Operational Oceanography as a basis for new scientific understanding

Nadia Pinardi
Department of Physics and Astronomy
University of Bologna

Outline

- Operational Oceanography (OO) and the new science paradigms
- The OO service for science questions and new answers
- The OO service for new applications
- Conclusions and Outlook

The new science paradigms: data intensive scientific discoveries

- From Microsoft's 'The Fourth Paradigm: Data-Intensive Scientific Discovery'
  - **"Science should be data explorative, *unifying experiment, theory and simulations*"**
  - **"*Science of applications* will introduce innovative thinking and new understanding"**
- OO generates observational and model products, unifying knowledge of ocean processes and measurements allowing exploration of ocean dynamics at unprecedented resolution and accuracy
- OO generates products that, due to their time-space consistency, are at the basis of new applications

The new science paradigms: unification of engineering and science

- From MIT White paper on ‘Convergence’:
  - **“Scientific innovation involves the coming together of different fields of study - particularly *engineering, physical sciences, and life sciences* - through collaboration among research groups and the integration of approaches that were originally viewed as distinct and potentially contradictory”.**
- OO is the ocean field which merges engineering with science to obtain the optimal continuous monitoring and improved understanding

The OO service for science questions and new answers

- Gauss, 1809: .... we need ... a suitable combination of all observations to approximate as much as possible the truth. The problem can be only undertaken properly when the model (theory) will be corrected so as to satisfy all of the observations in the most accurate manner possibly
- We have today two major knowledge sources: observations and numerical models (deduced from first principles). The OO analysis systems put them together with an estimate of their respective error:

Model fields errors — Observation errors

$$J = \frac{1}{2}\delta\mathbf{x}^T\mathbf{B}^{-1}\delta\mathbf{x} + \frac{1}{2}[\mathbf{H}(\delta\mathbf{x}) - \mathbf{d})]^T\mathbf{R}^{-1}[\mathbf{H}(\delta\mathbf{x}) - \mathbf{d})]$$

The European OO service:

The European Earth Observation Programme

QC OBSERVATIONS
in real time and
10-20 years t.s.

→

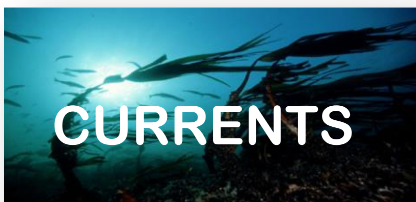
ANALYSES
Daily/weekly

→

FORECASTS
2 to 10 days

→

REANALYSES
10 to 45 years



DISCOVER

VIEW

DOWNLOAD

Open & Free

The science questions requiring new answers

- Using the Copernicus re-analysis (1987-2007) several science questions have been answered in a new way:
  - What powers the Mediterranean Sea circulation?

    (Cessi, Pinardi and Lyubartsev, J.Phys. Ocean, march 2014)
  - What causes the mean sea level trend in the Mediterranean Sea?

    (Pinardi et al., Jour. Climate, January 2014)

First question: what powers the Mediterranean Sea circulation?

- **Munk and Wunsch (1998) and Wunsch and Ferrari (2004)** show that mechanical energy in the GLOBAL ocean are accumulated under the action of winds and tides (not by buoyancy fluxes)
- **Paparella and Young (2002)** demonstrate that surface buoyancy fluxes are not capable to induce enough turbulence in the ocean to produce an energetic circulation
- **What is powering the circulation in semi-enclosed Seas?**

First question: what powers the Mediterranean Sea circulation?

- Volume average energetics of semi-enclosed seas:

$$\partial_t \langle \frac{u^2+v^2}{2} - zb \rangle = \int_A \frac{\boldsymbol{\tau}\cdot\boldsymbol{u}_s}{\rho_o}\,dx\,dy + F + \langle \kappa_v b_z \rangle - \langle \nu(|\nabla_h u|^2 + |\nabla_h v|^2)\rangle$$

$$- \langle \nu_v (u_z^2 + v_z^2)\rangle - \int_{OB}\!\!\int \left[\nu \frac{\nabla(u^2+v^2)}{2}\right]\cdot\hat{\boldsymbol{n}}\,dz\,dl + D\,,$$

$$F \equiv -\int_{OB}\!\!\int \left(\frac{u^2+v^2}{2} + \frac{p}{\rho_o} - z\,b\right)\boldsymbol{u}\cdot\hat{\boldsymbol{n}}\,dz\,dl\,,$$

?

$$D \equiv -\int_{OB}\!\!\int \kappa z \boldsymbol{\nabla}_h b\cdot\hat{\boldsymbol{n}}\,dz\,dl\,.$$

First question: what powers the Mediterranean Sea circulation?

- For two-layer flows at the Strait, where h_1 is the interface at the Strait:

$$F + D \approx -h_1 \left[\int_A Q_b \, dx \, dy - \partial_t \langle b \rangle \right]$$

- The theory has been verified by the MyOcean re-analysis

First question: what powers the Mediterranean Sea circulation?

- In conclusion the energy equation for semi-enclosed seas with two layer flow at the Strait is:

$$\partial_t \langle \frac{u^2+v^2}{2} \rangle - \langle (z+h_1)\, b_t \rangle \approx \boxed{-h_1 \int_A Q_b \, dx\, dy + \int_A \frac{\boldsymbol{\tau} \cdot \boldsymbol{u}_s}{\rho_o} \, dx\, dy} + \langle \kappa b_z \rangle$$

$$- \langle \nu (|\nabla u|^2 + |\nabla v|^2) \rangle - \langle \nu_v (u_z^2 + v_z^2) \rangle - \int_{OB} \int \nu \frac{\nabla (u^2+v^2)}{2} \cdot \hat{\boldsymbol{n}} \, dz\, dl \, .$$

Sea name	Buoyancy energy input (x 10^{-10})	Wind work (x 10^{-10})	
Mediterranean	8	10	**Comparable**
Black	-3	4	**Opposite**
Red	30	1	**Buoyancy larger**
Baltic	-7	90	**Wind work larger**

Second question: what controls the mean sea level dynamics?

- Global ocean estimate from reconstruction (Church et al., 2004):
  1.8 ± 0.3 mm year^{-1}
- Mediterranean Sea estimate from reconstruction (Calafat and Gomis, 2009):
  0.7 ± 0.2 mm year^{-1}
- Why are so different? What is the mean sea level trend due to in the Mediterranean?

Second question: what controls the mean sea level dynamics?

The Mediterranean Mean sea level equation

$$\frac{d\langle\eta_R\rangle}{dt} = -\left\langle\nabla\cdot\left[(H+\eta)\vec{u}\right]\right\rangle_R - \langle q_W\rangle_R$$

MASS part

$$= \textit{Gibraltar net trans} - \textit{waterflux}$$

$$+\frac{1}{\rho_f}\left\langle\alpha_T\frac{Q}{C_W}\right\rangle - \frac{\rho_o\beta\langle S_o q_W\rangle_R}{\rho_f}_R - \frac{1}{\rho_f}\left\langle\int_{-H}^{\eta}\nabla\cdot\left(K_H\nabla\tilde{\rho}\right)\right\rangle$$

STERIC part

$$+\textit{steric terms (thermosteric + halosteric + density adv. at Gib.)}$$

where $q_W = E - P - \frac{R}{F_M}$

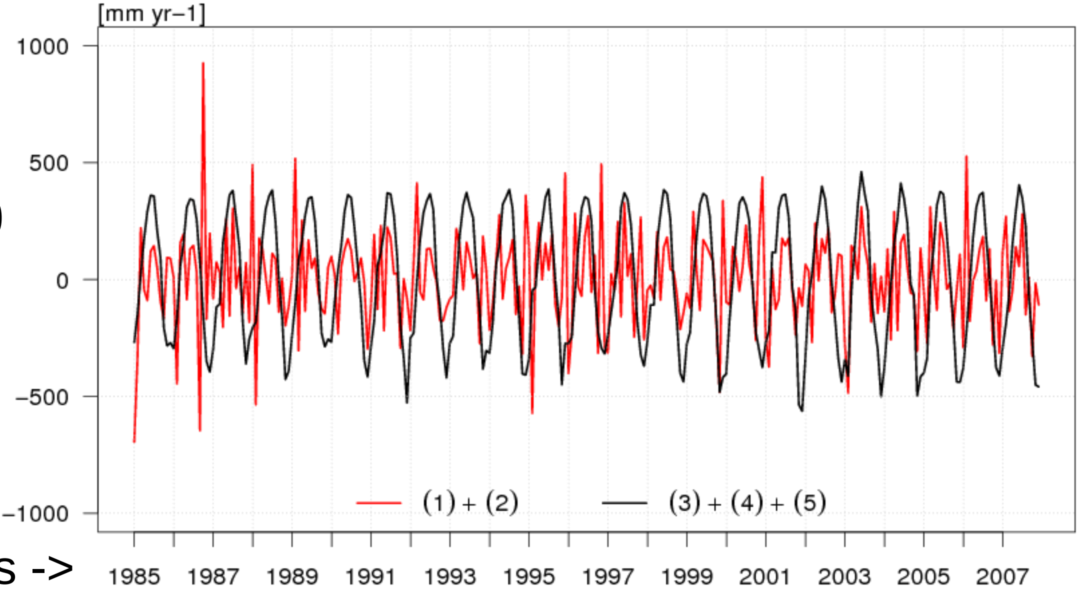
Second question: what controls the mean sea level dynamics?

From the reanalysis mean sea level eq terms can be computed

$$\frac{d\langle\eta_R\rangle}{dt} = -\left\langle\nabla\cdot\left[(H+\eta)\vec{\bar{u}}\right]\right\rangle_R - \langle q_W\rangle_R - \left\langle\frac{\rho_o\beta\langle S_o q_W\rangle_R}{\rho_f}\right\rangle_R + \frac{1}{\rho_f}\left\langle\alpha_T\frac{Q}{C_W}\right\rangle - \frac{1}{\rho_f}\left\langle\int_{-H}^{\eta}\nabla\cdot\left(K_H\nabla\tilde{\rho}\right)\right\rangle$$

$$= \quad (1) \quad + \quad (2) \quad + \quad (3) \quad + \quad (4) \quad + \quad (5)$$

$\frac{d\langle h_R\rangle}{dt}\ (mm\,yr^{-1})$



Years ->

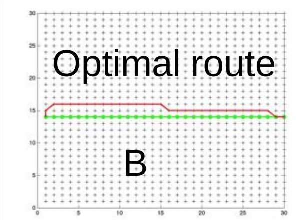
MASS TERMS FOR MEAN SEA LEVEL ARE STOCHASTIC IN NATURE

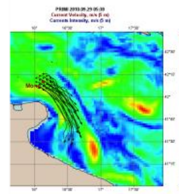
The OO service for new applications:

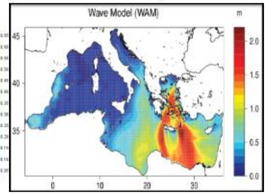
Copernicus (The European Earth Observation Programme) + EMODnet (European Marine Observation and Data Network)

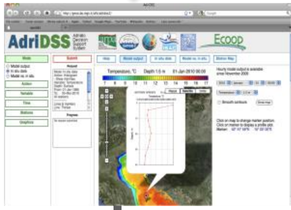
OPEN AND FREE DATA WAREHOUSE

- Nested FCST models
- Sea-Conditions
- DSS Oil spill
- DSS Ship routing
- DSS search and rescue
- DSS early warning
- DSS env. quality

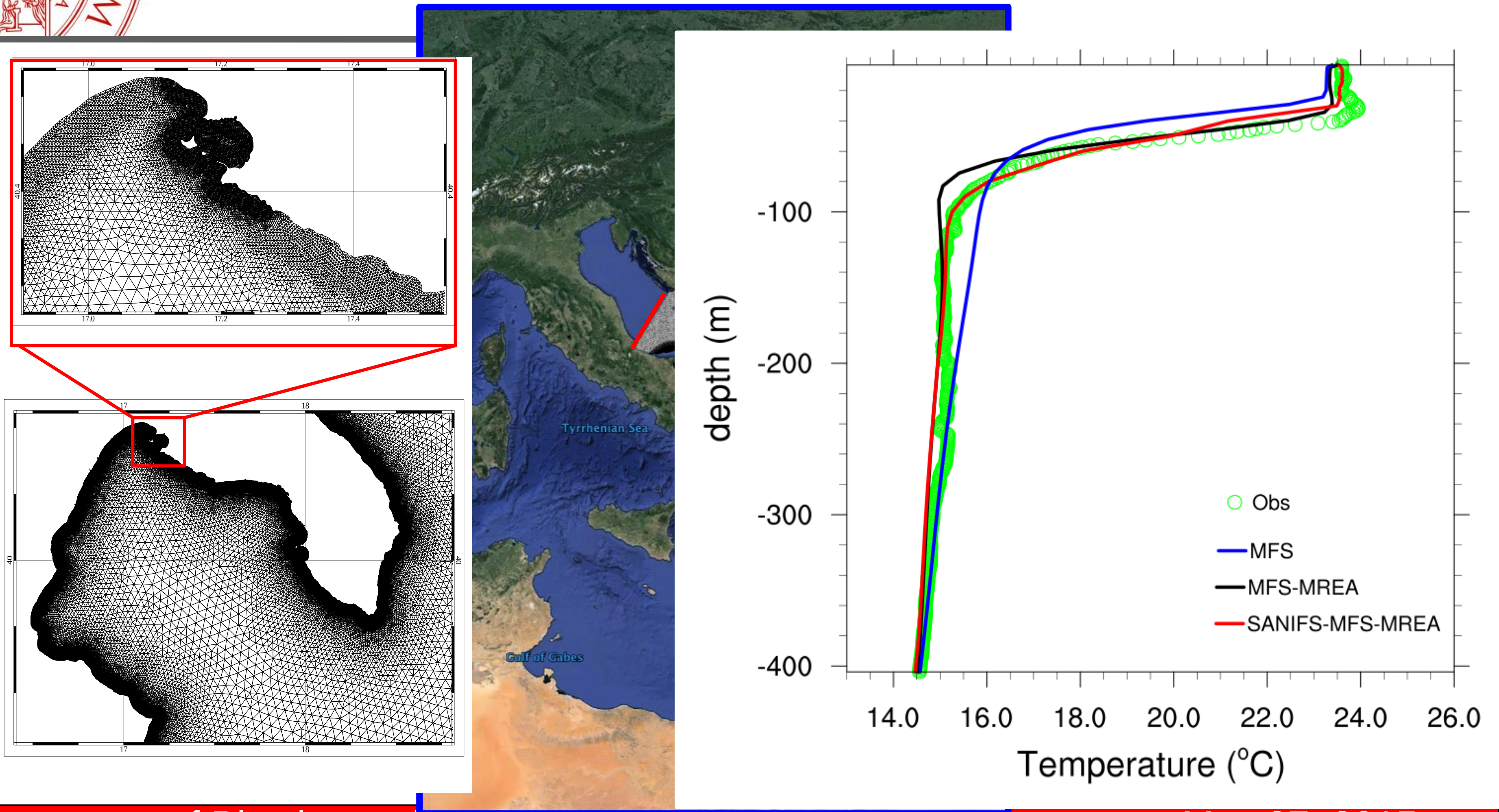








One example: downscaling to the coasts with advanced unstructured grid models (Federico, 2015)



Conclusions and Outlook

- In synthesis the OO service has allowed to discover:
  - 1) that the Med Sea is both wind and buoyancy driven and this has important consequences on the ecosystem
  - 2) that the mean sea level tendency is partly controlled by stochastic-like mass terms due to unbalance between Gibraltar and water flux at the surface. This requires a monitoring system at Gibraltar
- The OO service is capable to support innovative applications in all maritime economy and marine environment sectors

Conclusions and Outlook

- What is needed next?
  - Incorporate scientific improvements in all the OO service components (observations, models, data assimilation, etc.)
  - Further develop the European in situ data collection infrastructure, open and free, real time and delayed mode
  - Enlarge the interoperability of the OO service with the meteo-marine and climate services
  - Develop the OO modelling and observational components for biology, biodiversity, fisheries, etc.
  - Promote big data science and HPC developments

We owe Kostas to continue his visionary work

- *Considerate la vostra semenza: fatti non foste a viver come bruti, ma per seguir virtute e canoscenza.*

- *Consider the seed from which you sprang;
You were not made to live like brutes, but for pursuit of virtue and of knowledge.*

The Canto of Ulysses, XXVI, Dante Alighieri, 1306