Eastern upwelling regional model with open boundaries

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May 13, 2012

The test case `mom4_atlantic` is derived from a regional ecosystem model of the Benguela Upwelling area. Elements of this test case were published by Herzfeld et al. (2011).

The test case consists of a rectangular box delimited at the eastern side by the Namibian shelf, but by three open boundaries to the south, west and north respectively. The topography is derived from the `etopo5` dataset. The circulation in the model area is driven by local wind fields, but is also influenced by coastal trapped waves originating from the equatorial current system. For experiments covering several model years a large model domain is needed, which includes the equatorial current system. However, in the framework of an ecosystem model with many nutrient, phytoplankton and zooplankton variables such a model system appears to be computationally expensive. In detail, it needs to much compute time for sophisticated sensitivity studies. For this purpose, regional sub-models may be of great help and the original purpose of this model configuration is to perform such sensitivity studies. The large model is implemented with `MOM-31` as an ecosystem model, but the regional test case configured with `mom4_atlantic` has only the temperature and salinity tracer enabled.

The circulation at the shelf has three main components, a westward Ekman transport in connection with a coastal jet driven by the trade winds, an intermittent southward undercurrent and an Ekman compensation current which drives deep circulation onto the shelf The more or less permanent off-shore Ekman transport implies strong coastal upwelling.

The regional model should reproduce these features. The specific boundary conditions at the open model boundaries (OBC) apply for tracer points and involve a radiation condition and relaxation to prescribed values as well. In the ARAKAWA B-grid, velocity points are internal points, but momentum advection is not well defined and requires approximations. Hence, only information on tracers and sea level is passed from the large model to the regional sub-model.

Grid and topography in the sub-model and the large model are the same in the sub-model domain. Also the atmosphere forcing is similar and this test case could also be considered as a one sides nesting problem. However, the numerical schemes of the large and the regional model are different. Open boundary conditions are one method to control inconsistency near the boundaries, which eventually may grow large with nesting.

The large model is implemented with `MOM-31`. It is a regional model itself and covers the area from 10° W to 18° E and 35° S to 8° N. Boundary values for temperature, salinity and sea level are taken from the ECCO-model. The OBC for the large model are very similar to those used in MOM4p1. 10 day averages of most model variables can be found at the LAS-server

$$\texttt{http://las.io-warnemuende.de:8080/las/servlets/dataset}.$$

Some details on the large model will be given below, which may be helpful to understand differences to the regional MOM4p1 implementation:

- coupled model with atmosphere data provided from external files,
- leapfrog time stepping with Robert time filter, time step 720 s,
- tracer conserving time stepping scheme as described in Griffies et al. (2001), explicit fresh water flux from rivers and precipitation,
- tracer advection with the `quicker` scheme, in MOM4p1 this is `quickermom3`,
- vertical diffusion with a modified kpp-scheme. Only that part of the short wave radiation, which is absorbed to a certain depth is added to the non-local vertical heat flux. This avoids numerical artifacts with unstable water column at daytime.

- horizontal diffusion and viscosity using the Smagorinsky closure scheme with a Prandl number of 10, and a Smagorinski factor of 4. Background values for viscosity and mixing are chosen as small as possible.

- Ocean-atmosphere fluxes are updated every hour and are kept constant in-between.

- The wind stress is calculated from composites of three day `QuikSCAT` based wind fields with high spatial resolution superimposed with a daily cycle derived from `NCEP` reanalysis data. The wind stress is parametrized following Large and Pond (1981).

- Short wave radiation is calculated from the top atmosphere insolation modified by total cloud cover taken from `NCEP` reanalysis data. Transmissivity depends on sun angle and absorption is calculated from the optical path length. The albedo is calculated from Fresnel's formula.

- Long-wave upward radiation is calculated from a gray body formula with an emissivity of 0.96. Long-wave downward radiation is taken from a gray body radiation formula with atmosphere 10 m temperature, modified by humidity and cloud coverage.

- Latent heat flux is calculated from virtual air temperature and SST by a usual bulk formula.

- Evaporation is calculated from 2m water vapor pressure. Specific humidity and air temperature are from `NCEP` reanalysis data. The enthalpy corresponding to the mass flux with evaporation is also taken into account.

- Precipitation data from `NCEP` reanalysis are used. To calculate the heat flux from precipitation (heavy rain falls are possible in the model domain) the rain temperature is approximated by the air temperature.

- Atmosphere bottom pressure gradients are taken into account from ocean model pressure gradients. This point is important for the performance of the OBC scheme.

Figure 1 shows the topography of the large model and the embedded sub-model area for this test case. Along the sub-model boundaries time averages of sea level and tracers were stored every 6 model hours. For the western boundary these data are in the input files *obc_trop_west.dta.nc* and *obc_clin_west.dta.nc*. Similar files are written for the northern and southern boundary. For MOM4p1 a calendar attribute was added to the time axis and the sea level values are transformed to be given in meters.

Subsequently some corner points for the regional MOM4p1 implementation are given. The namelist specifies more details:

- coupled model with atmosphere data provided from external files by data overriding,

- two-level (Adams-Bashford) time stepping with a baroclinic time-step of 1200 s,

- predictor-corrector free surface scheme,

- explicit fresh water flux precipitation, rivers are not in the model domain,

- geopotential coordinates. z^*-coordinates have been also verified to work, but OBC are not ready for pressure coordinates.

- The model domain is an upwelling area. The baroclinic Rossby radius is almost resolved. Hence, `sigma-diffusion` and `neutral physics` are disabled.

- Vertical diffusion is calculated from the `kpp`-scheme. This differs slightly from the method used in `MOM-31`, but the consequences have not been investigated yet.

- Horizontal diffusion is calculated from the Laplacian scheme, with a small value for *vel_micom* = $0.001 \mathrm{m\ s^{-1}}$.

- Horizontal friction is calculated from the Laplacian Smagorinsky scheme, with a small value for *vel_micom_iso* = $0.0005 \mathrm{m\ s^{-1}}$ and *k_smag_iso* = 4.0.

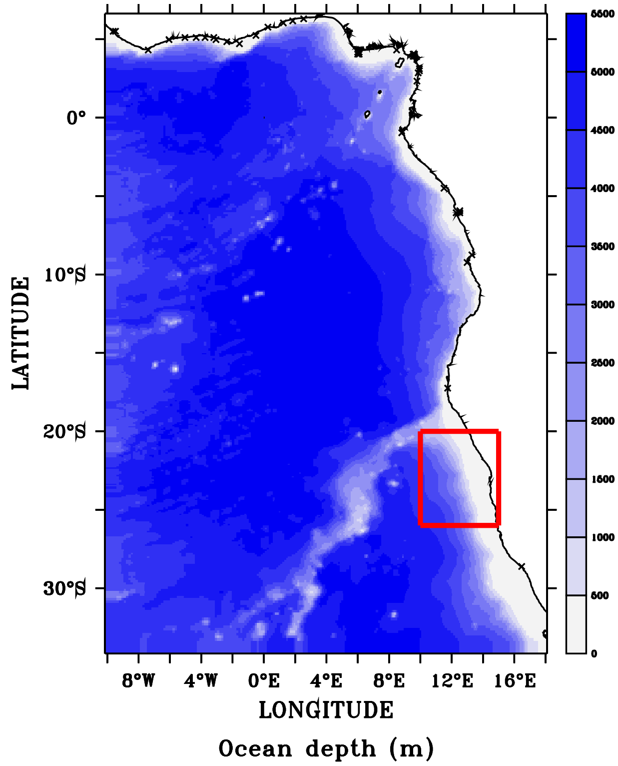

Figure 1: The topography of the large model and the embedded region of the sub-model.

- Tracer advection is carried out with the `mdfl_sweby`-scheme for all tracers.
- Atmosphere data to calculate ocean atmosphere fluxes are the same as used for the large model. However, in MOM4p1 the ocean surface velocity is taken into account in the wind stress calculation, which is based on Monin-Obukhov similarity theory.
- Downward short- and long-wave radiation is not calculated but overridden from file instead. 6 hourly `NCEP` reanalysis data are used, with a coarse 4 degree spatial resolution. The daily cycle will be represented less accurate than in the large model. Long-wave upward radiation is approximated by a black body formula.

Remarks on file on file preprocessing
The input files of this test case do not fulfill all requirements for `fms` netcdf input files, but they are recognized correctly. A calendar attribute was added to the time axis if missing. Most files are preprocessed with `ferret`,

`http://ferret.pmel.noaa.gov/Ferret/`,

which adds information on axis boundaries. Possibly the *bnds*-specification is not recognized by the `fms` axis tools. For this reason the *bnds*-specification has been removed from all input files.

Plots of the input wind fields in *windx.mom.dta.nc* and *windy.mom.dta.nc* look strange near the coasts. The reason is, that the wind fields are based on scatterometer data with missing values at land points which let the horizontal interpolation tools of `fms` fail. Replacing missing values by zero should be a bad choice. Hence, ocean values are extrapolates into land. This can be done with the function `fill_xy` of `ferret` which is undocumented part of version 6 and later and may be used as follows:

```
use windx_inp.nc                     ! missing values at land
let mask = missing(windx_in,0)*0 + 1 ! do not mask anything
let windx = fill_xy(windx_in,mask,5) ! fill with 5 passes
```

Experiments
The regional model was run with several choices of the namelist parameters over 11 model month. To demonstrate the influence of the wind stress parameterization on the results, the parameterization according the Monin-Obukhov similarity theory and the neutral approximation are used.

Open boundary conditions with a radiation condition and prescribed external data are mathematically ill-posed. Hence, a prefect scheme does not exist and the optimal choice of the boundary conditions needs experiments with boundary code parameters. It is suggested to vary the parameters used for OBC, especially modify the strength of the relaxation toward external data and to test the different schemes for the calculation of the phase speed of baroclinic and barotropic waves.

Remarks on the wind stress parameterization
The scheme to calculate air-sea fluxes differs in many ways for the large and the regional model. The OBC should be robust against such inconsistency. A detailed discussion of the surface flux schemes in MOM4p1 is out of the scope of this test case, but some details need attention.

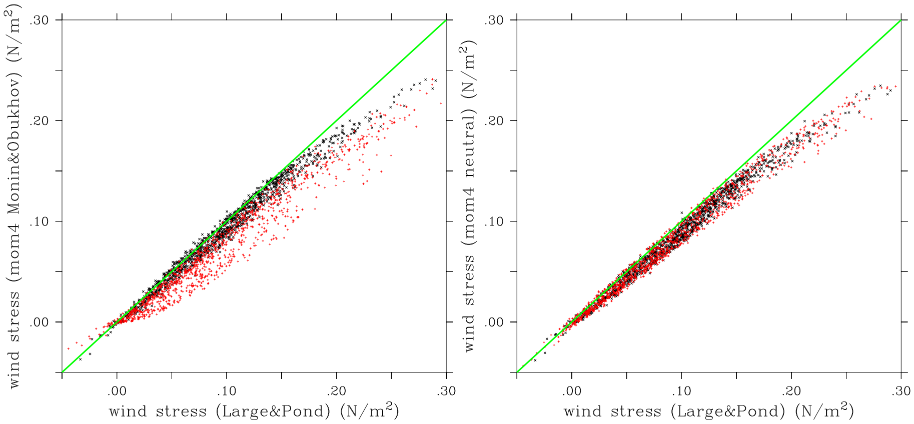

Figure 2: Scatter plots of the wind stress calculated in the large model (Large and Pond, 1981) versus the parameterization in `fms`, left: Monin-Obukhov similarity approach, right: neutral approximation. Black dots at 11° E and 21° S, where the boundary layer is often unstable, red dots from 14° E and 25° S in the upwelling area with low SST and a stable boundary layer.

Vertical momentum fluxes in the large model are estimated for a neutral boundary layer. This should be appropriate in a region of more or less permanent trade winds. In the regional model boundary layer stability was taken into account. Because there is no feedback from the ocean to the atmosphere, radiation can drive the SST away from the 2 m air temperature. Indeed this happens, because the cold band of upwelled water near the coast does not have its counterpart in the coarse `NCEP` data. On the other hand, calculated SST appears warmer than in remote sensing based data in the open ocean, which in turn leads to an unstable boundary layer.

Figure 2 shows scatter plots of the wind stress from the large scale model (Large and Pond, 1981, neutral boundary layer) and the `fms` schemes used in the regional model. Generally, the wind stress in `fms` is lower than in the large scale model. Especially for high wind speed large deviations can be seen. Results from the upwelling area (shown in red) show the influence of the stable boundary layer. It can be suspected, that the coarse `NCEP` reanalysis data do not resolve the narrow upwelling band and have to high atmosphere temperature. This corresponds to a very stable boundary layer in the upwelling band an in the tendency to reduced upwelling compared with a model driven by wind stress calculated for a neutral atmosphere-ocean boundary layer.

Here neither the neutral nor the Monin-Obukhov approach should be favored, but the differences should be mentioned as a source of differences between the large model and the regional model with open boundaries.

The mixing layer depth in the regional model is smaller than in the large model. The vertical mixing scheme is configured similarly and the differences should be traced back to the different wind stress scheme.

Remarks on the heat flux parameterization
Using the downward radiation from NCEP reanalysis data together with the default heat flux parameterization implemented infms, the calculated SST becomes to high within several model days. The resulting discrepancy between boundary data and the model interior, drives currents along the boundary. Comparing with the parameterization, used in the large scale model, it seems appropriate to introduce an albedo factor of .9 for the long wave radiation in the data_table. Such a ad hoc correction should be appropriate for a test case and removes the artificial boundary currents.

Mixing layer depth
The mixing layer depth in the regional model is smaller than in the large model. The vertical mixing scheme is configured similarly and the differences should be traced back to the different wind stress scheme.

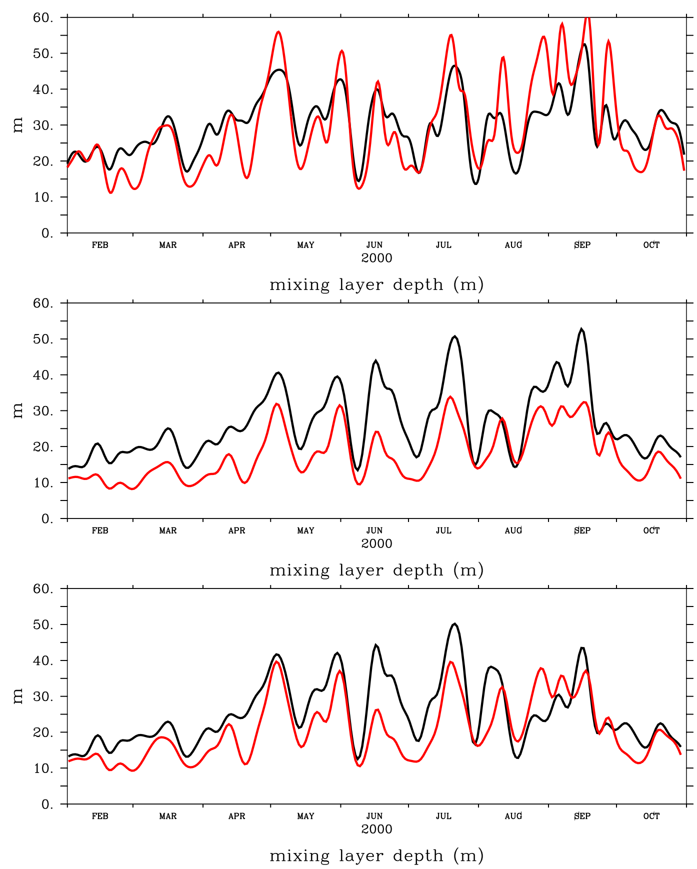

Figure 3: The mixing layer depth for the large scale model (upper part), MOM4p1 and wind stress from Monin-Obukhov similarity approach (middle) and MOM4p1 and wind stress for a neutral boundary layer. Black lines for 11° E and 21° S, where the boundary layer is often unstable, red dots from 14° E and 25° S in the upwelling area with cold SST and a stable boundary layer.

The differences between the large model and the regional model are significant, especially at 14° E and 25° S. The reduced wind stress in the regional model compared with the large scale model should be the major reason. However, a detailed investigation and evaluation with field data will be done elsewhere.

Ekman transport
Figures 4 and 5 show the wind driven transport in the mixing surface layer. Apparently, the parameterization in MOM4p1 gives smaller results than the large scale model based on MOM-31. The eddy like structure appearing in September 2000 are similar in all three models, but the amplitude in MOM4p1 is smaller.

Notably, the open boundaries in the regional model permit a smooth solution. An exception is the strong northward current to be seen in September in the model with Monin-Obukhov wind stress at the western boundary at about 24°S, which tends to erode also the salinity field. With a neutral boundary layer the wind stress is enhanced and this feature disappears.

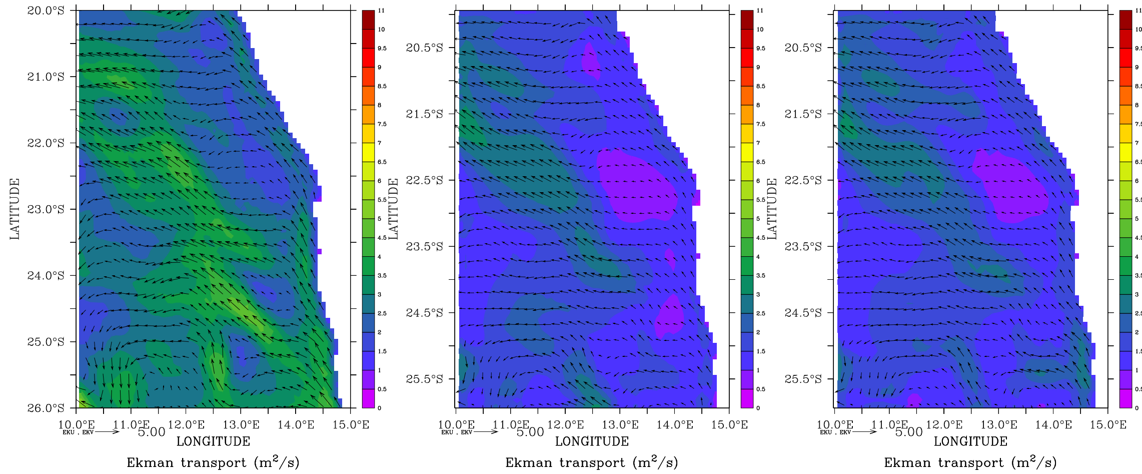

Figure 4: The vertically integrated transport in the mixing layer averaged from 2th March 2000 to 12th March 2000. Colours show the modulus. Left hand side the large scale model, middle MOM4p1 with Monin-Obukhov wind stress, right hand side MOM4p1 with neutral wind stress.

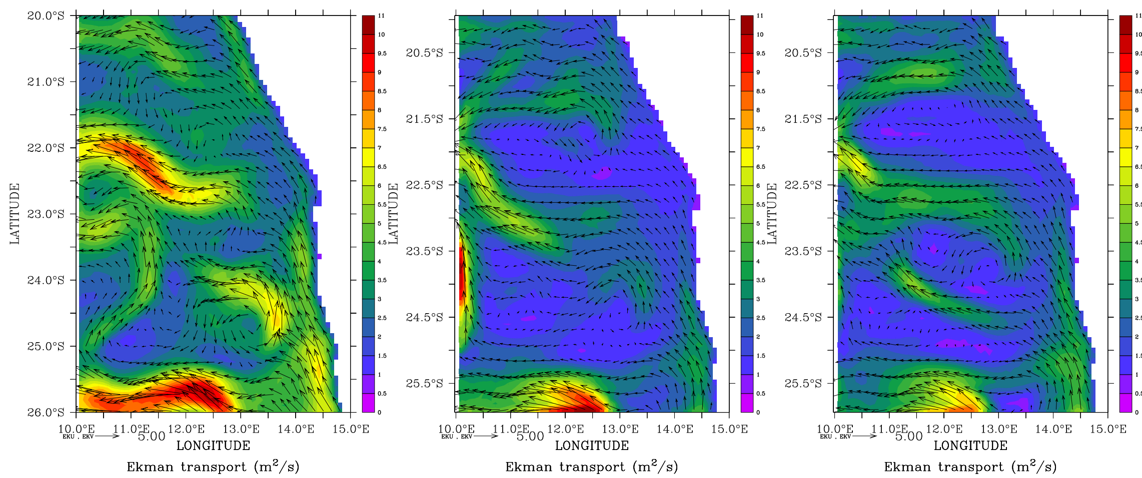

Figure 5: The vertically integrated transport in the mixing layer averaged from 2th September 2000 to 12th September 2000. Colours show the modulus. Left hand side the large scale model, middle MOM4p1 with Monin-Obukhov wind stress, right hand side MOM4p1 with neutral wind stress.

Undercurrent at the shelf

A typical feature for eastern boundary currents is an undercurrent at the shelf. Figure 6 shows an example. During strong upwelling it merges with the coastal jet and the direction may be reversed as shown in Figure 7.

The regional model performs well at the shelf, but the strong salinity signal at the western boundary cannot enter the model domain properly. Instead a strong along boundary current develops, which balances the pressure baroclinic pressure gradient. Again, the regional model with the stronger wind stress (neutral boundary layer scheme) is closer to the large scale model.

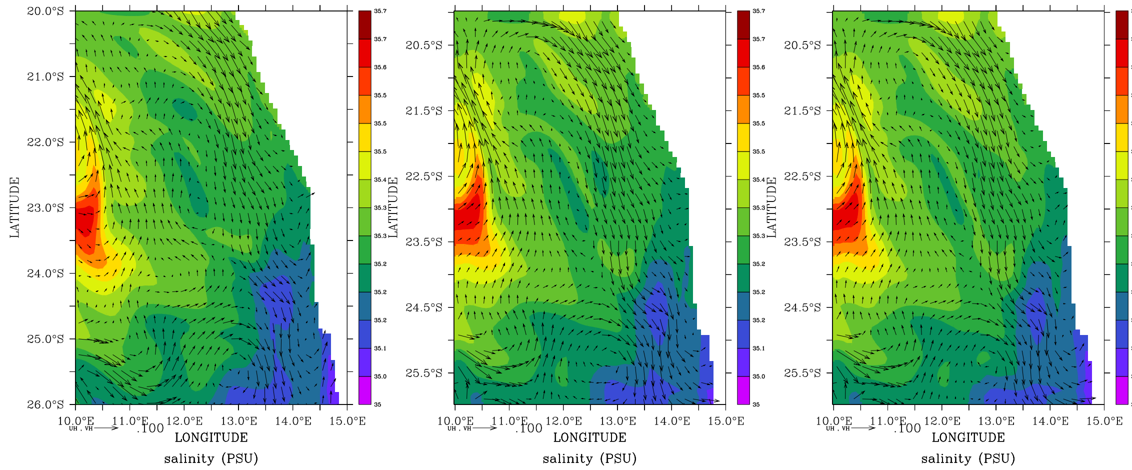

Figure 6: Salinity and undercurrent in 80 m depth averaged from 2th March 2000 to 12th March 2000. Left hand side the large scale model, middle MOM4p1 with Monin-Obukhov wind stress, right hand side MOM4p1 with neutral wind stress.

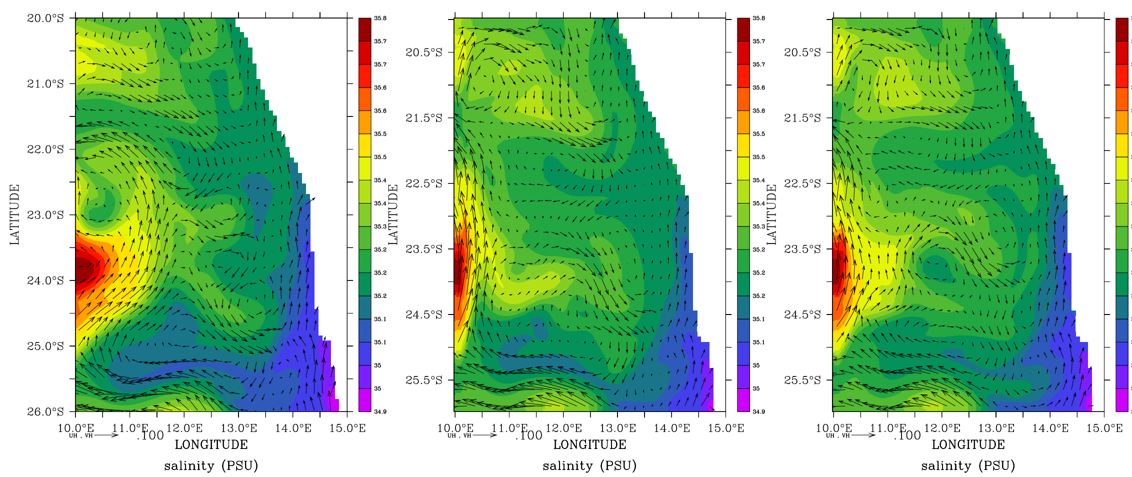

Figure 7: Salinity and current in 80 m depth averaged from 2th September 2000 to 12th September 2000. Left hand side the large scale model, middle MOM4p1 with Monin-Obukhov wind stress, right hand side MOM4p1 with neutral wind stress.

The cross shelf circulation

For the Namibian shelf the cross shelf circulation is an essential feature for the ecosystem dynamics. With the cross shelf circulation oxygen is advected onto the shelf which ventilates the shelf bottom water. The ability of the regional model to reproduce this part of the circulation system is very important.

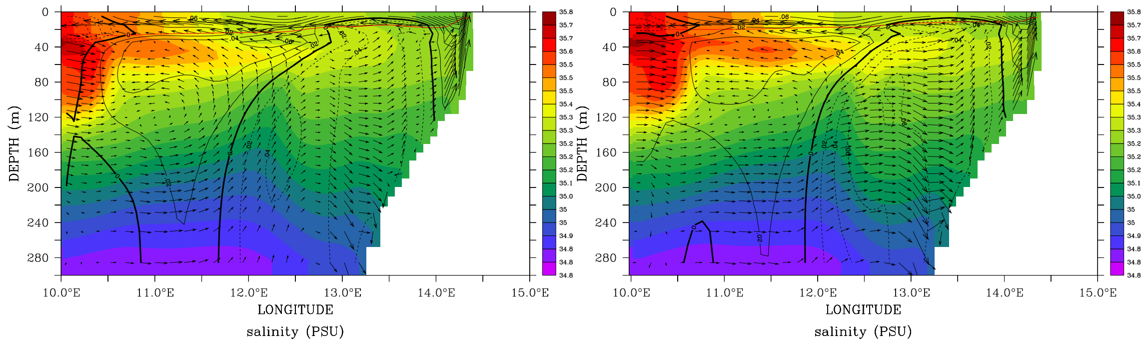

Figure 8: Salinity and cross shelf circulation at 23° S averaged from 2th March 2000 to 12th March 2000. Left hand side the large scale model, right hand side MOM4p1 with neutral wind stress. The red line marks the mixing layer depth, the contours the meridional currents. The vertical velocity is scaled with the figures aspect ratio.

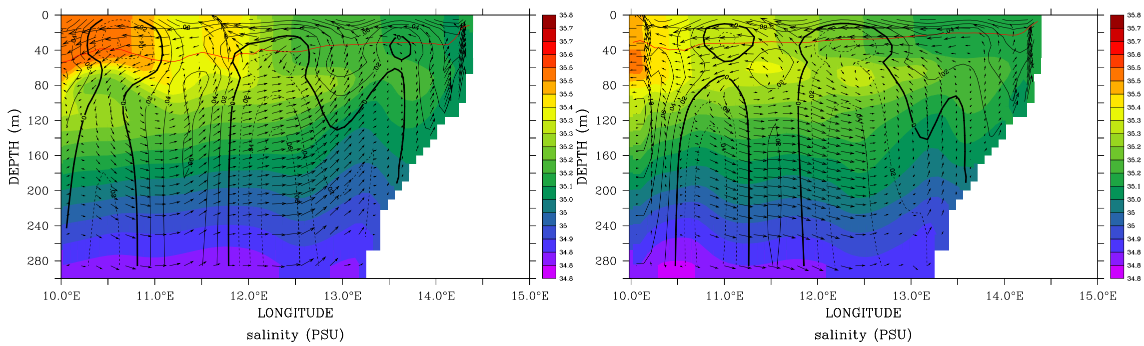

Figure 9: Salinity and cross shelf circulation at 23° S averaged from 2th September 2000 to 12th September 2000. Left hand side the large scale model, right hand side MOM4p1 with neutral wind stress. The red line marks the mixing layer depth, the contours the meridional currents. The vertical velocity is scaled with the figures aspect ratio.

Figures 8 and 9 show a typical upwelling dominated circulation. For March 2000 results from the large scale and the regional model are very similar. Note the tongue of more saline water in 60 m depth generated by the differential advection, which is also verified by field data. Upwelling goes along with a northward coastal jet within a narrow band at the coast. The figures reveal the vertical structure of the poleward undercurrent which is detached from the coast. In September 2000 its deeper parts move off-shore, but there develops a new core near the coast in about 40 m depth. There are differences between the large scale and the regional model in many details, but the general structure of the circulation pattern and the salinity distribution is the same. Especially near the western boundary the saline water appears deflected to the west in the regional model. Some strong upward vertical current develops, which is not in the large scale model. It should stem mostly from the inconsistency in the forcing of both models, which has to be smoothed by the open boundary condition.

A remark about the atmosphere pressure

Inclusion of atmosphere pressure gradients to the surface forcing is often considered as a marginal issue and minor correction because the sea level elevation rapidly adjusts to the air pressure. Slowly varying air pressure gradients are compensated by sea level elevations of the opposite sign and geostrophic currents balanced by surface pressure gradients should not be very different with and without air pressure. However, for a regional model with prescribed sea level elevation at the open boundaries a reference level for the sea level is defined. An air pressure gradient imposed to the model acts in the same manner as a prescribed sea level gradient at the boundary, if the boundary data are not produced consistently with this model configuration. This may happen, when the boundary data come from a model, which does not include air pressure gradients, but the regional model is run with air pressure “switched on”, or vice versa.

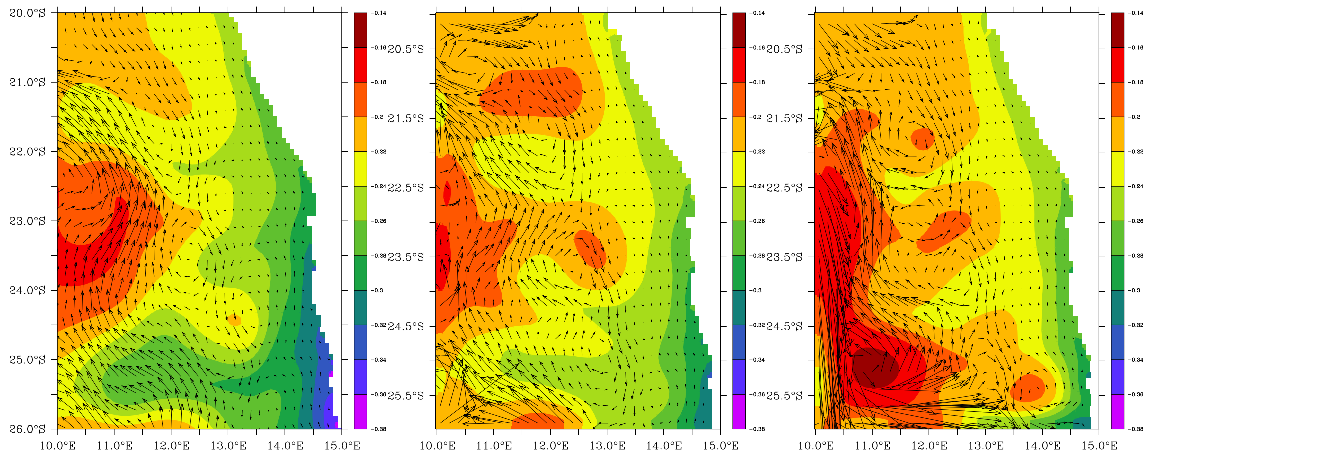

Figure 10: The sea level elevation in metres and the vertically integrated velocity in $m^2 s^{-1}$ averaged from 2th September 2000 to 12th September 2000. Left hand side the large scale model, middle MOM4p1 with air pressure taken into account, right hand side MOM4p1 with no air pressure gradients in the surface pressure.

The regional model of test case `mom4_atlantic` covers parts of the St.-Helena high pressure are, whose persistent pressure gradients are responsible for the permanent trade winds off Namibia. The boundary data from the large scale model consider air pressure, but the default of MOM4p1 is to have air pressure disabled. For the experiments discussed above, it is enabled in *ice_model_nml* defining *slp2ocean=.true.*.

In the surface currents, the influence of the wind stress dominates, but the deeper currents depend strongly on the a consistent treatment of air pressure in the boundary conditions. This should be clearly shown by Figure 10, where the regional model drifts away from the large model, when air pressure is not considered. However, in this case the eddy does not appear, which develops near the northern boundary in the regional model with air pressure.

Skills, shortcomings and limitations

The test case demonstrates, that OBC are suitable to drive a regional model with boundary data taken from another model. Many deviations between the results of the large reference model and the regional model can be traced back to different numerics and parameters. The numerical scheme used at the boundaries can be configured, to keep the influence of these deviations small and allows for reliable experiments with the regional model. However, one must be aware, that some perturbations generated near the boundaries may propagate as eddies into the model interior. Hence, mesoscale processes may be modified by perturbations from the OBC. The probability of such effects is increasing with the inconsistency between regional model dynamics and prescribed boundary values.

This test case is an extreme application in so far, that the length of open boundaries is large. For a semi-enclosed sea with a small connection to the open ocean the influence of the OBC scheme on the model results should be smaller.

It must be also noted, that the model area is situated within an eastern boundary current. Hence, artificial Rossby waves generated at the open boundaries are leaving the model domain. A similar test case within a western boundary current was not tested yet.

References

Griffies, S. M., Pacanowski, R., Schmidt, M., Balaji, V., 2001. Tracer conservation with an explicit free surface method for z-coordinate ocean models. Monthly Weather Review 129, 1081–1098.

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Large, W. G., Pond, S., 1981. Open ocean momentum flux measurements in moderate to strong winds. Journal of Physical Oceanography 11, 324–336.