EARTH OBSERVATION SUMMER SCHOOL

Earth System Monitoring & Modelling

30 July–10 August 2018 | ESA–ESRIN | Frascati (Rome) Italy

Satellite Oceanography: an integrated perspective
How to contribute/accelerate new skills/discoveries to help reveal and model unknow unknowns from all available multi-modal satellite ocean remote sensing measurements?

Some Earth Observation Challenges:

- **Upper vertical motions i.e. 3D dynamics (e.g. including time evolution) of the upper ocean**, Mesoscale and submesoscale circulation as key to control the vertical ocean pump and its impact on energy transport and biogeochemical cycles.

- **Climate modelling due to these vast and diverse scales of fluid motions**: in the upper ocean, horizontal scales as big as basins and as small as cm-mm (capillary-gravity surface waves) contribute non-negligibly to air-sea exchanges and climate, and dynamics of scales of less than 30 km, is characterized by departures from the Earth’s rotation constraint, i.e. ageostrophic motions and strong impact of wind/wave transient forcings.
Problem: 1/100(0) year events now occur yearly!
Ocean remote sensing: a privileged view

- Spatially detailed
  - Spatial resolution from meters to Kms
  - A synoptic picture that is 100 km - 10 000 km wide

- Regularly repeated
  - Revisit intervals between 30 min. and 35 days
  - Continuously repeated over years to decades

- Global coverage
  - Satellites see the parts where ships rarely go
  - Single-sensor consistency - no intercalibration uncertainties

- Measures parameters that cannot be observed in situ
  - Surface roughness at short length scales (2-50 cm)
  - Surface slope (a few cm over 100s of kilometres)
New Era - Nanosatellites - CubeSat

A CubeSat is a type of miniaturized satellite for space research that usually has a volume of exactly 10 cm cube, and mass of no more than 1.33 kilograms.
Big Data & AI/Data Science

Data

Big data infrastructure

DL/AI
Numerous questions and challenges

Some of the Living Planet Challenges to better assess the existing pressures on the marine environment (e.g. overfishing, pollution, habitat destruction, ...) potentially leading to increased risks to global food security, economic prosperity, ...

Evolution of coastal ocean systems including the interactions with land in response to natural and human-induced environmental perturbations

Mesoscale and submesoscale circulation and the role of the vertical ocean pump and its impact on energy transport and biogeochemical cycles

Response of the marine ecosystem and associated ecosystem services to natural and anthropogenic changes,

Physical and biogeochemical air/sea interaction processes on different spatio-temporal scales and their fundamental role in weather and climate

Sea level changes from global to coastal scales and from days (e.g. storm surges) to centuries (e.g. climate change)
Numerous questions and challenges

How can we map the distribution of marine plastic debris?
Has the Agulhas current strengthened in the last 5 years?
Is the surface circulation of the Black Sea and in the Mediterranean Sea stable?
How is the Arctic Ocean changing?
How is marine biodiversity changing, locally, regionally, globally?
What is the extent of ocean acidification?
Are western boundary currents changing, the Gulf Stream?
How can ship routing be optimised?
Why and where is regional sea level changing?
How are our coastal regions changing?
How can we map estuary systems from space?
• most observations are not yet sufficiently explored and used

Synergy between high and medium resolution observations to reveal mean states and trends, near-surface ocean-atmosphere dynamics, local and non-local interactions, convergence/divergence surface fronts and numerous roughness contrasts.

Atmospheric and Oceanic observations generally produce high quality data, but it is often too sparse (many gaps where information is missing, and/or often too local in both space and time).

How can we use observed data in combination with the physical knowledge of stochastic processes in nonlinear dynamical systems to estimate and model those effects on the variability of computationally resolvable scales of motion that are caused by the small, rapid, unresolvable scales of fluid motion that upscaling in data assimilation leaves out?
Climate models are too coarse to resolve clouds

Global model: ~100 km resolution

Cloud scales: ~10-100 m
SAF O&SI NAR pour AVHRR17 (2km, 2 passes/jour)

SAF O&SI NAR18 pour AVHRR17 (2km, 2 passes/jour)

MSG/SEVIRI (10km, 3 heures)

Avhrr 18

Avhrr 17

ENVISAT/AATSR (1 km, 14-15 orbites/jour)

Multi-satellite product
Sea surface temperature

High resolution daily product 2006-present, 2 km resolution
Global SST

Global reanalysis 2006-present at 10 km resolution
Small scales / mesoscale

SST - Modis(L2P)  
SST - AMSRE(L3)
Characterizing the submesoscale - Spectral approach

Modis (10-250 km) : - 2.1

AMSRE (80-250 km) : - 6.
Schematic illustrating the different remote-sensing methods and classes of sensors used in satellite oceanography, along with their applications (from Robinson, 2004).
Today ideal instrument \(\ldots\) (wide-swath, high-resolution, topography, roughness, Doppler, emissivity, reflectance, \(\ldots\)) = the combined use of observations, including in situ measurements

Very \(\text{(too) large}\) number of spatio-temporal scales under local and non-local interactions

Improved technologies (instruments, resolution, computer capabilities, storage, dissemination) all contribute to improved combined analysis

Theoretical frameworks and numerical simulations can be used to assess the causes and contexts of the different observations (including sensor physics, observability conditions and instrument capabilities), to refine dynamical/statistical gap filling methods

New challenges, new altimeter instruments (SARAL, Sentinel-3, SWOT, \ldots, CubeSat opportunities), possible new high-resolution microwave instruments (10-20 km), Doppler measurements to infer sea surface currents (SAR and/or RAR-SKIM or DopplerScat), and combined roughness contrasts as local quantitative proxies to trace strong surface gradient areas
Satellite instruments generally measure 2D surface expressions of 4D structures.
Typical Atmosphere Space-Time scales

- Horizontal scales
  - 100km
  - 10km
  - 100m
  - 1m

- Minute
- Hour
- Day
- Year

- Micro Turbulence
- Boundary layer motions
- Shallow Convection Cumulus
- Deep convection
- Convective Clusters
- Cyclone
- Planetary waves Monsoon
Satellite synthetic aperture radar (SAR)

light = more short waves
~ stronger wind forcing
~ air-sea heat, KE, momentum, gas exchange

dark = weak wind or surfactant

Corsica

10 km

February 19, 2015
Image: MPC Sentine-1 portal
Strong cold wind over warmer ocean

- Mistral
- Ekman spiral
- Ekman transport
- SQG anti-cyclonic eddy
- Langmuir circulation
- Internal waves
- Swell rays
- Stokes drift
- Wind waves
- Surface roughness anomaly
- Synoptic wind
- Inertial motion
- O(10 m)
- O(100 m)
- O(1000 m)

- February 19, 2015
- CORSICA
- 10 km

- February 24, 2015
- Toulon
- Strong cold wind over warmer ocean

- Light = more short waves
- ~ stronger wind forcing
- ~ air-sea heat, KE, momentum, gas exchange

- Satellite synthetic aperture radar (SAR)

- Image: MPC Sentine-1 portal
mixed layer

thermocline

warm

cold

~1 km

ABL rolls

strong mean wind

~1 km

SAR signature
mixed layer
thermocline
warm
cold
Non-uniform wind stress
proper atmosphere-wave-ocean coupling
We can illustrate this partitioning using the expression for the total momentum flux at the ocean surface (i.e., where the turbulent component becomes negligible) derived by Deardorff (1967). Deardorff (1967) derived this expression by evaluating the integrated horizontal momentum equation at the ocean surface to obtain

$$\tau_a = \rho_a \left[ - \frac{\partial \mathbf{\Phi}}{\partial x} + \rho_a \frac{\partial U}{\partial z} \right] = \rho_a \frac{\partial \mathbf{\Phi}}{\partial x} + \rho_a \frac{\partial U}{\partial z} \bigg|_{\eta} - \tau_{aw} + \tau_{ao}$$

Figure 2. Some of the processes that govern the transfer of heat, mass, and momentum within the coupled boundary layers.
Schematic illustration of the Langmuir circulation (first described by Langmuir, 1938). The separation scale of the convergence zones are typically 10-100 m.
Typical Ocean Space-Time Scales

- Tides
- Mesoscale circulation
- Sub-mesoscale circulation
- Internal Waves
- Inertial motions
- Mixed Layer Turbulence
- Langmuir
- Surface Micro Turbulence
- Basin circulation
- Thermo-Haline Circulation

Horizontal scales:
- 1000 km
- 100 km
- 10 km
- 1 km
- 1 m

Vertical scales:
- 1000 m
- 100 m
- 10 m
- 1 m
- 1-10 m

- Minute
- Hour
- Day
- Year

Horizontal scales:
- 1000 km
- 100 km
- 10 km
- 1 km
- 1 m

Vertical scales:
- 1000 m
- 100 m
- 10 m
- 1 m
- 1-10 m

- Minute
- Hour
- Day
- Year

Thermo-Haline Circulation
Basin circulation
Sub-mesoscale circulation
Internal Waves
Inertial motions
Mixed Layer Turbulence
Langmuir
Surface Micro Turbulence
Tides
Mesoscale circulation
Maximum Density Profile

\[ \frac{\partial}{\partial x} \]

Density Profile

Summer Heating

Winter Heating

Wind Stress

1 day

10 days

1 year

Ekman Spiral

Ekman Transport

Synoptic Wind

Swell Rays

Stokes Drift

Inertial Motion

Langmuir Circulation

Internal Waves

Maximun N

O(10m)

O(100m)

O(1000m)

Surface Roughness Anomaly

Anti-cyclonic Eddy

Ekman Spiral

Ekman Transport

SQG

Wind Waves

Internal Waves

Stokes Drift

Inertial Motion

Langmuir Circulation

Internal Waves

Maximun N

O(10m)

O(100m)

O(1000m)

Mixed Layer Depth

Remnant Layer Depth

Depth
Micro Turbulence

Internal Waves

Inertial motions

Mesoscale circulation

Basin circulation

Thermo-Haline Circulation

Horizontal scales

Tides

Sub-mesoscale circulation

1-10 m

100 m

1000 m

Vertical scales

Typical Ocean and Atmosphere Space-Time Scales

Ocean-Atmosphere Interactions
Figure 1. Future role of wave models as an essential coupling component for ocean-atmosphere-carbon-cycle models developed in the context of the World Climate and Global Change programs.
Dissipation}

10m

stratification

de domine

100m

cascade directe KE

1000m

Vertical scales

1m

turbulence 3D

1km

stratification stratifiée 3D

10km

ondes inertielles

100km

Sous-mésoéchelle

Couplément KE

(24h)

(99s jour)

(99s moite)

(99s min-24h)

(99s noise)

rotation domine

104km

Mésoéchelle

Couplément KE

(24h)

(99s jour)

(99s moite)

(99s min-24h)

(99s noise)

Gyres

(100s)

Thermohaline Circulation

(100-1000ans)

Dissipation aux frontières
Satellite synthetic aperture radar (SAR)

light = more short waves
~ stronger wind forcing
~ air-sea heat, KE, momentum, gas exchange

dark = weak wind or surfactant

Corsica

February 19, 2015

Image: MPC Sentine-1 portal
Inter-scale interactions

- dispersion of biochemical substances?
- High-resolution = Large Eddy Simulation (LES)
Atmosphere-wave-ocean coupling and the resulting flows alter dispersion.


cyanobacteria bloom (Baltic Sea)
Stirring and mixing: interplay and scale interactions.
Application to Oil Spills Detection

April 20

Deepwater Horizon
May 24, 2010
Terra/MODIS
Lagrangian advection to dynamically interpolate large-scale tracer (sea surface temperature field, left) onto a high-resolution product (right). Particle trajectories computed using altimetry-derived velocities (AVISO, weekly 1/3°) with 3 hours time steps.
Small scales / mesoscale

06-May-2010 17:00 modis aqua

18-May-2010 17:16
Small scales / mesoscale
The blended satellite products allow to estimate the impact of surface currents on the biogeochemical transport, on the dispersion of pollutants and oil spills.

Forecast of oil spill dispersion in the Gulf of Mexico on 25 June 2010: red and blue show regions of strong oil dispersion within 3 days. This diagnosis, based on altimetric data, compared well with what was observed (Mezic et al., Science, 2010).

However these satellite datasets (altimetric and microwave data) cannot capture ocean dynamics at scales smaller than 100 km because of the resolution (or/and noise level).
Observed data in combination with the physical knowledge of stochastic processes in nonlinear dynamical systems
LU : Adding random velocity

\[ \mathbf{v} = \mathbf{w} + \sigma \dot{\mathbf{B}} \]

**Resolved large scales**

**White-in-time small scales**

References:

- Mikulevicius and Rozovskii, 2004
- Flandoli, 2011
- Memin, 2014
- Resseguier et al. 2017 a, b, c
- Chapron et al. 2017
- Cai et al. 2017
- Holm, 2015
- Holm and Tyranowski, 2016
- Arnaudon et al., 2017
- Cotter and al 2017
- Crisan et al., 2017
- Gay-Balmaz & Holm 2017
- Cotter and al 2018 a, b
Advection of tracer $\Theta$

Large scales: 
$w$

Small scales: 
$\sigma \dot{B}$

Variance tensor:

$$a = a(x, x) = E\left[\sigma dB^T \sigma dB\right]$$

Multiplicative random forcing

Balanced energy exchanges

Drift correction

$$\partial_t \Theta + w^* \cdot \nabla \Theta + \sigma \dot{B} \cdot \nabla \Theta = \nabla \cdot \left( \frac{1}{2} a \nabla \Theta \right)$$
Goal is a hierarchical system that integrates data and models (and can also be used to design observing systems)
Upper ocean atmospheric forcing monitoring

- SAR wind
- ECMWF
- Ekman/Stokes
- WW3
- Argo MLD
- Trade winds/mean forcing
Upper ocean geostrophy monitoring

- SWOT SSH
- Microwat SST
- AMSR SST
- SMOS SSS
- Goce geoid
- Altimetry SSH
- Rossby waves
- Seasonal cycle
- El Nino

Spatial resolution: 1000km, 100km, 30km, 10km, 1km
Temporal resolution: 1 season, 10 days, 3 days, daily, 3 hourly
Upper ocean circulation monitoring

Spatial resolution

1000km 100km 30km 1km

1 season 10days 3days daily 3 hourly

Temporal resolution

SAR ATI
IR SST
SWOT SSH
SAR Doppler
Microwet SST
Submesoscale
Ekman/Stokes
Internal Waves
Inertial current
Tidal current
Goce geoid
Altimetry SSH
SMOS SSS
AMSR SST
Scat
Rossby waves
Seasonal cycle
El Nino
Upper ocean ageostrophic current monitoring

Spatial resolution

1000km, 100km, 30km, 10km, 1km

Temporal resolution

1 season, 10 days, 3 days, daily, 3 hourly

- Drifters
- Seasonal current
- El Nino
- SAR SSR
- IR&Vis
- MCC
- SAR Doppler
- Microwat SST
- Submeso ageo
- Boundary current
- Inertial current
- Tidal current
- Internal Waves
- Tidal model
• … most observations are not yet sufficiently explored and used

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