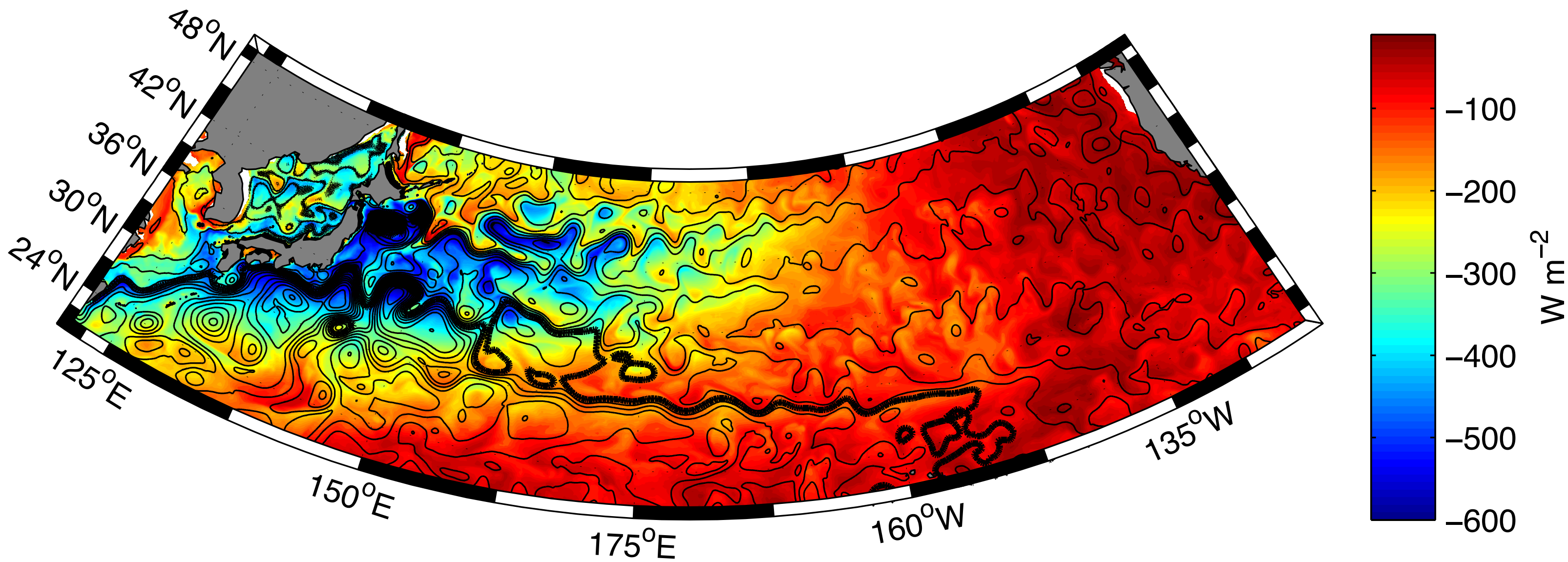
The influence of mesoscale eddies on wintertime air-sea interaction in the Kuroshio Extension region



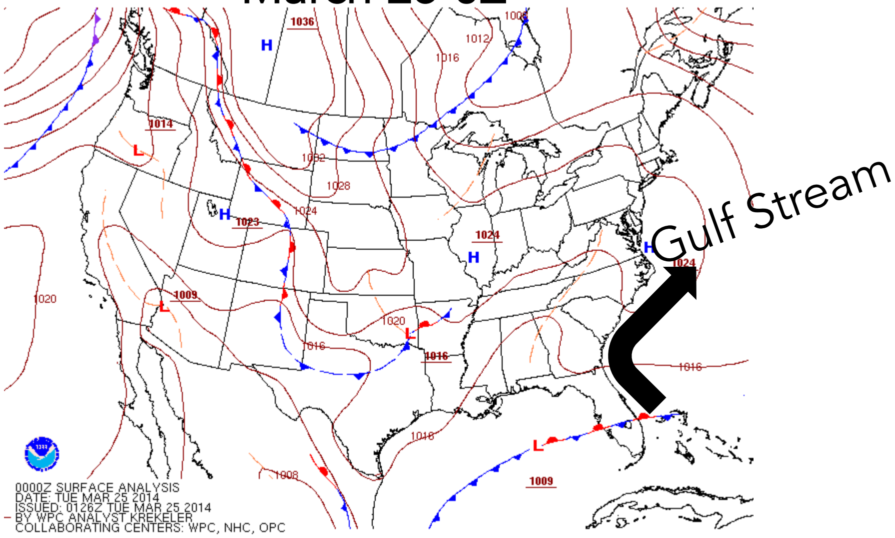
Stuart P. Bishop
California Institute of Technology
ASP Program at NCAR

Frank O. Bryan and Justin Small
National Center for Atmospheric Research

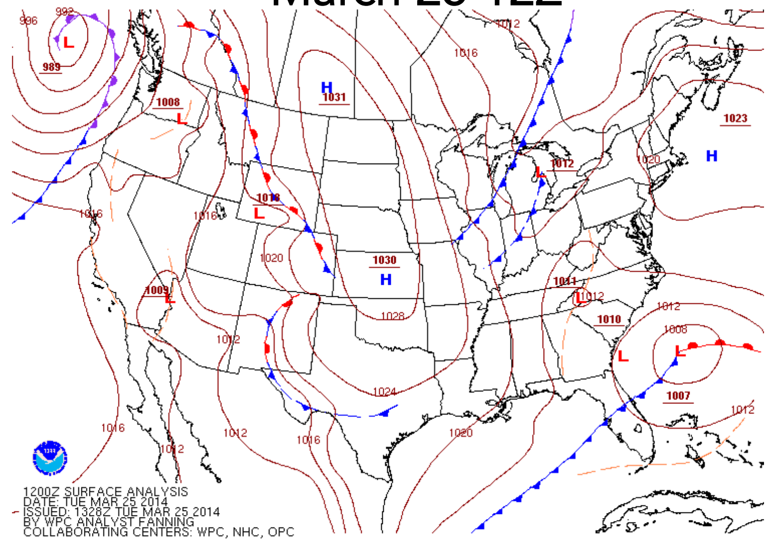
IPAM Workshop III: Geophysical and Astrophysical Turbulence
October 30, 2014

Bombogenesis

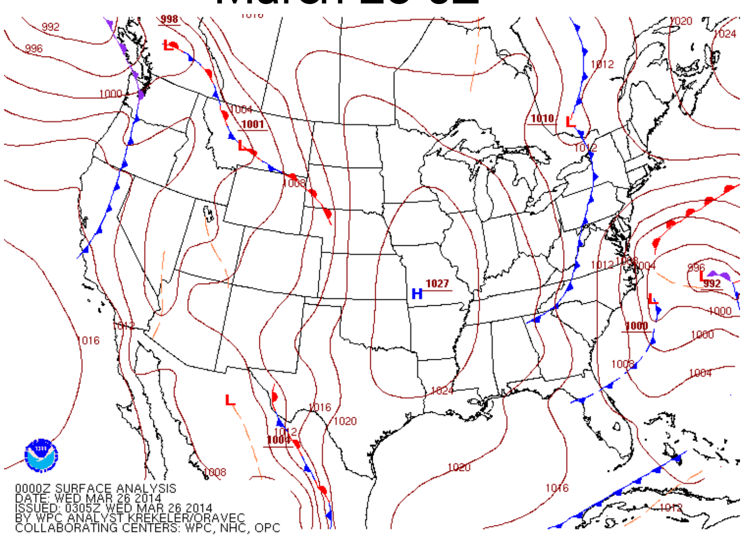
March 25 0Z



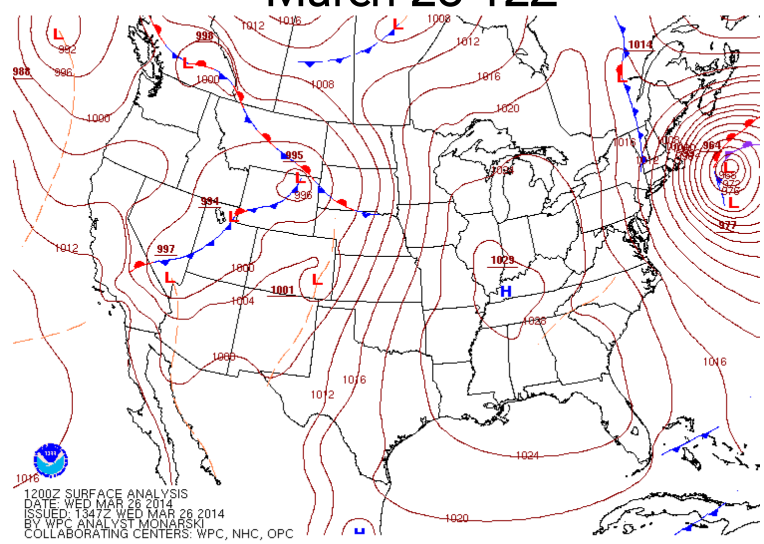
March 25 12Z



March 26 0Z



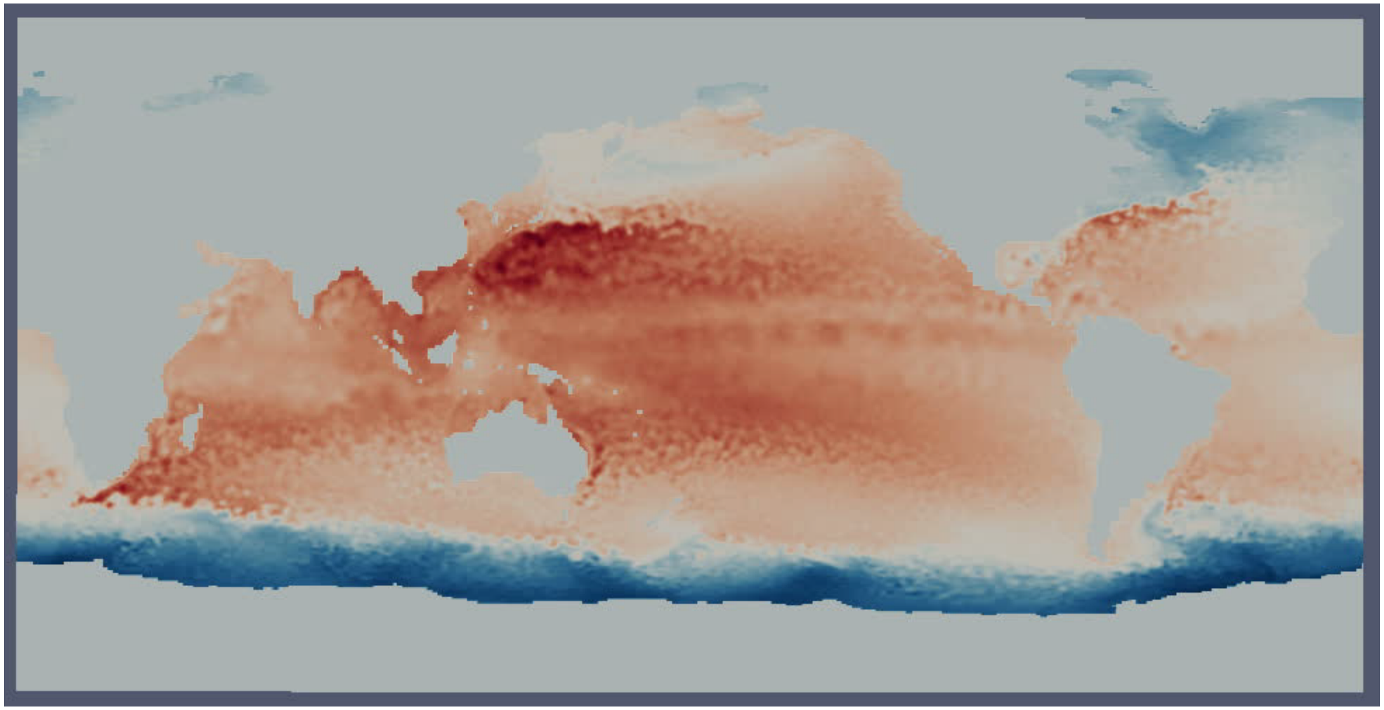
March 26 12Z



Outline

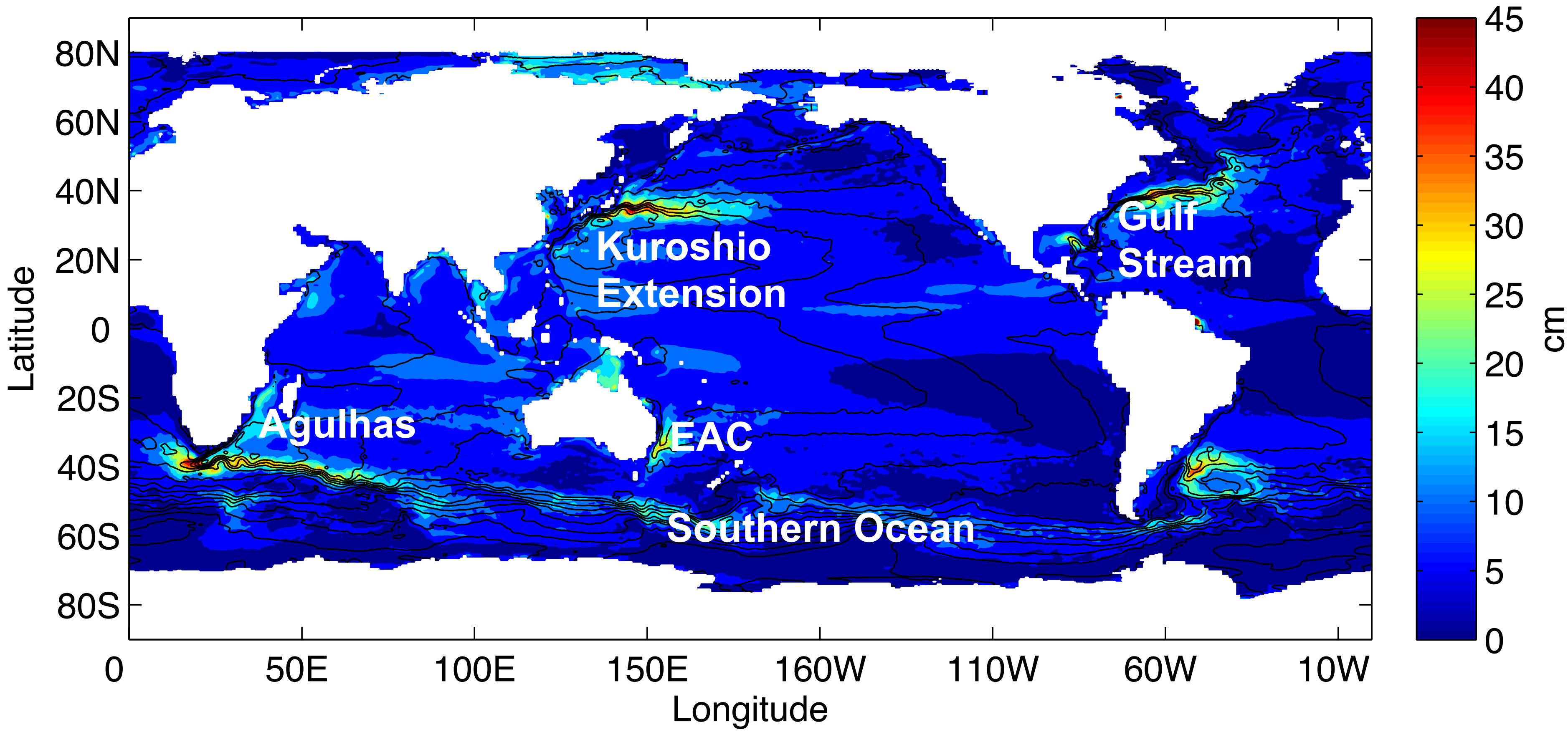
- Motivation:
  - Dissertation from KESS field program
  - NCAR
    - Model Comparisons
    - SST smoothing experiments at NCAR
- Introduction to mesoscale eddies, meridional heat transport, and Bjerknes compensation
- Kuroshio Extension decadal variability
- Ocean and atmospheric response in a high-resolution fully-coupled climate simulation

Mesoscale Eddies

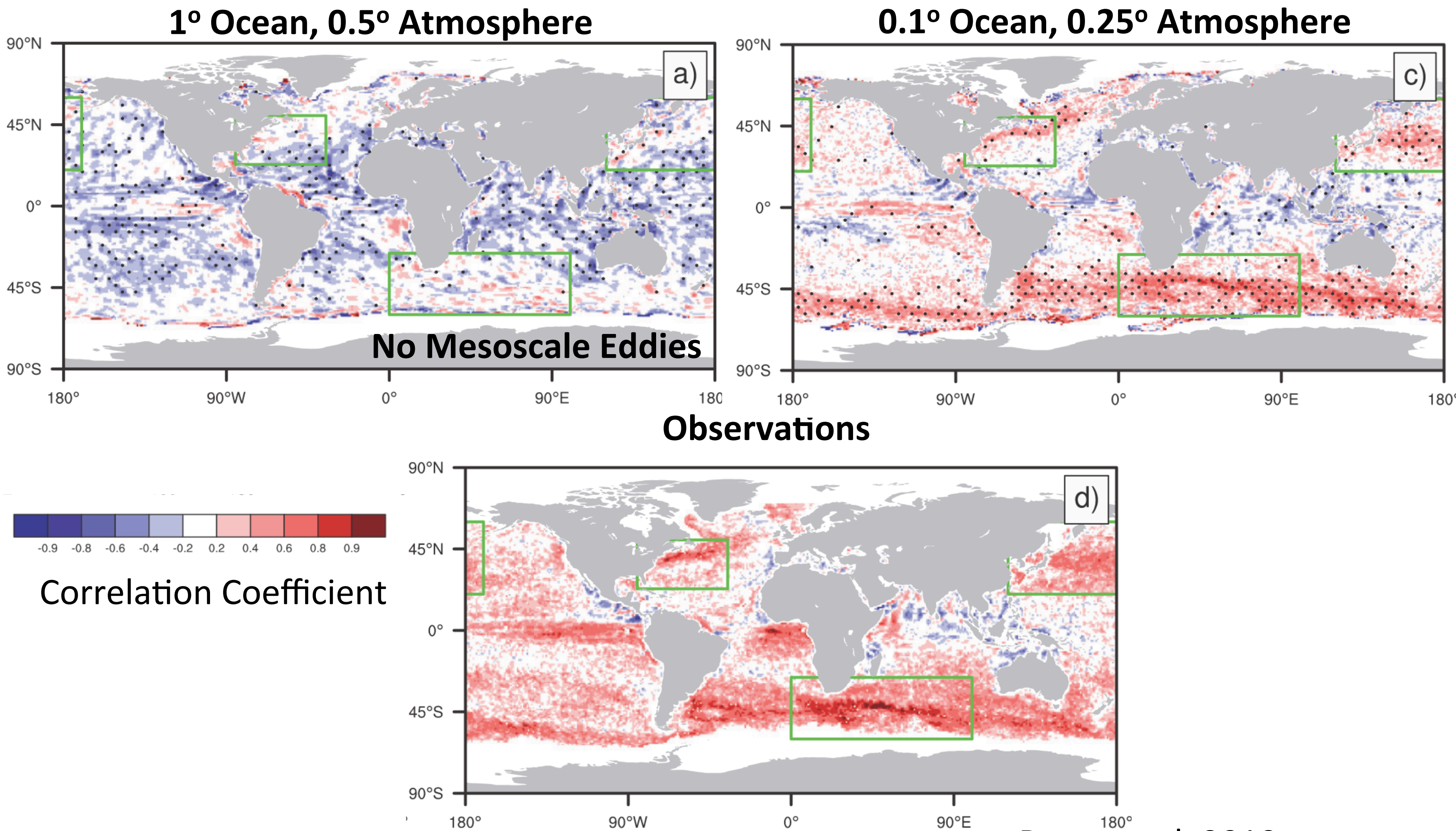


- Mesoscale (Synoptic) eddies
  - O(100 km) and vary on days to months time scales
  - Weather systems of the ocean (Deformation scale processes)
  - Not resolved by 1^0 climate models
- Important feedbacks on mean ocean circulation:
  - Stirring and mixing of water properties
  - Draw energy from the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

SSH Variance & WBCs

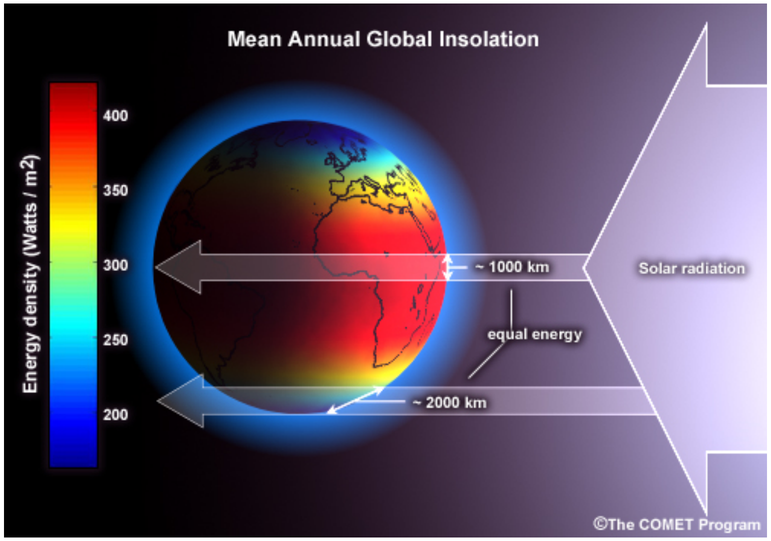


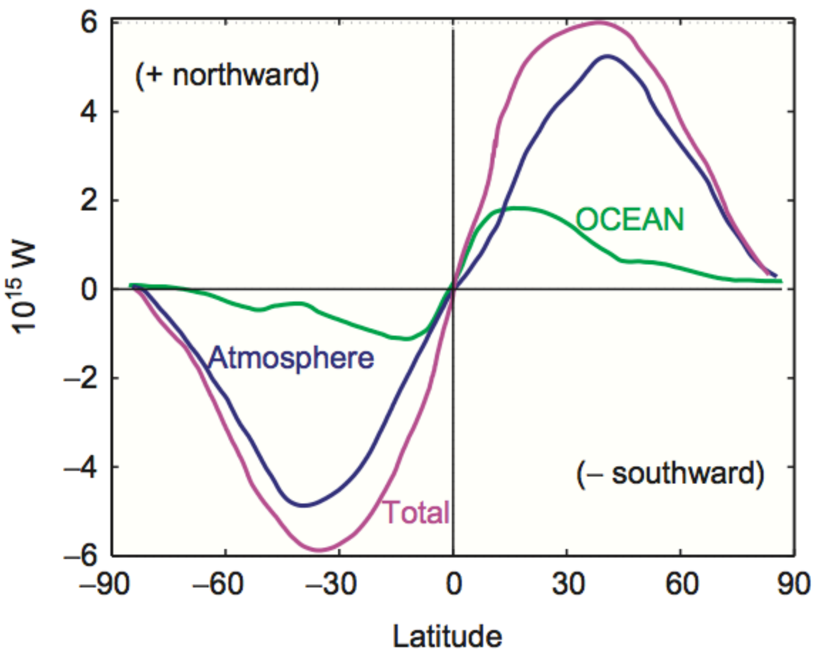
Mesoscale Eddies & Atmospheric Feedbacks: SST and Wind Stress



Bryan et al. 2010

Meridional Heat Transport





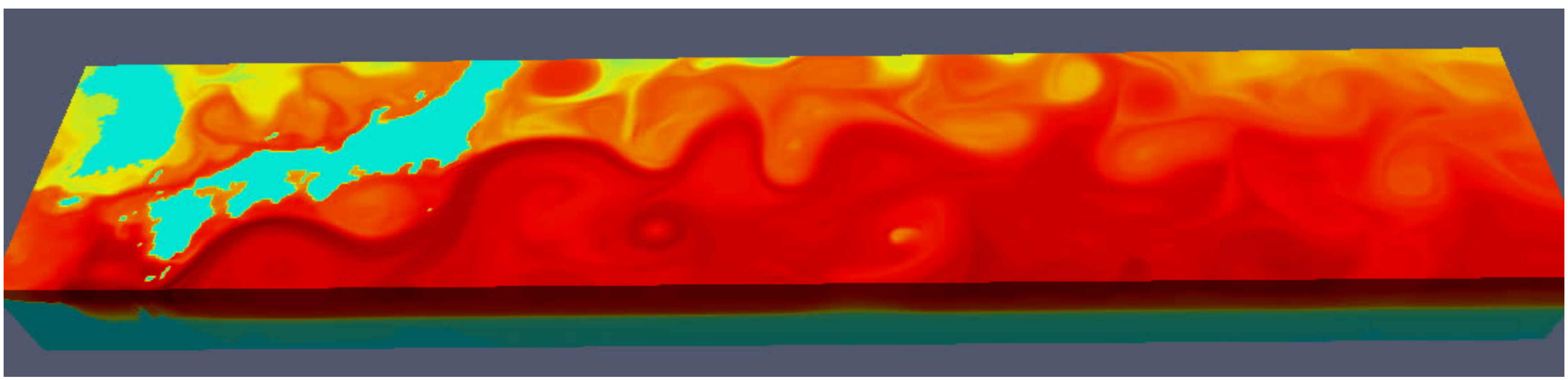
From *Ocean Circulation and Climate: A 21st Perspective*

- 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?

Eddy Heat Flux

$$\boxed{\rho_0 C_p \overline{vT} = \underbrace{\rho_0 \cancel{C_p \overline{v}}\,\overline{T}}_{\text{Mean}} + \underbrace{\rho_0 C_p \overline{v'T'}}_{\text{Eddy}}} \qquad \overline{(\ \ )} \equiv \frac{1}{\tau}\int_0^{\tau} (\ \ )\,dt$$

$$\boxed{\rho_0 C_p \overline{vT} \approx \rho_0 C_p \overline{v'T'}}$$



Bjerknes Compensation Theory

Compensation in Meridional Heat Transport

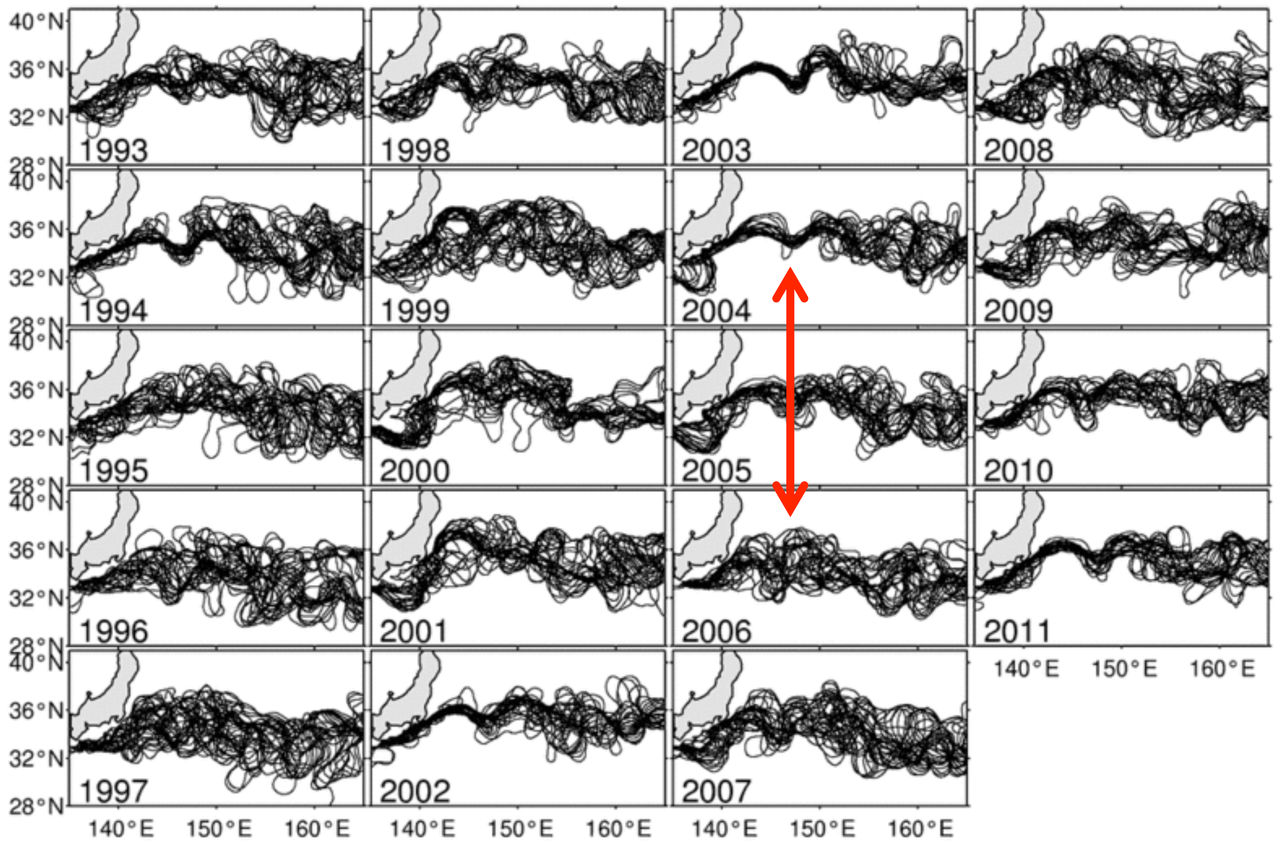
$$\delta \int_0^L \int_{-h}^0 \rho_0 C_p^o (\overline{v}_o \overline{T}_o + \overline{v_o' T_o'}) dz dx = -\delta \int_0^L \int_0^H \rho_a C_p^a (\overline{v}_a \overline{T}_a + \overline{v_a' T_a'}) dz dx$$

δH_{OCEAN} $\delta H_{ATMOSPHERE}$

Srokosz et al. 2013, BAMS

- 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

Kuroshio Extension
Decadal Variability

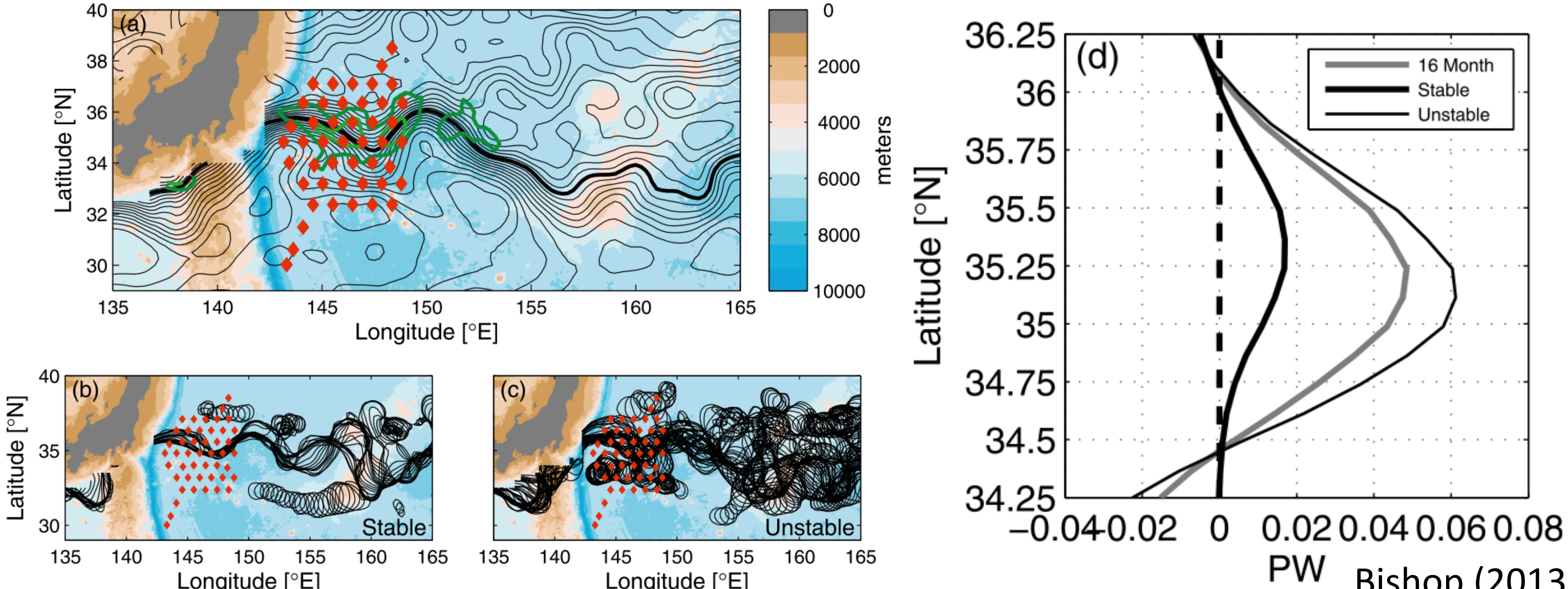


Updated from Qiu and Chen 2005

http://www.aviso.altimetry.fr/en/news/idm/2012/mar-2012-following-kuroshio-paths.html

- "Stable" years
  - 1993-1994, 2002-2005, 2011
- "Unstable" years
  - 1995-2001, 2006-1010
- Stable characteristics:
  - Strong transport (strong meridional SST gradient)
  - Weak small amplitude eddies
  - Small meridonal eddy heat transport (Presumably)
- Unstable characteristics:
  - Weaker transport (weaker meridional SST gradient)
  - Strong high amplitude eddies
  - Large meridional eddy heat transport

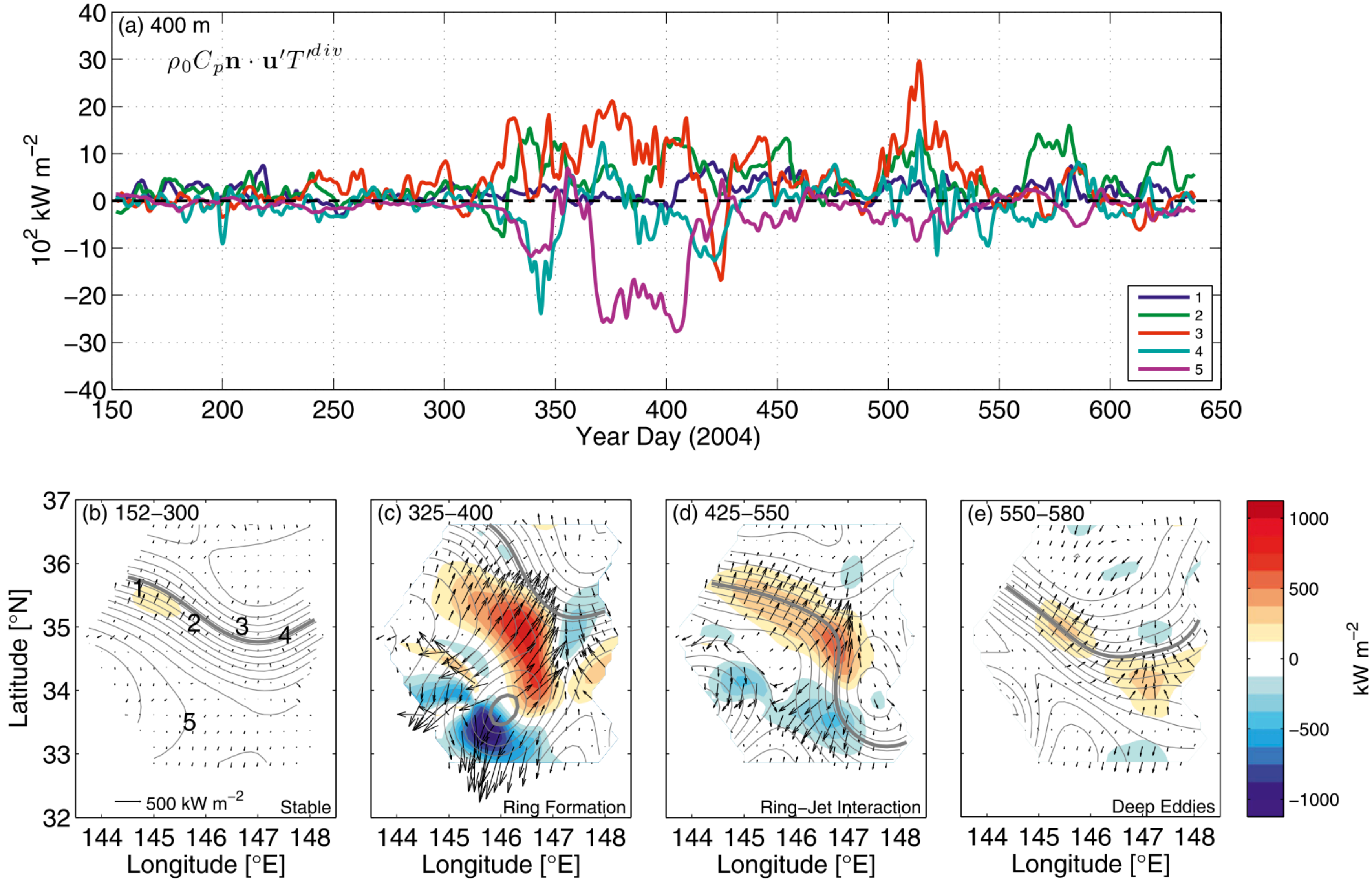
Kuroshio Extension System Study (KESS)



Bishop (2013)

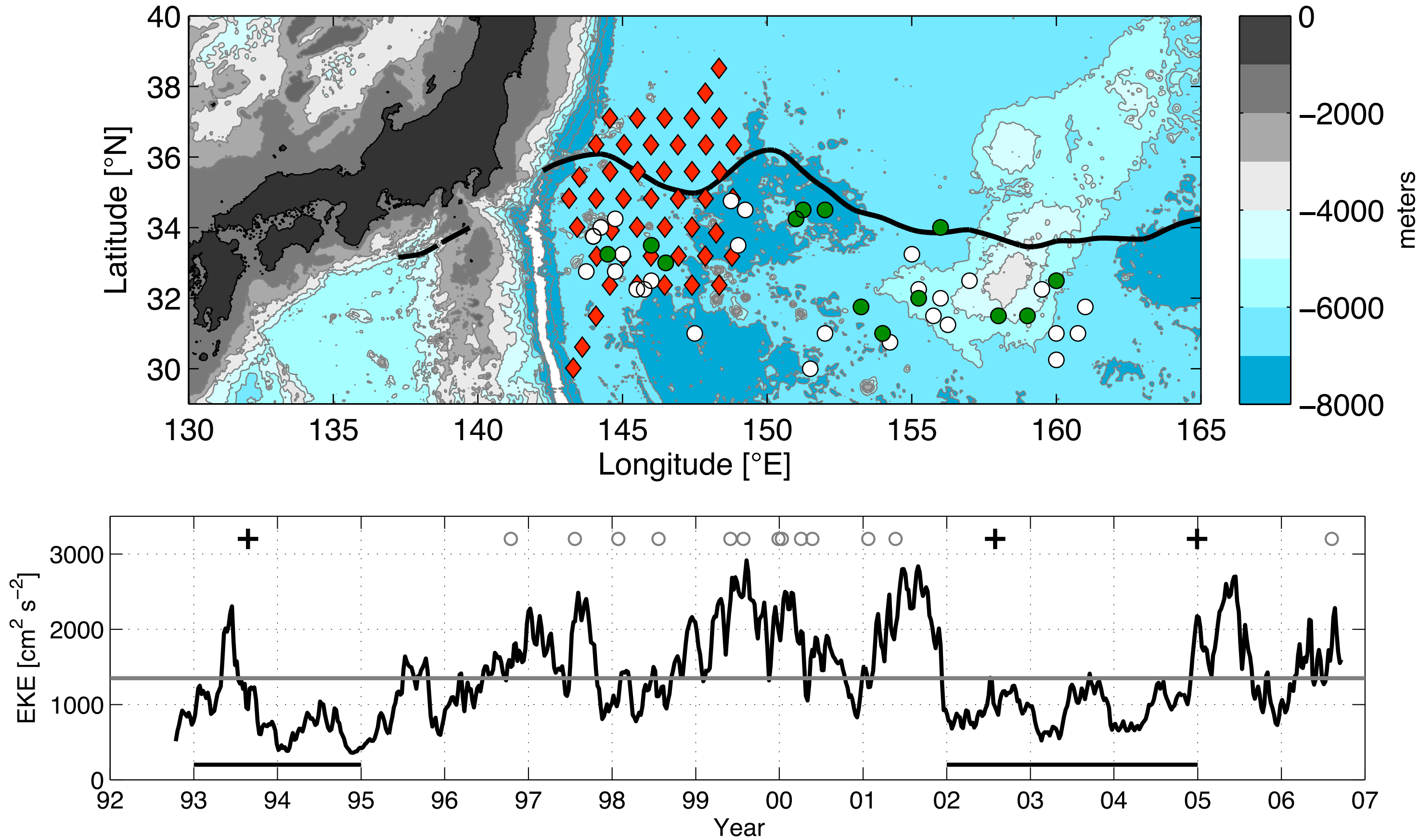
- Observational field study from 2004-2006
- Captured a transition from stable to unstable state
- Meridional eddy heat transport 3X larger during the unstable state

Strongest Eddy Heat Fluxes From Formation of Rings



Bishop 2013

Suppression of CCRs During Stable Regimes



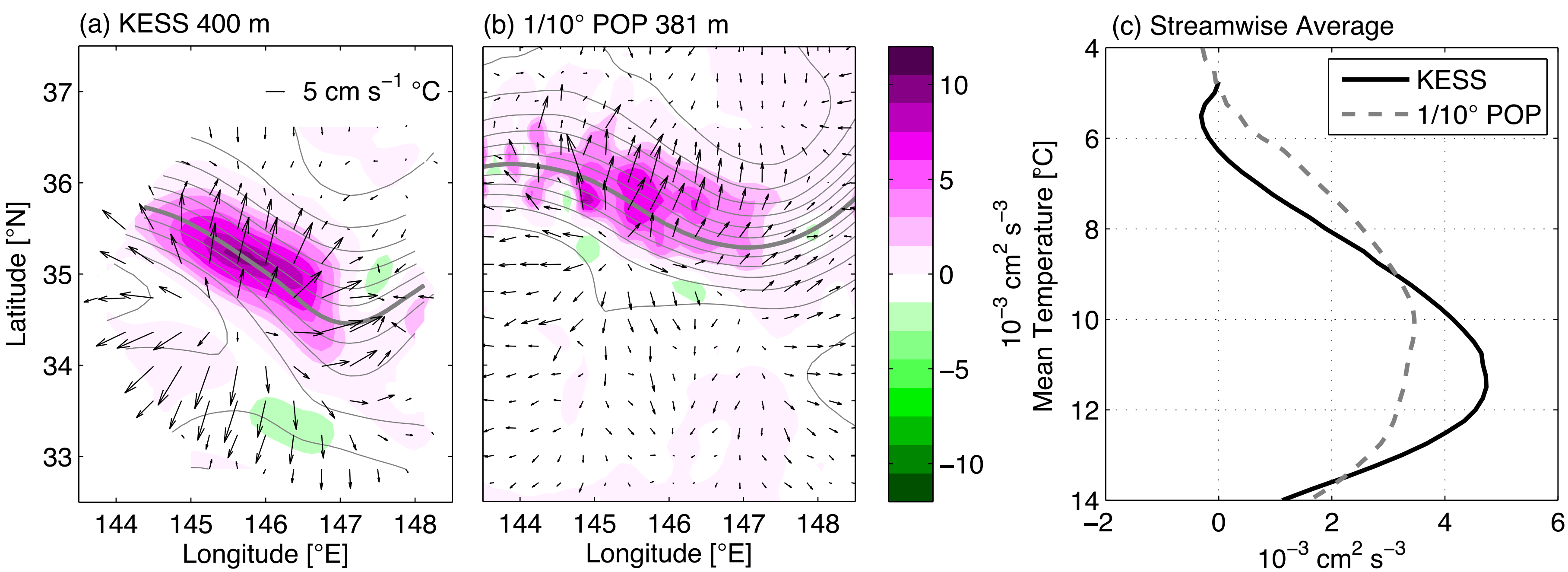
- 16 CCRs formed within KESS region from late 1993-2007
- 3 formed during stable Regimes
  - 2 formed during elevated levels of EKE at transition
  - 1 formed mid 2002
  - No CCRs formed from mid 2002-December 2004

NCAR

1st Snow in October 2012

KESS/POP Energy Conversion

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

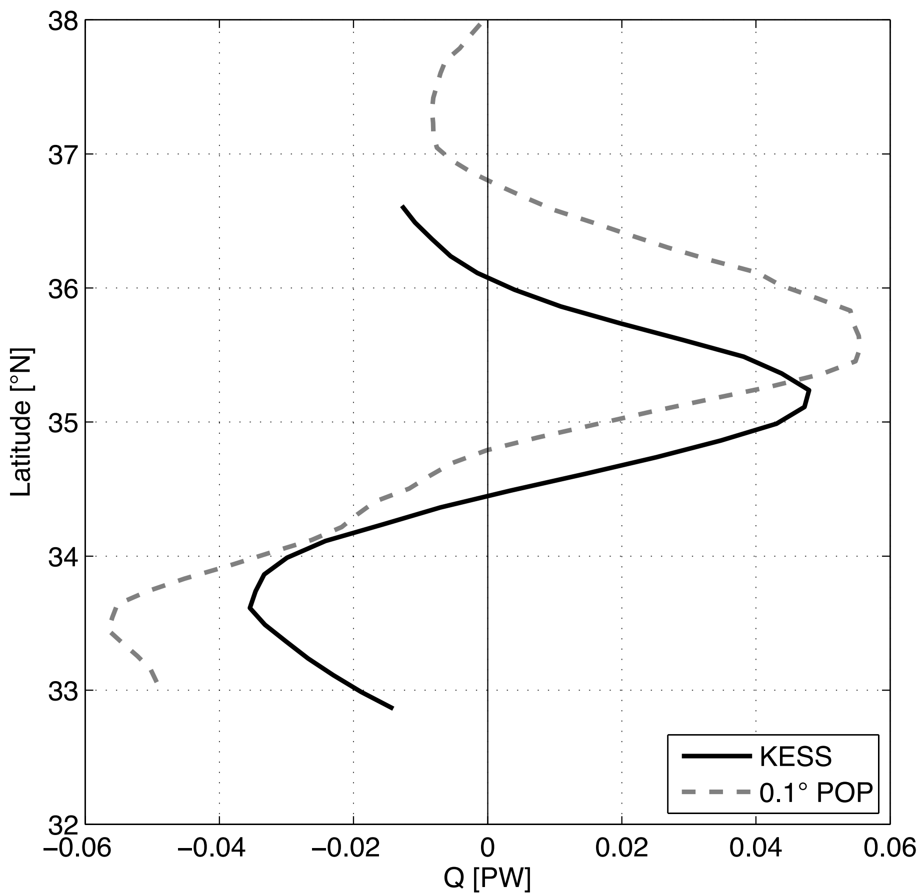


- Eddy heat fluxes are downgradient

Bishop and Bryan 2013

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

Meridional Eddy Heat Transport

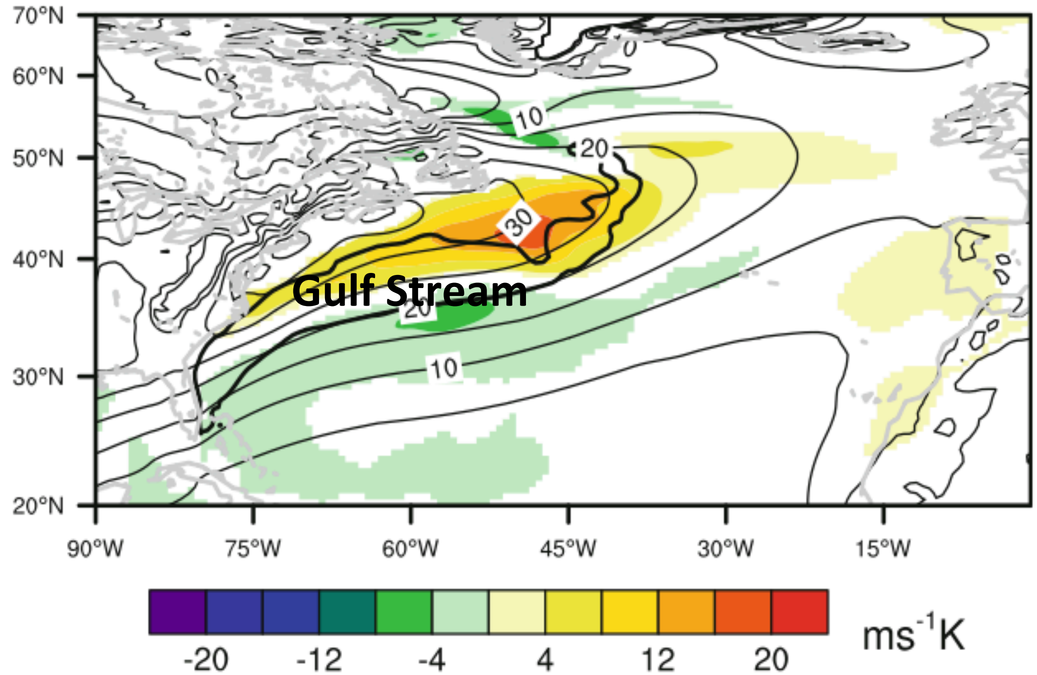


Bishop and Bryan 2013

$$Q = \rho_0 C_p \int_0^L \int_{-H}^0 \overline{v'T'}^{div} dz$$

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

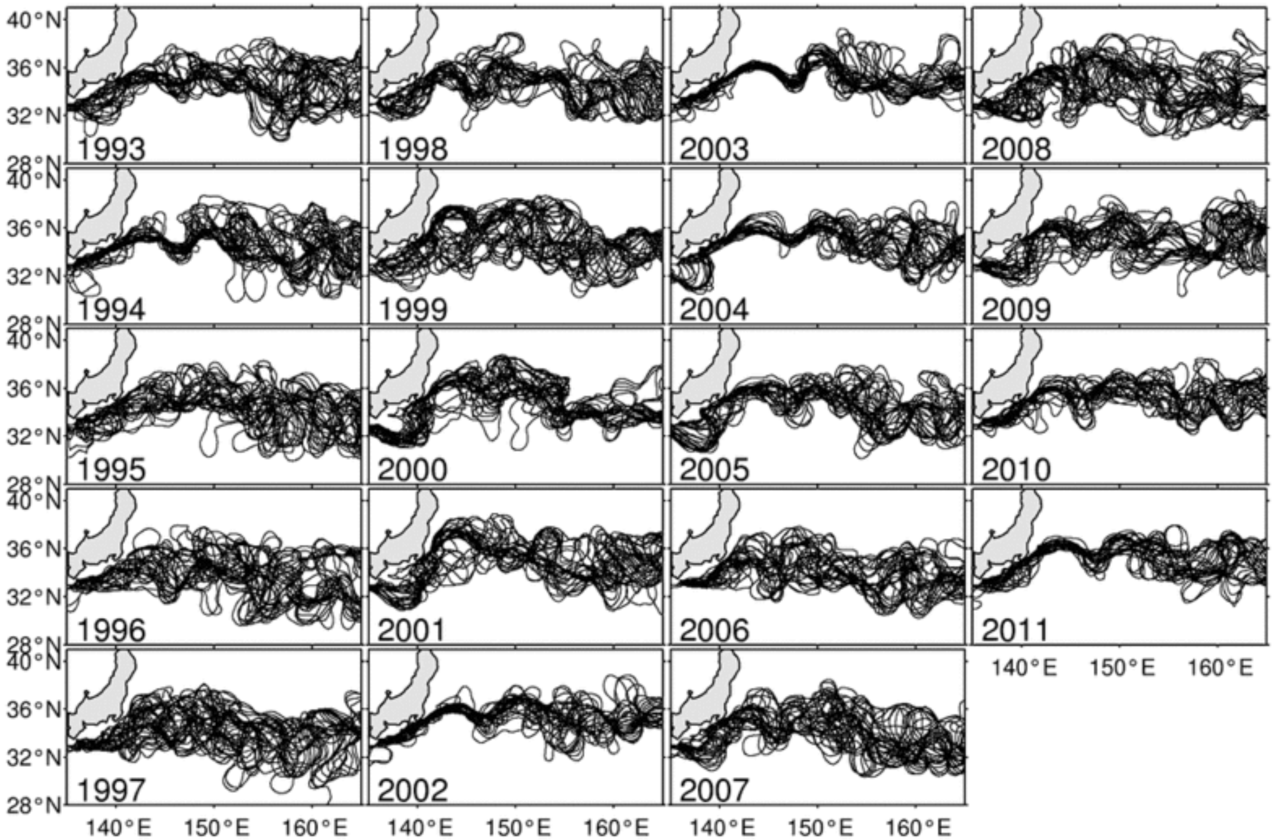
Atmospheric Response: Smoothed vs. Unsmoothed SST Fronts



Small et al. 2013

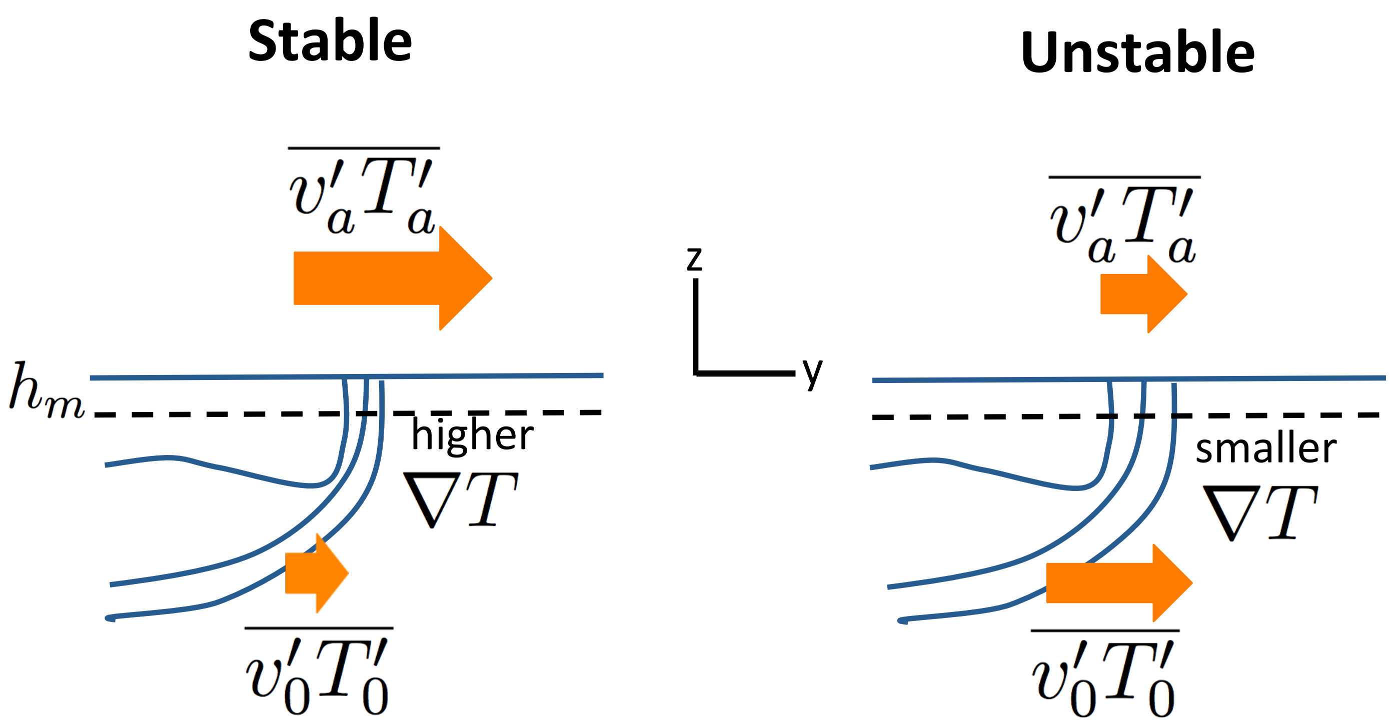
- Climate simulation with CAM4: 0.5° atmosphere with 0.25° Reynolds SST boundary conditions.
- Unsmoothed vs. smoothed fronts produced up to 20-40% higher eddy heat and moisture fluxes.
- Sharp fronts felt through the free troposphere.

Hypothesis



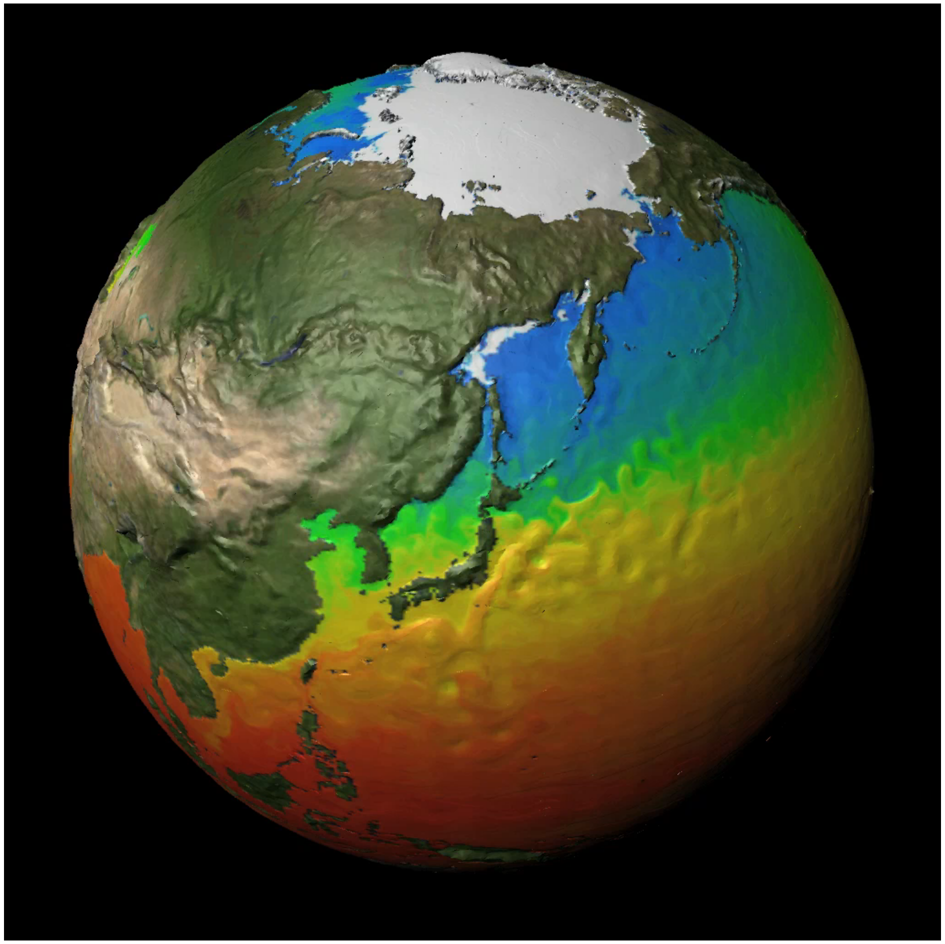
- Strongly meandering states have weaker fronts: **“smoothed”**
- Weakly meandering states have strong fronts: **“unsmoothed”**

Working Hypothesis



Is there a local Bjerknes Compensation?

High-Resolution Fully-Coupled CESM Simulation

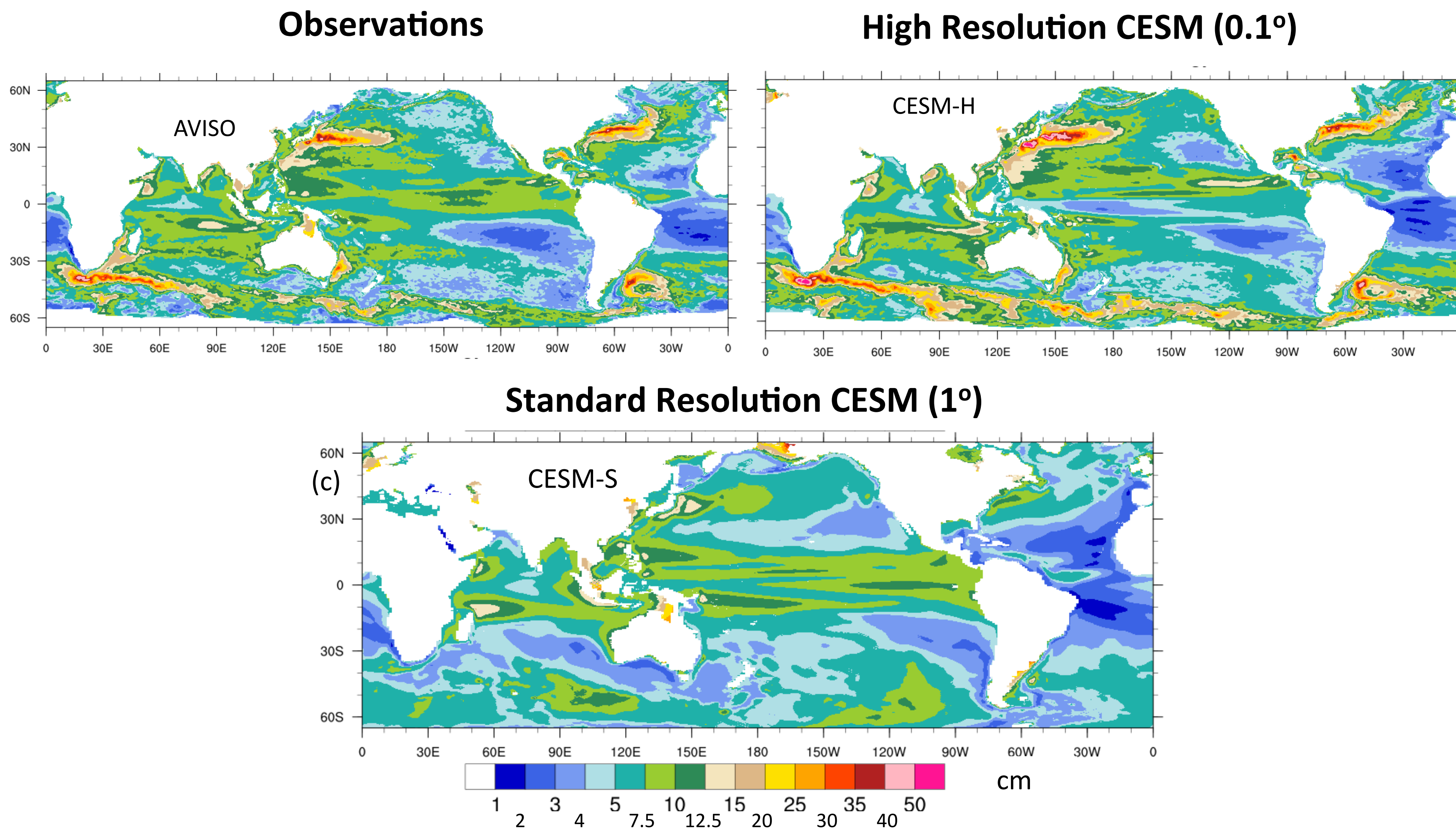


Movie courtesy of Tim Scheitlin (NCAR Visualization Lab)

Model

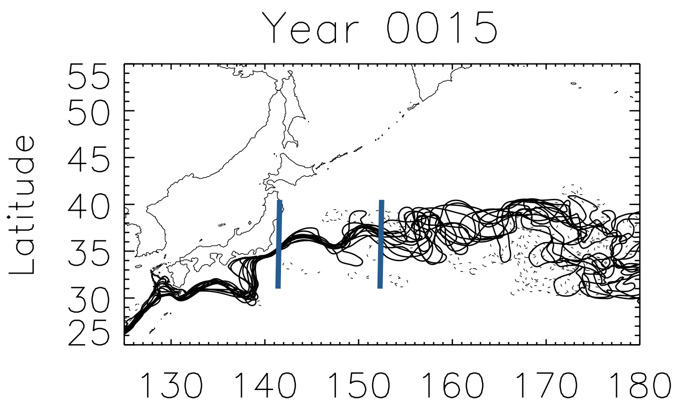
- Community Earth System Model:
  - 0.1^{0} Ocean (POP2)
  - 0.25^{0} Atmosphere (CAM5)
- Fully coupled (atmosphere-ocean)
  - 6 hourly
- 100 years
- Monthly archived data
- Advantages of model over observations:
  - Subsurface oceanic data
  - Long time series for statistical robustness

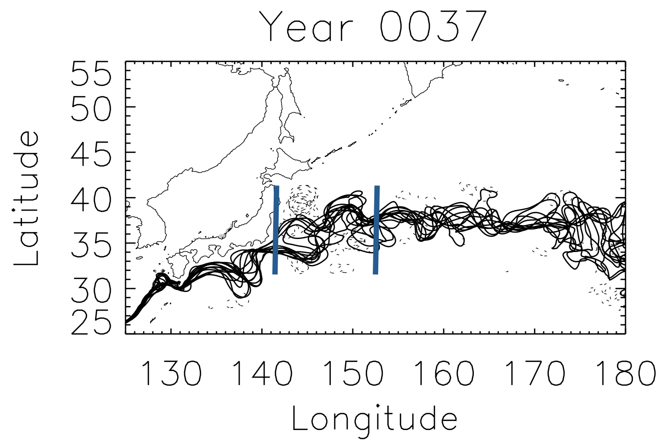
SSH Variance Versus Observations



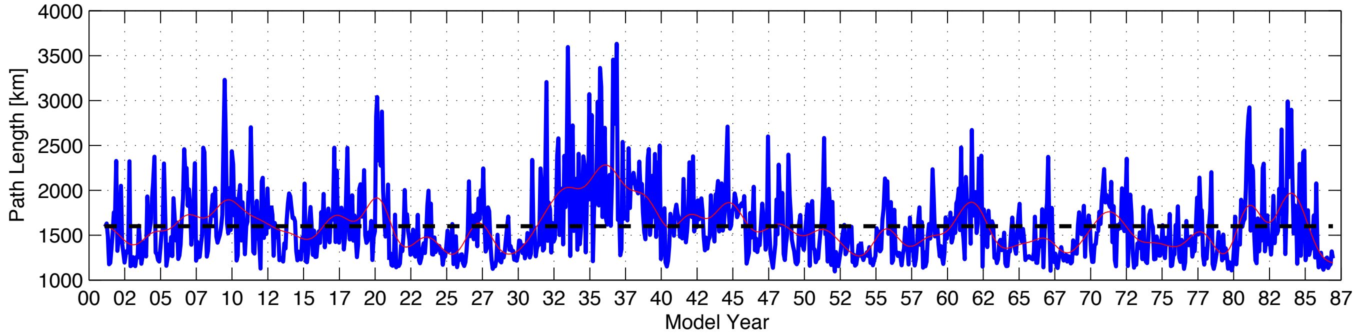
Small et al., accepted at JAMES

Decadal Variability in CESM-H

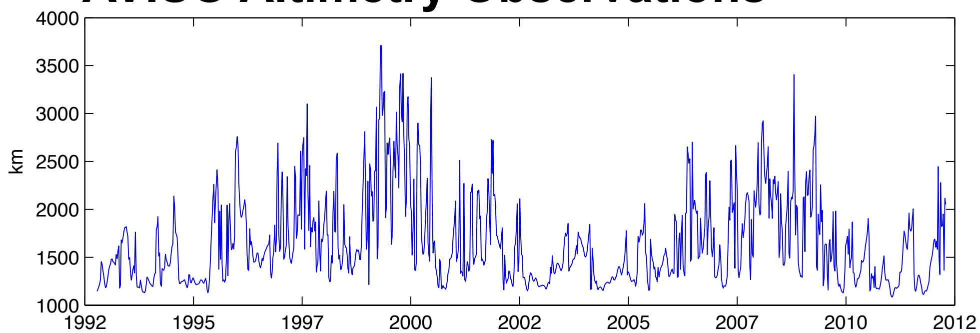




CESM-H



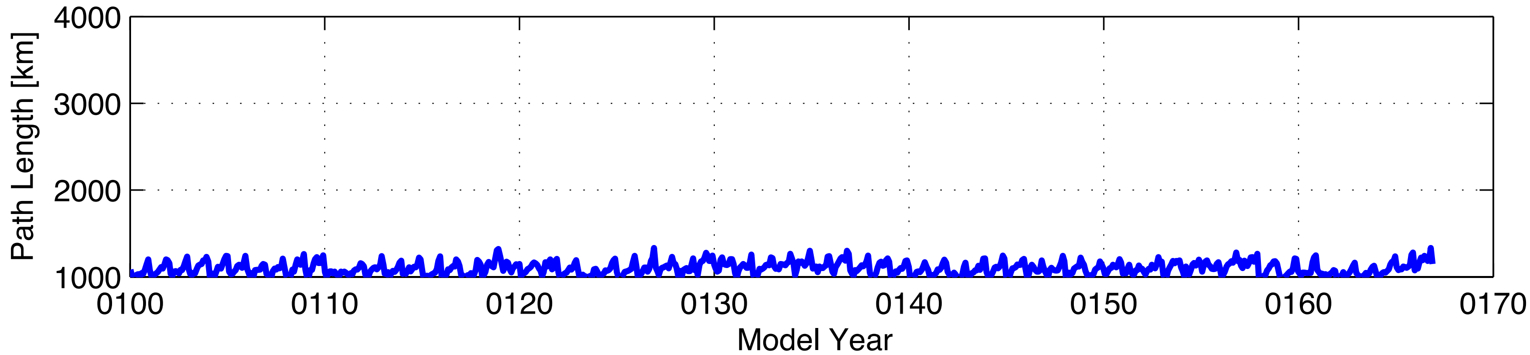
AVISO Altimetry Observations



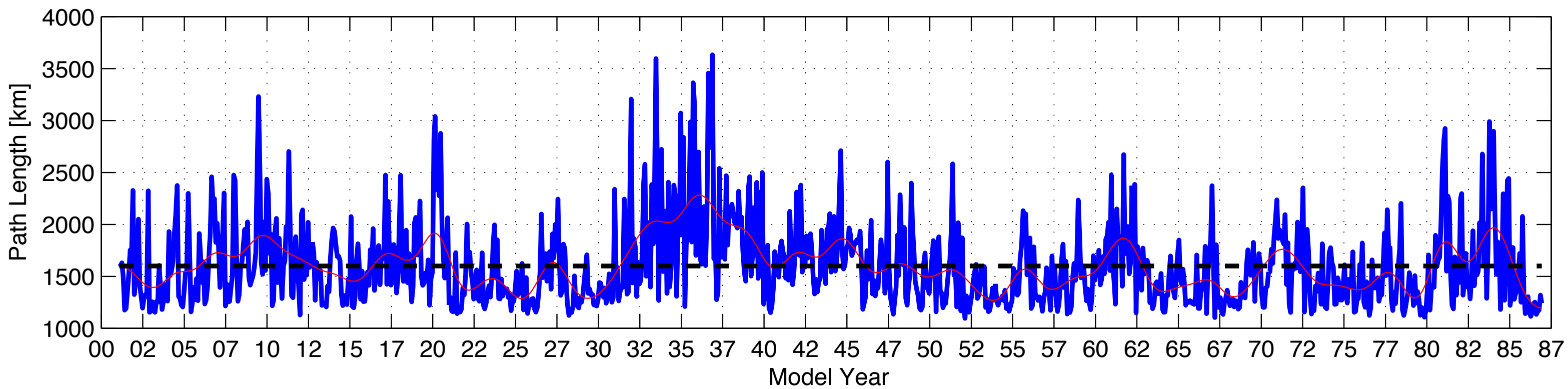
- Path length between 141^0-153^0E
  - Longer path length = more eddies
  - Shorter path length = less eddies
- Model exhibits variability similar to observations

Decadal Variability in Standard Climate Model

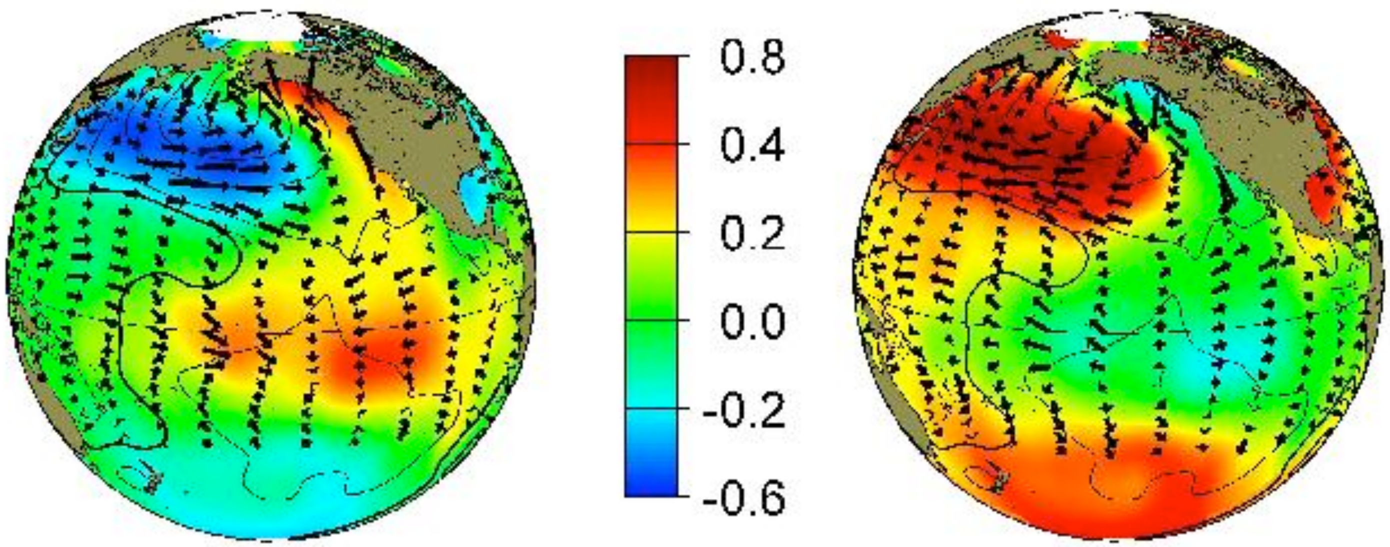
CESM-S: ~1° Typical Climate Simulation



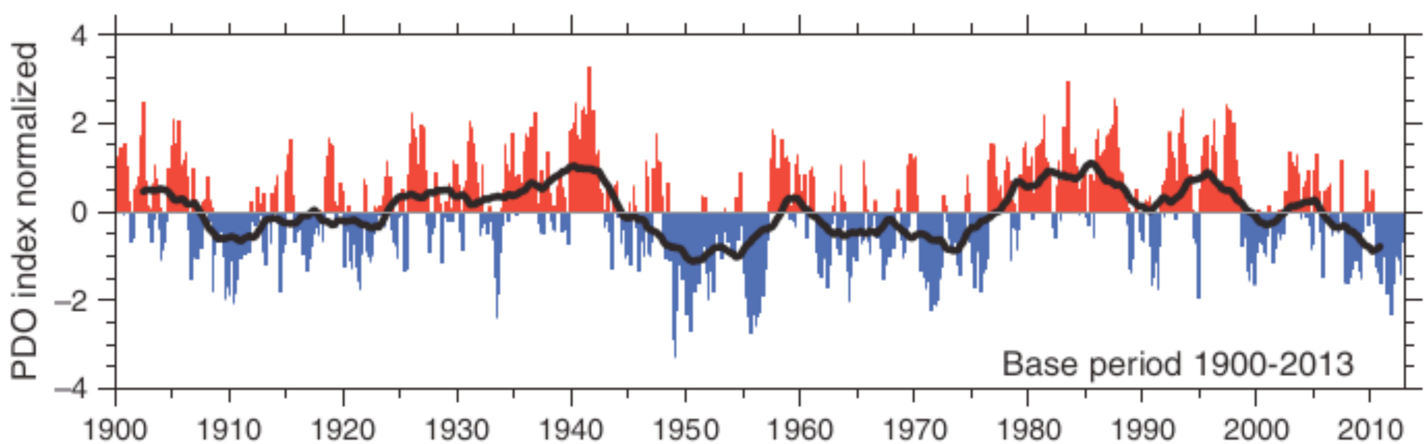
CESM-H: ~0.1°



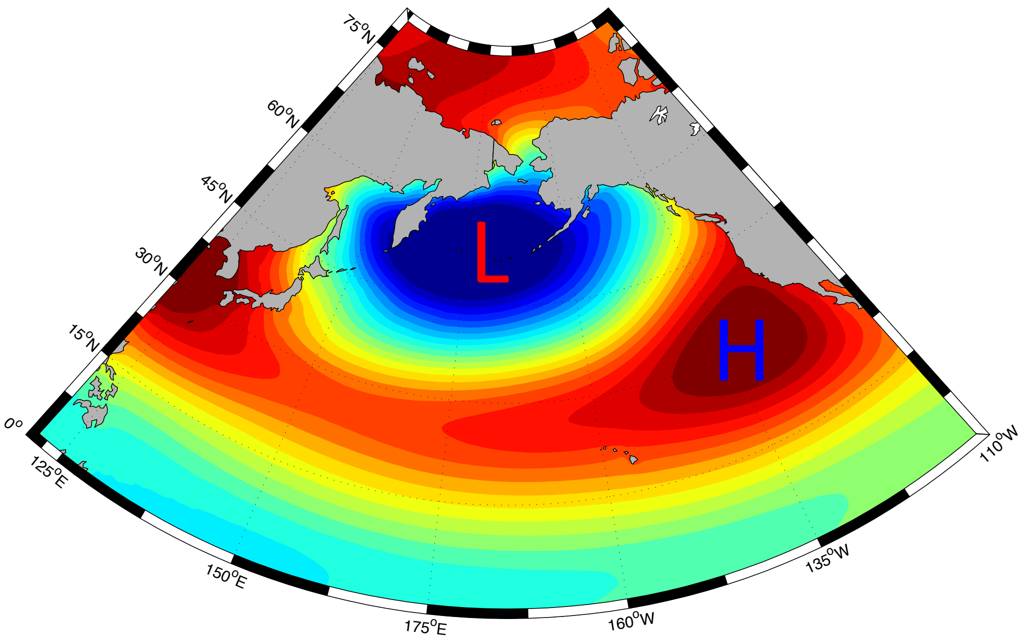
Pacific Decadal Oscillation (PDO)



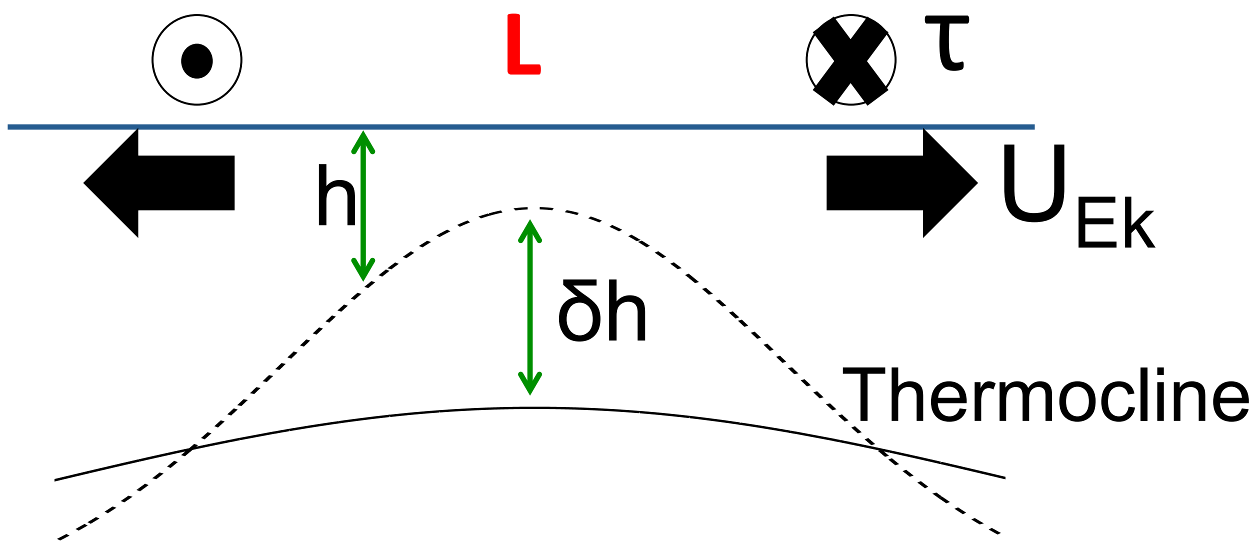
http://jisao.washington.edu/pdo/



PDO & Aleutian Low

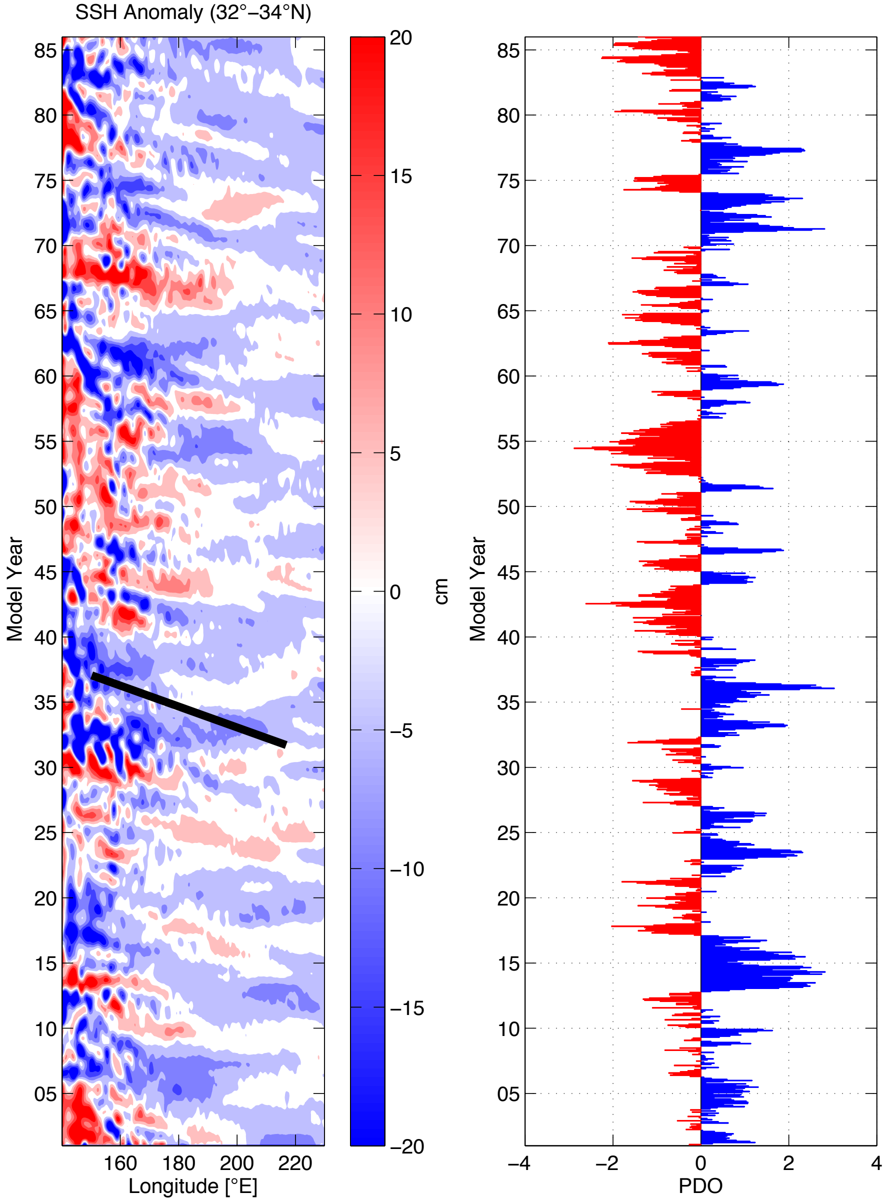


$$\frac{\partial h}{\partial t} - c_R \frac{\partial h}{\partial x} = -\frac{g' \,\mathrm{curl}\tau}{\rho_o g f}$$



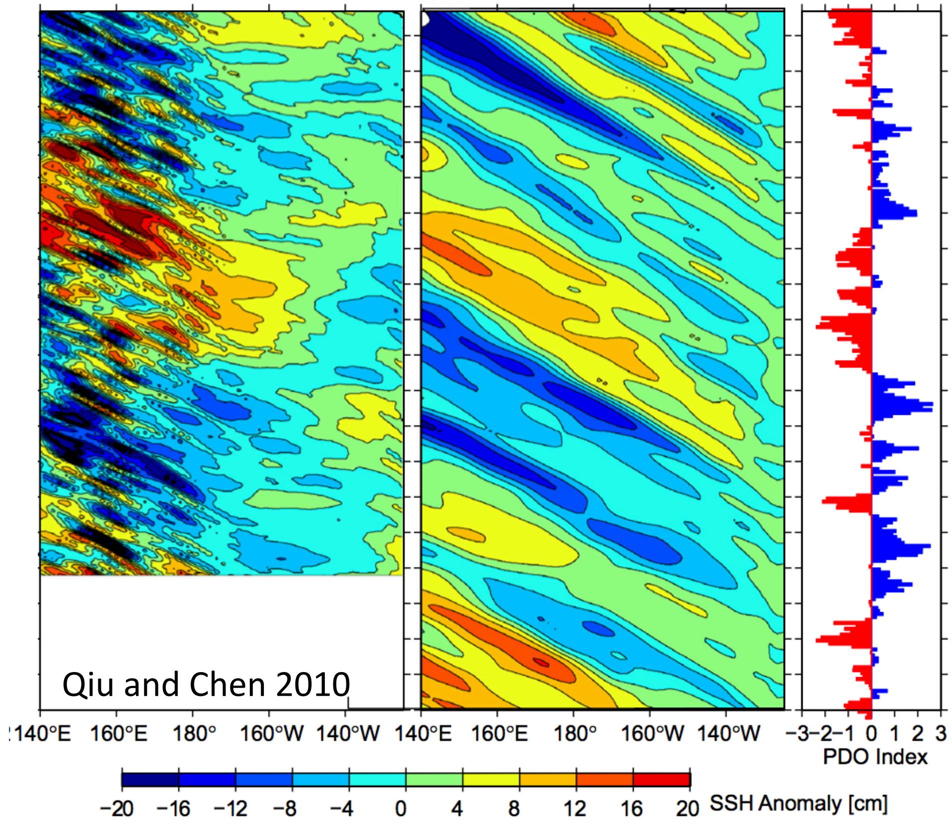
PDO & SSH Anomalies

CESM-H



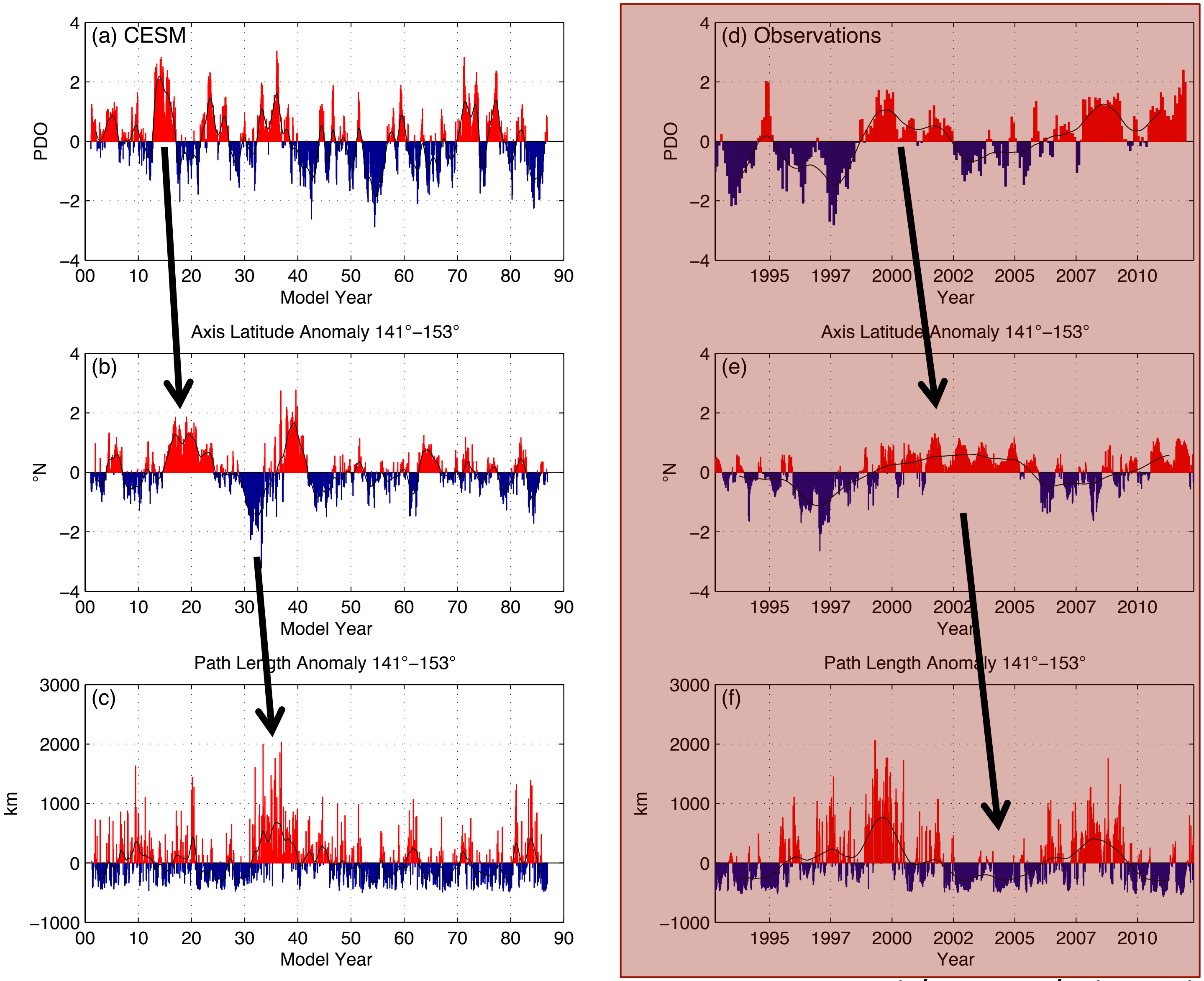
Bishop et al., in revision

Observations+Rossby Wave Model



- Phase of PDO drives SSH anomalies that propagate west from the central Pacific
- SSH anomalies → meridional shifts of jet
  - Positive SSHa shifts the jet North
  - Negative SSHa shifts the jet South

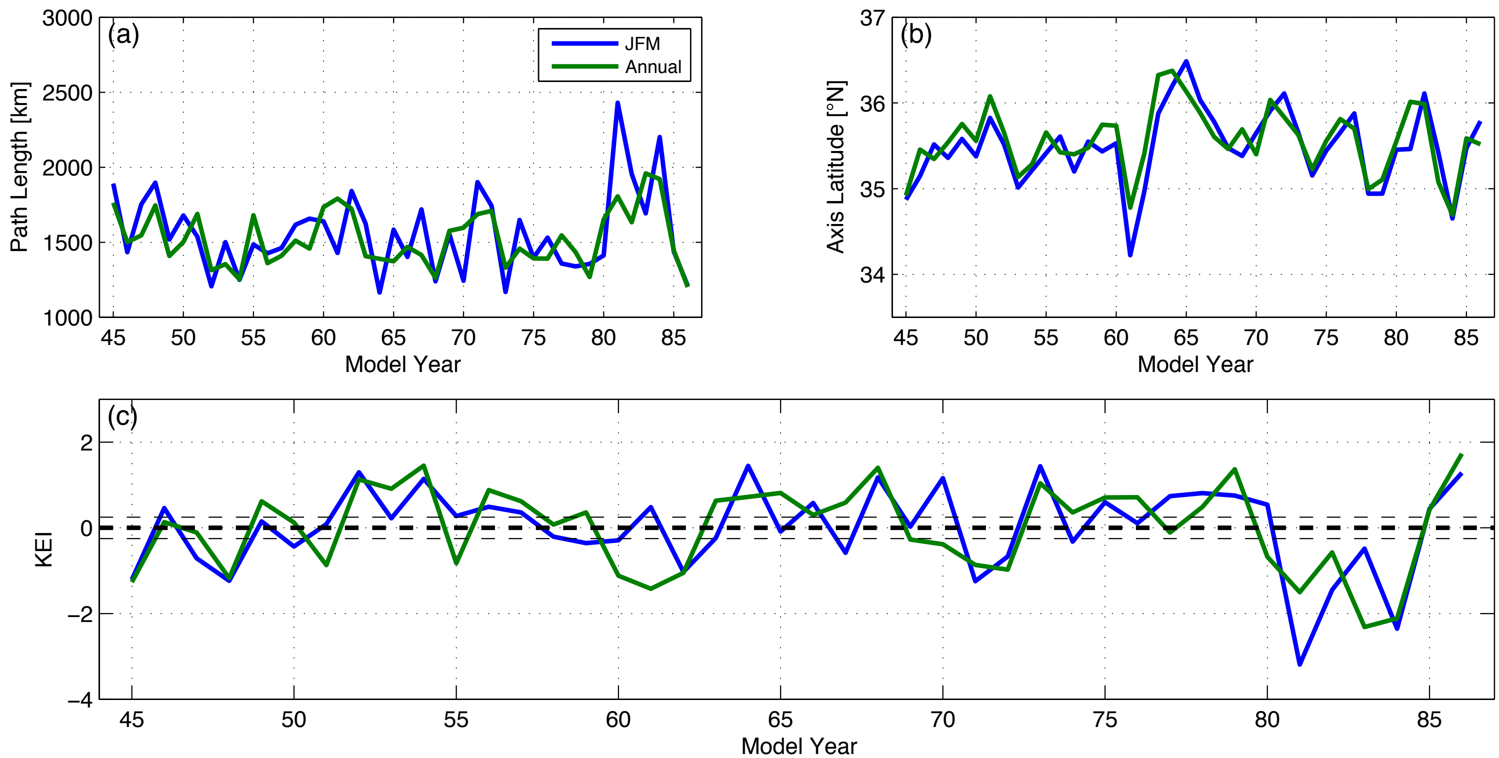
Kuroshio Variability and PDO



- 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)

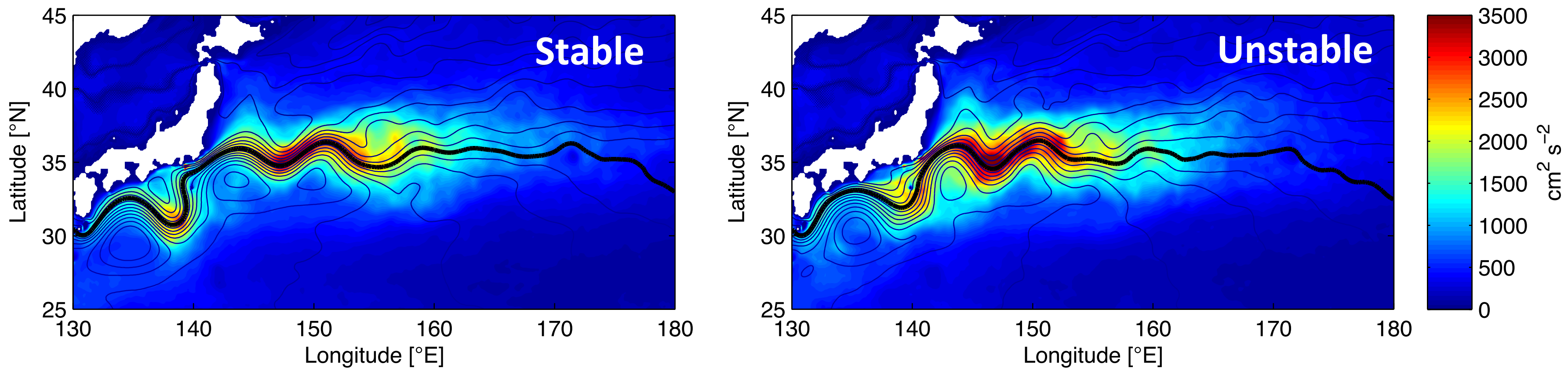


- Index: negative normalized path length
  - +ve “Stable”
  - -ve “Unstable”
- Index: JFM mean (blue), annual mean (green)
- Most years if JFM “stable” annual mean is “stable” too (68% chance)
- Composite threshold = 0.25 (1/4 standard deviation)

Bishop et al. in revision

Stable vs. Unstable SSH

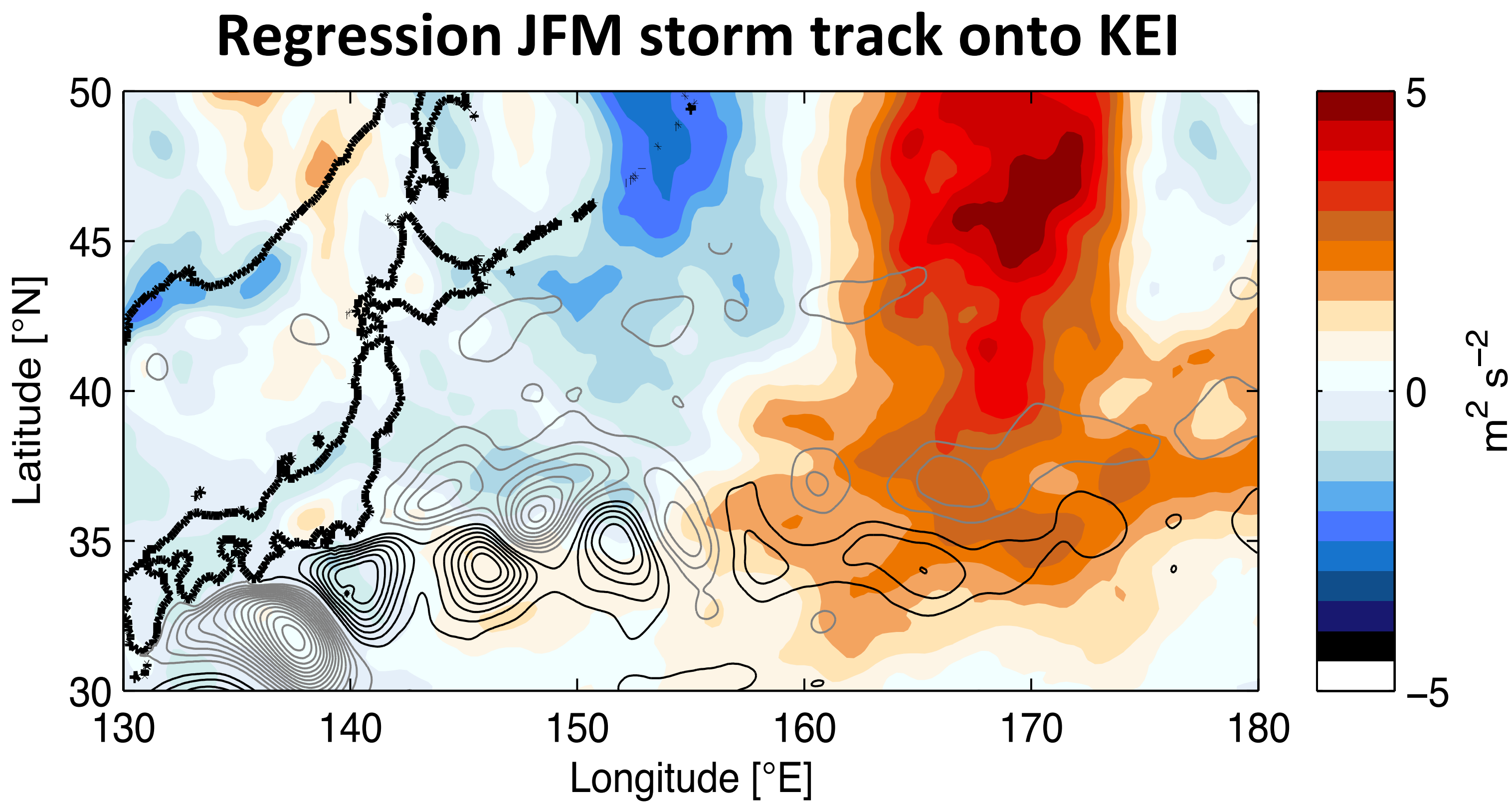
Composite of SSH and EKE



Bishop et al. in revision

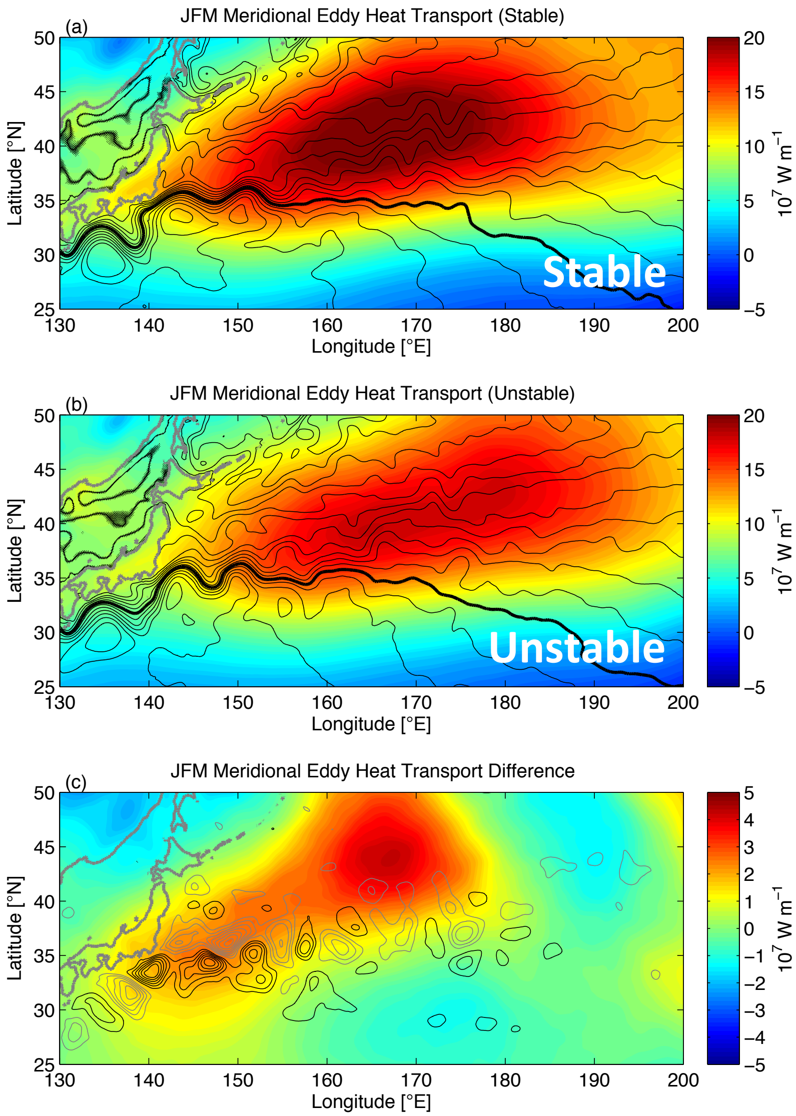
- Stable vs. Unstable:
  - Tighter front (ΔSSH of 84 vs. 60 cm between 34°-36°N at 145°E)
  - SSH is higher (lower) to the south (north) – higher transport
  - Stronger Southern Recirculation Gyre

Atmospheric Response: Storm Track



- Storm track defined as meridional wind variance at 850 hPa
- Storm track is enhanced downstream of Japan

Atmospheric Response: Eddy Heat Flux



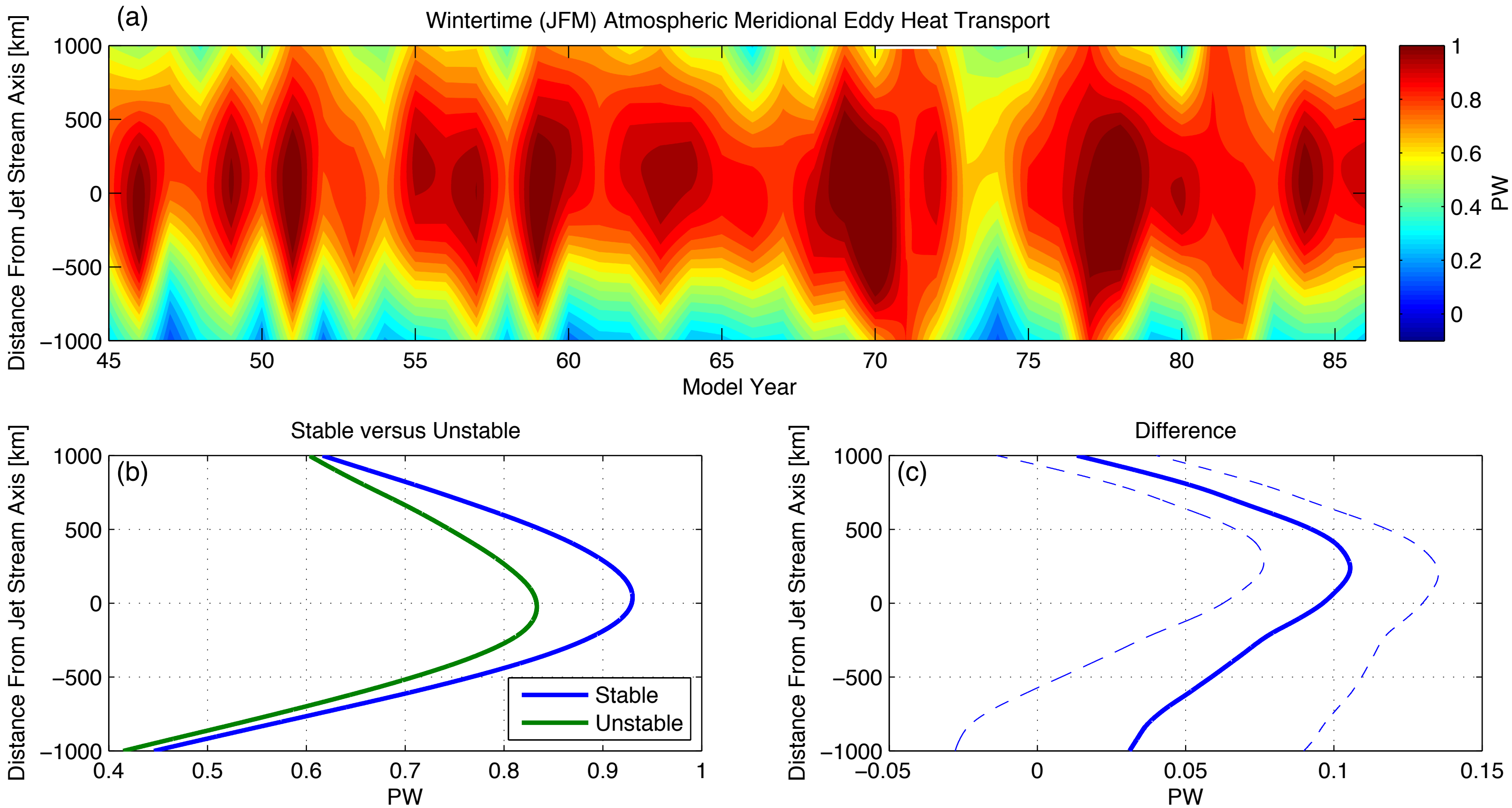
Bishop et al. in revision

Vertically-Integrated Eddy Heat Flux

$$\frac{1}{g}\int_{p_0}^{p_s}(C_p\overline{v'T'}+L\overline{v'q'})dp$$

- Meridional eddy heat fluxes (MEHFs) are enhanced during stable meandering states.
- MEHFs are enhanced geographically where storm track is enhanced.

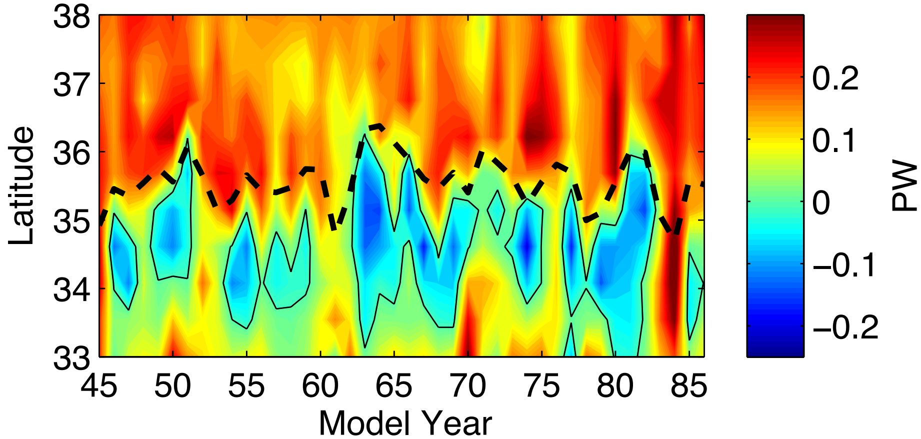
Meridional Eddy Heat Transport (Atmosphere)

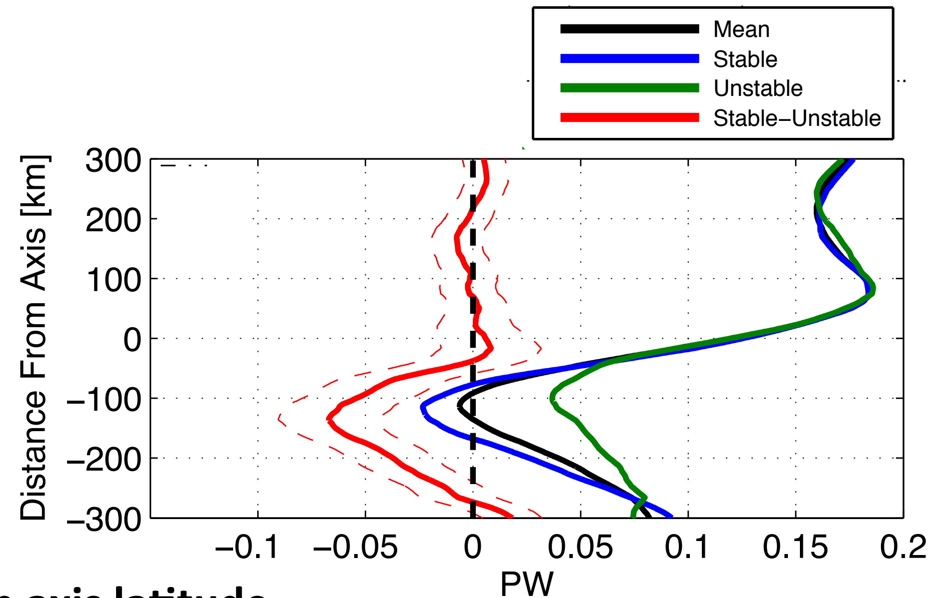


- MEHT was calculated relative to Jet Stream axis (maximum 850 hPa zonal mean wind, Ari Solomon personal communication)
- MEHT is enhanced by ~0.1 PW at its maximum during +ve KEI

Bishop et al. in revision

Meridional Eddy Heat Transport (Ocean)





-- Kuroshio Extension axis latitude

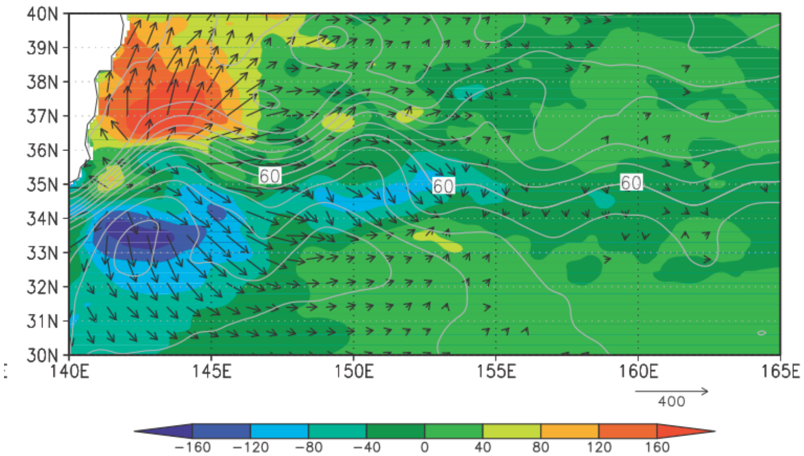
- Stable states have the persistence of equatorward MEHT just south of the Kuroshio Extension
- Aoki et al. (2013) notes persistence of negative MEHT south of the Gulf Stream and Kuroshio Extension (only 5 years of OFES simulation)
- Attributed to southward migration of warm water cores from cold-core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

Bishop et al. in revision

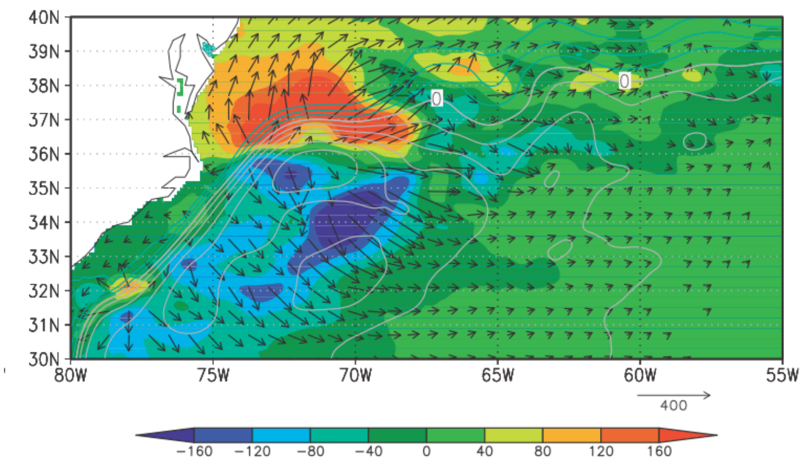
Equatorward Eddy Heat Flux

OFES Model

Kuroshio Extension

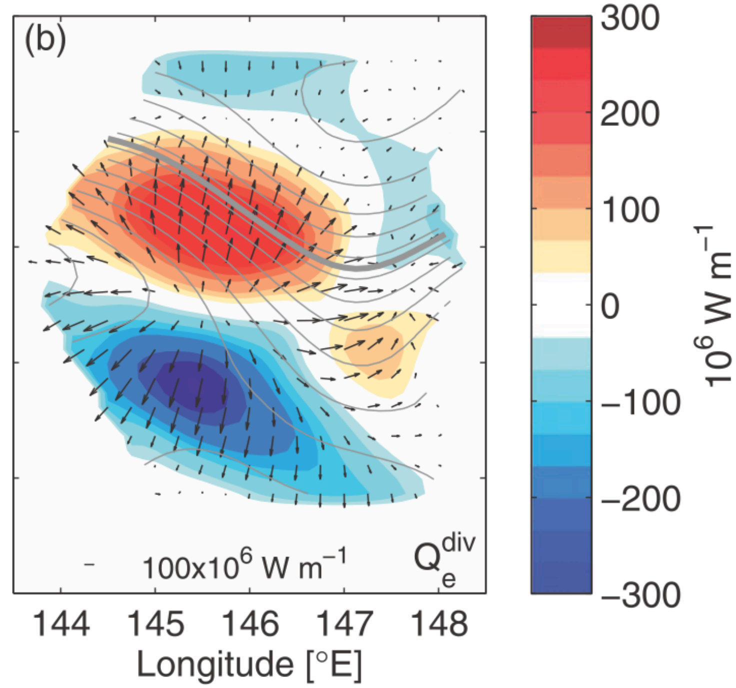


Gulf Stream



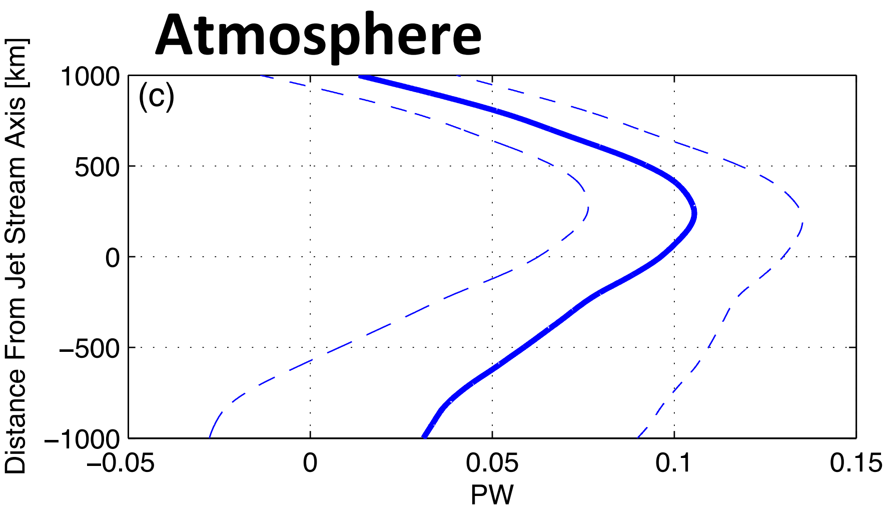
10^6 W m^{-1} Aoki et al. 2013

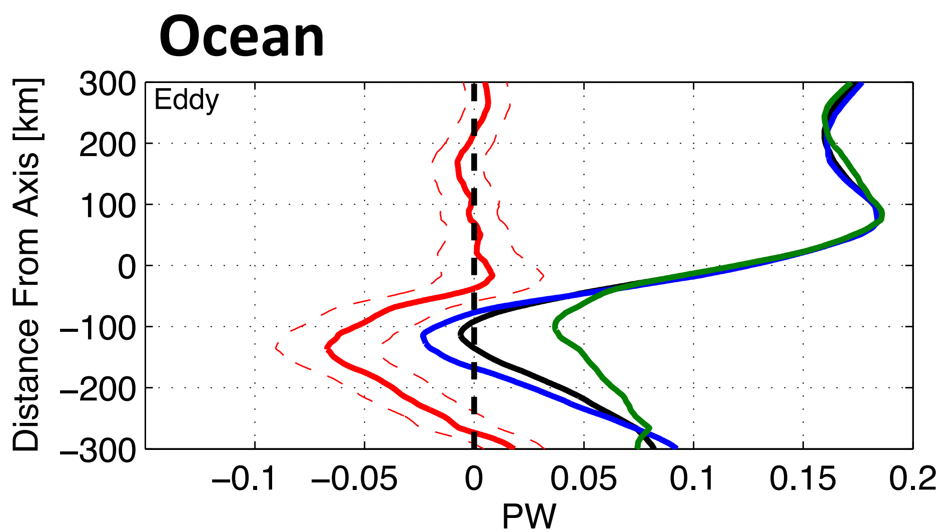
KESS Observations



Bishop et al. 2013

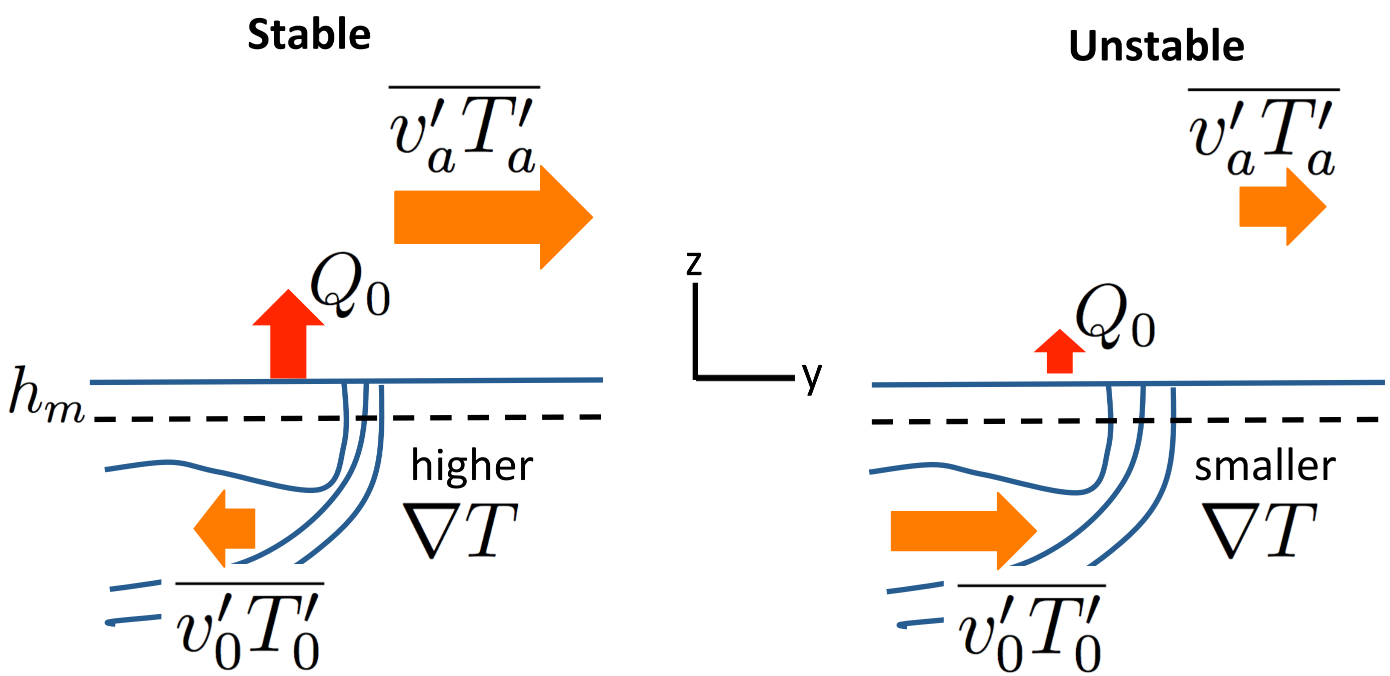
"Local" Bjerknes Compensation?





- 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!

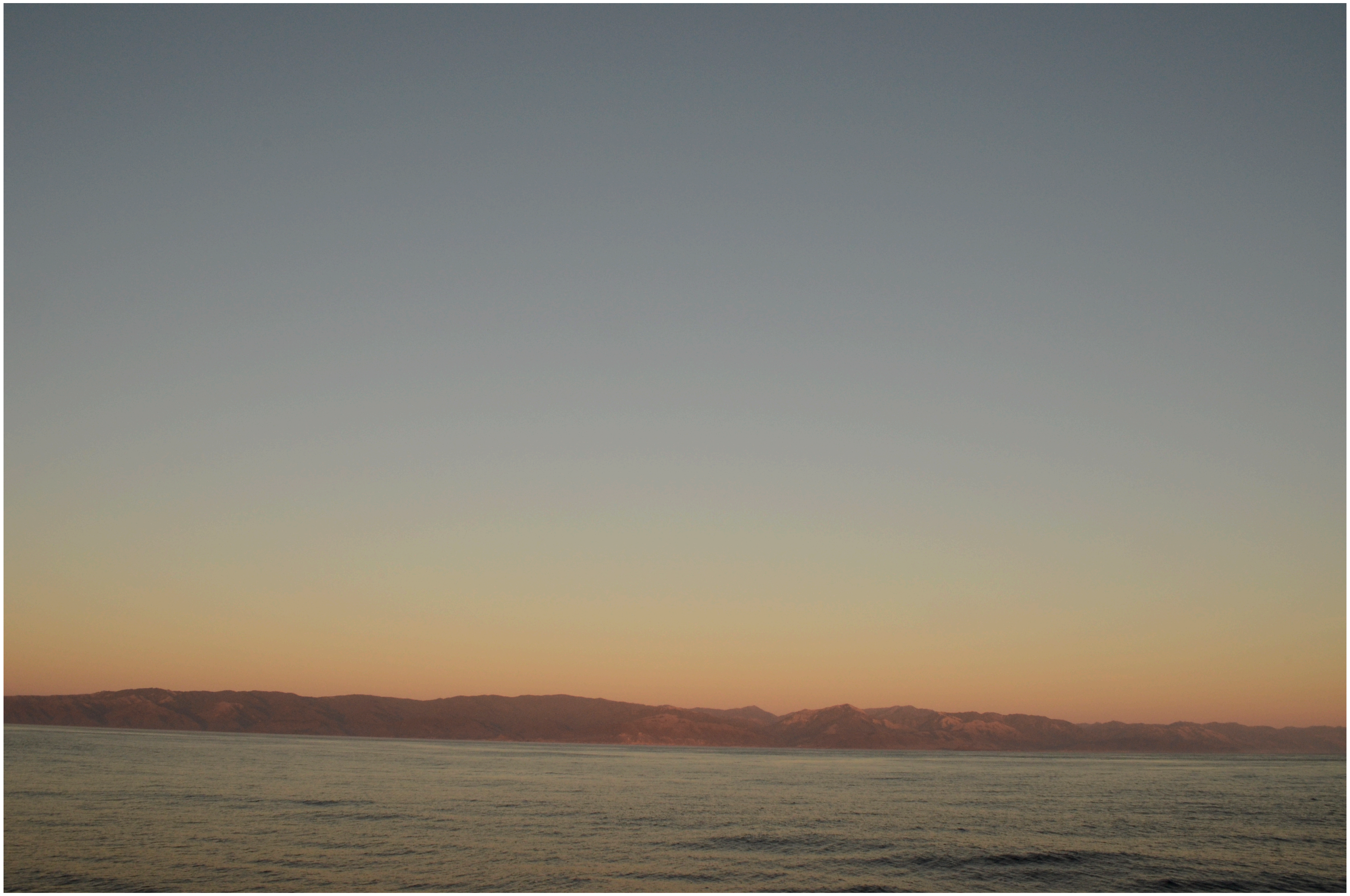
Schematic Summary



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)