Experimental and Numerical Modelling of Large-Scale Phenomena in Physical Oceanography

Theses of the PhD Dissertation

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1 Introduction

The oceans and the atmosphere of Earth form a complex coupled hydrodynamical system that is basically driven by spatially and temporally varying Solar incoming radiation, tidal forces, and is largely affected by inertial forces caused by the rotation of the planet. The atmospheric and oceanic transport processes play a key role in distributing important physical quantities (e.g. heat, angular momentum, etc.) around the globe.

The circulation system of the oceans is devided into two parts: wind-driven and buoyancy-driven circulation. In the case of the former, wind shear drives the motion of the uppermost layer of the water body. This is the effect that dominantly shapes the structure of the well-known surface ocean currents (e.g. Gulf stream). Meanwhile, the buoyancy-driven circulation is governed by fresh water and heat fluxes that locally alter the density distribution of the oceans, and thus initiate flows tending towards stable stratification. Buoyancy-driven circulation is also widely referred to as Thermohaline Circulation (THC). It is important to note, that the effects of THC (in contrast to the wind-driven circulation) is not confined to the uppermost layer but also affects the full depth of the ocean. THC is responsible for the greatest water mass transport on Earth, which is twenty times as large as the combined water flux of all the rivers, and slightly larger than the total global flux of precipitation.

The ruling paradigm in physical oceanography is the concept of Great Ocean Conveyor (GOC). GOC is a well-established framework to describe large-scale matter and heat transport processes that connect oceanic basins and the circulation systems of the surface and the deep ocean.

2 Scientific goals

There are many unresolved issues of key importance regarding the basic underlying dynamics of GOC. One of these open questions is why the so-called deep water formation (DWF) regions are all located in the Atlantic. These regions are compact locations in the subpolar ocean where the interplay between temperature and salinity yields an unstable vertical density profile. This forces the surface water parcels to descend to the seafloor thus connecting the surface and deep branches of GOC.

The mechanism that forms the ascending branch of the global vertical water transport is also a matter of debate. According to the ruling consensus, this process is not confined to compact regions (like DWF), but takes place uniformly in the basins, driven by the interaction of internal tidal waves and bottom topography. However, the dynamics of these interactions is also one of the important detailes that are need to be resolved.

A third GOC-related open problem is the origin of the Atlantic Multidecadal Variability (AMV), a low frequency component of temporal sea surface temperature (SST) changes in the North Atlantic basin. AMV has been identified in instrumental records since the 19th century, and in proxy data for centuries. Yet the debates about even the most basic questions regarding its driving forces have remained unsettled so far.

In our research projects we addressed these three important elemets of GOC (the mechanism of DWF, the interactions between internal waves and bottom obstacles, and the origin of AMV) via laboratory experiments, numerical modelling and by analysing actual climatological time series.

3 Methods

The main principle of our studies lied in the parallel usage of numerical and experimental methods.

While modelling DWF, we were mainly focusing on numerical simulations. To obtain approximate solutions of the governing Boussinesq equations we implemented a non-hydrostatic slab model using the elements of the open-source "Advanced Ocean Modelling" software package. In addition to the numerical simulations we also performed laboratory experements in a tank filled with water. The differential heating at the surface and the bottom was produced by computer-controlled heating and coolong thermostats and electric heating elements. The visualisation of the flows was carried out by tracking dye patterns in the setup.

In the second project, which investigated internal wave dynamics, the experimental and numerical approach was of equal importance. The experiments were performed in a rectangular laboratory tank and our data processing technique was based on the digital processing of video recordings of the painted density interface. For the numerical simulations, again, we relied on the "Advanced Ocean Modelling" software package.

The basic dynamics of AMV was modelled in a rotating, differentially heated laboratory tank. The spatial and temporal properties of the temperature field at the water surface were detected by a system of digital thermometers. Besides the experiments we carried out statistical analyses of actual oceanic AMV data, obtained from the

NOAA Kaplan V2 reanalysis data set. The time series analysis was largely based on the standard method of Detrended Fluctuation Analysis.

4 Theses

The study of Deep Water Formation (DWF)

(1) In a numerical minimal model we studied whether the inhomogeneous distribution of geothermal heat flux at the seafloor may be responsible for the compactness of DWF regions (Vincze et al. 2011).

- We demonstrated that, as the “meridional” surface temperature difference exceeds a critical value, a full-depth circulation mode is initiated, involving DWF at the “Northern” end of the basin (i.e. where cooling occurs at the surface).
- We showed that a small “geothermal” heat source located underneath the “cold” end of the basin is able to initiate full-depth convection at a significantly smaller critical “meridional” surface temperature difference.

(2) Besides the simulation we also performed laboratory experiments in a similar setup. Here too, we demonstrated that the penetration depth of the upper-layer convection increases as a small additional bottom heat flux is present. This result underlines that DWF can be triggered by a localized bottom heat source even if the surface heat forcing alone is not sufficient to maintain this state.

The study of internal wave-bottom topography interactions

(3) In a laboratory experiment of a two-layer fluid we studied how the internal waves, propagating along the interface between the two layers interact with bottom obstacles (Boschan et al. 2012).

- We observed that the amplitudes of internal standing waves between two thin bottom sills can be largely amplified via resonant interaction with small amplitude surface waves. Because of their large amplitudes, the excited internal waves were then apparently nonlinear.
- We discussed the conditions of the observed resonance and measured the parameters of the resonance curve as a function of sill distance.

- We found and analysed the same phenomenon in our numerical model.

(4) We found the appropriate theoretical framework that is consistent with our experimental and numerical results. This mathematical approach is based on the periodic solutions (cnoidal waves) of the two-layer KdV equation. (Boschan et al. 2012).

The study of Atlantic Multidecadal Variability (AMV)

(5) We have built the experimental equivalent of a widely used numerical minimal ocean model to investigate the dynamics of the 20-30 year AMV mode (Vincze et al. 2012).

- We verified the earlier numerical results on the necessary and sufficient conditions for the excitation of an AMV-type low-frequency temperature oscillation. These conditions are: the rotation of Earth, meridional temperature gradient and the presence of a spatially and temporally correlated thermal noise, representing atmosphere-ocean interactions.
- We showed that – in agreement with earlier numerical findings – the characteristic period of the AMV-like variability gradually decreases with the increase of meridional temperature difference.
- We observed and described a specific spatial pattern in the surface temperature fields in the setup, associated with the low-frequency variability.

(6) Comparing our experimental results to Atlantic Sea Surface Temperature (SST) reanalysis data we demonstrated the dynamical similarity of the two systems and gave the appropriate non-dimensional parameters for the rescaling. (Vincze et al. 2012).

(7) We analysed the AMOI (Atlantic Multidecadal Oscillation Index) time series and the significance levels of its consistency with traditional AR(m) time series models and long-range correlated (lrc) processes as null hypotheses. We showed that according to instrumental records of the past 150 years the 50-70 year mode of AMV rather seems to be consistent with an lrc process, which also fits fairly well to the SST variabilities observed on smaller (monthly-annual) timescales. (Vincze & Jánosi 2011).

5 Conclusions

We can conclude that in our research projects we have revealed interesting partial answers to the open questions of GOC using largely simplified minimal models. Our results have been published in referred scientific journals. The future comparison of the processes uncovered by our studies with in-situ measurements and more advanced numerical model results will probably provide a considerable contribution to the better understanding of large-scale ocean circulation.

References

Publications on which the theses are primarily based:

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Other publication:

Várai, A., Vincze, M., Lichtenberger, J. and Jánosi, I.M.: *Search for possible relationship between volcanic ash particles and thunderstorm lightning activity.* IOP Journal of Physics: Conference Series, **333**, 012016 (2011). doi:10.1088/1742-6596/333/1/012016