Geophysics from Kolmogorov to Climate

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Climate Fluctuations and Non-equilibrium Statistical Mechanics: an interdisciplinary dialogue
Dresden 7/17/17, 11-11:50

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The Ocean is Vast & Diverse

The climate also depends on atmosphere, cryosphere, biosphere, pedosphere, lithosphere & coupled modes!
The Earth's Climate System is driven by the Sun's light (minus outgoing infrared) on a global scale.

KE dissipation concludes turbulence cascades to scales about a billion times smaller.
CLIMATE

Thermal Energy Budget
**Insolation**: The amount of energy per unit time in arriving electromagnetic radiation that through a unit surface area.

Dimensions (Energy/T/L² = Power/L²) = \( S_0/4 = 1370 \text{ W/m}^2/4 = 342 \text{ W/m}^2 \)

Away from tropics, the Sun’s light does not arrive perp. to the Earth’s surface (sun not directly overhead).

So poles have shorter days, increased albedo, decreased perp. component.

Reduced Polar Power!
Simple: Planetary Energy Balance

\[ c \frac{dT}{dt} = R_{\text{incoming}}(T) - R_{\text{outgoing}}(T) \]
E.g., Water Vapor Feedback & $R_{\text{outgoing}}(T)$:

Water Vapor is the most important GHG on Earth, not only because it absorbs most of the outgoing IR, but also because it responds to surface temperature changes.

$T_s$  

Warmer Surface  More Vapor  

$H_2O$  

Greenhouse effect  

More Outgoing IR Absorbed  
Warmer Atmosphere  
More Downward IR  
Warmer Surface Temp.

earthobservatory.nasa.gov
Surface, Mixed Layer, Seasons?

Atmosphere: 1.5K/yr = 3.4m
Ocean: 0.15K/yr = 34m = 1% of mixed layer seasonality

Beginning December 1949, a weathership or mooring at Ocean Station P (50°N, 145°W, depth 4220 meters)

http://www.oc.nps.edu/
Air-Sea Exchanges

- Ocean heat capacity, even just mixed layer, is vastly larger than the atmosphere.

- Air-sea heat fluxes are sensitive to air-sea temperature differences (and wind—i.e. momentum differences).

- Thus heat anomalies end up in the ocean.
3.4m of ocean has heat capacity of whole atmosphere
Ocean Mixed Layer is about 100m deep.
Effect of Climate Modes, e.g., Hu & Fedorov (2017)

\[
\frac{dT_g}{dt} = -\frac{T_g}{\tau} + a \cdot \log\left(\frac{CO_2}{CO_2,\text{ref}}\right) + b \cdot T_{\text{NINO}} + c \cdot \text{SAOD} + d,
\]
Effect of Climate Modes, e.g., Hu & Fedorov (2017)
Modeling of variability
Still, these are systems in thermodynamic equilibrium

- These toy models are interesting and useful, but they have only one temperature.
- The real system is inherently unable to achieve a (thermodynamic) equilibrium state.
- However, we do normally assume that “infinitesimal parcels” of air or water can be described with a single temperature, entropy, etc., and thus yield to standard thermodynamics.
Consider lots of 1D Oceans: one per watermass.

Wind (Ekman) flushing gives upper limit to $\lambda^{-1}$ timescale.
But what if heating is uneven (but steady state)?

Incomplete Redistribution!—A Nonequilibrium Steady-State
How does Energy Flow?:

Energy may flow by Conduction, Radiation, and Convection of Sensible and Latent Heat (vapor & ice transport).

**Convection:** transfer of energy by fluid motion when heated from below

**Conduction:** transfer of energy by direct contact between molecules (not fluid motion)

**Radiation:** transfer of energy by electromagnetic waves, or by transfer through other force fields
If Connections Occur Between Regions—Probability Currents Can Arise.

This is the root of most stochastic model predictability beyond persistence.

KOLMOGOROV

Mechanical Energy Budget
and
Nonequilibrium Mechanisms
Atmospheric Redistribution/Heat Engine might be like this:

Halley’s Idea, essentially

Except, the planet is rotating! (Hadley’s idea)
With the Coriolis Force, the winds are more zonal... and considerably less efficient.
How is Mechanical Energy created?

Carnot Cycle with $342 \text{ W/m}^2$? No, but simplified (dry, no continents) atmospheres are proportionally so.

To a lesser degree, there is also energy from tides and radioactive decay, and residual energy from planetary accretion.
Weather, Atmosphere

Fast
Ocean, Climate
Slow

3.4m of ocean water has same heat capacity as the WHOLE atmosphere
Weather, Atmosphere

Fast

Ocean, Climate

Slow

3.4m of ocean water has same heat capacity as the WHOLE atmosphere

ECCO Movie: Chris Henze, NASA Ames

tau / qflux / theta200m / kppMLD

Jan 1  00:30  2001
So, if both ocean & atmosphere are turbulent...

The classic statistical physics prob. is fully-developed, homogenous, isotropic turbulence.

Richardson, Kolmogorov, Oboukhov, Monin, Yaglom, Kraichnan, Charney, Mandelbrot, Frisch, etc.

The key idealization involves flows that are much larger than the damping scale and much smaller than the forcing scale—an inertial range.

The challenge in applying this approach in the earth system is that new parameters (f, N) introduce other significant scales along the way.
1963: Smagorinsky Devises Viscosity Scaling, Energy Flow is Preserved, but order-1 gridscale Reynolds #: $Re^* = UL/\nu_*$.
Climate model resolution introduces a scale...
Can Atmospheric “turbulent mixing” do the meridional transport?

Fig. 1. TOA annualized ERBE zonal mean net radiation (W m$^{-2}$) for Feb 1985–Apr 1989.

Fig. 2. The required total heat transport from the TOA radiation RT is given along with the estimates of the total atmospheric transport AT from NCEP and ECMWF reanalyses (PW).

Trenberth & Caron 01
What’s Left is Ocean Transport

Not just mixing: different basins differ in direction and magnitude!

Fig. 5. Implied zonal annual mean ocean heat transports based upon the surface fluxes for Feb 1985–Apr 1989 for the total, Atlantic, Indian, and Pacific basins for NCEP and ECMWF atmospheric fields (PW). The 1 std err bars are indicated by the dashed curves.
Pot’l Temperature & Salinity of the Ocean

Seawater is fairly incompressible, pressure increases linearly with depth, and conversion from internal to mechanical is negligible.

Cooling & Heating at same pressure: Ocean is NOT a heat engine

Data from Gouretski & Kolterman 04
Mean wind stress (arrows) and zonal wind stress (color shading) (N/m²): (a) annual mean, (b) February, and (c) August, from the NCEP reanalysis 1968–1996 (Kalnay et al., 1996).

So, the ocean receives much of its mechanical energy from other more direct sources: winds and tides.
Another problem... Turbulence isn’t 3d Turbulence at the 10-100km scale

- The ocean is wide (10,000km)
- But not deep (4km)
  - Motions in upper 1km
- The layer of blue paint on a globe has roughly the right aspect ratio!
- Atmosphere is a little taller (30km), but eddies are bigger (1000km)
- Motions are largely 2d
In addition to energy, other invariants are conserved (Kraichnan 67; Charney 71).

Enstrophy or potential enstrophy result from isotropy/particle-relabelling symmetry (Salmon 88).

1996: Leith Devises Viscosity Scaling, 2D Enstrophy Flow is Preserved


Where does ocean energy go?
Spectrally speaking

Where does ocean energy go?
Statistically & geographically speaking

Fig. 9. Global energy extraction rates by dissipation, bottom drag, vertical friction in the boundary layer, and vertical friction below the boundary layer for each simulation. The solid line shows the observed global bottom drag energy extraction calculated by Wright et al. (2013), along with error bars (dotted lines). This figure uses a snapshot of the flow field. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
The Mesoscale

- Boundary Currents
- Eddies
- 100km, months
- Full Depth (4km)

Eddy Potential Energy: $13EJ$ vs. $20EJ$ in Mean Circulation

Eddy Kinetic Power: About equal to mean circ. $2-3TW$ (Wunsch & Ferrari, 2004)

Satellite altimetry view of mesoscale flows

AVISO: $\log_{10}(0.5 (u^2+v^2))$ on 19940101

Thanks to Michael Bramble's Lunch Bunch — A Mesoscale Eddy can be covered with 1-10 Rhode Islands.
Too Simple: What about directly modeling processes in climate models? Don’t we have big enough computers or won’t we soon?

Here are the collection of IPCC models...

If we can’t resolve a process, we need to develop a parameterization or subgrid model of its effect.

200km x 600km x 700m domain

1000 Day Simulation
What about modeling important processes in climate models? Don’t we have big enough computers? or won’t we soon?

Here are the collection of IPCC models...

If we can’t resolve a process, we need to develop a parameterization or subgrid model of its effect.

100m grid = 1 soccer field/grid
The Character of the Submesoscale

(Capet et al., 2008)

- Fronts
- Eddies
- $Ro=O(1)$
- $Ri=O(1)$
- near-surface ($H=100m$)
- 1–10km, days

Eddy processes often baroclinic instability

Parameterizations = BFK et al (08–11).


Global Ocean Climate is SENSITIVE to these Submesoscale Eddies! At least in parameterized form Implemented in IPCC AR5 & 6: NCAR, GFDL, Hadley, NEMO,…

Deep Mixed Layer Bias reduced

Climate Model Resolution: an issue for centuries to come!

Here are the collection of IPCC models...

If we can’t resolve a process, we need to develop a parameterization or subgrid model of its effect.
The Character of Langmuir Turbulence

- Near-surface
- $\text{Ro} \gg 1$
- $\text{Ri} < 1$: Nonhydro
- 1-100m (H=L)
- 10s to 1hr
- $w, u=O(10\text{cm/s})$
- Stokes drift
- Eqtns: Wave-Averaged
- Resolved routinely in 2170
Langmuir Scale

20km x 20km x 150m domain
10 Day Simulation

1km x 1km x 40m sub-domain
about 1 day shown

Colors=Temp.
Surfaces are Large w


Turbulence: what to do?

- Climate modelling requires that we truncate the model grid at coarse resolution (albeit improving slowly)

- Whatever resolution we can afford will leave some physics unresolved or partially-resolved, so we need subgrid closures!

- The vast & diverse scales of motion in the ocean suggest that we cannot use a one-size-fits-all approach, e.g., a turbulent cascade of 3d turbulence

- So, we have to invent new subgrid closures repeatedly, parameterizing processes important at each gridscale
Between Climate & Kolmogorov

Climate “Cells”, “Gyres” and “Modes”

“Modes”?=?“Fluctuations”?
Atmospheric Cells

Thermally direct, e.g., Hadley Cells, are heat engines. Thermally indirect are rectification of turbulence (storms).
Oceanic Gyres

Flow along pressure contours (due to Coriolis)

These wind-driven features dominate thermal transport

Figure 6: Pressure relative to atmospheric pressure just below the sea surface (5 meters depth) from the ECCO2 ocean data assimilating ocean model (Menemenlis et al. 2008, ecco2.org). Contour interval is 0.2 decibars.
Climate Variability “Modes”

The most famous is El Nino/Southern Oscillation: By most metrics, it is the largest mode of variability on the Earth after seasonal & diurnal cycles.
Effect of Climate Modes, e.g., Hu & Fedorov (2017)

\[
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\]
Observing & Prediction Challenges

“Cells”, “Gyres”, “Modes”, & “Weather”
What does a climate model—WITHOUT WARMING—look like in Ocean Heat Content Variability?

Doesn’t even include mesoscale eddies

From the >1000yr steady forcing CCSM3.5 runs of Stevenson et al. 2012

Sophisticated analysis to overcome Ship & Argo sampling problems—inaherent uncertainty, $O(0.2W/m^2)$, on interannual to decadal timescales in global average. $O(10W/m^2)$ without analysis.

Prediction of variability

Predictability of ENSO events limited to < 1yr

ENSO statistics more predictable?
Does ENSO variability change with climate?...
(>200 yr to detect)

Big GHG Change to ENSO impacts!

INDIRECT Proxy Reconstructions won't work!!!
Climate: What is important?

- To approximate absorption, reemission, and redistribution of the Sun's energy across the globe.
- Need atmospheric, biological, & geological chemistry (greenhouse gasses) & clouds for absorption & reemission.
- Need atmospheric & oceanic motions to redistribute.
- Important motions are structured (cells, gyres, modes) and turbulent (weather, eddies, storms).
- Oceans are the relevant energy reservoir.
- On longer timescales, changes to the lithosphere affect the cells, gyres, & modes.
Another reason to care about ocean warming—and to observe it (by subtraction): Sea Level Rise

\[
\text{Sea Level Rise} = \frac{(\text{Sea Level}) - (\text{Ocean Mass})}{\text{Density} \times \text{Area}} = \text{Thermosteric Expansion}
\]

IPCC AR5, 2013

[Graph showing changes in GMSL from 2005 to 2013 with different data sets for Total SSH (Altimetry), Ocean Mass (GRACE), Thermosteric (Argo), and GRACE + Argo.]

nesdis.noaa.gov

podaac.jpl.nasa.gov