Workshop on Ocean-Atmosphere Interactions
10 - 12 November 2008

Introduction

A workshop on '*Atmosphere-Ocean Interaction*' was held at ECMWF from 10 to 12 November 2008. The objective of the workshop was to address the requirements for ocean-atmosphere coupling from the very short time ranges to the seasonal time range with focus on ocean near-surface processes. Also the following questions were to be considered.

- Which processes need to be taken into account (e.g. ocean waves, currents, diurnal cycle of SST, ocean mixed layer dynamics and horizontal resolution of SST)?
- What is the impact of air-sea processes on atmospheric phenomena, including extreme events (e.g. tropical cyclones, extra-tropical explosive genesis, monsoons and MJO)?
- Which models are the most appropriate at different time scales, and what are the implications for seamless forecasting?

This workshop attracted about 25 scientists from outside ECMWF and 14 scientists from France, Germany, Sweden, UK and USA were invited to give a presentation. The talks were organized in two sessions: "*Processes of atmosphere-ocean interaction*", and "*The impact of atmosphere-ocean interaction on the atmosphere*".

The presentations were followed by two working groups that reviewed an area of research and made recommendations for further research. Consideration was given to three time scales: short to 10 days, monthly, and seasonal. The results of the discussions and the recommendations are in the working group reports.

ECMWF would like to thank all participants for their excellent contributions. The guidance given by the working group discussions and the recommendations will be extremely helpful for the planning of further work at ECMWF and at other centres.

The contributions are also available from the ECMWF website (http://www.ecmwf.int/publications/).

Working group 1

1. General Issues

When unconstrained, general circulation models of the atmosphere (AGCMs) and ocean (OGCMs) tend to develop much of their climatological biases in about 5 days and a few months, respectively. Therefore, a coupled model will inevitably develop surface flux biases and its sea surface temperature (SST) may not necessarily be the best bottom boundary condition for its evolving atmosphere. However, coupling may allow the system to progress more faithfully than otherwise by evolving the SSTs with more fidelity than persistence and by providing negative feedbacks in the system that retard the growth of some errors. The latter implies that it may be important to have the correct coupling physics, and hence the best flux exchange coefficients possible, even though individual model errors are expected to affect surface fluxes by more that uncertainties in flux formulations. These possibilities are the motivation behind the ECMWF Workshop of Ocean-Atmosphere Interaction and hence this report.

An underlying consideration is that atmospheric and oceanic model biases are due, in general, to a combination of model error and forcing error. Forcing errors are more of issue with OGCMs, because they are more of a forced system than AGCMs. Often it is difficult, if not impossible, to discriminate between model and forcing error when investigating model biases and poor evolution. Therefore, it is important to use independent verification of model behaviour and forcing against observations and/or process models whenever possible. Tuning model parameters to give agreement with some metrics can and often does get a better result for the wrong reason, so that latter improvements can lead to a degradation of model performance.

This report is organized into three parts; Ocean Processes, Forcing and Implementation and with each are 'recommendations' resulting from the workshop presentations and working group discussions. When possible these are prioritized into High, Medium and Low for each of three timescales; short 10-days, 1-month and seasonal.

2. Ocean processes

2.1. Initialization

Though not strictly an ocean process, it is known that ocean model evolution on time scales less than many years will depend strongly on the initial condition. In order to avoid geostrophic spin-up issues the velocity fields as well as the usual temperature and salinity fields should be initialized. In general, initial fields to a depth of about 200m should suffice, but deeper values would be required in regions such as the Western Pacific Warm Pool and on seasonal time scales. Shallower initialization may be sufficient for shorter time scales and regions of the summer hemisphere.

In order to minimize coupling shock at the beginning of a coupled integration it is necessary to initialize the atmosphere and ocean with the same SST. However, this SST needs to be compatible with the deeper temperature structure, or it will quickly lose its identity and a delayed "shock" may occur.

The initial fields, including the ECMWF ocean analyses, should be evaluated against independent data, because interpretation of coupled results will depend on understanding regional and global, as well as short term and climatological deficiencies.

Initialization of sea ice concentration is a necessity. It is also desirable to include ice thickness and temperature as well, but not velocity. However, given the difficulty, it may be sufficient to find regional relationships between the more easily obtained concentration and thickness and surface temperature.

Recommendations

- Initialize the atmosphere and ocean with the same SST and ensure that deeper ocean has compatible temperatures (High Priority at all time scales).
- Initialize temperature, salinity and velocity to a depth appropriate for the ocean region. (Medium Priority at all time scales).
- Evaluate the analyzed ocean fields used for initialization. (High Priority at all time scales).
- Initialize sea-ice concentration (High Priority for monthly to seasonal, less for 10-day timescales), and sea-ice thickness (Medium Priority), and sea-ice temperatures (Low Priority).

2.2. Diurnal cycle

The upper ocean has been observed to respond to diurnal cycles in stratifying surface forcing (solar heating and precipitation) that are not matched in the opposing processes such as molecular and radiative surface cooling. The net result is a diurnal warming of SST by 2°C or more. The underlying physics is well known, but numerical constraints can make explicit representation within an OGCM difficult, especially if the molecular scales of air-sea transfer are to be resolved. However, embedding a “parameterization” of diurnal cool skin and warm layer effects may be a practical alternative that can be verified against ocean observations and satellite measurements.

Recommendation

- Compute surface fluxes every atmospheric time step with SSTs that are evolving on this time scale, as they follow the diurnal cycle of atmospheric forcing (Highest Priority for 10-day to seasonal unless shown to be otherwise).

Note that it assumed that the underlying ocean model component does represent well the diurnal evolution of the SST. Validation of the diurnal cycle in surface temperature of such a model is crucial.

2.3. Vertical processes

The upper ocean is mixed by a variety of processes and stratified by others. These processes depend on the forcing, and on the temperature, salinity, density and velocity structure of the upper ocean. The balance between these processes determines the SST evolution and hence the coupling with the atmosphere. The combined effects should be verified against observations (e.g. ARGO profiles), and process modelling. In principal vertical processes can be represented by 1-dimensional mixing models. This option is attractive from the simplicity and computational cost points of view, but when dynamics (currents) are included care must be taken at the equator to balance the momentum flux in the absence of Coriolis force.

Recommendations

- Represent penetrative convection (High Priority for seasonal and less for shorter time scales).
- Represent the resonant response to inertial wind forcing (High Priority for hurricane and less for longer time scales)
- Use absorption coefficients for solar radiation in the upper ocean as derived from satellite observations of ocean colour (High Priority for seasonal and less for shorter time scales).
- Resolve or impose (preferably using neighbouring model grid points) Ekman pumping (Medium Priority for all time scales).
- Parameterize the effects of Langmuir circulation using inputs from a coupled wave model, provided observations in N.E. Pacific of limited penetration depth are reproduced (Medium Priority on all time scales).
- Parameterize the effects of wave breaking (Low Priority), after ensuring that freshwater barrier layers can be maintained.

2.4. Three-dimensional ocean processes

Representation of full 3-dimensional processes requires a full OGCM, with the associated complexity and cost. Horizontal resolutions of order 10 km are needed to resolve the ocean meso-scale eddy field, but for this aspect, the demonstrated benefits on time scales shorter than seasonal do not yet justify the costs. Therefore, a coarser resolution might suffice, with meso-scale eddies either parameterized or neglected.

Recommendations

- Parameterize meso-scale eddy effects provided that their isopycnal mixing in the interior ocean becomes sensibly more diapycal (horizontal) in the upper ocean; otherwise they should be neglected. (Low Priority at all time scales, with the possible exception of the Antarctic Circumpolar Current region at seasonal timescales).
- Parameterize the re-stratification effects of sub-mesoscale instabilities using the horizontal buoyancy gradients of either an OGCM, or from neighbouring 1-dimensional vertical mixing models. (Low Priority for 10-day and increasing to Medium Priority for Seasonal time scales).

2.5. Sea-ice

Sea-ice is a very effective insulator between the atmosphere and ocean, limiting ocean heat loss to order 10 W/m2 compared to as much as order 1000 W/m2 from neighbouring leads. Fortunately, the sea-ice concentration, and hence lead fraction is known from satellites. However, ice thickness is not easily estimated, but could possibly be related to concentration on a regional basis. Concentration tends to have a maximum in late winter and a minimum in late summer. Its most rapid increases are in late fall to early winter, and most rapid decreases in late spring early summer. The positive ice-albedo feedback makes the transitions potentially important.

Recommendations

- Provide the surface inhomogeneity implicit in sea-ice concentration to the atmospheric boundary layer.
- Include prognostic evolution of sea-ice concentration (High Priority for seasonal and less, except in regions like the Gulf of St. Lawrence that are adjacent to evolving ice cover, at shorter timescales).
- Include prognostic evolution of sea-ice thickness and motion (Medium Priority for seasonal and less, except in regions like the Gulf of St. Lawrence that are adjacent to evolving ice cover, at shorter timescales).

2.6. Western Boundary Currents and Fronts

Accurate representation of western boundary currents (e.g. the Gulf Stream) and their extensions is very challenging for OGCMs. High resolution is necessary but not sufficient to produce the correct mean path and variability. For coarser resolutions, getting the western boundary currents right is even more difficult.

Recommendation

- At the moment, it is assumed that ocean model resolution that can be afforded will still be too coarse to meet the necessary condition , therefore after initialization, the path of western boundary currents and associated fronts may need to be constrained from drifting too far toward their climatological biases (Low Priority for 0-10 to monthly and Medium Priority for seasonal time scales)

2.7. SST spatial variability

Satellite observations show a strong correlation between wind speed and persistent ocean generated SST variability in many regions (e.g. SST frontal areas). Modelling this correlation may be more a validation of atmospheric mixing than a requirement for model evolution. Certainly, such variability in the ocean models recommended above will at best be weak and possibly absent, so the wind variability would be expected to much weaker than observed. It is safe to say that coupled modelling has not yet advanced to a point where it is possible to say how important this coupled phenomenon is.

Recommendation

- The importance of this phenomenon is not yet sufficiently known for either the atmosphere or the ocean. It was therefore felt that this phenomenon should be studied further before making any recommendation.

3. Forcing

3.1. Monin-Obukhov similarity

Recent field experiments have confirmed that MO similarity is generally valid in the marine surface layer. The main exception is under low wind, swell conditions where MO similarity is not applicable due to wave driven flow. These wave-driven processes have a strong impact on the pressure transport term in the KE budget. However, flux-profile relationships based on the dimensionless shear and scalar gradient functions remain are in good agreement with measurements over a wide range of conditions. As with land-based results, there is greater uncertainty in these functions under stratified conditions. It should be noted that stratified conditions are commonly encountered in the marine surface layer; particularly in the spring and early summer over regions with strong wintertime cooling and over regions of strong coastal upwelling.

Recommendation

- We recommend the continued use of functions based on MO-similarity theory in numerical models of the marine surface layer.

3.2. Exchange coefficients

It is only natural to take advantage of ECMWF coupled atmosphere-wave models and use a sea-state dependent drag coefficient. The implementation of this parameterization in a coupled model will also require some tuning. The same can be said for the transfer coefficients of heat and momentum. However, one will hope that the transfer coefficients used in the model match the wind speed dependent transfer coefficients within the uncertainty of the measurements. This includes the observed linear increase of the transfer coefficients for heat and mass with wind speed, which is also predicted by semi-empirical theory. A good candidate model for model comparison is the widely used COARE 3.0 algorithm, which has these characteristics for heat transfer and has been validated up to approximately 20 m/s for drag. The uncertainty is estimated to be 10% for momentum and 20% for heat and mass up to 20 m/s. Very recent data, presented at the workshop as COARE 4.0 (unpublished), is about 10% above COARE 3.0 at 20 m/s. Also the ECWMF model is near the upper uncertainty bound of the COARE 3.0 algorithm. At very low winds, observations have shown that non-locally generated waves (swell) can have a significant impact on momentum transfer. They provide momentum to the atmosphere when the wind and swell are aligned, which acts to reduce the drag and the total (wind plus wave) momentum flux. Observations have also shown that they enhance the drag when the swell propagates against the wind (counter swell). However, the momentum flux remains small under these low wind conditions and it is not clear whether this will have a significant impact on forecasts. Lastly, there is substantially less community consensus on the behavior of the transfer coefficients at stronger winds. As such, we cannot make any strong recommendations for use of transfer coefficients under these conditions. Instead, the form of the transfer coefficients that give reasonable predictions of, particularly, wind speed and wave heights provide significant insight on the nature of heat, mass and momentum transfer under extreme winds. The effect of sea spray on surface fluxes might also be important.

Recommendation

- The surface flux parameterizations used in models should agree with the COARE algorithm within 10% for momentum (drag) and 20% for heat and mass up to approximately 20 m/s. It is not clear whether the wave-driven wind situation will have an impact on weather forecasts due to the small magnitude of the stress under these conditions. However, ECMWF use of a wave model to provide the surface stress can mimic these conditions. Therefore, we recommend that the stress parameterization be adjusted to allow upward momentum flux under these conditions. Lastly, we cannot recommend any particular formulation at higher wind speeds other than the requirement that they agree with COARE at lower winds. However, the form of the parameterizations that give reasonable agreement between the model and available observations provide useful information to the marine science community.

3.3. Direction of the surface stress

Additionally, observations have shown that the stress and wind vectors become unaligned when the wind and waves are unaligned but the atmosphere and ocean remain strongly coupled. Observations have shown that the direction of the stress vector lies somewhere between the wind and wave directions. Such conditions are commonly encountered during frontal passages with moderate to strong winds. Presumably, similar situations are found in hurricanes where the wind and waves are often unaligned for a variety of reasons. However, it is unclear whether this misalignment has a significant impact on model forecasts, particularly if the magnitude of the stress is properly modelled.

Recommendation

- It would be a useful exercise for the observational community to test how sensitive the model forecast is to this misalignment. For example, the two runs could be conducted where the stress is aligned with the wind in one case and the dominant waves in the other. A significant difference in the model output would provide motivation for further study for both the observations and modeling communities.

3.4. Surface currents

The effects on ocean surface currents on the surface stress have been observed in different areas. In a fully coupled system, surface currents are part the prevailing conditions at the interface between the atmosphere and the ocean. Research on the inclusion of those currents as part of the boundary conditions at that interface has already shown non trivial impact on the surface stress and the associated surface winds as well as on the wave fields. Certain types of observations are actually sensitive to surface currents (e.g. scatterometer). In principle, a data analysis system requires that a model estimate of the observations is made in order to determine the departure between model and observations. Inclusion of the surface current is therefore desirable to extract a maximum of information from the data.

Recommendation

- The impact of surface currents on wave field evolution, data analysis and air-sea transfer should be pursued further.

4. Implementation

The current solution of keeping separate executables of the main models and using an external coupler for the interaction is acceptable at current resolution with today’s computers. It is not necessarily the most efficient solution but it is the most practical to implement. However, future changes to model resolution, coupling complexity and computer architecture might require for efficiency a more integrated solution. Note that it does not mean that entirely new tools will need to be written, existing tool might be adapted.

Recommendations:

- At this time, the working group feels that no explicit recommendation for the best technical solution for the implementation of the coupling could be made.

Working group 2: Impact on the Atmosphere

Discussions of this working group were organized around four timescales: diurnal, meso-synoptic, intraseasonal, and seasonal. In this report, summaries of discussions for each timescale are given first, followed by recommendations.

1. Diurnal Cycle

Up-scale impacts of the diurnal cycle in tropical SST on the MJO, monsoon, and possibly ENSO are recognized. For the MJO, the rectification of the diurnal heating of the upper ocean warm layer on the intraseasonal timescale helps maintain the amplitude of intraseasonal fluctuations in SST associated with the MJO. Modeling studies have shown that the intraseasonal amplitude of SST would be underestimated when daily mean surface fluxes were used to drive an ocean mixed layer model. Coupling between the intraseasonal fluctuation in SST and the MJO then helps maintain the strength and realistic propagation speed of the MJO. Similar effects of the diurnal cycle also apply to intraseasonal variability of the Monsoon (e.g., onset, break). It has been demonstrated in one model that when the diurnal cycle in SST is incorporated in an OGCM, the zonal distribution of Pacific equatorial SST is improved. This may in turn benefit seasonal and ENSO prediction but direct evidence has yet to be obtained.

There are many published results that show improvement in MJO prediction and simulation by coupling an AGCM to an ocean mixed layer model. It is unclear whether there are unpublished negative or benign results on this subject.

High vertical resolution in the upper ocean (e.g., 1 m for the upper 10 meters) is essential to fully resolve the diurnal cycle in SST but it alone is not sufficient. Mixing processes have to be properly treated. Fairall scheme appears to underestimate the diurnal cycle in skin temperature, although it is probably the best flux scheme overall for the tropics.

In addition to increasing the vertical resolution in the upper ocean of an OGCM, there are other exercises that could be considered:

(1) Use a 1-dimensional mixed layer model to correct SST tendency of an OGCM with low vertical resolutions (in a way similar to correction of tendency in AGCMs by cumulus parameterizations).

(ii) Because the diurnal cycle occurs only under low wind conditions, a high-resolution mixed layer model might be turned on only when it is needed (e.g., low wind). But it remains unclear whether low-resolution OGCM is adequate to reproduce entrainment cooling related to high wind.

(iii) The effect of diurnal warm layer might be parameterized without an OGCM with high vertical resolutions.

To fully capture the impact of the diurnal cycle in SST on the atmosphere, it is crucial to have compatible atmospheric parameterizations (intrinsic diurnal cycle in different types of marine convection, PBL schemes, etc.) and correct atmospheric fluxes into the ocean (solar radiation, precipitation, wind stress). Otherwise, either diminished or even negative impacts might be resulted.

2. Cyclones

On meso to synoptic scales, prediction of cyclones, including tropical cyclones (TC), extratropical transitions (ET) and extratropical cyclones (EC), remains a challenge. A better representation of TC tracks, structure and intensity may have impacts on medium-range forecasts for midlatitudes because of ET.

There are many similar issues for TC and ET. It has been demonstrated that coupling and more accurate SST may improve TC/ET intensity forecast. This improvement might be capitalized only when the eye wall structure is fully resolved by an atmospheric model, which requires horizontal resolution of 1 – 2 km. It remains unknown whether and how much TC/ET prediction by a low-resolution (T799 or T1279) atmospheric model can benefit from coupling to the ocean. This needs to be investigated over a various types of storms. It has been suggested that 3-dimensional currents (inertial waves) might be important for producing correct upper ocean structures (e.g., restratification).

Currently, the best model configuration for TC forecasts incorporates moving two-way nested domains that resolve the eye wall structure and regional atmosphere-wave-ocean coupling. TC hindcasts by this type of model have been shown to be much better than non-coupled models with fixed grids. These regional models need initial and time dependent boundary conditions from global forecast. The ECMWF 10 day forecast has consistently been better than other global forecasts to drive such high-resolution TC models. It needs to be investigated whether and how the oceanic coupling of global forecast models may provide better boundary conditions for high-resolution TC models.

ET and EC, on the other hand, also share many similar issues. Surface heat fluxes are important to both but this might be seasonally dependent. The implication is that the quality and sharpness of the SST analysis is crucial (to have more accurate SST gradient) even for uncoupled forecasts. Effects of air-sea coupling (i.e., oceanic response to atmospheric forcing and its feedback to the atmosphere) require more studies to be quantified. Studies so far have suggested that sea spray may either have little impact, or else have non-negligible effects on ET/EC. Wave information needs to be included in sea spray parameterizations. The problem is that there is no in situ sea spray observation for model validation. Waves are known to be important but wave models have yet to include ocean currents. Spindown of ET by a stable ABL poses a challenge to ABL parameterization. Communication between swell direction and flux scheme should be considered.

Effects of sea ice on EC are recognized. Sea ice affects the ABL structure, surface pressure and thereby wind; its edge affects cyclone tracks. Interactions between EC and sea ice can happen on synoptic timescales. It is clear that thermodynamic sea ice models are inadequate and dynamical sea ice models are needed. Initialization can be a complication for sea ice models. A 25 km horizontal resolution and 6 hourly coupling frequency appear to be adequate for sea ice models for 10 day forecast. A substantial benefit from including an interactive sea ice and ocean model in a regional weather prediction system has been demonstrated in Canada.

3. Tropical intraseasonal variability and the MJO

It has been shown that resolving the diurnal cycle in SST is important to predicting the MJO. This, through the potential influence of the MJO on ENSO, may also benefit seasonal forecasts. But the benefit of coupling is limited by deficiencies in cumulus parameterizations and by errors and biases in surface fluxes produced by atmospheric models.

Improvement in MJO prediction when changing from prescribed SST to coupling to a 1-dimensional ocean mixed layer model has been reported. It is unclear, however, whether and how much further improvement can be gained by coupling an atmospheric model to a 3-dimensional OGCM with the same high vertical resolution. This should be investigated and quantified. Another issue that may argue for coupling to a 3-dimensional OGCM is fine SST structures related to coastal upwelling and Kelvin waves, which are important to intraseasonal variability of the monsoon (onset, break, etc.).

4. Seasonal prediction

The dominant source of seasonal predictability is ENSO, which is an inherently coupled ocean-atmosphere phenomenon. The seasonal forecasting system at ECMWF has been designed to initialise and forecast ENSO, and despite its imperfections does a reasonable job of this. Better representation of upper ocean mixing and currents in the tropical oceans is likely to give positive impacts on forecasts of tropical SST, but was not discussed in any detail. Outside the tropics, sea ice is important to seasonal prediction both locally and regionally. Evidence has been shown that apart from ice concentration, changes in ice thickness can also influence seasonal mean temperatures. Meanwhile, seasonal prediction skill is likely to be helped by accurate representations of fine structures of SST. For example, an accurate position of the Gulf Stream may be important to seasonal prediction for Europe and the cold water along the Californian coast and especially Peruvian coast is important to ENSO prediction. It is difficult or impossible for coarse-resolution OGCM to resolve such fine structures of SST.

5. Other issues:

In current OGCMs, there is no proper treatment of deep convection at high latitude that involves with mass transport in vertical. Turbulence mixing is insufficient to represent such deep convection. The impact of such deep convection on prediction, however, remains unknown.

6. Recommendations:

Recommendations from this working group are given for each of the three tiers in the ECMWF forecast system.

6.1. 10-day forecast

The working group recommends the strategy of coupling the atmospheric model to a 1-dimensional ocean mixed layer model. This has been shown to be beneficial in improving prediction of the MJO. The operational system should adapt this strategy as soon as possible.

Given the uncertainty in the potential additional benefit to medium-range weather forecasts from coupling to a 3-dimensional OGCM, the working group recommends quantifying possible improvements using an OGCM with ¼° horizontal resolution and the same high vertical resolution as the 1-dimensional ocean mixed layer model. Specific targets for such improvement include the MJO and cyclones (TC, ET, EC). It should be borne in mind that one possible outcome is that coupling may benefit forecasts of one target (e.g., the MJO) but deteriorate the other (e.g., cyclones).

Research is recommended for the general science community as well as ECMWF on three topics:

(i) Impact on ET forecasts of coupling atmospheric models to dynamical sea ice models. Because of the uncertainty related to the potential benefit on ET forecast by coupling to a 3-dimensional OGCM, both of the following two coupling strategies should be considered: (a) atmosphere model + sea ice model + 1-dimensional ocean mixed layer model, and (b) atmosphere model + sea ice model + 3-dimensional OGCM.

(ii) Effects of sea spray on cyclone forecast – Effects of sea spray on TC have been demonstrated. But its effects on ET and EC forecast are uncertain.

(iii) Treatment of ET spindown in forecast models – While such spin down is known to occur when a cyclone moves over a stable atmospheric boundary layer, whether this is properly treated in forecast models has yet to be determined.

6.2. Monthly forecast

To maintain a "seamless" forecast system, it is desirable that most recommendations made for 10-day forecast are also applied to monthly forecasts. It is highly possible that a set of new model configurations proven beneficial to 10-day forecasts would also be so to monthly forecasts. A case in point is prediction of the MJO. If coupling to 1-dimensional ocean mixed layer model may improve its 10-day forecast, it is likely to be beneficial to its monthly forecast. For this reason, it is recommended that the same configuration of atmosphere model + 1-dimensional ocean mixed layer model is used in monthly forecasts. By the same token, quantifying potential benefit to monthly forecast by coupling to a 3-dimenional OGCM of the same vertical resolution as the 1-dimensional ocean mixed layer model is recommended. In this case, however, the optimal horizontal resolution of the OGCM remains to be determined.

On the research part, the same recommendation concerning sea-ice for 10-day forecasts is also made for monthly forecasts: Potential impact on monthly ET forecast by coupling atmospheric models to dynamical sea ice models should be quantified using both configurations (atmosphere model + sea ice model + 1-dimensional ocean mixed layer model, and atmosphere model + sea ice model + 3-dimensional OGCM).

In addition, given limited computing resources, it is unlikely that OCGMs for monthly forecasting can soon reach the resolutions that resolve the important fine SST structures (e.g., Gulf Stream, coastal upwelling). A possible alternative would be adaptive or unstructured grids that are sufficiently high resolution in regions where these fine SST structures are expected to occur but otherwise remain relatively low. Research on this numerical problem should be encouraged.

6.3. Seasonal forecast

Consistent with the medium-range and monthly forecasts, improvement in the vertical resolution of the ocean model is considered of high priority. Ideally, the same vertical resolution as in the monthly forecast model should be used for the same benefit to the MJO, which may help improve ENSO prediction. It is also clear that a dynamic sea ice model should be tested as soon as resources allow.