The impact of horizontal atmospheric resolution in modelling air–sea heat fluxes

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Abstract
Climate modes as simulated by global climate models are often found to be considerably weaker than are observed. One possibility is that coarse-resolution climate models do not capture turbulent air–sea fluxes sufficiently. Ensemble experiments with the same atmospheric configuration of the Met Office Hadley Centre climate model, forced with observed sea-surface temperatures (SST) and at three different horizontal model resolutions (approximately 130, 60 and 25 km), are used to test the sensitivity of air–sea surface heat and moisture fluxes. We find that, although global mean budgets at the three resolutions are very similar, substantial differences appear in regional air–sea flux patterns. Increased model resolution consistently enhances zonal-mean air–sea fluxes in the mid–high latitudes while suppressing heat fluxes in the low latitudes and weakening the Hadley Circulation. In the North Atlantic, annual mean surface heat fluxes into the atmosphere along the Gulf Stream/North Atlantic Current and over the sub-polar gyre can increase by up to 10 W/m² when atmospheric model resolution increases from 130 to 60 km. In the Pacific, increased model resolution tends to weaken the Walker Circulation with increased heat fluxes from the east but markedly reduced fluxes from the western Pacific, leading to significantly improved precipitation over the tropical western Pacific and the Maritime Continent. Changes in air–sea heat fluxes come about mainly as a result of changed near-surface ventilation. Generally, increasing resolution strengthens surface winds and reduces specific humidity in the mid–high latitudes while weakening surface winds over the Tropics and subtropics.

KEYWORDS
air–sea fluxes, climate modelling, model resolution effect

1 | INTRODUCTION

Modelling has nowadays taken a predominant position in climate research. Climate dynamics cover a rich spectrum of phenomena with different spatial and temporal scales (Collins et al., 2018). Modellers can quickly exhaust whatever supercomputers that modern technology can provide. Higher-resolution models are often believed to give better answers mathematically as numerical models use essentially approximated equations, and truncation errors decrease with...
grid sizes. However, modellers know too well that increasing model resolution does not always lead to improved model simulations. Some aspects get better while some others get worse, often due to compensational model errors. Whatever resolution one can afford leaves some smaller scales unresolved, and hence, parametrizations remain an important part of climate models. Model outputs in the foreseeable future will still include some sort of compensational errors. The question is, what is to be gained from a particular resolution increase and would such a change bring the model any closer to observations?

The classic view of minimum dynamical requirement for model resolution is to resolve the Rossby radius of deformation, which is in 1,000s of kilometres for the atmosphere and 10s of kilometres for the oceans (Hallberg, 2013), in order for baroclinic instability to take place. Cloud-resolving modelling (at resolutions of kilometres to 100 m) remains experimental, mostly on regional scales (Hohenegger and Schär, 2007; Guichard and Couvreux, 2017). Are there any significant benefits for intermediate model resolution between resolving baroclinic eddies and resolving clouds, apart from better coastlines, orographic characteristics and generally finer structures? It has been shown that higher-resolution models generally improve the simulation of the water cycle (Roberts et al., 2018), and specifically precipitation extremes and tropical cyclones (Giorgi and Marinucci, 1996; Wehner et al., 2010; Strachan et al., 2013; Roberts et al., 2015; Zhang et al., 2016). Demory et al. (2014) have shown that increasing horizontal model resolution can significantly increase moisture convergence over land and, therefore, the local ratio of evaporation over precipitation. The latest multi-model evaluation by Vannière et al. (2018) shows a strengthening of the global hydrological cycle with increased model resolution by an increase in surface latent-heat flux driven by more outgoing long-wave radiation and less outgoing short-wave radiation at the top of the atmosphere. This is because, globally, evaporation and precipitation are more sensitive to net surface short-wave radiation (Wu et al., 2010; 2013). Reports also suggest higher-resolution models generally improve some aspect of monsoon simulations (Johnson et al., 2015; Fang et al., 2017; Zhang et al., 2016) and regional rainfall distributions (Schiemann et al., 2014; Vellinga et al., 2015; Yao et al., 2017).

Poleward ocean heat transport peaks near 20° at a rate of two petawatts (Trenberth and Solomon, 1994). All this heat is returned to the atmosphere at the mid–high latitudes poleward of 20°. Climate predictions, however, show very little skill outside the Tropics (Li et al., 2016; Scaife et al., 2019). This may be partly due to the strong baroclinicity and internal dynamics of the midlatitude atmosphere. The inadequacy of low-resolution models may also have a role to play. It has long been suggested that climate models may inadequately simulate turbulent air–sea fluxes and consequently underestimate coupled climate variability and predictability (Rodwell et al., 1999; Rodwell and Folland, 2002; Wu and Gordon, 2002; Wu and Rodwell, 2004). A recent study suggests potential underestimation of rainfall projections by coarse-resolution climate models (Chen et al., 2018). Rodwell et al. (1999) were able to identify co-varying patterns between observed sea-surface temperature (SST) and 500 hPa geopotential height over the North Atlantic region, but they could not find the same patterns from models at the same statistical significance level. It was only possible to show similar patterns with statistical significance between surface heat fluxes and 500 hPa geopotential height (Wu and Rodwell, 2004), suggesting weaker oceanic forcing in models. An early study by Wellick et al. (1971) suggested that modelled winds are sensitive to horizontal model resolution. As air–sea fluxes are usually parametrized using the bulk formulation, heat fluxes would be sensitive to model resolution.

This study focuses on the impact of horizontal atmospheric model resolution on modelling air–sea surface heat fluxes. As the atmosphere model is forced with prescribed SSTs, major changes in large-scale atmospheric circulation patterns and modes of climate variability are not expected. We are aiming to find consistent and robust changes in simulated air–sea heat fluxes from increasing horizontal model resolutions. Ideally one would use fully coupled simulations in such analysis, since this would enable more realistic air–sea interactions and allow both ocean and atmosphere to adjust. However, free-running coupled simulations develop their own biases at different model resolutions in both atmosphere and ocean (for example in SST), which are often largest in the key regions of strongest air–sea fluxes. In addition, coupled models are considerably more expensive to run, and have issues with model drift. The present study aims to isolate the role of the atmosphere model resolution, and the results can be contrasted with fully coupled models in future work.

We use two sets of model configurations of the Met Office’s Unified Model (MetUM) both forced with prescribed SSTs. One set of simulations is based on the Global Atmosphere 3 (GA3: Walters et al., 2011) and the other on GA7.1 (Walters et al., 2019). The simulations described here were part of large campaigns, UPSCALE (Mizielinski et al., 2014) and PRIMAVERA (www.primavera-h2020.eu), which enabled production of ensembles of simulations at a range of model resolutions.

Section 2 describes the model and experimental design. Section 3 reports the main results and conclusions are presented in section 4.

## 2 MODEL DESCRIPTION AND EXPERIMENTAL DESIGN

Two sets of MetUM model simulations are analysed. The first set is based on the Global Atmosphere 3 (GA3) and
Global Land 3 (GL3) configurations of the MetUM and the Joint UK Land Environment Simulator (JULES) respectively, as documented in Walters et al. (2011), and specifically for the UPSCALE simulations in Mizielinski et al. (2014). All these models use the same forcings, broadly in line with the Atmospheric Model Intercomparison Project II (AMIP-II) but using a more recent, higher-resolution daily SST and sea-ice dataset based on the Ocean Surface Temperature and sea-Ice Analysis (OSTIA) product (Donlon et al., 2012). The native resolution of this dataset in 1/20° and is remapped to the model grid for use in the simulations. Each ensemble member simulation spans the period 1985–2011, with at least three ensemble members per model resolution. The initial conditions for each ensemble member were taken from consecutive days of a previous simulation, as documented in Mizielinski et al. (2014).

The second set is based on the newer GA7.1 model configuration (Walters et al., 2019) and uses the Coupled Model Intercomparison Project (CMIP6) HighResMIP experiment protocol and forcings (Eyring et al., 2016; Haarsma et al., 2016), with implementation described in Vidale et al. (in preparation). In particular the SST and sea-ice forcings are derived from the 0.25° daily Hadley Centre global sea-Ice coverage and Sea-Surface Temperature (HadISST 2.2.0.0) dataset (Kennedy et al., 2017), as specified by the protocol, in order that these experiments can start in 1950. The first ensemble member at each resolution uses ECMWF ReAnalysis ERA-20C (Poli et al., 2016) as the initial condition in 1950; successive members use the state of the atmosphere in the highest-resolution model at 10-year intervals.

The MetUM uses (longitude, latitude) global horizontal grids with consequent changes to the zonal grid spacing with latitude as the meridians converge. In these experiments, a hierarchy of global models with horizontal grid names of N96, N216 and N512 was used, equivalent to grid spacings (at midlatitudes) of 130, 60 and 25 km. Figure 1 contrasts the representation of observed SST fields in the three different model grids, with a focus over the Gulf Stream/North Atlantic Current region. Only essential parameter changes are made between model resolutions to enable the models to run stably (Mizielinski et al., 2014; Walters et al., 2019) and hence there is no resolution-specific parameter tuning. All models have 85 vertical levels with a model top at 85 km. Three ensemble members are used at each model resolution for each model version. Because of high similarities between the two sets of model simulations, results presented below are ensemble means of the two sets simulations with six ensemble members.

The model resolutions used in this study reflect the standard Met Office model configurations, ranging from grid spacings typical of climate simulations for CMIP6 (130 km), through those used in seasonal forecasting (60 km: MacLachlan et al., 2015) to the highest resolutions currently affordable in ensemble simulation mode (25 km). While we do not necessarily expect many aspects of climate simulation to converge at these resolutions, examination of the magnitude of changes between each resolution may reveal plateaus in performance.

3 | RESULTS

3.1 | Global mean characteristics

Figure 2 is an illustration of potential differences in simulated surface heat fluxes. It compares seasonal mean surface heat flux...
FIGURE 2 Contrast of surface turbulent heat flux patterns between (a) low- and (b) high-resolution models to qualitatively illustrate the impact of horizontal model resolution in modelling air–sea fluxes. Both models are forced with the same observed SSTs but are different in horizontal resolution (130 and 25 km). These are total surface sensible- plus latent-heat fluxes (W/m²) averaged over the period of January to March 2005 fluxes (latent plus sensible) of January, February and March of 2005 simulated by GA7.1 with two different horizontal resolutions (130 vs. 25 km). Although the model is forced with the same SSTs, simulated model surface heat fluxes are drastically different. Of course, there is the possibility of different internal variability in the atmosphere, even prescribed with the same SSTs. One cannot be sure that such differences solely result from different model resolution, even if that is the only difference in the experimental set-up. The aim of this study is to investigate consistent changes in simulated surface air–sea fluxes as horizontal model resolution increases. The following discussions are all based on ensemble mean diagnostics.

The global budgets and land–sea contrasts are summarized in Table 1. The model overall simulates globally realistic annual mean sensible-heat flux ranging between 17.7 and 20.1 W/m² comparing to observational estimate of 20 W/m² by the latest IPCC report (IPCC, 2013; Wild et al., 2013), but overestimates latent-heat flux by more than 4 W/m² to between 88.3 and 91.4 W/m² compared to the 84 W/m² estimate from the same report. The latest estimate from Wild et al. (2015) is 82 W/m² with an uncertainty range (70, 85). So the GA3 and GA7.1 models overestimate the strength of the global hydrological cycle. As shown by Demory et al. (2014), this is mainly because too little short-wave radiation is absorbed by the atmosphere and too little reflected by clouds and aerosols. The partitioning of sensible-heat fluxes between land and oceans in the model is also realistically consistent with observational estimates by Wild et al. (2015), ranging from 29.6 to 31.5 W/m² compared to 32 W/m² over land, and 12.7–15.4 W/m² compared to 16 W/m² over the oceans. Modelled sensible-heat flux is slightly lower than observed over both land and oceans, particularly for GA7.1. However, models overestimate latent-heat fluxes over both land and oceans. Modelled latent-heat flux over land ranges from 42.7 to 46.4 W/m² comparing to 38 W/m², close to the upper bound of the observational uncertainty range of (34, 45). Over the oceans, modelled latent-heat flux is well above the observational estimate of 100 W/m² with an uncertainty range of (90, 105), ranging from 106.2 to 111.5 W/m².

Increasing horizontal model resolution does not significantly change the global mean surface temperature, precipitation and surface heat fluxes. Consistent with Demory
et al. (2014), the hydrological cycle between land and sea strengthens in higher-resolution simulations. In both GA3 and GA7.1, land precipitation increases while ocean precipitation decreases as horizontal model resolution increases from 130 to 60 and 25 km. This reduces the local recycling rate over land as precipitation minus evaporation (P–E) increases over land while P–E decreases over the ocean. Spatially, the increase of land precipitation with increasing model resolution mainly occurs in the low latitudes. There are no significant consistent changes in land precipitation over the major continents in the mid–high latitudes. Despite the systematic shift of precipitation from ocean to land, globally there is no systematic change in surface air–sea fluxes across the three different model resolutions, although land mean sensible- and latent-heat fluxes both increase slightly at the highest model resolution. We will show in the next section that increasing model horizontal resolution significantly alters the large-scale patterns of air–sea fluxes that largely cancel in the global average.

### 3.2 Zonal mean structure and spatial patterns

Figure 3 shows the zonal mean differences, for oceans only, of (a) sensible ($Q_S$) and (b) latent ($Q_L$) surface heat fluxes between different model resolutions. Each solid line shows the six-member ensemble mean from both GA3 and GA7.1 and the shading shows the model spread. A clear consistent picture now emerges. Increasing horizontal atmospheric model resolution significantly enhances air–sea heat fluxes in the mid–high latitudes of both hemispheres while suppressing air–sea heat fluxes from the Tropics. The magnitudes of the differences are 2–4 W/m$^2$. The changes are much larger when model resolution increases from 130 to 60 km than the changes from 60 to 25 km.

Figure 4 shows the spatial distribution of difference in sensible (left column) and latent (right column) air–sea heat fluxes between different model resolutions. The stippling shows where all six members of the ensemble have the same sign of changes. It is a way of showing the statistical significance in line with the methodology followed in the IPCC report (see Box 12.1: IPCC, 2013). Latent-heat flux clearly dominates, apart from a high-latitude location such as the Greenland coast where changes in sensible-heat flux show comparable magnitude. The large-scale patterns over the oceans are remarkably similar. Separate figures for GA3 and GA7 ensembles as well as individual members are

### TABLE 1 Global annual mean budgets and land–sea contrast

| Runs | Global          | Land          | Ocean         |
|------|-----------------|---------------|---------------|
|      | $T$   | $P$   | $Q_S$ | $Q_L$ | $T$   | $P$   | $Q_S$ | $Q_L$ | $T$   | $P$   | $Q_S$ | $Q_L$ |
| N96  | 287.3 | 3.05  | 19.7   | 88.3  | 282.4 | 2.24  | 30.0   | 45.1  | 289.3 | 3.39  | 15.4   | 106.5 |
| N216 | 287.2 | 3.05  | 20.1   | 88.3  | 282.0 | 2.35  | 31.5   | 44.9  | 289.4 | 3.34  | 15.4   | 106.5 |
| N512 | 287.2 | 3.06  | 19.8   | 88.8  | 281.8 | 2.46  | 31.0   | 46.4  | 289.4 | 3.31  | 15.1   | 106.5 |
| N96  | 287.4 | 3.11  | 17.9   | 89.9  | 281.9 | 2.16  | 30.0   | 42.7  | 289.7 | 3.50  | 12.8   | 109.6 |
| N216 | 287.4 | 3.15  | 17.7   | 91.3  | 282.0 | 2.34  | 29.6   | 43.4  | 289.7 | 3.49  | 12.8   | 111.2 |
| N512 | 287.5 | 3.16  | 17.7   | 91.4  | 282.2 | 2.44  | 29.8   | 43.2  | 289.7 | 3.45  | 12.7   | 111.5 |

Units: $T$ (K), $P$ (mm/day), $Q$ (W/m$^2$).

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**Figure 3** Zonal mean changes (for oceans only) of annual mean surface (a) sensible and (b) latent air–sea heat fluxes between different atmospheric model resolutions, showing a consistent increase in oceanic forcing in mid–high latitudes of both hemispheres in higher-resolution models with a decrease in the Tropics leading to similar values in the global mean. Solid lines show the six-member ensemble means and colour shadings are ensemble spreads. x-axis is latitude.
provided as appendix S1. There is a distinctive feature over the North Atlantic Ocean associated with the Gulf Stream and the North Atlantic Current. Increased model resolution enables the atmosphere to extract significantly more heat out of the warm Gulf Stream and its extension into the sub-polar gyre while reducing heat fluxes from the tropical Atlantic. The reasons are discussed in section 4. In the Pacific basin, there seems to be a tendency of reduced heat fluxes from the western Pacific but increased heat fluxes from the eastern Pacific with increasing atmospheric model resolution, indicating a possible weakening of the Walker Circulation in higher-resolution models.

3.3 Impacts on atmospheric circulation

Surface air–sea heat flux changes shown in Figures 3 and 4 would suggest a weakening of the mean Hadley Circulation and the Walker Circulation. This is indeed the case. Figure 5 shows the ensemble mean differences between different model resolutions in terms of vertical mass stream function, where contours are the climatological mean and colour shadings are the differences. The left column contrasts the Hadley Circulation and the right the Walker Circulation. A weakening (blue colour) of the positive mean (solid contour) and strengthening (red colour) of the negative mean (dashed contour) clearly shows a weakening of the mean vertical circulation in higher-resolution models as we have speculated above based on the surface heat flux changes.

Other consistent changes (figures not shown) include warming of the middle to upper troposphere temperature in both hemispheres over the mid–high latitudes and cooling of the stratosphere. Relative humidity changes are in the opposite direction with an increase in subtropical mid-troposphere
FIGURE 5 Ensemble mean differences in simulated (a,c,e) Hadley circulation and (b,d,f) Walker circulation between different model resolutions in terms of vertical mass stream function (colour shadings; unit: 10^{10}/kg) in comparison to model climatological mean (contours). The stippling indicates the same sign of changes across the six ensemble members. x-axis is latitude (Hadley) or longitude (Walker)

and significant decreases in mid–upper troposphere midlatitudes in both hemispheres.

3.4 Comparison with observational analysis

All the above discussion has been focused on what difference does horizontal atmospheric model resolution increases make. Numerical models are always an approximation of the real climate system through a discretization of the governing equations (if one assumes the equations accurately describe the dynamics and thermodynamics of the atmosphere and the oceans) and a set of parametrizations of the most important physical processes. Numerical truncation errors and misrepresentation of the physics will continue to play a part in any model output, no matter how good that model is. It is helpful to understand why one model is better or worse than the other in order to continue improving models. To do so, it is often necessary to perform sensitivity experiments for tracking down the role of a single factor and its feedbacks. The main body of this work has been to serve just such a purpose. However, the ultimate goal is to perfectly reproduce the real world. Do higher-resolution models bring the simulations closer to “observations”?

We choose the latest version of the Japanese Ocean Flux Data Sets with Use of Remote-Sensing Observations
FIGURE 6  (a–c) Ensemble mean model biases of total surface turbulent heat flux relative to the latest observational analysis J-OFURO3, and (d,e) changes between different model resolutions, where only values above the 95% (greater than $2\sigma$) significance level are plotted

(J-OFURO), J-OFURO3 (Tomita et al., 2019), as our observational reference. The original dataset is on a 0.25° grid from 1988 to 2013. Sensible- and latent-heat fluxes are added together to produce the climatological annual mean. For fair comparison, the observational data and all model simulations are re-gridded to the coarsest N96 (130 km) resolution. Figure 6 shows the ensemble mean model biases for the three different model resolutions in the left column (Figure 6a–c) and relative differences between two model resolutions in the right column (Figure 6d,e). In Figure 6d,e, only values above the 95% ($2\sigma$ with $\sigma$ being standard deviation) significance are plotted. The standard deviation $\sigma$ is calculated across the six ensemble members. Changes shown in Figure 6d,e are the ensemble mean differences between the two model resolutions greater than two times the ensemble model spread, which are statistically significant at the 95% level. It is clear by looking through the left column plots that models overestimate surface heat flux in the Tropics while underestimating air–sea heat fluxes in the mid–high latitudes. In the Northern Hemisphere, the Gulf Stream region in the North Atlantic and the Kuroshio Current area in the Pacific are clearly highlighted. Such a general feature remains across the three model resolutions tested, although the model biases decrease as model resolution increases. The reduction in model bias is clearly shown by Figure 6d,e. There are certain areas, particularly along the eastern coast of the Pacific, where model biases seem to increase with model resolution.

4 | DISCUSSION

We have seen from above that, although the global mean air–sea heat fluxes remain little changed with increasing horizontal atmospheric model resolution, regional air–sea
heat fluxes undergo significant alterations. Large changes occur where ocean dynamics are most active such as the Gulf Stream and North Atlantic Current, and in regions where better resolution of coastlines may have an impact, e.g. around the Maritime Continent. In order to understand why these changes take place in such a specific manner, we now examine how different air–sea exchanges work in different model resolutions. Turbulent heat flux involves the transfer of sensible heat $w^T T'$ and water vapour $w^q q'$ at the air–sea interface that are usually parametrized using the bulk formulation (see Kondo, 1975)

$$Q_S = \rho C_p C_H u (T_s - T_a)$$

$$Q_L = \rho L C_E u (q_s - q_a)$$

where $Q_S$ is sensible and $Q_L$ latent heat flux, $\rho$ air density, $u$ surface wind speed, $T_s$ SST, $T_a$ air temperature, $q_s$ saturated and $q_a$ near-surface air specific humidity, $C_p$ the specific heat of air at constant pressure, $C_E$ and $C_H$ the bulk transfer coefficients of water vapour and sensible heat and $L$ the latent heat of vaporization. The key factors are ventilation efficiency reflected by wind speed and air–sea temperature difference for sensible-heat and surface humidity for latent-heat flux. In all our model configurations, each experiment is forced with SSTs derived from the same original observational fields and there is no atmospheric feedback to the SSTs. Higher model resolution is primarily expected to retain finer dynamic structures reflected in SST gradients to the limit that observations can provide, which here is approximately 5 km (1/20°). Secondly, higher model resolution requires a shorter time step (e.g. 10 min for ∼25 km resolution compared with 20 min for ∼130 km resolution) which could enable better ventilation by capturing shorter time-scale variations in wind speed. As latent-heat flux is dominant, we shall focus on surface humidity and surface winds. Thirdly, higher model resolution allows finer details of coastlines and islands to be captured, altering the land fraction in regions such as the Maritime Continent (Schiemann et al., 2014) as well as resolving orographic features (Johnson et al., 2015). Both of these changes alter the low-level winds, specific humidity, surface fluxes and precipitation in the local region (Johnson et al., 2015).

Figure 7 shows the diagnosed mean difference of near-surface wind speed (left column) and specific humidity (right column) between different model resolutions similar to Figure 4. Over most ocean areas, it is the combined effects of surface winds and humidity that lead to the difference in surface latent-heat flux shown in Figure 4. Specific humidity changes may be a consequence of changes in surface winds that ventilate the boundary layer. Over the subpolar North Atlantic where we see the most striking increase in surface heat fluxes with increased model resolution, increased winds and reduced specific humidity work together to enhance heat fluxes from the ocean into the atmosphere. Over the tropical Pacific, weakening of the Walker Circulation reduces surface winds, and consequently surface evaporation, from the central to western equatorial Pacific. Over the central to western South Pacific, reduced near-surface winds with increased near-surface humidity cause significantly reduced surface evaporation and latent-heat flux. Over the Southern Ocean, there is a southward shift of the near-surface jet stream in higher-resolution models corresponding to no significant surface heat flux changes partially because of sea-ice coverage which effectively isolates the ocean below.

5 SUMMARY

This article has examined the sensitivity of modelled air–sea heat fluxes to horizontal atmospheric model resolution with three ensemble simulations at horizontal resolutions at approximately 130, 60 and 25 km using two versions of the MetUM GA3 and GA7.1. GA3 simulations are forced with OSTIA and GA7.1 with HadISST2. With each model version, three ensemble members are run for each resolution and the experiments are designed such that, as far as possible, the only difference between each ensemble of three simulations is horizontal model resolution. Because the responses from the two model versions are very similar, the two model version ensembles are combined to make a six-member ensemble for each of the three resolutions to test the sensitivity of modelled surface air–sea heat fluxes.

The main findings are: (a) Changing model resolution does not significantly affect the global mean surface air temperature and precipitation as well as the overall radiative budgets. (b) Consistent with Demory et al. (2014) and Schiemann et al. (2014), increasing model resolution strengthens the global land–sea hydrological cycle with increased precipitation over land at the expense of reduced precipitation over the oceans. However, in the current range of resolution changes, most of the land precipitation increase occurs in the low latitudes. (c) Increasing horizontal model resolution significantly enhances air–sea heat fluxes in the mid–high latitudes in places where SST gradients are strong, while suppressing heat fluxes in the Tropics. This is because of improved ventilation efficiency at higher model resolutions with strengthened surface wind speed. (d) In atmosphere-only model simulations, the tropical Hadley Circulation and Walker Circulation tend to weaken with increasing model resolution associated with weakened precipitation (hence convective heating) over the tropical western Pacific. (e) A comparison with the latest observational analysis J-OFURO3 (Tomita et al., 2019) shows that all three model resolutions tested overestimate turbulent heat flux over the Tropics and underestimate it over the mid–high latitudes. Increasing horizontal atmospheric model resolution consistently reduces these model biases.

It is known from earlier model evaluation of Stratton (2004) and more recently Walters et al. (2017) that, in a semi-Lagrangian dynamical model such as the current
Ensemble mean difference of annual mean (a,c,e) 10 m winds (m/s) and (b,d,f) 1.5 m specific humidity (g/kg) between different model resolutions to show their contribution to the surface heat flux differences shown in Figure 3. The stippling indicates the same sign of changes across the six ensemble members.

MetUM, increasing horizontal model resolution increases the transient eddy kinetic energy. As shown by Walters et al. (2017), the steepest increase in eddy kinetic energy occurs between 130 and 60 km resolution. We also see the largest surface flux variation for the same resolution change. The present analysis reconfirms the previous evaluation. Increased air–sea fluxes at higher resolution resulting from improved ventilation efficiency can therefore be expected. The strong SST gradients retained in high-resolution models also play an important role for enhanced surface evaporation as shown by Minobe et al. (2008) and Kuwano-Yoshida et al. (2010). The implication of the current article is that better predictability could be achieved in higher-resolution models because of improved air–sea coupling. This may address the long overdue issues of slack oceans in coupled climate modelling (Rodwell et al., 1999; Wu and Gordon, 2002; Wu and Rodwell, 2004) and help to achieve better prediction skills of the true predictability that nature has to offer.

The above conclusions are only valid for atmospheric models forced with prescribed SSTs, but nevertheless shed light on the potential influence of atmospheric model resolution on the hydrological cycle without the complication of coupled atmosphere–ocean model feedbacks and biases. The resolution sensitivity for fully coupled models is more complicated, requiring further investigation.

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DATA AVAILABILITY STATEMENT

The UPSCALE dataset is available to access via the CEDA JASMIN platform as detailed at http://proj.badc.rl.ac.uk/upscale. The HighResMIP data will become available as part of the CMIP6 data archive on the Earth System Grid Federation (ESGF), with doi: 10.22033/ESGF/CMIP6.1321, 10.22033/ESGF/CMIP6.1902, and 10.22033/ESGF/CMIP6.446.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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