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Progress and challenges in short- to medium-range coupled prediction

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The availability of GODAE Oceanview-type ocean forecast systems provides the opportunity to develop high-resolution, short- to medium-range coupled prediction systems. Several groups have undertaken the first experiments based on relatively unsophisticated approaches. Progress is being driven at the institutional level targeting a range of applications that represent their respective national interests with clear overlaps and opportunities for information exchange and collaboration. The applications include forecasting of the general circulation, hurricanes, extra-tropical storms, high-latitude weather and coastal air–sea interaction. In some cases, research has moved beyond case and sensitivity studies to controlled experiments to obtain statistically significant metrics and operational predictions.

Introduction

The Global Ocean Data Assimilation Experiment (GODAE) (Bell et al. 2009) succeeded in demonstrating the feasibility of constraining a mesoscale ocean model to perform routine analyses and forecasts through the assimilation of data from the Global Ocean Observing System (GOOS). Development of ocean forecasting has since been consolidated and extended under GODAE OceanView (GOV) (Bell et al. 2014). There are now several agencies and centres supporting first- or second-generation global and basin-scale pre-operational and operational ocean prediction systems as described in this special issue. These systems provide routine estimates of the ocean state for both nowcasts and short-range forecasts. Their performance has been shown to have sufficient skill in the upper ocean to positively impact a wide range of ocean specific applications (e.g. defence – Jacobs et al. 2009; search and rescue – Davidson et al. 2009, etc.). Unlike waves where there is a very tight relationship between the skill of the winds and the skill of the waves, the ocean's inertia and heat capacity lead to a circulation that has time and space scales that are related more to the time integrated of surface fluxes of mass, heat and momentum than an immediate response to the atmospheric weather. Important exceptions apply, however, for example over the continental shelf and in the turbulent surface layer where the time and space scales are a blend between the atmosphere, waves, sea-ice and ocean systems. These regions also correspond to the highest biological and human activity and the majority of applications for ocean prediction. Therefore, minimizing the errors of the applied stress and buoyancy flux will lead to improved ocean predictions.

The availability of the GOOS and of GOV-type and seasonal forecast systems provides the opportunity to include high-resolution ocean components in short- to medium-range prediction systems for the coupled earth system. Making progress in this field is a significant challenge owing to the complexities of coupled frameworks, coupled modelling and coupled initialization and their observational requirements (including experimental campaigns), and the consequent need for more diverse teams of scientific experts. There have been several vision papers (Brassington 2009; Brunet et al. 2010) and workshops relevant to this area (Proceedings of the ECMWF Workshop on Atmosphere–Ocean Interaction, 10–12 Nov 2008; Proceeding of the Ocean Atmosphere Workshop, UK Met Office, 1–2 Dec 2009). The GOV SMRCP Task Team (TT) was set up in 2009 to coordinate an information exchange for the new developments beginning at some centres in the area of coupled prediction in the medium range. The scope and objectives of the TT were defined to focus on issues of direct relevance to GOV activities and expertise while recognizing that the area of coupled prediction requires inputs from a number of other disciplines coordinated by other

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international bodies. The scope of the TT was therefore defined as covering: SMRCP of the ocean, marine boundary layer, surface waves and sea-ice; on global and regional scales; to pursue the development of coupled prediction systems to improve the state estimation and forecast skill; with specific coupling focii: ocean–wave–atmosphere and ocean–sea–ice–atmosphere. A key achievement of this group was initiating a linkage with the Working Group for Numerical Experimentation and to convene a Joint GOV-WGNE workshop in March 2013 (Joint GODAE Ocean-View/WGNE workshop on short- to medium-range coupled prediction for the atmosphere–wave–sea–ice–ocean: status, needs and challenges, 19–21 March 2013).

Land-surface modelling for atmospheric forecasting has a longer history (Ek et al. 2003; Pitman 2003; De Rosnay et al. 2014) than atmosphere–ocean forecasting, predating the development of earth-modelling frameworks, and is beyond the scope of this paper.

Earth-system modelling has evolved through specialist communities for each of the major components. The requirement to develop coupled earth-system models, primarily for climate applications, has seen the development of computational frameworks to permit component models to be coupled through the synchronous and efficient exchange in fluxes for high-performance computational environments. The US government agencies have adopted the Earth System Modeling Framework (ESMF; http://www.earthsystemmodeling.org) as the basic architecture for coupling models. ESMF allows for the passing of variables among the models in memory and organizes horizontal interpolation between the fields in the different model components via an exchange grid. Building on ESMF, the National Unified Operational Prediction Capability (NUOPC; http://www.weather.gov/nuopc) standardizes ESMF interfaces further to promote plug compatibility of models in couplers and passes information through separate flux computation modules. Similar efforts have been undertaken within Europe such as the Ocean Atmosphere Sea Ice Soil coupler version 4 (OASIS4) (Redler et al. 2010). Achieving all of the requirements for earth-system frameworks such as platform independence, interoperability and scalability has been elusive, but major progress has been achieved in the past decade of development. The availability of these frameworks has aided and accelerated research and development for SMRCP.

This paper summarizes some of the progress being made to develop coupled prediction systems relevant to SMRCP. The section 'Institutional programmes' provides brief descriptions of the system configurations being developed by each institution and their motivations. The section 'Selected examples of demonstrated impacts' organizes the advances being made relative to the target application. This serves to show the breadth of applications already published and the depth in terms of the number of institutions pursuing common applications. A brief overview of some of the known challenges is provided, and the paper concludes with a discussion on the future outlook for this field.

Institutional programmes

Coupling of the ocean, atmosphere and sea-ice has been developed over a number of years for seasonal and longer-range prediction, but the development of SMRCP forecasts is a relatively new area. During the past 5 years, research programmes have emerged within the leading centres: Bureau of Meteorology, Australia; Met Office, United Kingdom (UK); NOAA/NCEP, United States of America (USA); ECMWF; Naval Research Laboratory, USA; Environment Canada, Canada; Mercator-Océan/Meteo-France, France; and NASA, USA. The present systems being developed to study the impacts of coupling are summarized in Table 1 and outlined below in more detail. The modelling systems range from regional to global and are relatively sophisticated given the availability of earth-system frameworks from the climate community, an example of which is shown in Figure 1. These systems however use relatively unsophisticated approaches to data assimilation (DA) where the background error covariances are uncoupled or weakly coupled, and a variety of approaches are adopted to initialize the coupled model.

Australian Bureau of Meteorology

The Australian Bureau of Meteorology has pursued research into the impact of coupling between the Ocean-MAPS forecast system and operational NWP systems using a regional nested framework referred to as the Coupled Limited Area Model (CLAM). CLAM is based on the UK Met Office Unified Model (UM) version 6.4 (Davies et al. 2005), the Ocean Atmosphere Sea Ice Soil coupler version 4 (OASIS4) (Redler et al. 2010) and MOM4p1 (Griffies 2009). The NWP system known as the Australian Community Climate Earth System Simulator (ACCESS), comprises a suite of atmospheric model configurations from global to regional using four-dimensional variational data assimilation (4DVAR), which was developed for the UM (Rawlins et al. 2007). The ocean forecast system is known as the Ocean Model, Analysis and Prediction System (OceanMAPS) (Brassington et al. 2012), which uses an eddy-resolving ocean model and an ensemble optimal interpolation scheme called the Bluelink Ocean Data Assimilation System (BODAS) (Oke et al. 2008).

The CLAM infrastructure has been used both in Tropical Cyclone (TC) forecasting research (Sandery et al. 2010) and in ACCESS-RC [RC stands for the operational regional atmospheric model (ACCESS-R) coupled to a matching nested regional ocean model], an application of CLAM designed to study the impact of coupling on regional ocean and weather prediction. CLAM was recently used to develop an ensemble coupled initialization method

Table 1. Overview of the types of systems being employed to examine the impact of coupled modelling together with the type of target applications.

System	Ocean (Model DA)	Atmos (Model DA)	Wave (Model DA)	Sea-ice (Model DA)	Coupler	Interfacial flux param.	Global/ Regional	Target app(s)
BLUElink	OFAM (MOM4p1) BODAS	ACCESS 4DVAR WRF	High-wind param. roughness, WW3		OASIS4	–	Regional	Tropical Cyclones, Rainfall, East Coast Lows
UK Met Office	NEMO vn3.4, NEMOVAR 3DVar	UM, Hybrid 4DVar	WWIII, no DA	CICE, NEMOVAR 3DVar	OASIS		Global, Local	Global for seamless forecasting: NWP out to seasonal. Local for environmental prediction around UK
NOAA/NCEP	HYCOM, MOM5	NCEP	WW3	CICE, GFDL sea ice	ESMF plus NUOPC	–	Global/ Regional	NWP, Monthly, Seasonal forecast Hurricane prediction
ECWMF	NEMO	IFS	WAM	LIM2	Single Executable	–	Global	NWP, Monthly, Seasonal forecast and climate reanalyses
GOFS COAMPS	HYCOM NCOM NCODA 3DVAR NCOM 4DVAR	NAVGEM COAMPS NAVDAS 4DVAR	WW3 NCODA 2DVAR	CICE NCODA 3DVAR	ESMF plus NUOPC on global scale	(see Figure 1)	Global and Regional	High Impact Weather, Extended Forecasts
CONCEPTS	NEMO	GEM	WW3	CICE	GOSSIP	Coupling by GEM fluxes	Global/regional	Global and regional Canadian NWP, Operational marine support in ice infested waters
Mercator	NEMO. GLORYS ¼° reanalysis. Forecast : Coupled regional 1/12° configuration	ALADIN 10 km Forecast : AROME 2.5 km	NO	NA	OASIS3	ECUME	Regional, Indian Ocean (46–68E/9–22° S)	TCs forecast
GEOS-DAS	iODAS (MOM4p1)	GEOS	–	CICE	ESMF	–	Global	TCs; Reanalysis

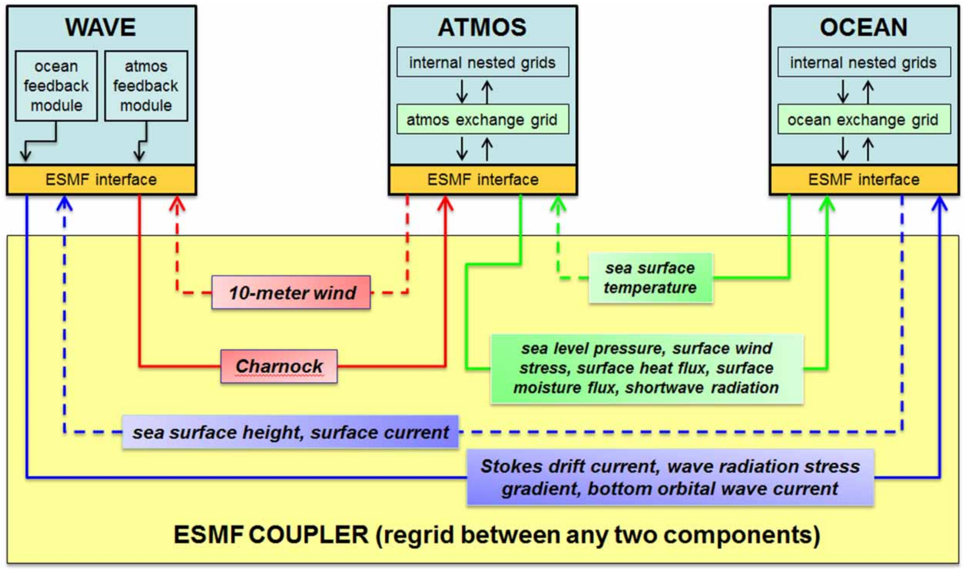

Figure 1. ESMF coupling framework for the COAMPS air/ocean/wave system showing the variables and exchange parameters passed among the coupled models.

using cyclic bred vectors (Sandery & O'Kane 2014). CLAM offered a significant improvement in the forecast of rainfall for the Brisbane flooding event of 2011 (Barras & Sandery 2012). While ACCESS-RC is nested inside data-assimilating component systems, until recently it has not explicitly had its own DA.

A collaborative project between the Bureau of Meteorology and the University of Melbourne funded by the Lloyd's Register Foundation is examining the impact of coupling on the prediction of marine extremes. This research makes use of a multiply nested Weather Research and Forecasting model (WRF) (Skamarock et al. 2005), which resolves convective storm development and ocean surface conditions from OceanMAPS (Brassington et al. 2012) and regional/nested ocean model simulations based on MOM4p1. Initial focus has been on the sensitivity to the mesoscale sea surface temperature (SST) gradients of storm development (Chambers et al. 2014) to justify further research into the coupled response.

Met Office, UK

The development of coupled predictions for short-range forecasting at the UK Met Office is being undertaken through a number of projects, all using versions of the Hadley Centre Global Environment Model version 3 (HadGEM3). HadGEM3 combines the Met Office UM atmosphere and JULES land-surface model (Walters et al. 2011; Brown et al. 2012) coupled using the OASIS coupler to the Nucleus for European Modelling of the Ocean (NEMO) ocean model (Madec 2008) and the CICE sea-ice model (Hunke & Lipscomb 2010). The assessment of the impact of coupled predictions over atmosphere- and ocean-only predictions demonstrated a positive impact on 1–15-day atmosphere forecasts from coupling most notably in the Tropics (Johns et al. 2012). The HadGEM3 model runs operationally on a daily basis to produce seasonal forecasts in the GloSea5 system (MacLachlan et al. 2014). The ocean component of these operational coupled forecasts has been compared with the operational Forecast Ocean Assimilation Model (FOAM) (Blockley et al. 2014) ocean forecasts for the first 7 days of the forecast, and shown to be of comparable accuracy. The ocean fields from these coupled forecasts are now being provided operationally to users through the MyOcean project (www.myocean.eu.org).

The assessment, development and operational running of the coupled forecasts described above have all been carried out using initial conditions generated separately for the atmosphere and land by the Met Office NWP analysis, and for the ocean and sea-ice by the FOAM analysis. A 'weakly' coupled DA system is being developed in parallel with the above work in order to provide improved initial conditions for the coupled forecasts. For this work, and the work described above, the UM is run at 60 km horizontal resolution on 85 vertical levels, NEMO is at 25 km horizontal resolution on 75 vertical model levels, and CICE is run with five thickness categories. The coupled model is corrected using two separate 6-h-window DA systems: a 4DVAR system for the atmosphere assimilating the standard set of atmosphere data (Rawlins et al. 2007) (with associated soil moisture content nudging and snow analysis schemes); and a 3DVAR First Guess at Analysis Time system NEMOVAR (Waters et al. 2014) for the ocean and sea-ice (using *in situ* SST, temperature and salinity profile, satellite SST, satellite altimeter, and sea ice concentration data).

The background information in the DA systems comes from a previous 6-h forecast of the coupled model. Given the short time window, the coupling frequency was increased from the default 3 h to 1 h. This has a particular benefit in improving the model representation of the diurnal cycle.

NOAA/NCEP, USA

Whereas coupled modelling has been part of the operational model suite at NCEP (and in a broader scale within NOAA) for almost a decade, efforts of systematic model coupling have been taking off only in the last few years.

Historically, coupled modelling has been used in TC (hurricane in the US) modelling and in seasonal modelling. In hurricane modelling, the impact of ocean temperature and heat content on intensification has been long recognized, and operational GFDL and HWRF models have included an active ocean component for more than a decade (Bender et al. 1993, 2007; Bender & Ginis 2000; Yablonsky & Ginis 2008, 2009; Tallapragada et al. 2013; Kim et al. 2014). Similar approaches have also been used by the US Navy (Hodur 1997). Experimental coupled hurricane modelling has also focused on the air–sea interactions including explicit modelling of wind waves in a coupled system (Moon et al. 2004, 2007; Chen et al. 2007; Fan et al. 2009). The wave coupling has not (yet) made its way into operations at NCEP, but the results of the coupling experiments have contributed to much improved surface flux parameterizations in the coupled ocean–atmosphere models for hurricanes.

Coupled modelling has also been the staple of reanalysis and seasonal forecasting at NCEP. The most recent reanalysis (Saha et al. 2010) and the presently operational Climate Forecast System (CFS-v2) (Saha et al. 2014) use a coupled atmosphere–ocean–land–ice system, albeit with uncoupled DA for all sub-systems. Land-surface models within atmospheric models have a fairly long history at NCEP for mesoscale models (Ek et al. 2003) and are used in the global and seasonal operational models (Meng et al. 2012; Wei et al. 2013).

Within NOAA, ESMF and the NUOPC layer are used in NOAA's Environmental Modeling System (NEMS). NEMS now incorporates, and is the model driver for, most weather models at NCEP. Ocean, ice and wave models such as HYCOM, MOM5, CICE, GFDL ice model and WAVEWATCH III are now available in NEMS, or will be available in late 2014.

ECMWF, Europe

Development of coupled forecasting systems at ECMWF follows three lines: improvement in the modelling of air–sea interaction processes, use of coupled ocean–wave–sea–ice–atmosphere models in forecasts at all time ranges (medium range, monthly and seasonal), and the development of ocean–atmosphere coupled data-assimilation systems.

Growing ocean waves play a role in the air–sea momentum and heat transfer, while breaking ocean waves affect the upper ocean mixing. Ocean waves also provide an additional force on the mean circulation, the so-called Stokes-Coriolis force. Furthermore, the surface stress felt by the mean circulation is the total surface stress applied by the atmosphere minus the net stress going into the waves. Finally, momentum transfer and the sea state are affected by surface currents. These effects have been introduced in the ECMWF coupled forecasting system, and are currently being assessed. The impact of breaking waves in the upper ocean mixing has been shown to have a large impact on the prediction of SST. Janssen et al. (2013) provide a detailed description on the representation of these effects and illustrate their impact on ocean-only simulation and on coupled forecasts.

Since thermodynamical coupling is thought to be important in the modelling of tropical convection, the coupled ocean–atmosphere–wave model, traditionally used only for the monthly and seasonal forecasts ranges, has also been used in the medium-range weather predictions, since November 2013. Results show that the coupled model provides better forecasts of the tropical atmosphere and improved forecasts of the Madden Julian Oscillation (MJO), and has impacts on the representation of slow-moving TCs (Janssen et al. 2013).

ECMWF has implemented a coupled ocean–wave–atmosphere DA system called CERA (Coupled ECMWF ReAnalysis). This system uses the ECMWF coupled model with an incremental variational approach to assimilate simultaneously ocean and atmospheric observations. The ultimate purpose is to generate better and self-consistent coupled states for atmosphere–ocean reanalysis. The CERA system is based on an incremental variational approach where the ECMWF coupled system is used to compute the misfits with ocean and atmospheric observations in the outer loop. The ocean and the atmosphere share a common 24-h assimilation window but still run separate inner loops. The ocean increment is computed using a 3DVAR method based only on the first misfit computation, while the computation of the atmospheric increment is based on a 4DVAR approach with two outer iterations. An SST nudging scheme has been developed in the ocean model to avoid the rapidly growing bias of the coupled model.

Naval Research Laboratory, USA

The US Navy is actively operating and developing coupled forecasting systems on global and regional scales. For regional scales, the air–ocean version of the Coupled Ocean Atmosphere Mesoscale Prediction System (COAMPS) (Holt et al. 2011) was declared operational in

2011. Air–ocean coupled model runs are routinely performed at the Navy operational production centres. The COAMPS system is being updated to include coupling of a wave model (Allard et al. 2012) and is shown schematically in Figure 1.

A coupled global atmosphere–ocean–ice–wave–land prediction system providing daily predictions out to 10 days and weekly predictions out to 30 days is being developed as a Navy contribution to the Earth System Prediction Capability (ESPC). Initial Operational Capability is targeted for 2018. ESPC is a national partnership among federal agencies and the research community in the US to develop the future capability to meet the grand challenge of environmental predictions in the rapidly changing environment. The system will be based on NUOPC, use analysis fields of each component as initial conditions and make daily forecasts out to 10 days. Throughout each weekly cycle, predictions out to 30 days will be constructed.

DA in coupled COAMPS currently consists of independent 3DVar analyses in the ocean and atmosphere. The first-guess fields (6- or 12-h forecasts) for each fluid are obtained from the coupled model state. This assimilation configuration is referred to as weakly coupled. For the global ESPC coupled model, a hybrid version of the Navy Coupled Ocean Data Assimilation (NCODA) 3DVAR (Cummings & Smedstad 2013) has been developed. The hybrid covariances are a weighted average of the static multivariate correlations already in use and a set of coupled covariances derived from a coupled model ensemble. The coupled model ensemble is created using the Ensemble Transform (ET) technique in both the ocean and atmosphere. One idea being explored is to form a combined ocean/atmospheric innovation vector that is assimilated in independent hybrid 3DVAR-ocean and 4DVAR-atmosphere assimilation systems using ensemble-based coupled covariances. An observation operator has been developed for direct assimilation of satellite SST radiances using radiative transfer modelling (Cummings & Peak 2014). The radiance assimilation operator has been integrated into NCODA 3DVAR.

Environment Canada

The Canadian Operational Network of Coupled Environmental PredicTion Systems (CONCEPTS) including Mercator-Océan participation (France) is providing a framework for research and operations on coupled atmosphere–ice–ocean (AIO) prediction. Operational activity is based on coupling the Canadian atmospheric Global Environmental Multi-scale (GEM) model with the Mercator system based on the NEMO, together with the CICE sea ice model. Within CONCEPTS, two main systems are under development: a short-range regional coupled prediction system and a global coupled prediction system for medium- to long-range applications (Smith et al. 2013).

A fully coupled AIO forecasting system for the Gulf of St. Lawrence (GSL) has been developed (Faucher et al. 2010) and has been running operationally at the Canadian Meteorological Centre (CMC) since June 2011. The original ocean–ice component of this system (Saucier et al. 2003) is currently being replaced by NEMO and CICE. This system is also the basis for the development of an integrated marine Arctic prediction system in support of Canadian METAREA monitoring and warnings. Specifically, a multi-component (atmosphere, land, snow, ice, ocean, wave), regional, high-resolution marine DA and forecast system is being developed for short-term predictions of near-surface atmospheric conditions, sea ice (concentration, pressure, drift, ice edge), freezing spray, waves and ocean conditions (temperature and currents).

More recently, a coupled global AIO system is under development. The first step was the development of the Global Ice–Ocean Prediction System (GIOPS) (Smith et al. 2014). GIOPS is now producing daily 10-day forecasts in real-time at CMC. A 33-km resolution global version of the GEM model has been interactively coupled with GIOPS. The models are coupled via a TCP/IP socket server called GOSSIP and exchange fluxes at every timestep. Fluxes are calculated on the higher-resolution ¼° NEMO grid. Coupled and uncoupled medium-range (16-day) forecasts have been made and evaluated over the summer and winter of 2011. These forecast trials show statistically significant improvements with the coupled model.

Mercator-Océan/Meteo-France

Meteo-France La Réunion is one of the six Tropical Cyclone Regional Specialized Meteorological Centers handled by the World Meteorological Organization. It is responsible for the tracking of TC and issues advisories for the South-West Indian Ocean (SWIO). In order to provide better guidance to TC forecasters, Meteo-France has developed ALADIN-Réunion (Faure et al. 2008), a regional adaptation of ALADIN-France (Fischer et al. 2005). This model has been run operationally since 2006 at 10-km resolution with an assimilation scheme including a bogussing technique designed to accurately reproduce the structure, intensity and positions of TCs in the analyses based on information provided by TC forecasters.

Since 2008, Meteo-France has run a new operational limited-area model AROME-France (Seity et al. 2011) at 2.5-km resolution. This system is designed to improve very short-range forecasts of extreme weather events. The AROME mesoscale DA system takes advantage of mesoscale data such as radar data. Meteo-France is planning to operate an SWIO regional AROME configuration in the near future.

Mercator-Océan develops and operates global and regional ocean analyses and forecast systems based on the NEMO ocean model (Madec 2008). In a close, long-term collaboration with Meteo-France, Mercator-Océan also provides ocean initial states for the seasonal coupled forecast system.

Since 2012, Meteo-France and Mercator-Océan have started a new collaboration to explore the potential benefit of developing an operational coupled version of AROME with a NEMO regional configuration at 1/12°. This technological demonstrator has been developed in 2013 to explore its feasibility and the impact of air–sea coupling on SWIO TC prediction. As the AROME assimilation system is not available yet for the SWIO region, the atmospheric model is initialized from ALADIN-Réunion 10 km analyses, which are generated every 6 h. ALADIN-Réunion is also used as forcing for AROME lateral boundary conditions. NEMO is initialized from the global ¼° reanalysis GLORYS (Ferry et al. 2012). Because of the resolution difference between GLORYS and the NEMO regional configuration, an adjustment period is needed for the model to reach its new equilibrium state. This step is performed using a digital filtering initialization (DFI) procedure during a 3-day integration period. During this period, the ocean model is also forced with a 6-h ALADIN analysis, which allows the ocean surface mixed layer to come into 'equilibrium' with the high-resolution atmospheric forcing. After the spinup phase, the coupled system is then integrated for 96 h with a coupling frequency of 15 min via the OASIS3 coupler (Valcke 2013). The comparison of forced and coupled hindcast ensembles is presented in the next section.

NASA, USA

In the framework of the Goddard Earth Observing System (GEOS) DA System (Rienecker et al. 2011) of the NASA Global Modelling and Assimilation Office, coupling of the atmosphere–ocean assimilation systems with a focus on SST is ready for implementation in GEOS-5 atmospheric DA system (a quasi-operational NWP system). Full coupling with integrated Ocean DAS (iODAS) (Vernieres et al. 2012) is currently being explored. The atmospheric analysis is carried out by Gridpoint Statistical Interpolation (GSI) (Kleist et al. 2009) with the GEOS (Molod et al. 2012) atmospheric model. The iODAS is based on MOM4-(ocean) and CICE (sea-ice) and is coupled to GEOS through the ESMF.

The above system uses an atmosphere–ocean interface layer, based on atmospheric surface fields and fluxes, to model the effects of diurnal warming (Takaya et al. 2010) and cool-skin (Fairall et al. 1996) upon the SST boundary condition. The skin SST thus computed is then used by the atmospheric DAS to directly assimilate (infrared and microwave) radiance observations using the CRTM (http://www.star.nesdis.noaa.gov/smcd/spb/CRTM/) and GSI. Emphasis is on surface temperature sensitive channels of the AVHRR (IR), followed by MW instruments such as TMI-TRMM, AMSR-2 and GMI-GPM. In addition, a plan to assimilate *in situ* observations within the interface layer is being considered. Other experiments are in progress to evaluate the impact of the two-way feedback of interactive aerosols at ¼° resolution configuration. The current and near-future plan is to use a simplified version of CICE to provide sea-ice temperature and WavewatchIII so that wave effects can also be included in the interface layer.

Selected examples of demonstrated impacts

As noted in the Introduction, despite the relatively simple approaches to SMRCP, there are many examples that demonstrate quantifiable benefits. At this early stage of research and development, it is important to highlight for which applications these benefits are being realized to identify leading centres, encourage other institutions to undertake similar research and encourage collaboration between centres for common applications. Importantly, the examples described have been provided by groups participating in the GOV TT-SMRCP and identified through the Joint GOV-WGNE workshop and do not represent an exhaustive review of all current work.

Global atmosphere–ocean forecasts

An example of the impact of atmosphere–ocean coupling on the ocean forecast skill out to 15 days ahead from the UK Met Office system is shown in Figure 2 for the Tropical Pacific region, the area with the largest positive impact. The coupling clearly benefits ocean forecast skill compared with running the same ocean model in forced mode from the same initial conditions, with lower RMS and mean errors throughout the 15-day forecasts [this is based on submitted/unpublished research from experiments detailed in Johns et al. (2012), Daniel Lea, personal communication, 5 November 2014].

To assess the benefit of its weakly coupled DA, the Met Office has also carried out a set of 1-month experiments including (1) a full atmosphere/land/ocean/sea-ice coupled DA run, (2) an atmosphere-only run forced by OSTIA (Donlon et al. 2012) SSTs and sea-ice with atmosphere and land DA, and (3) an ocean-only run forced by atmospheric fields from run 2 with ocean and sea-ice DA. In addition, 5-day coupled forecast runs, started twice a day, have been produced from initial conditions generated either run 1 or by combining the outputs of runs 2 and 3. Figure 3 shows the monthly average surface air-temperature increments and SST increments from the integrations performed for December 2011. The ocean and atmosphere increments from the coupled runs are slightly smaller in large parts of the globe, suggesting a better balance of the

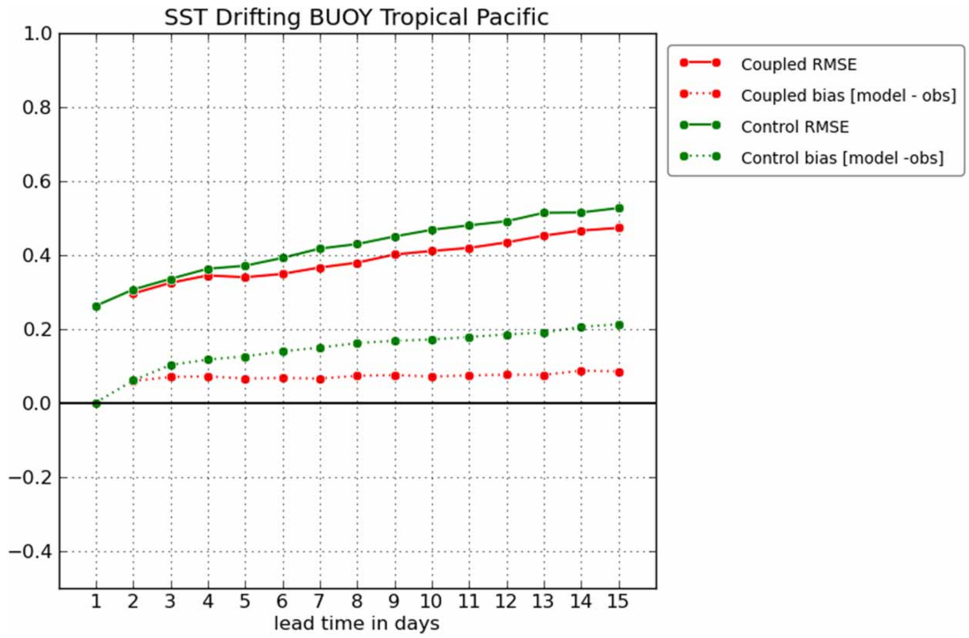

Figure 2. SST (K) observation-minus-forecast RMS (solid) and mean differences (dotted) for a set of coupled HadGEM3 forecasts (red) and ocean-only forecasts (green) in the Tropical Pacific region. The observations used in this assessment are the drifting buoys.

fluxes in these runs. There are some locations where this is not the case, but this may be useful to suggest improvements to coupled DA systems and also to highlight coupled model biases. In particular, improvements to the lake assimilation may be needed. There are also clearly some issues at high latitudes that merit further investigation. Atmospheric forecast assessments (not shown) indicate the coupled DA system to be producing improved forecast skill in some variables and regions near the surface such as temperature and relative humidity in the tropics. Ocean-forecast skill is similar in coupled runs starting from both coupled and uncoupled analyses at least for the first 5 days. The impact on longer lead-time forecasts and forecasts of diurnal variations will be investigated in the future.

The ECMWF CERA system produces coupled 10-day forecasts that have been compared with ones produced by an atmospheric operational-like system using the ECMWF atmospheric model at the same resolution (T159L91) as the CERA system. The operational-like system is forced by observed SST during the assimilation, and the corresponding atmospheric-only 10-day forecasts are forced by persistent SST anomalies. Figure 4 shows the root mean square error (RMSE) of the SST from the 10-day forecasts in the Tropics for September 2010 with respect to the OSTIA SST analysis. The CERA system provides an initial SST state that is farther from the reference than the operational-like system. However, as the RMSE in the operational-like system increases more rapidly, the CERA system shows better forecast skill for SST by day 4 of the forecast.

Experiments undertaken by NRL have been performed where the local ET analysis perturbation scheme is adapted to generate perturbations to both atmospheric variables and SST. The adapted local ET scheme is used in conjunction with a prognostic model of SST diurnal variation and the Navy Operational Global Atmospheric Prediction System global spectral model to generate a medium-range forecast ensemble. When compared with a control ensemble, the new forecast ensemble with SST variation exhibits notable differences in various physical properties including the spatial patterns of surface fluxes, outgoing long-wave radiation, cloud radiative forcing, near-surface air temperature and wind speed, and 24-h accumulated precipitation. The structure of the daily cycle of precipitation also is substantially changed, generally exhibiting a more realistic midday peak of precipitation. Diagnostics of ensemble performance indicate that the inclusion of SST variation is very favourable to forecasts in the Tropics. The forecast ensemble with SST variation outscores the control ensemble in the Tropics across a broad set of metrics and variables. The SST variation has much less impact in the mid-latitudes. Further comparison shows that SST diurnal variation and the SST analysis perturbations are each individually beneficial to the forecast from an overall standpoint. The SST analysis perturbations have a broader benefit in the tropics than the SST diurnal variation, and inclusion of the SST analysis perturbations together with the SST diurnal variation is essential to realize the greatest gains in forecast performance (McLay et al. 2012).

The Environment Canada global coupled model based on GIOPS (Smith et al. 2014) shows robust performance

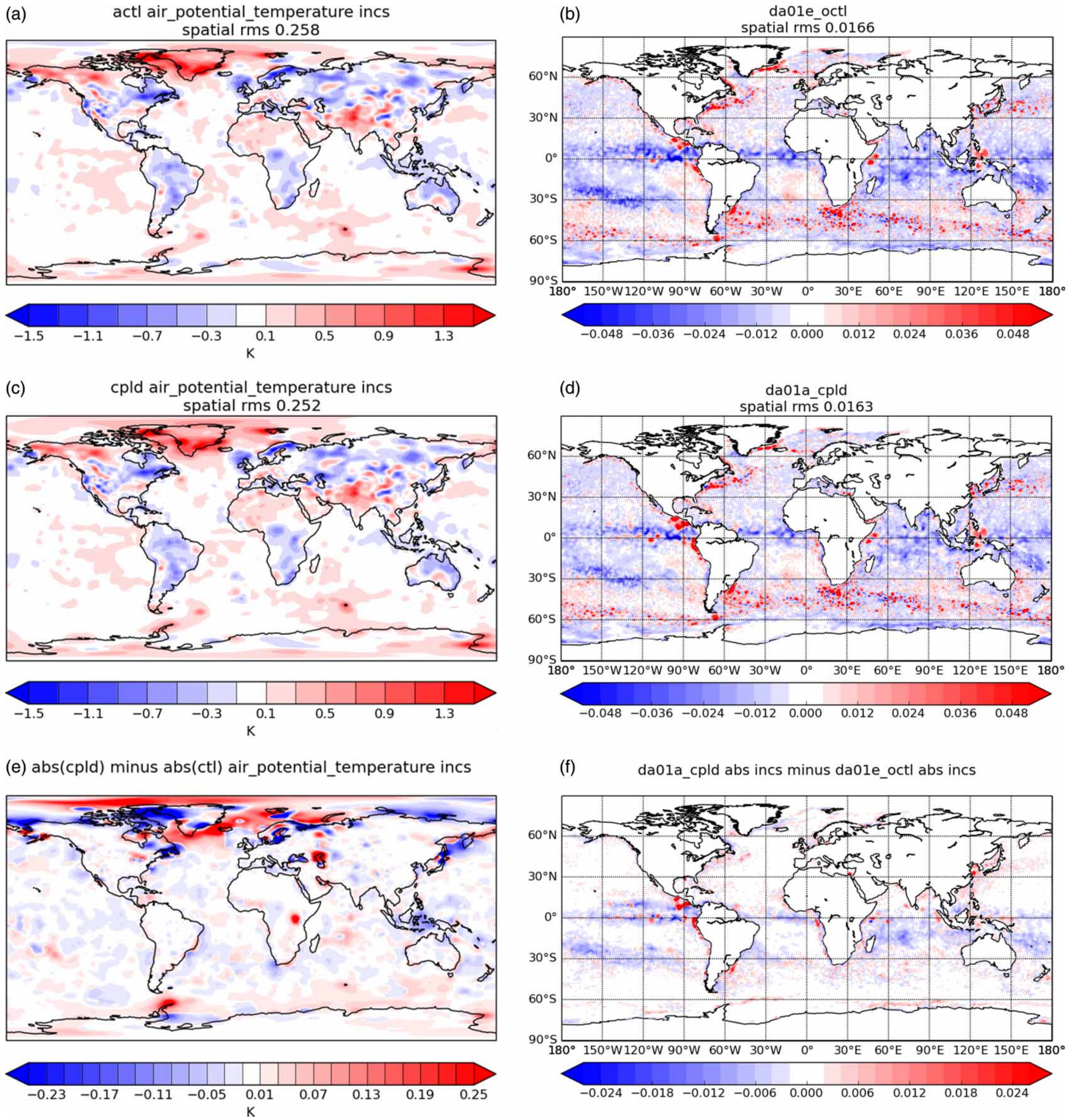

Figure 3. Monthly average assimilation increments for December 2011 for surface-air temperature (left column) and SST (right column) for the uncoupled systems (top row) and the Met Office weakly coupled system (middle row). The difference in absolute increments between the coupled and uncoupled is in the bottom row. Negative numbers indicate that the coupled system has smaller absolute mean increments.

in the tropical atmosphere compared with both tropical moored buoys and analyses produced by the European Centre for Medium Range Weather Forecasts. Figure 5 shows an example of impacts (Cummings & Peak 2014). Evaluation against CMC ice analyses in the northern hemisphere marginal ice zone shows the strong impact that a changing ice cover can have on coupled forecasts. In particular, the coupled system is very sensitive to the ice lead fraction in pack ice and the formation of coastal polynyas. As the ice model does not explicitly model land-fast ice, there is a tendency to overpredict the opening of the ice cover along coastal regions, which has a strong impact on

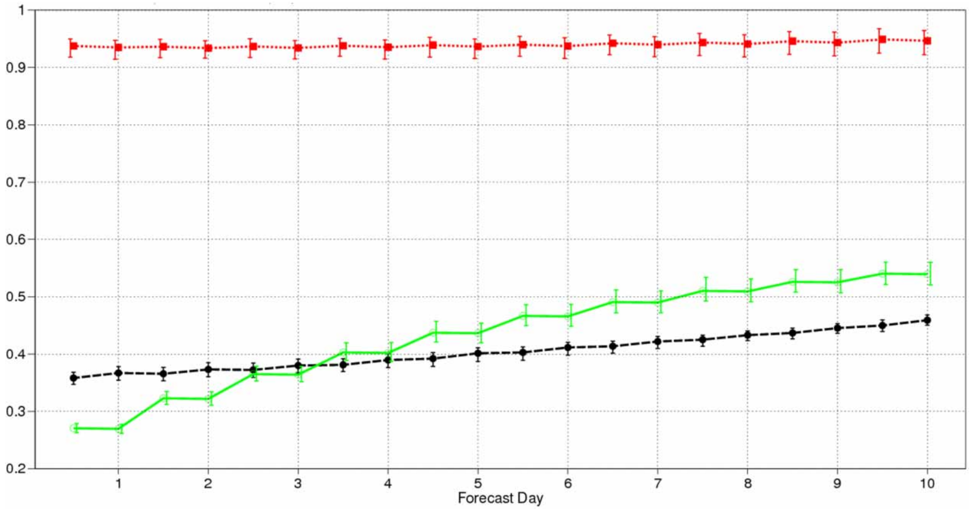

Figure 4. RMSE of the SST forecast in the Tropics from the CERA system (black) and from the operational-like system (green) for September 2010. The OSTIA SST analysis is used as a reference. The red curve is the RMSE of the SST climatology used to create the SST anomalies persisted in the forecasts from the operational-like system.

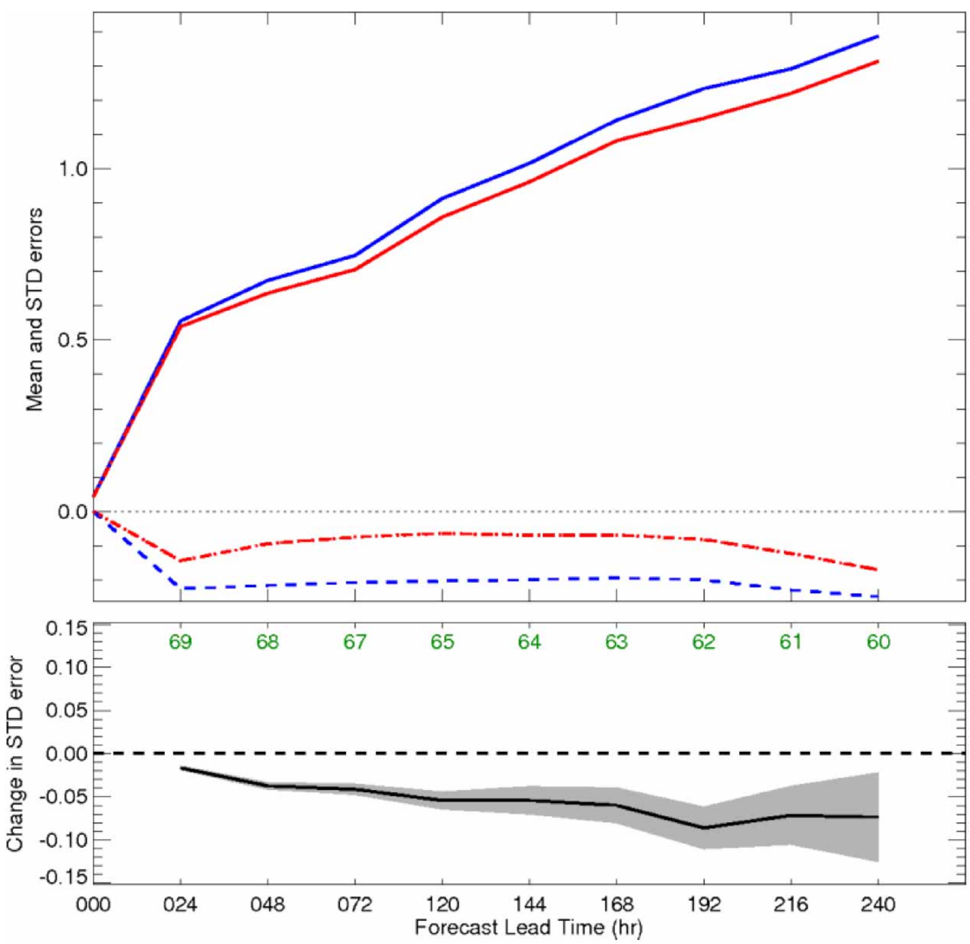

Figure 5. Evaluation of global coupled forecasts over the tropical Indian Ocean from CMC over the winter 2011 period. The mean (dashed) and standard deviation (solid) differences between the 925 hPa temperature forecasts and ECMWF analyses are shown for uncoupled (blue) and coupled forecasts (red). The bottom panel indicates the statistical significance of the standard deviation.

heat and moisture fluxes to the atmosphere. This sensitivity is under further investigation.

Madden Julian Oscillation

The impact of the representation of the SST on monthly forecasts of the MJO has been explored at ECMWF by using the monthly forecasting system to conduct sets of monthly hindcasts in which the SSTs have been modified in a controlled manner. The impact of the temporal and spatial resolution of SST analyses has been assessed, as well as the impact of coupling with an active ocean. It is found that while the temporal resolution of the SST matters, the temporal coherence between the ocean and atmosphere seems to be more important for the simulation of tropical convection and propagation of the MJO. By increasing the temporal resolution of the SST analyses from weekly to daily, the hindcasts of the MJO do not improve, probably because in this experimental setting, the high frequency is uncorrelated between ocean and atmosphere. However, MJO hindcasts are improved by coupling to an ocean model instead of using an uncoupled atmosphere model forced by observed SST. In the past, it had been shown that ocean–atmosphere coupling produced better MJO hindcasts than prescribing *persistence of SST anomalies* as lower boundary conditions for the atmosphere. However, this was the first time that results were obtained with the ECMWF system in which ocean–atmosphere coupling produced better MJO forecasts than prescribing *observed SST* (de Boisseson et al. 2012). The impact of coupling on medium-range weather forecasts and the MJO has also been explored (Meng et al. 2012) using a more recent model version.

The number of days ahead for which there is useful prediction skill for the MJO was increased from 10–15 days to around 20 days on upgrading from CFSv1 to CFSv2 (Wang et al. 2013). This improvement was mostly realized by having better model physics and more accurate initializations. But it did not eliminate all biases for weaker amplitudes and slower propagation of MJO events as compared with observations. While the weak amplitude could be due to the slower response of the convection to the large-scale dynamical fields, the slow eastward movement is related to lower skill in predicting the propagation across the Maritime Continent, a common problem for several statistical and dynamical models (Seo et al. 2009; Rashid et al. 2010; Matsueda & Endo 2011).

Hurricane/TC prediction

In order to assess the potential benefit of ocean–atmosphere coupling on TC forecasts in the SWIO, Mercator-Océan has developed a coupled regional model based on the Meteo-France operational atmospheric model AROME and the NEMO ocean model. The coupled model performances have been evaluated against AROME forecasts forced with the Meteo-France operational SST analysis over an ensemble of 23 intensifying TC simulations (five different TCs from the 2008–2012 seasons). SST forecast biases are then calculated by comparing the averaged SST within a 150-km radius centred on the TC with the SSMI TMI-AMSRE product (Gentemann et al. 2003). TC forecasts are evaluated against TC best tracks provided by Meteo-France La Réunion. The ensemble averaged SST and minimum pressure errors are presented in Figure 6 as a function of the forecast time for the coupled and forced ensembles.

Concerning SST [Figure 6(a)], an important improvement is achieved with the coupled model when compared with the forced model. Averaged SST forecast bias never exceeds ±0.4°C in the coupled model, while it can reach +1.2°C with the Meteo-France SST analysis. The initial SST error (+0.8°C) is mainly due to the absence of a TC cold wake in the operational SST analysis. The initial oceanic state generated from GLORYS (Ferry et al. 2012) with the DFI procedure is much closer to the observations. In the forced ensemble, the mean SST error slowly increases with the forecast time, while it stays close to zero in the coupled ensemble. Hence, the coupling effectively limits SST error growth during the forecast.

The SST improvements in the coupled ensemble lead to a better TC intensity forecast as shown in Figure 6(b). While both coupled and forced ensembles show good skills in predicting TC intensity during the first 30 h (bias <10 hPa), model behaviour diverges at longer ranges. Coupled forecasts tend to slightly underestimate TC intensity at all forecast times but with bias <10 hPa even at a 96-h range. In forced simulations, intensity error quickly increases with time and reaches up to 35 hPa at a 96-h range, suggesting a systematic overestimation of TC intensity. Consequently, the coupling with NEMO greatly improves AROME TC intensity forecast for ranges greater than 30 h through a more realistic SST representation. However, it is currently not possible with the available set of simulations to clearly distinguish the effect of the SST initial conditions from the SST coupling impact. Supplementary experiments will be carried out to precisely measure the relative importance of these parameters.

These encouraging preliminary results achieved with AROME-NEMO will lead to the development of a real-time operational version to assist TC forecasters in La Reunion. New regional configurations will also be developed for the other French overseas territories where Meteo-France provides weather forecasts (South-West Pacific Ocean New Caledonia and Polynesia, Atlantic Ocean French Guinea and Caribbean). AROME-NEMO will also benefit from the new operational Mercator-Océan global 1/12 degree daily forecasts, which should improve the oceanic initial and boundary conditions.

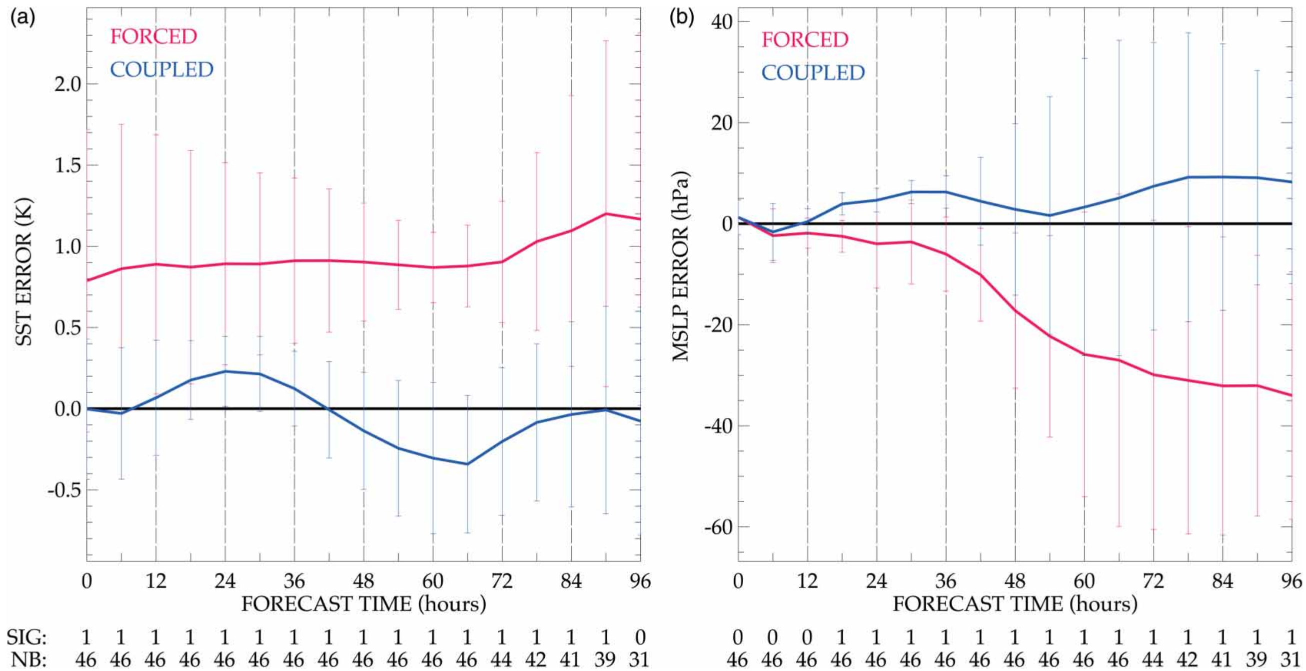

Figure 6. (a) SST ensemble mean error evolution (K) as a function of forecast time. (b) Central Pressure ensemble mean error evolution (hPa) as a function of forecast time. The total number of forecasts and the statistical significance (represented as either 0 when it is not significant or 1 when it is significant) of the difference between the forced and coupled ensembles are given for each forecast time below the figure.

The NOAA-GFDL coupled hurricane prediction system that has been run operationally for many years was designed to account for the effects of upper ocean heat content and the role of the ocean response on TC forecasts. This system has demonstrated significant improvements in TC forecasting skill in the Gulf of Mexico (Bender et al. 2007).

Experiments using a coupled limited area modelling system for tropical cyclones (CLAM-TC) for a number of cases in the Australian region have shown that the representation of the ocean cooling response to the passage of a TC improves in the coupled system both because surface fluxes are more realistically represented with a high-resolution regional atmospheric model compared with a global model and because the negative feedback provided by the ocean response tends to limit overestimates of the storm intensity (Sandery et al. 2010). The ocean component of this system is initialized using the data assimilating OceanMAPS, which provides an improved representation of subsurface heat content. The CLAM-TC system was extended to study coupled initialization, and in turn an ensemble method was developed that provided further improvements in forecasting the ocean response to TC-Yasi for both SST and sea-level anomalies (Sandery & O'Kane 2014). Figure 7 shows the improvement obtained using the coupled ocean–atmosphere ensemble initialization method in the prediction of SST with a 24-h lead-time resulting from the ocean response to TC Yasi in the Coral Sea on 2 February 2012.

Extra-TCs – East Coast Lows

East Coast Lows (ECLs) are subtropical low-pressure weather systems that can intensify rapidly as they propagate over the marine boundary of Australia's east coast producing strong localized convection, lightning and heavy precipitation. Several storms have had severe impacts in terms of coastal flooding, damage from hailstones and, in some cases, the grounding of ships and losses of life. Adjacent to the east coast is the so-called East Australian Current, a western boundary current of the South Pacific subtropical gyre transporting warm/fresh seawater poleward from the Coral Sea to the Tasman Sea. The East Australian Current is frequently unstable, producing several anticyclonic eddies per year from the separation point and along the northern New South Wales coast, which can persist for months (Brassington et al. 2010), providing sources of heat into the Austral winter. A specific case on 7–9 June 2007 that occurred off Newcastle, NSW has been studied using downscaled WRF simulations. A simulation initialized with highly resolved SST (BLUElink) was compared with a second simulation initialized with coarse-resolution (Ctrl) SST boundary conditions to examine the impact of the gradients in SST arising from

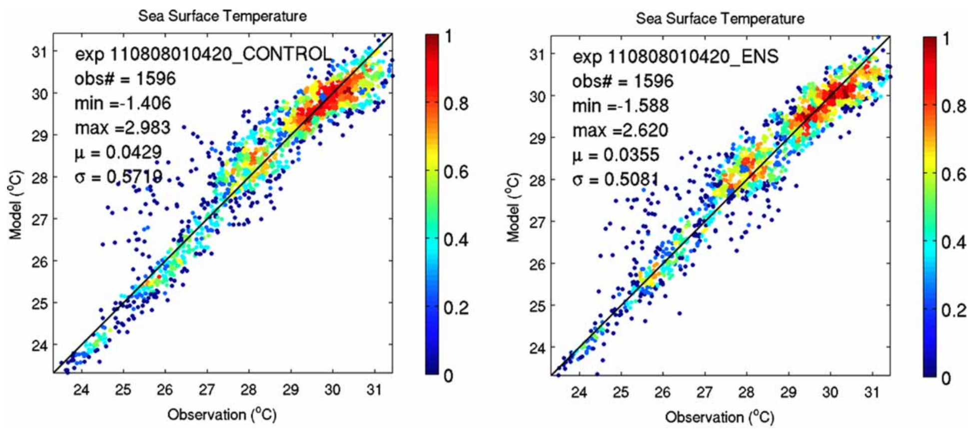

Figure 7. Prediction (24 h) of SST resulting from the ocean response to TC Yasi in the Coral Sea on 2 February 2012 was improved using a coupled ocean–atmosphere ensemble initialization method. The colours represent a normalized 2D histogram.

the large-scale warm ocean eddies that persist into the Austral winter (Chambers et al. 2014). Simulations based on the highly resolved SST produce higher values of 48-h total precipitation downwind of the SST front along ~33S between 153E and 156E (see Figure 8). These simulations result in more localized convection consistent with observations of lightning strikes and improved precipitation distribution and totals along the coast based on rain gauge observations (Chambers et al. 2014). This experiment establishes the sensitivity of ECLs to the resolution of SST boundary conditions. The predictability of ECLs will be pursued further using a coupled prediction system. Coupled forecasting is expected to be important for ECLs as: (a) wind speeds for ECLs can exceed 124 km/h (About East Coast Lows, Australian Bureau of Meteorology, viewed 1 Dec 2014) resulting in significant mixing of the upper ocean and changes to the surface temperature, and (b) the prevalence of cloud and convection during east-coast low events reduces the coverage and quality of SST observations.

High-latitude weather and sea-ice forecasting – Gulf St Lawrence

Sea-ice acts as a barrier between the atmosphere and the ocean, modulating the fluxes of heat and moisture across an interface often with temperature differences of greater than 20°C. As such, rapidly evolving changes in the ice cover can have important impacts for polar weather prediction. This can result from a variety of processes such as ice formation and break-up, coastal polynyas and leads in pack ice. Differences between coupled and uncoupled model forecasts after 12 h from the Canadian Gulf of St. Lawrence coupled forecasting system are shown in Figure 9. This system has shown the strong impacts that a dynamic sea-ice cover (Smith et al. 2012) can have on 48-h atmospheric forecasts leading to large changes in surface air temperature (up to 10°C), low-level cloud cover and precipitation. The top panel is for a winter case (10 March 2012) with sea-ice concentration on the left and 2 m temperature on the right showing that rapid ice changes can cause surface temperature changes of up to 7–8°C over the open water. Owing to the presence of a relatively thin seasonal thermocline (~20 m) with cold (<0°C) winter surface waters below, upwelling events in summer can also lead to important impacts on weather predictions. For example, the bottom panel shows a summer case (10 July 2012) with 10 m winds on the left and 2 m temperature on the right showing that coastal upwelling in the coupled forecasts can produce surface temperature changes of several degrees Celsius locally.

Nearshore coastal weather – Adriatic Sea

A coupled COAMPS (Holt et al. 2011) model was executed in the Adriatic Sea from 25 January to 21 February 2003. The atmospheric model configuration was triply nested (36, 12 and 4 km horizontal resolution), while the ocean model consisted of two nests (6 and 2 km), with the innermost nests of both models centred over the northern Adriatic. Both coupled and uncoupled model runs were performed. In the coupled model run, the winds, wind stresses and heat fluxes were interchanged between the atmosphere and ocean (i.e. the ocean feeds back to the atmosphere and the atmosphere feeds back to the ocean) every 12 min using grid exchange processors based on the ESMF. In the uncoupled run, wind forcing from the atmospheric model was passed to the ocean model, but the ocean *did not* feed back to the atmosphere, i.e. the heat fluxes calculated by the atmospheric model were computed using daily averaged analysis-quality SST rather than the time-dependent ocean model forecast SST used in the coupled run. Coupled and uncoupled statistics are presented for the Acqua Alta platform near Venice,

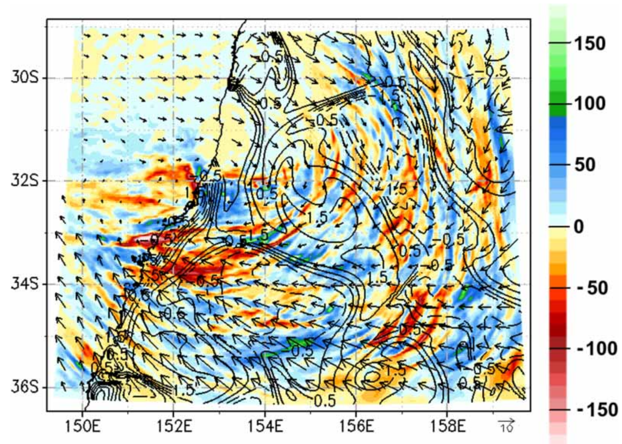

Figure 8. 48 h (0000 UTC 7 June to 0000 UTC 9 June 2007) total rainfall differences (colours, mm) (BLUElink – Ctrl). SST differences (°C) between the simulations overlaid as contours. In addition, the BLUElink simulation average 10 m wind vectors are overlaid as arrows to indicate the surface flow (m s^{-1}, representative vector in bottom right).

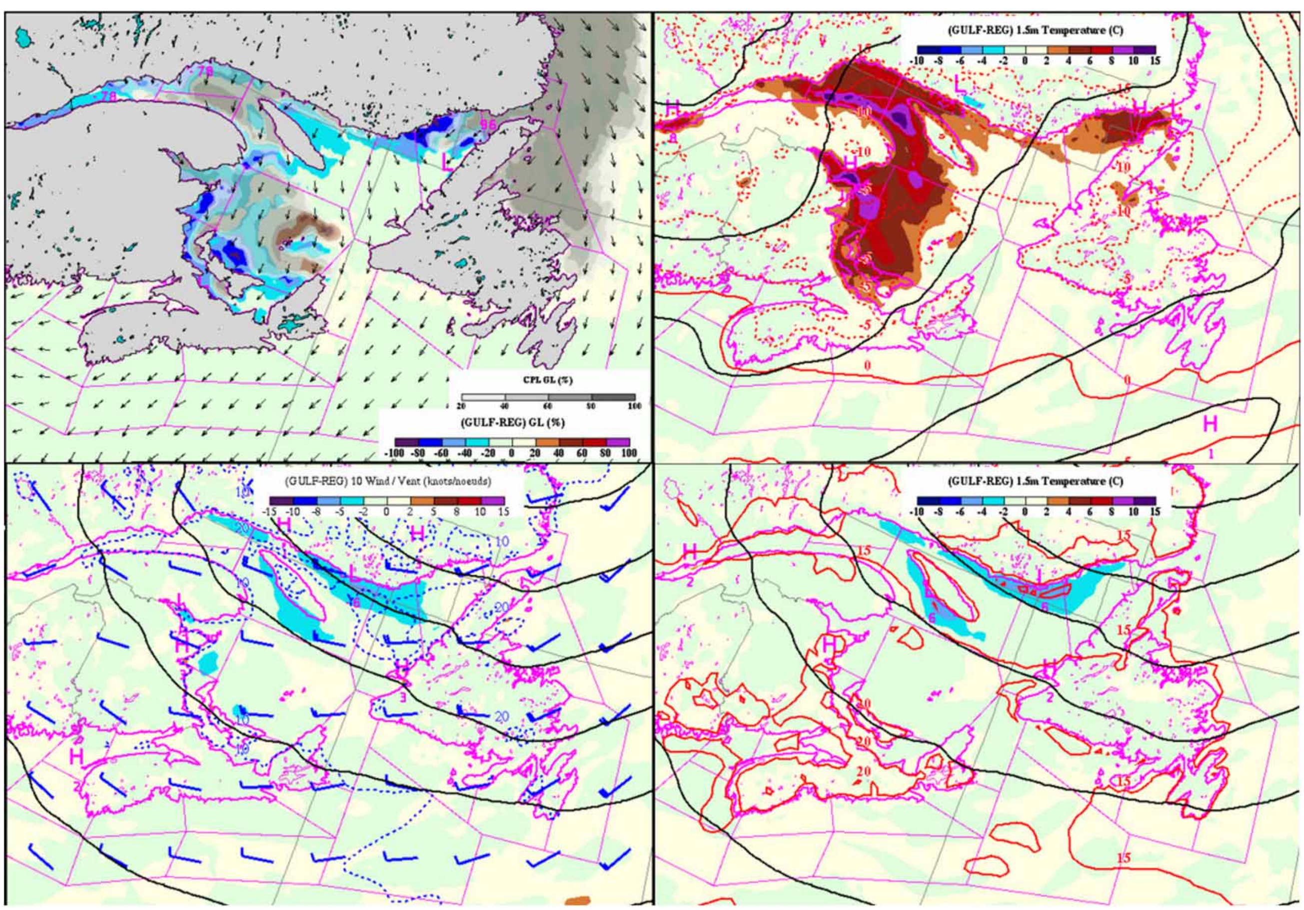

Figure 9. Differences between coupled and uncoupled model forecasts after 12 h in the Canadian Gulf of St. Lawrence forecasting system. The top panel is for a winter case (10 March 2012) with sea-ice concentration on the left and 2 m temperature on the right showing that rapid ice change can cause surface-temperature changes of up to 7–8°C over the open water. The grey colour shows the ice concentration, and the colour scale shows the coupled minus uncoupled model differences in ice concentration. The bottom panel shows a summer case (10 July 2012) with 10 m winds on the left and 2 m temperature on the right showing that coupling induced coastal upwelling can produce surface temperature changes of several degrees Celsius locally.

Italy in Figure 10. Inspection of the wind-stress time series shows good agreement, with the RMSE slightly larger in the coupled run (0.112) versus the uncoupled run (0.108). The overall smaller mean stresses in the COAMPS runs (0.118 coupled, 0.135 uncoupled) compared with the observations (0.151) are attributed to intensity and positional differences of the Trieste bora jet during the time period of the experiment. The sensible and latent heat flux comparisons, however, showed a clear improvement in the coupled model run. These results illustrate how the coupled model can more accurately predict surface heat fluxes in near-shore regions where a complex SST field is subject to intense atmospheric events, and turbulent heat fluxes have high spatial inhomogeneity and large gradients (Holt et al. 2011).

DA of brightness temperature (radiance)

The NASA, coupled GEOS-DAS have explored the DA of brightness temperature using a surface-sensitive (10.35 μm) channel of the AIRS instrument on the AQUA satellite. The comparison of an experiment that had an active interface-layer with a control experiment with no interface layer (the bulk SST boundary condition was used as the skin SST) was used to diagnose the benefit. Preliminary results, at 1° resolution, show improved assimilation of all 10–12 μm IR observations and decreased bias in precipitation with respect to GPCP data. The three panels of Figure 11 show time series of the total number of observations assimilated (top panel), the global mean of observation-minus-background (OmB), middle panel, and the standard deviation of the OmB (bottom panel). The use of an improved skin temperature estimate reduced the number of observations rejected by the analysis quality control and reduced the standard deviation in OmB. Similar results were obtained for other 10–12 μm IR channels of AIRS-AQUA, IASI-METOP-A, HIRS4-METOP-A, N19 (not shown).

The NRL has also developed an observation operator to directly assimilate satellite SST radiances using radiative transfer modelling (Cummings & Peak 2014). The radiance assimilation operator has been integrated into NCODA 3DVAR. The operator takes as input prior estimates of SST from the ocean forecast model and profiles of atmospheric state variables (specific humidity and air temperature) known to affect satellite SST radiances from the NWP model. Observed radiances are simulated using a fast radiative transfer model, and differences between observed and simulated radiances are used to force an SST inverse model. The inverse model outputs the change in SST that takes into account the variable temperature and water vapour content of the atmosphere at the time and location of the satellite radiance measurement. Direct assimilation of satellite SST radiances is an example of coupled DA. An observation in one fluid (atmospheric radiances) creates an innovation in a different fluid (ocean surface temperature). The observed radiance variables depend on both ocean and atmosphere physics. The radiance assimilation operator is ideally suited for coupled ocean/atmosphere forecasting systems where the atmosphere and ocean states have evolved consistently over time.

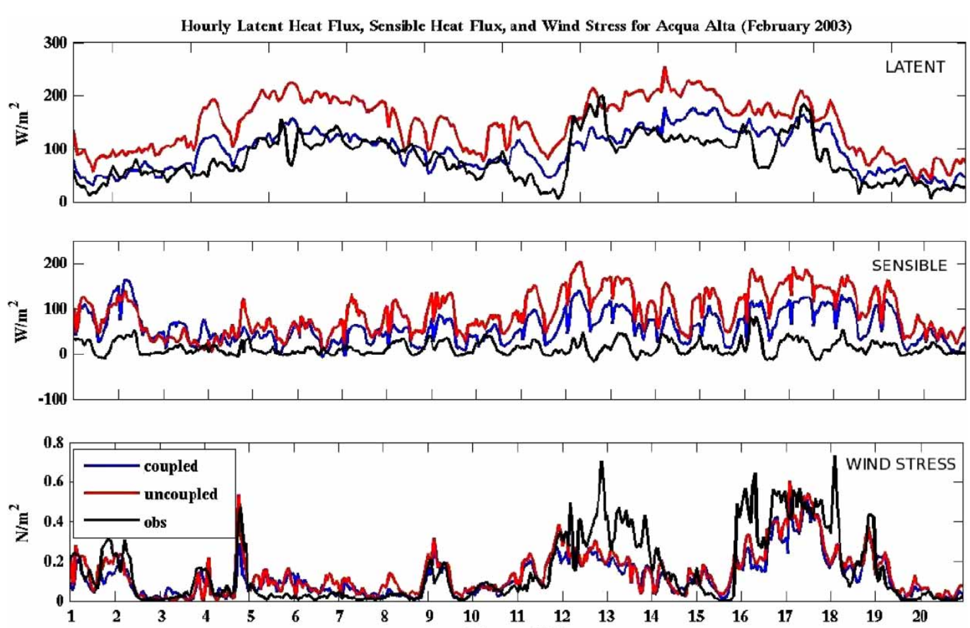

Figure 10. Hourly latent and sensible heat fluxes (W/m^2) and wind stress (N/m^2) for the fully coupled COAMPS run and observations at Acqua Alta (Venice)49. Allard et al. (2010).

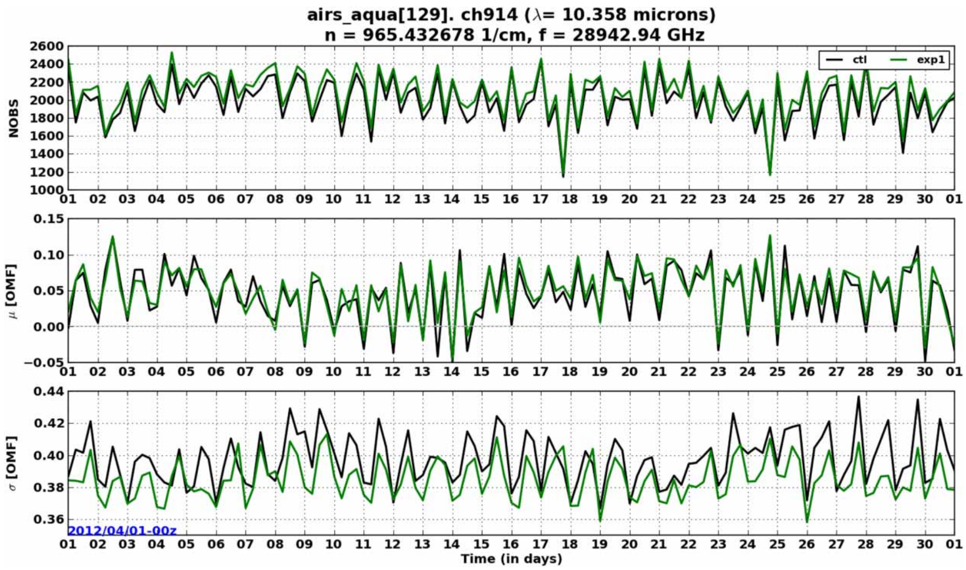

Figure 11. Improved assimilation of brightness temperature from a surface-sensitive (10.35 μm) channel of the AIRS instrument on AQUA satellite in an experiment (exp1 – black lines) that had an active interface-layer compared with a control (ctl – green lines) with no interface layer which used a bulk SST as the skin SST boundary condition. The three panels plot time series of the total number of observations assimilated (top panel), global mean of observation-minus-forecast (OmB), middle panel and standard deviation of the OmB (bottom panel). Notice that the analysis quality control accepts more observations in exp1, with a lower standard deviation in OmB. Similar results are obtained for other 10–12 μm IR channels of AIRS-AQUA, IASI-METOP-A, HIRS4-METOP-A, N19 (not shown).

Known challenges

From the two previous sections, it is clear that many challenges in coupled prediction have already been addressed, and SMRCP is feasible and beneficial for several applications.

Several software frameworks that facilitate the coupling of component model software have been developed for seasonal prediction and climate simulation. In practice, there are several shortcomings in their design for GOV-type forecasting and eventual operational applications that require frequent restarting and data exchanges. The differing time-scales of the atmosphere, ocean, waves and sea-ice impose further challenges for conservative and synchronous interfacial exchange. These challenges are not impeding progress in basic research but are impacting the efficiency of work and the size of the problems being tackled, and the coupling systems will require further optimization before implementation into operational applications.

The pursuit of coupled modelling for hurricane prediction has yielded several advances in air–wave–sea coupled parameterizations for high-wind conditions in the tropics. Significant effort will be required to generalize the coupled parameterizations across all applications. However, less sophisticated parameterizations from existing models are demonstrating positive impacts for a wide range of environments.

The initialization of coupled models is currently based on uncoupled or weakly coupled DA for each component model and an inefficient coupled initialization procedure to produce balanced fields in the coupled model. Some promising results are evident from research focusing on the coupled assimilation of brightness temperatures. Coupled DA is required to provide the optimum dynamical balance between coupled fields, but several challenges need to be faced to realize this goal:

(1) Proper handling of different time-scales in the ocean and atmosphere. These scales may be similar enough in the atmosphere boundary layer and ocean mixed layer to allow coupled modelling and coupled DA to succeed. This aspect of the problem needs to be thoroughly studied.
(2) Reduction in the biases in interfacial fluxes that occur in each component model in their uncoupled form. Residual biases in a coupled model will be distributed throughout the coupled model state requiring more sophisticated analyses to diagnose, attribute and develop bias correction schemes.
(3) Optimization of the weighting of coupled covariances from forecast ensembles, development of methods for coupled initialization and maintenance of coupled model ensemble spread given the disparate temporal and spatial scales of the ocean and atmosphere. It is also unclear how large an ensemble is needed.
(4) Establishment of community benchmarks, test cases, or metrics to assess the beneficial impact of fully coupled analyses.

In the near-surface ocean, the diurnal cycle imposes time-scales of a few hours (Fairall et al. 1996). Modelling of the diurnal warming layer is important for computation of the skin temperature. For coupled DA, it is essential to incorporate observational information *directly* from satellite brightness temperature observations and near-surface buoys so that the modelled skin and near-surface temperature profile is estimated accurately, and thus temporally evolved by the model at the *correct* time-scale. It is also relevant to note the different vertical length-scales observed by the observations: IR observations measure ‘closest’ to the skin or air–sea interface (few microns deep); MW observations penetrate slightly deeper (a few millimetres); and further down to centimetre and metre scales, we have *in situ* measurements, e.g. ships and buoys.

For coupled prediction in polar environments, a significant uncertainty lies in the extent to which we can accurately predict small-scale ice features and the evolution of the ice cover. Coupled forecasts are strongly sensitive to variations in the ice cover in the marginal ice zone, coastal polynya formation and leads in the pack ice. As most sea ice observational data are of fairly low resolution, the evaluation of small-scale features like leads remains a challenge. The use of ever-finer-resolution models demands the development of new sea-ice rheologies suitable for resolving kilometre scale features. Currently, it is not clear how significant these errors are for coupled polar prediction, and further study is required (Smith et al. 2013).

The majority of the applications presented have focused on atmospheric phenomena reflecting the maturity of this community and the extensive range of peer-reviewed benchmarks for uncoupled systems from which the impact of coupling can be assessed more readily. Coupled prediction is expected to also have a significant impact on several ocean applications e.g. sonar prediction, search and rescue and hazardous chemical spills. In addition to the fact that the ocean community is less mature the emphasis on atmospheric impacts also reflects the paucity of observations available to establish benchmarks for the leading parameters for applications such as the sonic layer depth and surface currents.

Future outlook

All groups contributing to this paper have developed research programmes specifically targeting a subset of applications that represent their national interest. In many cases, the research challenges identified are common across these programmes indicating significant benefit from a community-based approach to share advances in coupled science and promote international experiments and observation campaigns. Despite the challenges of achieving skilful forecasts from such complex systems, the results to date using relatively unsophisticated techniques have already yielded positive results. Most groups are optimistic that coupled prediction will yield further improvements with continued research and development.

The medium-term outlook indicates that groups will continue to pursue weakly coupled systems. Continuation of this approach will help to outline the full extent of applications impacted by coupling prediction for short- to medium-range forecasting, the optimum modelling configurations and establish collaborative research. In some instances the impacts have been sufficient for institutions to consider operational implementation of these systems.

Several centres including NRL, ECMWF and UK Met Office have initiated development work toward fully coupled DA based on variational, ensemble and hybrid approaches. This research is essential to quantify the full extent of impacts from coupled prediction systems as well as the other corollary information such as observing system design and observation impact studies. Given the technical challenges of this work, it is likely that the results will begin to emerge on the 3–5-year time frame. Investment to accelerate this work by institutions, stakeholders and funding agencies is encouraged.

Following the initial concept papers (Brassington 2009; Brunet et al. 2010) and early workshops in 2008 (Proceedings of the ECMWF Workshop on Atmosphere–Ocean Interaction, 10–12 Nov 2008) and 2009 (Proceeding of the Ocean Atmosphere Workshop, UK Met Office, 1–2 Dec 2009), research and development in this field has made significant advances in terms of the sophistication of the modelling systems being implemented, as outlined in Table 1, and the rigour of the experiments to quantify impacts and the range of applications. The GOV science team initiated the SMRCP TT to promote the use of coupling based on GOV-type ocean prediction systems and to establish a linkage with the atmospheric community. Outlined in this paper, there are many examples where coupled systems are now being based on GOV-type ocean prediction systems for short- to medium-range forecasting with demonstrated impacts. The next steps for the SMRCP-TT are to continue to develop linkages with WGNE and other communities involved in coupled forecasting to jointly set targets and promote international initiatives to address the known challenges.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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