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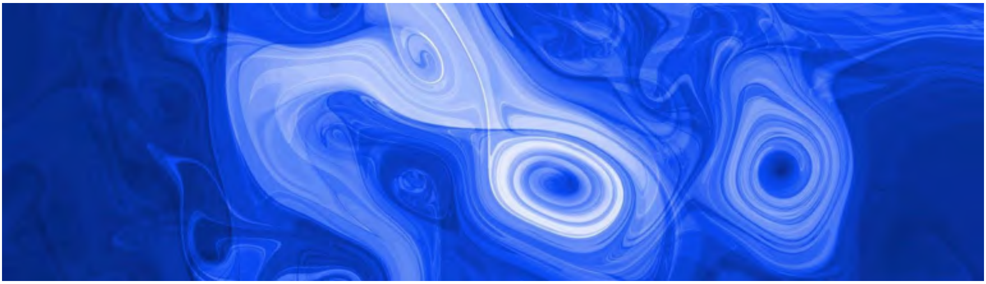

Nonlinear processes in oceanic and atmospheric flows

Madrid, July 6-8, 2016

List of contributions

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Invited talks

Predicting in a turbulent environment: The Iberian-Biscay-Ireland Copernicus Marine Forecasting System

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The present study is aimed at intercomparing the ocean physical daily forecast and 10-year (2002-2012) reanalysis products provided by the Iberia-Biscay-Ireland Monitoring and Forecasting Center (IBI-MFC), in the framework of the Copernicus Marine Environment Monitoring Service (CMEMS), over an overlapping 9-month period (April-December 2011). These two products differ in their spatial resolution and in the use of an observational data assimilation scheme in the reanalysis. Both modeled solutions are compared at regional and local scale against several observational data sources. At regional scale, the forecast and reanalysis show realistic patterns in the area of study. However, at finer scales the results highlight better performances of the 1/36 forecast in coastal areas and the 1/12 reanalysis over open waters. The comparison emphasizes the possible benefits of the data assimilation scheme in areas away from the coastline, but also its limitations in complex coastal regions. Spatial resolution seems to play a key role in such areas, especially around the Iberian Peninsula, where the higher resolution forecast brings in general better results than the coarser resolution reanalysis. The study suggests that the observational data assimilation represents a crucial step towards improving the performance of regional modeled solutions, as long as the spatial resolution is kept at fine-enough meshes in order to prevent higher uncertainties in coastal and shelf areas.

Data Assimilation in nonlinear models

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The concept of data assimilation encompasses the various methodologies used to blend the information from observations and model outputs to provide a suitable model solutions incorporating data from observations and able to initialize the ocean model. Since the pioneering failure of the first meteorological application of data assimilation in 1922, much has been understood about model filtering, initialization and interpolation procedures. The optimal solution of the data assimilation problem is based on the Bayes theorem, which allows to calculate the probability distribution of the model states conditioned by the observed state. However, closed optimal solutions of the Bayes theorem exist only for linear models. For non-linear models, only approximate solutions do exist, and a richness of sub-optimal methods have been proposed in the last twenty years. Each sub-optimal approach differs on the strategy used to beat the curse of dimensionality. A review of these approaches in given here.

Gyrotactic phytoplankton in turbulent flows

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Many unicellular algae, which compose phytoplankton, are able to swim. Some species have simple orientation mechanisms allowing them to swim against gravity towards the photic zone. A standard mechanistic model allows to account for several experimental observations as resulting from the balance between fluid torque and directed vertical motion, the so-called gyrotaxis. I will discuss how (turbulent) fluid motion and gyrotactic motility can generate patchy distributions.

Reconstruction of ocean currents from existing satellite observations: the challenge of high resolution dynamics

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Infrared and visible satellite observations have revealed that the ocean surface is crowded with eddies with scales O(10 -100 km) and submesoscale structures, like fronts and filaments, with scales O(1-10 km). Satellite infrared measurements of Sea Surface Temperature (SST) have resolutions high enough to observe submesoscales (1 km), and the existence of multiple platforms with infrared sensors can provide observations of the same area with temporal samplings of less than 6 h. The key problem to be addressed is the extraction of quantitative dynamical information at the scales of interest from existing observations. Indeed, along-track altimetric measurements of Sea Surface Heights (SSH) are very well suited to quantify across-track currents. However, the spatial resolution of derived 2D velocities is restricted to scales above 100-150 km and the limited number of altimeters can lead to errors in the location of currents. To overcome the previous constrains, new theoretical frameworks that model the dynamics of the upper ocean have been proposed. Here, we discuss the strengths and weakness of dynamical approaches like the Surface Quasi-Geostrophic (SQG) equations to retrieve the three-dimensional dynamics of the ocean, as well as other approaches that exploit the synergy between SST and SSH measurements to provide enhanced 2D surface currents. Recent results showing the current capabilities to retrieve the velocity field at scales of the order of 10 km will be also shown.

Modelling Oceanic Dispersion : an application to the Lagrangian Transport in the Sicily Channel

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A correct description of Lagrangian dispersion in the ocean has great relevance, but it is a delicate task because of the finite space and time resolution of the circulation models. These are mostly affected by two main limitations: i) unresolved scale motions, and mesoscale motions that are largely smoothed out at scales close to the grid spacing; (ii) poorly resolved time variability in the profiles of the horizontal velocities in the upper layer. In the talk, I will discuss how we can use observations to improve numerical modeling of dispersion processes. As an application, I will discuss a case of Lagrangian transport in the Central Mediterranean Region.

Small Scales of variability of the Sea Surface Salinity: a regional and global survey.

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Recent research, mostly from numerical simulations at very high resolution, suggests that mesoscale and submesoscale variability and the associated exchange processes are not independent but coupled in a subtle but important way, which includes a variety of potential mechanisms for the nonlinear transfer of energy between different scales. Consequently, new and high-resolution global observations of upper ocean motions are required to make progress in the critical areas of the mesoscale and submesoscale variability and their associated upper-ocean lateral and vertical exchange processes. The goal here will be to provide a regional and global survey of the small scales of variability of the SSS field with typical range from 10 to 100 km, that could be observed from in situ observations, and mainly shipboard thermosalinographs (TSGs). Salinity variability at these scales also has implications for the validation of satellite-based measurements, characterized by a spatial footprint of 50-150 km. Different oceanic areas will be investigated to give an overview of the SSS variability under different climatic and oceanographic large-scale conditions, and potentially to report some evidences of different dynamical regimes. A more precise view of the connection between a mesoscale structure and its signature at the surface will be presented w ithin the dynamical context of the Coral Sea in the southwestern Pacific Ocean. Finally, in terms of perspectives, we would like to explore additional points such as vertical stratification, dissipation or turbulence at the very small scale, high-frequency variability and potential effects on the biogeochemistry fields.

SPace of Eulerian MeasureS (SPEMS) application to Oceanographic Flows

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Through the application of multiple Eulerian measures of a fluid flow, a measurement space is created which is comprised of one axis for each measurement, where currently at least six Eulerian measures are being applied to oceanographic flows. The SPace of Eulerian MeasureS (SPEMS) is analyzed using high dimensional cluster analysis, where the data for the flows aggregate into clusters, which can then be interpreted more traditionally as gyres, steady flow, turbulence, hyperbolicity, etc... A novel approach to correlating the clusters from the SPEMS with Lagrangian techniques will be presented. Areas of interest include the mouth of the Chesapeake Bay and the Kuroshio.

Lagrangian Studies of the Southern Stratosphere

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Unique datasets have been collected by field campaigns that released from Antarctica super-pressure balloons capable of drifting for months in the lower southern stratosphere during the springs of 2005 and 2010. The existence of these datasets provided a major motivation for Lagrangian studies of this region of the atmosphere wherein the "Antarctic Ozone Hole" forms. In this presentation we review the results of our analyses that used this data complemented by modeling studies to examine the transport inside the strong circumpolar vortex that characterizes the region during spring and the kinematics of the large-scale (Rossby) waves that perturb the vortex.

The data analysis applied by the first time to the stratospheric flow the Lagrangian descriptor known as the function M (e. g. Madrid and Mancho 2009). The modeling approach was based on the simulation by a conceptual numerical model of the flow both inside the vortex from realistic initial conditions.

The results obtained have demonstrated that the function M provides a sharp depiction of key Lagrangian features of a highly transient flow, presented plausible routes of large-scale horizontal transport across the vortex edge, highlighted the importance of lobe dynamics as a transport mechanism across the Antarctic polar vortex, and identified episodes of planetary (Rossby) wave breaking both inside and outside the vortex. The modeling studies showed how hyperbolic trajectories can be used to detect kinematic structures associated Rossby wave breaking. Current research focuses on the interannual variability of the winter-to-summer transition in the southern stratosphere.

Coherent sets in nonautonomous dynamics

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Transport properties of nonautonomous dynamical systems over a finite-time interval can be described within a probabilistic framework. Of particular interest are coherent sets. These are time-dependent macroscopic structures that hardly mix with the rest of phase space over the considered time span. Such behavior can be observed in many real-world phenomena, including the polar vortex, gyres and eddies in the ocean as well as thermal plumes in convection. Coherent sets can be efficiently detected and approximated within a transfer operator based approach and by recently developed clustering techniques. In this talk, we discuss the theory and numerics of coherent sets constructions and demonstrate their properties in a number of example systems.

Atmospheric rivers and their contribution to a 40-year Lagrangian "climatology"

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The transport of moisture from the tropics to mid-latitudes is not continuous and uniform, but rather intermittent. More than 90% of poleward water vapor is transported by narrow and elongated structures (longer than 2000 km and narrower than 1000 km). These structures, referred to as Atmospheric Rivers (ARs), are a key process for the latent heat redistribution and atmospheric mixing. They are responsible for extreme precipitation and flood events as they approach coastal areas.

Based on an integrated water vapor flux obtained from the ERA-Interim database, AR events have been clearly identified with attracting Lagrangian Coherent Structures (LCS) (Chaos 25, 063105 (2015)). From a Lagrangian point of view, the attracting LCS accumulates water vapor in front of the pattern moving towards the east.

Given that ARs over the Atlantic and Pacific Ocean appear as coherent filaments of water vapor with a persistence time of several days up to a week and they occur periodically, we will address their contribution to the atmospheric mixing in the troposphere. To that end, a 40-year Lagrangian climatology based on the calculation of Finite-Time Lyapunov Exponents (FTLE) has been calculated. Different geophysical drivers as ENSO and ARs were identified in the FTLE climatology. Our results suggest that ARs contribution to the atmospheric mixing ranges from 15 to 25%.

Lagrangian path planning for the first Autonomous Underwater Vehicles in transoceanic missions: The new boundaries of the operational oceanography

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Keywords: South Atlantic Crossing. Autonomous Underwater Vehicles (AUVs). Path planning. Lagrangian Descriptors. Hyperbolic Trajectories. Decision Support.

Unmanned Underwater Vehicles (UUVs) are used in Oceanography due to their relative low cost and wide range of capabilities. Gliders change their buoyancy in order to dive and climb, describing a vertical saw tooth route. These diplacements produce an effective although low horizontal speed which makes the glider strongly sensitive to the ocean dynamics. In order to control the glider path its heading is adapted by using information obtained from verified 4D current data sets. In particular from these data, Lagrangian descriptors have supplied potentially useful paths for piloting the RU-29 Challenger glider in the first South Atlantic Circunnavigation crossing flight (760 days-sea, 17400 km) held from 16 th January 2013 to 31 st March 2016). A description of the Challenger glider mission is found at `http://challenger.marine.rutgers.edu/`.

Invariant manifolds of hyperbolic trajectories were obtained from the real time 4D current fields (1o/12) forecast (+5 days) provided by the european marine forecasting system COPERNICUS in the South Atlantic domain during the last quarter of the mission (1500km far from S Africa). Manifolds outputs were then compared with the ground true paths and the ground currents provided by RU29 when surfaced (every 14 hours). Preliminary results reported by the glider at its arrival at Cape Town (end of March, 2016), showed that the strong Agulhas current/mixing dynamics, was not captured by any of the 5 current models (Copernicus, Hycom, Oscar, NRTOFS, Glory) used for the comparison. Prior to this stage however (December 2015-mid March

2016) the manifolds obtained from the COPERNICUS current fields showed a high percentage of confident good routes that were confirmed by the ground true flying paths reported by the glider nearing the South African ZEE border (10 th March 2016). The preliminary combination of the glider data with the invariant manifolds suggests a potentially useful tool for gliders path planning in future long range transoceanic glider missions (Indian Ocean 2017-).

Challenges in observation and modelling of Arctic climate change

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It is a major challenge to develop an integrated Arctic Observation System that is required to understand and predict the changes in the Arctic climate system. There are numerous ongoing efforts to extend and improve existing systems in the different regions of the Arctic. Satellite earth observation data plays an increasingly important role in such observing system, because the amount of EO data for observing the global climate and environment grows year by year. In situ observing systems are much more limited due to logistical constraints and cost limitations. The sparseness of in situ data is therefore the largest gap in the overall observing system.. The development of a sustainable Arctic observing system requires coordination, mobilization and cooperation between the existing European and international infrastructures (in-situ and remote including space-based) the modelling communities and relevant stakeholder groups. An integrated Arctic Observation System will enable better-informed decisions and better-documented processes within key sectors (e.g. local communities, shipping, tourism, fishing), in order to strengthen the societal and economic role of the Arctic region and support the EU strategy for the Arctic and related maritime and environmental policies.

Contributed talks

Variational Destriping on Remote Sensing Imagery

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A commonly pronounced artifact in many remote sensing (satellite) images are stripes, mainly due to the variations of calibrations, sensor arrangement and the view angles from detector to detector. We present a destriping method by developing a functional with anisotropic smoothing transverse to the stripes, while preserving the rest of the features of the image. The destriped image is uncovered by optimizing the functional using variational methods, followed by numerical methods from finite difference approximations. We demonstrate our method on two different striped data sets (VIIRS and HICO).

Image Based Analysis Coherency Directly From Movies

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There has been significant emphasis in recent dynamical systems literature to define, and find "coherent structures". It could be said that these methods generally fall into categories: those that follow interiors of sets by transfer operators, or those that define a property of boundaries of such sets and follow boundary curves. Perhaps most would agree that coherency should be defined in some manner to describe ensembles of particles that "hold together for some time," or measurements thereof. In essentially all of the studies that have appeared in recent literature, one starts with a dynamical system. What we mean is that an underlying flow is assumed in the sense that generally a differential equation is required to proceed, explicitly as a vector field or flow map, or implicitly through observations of an experiment. However, it can be said that people "recognize" coherent sets when they see them; consider that the Great Red Spot of Jupiter is clear to any and all that have seen it as perhaps the most famous coherent set in the solar system. With this motivation we will develop an observer based perspective of coherence. If we do not have a model, as the dynamical system is known only by remote experimental observation. Here we will develop vision based analysis to infer coherency directly from observed measurements. We write an affinity matrix of observations that rewards like vector-valued measurements that are nearby in space, and nearby in time. From there, analogous to directed random walks through this affinity representation, we find coherency as "bottleneckyness" as the weighted directed graph generalization of spectral graph theory to generalize the Cheeger constant, and from this we can infer sets that directed diffusion nonetheless partitions into coherency. Thus directly from image sequences we infer a concept of coherent sets, without developing a model or inferring a vector field as an intermediate step. There is an interesting interpretation of the affinity matrix we develop as a nave Bayesian update estimator of a transfer operator, that we will discuss briefly.

Benchmarking mesoscale variability in global eddy-permitting simulations against satellite-derived data

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Mesoscale turbulences have been mainly addressed through regional-dependent techniques and ad-hoc tuned simulations. Few and sparse information can be inferred from in-situ data, while recently available satellite maps monitor surface physics only, missing any detail of their vertical profiles.

We present a study of three-dimensional eddy structures throughout the whole ocean basin, coming from the eddy-permitting C-GLORS reanalysis dataset [1] that covers more than 30 years time-window. Thanks to assimilative procedure, eddy population is comparable in size with higher resolution run in literature [2]. We focus on a recent 10-year period (2004-2013) where a comparison with a global free-run and 2D eddies from satellite Sea Level Anomaly (SLA) maps, is assessed. The reanalysis is actually able to catch most of the variability shown in the surface satellite maps, furthermore allowing a vertical study of their features. A census of baroclinic/barotropic field anomalies trapped and dragged by eddies as function of eddy life-time is presented at a global level.

Results are constrained by two different eddy-detection methods. They both belong to the family of Sea Surface Height segmentation algorithms that are presently ameliorated by adding a simultaneous vortex detection in current field. The latter captures eddy vertical extension as long as filtering out too-shallow spurious eddy-like pattern. To identify the eddy, a parameter-less technique based on local SLA extreme [3], is employed and compared to a more physical algorithm based on a maximum eddy-size cutoff.

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An eddy tracking algorithm from dynamical systems theory

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The search for coherent structures in oceanic flows has received an increasing attention in the last decades thanks, in part, to the improvement in ocean observing platforms as well as in the development of reliable ocean modeling systems (IsernFontanet et al., 2006; Mendoza and Mancho, 2010). Many works have been devoted to study these structures under a Lagrangian point of view, usually by means of the stretching by advection (Mancho et al., 2008), or by means of the Lyapunov exponents (Hernández-Carrasco et al., 2011).

In this area, not too many works have applied the theory of stationary dynamical systems since the stationary condition is violated in unsteady flows. However, under certain circumstances ocean structures evolve slowly and can be treated as quasi-stationary. In such situations, one can identify the structures in the Eulerian framework as stationary fields (snapshots of the time-dependent field), and track them in time to infer their time evolution.

Among the mesoscale structures, one relevant are eddies. Eddies are coherent circular flows, persisting for more than four weeks and with radius larger than 50 km that are present in all oceans (Carton, 2001). They are of key importance in regulating the global climate (Chelton et al., 2011) and their detection is nowadays an active research area. Several works developed different methodologies for the detection and tracking eddies from surface velocities or altimetry data. Fang and Morrow (2003) proposed to search eddies departing from sea surface height anomalies above a particular threshold. Other methods detect eddies by determining closed streamlines and analyzing their curvature (Sadarjoen and Post, 2000), by detecting oscillatory patterns in Lagrangian trajectories (Lilly et al., 2011) or by data mining methods from model velocity data (Petelin et al., 2015). A large set of methods are based on the Okubo-Weiss parameter derived from a velocity field which is a magnitude that discriminates regions dominated by strain or vorticity.

Here we present a new method for ocean eddy detection that applies concepts from stationary dynamical systems theory. The method is composed of three steps: first, the centers of the eddies are obtained from the fixed points and their linear stability analysis; second, the size of the eddies are estimated from the vorticity profile between the eddy center and its neighboring fixed points and, third, a tracking algorithm connects the different frames. The tracking algorithm has been designed to avoid mismatching connections between different frames. Finally, we obtain a global database of eddies from geostrophic velocities between 1992 and 2012 derived from satellite altimetry and some results have been tested against other available databases.

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Transfer Operator Families and Coherent Sets

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The computation of sets in phase space of a time variant dynamical system which are separated by transport barriers, so called coherent sets, is of interest for systems at the onset of turbulence, e.g. atmospheric flows or plasma physics. In this talk we present a way to compute finite-time coherent structures via considering the system at all time instants. This is done by analysing a corresponding transfer operator family as a whole. We furthermore discuss different discretizations, some of them leading to recently developed, purely data-driven algorithms and so providing a set oriented justification for those.

The Assessment of Marine Oil Spills with Lagrangian Descriptors and Remote Sensing

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In this talk we will describe how an interdisciplinary approach that combines techniques both from Dynamical Systems Theory and satellite Remote Sensing could greatly contribute to the effective assessment of marine oil spills and the future development of contingency strategies. This work focuses on the sinkage of Oleg Naydenov fishing trawler ship, an environmental crisis that took place in the Canary Islands on April 2015.

From the context of Dynamical Systems, our analysis is based on Lagrangian Descriptors (Madrid and Mancho, 2009; Mancho et al., 2013). This technique, which has the capability of revealing the dynamical barriers within a fluid flow that govern transport and mixing processes, allows for the assessment in almost real-time of the potential danger of the sinking point regarding the possible fuel arrival to the coast. Concerning the spill evolution, we have applied contour advection tools (Dritschel, 1989; Mancho et al., 2003) to track fuel slicks. The results obtained remarkably reproduce the fuel sightings during the event. Undoubtedly, all this valuable information could have been of great help to the emergency services for the effective management of the catastrophe.

In the framework of satellite detection of oil spills, this work benefits from the application of Remote Sensing tools to analyze the reflectance spectra of ocean regions (Bulgarelli and Djavidnia, 2012) in order to address the presence of fuel, helping the sea/air operatives in their real-time monitoring and cleaning tasks during the crisis.

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Parametric instability of point-vortex systems in a multi-layer flow under linear deformation

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Systematic studies of point vortex systems started in the middle on the nineteenth century with the works of H. Helmholtz and G. Kirchhoff. Nevertheless, the point vortex systems have still been drawing a lot of attention since they find applications in a vast spectrum of physical problems. Here we consider a dynamical system governing the motion of many point vortices located in the different layers of a multi-layer flow under influence of an external deformation field. We show that the vorticity center of the system behaves just as the one of two point vortices interacting in a deformation flow. In particular, the vorticity center may experience parametric instability leading to its unbounded growth under the influence of non-stationary shear and rotational components oscillating with different magnitudes. We then show that, in a reference frame moving with vorticity center, the equation of relative vortex motion look the same as if the vorticity center stays in the origin of the reference frame. In addition, we study the relative motion of two point vortices located in different layers of a two-layer deformation flow. We analyze phase portraits of the relative motion and establish the conditions leading to parametric instability of vortex trajectories near the elliptic points. Also, we establish that the relative vortex motion can be chaotic.

The transfer operator approach: Limitations, ambiguities, and potential remedies

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Eddies, mesoscale masses of coherent rotating fluid volume, are considered to have a substantial impact on the the transport of heat, nutrition and oxygen in the ocean. Since coherent sets in time-dependent flows are of Lagrangian nature by definition, localizing the boundaries of eddies requires Lagrangian tools. In this respect, the use of transfer operators has proven to be a promising approach: Approximating a given, possibly time-dependent flow, as a probabilistic Markov process on a grid, this method yields coherent sets as eigenvectors related to the process' transfer operator. However, testing this approach on time-invariant Hamiltonian systems reveals ambiguities of the resulting set and limitations concerning the detection of separatrices. In our study, we aim to overcome these ambiguities and limitations by use of physical arguments.

The drift of objects floating in the sea

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The question how buoyant objects drift and where are they ultimately washed ashore must have troubled humans since the beginning of civilization. A good summary of the observational aspect of the problem is given in Ebbesmeyer (2015) and the references given therein. It includes the journey of shoes originally housed in containers that were accidently swept from the deck of cargo ships to the ocean as well as the famous world war two case of a corpse released by the British Counter Intelligence agency near the Spanish Coast. Of practical modern importance is the question how did the flaperon, belonging to the Malaysian Airplane lost last year (supposedly over the Indian Ocean near Western Australia), travelled almost across the entire Indian Ocean in just 15 months (corresponding to the very high speed of six centimeters per-second, about three times the speed of most ocean currents away from boundaries). Traditionally, it has been thought that three processes affect the drift–ocean currents, surface waves and wind. Of these, the last two are usually regarded as small. The waves effect (Stokes drift) is nonlinear and is probably indeed very small in most cases because the amplitudes are small. It is not so easy to estimate the wind effect and we will argue here that it is not necessarily small though it is obviously close to zero in some cases. The wind speed is typically two orders of magnitude faster than the water (meters per second compared to centimeters per second) and the stress is proportional to the square of the wind speed implying that the wind is important even if only a very small portion of the object protrudes above the sea-level. It is argued that wind, rather than ocean current dominated the drift of both the WWII corpse and the modern day flaperon.

Nonlinear simulation of Trapped, and Harmonic, Rossby waves in a zonal β-plane channel

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Harmonic Rossby waves are the traditional solutions of the Shallow Water Equations (SWE). A new type of solutions of the SWE was developed in recent years that represent Trapped Rossby waves that do not spread over the entire meridional domain. The two types of waves are obtained as analytic solution of a Schrdinger eigenvalue with constant potential in the case of Harmonic waves and linear potential in the case of Trapped waves. Here we report on 100 days numerical simulation by a finite difference Shallow Water solver that is initialized with the two types of waves. As anticipated by the theory in the linear simulation (i.e. when the advection terms of the time variation are omitted from the model equations) Harmonic waves are accurately simulated in narrow channels and Trapped waves are destroyed while in wide channels Trapped waves are accurately simulated and Harmonic waves are destroyed. Surprisingly, in the nonlinear simulations, when the advective terms are added to the model's equations, Harmonic waves are destroyed within 2-3 weeks of the simulation in a narrow channel while Trapped waves with the same small amplitude are accurately simulated throughout the entire 100 days. The reason for this superiority of Trapped waves over Trapped waves in the nonlinear simulation is not understood and is currently under investigation.

Lagrangian statistical analysis of near-surface transport in the Japan Sea based on altimetry data

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Co-authors: *M.V. Budyansky (Pacific Oceanological Institute), M.Yu. Uleysky (Pacific Oceanological Institute)*

Northward near-surface transport of subtropical waters in the Japan Sea frontal zone is simulated and analyzed based on altimeter data for the period from January 2, 1993 to June 15, 2015. Computing a few Lagrangian indicators for a large number of synthetic tracers launched weekly for 21 years in the southern part of the Sea, we find preferred transport pathways across the Subpolar Front. This transport is shown to be meridionally inhomogeneous with “gates” and “barriers” whose locations are determined by the local advection velocity field. The eastern and western gates are provided mainly by the Tsushima Warm Current and the East Korean Warm Current, respectively. The central gates “open” due to suitable dispositions of mesoscale eddies along the Subpolar Front. The transport via the central gates occurs by a portion-like manner due to large-scale intrusions of subtropical waters round the eddies which have been documented with the help of Lagrangian drift maps. There are some “forbidden” zones in the frontal area where the northward transport has not been observed during all the observation period. They exist due to long-term peculiarities of the advection velocity field there.

Lagrangian Flow Network: theory and applications

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Co-authors: *E. Ser-Giacomi (IFISC,CSIC-UIB) , P. Monroy (IFISC,CSIC-UIB), M. Dubois (CRIOBE; IFISC,CSIC-UIB), E. Hernandez-García (IFISC, CSIC-UIB), C. López (IFISC,CSIC-UIB)*

The last two decades have seen important advances in the Lagrangian description of transport and mixing in fluid flows driven by concepts from dynamical systems theory. In the meantime, Network Theory approaches continue arousing scientific interests and have been successfully used, among other, for geophysical systems with climate networks. Linking the network formalism with transport and mixing phenomena in geophysical flows, we develop a new paradigm which we call Lagrangian Flow Network. It consists in analyzing a directed, weighted, spatially embedded and time-dependent network which describes the material fluid flow among different locations. We relate theoretically dispersion and mixing characteristics, classically quantified by Lyapunov exponents, to the degree of the network nodes and then to a family of network entropies defined from the network adjacency matrix. Among possible applications, this new framework allows studying the connectivity and structural complexity of marine populations by providing a systematic characterization of larval transport and dispersal. The simulated networks are composed of an ensemble of oceanic sub-regions which are interconnected through the transport of larvae by ocean currents. The analysis of such networks allows the identification of hydrodynamical provinces (coherent oceanic regions, i.e. areas internally well mixed, but with little fluid or larvae interchange between them) and the computation of connectivity proxies measuring retention and exchange of larvae at multiple scales. These diagnostics, whose sensitivity and robustness have been tested, provide useful information to design management and protection plans for marine ecosystems.

Coherent propagation of a heton near a submerged cylinder in a two layer fluid

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Co-authors: *Mikhail Sokolovskiy (Institute of Water Problems of RAS)*

Vortices are omnipresent in the ocean playing an important role in generating synoptic and mesoscale dynamics. Especially intense vortex dynamics is usually observed near bottom irregularities. Different approaches are exploited to get insights into vortex-topography interactions. The point vortex model presents possibly the simplest approach, allowing one to formulate closed ordinary differential equation systems that govern the point-vortex dynamics. These systems can vary in complexity given varied vortex interactions in question, often rendering them impossible to deal with analytically. However, one can manage relatively easily to solve these systems numerically. Another approach represents a vortex structure as a closed region with some constant distributed vorticity. Then, contours comprising different vorticities evolve according to the vorticity equation. During the evolution, the contours can merge or decompose creating new contours. The papers goal is to analyze the dynamics of a heton, i.e. compensated two-layer vortex pair, interacting with a submerged cylindrical bottom feature. First, we emphasize a typical behavior of the system with the use of the contour dynamics technique. Then, where applicable, we demonstrate and analyze the similar behavior observed in the point vortex model.

Posters

Arctic circulation from a Lagrangian perspective

Francisco Balibrea-Iniesta
ICMAT

Co-authors: *V. J. Garcia-Garrido (ICMAT), S. Wiggins (U. Bristol), A. M. Mancho (ICMAT)*

In the context of rapid increase of temperature in the polar regions, inducing a dramatic ice melting, Lagrangian transport in the Arctic Ocean becomes an area of key interest. The aim of this work is to show the phase portrait of the sea currents throughout the Arctic Ocean, which allows us to study aspects of their dynamics. This is done by means of the numerical method known as Lagrangian descriptors, which computes and graphically displays flow structures over a given domain of the ocean, highlighting coherent jet circulation patterns, eddy-like structures and distinguished trajectories. This method was originally based on the computation of the Euclidean arc length of trajectories of a dynamical system. In this work the considered dynamical system is a velocity field given by data sets from COPERNICUS which assimilate observations. The images provide us both a validation of already known and well reported flow structures, and also the discovery of singular features in the ocean which correspond to extreme weather events.

Acknowlegdements: We acknowledge L. Bertino and Jiping Xie from NERSC for providing us with the dataset used in this study.

Submesoscale blocking of Chl by HF Radar LCSs

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The Ibiza channel is one of the major sites in relation to water circulation in the Western Mediterranean basin. While the large scale dynamics is well described by geostrophy, the small scale processes and their relevance in this region are still poorly understood. A preliminary study using the average of FSLE from HF Radar surface currents shows the apparition of Richardson regimen at pair particle separation of 8 km, scales not well resolved by altimetric data. This confirms that relative dispersion, at surface, is controlled locally by submesoscale structures and not only by larger and slower mesoscale structures. To study the influence of local dynamics on the accumulation or dispersion of chlorophyll in the Ibiza Channel we have used high-resolution satellite-derived Chlorophyll-a data from MODIS/Aqua and GLOBCOLOUR products. We have found that Lagrangian Coherent Structures (LCSs) deduced from HF Radar measurements strongly organize the surface distribution of Chl in coastal regions. For instance, in autumn, high values of Chl-a concentration are accumulated at the southwest of Ibiza Island, due to the blocking effect of nutrient rich waters coming from the Atlantic Ocean by a quasi-permanent coherent structure that acts as barrier. Similar relationship between these LCSs and Chl distributions have been found over the year. These barriers prevent Chl-a from traveling towards northern regions of the Western Mediterranean Sea. Thus, such LCSs deduced from HF Radar are a major mechanism for the transport and dispersion of rich coastal waters, impacting physical and biological connectivity over large scales. These results are of great importance as they allow us to infer spatial distribution of relevant ocean variables (Chl-a, SST, salinity) by using hourly HF Radar surface currents. Furthermore these Radar LCSs could be an important tool to localize zones of convergence and divergence for plastic debris accumulation or jellyfish aggregations.

Pathways of dominant transport in atmospheric and oceanic flows

Emilio Hernández-García
IFISC (CSIC-UIB)

Co-authors: *Enrico Ser-Giacomi (ENS, Paris), Ruggero Vasile (Ambrosys, Potsdam), Cristobal Lopez (IFISC)*

The last decades have seen very important developments in the Lagrangian description of geophysical fluid transport. Most of the new techniques have focused in the determination of barriers to transport, or of coherent regions with little fluid interchange with the surrounding medium. Less tools are available to identify the actual routes of transport, the dominant pathways along which fluid particles travel and reach different regions. Building on tools from network theory, applied to a discretization of the advection dynamics driven by available velocity fields, we determine optimal paths connecting different regions, quantify the fraction of transport following alternative routes, and highlight regions crossed by a large number of pathways. The approach is illustrated for the surface circulation of the Mediterranean Sea and for an atmospheric blocking event over Eastern Europe.

Evolution of secondary whirls in thermoconvective vertical vortices in a route to chaos

Henar Herrero
Departamento de Matemáticas, Universidad de Castilla-La Mancha

Co-authors: *D. Castaño (UCLM), M. C. Navarro (UCLM)*

The last decades have seen very important developments in the Lagrangian description of geophysical fluid transport. Most of the new techniques have focused in the determination of barriers to transport, or of coherent regions with little fluid interchange with the surrounding medium. Less tools are available to identify the actual routes of transport, the dominant pathways along which fluid particles travel and reach different regions. Building on tools from network theory, applied to a discretization of the advection dynamics driven by available velocity fields, we determine optimal paths connecting different regions, quantify the fraction of transport following alternative routes, and highlight regions crossed by a large number of pathways. The approach is illustrated for the surface circulation of the Mediterranean Sea and for an atmospheric blocking event over Eastern Europe.

Discrete and Continuous Lagrangian Descriptors for Hamiltonian systems.

Carlos Lopesino
ICMAT-CSIC

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The goal of this work is to discuss the generalization of the method of Lagrangian descriptors [3]. This method visualizes the phase space structure of Hamiltonian systems, in particular the stable and unstable manifolds of hyperbolic trajectories, in the case of both discrete [1] and continuous [2] dynamical systems. Such a method consists of the sum of the p-norm of the velocity field evaluated on the trajectory of points. In this work we discuss formal proofs on why this method highlights invariant manifolds.

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Probability density of the Thorpe displacements at the Spanish planetary boundary layer

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The results presented in this paper are based on three ABL field campaings made at Spain and called Almaraz94-95, Sables98 and Sables2006. ABL data from 98 zeppelin-shaped tethered balloon soundings ranking from 150 m to 1000 m under different stratification conditions. In previous works, we have analyzed the behaviour of the maximum Thorpe displacement (dT)max and the Thorpe scale LT. The maximum Thorpe displacements varyes between -900 m and 950 m and the scale LT ranges between 0.2 m and 680 m for the different data sets which cover different stratified mixing conditions. We also deduced that the relation between (dT)max and the Thorpe scale LT is a power law. There is a difference in exponents of the power laws for convective conditions and shear-driven conditions. Now we analyze the probability distribution of Thorpe displacemente P(dT) over a profile. We want to verify if the probability of a small Thorpe displacement is much greater than that of a large dT. We also analyze if the probability density function of Thorpe displacements follow a universal form at ABL and if there is differences between the daytime and nighttime data sets.

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Boundaries of the Peruvian Oxygen Minimum Zone shaped by coherent mesoscale dynamics

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Dissolved oxygen in sea water is a major factor affecting marine habitats and biogeochemical cycles. Oceanic zones with oxygen deficits represent significant portions of the area and volume of the oceans and are thought to be expanding. The Peruvian oxygen minimum zone is one of the most pronounced and lies in a region of strong mesoscale activity in the form of vortices and frontal regions, whose effect in the dynamics of the oxygen minimum zone is largely unknown. Here, we study this issue from a modeling approach and a Lagrangian point of view, using a coupled physical-biogeochemical simulation of the Peruvian oxygen minimum zone and finite-size Lyapunov exponent fields to understand the link between mesoscale dynamics and oxygen variations. Our results show that, at depths between 380 and 600 meters, mesoscale structures have a relevant dual role. First, their mean positions and paths delimit and maintain the oxygen minimum zone boundaries. Second, their high frequency fluctuations entrain oxygen across these boundaries as eddy fluxes that point towards the interior of the oxygen minimum zone and are one order of magnitude larger than mean fluxes. We conclude that these eddy fluxes contribute to the ventilation of the oxygen minimum zone.

On the Fate of Debris Associated with the Disappearance of Flight MH370: a Dynamical System Perspective

Ana María Mancho
ICMAT, CSIC

Co-authors: *V. J. Garcia-Garrido (ICMAT), S. Wiggins (U. Bristol), C. Mendoza (UPM)*

The disappearance of Malaysia Airlines flight MH370 on the morning of the 8th of March 2014 is one of the great mysteries of our time. One relevant aspect of this mystery is that not a single piece of debris from the aircraft was found during the intensive surface search carried out in the months following the crash. Difficulties in the search efforts were due to the uncertainty in the planes final impact point and the time passed since the accident and rise the question on how the debris was scattered in an always moving ocean, for which there exist multiple datasets that do not uniquely determine its state. Our approach to this problem is based on dynamical systems tools that identify dynamic barriers and coherent structures governing transport. By combining publicly available information supplied by different ocean data sources with these mathematical techniques, we are able to assess the spatio-temporal state of the ocean in the priority search area at the time of impact and the following weeks. Using this information we propose a revised search strategy by showing why one might not have expected to find debris in some large search areas targeted by the search services and determining regions where one might have expected impact debris to be located and that were not subjected to any exploration.

Acknowlegdements: This research has been supported by MINECO under grants MTM2014-56392-R and ICMAT Severo Ochoa project SEV-2011-0087 and ONR grant No. N00014- 01-1-0769. Computational support from CESGA is acknowledged.

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[1]V. J. García-Garrido, A. M. Mancho, S. Wiggins, and C. Mendoza. A dynamical systems approach to the surface search for debris associated with the disappearance of flight MH370. Nonlin. Processes Geophys 22 (6) (2015) 701-712.

Sinking of Inertial Particles in Ocean Flows

Pedro Monroy-Pérez
IFISC (CSIC-UIB)

Co-authors: *V. Rossi (IFISC,CSIC-UIB), C. López (IFISC,CSIC-UIB) and E. Hernández-García (IFISC,CSIC-UIB)*

Although most of the organic material produced by photosynthesis in the upper ocean is metabolized and recycled in the surface water, a significant portion sinks into the deep ocean, where it is stored for long time-scales. Therefore, knowledge of the export flux of organic carbon from the sea surface to depths is needed to estimate the magnitude of the biological carbon pump, a key process of the global carbon cycle. We can get this knowledge only by understanding the production of sinking particles and how they sink to depth.

In this study we focus on the dynamical sinking of biogenic particles and how it is affected by oceanic flow. Our analysis assumes the single-particle approximation where one neglects the interaction among the particles. Due to small sizes of marine paticles, the evolution of the particles position r and the particles velocity v is given by the Maxey-Riley equation [1]. The Stokes number, S_t, measures the inertial effects and is defined as the ratio of the characteristic time of a particle to a characteristic time of the flow. For small Stokes number $S_t \ll 1$ and if the bouyancy forces are significant, we get this approximation of MaxeyRiley equation

$$v = u + v_s,$$

where v_s is the falling velocity in quiescent fluid. This approximation is often used in to analyze the export of particulate carbon from the upper ocean. However, for S_t small enough, the Maxey-Riley equation admits a globally attracting invariant slow manifold [2]. This three-dimensional time dependent surface of particle trajectories can be calculated explicitly to any order of precision by expanding it around its $S_t = 0$ solution. Hence, at leading order

$$v = u + v_s \tau_p (1 - \beta) \frac{D\mathbf{u}}{Dt}, \qquad (1)$$

where β is the density ratio and p the Stokes response time. Basically, the inertial effect corresponds to the last term in (1). We aim here at addressing the impact of this inertial term on the sinking trajectories of marine particles using the velocity field from a regional ocean model (ROMS). The results are discussed for different particle sizes and densities. We found that, in mesoscale process, the inertial term have influence in horizontal directions for particles bigger than 10cm, and in the vertical directions for particles larger than 1cm. Hence we conclude that the inertial effects can be neglected in the typical sizes of marine particles, between 1m and 10mm. We discuss the geophysical implications of these theoretical considerations, identifying current limitations and providing recommendations for future research about modelling inertial particles in oceanic flow.

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Vortices, Streaks and Fronts in Ocean/Atmosphere interfaces

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Remote sensing by electromagnetic wave (IR, visible, UV, radar) technology, both in active and passive methods (Synthetic Aperture Radar (SAR), Spectra/ Wavelet, etc) provide better discrimination and higher resolution in complex geophysical flows. In the ocean surface, and even more so, in the coastal zone, where turbulent flow is generated in the ocean surface either by waves, wind or/and local currents. The conditions are non-homogeneous, and in the presence of a pollutant the SAR detects many interesting topological features [1, 2]. New techniques are used for the analysis, of Images provided by the ESA ERS1/2, ASAR, ENVISAT, RADARSAT and other Canadian and Russian Satellites. We shall concentrate and provide statistics, as well as describing some events detected by several satellites and with additional cruise observations and measurements [3] in the North-west Mediterranean Sea area between 1996 and 2012 as well as in other European Coastal regions. The structure of the flows are presented and used to parametrize mixing at their relevant scales. The PDF of the basic instabilities are different if they are analysed at scales smaler, or greater than the Rossby Deformation Radius scale. RL. The Results show the ability to identify different SAR signatures and provide calibrations for the different configurations of vortices, (round or eliptical), fronts, spirals, Langmuir cells, oil spills and tensioactive slicks are all relevant and eventually allow some predictions of the self-similar structure of the environmental rotating/stratified turbulence. Such complex coastal field-dependent behavior is strongly influenced by stratification and rotation of the turbulence [2]; non homogeneous, and non local spectra are observed only in the range smaller than the local RL. The measures of diffusivity from buoy or tracer experiments are used to calibrate the behavior of different tracers and pollutants. Using different polarization and intensity levels from satellite imagery, we may distinguish between natural and man-made sea surface features due to their distinct self-similar and fractal appearece as a function of spill parameters [4], environmental conditions and history of both oil release and coupled Atmosphere-Ocean interface weather conditions.

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Wednesday 6 July	
8:45-9:20	Registration
9:20-9:30	Welcome
9:30-10:15	V. Pérez-Muñuzuri
10:15-11:00	C. R. Mechoso
11:00-11:30	coffee break
11:30-12:15	A. G. Ramos
12:15-12:45	N. Paldor
12:45:13:15	V. Rossi
13:15:13:45	S. Prants
13:45-15:45	Lunch
15:45-16:15	D. Nof
16:15-17:00	K. Padberg-Gehle
17:00-17:30	coffee break
17:30-18:15	A. Lanotte

Thursday 7 July	
9:30-10:15	K. McIlhany
10:15-11:00	C. Maes
11:00-11:30	coffee break
11:30-12:15	S. Stein
12:15-12:40	V. J. Garcia-Garrido
12:40-13:05	R. Basnayake
13:05-13:25	B. Lünsmann
13:25:13:45	D. Conti
13:45-15:45	Lunch
15:45-16:15	K.Koshel
16:15-17:00	M. Cencini
17:00-17:30	coffee break
17:30-18:00	E. Bollt
18:00-19:30	Poster session
Dinner 19:45	

Friday 8 July	
9:30-10:15	E. Alvarez-Fanjul
10:15-11:00	J. Ballabrera
11:00-11:30	coffee break
11:30-12:15	J. Isern-Fontanet
12:15-12:45	E. Ryzhov
12:45:13:15	A. Cipollone
13:15:13:45	A. Denner
13:45-15:45	Lunch
15:45-18:00	Discussions