The influence of mesoscale eddies on wintertime air-sea interaction in the Kuroshio Extension region

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Bombogenesis

March 25 0Z

March 25 12Z

March 26 0Z

March 26 12Z

Gulf Stream
Outline

• Motivation:
  – Dissertation from KESS field program
  – NCAR
    • Model Comparisons
    • SST smoothing experiments at NCAR

• Introduction to mesoscale eddies, meridional heat transport, and Bjerknes compensation

• Kuroshio Extension decadal variability

• Ocean and atmospheric response in a high-resolution fully-coupled climate simulation
Mesoscale Eddies

- Mesoscale (Synoptic) eddies
  - $O(100 \text{ km})$ and vary on days to months time scales
  - Weather systems of the ocean (Deformation scale processes)
  - Not resolved by $1^0$ climate models
- Important feedbacks on mean ocean circulation:
  - Stirring and mixing of water properties
  - Draw energy from the mean flow (Foundation for GM parameterization)
- Important feedbacks on overlying atmosphere
SSH Variance & WBCs

Longitude

Latitude

Kuroshio Extension

Gulf Stream

Agulhas

EAC

Southern Ocean
Mesoscale Eddies & Atmospheric Feedbacks: SST and Wind Stress

1° Ocean, 0.5° Atmosphere

0.1° Ocean, 0.25° Atmosphere

No Mesoscale Eddies

Correlation Coefficient

Bryan et al. 2010
Meridional Heat Transport

- Earth receives insolation from the sun:
  - Surplus of heat in the tropics
  - Deficit at high latitudes

- From the tropics:
  - WBCs in the ocean
  - Hadley cell and tropical cyclones

- Ocean hands over heat transport to the atmosphere in the midlatitudes

- How does the ocean do this?

From *Ocean Circulation and Climate: A 21st Perspective*
Eddy Heat Flux

\[ \rho_0 C_p \overline{vT} = \rho_0 \overline{CT} + \rho_0 C_p \overline{v'T'} \]

Mean \quad Eddy

\[ \overline{\text{\(\rho_0 C_p vT\)}} \approx \rho_0 C_p \overline{v'T'} \]

\[ \frac{1}{T} \int_0^T (\text{\(\rho_0 C_p vT\)}} \) dt \]
Bjerknes Compensation Theory

Compensation in Meridional Heat Transport

\[ \delta \int_0^L \int_{-h}^0 \rho_0 C_p^o (\bar{v}_o \bar{T}_o + \bar{v}_o' \bar{T}_o') \, dz \, dx = -\delta \int_0^L \int_0^H \rho_a C_p^a (\bar{v}_a \bar{T}_a + \bar{v}_a' \bar{T}_a') \, dz \, dx \]

\[ \delta H_{\text{OCEAN}} \quad \delta H_{\text{ATMOSPHERE}} \]

- Bjerknes (1964), Atlantic Air-Sea Interaction

- When change in TOA radiation is zero, a reduction in MHT by the ocean must be compensated by the atmosphere

- North Atlantic was favored as a region for this due to the MOC and decadal time scales linked to the Atlantic Multidecadal Oscillation, AMO

Srokosz et al. 2013, BAMS
Kuroshio Extension
Decadal Variability

• “Stable” years

• “Unstable” years

• Stable characteristics:
  – Strong transport (strong meridional SST gradient)
  – Weak small amplitude eddies
  – Small meridional eddy heat transport (Presumably)

• Unstable characteristics:
  – Weaker transport (weaker meridional SST gradient)
  – Strong high amplitude eddies
  – Large meridional eddy heat transport

Updated from Qiu and Chen 2005
Kuroshio Extension System Study (KESS)

• Observational field study from 2004-2006
• Captured a transition from stable to unstable state
• Meridional eddy heat transport 3X larger during the unstable state
Strongest Eddy Heat Fluxes From Formation of Rings

\[ \rho_0 C_p n \cdot u'T_{\text{div}} \]

![Graph showing heat fluxes over time](image)

![Maps showing different regions and periods](images)

Bishop 2013
Suppression of CCRs During Stable Regimes

- 16 CCRs formed within KESS region from late 1993-2007
- 3 formed during stable Regimes
  - 2 formed during elevated levels of EKE at transition
  - 1 formed mid 2002
  - No CCRs formed from mid 2002-December 2004
NCAR

1st Snow in October 2012
KESS/POP Energy Conversion

\[ BC = -\mathbf{u}'\mathbf{b}'^{div} \cdot \nabla \left( \frac{\mathbf{b}}{N^2} \right) \]

- Eddy heat fluxes are downgradient
- POP underestimates BC: 27% smaller along 11°C
- Kuroshio Extension takes a more northerly path in POP

Bishop and Bryan 2013
Meridional Eddy Heat Transport

- Peak heat transport:
  - KESS: 0.048 PW at 35.2N
  - POP: 0.055 PW at 35.5N
- POP ≈14% larger
- Latitudinal offset

\[ Q = \rho_0 C_p \int_0^L \int_{-H}^0 \overline{v'T'} \text{div} d\tau \]

Bishop and Bryan 2013
Atmospheric Response: Smoothed vs. Unsmoothed SST Fronts

- Climate simulation with CAM4: 0.5° atmosphere with 0.25° Reynolds SST boundary conditions.
- Unsmoothed vs. smoothed fronts produced up to 20-40% higher eddy heat and moisture fluxes.
- Sharp fronts felt through the free troposphere.

Small et al. 2013
Hypothesis

- Strongly meandering states have weaker fronts: “smoothed”
- Weakly meandering states have strong fronts: “unsmoothed”
Working Hypothesis

Is there a local Bjerknes Compensation?
High-Resolution Fully-Coupled CESM Simulation

Model

- Community Earth System Model:
  - $0.1^0$ Ocean (POP2)
  - $0.25^0$ Atmosphere (CAM5)

- Fully coupled (atmosphere-ocean)
  - 6 hourly

- 100 years

- Monthly archived data

- Advantages of model over observations:
  - Subsurface oceanic data
  - Long time series for statistical robustness

Movie courtesy of Tim Scheitlin (NCAR Visualization Lab)
SSH Variance Versus Observations

Fig. 19. Standard deviation of sea surface height (SSH) variability (in cm) from a) observations (AVISO), b) CESM-H and c) CESM-S. Note non-linear color scale. CESM-H data has been put on the AVISO grid.

Small et al., accepted at JAMES
Decadal Variability in CESM-H

- Path length between $141^\circ-153^\circ$E
  - Longer path length = more eddies
  - Shorter path length = less eddies
- Model exhibits variability similar to observations
Decadal Variability in Standard Climate Model

CESM-S: ~1° Typical Climate Simulation

CESM-H: ~0.1°
Pacific Decadal Oscillation (PDO)

http://jisao.washington.edu/pdo/
PDO & Aleutian Low

$$\frac{\partial h}{\partial t} - c_R \frac{\partial h}{\partial x} = - \frac{g' \text{curl}\tau}{\rho_o g f}$$
PDO & SSH Anomalies

- Phase of PDO drives SSH anomalies that propagate west from the central Pacific

- SSH anomalies $\rightarrow$ meridional shifts of jet
  - Positive SSHa shifts the jet North
  - Negative SSHa shifts the jet South

Bishop et al., in revision
Kuroshio Variability and PDO

- Phase of PDO leads jet latitude by ~3-4 years
- Seen in both observations and model
- Jet latitude precedes meander variability
  - Northerly jet has a more “stable” meander state
  - Southern jet has a more “unstable” meander state

Bishop et al., in revision
“Waviness” Index (KEI)

- **Index**: negative normalized path length
  - +ve “Stable”
  - -ve “Unstable”

- **Index**: JFM mean (blue), annual mean (green)

- Most years if JFM “stable” annual mean is “stable” too (68% chance)

- Composite threshold = 0.25 (1/4 standard deviation)

Bishop et al. in revision
Stable vs. Unstable SSH

Composite of SSH and EKE

- **Stable vs. Unstable:**
  - Tighter front (ΔSSH of 84 vs. 60 cm between 34°-36°N at 145°E)
  - SSH is higher (lower) to the south (north) – higher transport
  - Stronger Southern Recirculation Gyre

Bishop et al. in revision
Atmospheric Response: Storm Track

Regression JFM storm track onto KEI

- Storm track defined as meridional wind variance at 850 hPa
- Storm track is enhanced downstream of Japan
Atmospheric Response: Eddy Heat Flux

- **Vertically-Integrated Eddy Heat Flux**
  \[
  \frac{1}{g} \int_{p_0}^{p_s} (C_p \overline{\nu' T'} + L \overline{\nu' q'}) dp
  \]

- Meridional eddy heat fluxes (MEHFs) are enhanced during stable meandering states.

- MEHFs are enhanced geographically where storm track is enhanced.
Meridional Eddy Heat Transport (Atmosphere)

- MEHT was calculated relative to Jet Stream axis (maximum 850 hPa zonal mean wind, Ari Solomon personal communication)
- MEHT is enhanced by \( \sim 0.1 \) PW at its maximum during +ve KEI

Bishop et al. in revision
Meridional Eddy Heat Transport (Ocean)

- Stable states have the persistence of equatorward MEHT just south of the Kuroshio Extension
- Aoki et al. (2013) notes persistence of negative MEHT south of the Gulf Stream and Kuroshio Extension (only 5 years of OFES simulation)
- Attributed to southward migration of warm water cores from cold-core rings interacting with meanders
- Unstable state has a larger MEHT by 0.07±0.02 PW

Bishop et al. in revision
Equatorward Eddy Heat Flux

OFES Model
Kuroshio Extension

KESS Observations

Gulf Stream

Bishop et al. 2013

Aoki et al. 2013
“Local” Bjerknes Compensation?

- The atmosphere and ocean have a degree of compensation.
- Compensation is not coincident in space.
- Local compensation was not expected since the atmosphere could compensate for the ocean anywhere on the globe!
Schematic Summary
Conclusions & Future Work

• The dynamic state of the Kuroshio Extension plays an $O(1)$ role in jet stream variability and eddy heat transport.

• Fully-coupled simulation resembles observations with interannual to decadal variability in the Kuroshio Extension.

• The atmosphere and ocean eddy heat transport partially compensate as in a “local” Bjerknes Compensation in the North Pacific during winter months.

• Climate simulations need to include ocean mesoscales in order to better simulate atmospheric variability.
Thanks

Big Sur from R/V Point Sur: Picture Courtesy of Amanda Netburn (SIO)