Characterization of frontal air-sea interaction by spectral transfer functions

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\[ \hat{e}_u \cdot \vec{u}^{(1)} \]

\[ \hat{e}_u \times \vec{u}^{(1)} \]
Air-sea interaction at SST fronts
Schneider and Qiu, JAS, 2015

- Reduced gravity model capped by sharp inversion
- Forced by barotropic tropospheric pressure gradient
- Background state: SST constant

\[ h^{(0)} \text{ inversion, } \Delta \Theta, \text{ no flux} \]

\[ U_g \]

\[ u^{(0)}, v^{(0)} \text{ Ekman spiral} \]

\[ \Theta^{(0)} \text{ constant} \]

\[ \text{no ocean current, } T^{(0)} \text{ constant} \]
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- Reduced gravity model capped by sharp inversion
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\( h^{(0)} \) inversion, \( \Delta \Theta \), no flux

\( U_g \)

\( u^{(0)} \), \( v^{(0)} \) Ekman spiral
\( \Theta^{(0)} \) constant

no ocean current, \( T^{(0)} \) constant

- consider weak fronts \( T^{(0)} + \epsilon T^{(1)} \), linear response
Air-sea interaction at weak SST front
Schneider and Qiu, JAS, 2015

1st order (linear) response

\[ \bar{u}^{(0)} \cdot \nabla \Theta^{(1)} = \gamma \left( T^{(1)} - \Theta^{(1)} \right) + A_h \nabla^2 \Theta^{(1)} \]

\[ \bar{u}^{(0)} \cdot \nabla h^{(1)} + \nabla \cdot \bar{u}^{(1)} + \partial_s w^*(1) = 0 \]

\[ \bar{u}^{(0)} \cdot \nabla \bar{u}^{(1)} + w^*(1) \partial_s \bar{u}^{(0)} + \hat{e}_3 \times \bar{u}^{(1)} + \nabla h^{(1)} - \partial_s \begin{bmatrix} E^{(0)} \partial_s \bar{u}^{(1)} \end{bmatrix} = \bar{F} \]

\[ \bar{F} = \nabla \int_s^1 \Theta^{(1)} ds' + \partial_s \begin{bmatrix} \delta^{(1)} \frac{\partial E}{\partial \delta} \bigg|_{\delta^{(0)}} \partial_s \bar{u}^{(0)} \end{bmatrix} \]

\[ \delta^{(1)} = T^{(1)} - \Theta^{(1)} \]

pressure gradient mechanism
vertical mixing mechanism
air-sea temperature differences modulates vertical eddy viscosity
Transfer function

Find solution in wavenumber space

\[ A_k \Phi_{k}^{(1)} = T_k^{(1)} \]

- \( A_k \) \text{ dependent variables}
- \( \Phi_{k}^{(1)} \) \text{ spectral SST amplitudes}
- \( T_k^{(1)} \) \text{ Operator matrix}
Transfer function

Find solution in wavenumber space

\[
\mathbf{A}_{\vec{k}} \Phi_{\vec{k}}^{(1)} = \mathbf{T}_{\vec{k}}^{(1)}
\]

- $\mathbf{A}_{\vec{k}}$: Operator matrix
- $\Phi_{\vec{k}}^{(1)}$: spectral SST amplitudes
- $\mathbf{T}_{\vec{k}}^{(1)}$: dependent variables

\[
\Phi_{\vec{k}}^{(1)} = \mathbf{A}_{\vec{k}}^{-1} \mathbf{T}_{\vec{k}}^{(1)}
\]

Transfer or spectral response function

dependent on background wind speed, direction mixing formulation
Surface wind transfer function
linear model
Surface wind transfer function
linear model

Speed

Direction

$R=0.50, e_u \cdot u$

$R=0.50, e_u \times u$

a. Real

b. ImcG

$e_u \times k$

$e_u \cdot k$
Atmospheric model for the Earth Simulator
AFES v3

T239, L48 (approx. 59km grid spacing)
NOAA 1/4° SST (Reynolds et al. 2007)

1982-2000, daily averages
Southern Ocean, 0°-360°, 60°S-44°S
Kuroshio Extension, 125°E-180°, 30°N-46°N

January-March

Transfer function estimated from 8°x8° ‘tiles’ from AFES output

Ohfuchi et al., 2004: 10-km mesh mesoscale resolving simulations of the global atmosphere on the Earth Simulator: Preliminary outcomes of AFES (AGCM for the Earth Simulator). *J. Earth Simulator*, 1, 8-34.
Speed
Southern Ocean, JFM

linear model

Speed scale: Gravity wave speed/inversion strength factor of ~2
AFES linear model

Speed
Southern Ocean, JFM

Response function, $e_u u$, Agulhas.AFES

Speed scale: Gravity wave speed/inversion strength factor of $\sim 2$

linear model

AFES
Speed
Kuroshio Extension, JFM

Response function, $e_u u$, Kuroshio.X.AFES

- $u^{(w)} < 5 \text{ms}^{-1}$
- $5 < u^{(w)} < 7 \text{ms}^{-1}$
- $7 < u^{(w)} < 9 \text{ms}^{-1}$
- $u^{(w)} > 9 \text{ms}^{-1}$

$f/|f| e_u/k, \text{cyc}^{-1}$

$e_u/k, \text{cyc}^{-1}$

AFES

linear model

Speed scale: Gravity wave speed/inversion strength factor of $\sim 2$
Direction
Southern Ocean, JFM

linear model

Speed scale: Gravity wave speed/inversion strength factor of \( \sim 2 \)
Direction
Southern Ocean, JFM

Response function, $f/|f|$ e$_u$ x $u_*$, Agulhas.AFES

- $0^o < 5 \text{ms}^{-1}$
- $5 < 0^o < 7 \text{ms}^{-1}$
- $7 < 0^o < 9 \text{ms}^{-1}$
- $0^o > 9 \text{ms}^{-1}$

Speed scale: Gravity wave speed/inversion strength factor of $\sim 2$

linear model
Direction
Kuroshio Extension, JFM

Response function, $f / |f| e_x u_k$, KuroshioX.AFES

AFES

linear model

Speed scale: Gravity wave speed/inversion strength factor of ~2
Conclusions

• Spectral transfer functions of the SST induced atmospheric boundary layer response extend coupling coefficients to include scale dependence and spatial lags.

• Comparison of spectral transfer functions based on AFES compare favorably with the linear model in the Southern Ocean and the Kuroshio Extension. Difference may be due to the vertical mixing formulation.