Perspectives talk

The ocean mesoscale: physics, observations, simulations, and climate impacts

Transport in Unsteady Flows:
Deterministic Structures to Stochastic Models and Back Again
Banff International Research Station (BIRS)
Banff, Canada (part of the Nakoda (Stoney) First Nation)
15-20 Jan 2017

Stephen.Griffies@noaa.gov

NOAA/GFDL/Princeton/USA

Outline

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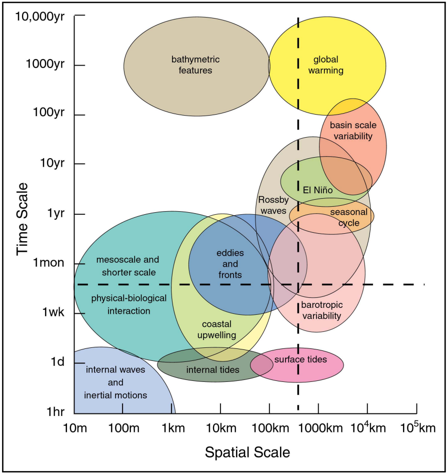
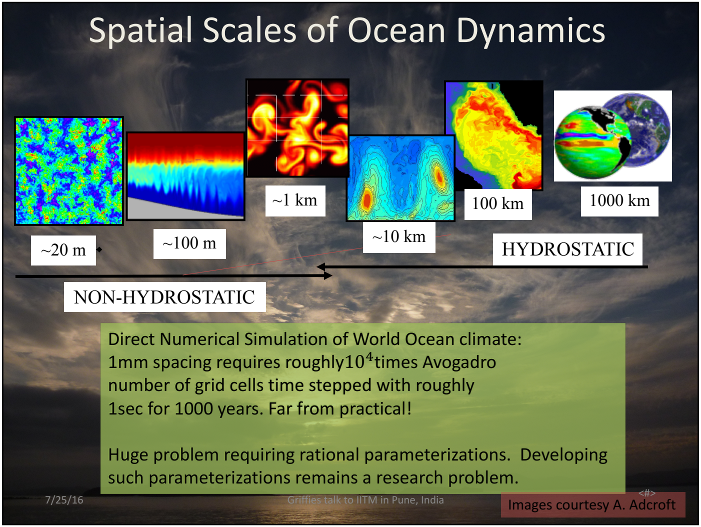
Space-time diagram of ocean dynamical processes



From Chelton (2001)

- Broad range of space-time scales
- Absence of a clear spectral gap except for scales larger than 1000 km.
- Direct implications for representation and parameterization of the ocean's role in climate and ecosystems.

Spatial scales for ocean dynamical processes

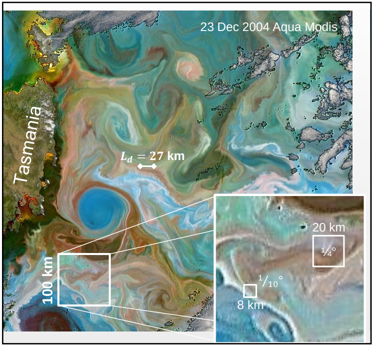


Courtesy A. Adcroft (NOAA/GFDL)

Outline

2 Features of the ocean mesoscale

Ocean mesocale



MODIS satellite w/ inserts by A. Adcroft (GFDL)

- Eddy size $\propto$ first baroclinic Rossby Radius

$$\lambda_{m=1} = \left(\frac{c_{m=1}}{|f|} \right),$$

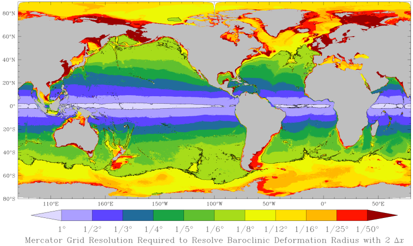
where the phase speed is approximated by (Chelton et al. 1998)

$$c_m \approx \frac{1}{m\,\pi} \int_{-H}^{0} N \, \mathrm{d}z.$$

- Global models are marginal at representing this scale.
- Regional and process models reach into the submesoscale.

Map of 1st baroclinic Rossby radius

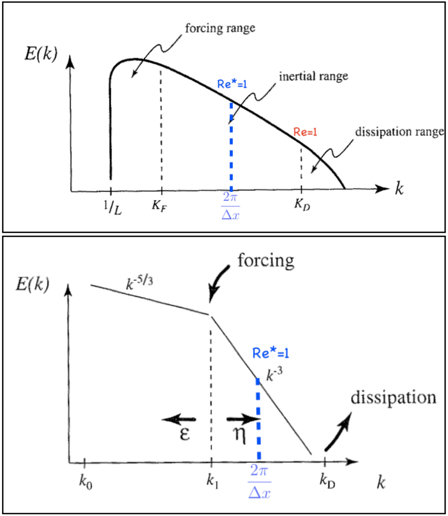
A measure of the grid spacing needed for simulations to admit ocean mesoscale



From Hallberg (2013)

- Map indicates the necessary Mercator spacing for $2\Delta = \lambda_1$.
- Finer spacing to accurately represent eddy flux convergences.
- Finer spacing for higher baroclinic modes, submesoscale, gravity waves, Langmuir...
- What does it mean (physically and numerically) to “resolve”?
- What processes in fact need to be resolved (for climate? ecosystems?...)

Turbulent cascade of mechanical energy



Compliments of Baylor Fox-Kemper, Brown University, USA

- 3d turbulence: energy cascade to small scales (direct cascade)
- 2d/QG turbulence: energy cascade to large space and time scales (inverse cascade)
- Cascades couple space-time scales.
- Inverse cascade organizes large-scale flow features (e.g., coherent structures, maxEntropy).

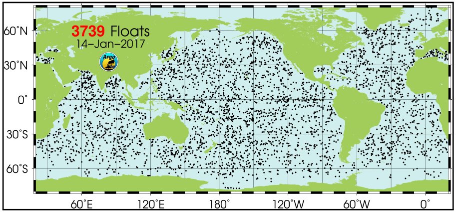
Outline

3. Observing turbulent ocean fluid dynamics at the planetary scale

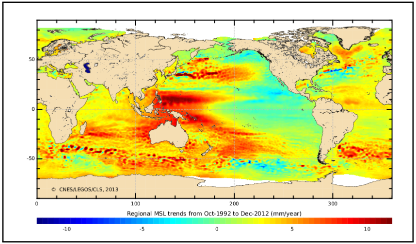
Argo floats + satellite altimetry

Turbulent ocean fluid dynamics at the planetary scale

Argo profiling floats + surface measurements from satellites offer planetary scale measures of the ocean of use for predictions and climate change detection. The data also supports a growing suite of scientific investigations into the turbulent ocean fluid dynamics at the planetary scale.

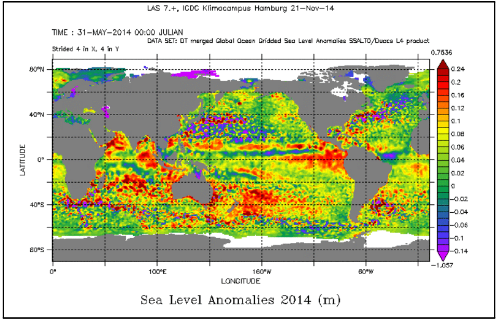


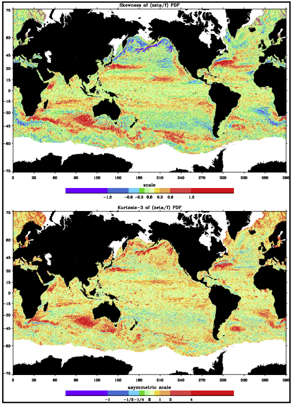
Float snapshot from Argo at UCSD



Climatological sea level change from AVISO

Patterns of sea level and derived surface geostrophic vorticity

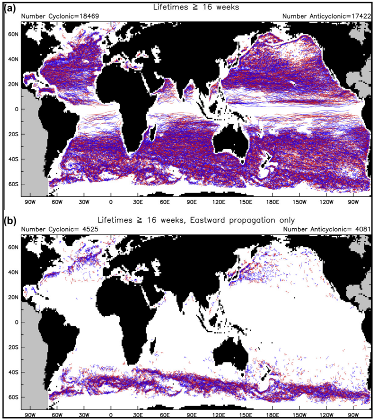




SSH daily anomaly from AVISO and Un Hamburg. Eddy features typically associated with mesoscale fluctuations: the ocean's weather.

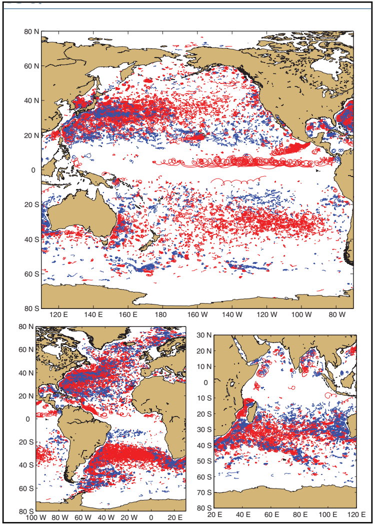
Skewness and kurtosis in geostrophic vorticity (Hughes et al 2010). Hypothesized to be of use to identify jets and mixing barriers.

Trajectories of sea level eddies: (Chelton)



Cyclonic (blue) and anticyclonic SSH 16-week SSH-defined eddies from Chelton, Schlax, Samelson (2011). Inferences of associated mass/tracer transport suggests large role for nonlinear (coherent) eddy structures. But conclusions are not without controversy.

Loopers identified from drifting surface floats: (Lumpkin)



Looper climatology from surface drifters (Lumpkin 2016). Results largely support Chelton.

Surface Water and Ocean Topography (SWOT)

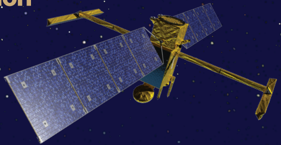
Fingers crossed that NASA and CNES can make it happen (planned for 2021)!

Potential for 1km resolution of ocean dynamics, and 10m for land hydrology!

Mission Applications Support at NASA:

Surface Water and Ocean Topography Mission*

National Aeronautics and Space Administration



Margaret Srinivasan
margaret.srinivasan@jpl.nasa.gov
Jet Propulsion Laboratory,
California Institute of Technology

Craig Peterson
craig.a.peterson@nasa.gov
Stennis Space Center

Abstract

The NASA Applied Sciences Program is actively supporting an agency-wide effort to formalize a mission-level data applications approach. The program goal is to engage early-phase NASA Earth satellite mission project teams with applied science representation in the flight mission planning process. The end goal is to "to engage applications-oriented users and organizations early in the satellite mission lifecycle to enable them to envision possible applications and integrate end-user needs into satellite mission for early-phase missions to optimize the reach of existing applications efforts to enhance the applications value of the missions. There is high value in project-level awareness of mission planning decisions that may increase or decrease the utility of data products to diverse user and potential user communities (communities of practice and communities of potential, respectively).

Successful strategies to enhance science and practical applications of the proposed

Science Goals

Hydrology: First global inventory of fresh water storage and discharge on land.

Oceanography: First global determination of the ocean circulation, kinetic energy and dissipation at mesoscales and submesoscale processes.

NASA Earth Science Directorate, Applied Sciences Program

NASA supports applications activities for early phase missions based on the 2007 NRC Decadal Survey objectives to "enhance economic competitiveness, protect life and property, and assist in the stewardship of the planet for this and future generations."

- SWOT – Tier 2 Decadal Survey proposed mission

Surface waters in the Arctic.
Image; L. Smith, UCLA

SWOT* Mission Applications Concentrations

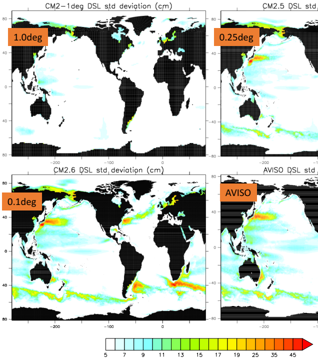
- Water management: reservoirs, floods, ecology
- International rivers: flood and drought

Outline

4. An emergent role for the ocean mesoscale in earth climate

Sea level temporal std: models vs. satellites

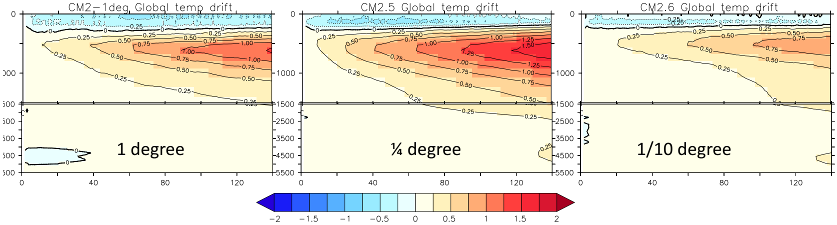
climate model hierarchy based on ocean resolution changes $(1^\circ \& 1/4^\circ \& 1/10^\circ)$



From Griffies et al (2015)

- 20 years of daily output from models; 18 years from satellites.
- Most of the satellite fluctuations are due to mesoscale eddies.
- $1/10^\circ$ resolves bulk of the ocean mesoscale SSH variance measured by AVISO.

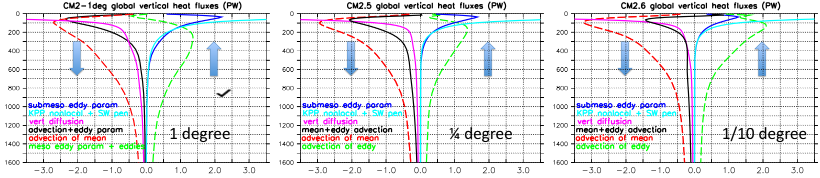
Impacts of grid resolution on model heat drift



From Griffies et al (2015)

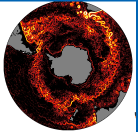
- Surface ocean cooling and intermediate depth ocean warming.
- Movement of heat from surface into the interior.
- 0.1° model shows least drift, about 50% that of 0.25°. Differences are solely due to resolution of ocean.

Vertical heat transport: mesoscale eddy transport is critical

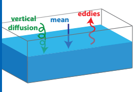


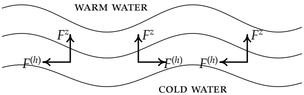
From Griffies et al (2015)

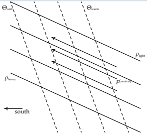
- Heat transport from time mean flow is downward into ocean (mechanical forcing).
- Heat transport from transient eddies is upward: 0.1° is roughly 50% larger than 0.25° at intermediate depths.
- Compensation between mean and eddy transport is more complete for 0.1° (interior is more adiabatic).



Mechanisms for vertical heat transport



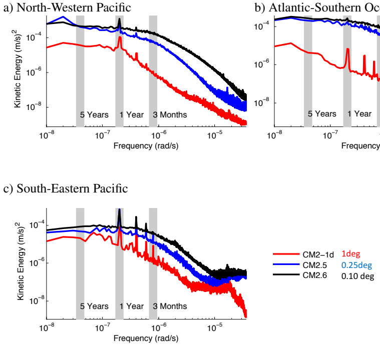




- Neutral directions in low & mid latitudes are dominated by temperature.
  - Upward mesoscale eddy heat flux decreases available potential energy.
  - Process is reflected in parameterizations of Gent and McWilliams (1990), Greatbatch and Lamb (1990), Gent et al. (1995), Griffies (1998).
- Neutral directions in high latitudes are strongly impacted by salinity, so that eddy-induced diffusion greatly impacts on heat transport.
  - Eddy diffusion along neutral directions (as per Solomon (1971) and Redi (1982)) generally moves heat upward (cold above warm on isopycnals), especially in Southern Ocean. Gregory (2000), Morrison et al (2013), Hieronymus and Nycander (2013), Griffies et al (2015).

Surface ocean geostrophic KE spectra

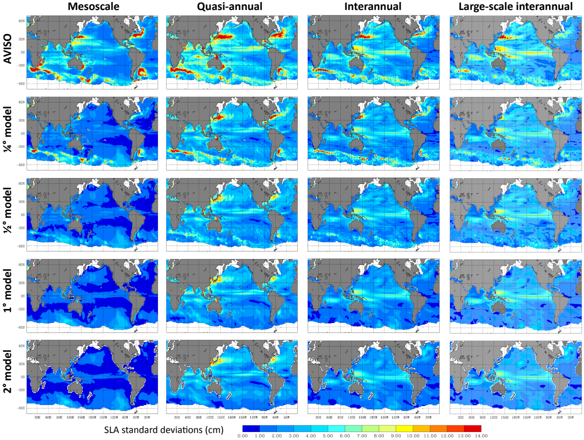
temporal inverse cascade



Surface ocean kinetic energy spectra from O'Rourke, Arbic, Griffies (2017) submitted

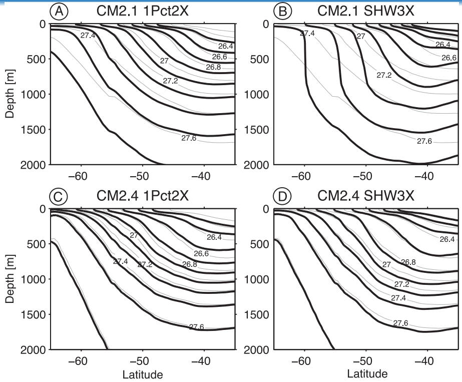
- Temporal inverse cascade: Arbic et al (2012) and Arbic et al (2014)
- Low frequency power is enhanced by high frequency mesoscale eddy fluctuations: Speich, Dijkstra, Ghill (1995), Berloff and McWilliams (1999), Hogg, Killworth, Blundell, Dewar (2005) Penduff et al (2011) Grégorio et al (2016).

Intrinsic ocean variability from mesoscale eddies



- Variability in sea level decomposed into time scales from Penduff et al (2011).
- Power at low frequency is enhanced with eddying models.

Southern Ocean density structure and wind stress



- Sensitivity of overturning to wind stress changes can be quite distinct depending on eddy-induced overturning Hallberg and Gnanadesikan (2006), Farneti et al (2010), Meredith et al (2012).
- Important role for vertical structure to the eddy diffusivity in order to realize “eddy compensation” whereby parameterized eddies compensate for changes in the mean: Farneti and Gent (2011), Gent and Danabasoglu (2011), Hofmann and Morales-Maqueda (2011), Farneti et al (2015).

Outline

5 Questions and concluding comments

Sampling of research questions that brought me here

- How much of the turbulent ocean consists of coherent material regions, and how much is chaotic whirling flotsam and jetsom?
  - The answer is important for biology, parameterizations, climate.
  - More work is needed to understand the 3D nature of this question. Argo facilitates these investigations. Yet far more data intensive Lagrangian analyses, and more difficult theory (3d versus 2d).
- Are we optimally transferring a better kinematic understanding of oceanic flow into a deeper dynamical understanding?
- Will stochastic parameterizations be ubiquitous in ocean models, as they seem to be trending for atmospheric models? How important are details of the noise?
- Are there optimal numerical frameworks to represent/parameterize ocean motions across the range of turbulent planetary fluid dynamical scales.

A few personal reflections on the science

- We have entered an era of where observations, models, and theory (and lab experiments) can coalesce to explore and to rationalize the mechanics of a planetary scale turbulent ocean fluid.
- We need smart, efficient, and rigorous methods for analysis, visualization, manipulation of the massive observational-based and model-based datasets for this exploration.
- Motivation comes from suggestions of emergent impacts on climate and ecosystem variability from turbulent fluctuations. This motivation generally funds proposals.
- Motivation also comes from curiosity. Developing a mechanistic understanding of how the ocean (and climate) works is interesting, compelling, and deeply challenging. This motivation generally attracts smart students!

Many thanks for your time

King George VI and Queen Elizabeth greet Stoney chiefs in 1939. They brought a photo of Queen Victoria (1837-1901). From Wikipedia