Coupled Atmosphere-Ocean Data Assimilation

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Abstract

This seminar provides a review of the rapidly growing field of coupled data assimilation, first looking at the motivation for changing the current separate atmosphere and ocean assimilation methods, looking at the phenomena that could be better represented, the datasets that could be more effectively used, and some of the challenges involved. The second part of the seminar provide a review of the current progress and plans at a number of international centres for implementing coupled prediction and coupled data assimilation schemes. The seminar ends with some thoughts on the role of 4DVar and Ensemble methods applied to coupled data assimilation problems and some conclusions on the way forward.

1. Introduction

Data assimilation into coupled climate models is a challenging new area requiring the application of sophisticated data assimilation methods, while at the same time practically managing complex interacting physics and dynamics of the coupled system, particularly at the air-sea interface and boundary layers. For more than a decade, coupled ocean-atmosphere models have been used operationally for the production of seasonal forecasts. Usually the initialization of these coupled forecasts has been done in uncoupled mode i.e., the ocean and atmospheric components are initialized separately, and because the coupled system itself has large biases the initial conditions are far from the natural state of the coupled system. This leads to rapid shocks at the atmosphere-ocean interface eg. to the SST, followed by a linear or non-linear drift of the coupled system towards its preferred climatology, which needs to be taken into account when interpreting the predictions (Stockdale 1997). It is not clear what the impact of these coupling shocks or the subsequent climate drift have on the skill of the seasonal forecasts at different lead times, but it is reasonable to assume that reducing coupling shocks through a more balanced assimilation, particularly of near surface observations, tuned to the coupled model systems, would have substantial positive impacts.

However seasonal forecasting interests alone would not be enough to explain the current growth of interest in coupled Data assimilation. In the last few years two additional areas of coupled modelling have arisen, decadal forecasting for interannual climate prediction purposes, eg. as pioneered by Smith et al (2007), and medium range to monthly forecasting, both of which are using coupled ocean atmosphere models. Operational centres are therefore starting to look to develop seamless prediction systems which would allow a single coupled model and data assimilation code base that could form the basis for initialising predictions across all these timescales.

Coupled reanalyses also offer the potential for improving the assessment of air-sea exchange processes for heat and freshwater, which are critical to understanding the functioning of the climate system. Despite the wealth of surface observations now available these quantities are not well quantified from current separate assimilation systems in which the surface atmosphere or ocean conditions are kept constant and therefore coupled feedback processes are excluded. If coupled models are to become the normal prediction tools on timescales from NWP to decadal, then the growth of bias errors within the coupled systems must also be better understood. Projects such as TRANSPOSE AMIP (www.metoffice.gov.uk/hadobs/tamip) which evaluates initialised coupled model errors at different lead times should help with this process.

Despite this increased interest the challenges for developing a coupled data assimilation system remain large. Ocean and atmospheric assimilation schemes have both developed to a mature stage as separate systems at most operational centres and the schemes used for each are not easy to combine. The timescales are very different, for example at ECMWF atmospheric assimilation (Dee et al 2011) used a 12hr window 4DVar scheme, while the ocean assimilation window is 5-10 days and based on a 3DVar-IAU scheme (Mogensen et al 2011). These different timescales reflect (i) the availability of data (ii) the internal error growth rates in the atmosphere and ocean systems, and (iii) the transition to non-linear evolution. Other factors that may need to be considered in implementing a coupled data assimilation system are the inherent coupling methodology between the models. This may vary between a few minutes and several hours in some systems which would then limit the ability to properly represent diurnal timescales. Bias correction schemes (Dee 2005) in current individual forecast systems may also need to be modified. Ocean bias schemes such as the Bell et al (2004) are explicitly designed to allow appropriate SST gradients along the Equator without inducing large pressure gradients associated with these because the difficulty of achieving a proper momentum balance. Some of these biases need to be revisited in order to achieve an appropriate approach for correcting a fully and continuously coupled modelling system.

Finally there is considerable potential for improved use of near surface observational data along with their properly weighted errors. Sea surface temperature measurements, surface wind information deduced from scatterometer data over the oceans, and surface sea state and wave characteristics derived from altimetry, sea surface salinity information and, over land, soil moisture, are all influenced strongly by surface fluxes (heat, momentum, freshwater) and could all be assimilated more effectively within a coupled data assimilation system. These quantities also often show large transient behaviour at the start of predictions which affect both the atmospheric and ocean boundary layers introducing anomalous Turbulent Kinetic energy into the mixing schemes, which a more balanced coupled assimilation approach could reduce.

2. Coupled Phenomena

On short timescales the Diurnal cycle leads to very strong variability in near surface properties of the atmospheric and oceanic boundary layers, Embury et al (2011). Sea surface temperatures can show large or small diurnal variability depending on conditions, as illustrated in Fig 1a.

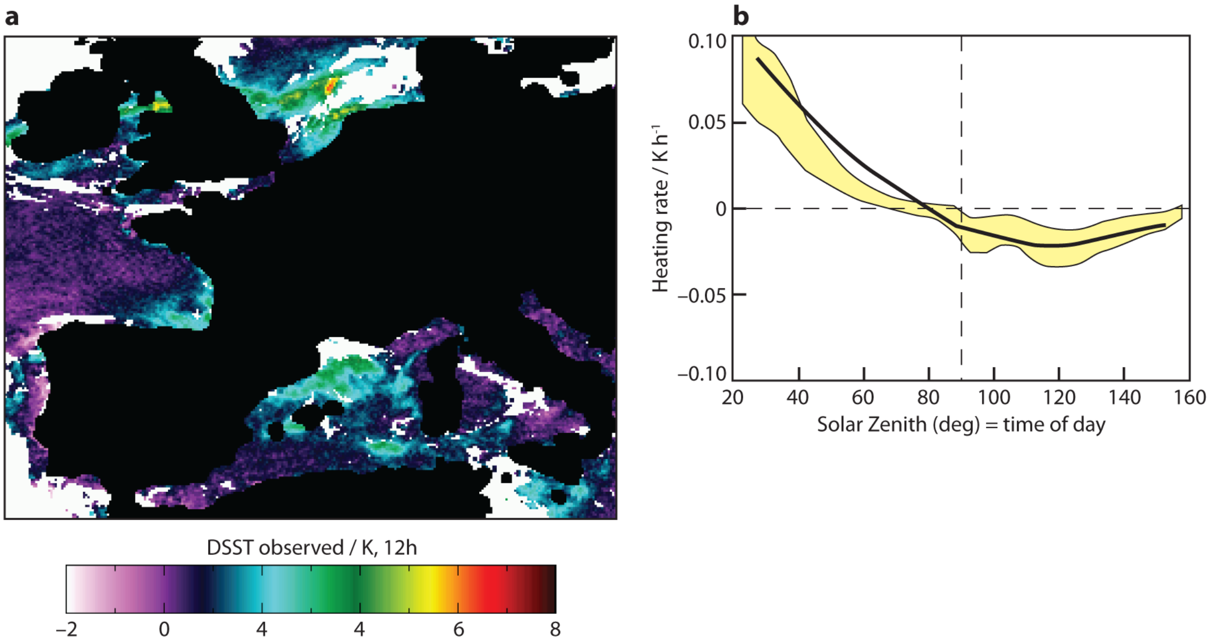
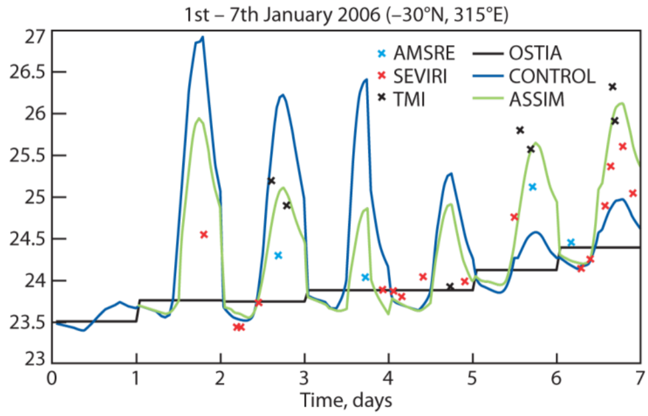


Figure 1 a) shows the diurnal cycle from ATSR measurements from the ARC project, Merchant et al (2008). b) Heating rates from satellite data (solid line) and comparable estimates from NWP models, plotted as a function of solar zenith angle equivalent to time of day.

The observations of sea surface temperatures from satellites, particularly the ESA ATSR series, are now reaching similar accuracies to in situ buoy measurements and these data could be effectively assimilated. Coupled models can capture alot of this diurnal variability based on the cycle of solar fluxes alone, as illustrated in Fig 1b (see also Fig 6a). To properly use, for example, measurements of SST made during the day, it would be important to understand errors in wind forcing and cloud cover at least, eg. Fig. 2, Pimentel et al (2008).



	Mean	STD	RMS
Control	0.07	0.79	0.79
Cloud check	0.06	0.78	0.78
Wind correction	0.10	0.52	0.53
Wind then cloud correction	0.07	0.49	0.49

Figure 2: Modelling of the diurnal cycle in EO measurements compared with an ocean mixed layer model with tuning of the bulk forcing adjusting surface wind speeds and the cloud cover fraction. Model-EO difference statistics shown in the right. From Pimentel et al (2008).

On slightly longer timescales in the tropics the Madden Julian Oscillation (MJO) is a coupled phenomenon where the timing of atmospheric convection above SST anomalies depends on modelling the coupled feedbacks correctly. Without coupled feedbacks atmospheric convection is too strong and too early, leading to cloud induced damping of the SST anomalies, (Vitart et al 2007). A coupled assimilation cycle should improve phase of MJO behaviour. This can have larger scale implications as suggested by Cassou et al (2008) who looked at teleconnections from the MJO affecting the North Atlantic Oscillation.

Extreme air-sea flux events during tropical cyclone evolution may have significant impacts on forecasting. Fixed SSTs below an atmospheric model imply a potentially infinite heat source at the lower boundary which can strengthen storms too much. Higaki (2009) at the JMA found for example that storm Morokot was forecast more accurately using a coupled model in which significant SST cooling develops as a response to extreme wind induced ocean mixing, see Fig 3a. They also showed that a 3D ocean model was required to simulate this because Ekman induced suction provides a considerable component of the SST cooling, Fig 3b. Under these circumstances coupled initialisation of the ocean and atmospheric boundary layers below the storm would be very important.

At higher latitudes coupled processes involving ice become important. In particular the presence or absence of ice at the ocean surface has a large influence on air sea fluxes which will strongly affect surface air temperature forecasts. Examples from the Gulf of St Lawrence are shown in section 4.3.

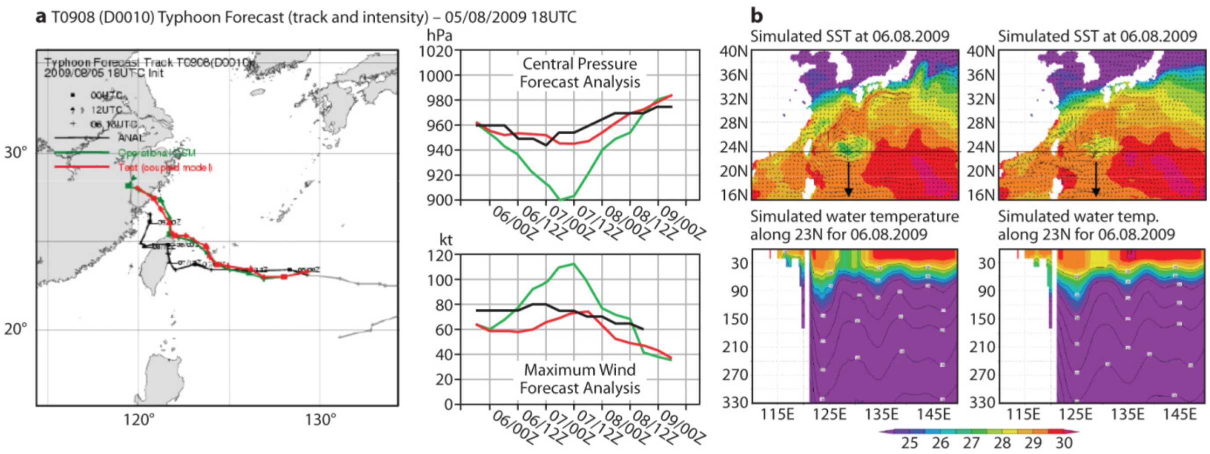


Figure 3a) shows cyclone tracks and intensities for storm Morokot using JMA coupled and uncoupled models. b) shows the surface temperatures within the coupled model with and without 3D circulations. From Higaki (2009).

3. Coupled Model Errors including Bias

Coupled model biases develop on all timescales with fast timescale errors mostly associated with vertical parameterizations of ocean mixing, air-sea exchanges and atmospheric convection. These rapidly lead to horizontal pressure errors which generate erroneous circulation in the horizontal. Once non-linear circulation biases are involved large scale errors develop whose original process origins become hard to identify. Thus the development of coupled model biases on short timescales of hours to days after initialisation can provide new information about climate model drifts. This is one of the ideas behind the TRANSPOSE_AMIP project which is a WMO working group project developing a database of climate models run in NWP mode for short term forecasts. Coupled data assimilation needs to take account of the interest in these biases and this makes the reduction of initialisation shocks clearly quite important.

Other methods for studying model biases include study of data assimilation increments which contain information about model bias errors as the data assimilation operates to prevent model drift. Examples can be found in atmospheric (Rodwell and Palmer 2007) and ocean (Fox and Haines 2003) increments but such methods have not been used in coupled models. Other approaches could involve the study of perturbed physics experiments, eg. Murphy et al (2004) to try to identify the patterns of change associated with changing coupled model parameters eg. the mixing or convection parameters.

The development of ensemble spread in coupled models also needs further work. The spread from an ensemble provides uncertainty information in a forecast which then needs to be verified by study over sufficient forecast cases, Palmer et al (2008). In assimilation however the spread also provides critical background error covariance information for the data assimilation system allowing new observations to be correctly weighted against the prior results. The size of the ensemble needed to provide this information, and the best method to initialise that ensemble, may depend on the lead time between analyses or the length of forecasts, from days to decades. If the ensemble is to be used to assess coupled covariance information between atmospheric and ocean fields this will also influence the initialisation methods and ensemble sizes needed, see section 4.4. Re-initialising the ensemble spread for example at each analysis time risks losing uncertainty information in the ocean if the analyses are performed on the short atmospheric analysis timescales.

4. Coupled Prediction and Reanalysis: Systems Review

As a paradigm for the coupled data assimilation approach we consider weak and strongly coupling within the assimilation process. The default position for most current seasonal forecast systems with coupled models is to perform the coupling after separate analysis cycles have been run on the atmospheric and ocean models. This can result in significant imbalances in the atmospheric and oceanic boundary layers which then result in rapid transients or coupling shocks. One methodology to reduce this problem would be to always use a coupled model run for the background state of the assimilation instead of running the ocean and atmosphere models separately. This "Weak" coupling paradigm will ensure that at least the background state coupled fields should be reasonably well balanced and not subject to high frequency boundary transients. If the ocean and atmospheric assimilation schemes remain separate then the increments themselves may introduce boundary layer imbalances, but these will be small if the analyses are fairly frequent (not too much model drift) and there is plenty of data. This weak coupling approach is reasonably easy to implement within current operational systems. To go beyond this to a strong coupling scenario requires coupling between ocean and atmospheric increments. This could be achieved directly through coupled covariances, or through using a coupled adjoint within a 4DVar procedure. Any method that focused on modifying the ocean-atmospheric coupling parameters in order to achieve the assimilation would also allow the boundary layers to remain balanced. Finally physical constraints could be imposed on the increments which sought to achieve the same effects, e.g. recognizing the sensitivity of diurnal SSTs to wind strength and to cloud cover and adjusting these parameters together.

Examples of some of these approaches are exhibited in the plans for the operational systems now discussed below.

4.1. The NCEP Coupled Forecasting System Reanalysis (CFSR)

The CFSR is the first reanalysis that has attempted to use the weak coupling methodology throughout from 1979-present, as described in Saha et al (2010). The model has a T382/L64 atmosphere coupled every 30mins to a MOM4 0.5/L40 ocean and with a Noah land surface model. The assimilation cycle is shown in Fig 4, reproduced from Saha.

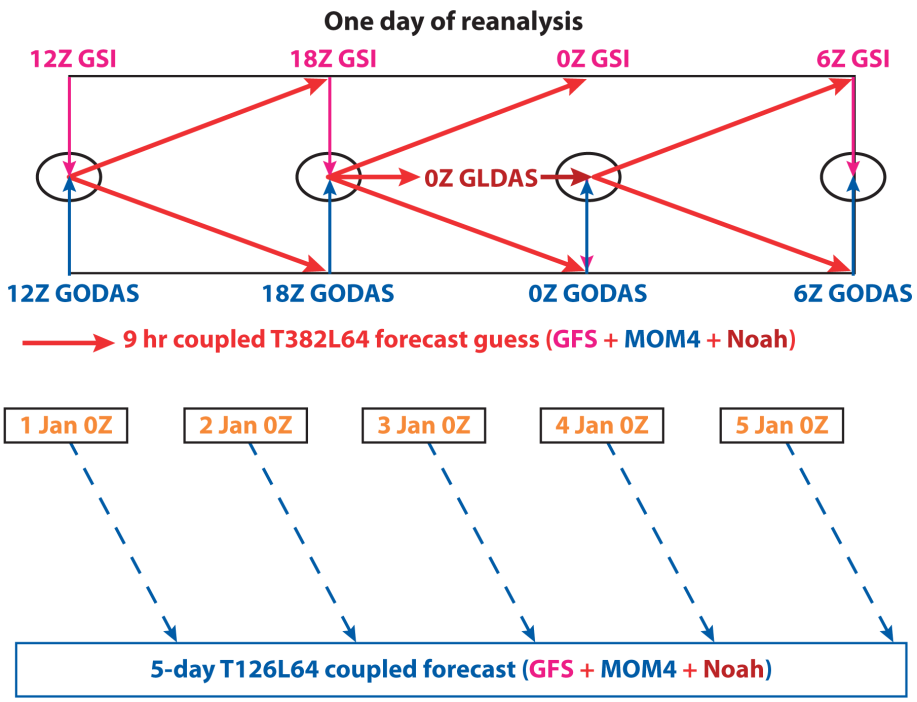


Figure 4 Schematic showing NCEPs CFSR, weakly coupled reanalysis procedure. From Saha et al (2010).

The assimilation of both atmosphere and ocean data take place every 6 hours using a 3DVar scheme for both systems. The land assimilation is only carried out once per day. The reanalysis system does not use ensembles but the background error covariances are still flow dependent because climatological variances are scaled by the 6 hour tendencies centred on analysis times from the 9 hour forecasts made after the preceding analysis (see Fig 5a). Despite use of the coupled model and the high frequency of the assimilation, which should allow for improved assimilation of near surface data, the analysis system has only assimilated pre-analysed gridded products for SST, precipitation, sea-ice concentration and snow cover, developed or interpolated as daily varying fields, see Saha for details. This provides a strong constraint on surface conditions which are not allowed to evolve too far away from these analyses.

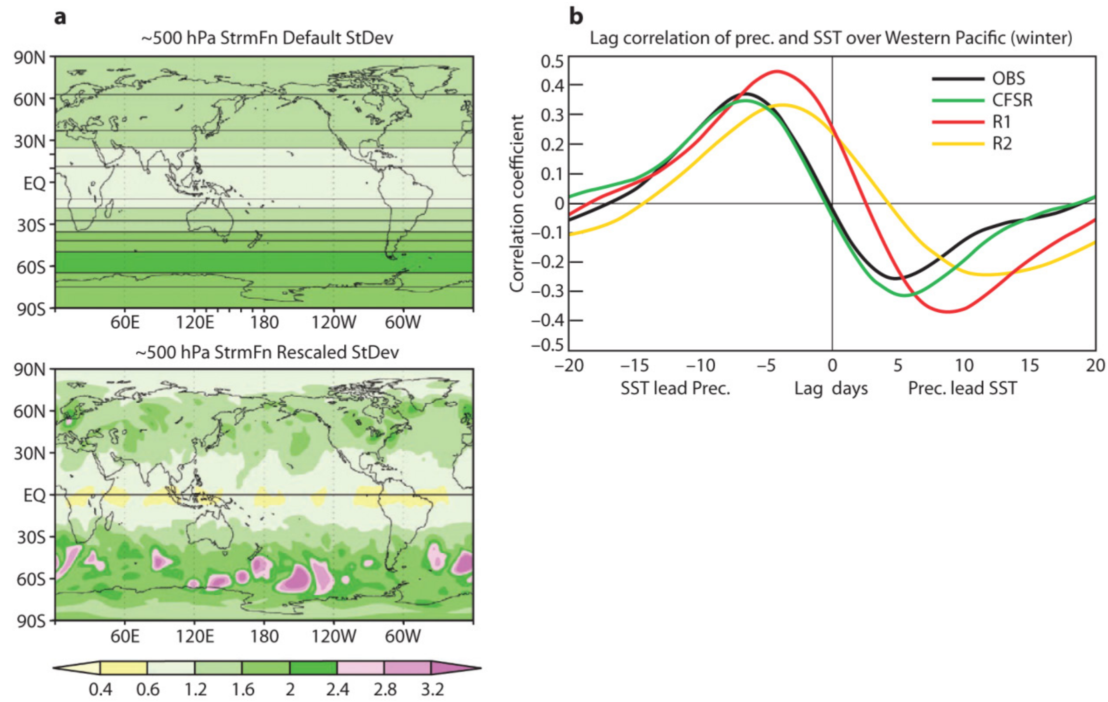


Figure 5 a) shows how background error variances become flow dependent through scaling of climatological variances with current 6hr tendencies, b) shows the lag correlation between precipitation and SST anomalies in the western pacific from coupled (CFSR) and uncoupled (R1,2) reanalyses. From Saha et al (2010).

One clear improvement in the CFSR reanalysis over previous uncoupled NCEP reanalyses which is clearly attributable to the coupling is the reproduction of the MJO. The phase relationship between SST and precipitation in the tropics for the whole 1979-2008 period is shown in Fig 5b clearly indicating the improved phase relationship and improved precipitation strength over previous results.

4.2. The Met Office Experiments in Monthly forecasting

At the Met Office plans are underway to use coupled modelling for NWP forecasting out to the 1 month timescale. Eventually the plans are to develop a weakly coupled assimilation system and to progress to using coupled covariances on longer timescales. So far comparisons have been made with the UM N216L85 atmospheric model coupled to the NEMO ¼º L50 ocean with a 3 hourly coupling timescale. Coupled short range forecasts out to 15 days ahead, with verifying atmospheric and ocean analyses and with equivalent uncoupled ocean and atmosphere forecasts, are reported in Shelly et al (2011). The atmospheric assimilation is 6 hour 4DVar and the ocean system is based on the operational FOAM OI. A set of 12 summer and winter single hindcasts were made through 2007-2008. Results of the coupled system are broadly similar to those of the separate uncoupled forecasts for atmospheric and SST forecast skill. The one tropical cyclone track studied showed similar behaviour. It was established that the diurnal cycle in SSTs is reasonably well captured in both the coupled model and the control ocean forced with atmospheric forecasts which used daily mean SSTs at the lower boundary, see Fig 6a. This shows that the diurnal radiation forcing cycle alone (without any coupled feedbacks from the SST) is sufficient to capture reasonable amplitudes of diurnal cycle in this case.

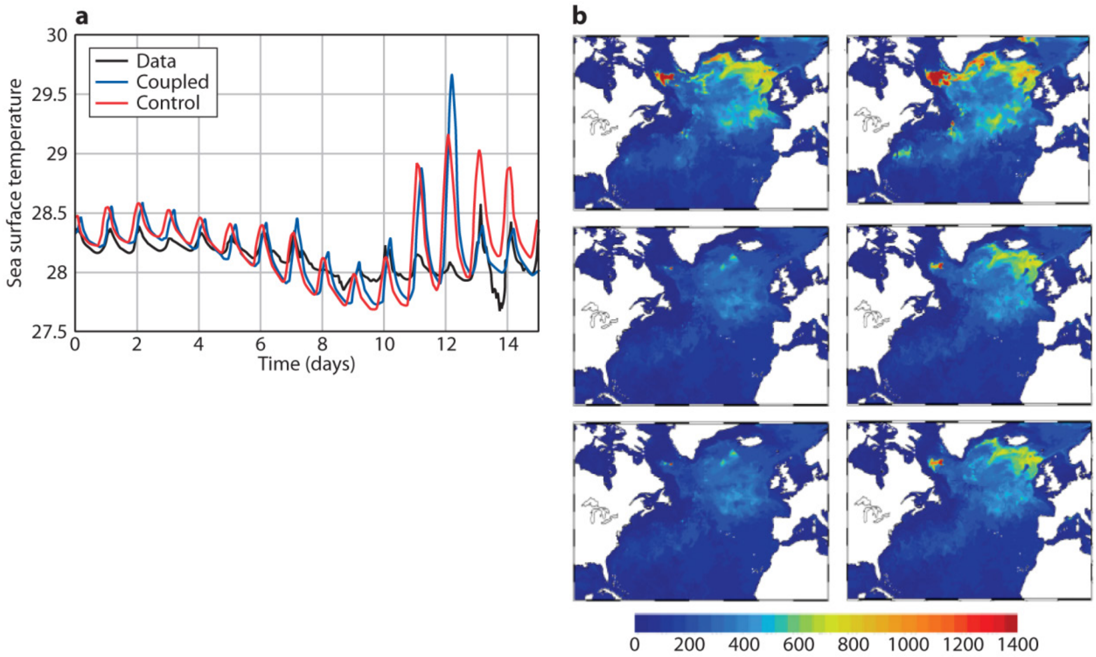


Figure 6 a) Diurnal cycle SST predictions from coupled and uncoupled (control) Met Office 15 day forecasts. b) Mixed layer depth analyses at days 1 (left) and 15 (right) and coupled and uncoupled forecasts. From Shelley et al (2011)

Figure 6b shows mixed layer depth forecasts and analyses for the coupled system and the ocean control. Here both forecasts appear to show initialisation shocks because the Mixed layer depths reasonably match the FOAM analyses after 15 day forecasts but are considerably too shallow in the early phases, after 1 day. It is possible that the ocean initial conditions had too shallow mixed layers but this seems unlikely given the data quantity and quality in 2007.

4.3. The Canadian Atmosphere-Ice-Ocean Coupled forecasts

The Canadian Met service is in the process of introducing a coupled NWP system into operations after considerable successes in forecasting both summer and winter temperature variability and particularly extreme temperature events in winter. So far tests have been performed with a regional coupled model focussing on the Gulf of St Lawrence. A 4DVar is used over 6 hours for the Atmospheric assimilation, along with a 3DVar system to initialise the ice thicknesses, and a SEEK (Singular Evolutive Extended Kalman) filter for the ocean properties. Figure 7a shows an example of 48 hour forecasts for the uncoupled operational system and the new coupled system, for air temperatures in the Gulf of St Lawrence, and verifying analysis. The uncoupled system tends to forecast much colder temperatures due to too much ice cover. The existence of a dynamic ice field together with initialised thicknesses in the coupled system allows large bodies of open water to develop which buffer surface temperature changes through air-sea fluxes. Figure 7b shows a statistical sample of improved errors and biases for the coupled system, which will be put into operational use shortly.

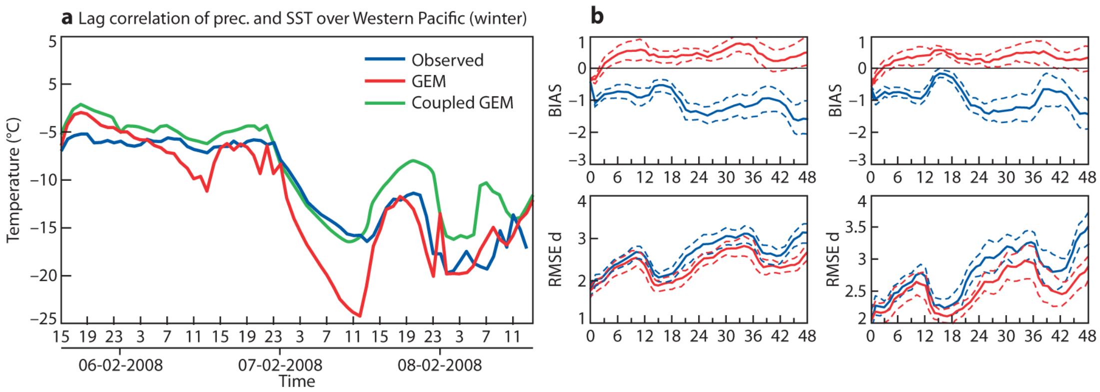


Figure 7 a) 48 hour regional forecasts of surface air temperatures over the Gulf of St Lawrence from coupled and uncoupled models of the Canadian Met Agency. b) Errors in coupled(red) and uncoupled (blue) models over 48 hour forecasts in Feb 2008 for Surface air temperatures (left) and Dew point temperatures (right). From Faucher et al (2011).

4.4. Australian Bureau of Meteorology (BMRC) experiments with Coupled Covariances

At the BMRC the route to coupled data assimilation is being explored using ensembles to study coupled covariances. The seasonal forecasting model used for tests is based on the UK Met Office atmosphere N96L38 and the MOM4 ocean at 1° resolution. An ensemble assimilation system is envisaged using cross covariances as part of the initialisation procedure. In order to prepare for this, a study of cross covariances has been performed using 90 member ensemble integrations of the coupled model forecasting the 1998 ENSO event.

Figure 8 shows some of the coupled covariances in the Pacific Ocean in February 1997 after 2 months of ensemble integration. Covariances with the 100m temperature at 180E are shown. In the ocean the strongest correlations are just below the 100m depth level (top) where the thermocline gradients are strongest, but the SSTs in the regions above are also clearly correlated. The zonal currents are correlated through the changes in the zonal temperature gradients driving the undercurrent. Turning to the atmosphere there is a response in the outgoing long-way radiation as expected for the given SST changes. There are also strong correlations in the wind field, mainly positioned further west and showing a strong MJO like signal (all results from Oakly et al; 2011).

These results show that the signal of coupled modes can be clearly captured by ensemble variability in coupled models and clearly these background error covariances, combined with observational data, would have good prospects for initialising the phase and amplitude of such coupled variability more accurately.

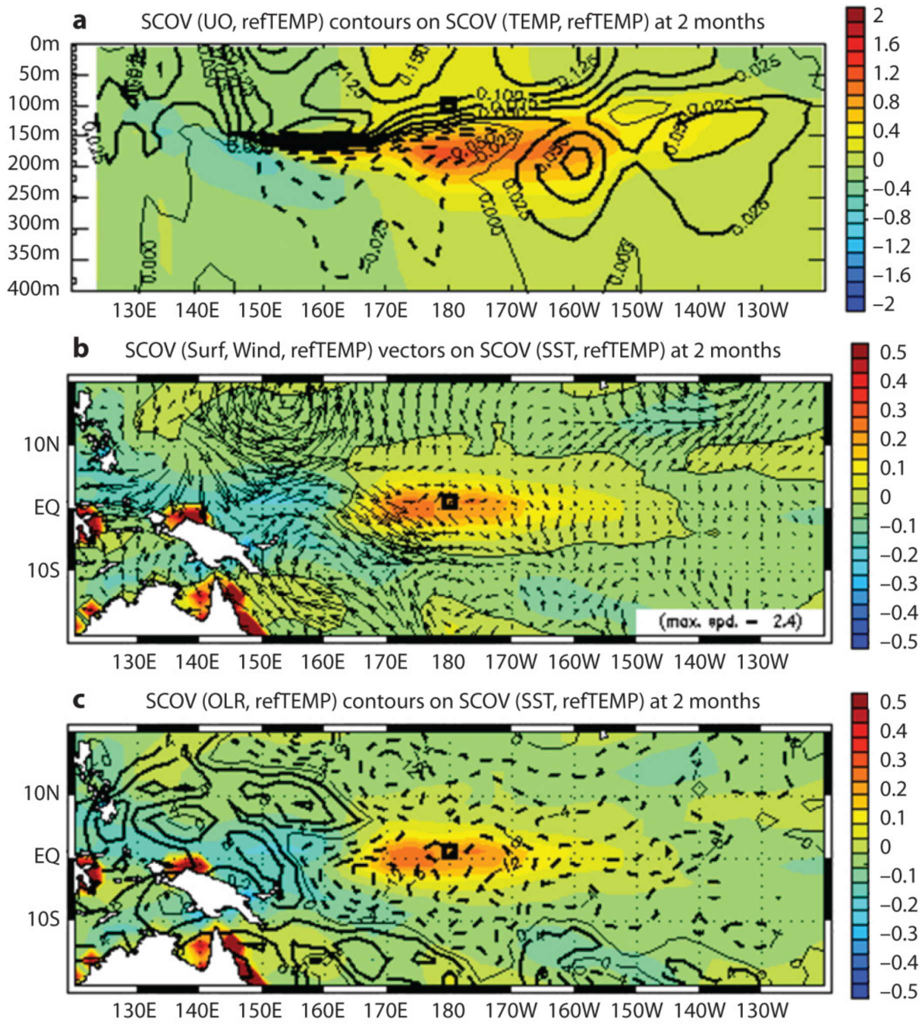


Figure 8. Covariances against 100m ocean temperatures at 180W, from 90 member ensemble 2 month forecasts in February 1997. Top: Zonal section of temperatures and zonal currents (contoured), Middle: SSTs and surface wind speeds (vectors), Bottom: SSTs and OLR (contours). From Oakly et al (2011)

4.5. JAMSTEC Coupled 4DVar for seasonal forecasting

The JAMSTEC group are still the only large group to have developed a 4DVar coupled assimilation approach. The system uses 4DVar over 9 month windows with a 10 day smoothing window to reduce noise for all observations in the forward modelling. In the adjoint model the Lagrange multipliers are subject to linear damping to reduce the chaotic growth of sensitivity, mainly arising from atmospheric instability. This seems to be effective in allowing convergence of the cost function, see Fig 9. More details can be found in Sugiura et al (2008), and also in the previous ECMWF seminar Haines (2007).

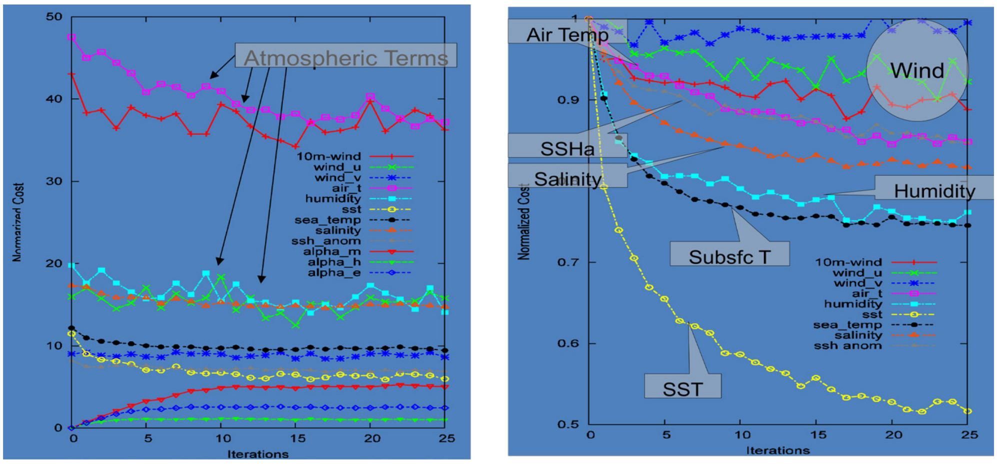


Figure 9 Cost function minimisation from the JAMSTEC coupled 4dVar system showing Left: the atmospheric state minimisation for the 9 month period beginning in July 1996, including surface coupling coefficients; and Right: the normalised cost function minimisation for atmospheric and oceanic state variables for minimisations throughout the 1990's. Sugiura et al (2008)

An important element of the JAMSTEC system is the 4DVar tuning of the coupling parameters for momentum and sensible and latent heat exchanges, which are allowed to vary spatially and on the same 10 day timescale as the observations. This tuning of the coupling strengths (within background error bounds, see the cost function contributions from these terms in Fig 9) allows coupled processes to account for assimilation changes to a significant extent thus contributing to maintaining well balanced coupled boundary layers. An interesting example of the contribution of this tuning is in the reproduction of the Indian Ocean Dipole during the 1998 ENSO event, Fig 10.

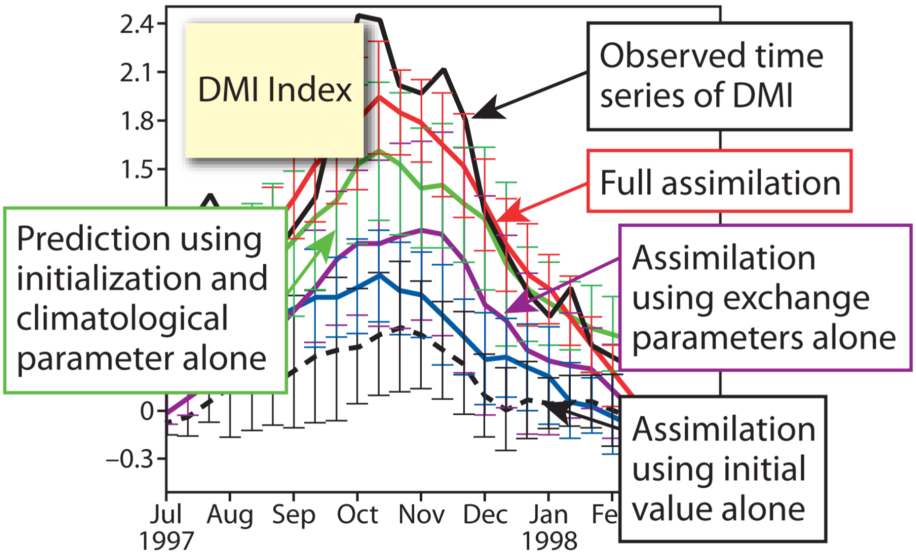


Figure 10: Indian Ocean Dipole (Dipole Mode Index) over 9 month minimisation period in 1997-98. Sensitivity of analysis to initial condition and coupling coefficient tuning, and also use of 3 year average coupling coefficients.

The figure shows that the ability to reproduce the DMI (Dipole Mode Index) over a 9 month period depends as much on tuning the coupling parameters as it does on setting the initial conditions. The figure also shows the results of tuning the coupling parameters to 3 year average values, which still considerably enhances the DMI reproduction. (Prof. Awaji, personal communication).

The disadvantages of this system is that it is very much focussed on the longer lead time forecasting capabilities, it does not allow improved use of surface dataset eg. with diurnal variability, and it does not lend itself easily to initialising coupled NWP type forecasts. This is one reason why the approach is not being pursued elsewhere.

4.6. The GFDL Coupled Ensemble system

At GFDL an Ensemble Adjustment Kalman filter is being used with a coupled model, as described in the Zhang et al (2007) study based on CM2.0 2° 24L model and MOM4 at 1° 22L. Here typically a 6-10 member ensemble may be run, with the coupled probability distribution function (PDF) updated to fit with observations entirely based on the coupled covariances represented within the ensemble, see schematic Fig 11. This has the potential advantage of building in strong coupling into the increments and so really represents a strongly coupled assimilation system. Results demonstrate that the coupled covariances do successfully represent geostrophic relationships within atmospheric variables, and also successfully capture S(T) relationships in the ocean which are needed to successfully assimilate stand-alone temperature data, Troccoli et al (2002). It is much more difficult to use the ensemble covariances across the air sea boundary without introducing noise, due to the different timescales of the atmosphere and ocean systems, and therefore there are limits placed on the use of the cross-covariance information. This system has mostly been used for seasonal to decadal forecasting regime in which atmospheric assimilation is restricted to assimilation of pre-analysed fields e.g. from NCEP.

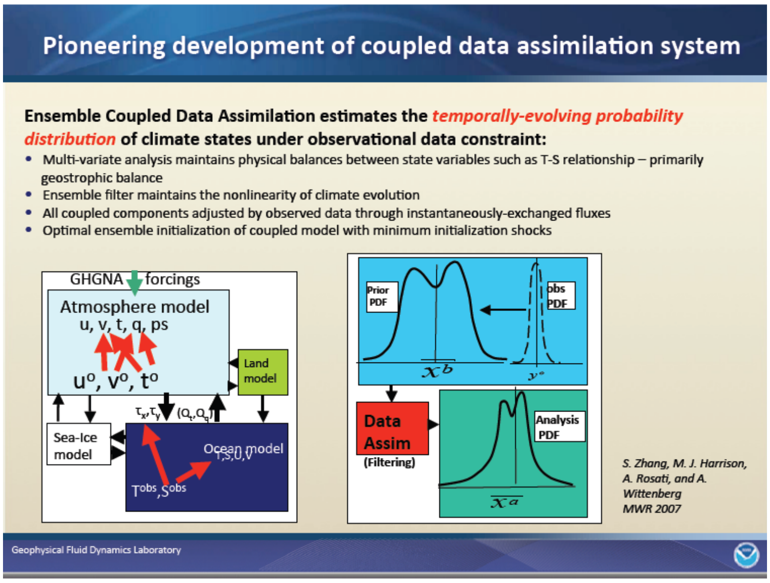


Figure 11: Schematic GFDL Ensemble Adjustment filter for the coupled model methodology, from Zhang et al (2007).

4.7. The DePreSys Anomaly assimilation system

The DePreSys anomaly assimilation approach to coupled decadal forecasting developed at the Hadley Centre, Smith et al (2007), has been taking a different approach to initialization in order to try to (i) avoid issues of model bias, and also (ii) reduce coupling shocks. This anomaly approach does not sit well with the desire for a seamless coupled assimilation system but it makes some sense on longer forecasting timescales to avoid dealing with major non-linear model drifts during the forecast periods (drift correction methods are usually linear). Problems with the approach include, how to define the climatology under changing greenhouse gas forcing, and recognizing that it does not entirely remove initialization shocks, as can be seen in Fig 12, from Robson (2010). The size of these shocks obviously depends on the size of the anomalies being introduced, and in present algorithms no attempts have been made to ensure balance between the atmospheric and oceanic increments.

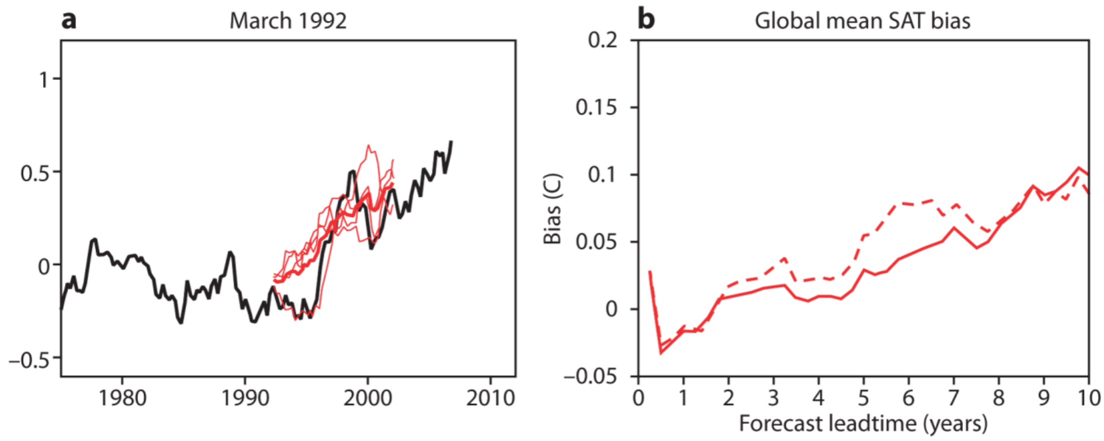


Figure 12 a) Observations of N. Atlantic upper ocean heat content (black) and DePreSys predictions from March 1992 hindcast (red). Note that three ensemble members predict a rapid warming, and one follows the observations more closely. b) Growth of surface air temperature bias in DePreSys hindcasts showing initialisation shock in the first two seasons. Both from Robson (2010, PhD thesis).

5. Summary and Conclusions

Coupled assimilation is still in the early stages of development but with the growing plans to use coupled models for NWP as well as for longer range forecasts it is an area which will attract much new work in the coming years. If we consider the potential role of ensemble approaches these seem well suited to coupled assimilation. They provide a natural method for developing flow dependent coupled error covariances, which would then allow a better background weighting against surface data uncertainties. It is important to recognize the different rate of spread in the atmospheric and ocean components and the different volumes of data which constrain that spread, so that it could be necessary to maintain appropriate spread in the ensemble ocean components through many cycles of atmospheric assimilation. It will also be very important to assess the impact of any bias correction methods used on the development of the ensemble spread.

As for 4DVar methods, these are the best way of achieving balanced initial conditions and for NWP purposes these would likely continue to be necessary at least for the atmospheric components of the system. They would also have the potential for reducing boundary condition coupling shocks if the surface ocean could be included in this process. They offer the possibility of directly tuning the atmosphere-ocean coupling parameters, which is being looked at by several of the systems discussed above. However time windows are constrained to be low by the error growth rates in the atmosphere, perhaps too low to allow useful ocean data assimilation. The averaging methods used by JAMSTEC for their long-window 4DVar methodology seem to have nice properties for longer range predictions and the slow mode adjoint is a useful diagnostic methodology for long term changes. However the system is very expensive and it is not useful for NWP or the assimilation of rapidly varying fields such as diurnal SST observations, which is why it is not now being pursued elsewhere.

There are very few systems currently implemented that could be called coupled data assimilation. Those planned for development nearly all use a weak coupling methodology where the emphasis is on using a coupled model for the forecasts and background analyses rather than accounting for coupling in the assimilation algorithms. Transition to a more strongly coupled assimilation approach will require more research on both coupled state covariances and also on the tuning of coupling parameters, which are certainly poorly known for the full range of surface state conditions. The future of anomaly assimilation is currently uncertain although it is being widely used for IPCC decadal forecast work at the current time. It seems likely that as coupled data assimilation methods are developed there will continue to be a need for bias correction methods and there could well be value in exploring more rigorously the relationships between bias corrections and anomaly assimilation, which is itself an extreme form of bias correction.

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