Introduction

The workshop covered air-sea interaction on a variety of timescales from days to months, the challenges in assimilating data into ocean models and of making forecasts on seasonal and shorter timescales. Seasonal forecasting using full atmosphere and ocean general circulation models is a maturing field of endeavour. Four different groups which are using fully coupled GCMs presented their experiences. In running a routine forecasting system one has to deal with the systematic error in the coupled models as well as with how best to initialise them. The ocean initial state plays a major role in providing the information on which a climate forecast is based. Determining the ocean state from the limited ocean observations available is not easy. There is no agreed strategy for dealing with systematic model error when assimilating data. Model error in this context includes error in the fields used to force the ocean model. Recent advances in ocean data assimilation including 4d variational assimilation, Ensemble Kalman filtering and generalisation were discussed. Potential advances in ocean models, including the use of a sea-ice module were discussed.

Although ENSO is clearly the largest mode of climate variability on seasonal timescales, it is not the only one. There is evidence of potentially important and at least partly predictable variability in the Indian and Atlantic oceans. At intraseasonal time scales the Madden Julian Oscillation (MJO) is an important energetic process which may involve air sea interaction. Although it is unclear how the MJO affects variability such as ENSO and the "Indian Ocean Dipole" or how these processes affect the MJO, it is clear the coupled models have difficulty representing variability in this time range.

There is evidence of important air-sea interaction on the timescale of hours to days in the tropical oceans. The advent of satellites to measure accurately the surface wind and SST allows a comparison of this interaction in nature and in the models, as well as an assessment of the spatial extent of this interaction. The ECMWF model includes a wave model though this is still not as fully coupled as it could be. The potential importance of more tightly coupling the ocean atmosphere exchanges through the wave model was discussed.

The workshop followed the usual format of invited lectures followed by discussions in working groups and concluded with a plenary session. Groups addressed the following issues: "operational forecasting with coupled models", "ocean data assimilation", and "mechanisms and model development". The discussions and recommendations of the three working groups are summarised in the following reports. Lecturers provided extended abstracts for this volume. The slides of the presentations are available on the web at http://www.ecmwf.int/publications/library/ecpublications/proceedings/upper_ocean_workshop_Nov2002/

1. Working Group 1: Operational forecasting with coupled models

Mike Davey (Ch), Max Suarez(Ch), Oscar Alves, Renate Hagedorn, Paco Doblas Reyes, Sarah Ineson, Laura Ferranti, Tim Stockdale, Alberto Troccoli, Frederic Vitart.

The group considered scientific and technical issues to be important, but noted that product and data issues are also vital to the practical development of operational forecasting. These will be discussed in turn.

1.1. Scientific and technical issues

Forecast errors should remain a focus in the development of our coupled forecasting systems. It is important to focus on those errors that directly impact the quality of our forecast and forecast products. There is scope for better diagnostics of existing forecasts, in particular looking at the evolution of errors. More use can be made of the ocean analysis in the attribution of errors. Distinguishing between component model error, forcing error, and errors due to the coupled system as a whole is an important part of error diagnosis.

The group considered the present focus on model development, rather than correcting for model errors with techniques such as flux correction, to be the correct strategy. Model assessment needs to done using both the coupled model and individual components as appropriate. The atmosphere model is a critical component of the seasonal forecasting system, and there needs to be close coordination with the atmosphere model development group. A strong emphasis on the tropical regions is needed, in particular for the equatorial wind stresses on different timescales. The coupled model should also be tested in long integrations. There should be coordination on targeting of resources for investigating model errors.

Ensemble generation is seen as another key aspect of forecasting. The present burst mode of sampling has many advantages over a lag average approach, but it was noted that the one month interval between forecast updates may be too long for some applications, such as monitoring the development of an El Nino event.

There is no clear best technique for ensemble generation. For targeted methods, it is recommended that the Centre maintain links with research in this area. For random perturbations, improvements should be made to the present system:

- Perturbing the data
- Error sampling strategy - should change with time, due to evolution of observing system
- Lorenz type analysis of the forecast errors may be helpful

The possibility of adding artificial forcing during the forecast run (e.g. to simulate MJO activity) should be considered.

Multi-model ensembles are important, and the positive results from DEMETER should be pursued. More work is needed on the criteria for choosing models and the weight given to each model. Co-ordination with other multi-model efforts should be a priority - IRI, APCN (Asia Pacific Climate Network), CLIVAR: SMIP-HFP (Seasonal Model Intercomparison Project - Historical Forecast Project). Practical issues will need to be considered, including timeliness, ensemble size, methodologies. Data exchange issues are discussed below.

Sub-seasonal timescales: the Centre's initiative to use coupled models for extended range forecasting is strongly supported. NWP/tropical cyclone forecasting has different requirements for both model and data assimilation, e.g. a better resolution of the mixed layer and eddy field.

Land and sea ice. The land surface is recognised as important on seasonal and sub-seasonal timescales, both in terms of modelling and initialization. These are specialized challenges, and a workshop on this topic should be considered (soil moisture, snow, and reanalysis issues).

Sea ice is of interest to some Member States, and the Centre should collaborate with other institutes (eg UKMO, Alfred Wegener Institute, Bremerhaven) to investigate the feasibility and potential benefits.

1.2. Product and data issues

Research products should be available for the purpose of model error diagnosis, model development and intercomparison. The group recommended that the main institutes should share model output and derived products through a live access server. Products should include standard hindcasts and archived real-time forecasts. There should be enough detail for scientific analysis: some variables should have daily resolution; upper air, surface and sub-surface data should be included; and all ensemble members should be present. If necessary, data could be limited to contributing partners.

Forecast products are important for real-time monitoring, understanding and guidance. The main institutes should share real-time limited model output and derived products. Products should include standard forecasts and other fields to aid interpretation, eg Nino indices, equatorial Hovmoller diagrams etc. These products should be in the form of numerical data. If necessary they should be limited to contributing partners.

Public web-based products. The group were happy with the general level of output. It was felt that providing forecasts for individual months was unlikely to be justified. More information to allow comparison of forecasts would be useful. It would be good to augment the raw model terciles with calibrated tercile products. Past forecasts should be available with verification. There was no recommendation on skill scores - the group felt it too early to say what best practice will turn out to be.

2. Working group 2: OCEAN DATA ASSIMILATION

Keith Haines (Ch), Erik Anderson, Magdalena Balmaseda, Mike Fisher, Matt Huddleston, Peter Jan van Leeuwen, Matt Martin, Michele Reinecker, Arthur Vidard, Anthony Weaver

2.1. Introduction

Ocean initial conditions are an essential component of the seasonal forecast system. Having a good estimate of the ocean subsurface temperature has proved beneficial for seasonal forecasts (Alves et al. 2002). However, there is growing evidence that to get the very best results from the temperature data requires the application of additional dynamical constraints (Bell et al. 2002, Burgers et al. 2002, Vialard et al. 2003), and conservation principles (Troccoli et al. 2002). Often these additional constraints can be applied in an ad hoc way at the time of assimilation to obtain a "balanced" estimate of the ocean state, but it is preferable to improve the formulation of the error covariance matrices to achieve this result and this was one of the key issues discussed. The recommendations made here are mainly concerned with this aspect, and they have been formulated in a way general enough to be applicable to any assimilation method, either sequential or variational.

Although the current ECMWF operational ocean analysis only makes use of subsurface temperature observations, there has been work on developing schemes to assimilate altimeter information (sea level anomalies are available in near real time), together with subsurface temperature data. One of these schemes (Segschneider et al 2001) will soon be ready for operational use. With this scheme, the inclusion of altimeter information in the ocean assimilation improves the estimation of the ocean state, especially in areas where the subsurface data coverage is sparse. In other areas, such us the equatorial Pacific, where the TAO array provides better spatial and temporal coverage, the impact of the altimeter data (through the current scheme) on the upper ocean thermal structure is not so noticeable, which may be due to the redundancy of the information, or due to the sub-optimal use of the altimeter information in the TAO region

Another important untapped data source is SST. Most of the current ocean data assimilation systems do not "assimilate" SST, but use a very strong relaxation to some kind of separately analyzed SST product. It was recognised that strong variations in SST often occur at the beginning of coupled model forecasts suggesting that the initial SST conditions are not well matched to the atmosphere above. Therefore the possibility of performing an SST analysis was discussed in the context of coupled initialization. In general, the growing number of observations of different nature (altimeter, salinity profiles from ARGO floats, sea surface temperature, etc) poses the problem of how to make optimal use of all the information, particularly the complimentary information, in these data.

The use of dynamical coupled models for extended range forecasts (10 days and beyond), requires that the ocean estimates provided by the ocean data assimilation system be used as initial states for an ensemble of coupled forecast. Ensemble initialisation requires not only a single "best" analysis, but also an estimate of the uncertainty in the analysis. This issue was recognised as important but there was insufficient time to discuss it in detail. Clearly there are different ways of estimating uncertainty in the analysis and these must be considered carefully in the context of ensemble forecasting.

This report is a summary of the discussions that were held as prompted by some of these key issues, followed by a list of recommendations that try to encompass the spirit of the debate.

Issues:

1. Dealing with bias in the data assimilation problem
2. Importance of dynamical balances at the equator
3. New observation types (Salinity, Altimeter) and extending the concept of balance
4. Coupled data assimilation and SST
5. Generation of an ensemble of initial conditions for probabilistic forecasts
6. Adaptive methods and consistency checks on errors.

2.2. Dealing with bias in the data assimilation problem

It has been shown that many ocean data assimilation systems share the problem that the background state can be seriously biased. In systems designed under the assumption of a bias-free background, the presence of bias leads to a suboptimal analysis (Dee and DaSilva, 1998) if not to more serious consequences such as data rejection by instability of the analysis or by quality control procedures. For initialization of seasonal forecasts, the presence of model bias poses a problem when observations are sparse in time since assimilation can generate spurious time variability and contaminate the interannual signal.

The consensus was that it is important to identify and understand the bias. It may come from errors in the model formulation, errors in the surface forcing fields or errors induced by the assimilation system itself. An example of the latter, which was highlighted in this workshop, is the bias induced by univariate data assimilation. Near the equator, univariate assimilation can upset the balance properties in the model and lead to spurious circulations that can significantly bias the model background state. This particular bias can be greatly reduced by using multivariate assimilation procedures. This illustrates the need of clearly identifying the nature of the bias before answering the question of how to deal with it. Diagnostics are essential for this purpose.

Three possibilities were put forward to address the problem of bias in data assimilation:

a) To develop models for the bias evolution, and its online estimation within the data assimilation algorithm. One example of this is the pressure correction method of Bell et al. (2002).

b) To assimilate only anomalies, without any attempt to correct the bias in the background. A separate estimate of the mean state is then required. The example here is assimilation of altimeter sea level anomalies when the absolute sea level relative to the geoid is not known. The mean sea level is often provided by the model and any biases in this mean sea level are left in place.

c) To use the information given by the assimilation statistics (innovations, analysis residuals and increments) to diagnose model bias. The bias however is not separated out . This approach was used by Weaver et al. (2003) to identify the bias associated with univariate data assimilation described above.

Option a) for bias correction is especially tempting when considering coupled initialization and coupled forecasts, since the bias identified during the assimilation stage could be used in the forecast phase. However tempting, it was considered premature, especially because of the dangers of flux corrections (one may end up introducing errors that would not exist in a non-flux corrected system). Also, the bias identified in uncoupled data assimilation may be quite different from the bias in the coupled system itself.

Option b) poses the problem of having a separate, good quality mean state, which may not be available. Besides, the anomalies are usually dependent on the mean flow (for instance, the anomalies of subsurface temperature tend to occur near the thermocline), and anomaly initialization may lead to imposing the right anomaly in the wrong place, which may make matters worse.

Option c) has many useful aspects provided the assimilation statistics are interpreted carefully. Routine evaluation of the assimilation statistics (e.g., to identify biases) should be done regardless of which option is adopted.

In many sequential schemes, such as the ECMWF OI, time-distributed observations are assimilated simultaneously, usually by comparing with the background state at the centre of the assimilation window. This procedure can result in artificially large innovations being computed if there is significant variability in the observations at time-scales less than the window width and spatial scales larger than the length scale of the background error. This could easily occur, for example, for a low baroclinic mode equatorial Kelvin wave, which can travel nearly 2500 km in the 10-day window width currently used in the ECMWF OI. These artificial innovations could lead to a source of bias in the analysis. The incremental FGAT (First-Guess at Appropriate Time) procedure, in which the background is first compared with the observations at their appropriate measurement times, was proposed as a straightforward way for reducing model-data inconsistencies in sequential assimilation schemes.

2.3. Importance of dynamical balance at the equator

There are suggestions that ocean data assimilation can disturb the dynamical balance at the equator, which can become an important source of error in the background state. It is important to investigate the nature of the dynamical balances that operate in ocean models, especially at the equator, and implement them as constraints in the formulation of the background-error covariance matrix. Balanced background-error covariances would also be beneficial for 4D-Var methods by helping to eliminate physically unrealistic solutions from the control space in which the analysis is performed.

Monte Carlo methods can help in the formulation of the balance relationships, and special attention should be paid to the vertical structure of the geostrophic balance and to the symmetry characteristics near the equator. At the equator, there may be other higher order dynamical balances operating, which are not necessarily linear. Nonlinear balance relationships can always be linearised about the background state to make them suitable for implementation within a covariance matrix.

Data assimilation near the equator is prone to generate spurious equatorial gravity waves unless special measures are taken. Digital filters were proposed as an effective way of reducing gravity wave "noise". For sequential methods, the digital filter could be applied as an a posteriori correction to the analysis. This could be considered as an alternative to the simple "time filtering" method currently employed in the ECMWF OI system, which involves gradually updating the model with the analysis increment. In 4D-Var, it is best to introduce the digital filter directly in the cost function of the assimilation problem through a weak constraint term that penalises departures from a temporally "smooth" state trajectory.

New ensemble techniques, like sequential importance re-sampling, do not update ensemble members at measurement times, but are re-weighted instead. Consequently, the balance problems are not present in these methods.

2.4. Assimilation of Altimeter, Salinity, and extending the concept of balance

An effective way of exploiting different observational data sets is by means of the separation of the background-error covariance matrix into balanced and unbalanced parts. The term "balance" might have its origins in the "geostrophic balance" constraint that was first introduced to constrain the covariances in atmospheric analyses. However, here the meaning is now much wider, and refers to any kind of constraint that can be explicitly introduced in the formulation of the background error statistics to describe the important relationships between variables which may be derived by non-statistical means.

Some of these constraints are already used in operational ocean data assimilation at ECMWF. For instance, a preservation of the background Temperature/Salinity (T/S) relationship is imposed when assimilating temperature data only. However, in the current formulation, this constraint is applied a posteriori and thus does not feature in the computation of the analysis increment.

Many oceanic processes such as wave motions can be considered Lagrangian and adiabatic. The introduction of these principles in the formulation of the covariance matrix can greatly reduce the number of degrees of freedom in the analysis. It may also be a natural way of introducing flow-dependent error statistics. Here are some examples of how to introduce Lagrangian constraints:

- The use of isopycnal coordinates for the analysis framework (which does not necessarily imply an isopycnal model) may allow for a better analysis in regions of strong density gradients (e.g., the thermocline). An isopycnal-based analysis system would favour the spreading of information along the isopycnals and thus may allow for much longer “horizontal” (along isopycnal) correlation length scales than in a geopotential coordinate system.

- Preservation of the background T/S relationship, unless there is enough information to modify the background water mass characteristics. This would be the case only when there are simultaneous measurements of temperature and salinity (e.g., from ARGO floats).

- Altimeter assimilation assuming redistribution of the waters (conserving water volumes and T/S properties): for instance, by the vertical displacement of the water column.

The introduction of constraints in a covariance formulation may be difficult, especially if the increments are large and the linear approximation is no longer valid. A possibility is to relinearize the non linear constraints using updated estimates of the background state..

Even if the constraints are introduced in the "balanced" part of the covariance matrices, it is still necessary to specify the error characteristics (spatial correlations and variances) of the "unbalanced" part. These can be estimated by, for example, Monte Carlo techniques, and may require periodic retuning (e.g., each time a new component is added to the observing network and included in the assimilation system).

At ECMWF, the current method to assimilate altimeter data in conjunction with subsurface data involves the creation of pseudo subsurface temperature profiles that the univariate OI method is then able to assimilate. A preferred option is the use of a multivariate covariance formulation, which would allow the direct assimilation of sea level information. An effective formulation of the background error covariances is crucial for exploiting the valuable information provided by altimeter data.

2.5. Coupled Data Assimilation and SST

Most of the coupled models suffer an initialization shock when starting the coupled forecast, but the extent to which the initialization shock damages the quality of the forecasts is unknown. Sea surface temperature often sensitively detects this shock and a method for dealing with this is likely to be necessary before an effective method for SST assimilation is developed. Coupled initialisation was considered to be an important new area to develop.

Assuming that there were robust methods for bias correction during the assimilation phase, and that the systematic error would be the same during the initialization and during the forecast, applying the bias correction during the forecast phase may improve results. Data assimilation in coupled mode would be a step forward on ensuring that the systematic error during the assimilation and the forecasts phase were the same.

The possibility of having a coupled ocean atmosphere model for forecasts for the medium range as well as for the seasonal range raises the question of having a coupled ocean-atmosphere initialization system as well. However attractive the idea of a seamless system may look, there are several difficulties of a theoretical and practical nature.

The most challenging problem is the presence of two different time scales in a chaotic system (fast atmosphere, slow ocean), and the need to initialize both of them. A 2-tier approach, whereby the fast and slow time scales are initialized separately may be a promising way forward.

For the fast atmospheric time scales, the possibility of data assimilation in an atmosphere model coupled to an ocean mixed layer was discussed. The inclusion of the ocean mixed layer may improve the estimation of atmospheric fluxes, and offer a suitable framework for assimilating SST information. The ocean mixed layer could be a common element between the ocean and the atmosphere. Even if the data assimilation in the ocean and atmosphere were done separately, sharing a common element (the ocean mixed layer and SST) might help to maintain some thermodynamical balances. The ocean mixed layer should already contain information about the subsurface ocean temperature and heat content from data such as TAO when it is used for the atmospheric assimilation. Then assimilating SST to control the mixed layer would allow the further spreading of information to both the atmosphere and the subsurface ocean. It is recommended to follow closely the developments in GODAE on SST accuracy and availability.

2.6. Generation of an ensemble of initial conditions for probabilistic forecasts

Little was discussed because of lack of time.

The ensemble sequential methods offer one advantage since estimates of the analysis error covariance matrix or PDFs are direct by-products of the assimilation method. But adjoint models used in 4D-Var methods offer the possibility of computing optimal perturbations (singular vectors, stochastic optimals) to the analysis. A combination of the two approaches is not impossible.

In an operational system with nested different range coupled forecasts, it is possible to envisage the use of the ensemble created by the EPS as the first guess for the assimilation system for seasonal forecasts.

2.7. Adaptive methods and consistency checks

Very little was discussed although it was noted as a useful area for further investigation. A suggestion for a simplified scheme is to retune the variances, rather than the full covariance matrix.

It is desirable to have a consistent programme to examine the assimilation statistics, to identify biases and to estimate covariances. The ENACT project would offer a good opportunity to develop such a programme.

2.8. Recommendations

Recommendation 1:

Need to develop multivariate covariances, following the approach of "constrained" and "unconstrained" (balanced/unbalanced) partition.

1. To identify functional relationships between variables.
2. To explore the nature of the dynamical balances at the equator, with emphasis on the Kelvin wave initialization.
3. To adapt the coordinate system in the analysis to reflect the dynamics and thermodynamics of the system. For example assimilation in isopycnal coordinates, makes it easier to apply thermodynamic constraints with the objective of preserving a) water mass volume and b) T/S relationships.
4. To estimate the "unconstrained" part of the covariances statistically.

Recommendation 2:

To evaluate the effectiveness and feasibility of flow-dependent formulations of the background-error covariances.

Flow-dependent formulations should be investigated for the correlations, the variances and/or the balance relations. The formulation may need to depend on:

1. The background flow
2. The amplitude of the analysis increments to allow for non-linearity.

Recommendation 3:

Introduction of the FGAT approach in sequential methods.

Recommendation 4:

Sequential and 4D-variational methods should be closely compared for cost/benefit, after flow-dependent multivariate constraints have been built into the 3D covariances.

Recommendation 5:

The possibility of coupled ocean-atmosphere data assimilation should be explored to reduce initialisation shock.

1. Atmospheric data assimilation should be tested with the atmosphere model coupled to an ocean mixed layer. The ocean mixed layer could be shared in the oceanic and atmospheric analysis to ensure consistency in the air-sea fluxes. Assimilation of SST should be tested in this context.
2. There should be a workshop to develop workable strategies towards coupled ocean-atmosphere data assimilation.

Recommendation 6:

There should be a consistent program for looking at the assimilation statistics (innovations, residuals and increments)

1. To identify biases.
2. To check consistency in the treatment of the random component of the error.

Recommendation 7:

The problem of bias correction should be revisited only after better formulations of the background-error covariances have been developed.

(Since it is not clear to what extent the existing bias error is related to the inadequate formulation of the error characteristics).

The last recommendation was raised during the final discussion/presentation at of the working group meetings.

Recommendation 8:

The merits of ensemble based data-assimilation methods (EnKF, SIR) for initialization of ensemble seasonal forecasts should be investigated further. (Since these methods give explicit estimates of the uncertainty in the initial conditions).

2.9. References

Alves O., M. Balmaseda, D Anderson, T Stockdale, 2002, Sensitivity of dynamical seasonal forecasts to ocean initial conditions. *ECMWF Technical Memorandum* 369. (to appear in Quart. J. Roy. Met. Soc.)

Bell, M.J., M.J. Martin and N.K. Nichols, 2002. Assimilation of data into an ocean model with systematic errors near the equator. Accepted by *Quart. J. R. Meteorol. Soc.*

Burgers G., M. Balmaseda, F. Vossepoel, G.J van Oldenburgh, P.J. van Leeuwen 2002, Balanced ocean data assimilation near the equator. *J. Phys. Ocean.*, **32**, 2509-2519.

Dee, Dick P, Da Silva, Arlindo M 1998: Data assimilation in the presence of forecast bias. *Quart. J. Roy. Met. Soc.*, **124**, 269-295.

Segschneider, J., D.L.T. Anderson, J. Vialard, M. Balmaseda, T.N. Stockdale,A. Troccoli, and K. Haines, 2001. Initialization of seasonal forecasts assimilating sea level and temperature observations. *J. Climate*, **14**, 4292-4307.

Troccoli A., M Balmaseda, J Segschneider, J Vialard, D Anderson, K Haines, T Stockdale and F Vitart, 2002, Salinity adjustments in the presence of temperature data assimilation. *Mon.Wea.Rev.*, **130**, 89-102. (Also available on line as ECMWF Tech Memo 305, at www.ecmwf.int)

Vialard J., A.T. Weaver, D.L.T. Anderson, P.Delecluse, 2003: Three- and Four-Dimensional Variational Assimilation with a General Circulation Model of the Tropical Pacific Ocean. Part II: Physical Validation. *Mon.Wea.Rev.*, **131**, 1379-1995.

Weaver A, J Vialard, D Anderson2003. Three and four dimensional vartiational assimilation with a general circulation model of the tropical Pacific ocean. Part 1: Formulation, internal diagnostics and consistency checks. *Mon. Wea. Rev.*, **131**, 1360-1378.

Working Group 3: Mechanisms and model development.

Rowan Sutton (Ch), David Adamec, David Anderson, Swadhin Behera, Anton Beljaars, Dudley Chelton, Hugues Goosse, Chris Gordon, Peter Janssen, Gurvan Madec, Pedro Viterbo, Steve Woolnough, Toshio Yamagata

The following topics were covered:

2.10. Ocean Physics

2.10.1. 3.1.1 The cold tongue

The cold tongue is a region in which many processes are important and which is difficult to model correctly. The representation of mixing, both lateral and vertical seems to be important and alternative mixing schemes such as isopycnic mixing of momentum as well as heat and salt might be desirable. Interleaving processes in the west pacific are also potentially important. There is evidence that properly resolving the Tropical Instability Waves (TIWs) is important since the heat transport by TIWS is large and they are associated with intense air-sea interaction. For the atmospheric model to respond correctly to the ocean, it is necessary to have higher resolution than currently used. This was thought to be especially important in the vicinity of the cold tongue along the equator and in the vicinity of the front just to the north. The group recommended an intercomparison study to understand local ocean dynamical balances in this region.

2.10.2. The air-sea interface

The group recommended investigating the atmospheric model response to sea surface temperatures that have a finer scale structures than the current Reynold's SST product which is quite smooth. The AMSR has provided global data at a resolution of ~50km since July 2002, though it will take some time to build a microwave climatology of SST. The TRMM TMI has been providing SST since December 1997 but only between 38N and 38S. These instruments are less affected by clouds but rain contamination is a problem. There are differences in the curl and divergences between those estimated from QSCAT and those from ECMWF analyses. Whether these differences arise due to SST boundary conditions, model grid resolution or boundary layer parameterization needs to be resolved. For an update on these issues concerning SST modification of low level winds see the contribution by Chelton, this volume.

2.10.3. The Indonesian Throughflow

This is a potentially difficult region to model correctly because of the narrowness and shallowness of the various passages. Higher horizontal and vertical resolution may be required, and attention given to the handling of bottom topography.

2.10.4. Mixed layer physics

Over the last two decades there have been field campaigns and developments of wave model/parameterizations which should be included in the treatment of the ocean mixed layer. Presently the atmosphere and ocean communicate daily in the seasonal forecast system (but hourly in the monthly forecast system). To properly resolve the diurnal cycle in the ocean it may be necessary to use enhanced vertical resolution near the surface (1-2m) or a suitable parameterisation. The diurnal cycle might affect the structure of the atmospheric boundary layer. There are areas of the ocean where the impact of biology on the extinction of solar radiation can affect sea surface temperature but it is not yet clear that such a formulation affects longer term coupled simulation in a significant way.

2.10.5. Extratropical processes

It is recommended to examine how the model copes with the restratification of the water column in e.g. the Labrador sea, to explore methods of better representing eddy mixing in this region, and to study the structure and variability of thermohaline circulation, initially in longer climate simulations.

2.11. The Indian and Atlantic Oceans.

Although the largest interannual climate signals are found in the tropical Pacific, there is variability in the other tropical oceans, some of it linked to ENSO and some not. An example is the Indian Ocean 'Dipole' (IOD). The group recommended checking that the dipole is well represented in the model, both in the east, off Sumatra and in the west, off East Africa. The upwelling off Sumatra extends too far to the west in some models, though this may depend on model resolution and mixed layer physics. It is desirable to quantify ENSO effects on the Indian ocean in general and on the Dipole in particular. In one coupled model, the Indian Ocean dipole can occur even if ENSO is suppressed, but it is not known if this is a general result. The role of the MJO on Indian ocean variability needs to be clarified as there are suggestions that the MJO can trigger the IOD. Likewise it is unknown the extent to which the IOD influences the MJO. The role of the MJO on ENSO and of ENSO on the MJO are also poorly understood.

The group recommended that simulations of Atlantic ocean variability, including tropical modes of coupled variability be evaluated. There is evidence from observations that Atlantic ocean conditions can impact European climate, particularly the NAO in early winter. There is a need to understand why the observed link between the N Atlantic horseshoe pattern and the NAO is not well captured. The group also recommended understanding the effect of ENSO on the Atlantic ocean and to understand and assess atmospheric teleconnections, including those between the Atlantic and Indian ocean in boreal Autumn.

2.12. The Madden Julian Oscillation

The group considered it important both for monthly forecasting and seasonal forecasting to get a faithful representation of MJO variability in the atmospheric model. Part of this task may involve determining the extent to which the MJO is a coupled mode. There is a need to investigate whether current atmospheric convection schemes are adequate for simulating MJO variability. For example, is there enough sensitivity to SST anomalies, to mid-tropospheric temperature and humidity anomalies and is midlevel convection adequately represented?

2.13. Climate Drift

The group considered it highly desirable to continue efforts to reduce mean climate drift, baring in mind that the spatial structure of the drift has implications for specific variability and teleconnection patterns (e.g. if the Atlantic gets relatively colder than the Indo-Pacific, sensitivity to Atlantic anomalies will be underestimated). However, more attention should be paid to variability than mean state when performing model development and tuning since a degradation in mean state with improved variability may be an acceptable trade off. Improvements in component models should be tested in the coupled system with specific attention paid to surface tropical winds. Stable numerics shouldn't be pushed to the extent that it affects desirable high frequency variability.

2.14. Sea Ice

Variations in the extent, concentration and thickness of sea ice have an important local effect both on the atmosphere and ocean since the heat and moisture fluxes from the ocean are strongly affected. From our current knowledge base, although the impact for Northern Europe is probably large, the importance of sea-ice variability for large-scale atmospheric circulation including much of Europe is unclear. A sea-ice module is available for inclusion in the ocean model. In order to perform forecasts, it is necessary to know the initial conditions of the sea-ice as well as for the ocean and atmosphere. Ice concentration can be obtained from satellite. Ice thickness is less easily obtained but some progress is expected in the future and until then the initial conditions can be guessed from previous simulations.

The group recommended a structured programme of work in developing a sea-ice prediction capability, if warranted. First sensitivity studies to quantify the possible impact of sea-ice variability on the atmospheric response should be carried out. Secondly, a sea-ice module should be included in the coupled system. Close collaboration with the physics group with respect to coupling of ice thermodynamics to the atmospheric model is important. Inclusion of a sea-ice model will undoubtedly exacerbate problems with climate drift associated with ice albedo feedback. Thirdly, the predictability of sea-ice using the coupled atmosphere ocean sea-ice model as well as the positive and negative impacts on other components of including sea-ice should be evaluated.

2.15. Other Issues

The group suggested 1) considering the inclusion of coastal processes in medium range and monthly forecasts with an eye toward applications such as wave modelling and fishery applications and 2) including an interactive ocean model (possibly initially a mixed-layer model) under a medium range forecast model as there are potential benefits for forecasting tropical cyclones, the MJO, the effect of ocean variability (TIWs, Gulf Stream) on surface winds, the ice edge location and cyclogenesis over newly-exposed water previously under ice.