Synergy between ocean observations and numerical simulations: CLIPPER heritage and DRAKKAR perspectives

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SYNERGY BETWEEN OCEAN OBSERVATIONS AND NUMERICAL SIMULATIONS: CLIPPER HERITAGE AND DRAKKAR PERSPECTIVES

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ABSTRACT

Between 1996 and 2005, the French CLIPPER project team performed numerical simulations of the Atlantic Ocean over the WOCE years (1980-2000). Since 2002, the DRAKKAR program extends this framework: international collaboration, global and basin-scale simulations of the ocean circulation, sea-ice and biogeochemical tracers over the 1950-2000+ period at increased resolutions with local grid refinement capabilities, improved physics and numerics. Both projects were designed to strengthen the complementarity between ocean simulations and observations, for the study of the oceanic variability. This review paper illustrates the scientific benefits of such synergies as performed during the CLIPPER experiment, and as presently done within the DRAKKAR program.

1. OBSERVATIONAL AND NUMERICAL OCEANOGRAPHY

The quantity and quality of oceanic observations has strongly increased over the last decades, especially during the World Ocean Circulation Experiment (WOCE) and since the advent of spatial oceanography. The global ARGO array of profiling floats extends since 2000 the satellite monitoring of the global oceanic surface to the uppermost 2 kilometers. These datasets have highlighted the complexity and ubiquity of the ocean’s variability over a wide range of space and time scales. However, observational datasets remain too short, too superficial (satellites) or too dispersed in time and space (drifters) to allow detailed studies of physical processes across their full range of scales. This is particularly true for nonlinear processes (dynamical interactions across wide time and space scale ranges, complex interplays between ocean physics and biogeochemistry, mesoscale and sub-mesoscale dynamics). Combined investigations of observations and numerical simulations are necessary to investigate such issues.

Primitive equation ocean models have substantially improved in terms of physics and numerics (forcing functions, subgrid-scale parameterizations, etc). Thanks to the growing computational power, the size and resolution of numerical domains and the duration of simulations have increased, thus extending the range of space/time scales that can be explicitly simulated and improving the realism of solutions. These observational and numerical developments, along with improvements of data assimilation techniques, have led to ocean reanalysis experiments and to operational oceanography. Data assimilating systems constitute a well-known example of model-data synergy: ocean models are used as dynamical interpolators between various types of dispersed observations while observations maintain the model trajectories close to reality.

Modeling the ocean realistically is impossible without observations: initial states, boundary forcings, the adjustment of model parameterizations, the scientific validation and analysis of the solutions largely depend on the available data. Despite truncation errors, forcing errors, and imprecise initial states, the realism of ocean simulations generally increase as the model grid allows the explicit resolution of mesoscale dynamics (that are involved in most ocean processes). In high-resolution assimilating experiments, observations are used where and when available to reconstruct the actual evolution of the large-scale circulation and of individual eddies. The approach followed during the CLIPPER and DRAKKAR studies is somewhat different and complementary: models are forced by reconstructed (reanalyzed) atmospheric fields, but mesoscale, regional and large-scale oceanic fields are totally free to interact. Because they are nonlinear and barely constrained, these solutions cannot not be as realistic as their assimilated counterparts with respect to individual observations. But for the same reason, they help analyze complex dynamical responses, generated internally or forced the atmosphere, scale interactions over large time/space scales, feedbacks between dynamics, thermodynamics and biogeochemistry, including over the pre-satellite era when observations were rare. Once their actual realism is evaluated, the oceanic scenarios produced by these models can be precisely analyzed in terms of dynamical balance. The following sections present various aspects of the complementarity between observational datasets and numerical simulations.

2. OVERVIEW OF THE CLIPPER AND DRAKKAR PROGRAMS

In 1996, scientists from five French laboratories designed the CLIPPER Program (http://www.ifremer.fr/lpo/clipper/index.html) with the objective to model and study the variability of the whole

Atlantic Ocean over the WOCE period (1980-2000). About 20 multi-year sensitivity experiments were performed at various resolutions (1°, 1/3°, 1/6°, up to 1/15° regionally) using different surface forcing functions derived from reanalyzed air-sea flux products (mostly from ECMWF). CLIPPER simulations have been to used in about 35 peer-reviewer papers since 1999, most of which in combination with observational datasets. This research program stimulated the development of the OPA8 ocean model for high-resolution basin-scale modeling (numerical schemes, surface and lateral boundary conditions, grid refinement techniques, etc.) The 1/3° North Atlantic CLIPPER configuration has been transferred to the MERCATOR-Ocean centre and is being used since January 2001 for operational forecasts.

The DRAKKAR Program, designed in 2002, extends the framework of its predecessor CLIPPER in terms of scientific objectives, numerical tools, and multi-disciplinary collaborations with associated scientists (http://www.ifremer.fr/lpo/drakkar/index.htm). The DRAKKAR Project Team includes ocean, atmosphere, sea-ice scientists and applied mathematicians from 8 research laboratories in 5 countries and from the MERCATOR-Ocean operational oceanography center. The general objective is to model and study the 3-dimensional evolution of the ocean circulation, sea-ice, and passive tracers (CFCs, bomb ^{14}C) over the last 50 years, in close relationship with observationalists and associated scientists. A hierarchy of models based on the NEMO modeling framework has been constructed and is presently running in coordination among the groups: global configurations at 2°, 1/2°, and ¼° resolution, North Atlantic/Nordic Seas regional models at ¼° and (soon) 1/12°, and idealized configurations. Besides its research applications, the ¼° global model is being used for global ocean forecasting at the MERCATOR operational center since October 2005.

3. MODEL SETUP AND FORCING

The aim of CLIPPER or DRAKKAR simulations is to mimic the real ocean variability with constraints limited to the atmospheric forcing (and lateral boundaries in regional models). Observations are involved for the setting up the discrete domain geometry, adjusting model parameters and building the atmospheric forcing function

3.1 Model setup

Bottom topography strongly affects the dynamics and distribution of eddies, fronts and currents up to the surface [1]. In addition, the representation of topographic constraints in numerical models and their subsequent solutions at regional and basin scales depend on their numerical formulation and on bottom boundary conditions [2, 3, 4]. Unlike in sigma-coordinate models where topographies are smoothed to reduce numerical errors, topographic datasets are generally used as is (i.e. keeping the finest scales present in altimeter-derived fields) in geopotential-coordinate models like OPA/NEMO. A detailed comparison of CLIPPER outputs with all the WOCE current-meter measurements available in the Atlantic showed that these fine structures distort the vertical distribution of mean and eddy kinetic energy [5, 6], especially where the spatial scales of oceanic currents are marginally resolved (high latitudes). This reference to in-situ observations to evaluate CLIPPER dynamics helped setting up the DRAKKAR topographies and interpret several sensitivity experiments: comparison of near-surface [7] and full-depth [8] circulations, and numerical study of the near-bottom origin of these differences [9].

More generally, numerous sensitivity experiments are performed and carefully compared to ocean observations to develop and adapt model parameterizations. They are used to take small-scale processes (eddy fluxes, entrainment/detrainment, surface and bottom non-hydrostatic mixed layer processes, etc.) into account in basin-scale and global ocean simulations. For instance, EQUALANT ADCP velocity measurements [10] were used as a reference to improve the parameterization of near-surface equatorial momentum eddy fluxes in the CLIPPER models [11]. Consistently with dedicated studies of inertial instabilities [12], the representation of the Atlantic undercurrent was improved by the local addition of a down-gradient Fickian diffusion of momentum. The DRAKKAR project team has started collaboration with observationalists from the Grenoble glaciology laboratory (LGGE) to evaluate the sea-ice visco-plastic component of the NEMO model used in DRAKKAR. The simulated sea-ice deformation tensors and distribution variability will be carefully compared to satellite observations with the objective of evaluating and (possibly) improving the model. Other model data-comparisons are being performed presently to improve the fit to globally observed mixed layer depths (parameterization of Langmuir and surface waves) or the three-dimensional density field downstream of topographic sills (entrainment in overflows).

3.2 Model forcing

The choice and formulation of the external forcing is of major importance in ocean modeling and is largely based on observational datasets. CLIPPER simulations were initialized from a seasonal T/S climatology based on historical hydrography [13] that was developed for the project but used in various other studies. The CLIPPER Atlantic models required physically-consistent open boundary conditions (OBCs) able to evacuate outgoing perturbations transparently and to simulate the presence of a variable outer ocean [14]. The aforementioned climatology was used to constrain tracer and velocity shears along OBCs. Synoptic hydrographic sections were used (with an equivalent barotropic hypothesis and after removing synoptic eddies) to constrain absolute velocities at both openings of the austral Atlantic sector ([15] at 68°W, [16] at 30°E). This combined use of climatological and synoptic hydrography was necessary and proved successful in controlling the model over 20 years [6, 14]. The CLIPPER atmospheric forcing was derived from the ECMWF reanalysis and analysis, and was applied in terms of heat, salt and momentum fluxes. A relaxation term was applied on surface temperatures and salinities to compensate for forcing uncertainties (thus letting the model correct them where needed), and to roughly mimic the ocean feedback on air-sea fluxes [17]. The use of scatterometer winds in CLIPPER was shown to improve the simulated variability at low latitudes.

A more consistent formulation of air-sea interactions has been introduced in DRAKKAR through bulk formulae. These parameterizations provide turbulent air-sea fluxes of heat, freshwater and momentum from the instantaneous simulated ocean and reanalyzed atmospheric variables [7]. The DRAKKAR hierarchy of models (simple planetary boundary layer model, global ocean/sea-ice models at increasing resolutions) is currently used to develop a forcing function that hybridizes reanalyzed atmospheric fields with air-sea interface satellite observations. This “more observational” approach is likely to improve the long-term stability of unconstrained ocean simulations.

4. MODEL VALIDATION

The realism of unconstrained numerical simulations is generally the result of reasonable physics (section 6) and forcings (section 3), and should be systematically assessed with respect to available observations. Most scientific studies that make use of model outputs actually start by such model-data comparisons thus contributing to the validation of large simulations. CLIPPER solutions have been evaluated by several authors who extracted model counterparts of real data colocalized in space (and possibly time), treated both datasets identically and could quantify model-data misfits. For example, lagrangian time/space eddy scales [18], deep subtropical zonal flows [19], Agulhas rings properties [20], interannual variations of Labrador Sea Water characteristics [21] and of basin-scale eddy distribution [22] were validated and studied from colocalized datasets (drifters, ADCP, BRAVO timeseries, and altimeter fields, respectively). More quantitative validation studies have involved model-data correlations for tropical sea level anomalies [23], or stimulated the development of model skills with respect to current meter data [6]. These comparisons contribute to characterize the quality of numerical solutions and evaluate their relevance to interpret observations.

To validate eddy-permitting global ocean simulations more precisely (and to take advantage of the available datasets) requires additional developments that are underway in DRAKKAR with the support of the CNES/NASA Ocean Surface Topography Science Team. Local and global quantities (maps, sections, integral budgets, transports, etc) are computed during model simulations, and regularly compared to corresponding observations when and where available. This monitoring helps comparing various sensitivity experiments mutually and/or against the same references, such as the 3D evolution of temperatures and salinities, mass and heat transport of the main currents, global distribution and properties of the surface mixed-layer, of the sea-ice cover, of passive tracers, or the evolution of surface temperatures in the equatorial Pacific (NINO boxes, Fig. 1). Synthetic observations, colocalized with available observations, are extracted from model outputs and archived as observed databases to facilitate exchanges with real data users. The validation of long DRAKKAR simulations will be based on colocalized model-data comparisons with respect to the main observational datasets (historical hydrography, ARGO and altimeter fields). Identical diagnostics will be applied on real and synthetic observations to characterize model misfits on various periods, in various regions and depths ranges.

5. OBSERVING SYSTEM SIMULATION EXPERIMENTS (OSSE)

Ocean simulations provide a dynamical context to design observing systems and evaluate their performances a priori. Synthetic observations can be extracted from model outputs to assess observation/mapping errors or the potential for combining various datasets. For instance, high-resolution CLIPPER synthetic datasets helped evaluate the representativeness of hydrographic transects in terms of meridional overturning and transports, the impact of eddies on such observational estimates, and the uncertainty linked with the use of neighboring sections in estimating year-to-year changes of the meridional transports [24]. A dedicated high-resolution simulation has also been conducted by the CLIPPER team to characterize the space/time variability of sea-surface salinity over its full range of simulated scales, and their expected observability [25]. This run helped characterizing this virtually unknown field, and to design the SMOS (Soil Moisture and Ocean Salinity) mission. CLIPPER outputs were also used to demonstrate that the fluctuations of the Deep Western Boundary Current transport could be estimated from XBT-derived dynamics heights and SSH measurements in the North and South Atlantic [26]. Other observational systems were also assessed from CLIPPER outputs, including the ARGO float array alone [27] or in combination with SSH and SST satellite data [28], the GRACE (Gravity Recovery And Climate

Experiment) and GOCE (Gravity-field and steady-state Ocean Circulation Explorer) missions [29, 30].

One of DRAKKAR objectives is to pursue such collaborative investigations of observational systems, to characterize their representativeness and the observability of small-scale processes or climate indexes. The DRAKKAR group wishes to produce, distribute and analyze synthetic datasets (satellite, in-situ, up to kilometric resolutions) in collaboration with the OST/ST and observational communities.

6. PHYSICAL PROCESSES AND CIRCULATION FEATURES

The CLIPPER ensemble of 20-year Atlantic Ocean simulations has been widely used to put observed features (in particular WOCE and satellite data) into a broader context and to gain insight into their dynamical origin. These process studies, conducted in a realistic context, have concerned various time/space scales (days to decades, a few kilometers to thousands), regions (subpolar to equatorial, surface to bottom) and processes (water masses, dynamics, mutual interactions). Among other examples, theories and observations were compared with the four-dimensional model solution to investigate the equatorial circulation [31] and wave activity [23, 32], the link between Loop Current Eddy shedding and vorticity fluxes into the Gulf of Mexico [33], or the origin of subtropical zonal flows at depth [34].

Some authors took direct advantage of the wide range of time and space scales resolved in CLIPPER experiments. They showed the importance of mesoscale eddies in processes involved in climate variability, and in several cases, the limits of eddy parameterizations used in most non-turbulent climate models. For instance, the eddy-driven character of the post-convective restratification in the Labrador Sea was demonstrated by nesting a 1/15° model of this region into a 1/3° CLIPPER configuration [35]. Combined examinations of modeled and observed mesoscale activity showed the importance of instabilities and eddies in controlling the Indian-Atlantic heat flux in the Agulhas basin [20], the subduction process and its overall effect on North Atlantic mode waters [36], or the sensitivity the large-scale and mesoscale circulation to the North Atlantic Oscillation [22].

The realism of CLIPPER solutions against mean circulation schemes and water masse properties was shown to improve at each resolution increase (runs performed at 1°, 1/3°, 1/6°, up to 1/15° in the Labrador Sea). This is expected from the improved representation of the currents' natural scales, but three independent studies [22, 37, 38] based on CLIPPER and observed data led to another result, only showed in idealized models at that time. The resolution of mesoscale turbulence in ocean models increases the variance of important large-scale ocean indices (distribution and magnitude of eddies, intergyre heat fluxes) at interannual timescales (possibly slower). Non-linear scale interactions are increased by mesoscale processes and can generate intrinsic fluctuations of these indices (up to 40% of the large-scale interannual variability), even without interannual atmospheric forcing. In non-eddy-admitting coarse-resolution ocean models, these important contributions to climate variability are not resolved and cannot be parameterized through usual Fickian operators.

DRAKKAR extends the dynamical spectrum resolved in CLIPPER toward longer timescales (up to 50 years), larger and shorter space scales (up to global, down to 1/12° over the whole Atlantic). Along with better parameterizations and the explicit simulation of sea-ice and passive tracers, this spectral extension is expected to improve the consistency of simulated dynamics, the value of process studies, and the potential for fruitful collaborations with associated scientists.

7. CONCLUSIONS AND PERSPECTIVES

The aim of this paper was to illustrate various connections between numerical and observational oceanography. Observations are vital for the setup, improvement, validation, and analysis of simulations; simulated fields provide a framework to design and evaluate observing systems, to complement and interpret incomplete pictures of the real ocean. These expectations are certainly fulfilled in assimilation experiments, where the four-dimensional oceanic evolution is reconstructed from dispersed datasets of various origins (reanalyzes). Unconstrained simulations are globally less realistic than their assimilated counterparts with respect to individual observations, but they are complementary to such reanalyzes. Indeed, they are not limited to the years of sea-surface altimetry over which most ocean reanalyzes are performed; their realistic features, i.e. those that were actually observed, can be fully interpreted in terms of discrete primitive equation terms; they are necessary to simulate the free, non-linear oceanic response to changes in physical parameters or atmospheric forcings, thus allowing process studies of cause-to-effect relationships.

Both observational and numerical oceanography have improved and converged toward each other, especially during the WOCE years over which CLIPPER simulations were performed. Just like their observed counterparts, modeled datasets have strongly increased in size and quality, but much remains to be done to improve their complementarity. Quantitative model-data comparison approaches need to be developed on physical bases to distinguish model biases (thus guide numerical improvements) from realistic simulated features (thus orient physical investigations). When possible, ocean reanalyzes need to be included in these validation exercises and in dynamical investigations.

Theoretical investigations, high-resolution modeling programs, observational missions, and reanalysis efforts tend toward a better understanding of the ocean dynamics in complementary ways. Convergences between the first approach and the other ones were not addressed in this paper, but they are crucial and deserve dedicated efforts. By making model outputs available to associated teams, the CLIPPER and DRAKKAR programs aim at stimulating and extending such interactions within the scientific community.

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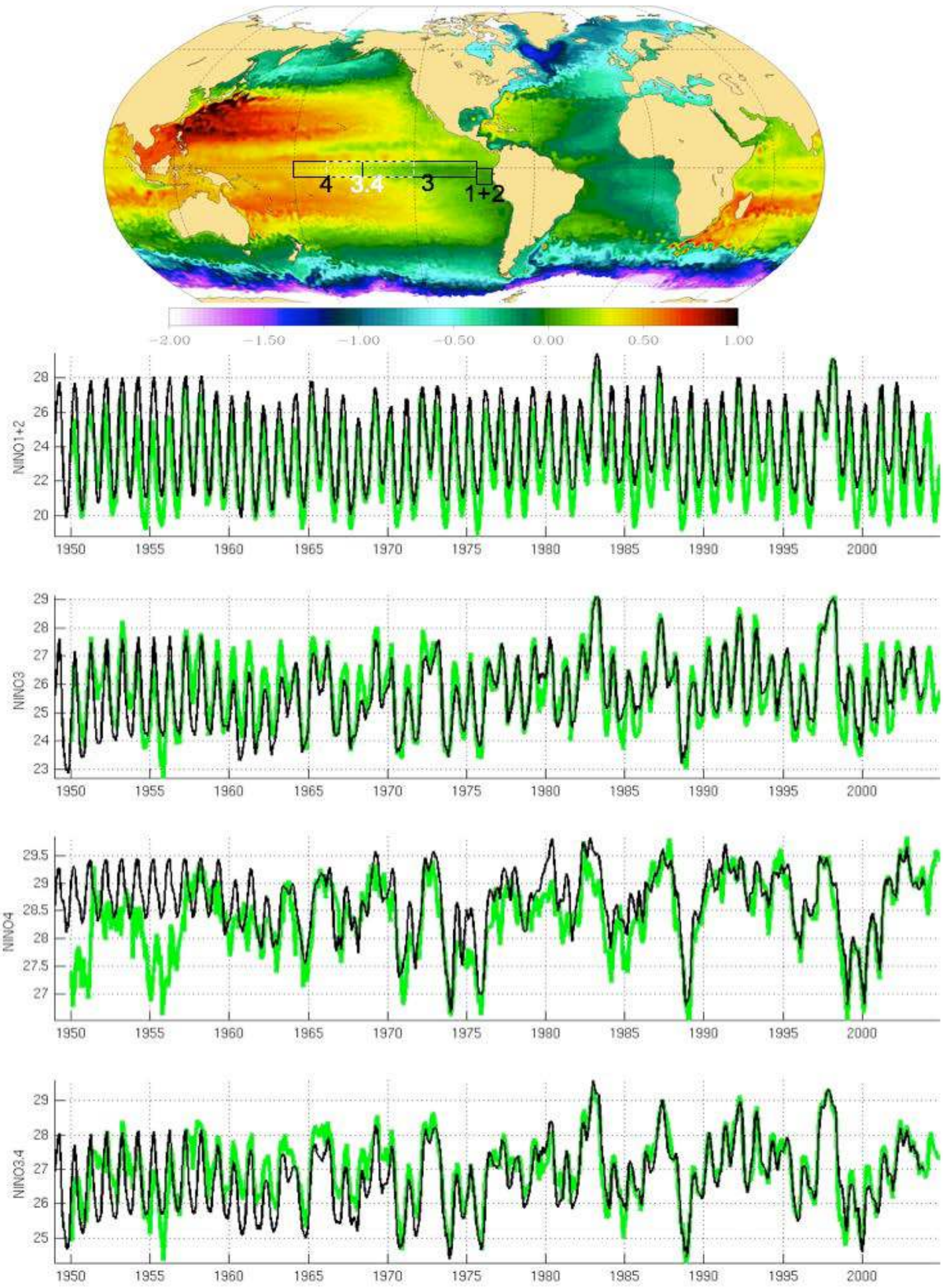

Figure 1: Upper : December snapshot of sea-surface height (m) from the DRAKKAR 1/4° model. Lower : 1949-2003 evolution of observed (green) et simulated (black) monthly sea-surface temperatures (SST) in the Tropical Pacific boxes shown in the upper plot. DRAKKAR 1/2° run, CORE interannual forcing[1]. Over the post-spinup phase (1958-2003), correlation coefficients between model and real SSTs lie between 0.88 et 0.95.

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