Statement of Research

I work on problems on atmospheric and oceanic geophysical flows as well as in fundamental fluid dynamics. To understand the climate we first must understand the dynamics of two of its basic components: the atmosphere and the ocean. Turbulence is ubiquitous in both the atmosphere and ocean at a multitude of scales, affecting everything from weather patterns and large-scale oceanic eddies to the swimming of fish and plankton.

In my research I combine a variety of analytical tools with computational experiments used to augment our understanding and give insight into the problems. Specifically, I study:

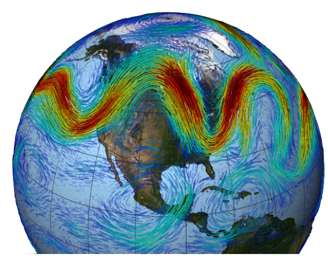
I. *Organization of large-scale coherent structures in planetary atmospheres and wall-bounded turbulence*,

II. *Interaction of large-scale oceanic currents with mesoscale eddies and topographic features*.

I. Coherent large-scale structures in planetary and wall-bounded turbulence

Planetary atmospheres self-organize into large-scale coherent structures that vary at time-scales much longer than those of the co-existing turbulent eddy motions. Prominent examples are the Earth's subtropical and polar jet streams, the zonal winds in Jupiter and its Great Red Spot. Often these large-scale features get their energy from the turbulence in which they are embedded, that is, they are *eddy-driven*. Understanding the dynamics of such structures is of vital importance for understanding the climate.

However, the dynamics of the coexistence of coherent structures and turbulence is difficult to understand because many standard techniques, such as classical stability analysis, are ineffective. These methods assume that a mean state exist in the absence of the fluctuations and also disregard the effect of these fluctuations on the mean state. This is not the case in planetary atmospheres; the mean state is inseparably connected with turbulence. Recent developments, some in my doctoral thesis, have broken through this impasse. The key is to study the *Statistical State Dynamics* (SSD) of the flow; i.e., the dynamics of the statistics themselves rather than of individual flow realizations. One aspect of SSD is a new type of stability theory that addresses mean flows in the presence of turbulent fluctuations.



Earth's atmosphere is turbulent. Most of the energy of the flow is concentrated in large-scale zonal or wavy jets which persist in the flow enhancing its large-scale long-time range predictability. Credits: NASA GSFC.

Climate is the statistics of the weather and thus the study of its SSD is the proper way forward. However, evolving the unclosed hierarchy of the flow statistics is intractable. An essential step is to neglect or approximate third-order statistical moments. Third-order discard is disastrous in the problem of homogeneous and isotropic turbulence, but in meteorology and oceanography, with strong anisotropy and structured coherent mean flows, third-order discard is successful [1, 2]. SSD reveals some key relevant physical processes which are often obscure in the single realization flow dynamics. Many such phenomena are intrinsically associated with the dynamics of the statistical state and have an analytic expression only in SSD. More importantly, within the framework of SSD, for the first time we can determine the possible climate regimes and study their sensitivity to parameter variations. My long-term goal is to pursue this program during the course of my academic career.

In my doctoral work, I studied the symmetry breaking of homogeneous turbulence in planetary atmospheres and its self-organization leading to the formation of jets and large-scale coherent waves. Using SSD, I predicted that jets and large-scale waves emerge through a bifurcation that occurs as the intensity of turbulence increases. Subsequently, I confirmed this prediction with comparison to direct numerical simulations [3]. Furthermore, I studied the mechanisms by which homogeneous turbulence in planetary atmospheres self-organizes to form jets large-scale or waves [4].

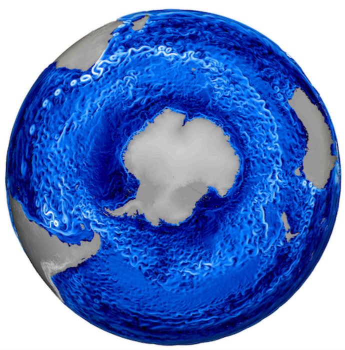
SSD is not limited to the study of the stability of the homogeneous turbulent flows. I have developed analytical and numerical methods for studying the stability of zonal jets within inhomogeneous background turbulence. Using these methods, I developed a theory for the coherent jet–wave coexistence in planetary atmospheres [5]. This paves the way for constructing a comprehensive theory for the maintenance of stationary waves and their interaction with the turbulent eddies that surround them. Understanding stationary wave dynamics has implication both for predicting the climate state but also for improving medium- and long-time weather predictions.

In parallel to my work on geophysical flows, I also had also the opportunity to apply the SSD ideas of self-organization to wall-bounded turbulence when I participated in the First Multiflow Summer Program in 2013, held in Universidad Politécnica in Madrid. There, I studied the symmetry breaking in three-dimensional flows and specifically the existence of very-large-scale motions in the region away from the wall. Further, we showed with my collaborators, that a regeneration mechanism of turbulence occurs in the weak-shear regions away from the wall [6, 7]. I plan to continue the study of boundary-layer and wall-bounded flows because it is crucial for improving parameterizations in climate models, for example that of momentum and contaminant transport in the atmospheric boundary layer. This study lies between geophysical fluid dynamics and engineering and comprises an ideal field of research for interdisciplinary collaboration.

II. Oceanic currents: interaction with mesoscale eddies and topographic features

During my postdoc at the Scripps Institution of Oceanography, I have been investigating the effects that mesoscale eddies and bottom topography have on large-scale currents and meridional heat transport in the Southern Ocean. In the Southern Ocean, the absence of continental boundaries along a range of latitudes implies that momentum imparted by the wind at the ocean's surface is almost entirely balanced by topographic form stress (that is the correlation of pressure and bottom topographic slope). This momentum balance controls the strength of the Antarctic Circumpolar Current (ACC) and sets the meridional mass and heat transport. Additionally, mesoscale eddies are an integral part of the cycle responsible for the meridional transport of heat across the ACC.

To understand how bottom topography sets the momentum balance and also understand what impact might an increase in the wind stress have on the ACC, I have been using a quasi-geostrophic model of beta-plane turbulence forced by wind stress. This idealization allowed me to delineate the flow regimes in a wide range of the parameter space. The main finding is that there exist two main flow regimes depending on the ratio of the planetary vorticity gradient to the r.m.s. of the topographic PV gradient. When this ratio is large then the large-scale flow does not depend on the actual structure of the bottom topography but rather only on gross statistical properties, for example r.m.s. height or r.m.s. topographic slope. However, when the ratio is small, as for example is the case for parameter values in the Southern Ocean, the large-scale flow depends crucially on the geometric details of the topography. This implies that the small-scale structure of ocean topography, which is not known for most part of the ocean floor, may have a large impact on the predictions of ocean circulation models. Further, I showed that, in this idealized model, the requirement of enstrophy balance among the flow components implies that as the strength of the wind stress increases the flow transitions from a regime in which the form stress suddenly vanishes and very large transport ensues [8]. Currently, I am studying the effect of small-scale bottom topography on the baroclinic growth of mesoscale eddies and their effect on large-scale currents.



The Antarctic Circumpolar Current is one of the largest coherent oceanic features. Credit: NASA/JPL.

A remarkable feature observed in eddy-resolving oceanic models is the so-called eddy saturation, that is that the total mass transport of the ACC insensitive to the wind stress strength. This problem acquires particular importance since there has been increasing evidence that climate change produced increase on the strength of the westerly winds that force the ACC. Baroclinicity and side boundaries are currently believed to be key to the development of eddy- saturated states. However, I have demonstrated that eddy saturation occurs in fact without baroclinicity or side boundaries, in a barotropic flow over uneven topography. I showed that what controls the appearance or not of eddy saturated state is the existence of open geostrophic contours, that is geostrophic contours that span the whole zonal extent of the domain. [9]

I plan to continue studying the ocean's role in the Earth's climate system. Particularly, I am interested in elucidating atmosphere–ocean coupling thereby shedding light on the key processes by which tracers, such as carbon, are exchanged between the two fluids.

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Statement of Teaching Philosophy

My pedagogy is centered around three ideas:

(i) Understanding of the fundamentals must be reached before moving to more specialized topics.

(ii) Examples and "hands-on" work form the basis for learning science.

(iii) The lecturer should convey his enthusiasm for the subject to the students.

Content of courses

I believe that understanding must be built from the ground up. Without a solid foundation in the basics, any understanding the students develop about more complicated concepts is doomed to be shallow. Mathematics and physics require reduction of complex ideas into simple building blocks. This form of deduction relies on a strong understanding of those building blocks and how they might blend together. For this reason, I also support adhering to prerequisite requirements in upper level courses.

Lectures should contain lots of examples and exercises of various difficulty throughout the course. These should be pedagogical, inspiring and, to the degree possible, fun. Also repetition and recapitulation are important: the first three minutes of a lecture should be devoted to remind the audience what were we dealing on the previous time, and the last three minutes to sum up what we have achieved that day.

Tools of learning

Mathematics and physics should be presented on the board, not through lecture slides. This makes the material easier for the students to digest. A board presentation also gives more freedom to the lecture, allowing the professor to explore pedagogical tangents useful to the students. Finally, solving problems can show the students that it is "OK" to struggle in deriving something and even make mistakes.

Mathematics and physics are not "spectator sports." The students should be motivated to solve problems and the basic pillars for achieving this are the following.

(i) The students should be provided with weakly problem sets. The problems should be pedagogical, inspiring and, to the degree possible, fun. The best problems string students along until they find themselves in the heart of a difficult premise, making it all seem very easy so that they do not notice they have been doing "hard stuff."

(ii) To quote the mathematician and excellent teacher P. Halmos, and in the spirit of inquiry-based learning (IBL), I believe that *"students should do research, in their subject, at their level."* Even undergraduates. In this vein the teacher can give a simple problem and then ask some questions, provide some motivation and then tell the students to find out the answer. Either by going on the board and trying to think out loud or thinking about it in the privacy of their home, but not by rooting the answer off the internet or copying from a textbook. This should also be the spirit of the problem sets: After some few, easy problems there should be a couple problems with a "research" flavor. Ideally, the students should be excited to receive a new problem set every week and not feel it as yet another burden.

(iii) The learning process does not end with returning a graded homework. Weekly recitation classes consist an important part of a course. There students have the opportunity to discuss with the lecturer possible difficulties they had while doing the homework problems or ask for a concept to be revisited.

Engagement

A good teacher provides source of inspiration for the student. Grasping the interest of of all students in a classroom is challenging. Any classroom is diverse with respect of the learning styles of the students, their background and their learning pace. It is important, therefore, to facilitate diverse learning styles. Some students learn better through reading, so for each lecture I must point out the pages in the textbook/notes that correspond to the material. Others learn better in groups, so therefore it is important to provide the class with common homework problems that can be worked in groups. Often, the need to explain a concept to a fellow student reinforces the learning that has taken place. Moreover, the teacher ought to excite the students. For example by connecting the subject of a given lecture subject with something that the students are familiar with from their everyday experience. A seemingly dull lecture in a Numerical Linear Analysis course with the subject of eigenvalues and eigenvectors immediately engages the students if presented with the title: "The algebra behind Google's search algorithm".

Finally, a teacher must aim to include students who, for whatever reason, might have trouble keeping up during a lecture, whether that is because English is not their first language, or they have a weaker mathematical background than others, or they have a learning disability. One way to meet this goal is by providing a comprehensive set of typeset notes to alleviate the pressure on the students to compulsively copy down everything that is said in class. Additionally, if the size of the class allows it, I also make a point of learning the names and a bit about each student. By using the students names during lectures or recitations helps students feel more "at home" and less stressed. Also, it makes them feel more comfortable coming to office hours and talking to me one-on-one. It is my responsibility as an instructor to find those students that are struggling and encourage them to come for extra help. Every motivated student should have every possible opportunity to learn, advance and succeed.