Personal introduction:

- Researcher at Météo France lab, in the climate modelling group. Météo France's missions are to follow and forecast the weather and climate of the atmosphere, snow and superficial ocean. The climate modelling group focuses on global and regional climate modelling and projections, and subseasonal to decadal forecasts.
- Personal focus: physical oceanographer, involved into ocean modelling, main areas of expertise cover rather mid-latitude to high-latitude ocean and semi-enclosed seas.
- Possibilities at Météo France: internship, PhD on topics related to climate variability.

Main objectives of these lectures:

What these lectures aim at covering:
- Provoke your curiosity to understand the functioning of the oceanic dynamical and thermodynamic machine. Introduce great questions of oceanography and stress the largely open question regarding oceanic processes.
- Develop your common sense on the oceanic physical state and variability. Analysis and understanding of the general distributions and variability of currents, T, S.
- Initiate you to ocean modelling with the use of NEMO model. From the equations of oceanic circulation to the formulation of NEMO model, in the 3D and 1D versions.
- Introduce you to the main theories of the oceanic circulation. The dichotomy between wind-driven and buoyancy-driven circulations, understanding main circulation features, the horizontal and vertical distributions of T, S.

What is outside of our scope:
- Most of the questions regarding coupling and the analysis of low-frequency oceanic variability
- Operational oceanography issues: observing networks, assimilation and ocean forecasts
- Most of the issues related to in situ and satellite observations of the ocean
- Most of the turbulent scales below mesoscale ~100km (submesoscale, fully 3D turbulence)
- The description of rapid external gravity waves (tidal waves, wind waves and swell) and most oceanic internal waves (unstable Rossby waves, inertial oscillations, internal gravity waves, tropical waves: Kelvin, Yanai, tropical instability waves)
- Ocean biogeochemistry: the carbon cycle, biological activity.

It is totally normal if you do not understand everything at first. It takes years to gain maturity and insight into a research topic. Many climate scientists do not have a pure physics - math background. The most recognized scientists of my group started with agronomy, veterinary, physics and earth sciences degrees. What I think makes a good scientist is far from the very academic abilities that are too often evaluated at the university:
- curiosity (source of energy)
- autonomy (posing 100% of your research topic, from que question to elements of answers, self-training)
- methodology (not too dispersive, stick to a work sheet and deadlines)
- teamwork (not fearing to ask "dumb" questions, going to others and including them to do the best quality science)
- communication (generating interest around you in what you do, gaining a legitimacy in your community).

Lectures

First 4h

1. Introduction to oceanic circulation.

- preamble: on the difficulty to observe the ocean. The three revolutions of observational oceanography. An accurate but recent satellite measurement of the surface: SSH for circulation and SST for OA fluxes, ocean color as a proxy of vertical exchanges. The ARGO era and the difficult task of observing the ocean interior: mostly T, S measurements, almost no current-meters (most of the time deduced from floaters' drift). The glider revolution and the possibility to explore meso-submesoscales. The big gaps in ocean observations: the abyssal ocean (>2000m), direct current measurements, measuring turbulence and the associated mixing, continuous arrays to close basin-scale budgets, surface measurements of OA fluxes.
- Description of the main oceanic currents: Why is it so messy with eddies? **Exercise: estimate the Rossby radius of deformation in the ocean.** Why are currents more intense in the deep tropics and along western boundaries? Are there really oceanic gyres? Why do western boundary currents drift at mid-latitude? Why is the Southern Ocean the only one to display a continuous zonal circulation? How are the basin-scale features generated? What does the decoupling in timescales between ocean-atmosphere imply for ocean and climate modelling? **Exercise: from the typical horizontal and velocity scales of the ocean, estimate the time scale of the oceanic circulation and compare it to the atmosphere.**
- The most visible part of ocean physics: external gravity waves (tides and wind waves / swell). They mostly do not actually impact directly the circulation, only indirectly through mixing which changes water masse properties and in turn impact the dynamics.
- The "only stuff that matters" for atmospheric scientists: the SST. Logical meridional gradient. But why an intense zonal gradient, reversed between sub/tropical and subpolar latitudes? Why a minimum at eastern boundaries and along the Equator?
- The oceanic counterpart of water vapor: SSS. To a certain, describes the E-P budget at the OA interface. In particular, the ITCZ, subtropics and HL. Plus river plumes and great inbalances between basins. Example of a semi-enclosed sea?
- Distribution of T,S at depth: why do they form a blob that is symmetric to the SSH? **Exercise: derive the Margulhes relation from a 2-layer ocean with the lower layer at rest.**
- Fluxes at the air-sea interface: momentum, heat and water determine the oceanic circulation. How is the net heat flux determined? **Exercise: qualitatively, what negative feedbacks in the air-sea fluxes occur if the shortwave incoming radiation is increased?**
- Vertical structure of the ocean: how is the mixed layer generated? Why is the layer underneath highly stratified? What does a quasi-homogeneous interior ocean imply for the circulation? **Exercise: what heat flux is required to cool down the mixed layer by 1°C, and what are the consequences for static stability? Assuming an advective-diffusive balance in the interior ocean with an eddy diffusivity of $10^{-4}m^2/s^2$, estimate the vertical upwelling rate of deep waters.**
- The missing contribution to the Earth's meridional heat budget

2. The equations and approximations of the oceanic circulation. Including the description of the equation of state of seawater.

- Driving forces in oceanography
- Equations of motion, approximations and resulting primitive equations
- Analysis of each equation and 0-order balance. **Exercise: deduce horizontal transports from a hydrographic sections and an assumption of the level of no motion.**

3. Application to NEMO numerical model

- Model equations and approximations
- Time and space discretization, and the importance of numerics
- Boundary conditions: initial state, open and closed lateral boundary conditions, surface forcing

Next 4h: the wind-driven oceanic circulation

1. Ekman currents/pumping

- Ekman theory: from the balance vertical friction - Coriolis to the Ekman spiral, depth and transport. **Exercise: try to derive it.**
- Ekman pumping: illustration in upwelling areas and **exercise: estimating the pumping rate.**

2. The Sverdrup balance

- Hypothesis and main balance
- Derivation
- Results and (many) limitations (illustrations: estimations of the oceanic BSF, comparison to Sverdrup theory, Lagrangian drifters) **Exercise: estimate the Sverdrup transport for Atlantic and Pacific, subtropical and subpolar.**

3. The western intensification of gyres

- Stommel model (bottom friction, but too low magnitude)
- Munk model (lateral dissipation, but the ocean is not so dissipative)
- The role of topography (gyres following isobaths and the bottom pressure torque)
- The role of nonlinear advection and stratification (recirculation gyres to the west), shadow zones (low ventilation rate to the east)

4. The Antarctic Circumpolar Current

- Ekman pumping and response of interior geostrophic flow
- Zonally-integrated momentum-vorticity balance and importance of bottom pressure
- Pentagonal shape and role of topography

5. The equatorial circulation

- Zonal circulation. **Exercise: given a zonal wind stress, what surface pressure gradient to balance it? To what zonal sea level difference does it correspond?**
- Meridional circulation. **Exercise: given a zonal zond stress at 4°N and 4°S, determine the Ekman transport divergence in between. Deduce from continuity the resulting equatorial upwelling.**
- ENSO variability and coupling with the atmosphere.

Last 4h: the buoyancy-driven oceanic circulation

1. Influence of buoyancy forcing on the gyre circulation

bottom pressure torque of subpolar gyres (illustration: SPG in the North Atlantic)

2. Mesoscale eddies

- their domination of oceanic currents: the decomposition between mean and eddy currents
- their generation by baroclinic instability: the Lorenz energy cycle, comparison with the atmosphere.

- their role in restratification / meridional heat transport: the transformed Eulerian mean and the eddy-driven overturning.

3. The oceanic mixed layer

- phenomenology
- global distribution and seasonal variability. **Exercise: for a given surface heat flux, estimate the resulting mixed layer cooling for a mixed layer depth of resp. 10m, 100m and 1000m. What do you conclude regarding the possibility of ocean-atmosphere coupling as a function of latitude?**
- ventilation of the interior ocean by subduction and water mass formation

4. The meridional overturning circulation

- characterization: magnitude per basin, properties of water masses transported
- its buoyancy forcing: either open-ocean convection (eg: Labrador Sea) or density currents from buoyancy-driven internal seas (eg: Nordic Seas). **Exercise: determine the mixing ratio of the Denmark Strait overflow water and that of the Indo-Pacific deep waters from the (T,S) properties of the respective source waters.**

5. The role of interior mixing in the overturning circulation

- Relation between interior mixing and diapycnal~vertical velocities. **Exercise: deduce the diapycnal velocity from given climatological values of diapycnal mixing.**
- Physical drivers and location of abyssal ocean mixing: internal tides and gravity waves, bottom friction, submesoscale instabilities.

6. The oceanic meridional heat transport

- How can the ocean impact the atmosphere and hence climate? Directly through heat flux (SST, sea ice extent and marginally ocean albedo), momentum flux (surface roughness related to wind waves and swell, surface currents are negligible), water flux (strongly impacted by SST and sea ice extent). **Exercise: estimate the current feedback impact on wind stress over an eddy for a wind at 10m/s and surface currents of 50cm/s. What do you deduce regarding the current feedback impact on the atmosphere and ocean?** Hence circulation does not matter directly for climate, it only matters in its transport of heat (and its impact of sea ice at high latitudes).
- The oceanic heat transport, repartition between basins, depth and latitude, between gyre and overturning circulations.

Tutorials

First tutorial: NEMO 1D case study at the PAPA station

1. Formulation of NEMO 1D model + general description of PAPA case study
2. Sensitivity experiments: parameters of the TKE scheme, inclusion of a specific EVD scheme, value of the background Kz, magnitude of the heat vs momentum vs water flux, vertical penetration of shortwave radiation, Bulk vs flux forcing, timestep

Second tutorial: NEMOMED12 hindcast simulation

1. continuation of the NEMO 1D case study
2. Formulation of the NEMO 3D model + general description of NEMOMED12
3. Hindcast simulation with the online tracer trend diagnostic in the mixed layer: 1. oceanic heat waves; 2. spring warming; 3. fall cooling; 4. main balance in the winter vs summer; 5. importance of lateral processes; 6. integrated heat budget; 7. long-term trends; 8. initialization shock.

Last tutorial: the ocean in CNRM-CM6 climate model

1. Continuation of the hindcast simulation analysis
2. General description of the CNRM-CM6-LR coupled model
3. Analysis of the main oceanic features in the pre-industrial control run: gyre circulation, upwelling areas, ACC, equatorial circulation, meridional overturning circulation, meridional heat transport (gyre vs overturning), mixed layer depth and convection, vertical stratification, sea ice
4. Analysis of the main global warming signals in the ocean (either last 30yr of historical or of an abrupt 4xCO2 run): SST, sea ice, MLD, vertical profile of T,S, meridional overturning circulation, meridional heat transport.