An overview of CheapAml: An atmospheric boundary layer for use in ocean only modelling

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1. Introduction

As more attention is drawn toward oceanic low-frequency variability, there is a need to run longer ocean simulations at high resolution. An important associated consideration is the method by which the ocean is forced. Reanalysis atmospheric data is often limited to ~60 years and comes at low resolution (generally ~1 degree). On one hand, imposing an atmospheric state without any knowledge of the ocean state is appealing because it maintains the ocean model close to a realistic state. On the other hand, this strategy might damp intrinsic modes of variability and air-sea interaction at small scales is completely lost.

A way to tackle this problem is to use a full high resolution coupled model, but this comes at a price in terms of computing resources. Deremble et al. (2013) proposed a third option, i.e. forcing the ocean with a thermodynamically active atmospheric boundary layer model that responds to the model Sea Surface Temperature (SST). This model, namely CheapAML, was inspired by the earlier work of Seager et al. (1995) and uses a prescribed wind field to advect the atmospheric temperature and humidity. The latter are also modified by air-sea fluxes. In this short note, we first review the main equations of the model and illustrate its utility via a simple example.

2. Main equations

The basic assumptions of CheapAML are that atmospheric reanalysis variables like humidity and temperature are accurate on large scales and of these the least sensitive to ocean surface structure is (nominally ten meter) velocity (u). We thus accept atmospheric velocity as a known and develop equations governing the atmospheric tracer fields of temperature and water. This shortcut avoids the complexities of atmospheric dynamics and instead concentrates on thermodynamics. There are two fundamental equations solved by CheapAML. The first is the equation for atmospheric boundary layer potential temperature T

$$\frac{\partial T}{\partial t} = -u.\nabla T + \nabla\cdot(K_T \nabla T) + \frac{SH + F_{ol}^{\uparrow} - F_l^{\downarrow} - F_l^{\uparrow}}{\rho_a c_p H}, \quad (1)$$

with

$$\begin{aligned} SH &= C_{dh}|u|(SST - T) && (2a)\\ F_{ol}^{\uparrow} &= \varepsilon\sigma SST^4 && (2b)\\ F_l^{\downarrow} &= \frac{1}{2}\varepsilon\sigma T^4 && (2c)\\ F_l^{\uparrow} &= \frac{1}{2}\varepsilon\sigma[T(z_l)]^4, && (2d)\end{aligned}$$

with SH the sensible heat flux computed with a bulk formula, $F_{ol}^{\uparrow}$ the upward longwave emitted by the ocean, $F_l^{\downarrow}$ the atmospheric downward longwave, and $F_l^{\uparrow}$ the atmospheric upward longwave. In principle, to get the right radiative fluxes, one needs a full atmospheric model (multiple layers). The parameterisation of the optical depth is done by adjusting the temperature at which the long wave is emitted. This parameter is the height z_l in Eq.(2d). See Deremble et al. (2013) for a full description of this equation.

The second equation governs atmospheric water content

$$\frac{\partial q}{\partial t} = -u.\nabla q + \nabla\cdot(K_q \nabla q) + \frac{E - F_q^{\uparrow} - \lambda P}{\rho_a H}, \quad (3)$$

where q is atmospheric specific humidity and

$$\begin{aligned} E &= C_{de}|u|(q_s^{SST} - q) && (4a)\\ F_q^{\uparrow} &= \mu C_{de}|u|q && (4b)\\ P &= \frac{\rho_a H}{\tau}^T (q - 0.7q_s)\frac{w}{w_0}, && (4c)\end{aligned}$$

with E the evaporation computed with a bulk formula, $F_q^{\uparrow}$ the entrainment at the top of the boundary layer and P the precipitation. Equation (4c) is a proxy for the precipitation occurring in the entire atmosphere. Only a fraction λ is occurring at the top of the boundary layer since we are considering a sub-cloud layer (see Deremble et al., 2013, for details).

3. Example

Let us illustrate the utility of this model with a simple example. Our purpose is to show that we obtain better values for atmospheric forcing when we use CheapAML, rather than imposing an atmospheric state decorrelated with the ocean state. To demonstrate this, we select two random years 2000 and 2005. All data in this example come from ERA-Interim (Dee et al., 2011). The reanalysis SST pattern in each of these years is different and is representative of a certain state of the ocean. Moreover the reanalysis atmospheric state in 2000 is 'consistent' with the SST in 2000. In a forced ocean model, given the chaotic nature of the ocean, the SST in model year 2000 will differ from that of the real ocean, particularly at small scales, and will no longer 'agree' with the imposed atmospheric structure.

To illustrate the error realised in that case, we plot in Fig.1 the mean surface air temperature in 2005 minus the mean surface air temperature in 2000 from the reanalysis data. This map exhibits warmer and cooler regions distributed all over the globe. In fact, these regions are well correlated with the SST difference between 2005 and 2000 (not shown). The mean value of this map (excluding land and parts of the ocean covered by ice) is 0.3 K and the standard deviation 0.6 K. Similar conclusions are obtained with humidity but are not presented here for brevity. We compare the error obtained in that case with the error that we would get when

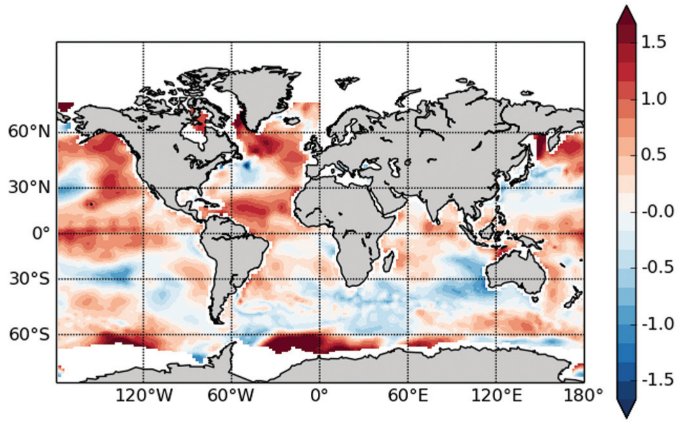

Figure 1: T(2005) - T(2000). Units: ˚K. The colour bar is limited to a maximum anomaly of 1.5 K for visibility, but the magnitude of the anomaly is more than 1.5 in certain places. The regions where sea-ice is present is masked.

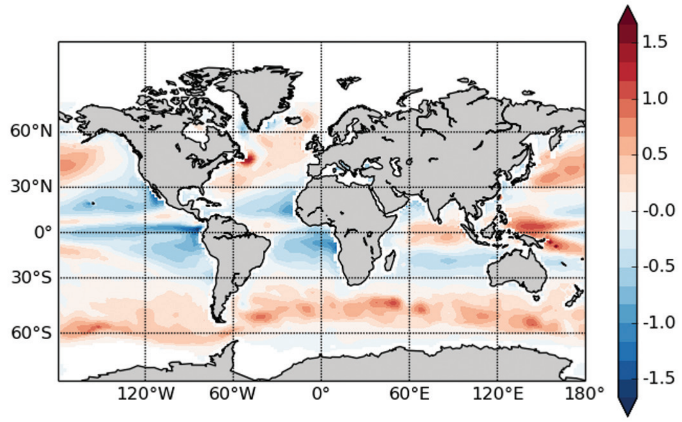

Figure 2: T(AML) - T(2000). CheapAML experiment with the wind of 2000 and land temperature of 2000

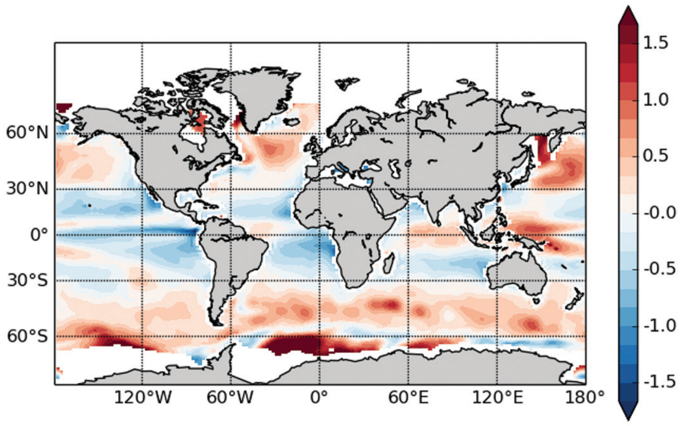

Figure 3: T(AML) - T(2000). CheapAML experiment with the wind of 2005 and land temperature of 2005

using CheapAML. We run CheapAML with a prescribed SST (2000, monthly mean). We use the wind of 2000 and over the continents the atmospheric variables are restored to the values of year 2000. The atmospheric variables are updated every 6 hours. We use a constant atmospheric boundary layer height of 1000 m and an 'optical depth' of z_l = 100 m. Figure 2 is the difference between the mean temperature reconstructed by CheapAML and T(2000). The visual comparison with Fig. 1 illustrates that the magnitude of the anomaly is lower for the latter case. The mean anomaly is in fact 5x10-3 K and the standard deviation is 0.4 K. The pattern of this anomaly resembles the climatological cloud fraction (not shown). An advanced radiation scheme with a cloud parameterisation would certainly decrease this bias. Nevertheless the comparison argues in favour of CheapAML which is able to reconstruct an atmospheric temperature that matches the SST. In this example however, we used the atmospheric wind and land boundary condition of 2000, that is in agreement with the underlying SST.

To unambiguously assess the validity of CheapAML, we run the model with the SST of 2000, the wind of 2005 and the atmospheric land boundary conditions of 2005. The map of the mean temperature obtained by CheapAML minus the temperature in 2000 is shown in Fig.3. This map is reminiscent of the map in Fig. 2: we recognise the same patterns with the same amplitude that we attribute again to the missing physics in our model (mostly clouds). We attribute the several warm biases near Antarctica to a different position of the ice cover in 2005 which affects substantially the surface atmospheric temperature. The mean value of the anomaly is 0.1 K and the standard deviation is 0.5 K.

This simple example emphasises the advantages of moving from the traditional practice of applying a prescribed atmospheric field to an ocean model to applying an atmospheric boundary layer model. CheapAML permits the atmospheric field in adapt in a realistic way to underlying SST. The icing on the cake is the minimal cost associated with this model in terms of implementation and computing resources.

Amongst the most significant concerns we have heard voiced about using CheapAML comes when considering ensemble experiments. In this case, due to intrinsic ocean variability, the literal ocean-atmosphere exchange varies between ensemble members and this raises issues about whether individual realizations can be properly thought of as a controlled ensemble. We would suggest in response the way to consider ensemble generation is to think of the exchange variability as a natural consequence of the evolution. The classification of a set of experiments as an 'ensemble' then becomes an issue of using identical winds, land temperatures and solar radiation, i.e. the elements to force CheapAML to allow it to force the ocean.

4. Conclusions

The value of this model is to capture part of the non-local feedback of the ocean surface on air-sea exchanges, while stopping well short of computing a full coupled ocean-atmosphere model. We believe that for an oceanic model, it is preferable to use CheapAML than to prescribe the temperature and humidity (or fluxes) from a reanalysis data set: as soon as the oceanic state deviates from the observed state, the reanalysis temperature and humidity fields and the oceanic state are not related anymore. The computational cost of using CheapAML is minimal, and does not materially increase the execution time of the model run. Furthermore, CheapAML captures the 'weather' impacts of the atmosphere on air-sea exchange with improved fidelity relative to its predecessor, Seager et al. (1995).

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