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

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Synopsis

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. These include general circulation, hurricanes, extra-tropical storms, high-latitude weather and sea-ice forecasting as well as coastal air-sea interaction. In some cases, research has moved beyond case and sensitivity studies to controlled experiments to obtain statistically significant metrics.

Lead author’s biography

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Introduction

The Global Ocean Data Assimilation Experiment (GODAE)[1] (Bell et al., 2010) succeeded in demonstrating the feasibility of constraining a mesoscale ocean model to perform routine analyses and forecasts through the data assimilation of the Global Ocean Observing System (GOOS). Development of ocean forecasting has since been consolidated and extended under the GODAE OceanView (GOV)[2] (Schiller and Dombrowsky, 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. The 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[3], search and rescue[4] etc). Unlike waves where there is a very tight relationship between the skill of the winds and the skill of the waves, the oceans inertia and heat capacity leads to a circulation that has unique time and space scales that is related more to the integrated (time history) of surface fluxes of mass, heat and momentum rather 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, minimising errors in the applied stress and fluxes will have a high yield for the benefit of ocean prediction.

The availability of GOOS and GOV-type forecast systems provides the opportunity to develop high-resolution, short- to medium-range coupled prediction systems (SMRCP) for the earth system. Making progress in this field is a significant challenge due to the added complexity in all areas of development, coupled frameworks, coupled modelling, coupled initialisation, observational requirements (including experimental campaigns) and large and more diverse teams of scientific experts. There have been several vision papers[5,6] (Brassington, 2009; Brunet et al., 2010) and workshops relevant to this area driven predominantly by the needs of Numerical Weather Prediction (NWP) at ECMWF[7] and followed on by the UK Met Office[8]. The GOV science team recognised the need to explore the potential benefit to both oceanic and atmospheric prediction through the use of GOV-type system in coupled prediction research. The Short- to Medium-Range Coupled Prediction Task Team (SMRCP-TT) was set-up at the beginning of GOV in 2009 to coordinate an information exchange for the new developments beginning at some centres in the area of coupled prediction on 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 recognising that the area of coupled prediction requires inputs from a number of other disciplines coordinated by other 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 for improving and extending ocean/wave/sea-ice state estimation and forecast skill; with specific coupling focii: ocean-wave-atmosphere and ocean-sea-ice-atmosphere. A key achievement of this group was to initiate a linkage with the Working Group for Numerical Experimentation and to convene a Joint GOV-WGNE workshop was held March 2013, Washington DC, USA (https://www.godae-oceanview.org/outreach/meetings-workshops/task-team-meetings/coupled-prediction-workshop-gov-wgne-2013/).

Land surface modelling for atmospheric forecasting has a longer history[9,10,11] (de Rasnay et al 2014, Ek et al 2003, Pitman 2003) than atmosphere-ocean forecasting and predates the development of earth modelling frameworks. Land-surface schemes were first introduced as a sub-model and embedded within the atmospheric model software. As land-surface models have increased in sophistication these have matured into stand alone models. This component of the earth system 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, initially for climate applications, has seen the development of computational frameworks to permit component models to be coupled through the synchronous and efficient exchange of 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 organises horizontal interpolation between the fields in the different model components via an exchange grid. On top of ESMF, the National Unified Operational Prediction Capability (NUOPC; http://www.weather.gov/nuopc) standardises ESMF interfaces further to promote plug-compatability of models in couplers and passes information through separate flux computation modules. NUOPC is a consortium of the Navy, NOAA, and Air Force modelers and their research partners. Similar efforts have been undertaken within Europe such as the Ocean Atmosphere Sea Ice Soil coupler version 4 (OASIS4)[12] (Redler *et al.,* 2010). Achieving all of the requirements for earth system frameworks including platform independence, interoperability, scalability and others has been elusive but major progress has been achieved in the past decade of development. Availability of these frameworks has aided and accelerated research and development for SMR applications.

In this paper we summarise some of the progress being made within national/international centres in section 2, identify a selection of applications that demonstrate the impact of coupling in section 3; provide a brief overview of some of the known challenges in section 4 and conclude with a discussion on the future outlook for this area.

Progress by national programs

Coupling of the ocean, atmosphere and sea-ice has been developed over a number of years for seasonal and longer-range prediction, but it has been a relatively new area for the development of SMRCP forecasts. During the past 5 years research programs have emerged within the leading centres: Bureau of Meteorology, Australia; Met Office, United Kingdom (UK); National Oceanic and Atmospheric Administration (NOAA)/National Centers for Environmental Prediction(NCEP), United States of America (USA); European Centre for Medium-range Weather Forecasting (ECMWF); Naval Research Laboratory, USA; Environment Canada, Canada; Mercator-Océan/Météo France, France; and NASA, USA. The present systems being applied to study the impacts of coupling are summarised in Tab **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 Fig **1**. These systems however use relatively unsophisticated approaches to data assimilation where the Background error covariances are uncoupled or weakly coupled and a variety of approaches are adopted to initialise the coupled model.

Bureau of Meteorology, Australia

The Australian Bureau of Meteorology has pursued research into the impact of coupling between the OceanMAPS forecast system and operational NWP systems using a regional nested framework referred to as CLAM (Coupled Limited Area Model). CLAM is based on the UK Met Office Unified Model (UM) version 6.4[13] (Davies *et al.,* 2005), the Ocean Atmosphere Sea Ice Soil coupler version 4 (OASIS4)[12] (Redler *et al.,* 2010) and MOM4p1[14] (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[15] by Rawlins et al. (2007). The ocean forecast system is known as the Ocean Model, Analysis and Prediction System (OceanMAPS; Brassington et al., 2012)[16], 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)[17].

The CLAM infrastructure has been used both in Tropical Cyclone (TC) forecasting research[18] (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 initialisation method using cyclic bred vectors[19] (Sandery and O'Kane, 2014). Results using ACCESS-RC have found that ocean-atmosphere coupling offers improvements in the atmospheric model sea surface temperature (SST) boundary condition in the tropics and in significant to severe weather events at three day lead time compared to persisting an SST analysis initial condition. CLAM offered a significant improvement in the forecast of rainfall for the Brisbane flooding event of 2011[20] (Barras and Sandery, 2012). Whilst ACCESS-RC is nested inside data assimilating component systems, until recently it has not explicitly had its own data assimilation.

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)[21] with resolution to resolve convective storm development and ocean surface conditions from OceanMAPS[16] and regional/nested ocean model simulations based on MOM4p1. Initial focus has been on the sensitivity to the mesoscale SST gradients of storm development[22] 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 Unified Model (UM) atmosphere[23,24] (Walters et al., 2011; Brown et al., 2012) and JULES land surface model coupled using the OASIS coupler to the Nucleus for European Modelling of the Ocean (NEMO)[25] (Madec 2008) and the CICE sea-ice model[26] (Hunke and Lipscombe 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[27]. The HadGEM3 model is running operationally on a daily basis to produce seasonal forecasts in the GloSea5 system[28] (MacLachlan et al. 2014). The ocean component of these operational coupled forecasts have been compared with the operational Forecast Ocean Assimilation Model (FOAM)[29] (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 from the Met Office NWP analysis, ocean and sea-ice from the FOAM analysis. A “weakly” coupled data assimilation (DA) system is being developed in parallel with the above work in order to provide improved initial conditions for the coupled forecasts (see Tab **2**). For this work, and the work described above, the UM is run at 60km horizontal resolution on 85 vertical levels, NEMO is at 25km horizontal resolution on 75 vertical model levels, and CICE is run with 5 thickness categories. The coupled model is corrected using two separate 6-hour window DA systems: a 4DVAR system for the atmosphere assimilating the standard set of atmosphere data[15] (Rawlins et al. 2007) with associated soil moisture content nudging and snow analysis schemes on the one hand, and a 3DVAR First Guess at Analysis Time (FGAT) system NEMOVAR[30] (Waters et al 2013) 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-hour forecast of the coupled model. Given the short time window the coupling frequency was increased from the default 3 hours to 1 hour. This also 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 tropical cyclone (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 recognised, and operational GFDL and HWRF models have included an active ocean component for more than a decade[31,32,33,34,35,36,37] (e.g., Bender et al., 1993, 2007, Bender and Ginis, 2000, Yablonsky and Ginis, 2008, 2009, Tallapragada et al., 2013, Kim et al., 2014). Similar approaches have been used by the US Navy38 (e.g., Hodur, 1997). Experimental coupled hurricane modelling has also focused on the air-sea interactions including explicit modelling of wind waves in a coupled system[39,40,41,42] (e.g., Moon et al., 2004, 2007, Fan et al, 2009, and academia (e.g., Chen et al. 2007). 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 parameterisations 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[43] (Saha et al. 2010) and the presently operational Climate Forecast System (CFS-v2, Saha et al., 2014)[44], represents a coupled atmosphere – ocean – land – ice system, albeit with uncoupled data assimilation efforts for all sub-systems. Land surface models within atmospheric models, has a fairly long history at NCEP for mesoscale models[10] (e.g., Ek et al., 2003), and is in operations in the global and seasonal models[45,46] (e.g., Wei et al., 2012, Meng et al., 2012). Since the underlying land model is a full model that has been used as a standalone model, this is affectively an example of coupled modelling, although historically this modelling has not been labeled as such.

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. This provides NOAA with a set of well-defined building blocks for coupling in general.

ECMWF, Europe

Developments of coupled forecasting systems at ECMWF follow three lines: improvement in the modelling of air-sea interaction processes, use of coupled ocean-wave-seaice-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[47] provide a detailed description on the representation of these effects, and illustrate their impact on ocean-only simulation and on coupled forecasts.

Since the thermodynamical coupling is thought to be important in the modeling of tropical convection the coupled ocean-atmosphere-wave model, traditionally used only for the monthly and seasonal forecasts ranges, is also used in the medium range weather prediction, since November 2013. Results show that the coupled model provides better forecasts of the tropical atmosphere, improved forecasts of the MJO, and has impacts on the representation of slow-moving tropical cyclones[47] (Janssen et al 2013).

ECMWF has implemented a coupled ocean-wave-atmosphere data assimilation 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-hour 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)[48](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[49] (Allard *et al*. 2012). Operational implementation of a regional, air-ocean-wave coupled system is planned for 2015. Fig **1** shows the coupling interfaces for the fully coupled COAMPS. The various components of the coupled system are integrated through ESMF.

A coupled global ocean/ice model will be operational in 2014. At the present time, the coupled ocean/ice model is restricted to the Arctic Ocean (Arctic Cap Nowcast Forecast System). The new global ocean/ice system will produce nowcasts and 120-hour coupled model forecasts of ice fields from CICE and ocean fields from HYCOM at 1/12 degree resolution.

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). A schematic of the system is shown in Fig **2**. Initial Operational Capability (IOC) is targeted for 2018. ESPC is a national partnership among federal agencies and the research community in the U.S. 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 and 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.

Data assimilation in coupled COAMPS currently consists of independent 3DVar analyses in the ocean and atmosphere. The first-guess fields (6- or 12-hour forecasts) for each fluid are obtained from the coupled model state. This assimilation configuration is referred to as weakly-coupled. A strongly coupled 4DVAR assimilation system for both the ocean and atmospheric components of COAMPS is under development. In this scheme separate 4DVAR assimilation systems of the atmosphere and ocean models will be linked through the existing coupling terms and ESMF coupling infrastructure in COAMPS. The tangent linear and adjoint components of these coupling terms will be developed and used to minimise the cost function of the coupled system. The state and observation vectors in the assimilation will be extended to include both ocean and atmosphere variables.

For the global ESPC coupled model a hybrid version of the Navy Coupled Ocean Data Assimilation (NCODA) 3DVAR[50](Cummings and 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 modeling[51] (Cummings and 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 a 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 data assimilation. 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.

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[52] (Smith et al., 2013).

A fully coupled AIO forecasting system for the Gulf of St. Lawrence (GSL) has been developed[53] (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[54] (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 data assimilation 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)[55] Smith et al. (2014). GIOPS is now producing daily 10-day forecasts in real-time at CMC. A 33km 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/Météo France

Mercator Océan is developing and operating global and regional ocean analysis and forecast systems. In a closer and long term collaboration with Météo France, Mercator Océan provides ocean initial states for the seasonal forecast systems. More recently, new developments were conducted to investigate high resolution ocean and atmosphere coupling. 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 issuing advisories and tracking of tropical cyclones (TC) in the South-West Indian Ocean (SWIO). In order to provide better guidance to TC forecasters, Meteo-France has developed ALADIN-Reunion[56] (Faure et al., 2008), a regional adaptation of ALADIN-France[57] (Fischer et al. 2005). This model has been run operationally since 2006 at 10 km resolution with a specific assimilation scheme, which provides better TC analysis.

Since 2008, Meteo-France has run a new operational limited-area model AROME-France[58] (Seity et al., 2011) at 2.5km-resolution. This system is designed for very short range forecast in order to improve the representation of mesoscale phenomena and extreme weather events. AROME has its own mesoscale data assimilation system that enable to take benefits from mesoscale data such as radar data. Meteo-France is planning to operate an SWIO regional AROME configuration in the near future.

Meteo-France and Mercator-Ocean are also exploring the potential benefit of developing an operational coupled version of AROME with a 1/12 degree regional configuration of the NEMO ocean model[25] (Madec, 2008). This technological demonstrator has been developed in 2013 to explore its feasibility and the impact of air-sea coupling on TC prediction. The ocean surface can cool by several degrees during the passage of a tropical cyclone (TC) due to the associated extreme winds. This cooling decreases the ocean-to-atmosphere heat and moisture supply, which can modulate the TC intensity. Hence, atmospheric models need an accurate description of the sea surface temperature (SST) under TCs to correctly predict their intensities. This SST evolution and its feedback on the TC evolution can only be captured by ocean-atmosphere coupled models.

NASA, USA

In the framework of the Goddard Earth Observing System (GEOS) Data Assimilation System[59] (Rienecker et al., 2011) of the NASA Global Modelling and Assimilation Office, coupling of the atmosphere-ocean assimilation systems with focus on SST is ready for an operational atmospheric assimilation system. Full coupling with integrated Ocean DAS (iODAS)[60], Vernieres et al., (2012), is currently being explored. The atmospheric analysis is carried out by Gridpoint Statistical Interpolation (GSI)[61], Kleist et al., (2009), with the GEOS[62] (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.

Using atmospheric surface fields and fluxes, an atmosphere-ocean interface layer models diurnal warming[63] (Takaya et al., 2010) and cool-skin[64] (Fairall et al., 1996) effects 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, 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 1/4 degree 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.

Demonstrated benefits

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 where these benefits are being realised relative to applications to identify leading centres, encourage other institutions to undertake similar research, encourage collaboration between centres for common applications and attract additional funding. Importantly, the list of applications and the examples described represent those of the groups participating in the GOV TT-SMRCP and identified through the Joint GOV-WGNE workshop and represent is not an exhaustive review of all the activities being undertaken by the international community.

General atmospheric circulation

An example of the impact of the coupling on the ocean forecast skill from the UK Met Office system out to 15 days is shown in Fig **3** 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, with lower RMS and mean errors throughout the 15-day forecasts. To assess the benefit of the weakly-coupled data assimilation, one-month experiments have been carried out, including 1) a full atmosphere/land/ocean/sea-ice coupled DA run, 2) an atmosphere-only run forced by OSTIA[65] (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 by either run 1 or a combination of runs 2 and 3.

Fig **4** shows the monthly average surface air temperature increments and sea surface temperature increments from the Met Office weakly-coupled and un-coupled analysis runs over December 2011. The ocean and atmosphere increments from the coupled runs are a little smaller in large parts of the globe suggesting a better balance of the 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 system 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 which merit further investigation. Atmospheric forecasts 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 un-coupled analyses at least for the first 5-days, and the impact on longer lead-time forecasts will be investigated in the future.

THE ECMWF CERA system produces a coupled 10-day forecast where ocean and atmosphere evolve freely. These coupled forecasts have been compared with the 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 persisted SST anomalies. Fig **5** 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. But, as the RMSE in the operational-like system increases faster, 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 ensemble transform (ET) analysis perturbation scheme is adapted to generate perturbations to both atmospheric variables and sea surface temperature (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 (NOGAPS) global spectral model to generate a medium-range forecast ensemble. When compared to 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 (OLR), cloud radiative forcing, near-surface air temperature and wind speed, and 24-hour 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 favorable 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 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 realise the greatest gains in forecast performance[66] (McLay *et al*. 2012).

The Environment Canada global coupled model based on GIOPS[55] (Smith et al., 2014) shows robust performance in the tropical atmosphere compared to both tropical moored buoys and analyses produced by the European Centre for Medium Range Weather Forecasts. 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 landfast ice there is a tendency to overpredict the opening of the ice cover along coastal regions, which has a strong impact on heat and moisture fluxes to the atmosphere. This sensitivity is under further investigation.

Madden Julian Oscillation

The impact of representing the SST in monthly forecasts of the Madden Julian Oscillation (MJO) has been explored at ECMWF. The ECMWF monthly forecasting system has been used to conduct sets of monthly hindcasts where the SSTs have been modified in a controlled manner. The impact of temporal and spatial resolution of SST products 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 ocean and atmosphere seems important to simulate tropical convection and propagation of the MJO. By increasing the temporal resolution 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 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 we have obtained results indicating that ocean-atmosphere coupling produced better MJO forecasts than prescribing *observed SST*[67] Boisseson et al 2012. See also Janssen et al 2013[47] for the impact of coupling in the medium range weather forecasts and MJO, using a more recent model version.

CFSv2 increased useful prediction skills for MJO from 10-15 days for CFSv1 to around 20 days[68] (Wang, W. 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 to 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[69,70,71] (Seo et al., 2009; Matsuedo and Endo, 2011; Rashid et al., 2010).

Hurricane/Tropical Cyclone prediction

In order to evaluate the potential benefit of the ocean atmosphere coupling on TC forecasts in the South West Indian Ocean, Mercator-Ocean has developed a new coupled regional model based on the Meteo-France operational atmospheric model AROME and the NEMO ocean model. As the AROME assimilation system is not available yet for the SWIO region, the atmospheric model is initialised from ALADIN-Réunion 10km analyses, which are generated every 6 hours. The TC specific assimilation scheme allows representing accurately the TC structure, intensity and position in the analysis based on the best estimates provided by TC forecasters. ALADIN-Réunion is also used for lateral boundary conditions. Experiments have been conducted with TCs from the last 6-years using NEMO, which is initialised from the global ¼ degree reanalysis GLORYS[72] (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 achieved by using a digital filtering initialisation procedure during a 3-days integration period. During this period, the ocean model is also forced with 6-hours ALADIN analysis, which allows equilibrating the ocean surface and mixed layer with the high resolution atmospheric forcing. The coupled system is then integrated during 96-hours with a coupling frequency of 15-minutes via the OASIS3 coupler[73] (Valcke et al., 2013).

The coupled model performances have been evaluated against AROME forecasts forced with the Meteo-France SST analysis over an ensemble of 23 intensifying TC simulations (5 different TCs from the 2008-2012 seasons). Sea surface temperature (SST) forecast errors are then calculated by comparing the averaged SST within a 150 km radius centered on the TC with the SSMI TMI-AMSRE product[74] (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 Fig **8** as a function of the forecast time for the coupled and the forced simulations.

Concerning SST (Fig **8**a), an important improvement is achieved with the coupled model when compared to the forced model. Averaged SST forecast error never exceed ±0.4°C in the coupled model, while it can reach +1.2°C with Meteo-France SST analysis. The initial SST error (+0.8°C) is mainly due to the lower spatial resolution and the temporal smoothing of the operational SST analysis. The initial oceanic state generated from GLORYS with the DFI procedure is really close to the observations. In the forced ensemble, the SST error slowly increases with the forecast time while it stays close to zero in the coupled ensemble. Hence, the coupling limits effectively SST error growth during the forecast.

The SST improvements lead to a better TC intensity forecast in the coupled ensemble as shown in Fig **8**b. While both coupled and forced ensembles show good skills in predicting TC intensity during the first 30-hour (error < 10hPa), models behaviours differ quickly at longer ranges. Coupled forecasts tends to slightly underestimate TC intensity at all forecast times, but with error < 10hPa even at 96-hour range. In forced simulations, intensity error quickly increases with time and reaches up to 35hPa at 96-hour range. Consequently, the coupling with NEMO greatly improves AROME TC intensity forecast for ranges greater than 30 hours through a more realistic SST representation.

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 forecast (South-West Pacific Ocean New Caledonia and Polynesia, Atlantic Ocean French Guinea and Caribbean). NEMO will also benefit of the new operational Mercator-Ocean global 1/12 degree daily forecasts which should improve oceanic initial and boundary conditions.

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[32] (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 Tropical Cyclone improves in the coupled system both because surface fluxes are more realistically represented with a high resolution regional atmospheric model compared to a global model and that the negative feedback provided by the ocean response tends to limit over-estimates of the storm intensity[18] (Sandery et al , 2010). The ocean component of this system initialises from the data assimilating OceanMAPS providing an improved representation of sub-surface heat content, which is also an additional benefit of running such a system. The CLAM-TC system was extended to study coupled initialisation 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[19] (Sandery and O'Kane, 2014). Prediction of SST resulting from the ocean response to tropical cyclone Yasi in the Coral Sea on the 2nd of February 2012 was improved using a coupled ocean-atmosphere ensemble initialisation method as shown in Fig **9**.

Extra-tropical cyclones – East Coast Lows

East Coast Lows are subtropical low pressure weather systems that can rapidly intensify as they propagate over the marine boundary of Australia's east coast producing strong localised convection, lightning and heavy precipitation. Several storms have produced 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 sub-tropical gyre transporting warm/fresh seawater poleward from the Coral Sea to the Tasman Sea. The EAC 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[75] (Brassington et al., 2010) providing sources of heat into the Austral winter. A specific case on the 7-9 June 2007 that occurred off Newcastle, NSW has been studied using downscaled Weather Research and Forecast model (WRF) simulations. A simulation is initialised with highly resolved SST (BLUElink) and then compared to a second simulation initialised with coarse resolution (Ctrl) SST boundary conditions to examine the impact of the gradients in SST arising from the large scale warm ocean eddies that persist into the Austral winter[22] (Chambers et al). Simulations based on the highly resolved SST produced higher values of 48-hour total precipitation along an SST front (see Fig **10**) resulting in more localised convection consistent with observations from coastal rain gauges and with lighting strike locations. It is concluded that the SST gradient along the southern flank of a large warm eddy significantly increased the severity of the coastal weather impacts that occurred during this storm.

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-hours from the Canadian Gulf of St. Lawrence coupled forecasting system are shown in Fig **11**. This system has shown the strong impacts that a dynamic sea-ice cover[76] (Smith et al., 2012) can have on 48-hour 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 (Mar. 10, 2012) with sea-ice concentration on the left and 2m temperature on the right showing that rapid ice changes can cause surface temperature changes of up to 7-8°C over the open water. Due to the presence of a relatively thin seasonal thermocline (~20m) 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 in Fig **11** shows a summer case (Jul. 10, 2012) with 10m winds on the left and 2m temperature on the right showing that coastal upwelling in the coupled forecasts can produce surface temperature changes of several degrees Celcius locally.

Nearshore coastal weather – Adriatic Sea

A coupled COAMPS[48] model was executed in the Adriatic Sea from 25 January to 21 February, 2003. The atmospheric model configuration was triply nested (36, 12, 4 km horizontal resolution), while the ocean model consisted of two nests (6 and 2 km), with the inner-most nests of both models centered 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 minutes using grid exchange processors based on the Earth System Modeling Framework (ESMF). In the uncoupled run, wind forcing from the atmospheric model was passed to the ocean model, but the ocean *did not* feedback 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. Couple and uncoupled statistics are presented for the Acqua Alta platform near Venice, Italy in Fig 12. 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 to 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.

Data assimilation of brightness temperatures

The NASA, coupled GEOS-DAS have explored the data assimilation of brightness temperature using a surface sensitive (10.35μm) channel of the AIRS instrument on AQUA satellite. The comparison of an experiment that had an active interface-layer with a control experiment with no interface layer (the SST boundary condition was skin SST) was used to diagnose the benefit.

Preliminary results, at 1 degree resolution, show improved assimilation of all 10-12micron IR observations and decreased bias in precipitation with respect to GPCP data. Fig **7** shows three panels with time series of total number of observations assimilated (top panel), global mean of observation-minus-background (OMB), middle panel, and 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, corresponding also to a reduced 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).

Known challenges

Based on the current sophistication of the coupled modelling systems and the range of applications under active investigation many challenges toward coupled prediction have already been addressed. Sufficient progress has been made in observing, modelling and initialisation to forecast waves, the ocean state and sea-ice to suggest that coupled modelling of the marine environment is feasible. The pursuit of seasonal and climate modelling has introduced several software frameworks that facilitate the coupling of component model software that is scalable for super-computing environments. In practice there are several short-comings in their design for GOV-type forecasting and eventual operational applications which require more frequent restarting and data exchanges. This is not impeding progress in basic research but is impacting the efficiency and size of the problems being undertaken and will require further optimisation in design before implementation into operational applications.

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

The initialisation of coupled models is currently based on uncoupled or weakly coupled data assimilation for each component model and an inefficient coupled initialisation 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 data assimilation is required to provide the optimum dynamically balanced coupled fields but there are several challenges to realising 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 data assimilation to succeed. This aspect of the problem needs to be thoroughly studied.
2. A goal of coupling is to reduce some of the biases in interfacial fluxes that occur in each component model in their uncoupled form. However, any residual biases in a coupled model will distribute throughout the coupled model state requiring more sophisticated analyses to diagnose, attribute and develop bias correction schemes.
3. It is still a remaining challenge to decide the best way to weight coupled covariances from ensembles in the hybrid schemes. Similarly, to find appropriate methods for coupled initialisation and maintaining 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. Progress would benefit from community-established benchmarks, test cases, or metrics to establish beneficial impact of fully coupled analyses

In the near-surface ocean, the diurnal cycle imposes time-scales of a few hours[64] (Fairall et al., 1996). Modelling of the diurnal warming layer is important for computation of the skin temperature. For coupled data assimilation, it is essential to incorporate observational information *directly* from satellite brightness temperature observations and near-surface buoys so that the modeled 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 (to few mm); and further down to centimeter – and meter scale – 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 as well as due to 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[52] Smith et al., (2013).

Notably 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 more readily be assessed. 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 it also reflects the paucity of observations available to establish benchmarks for the leading parameters for these applications such as the sonic layer depth and surface currents.

Future/outlook and conclusion

All groups contributing to this paper have developed research programs specifically targeting a subset of applications that represent their national interest. The modelling systems range from regional to global and the initialisation and data assimilation is uncoupled or weakly coupled. In many cases the research challenges identified are common across these programs 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 deliver yield further improvements with continued research and development.

The Bureau of Meteorology plan to extend the research into East Coast Lows focusing on diagnosing the dynamical response of the atmospheric boundary layer and the impact of coupled modeling. Ensemble Kalman Filter data assimilation has been extensively investigated for regional ocean prediction and preliminary work is being pursued into their extension to coupled DA. With the implementation of a near-global 1/10 degree BLUElink OceanMAPS the impact of these boundary conditions will be assessed for the ACCESS-G NWP system.

Work at the UK Met Office on coupled prediction at short time-scales is targeted at three main areas: coupled model development; coupled data assimilation development; and UK environmental prediction. Assessment and development of the coupled model HadGEM3 at these time-scales is an on-going area of work; current developments include improvements to the representation of the diurnal cycle of SST, and implementation of a wave model within the coupled model framework. A higher-resolution version of this global system (12km atmosphere and 1/12° ocean) is also being developed in order to assess its performance compared to the uncoupled NWP system. The weakly coupled data assimilation system described in section 2 is being further assessed and developed, and is planned to be implemented as a demonstration operational system in the Met Office’s operational suite in 2015. Work to develop a coupled modeling framework around the UK to provide environmental predictions is also underway.

NOAA/NCEP have established a wide range of coupling projects that are underway or planned using the ESMF - NEMS environment, including: Completing ESMF and NUOPC versions of all component models mentioned in section 2; Converting the coupled HWRF hurricane weather model to the NNMB core in NEMS by 2016, transitioning this coupled model from a custom coupling environment to ESMF – NEMS. In this time frame, the HWRF model will be coupled to a full HYCOM ocean model, and coupling with the wave model will begin; A NEMS based prototype for Arctic modelling is intended to be delivered by 2016, tentatively providing a coupled ocean – sea-ice – atmosphere system, possibly also with a wind wave component added; global model coupling using an atmosphere – ocean – sea-ice coupling will be extended for the CFS-v3, and considered for inclusion in the Global Ensemble System (GEFS) and the deterministic Global Forecast System (GFS); a Nearshore Wave Prediction System (NWPS) will be rolled out to the NWS field offices in the coming year[77] (Van der Westhuysen et al., 2013). Initially this will consist of a wind wave model with input from weather, ocean and coastal circulation (inundation) models. In future upgrades, this model is intended to become a coupled wave-surge model; NOAA has also funded a project to develop the next generation forecast system for the Great Lakes, consisting of a 3D unstructured grid circulation model, an ice model and a wave model. In operations, this coupled lake model is likely to be fully coupled to a regional mesoscale weather model.

ECMWF will continue developments on coupled forecasting systems. It is planned to include a dynamical sea-ice model in the medium-range, monthly and seasonal forecasting systems, as well as increasing the resolution of the ocean and atmospheric models. For the time being, the initial conditions for the coupled forecasting system will continue being produced by separate atmospheric and ocean/sea-ice assimilation systems. The developments of the coupled assimilation will continue under the CERA system, targeting a fully coupled assimilation system. The computation of several outer iterations in the incremental variational approach of the CERA system has already allowed the observations in one media to impact the analysis of the other media within the same assimilation cycle. It is expected that the combination of variational and ensemble data assimilation methods will improve the formulation of the background error covariances. In the next few years, ECMWF has planned to produce with the CERA system several extended climate coupled reanalyses spanning the 20th century and the satellite era in the context of the ERA-CLIM2 project funded by the European Commission.

Within CONCEPTS the future activities include research and development to address the challenges outlined above, particularly for polar prediction. This will include evaluating and improving the representation of leads, incorporating wave-ice interactions, atmosphere-ice-ocean momentum transfer, constraining sea-ice thickness and sea-ice forecast verification. Regional coupled systems will also be further developed and applied to the Great Lakes and the North Pacific to support high resolution modelling of the Canadian west coast. The development of global coupled modelling systems will continue for applications of medium- and long-range forecasts. In this context there will be an expansion to coupled models for probabilistic forecasting through the Global Ensemble Prediction System at the Canadian Meteorological Centre.

Based on Mercator's encouraging results, Meteo-France will develop operational systems covering overseas territories using same modelling tools as described in section 2. The Global Mercator-Ocean operational system will be used to initialise the coupled forecast and dedicated ocean configurations could be developed to improve the consistency between the initialisation phase and the forecast one.

NASA plans have some commonalities with the Canadian CONCEPTS in terms of constraining sea-ice thickness. Along the same lines, they plan to improve near-surface heat transfer over sea-ice by modelling ice skin temperature using CICE thermodynamics. Plans have been outlined to couple the GMAO ocean analysis (iODAS) to its atmospheric analysis system so that the *foundation temperature* (currently OSTIA SST, used by the atmospheric analysis) is replaced with the corresponding temperature analyzed in the ocean model.

Following the initial concept papers[5,6] and early workshops in 2008[7] and 2009[8] research and development in this field has made significant advances in terms of the sophistication of the modeling systems being implemented as outlined in **Tab 1**, the rigor of the experiments to quantify impacts and the range of applications. The GOV science team initiated the SMRCP task team 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 and to jointly develop and promote international initiatives to address the known challenges.

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78.

TABLES

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 3)	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 10km. Forecast : AROME 2.5km	NO	NA	OASIS3	ECUME	Regional, Indian Ocean (46E-68E/9°S-22°S)	Tropical cyclones forecast
GEOS-DAS	iODAS (MOM4p1)	GEOS	-	CICE	ESMF	-	Global	Tropical Cyclones;Reanalysis

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

	Model	**Observations**	**DA**	**Initialisation**
Atmosphere	UM ~60km/L85	AIRS, IASI, ATOVS, GPSRO, SSMI, Aircraft, Sondes, Surf-Scat	4D-Var ~120km	Direct
Land	JULES ~60km/4 layers	3D-Var Screen, ASCAT, NESDIS	Nudging Analysis	T/2 Direct
Ocean	NEMO ~25km/L75	In situ SST, T/S profiles, AATSR, AVHRR, AMSRE, Jason 1+2, ENVISAT	3D-Var FGAT	IAU
Sea Ice	CICE ~25km 5 categories	SSMI	3D-Var FGAT	IAU

Tab 2 Model, observations, data assimilation and initialisation methods used in the UK Met Office’s weakly coupled data assimilation system.

FIGURES

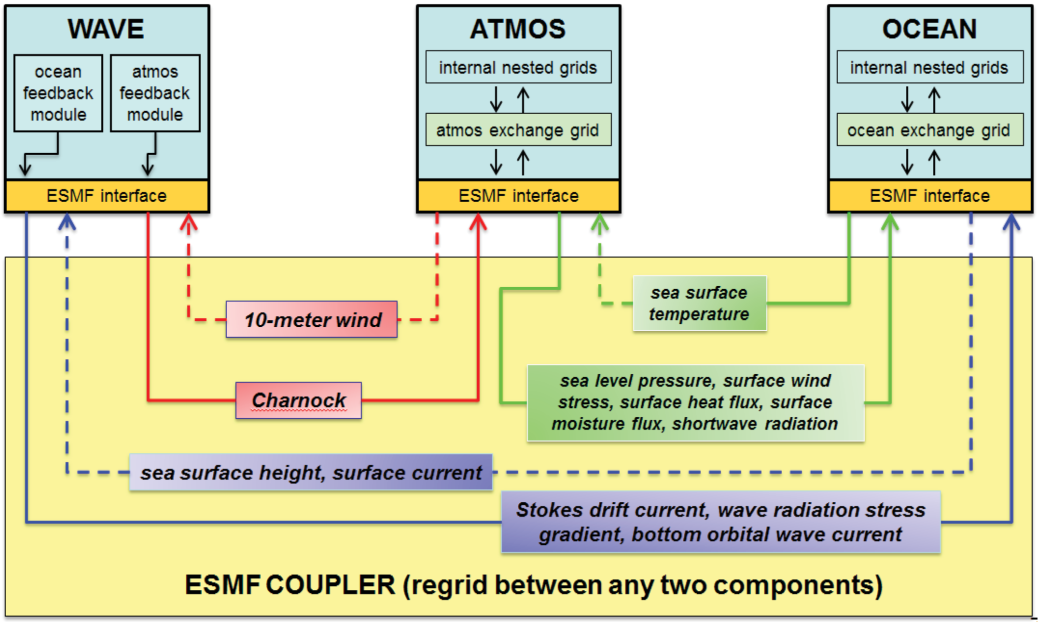

Fig 1 ESMF coupling framework for the COAMPS air/ocean/wave system showing the variables and exchange parameters passed among the coupled models.

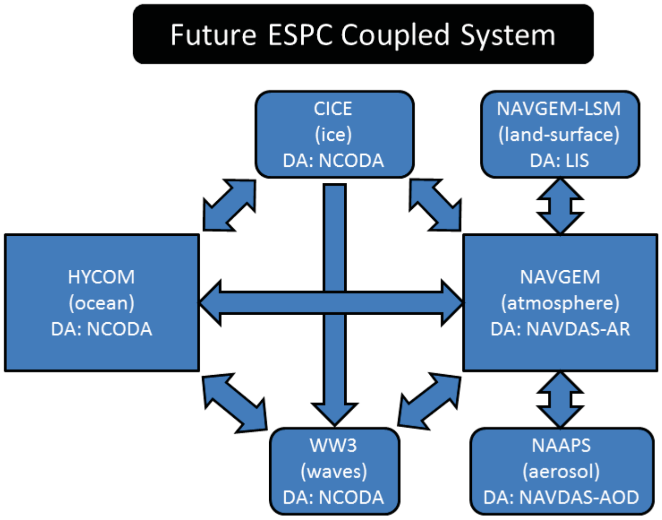

Fig 2 A schematic of the future ESPC coupled system.

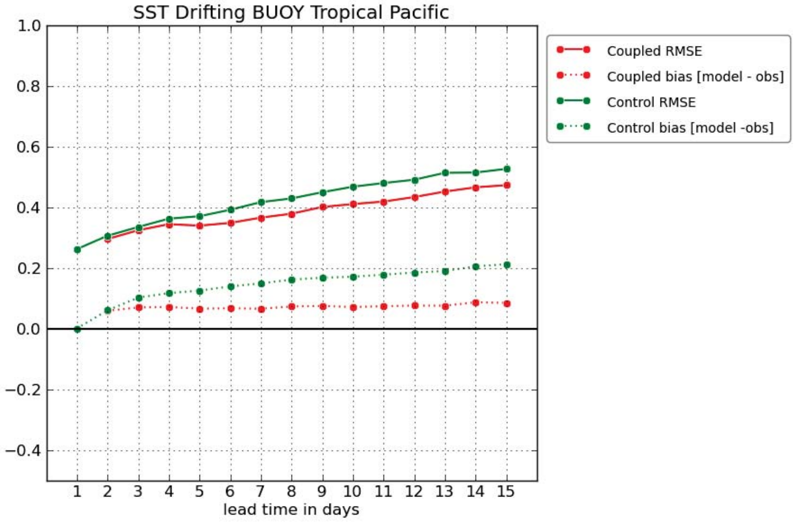

Fig 3 SST (K) observation-minus-forecast RMS (solid) and mean differences (dotted) for a set of coupled forecasts (red) and ocean-only forecasts (green) in the Tropical Pacific region. The observations used in this assessment are the drifting buoys.

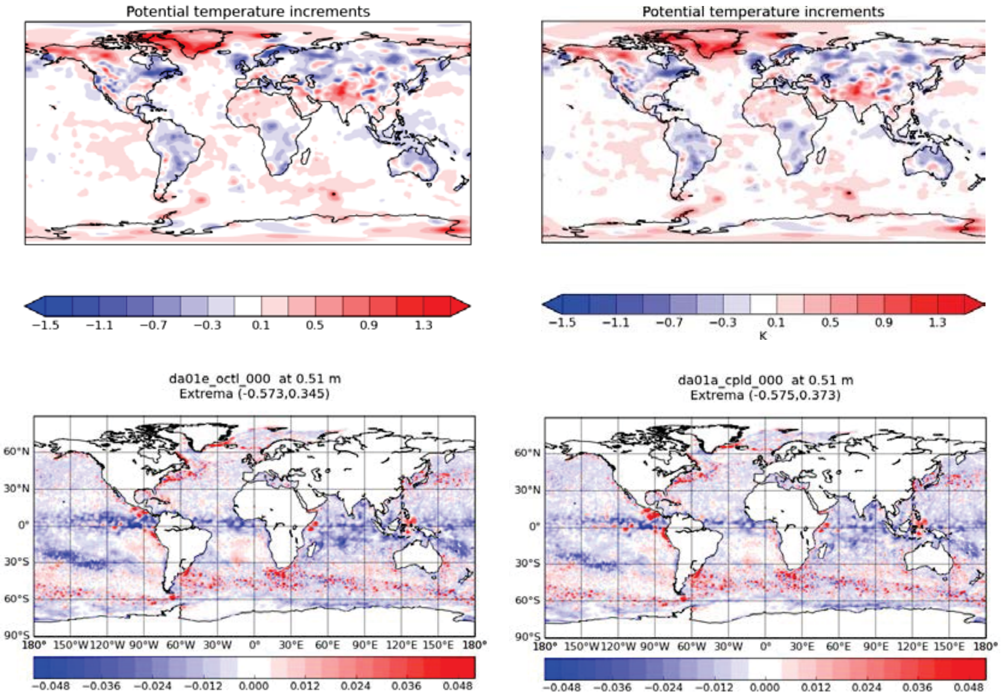

Fig 4 Monthly average assimilation increments for Dec 2011 for surface air temperature (top row) and sea surface temperature (bottom row) for the un-coupled systems (left column) and the weakly coupled system (right column).

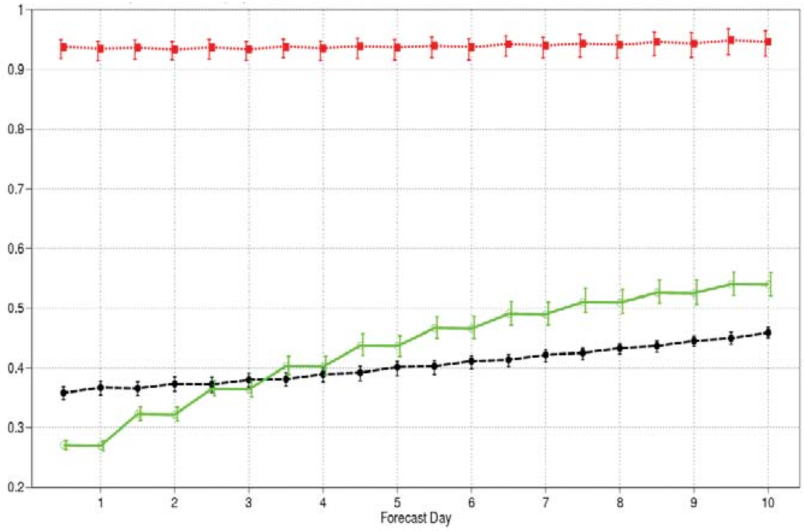

Fig 5 Root mean square error (RMSE) of the SST forecast in the Tropics from the CERA system (black) and from the operational-like system (green) for September 2010. The OSTIA SST analysis is used as reference. The red curve is the RMSE of the SST climatology used to create the SST anomalies persisted in the forecasts from the operational-like system.

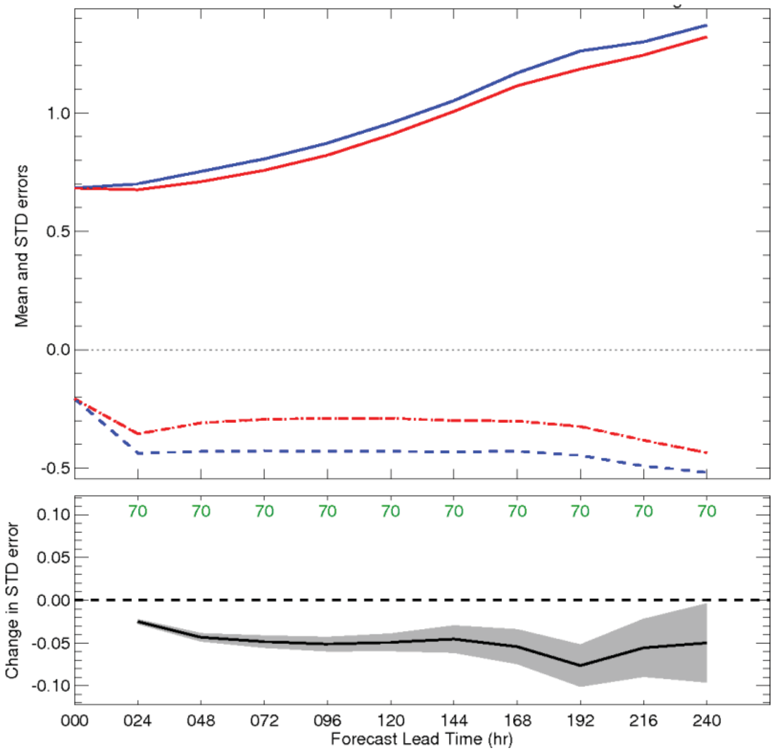

Fig 6 Evaluation of global coupled forecasts over the tropical Indian Ocean from CMC over the winter 2011 period. Mean (dashed) and standard deviation (solid) differences between 925 hPa temperature forecasts and ECMWF analyses are shown for uncoupled (blue) and coupled forecasts (red). The bottom panel indicates the statistical significance of standard deviation.

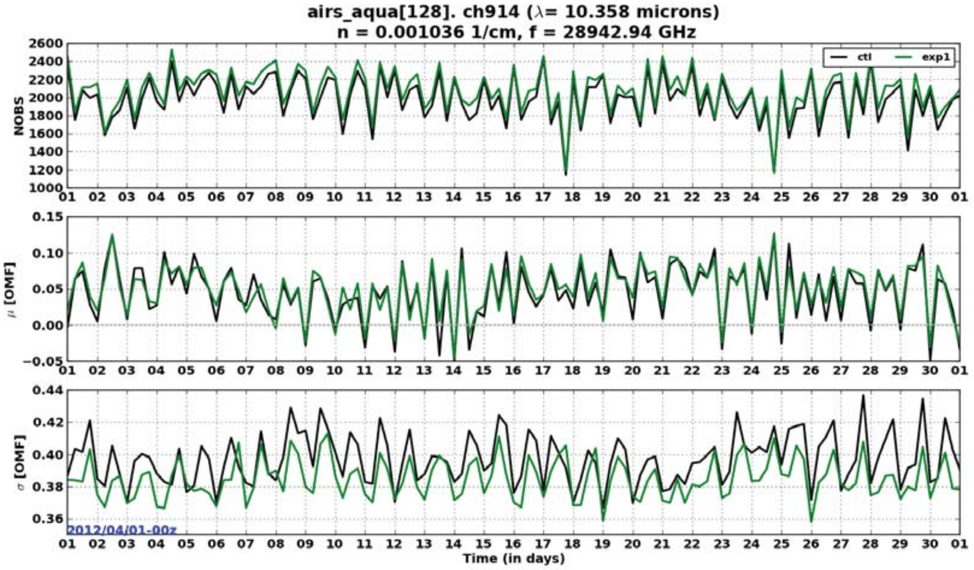

Fig 7 Improved assimilation of Brightness Temperature from a surface sensitive (10.35 \mu m) channel of the AIRS instrument on AQUA satellite. We compare an experiment (exp1) that had an active interface-layer with a control (ctl) with no interface layer and hence used SST boundary condition as skin SST. The three panels plot time series of 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 lesser standard deviation in OMB. Similar results are obtained for other 10-12 \mu m IR channels of AIRS-AQUA, IASI-METOP-A, HIRS4-METOP-A, N19 (not shown).

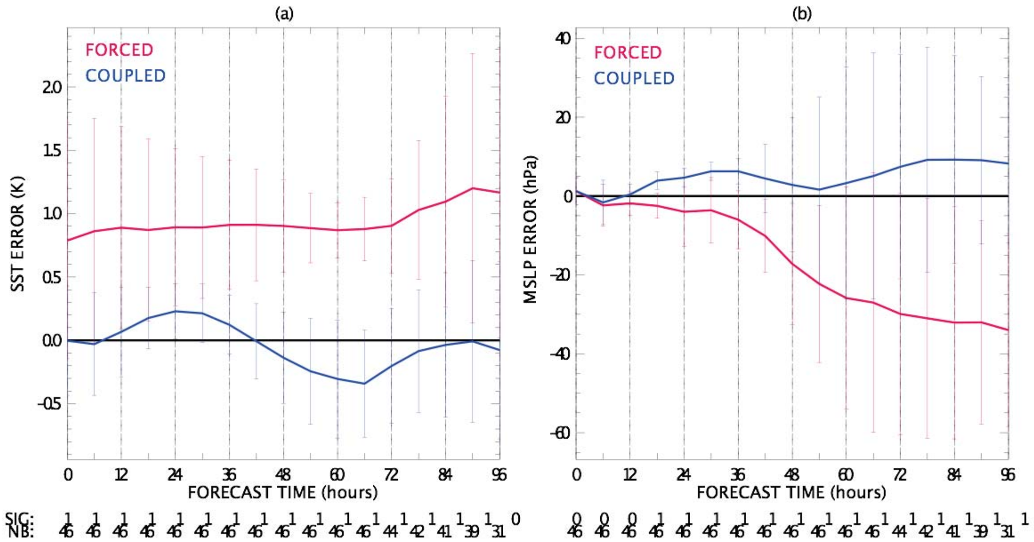

Fig 8 (a) SST error ensemble mean evolution (K) as a function of forecast time. (b) Central Pressure error ensemble mean evolution (hPa) as a function of forecast time. The total number of forecasts and the statistical significance of the difference between the forced and coupled ensembles are given for each forecast time below the figure.

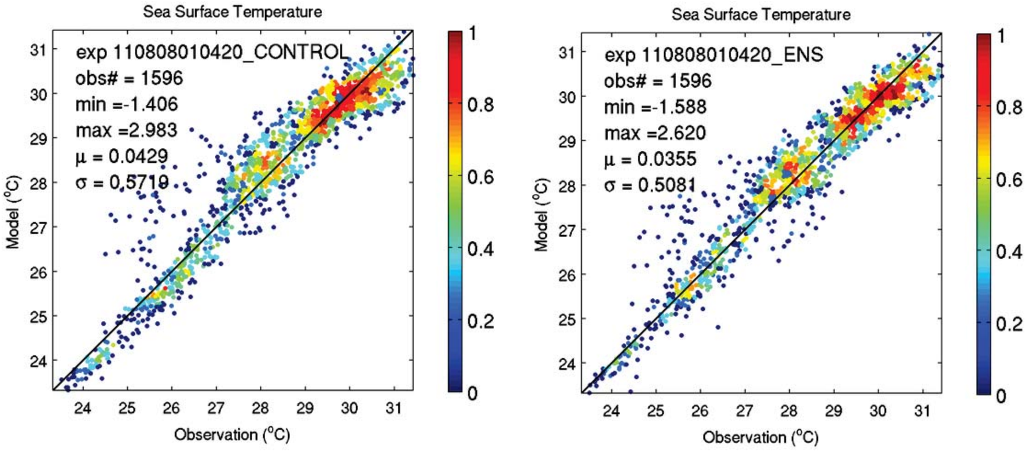

Fig 9 Prediction of SST resulting from the ocean response to tropical cyclone Yasi in the Coral Sea on the 2nd of February 2012 was improved using a coupled ocean-atmosphere ensemble initialisation method. The colours represent a normalised 2D histogram.

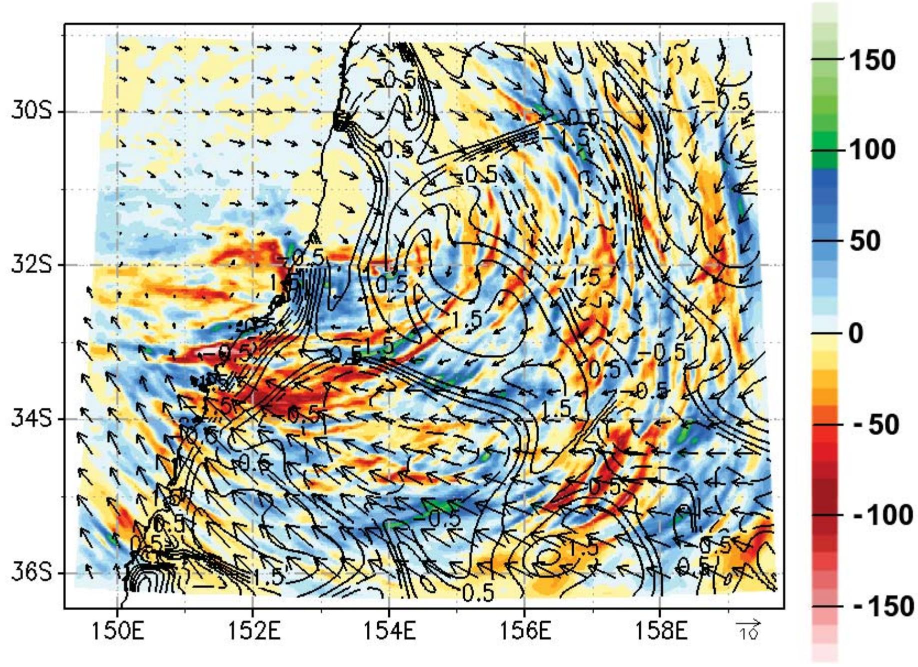

Fig 10 48 hour (0000 UTC 7 June to 0000 UTC 9 June, 2007) total rainfall differences (colours, mm) (BLUElink - Ctrl). SST differences (°C) between the simulations overlaid as contours. In addition the BLUElink simulation average 10 metre wind vectors are overlaid as arrows to indicate the surface flow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

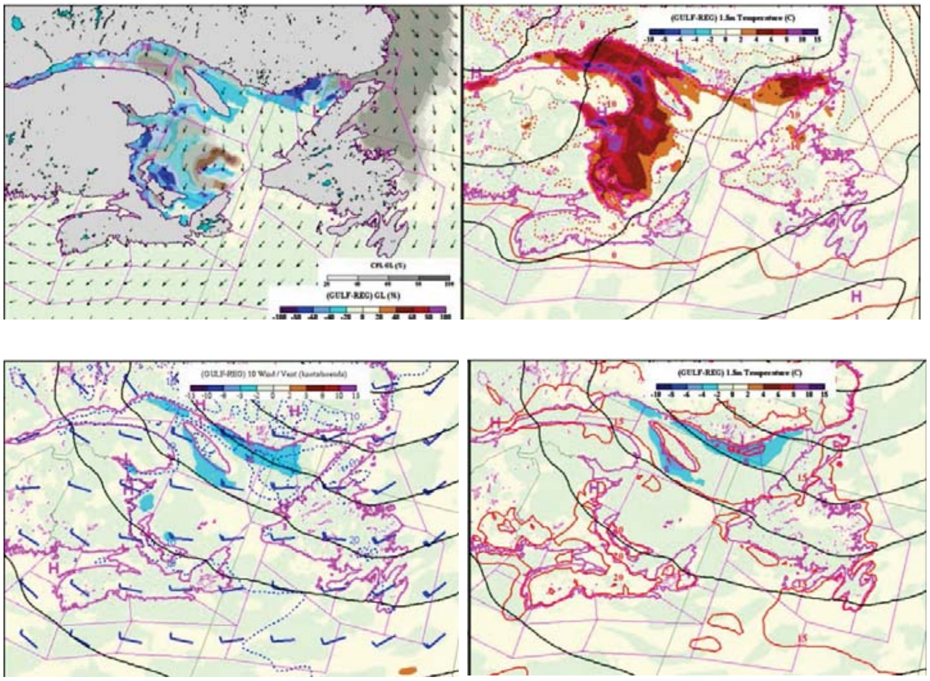

Fig 11 Differences between coupled and uncoupled model forecasts after 12 hours in the Canadian Gulf of St. Lawrence forecasting system. Top panel is for a winter case (Mar. 10, 2012) with sea ice concentration on the left and 2m temperature on the right showing that rapid ice change can cause surface 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 (Jul. 10, 2012) with 10m winds on the left and 2m temperature on the right showing that coupling induced coastal upwelling can produce surface temperature of several degrees C locally.

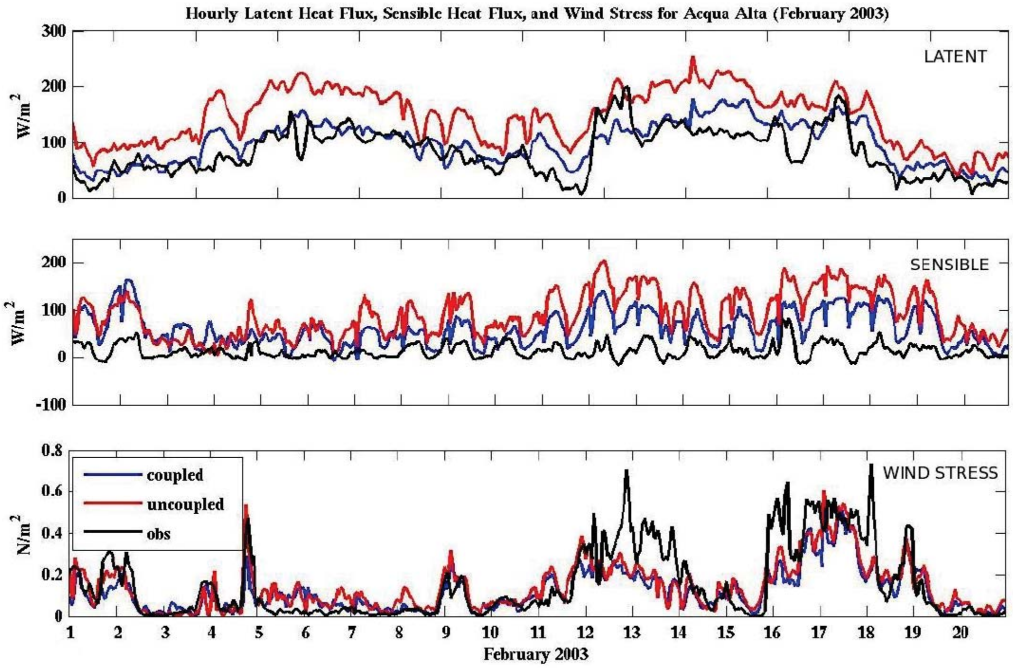

Fig 12 Hourly latent and sensible heat fluxes (W/m^2) and wind stress (N/m^2) for the fully-coupled COAMPS run and observations at Acqua Alta (Venice). From Allard *et al*. 2010.