Nonlinear Processes in Geophysics

Preface
"Nonlinear processes in oceanic and atmospheric flows"

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Abstract. Nonlinear phenomena are essential ingredients in many oceanic and atmospheric processes, and successful understanding of them benefits from multidisciplinary collaboration between oceanographers, meteorologists, physicists and mathematicians. The present Special Issue on "Nonlinear Processes in Oceanic and Atmospheric Flows" contains selected contributions from attendants to the workshop which, in the above spirit, was held in Castro Urdiales, Spain, in July 2008. Here we summarize the Special Issue contributions, which include papers on the characterization of ocean transport in the Lagrangian and in the Eulerian frameworks, generation and variability of jets and waves, interactions of fluid flow with plankton dynamics or heavy drops, scaling in meteorological fields, and statistical properties of El Niño Southern Oscillation.

In recent years atmospheric and oceanic data sets arising from new observational and computational capabilities have become widely available. These data sets, and the variety of geophysical nonlinear phenomena that they reveal, are giving rise to new challenges and opportunities that are benefiting greatly from a multidisciplinary approach. Methods from diverse areas of mathematics such as dynamical systems theory and statistics have been combined with sophisticated computational methods and have been brought to bear on a variety of data sets taken in very diverse physical settings. These new approaches have been developed in collaborations between mathematicians, physicists, oceanographers, and meteorologists.

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On 2–4 July 2008 such a group gathered for a workshop entitled "Nonlinear Processes in Oceanic and Atmospheric Flows" held at Castro Urdiales, Cantabria, Spain, with the generous support of the United States Office of Naval Research (ONR Global), Consejo Superior de Investigaciones Científicas (CSIC), Ministerio de Educación y Ciencia (MEC), Centro Internacional de Encuentros Matemáticos (CIEM), Consolider i-MATH and SIMUMAT. The fourteen papers in this Special Issue describe the breadth of ideas and results discussed at this workshop and illustrate the exciting opportunities for multidisciplinary collaborations in the oceanic and atmospheric sciences.

The paper of Boucharelet al. (2009) introduces novel ideas from statistics, taken from the field of financial mathematics, to perform a more detailed diagnosis of the properties of the El Nino Southern Oscillation (ENSO). The authors analyze data from the Zebiak-Cane model, models used by the Intergovernmental Panel for Climate Change (IPCC), as well as in situ data. Their analysis raises a number of provocative points and conclusions that should be considered in the context of the fidelity of climate models in general.

Rossi et al. (2009) analyze the interaction between eddy induced mixing and phytoplankton distributions on small scale (1–100 km) processes using satellite data. Their analysis leads to the surprising conclusion that strong mixing in nutrient-rich waters along Eastern Boundary Upwelling Systems (e.g. the Benguela and Canary currents in the Atlantic Ocean, and the Humboldt and California currents in the Pacific) appear to reduce, rather than stimulate, growth of phytoplankton.

The paper by Sánchez-Garrido and Vlasenko (2009) addresses the behaviour of internal solitary waves in a rotating and laterally confined domain, with emphasis in the non-linear regime. According to the classical weakly nonlinear theory, energy is damped through radiation of secondary Poincaré gravity waves due to rotational dispersion.

However, under strong non-linearity conditions, the energy damping is partially suppressed due to non-linear wave-wave interactions. This leads to a regime where internal solitary waves evolve into a slowly decaying packet of Kelvin waves that may propagate for a long time. An understanding of phenomena of this type is fundamental for obtaining a deeper insight into energy pathways in the oceans.

Using a variety of meteorological variables (derived either directly from numerical simulations or from re-analysis which combine observed values with numerical models assimilating them), Stolle et al. (2009) demonstrate that the scaling properties of these variables can be explained in terms of underlying multifractal cascades, beyond the usual, single-exponent characterization. Their findings can be applied to improve the parametrization of numerical models, as well as to validate the correctness of the implementation of non-linear effects.

Using a simple idealized plankton model, McKiver at al. (2009) analyze the importance of horizontal advection on phytoplankton biomass. They use a single species model with multiple steady states depending on the values of the carrying capacity, and show that small changes in the ratio of biological to hydrodynamic time scales can greatly modify plankton production. As a consequence, they argue that this effect may be a possible mechanism for explaining plankton blooms or regime shifts in some oceanic regions.

Dellnitz et al. (2009) consider the fundamental issue of detecting regions in the ocean that are coherent over an extended period of time. These structures, such as gyres, are important with respect to the movement of heat around the planet, distribution of nutrients, etc. The authors use a realistic numerical model to study a 3-D coherent structure in the Southern Ocean using a methodology based on transfer operators. They show that transfer operators are a useful tool for identifying circulating pathways across these structures.

Pierini and Dijkstra (2009) review the proposed ways to understand the bimodal characteristics of the low-frequency variability of the Kuroshio System: a state with the presence of a zonally elongated energetic meandering jet alternating, on decadal time scales, with a state of a weaker jet with reduced zonal penetration. The origin of such bimodality can be either in the ocean response to changes of wind stress fields, and then due basically to the atmospheric forcing of the ocean, or identified as intrinsic ocean variability. As expected both aspects should be taken into account, but what is remarkable is that the non-linear behavior of the bimodal system is quite well reproduced and understood both quantitatively and qualitatively just by considering the internal variability caused from homoclinic transitions involving multiple equilibrium states of an ocean reduced gravity model under steady wind forcing.

Zahnow and Feudel (2009) consider the effects of collision, coagulation and fragmentation processes on the size distribution of heavy drops moving in a turbulent fluid. The problem is relevant, for example, to the growth of cloud droplets. The particle-based approach goes beyond simple transport models of inertial particles, without the complications of a fully hydrodynamic simulation. Scaling laws of mean sizes and distributions with respect to the different flow and particle parameters are obtained by a combination of numerical and theoretical arguments.

Branicki and Wiggins (2010) give a critical analysis of the use of hyperbolic trajectories, their stable and unstable manifolds, and finite time Lyapunov exponents for revealing flow barriers and organized structures in aperiodically time-dependent flows that exist only for a finite time. This is a rapidly developing area due to the explosion in the availability of observational and computational data sets for geophysical flows. This paper takes a different point of view and describes a series of specific examples that highlight different phenomena and their interpretation, as well as problems and pathologies that can arise. Consequently, this paper provides "benchmarks" for the necessary further development of the theory and for the application of these methods to complex geophysical flows.

Koszalka et al. (2010) explore how vertical transport within wind-forced eddies is affected by stratification. They show that the wind energy injected at the surface is transferred to depth through two stratification-dependent mechanisms: vortex Rossby waves and near-inertial internal oscillations. In view of their results on the role of wind-forced mesoscale vortices in the transmission of wind energy into the ocean and vertical transport, the authors stress the need to resolve the vertical transport and mixing by mesoscale eddies in models designed to study oceanic circulation under different climatological conditions.

Marié (2010) studies mechanisms for the generation of zonal jets by β-plane turbulence. The work begins with a simple situation – a study of linear perturbations of Rossby waves by zonal flow in an infinite β-plane. He then considers a more realistic situation consisting of a reduced-gravity model in a quasi-geostrophic setting and shows that essentially the same results hold. This work provides insight into a complex phenomenon resulting from a turbulence-mediated, subtle interaction, between two very different scales.

The paper by Mendoza et al. (2010) applies a combination of Lagrangian tools, some of them new and others well established, for studying transport in velocity data sets obtained from altimetry over the Kuroshio current region. The study shows how distinguished hyperbolic trajectories and their stable and unstable manifolds can be computed in realistic data sets. It also addresses how to achieve an accurate analysis of transport from the stable and unstable manifolds. The method successfully characterizes the turnstile mechanism across this area and this mechanism is shown to persist over the spring months of year 2003.

Branicki and Malek-Madani (2010) consider transport in a realistic time-dependent-velocity data set obtained from a shallow water model of the Chesapeake Bay. In this context they assess the limit of validity of 2-D Lagrangian tools

for analyzing estuarine flows. The 2-D Lagrangian analysis of the surface flow captures the spatio-temporal variability of the freshwater outflow events. The computation of finite time Lyapunov exponents reveals a network of ridges, but these are often too short for a meaningful transport analysis, while computation of stable and unstable manifolds of relevant hyperbolic trajectories has the comparable challenge of first computing the hyperbolic trajectories on a sufficiently long time interval. It is anticipated that a symbiotic combination of these Lagrangian diagnostics might overcome these difficulties. Their work points out that further development of 3-D Lagrangian techniques is still required for reliable transport analysis of complex coastal flows.

Hydrodynamic forcing is known to play an important role in plankton dynamics. Pérez-Muñuzuri and Huhn (2010) consider the influence of the spatial and temporal scales of the flow on the spatial extension of a plankton bloom using a reaction-diffusion-advection equation in which the reaction part models a Nutrient-Phytoplankton-Zooplankton biological dynamics. Their analysis shows that the bloom size is larger for certain length and time scales of the flow. This is related to the fact that the balance of two processes, trapping fluid inside eddies on the one hand, and mixing and diluting on the other hand, is optimal for bloom growth at these particular length and time scales.

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