Understanding Mid- and High-Latitude Ocean and Climate Dynamics from Long-term Satellite Altimetry Measurements

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Satellite Altimetry vs. Mid- and High-Latitude Ocean Circulation

- Regional descriptions of meso-scale eddy variability and its seasonal-to-decadal modulations
- Eddy-mean flow interaction along major ocean currents (e.g. WBCs, ACC, STCCs, Agulhas Retroflection)
- Monitoring the surface transport of major ocean currents and the strength of gyres
- Eastern boundary current variability – local forcing vs. ENSO-related remote forcing
- Wind-driven high-frequency barotropic signals in subpolar ocean basins
- Time-dependent Sverdrup response to large-scale wind forcing in subpolar ocean basins
- Inter-gyre / inter-basin eddy flux transport
- Ocean’s roles in mid- and high-latitude climate variability
Ocean’s Roles in Mid- and High-Latitude Climate Variability

- Through manifestation of ENSO, ocean’s role in the coupled climate system has been well demonstrated in the tropics.
- Ocean’s impact upon the mid- and high-latitude climate system is less well established (especially from observations).
- Long-term satellite altimetry measurements can play an essential role in enhancing our understanding of the mid- and high-latitude coupled climate system.
Point 1

- Long-term SSH measurements from satellite altimeters provide a global data base that can lead to new physical insights into our understanding of mid- and high-latitude climate phenomena.
Pacific Decadal Oscillation

positive phase

negative phase

PDO Index

T/ P, ERS-1/ 2, Jason-1
NCEP Wind Stress Curl: EOF Mode 1
RMS Amplitude of Interannual SSH Signals (AVISO)

(white contours: mean SSH)
\[ \delta h = h_S - h_N \]

\[
\langle \delta h \rangle \text{ across KE axis averaged in } 142^\circ E - 180^\circ
\]
T/P Yearly SSHA Fields

1993

1994

1995

1996

1997

1998

1999

2000

2001
Dynamic Model

- Interested in the baroclinic upper ocean response due to basin-scale surface wind forcing.

- Under the longwave approximation (cf. local $L_R \approx 35$ km), large-scale SSH, $h$, changes are governed by the linear vorticity equation:

\[
\frac{\partial h}{\partial t} - c_R \frac{\partial h}{\partial x} = -\frac{g' \nabla \times \tau}{\rho_0 g f},
\]  

(1)

where $c_R$: speed of long baroclinic Rossby waves.

- Integrating Eq. (1) from the eastern boundary $x_e$ along the wave characteristic:

\[
h(x, t) = h\left(x_e, t + \frac{x - x_e}{c_R}\right) + \frac{g'}{\rho_0 g f c_R} \int_{x_e}^{x} \nabla \times \tau\left(x', t + \frac{x - x'}{c_R}\right) dx'.
\]

- To hindcast the $h(x, t)$ field:

  $c_R$: evaluated from the T/P data,
  $\nabla \times \tau$: monthly data from NCEP reanalysis,
  $h(x_e, t) = 0$: no eastern boundary forcing (see Fu and Qiu, 2002)
\[ T/P\text{-derived } C_R \text{ vs. Latitude} \]

![Graph showing T/P-derived \( C_R \) vs. Latitude](image)

2.3 cm/s

4.1 cm/s

Note: \( C_R = \beta g' R / f^2; \, f_N^2 / f_S^2 = 1.33 \)

(cf. Chelton and Schlax 1996)
Hindcast using NCEP wind stress data: 1948–2001
Wind stress curl spectrum averaged in region (32°–38°N, 160°–140°W)

NCEP reanalysis: 1948–2001
Magnitude of the wind-forced $\langle \delta h' \rangle$ across the Kuroshio Ext. jet is sensitive to the period of the wind forcing.

- Consider the following stochastic forcing problem:
  \[ \frac{\partial h'}{\partial t} - c_R \frac{\partial h'}{\partial x} = F(x)W(t), \]
  where the wind forcing has a "white" spectrum in time.
  For simplicity, let $F(x) = \delta(x - x_o)$ and $x_o = 0$.

- West of $x_o = 0$:
  \[ h'_w(x, t) = \frac{1}{c_R} \int_x^0 F(x') W \left( t + \frac{x - x'}{c_R} \right) dx' = \frac{1}{c_R} W \left( t + \frac{x}{c_R} \right). \]

- Averaging $h'$ over the jet length $L$ along latitude $A$:
  \[ \langle h'_A \rangle(t) = \frac{1}{L} \int_{-C-L/2}^{-C+L/2} \frac{1}{c_{RA}} W \left( t + \frac{x}{c_{RA}} \right) dx \]
  and taking the Fourier transform:
  \[ \langle \vec{h}'_A \rangle(\omega) = \frac{2}{\omega L} \hat{W}(\omega) \sin \left( \frac{\omega L}{2c_{RA}} \right) \exp \left( \frac{i\omega C}{c_{RA}} \right). \]

- Similarly, along latitude $B$:
  \[ \langle \vec{h}'_B \rangle(\omega) = \frac{2}{\omega L} \hat{W}(\omega) \sin \left( \frac{\omega L}{2c_{RB}} \right) \exp \left( \frac{i\omega C}{c_{RB}} \right). \]
Taking the SSH difference across the zonal jet, the power spectrum for $\langle \delta h' \rangle$ under $|\tilde{W}(\omega)|^2 = 1$ is:

$$
|\langle \delta h' \rangle(\omega)|^2 = \frac{T^2}{\pi^2 L^2} \left[ \sin^2 \left( \frac{\pi L}{T_{CR}} \right) + \sin^2 \left( \frac{\pi L}{T_{CR2}} \right) - 2\sin \left( \frac{\pi L}{T_{CR}} \right) \sin \left( \frac{\pi L}{T_{CR2}} \right) \cos \left( \frac{2\pi C}{T_{CR}} - \frac{2\pi C}{T_{CR2}} \right) \right].
$$

In the high-freq limit, the power spectrum has an upper bound:

$$
|\langle \delta h' \rangle(\omega)|^2 \leq \frac{4T^2}{\pi^2 L^2},
$$

which increases with the forcing period $T$.

In the low-freq limit, the power spectrum simplifies to:

$$
|\langle \delta h' \rangle(\omega)|^2 \sim \left( 1 + \frac{4\pi^2 C^2}{c_{RB}c_{RA}T^2} \right) \left( \frac{1}{c_{RB}} - \frac{1}{c_{RA}} \right)^2,
$$

which decreases with increasing $T$.

In between these two limits, an optimum $T$ exists for which $|\langle \delta h' \rangle|^2$ is a maximum. Using values appropriate for the N Pacific, we have:

$$
T_{optimum} \approx 10 \text{ yrs.}
$$

This “preferred” forcing period is not very sensitive to the detailed values of the chosen $C$, $L$, $A$ and $B$. 
Power spectra under “white” freq forcing

\[ F(x) = \delta(x-x_0) \] vs. \[ F(x) = \exp\left[-\left(x-x_0\right)^2/a^2\right] \]

Theory

NCEP wind hindcast
Forced SSHA Patterns
(contour interval: \(\pi\))

- T: short
- T: intermediate
- T: long
Vivier et al. (2002)

Kuroshio Extension Modulation

Basinwide Wind Stress Forcing
Summary of Point 1

- Given the relative positions between the atmos. forcing and the KE jet, the lagged oceanic response across the KE jet preferentially enhances the *decadal* timescale variability.

- This insight regarding the KE jet modulation stems from the detailed SSH information provided by the long-term satellite altimeter data.

- Continued SSH measurements will provide more new insights into our understanding of the mid- and high-latitude climate phenomena.
Point 2

- Long-term SSH measurements from satellite altimeters can be used to test dynamic hypotheses underlying an observed physical phenomenon.
ACWs: Is it a coupled phenomenon?

White and Peterson (1996)
White and Chen (2002)

phase speed = 6~8 cm/s
wave period = 4~5 yrs
wavenumber = 2
Dynamic Models for ACWs

- Jacobs and Mitchell (1996): GRL, 23, 2947-2950
- Qiu and Jin (1997): GRL, 24, 2585-2588
- Christoph et al. (1998): JClim, 11, 1659-1672
- White et al. (1998): JPO, 28, 2345-2361
- Cai et al. (1999): JClim, 12, 3087-3104
- Carril and Navarra (2001): GRL, 28, 4623-4626
- White and Chen (2002): JClim, 16, 2577-2596
- Venegas (2003): JClim, 16, 2509-2525
Jacobs and Mitchell (1996)
A Simple Ocean-Atmos. Model for the Southern Ocean

- ACC: wind-driven, 2-layer QG model

\[
\begin{align*}
\left( \frac{\partial}{\partial t} + U_1 \frac{\partial}{\partial x} \right) (\phi_1 - \phi_2) - (c_1 + U_1 - U_2) \frac{\partial \phi_1}{\partial x} &= -\frac{g'}{\rho_o f_o} \nabla \times \tau \\
\left( \frac{\partial}{\partial t} + U_2 \frac{\partial}{\partial x} \right) (\phi_1 - \phi_2) + (c_2 - U_1 + U_2) \frac{\partial \phi_2}{\partial x} &= 0,
\end{align*}
\]

mean zonal flows: \( U_i \)

\( c_i = \beta g' H_i / f_o^2 \)

anomalous wind stress: \( \tau / \rho_o = \epsilon (K \times \nabla p') / \rho_o f_o \)

- SST:

\[
\left( \frac{\partial}{\partial t} + U_1 \frac{\partial}{\partial x} \right) T' + \frac{1}{f_o} \frac{\partial \phi_1}{\partial x} \frac{\tau}{\rho_o f_o} \frac{\partial T_y}{\partial x} - \frac{\tau}{\rho_o f_o} \frac{\partial T_y}{\partial y} = Q',
\]

mean SST gradient across ACC: \( \bar{T}_y \)

anomalous heat flux: \( Q' = \kappa_a (T'_a - T') \)

- Atmospheric: heat balance in lower troposphere equilibrated with the oceanic state

\[
U_a \frac{\partial T'_a}{\partial x} + v'_a \frac{\partial T'_a}{\partial y} = -\frac{\kappa_a}{\kappa_o} Q',
\]

\( v'_a = (\partial p' / \partial x) / \rho_o f_o \)

equivalent barotropic: \( p' = \lambda T'_a \)
A Passive Ocean Scenario:

\[
\begin{align*}
\left( \frac{\partial}{\partial t} + U_1 \frac{\partial}{\partial x} \right) (\phi_1 - \phi_2) - (c_1 + U_1 - U_2) \frac{\partial \phi_1}{\partial x} &= -A \nabla^2 p' \\
\left( \frac{\partial}{\partial t} + U_2 \frac{\partial}{\partial x} \right) (\phi_1 - \phi_2) + (c_2 - U_1 + U_2) \frac{\partial \phi_2}{\partial x} &= 0 \\
\left( \frac{\partial}{\partial t} + U_1 \frac{\partial}{\partial x} \right) T' - D \frac{\partial \phi_1}{\partial x} - E \frac{\partial p'}{\partial y} &= \kappa_0 \left( \frac{p'}{\lambda} - T' \right)
\end{align*}
\]

where

\[
\begin{align*}
A &= g' \epsilon / \rho_a f_0^2 \\
D &= -T_y / f_0 \\
E &= -c T_y / \rho_a f_0^2 h
\end{align*}
\]
• Assume $p' \propto \exp (kx + ly - \omega t)$;

\[
\phi_i' = \frac{iA(k^2 + l^2)(c - U_1 + c_2)}{k(c_1 + c_2)(c - c_R)} p'
\]

\[
\tau' = \frac{1}{(\kappa_0 - i\omega + ikU_1)} \left[ \frac{\kappa_0}{\lambda} - i\lambda + \frac{DA(k^2 + l^2)(c - U_1 + c_2)}{(c_1 + c_2)(c - c_R)} \right] p'
\]

where

\[
c_R = \frac{H_1U_1 + H_2U_2}{H_1 + H_2} - \frac{\beta g' H_1 H_2}{f_0^2(H_1 + H_2)}
\]

is the Rossby wave speed of the 2-layer ACC system.

• For parameter values appropriate for the Southern Ocean and with $k = 2$, $2\pi/\omega = 4.5$ yrs.
A Coupled System Scenario:

\[
\begin{align*}
\left( \frac{\partial}{\partial t} + U_1 \frac{\partial}{\partial x} \right) (\phi_1 - \phi_2) - (c_1 + U_1 - U_2) \frac{\partial \phi_1}{\partial x} &= -A \nabla^2 p' \\
\left( \frac{\partial}{\partial t} + U_2 \frac{\partial}{\partial x} \right) (\phi_1 - \phi_2) + (c_2 - U_1 + U_2) \frac{\partial \phi_2}{\partial x} &= 0 \\
\left( \frac{\partial}{\partial t} + U_1 \frac{\partial}{\partial x} \right) T' - D \frac{\partial \phi_1}{\partial x} - E \frac{\partial p'}{\partial y} &= \kappa_o \left( \frac{p'}{\lambda} - T' \right) \\
U_u^* \frac{\partial p'}{\partial x} &= -\frac{\kappa_o}{\kappa_o} \left( \frac{p'}{\lambda} - T' \right)
\end{align*}
\]

where \( U_a^* = U_a + \lambda \bar{T}_{ay} / \rho_o f_o \)
• Assuming $p' \propto \exp i(kx + ly - \omega t)$ leads to the dispersion relation:

$$(\omega - \omega_R)(\omega - \omega_S) + \frac{\kappa_a AD(k^2 + \ell^2)(\omega + k\ell_2 - kU_1)}{\kappa_0(kU_\ast - i\kappa_a)(c_1 + c_2)} = 0$$

• If $\kappa_a = 0$ (uncoupled system):

$$\omega_1 = \omega_R \equiv k \left[ \frac{H_1 U_1 + H_2 U_2}{H_1 + H_2} - \frac{\beta g' H_1 H_2}{f_0^2(H_1 + H_2)} \right]$$

$\Rightarrow$ neutral baroclinic Rossby mode in sheared ACC

$$\omega_2 = \omega_S \equiv kU_1 - i\kappa_0 \frac{\kappa_a(iE + \kappa_0/\lambda)}{\kappa_0(kU_\ast - i\kappa_a)}$$

$\Rightarrow$ decaying SST mode

• When $\kappa_a \neq 0$, the coupled Rossby mode is unstable for parameter values appropriate for the Southern Ocean and its overlying atmosphere.
- Parameter values appropriate for the Southern Ocean and atmosphere (based on WOA01, NCEP reanalysis data):

\[ f_o = -1.19 \times 10^{-4}\text{s}^{-1} \quad \pi/l = 10^2\text{lat.} \quad g' = 0.015\text{ m s}^{-2} \]
\[ \beta = 1.32 \times 10^{-11}\text{s}^{-1}\text{m}^{-1} \quad H_1 = 500\text{ m} \quad H_2 = 4500\text{ m} \]
\[ \bar{T}_y = 0.4^\circ\text{C}/^\circ\text{lat.} \quad \bar{T}_{aw} = 0.4^\circ\text{C}/^\circ\text{lat.} \quad h = 200\text{ m} \]
\[ U_1 = 0.12\text{ m s}^{-1} \quad U_2 = 0.08\text{ m s}^{-1} \quad U_a^* = 5.0\text{ m s}^{-1} \]
\[ \epsilon = 0.9 \times 10^{-5}\text{ m s}^{-1} \quad \kappa_a^{-1} = 2\text{ yrs.} \quad \kappa_a^{-1} = 2\text{ weeks} \]
\[ \lambda = 400\text{ N m}^{-1}\text{ s}^{-1}\text{C}^{-1} \]
Coupled Mode (k=2)
Forced Mode \( (k=2) \)

Coupled Mode \( (k=2) \)
Joint CEOF Mode-1 Anomalies along the ACC Band

- $T'$
- $h'$
- $p'$
Observed Phases
Along 110W
(CEOF Mode-1)
Observed Phases
Along 110W
(CEOFT Mode-1)

Forced Mode

Coupled Mode
Summary of Point 2

- Altimetrically-derived SSH signals are an important dynamic variable and can be used to test physical hypotheses of an observed phenomenon.
- The decade-long SSH data indicates that the oceanic ACWs are better described as coupled signals rather than as passive signals forced by the atmosphere.
- As with other low-frequency climate signals, longer SSH measurements are desired to confirm the coupled nature of the ACWs.