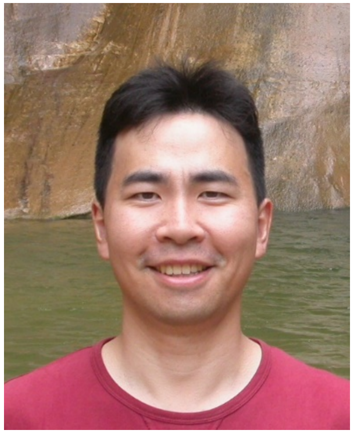
Extension of coastal oceanography to polar environmental sciences
연안해양 연구의 극지 해양환경 연구로의 확장

Sung Yong Kim

Environmental Fluid Mechanics Laboratory (EFML)
Department of Mechanical Engineering, KAIST

EFML @ KAIST

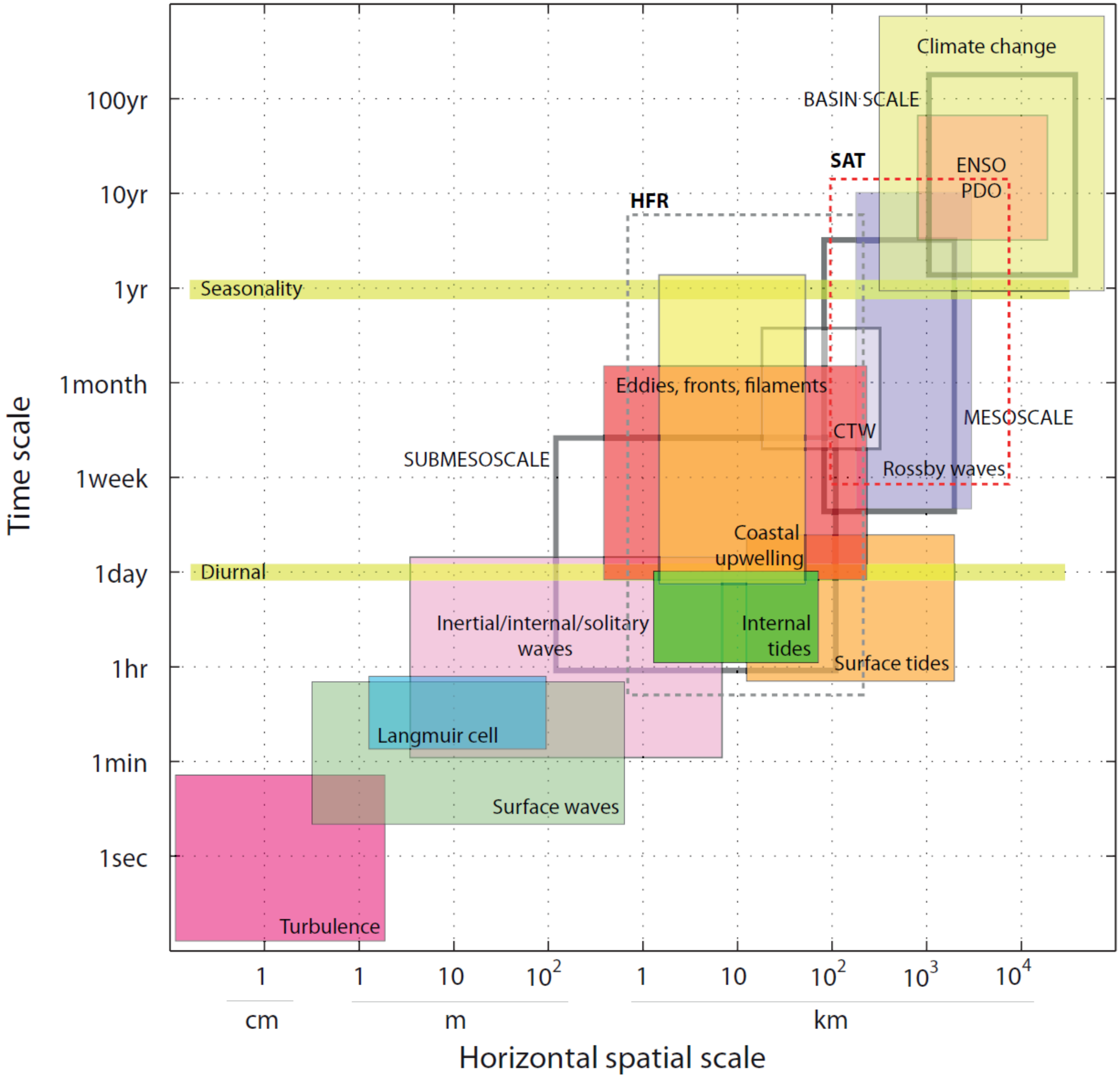


- Prof. Sung Yong Kim (김 성용)
- Education
  - Ph.D. in Oceanography, Scripps Institution of Oceanography (SIO)/UC San Diego (2009)
  - B.S. in Naval Architecture and Ocean Engineering, Seoul National University (1999)
- Research Interests
  - Air-sea and air-sea-land interactions
  - Mesoscale and submesoscale eddies
  - Environmental sensing using acoustic and electromagnetic sensors
  - Environmental big data analysis and mining
  - Coastal oceanography and environmental hydrodynamic models (ROMS, MITgcm, Delft3d)
- Lab: http://efml.kaist.ac.kr
- Email: syongkim@kaist.ac.kr

Classic ways to study ocean physics

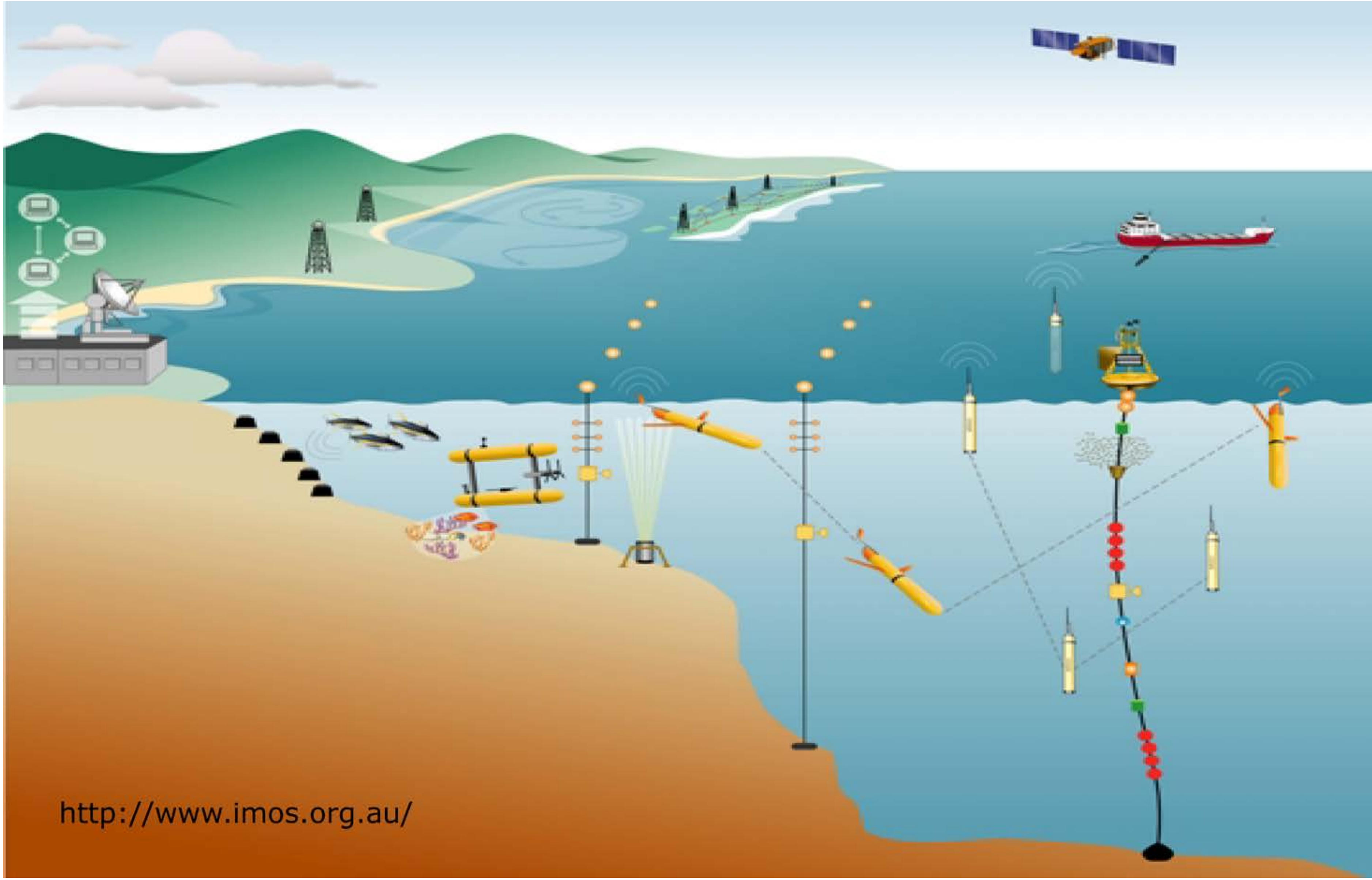
- Experimental and theoretical studies
- Numerical simulations
- Observations

"The chief source of ideas in oceanography comes, I think, from new observations... On the whole, when it comes to the phenomenology of the ocean, there are more discoveries than predictions. Most theories are about observations that have already been made." - Henry Stommel (NAS 1959; National Medal of Science)

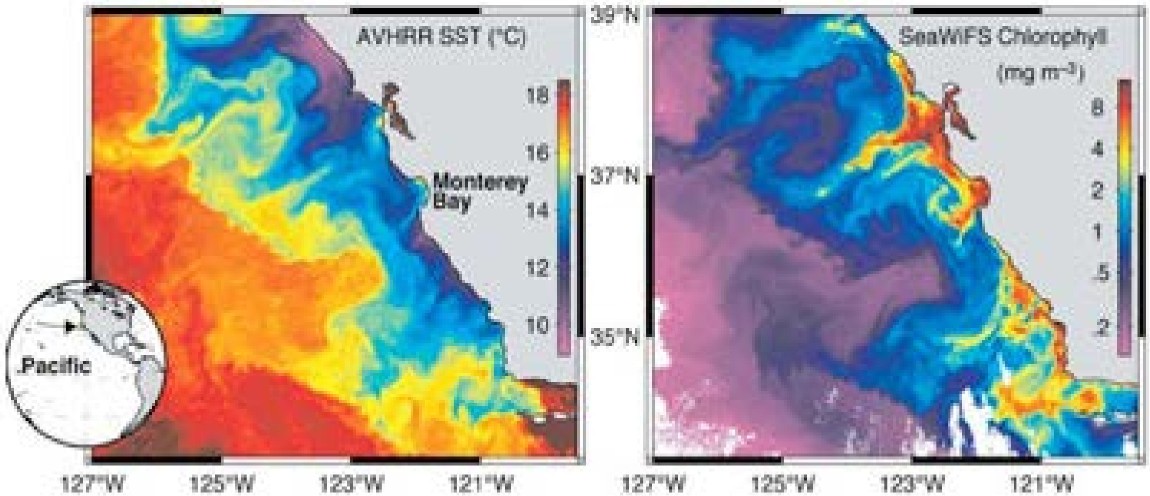


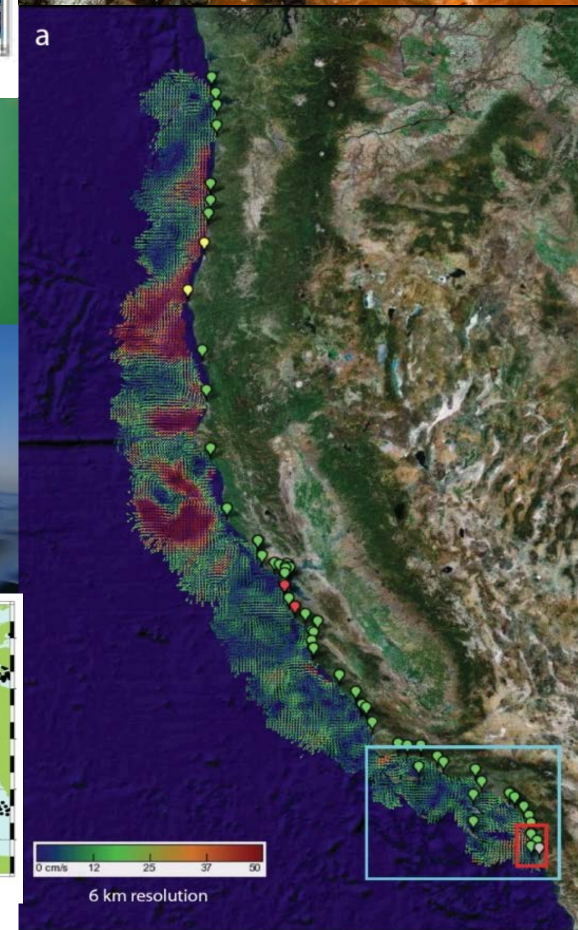
Climate change
BASIN SCALE
ENSO
PDO
SAT
HFR
Seasonality
Eddies, fronts, filaments
CTW
MESOSCALE
SUBMESOSCALE
Rossby waves
Coastal upwelling
Diurnal
Inertial/internal/solitary waves
Internal tides
Surface tides
Langmuir cell
Surface waves
Turbulence
100yr
10yr
1yr
1month
1week
1day
1hr
1min
1sec
Time scale
1
1
10
10^2
1
10
10^2
10^3
10^4
cm
m
km
Horizontal spatial scale

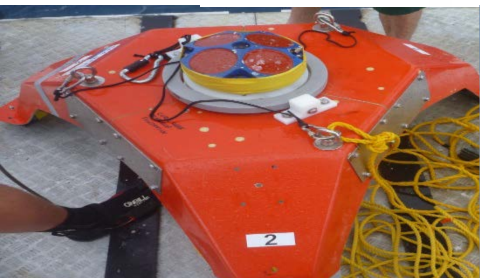
Coastal ocean observing system (COOS)

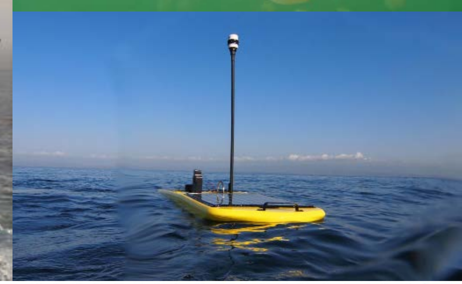


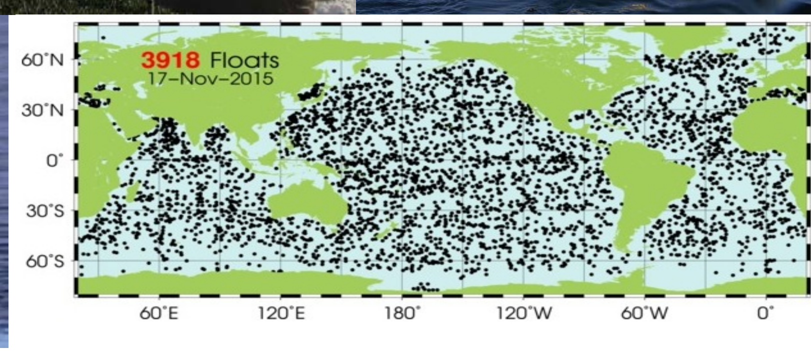
Ocean sensing and BIG data



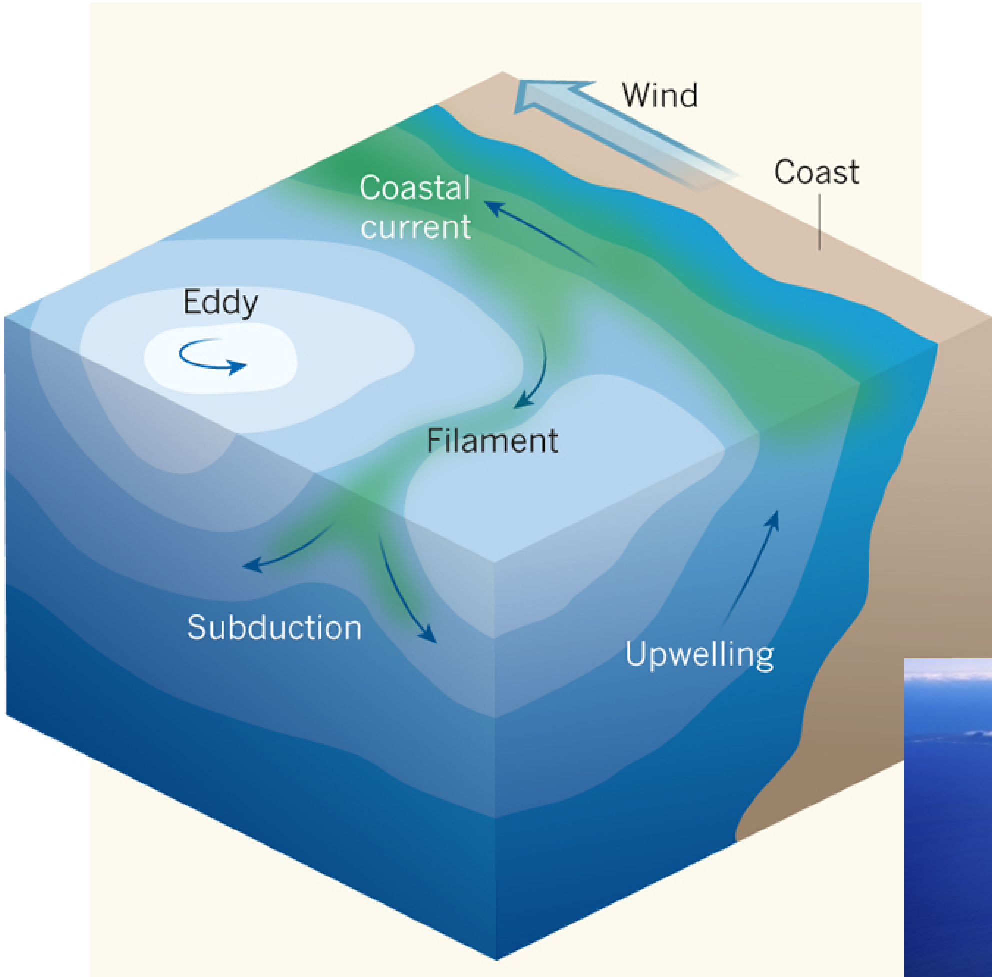








Boundary layer flows: At air-sea-land interfaces



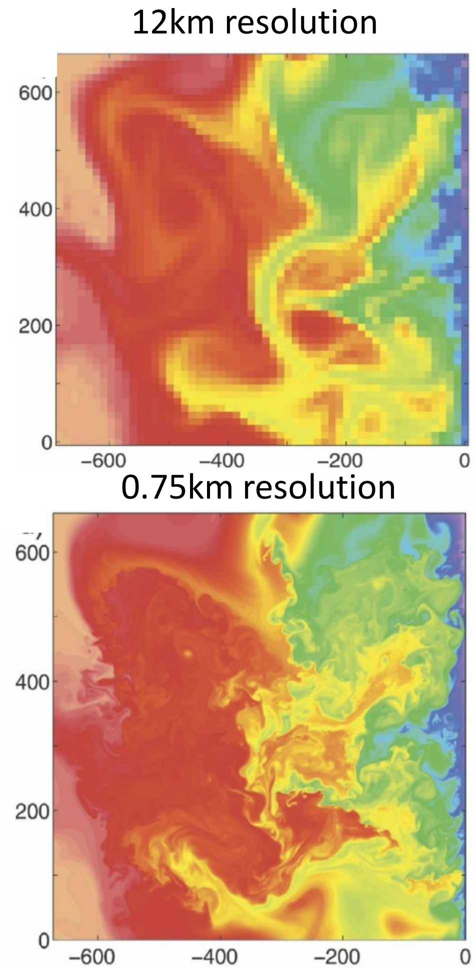
(A. Mahadevan, Nature 2014)

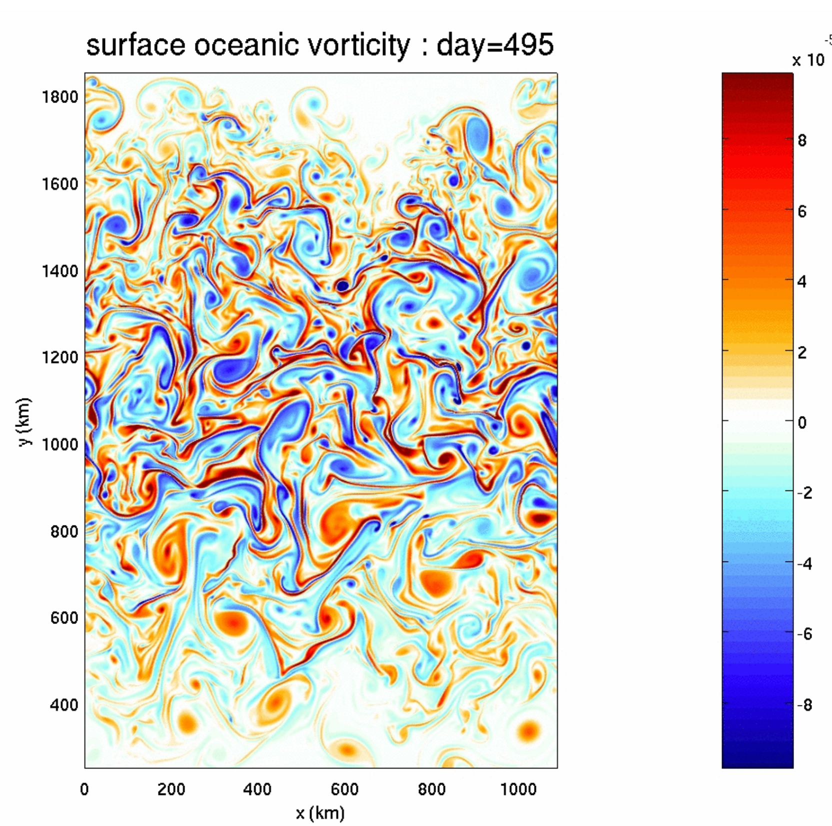
(An aerial image of red tide)

Submesoscale processes

- O(1) Rossby number [Ro = ζ/f]
- A horizontal scale smaller than the first baroclinic Rossby deformation radius; O(1-10) km
- Frequently observed as fronts, eddies, and filaments

Simulations on mesoscale and submesoscale grids (SST)

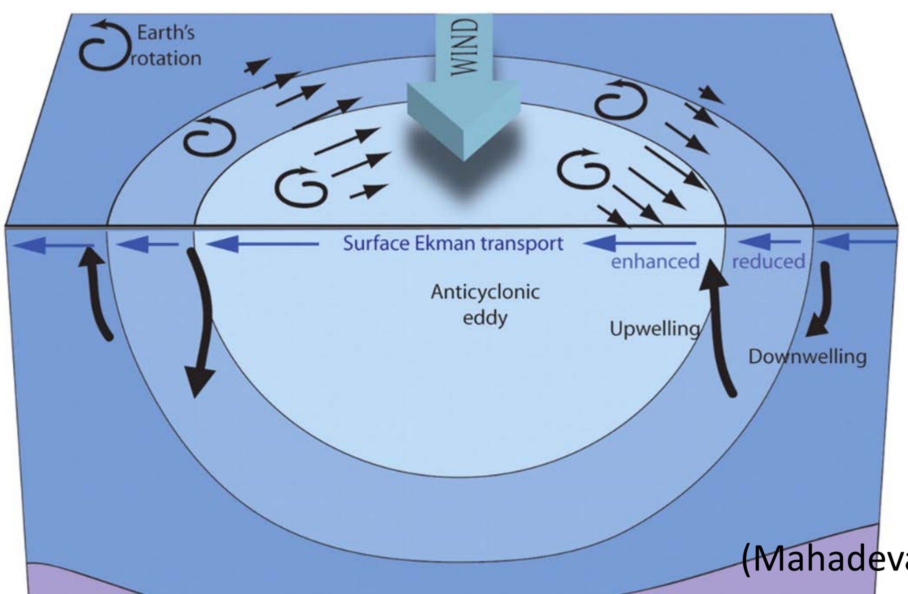




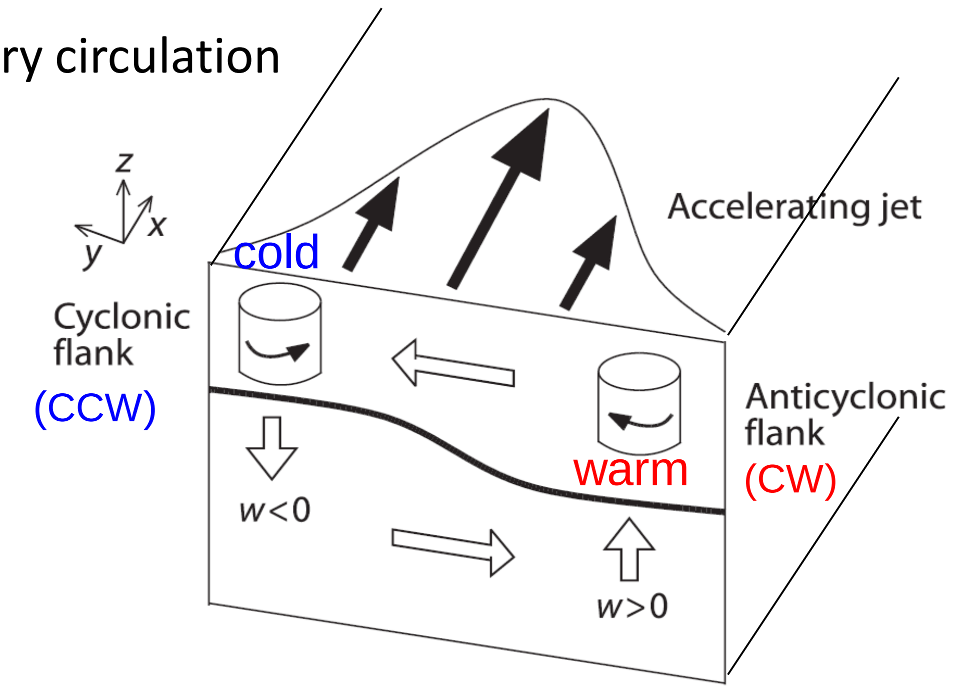
(Courtesy of X. Capet and P. Klein)

Submesoscale processes

- O(1) Rossby number [Ro = ζ/f]
- A horizontal scale smaller than the first baroclinic Rossby deformation radius; O(1-10) km
- Frequently observed as fronts, eddies, and filaments
- Contribute to the vertical transport of oceanic tracers, mass, and buoyancy and rectify the mixed-layer structure and upper-ocean stratification
  - e.g., vertical frontal scale secondary circulation

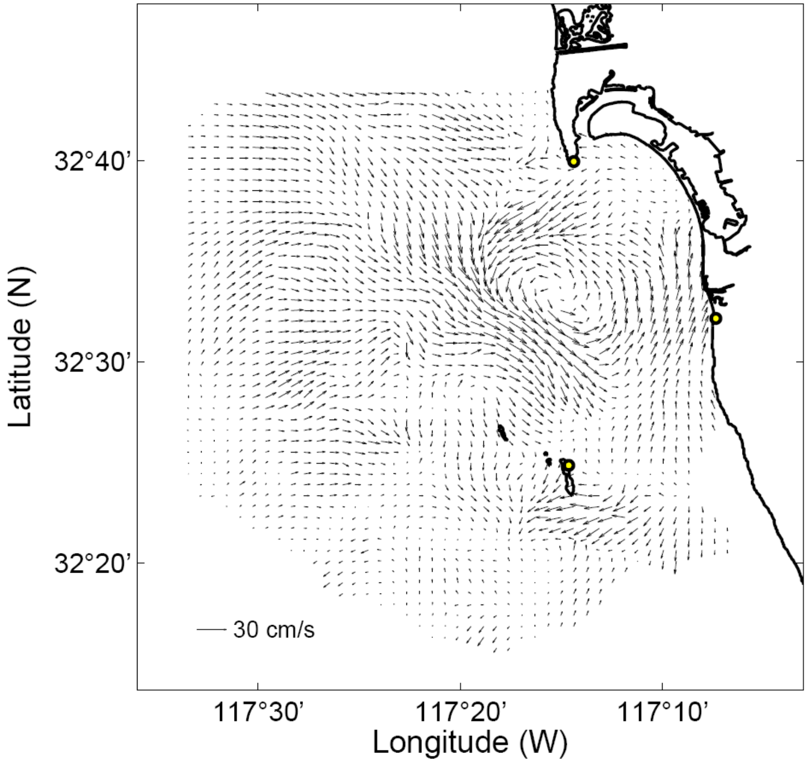


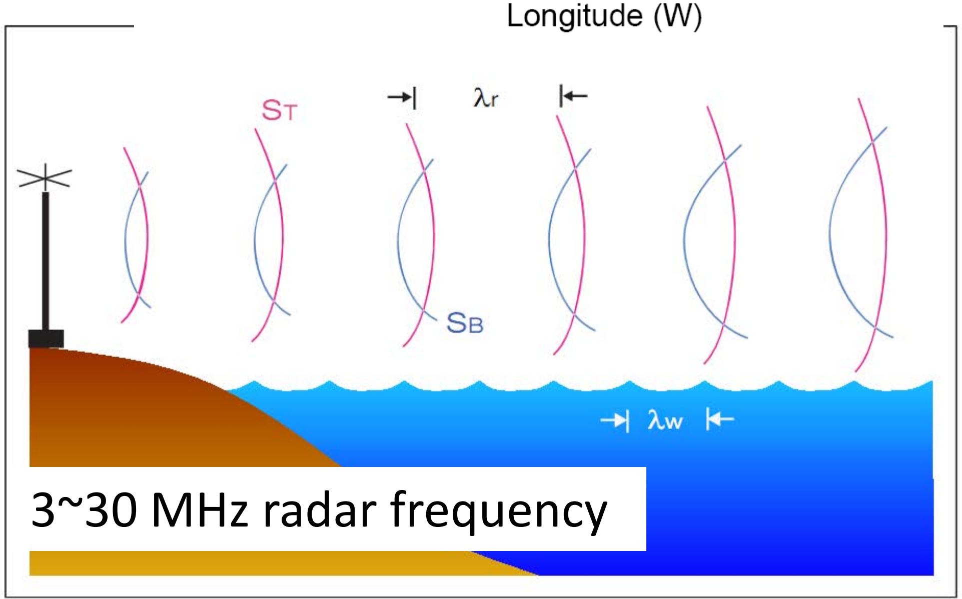
(Mahadevan et al, Science, 2008)



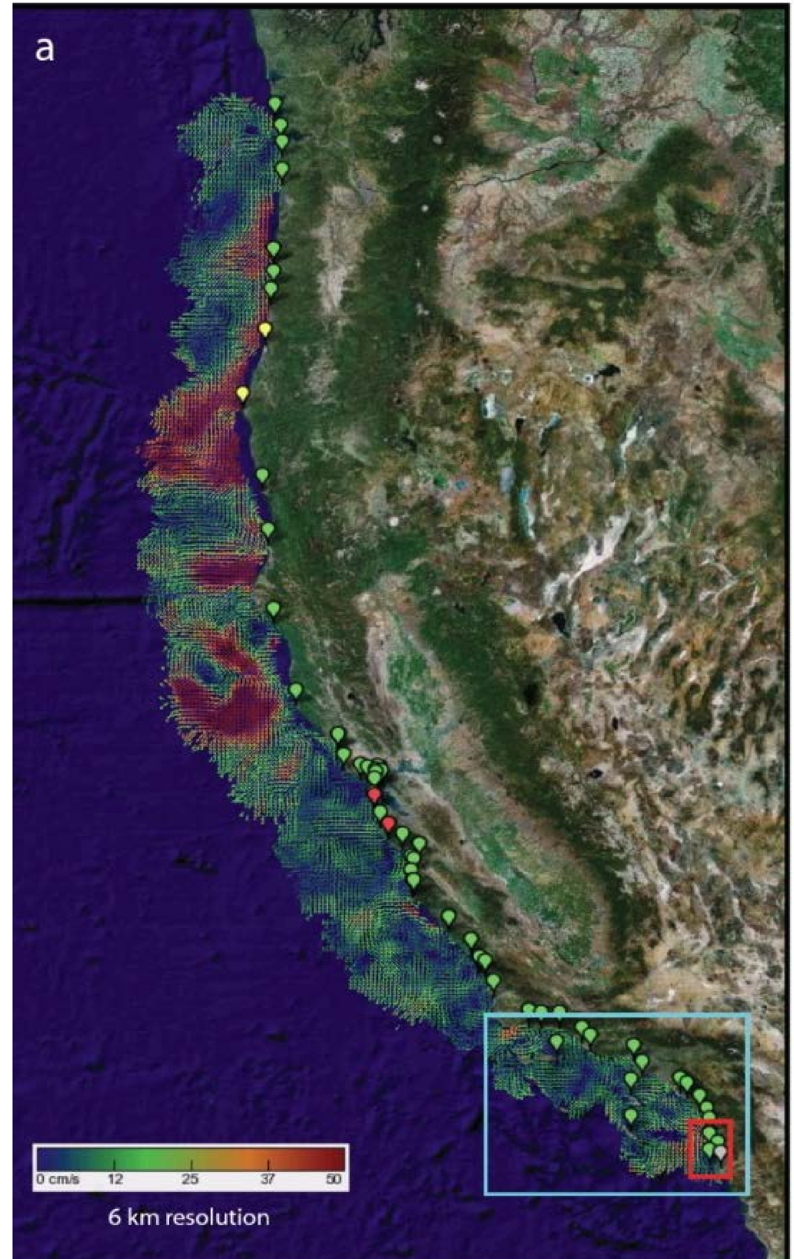
(Williams and Follows, 2003)

Remote sensing – High-frequency radars

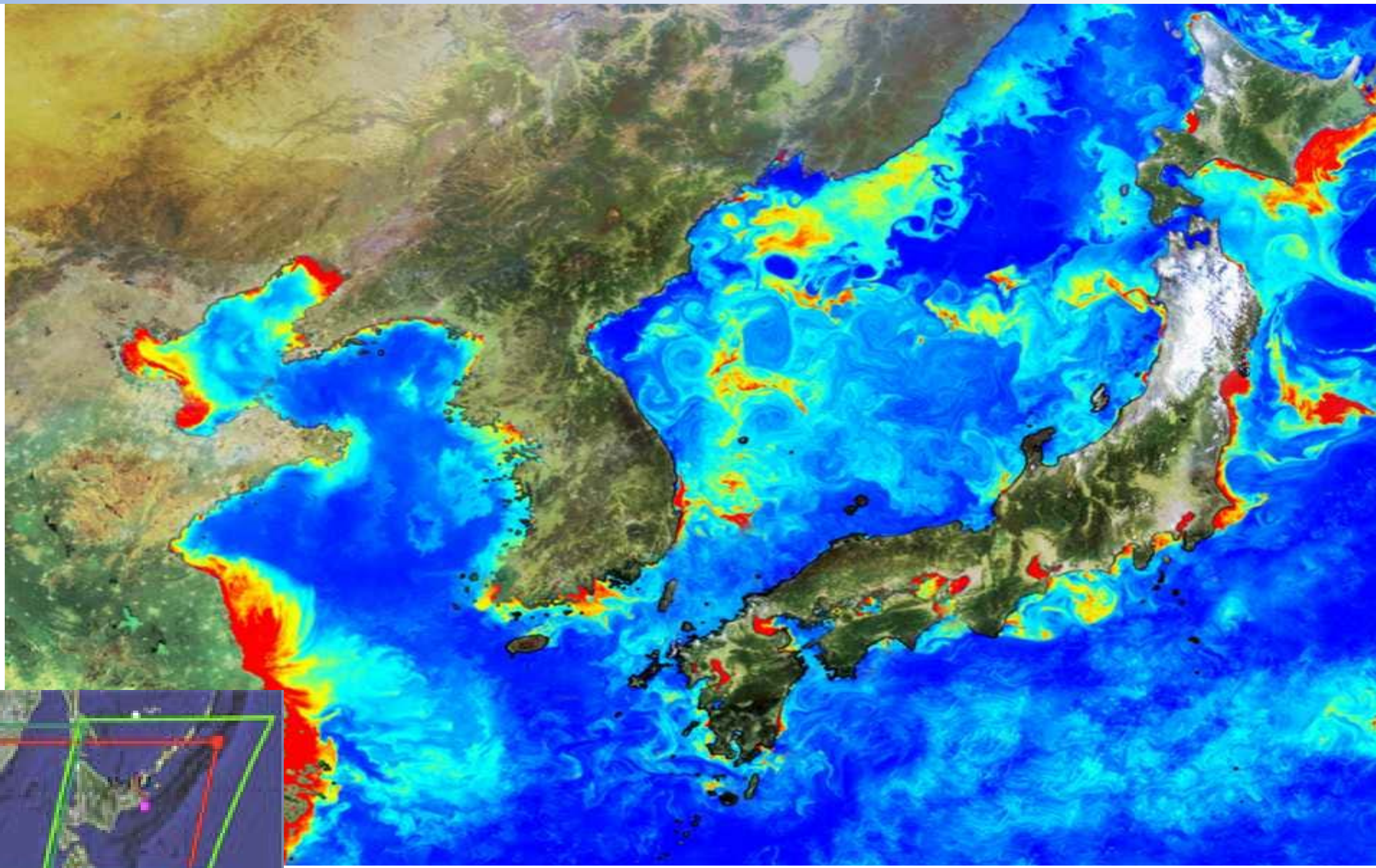


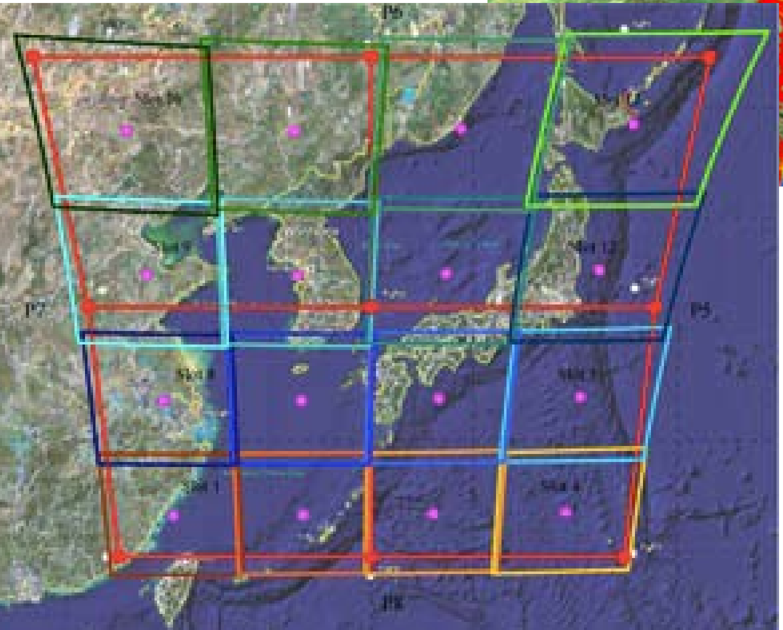


3~30 MHz radar frequency



Remote sensing – Geostationary Ocean Color Imagery

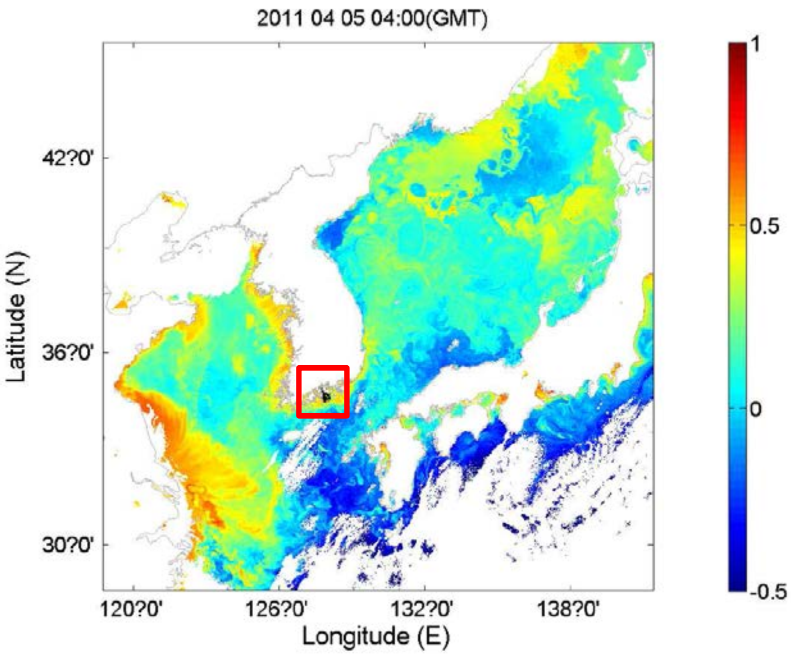


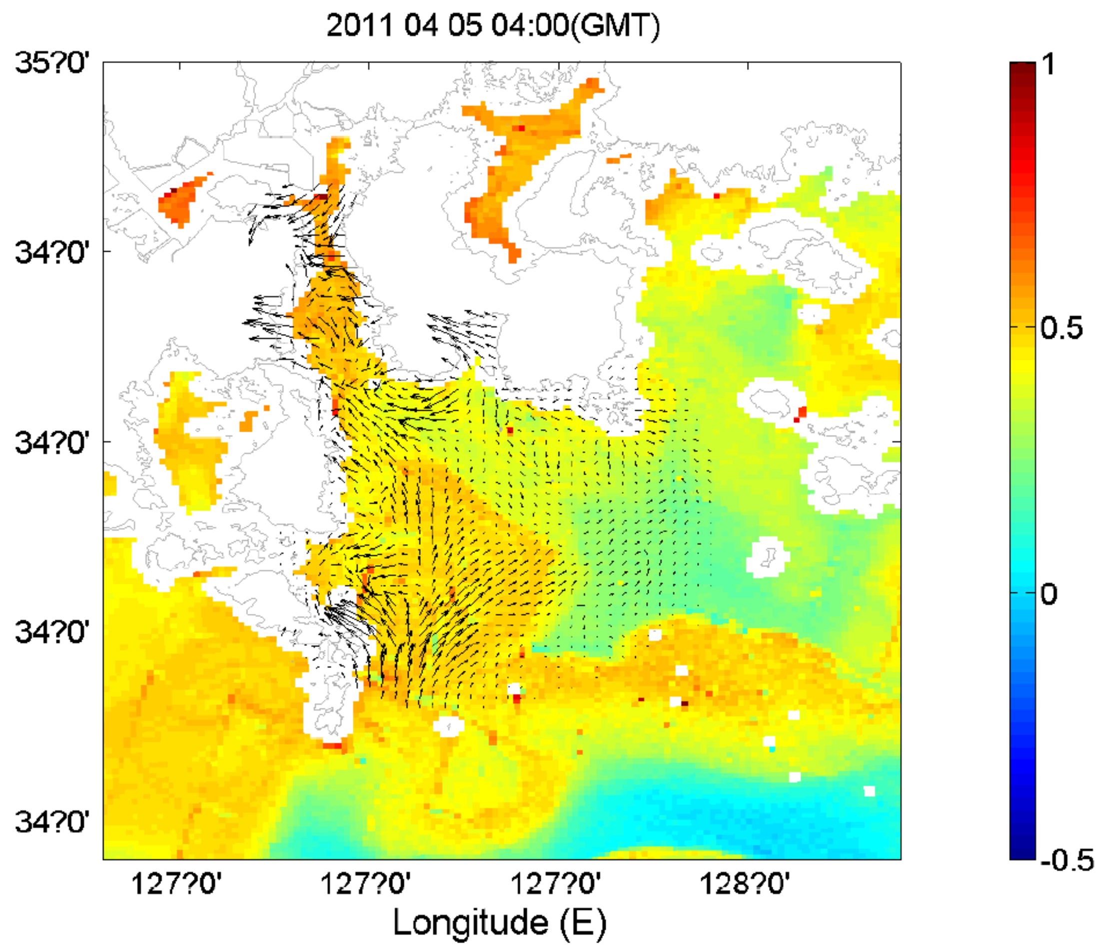


(0.5 km and hourly; GOCI @ KOSC)

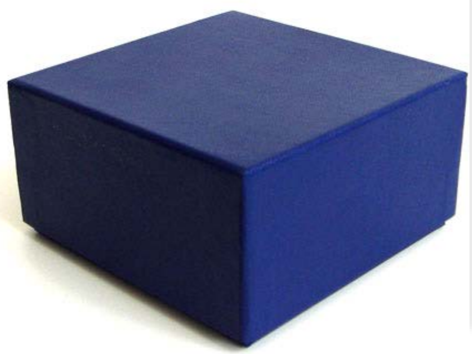
Submesoscale process studies

- have benefited from primarily idealized numerical models and theoretical frameworks because they require the use of high-resolution observations of less than one hour in time and O(1-10) km in space.





How can we identify a system?



sys·tem

/ˈsistəm/

noun

1. a set of connected things or parts forming a complex whole, in particular.
2. a set of principles or procedures according to which something is done; an organized scheme or method.
   "a multiparty system of government"
   synonyms: method, methodology, technique, process, procedure, approach, practice; More

How can we identify a system?

- Governing equations

$$F = ma = m\left(\frac{\Delta v}{\Delta t}\right)$$

$$\frac{\partial \vec{v}}{\partial t} + \vec{v} \cdot \nabla \vec{v} = -\frac{1}{\rho_0}\nabla p + \nu \nabla^2 \vec{v} + \frac{\rho}{\rho_0}\vec{g} - 2(\vec{\Omega} \times \vec{v})$$

The movement of fluid depends upon:

pressure

viscosity

gravity

rotation

How can we identify a system?

- Governing equations

$$F = ma = m\left(\frac{\Delta v}{\Delta t}\right)$$

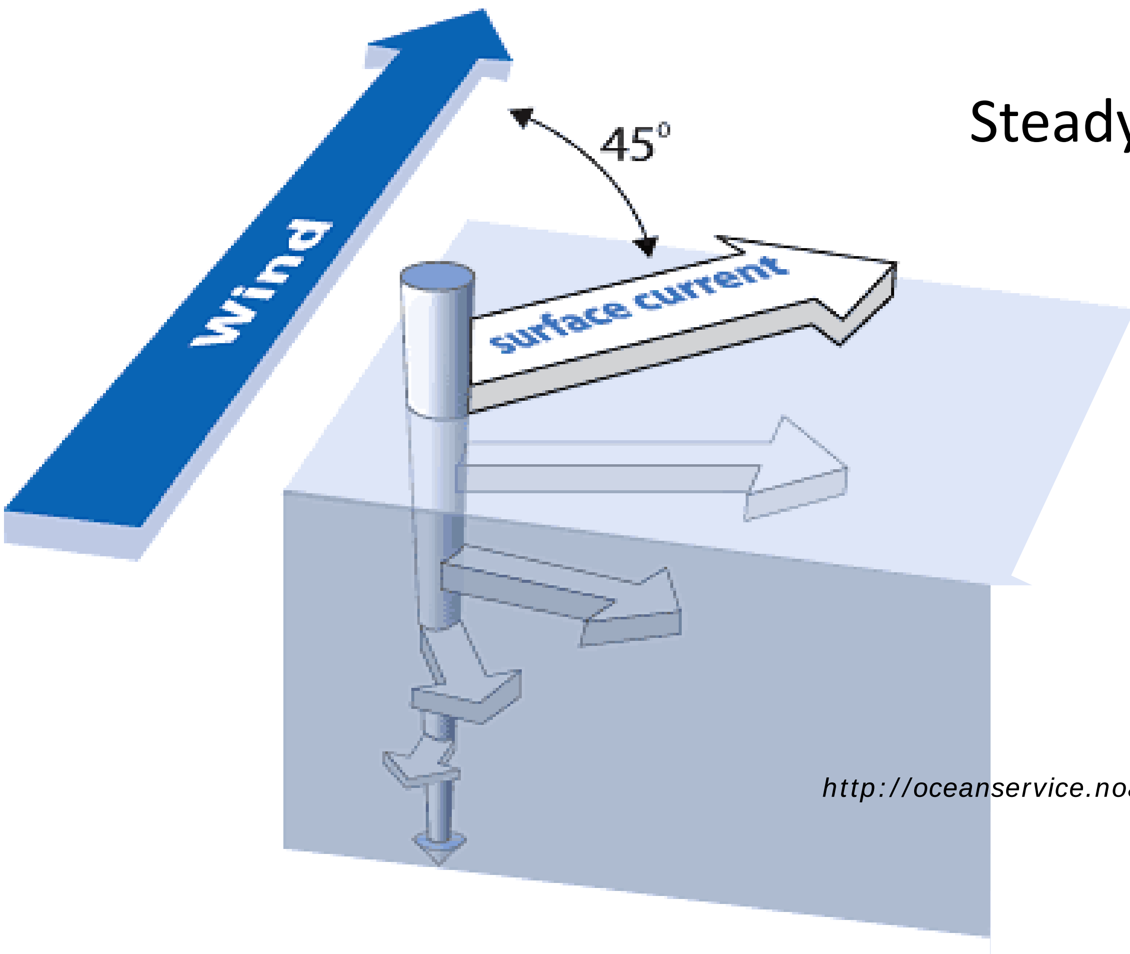
- A statistical relationship between inputs and outputs
  - Transfer function or response function

$$\hat{\mathbf{u}}(z,\omega) = \mathbf{H}(z,\omega)\hat{\boldsymbol{\tau}}(\omega) \qquad \mathbf{u}(z,t) = \int_{t'} \mathbf{G}(z,t-t')\boldsymbol{\tau}(t')\,\mathrm{d}t',$$

- Examples of a linear ‘ocean’ system using two approaches

Isotropic ocean responses

- "In the Northern Hemisphere, the wind-driven current at the very surface will be directed 45° to the right of the wind direction." (Phys. Oceanogr. 101; Ekman 1905)



Steady state wind!

http://oceanservice.noaa.gov/education/kits/currents/

Linearized (momentum) equations – isotropic case

$$\frac{\partial u}{\partial t} - f_c v = \frac{1}{\rho}\frac{1}{\partial z}\left(\mu\frac{\partial u}{\partial z}\right)$$
$$\frac{\partial v}{\partial t} + f_c u = \frac{1}{\rho}\frac{1}{\partial z}\left(\mu\frac{\partial v}{\partial z}\right)$$

$$\mathbf{u} = u + iv \qquad \boldsymbol{\tau} = \tau_x + i\tau_y$$

Then, Fourier transform

$$\lambda^2 \hat{\mathbf{u}}(z,\omega) = \frac{\partial^2 \hat{\mathbf{u}}(z,\omega)}{\partial z^2},$$

where $\lambda = \sqrt{i(\omega + f_c)/\nu}$,

ν = Depth independent eddy viscosity

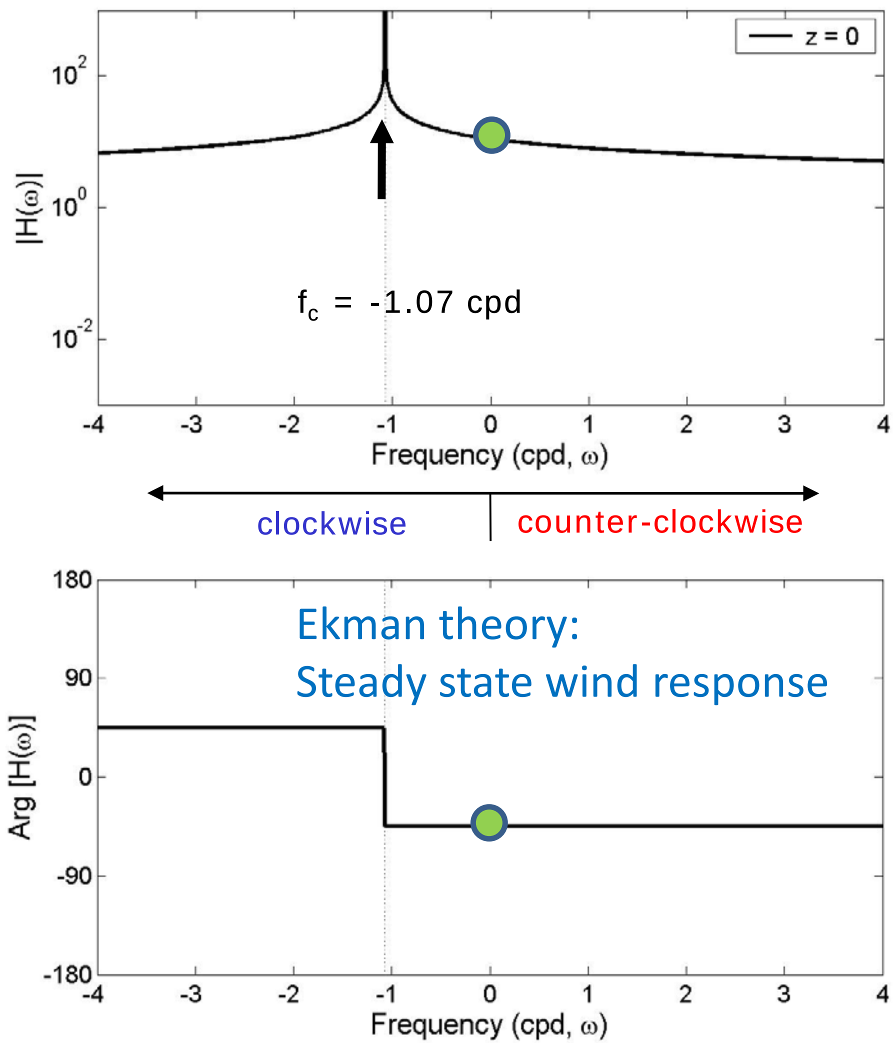
With BCs (finite or infinite depth)

$$\left.\frac{\partial \hat{\mathbf{u}}(z,\omega)}{\partial z}\right|_{z=0} = \frac{\hat{\boldsymbol{\tau}}(\omega)}{\rho\nu}. \qquad \hat{\mathbf{u}}(z,\omega)|_{z=-\infty} = 0,$$

$$\mathbf{H}(z,\omega) = \frac{\hat{\mathbf{u}}(z,\omega)}{\hat{\boldsymbol{\tau}}(\omega)} = \frac{e^{-\lambda z}}{\lambda\rho\nu},$$

(Gonella, DSR 1972)

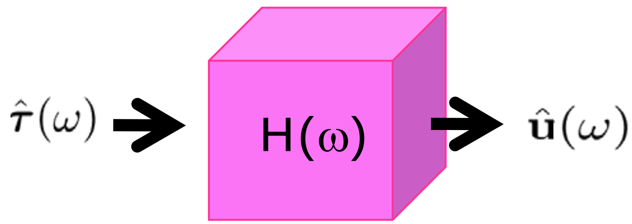
Wind-current relationship at 32°N

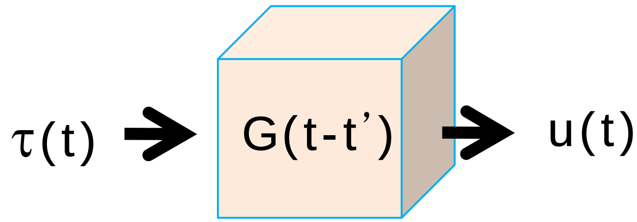


(Kim et al, JPO 2009)

Statistical linear relationship

- A statistical framework to represent the link between wind and currents in the frequency and time domains.
- Isotropic analyses and models.





Transfer function

$$\hat{\mathbf{u}}(z,\omega) = \mathbf{H}(z,\omega)\hat{\boldsymbol{\tau}}(\omega)$$

$$\mathbf{H}(z,\omega) = \left(\langle \hat{\mathbf{u}}(z,\omega)\,\hat{\boldsymbol{\tau}}^{\dagger}(\omega)\rangle\right)\left(\langle \hat{\boldsymbol{\tau}}(\omega)\,\hat{\boldsymbol{\tau}}^{\dagger}(\omega)\rangle + \mathbf{R_a}\right)^{-1}$$

$\mathbf{R_a}$: Regularization matrix

Response function

$$\mathbf{u}(z,t) = \int_{t'} \mathbf{G}(z,t-t')\boldsymbol{\tau}(t')\,\mathrm{d}t',$$

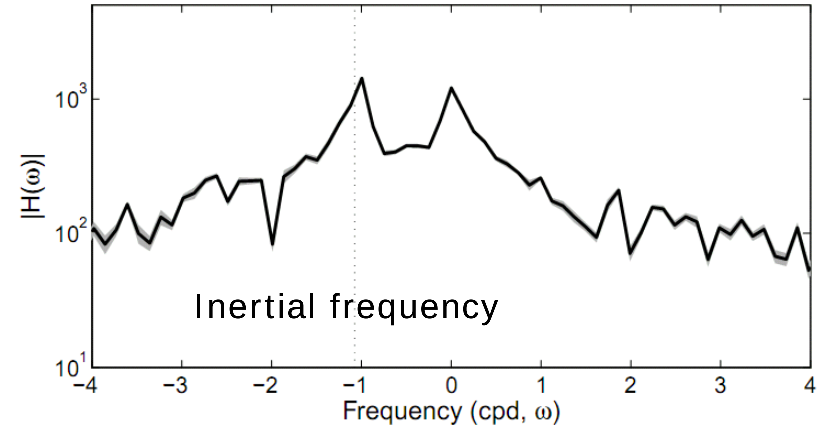
$$\mathbf{G}(z,t) = \left(\langle \mathbf{u}(z,t)\,\boldsymbol{\tau}_N^{\dagger}(t)\rangle\right)\left(\langle \boldsymbol{\tau}_N(t)\,\boldsymbol{\tau}_N^{\dagger}(t)\rangle + \mathbf{R_b}\right)^{-1}$$

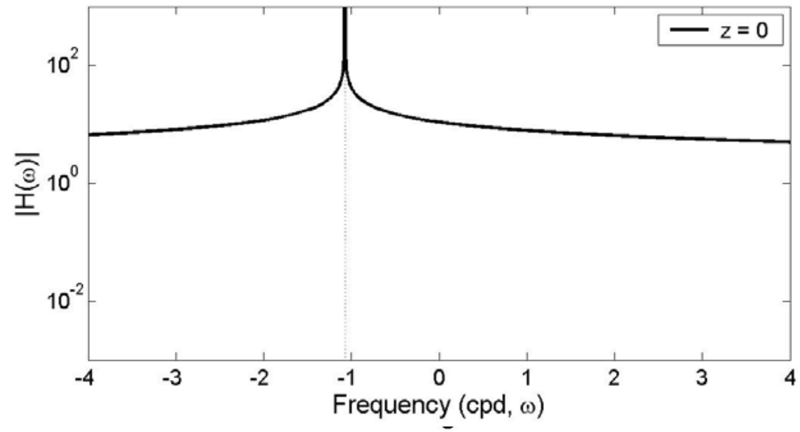
$\boldsymbol{\tau}_N$: *N*-hour advanced time lagged wind stress

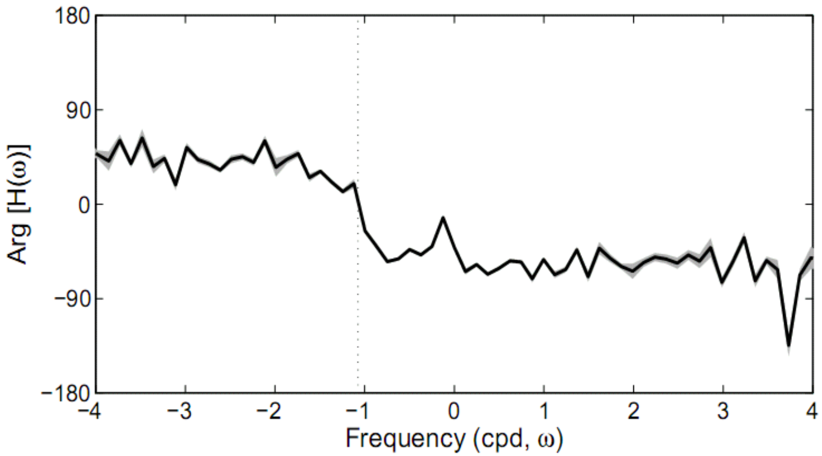
$\mathbf{R_b}$: Regularization matrix

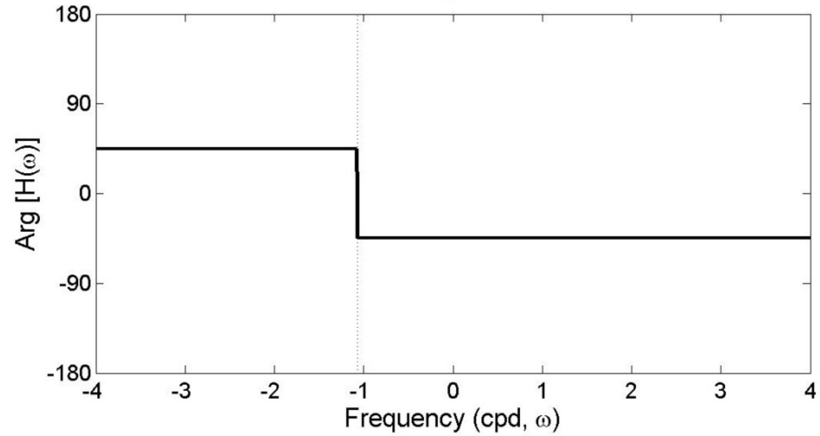
(Kim et al, JPO 2009)

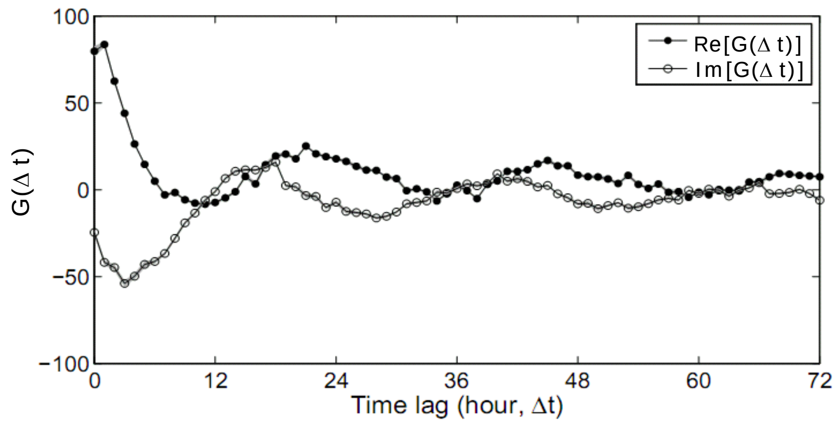
Wind transfer function and response function











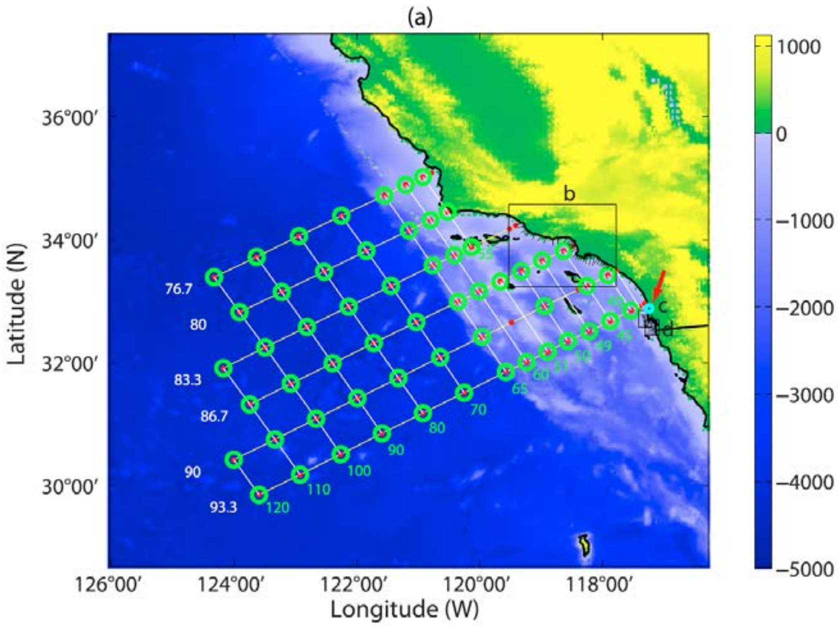
$$\mathbf{u}(z,t) = \int_{t'} \mathbf{G}(z, t-t')\boldsymbol{\tau}(t')\,\mathrm{d}t',$$

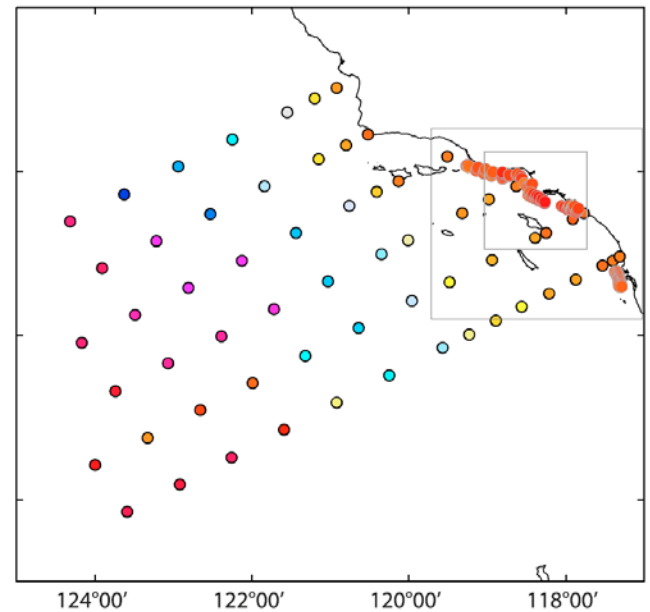
$$\boldsymbol{\tau}(t') = \delta(t'-\alpha)\ (\alpha > 0)$$

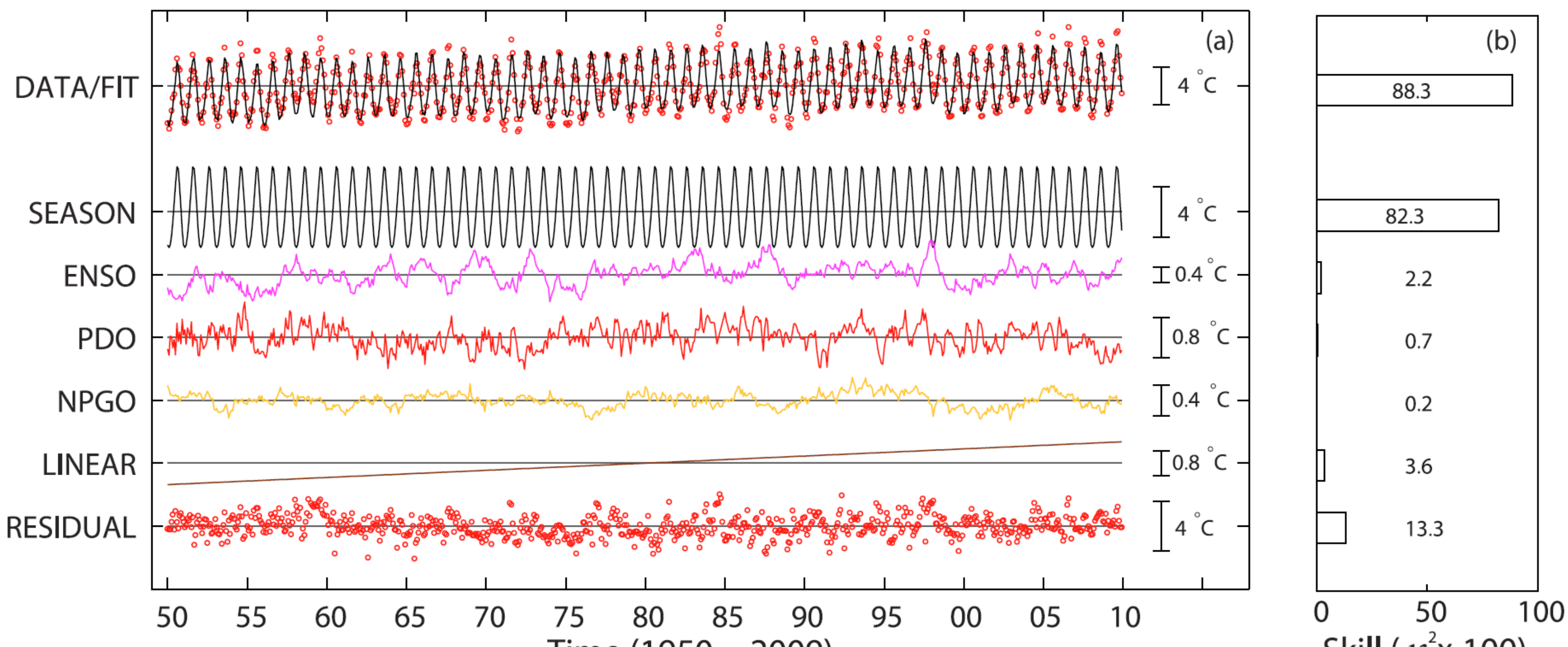
$$\mathbf{u}(z,t) = \mathbf{G}(z, t-\alpha)$$

(Kim et al, JPO 2009)

Long-term data analysis – CTD data w/ season and climate indices







Long-term data analysis – sea ice coverage w/ AOI