MHRD Scheme on Global Initiative on Academic Network (GIAN)

"Computational Geophysical Fluid Dynamics"

1.0 Overview:

This course aims at studying, from first principles, various approaches that are used to model flows in the atmosphere, the oceans, and in other geophysical and space physics contexts (such as the Earth's core and the interplanetary medium). Among other problems, we will consider: Predictability in geophysical flows (e.g., for how long the state of the atmosphere can be predicted?), how large-scale winds and flows are generated in these systems, and how to model turbulence in regimes relevant for the atmosphere and the oceans. The motivation of this course is to introduce students to these problems combining theoretical tools with state-of-the-art numerical studies and showing how numerical simulations can be used as table-top-like experiments to learn from these systems, to validate simple models, and to formulate further theoretical reductions. This course is indented for physicists interested in fluid dynamics and computational physics; however, it will also be of interest to students of geosciences, applied mathematics, atmospheric sciences, oceanography and computer sciences.

2.0 Objectives:

The main objective of the course is to introduce students to state-of-the-art theoretical and numerical tools used for the modeling of geophysical flows, which are often presented to them separately. The idea here is to combine theory and numerical simulations, and to apply them to multidisciplinary topics: computational modeling, atmospheric sciences, oceanography, space physics, and geophysics. The choice of applications aims at showing graduate students how tools developed in related areas can be useful for their own research projects, and at creating synergy between undergraduate and graduate students interested in similar problems. Finally, as part of the course students are introduced to parallelization methods that are useful to study many problems in computational fluid dynamics.

3.0 Teaching Faculty with allotment of Lectures and Tutorials

1. Prof. Pablo Mininni (PM): 18 hrs lectures and 10 hrs tutorials
2. Dr. Vishwanath Shukla (VS): 4 hrs lectures and 4 hrs tutorials

4.0 Course details:

The course has 11 broad modules, each consisting of two lectures and a tutorial session. Lectures present a specific problem of interest, and a set of theoretical tools to the students. In the tutorial sessions, a numerical code is provided to the students and is used to solve a list of exercises, each associated with one of the topics introduced in the lectures. Students are encouraged not only to solve these problems, but also to use the numerical set-up as a playground to explore other possible configurations and physical effects. At the end of the course, students are expected to present a report with their findings, followed by the final examination.

The first three-quarters of the course focuses on a physical point of view, considering different topics in geophysical fluid dynamics, and using a numerical code in the tutorial sessions as a tool to explore different problems and as a way to solve exercises. In this stage, only general concepts about how to run a code and how to process and analyze output data (using languages such as Matlab or Python), are provided to the students during the first tutorial session. In the final modules, inner details of the code are explained, together with concepts of parallel programming. This approach aims at motivating students to dwell into numerical methods after understanding equation of motions, and at seeing numerical model as a useful tool to deepen their understanding of the dynamics of complex systems.

Proposed modules cover the following main topics and subtopics:

1. *Rotating and stratified flows:* Their relevance to geophysics and space physics – Overview of the equations of motion – The Boussinesq approximation – Conservation laws – Energy, Enstrophy, and Palinstrophy – Dissipation.

2. *Inertial and Rossby waves:* The centrifugal force – The Taylor-Proudman theorem – Structures in rotating flows – Inertial waves – Rossby waves.

3. *Internal gravity waves:* Atmospheric blocking – Beta-plane approximation – Internal gravity waves – Baroclinic instability – Geostrophic flows and the quasi-geostrophic approximation from the physical point of view.

4. *Turbulence:* The Richardson cascade – Structure and correlation functions – Kolmogorov 1941 theory – Triadic interactions – Turbulence in two- and three-dimensions – Predictability.

5. *Wave turbulence*: General introduction and its formalism – Fluxes of conserved quantities – Comparison with hydrodynamic turbulence – Wave kinetic equations – Discussion of examples relevant to the course.

6. *Rotating turbulence:* Waves and turbulence – Structure formation – Anisotropy development – Resonant interactions in rotating flows – Phenomenological theories – Scaling laws.

7. *Stratified turbulence:* Spectral description of stratified turbulence – Resonant interactions in the stratified case – Front and strata formation – Transport in stratified flows.

8. *Magnetohydrodynamic (MHD) flows:* Conducting fluids - The MHD approximation – Its relevance in space physics – Alfvén waves – Introduction to dynamo theory.

9. *The Lagrangian approach to turbulence:* Lagrangian description of a fluid – Lagrangian properties of turbulent flows - Tracers and inertial particles – The Maxey-Riley equations – Modeling of particle-laden flows.

10. *Computational approaches to geophysical fluid dynamics:* Overview of Numerical

methods – The pseudo-spectral method and Fast Fourier Transforms – The GHOST code – Optimization for serial computation of fluid dynamics – Cache missings, cache blocking, and other serial optimization techniques.

11. *Parallelization methods:* Parallelization of computational fluid dynamics codes - The MPI library – Communication optimization –OpenMP directives and hybrid parallelization methods.

Recommended bibliography:

- *"Turbulence in rotating, stratified, and electrically conducting fluids", P.A. Davidson, Cambridge University Press (2013).*
- *"Topics in geophysical fluid dynamics: Atmospheric dynamics, Dynamo Theory, and Climate Dynamics," M. Ghill and S. Childress, Springer-Verlag (1987).*
- *"Atmospheric and oceanic fluid dynamics," G.K. Vallis, Cambridge University Press (2005).*
- *"An introduction to atmospheric physics," D.G. Andrews, Cambridge University Press (2000).*
- *"A hybrid MPI-OpenMP scheme for scalable parallel pseudospectral computations for fluid turbulence," P.D. Mininni, D. Rosenberg, R. Reddy, and A. Pouquet. Parallel Computing 37(6), 316-326 (2011).*
- *"Wave turbulence", S. Nazarenko, Springer (2011).*

4.1 Duration: December 4th to 15th (10 days) 2023.

4.2 Tentative Lecture Schedule

Day 1

M1: Rotating and stratified flows

Lecture 1 (PM): 1 hrs: (Geophysics and space physics, equations of motion)
Lecture 2 (PM): 1 hrs: (Boussinesq approximation, conservation laws)

Tutorial 1 (PM): 1 hrs: General concepts for running the provided code.

Day 2

M2: Inertial and Rossby waves

Lecture 3 (PM): 1 hrs: (The centrifugal force, Taylor-Proudman theorem)
Lecture 4 (PM): 1 hrs: (Structures, Inertial waves, Rossby waves)

Tutorial 2 (PM): 1 hrs: Inertial and Rossby waves

Day 3

M3: Internal gravity waves

Lecture 5 (PM): 1 hrs: (Atmospheric blocking, Internal gravity waves)
Lecture 6 (PM): 1 hrs: (Baroclinic instability, Quasi-geostrophic flows)

Tutorial 3 (PM): 1 hrs: Internal gravity waves

Day 4

M4: Turbulence

Lecture 7 (VS): 1 hrs: (Richardson cascade, Kolmogorov 1941 theory)
Lecture 8 (VS): 1 hrs: (Triadic interactions, 2D and 3D flows, Predictability)

Tutorial 4 (VS): 2 hrs: Turbulence

M5: Wave turbulence – Part 1

Lecture 9 (VS): 1 hrs: (General introduction and its formalism – Fluxes of conserved quantities)

Day 5

M5: Wave turbulence – Part 2

Lecture 10 (VS): 1 hrs: (Comparison with hydrodynamic turbulence – Wave kinetic equations – Discussion of examples relevant to the course.)

Tutorial 5 (VS): 2 hrs: Wave turbulence

M6: Rotating turbulence

Lecture 11 (PM): 1 hrs: (Waves and turbulence, Structures and anisotropy)
Lecture 12 (PM): 1 hrs: (Resonant interactions, Phenomenology, Scaling)

Tutorial 6 (PM) : 1 hrs: Rotating turbulence

Day 6

M7: Stratified turbulence

Lecture 13 (PM): 1 hrs: (Spectral description, Resonant interactions)
Lecture 14 (PM): 1 hrs: (Front and strata formation, Transport)

Tutorial 7 (PM): 1 hrs: Exercises on stratified turbulence

Day 7

M8: Magnetohydrodynamic (MHD) flows

Lecture 15 (PM): 1 hrs: (Conducting fluids, The MHD approximation)
Lecture 16 (PM): 1 hrs: (Space physics, Alfvén waves, Dynamo theory)

Tutorial 8 (PM): 1 hrs: MHD flows and dynamo theory.

Day 8

M9: Lagrangian approach to turbulence

Lecture 17 (PM): 1 hrs: (Lagrangian approach, Tracers and inertial particles)
Lecture 18 (PM): 1 hrs: (Maxey-Riley equations, Particle-laden flows).

Tutorial 9 (PM): 1 hrs: Exercises on Lagrangian dynamics of particles in model flows.

Day 9

M10: Computational approaches to geophysical fluid dynamics

Lecture 19 (PM): 1 hrs: (Pseudo-spectral methods, GHOST code)
Lecture 20 (PM): 1 hrs: (Optimizations, Cache missings and cache blocking)

Tutorial 10 (PM) : 1 hrs: Exercises on pseudo-spectral method.

Day 10

M11: Parallelization methods

Lecture 21 (PM): 1 hrs: (MPI library – Communication optimization)
Lecture 22 (PM): 1 hrs:(OpenMP directives, Hybrid parallelization methods)

Tutorial 11 (PM): 2 hrs: Parallelization methods.

Date of Examination: 15th December 2023

Students are expected to work on their final report during the last two days of the course (while using previous tutorial sessions to learn how to use numerical tools in geophysical fluid dynamics and to solve exercises).

Presentation of a report by the students will also be evaluated.

5.0 Who can attend:

- Advanced Undergraduates (B. Tech./B.Sc./Integrated M.Sc.)
- Masters students (Science and Engineering)
- PhD students (Science and Engineering)
- Junior researchers (Postdocs and young faculty)
- Faculty from academic and technical institutions
- Researchers from private and government organizations