The Time-Scale-Dependent Response of the Wintertime North Atlantic to Increased Ocean Model Resolution in a Coupled Forecast Model

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ABSTRACT

This study uses initialized forecasts and climate integrations to evaluate the wintertime North Atlantic response to an increase of ocean model resolution from ~ 100 km [low-resolution ocean (LRO)] to ~ 25 km [high-resolution ocean (HRO)] in the European Centre for Medium-Range Weather Forecasts Integrated Forecasting System (ECMWF-IFS). Importantly, the simulated impacts are time-scale dependent such that impacts in subseasonal and seasonal forecasts cannot be extrapolated to climate time scales. In general, mean biases are reduced in HRO relative to LRO configurations and the impact is increased at longer lead times. At subseasonal to seasonal lead times, surface heating anomalies over the Gulf Stream are associated with local increases to the poleward heat flux associated with transient atmospheric eddies. In contrast, surface heating anomalies in climate experiments are balanced by changes to the time-mean surface winds that resemble the steady response under linear dynamics. Some aspects of air–sea interaction exhibit a clear improvement with increased resolution at all lead times. However, it is difficult to identify the impact of increased ocean eddy activity in the variability of the overlying atmosphere. In particular, atmospheric blocking and the intensity of the storm track respond more strongly to mean biases and thus have a larger response at longer lead times. Finally, increased ocean resolution drives improvements to subseasonal predictability over Europe. This increase in skill seems to be a result of improvements to the Madden–Julian oscillation and its associated teleconnections rather than changes to air–sea interaction in the North Atlantic region.

1. Introduction

Recent studies have emphasized the importance of ocean–atmosphere coupling for numerical weather prediction (e.g., de Boissésou et al. 2012; Brassington et al. 2015; Mogensen et al. 2017). The importance of coupling between Earth system components is also reflected in the complexity of the European Centre for Medium-Range Weather Forecasts Integrated Forecasting System (ECMWF-IFS). As of June 2018, all operational configurations of ECMWF-IFS have included dynamic representations of the ocean, atmosphere, sea ice, land surface, and ocean waves. However, the ocean models used in

weather and climate forecasting applications, at ECMWF and elsewhere, typically have insufficient horizontal resolution to fully resolve finescale ocean fronts or transient ocean processes at all latitudes. It has thus been argued that increases in ocean model resolution will lead to improved predictions across weather and climate time scales (Hewitt et al. 2017).

A commonly used metric for classifying ocean models is the ability of the horizontal resolution to adequately resolve the first baroclinic Rossby radius of deformation (L_R) (Hallberg 2013). For a grid spacing of ~ 100 km, which is typical of Earth system models used for climate projections, L_R is unresolved and the effects of eddies on the large-scale circulation must be parameterized. Ocean models with a resolution of ~ 25 km are considered eddy-permitting as L_R is resolved in the low latitudes and the circulation permits the development of nonlinear mesoscale eddies and sharp gradients associated with ocean fronts. However, it is only for a grid spacing of ~ 10 km or less that L_R is resolved over the majority of the mid- and high-latitude oceans, and much finer resolution is required to resolve L_R over the

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shallow continental shelves (Hallberg 2013; Hewitt et al. 2017). Unfortunately, so-called eddy-resolving configurations are currently prohibitively expensive for operational applications at ECMWF, particularly for forecast systems that rely on large ensembles.

Here, we systematically evaluate the sensitivity of ECMWF-IFS to an increase of ocean model resolution from ~ 100 to ~ 25 km, which corresponds to a transition from the “eddy-parameterized” to “eddy-permitting” regime. The novel aspect of this work is the combination of results from operational forecast systems and climate integrations to investigate the climate system response at time scales ranging from weeks to decades. We focus our analysis on the North Atlantic and surrounding regions as it has recently been shown that extended-range forecasts (i.e., weeks 1–4) with ECMWF-IFS are improved when sea surface temperature (SST) biases in this region are reduced using an online bias correction scheme (Vitart and Balmaseda 2018). Furthermore, this is a region that is known to be particularly sensitive to changes in ocean model resolution in multidecadal climate integrations with ECMWF-IFS (Roberts et al. 2018). We focus on the wintertime as there is a strong link between North Atlantic sea surface temperature gradients, surface wind convergence, and precipitation during this season (Minobe et al. 2008, 2010). The motivations for our analysis across different time scales are outlined below.

First, although one of the drivers for increased ocean model resolution is the impact on predictions (Hewitt et al. 2017), previous studies with coupled models have typically focused on decadal/multidecadal time scales in which ocean biases are well established (e.g., Siqueira and Kirtman 2016; Small et al. 2019). The impacts on initialized predictions that cover operational time scales ranging from days to months are much less well understood. To our knowledge, this is the first study to systematically evaluate the impact of increased ocean model resolution across subseasonal, seasonal, and climate time scales.

Second, in preparation for the time when eddy-resolving ocean configurations become computationally feasible for ensemble forecast applications, it is necessary to consolidate our scientific understanding of the impacts of ocean resolution on operational time scales. Recent work has demonstrated that the change from eddy-parameterized to eddy-permitting ocean resolutions is associated with large improvements to the North Atlantic region in multidecadal climate simulations with ECMWF-IFS (Roberts et al. 2018). Whether or not these benefits translate to operational forecasts will depend on the dominant time scales of the resolution-sensitive processes and the extent to which

initialization can mitigate the impact of forecast model deficiencies.

Third, the move toward coupled prediction systems has substantially increased the computational cost of research and development activities at ECMWF. For some aspects of atmospheric model development, particularly those that require large ensembles, it is desirable to have cheaper test configurations with reduced horizontal resolution. For uncoupled atmospheric model developments, it is standard practice to perform test experiments with a reduced resolution prior to implementation at full operational resolutions. This approach is justified for the atmosphere because L_R (~ 1000 km in the midlatitudes) is well resolved even for lower-resolution (~ 100 km) model configurations. In contrast, eddy-parameterized and eddy-permitting ocean configurations are a long way from adequately resolving L_R (~ 25 km in the midlatitudes). However, for some atmospheric model development activities (e.g., testing convection schemes in coupled mode at short lead times) the efficiency savings from use of a cheaper model may outweigh the penalty of a reduced ocean resolution. For this reason, it is important to have a clear understanding of the time scales, regions, and processes for which different resolution ocean models can be considered comparable.

The remainder of this paper is organized as follows: section 2 provides a review of ocean–atmosphere interaction in the midlatitudes. Section 3 describes the ECMWF-IFS model, the ensemble forecast datasets used in this study, and the methods used to generate consistent initial conditions for different ocean model resolutions. Section 4 presents the time-scale-dependent impacts of ocean model resolution on the mean state, selected aspects of atmospheric variability, and subseasonal predictability. Section 5 discusses the role of atmospheric resolution in evaluating the impacts of ocean resolution in a coupled modeling framework. Our main conclusions are summarized in section 6.

2. Impacts of horizontal resolution on ocean–atmosphere interaction

Previous studies have demonstrated that increasing ocean model resolution can have positive impacts on the representation of many oceanic processes, including mean surface temperature biases (Roberts et al. 2009; Marzocchi et al. 2015), the strength and position of western boundary currents and associated jets (Kirtman et al. 2012; Marzocchi et al. 2015; Chassignet and Xu 2017), the kinetic energy of the water column (Scott et al. 2010), interactions with topography (Thoppil et al. 2011; Hurlburt et al. 2008), air–sea interactions (Roberts

et al. 2016; Bryan et al. 2010), and large-scale mass, heat, and freshwater budgets (e.g., Hewitt et al. 2016; Kirtman et al. 2012; Griffies et al. 2015).

Here, we focus on the regional atmospheric response to a global increase in ocean resolution in a coupled forecast model. This approach allows a realistic assessment of the benefits of increased ocean model resolution in an operational setting. However, the global increase in resolution introduces the potential for both local and remote drivers of the regional atmospheric response. Thus, in contrast to more idealized studies, it is difficult to identify the physical mechanisms that drive changes in the atmosphere. Nevertheless, it is still possible to interpret the atmospheric response as a function of lead time within the context of previously identified physical mechanisms. The following sections review several important aspects of resolution-sensitive ocean–atmosphere interaction that guide our interpretation of the results presented in section 4.

a. The atmospheric response to surface heating anomalies

A large number of observational, theoretical, and modeling studies have investigated the impact of SST and surface heat flux anomalies on the atmosphere (see Alexander et al. 2002; Kushnir et al. 2002; Hoerling and Kumar 2002, and references therein). Such studies have typically focused on the atmospheric response during a particular season or phase of variability, but the results and associated mechanisms are also instructive for interpreting the impact of changes to mean SST introduced by changes in ocean model resolution. In the tropics, the ocean and atmosphere are strongly coupled such that large-scale SST anomalies and the associated anomalies in latent heat release have a strong impact on convection, rainfall, and the large-scale tropical circulation (e.g., Cane 2005; McPhaden et al. 2006). The associated changes in upper-atmosphere divergence can also stimulate a remote response in the extratropics through the excitation of Rossby waves (Hoskins and Karoly 1981; Trenberth et al. 1998; Simmons et al. 1983; Held et al. 1989; Latif et al. 1998).

The response of the atmosphere to large-scale SST anomalies in the extratropics is more equivocal, although there is some observational evidence for a tropospheric response to North Atlantic SST anomalies that occurred several months earlier (Czaja and Frankignoul 2002, 1999; Ossó et al. 2018). Using a steady-state model, Hoskins and Karoly (1981) demonstrated that the linear response to midlatitude heating anomalies is characterized by a surface low and upper-level high about 20° and 60° to the east of the imposed forcing, respectively. Furthermore, the magnitude of the linear response to midlatitude forcing was

found to be weaker and less extensive than the linear response to a subtropical forcing. This led Hoskins and Karoly (1981) to conclude that it is easier to force an appreciable response in the middle and high latitudes with a heating anomaly in the subtropics than with the same forcing in the middle or high latitudes. However, this result is sensitive to the treatment of diabatic heating (Hendon and Hartmann 1982) and later work has emphasized the importance of nonlinear dynamics and transient eddy feedbacks, which amplify the downstream impact of a midlatitude forcing and rapidly modify the initial baroclinic response to be equivalent barotropic in nature (e.g., Kushnir et al. 2002; Ferreira and Frankignoul 2005, 2008; Deser et al. 2007; Keeley et al. 2012).

Based on a review of coupled and atmosphere-only modeling studies, Kushnir et al. (2002) concluded that the atmospheric response to extratropical SST anomalies is weak compared to unforced internal variability. However, this conclusion was based on studies using models with a typical horizontal resolution of ~200 km. Smirnov et al. (2015) recently demonstrated that the simulated response to an idealized shift in the position of Oyashio Extension SST front changes substantially at different atmospheric resolutions. At 100-km resolution, the atmospheric response was characterized by linear dynamics and changes to the mean flow such that the SST anomaly-induced heating anomaly was balanced by near-surface equatorward advection. At 25-km resolution, the surface wind response was much weaker and the imposed heating anomaly was balanced by a strong vertical circulation and poleward fluxes of heat and moisture associated with nonlinear transient eddies.

Other recent studies have also emphasized the role of convection and vertical motion associated with synoptic systems in the response of the atmosphere to extratropical SST anomalies (Czaja and Blunt 2011; Lee et al. 2018). Consequently, the response of the atmosphere to changes in ocean model resolution is likely to depend on atmospheric model resolution and the accurate representation of transient eddy feedbacks. This topic and its relevance for the present study are discussed further in section 5.

b. Interaction between ocean and atmosphere fronts

It has long been known that strong SST gradients associated with ocean fronts affect the baroclinicity of the overlying atmosphere (Hoskins and Valdes 1990) and thus play an important role in extratropical cyclogenesis (Sanders 1986; Hobbs 1987) and the strength and position of the of the midlatitude storm tracks (Brayshaw et al. 2011).

The sharp SST gradients associated with the Gulf Stream have also been shown to induce a wintertime

atmospheric response that extends out of the marine atmospheric boundary layer (MABL) and into the free troposphere (Minobe et al. 2008, 2010). This relationship manifests as a correlation between near-surface wind convergence and the Laplacian of SST, which appears to anchor a band of precipitation along the warm edge of the Gulf Stream. This association was initially interpreted as a response of the MABL to sea level pressure anomalies forced by the time-mean SST distribution (Minobe et al. 2008), similar to the pressure adjustment mechanism described by Lindzen and Nigam (1987). However, although these relationships emerge in the time mean, recent work has shown that the atmospheric response to Gulf Stream SST gradients largely reflects the accumulated effect of frontal circulations within individual synoptic systems (Parfitt and Czaja 2016; Parfitt and Seo 2018; O'Neill et al. 2017).

The importance of horizontal resolution for accurate simulation of atmosphere–ocean frontal interaction in the Gulf Stream region has been emphasized in several recent studies. Vannire et al. (2017) used idealized SST smoothing experiments to demonstrate that strong SST gradients associated with the Gulf Stream anchor near-surface wind convergence and precipitation anomalies through their influence on convective instability in the cold sector of extratropical cyclones. Furthermore, Parfitt et al. (2016) showed that the strong SST gradients associated with the Gulf Stream increase the frequency of atmospheric cold fronts due to a positive feedback mediated by a thermal interaction between ocean and atmospheric fronts.

Finally, Sheldon et al. (2017) described a mechanism of ocean–atmosphere interaction in the warm sector of extratropical cyclones that can only be resolved with high resolution in both the ocean and atmosphere. They used simulations with a 12-km atmosphere to demonstrate that the “warm tongue” of the Gulf Stream enhances frontal circulations and deep ascent in the warm conveyor belt of tropical cyclones, a mechanism with a weak signature in surface turbulent heat fluxes. In contrast, ocean–atmosphere interaction in simulations with a 40-km atmosphere was dominated by shallow thermal forcing and strong air–sea interaction in the cold sector of extratropical cyclones.

c. The atmospheric response to mesoscale ocean eddies

At the scale of ocean basins, midlatitude SST anomalies largely reflect the integrated response of the ocean mixed layer to stochastic forcing from the atmosphere (Frankignoul 1985; Cayan 1992a,b; Bishop et al. 2017). However, recent work has emphasized the important role for ocean dynamics in driving surface temperature

anomalies in western boundary currents and regions of substantial ocean eddy activity (e.g., Kelly et al. 2010; Roberts et al. 2017). Furthermore, the advent of high-resolution all-weather satellite observations of SST and surface wind stress has revealed a fundamentally different character to air–sea interaction at the ocean mesoscale (Xie 2004; Chelton and Xie 2010).

At spatial scales of ~ 1000 km and larger, positive surface wind stress anomalies are associated with a cooling SST tendency, which is interpreted as the atmosphere driving an ocean response (Cayan 1992a,b; Kushnir et al. 2002; Bishop et al. 2017). However, at the scale of the ocean mesoscale there is a transition to a positive correlation between surface wind stress and SST anomalies (Chelton and Xie 2010; Bishop et al. 2017). This behavior is interpreted as evidence for the ocean driving an atmospheric response and is associated with a positive correlation between SST and turbulent heat fluxes,¹ although Sutton and Mathieu (2002) note that the influence of the ocean on the atmosphere does not always manifest through SST anomalies.

One of the proposed mechanisms to explain the influence of the ocean on near-surface winds is related to the inability of the atmosphere, under strong wind conditions, to fully adjust to small-scale changes in SST associated with ocean boundary currents and mesoscale eddies (Xie et al. 1998; Xie 2004; Frenger et al. 2013; Chelton et al. 2001; Small et al. 2008). Under these conditions, surface wind speeds are increased over warmer waters due to increased atmospheric instability, which enhances vertical mixing in the MABL resulting in a net transfer of momentum to the surface (Small et al. 2008; Wallace et al. 1989). In turn, the induced changes in the surface winds drive changes in surface wind divergence and curl, depending on the relative orientation of the prevailing winds and SST gradient (Xie 2004; Chelton et al. 2001, 2004).

The observed relationships between mesoscale SST anomalies and surface winds are not present in coarse-resolution (>100 km) ocean models (Maloney and Chelton 2006) but are qualitatively reproduced in coupled climate model simulations with eddy-permitting and eddy-resolving ocean components (Roberts et al. 2016; Bryan et al. 2010). However, the strength of the coupling between wind stress and SST, and thus potentially the impact of SST anomalies on the atmosphere, is generally underestimated in models (Song et al. 2009).

¹ A positive correlation assumes the convention that air–sea heat fluxes are positive when heat is leaving the ocean and entering the atmosphere.

TABLE 1. Model configurations used in this study.

Name	Type	Members	Period	Reforecasts per year	Atmosphere resolution	Ocean resolution
INI-LRO	Ocean/sea ice analysis	5	1979–2016			~100 km
INI-HRO	Ocean/sea ice analysis	5	1979–2016			~25 km
ENS-LRO	Subseasonal ensemble reforecast	5	1989–2016	12 × 32 days	~31 km	~100 km
ENS-HRO	Subseasonal ensemble reforecast	5	1989–2016	12 × 32 days	~31 km	~25 km
SEAS-LRO	Seasonal ensemble reforecast	5	1981–2016	2 × 7 months	~31 km	~100 km
SEAS-HRO	Seasonal ensemble reforecast	5	1981–2016	2 × 7 months	~31 km	~25 km
CLIM-LRO	Climate simulation	1	1950–2014		~25 km	~100 km
CLIM-HRO	Climate simulation	1	1950–2014		~25 km	~25 km
CLIM-LRO-LRA	Climate simulation	1	1950–2014		~50 km	~100 km
CLIM-HRO-LRA	Climate simulation	1	1950–2014		~50 km	~25 km

Although the influence of ocean eddies on the MABL is clear, their impact on the free atmosphere and potential to drive remote responses is less well understood. Several recent studies have investigated the potential of ocean eddies to induce a remote atmospheric response through their interaction with the midlatitude storm track and eddy-driven jet (e.g., [Ma et al. 2015, 2017](#); [Piazza et al. 2016](#); [Foussard et al. 2019](#)).

In particular, [Ma et al. \(2015, 2017\)](#) performed idealized studies with a 25-km regional atmospheric model forced with SST boundary conditions with and without the imprint of mesoscale ocean eddies in the Kuroshio Extension. They demonstrated that mesoscale SST variability has a rectified impact on the atmospheric heat and moisture budgets, which is in part due to the asymmetric impact of cold and warm eddies on the saturation vapor pressure of the overlying atmosphere. The increased diabatic heating associated with the presence of mesoscale ocean eddies was found to promote moist baroclinic instability, which led to intensified wintertime cyclogenesis and a remote response of the North Pacific storm track and eddy-driven jet. Importantly, this response to the ocean mesoscale was not evident in simulations with an atmosphere resolution of 160 km, which was attributed to the inability of coarse-resolution models to resolve the diabatic processes associated with moist baroclinic instability ([Ma et al. 2017](#)).

More recently, [Small et al. \(2019\)](#) investigated the impact of the ocean mesoscale on midlatitude storm tracks by comparing two coupled climate models at eddy-parameterized and eddy-resolving ocean resolutions. They found no systematic increase in surface storm track magnitude driven by increased variability associated with ocean eddies. However, in those locations where ocean resolution had an impact, storm track biases were improved in simulations with increased

ocean resolution. This impact was attributed to a reduction of mean SST biases rather than differences in SST gradients or variability.

3. Methods

a. Model description

ECMWF-IFS is a global Earth system model that includes dynamic representations of the atmosphere, sea ice, ocean, land surface, and ocean waves. This study presents results derived from operational versions of ECMWF-IFS that were implemented in November 2016 (cycle 43r1) and June 2018 (cycle 45r1). The model configurations used in this study are summarized in [Table 1](#). The atmosphere component of ECMWF-IFS is based on a hydrostatic, semi-implicit, semi-Lagrangian dynamical core that utilizes the spectral transform method to alternate between between spectral and grid point representations each time step ([Hortal and Simmons 1991](#); [Hortal 2002](#); [Ritchie et al. 1995](#); [Simmons et al. 1989](#); [Temperton 1991](#); [Temperton et al. 2001](#)). The vertical discretization is a hybrid sigma-pressure coordinate ([Simmons and Burridge 1981](#)) with 91 levels extending to 0.01 hPa. Advection and parameterized processes are calculated in grid-point space on a cubic octahedral reduced Gaussian (Tco) grid, which is defined such that the shortest wavelengths in spectral space are represented by four model grid points. The land surface is represented by the four-layer HTESSEL model ([Balsamo et al. 2009](#); [Dutra et al. 2010](#); [Boussetta et al. 2013](#)) and the ocean wave model is based on an updated version of WAM (Wave Model; [Komen et al. 1994](#); [Janssen 2004](#)).

Coupling between submodels is achieved by hourly exchange of energy, mass, momentum, and turbulent kinetic energy fluxes every hour using the sequential

single-executable strategy described in [Mogensen et al. \(2012\)](#). Air–sea exchanges are modulated by the prognostic ocean wave model through its impact on the Charnock parameter ([Janssen 2004](#)) and the turbulent kinetic energy flux available for ocean mixing ([Janssen et al. 2013](#); [Breivik et al. 2015](#); [Gaspar et al. 1990](#)). A more comprehensive overview of the ECMWF-IFS model is provided by [Roberts et al. \(2018\)](#) and further technical details can be found in the online documentation (<https://www.ecmwf.int/en/publications/ifs-documentation>).

b. Ocean/sea ice configurations

All model configurations are coupled to version 3.4 of the Nucleus for European Models of the Ocean (NEMO) ([Madec 2008](#)) and version 2 of the Louvain-la-Neuve Sea Ice Model (LIM2; [Bouillon et al. 2009](#); [Fichefet and Morales Maqueda 1997](#)). Higher-resolution ocean configurations are identified with the suffix “HRO” and use the ORCA025 tripolar grid, which has an eddy-permitting horizontal resolution of $\sim 0.25^\circ$. Lower-resolution ocean configurations are identified with the suffix “LRO” and use the ORCA1 tripolar grid, which has a nominal horizontal resolution of $\sim 1^\circ$ and meridional refinement to $\sim 0.3^\circ$ near the equator. Both NEMO configurations are configured as described in [Roberts et al. \(2018\)](#), with the key differences highlighted in their Table 1. Importantly, the [Gent and McWilliams \(1990\)](#) parameterization for the effect of mesoscale eddies is enabled in LRO configurations and disabled in HRO configurations. Both HRO and LRO configurations use a z coordinate with 75 levels and partial cell thicknesses at the sea floor.

c. Multidecadal climate integrations (CLIM)

The impacts of ocean model resolution on the model climate of ECMWF-IFS (cycle 43r1) are evaluated using multidecadal integrations covering the period 1950–2014, which correspond to the “hist-1950” experiments in [Roberts et al. \(2018\)](#). External climate forcings are specified following the protocols of the High Resolution Model Intercomparison Project (HighResMIP; [Haarsma et al. 2016](#)) and phase 6 of the Coupled Model Intercomparison Project (CMIP6; [Eyring et al. 2016](#)). Each experiment is initialized from the end of a corresponding spinup integration (HighResMIP experiment “spinup-1950”) that was run for 50 years with external forcings fixed at values representative of the year 1950.

CLIM-HRO and CLIM-LRO have a common atmospheric resolution of ~ 25 km (Tco399) and ocean/sea ice models configured as described above. CLIM-HRO corresponds to the ECMWF-IFS-HR configuration described by [Roberts et al. \(2018\)](#), whereas CLIM-LRO is a new configuration for this study that combines the

Tco399 (25 km) atmosphere with the ORCA1 (~ 100 km) ocean. The 25-km atmosphere used in our CLIM configurations is a higher resolution than used in the SEAS and ENS experiments described below. To evaluate the impact of this difference in atmospheric resolution, we also present selected results from two additional experiments with a lower-resolution atmosphere (LRA; 50 km; Tco199) that we term CLIM-HRO-LRA and CLIM-LRO-LRA (see section 5). These experiments correspond to the ECMWF-IFS-MR and ECMWF-IFS-LR configurations described by [Roberts et al. \(2018\)](#).

d. Seasonal ensemble reforecasts (SEAS)

The impacts of ocean model resolution in seasonal integrations are evaluated using ensemble reforecasts (termed SEAS-LRO and SEAS-HRO) based on ECMWF-IFS cycle 43r1 as used in the latest version of the ECMWF seasonal forecast system (SEAS5; [Johnson et al. 2019](#)). Seasonal reforecasts are composed of five-member ensembles of coupled ECMWF-IFS integrations initialized on 1 May and 1 November each year between 1981 and 2016. Each forecast is run for 7 months with an atmospheric resolution of ~ 31 km (Tco319). Atmosphere and wave models are initialized using the ERA-Interim reanalysis ([Dee et al. 2011](#)) and land initial conditions are derived from an offline analysis constrained by ERA-Interim boundary conditions ([Balsamo et al. 2015](#)). Ocean initial conditions are as described below. Ensemble generation is achieved through a combination of initial condition perturbations and stochastic parameterizations in the atmospheric model. Further details are provided by [Johnson et al. \(2019\)](#).

e. Subseasonal ensemble reforecasts (ENS)

The impacts of ocean model resolution at lead times of 1–4 weeks are evaluated using ensemble reforecast experiments (termed ENS-LRO and ENS-HRO) performed with the ECMWF subseasonal forecasting system ([Vitart 2014](#)). Subseasonal reforecasts are composed of a five-member ensemble of coupled ECMWF-IFS integrations initialized at the beginning of each month for each year between 1989 and 2016. Forecasts are run for 32 days with an atmospheric resolution of ~ 31 km (Tco319). Note that we refer to weekly means from the ENS system using the following convention: week 1 corresponds to days 5–11, week 2 corresponds to days 12–18, week 3 corresponds to days 19–25, and week 4 corresponds to days 26–32.

The ENS model configuration is as described above for SEAS experiments, albeit with a more recent version of the atmosphere–wave–land model (cycle 45r1). Changes to ECMWF-IFS between cycles 45r1 and 43r1 include improvements to the representation of supercooled

liquid water during convection, improved numerics for warm-rain cloud microphysics, and modifications to the nonorographic gravity wave drag scheme. There are no differences in the configuration of the ocean/sea ice model. These changes have a meteorological impact in forecast experiments when comparing different ECMWF-IFS cycles, but should not substantially alter our conclusions when comparing the impact of different ocean resolutions within the same ECMWF-IFS cycle.

There are two important differences between ENS experiments in this paper and the operational configuration of the ECMWF subseasonal forecast system. First, we use full coupling between the ocean and atmosphere at all locations. This contrasts with the operational strategy to use partial coupling in the extratropics during forecast days 1–4, which consists of coupling SST tendencies rather than absolute SSTs in order to preserve the high-resolution features in the SST boundary conditions used to constrain the atmospheric analysis. Second, we use the same atmospheric resolution throughout the forecast, rather than a higher resolution during days 1–15 as is done in operations.

f. Ocean initial conditions

Initialized coupled forecasts are sensitive to the quality of the analysis that provides ocean and sea ice initial conditions. Ocean model resolution can affect the quality of a dynamical ocean analysis in two ways: 1) through impacts on the mean state and variability of the underlying ocean model and 2) by modifying the ability of the data assimilation strategy to exploit the available observational constraints. However, our focus in this study is to evaluate the impact of ocean model resolution in forecasts that are initialized from comparable ocean/sea ice initial conditions. We describe below the method used to ensure that ocean and sea ice initial conditions in both HRO and LRO configurations are as similar as possible.

Ocean and sea ice initial conditions in ENS-HRO and SEAS-HRO are provided by a five-member ensemble of eddy-permitting ocean/sea ice analyses from the latest version of the ECMWF Ocean Reanalysis System (Zuo et al. 2019), which we term INI-HRO. This system uses the same ORCA025 resolution as our HRO experiments. For ENS-LRO and SEAS-LRO, ocean and sea ice initial conditions are generated using a simple Newtonian damping methodology. For each member of the higher-resolution analysis, an additional lower-resolution experiment is run with identical surface boundary conditions (including a $-200 \text{ W m}^{-2} \text{ K}^{-1}$ restoration toward observed SSTs) and additional relaxation terms that constrain 3D ocean temperature, 3D ocean salinity, sea ice thickness, and sea ice concentration toward monthly

mean values in the target experiment. These additional terms modify the model equations as follows:

$$\frac{d\mathbf{x}}{dt} = G(\mathbf{x}) - \mathbf{A}(\mathbf{x} - \mathbf{x}_{\text{target}}), \quad (1)$$

where $\mathbf{x}$ is the state vector in the LRO experiment, $\mathbf{x}_{\text{target}}$ is a vector corresponding to monthly means interpolated in time in the HRO experiment, G is the nonlinear operator corresponding to the forward model, $\mathbf{A}$ is a diagonal matrix with nonzero values of $1/\tau$ for variables constrained by INI-HRO, and τ is a characteristic relaxation time scale. Ocean fields are constrained with a time scale of 5 days and sea ice fields are constrained with a time scale of 10 days. The resulting experiments (INI-LRO) provide balanced ocean state estimates suitable for initializing LRO experiments that faithfully reproduce the high-frequency SST variability and lower-frequency subsurface variability of the INI-HRO ensemble of analyses.

4. Results

a. Mean state

1) SST BIASES

The impacts of ocean model resolution on wintertime SST biases in different systems are shown in Fig. 1. SST biases in INI-LRO and INI-HRO are very similar (Figs. 1a,b) and are dominated by a warm bias $> 2 \text{ K}$ associated with a northward displacement of the Gulf Stream and a warm bias of 1–2 K in the Labrador Current. There are some small differences between INI-LRO and INI-HRO associated with tighter gradients across the Gulf Stream in the higher-resolution ocean (Fig. 1c), but these are generally much smaller in magnitude than the absolute biases.

SST biases averaged over forecast weeks 1–4 during the period 2000–14 are shown in Figs. 1d–f. This subset of forecast start dates was chosen because the ocean is comparatively well observed during this period and therefore forecast biases are representative of deficiencies in the model rather than the availability of observations to constrain the ocean initial conditions. At these lead times, SST biases in ENS-HRO and ENS-LRO configurations are very similar and in part inherited from the initial conditions. Even so, there is some resolution dependence to SST biases at subseasonal lead times. The main areas of difference relative to the initial conditions are a northward shift of the Gulf Stream and the development of a cold bias at the so-called northwest corner, each of which are slightly degraded in ENS-LRO compared to ENS-HRO.

Differences in sea surface temperature (DJF)

FIG. 1. (left),(center) SST biases for the December–February (DJF) period relative to HadISST2 observations (Titchner and Rayner 2014). Contour lines indicate the position of the northern boundary of the Gulf Stream as identified by the 12°C isotherm in simulations (solid lines) and observations (dashed lines). (right) Difference between HRO and LRO configurations at different time scales.

The impact of ocean model resolution becomes more apparent at forecast lead times of 2–4 months (Figs. 1g–i). SST biases in SEAS-HRO are similar to ENS-HRO, whereas SEAS-LRO exhibits more severe SST biases than ENS-LRO due to a more northerly Gulf Stream separation and further degradation in the northwest corner and Gulf Stream extension.

On multidecadal time scales there is a clear divergence between HRO and LRO configurations (Figs. 1j–l). The pattern of SST biases in CLIM-HRO is similar to

SEAS-HRO. However, they are increased in magnitude and include an expansion and intensification of the warm bias at the perimeter of the subpolar gyre, a degradation in the path of the Gulf Stream extension, and a negative bias from -1 to -2 K across much of the subtropical gyre. In contrast, CLIM-LRO is characterized by a widespread cold bias that is associated with a southward expansion of the subpolar gyre and a Gulf Stream extension that is too zonal (Fig. 1k). There remains a small region of positive SST biases in

FIG. 2. Spatially weighted mean absolute error (MAE) of biases relative to HadISST2 (Titchner and Rayner 2014) in the region 90°W–10°E, 30°–70°N. Biases are calculated for different lead times using all available seasons and start dates. MAE errors are calculated using data from the following model configurations: ENS (weeks 1–4), SEAS (months 2–7), spinup-1950 (years 1–50), and CLIM (years 51–100).

CLIM-LRO associated with a persistent error in the latitude of Gulf Stream separation from the North American coast. The extreme cold bias in CLIM-LRO is a consequence of a gradual weakening of the Atlantic meridional overturning circulation (AMOC) and a reduction of its associated northward heat transport combined with a coupled sea ice feedback.

The impact of ocean model resolution on North Atlantic SST biases is summarized in Fig. 2, which shows the mean absolute error of SST biases in the North Atlantic region as a function of lead time. It is clear that HRO and LRO configurations of ECMWF-IFS have very different climatological biases in the North Atlantic that arise due to fundamentally different representations of the ocean mesoscale that rectify onto the mean state. However, at lead times of several weeks the North Atlantic SST biases in HRO and LRO configurations are very similar and in part inherited from the ocean initial conditions. The differences between HRO and LRO configurations become more evident at seasonal lead times but take several decades to saturate.

2) ATMOSPHERIC RESPONSE AT SUBSEASONAL TIME SCALES

Figures 3–5 show the lead-time-dependent response of several meteorological variables to a change in ocean model resolution in ECMWF-IFS. The corresponding biases relative to the ERA-Interim reanalysis are provided in the online supplemental material (Figs. S1–S9). At all lead times there is a clear relationship between the pattern of SST changes (Fig. 1) and the local response of precipitation, turbulent heat fluxes (Q_{turb} , positive upward), and 2-m temperature T_{2m} (Fig. 3). However, the dynamical changes in the atmosphere, and in

particular the relative roles of local and remote forcings, are more complex to interpret.

At subseasonal lead times (i.e., weeks 1–4), increased ocean resolution is associated with modest increases in Q_{turb} and precipitation over regions of increased SST along the western boundary of the subtropical and subpolar gyres (Figs. 3d,g). This local precipitation response is consistent with previous studies that investigated the impact of Gulf Stream SST gradients on the overlying atmosphere (e.g., Minobe et al. 2008, 2010). The atmospheric circulation response has an equivalent barotropic structure that is characterized by increases to mean sea level pressure (MSLP) and geopotential height at 500 hPa (Z_{500}) in the northeast Atlantic, which in turn balance anticyclonic circulation anomalies in near-surface and upper-level winds (Figs. 4a,d,g,j and 5a,b). We find some evidence for anomalous ascent over the Gulf Stream and anomalous descent over Europe in ENS-HRO relative to ENS-LRO, although the signal is noisy (Fig. S10). These changes generally reflect improvements in ENS-HRO relative to ENS-LRO, but the signals are small compared to the absolute biases (Figs. S1–S9), particularly for near-surface fields.

Although our experimental design does not allow us to cleanly attribute the atmospheric response to changes in air–sea interaction in a particular geographic region, it is still possible to evaluate the consistency of the response with the mechanisms reviewed in section 2. In some areas of the Gulf Stream, Q_{turb} differences at subseasonal lead times are larger than 100 W m^{-2} (Fig. 3d), which is comparable to the heat flux associated with imposed SST anomalies in more idealized studies (e.g., Smirnov et al. 2015; Lee et al. 2018). These heating anomalies are not

FIG. 3. Impact of ocean model resolution on wintertime (DJF) climatologies of (a)–(c) 2-m temperature T_{2m} , (d)–(f) turbulent heat fluxes over the ocean ($Q_{turb} = Q_{sensible} + Q_{latent}$, positive upward), and (g)–(i) precipitation. Contours correspond to climatological values in the ERA-Interim reanalysis for the period 1979–2014. Stippling indicates regions where the mean of differences is statistically different from zero (i.e., $p < 0.05$ for a two-tailed t test assuming that each season or start date is independent).

balanced by local changes in near-surface horizontal winds (Figs. 4a,d), which is the response expected under linear dynamics and in coarser-resolution atmospheric models (e.g., Hoskins and Karoly 1981; Smirnov et al. 2015). Instead, heating anomalies in the Gulf Stream region drive vertical motion (Fig. S10) and an increased poleward heat flux associated with transient atmospheric eddies $\overline{v'T'}$ (Fig. 6a), which is consistent with the non-linear response found to dominate in idealized modeling studies with atmospheric resolutions of 25–60 km (e.g., Smirnov et al. 2015; Lee et al. 2018).

To evaluate the transient eddy forcing of the zonal jet at 200 hPa we compute $\mathbf{E} = (\overline{v'^2} - \overline{u'^2}, -\overline{u'v'})$, where $-\mathbf{E}$ can be considered as a westerly momentum flux (Hoskins et al. 1983). The divergence of $\mathbf{E}$ is thus indicative of a convergence of momentum by transient eddies that accelerates the mean westerly flow. Although there are significant changes to both the zonal and meridional components of $\mathbf{E}$ (Figs. 6d,g), and thus the direction of eddy propagation, we see little evidence for systematic changes in either the meridional convergence of westerly momentum (Fig. 6j) or $\nabla \cdot \mathbf{E}$ (Fig. 6m) that

explain the upper-level wind response in the northeast Atlantic (Fig. 5a), which indicates another mechanism is responsible.

To evaluate the potential for a remote forcing of the North Atlantic region, we inspect changes in zonal and meridional winds at 200 hPa (U_{200} and V_{200} , respectively) over an expanded Northern Hemisphere domain (Figs. 5a,b). There is some tentative evidence for a planetary wave response connecting the North Atlantic and tropical Pacific, which is most evident as a sequence of alternating positive and negative anomalies in the meridional winds (Fig. 5b). However, tropical ocean forcing does not change substantially at subseasonal lead times, with maximum SST changes of 0.1–0.3 K in the equatorial Pacific (not shown). Furthermore, Lee et al. (2018) demonstrated that hemispheric-scale planetary wave trains can also be stimulated by enhanced vertical motion associated with the transient eddy response to Gulf Stream SST perturbations. For this reason, we cannot robustly attribute the upper atmosphere response in the North Atlantic region to either a local or remote forcing without further investigation and/or

FIG. 4. As in Fig. 3, but for (a)–(c) zonal wind at 1000 hPa, (d)–(f) meridional wind at 1000 hPa, (g)–(i) mean sea level pressure, and (j)–(l) geopotential height at 500 hPa.

experimentation that is beyond the scope of the present study.

3) ATMOSPHERIC RESPONSE AT SEASONAL TIME SCALES

At seasonal lead times, the response of precipitation, Q_{turb} , and $T_{2\text{m}}$ to increased ocean model resolution resembles an intensification of the subseasonal response (Figs. 3b,e,h). These differences reflect a reduction of biases in SEAS-HRO relative to SEAS-LRO, particularly in the Gulf Stream region (Figs. S1–S3). In contrast, the circulation response to increased ocean resolution is different in ENS and SEAS experiments. At seasonal lead times, the atmospheric response still has an approximately

equivalent barotropic structure, but it is characterized by a significant reduction of positive biases in MSLP and Z500 centered on the Labrador Sea and Newfoundland, respectively (Figs. 4h,k and Figs. S4 and S5). The near-surface winds do not change substantially compared to the absolute biases (Figs. 4b,e, Figs. S6 and S8) but SEAS-HRO exhibits a significant increase in U200 that manifests as an increase in the intensity of the midlatitude jet (Fig. 5c).

As was the case for subseasonal lead times, the increased turbulent heat loss from the Gulf Stream in SEAS-HRO relative to SEAS-LRO is associated with a local increase in $\overline{v'T'}$ (Fig. 6b) rather than changes to the near-surface winds. However, despite the larger

Impact of increased ocean resolution on 200 hPa winds (shading) and ERA-interim climatology (contour spacing 5 m/s)

FIG. 5. Impact of ocean model resolution on wintertime (DJF) zonal and meridional winds at 200 hPa. Contours correspond to climatological values in the ERA-Interim reanalysis for the period 1979–2014. Stippling indicates regions where the mean of differences is statistically different from zero (i.e., $p < 0.05$ for a two-tailed t test assuming that each season or start date is independent).

magnitude differences in Q_{turb} over the Gulf Stream in SEAS relative to ENS, the local changes in $\overline{v'T'}$ at 850 hPa have similar values of $\sim 1 \text{ K m s}^{-1}$ in both experiments (Figs. 6a,b). Furthermore, there is a decrease in $\overline{v'T'}$ in the northwest North Atlantic in SEAS-HRO relative to SEAS-LRO that has no equivalent at subseasonal time scales (Figs. 6a,b). Unfortunately, vertical velocity data were not archived for SEAS-LRO, so we cannot assess whether changes in vertical motion play a role in balancing surface heating anomalies at seasonal time scales.

Consistent with our results at subseasonal time scales, the increased intensity of the midlatitude jet in SEAS-HRO relative to SEAS-LRO (Fig. 5c) cannot be explained by increased convergence of westerly momentum by transient eddies (Fig. 6). There is some tentative evidence for the existence of a planetary wave train connecting the Atlantic with the western Pacific via Southeast Asia, but the signal is far from conclusive (Fig. 5d). As we concluded for the subseasonal time scale, we cannot robustly identify the drivers of the upper atmosphere circulation response at seasonal time scales without further investigation and/or experimentation that is beyond the scope of the present study.

4) ATMOSPHERIC RESPONSE AT CLIMATE TIME SCALES

On multidecadal time scales, differences in T_{2m} , precipitation, and Q_{turb} are dominated by the severe North

Atlantic cold bias in CLIM-LRO that develops in response to errors in the large-scale ocean circulation and sea ice distribution [see Roberts et al. (2018) for a review of the mechanisms in CLIM-LRO-LRA, which are also relevant for CLIM-LRO]. The differences in T_{2m} largely reflect changes in SST and extend from the North Atlantic into the surrounding continents (Fig. 3c). These changes are particularly large over the Labrador Sea as a result of the combined impact of a large-magnitude cold bias associated with excessive sea ice cover in CLIM-LRO and a warm bias in CLIM-HRO (Fig. S1). Changes to Q_{turb} and precipitation reflect improvements in CLIM-HRO relative to CLIM-LRO that have large signals over ocean boundary currents, regions of ocean convection, and the sea ice margin (Figs. 3f,i; see also Figs. S2 and S3).

The response of the atmosphere to increased turbulent heat loss from the ocean in CLIM-HRO relative to CLIM-LRO is fundamentally different from the response seen at seasonal and subseasonal time scales. In our initialized experiments, heating anomalies over the Gulf Stream are associated with local increases to $\overline{v'T'}$ at 850 hPa. Instead, the large increases to Q_{turb} in CLIM-HRO relative to CLIM-LRO are balanced by the time-mean advection of cold air from the north across the Labrador Sea and Gulf Stream (Figs. 4c,f). These changes in the near-surface winds are part of a cyclonic circulation anomaly associated with the development of a surface low (Fig. 4i) extending to the east of maximum

FIG. 6. (a)–(c) Impact of ocean model resolution on the mean wintertime (DJF) meridional heat flux at 850 hPa associated with transient atmospheric eddies $\overline{v'T'}$. Primes indicate residuals after the application of a 2–6-day bandpass filter. (d)–(i) As in (a)–(c), but for $\overline{v^2 - u^2}$ and $\overline{u'v'}$ at 200 hPa. (j)–(l) Meridional convergence of momentum by transient eddies $-(\partial \overline{u'v'}/\partial y)$ at 200 hPa. (m)–(o) Divergence of $\mathbf{E}$, where $\mathbf{E} = (\overline{v^2 - u^2}, -\overline{u'v'})$. Stippling in (a)–(i) indicates regions where the mean of differences is statistically different from zero (i.e., $p < 0.05$ for a two-tailed t test assuming that each season or start date is independent).

Q_{turb} anomalies, which reach up to 350 W m^{-2} in the northwest corner of the Labrador Sea (Fig. 3f). These surface changes are associated with the development of an upper-level high in CLIM-HRO relative to CLIM-LRO,

which reaches a maximum about 35° to the east of the surface low. This response has a strong resemblance to the steady linear baroclinic response to midlatitude surface heating anomalies described by Hoskins and

Karoly (1981). However, we also find a significant response in the vertical circulation, with increased ocean resolution associated with ascent anomalies over southern Greenland and the Labrador Sea and descent anomalies over the Gulf Stream and western Europe (Fig. S10).

The local response to surface heating anomalies described above is superimposed on zonally coherent changes to the midlatitude jet (Fig. 5e). In the Atlantic sector, there is a southward shift of the jet in CLIM-HRO relative to CLIM-LRO such that its intensity is reduced over western Europe. The resulting north–south dipole pattern in 200-hPa zonal winds (Fig. 5e) is associated with large changes to the westerly momentum fluxes associated with transient eddies (Figs. 6f,i). There is some evidence for a change in the meridional convergence of westerly momentum by transient eddies that has a dipole structure consistent with a southward shift of the zonal jet (Fig. 6l). However, this signal is less evident in $\nabla \cdot \mathbf{E}$ when the contributions from changes to the zonal divergence of $\overline{v^2} - \overline{u^2}$ are also included (Fig. 6o).

We interpret these changes in transient eddy fluxes as a response to the reduced large-scale meridional temperature gradient in CLIM-HRO relative to CLIM-LRO (Fig. S11), which in turn reduces atmospheric baroclinicity and leads strong reduction in $\overline{vT}$ at 850 hPa (Fig. 6c). We conclude that the response of the transient eddy heat fluxes in our climate experiments is dominated by the large-scale SST biases and associated changes in meridional temperature gradients rather than local adjustments to heating anomalies over the Gulf Stream.

b. Ocean–atmosphere interaction

1) RESPONSE OF THE STORM TRACK TO AIR–SEA INTERACTION AT THE OCEAN MESOSCALE

Positive correlations between SST and Q_{turb} are indicative of the ocean driving a response in the atmospheric boundary layer (see review in section 2c). Figures 7a and 7b shows covariances between collocated monthly mean SST and Q_{turb} anomalies for two different periods in the ERA-Interim reanalysis. The ability of the imposed SST boundary conditions to resolve mesoscale variability has a clear impact on the intensity of air–sea interaction. After 2001, ERA-Interim SSTs are specified with a resolution of $0.5^\circ \times 0.5^\circ$ or higher, and the Gulf Stream is characterized by strong air–sea interaction (Fig. 7a). Before 2001, SSTs are specified at resolution of $1.0^\circ \times 1.0^\circ$ and correlations between SST and Q_{turb} are extremely weak (Fig. 7b). See Parfitt et al. (2017) for further discussion of changes to the resolution of SST boundary conditions in ERA-Interim.

The intense air–sea interaction in the latter period of ERA-Interim is qualitatively reproduced in eddy-permitting configurations of ECMWF-IFS at all lead

times (Figs. 7c,e,g), albeit with some evidence for negative covariances in the southeastern portion of the Gulf Stream that are not present in the reanalysis dataset. In contrast, eddy-parameterized configurations of ECMWF-IFS cannot realistically simulate the variability of air–sea interaction in the North Atlantic (Figs. 7d,f,h). In ENS-LRO and SEAS-LRO, the positive covariances in the northern portion of the Gulf Stream are too weak, which is indicative of the reduced magnitude of SST variability and weaker correlations between SST and Q_{turb} anomalies. In CLIM-LRO, covariances are too weak in the Gulf Stream region but anomalously high in the eastern North Atlantic, which we attribute to the inaccurate position of the Gulf Stream extension and poor simulation of surface temperatures and sea ice extent in this experiment.

From these comparisons it is clear that eddy-permitting ocean models have an advantage over eddy-parameterized configurations for simulating air–sea interaction over western boundary currents such as the Gulf Stream. This impact is undiminished by initializing the ocean with observed conditions and is evident at subseasonal, seasonal, and climate time scales. This type of interaction is known to be important for the MABL, but its potential to drive a remote response in the atmosphere is less clear (see review in section 2c). However, several recent studies have suggested that the presence of mesoscale ocean eddies can induce a remote atmospheric response through their interaction with the midlatitude storm track and eddy-driven jet (e.g., Ma et al. 2015, 2017; Foussard et al. 2019).

Also shown in Fig. 7 is the location and strength of the winter storm track as indicated by the standard deviation of 2–6-day bandpass-filtered geopotential height at 850 hPa ($Z_{850_{2-6\text{day}}}$). Despite the large differences in the character of Gulf Stream air–sea interaction during different periods of the ERA-Interim reanalysis (Figs. 7a,b), the strength and position of the winter storm track is extremely similar. This could be because the synoptic atmospheric variability in the ERA-Interim reanalysis is well constrained by the available observations and therefore shows limited sensitivity to simulated changes in air–sea interaction. However, we also find little sensitivity of the location and intensity of the North Atlantic storm track to increased ocean resolution at subseasonal and seasonal lead times (Figs. 7c–f). In contrast, the storm track in CLIM-LRO is much stronger than both CLIM-HRO and the ERA-Interim reanalysis (Figs. 7g,h). This is consistent with the northward shift and intensification of the eddy-driven jet in CLIM-LRO (Fig. 5e), which we attribute to changes in the atmospheric meridional temperature gradient (see section 4a).

SST- Q_{turb} covariance (shading) and storm track intensity (contours)

FIG. 7. Covariance between monthly (DJF) anomalies of SST and Q_{turb} (shaded) and storm track intensity, diagnosed as the standard deviation of daily (DJF) geopotential height at 850 hPa after application of a 2–6-day bandpass filter (contour spacing of 5 m). Note that Q_{turb} is defined to be positive upward such that positive covariances are indicative of increased heat flux out of the ocean when SSTs are higher. (a) Data from ERA-Interim for the period December 2001–February 2017, which uses SSTs with a horizontal resolution of $0.5^\circ \times 0.5^\circ$ until 2009 and $0.05^\circ \times 0.05^\circ$ thereafter. (b) Data from ERA-Interim for the period December 1979–February 2001, which uses SSTs with a resolution of $1^\circ \times 1^\circ$. (c)–(h) As in (a) and (b), but for HRO and LRO configurations of ECMWF-IFS at different lead times.

We conclude that the position and intensity of the North Atlantic storm track in our experiments is more sensitive to changes in mean SST biases than changes to air–sea interaction associated with an improved representation of mesoscale ocean eddies. This interpretation

is consistent with the recent study of [Small et al. \(2019\)](#), which compared eddy-parameterized and eddy-resolving coupled simulations and concluded that the sensitivity of the surface storm track to ocean resolution is dominated by changes to mean SST biases. Furthermore,

Ma et al. (2015, 2017) emphasized the rectified effect of mesoscale SST variability onto the time-mean energy fluxes associated with transient eddies. It is possible that some of the changes to Q_{turb} and $\overline{v'T'}$ described in section 4 are driven by a similar mechanism, rather than changes to mean SST.

2) ATMOSPHERIC RESPONSE TO SST GRADIENTS

The climatological relationship between wintertime $\nabla^2\text{SST}$, the horizontal convergence of 10-m winds ($-\nabla \cdot \mathbf{u}_{10\text{m}}$), and precipitation in the North Atlantic (Minobe et al. 2008, 2010) is shaped by the impact of the Gulf Stream on convective instability in the cold sector of extratropical cyclones (Vannière et al. 2017; Parfitt and Czaja 2016; Parfitt and Seo 2018; O'Neill et al. 2017). The increased surface wind convergence associated with the warm edge of the Gulf Stream is present in the ERA-Interim reanalysis, but there is a clear sensitivity to changes in the resolution of the SST product used as a surface boundary condition (Figs. 8a,b). The higher-resolution SST boundary conditions used in the later period of the ERA-Interim analysis are associated with sharper SST gradients, stronger convergence in the MABL (Fig. 8a), and more intense rainfall in the Gulf Stream rainband (Fig. S12). This sensitivity indicates that the ERA-Interim data assimilation is insufficient to accurately constrain the circulation of the MABL in the presence of lower-resolution SST boundary conditions.

The $\nabla^2\text{SST}$ and $\nabla \cdot \mathbf{u}_{10\text{m}}$ patterns diagnosed using the later period of the ERA-Interim reanalysis are qualitatively reproduced at subseasonal lead times in both ENS-HRO and ENS-LRO (Figs. 8c,d and S12). However, both ENS configurations suffer from a more northerly separation of the Gulf Stream that results in larger-magnitude values of ∇SST and $\nabla^2\text{SST}$ along the western boundary. This feature is also present in the ocean initial conditions (not shown) and is responsible for a spurious westward extension of peak rainfall and 10-m wind convergences toward the North American continent. The patterns of $\nabla^2\text{SST}$, $\nabla \cdot \mathbf{u}_{10\text{m}}$, and precipitation are very similar in ENS-HRO and SEAS-HRO (Figs. 8c,e and S12). In contrast, the SST gradients in the eastern portion of Gulf Stream extension are weaker in SEAS-LRO than those in ENS-LRO and there is a corresponding reduction in the intensity of the Gulf Stream rainband (Figs. 8d,f and S12).

On multidecadal time scales, there is a reduction of the intensity of $\nabla^2\text{SST}$ and $\nabla \cdot \mathbf{u}_{10\text{m}}$ in CLIM-HRO compared to SEAS-HRO, but the main features associated with the Gulf Stream SST gradient are still present (Figs. 8g and S12). In contrast, CLIM-LRO shows a notable weakening of SST gradients, and large changes to the spatial structure of $\nabla^2\text{SST}$, $\nabla \cdot \mathbf{u}_{10\text{m}}$, and precipitation patterns (Figs. 8h and S12). From these comparisons

it is evident that ocean model resolution impacts $\nabla \cdot \mathbf{u}_{10\text{m}}$ and precipitation through its impact on Gulf Stream SST biases. However, these impacts are a function of forecast lead time and are mitigated at subseasonal and seasonal time scales by initialization with observed ocean conditions.

c. Large-scale atmospheric variability

1) ATMOSPHERIC BLOCKING

Figure 9 shows Euro–Atlantic winter blocking frequency in CLIM and SEAS experiments compared to the ERA-Interim reanalysis (results from ENS are not shown due to their shorter lead time). In general, all configurations of ECMWF-IFS underestimate the frequency of blocked days compared to ERA-Interim in the region 20°W–20°E. A previous study with the Met Office climate model found that Atlantic winter blocking frequency was greatly improved when the NEMO ocean model was upgraded from an eddy-parameterized to eddy-permitting resolution (Scaife et al. 2011). The improvements to blocking statistics were attributed to a better representation of the Gulf Stream and reduced North Atlantic SST biases.

We find a similar impact on Atlantic winter blocking when comparing CLIM-LRO and CLIM-HRO configurations, which supports the previously reported sensitivity to improved SST biases in the North Atlantic region (Scaife et al. 2011). However, winter blocking frequency shows limited sensitivity to the same increase in ocean model resolution when our analysis is limited to seasonal lead times (months 2–4). In fact, the frequency of blocked days in SEAS-LRO and SEAS-HRO is very similar to the blocking frequency in an atmosphere-only configuration of ECMWF-IFS forced with observed SST and sea ice conditions (CLIM-SST in Fig. 9). From these comparisons we infer that although Atlantic winter blocking is sensitive to ocean resolution, the atmospheric response depends on the magnitude and structure of the simulated SST biases and is likely to be larger in multidecadal climate integrations compared to seasonal forecasts.

2) THE NORTH ATLANTIC OSCILLATION

The NAO is the most prominent mode of year-to-year wintertime atmospheric variability in the North Atlantic and surrounding regions (Hurrell et al. 2003). Figure 10 shows the spatial patterns associated with the positive phase of the NAO in SEAS/CLIM experiments and the ERA-Interim reanalysis. As above, results from ENS are not shown due to their shorter lead time.

In general, ECMWF-IFS accurately captures the spatial pattern and magnitude of 500-hPa geopotential height

FIG. 8. Wintertime (DJF) $-\nabla^2 \text{SST}$ (shading) and the horizontal convergence of 10-m winds ($-\nabla \cdot \mathbf{u}_{10m}$; contour spacing of 10^{-6} s^{-1}). (a) Data from ERA-Interim for the period December 2009–February 2017, which uses SSTs with a horizontal resolution of $0.05^\circ \times 0.05^\circ$. (b) Data from ERA-Interim for the period December 1979–February 2001, which uses SSTs with a resolution of $1^\circ \times 1^\circ$. (c)–(h) As in (a) and (b), but for HRO and LRO configurations of ECMWF-IFS at different lead times. Horizontal derivatives are calculated after interpolation to a common $0.5^\circ \times 0.5^\circ$ grid and smoothed prior to plotting to reduce the influence of gridpoint noise.

variability associated with the NAO (Fig. 10 and Table 2). Increased ocean resolution has no discernible impact on the magnitude or pattern of NAO variability at seasonal lead times. However, there is some evidence for an

increase in the magnitude of the southern node of the NAO in CLIM-HRO relative to CLIM-LRO (Fig. 10). This difference is also present in simulations with a reduced atmospheric resolution (Fig. S13). A number of

FIG. 9. Frequency of wintertime (DJF) blocked days calculated using the index of [Tibaldi and Molteni \(1990\)](#) in the ERA-Interim reanalysis, coupled configurations of ECMWF-IFS, and an atmosphere-only configuration of ECMWF-IFS forced with observed SST and sea ice conditions, CLIM-SST, which corresponds to the highresSST-present experiment with ECMWF-IFS-HR described in [Roberts et al. \(2018\)](#).

studies have emphasized the importance of Rossby wave breaking and transient eddy feedbacks for developing and maintaining the NAO (e.g., [Hurrell 1995](#); [Woollings et al. 2008](#)). It is thus plausible that the significant differences between CLIM-HRO and CLIM-LRO in the representation of the North Atlantic storm track and eddy-driven jet (see [section 4a](#)) are responsible for the differences in NAO dipole structure. However, a detailed investigation of the mechanisms that drive NAO differences between CLIM-LRO and CLIM-HRO is beyond the scope of the present study.

Interestingly, ECMWF-IFS generally underestimates the month-to-month persistence of the NAO variability during the early winter ([Fig. 11](#)). Despite the large sampling uncertainties, this bias appears to be present in both seasonal and climate configurations, and there is no evidence that increasing ocean resolution improves this aspect of NAO variability. Importantly, it has been suggested that differences between the model and real-world persistence of the NAO can explain the origins of an apparent “signal-to-noise paradox” in seasonal forecasts ([Strommen and Palmer 2019](#); [Zhang and Kirtman 2019](#); [Eade et al. 2014](#)). These results provide motivation for further work to understand the links between NAO persistence and forecast skill in the ECMWF model.

d. Subseasonal predictability

In this section we evaluate the impact of increased ocean model resolution on subseasonal predictability over the European region. We focus our predictability analysis at lead times of 1–4 weeks and use all available start states in the reforecast period to increase the sample size. Forecast skill is quantified using a fair

version of the continuous ranked probability score (CRPSF; [Ferro 2014](#)), which includes a correction for ensemble size such that CRPSF is an unbiased estimator of the CRPS that would be achieved with an infinite ensemble size. CRPSF is computed using the kernel representation described by [Leutbecher \(2019\)](#):

$$\text{CRPSF} = \sum_{i=1}^N w_i \left[\frac{1}{m} \sum_{j=1}^m |x_i^j - o_i| - \frac{1}{2m(m-1)} \times \sum_{j=1}^m \sum_{k=1}^m |x_i^j - x_i^k| \right], \quad (2)$$

where x_i^j is member j of forecast i , o_i is the observed outcome, m is the number of ensemble members in each forecast, N is the total number of forecasts (all locations and start dates combined), and w_i is a weight for each forecast to account for variations in the area of grid-boxes as a function of latitude. Skill scores (CRPSSF) are calculated relative to a reference score derived from climatological forecasts ($\text{CRPSF}_{\text{clim}}$) such that a perfect forecast has a score of 1:

$$\text{CRPSSF} = 1 - \frac{\text{CRPSF}}{\text{CRPSF}_{\text{clim}}}. \quad (3)$$

To evaluate the impact of ocean model resolution on forecast uncertainties, we also calculate the fractional change in ensemble spread (FCES) as follows:

$$\text{FCES} = 1 - \frac{\sum_{i=1}^N w_i \sigma_i^{\text{lro}}}{\sum_{i=1}^N w_i \sigma_i^{\text{hro}}}, \quad (4)$$

where σ_i^{hro} and σ_i^{lro} correspond to the standard deviation in ensemble forecasts with ENS-HRO and ENS-LRO, respectively. Positive values of FCES indicate that ensemble spread is higher in ENS-HRO relative to ENS-LRO. The impacts of ocean model resolution on subseasonal forecasts for the European region are summarized in [Fig. 12](#). These scorecards show changes in CRPSSF and ensemble spread for 20 different near-surface and upper-atmosphere fields at lead times of 1–4 weeks.

CRPSSF over Europe is generally increased in ENS-HRO relative to ENS-LRO ([Fig. 12](#)), with the positive impacts most evident at longer lead times (i.e., week 4). When considered in isolation, the calculated differences in CRPSSF are generally not statistically significant, which could be a limitation of the small ensemble size used in this study ($m = 5$). However, the positive impact across a range of variables and lead times is indicative of a genuine improvement in forecast performance in ENS-HRO relative to ENS-LRO. Furthermore, we see

FIG. 10. Spatial patterns corresponding to the positive phase of the North Atlantic Oscillation in the ERA-Interim reanalysis (ERA-I) and different configurations of ECMWF-IFS. The spatial maps are in units of meters and correspond to linear regression coefficients obtained by regressing 500-hPa geopotential height (Z500) anomalies against the standardized principal component time series corresponding to the leading empirical orthogonal function (EOF) of monthly mean Z500 for the extended wintertime period (November–April) in the region 80°W–40°E 20°–85°N. Annotations give the fraction of total variance explained by the first EOF.

other other significant differences between ENS-LRO and ENS-HRO that are physically consistent with improved subseasonal predictions in the Euro–Atlantic region.

In sections 4a and 4b we identified small but significant reductions in mean biases and a significant improvement to the intensity of air–sea interaction over the Gulf Stream in ENS-HRO relative to ENS-LRO.

However, we found little impact of ocean model resolution on the position and intensity of the midlatitude surface storm track at subseasonal time scales. The limited impact of ocean resolution on atmospheric variability in the North Atlantic/European domain is also evident in the ensemble spread of subseasonal forecasts, where only SST shows a substantial change (Fig. 12).

TABLE 2. This table summarizes the following statistics of the EOF analysis of SEAS and CLIM experiments presented in Fig. 10: 1) the fraction of total variance explained by EOF1, 2) the root-mean-square (RMS) amplitude of the spatial patterns in Fig. 10, and 3) the spatial correlation of patterns with the ERA-Interim reanalysis.

Name	Percent variance (EOF1)	RMS amplitude (m)	Spatial correlation
ERA-Interim	32.3	33.5	
SEAS-LRO	29.5	32.6	0.977
SEAS-HRO	27.9	31.9	0.977
CLIM-LRO	27.1	32.1	0.991
CLIM-HRO	27.2	31.4	0.990

FIG. 11. Month-to-month autocorrelation properties of the principal component time series associated with the EOFs plotted in Fig. 10. Autocorrelations are calculated for each pair of months over the extended wintertime season using data from the common period of November 1981–April 2014. Uncertainty estimates are derived from a bootstrap resampling of the available dates ($n = 10\,000$), with vertical error bars corresponding to the 2.5 and 97.5 percentiles of the resulting distributions.

To assess the potential for remote forcing of increased skill over Europe, we evaluate the Madden–Julian oscillation (MJO) and its associated tropical–extratropical teleconnections (Vitart 2014). MJO events are known to modulate the probability of weather regimes in the North Atlantic with a lag of 10–15 days (Cassou 2008). For this reason, we may expect that increased skill in the extratropics during weeks 3–4 will be associated with improvements to MJO predictability during weeks 1–2. Consistent with this hypothesis, ENS-HRO exhibits small but significant improvements in the amplitude and deterministic predictability of the real-time multivariate MJO index (RMM; Wheeler and Hendon 2004) during the first 20 days of subseasonal forecasts (Fig. 13). Furthermore, 500-hPa geopotential height anomalies 10–15 days after an active MJO in the Indian Ocean have larger magnitudes in ENS-HRO compared to ENS-LRO, although both are too weak compared to observations (Fig. 14). This pattern projects onto the positive phase of the NAO. However, we find no significant difference in NAO predictability between ENS-HRO and ENS-LRO (Fig. S14), which is likely a

consequence of the small ensembles used in this study (Eade et al. 2014). We conclude that improvements to the MJO and its associated extratropical teleconnections are an important driver of increased skill over Europe in ENS-HRO relative to ENS-LRO. However, further work is required to understand how improvements in the tropics interact with local changes in the North Atlantic to drive improved predictability over Europe.

5. Discussion

Section 4a describes a time-scale dependence of the local response of the atmosphere on surface heating anomalies in the Gulf Stream region. In subseasonal and seasonal reforecast experiments, which use an atmospheric resolution of ~ 31 km, surface heating anomalies over the Gulf Stream are associated with local increases to the poleward heat flux by transient eddies (i.e., $\overline{v'T'}$). In multidecadal climate experiments, which use an atmospheric resolution of ~ 25 km, large increases to Q_{turb} over the Gulf Stream and Labrador Sea are balanced by

ENS-HRO vs ENS-LRO (1989-2015): Europe

FIG. 12. Summary scorecards for the European region (12.5°W–42.5°E, 35°–75°N) showing (left) differences in the fair continuous ranked probability skill score ($\Delta\text{CRPSSF} = \text{CRPSSF}_{\text{HRO}} - \text{CRPSSF}_{\text{LRO}}$) and (right) fractional changes in ensemble spread (FCES). Scores are calculated using data interpolated to a $2^\circ \times 2^\circ$ grid, and their magnitude is proportional to the area of the black dots above the legend. Darker shading corresponds to differences that are determined to be statistically significant using a bootstrap resampling procedure ($p < 0.01$). The variables shown are precipitation over land (tp), 2-m air temperature over land (t2m), surface temperature (stemp), sea surface temperature (sst), mean sea level pressure (mslp), temperature at 50 hPa (t50), zonal wind at 50 hPa (u50), meridional wind at 50 hPa (v50), streamfunction at 200 hPa (sf200), velocity potential at 200 hPa (vp200), temperature at

changes to the time-mean surface winds that have similarities with the steady linear response to midlatitude surface heating anomalies described by Hoskins and Karoly (1981). Recent studies have found comparable differences in the atmospheric response to idealized SST anomalies when comparing different atmospheric resolutions, albeit with nonlinear transient eddy feedbacks becoming more important at higher, rather than lower, atmospheric resolutions (e.g., Smirnov et al. 2015; Ma et al. 2017).

Here, we test the sensitivity of our results to a change in atmospheric resolution by comparing the impact of increased ocean resolution in two additional climate experiments coupled to a 50-km atmosphere (CLIM-HRO-LRA and CLIM-LRO-LRA; see Table 1). The spatial structure of the SST response to increased ocean resolution is extremely similar at atmospheric resolutions of 25 and 50 km (cf. Fig. 1 and Fig. S15). The most visible impact of the reduced atmospheric resolution is an increase in the magnitude of the subpolar gyre cold bias in CLIM-LRO-LRA compared to CLIM-LRO. Figures S16–S19 reproduce Figs. 3–6 using CLIM-HRO-LRA and CLIM-LRO-LRA. Although there are some differences in the details of the atmospheric response, our main conclusions regarding the response of ECMWF-IFS at multidecadal time scales are unaffected by the change in atmospheric resolution from 25 to 50 km.

Our interpretation of this comparison is that the atmospheric responses described in this study are dominated by processes that are adequately resolved with an atmospheric resolution of 30–50 km, such as air–sea interaction in the cold sector of extratropical cyclones (Vannière et al. 2017; Parfitt et al. 2016) and transient eddy feedbacks associated with (moist) baroclinic instability (Ma et al. 2015, 2017; Smirnov et al. 2015). However, we note that the sensitivity to changes in ocean model resolution may be larger in higher-resolution atmospheric models that are capable of resolving other modes of air–sea interaction, such as deep ascent in the warm conveyor belt of extratropical cyclones (Sheldon et al. 2017).

Therefore, we conclude that the fundamental differences in the atmospheric response to increased ocean resolution at (sub)seasonal and climate time scales in ECMWF-IFS are a result of the evolution of SST biases rather than differences in atmospheric resolution. We

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200 hPa (t200), zonal wind at 200 hPa (u200), meridional wind at 200 hPa (v200), geopotential height at 500 hPa (z500), temperature at 500 hPa (t500), zonal wind at 500 hPa (u500), meridional wind at 500 hPa (v500), temperature at 850 hPa (t850), zonal wind at 850 hPa (u850), and meridional wind at 850 hPa (v850).

MJO scores: ENS-HRO minus ENS-LRO

FIG. 13. (a) Lead-time-dependent differences in bivariate root-mean-square error (RMSE) for predictions of the real-time multivariate MJO index (RMM; [Wheeler and Hendon 2004](#)). (b),(c) As in (a), but for bivariate amplitude and correlations, respectively. Bivariate scores are calculated relative to the ERA-Interim reanalysis following [Rashid et al. \(2011\)](#). Vertical bars are estimates of uncertainty in the difference and black diamonds indicate lead times at which the difference between ENS-LRO and ENS-HRO is considered statistically significant.

surmise that this time dependence is a result of differences in the location and magnitude of the surface heating anomalies and the subsequent impacts on large-scale meridional temperature gradients. In particular,

changes to $\overline{v'T'}$ in CLIM-HRO relative to CLIM-LRO are a consequence of changes to the strength of the eddy-driven jet rather than a local response to surface heating anomalies.

6. Summary and conclusions

In this study we have systematically evaluated the sensitivity of ECMWF-IFS to a global increase of ocean model resolution from ~ 100 to ~ 25 km, which corresponds to a transition from the “eddy-parameterized” (LRO) to “eddy-permitting” (HRO) ocean regime. In particular, we have combined results from initialized ensemble forecast systems (ENS and SEAS) and climate integrations (CLIM) to investigate the wintertime response of the North Atlantic and surrounding regions at time scales ranging from weeks to decades.

In general, mean biases are reduced in HRO relative to LRO configurations. However, the impacts are highly dependent on lead time such that impacts seen in subseasonal and seasonal forecasts cannot be generalized to climate time scales. SST biases are similar in ENS-HRO and ENS-LRO and partly inherited from the ocean initial conditions. The differences between HRO and LRO configurations become more evident at seasonal lead times but take several decades to saturate. At multidecadal time scales, differences in the time-mean are dominated by the development of a severe North Atlantic cold bias in CLIM-LRO.

The time-scale dependence of the atmospheric response to increased ocean resolution is particularly evident in the local response to surface heating anomalies. In subseasonal and seasonal reforecast experiments, surface heating anomalies over the Gulf Stream are associated with local increases to the poleward heat flux by transient eddies (i.e., $\overline{v'T'}$). In contrast, large increases to Q_{turb} over the Gulf Stream and Labrador Sea in CLIM-HRO relative to CLIM-LRO are balanced by changes to the time-mean surface winds that resemble the steady linear response to midlatitude surface heating anomalies described by [Hoskins and Karoly \(1981\)](#). Furthermore, $\overline{v'T'}$ is reduced in CLIM-HRO relative to CLIM-LRO due to a weakening of meridional temperature gradients and a reduction in the strength of the eddy-driven jet.

Our results confirm that eddy-permitting ocean models have a clear advantage over eddy-parameterized configurations for simulating some aspects of air–sea interaction, such as the covariance between SST and turbulent heat flux anomalies over the Gulf Stream. This impact is independent of lead time and is evident at subseasonal, seasonal, and climate time scales. Unlike mean biases, deficiencies in the representation of this type of variability cannot be mitigated by ocean model initialization.

FIG. 14. Composites of 500-hPa geopotential height (Z500) anomalies for periods 10–15 days after phase 3 of the Madden–Julian oscillation (MJO), which corresponds to enhanced convective activity in the tropical Indian Ocean, in (a) ERA-Interim, (b) ENS-HRO, and (c) ENS-LRO.

However, it is difficult to identify the impacts of improved air–sea interaction on the variability of the overlying atmosphere. For example, atmospheric blocking and the intensity of the storm track show little sensitivity to ocean resolution at seasonal time scales. These aspects of atmospheric variability respond more strongly to biases in the mean ocean state and thus have a larger response at climate time scales.

Subseasonal predictability over Europe is generally increased in ENS-HRO compared to ENS-LRO, with the improvements most evident at longer lead times (i.e., week 4). The positive impacts are consistent across a range of atmospheric variables and are associated with significant improvements to the predictability to the MJO and its associated extratropical teleconnections. A more thorough understanding of the impacts of ocean model resolution on subseasonal predictability will require additional sensitivity experiments designed to isolate the relative importance of different regions (i.e., local vs remote forcings) and ocean processes (i.e., mean bias vs variability effects). Furthermore, the sensitivity to ocean resolution may be larger in simulations that are capable of resolving other modes of air–sea interaction, such as deep ascent in the warm conveyor belt of extratropical cyclones (Sheldon et al. 2017).

Finally, we note that mean SST biases in ENS-LRO and ENS-HRO are very similar and are in part inherited from the ocean initial conditions. Recent work by Vitart and Balmaseda (2018) has demonstrated that reducing such North Atlantic SST biases using an online bias correction scheme can improve subseasonal forecasts, particularly over Europe following an active MJO in the western Pacific. For this reason, we believe that an important way that future eddy-resolving ocean models

will benefit subseasonal forecast systems is as part of data assimilation systems that provide improved ocean initial conditions and reduced SST biases associated with a more realistic representation of the Gulf Stream.

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