10.
Coupled Prediction: Integrating Atmosphere-Wave-Ocean forecasting

CHAPTER COORDINATOR

John Siddorn

CGAPTER AUTHORS *(in alphabetical order)*

Natacha B. Bernier, Øyvind Breivik, Kai H. Christensen, Stephen G. Penny, and Keguang Wang

10. Coupled Prediction: Integrating Atmosphere-Wave-Ocean forecasting

10.1. Introduction to coupled prediction

In the early days of numerical modelling of the various components of the Earth system, each component was treated individually. Figure 10.1 shows a representation of two systems, ocean and atmosphere, that run independently: the output of one system is used to "force" the other. The interface between the ocean and the atmosphere was considered a phenomenon that had to be modelled independently of the two media.

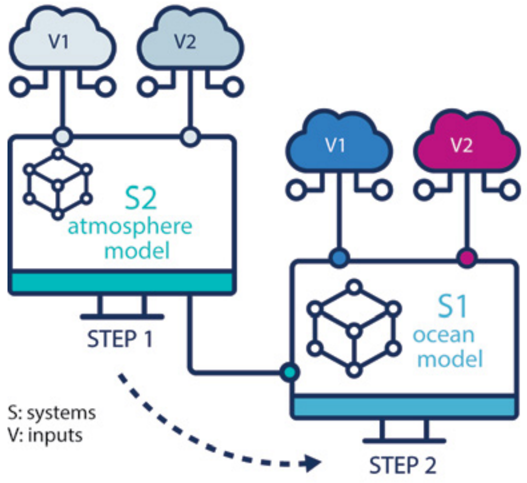

Figure 10.1. Traditional modelling platform characterised by Systems (S), like ocean model and atmosphere model, and inputs to each System (V).

This representation of the Earth system interactions is in some sense arbitrary. As the complexity of models grew, attempts were made to integrate the components more tightly, particularly in the field of climate modelling. Weather forecasting has a time scale of days to a couple of weeks (Lorenz, 1967) and, as new forecasts would be initialised regularly (typically every day), excessive diffusivity was never considered a problem. Making the early numerical weather prediction models *conservative* was therefore not a priority. The problem of conserving quantities such as heat, moisture, or momentum to avoid *model drift*, began to manifest itself only with the advent of long integrations of climate models. It became clear that long climate integrations of the atmosphere needed to also consider the impact of a (slowly) changing ocean, not least because the various climate components interact in nonlinear ways. This produces feedback loops that can fundamentally alter the state of each climate component. Numerical weather prediction models also needed to close the energy budget at the top of the atmosphere (or in the case of climate change, get that imbalance right). This led to the first attempts at coupling ocean and atmosphere models. The ice floating on the ocean and the soil in the ground were also separate from the ocean and the atmosphere. The latter was the first to be incorporated into more complex models, leading to the first coupled models.

Figure 10.2 shows a conceptual representation of systems that can interact through a "mechanism" called coupler. Figure 10.3 shows a more detailed and realistic representation of this coupling process.

Theoretical challenges to producing skilful weather forecasts were noted early in the history of NWP. For example, Lorenz (1963) pointed to the phenomenon of sensitive dependence on initial conditions. This means that small changes in our current best guess of the atmosphere or ocean could lead to very large changes in the forecasts. As a consequence, skillful weather prediction is limited to a finite time horizon of around 1-2 weeks. However, this perspective tends to focus on synoptic scale atmospheric dynamics. When a numerical model of the atmosphere is coupled to numerical models of the ocean and other Earth system components, new timescales are introduced into the system. In such multiscale systems,

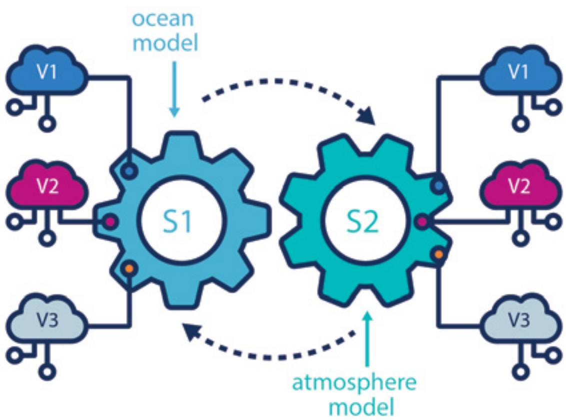

Figure 10.2. Coupling modelling platform where Systems (S) communicate with each other through an interface code called "coupler".

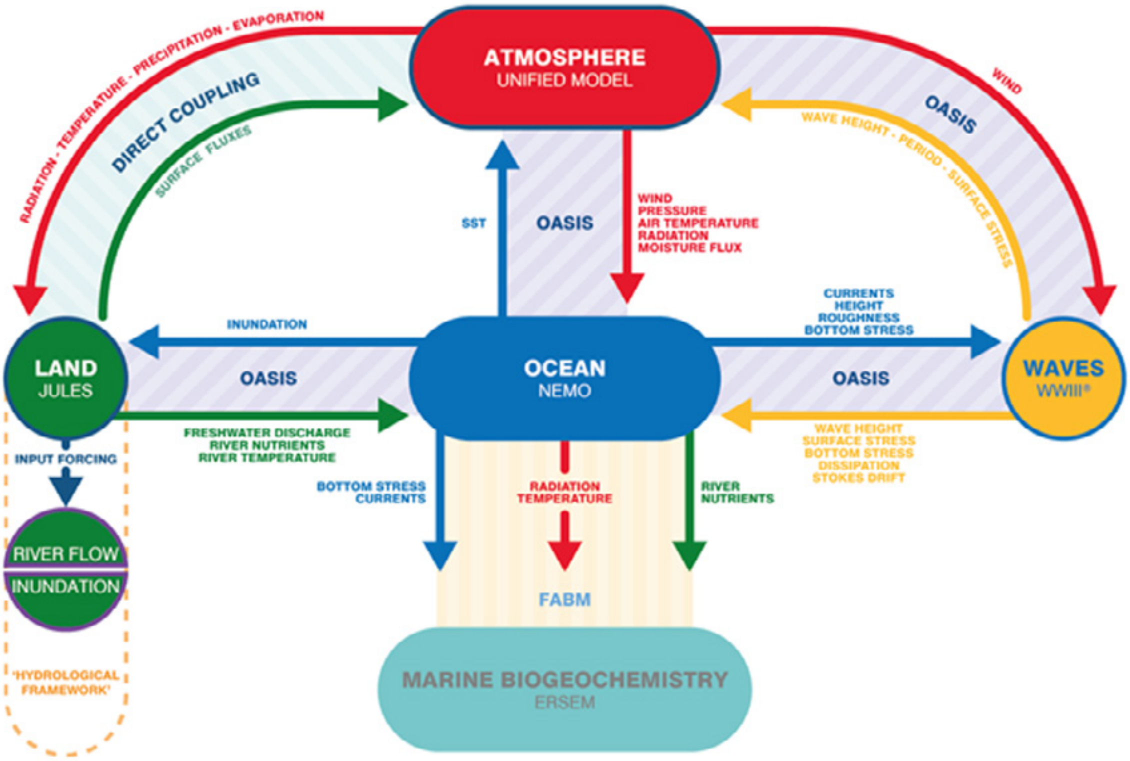

Figure 10.3. A schematic of the components (ocean, waves, etc.), the models (NEMO, WWIII, etc.), and the coupling exchanges between them, based on the system described in Lewis et al. (2019). Note the use of the coupler OASIS, the use of input forcing between Jules and the river flow model, direct coupling between Jules and the UM and direct forcing between the NEMO and ERSEM systems. A relatively simple coupled system (no ice) that includes 6 different models and 4 different approaches to coupling between them.

fast growing errors tend to be associated with processes that evolve quickly but saturate at smaller scales (Harlim et al., 2005), while slower growing or decaying errors tend to be associated with larger scale oscillations (Penland and Sardeshmukh, 1995; Penland and Matrosova, 1998; Vannitsem and Duan, 2020).

DA is the process of integrating information from numerical models with observations derived from real world measurements. At operational centres, DA systems have typically been built for each Earth system component independently. Early efforts to produce coupled forecasts maintained this separation of components when applying DA to provide initial conditions (Saha et al., 2006, 2010, and 2014; Zhang et al., 2007), an approach that is now called WCDA. More recently, there have been efforts to treat the entire coupled Earth system as one state and update accordingly. This more integrated approach allows observations to have immediate influence across domain boundaries (e.g. the air-sea interface), and as such is called SCDA. There are also approaches that fall on the spectrum between these extremes, such as the CERA system at the ECMWF that applies different DA systems to the atmosphere and ocean but still allows influence across the air-sea interface via an iterative cycling over a moving 6-12 hour time window (Laloyaux et al., 2018).

Beyond these theoretical considerations, there are many technical complications involved in transitioning to coupled prediction. Many centres have developed monitoring and prediction tools independently for individual Earth components (e.g. atmosphere, ocean, land, waves, etc.). This is natural based on the historical context of their development and limitations on computing capabilities, but it has created an infrastructure within and across institutions that adds complexity to the task of unifying prediction systems. The major prediction centres are making progress towards an integrated approach by unifying software infrastructure for models and data assimilation capabilities, as well as providing opportunities to increase interactions among the development teams of each system component. Data formats for model output and observational data sets have not been fully standardised across the various Earth system domains, and so this adds further steps before seamless integration.

A very important practical limitation that has most certainly curtailed research and development in coupled prediction is the extreme demands it places on computational resources. The best performing applications for atmospheric prediction and ocean prediction have already been pushed to their limits of resource consumption. Acknowledging the fact that coupled systems can perform very differently at low resolutions versus high resolutions, there remain very few organisations with the resources needed to explore unanswered questions in coupled prediction at relevant resolutions for operational prediction. For this reason, there are efforts underway to identify methods to reduce the computational demands at bottlenecks within the cycled data assimilation and forecast systems.

10.2. Coupling processes

10.2.1.Waves and their role in air-sea exchange

Waves have been called the gearbox of the climate system (Semedo et al., 2011). The analogy highlights the mediating role of the wave field between the atmosphere and the ocean interior. It may seem surprising that the sea surface demands its own class of numerical model. The other components (atmosphere, ocean, sea ice, land surface) have real substance, i.e. they each represent a three-dimensional chunk of the Earth system. In contrast, the wave model is a representation of a *surface* between two media, namely the air and the sea (Figure 10.4). There are, however, good practical reasons for this split. If we had access to unlimited computing power, we could model the ocean and the atmosphere with a grid resolution approaching Kolmogorov's microscale. That would mean that the Navier Stokes equations could be solved in the approximative limit known as DNS (Moin and Mahesh, 1998). In this case, the (liquid) ocean would presumably interact with the (gaseous) atmosphere and on their interface would form a wavy surface that, given a sufficiently strong momentum flux (mostly from the atmosphere to the ocean), would form droplets and bubbles as the waves start to break. The computational reality is far from this. At present, we can model the ocean and the atmosphere with models that have grid cells of tens of metres in the horizontal if we limit ourselves to small domains, whereas the waves that form under the influence of the wind have wavelengths of the order of some metres to hundreds of metres and so cannot be explicitly resolved together with the bulk ocean properties.

The behaviour of these waves determines the mass and momentum fluxes between the ocean and the atmosphere. As waves grow under the influence of the wind, they become steeper. In this phase they are also choppier than they will

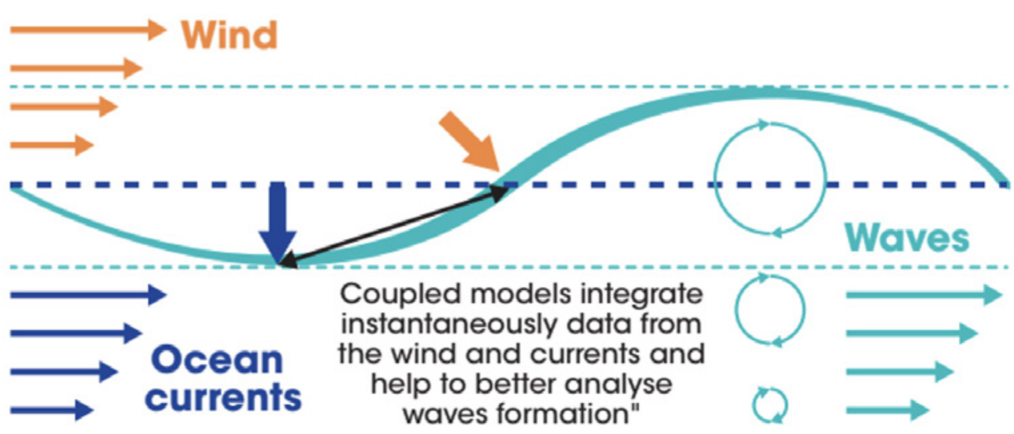

Figure 10.4. Representation of AWO coupled models.

be later on. All this means that the momentum flux between the atmosphere and the ocean is affected by the presence of waves (Janssen et al., 2004; Breivik et al., 2015). There is also very important feedback between the waves and the atmosphere. As waves grow, the sea surface becomes rougher, slowing the near-surface winds and increasing the momentum flux from the atmosphere to the wave field. This has the effect of stemming the deepening of low-pressure systems. This is important in the formation and growth of extratropical lows (Janssen, 1991 and 2004), but also in the evolution of tropical cyclones (discussed further below).

A secondary effect of waves on the air-sea interaction is through their ability to impart momentum and turbulent kinetic energy to the ocean interior (Figure 10.4). As waves grow, they absorb momentum that would otherwise go directly to the formation of ocean currents. As waves break, they part with this momentum, and also inject turbulent kinetic energy into the ocean (Janssen et al., 2004; Rascle et al., 2006; Ardhuin et al., 2008 and 2009). This leads to a redistribution of momentum and kinetic energy in time and space (Ardhuin and Jenkins, 2006; Breivik et al., 2015; Staneva et al., 2017; Wu et al., 2019), and has a profound effect on near-shore processes (Uchiyama et al., 2010; Kumar et al., 2012) where waves interact strongly with the currents. It is also clear that in open ocean conditions the mixed-layer depth is a function of the wave activity, in part sustained by the Langmuir turbulence (McWilliams et al., 1997; Fan and Griffies, 2014; Li et al., 2016 and 2017; Li and Fox-Kemper, 2017; Ali et al., 2019). The enhanced mixing due to waves is thus important for the sea surface temperature, which helps to determine the air-sea heat flux and thus constitutes an important feedback mechanism between the atmosphere and the ocean.

10.2.2. Land/sea exchanges

Land-sea interactions take place on a wide range of spatial and temporal scales. The presence of land modifies the weather in the coastal zone, e.g. the daily variations in wind speed and direction due to the sea breeze, and hence the atmosphere provides an indirect link between the land and the ocean. Another example of this indirect coupling is the way large-scale weather systems can influence the transport pathways of river water (Osadchiev et al., 2020).

The physical couplings between land, ocean, and atmosphere are not necessarily equal in strength and importance, and we often observed a lagged response. The runoff from rivers is dependent on the precipitation over a potentially very large catchment area, with significant lag between specific precipitation events and the freshwater discharge to the coastal ocean. This lag is particularly pronounced in temperate and polar regions where the precipitation accumulates as snow during parts of the year. This is reflected by the state-of-the-art of coupled modelling, as very few systems couple the ocean to the land, but rather use the atmosphere as a mediator.

10.2.3. Air-sea exchanges across sea ice

At high latitudes, air-sea exchange is modified by the presence of sea ice. Varying in thickness up to a couple of metres, sea ice is sensitive to forcing from both air and sea and the air, sea, and sea ice are strongly coupled. Geophysical scale sea ice is essentially a mixture of ice floes of varying size and thickness, with the added complexity of being rafted and ridged. Describing accurately the sea ice mechanical behaviour is extremely challenging, although modelling sea ice as plastic materials at the large scale has long been a successful approach (Coon et al., 1974; Hibler, 1979; Hunke and Dukwicz, 1997; Girard et al., 2011). In medium to high model resolutions (≤ 10km), such models can generate small-scale features such as the ice leads (Hutchings et al., 2005; Wang and Wang, 2009; Girard et al., 2011; Spreen et al., 2017). This thin ice cover has a very small heat content and easily melts away during summer, resulting in large seasonal variations of sea ice extent.

In much of the pack ice region, the thermodynamic and dynamic interactions between air and sea are greatly suppressed. During wintertime, the air-sea heat flux through leads is two orders of magnitude larger than that through thick ice (Maykut, 1978). Dynamically, pack ice behaves as a low-pass filter, the air and sea surface stresses act on the ice cover thus driving the advection and deformation of sea ice, while ocean waves are generally suppressed. The MIZ is a highly complex region consisting of ice floes of varying dimensions and shapes. Wave energy propagating into the MIZ can lead to rapid breakup. The damping of waves in sea ice is directly related to the amount of energy imparted on the sea ice. This is a field of active research, and it is presently not fully clear how the MIZ attenuates wave energy (Doble and Bidlot, 2013; Williams et al., 2013; Kohout et al., 2014; Sutherland and Rabault, 2016; Ardhuin et al., 2016; Rabault et al., 2020).

Landfast ice is a special region where the air-sea interaction nearly ceases. It generally appears in winter seasons and often occurs in shallow waters where ridged ice grounds on the seabed (Mahoney et al., 2014), or occurs where islands are close to each other (Divine et al., 2003). Modelling studies have shown that adding base stress due to grounding ridges and increasing ice tensile strength improve the simulation of landfast ice evolution (Lemieux et al., 2016), although in some Arctic shelf seas the time duration needs to be further improved.

In coupled modelling, a key consideration is whether to couple the sea ice directly to the atmosphere or only through the ocean model. In some recent coupled models, particularly for high-resolution short-term atmosphere, ocean, and sea ice forecasts, the timestep for coupling has decreased to one hour or less, e.g. the coupled ocean-ice model METROMS at the Norwegian Meteorological Institute (Naughten et al., 2018), or the atmosphere-ice coupled model at UKMO (Ridley et al., 2018). In these cases, the difference between using the atmosphere timestep or ocean timestep is generally negligible.

10.2.4. The importance of air-sea exchanges during storms and other extreme events

Air-sea exchange really comes to the fore in the development of tropical cyclones. The sea surface temperature must as a general rule exceed 26.5°C to sustain the growth of the cyclone (Emanuel, 1986). However, the depth to which the ocean's temperature must be above this critical threshold is also important. As the cyclone moves across the sea surface, the Ekman transport will lead to divergence, and vertical Ekman pumping will eventually lead cooler water to the surface. If the cyclone is moving sufficiently slowly, this will eventually kill the cyclone (Mogensen et al, 2017). Thus, it is essential to include an ocean model component that responds to the atmospheric forcing.

Polar lows are of a decidedly less extreme nature than tropical cyclones, but they share the same dependence on sea surface temperature (Rasmussen and Turner, 2003). As winds blow off the sea ice, the air is rapidly warmed by the (relatively) warm ocean surface. Under the appropriate atmospheric conditions (Kolstad, 2015), this can lead to the formation of polar lows. These are small-scale, intense cyclones, typically with gale-force winds. If the cyclone is rather stationary, a shallow layer of warmer water can mix with cooler waters through Ekman pumping. As the ocean temperature is key to sustaining a cyclone, the water mixing can sometimes be enough to inhibit further growth of the polar low.

Examples of instantaneous coupling between land, ocean, and atmosphere also include coastal inundation during landfall of tropical cyclones (Lee et al., 2019). In these cases, heavy precipitation leads to a swelling of local rivers, which is often coincidental with a large storm surge. The result is a rapid sea-level rise that may cause extensive damage to coastal infrastructure, especially when combined with large surface waves and strong winds.

10.3. Benefits expected from coupling

The importance of coupled ocean-atmosphere prediction systems in providing seasonal predictability is well-known (Kim et al., 2012, and references therein). Sources of predictability in seasonal forecasting systems tend to be, by their very nature, coupled systems driven by teleconnections that are functions of climate modes, such as the North Atlantic Oscillation and the El Niño–Southern Oscillation that have geographically far-reaching consequences. However, as timescales shorten and the dominance of these coupled climate modes become less fundamental to predictability of the atmosphere-ocean system, it becomes less obvious whether the benefits of fully coupled systems justify the computational cost or the technical and scientific complexity required. The coupling between atmospheric and wind wave models was first introduced operationally in 1998 at ECMWF. The method based on the theoretical work of Janssen (1991) contributed to an improvement of both atmospheric and surface wave forecasts at the medium range on the global scale. The usual approach of forcing the ocean with atmospheric conditions (Takano et al., 1973), and referred to in this section as "forced") using bulk parameterisations of the fluxes (Large and Yeager, 2009) is computationally and structurally far easier and cheaper than coupling approaches. However, the key boundary layer processes (see Section 9.1 for details) are not taken into account and thus the feedback between the atmospheric boundary layer and the upper ocean is not represented. It is necessary to understand how important these processes might be, bearing in mind that coupled models can suffer from systematic errors as a result of positive feedback leading to drifts in the forecast (Hyder et al., 2018).

Ocean forecasting systems have become increasingly high-resolution, resolving coastlines, bathymetry, and eddy-scale processes. The effect of coupling on model predictions becomes more important with increasing grid resolution (Janssen et al., 2004), and so the question of the benefits of coupling to ocean forecasting is perhaps more relevant now than ever. A small but growing body of literature demonstrates the benefits to ocean prediction of coupling at shorter time-ranges (Brassington et al, 2015; Allard et al., 2010; Lewis et al., 2018 and 2019).

Understanding the advantages of coupled over uncoupled predictions in short-range ocean forecasting is in its infancy. Although the future of advanced systems is clearly coupling, as several processes are better represented, predictive modelling without coupling is however possible thanks to parameterizations and should never be discarded as an option. At a recent science meeting of OceanPredict (Vinayachandran et al., 2020), the need for a careful evaluation of how ocean and atmosphere components interact and impact each other was highlighted. At monthly or shorter timescales, the benefits of running coupled systems need to be evaluated, balancing scientific and service benefits against complexity and computing costs. Intermediate complexity coupling may also be an appropriate approach if full coupling is not viable and the service is not reliant on the atmosphere and ocean information. Lemarié et al. (2021) provided an example of an atmospheric boundary layer approach that gives some of the benefits of coupling whilst being significantly simpler and computationally cheaper.

The potential benefits of using a coupled framework is reinforced by the move towards a multi-hazard approach to predictions. Natural hazards from multiple sources may combine or occur concurrently (Lewis et al., 2015). Large waves, storm surges, high-wind speeds, and extreme precipitation are all hazards that are likely to co-occur, and influence each other through coupled feedbacks that can compound one another (for example through over-topping). Coupled systems that predict these coupled feedbacks may enable an improvement in the range and consistency of actionable information to be provided through hazard warnings and guidance.

When considering providing services in multi-hazards frameworks, the opportunities that coupling provides should be considered alongside the scientific benefits. A coupled system combining the full water-cycle – including consistent precipitation, river runoff, wave, currents, and surge forecasts - can give users mutually consistent products in a joint probability framework. This can be important in coastal flooding, where the impacts for coastal communities or industries can come from high river flows and local heavy precipitation events, alongside overtopping waves and extreme surges. From a service perspective, it is attractive to provide probabilistic frameworks in which the timings and intensities of events are consistently incorporated and interact appropriately; these services increasingly rely on probabilistic information for decision making. An area that has had limited attention but seems likely to prove significant is the impact of feedback among Earth-system components upon ensemble spread, and hence the quality of the probabilistic information.

Ocean phenomena are usefully classified depending on their nature, which determines the timescale for oceanic predictive skill and whether a coupled ocean-atmosphere model would be advantageous. Some phenomena have strong dependence, and a rapid response, to the atmosphere forcing and can be thought of as forced-dissipative systems. This category includes, surface waves, responses to surface heating and wind in the ocean boundary layer, and storm surges. These systems largely depend upon skill in the atmosphere model, and so the benefits of coupling to the atmosphere can be a leading-order driver of the ocean system skill. The advantage of coupling and its impact upon predictability often focus on the benefits to the atmosphere (Brunet et al., 2010; Belcher et al., 2015). The impact of ocean coupling on tropical meteorology is well documented with tropical cyclones (Bender and Ginis 2000; Mogensen et al., 2017; Smith et al., 2018; Neetu et al., 2019), monsoons (Fu, 2007), and the Madden–Julian Oscillation (Bernie et al., 2008; Shelly et al., 2014; Seo et al., 2014), which predictability improved in coupled systems. There is also an increasing body of evidence that the oceans have a significant local (important for short-range forecasts) and non-local (increasingly significant at longer lead-times) influence on the extra tropics (Minobe et al., 2008).

In the literature, there is limited quantification of the impact of the coupled improvement in atmospheric parameters on ocean services but it is an increasing area of study. Guiavarc'h et al. (2019) explored the impact of a coupled (atmosphere-ocean) system on short-range ocean forecast skill and showed that there are benefits in SST predictability at the short-range, but with mixed results for other parameters. Given that the research system they used is at a relatively early stage in development, and the resolution of the atmosphere is significantly lower than in comparable forced systems, these results are encouraging.

Although the importance of coupling the wave-ocean interface for improving forecasts of surge and waves is well documented (Wolf, 2008; Lewis et al., 2018), most storm surge and wave prediction systems remain largely independent. As well as the atmospheric forcing, ocean currents have a significant role in modifying ocean wave properties. The presence of eddies, fronts, and filaments with length scales of tens to hundreds km and ubiquitous in the world's oceans, can be the main source of variability in significant wave heights at these scales. Ardhuin et al. (2017) made a compelling case for the importance of coupling the ocean surface currents to a wave model allowing adequate representation of wave height variability in the world's open oceans. Wave predictions in shelf seas environments are shown to be improved as a result of coupling to an ocean model (Allard et al., 2012; Wahle et al., 2017; Lewis et al., 2018). as well as the predictions of ocean current and other ocean parameters, including upwelling due to stokes drift effects, were enhanced (Wu et al, 2019). Fan et al. (2009) showed that time and spatial variations in the surface wave field, as a result of coupling to winds, are particularly strong in hurricanes, with significant additional feedback from ocean currents and near-surface temperatures.

The ocean eddy kinetic energy is damped when taking into account the feedbacks between ocean surface current and winds (Oerder et al., 2018; Jullien et al., 2020). As ocean models increasingly resolve the mesoscale explicitly, they are likely to have the tendency to over-predict the eddy activity. In uncoupled systems, there is an option to calculate the wind stress using relative wind speeds (taking into account the eddies and other ocean current interactions). However, in these systems there is no imprint of ocean eddies on the atmospheric wind stress curl (due to the lack of ocean eddies in the uncoupled atmospheric modelling system), and so the feedback onto the wind stress results in over-damping of the eddies. A fully coupled system will correctly allocate the feedback between the winds and currents, allowing the eddy and wind fields to co-evolve correctly. This coupling between the winds and currents can also lead to upscaling to the large scale, e.g. Renault et al. (2016) showed that current/wind feedback, through its eddy killing effect, resolves long-lasting biases in Gulf Stream path.

Marine heatwaves have recently been recognised for their importance (Holbrook et al., 2019). They are high impact events that can be induced by anomalous heating at the ocean surface; their predictability is dependent upon air-sea coupled phenomena (Jacox, 2019). At the other end of the temperature scale, Pellerin et al. (2004) showed that coupling can also have strong impacts in ice-infested seas even down to sub-daily time scales, due to rapid changes in coastal sea ice cover (i.e. the formation of coastal polynyas). The sea ice acts as a barrier between a relatively warm–wet ocean and cold–dry atmosphere, and changes in the sea ice cover can have dramatic effects on heat and moisture fluxes. The importance of coupling has also been recognized in polar regions (Jung and Vitart, 2006).

Coastal regions are particularly impacted by coupled processes, both between the ocean and atmosphere and coupling with river and estuaries. The impact of freshwater discharges on the ocean circulation is highlighted by Røed and Albretsen (2007) and, more broadly on the coastal marine environment, by Dzwonkowski et al., 2017. The inputs from the land surface, mediated through estuaries and lagoons, are generally poorly represented in ocean forecasting systems due to their scale (time and space) and their complexity. It is extremely difficult to accurately model nutrient inputs, which are mediated strongly by land use and societal factors, and the associated plankton response is therefore compounded. Although this problem is not fundamentally a coupling problem, there is still scope for improving the inputs to the coastal environment through specifying better the river-estuary-ocean interface.

10.4. Ocean Information Services based on Coupled Frameworks

Over the past decades, operational oceanography underwent a rapid transition and gradually became part of core systems of operational centres previously largely focusing on weather. Sufficient observations are now available to improve the estimation of the ocean state, including mesoscale variability, ice cover, or wave spectra for wave systems. The development of weakly coupled data assimilation techniques, the exploration of strongly coupled data assimilation using cross-domain error covariance (Sluka et al., 2016), the ability to assimilate an ever-growing source of observations, the improvements in physics and dynamics of the various components of the Earth system, and rapidly increasing computing capacities, keep pushing forward the quality of forecasts and reanalyses that can be produced. As a result, information available for products and services is continuously expanding and including a rapid increase in the quality and quantity of ocean and marine services. It is now well established that marine services are essential to any nation with coastal assets.

In the late 90s and early 2000s, operational marine services were limited to a few marine weather variables such as waves, tides, and surges. With coupled systems now in place in many operational centres and the continuous push for increased resolution to better reflect local conditions, a wide variety of new services has and continues to emerge. It is now common for service providers to be overwhelmed with information drawn from many prediction systems, and for users to be submerged with products. In the next subsections are discussed the few steps that should be followed to sort through the very large number of products that can be generated numerically, so that services are centred on needs in a fit for purpose and accessible approach. A few simple examples are used to demonstrate ways of tying together all this numerical knowledge and provide forecasts and services that are informative and tailored to various groups of users.

10.4.1. Establishing service needs

The first step when evaluating services' needs, including whether to use or not a coupled or forced system, is to clearly define the service gap and how current capacity can be leveraged to address it. The second step is to identify enough resources required to bring the project to completion. Numerous capacities are required to sustain timely and accurate services: i) reliable and sufficient computing resources including telecommunications, bandwidth, and storage, along with staff to operate and maintain the IT infrastructure; ii) physical scientist to install; optimise; run; validate, and verify numerical systems; iii) physical scientists to produce forecasts; iv) forecasters able to disseminate and explain forecasts; v) the ability to sustain such services through extreme conditions (e.g. during a powerful cyclone); and vi) the capacity to overcome throughout the years the changes in IT infrastructure, complexification of systems, increasing volumes of data, etc. However, it should never be forgotten that, whatever is the capacity and the complexity of a state-of-the-art forecast, it only has value if it reaches the users in the due time.

For those countries that choose to operate regional systems driven with data provided by major operational centres, the capacity to download the required data quickly enough to run regional systems and issue timely regional forecasts is also key. It should be also ensured that sufficient local expertise is available to monitor, , and fix any issue with the regional system.

When launching new or improved forecast services, another important step is to identify user groups (e.g. marine engineers, marine transportation industries, search and rescue operations, fisheries and aquaculture, coastal communities) and understand their needs. It should be also kept in mind that within each group there can be considerable modulation of needs and that needs can evolve with time and hence they should be reviewed periodically. See section 4.8 for more details on user requirements.

10.4.2. Identifying the required information

Search and rescue and coastal flooding cases are used to illustrate how to select the modelling tools that are required to best address the problem. They are also used to demonstrate how a fit for purpose approach may identify the numerical systems best suited to deliver services.

A search and rescue incident that requires drift predictions is an example of a service to illustrate the choices needed. Forecasts of the trajectory of the drifting object requires knowledge of tides, eddies, inertial oscillations, winds, and waves. Such incidents often occur during high winds and large waves conditions and, as discussed in 9.1, it is under such conditions that interactions between tides, waves, ocean, and atmosphere are most important. This suggests that coupled predictions could add value (Davidson et al., 2009) to the use of independent ocean, wave, and atmosphere forecasting systems. As already discussed, ensembles are essential to sampling uncertainty in various components of a system. In their comprehensive review of the Deepwater Horizon oil spill event, Barker et al. (2020) made a case for the importance of coupled atmosphere-wave-ocean systems for effective oil spill response. All these considerations point to the use of ensemble coupled ocean-wave-atmosphere systems that are post-processed though tracking systems capable of considering the characteristics of various objects, such as a person in the water or a vessel at drift. However, the simulation overhead (in time and computer resources) of the coupled system needs to be balanced with the need to quickly run ensemble simulations to provide probabilities of the search zone to help optimise search patterns. A case similar to that of search and rescue is the response to oil spill or tracking of nuclear debris, which also requires models to predict particulate dispersion but also need to consider other chemically induced processes, such as fate and behaviour.

Coastal flooding is the other example used here to illustrate how to select the best modelling tools. Local communities typically have precise questions such as: "How much water will there be and for how long?" "Will the water reach my street and my house?" "Will it damage my property?" "Will it erode my land or the cliff my house is perched on?" Local authorities and disaster management agencies might have further considerations such as: "What are the most likely and the worst-case scenarios?" "When should we consider evacuations and through what route?" "What critical infrastructures might be at risk?" However, the nature of the service will depend on local conditions. Consider for example a community living at high latitudes. In the event of a polar low (discussed in 9.1), ice can recede rapidly to expose long stretches of ocean leaving the coastline exposed to large swells. In these areas, wave-ice interactions can lead to rapid changes and coupled ice-ocean-wave-atmosphere systems should be preferred to provide accurate forecasts of the low's evolution, rapidly changing marine conditions, and to warn the coastal communities. On the other hand, locations exposed to tropical cyclones will need a system more focused on predicting ocean-atmosphere interactions in support of track and intensity prediction. However, the concept of a forecast based on total water level at the coast remains, although the fit for purpose numerical guidance to be used might have some differences. It is then particularly important to consider user orientated questions. User groups rarely care about technical issues, such as if the models are coupled or if the surge component is barotropic or baroclinic. They care that scientists put forward the combination that best addresses their concerns. They want to receive a fit for purpose service. Simulations of tide, surge, wave, erosion, hydrodynamic, and atmospheric may all be required, but to decide whether they should be coupled or not it is necessary to understand if this improves the specific predictions identified by the user questions outlined above.

Advanced knowledge of the risk of an upcoming event is useful to put in place mitigation measures. An outlook for several days to several weeks is of particular interest, as well as the early identification of upcoming risk for which ensemble systems are relevant. At early stages, the focus should be on identifying risk and uncertainties, and communicating them in a clear manner. As the high impact event nears (e.g. next couple days), ensembles can be replaced with resolution increases, so that the risk forecast is changed into an impact-based forecast (i.e. damage to housing, risk of cars being swept away, risk of cutting off of an evacuation route, etc.). This should make the scientists understand that for the users the waves, surges, tides, and other phenomena are relevant only as much as they affect flooding in their areas of interest. This further highlights the importance of metrics used to evaluate models and forecasts. When it comes to flooding, having a slightly better RMSD and thus a better representation of the mean state is useless if the total water level peaks are missed. Thus, relying on an overly complicated ocean system that results in little to no added skill in total water level forecasts is useless. Similarly, if a complicated system cannot be operated with sufficient resolution over long enough periods, or with enough ensemble members to sample uncertainties, it is not fit for purpose. In addition, coupling should be considered also in the context of the resources (always limited) of operational centres.

Finally, whether numerical systems are run locally or remotely and whether all systems required to produce such forecasts are coupled or not, the path forward should be one in which the forecasters are experts at providing added value taking into account the perspective of the public (e.g. placing in the context a particular expected extreme, comparing it to previous ones, explaining the subtle differences to be expected with the forecast risk, etc.). As such, the forecasters are the ultimate downscalers bringing added value based on local knowledge and history.

10.5. References

Ali, A., Christensen, K., Breivik, O., Malila, M., Raj, R., Bertino, L., Chassignet, E., Bakhoday-Paskyabi M. (2019). A comparison of Langmuir turbulence parameterizations and key wave effects in a numerical model of the North Atlantic and Arctic Oceans. *Ocean Modelling*, 137, pp 76-97, https://doi.org/10.1016/j.ocemod.2019.02.005

Allard, R. A., Campbell, T. J. , Smith, T. A., Jensen, T. G., Chen, S., Cummings, J. A., Chen, S., Doyle, J., Xiaodong, H., Small, R.J., Carrol, S.N. (2010). Validation Test Report for the Coupled Ocean Atmosphere Mesoscale Prediction System (COAMPS) Version 5.0 NRL/MR/7322–10-9283. Stennis Space Center, MS: Oceanography Division, Naval Research Laboratory, 172 pp.

Allard, R. A., Travis, A. S., Jensen, T. G., Chu, P. Y., Rogers, E., and Campell, T. J. (2012). Validation Test Report for the Coupled Ocean / Atmosphere Mesoscale Prediction System (COAMPS) Version 5.0: Ocean / Wave Component Validation. Naval Research Lab Tech Report, (NRL/MR/7320--12-9423).

Ardhuin, F., Rascle, N., Belibassakis, K. (2008). Explicit wave-averaged primitive equations using a generalized Lagrangian mean. *Ocean Modelling*, 20(1), 35-60, https://doi.org/10.1016/j.ocemod.2007.07.001

Ardhuin, F., Marie, L., Rascle, N., Forget, P., Roland, A. (2009). Observation and estimation of Lagrangian, Stokes and Eulerian currents induced by wind and waves at the sea surface. *Journal of Physical Oceanography*, 39, 2820-2838, https://doi.org/10.1175/2009JPO4169.1

Ardhuin, F., and Jenkins A., (2006). On the Interaction of Surface Waves and Upper Ocean Turbulence. *Journal of Physical Oceanography*, 36, 551-557, https://doi.org/10.1175/JPO2862.1

Ardhuin, F., Sutherland, P., Doble, M., Wadhams, P. (2016). Ocean waves across the Arctic: Attenuation due to dissipation dominates over scattering for periods longer than 19 s. *Geophysical Research Letters*, 43(11), 5775-5783, https://doi.org/10.1002/2016GL068204

Ardhuin, F., Gille, S. T., Menemenlis, D., Rocha, C. B., Rascle, N., Chapron, B., Gula, J., Molemaker, J. (2017). Small-scale open ocean currents have large effects on wind wave heights. *Journal of Geophysical Research: Oceans*, 122(6), 4500–4517. https://doi.org/10.1002/2016JC012413

Barker, C. H., Kourafalou, V. H., Beegle-Krause, C. J., Boufadel, M., Bourassa, M. A., Buschang, S. G., Androulidakis, Y., Chassignet, E.P., Dagestad, K.-F., Danmeier, D.G., Dissanayake, A.L., Galt, J.A., Jacobs, G., Marcotte, G., Özgökmen, T., Pinardi, N., Schiller, R.V., Socolofsky, S.A., Thrift-Viveros, D., D., Zhang, A., Zheng, Y. (2020). Progress in operational modeling in support of oil spill response. *Journal of Marine Science and Engineering*, 8(9), 1-55, https://doi.org/10.3390/jmse8090668

Belcher, S.E., Hewitt, H.T., Beljaars, A., Brun, E., Fox-Kemper, B., Lemieux, J.F., Smith, G., and Valcke, S. (2015). Ocean-Waves-Sea Ice- Atmosphere Interactions. In: Brunet, G., Jones, S. and Ruti, P. (eds.) "Seamless prediction of the Earth system: from minutes to months", WMO, 1156. World Meteorological Organisation, Geneva, pp. 155-170.

Bender, M. A., and Ginis, I. (2000). Real-Case Simulations of Hurricane–Ocean Interaction Using A High-Resolution Coupled Model: Effects on Hurricane Intensity. *Monthly Weather Review*, 128(4), 917-946, https://doi.org/10.1175/1520-0493(2000)128<0917:RCSOHO>2.0.CO;2

Bernie, D. J., Guilyardi, E., Madec, G., Slingo, J. M., Woolnough, S. J., and Cole, J. (2008). Impact of resolving the diurnal cycle in an ocean-atmosphere GCM. Part 2: A diurnally coupled CGCM. *Climate Dynamics*, 31(7-8), 909-925, https://doi.org/10.1007/s00382-008-0429-z

Brassington, G. B., Martin, M. J., Tolman, H. L., Akella, S., Balmeseda, M., Chambers, C. R. S., Chassignet, T., Cummings, J.A., Drillet, Y., Jansen, P.A.E.M., Laloyaux, P., Lea, D., Mehra, A., Mirouze, I., Ritchie, H., Samson, G., Sandery, P.A., Smith, G.C., Suarez, M., and Todling, R. (2015). Progress and challenges in short- to medium-range coupled prediction. *Journal of Operational Oceanography*, 8, s239-s258, https://doi.org/10.1080/1755876x.2015.1049875

Breivik, Ø., Mogensen, K., Bidlot, J.-R., Balmaseda, M.A., Janssen, P.A. (2015). Surface Wave Effects in the NEMO Ocean Model: Forced and Coupled Experiments. *Journal of Geophysical Research: Oceans*, 120, 2973-2992, https://doi.org/10.1002/2014JC010565

Brunet, G., Keenan, T., Onvlee, J., Béland, M., Parsons, D., and Mailhot, J. (2010). The next generation of regional prediction systems for weather, water and environmental applications. CAS XV Vision paper (Agenda item 8.2).

Coon, M. D., Maykut, G. A., Pritchard, R. S., Rothrock, D. A., and Thorndike A. S. (1974). Modeling the pack ice as an elastic-plastic material. AIDJEX Bull. 24, pp. 1-106, Univ. of Wash., Seattle, Washington.

Davidson, F.J.M., Allen, A., Brassington, G.B., Breivik, Ø., Daniel, P., Kamachi, M., Sato, S., King, B., Lefevre, F., Sutton, M., and Kaneko, H. (2009). Applications of GODAE ocean current forecasts to search and rescue and ship routing. *Oceanography*, 22(3), 176-181, https://doi.org/10.5670/oceanog.2009.76

Divine, D., Korsnes, R., and Makshtas, A. P. (2003). Variability and climate sensitivity of fast ice extent in the north-eastern Kara Sea. *Polar Research*, 22, 27-34, https://doi.org/10.3402/polar.v22i1.6440

Doble, M. J., and Bidlot, J.-R. (2013). Wave buoy measurements at the Antarctic sea ice edge compared with an enhanced ECMWF WAM: Progress towards global waves-in-ice modelling. *Ocean Modelling*, 70, 166-173, https://doi.org/10.1016/j.ocemod.2013.05.012

Dzwonkowski, B., Greer, A.T., Briseno-Avena, C., Krause, J.W., Soto, I.M., Hernandez, F.J., Deary, A.L., Wiggert, J.D., Joung, D., Fitzpatrick, P.J., O'Brien, S.J., Dykstra, S.L., Lau, Y., Cambazoglu, M.K., Lockridge, G., Howden, S.D., Shiller, A.M., Graham, W.M. (2017). Estuarine influence on biogeochemical properties of the Alabama shelf during the fall season. *Continental Shelf Research*, 140, 96-109, https://doi.org/10.1016/j.csr.2017.05.001

Emanuel, K.A. (1986). An Air-Sea Interaction Theory for Tropical Cyclones. Part I: Steady-State Maintenance. *Journal of the Atmospheric Sciences*, 43(6), 585-605, https://doi.org/10.1175/1520-0469(1986)043<0585:AASITF>2.0.CO;2

Fan, Y., Ginis, I., and Hara, T. (2009). The effect of wind-wave-current interaction on air-sea momentum fluxes and ocean response in tropical cyclones. *Journal of Physical Oceanography*, 39(4), 1019-1034, https://doi.org/10.1175/2008JPO4066.1

Fan, Y., and Griffies, S.M. (2014). Impacts of parameterized Langmuir turbulence and non-breaking wave mixing in global climate simulations. *Journal of Climate*, 27, 4752-4775, https://doi.org/10.1175/JCLI-D-13-00583.1

Fu, L.L. (2007). Intraseasonal variability of the equatorial Indian ocean observed from sea surface height, wind, and temperature data. *Journal of Physical Oceanography*, 37(2), 188-202, https://doi.org/10.1175/JPO3006.1

Girard, L., Bouillon, S., Weiss, J., Amitrano, D., Fichefet, T., and Legat, V. (2011). A new modeling framework for sea-ice mechanics based on elasto-brittle rheology. *Annals of Glaciology*, 52(57), 123-132, https://doi.org/10.3189/172756411795931499

Guiavarc'h, C., Roberts-Jones, J., Harris, C., Lea, D. J., Ryan, A., and Ascione, I. (2019). Assessment of ocean analysis and forecast from an atmosphere–ocean coupled data assimilation operational system. *Ocean Science*, 15(5), 1307-1326, https://doi.org/10.5194/os-15-1307-2019

Harlim, J., Oczkowski, M., Yorke, J. A., Kalnay, E., and Hunt, B.R. (2005). Convex Error Growth Patterns in a Global Weather Model. *Physical Review Letters*, 94, 228501, https://doi.org/10.1103/PhysRevLett.94.228501

Hibler, W. D. III (1979). A dynamic thermodynamic sea ice model. *Journal of Physical Oceanography*, 9, 815-846, https://doi.org/10.1175/1520-0485(1979)009<0815:ADTSIM>2.0.CO;2

Holbrook, N. J., Scannell, H. A., Sen Gupta, A., Benthuysen, J. A., Feng, M., Oliver, E. C. J., Alexander, L.V., Burrows, M.T., Donat, M.G., Hobday, A.J., Moore, P.J., Perkins-Kirkpatrick, S.E., Smale, D.A., Straub, S.C., Wernberg, T. (2019). A global assessment of marine heatwaves and their drivers. *Nature Communications*, 10(1), 1-13, https://doi.org/10.1038/s41467-019-10206-z

Hunke, E. C., and Dukowicz, J. K. (1997). An elastic-viscous-plastic model for sea ice dynamics. *Journal of Physical Oceanography*, 27(9), 1849-1867, https://doi.org/10.1175/1520-0485(1997)027<1849:AEVPMF>2.0.CO;2

Hutchings, J. K., Heil, P., and Hibler, W. D. III (2005). Modeling linear kinematic features in sea ice. *Monthly Weather Review*, 133, 3481-3497, https://doi.org/10.1175/MWR3045.1

Hyder, P., Edwards, J.M., Allan, R., Hewitt, H.T., Bracegirdle, T.J., Gregory, J.M., Wood, R.A., Meijers, A.J.S., Mulcahy, J., Field, P., Furtado, K., Bodas-Salcedo, A., Williams, K.D., Copsey, D., Josey, S.A., Liu, C., Roberts, C.D., Sanchez, C., Ridley, J., Thorpe, L., Hardiman, S.C., Mayer, M., Berry, D.I., Belcher, S.E. (2018). Critical Southern Ocean climate model biases traced to atmospheric model cloud errors. *Nature Communications*, 9, 3625, https://doi.org/10.1038/s41467-018-05634-2

Jacox, M. G. (2019). Marine heatwaves in a changing climate. *Nature*, 571, 485-487. https://doi.org/10.1038/d41586-019-02196-1

Janssen, P.A.E.M. (1991). Quasi-linear theory of wind wave generation applied to wave forecasting. *Journal of Physical Oceanography*, 21, 1631-1642.

Janssen, P. (2004). The interaction of ocean waves and wind. Cambridge University Press, Cambridge, UK.

Janssen, P., Saetra, O., Wettre, C., Hersbach, H., Bidlot, J. (2004). Impact of the sea state on the atmosphere and ocean. *Annales Hydrographiques 6e série*, 772, 3-23.

Jullien, S., Masson, S., Oerder, V., Samson, G., Colas, F., and Renault, L. (2020). Impact of ocean-atmosphere current feedback on ocean mesoscale activity: Regional variations and sensitivity to model resolution. *Journal of Climate*, 33(7), 2585-2602, https://doi.org/10.1175/JCLI-D-19-0484.1

Jung, T., and Vitart, F. (2006). Short-Range and Medium-Range Weather Forecasting in the Extratropics during Wintertime with and without an Interactive Ocean. *Monthly Weather Review,* 134(7), 1972-1986, https://doi.org/10.1175/MWR3206.1

Kim, H. M., Webster, P. J., and Curry, J. A. (2012). Seasonal prediction skill of ECMWF System 4 and NCEP CFSv2 retrospective forecast for the Northern Hemisphere Winter. *Climate Dynamics*, 39(12), 2957-2973, https://doi.org/10.1007/s00382-012-1364-6

Kohout, A., Williams, M.J.M., Dean, S.M., Meylan, M.H. (2014). Storm-induced sea-ice breakup and the implications for ice extent. *Nature*, 509(7502), 604-607, https://doi.org/10.1038/nature13262

Kolstad, E. (2015). Extreme small-scale wind episodes over the Barents Sea: When, where and why? *Climate Dynamics*, 1-14, https://doi.org/10.1007/s00382-014-2462-4

Kumar, N., Voulgaris, G., Warner, J.C., Olabarrieta, M. (2012). Implementation of the vortex force formalism in the coupled ocean-atmosphere-wave-sediment transport (COAWST) modeling system for inner shelf and surf zone applications. *Ocean Modelling*, 47, 65-95, https://doi.org/10.1016/j.ocemod.2012.01.003

Laloyaux, P., de Boisseson, E., Balmaseda, M., Bidlot, J. R., Broennimann, S., Buizza, R., Dalhgren, P., Dee, D., Haimberger, L., Hersbach, H., Kosaka, Y., Martin, M., Poli, P., Rayner, N., Rustemeier, E., Schepers, D. (2018). CERA-20C: A Coupled Reanalysis of the Twentieth Century. *Journal of Advances in Modeling Earth Systems*, 10(5), 1172-1195. https://doi.org/10.1029/2018MS001273

Large, W. G., and Yeager, S. G. (2009). The global climatology of an interannually varying air - Sea flux data set. *Climate Dynamics*, 33(2-3), 341-364, https://doi.org/10.1007/s00382-008-0441-3

Lee, C., Hwang, S., Do, K., and Son, S. (2019). Increasing flood risk due to river runoff in the estuarine area during a storm landfall. *Estuarine, Coastal and Shelf Science*, 221, 104-118, https://doi.org/10.1016/j.ecss.2019.03.021

Lemarié, F., Samson, G., Redelsperger, J.-L., Giordani, H., Brivoal, T., and Madec, G. (2021). A simplified atmospheric boundary layer model for an improved representation of air-sea interactions in eddying oceanic models: implementation and first evaluation in NEMO(4.0). *Geoscientific Model Development*, 14, 543-572, https://doi.org/10.5194/gmd-14-543-2021

Lemieux, J.-F., Dupont, F., Blain, P., Roy, F., Smith, G. C., and Flato, G. M. (2016). Improving the simulation of landfast ice by combining tensile strength and a parameterization for grounded ridges. *Journal of Geophysical Research: Oceans*, 121, 7354-7368, https://doi.org/10.1002/2016JC012006

Lewis, H., Mittermaier, M., Mylne, K., Norman, K., Scaife, A., Neal, R., ... Pilling, C. (2015). From months to minutes - exploring the value of high-resolution rainfall observation and prediction during the UK winter storms of 2013/2014. *Meteorological Applications*, 22(1), 90-104, https://doi.org/10.1002/met.1493

Lewis, H. W., Castillo Sanchez, J. M., Siddorn, J., King, R. R., Tonani, M., Saulter, A., Sykes, P., Pequignet, A.C., Weedon, G.P., Palmer, T., Staneva, J., Bricheno, L. (2018). Can wave coupling improve operational regional ocean forecasts for the North-West European Shelf? *Ocean Science*, 15, 669-690, https://doi.org/10.5194/os-15-669-2019

Lewis, H. W., Castillo Sanchez, J. M., Arnold, A., Fallmann, J., Saulter, A., Graham, J., Bush, M., Siddorn, J., Tamzin, P., Adrian, L., Edwards, J., Bricheno, L., Martinez-de la Torre, A., Clark, J. (2019). The UKC3 regional coupled environmental prediction system. *Geoscientific Model Development*, 12(6), 2357-2400, https://doi.org/10.5194/gmd-12-2357-2019

Li, Q., Webb, A., Fox-Kemper, B., Craig, A., Danabasoglu, G., Large, W.G., Vertenstein, M. (2016). Langmuir mixing effects on global climate: WAVEWATCH III in CESM. *Ocean Modeling*, 103, 145-160, https://doi.org/10.1016/j.ocemod.2015.07.020

Li, Q., and Fox-Kemper, B. (2017). Assessing the Effects of Langmuir Turbulence on the Entrainment Buoyancy Flux in the Ocean Surface Boundary Layer. *Journal of Physical Oceanography*, 47(12), 2863-2886, https://doi.org/10.1175/JPO-D-17-0085.1

Li, Q., Fox-Kemper, B., Breivik, O., Webb, A. (2017). Statistical Models of Global Langmuir Mixing. *Ocean Modelling*, 113, 95-114, https://doi.org/10.1016/j.ocemod.2017.03.016

Lorenz, E.N. (1963). Deterministic nonperiodic flow. *Journal of the Atmospheric Sciences*, 20, 130-141

Lorenz, E.N. (1967). The nature and theory of the general circulation of the atmosphere. *World Meteorological Organization*, 218. Available at; https://library.wmo.int/doc_num.php?explnum_id=10889

Mahoney, A. R., Eicken, H., Gaylord, A.G., and Gens, R. (2014). Landfast sea ice extent in the Chukchi and Beaufort Seas: The annual cycle and decadal variability. *Cold Regions Science and Technology*, 103, 41-56, https://doi.org/10.1016/j.coldregions.2014.03.003

Maykut, G. A. (1978). Energy exchange over young sea ice in the central Arctic. *Journal of Geophysical Research: Oceans*, 83(C7), 3646-3658, https://doi.org/10.1029/JC083iC07p03646

McWilliams, J.C., Sullivan, P.P., and Moeng, C.-H. (1997). Langmuir turbulence in the ocean. *Journal of Fluid Mechanics*, 334, 1-30, https://doi.org/10.1017/S0022112096004375

Minobe, S., Kuwano-Yoshida, A., Komori, N., Xie, S. P., and Small, R. J. (2008). Influence of the Gulf Stream on the troposphere. *Nature*, 452(7184), 206-209, https://doi.org/10.1038/nature06690

Mogensen, K. S., Magnusson, L., Bidlot, J-R. (2017). Tropical cyclone sensitivity to ocean coupling in the ECMWF coupled model. *Journal of Geophysical Research: Oceans*, 122(5), 4392-4412, https://doi.org/10.1002/2017JC012753

Moin, P. and Mahesh, K. (1998). Direct numerical simulation: A Tool in Turbulence Research. Annual Review of Fluid Mechanics, 30(1), 539-578, https://doi.org/10.1146/annurev.fluid.30.1.539

Naughten, K. A., Meissner, K. J., Galton-Fenzi, B. K., England, M. H., Timmermann, R., Hellmer, H. H., Hattermann, T., and Debernard, J. B. (2018). Intercomparison of Antarctic ice-shelf, ocean, and sea-ice interactions simulated by MetROMS-iceshelf and FESOM 1.4. *Geoscientific Model Development*, 11(4), 1257-1292, https://doi.org/10.5194/GMD-11-1257-2018

Neetu, S., Lengaigne, M., Vialard, J., Samson, G., Masson, S., Krishnamohan, K. S., and Suresh, I. (2019). Pre-monsoon/Postmonsoon Bay of Bengal Tropical Cyclones Intensity: Role of Air-Sea Coupling and Large-Scale Background State. *Geophysical Research Letters*, 2019, 46(4), 2149-2157.

Oerder, V., Colas, F., Echevin, V., Masson, S., and Lemarié, F. (2018). Impacts of the Mesoscale Ocean-Atmosphere Coupling on the Peru-Chile Ocean Dynamics: The Current-Induced Wind Stress Modulation. *Journal of Geophysical Research: Oceans*, 123(2), 812-833, https://doi.org/10.1002/2017JC013294

Osadchiev, A. A., Pisareva, M. N., Spivak, E. A., Shchuka, S. A., and Semiletov, I. P. (2020). Freshwater transport between the Kara, Laptev, and East-Siberian seas. Scientific Reports, 10(1), 1-14, https://doi.org/10.1038/s41598-020-70096-w

Pellerin, P., Ritchie, H., Saucier, F. J., Roy, F., Desjardins, S., Valin, M., and Lee, V. (2004). Impact of a two-way coupling between an atmospheric and an ocean-ice model over the Gulf of St. Lawrence. *Monthly*

Weather Review, 132, 1379-1398, https://doi.org/10.1175/1520-0493(2004)132<1379:IOATCB>2.0.CO;2

Penland, C., and Matrosova, L. (1998). Prediction of tropical Atlantic sea surface temperatures using Linear Inverse Modeling. *Journal of Climate*, 11, 483-496, https://doi.org/10.1175/1520-0442(1998)011<0483:POTASS>2.0.CO;2

Penland, C., and Sardeshmukh, P. D. (1995). The optimal growth of tropical sea surface temperature anomalies. *Journal of Climate*, 8, 1999-2024.

Rabault, J., Sutherland, G., Gundersen, O., Jensen, A., Marchenko, A., Breivik, O. (2020). An Open Source, Versatile, Affordable Waves in Ice Instrument for Scientific Measurements in the Polar Regions. *Cold Regions Science and Technology*, 170, 11, https://doi.org/10.1016/j.coldregions.2019.102955

Rascle, N., Ardhuin, F., Terray, E. (2006). Drift and mixing under the ocean surface: A coherent one-dimensional description with application to unstratified conditions. *Journal of Geophysical Research*, 111(C3), 16, https://doi.org/10.1029/2005JC003004

Rasmussen, E.A., Turner (2003). Polar lows: mesoscale weather systems in the polar regions, Cambridge University Press.

Renault, L., Molemaker, M. J., Gula, J., Masson, S., and McWilliams, J. C. (2016) Control and Stabilization of the Gulf Stream by Oceanic Current Interaction with the Atmosphere. *Journal of Physical Oceanography*, 46, 3439-3453, https://doi.org/10.1175/JPO-D-16-0115.1

Ridley, J. K., Blockley, E.W., Keen, A.B., Rae, J.G.L., West, A.E., and Schroeder, D. (2018). The sea ice model component of HadGEM3-GC3.1. *Geoscientific Model Development*, 11(2), 713-723, https://doi.org/10.5194/gmd-11-713-2018

Røed, L.P., and Albretsen, J. (2007). The impact of freshwater discharges on the ocean circulation in the Skagerrak/northern North Sea area Part I: Model validation. *Ocean Dynamics*, 57(4-5), 269-285, https://doi.org/10.1007/s10236-007-0122-5

Saha, S., Nadiga, S., Thiaw, C., Wang, J., Zhang, Q., Van den Dool, H.M., Pan, H.-L., Moorthi, S., Behringer, D., Stokes, D., Peña, M., Lord, S., White, G., Ebisuzaki, W., Peng, P., Xie, P. (2006). The NCEP Climate Forecast System. *Journal of Climate*, 19, 3483-3517, https://doi.org/10.1175/JCLI3812.1

Saha, S., Moorthi, S., Pan, H.-L., Wu, X., Wang, J., Nadiga, S., Tripp, P., Kistler, R., Woollen, J., Behringer, D., Liu, H., Stokes, D., Grumbine, R., Gayno, G., Wang, J., Hou, Y.-T., Chuang, H., Juang, H.-M.H., Sela, J., Iredell, M., Treadon, R., Kleist, D., Delst, P.V., Keyser, D., Derber, J., Ek, M., Meng, J., Wei, H., Yang, R., Lord, S., van den Dool, H., Kumar, A., Wang, W., Long, C., Chelliah, M., Xue, Y., Huang, B., Schemm, J.-K., Ebisuzaki, W., Lin, R., Xie, P., Chen, Y., Han, Y., Cucurull, L., Reynolds, R.W., Rutledge, G., Goldberg, M. (2010). The NCEP Climate Forecast System Reanalysis. *Bulletin of the American Meteorological Society*, 91, 1015-1057, https://doi.org/10.1175/2010BAMS3001.1

Saha, S., Moorthi, S., Wu, X., Wang, J., Nadiga, S., Tripp, P., Behringer, D., Hou, Y.-T., Chuang, H., Iredell, M., Ek, M., Meng, J., Yang, R., Peña Mendez, M., van den Dool, H., Zhang, Q., Wang, W., Chen, M., and Becker, E. (2014). The NCEP Climate Forecast System Version 2. *Journal of Climate*, 27, 2185-2208, https://doi.org/10.1175/JCLI-D-12-00823.1

Semedo, A., Suvselj, K., Rutgersson, A., Sterl, A. (2011). A global view on the wind sea and swell climate and variability from ERA-40. *Journal of Climate*, 24(5), 1461-1479, https://doi.org/10.1175/2010JCLI3718.1

Seo, H., Subramanian, A. C., Miller, A. J., and Cavanaugh, N. R. (2014). Coupled impacts of the diurnal cycle of sea surface temperature on the Madden-Julian oscillation. *Journal of Climate*, 27(22), 8422-8443, https://doi.org/10.1175/JCLI-D-14-00141.1

Shelly, A., Xavier, P., Copsey, D., Johns, T., Rodriguez, J.M., Milton, S., and Klingaman, N. (2014). Coupled versus uncoupled hindcast simulations of the Madden-Julian Oscillation in the Year of Tropical Convection. *Geophysical Research Letters*, 41, 5670-5677, https://doi.org/10.1002/2013GL059062

Sluka, T., Penny, S.G., Kalnay, E. and Miyoshi, T. (2016). Assimilating atmospheric observations into the ocean using strongly coupled ensemble data assimilation. *Geophysical Research Letters*, 43(2), 752-759, https://doi.org/10.1002/2015GL067238

Smith, G. C., Bélanger, J. M., Roy, F., Pellerin, P., Ritchie, H., Onu, K., Roch, M., Zadra, A., Surcel Colan, D., Winter, B., Fontecilla, J.S., Deacu, D. (2018). Impact of coupling with an ice-ocean model on global medium-range NWP forecast skill. *Monthly Weather Review*, 146(4), 1157-1180, https://doi.org/10.1175/MWR-D-17-0157.1

Spreen, G., Kwok, R., Menemenlis, D., and Nguyen, A. T. (2017). Sea-ice deformation in a coupled ocean-sea-ice model and in satellite remote sensing data. *The Cryosphere*, 11, 1553-1573, https://doi.org/10.5194/tc-11-1553-2017

Staneva, J., Alari, V., Breivik, O., Bidlot, J.-R., Mogensen, K. (2017). Effects of wave-induced forcing on a circulation model of the North Sea. *Ocean Dynamics*, 67, 81-101, https://doi.org/10.1007/s10236-016-1009-0

Sutherland, G., and Rabault, J. (2016). Observations of wave dispersion and attenuation in landfast ice. *Journal of Geophysical Research: Oceans*, 121(3), 1984-1997, https://doi.org/10.1002/2015JC011446

Takano, K., Mintz, Y., Han, Y.-J. (1973). Numerical simulation of the world ocean circulation. Paper presented at the 2nd Conference on Numerical Prediction. Am. Meteorol. Soc. (1973), Monterey, CA (unpublished).

Uchiyama, Y., McWilliams, J. C., Shchepetkin, A. F. (2010). Wave-current interaction in an oceanic circulation model with a vortex-force formalism: Application to the surf zone. *Ocean Modelling*, 34(1), 16-35, https://doi.org/10.1016/j.ocemod.2010.04.002

Vannitsem, S., and Duan, W. (2020). On the use of near-neutral Backward Lyapunov Vectors to get reliable ensemble forecasts in coupled ocean–atmosphere systems. *Climate Dynamics*, 55, 1125-1139, https://doi.org/10.1007/s00382-020-05313-3

Vinayachandran, P. N., Davidson, F., and Chassignet, E. P. (2020). Toward Joint Assessments, Modern Capabilities, and New Links for Ocean Prediction Systems. *Bulletin of the American Meteorological Society*, 101(4), E485-E487, https://doi.org/10.1175/bams-d-19-0276.1

Wahle, K., Staneva, J., Koch, W., Fenoglio-Marc, L., Ho-Hagemann, H. T. M., and Stanev, E. V. (2017). An atmosphere-wave regional coupled model: Improving predictions of wave heights and surface winds in the southern North Sea. *Ocean Science*, 13(2), 289-301, https://doi.org/10.5194/os-13-289-2017

Wang, K., and Wang, C. (2009). Modeling linear kinematic features in pack ice. *Journal of Geophysical Research: Oceans,* 114(C12), https://doi.org/10.1029/2008JC005217

Williams, T.D., Bennetts, L.G., Squire, V.A., Dumont, D., Bertino, L. (2013). Wave-ice interactions in the marginal ice zone. Part 1: Theoretical foundations. *Ocean Modelling*, 71, 81-91, https://doi.org/10.1016/j.ocemod.2013.05.010

Wolf, J. (2008). Coupled wave and surge modelling and implications for coastal flooding. *Advances in Geosciences*, 17, 19-22, https://doi.org/10.5194/adgeo-17-19-2008

Wu, L., Rutgersson, A., Breivik, O. (2019). Ocean-wave-atmosphere interaction processes in a fully coupled modelling system. *Journal of Advances in Modeling Earth Systems*, 11, 3852-3874, https://doi.org/10.1029/2019MS001761

Wu, L., Staneva, J., Breivik, Ø., Rutgersson, A., Nurser, A. J. G., Clementi, E., and Madec, G. (2019). Wave effects on coastal upwelling and water level. *Ocean Modelling*, 101405, https://doi.org/10.1016/J.OCEMOD.2019.101405

Zhang, S., Harrison, M. J., Rosati, A., and Wittenberg, A. T. (2007). System Design and Evaluation of Coupled Ensemble Data Assimilation for Global Oceanic Climate Studies. *Monthly Weather Review*, 135(10), https://doi.org/10.1175/MWR3466.1