RESEARCH ARTICLE

The impact of time-varying sea surface temperature on UK regional atmosphere forecasts

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Abstract
A new approach to improve the ocean surface boundary condition used in regional numerical weather prediction is proposed. Typically, regional atmosphere forecast systems assume a fixed sea surface temperature during a simulation. The study assesses the use of ocean temperature from an operational regional ocean model as an evolving lower boundary in a kilometre-scale regional atmospheric configuration centred on the UK. Simulations of a winter and two five day duration summer case studies associated with anomalously warm temperatures are considered. The largest impact is found in summer, when a growing cold bias in mean temperature over land compared with observations is apparent when using a fixed global-scale analysis lower boundary condition. The mean error is improved by 0.1 K when using a fixed temperature boundary condition from a kilometre-scale regional ocean model initial condition. When using hourly surface temperature data from the same regional ocean model, the error is improved by 0.5 K for this case. Prediction of daytime maximum air temperature is also improved during the summer heat wave cases. A winter case study shows marginal improvement over the ocean and negligible changes over land. These results are confirmed in longer duration experiments using an hourly cycling regional forecast system with data assimilation for summer and winter periods. A systematic and statistically significant improvement of near-surface temperature verification relative to the observations over land is demonstrated for both summer and winter using the new approach. This study supports future operational implementation of a time-varying lower boundary for regional numerical weather prediction.

KEYWORDS
air–sea interaction, atmosphere modelling, regional numerical weather prediction, sea surface temperature

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Meteorol Appl. 2021;28:e1983. wileyonlinelibrary.com/journal/met
1 | INTRODUCTION

Sea surface temperature (SST) plays a critical role in driving the exchange of heat, moisture and momentum across the ocean–atmosphere interface. The influence of air–sea interaction on the local marine atmospheric boundary layer and its non-local effects is well established, particularly on long timescales (e.g. Minobe et al., 2008; Small et al., 2008; Chelton, 2013; Frenger et al., 2013). More accurate simulation of the influence of ocean processes on the atmosphere for shorter timescales of hours to days has driven the development of global atmosphere–ocean-coupled prediction systems (e.g. Shelly et al., 2014; Perlin et al., 2020; Valdivieso et al., 2020). These are increasingly being used for operational numerical weather prediction (NWP) (e.g. Smith et al., 2018; Browne et al., 2019; Vellinga et al., 2020; Roberts et al., 2020).

In contrast, the representation of the ocean surface state within the regional NWP systems, typically based on the application of model configurations with horizontal grid spacings of the order a 1 km, remains relatively basic. For example, regional atmosphere forecasts at the Met Office are currently initialized with a global-scale SST analysis from the Operational Sea Surface Temperature and Ice Analysis (OSTIA) (Donlon et al., 2012; Fiedler et al., 2019). The initial SST distribution is then kept fixed for the duration of a forecast, which can run out to five days ahead. A recent informal survey of colleagues across other European meteorological organizations indicated that persisting an initial SST analysis through a forecast cycle is typical for leading regional forecast providers (with particular thanks to Christoph Schraff, Florian Meier and Benedikt Strajnar, personal communications).

The routine application of regional atmosphere forecast systems at the kilometre scale, in which convection is not parameterized and local heterogeneity in the land surface can be represented, has led to substantial improvements in forecast skill at increasingly local scales (e.g. Clark et al., 2016; Bengtsson et al., 2017; Bush et al., 2020; Ashrit et al., 2020). The present paper assesses whether further performance improvements can be achieved through better representing the SST lower boundary condition. This is achieved through use of a regional ocean model analysis and forecasts.

To date, research on the use of ocean models within the NWP-focused atmosphere simulations has taken place largely in the context of the development of regional-coupled prediction systems (e.g. Pellerin et al., 2004; Fallmann et al., 2019; Lewis et al., 2019; Thompson et al., 2019). As noted in several previous studies, one challenge of using free-running ocean model forecast information is that it can introduce initial condition biases, leading to poorer agreement with SST observations compared with persisted analyses (e.g. Rainaud et al., 2017; Strajnar et al., 2019). In the present paper, this challenge is overcome by using an assimilative operational regional ocean forecast system as a new source of fixed- or time-varying SST.

The remainder of the paper is structured as follows. The modelling systems and experimental design used in the present study are introduced in more detail in Section 2. Case study simulations and the NWP trial assessments over longer periods are discussed in Section 3. These results are set in the context of the annual evolution of SST around the UK. Conclusions and future directions are discussed in Section 4.

2 | MODEL AND METHODS

2.1 | Ocean surface temperature analysis

Ocean surface temperature analyses are integral to the NWP systems at many operational forecasting centres. For example, OSTIA has been used as a surface boundary condition for the NWP at the Met Office since 2004 (Donlon et al., 2012; Fiedler et al., 2019). OSTIA is a gridded global product with resolution of 0.05° (approximately 4 km spacing at mid-latitudes). As a daily foundation SST (SSTf), OSTIA nominally represents ocean temperature at 10 m depth. Daily temperatures are effectively integrated across any observed tidal influences and do not include diurnal warming effects. Updated OSTIA data representative of observations the previous day are available for operational use from around 0700 UTC daily. In practice, therefore, the SST initial condition used in an NWP forecast cycle can be indicative of the observed temperature as much as two days before initial time, depending on the forecast time and details of an operational NWP implementation.

2.2 | Regional atmosphere and ocean model descriptions

The study assesses simulations using the Met Office’s UK-centred variable resolution regional atmosphere model, referred to as the UKV (Tang et al., 2013; Bush et al., 2020). This is a convection-permitting configuration of the Unified Model. It has 70 terrain-following vertical levels. The horizontal grid is defined on a rotated pole with spacing of 1.5 km across a fixed resolution inner region covering the UK, Ireland and surrounding coastal seas (Figure 1), extending out to 4 km spacing through the outer parts of the domain. Full details of the
science configuration (RAL1-M) and UKV model grid used in the present paper are described by Bush et al. (2020) and are therefore omitted here for brevity. Since an operational system upgrade in December 2019, new UKV forecasts are initialized each hour. Two forecast cycles per day are run out to five days (120 hr) ahead of the initial time, another four out to 54 hr and the rest out to 12 hr. Lateral boundary conditions are provided at hourly frequency from the global Unified Model operational forecast (Walters et al., 2019), which was running at the time of interest in the present study on a grid with horizontal spacing of order 10 km at mid-latitudes. Initial conditions are derived from a four-dimensional variational data assimilation (4D-Var) regional Unified Model analysis (Milan et al., 2020) and simplified extended Kalman filter (SEKF) for soil moisture (Gómez et al., 2020). The SSTf lower boundary condition from OSTIA, which is then kept fixed through the forecast, is interpolated from its native resolution onto the UKV grid. Sea surface currents are also assumed to be zero in the calculation of near-surface wind shear and surface exchange. The influence of ocean waves on the near surface is parameterized using a fixed value of the Charnock parameter (Lewis et al., 2019).

Through its role as a national ocean forecasting service, the Met Office delivers a range of operational ocean simulations (Siddorn et al., 2016). A seamless approach to the development and application of the Nucleus for European Modelling of the Ocean (NEMO) ocean model (Madec and the NEMO System Team, 2020) configurations across different space and time scales is adopted. For regional-scale forecasts around the UK and North-West European Shelf, the Atlantic Margin Model 1.5 km configuration (AMM15) (Tonani et al., 2019; Graham et al., 2018) is run daily and routinely monitored as part of the European Union’s (EU) Copernicus Marine Environment Monitoring Service (CMEMS) (https://marine.copernicus.eu/; accessed October 22, 2020). The AMM15 ocean domain covers the same extent and uses the same rotated pole projection as the UKV atmosphere domain, but is defined on a fixed resolution grid everywhere. The regional ocean and atmosphere model grids match exactly within the UKV inner region, although each configuration has its own definition of the land–sea mask. The AMM15 system provides hourly forecasts of the 3D ocean state (e.g. temperature, currents, salinity, surface height) out to six days ahead, with updated model products available around 1100 UTC each day. The AMM15 is forced by hourly meteorological forecast fields (air temperature, wind components, mean sea level pressure, precipitation and evaporation) from the European Centre for Medium-range Weather Forecasts (ECMWF) global NWP system. These are currently provided at around 10 km resolution in mid-latitudes. Lateral boundaries are applied from a 1/12° regional deep-ocean configuration (Tonani et al., 2019). Initial conditions valid for the 00 UTC initialization time are derived from a 3D-variational regional ocean assimilation system. Satellite and in-situ observations of surface temperature are ingested within the assimilation together with vertical temperature and salinity profiles and altimeter sea level anomaly (King et al., 2018). The AMM15 assimilation system is run for two days before initial time, based on a 24 hr assimilation window to include as many observations as possible (Tonani et al., 2019). In common with the OSTIA, the AMM15 assimilation of SST aims to represent SSTf by filtering observations influenced by diurnal warming (King et al., 2018). After the assimilation step, the model is rerun for the same period applying a fraction of the increments to be applied at each time step (incremental analysis update). The AMM15 uses a stretched vertical co-ordinate grid (Siddorn and Furner, 2013) with 51 levels through the spatially varying ocean depth. Figure 1 shows the top ocean model-level thickness in the AMM15, indicating a layer depth of

![Figure 1](image-url)
0.5 m across much of the domain and shrinking to as little as 0.1 m in the shallowest part of the domain in the southern North Sea and towards the coastlines.

A comparison between the AMM15 forecast and in situ and satellite data from an initial two years’ trial conducted by Tonani et al. (2019) demonstrated the system SST forecasts to have a root mean squared error (RMSE) of order 0.5°C relative to the observations and a small warm bias, mostly in winter. The operational system has a similar incremental model upgrade cycle as for regional atmosphere models, with future improvements (e.g. a recent move to an ocean wave-coupled system) offering the potential for further impact on regional atmosphere forecast performance.

The convergence of the operational UK-focused regional atmosphere and ocean model domains at the Met Office over recent years has been enabled by regional atmosphere–ocean-coupled research aimed at understanding their impact on the skill of regional predictions (e.g. Lewis et al., 2019). This has aligned changes required by a user-driven need to extend the UKV domain to reduce the impact of lateral boundary spin-up effects on UK NWP performance, and an ocean user-driven need to increase the resolution of the AMM ocean to eddy-resolving scales (Tonani et al., 2019). This convergence, and associated operational infrastructure, offers a clear opportunity to make more direct use of AMM15 ocean forecasts within the regional NWP forecasts as a one-way forcing, even without the implementation of two-way coupling. The potential impact of this approach is the focus of the study.

### 2.3 Experimental design

The sensitivity of regional atmosphere forecasts to a time-varying rather than a fixed SST lower boundary condition is assessed. Three case study experiments for two summer and one winter period of five days’ duration are selected, focused on periods when anomalously warm temperatures were observed. Longer duration NWP trial experiments for summer and winter are also run to assess the likely impact of time-varying SST on the operational regional NWP performance metrics.

The experiments conducted are summarized in Table 1 and illustrated in Figure 2. In the FIX_OSTIA, the initial condition OSTIA SST\(_0\), interpolated from the global-scale NWP analysis, is a fixed lower boundary throughout the five day simulation. This matches the current operational UKV approach.

In the FIX_AMM15 simulations, the fixed SST lower boundary is provided by the operational AMM15 analysis valid at the forecast initial time, interpolated onto the UKV model grid. This represents the temperature of the top ocean model level (SST\(_{\text{L1}}\)). Area-weighted interpolation is performed from the AMM15 fixed resolution to UKV variable resolution grid, with a cell-filling algorithm applied to ensure the interpolated field is consistent where the land–sea masks are not aligned.

The hourly AMM15 forecast SST\(_{\text{L1}}\) is then used as a dynamic lower boundary condition in the UPD_AMM15 simulations. This is ingested in the Unified Model as a time-updating ancillary file, created using the ants software library (v0.13). In the UPD_AMM15, the Unified Model ancillary scheme applies updated surface boundary conditions at each model time step based on interpolation between the hourly input data.

### 2.4 Case study periods

Previous work considering the sensitivity of UK weather to SST variability around the North-West Shelf region has included case studies focused on sea breeze evolution (Tang, 2012; Sweeney et al., 2014), heavy precipitation (Warren et al., 2014), boundary layer clouds (Fallmann et al., 2017), sea fog (Fallmann et al., 2019), near-surface wind gusts (Gentile et al., 2020) and heat waves (McCarthy et al., 2019; Petch et al., 2020).

Three case studies assessed in the present paper focus on the prediction of maximum daytime temperatures during anomalously warm periods: two in summer and one in winter. This is because one of the key longstanding UKV model errors, of critical importance to forecast users, is the simulation of the diurnal cycle of near-surface temperatures (Bush et al., 2020). Forecast temperatures tend to be too cold during daytime and too warm overnight relative to the observations.

| Experiment     | Description                                                                                           |
|----------------|--------------------------------------------------------------------------------------------------------|
| FIX_OSTIA      | Regional atmosphere simulation with fixed Operational Sea Surface Temperature and Ice Analysis (OSTIA) global-scale resolution (order 10 km) for the foundation sea surface temperature (SST\(_{\text{L1}}\)) lower boundary. Current operational approach |
| FIX_AMM15      | Regional atmosphere simulation with fixed 1.5 km-resolution Atlantic Margin Model                        |
|                | 1.5 km configuration (AMM15) analysis top model level SST\(_{\text{L1}}\) lower boundary               |
| UPD_AMM15      | Regional atmosphere simulation with time-varying 1.5 km-resolution AMM15 ocean model forecast top model level SST\(_{\text{L1}}\) lower boundary. New proposed approach |

### Table 1 Summary of the model simulation experiments
The first case study from 00 UTC July 21 to 00 UTC July 26, 2019, occurred during a record-breaking summer heat wave over the UK (Christidis et al., 2020; Kendon et al., 2020a). Temperatures were > 35°C across south and eastern England on 25 July, and were > 30°C widely elsewhere in the southern UK. A new maximum UK temperature record of 38.7°C was observed at Cambridge Botanic Garden. A second summer heat wave case from 00 UTC 23 to 00 UTC August 28, 2019, is also considered for comparison.

Simulations between 00UTC February 22 and 00 UTC February 27, 2019 (Kendon et al., 2020b), are used to assess the impact of time-varying SST in winter, during a very settled and anomalously warm period. On February 26, 2019, a maximum UK winter temperature of 21.2°C was recorded at Kew Gardens (London).

2.5 | NWP evaluation trials

A set of standard regional NWP evaluation trials was also conducted to enable a more statistically robust assessment of likely operational impact. A summer and winter trial were run using the FIX_OSTIA and UPD_AMM15 configurations only. In contrast to the case study assessments, the NWP trials use the same hourly cycling approach as in the operational UKV system (Milan et al., 2020), but with forecasts run out to 36 hr ahead only to limit computational expense. The same approach to input SST is used in the NWP trials as in the case studies. In the FIX_OSTIA, a new OSTIA SSTf field is updated once per day on the 0900 cycle, while in the UPD_AMM15, the SST forecast valid at each time through a forecast is applied, with temporal interpolation used to update the SST at each model time step. The AMM15 SST is also consistently applied within the hourly cycling data assimilation through a dependence on the previous forecast cycle model background (i.e. there is no dependency on OSTIA or other SST data sources in the UPD_AMM15). Results are presented for a 77 day summer trial period between June 15 and August 30, 2019, and for a 45 day winter trial period between December 1, 2018, and January 14, 2019.

3 | RESULTS

3.1 | OSTIA five day temperature variability

The OSTIA data are used to assess the extent to which persisted SSTf over a forecast cycle provides a valid regional atmosphere boundary condition over a five day NWP simulation. Figure 3 shows the five day lagged OSTIA temperature difference (SST_{DAY 5} - SST_{DAY 0}) at selected points around the UK between April 2018 and July 2020 (see Figure 1 for locations). This reflects the change in the background SSTf over a forecast cycle that is neglected through a dependency on the initial condition SSTf. Note that additional SST errors may arise from the omission of skin effects and the absence of any sub-daily variability driven by solar radiation and tidally induced temperature cycles. A positive SST difference in Figure 3 reflects a warming five day period, and vice versa.

There is a clear seasonal cycle, generally indicative of SSTf warming between March and September and cooling during the remainder of the year. There is also considerable day-to-day variability. Depending on the phase of the 14 day tidal cycle for locations on the shelf, there are occasions when the SSTf difference is in the opposite sense to the seasonal tendency. The summary histogram of five day SSTf differences in Figure 3f shows that the spring–summer positive values tend to be larger, that is, more rapid warming than autumn–winter cooling. Largest SSTf differences, of up to 4 K in May 2018, are found in the southern North Sea. This is where the bathymetry is shallowest, and the ocean tends to remain well mixed throughout the year. For other locations, the five day SSTf differences are more typically within ±0.5 K, and tend to remain within 1 K. For the UK-focused NWP, this suggests that generally, though
not exclusively, cool biases are imposed during spring–summer and warm biases in autumn–winter through the application of a fixed SST$_{L1}$ lower boundary.

### 3.2 Case study results

Figure 4 shows the surface temperature differences between the FIX_OSTIA (persisted OSTIA SST$_L$), FIX_AMM15 (persisted AMM15 SST$_{L1}$) and UPD_AMM15 (time-varying AMM15 SST$_{L1}$) during the July 21–25 2019 case study. Results are averaged for the subregion of interest marked by the red box in Figure 1. The five day mean SST$_L$ in Figure 4a is simply the OSTIA initial condition available on July 21, 2019. This is between 0.5 and 1.5 K cooler than the five day mean SST observed by in-situ buoys around much of the UK coastal seas, with the exception of a small region on the
northeast England coast where the initial condition SST$_{I}$ is warmer than observed over the subsequent five days.

From the analysis shown in Figure 3, the July 21–25 2019 period coincides with rapidly warming sea temperatures, consistent with the developing heat wave conditions. The OSTIA SST$_{I}$ warmed by 1.8 K at the North Sea (south) location and by 1.0 K at the English Channel point over this period, for example. Note that the maximum five day warming trend at North Sea (north) point of 2.1 K in Figure 3 occurred subsequently between July 26 and 31, 2019.

The AMM15 analysis SST$_{L1}$, valid for 00 UTC on July 21, 2019 (Figure 4b) is warmer than the OSTIA SST$_{I}$ by about 0.5 K around much of the UK coastline and across broad areas of the coastal Atlantic and Celtic Sea to the west of the UK. Differences are less uniform in the North Sea, but the FIX_AMM15 is broadly cooler than the FIX_OSTIA and notably in the area where the OSTIA SST$_{I}$ was relatively warm compared with in situ observations. Shaded circles in Figure 4b show the relative change to absolute error to the observations between the FIX_AMM15 and FIX_OSTIA. Green circles indicate where the FIX_AMM15 is closer to the observed mean SST, and pink shading at locations where temperatures have relatively larger errors. For many coastal locations, the FIX_AMM15 provides a more representative boundary condition compared with the FIX_OSTIA. Temperatures are improved by $>0.5$ K at 25 locations, while being degraded by $>0.5$ K at only four.

This result might in part be attributed to the differences between the foundation and top model layer ocean temperature definitions. Observed SST from ocean buoys are nominally valid at 1 m depth (e.g. Kennedy, 2014). It should also be noted that in-situ temperature observations are assimilated in the AMM15 (King et al., 2018) and that the km scale ocean model resolution provides a representative simulation of the near-coastal areas (Tonani et al., 2019). In contrast, relatively wide-swath satellite data tend to have larger biases in coastal regions (e.g. Minnett et al., 2019). Figure 4 suggests that the AMM15 regional ocean analysis provides a more representative source of ocean surface temperature information, particularly in near-coastal regions. It also gives data valid for a near-surface ocean depth more consistent with the assumptions of an overlying NWP model, which is likely more important in anticyclonic heat wave conditions when diurnal surface warming will be more significant.

The five day mean SST$_{L1}$ from the subsequent AMM15 forecast is compared with the FIX_OSTIA in Figure 4c. This shows a relative warming across most of the region compared with the initial condition temperature, consistent with both diurnal radiation and tidally induced heating and the longer term warming through the case study period (Figure 3). The mean UPD_AMM15 SST$_{L1}$ agrees better with observed mean temperatures at most buoy locations around the UK. There is an improvement in the absolute error of at least 0.5 K at 48 locations for the UPD_AMM15 relative to the FIX_OSTIA results.

Figure 5 summarizes the net impact of the different SST assumptions on the prediction of near-surface air temperature $T_{1.5m}$. This is diagnosed in the Unified Model at a 1.5 m height above the surface. The FIX_OSTIA, FIX_AMM15 and UPD_AMM15 simulations are compared with surface weather station observations across the UK land area (observations over the sea are omitted) using the Met Office’s standard verification system. Figure 5a shows a clear diurnal cycle of mean temperature error for all simulations, as documented by Bush et al. (2020). Temperatures are relatively cooler than observed by around 1 K during daytime, with a reduced cold bias at night. The relative impact of the AMM15 SST$_{L1}$ boundary conditions is highlighted in Figure 5b. It shows a spin-up period of about 12 hr at the start of the run when the simulations begin to diverge from the same atmosphere initial condition state. Thereafter, differences arise within the first 24 hr of the forecast. The FIX_AMM15 results show a consistent relative improvement by 0.1 K in the mean $T_{1.5m}$ error. The UPD_AMM15 simulation is increasingly warmer than the FIX_OSTIA through the period, such that the mean error on days 4 and 5 is improved by up to 0.5 K. This indicates that the AMM15 forecast well captures ocean warming through the case study period. When neglected in the FIX_OSTIA and FIX_AMM15, there is a growing cold bias in the $T_{1.5m}$ over land, superimposed on the diurnal temperature error cycle. Comparable improvements in the $T_{1.5m}$ RMSE are evident in Figure 5c, d.

Figure 6 shows an assessment of the daily maximum simulated air temperature ($T_{\text{max}}$) on July 25, 2019, in the FIX_OSTIA, FIX_AMM15 and UPD_AMM15. The warmest simulated temperatures are towards the south and east of UK. The comparison with the observed $T_{\text{max}}$ in Figure 6a shows the FIX_OSTIA to be too warm towards the north and southern edges of that warmest region.

The results are in better agreement with observed temperatures towards the centre of this area, around Cambridge in eastern England. Elsewhere across the UK and surrounding seas, the $T_{\text{max}}$ is clearly biased cold by several degrees in places relative to the observations (Figure 6d). The mean model – observed $T_{\text{max}}$ error across all sites in the selected evaluation region (the red box in Figure 1) is $-1.38$ K for the FIX_OSTIA. In comparison, there is a relative improvement in the simulated $T_{\text{max}}$ in the FIX_AMM15 (Figure 6b, e), and further still
in the UPD_AMM15 (Figure 6c, f). The spatial pattern of the $T_{\text{max}}$ changes over the ocean broadly reflect the distribution and magnitude of SST differences between simulations in Figure 4. This is not the case along the eastern England coast where feature location differences within an area of strong convective activity between simulations is highlighted by large but localized $T_{\text{max}}$ differences. The most significant improvements to the $T_{\text{max}}$ are found in the UPD_AMM15, particularly over ocean areas such as the North Sea, but also broadly across UK land areas. The $T_{\text{max}}$ mean error is improved by at least 0.5 K at 129 of the observation locations. This is around 25% of observation sites in the selected region. The mean error against all observations in the selected region is reduced to $-0.93$ K (Figure 6f).

Although improved relative to the FIX_OSTIA results, it should be noted that a substantial cold error in the $T_{\text{max}}$ remains in the UPD_AMM15, as also evident in Figure 5. This is because the diurnal cycle temperature mean error over land is driven by a multitude of model factors, including land surface and cloud representation, for example (Bush et al., 2020; Petch et al., 2020).

The corresponding analysis of the simulated and observed $T_{\text{max}}$ on day 5 of the August 23–27, 2019, case study in Figure 7 shows consistent results compared with the July case. The five day SST$_f$ differences in Figure 3 indicate a 2.7 K warming in the southern North Sea (Figure 3d) during this period. The peak warming of 1.9 K in the English Channel occurred in the preceding five days between August 22 and 26, 2019.

As for the July case, the spatial pattern of the $T_{\text{max}}$ differences between simulations in Figure 7 match well the differences in mean SST (data not shown). Figure 7c shows the warmer UPD_AMM15 temperatures relative to the FIX_OSTIA across much of the region. Figure 7a shows a north–south split in the distribution of the $T_{\text{max}}$ errors in the FIX_OSTIA for this case. Temperatures are too warm in southern England and Wales by up to 4 K, and considerably too cold by up to 8 K further north and over the ocean. The cool bias is improved in the UPD_AMM15 for both ocean and land points, with the $T_{\text{max}}$ mean error improved by at least 0.5 K at 88 locations. Where the simulated $T_{\text{max}}$ was too warm in the FIX_OSTIA, the reduction of a growing cool bias in the
UPD_AMM15 clearly leads to a further degradation of the $T_{\text{max}}$ results, although the number of impacted locations is relatively small (24 points where the $T_{\text{max}}$ mean error degraded by at least 0.5 K). Overall, the mean error across all sites in the region of interest is improved from $-1.23$ K for the FIX_OSTIA to $-0.94$ K for the UPD_AMM15.

The impact of modifying the SST boundary condition during the February 22–26, 2019, winter case is summarized in Figure 8. This was an unseasonably warm period, with February 26 being remarkably cloud free across much of the UK. Figure 8a, c shows considerable cold bias in the simulated $T_{\text{max}}$ across the selected region, with a mean error across observation sites of $-2.7$ K. Unlike the two summer cases assessed, there is negligible impact of changing the SST boundary condition on the $T_{\text{max}}$ over land. Differences over the ocean are also more comparable between the FIX_AMM15 and UPD_AMM15. Figure 8c shows a relative warming in the UPD_AMM15 across the shelf region relative to the FIX_OSTIA. This results in a small improvement in the simulated $T_{\text{max}}$ over ocean points, but generally within 0.5 K since the ocean is more well mixed and diurnal heating effects are substantially reduced relative to the summer. The five day SST$_{\text{f}}$ change (Figure 3) was remarkably consistent across all on-shelf locations with a small cooling of between 0.29 and 0.42 K during this case. The modest change to the temperature structure over the ocean has little impact over land, with non-local effects perhaps inhibited by lack of land–sea breeze interactions. This results in broadly consistent $T_{\text{max}}$ errors for the FIX_OSTIA, FIX_AMM15 and UPD_AMM15 simulations.

3.3 | NWP UKV trial results

The encouraging results for improving the mean $T_{1.5\text{m}}$ and $T_{\text{max}}$ simulations for the summer heat wave case studies and negligible impact for the winter provide confidence in the potential benefits of using the regional ocean forecast SST as a time-varying surface boundary
FIGURE 7  As for Figure 6 for results on August 27, 2019 (day 5 of the August 23–27 case study)

FIGURE 8  As for Figure 6 for results on February 26, 2019 (day 5 of the February 22–26 case study)
condition for the regional NWP. To enable a more robust assessment, the NWP UKV trial experiments were conducted. These compare the UPD_AMM15 with the FIX_OSTIA approaches when run in an NWP configuration matching the operational system with hourly cycling mode and regional data assimilation (Milan et al., 2020). Given the cost of running the full NWP trials, and the known relative benefit of the UPD_AMM15, the FIX_AMM15 approach was not considered further. Note that unlike the case study simulations, the NWP trial system only ran forecasts out to 36 hr beyond the initial time.

Summary $T_{1.5m}$ mean error and RMSE statistics are shown in Figure 9 as a function of forecast lead time for the summer trial conducted between June 15 and August 30, 2019. With new 36 hr forecasts initialized every hour, the diurnal temperature error signal is translated into an oscillating error pattern with smaller amplitude and peaks every 6 hr.

The results show a marked improvement for the UPD_AMM15 relative to the FIX_OSTIA control, growing with increasing lead time to 0.1 K at 36 hr. This is slightly smaller but of comparable magnitude with the mean improvement in the $T_{1.5m}$ at a similar lead time for the July case study shown in Figure 5, giving confidence that the case study results are representative. The net warming results in the mean $T_{1.5m}$ error in the UPD_AMM15 reducing to, and remaining around, 0 K from 17 hr into the forecast. The RMSE is also consistently improved in the UPD_AMM15 by up to 0.02 K. The difference in the magnitude and evolution with lead time of the relative impact of the UPD_AMM15 on bias and RMSE metrics can be attributed to the diurnal evolution of the $T_{1.5m}$ errors, which tend to be too cool during the day and too warm at night (Figure 5). While a consistent relative warming in the UPD_AMM15 produces a consistent positive change in the mean error at all times of day, the change in the RMSE tends to be negative (i.e. beneficial) during daytime, but slightly positive (degraded) at night-time, producing a smaller average change in the metric.

**FIGURE 9** (a) Time series of model – observation mean error in near-surface air temperature at 1.5 m above the surface ($T_{1.5m}$) during a summer hourly cycling numerical weather prediction (NWP) trial between June 15 and August 30, 2019, comparing simulations with surface weather station observations over UK land only. (b) Relative difference in mean error for the UPD_AMM15 relative to the FIX_OSTIA. (c) Time series of model – observation root mean square error (RMSE) for each model run; and (d) relative differences. Statistics are generated by the Met Office’s standard verification system.
Assessment of the change in bias and RMSE as a function of time through the summer trial (data not shown) also highlights that the impact of the UPD_AMM15 is larger during June and July than in August, reflecting the changes in typical five day change in SST associated with warming through this period (Figure 3). An order 14 day cycle in the magnitude of the change in errors can also be seen, linked to the evolution of the magnitude of SST variability through a 14 day tidal cycle.

The equivalent $T_{1.5m}$ statistics for the winter trial in Figure 10 show a small increase in the growing cold bias by up to 0.015 K in the UPD_AMM15 relative to the FIX_OSTIA. This suggests that the magnitude of changes in winter are of order 10% of those in summer. Conversely, there is a small but systematic improvement in the $T_{1.5m}$ RMSE for this period.

A summary of the FIX_OSTIA and UPD_AMM15 configuration performance during the NWP trials is presented in the form of relative ranked probability scores as a function of model lead time for key near-surface meteorological variables in Figure 11. The basis for this assessment, termed HiRA, is detailed by Mittermaier (2014) and is now routinely adopted for the regional NWP performance assessment at the Met Office (e.g. Bush et al., 2020). Results shown in Figure 11 are computed considering a neighbourhood of seven model grid points surrounding observation locations. The green-shaded triangles show where the UPD_AMM15 performs better than the FIX_OSTIA control, and purple-shaded downward triangles where performance is relatively degraded. The area of each triangle is proportional to the absolute improvement (or deterioration) of the model, and those outlined in black indicate if the change is statistically significant ($p < 0.05$). There is a consistent improvement in near-surface air temperature in both the summer and winter trials, larger in summer when the improvement is statistically significant at all lead times out to 36 hr. The impact of time-varying SST on other meteorological variables is in general considerably smaller and objectively assessed to have neutral impact overall – that is,
no systematic improvement or degradation of forecast quality with results mostly not statistically significant and not showing systematic change at different lead times.

4 | CONCLUSIONS

The present study has provided evidence for the likely benefit of using an operational regional ocean model surface temperature forecast to provide a time-varying lower boundary condition for the regional numerical weather prediction (NWP). The largest impact of the use of ocean forecast sea surface temperature (SST) is a reduction in the bias of near-surface air temperature, with a relatively weak impact on other meteorological parameters. This marks a change from the current practice of assuming a persisted SST to provide sufficient information for short-range forecasting applications. The suggested new approach provides a relatively efficient and practical means with which to represent the first-order effect of shorter timescale ocean variability on the overlying atmosphere without transitioning directly to the more complex operational implementation of fully coupled systems (e.g., Vellinga et al., 2020).

It is particularly encouraging that conclusions on the benefit of time-varying SST in reducing model errors in the $T_{1.5m}$ and $T_{max}$ identified from the five day summer case studies, and its more limited impact in winter, are consistently replicated in the more operationally relevant NWP trials with hourly cycling and regional data assimilation. That around 20% of the impact of SST updating was apparent 36 hr into the five day simulations (Figure 4), and that the model error grows with lead time, gives confidence that the impacts would be magnified further were it computationally feasible to run the full-scale NWP trials with some cycles running out to five days ahead as performed in operations at the Met Office. As expected, it is also clear that the use of time-varying SST is not sufficient to address fully the longstanding diurnal pattern of temperature errors over land. While key model biases remain, time-varying SST can considerably mitigate an important source of increasing model error with lead time.

Based on the evidence presented in the present paper, the UPD_AMM15 approach is planned to be implemented within the Met Office’s regional NWP system at a future operational upgrade in order to target improved prediction of near-surface temperature. Further model trials will be required and are planned to assess the impact of this change in different seasons. Given that operational regional NWP and Atlantic Margin Model 1.5 km configuration (AMM15) ocean systems have their own forecast schedules and frequencies through the day, and that the AMM15 is forced by global-scale meteorological forcing, the only new dependency introduced into the operational infrastructure by this change is a need to ensure that the AMM15 forecasts run beyond the required lead time of any regional NWP forecast cycle (i.e. potentially out to five days beyond the initial time).
Given that the evidence from the study focused on the UK and surrounding seas, the use of time-evolving surface boundary conditions is expected to be beneficial in other regional NWP systems. Its value for regions in the Tropics, where short-timescale ocean processes are known to impact the evolution of weather systems, such as tropical cyclones, should be assessed. For these processes, where the role of air–sea interaction has a leading order effect, it may be more desirable to work towards the development and implementation of fully coupled regional systems, and the time-varying SST approach advocated here forms a practical bridge towards that vision.

Acknowledgements
This research builds on the work of many Met Office colleagues. We are particularly grateful for the advice from and productive discussions with Mike Bush, Joanne Carr, Gareth Dow, Bruce Macpherson, Jon Petch, John Siddorn, Marina Tonani and David Walters. We thank Christoph Schraff, Florian Meier and Benedikt Strajnar for providing information on different regional operational numerical weather prediction configurations. We appreciate the input of two reviewers whose comments supported the manuscript presentation.

Conflict of Interest
The authors declare no potential conflict of interest.

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References
Ashrit, R., Sharma, K., Kumar, S., Dube, A., Karunasagar, S., Arulalan, T., Mamgain, A., Chakraborty, P., Kumar, S., Lodh, A., Dutta, D., Momin, I., Bushair, M.T., Prakash, B.J., Jayakumar, A. and Rajagopalan, E.N. (2020) Prediction of the August 2018 heavy rainfall events over Kerala with high-resolution NWP models. *Meteorological Applications*, 27(2), e1906. https://doi.org/10.1002/met.1906.

Bengtsson, L., Andrae, U., Aspelien, T., Batrak, Y., Calvo, J., de Rooy, W., Gleeson, E., Hansen-Sass, B., Homleid, M., Hortal, M., Ivarsson, K.I., Lenderink, G., Mammelä, S., Nielsen, K.P., Onvlee, J., Rooy, W., Gleeson, E., Hansen-Sass, B., Homleid, M., Ivarsson, K.I., Lenderink, G., Niemelä, S., Nielsen, K.P., Onvlee, J., Rontu, L., Samuelsson, P., Muñoz, D. S., Subias, A., Tijm, S., Toll, V., Yang, X. and Koltzow, M.O. (2017) The HARMONIE–AROME model configuration in the ALADIN–HIRLAM NWP system. *Monthly Weather Review*, 145 (5), 1919–1935. https://doi.org/10.1175/MWR-D-16-0417.1.

Browne, P.A., de Rosnay, P., Zuo, H., Bennett, A. and Dawson, A. (2019) Weakly coupled ocean–atmosphere data assimilation in the ECMWF NWP system. *Remote Sensing*, 11, 234. https://doi.org/10.3390/rs11030234.

Bush, M., Allen, T., Bain, C., Boutle, I., Edwards, J., Finnenkotter, A., Franklin, C., Hanley, K., Lean, H., Lock, A., Manners, J., Mittermaier, M., Morcrette, C., North, R., Petch, J., Short, C., Vosper, S., Walters, D., Webster, S., Weeks, M., Wilkinson, J., Wood, N. and Zerroukat, M. (2020) The first Met Office unified model—JULES regional atmosphere and land configuration, RAL. *Geoscientific Model Development*, 13(4), 1999–2029. https://doi.org/10.5194/gmd-13-1999-2020.

Chelton, D. (2013) Mesoscale eddy effects. *Nature Geoscience*, 6(8), 594–595. https://doi.org/10.1038/ngeo1906.

Christidis, N., McCarthy, M. and Stott, P.A. (2020) The increasing likelihood of temperatures above 30 to 40 °C in the United Kingdom. *Nature Communications*, 11, 3093. https://doi.org/10.1038/s41467-020-16834-0.

Clark P., Roberts N., Lean H., Ballard S.P., and Charlton-Perez C. (2016) Convection-permitting models: a step-change in rainfall forecasting. *Meteorological Applications*, 23(2), 165–181. http://dx.doi.org/10.1002/met.1538.

Donlon, C.J., Martin, M., Stark, J., Roberts-Jones, J., Fiedler, E. and Wimmer, W. (2012) The operational sea surface temperature and sea ice analysis (OSTIA) system. *Remote Sensing of Environment*, 116, 140–158. https://doi.org/10.1016/j.rse.2010.10.017.

Fallmann, J., Lewis, H., Castillo, J.M., Arnold, A. and Ramsdale, S. (2017) Impact of sea surface temperature on stratiform cloud formation over the North Sea. *Geophysical Research Letters*, 44 (9), 4296–4303. https://doi.org/10.1002/2017GL073105.

Fallmann, J., Lewis, H., Sanchez, J.C. and Lock, A. (2019) Impact of high-resolution ocean–atmosphere coupling on fog formation over the North Sea. *Quarterly Journal of the Royal Meteorological Society*, 145(720), 1180–1201. https://doi.org/10.1002/qj.3488.

Fiedler, E.K., Mao, C., Good, S.A., Waters, J. and Martin, M.J. (2019) Improvements to feature resolution in the OSTIA sea surface temperature analysis using the NEMOVAR assimilation scheme. *Quarterly Journal of the Royal Meteorological Society*, 145, 3609–3625. https://doi.org/10.1002/qj.3644.

Frenger, I., Gruber, N., Knutti, R. and Münchm, M. (2013) Imprint of Southern Ocean eddies on winds, clouds and rainfall. *Nature Geoscience*, 6(8), 608–612. https://doi.org/10.1038/ngeo1863.

Gentile, E., Gray, S.L., Barlow, J.F., Lewis, H.W. and Edwards, J.M. (2020) The Impact of Atmosphere–Ocean-Wave Coupling on the Near-Surface Wind Speed in Forecasts of Extratropical Cyclones. *Boundary-Layer Meteorology*. (now accepted, https://doi.org/10.1007/s10546-021-00614-4), in review.

Gómez B., Charlton-Pérez C.L., Lewis H., and Candy B. (2020) The Met Office Operational Soil Moisture Analysis System. *Remote Sensing*, 12(22), 3691. https://doi.org/10.3390/rs12223691.

Graham, J.A., O’Dea, E., Holt, J., Polton, J., Hewitt, H.T., Furner, R., Guihou, K., Brereten, A., Arnold, A., Wakelin, S. and Castillo Sanchez, J.M. (2018) AMM15: a new high-resolution NEMO configuration for operational simulation of the European north-west shelf. *Geoscientific Model Development*, 11(2), 681–696. https://doi.org/10.5194/gmd-11-681-2018.

Kendon, M., McCarthy, M., Jevrejeva, S., Matthews, A., Sparks, T. and Garforth, J. (2020a) State of the UK climate 2019. *International Journal of Climatology*, 40, 1–69. https://doi.org/10.1002/joc.6726.

Kendon, M., Sexton, D. and McCarthy, M. (2020b) A temperature of 20°C in the UK winter: a sign of the future? *Weather*, 75, 318–324. https://doi.org/10.1002/wea.3811.
