Does internally generated hydrodynamic noise matter in the Baltic Sea?

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1. Prologue

The findings about unforced variability – here named "hydrodynamic noise" - in models of the dynamics of the South China Sea (Tang et al., 2019, 2020) are reviewed – namely the intensification of the emergence of such noise with increasing spatial resolution, and its dominance (in terms of signal-to-noise ratio) on small scales.

The formation of such noise is significant for the design and evaluation of numerical experimentation with high-resolution models of oceanic dynamics, and for the estimation of the impact related to regional and local manifestations of global change.

We discuss and speculate which physical mechanisms are significant for the generation of noise in the Baltic Sea? Which consequences have these findings for studying the hydrodynamics and impacts in the Baltic Sea.

2. Results for South China Sea

In a series of numerical experiments on the hydrodynamics in the South China Sea (SCS) with the model HYCOM, the issue of intra-ensemble variability has been addressed. The SCS model with a grid resolution of 0.04° is embedded in a West-Pacific model with 0.2° grid resolution – and this, again is, into an almost global model with a 1° grid resolution. The latter model is hardly describing macro turbulent eddy dynamics, but the other two models become better in doing so.

In a first series of experiments (Tang et al., 2019), the ocean models were exposed to atmospheric forcing with a smooth constant annual variation. The intra-seasonal variance of sea surface height in the SCS is rather weak in the 1° grid resolution but substantial in the 0.04° grid resolution grid resolution (Figure 1). This increase is, at least partly, related to the emergence of eddies: A count of eddies finds almost no eddies in the 1°-model, but many in the other two, with a doubling from the 0.2° to the 0.04° grid.

From this result, we conclude that it is not only stationary spatial detail, which is added by increasing resolution, but also the variability. To which level the variability would grow with further increase of resolution, is unknown at this time.

In a second set of simulations an ensemble of 4 simulations, all covering 2008, but with different initial values was constructed. In this case, realistic weather was prescribed. The initial values were 13, 15, 25 and 27 months before January 2008, the beginning of the year which was evaluated (Tang et al., 2020).

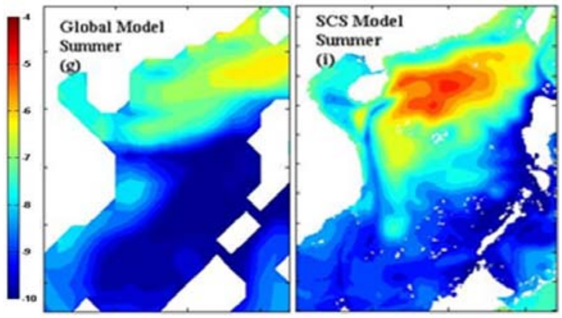

Figure 1. Logarithm of intra seasonal variability of sea surface height in summer in the 1°-grid model (left) and in the 0.04 °-grid model (right) of the SCS. After Tang et al. (2019)

The daily fields of barotropic stream-function (other variables would do as well) were expanded into Empirical Orthogonal Functions (EOFs). The variances represented by the EOFs (thus, their order) is indicative for the spatial scales. Signal-to-noise ratios (S/N) were constructed using the definitions:

Signal = annual intensity of the coherent variations of the four simulations (at the same day)

Noise = annual intensity of daily standard deviation of the four simulations (at the same day)

Three ranges of S/N were found – for the first 10 EOFs scales of on average 220 km and more, for a middle block of 40 EOFs scales of 110 km and for the remaining many EOFs scales of only 30 km. Higher-indexed, thus smaller scale EOFs go with smaller S/N, while low-indexed, thus large-scale EOFs with higher S/N. When recombining the spatial fields with the respective EOFs, we find higher S/N ratios in the coastal ocean, whereas smaller S/N ratios prevail in the deep ocean (Figure 2).

In short – noise dominates in deep water and on small scales – in the South China Sea.

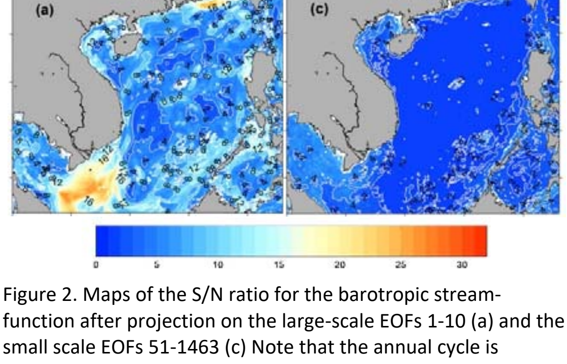

Figure 2. Maps of the S/N ratio for the barotropic stream-function after projection on the large-scale EOFs 1-10 (a) and the small scale EOFs 51-1463 (c) Note that the annual cycle is included in the EOF analysis. From Tang et al. (2020)

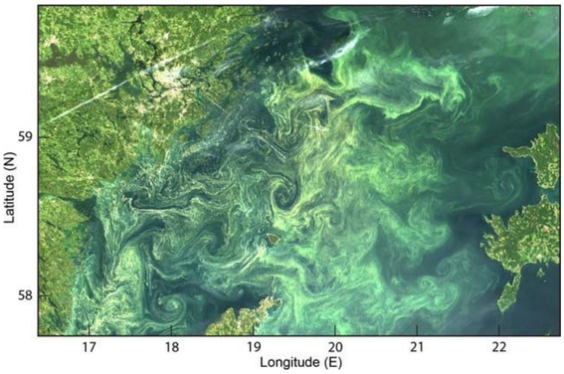

Figure 3. Cyanobacteria (primarily Nodularia spumigena) accumulations in Northern Baltic Proper on 11 July 2005 as shown on MODISTerra quasi true color image at 250 m resolution. Adopted from Kahru and Elmgren (2014)

3. Beddies in the Baltic Sea

The question is how strong such hydrodynamic noise is in the much less deep Baltic Sea, if there are preferred regions etc. We discuss the expectation given by our dynamical understanding of the Baltic Sea.

Most of this dynamical understanding is based on extensive simplifications on the hydrodynamic equations leading to Geophysical Fluid Dynamics (e.g. Cushman-Roisin and Becker, 2011). These simplifications highlight different aspects of the ocean dynamics and hide other aspects. Early studies in numerical modelling of the ocean were based not only on equation simplifications but on coarse model resolution and models with strong numerical viscosity and diffusion. In late 1970ies, when new satellite data became available, the observation of horizontal eddies (similar to Figure 3) challenged a reconsideration of ocean dynamics. In the Baltic Sea these mesoscale eddies (Beddies) have a typical horizontal diameter of 10 -20 km. But also, vertical eddies were found from direct measurements and often organized along the wind direction as Langmuir circulation. Recently, sub-mesoscale variability containing smaller spiral eddies and frontal filaments have gained attention of researchers. Meso- and sub-mesoscale Baltic ocean dynamics is considerably modulating environmental variables on the basin scales. Variability coming from the external forcing as e.g. upwelling, Langmuir circulation or inertial oscillation presents clear deterministic hydrodynamic signals. The question is now: do Beddies constitute part of hydrodynamic noise?

Beddies and sub-mesoscale features have been observed in most regions of the Baltic Sea. Mechanisms of their generation have been theoretically analyzed, suggesting mainly (1) baroclinic-barotropic instability as a random generation processes, and (2) forced vorticity generation when larger scale flow crosses the depth contours (so-called JEBAR effect, joint effect of baroclinicity and relief).

So far, neither in observed nor modelled situations, the mechanisms (1) and (2) have been clearly separated. Using ensemble simulations, as done in the SCS may help to determine signal-to-noise ratios, and thus improve our understanding of predictability of such features. If there are locations and regions, where forced variability dominates (in particular by specific coastlines or topography features), then by improving the models, then chances for skillful forecasts of eddies and filament features may be improved.

4. Outlook

The basic question to be asked is to what extent the dynamics of the Baltic Sea must be considered deterministic or stochastic. From a practical point of view, an answer has been given by forecast practitioners, who have begun to do ensemble forecasting (Büchner and Söderkvist, 2016) – there *is* a significant random component. This is not surprising, both in terms of physical expectation – Hasselmann's (1976) stochastic climate models points in this direction - but also from global modeling efforts such as that of Penduff et al. (2016),

For the longer period basin-scale oceanographic scenarios, it should be important to evaluate whether specific approaches of accounting the random and forced meso- and sub-mesoscale variability will converge when increasing the model resolution, and if there are "bifurcations" of the ocean system (e.g., different future paths for long-term changes in salinity: will be there "oceanization" or "freshening" of the Baltic Sea?).

Apart of these dynamical issues, the derivation of impacts of ocean variability and change need attention – what does a noisy component imply for mixing, what is the effect on sediment dynamics and on ecosystems, which interact with the physical system on smaller scales?

The presence of unprovoked variability has implications for numerical experimentation. It suffices no longer to just compare differences in two simulation, which differ by some specified modification, but null hypotheses need to be formulated and tested, as originally suggested in the 1970s for experiments with global atmospheric models (Chervin e al., 1974)

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