes and effective radiative forcing in HadGEM3 and UKESM1. Journal of Advances in Modeling Earth Systems, 10 (11). pp. 2786-2805. ISSN 1942-2466 doi: https://doi.org/10.1029/2018MS001464

Müller, W. A., Jungclaus, J. H., Mauritsen, T., Baehr, J., Bittner, M., Budich, R., Bunzel, F., Esch, M., Ghosh, R., Haak, H., Ilyina, T., Kleine, T., Kornblueh, L., Li, H., Modali, K., Notz, D., Pohlmann, H., Roeckner, E., Stemmler, I., Tian, F. and Marotzke, J. (2018) *A higher-resolution version of the Max Planck Institute Earth System Model (MPI-ESM1.2-HR).* Journal of Advances in Modeling Earth Systems, 10 (7). pp. 1383-1413. ISSN 1942-2466 doi: https://doi.org/10.1029/2017ms001217

Oliver, R. J., Mercado, L. M., Clark, D. B., Huntingford, C., Taylor, C. M., Vidale, P. L., McGuire, P. C., Todt, M., Folwell, S., Shamsudheen Semeena, V., and Medlyn, B. E.: Improved representation of plant physiology in the JULES-vn5.6 land surface model: photosynthesis, stomatal conductance and thermal acclimation, Geosci. Model Dev., 15, 5567–5592, https://doi.org/10.5194/gmd-15-5567-2022, 2022.

Pinnington, E., Quaife, T., and Black, E.: Impact of remotely sensed soil moisture and precipitation on soil moisture prediction in a data assimilation system with the JULES land surface model, Hydrol. Earth Syst. Sci., 22, 2575–2588, https://doi.org/10.5194/hess-22-2575-2018, 2018.

Pinnington, Ewan, Quaife, Tristan, Lawless, Amos, Williams, Karina, Arkebauer, Tim and Scoby, Dave (2020) The land variational ensemble data assimilation framework: LaVEnDAR v1.0.0. Geoscientific Model Development, 13. pp. 55-69. ISSN 1991-9603 doi: https://doi.org/10.5194/gmd-13-55-2020

Ranjini Swaminathan, Tristan Quaife, Richard Philip Allan. Evaluating Vegetation Modeling in Earth System Models with Machine Learning Approaches. *ESS Open Archive .* November 20, 2023.

Roberts, M. J. , Camp, J. , Seddon, J. , Vidale, P. L. , Hodges, K. , Vannière, B. , Mecking, J., Haarsma, R., Bellucci, A., Scoccimarro, E., Caron, L.-P., Chauvin, F., Terray, L., Valcke, S., Moine, M.-P., Putrasahan, D., Roberts, C. D., Senan, R., Zarzycki, C., Ullrich, P., Yamada, Y., Mizuta, R., Kodama, C., Fu, D., Zhang, Q., Danabasoglu, G., Rosenbloom, N., Wang, H. and Wu, L. (2020) Projected future changes in tropical cyclones using the CMIP6 HighResMIP multimodel ensemble. Geophysical Research Letters, 47 (14). e2020GL088662. ISSN 0094-8276 doi: https://doi.org/10.1029/2020gl088662

Roberts, M. J., Jackson, L. C., Roberts, C. D., Meccia, V., Docquier, D., Koenigk, T., et al. (2020). Sensitivity of the Atlantic Meridional Overturning Circulation to model resolution in CMIP6 HighResMIP simulations and implications for future changes. Journal of Advances in Modeling Earth Systems, 12, e2019MS002014. https://doi.org/ 10.1029/2019MS002014

Robson, J., Aksenov, Y., Bracegirdle, T. J., Dimdore-Miles, O., Griffiths, P. T., Grosvenor, D. P., et al. (2020). The evaluation of the North Atlantic climate system in UKESM1 historical simulations for CMIP6. Journal of Advances in Modeling Earth Systems, 12, e2020MS002126. https://doi.org/ 10.1029/2020MS002126

S. L. Lavender, A. J. Stirling, M. Whitall, R. Stratton, C. L. Daleu, R. S. Plant, A. Lock, and J.-F. Gu. The use of idealised experiments in testing a new convective parameterization: Performance of CoMorph-A. *To appear in: Q. J. R. Meteorol. Soc.*, 2024.

Schiemann, R., Athanasiadis, P., Barriopedro, D., Doblas-Reyes, F., Lohmann, K., Roberts, M. J., Sein, D. V., Roberts, C. D., Terray, L., and Vidale, P. L.: Northern Hemisphere blocking simulation in current climate models: evaluating progress from the Climate Model Intercomparison Project Phase 5 to 6 and sensitivity to resolution, Weather Clim. Dynam., 1, 277–292, https://doi.org/10.5194/wcd-1-277-2020, 2020.

Seddon, J., Stephens, A., Mizielinski, M. S., Vidale, P. L., and Roberts, M. J.: Technology to aid the analysis of large-volume multi-institute climate model output at a central analysis facility (PRIMAVERA Data Management Tool V2.10), Geosci. Model Dev., 16, 6689–6700, https://doi.org/10.5194/gmd-16-6689-2023, 2023.

Sellar, A. A., Jones, C. G., Mulcahy, J. P., Tang, Y., Yool, A., Wiltshire, A., et al. (2019). UKESM1: Description and evaluation of the U.K. Earth System Model. *Journal of Advances in Modeling Earth Systems*, 11, 4513–4558. https://doi.org/10.1029/2019MS001739

Senior, C. A., Jones, C. G., Wood, R. A., Sellar, A., Belcher, S., Klein-Tank, A., et al. (2020). U.K. community Earth system modeling for CMIP6. Journal of Advances in Modeling Earth Systems, 12, e2019MS002004. https://doi.org/ 10.1029/2019MS002004

Shataer, S., Lawless, A. S. and Nichols, N. K. (2023) *Conditioning of hybrid variational data assimilation.* Numerical Linear Algebra with Applications. e2534. ISSN 1099-1506 doi: https://doi.org/10.1002/nla.2534

Shipley, D., Weller, H., Clark, P. A. and McIntyre, W. A. (2021) Two-fluid single-column modelling of Rayleigh-Bénard convection as a step towards multi-fluid modelling of atmospheric convection. Quarterly Journal of the Royal Meteorological Society. ISSN 1477-870X doi: https://doi.org/10.1002/qj.4209

Smith, D. M., Gillett, N. P., Simpson, I. R., Athanasiadis, P. J., Baehr, J., Bethke, I., Bilge, T. A., Bonnet, R., Boucher, O., Findell, K. L., Gastineau, G., Gualdi, S., Hermanson, L., Leung, L. R., Mignot, J., Müller, W. A., Osprey, S., Otterå, O. H., Persad, G. G., Scaife, A. A., Schmidt, G. A., Shiogama, H., Sutton, R. T. , Swingedouw, D., Yang, S., Zhou, T. and Ziehn, T. (2022) Attribution of multi-annual to decadal changes in the climate system: The Large Ensemble Single Forcing Model Intercomparison Project (LESFMIP). Frontiers in Climate, 4. 955414. ISSN 2624-9553 doi: https://doi.org/10.3389/fclim.2022.955414

Smith, Polly J., Lawless, Amos S. and Nichols, Nancy K. (2020) The role of cross-domain error correlations in strongly coupled 4D-Var atmosphere-ocean data assimilation. Quarterly Journal of the Royal Meteorological Society, 146 (730). pp. 2450-2465. ISSN 1477-870X doi: https://doi.org/10.1002/qj.3802

Smith, R. S., George, S., and Gregory, J. M.: FAMOUS version xotzt (FAMOUS-ice): a general circulation model (GCM) capable of energy- and water-conserving coupling to an ice sheet model, Geosci. Model Dev., 14, 5769–5787, https://doi.org/10.5194/gmd-14-5769-2021, 2021a.

Smith, R. S., Mathiot, P., Siahaan, A., Lee, V., Cornford, S. L., Gregory, J. M., et al. (2021b). Coupling the U.K. Earth System model to dynamic models of the Greenland and Antarctic ice sheets. *Journal of Advances in Modeling Earth Systems*, 13, e2021MS002520. https://doi.org/10.1029/2021MS002520

Stein, T. , Hogan, R., Clark, P. , Halliwell, C., Hanley, K., Lean, H., Nicol, J. and Plant, R. S. (2015) The DYMECS project: a statistical approach for the evaluation of convective storms in high-resolution NWP models. Bulletin of the American Meteorological Society, 96 (6). pp. 939-951. ISSN 1520-0477

Stein, T. H. M. , Scovell, R. W., Hanley, K., Lean, H. W. and Marsden, N. H. (2020) The potential use of operational radar network data to evaluate the representation of convective storms in NWP models. Quarterly Journal of the Royal Meteorological Society, 146 (730). pp. 2315-2331. ISSN 1477-870X

Storer, Luke N., Gill, Philip G. and Williams, Paul D. (2020) *Multi-diagnostic multi-model ensemble forecasts of aviation turbulence.* Meteorological Applications, 27 (1). e1885. ISSN 1350-4827 doi: https://doi.org/10.1002/met.1885

Stretton, M. A., Hogan, R. J., Grimmond, S. and Morrison, W. (2023) Characterising the vertical structure of buildings in cities for use in atmospheric models. Urban Climate, 50. 101560. ISSN 2212-0955 doi: https://doi.org/10.1016/j.uclim.2023.101560

Tabeart, J. M., Dance, S.L., Lawless, A.S., Migliorini, S., Nichols, N. K., Smith, F. and Waller, J. A. (2020) The impact of using reconditioned correlated observation error covariance matrices in the Met office 1D-Var system. Quarterly Journal of the Royal Meteorological Society, 146 (728). pp. 1372-1390. ISSN 1477-870X doi: https://doi.org/10.1002/qj.3741
Thuburn, J., Weller, H., Vallis, G. K., Beare, R. J. and Whitall, M. (2018) A framework for convection and boundary layer parameterization derived from conditional filtering. Journal of the Atmospheric Sciences, 75 (3). pp. 965-981. ISSN 1520-0469 doi: https://doi.org/10.1175/jas-d-17-0130.1

Titley, H. A., Bowyer, R. L. and Cloke, H. L. (2020) *A global evaluation of multi-model ensemble tropical cyclone track probability forecasts.* Quarterly Journal of the Royal Meteorological Society, 146 (726). pp. 531-545. ISSN 1477-870X doi: https://doi.org/10.1002/qj.3712

Ukkonen, P., & Hogan, R. J. (2024). Twelve times faster yet accurate: A new state-of-the-art in radiation schemes via performance and spectral optimization. *Journal of Advances in Modeling Earth Systems*, 16, e2023MS003932. https://doi.org/10.1029/2023MS003932

Vanniere, B. , Roberts, M. J., Vidale, P. L., Hodges, K., Demory, M.-E., Caron, L.-P., Scoccimarro, E., Terray, L. and Senan, R. (2020) The moisture budget of tropical cyclones in HighResMIP models: large-scale environmental balance and sensitivity to horizontal resolution. Journal of Climate. ISSN 1520-0442

Vidale, P. L., and Coauthors, 2021: Impact of Stochastic Physics and Model Resolution on the Simulation of Tropical Cyclones in Climate GCMs. J. Climate, 34, 4315–4341, https://doi.org/10.1175/JCLI-D-20-0507.1.

Watson-Parris, D., Bellouin, N., Deaconu, L. T., Schutgens, N. A. J., Yoshioka, M., Regayre, L. A., et al. (2020). Constraining uncertainty in aerosol direct forcing. Geophysical Research Letters, 47, e2020GL087141. https://doi.org/10.1029/2020GL087141

Weller, H. and McIntyre, W. A. (2019) Numerical solution of the conditionally averaged equations for representing net mass flux due to convection. Quarterly Journal of the Royal Meteorological Society, 145 (721). pp. 1337-1353. ISSN 1477-870X doi: https://doi.org/10.1002/qj.3490

Weller, H., McIntyre, W. and Shipley, D. (2020) Multi-fluids for representing sub-grid-scale convection. Journal of Advances in Modeling Earth Systems, 12 (8). e2019MS001966. ISSN 1942-2466 doi: https://doi.org/10.1029/2019MS001966

Williams, Nicholas, Byrne, Nicholas, Feltham, Daniel, Van Leeuwen, Peter Jan, Bannister, Ross, Schroeder, David , Ridout, Andrew and Nerger, Lars (2023) The effects of assimilating a sub-grid scale sea ice thickness distribution in a new Arctic sea ice data assimilation system. The Cryosphere, 17 (6). pp. 2509-2532. ISSN 1994-0424 doi: https://doi.org/10.5194/tc-17-2509-2023 (In Press).

Wright, A., Lawless, A. S., Nichols, N. K. , Lea, D. J. and Martin, M. J. (2024) Assessment of short-range forecast error atmosphere-ocean cross-correlations from the Met Office coupled NWP system. Quarterly Journal of the Royal Meteorological Society. ISSN 1477-870X doi: https://doi.org/10.1002/qj.4735 (In Press)

Yool, A. , Palmiéri, J. , Jones, C. G. , de Mora, L. , Kuhlbrodt, T. , Popova, E. E., Nurser, A. J. G. , Hirschi, J. , Blaker, A. T. , Coward, A. C. , Blockley, E. W. and Sellar, A. A. (2021) Evaluating the physical and biogeochemical state of the global ocean component of UKESM1 in CMIP6 historical simulations. Geoscientific Model Development, 14 (6). pp. 3437-3472. ISSN 1991-9603

Zhang, W. , Villarini, G., Scoccimarro, E., Roberts, M., Vidale, P. L., Vanniere, B. , Caron, L.-P., Putrasahan, D., Roberts, C., Senan, R. and Moine, M.-P. (2021) Tropical cyclone precipitation in the HighResMIP atmosphere-only experiments of the PRIMAVERA Project. Climate Dynamics, 57. pp. 253-273. ISSN 0930-7575

Zhao, Zihui, Guo, Yan, Dong, Buwen , Zhu, Jiangshan, Luo, Neng and Gao, Zhibo (2023) A clustering-based multi-model ensemble projection of near-term precipitation changes over East China and its uncertainty. Environmental Research Letters. ISSN 1748-9326 doi: https://doi.org/10.1088/1748-9326/acef40 (In Press)

Zhu, J. and Bannister, R. N. (2023) The “Hydro-ABC model” (Vn 2.0): a simplified convective-scale model with moist dynamics. Geoscientific Model Development. ISSN 1991-9603 doi: https://doi.org/10.5194/egusphere-2022-1436 (In Press)