Observational Needs for Air-Sea Interaction in the Gulf Stream

Stu Bishop (NCSU)

Whither the Gulf Stream US CLIVAR Workshop

June 15, 2022

Outline

1. What do we know about coupling between sea surface temperature (SST) and turbulent heat fluxes (THF) at monthly and longer time scales?

2. Where and when?

3. What time and space scales are needed?

How to diagnose air-sea interaction?

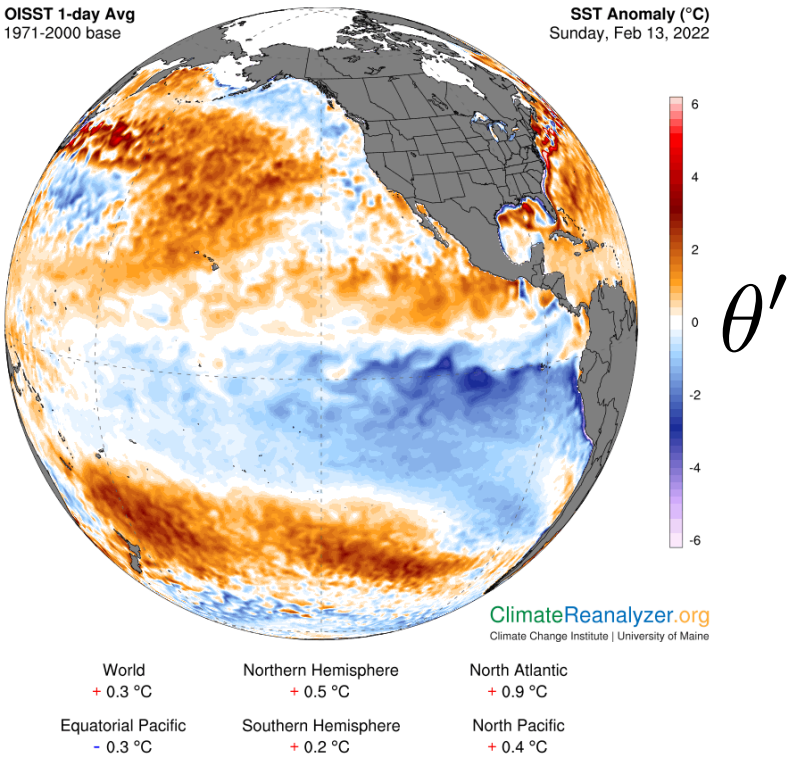
- Focus on the relationship between sea surface temperature and turbulent (latent) heat flux anomalies.

θ' = Sea Surface Temperature Anomaly (SSTa)

Q'_o = Latent Heat Flux Anomaly
(LHFa, +ve out of the ocean)

Covariance between SSTa-LHFa

$$\overline{\theta' Q'_o}$$



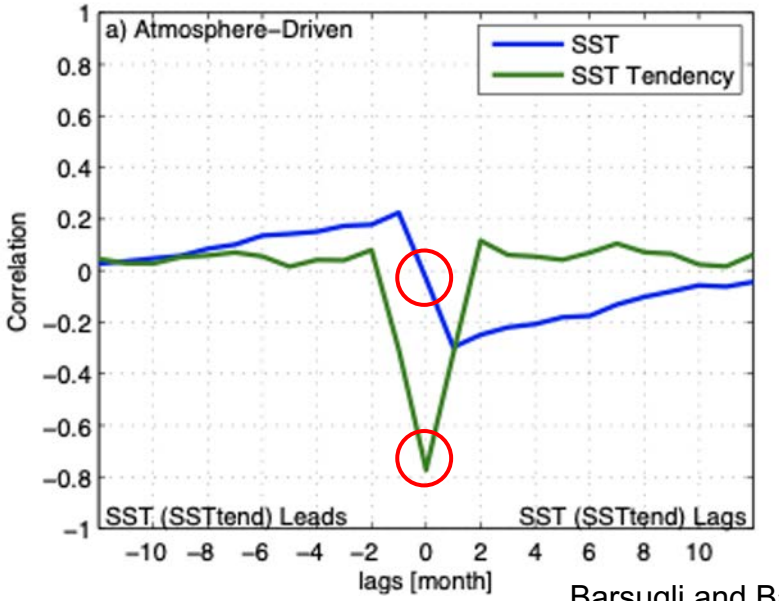
Stochastic Energy Balance Model

Weather noise

Monthly and longer time scales

$$\frac{dT_a}{dt} = \alpha(T_o - T_a) - \gamma_a T_a + N_a$$

$$\frac{dT_o}{dt} = \beta(T_a - T_o) - \gamma_o T_o$$



Barsugli and Battisti (1998), Wu et al. (2006)

Stochastic Energy Balance Model

Monthly and longer time scales

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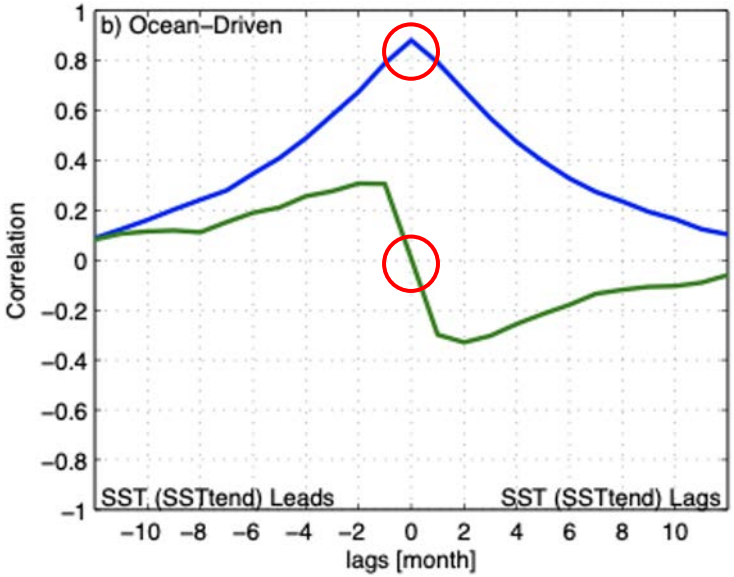
Ocean noise



Wu et al. (2006)

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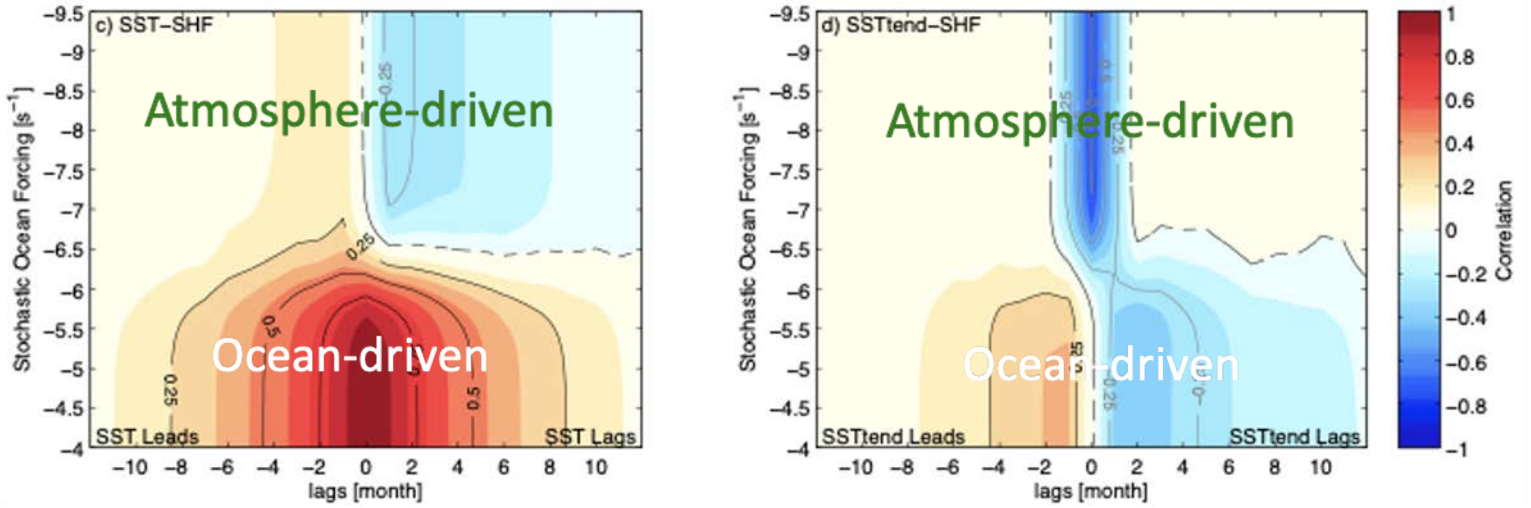


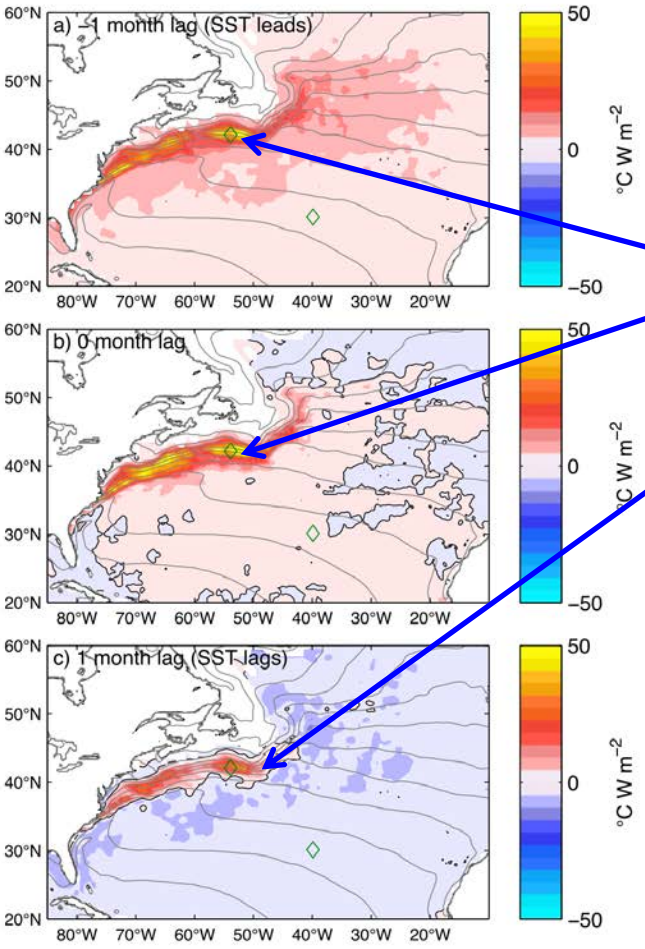
Bishop et al. (2017)

Where: Ocean-Driven?

SST Leads by 1 month

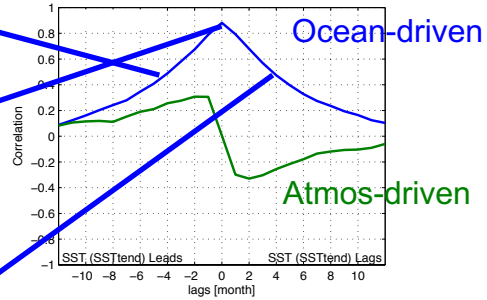
Simultaneous

SST Lags by 1 month



Symmetric

SST-SHF Correlation



Analysis Methodology

- 0.25° NOAA OISST
- 1° OAFlux Turbulent heat fluxes (latent+sensible)
  - 1985-present
  - Remapped to 0.25° NOAA OISST grid
- Monthly-averaged data
- Anomalies (mean climatology removed)
- Removed Niño 3.4 by linear regression

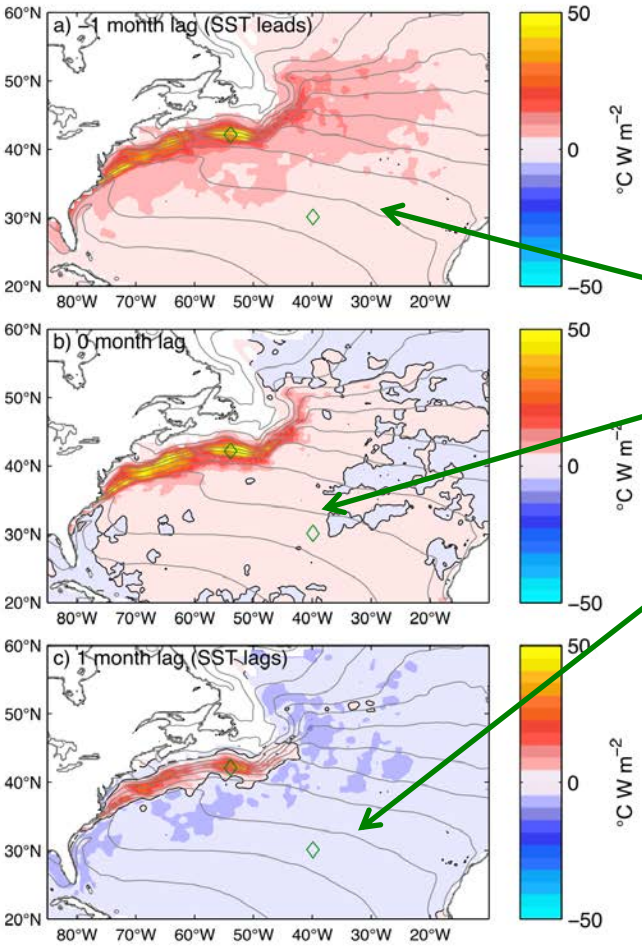
Bishop et al. (2017)

Where: Atmosphere-Driven?

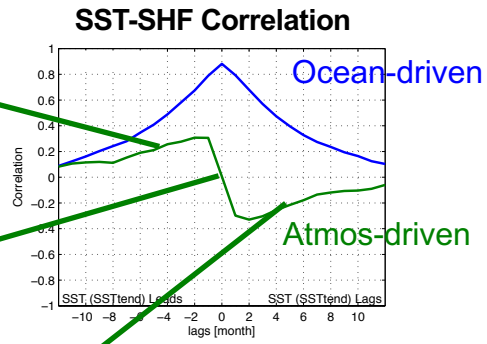
SST Leads by 1 month

Simultaneous

SST Lags by 1 month

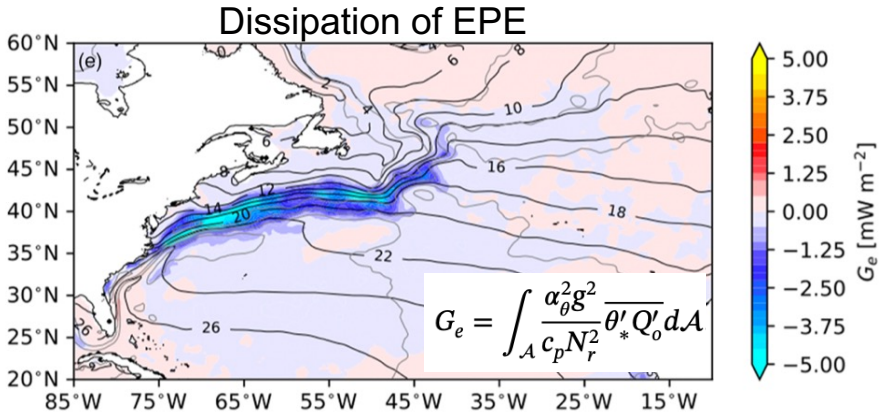


Asymmetric

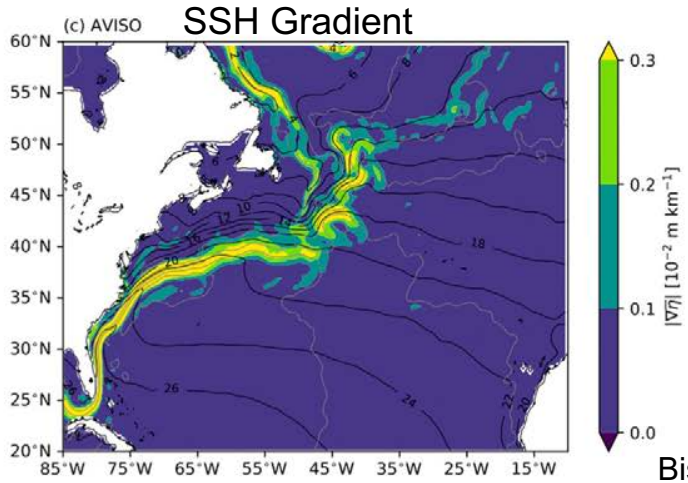


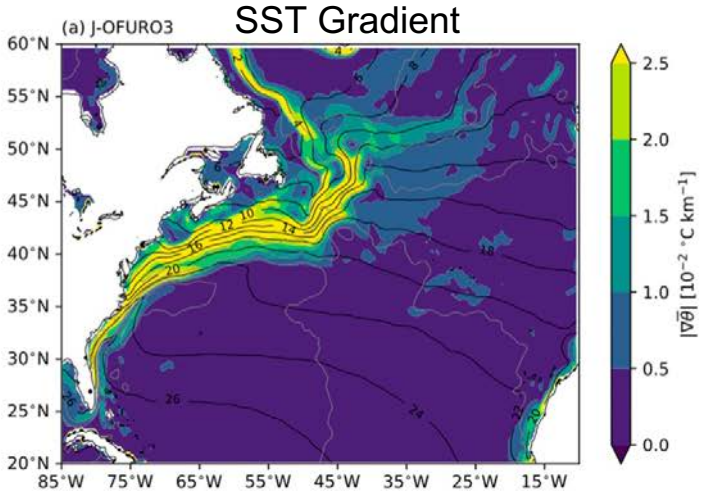
Bishop et al. (2017)

Where: Dissipation of EPE



- Air-sea interaction removes EPE up to 5 mW m^{-2} within the Gulf Stream SST front.
- Comparable results found in Kuroshio Extension region (Ma et al. 2016).
- Spatial offset of SSH vs. SST gradients with air-sea interaction favoring SST front on northern side of the Gulf Stream.





Bishop et al. (2020)

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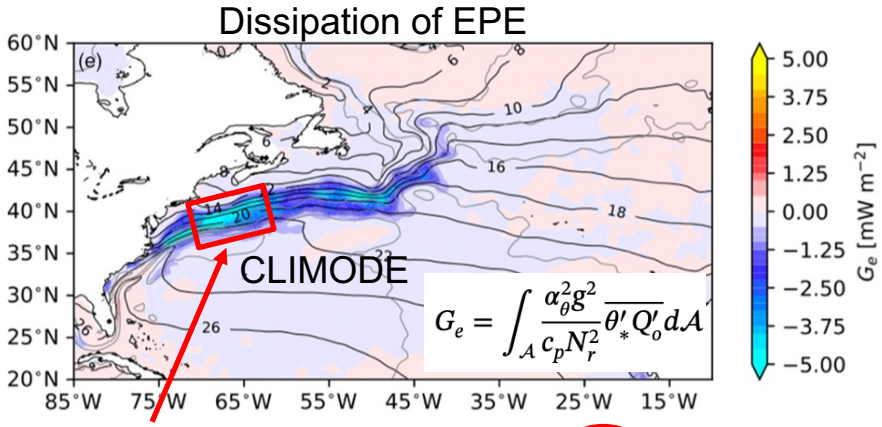

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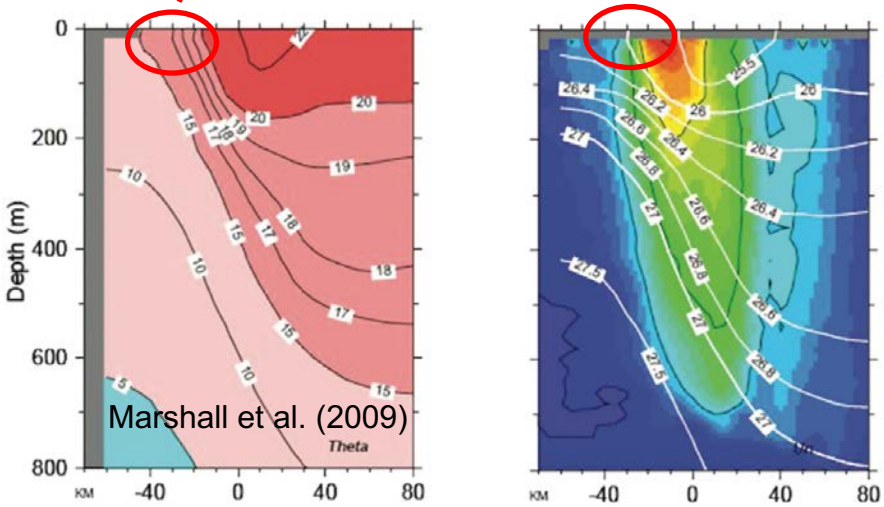
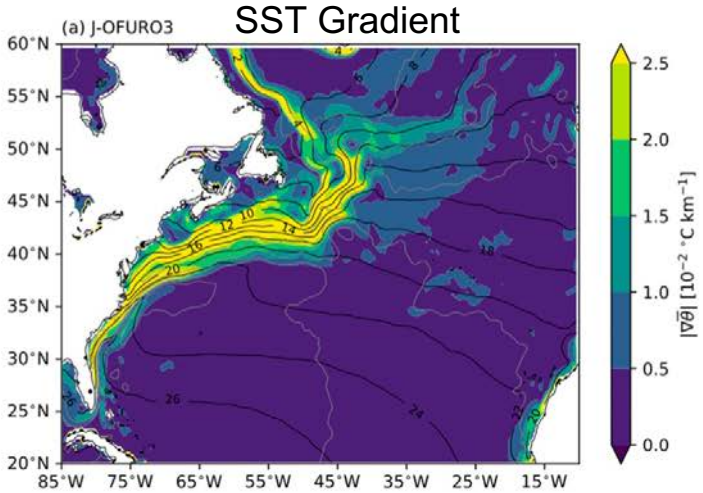
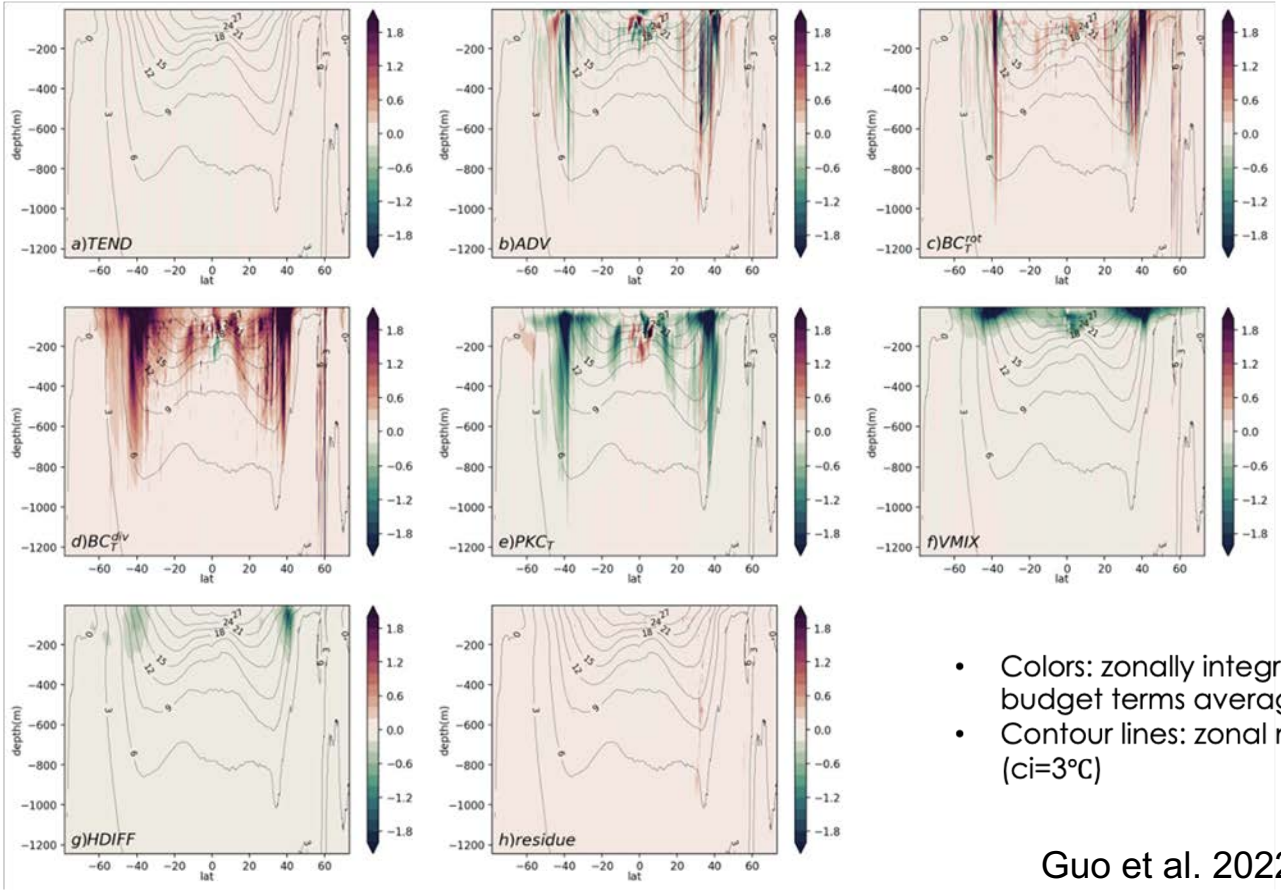




Closed Global EPE Budget in High-Resolution Model

$$TEND = ADV + BC^{rot} + BC^{div} + PKC + VMIX + HDIFF + residual$$



- Colors: zonally integrated T-variance budget terms averaged over 20 years.
- Contour lines: zonal mean temperature (ci=3℃)

Guo et al. 2022, in press JPO

Closed Global EPE Budget in High-Resolution Model

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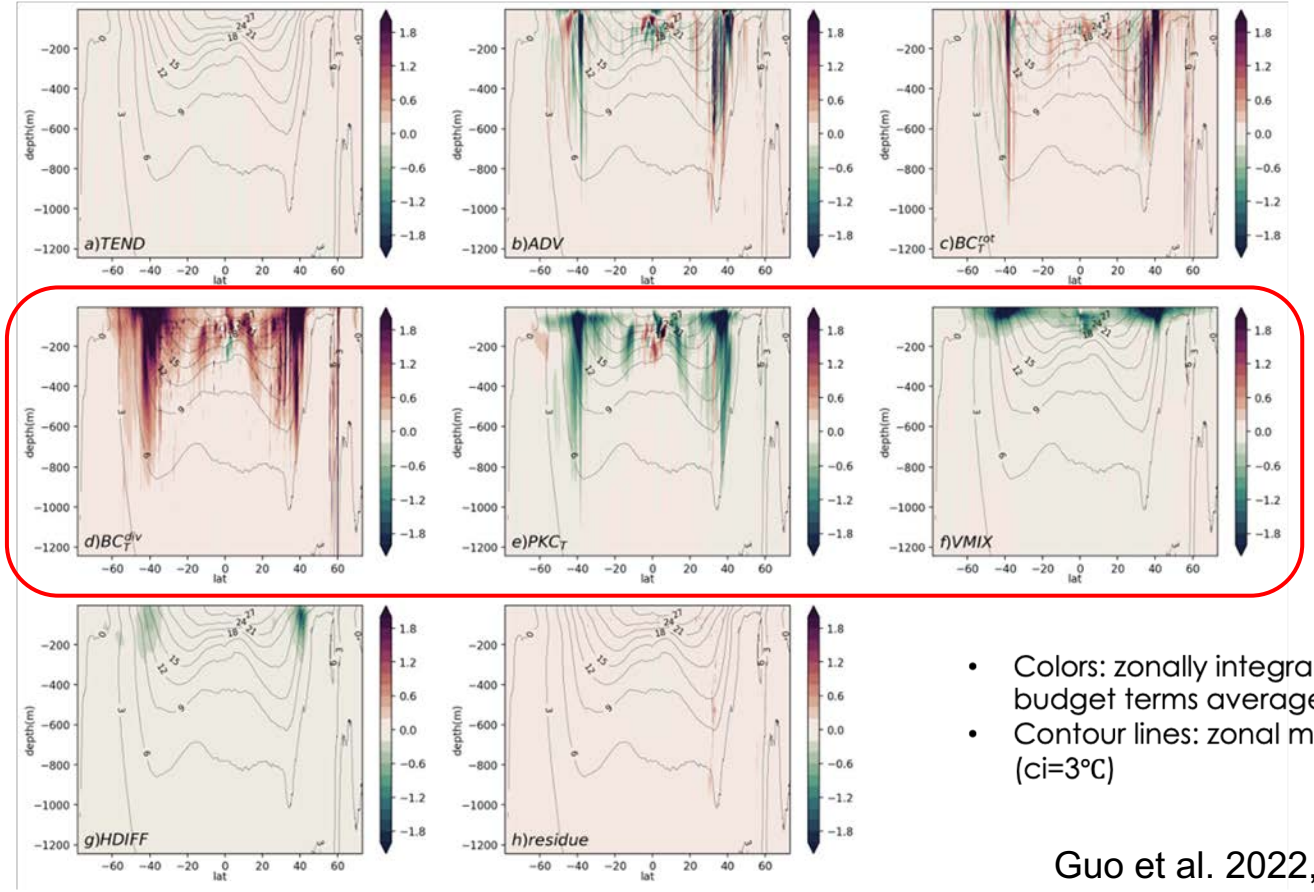

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Guo et al. 2022, in press JPO

Closed Global EPE Budget in High-Resolution Model

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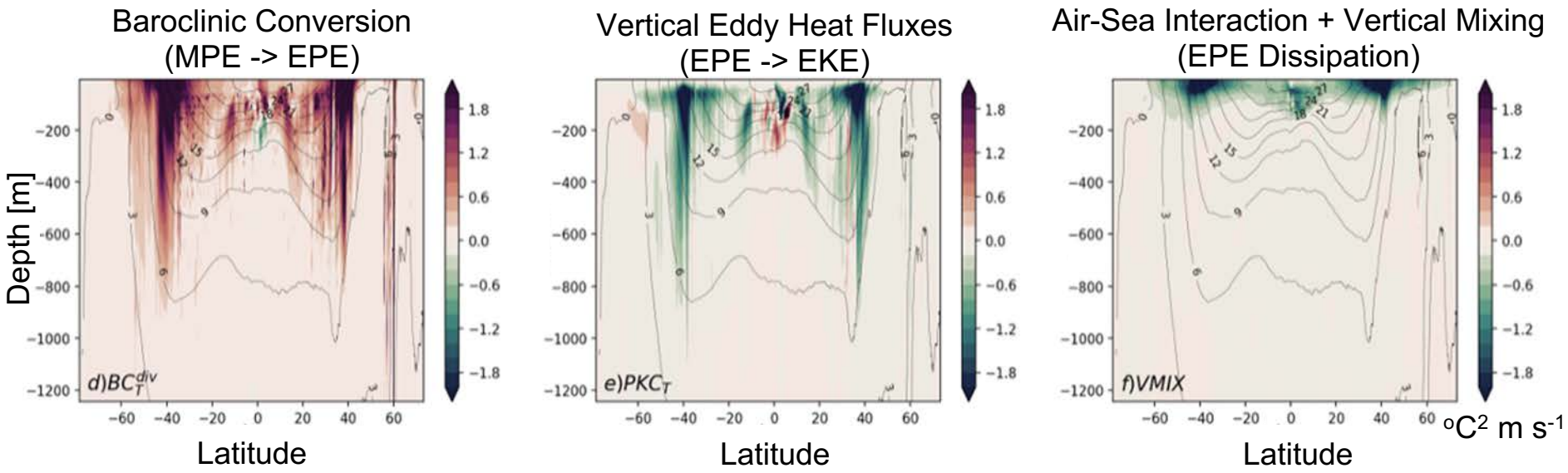
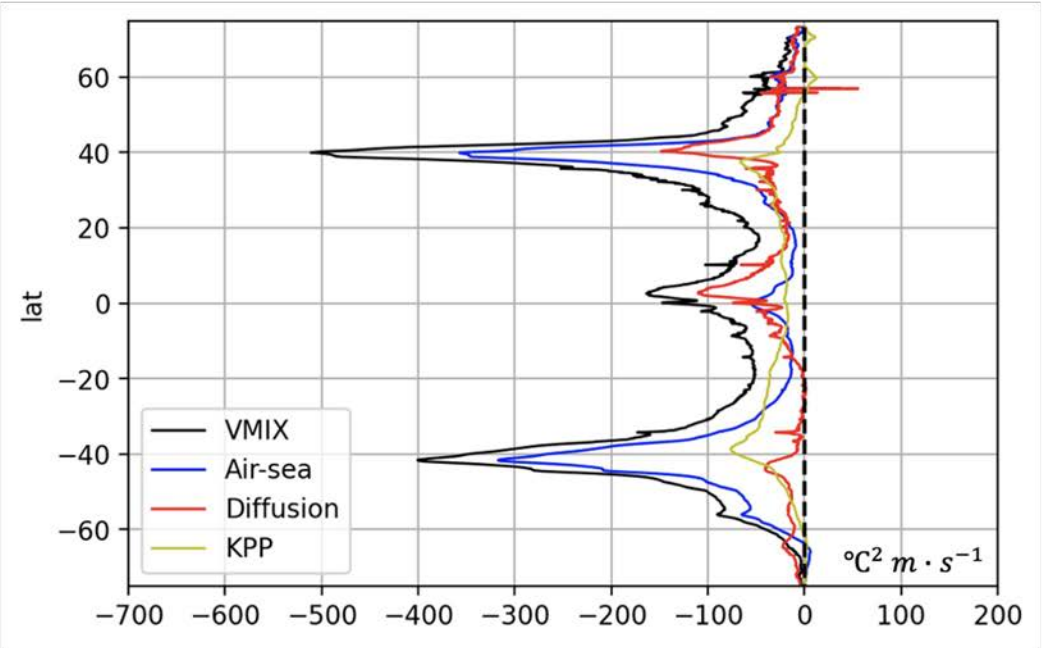


- Approximate 3-way EPE balance: Baroclinic Instability pathway MPE -> EKE.
- Vertical mixing (including air-sea interaction) confined to upper ocean.
- Baroclinic instability is ~60% efficient in the presence of vertical mixing + air-sea interaction.

Guo et al. 2022, in press JPO

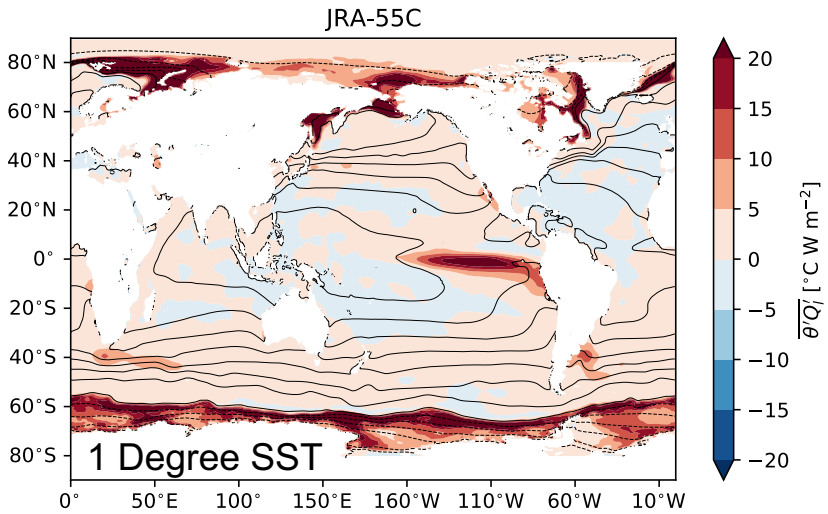
Air-Sea Interaction vs. Interior Mixing

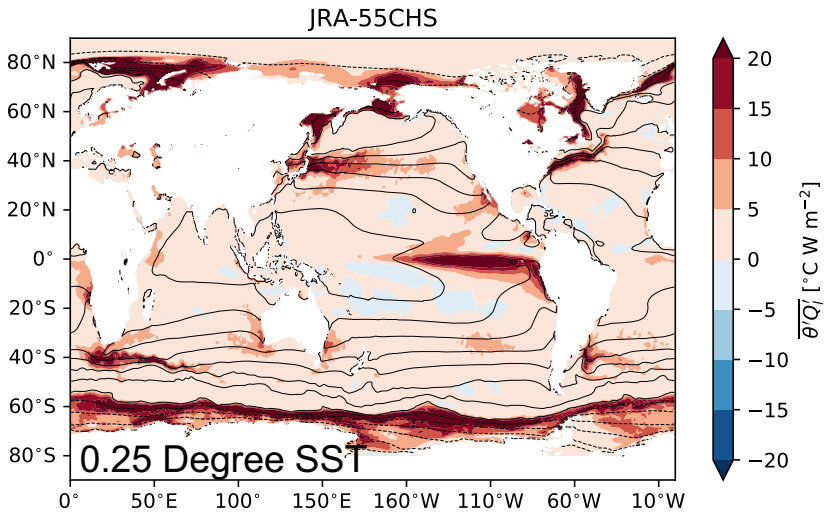


- Globally, air-sea interaction and interior mixing play comparable roles in EPE dissipation.
- In mid-latitudes, mesoscale air-sea interaction has the largest contribution to VMIX.
- In tropics, the mixing associated with diffusive flux dominates over other processes.

Guo et al. 2022, in press JPO

Time & Space Scales: Spatial Resolution



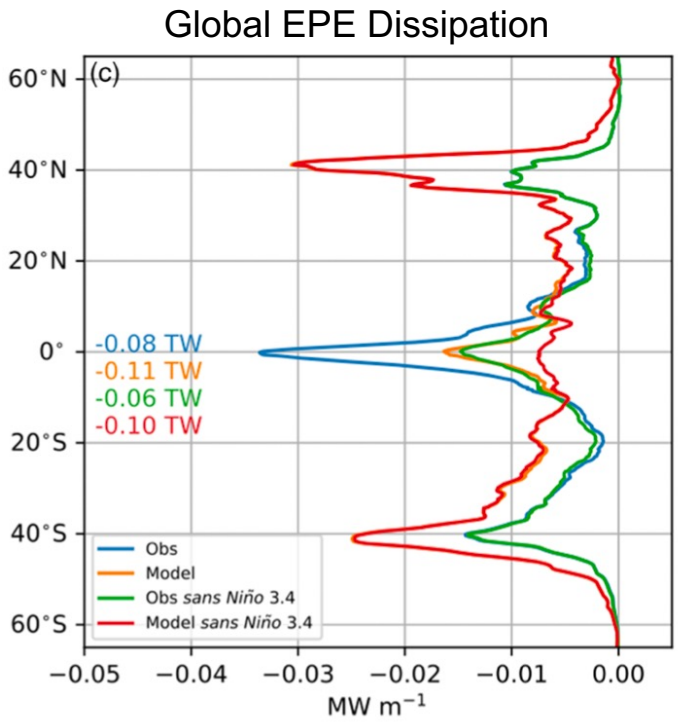


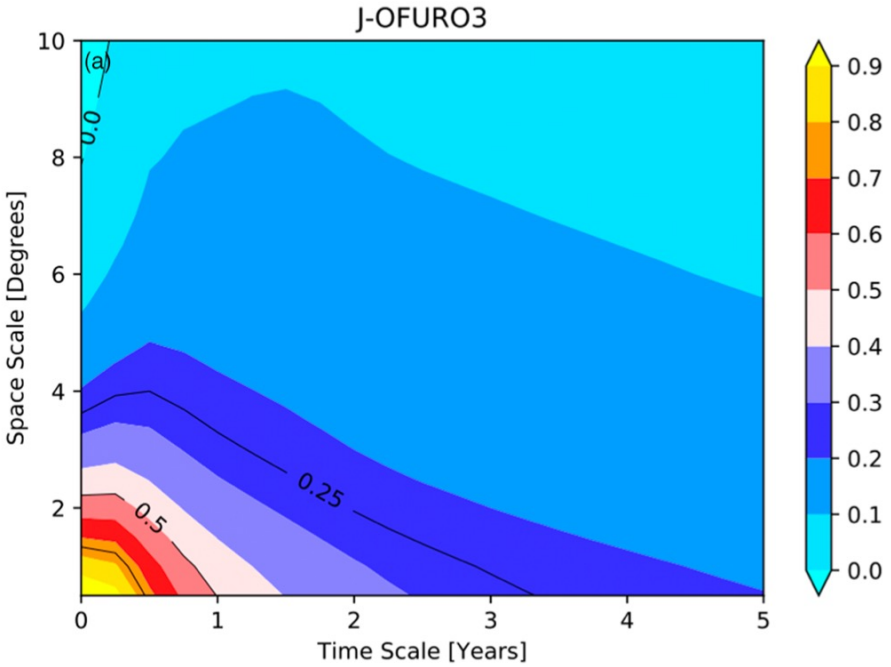
- Monthly-average data
- Positive values indicate SST-LHF anomalies co-vary
- Two Scenarios:
  - Warm SSTa associated with anomalous heat loss (SSTa > 0 & LHFa > 0)
  - Cold SSTa associated with anomalous heat gain (SSTa < 0 & LHFa < 0)
- Enhanced co-variability between SST-LHF anomalies in the Midlatitude Western Boundary Currents with high-res SST.

New JRA-55CHS reanalysis 1985-2012

- High-resolution SST
- **No satellites** for a more complete dataset
- Monthly and 3-hourly data datasets courtesy of Dr. Hisashi Nakamura (U. Tokyo)

Time & Space Scales Needed?

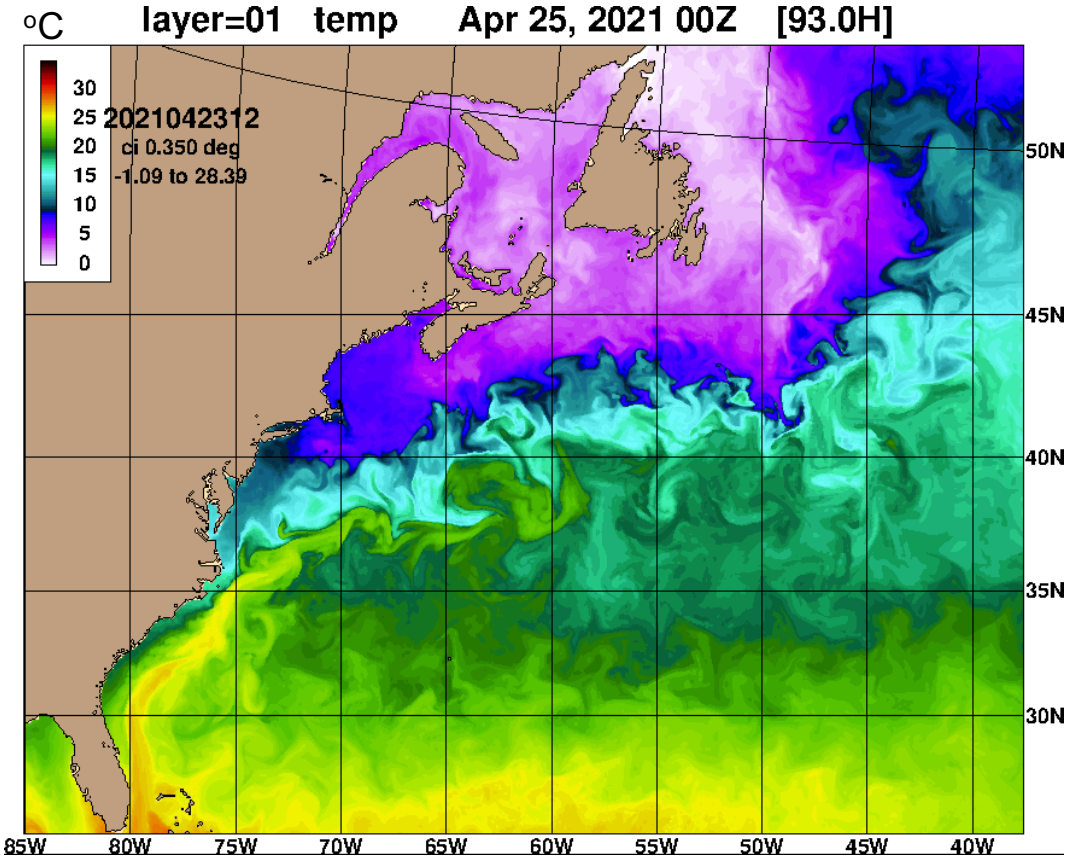




- EPE dissipation peaks at the equator and midlatitudes.
- Half of the EPE sink is confined to time scales less than a year and length scales less than 2°.

Bishop et al. 2020, JAMES

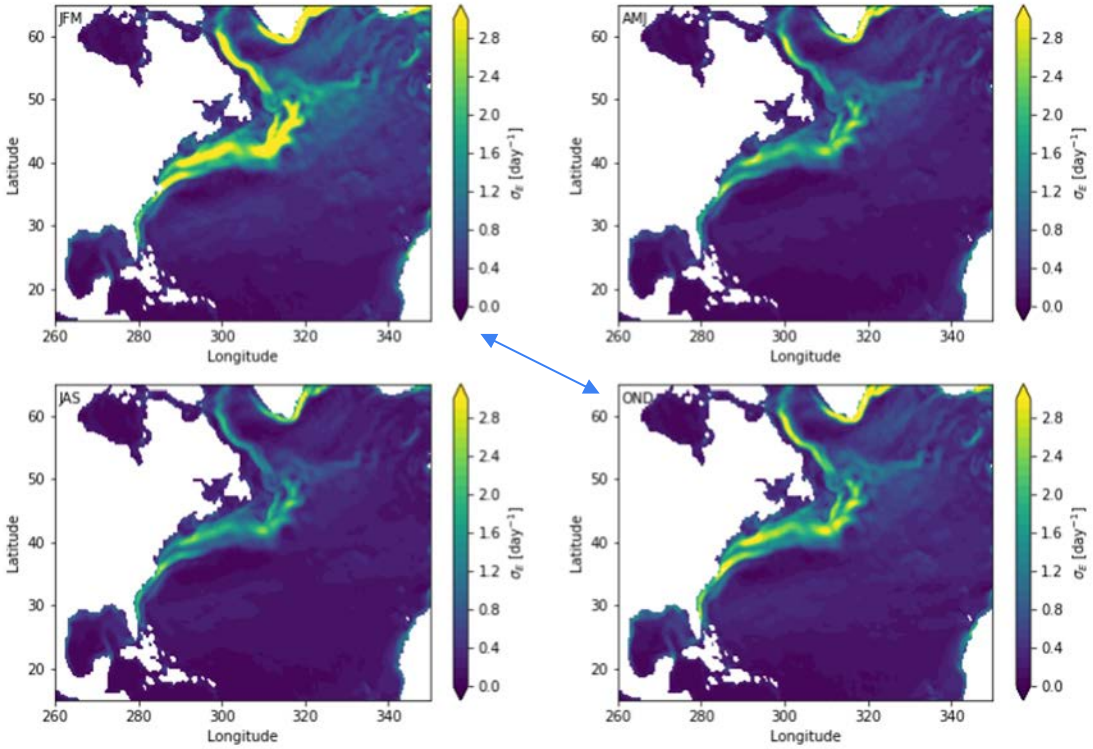
Time & Space Scales: Sea Surface Temperature



https://www7320.nrlssc.navy.mil/GLBhycomcice1-12/navo/glfstrsst_nowcast_anim365d.gif

Eady Growth Rates in the Mixed Layer

OISST + MIMOC Climatology

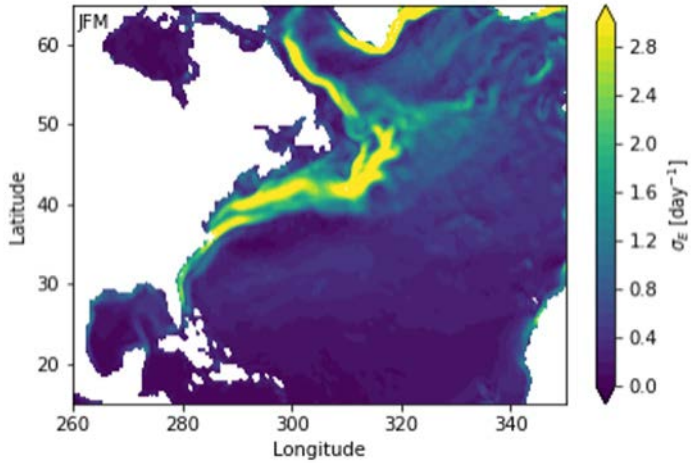


$$\sigma_E = 0.31\frac{f|\overline{\mathbf{u}}_z|}{N} \approx 0.7|\nabla\overline{\theta}|\sqrt{\alpha_\theta g H}$$

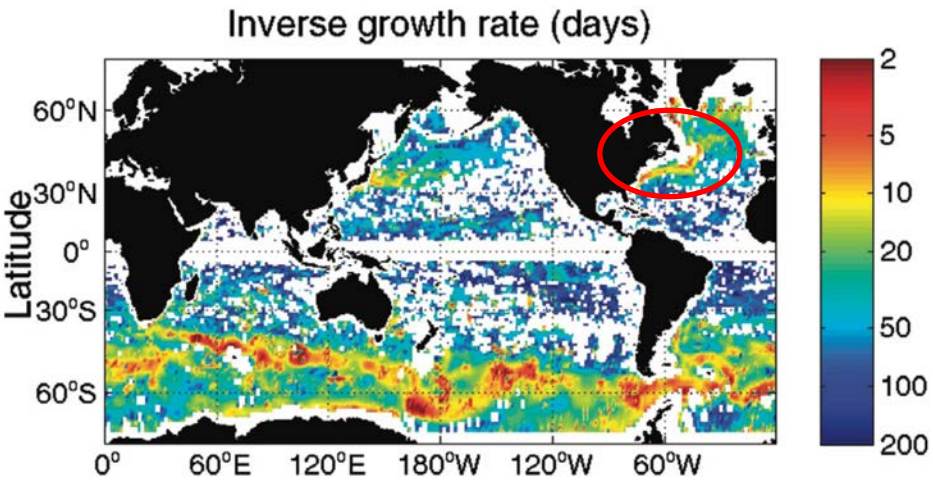
- Air-sea interaction confined to SST fronts, which are susceptible to instability.
- Fast Eady growth rates depend on both SST front strength and MLD.
- Wintertime Eady growth rates are the highest when frontal strength is strongest and mixed layers are deepest.

Eady Growth Rates in the Mixed Layer

Mixed Layer



Thermocline

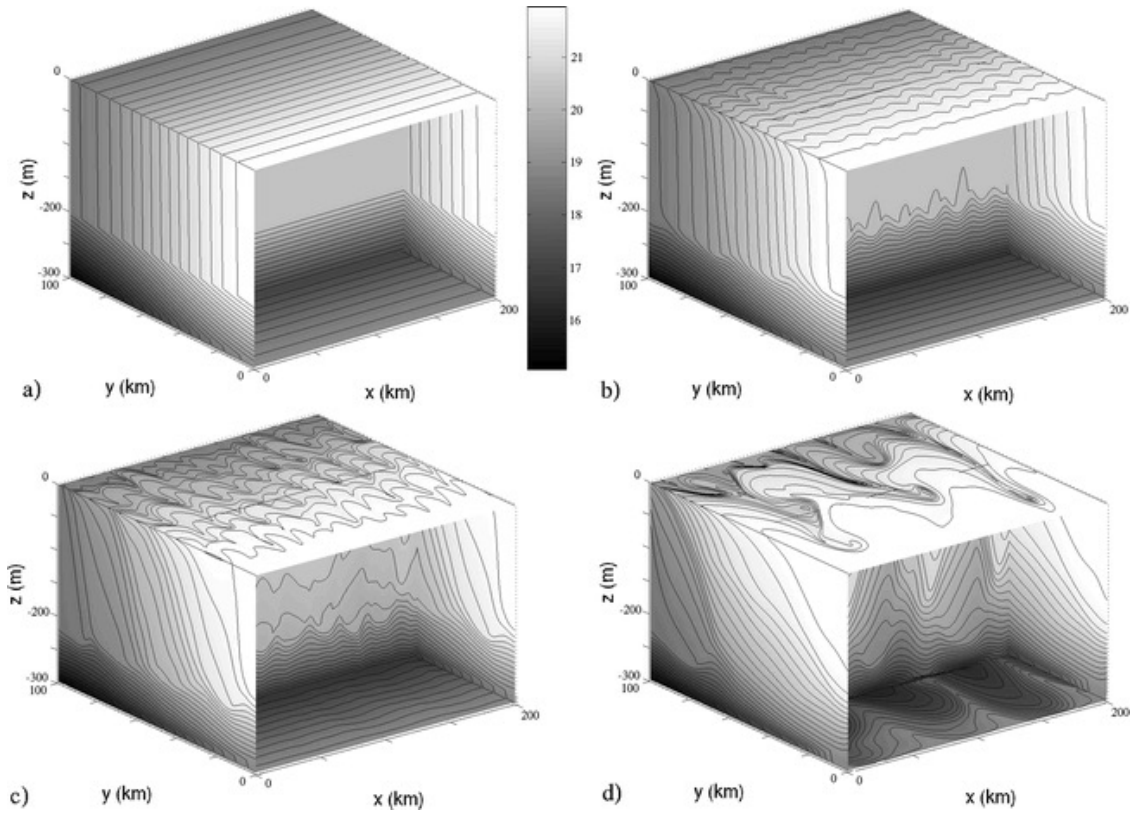


Smith 2007, JMR

- Fast Eady growth rates in ML (Submesoscale):
  - Less than 1 day inverse growth rates.
- Thermocline instabilities are slower (Mesoscale):
  - 5-10 day inverse growth rates.

Mixed Layer Instabilities

- Fronts relax (restratify) from baroclinic instability.
- In the process there is a transfer of energy from the mean state to eddies.
- This process is parameterized in coarse-resolution climate models (Fox-Kemper & GM parameterization).
- The GM parameterization does not include air-sea feedbacks. It is essentially an energy sink.



Boccaletti et al. 2007, JPO

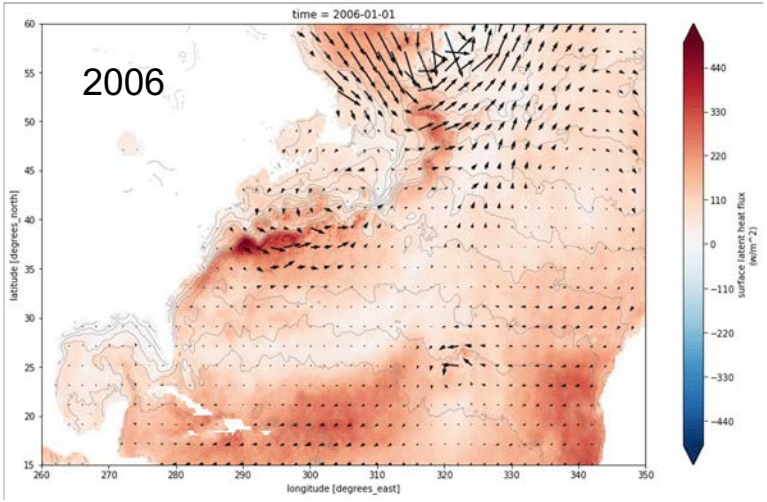
Submonthly Observations of Turbulent Heat Fluxes

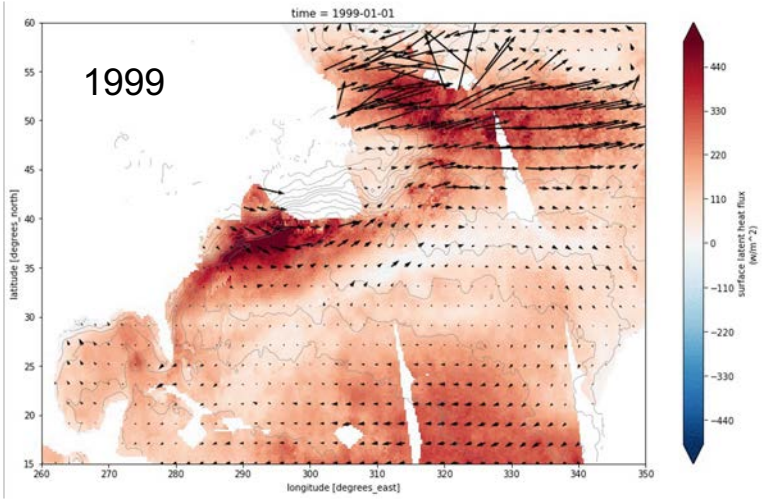
J-OFURO3 Reanalysis

- SST, LHF, SHF, SWR, LWR, NHF, TAUX, TAUY
- 0.25 degree spatial resolution
- Daily 1988-2018
- **Good coverage 2000-2018**

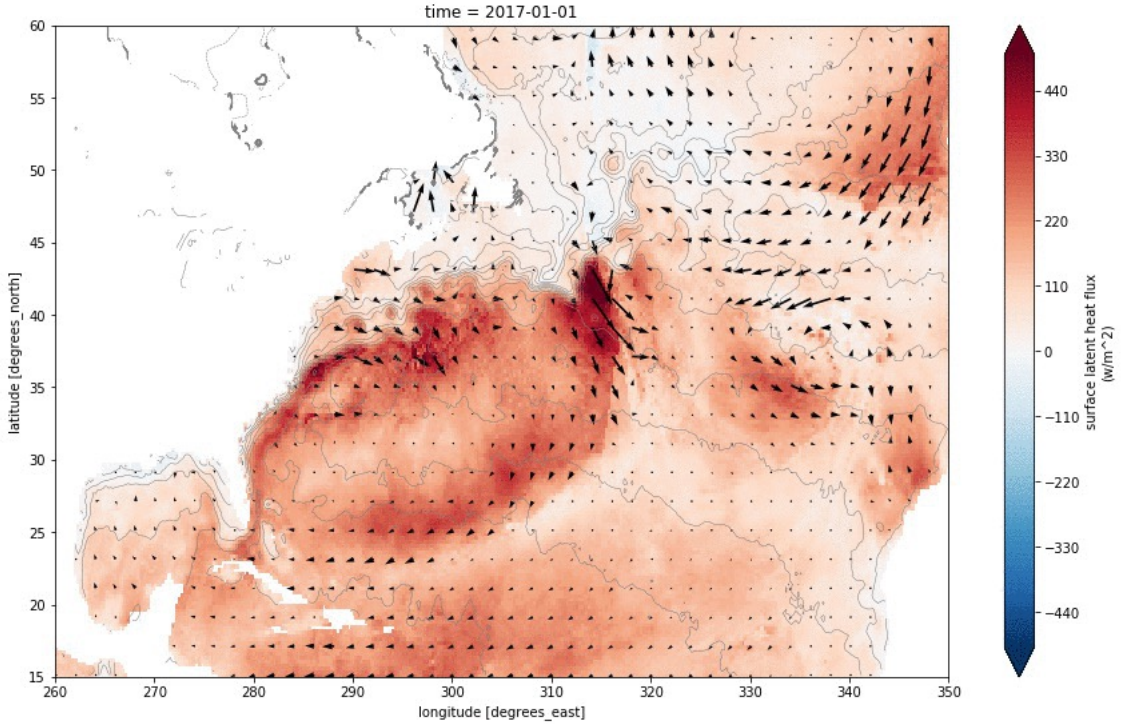
$$Q_o = \rho_a L C_E (q_s - q_a) |\mathbf{U}_{10}|$$

Latent heat flux (color contours)
Wind stress vectors
SST (gray contours)





2017


time = 2017-01-01
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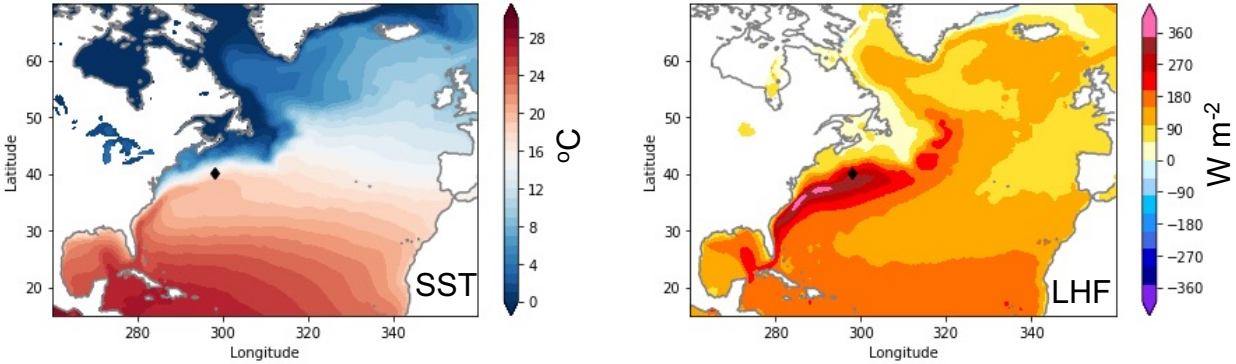
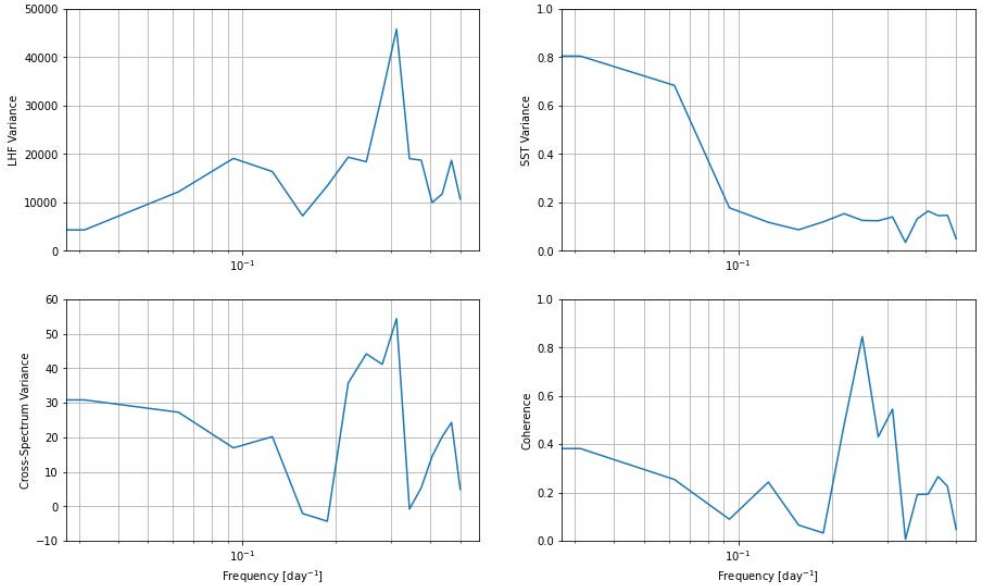
longitude [degrees_east]
60
55
50
45
40
35
30
25
20
15
260
270
280
290
300
310
320
330
340
350
440
330
220
110
0
−110
−220
−330
−440
surface latent heat flux
(w/m^2)

Power (Cross) Spectra

2000-2018 JFM Average



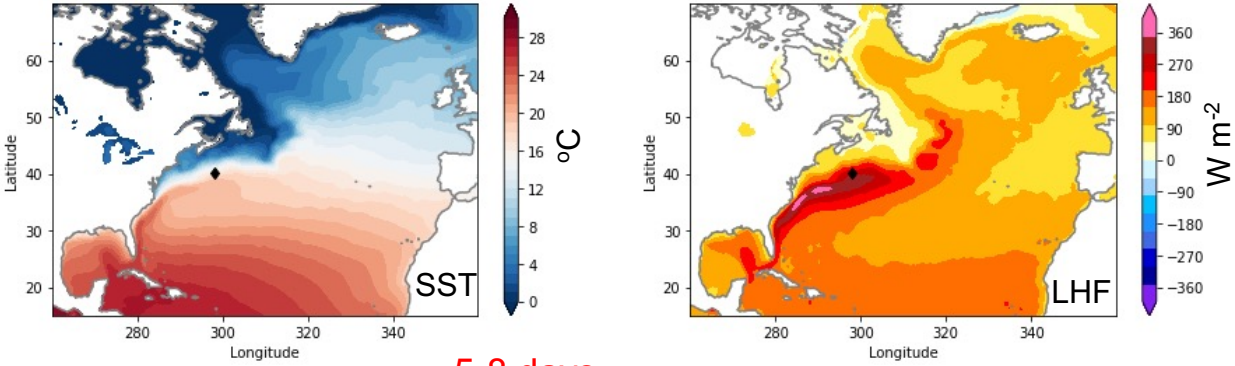
2007



Power (Cross) Spectra

- LHF power spectrum
  - Peaks 5-8 & ~10 days
  - Atmosphere Synoptic Scale

2000-2018 JFM Average



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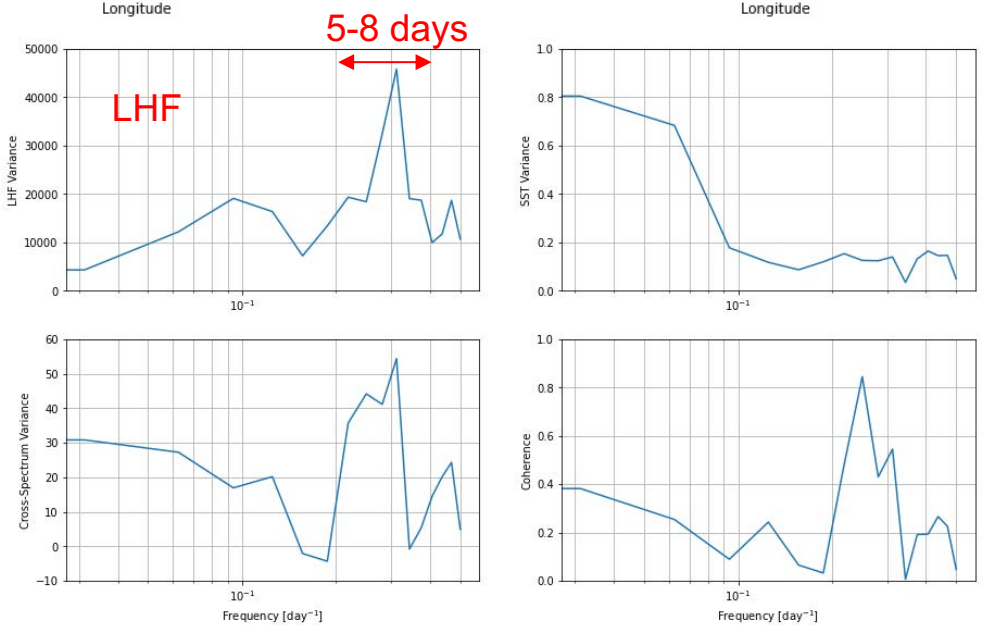

Power (Cross) Spectra

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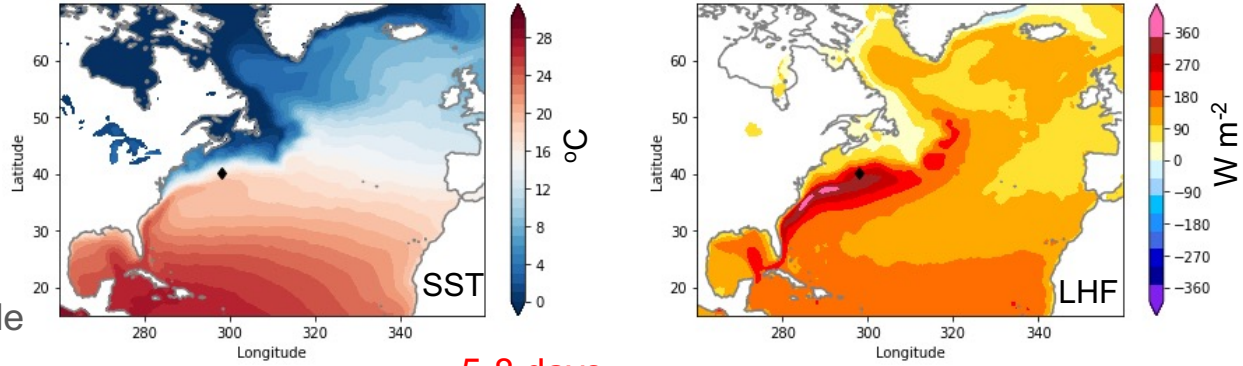
- SST power spectrum
  - Red spectrum with power greater than 15 days
  - Ocean Mesoscale



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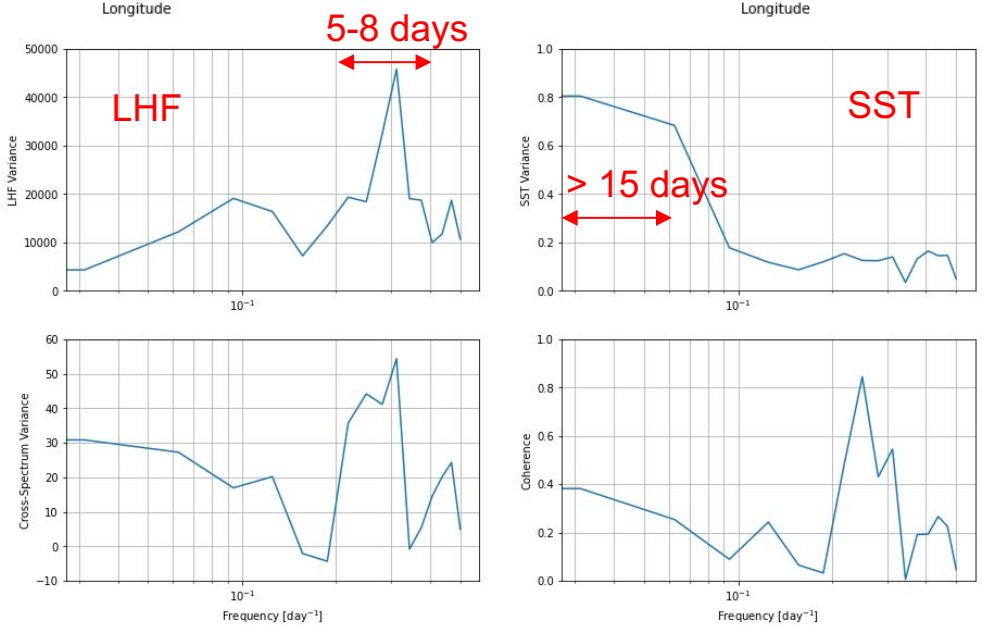

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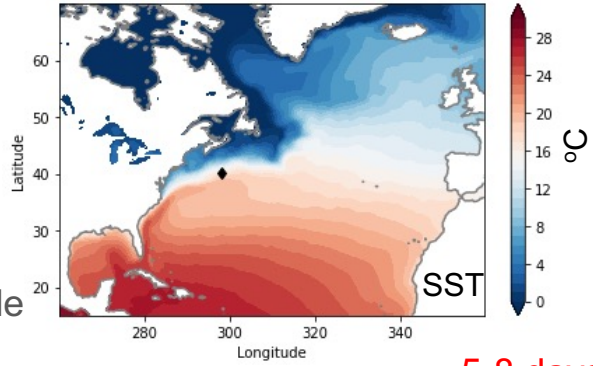
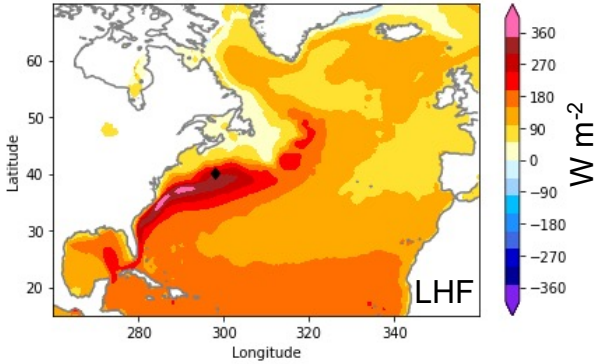
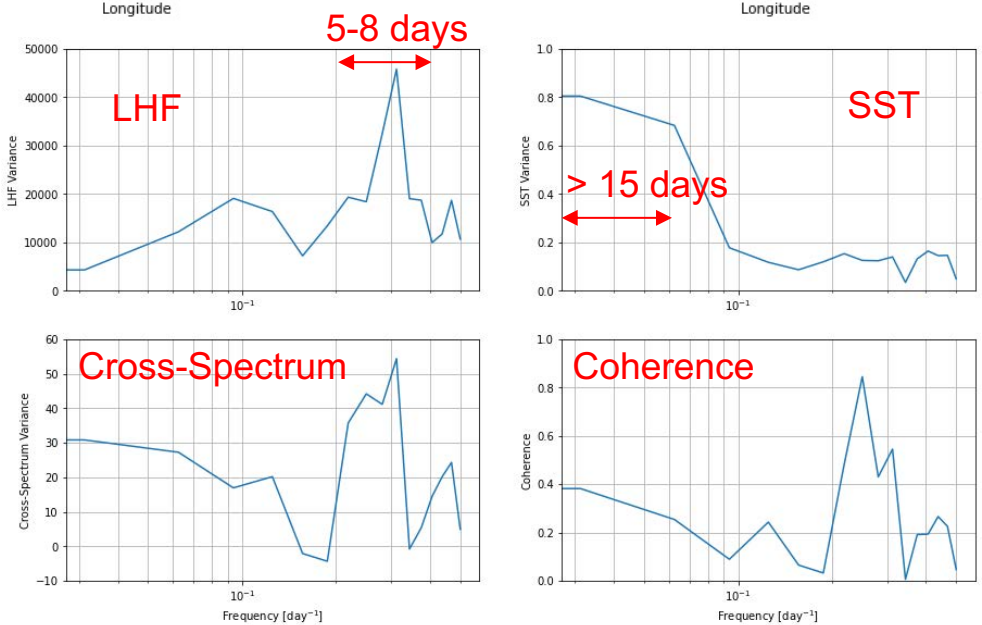


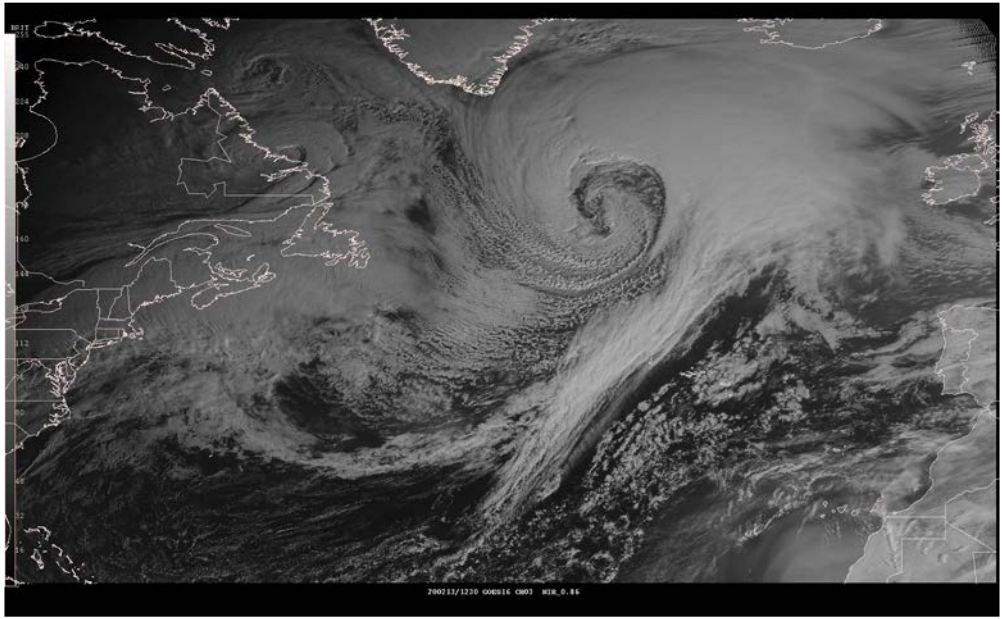


- LHF power spectrum
  - Peaks 5-8 & ~10 days
  - Atmosphere Synoptic Scale
- SST power spectrum
  - Red spectrum with power greater than 15 days
  - Ocean Mesoscale
- SST-LHF Cross-Spectrum
  - Peaks in Synoptic & Mesoscale
  - Higher coherence in Synoptic scale.

2007



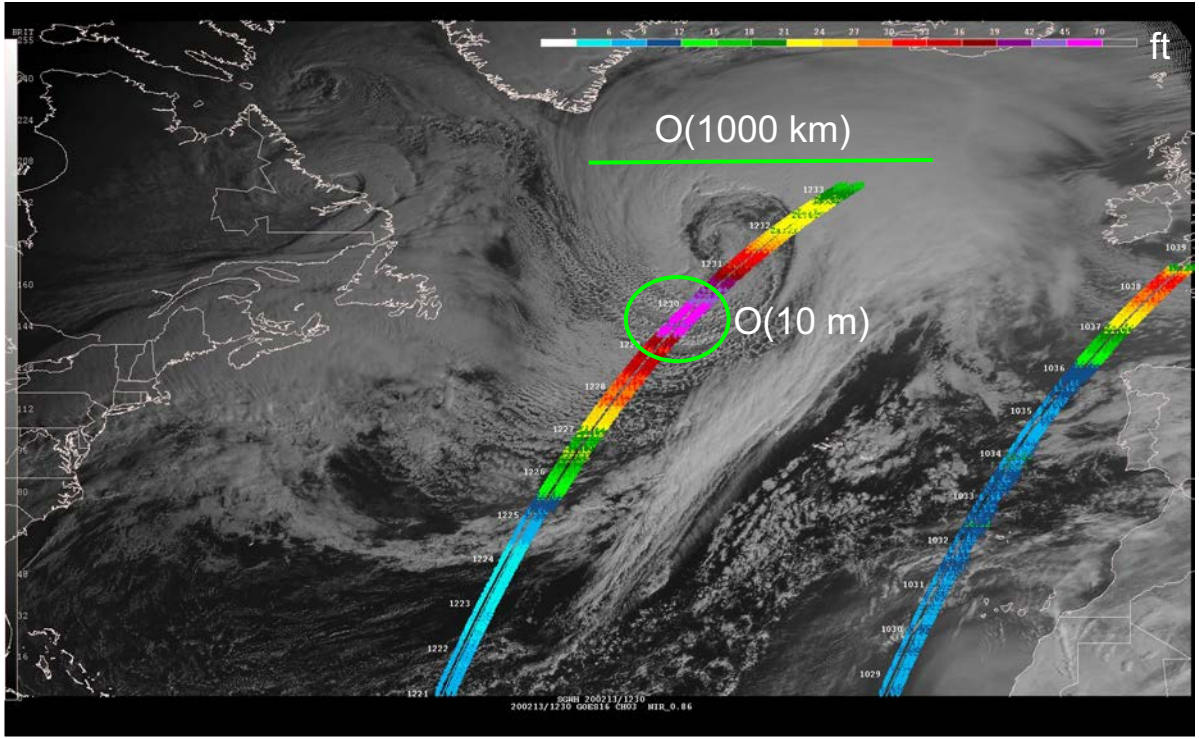
Hurricane-Force Lows



Hurricane force (HF) wind warnings are issued by the Ocean Prediction Center (OPC) when non-tropical sustained winds of 64 kt (74 mph) or greater are being observed, or are forecast to occur within 48 hours. These warnings represent the highest wind warning category issued by OPC and the National Weather Service.

https://storymaps.arcgis.com/stories/83038d799d7249b68e81be1aa7ff84fd

Hurricane-Force Lows



https://storymaps.arcgis.com/stories/83038d799d7249b68e81be1aa7ff84fd

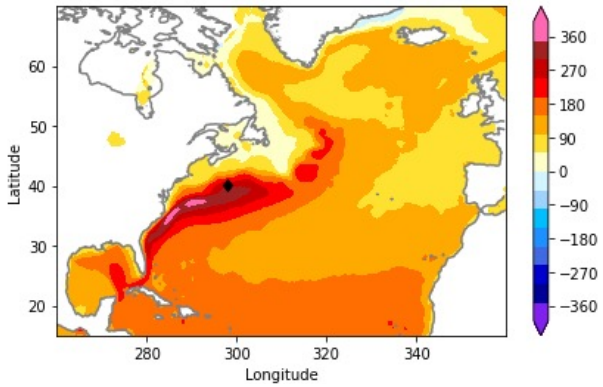
Cross-scale interaction atmosphere synoptic scale → surface gravity waves.

- Atmosphere synoptic scale is O(1000 km) length scales and 2-8 day time scales.
- Ocean mesoscale O(100 km) length scales and time scales of weeks to months.
- Ocean submesoscales O(1-10 km) and time scales of days.
- Langmuir mixing & SGWs O(10 m) and time scales of seconds to minutes.

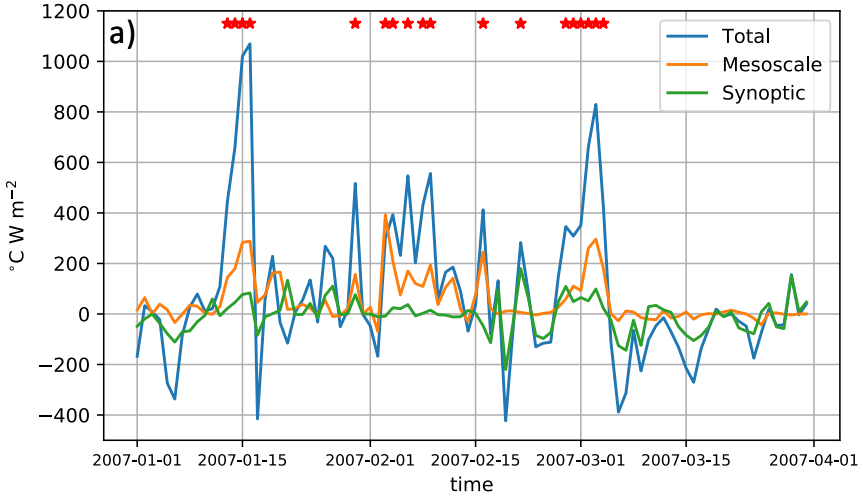
Atmosphere synoptic-ocean mesoscale interaction:

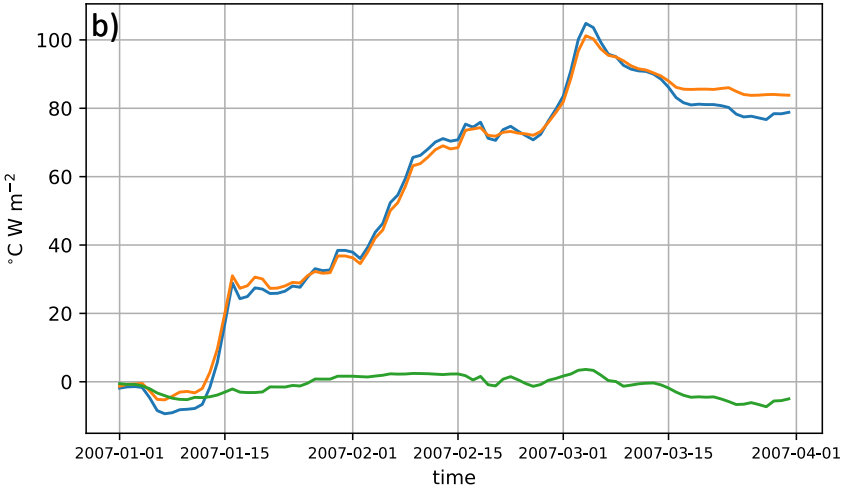
Spatial Decomposition

- Analyze daily data from J-OFURO3 product
- Spatially smooth anomalies with a cutoff of 500 km.
  - Ocean Mesoscale (< 500 km):
    - Includes meanders as well as a cut-off vortices.
  - Atmosphere Synoptic (> 500 km)



January-March 2007

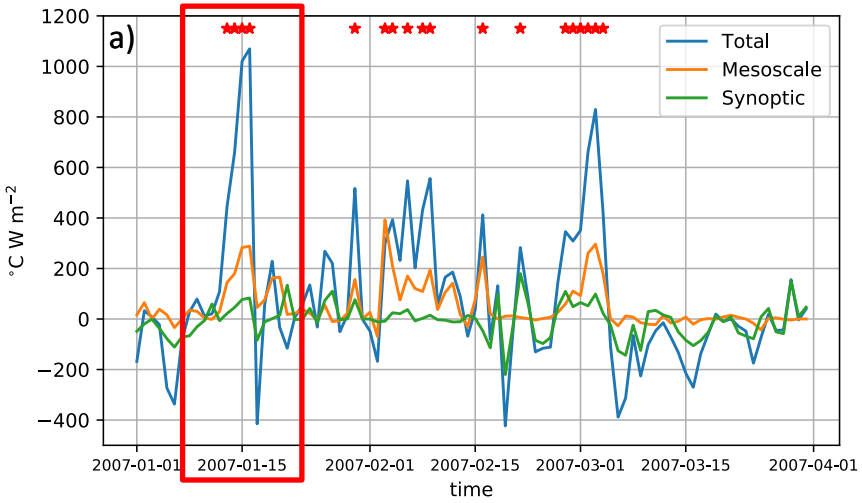


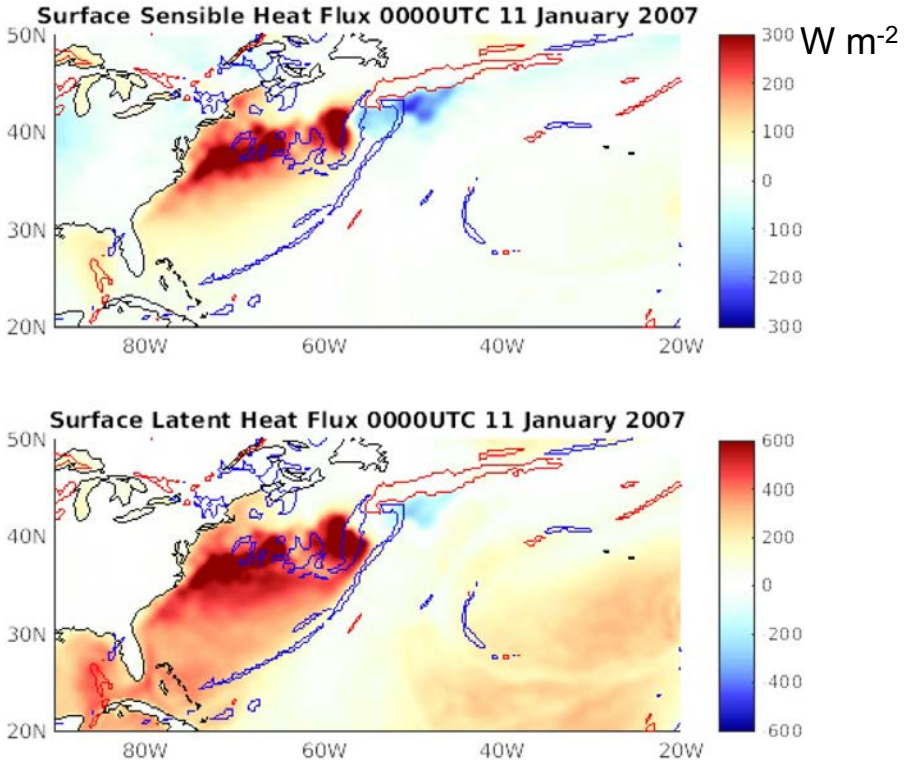


Collaboration with Rhys Parfitt & Philip Sura (FSU)

Atmosphere synoptic-ocean mesoscale interaction:

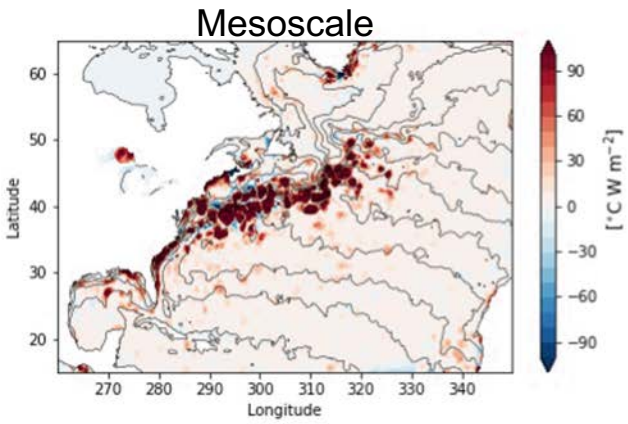
Spatial Decomposition

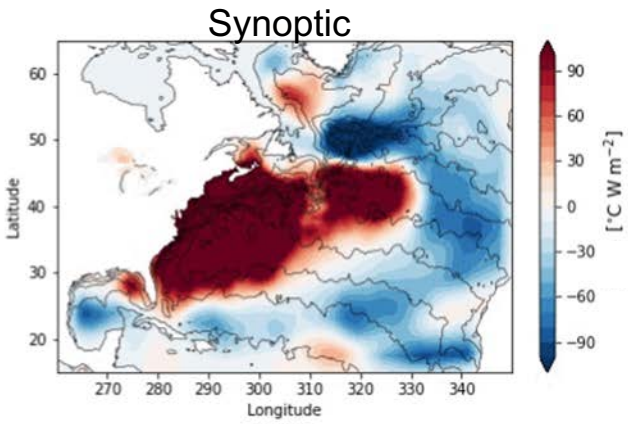




Collaboration with Rhys Parfitt & Philip Sura (FSU)

Mesoscale vs. Synoptic Scale Air-Sea Interaction

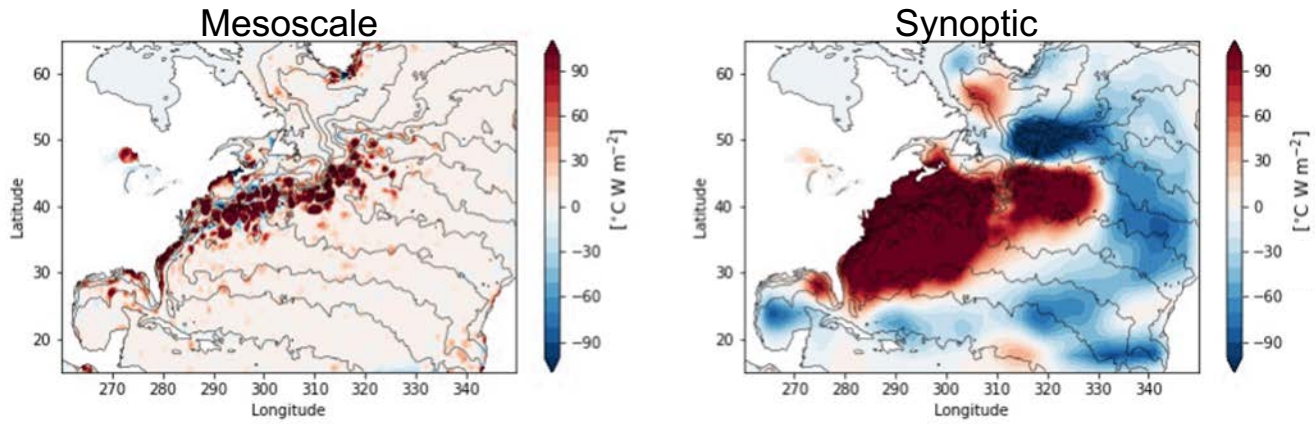


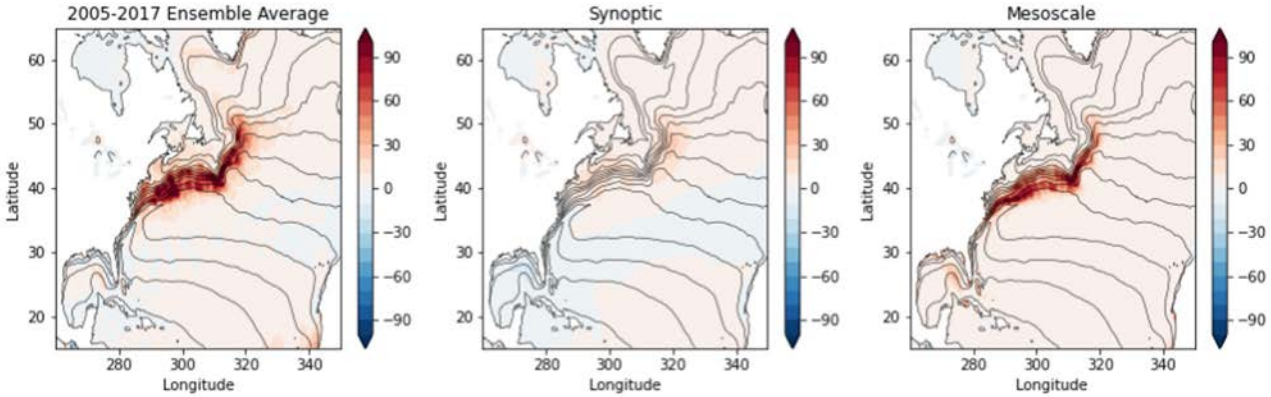


Daily snapshots January-March 2009

Collaboration with Rhys Parfitt & Philip Sura (FSU)

Mesoscale vs. Synoptic Scale Air-Sea Interaction





Ensemble Ave

Conclusions

1. What do we know about coupling between sea surface temperature (SST) and turbulent heat fluxes (THF) at monthly and longer time scales?
   - **At monthly and longer time scales the ocean mesoscale is the dominant player in driving coupling between sea surface temperature and turbulent heat fluxes in the midlatitude North Atlantic in the vicinity of the Gulf Stream front.**

2. Where and when?
   - **SST-THF coupling and EPE dissipation is highest on the northern side of the Gulf Stream where SST gradients are highest.**
   - **Wintertime is favored for THF extreme events.**

3. What time and space scales are needed?
   - **SST has variability that ranges from submesoscale to mesoscale that interacts with the atmosphere synoptic scale.**
   - **Long-term repeat measurements (i.e. Oleander) are needed that provide simultaneous observations (FluxSat, Gentemann et al. 2020) to resolve THF and mixed layer depths.**
   - **Targeted process studies to better understand how submesoscale to mesoscale eddies interact with wintertime synoptic weather systems.**

SST-LHF: January-March (JFM) Reynolds Decomposition

Sea Surface Temperature

$$\theta_n(x,y,t) = \overline{\theta}_n^{\mathrm{JFM}}(x,y) + \theta'_n(x,y,t)$$

n = year (2000-2018)

Latent Heat Flux

$$Q_{on}(x,y,t) = \overline{Q}_{on}^{\mathrm{JFM}}(x,y) + Q'_{on}(x,y,t)$$

SST-LHF Product: JFM average for a given year

$$\overline{\theta_n Q_{on}}^{\mathrm{JFM}} = \underbrace{\overline{\theta}_n^{\mathrm{JFM}}\overline{Q}_{on}^{\mathrm{JFM}}}_{\text{Mean}} + \underbrace{\overline{\theta'_n Q'_{on}}^{\mathrm{JFM}}}_{\text{Transient Eddy}}$$

- Partition SST and LHF into January-March (JFM) average and the deviation from the JFM average (prime value) for a given year.

Ensemble Averaging (2000-2018)

SST-LHF Product: Ensemble Average

$$[\overline{\theta_n Q_{on}}^{\mathrm{JFM}}] = [\overline{\theta}_n^{\mathrm{JFM}} \overline{Q}_{on}^{\mathrm{JFM}}] + [\overline{\theta'_n Q'_{on}}^{\mathrm{JFM}}]$$

Transient Eddy

$$[\overline{\theta}_n^{\mathrm{JFM}}][\overline{Q}_{on}^{\mathrm{JFM}}] + [\overline{\theta}^{\mathrm{JFM}*} \overline{Q}_{on}^{\mathrm{JFM}*}]$$

Mean

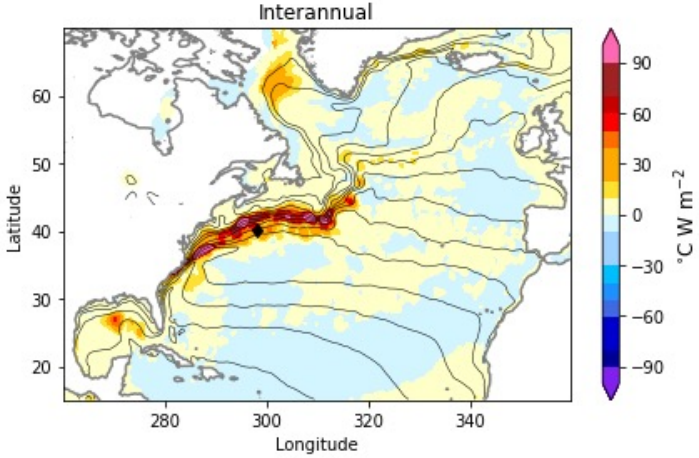
Interannual

- Brackets [( )] indicate ensemble average.
- Asterisks $(\ )^*$ indicate a deviation from ensemble average.

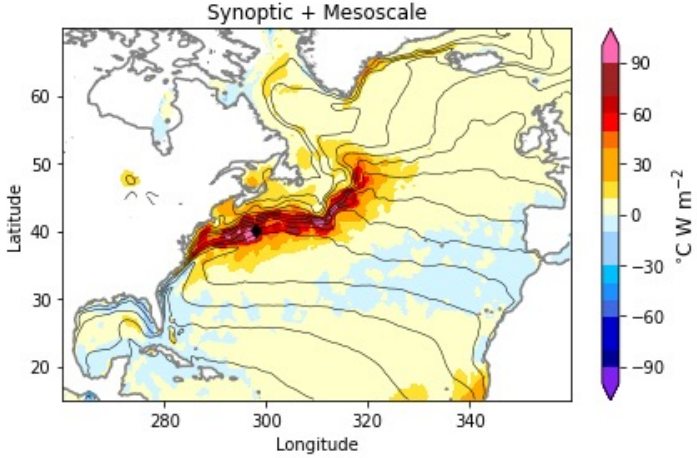
Ensemble Average (2000-2018)

Interannual vs. Transient Eddy (Synoptic + Mesoscale)

$[\overline{\theta}^{\mathrm{JFM}*}\overline{Q}_{on}^{\mathrm{JFM}*}]$

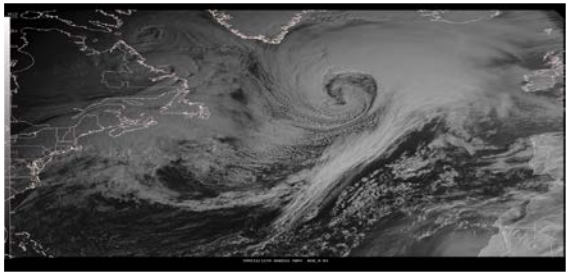


$[\overline{\theta'_n Q'_{on}}^{\mathrm{JFM}}]$



- Contributions from JFM season by transient eddies (synoptic + mesoscale) are comparable in value to year-to-year (interannual) variability in the JFM mean fields.

Hurricane-Force Lows



Hurricane force (HF) wind warnings are issued by the Ocean Prediction Center (OPC) when non-tropical sustained winds of 64 kt (74 mph) or greater are being observed, or are forecast to occur within 48 hours. These warnings represent the highest wind warning category issued by OPC and the National Weather Service.

	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	SEASON TOTALS
2005-2006	0	0	3	2	2	3	3	5	9	6	0	0	33
2006-2007	1	0	0	3	4	6	8	13	20	7	1	3	66
2007-2008	0	0	1	0	6	5	10	9	6	4	1	0	42
2008-2009	0	0	1	3	7	3	13	11	4	6	2	1	51
2009-2010	0	0	0	0	6	2	7	6	8	1	0	0	30
2010-2011	0	0	0	1	4	4	1	3	13	4	1	1	32
2011-2012	0	0	0	2	4	5	11	7	3	7	1	0	40
2012-2013	0	0	0	0	5	5	5	13	7	4	3	0	42
2013-2014	0	0	0	0	2	5	14	9	10	5	1	0	46
2014-2015	0	0	1	2	2	6	9	14	8	11	4	0	57
2015-2016	1	1	0	0	4	1	11	11	11	7	2	1	50
2016-2017	0	1	0	1	4	1	12	10	10	9	2	0	50
2017-2018	0	0	1	1	4	4	9	9	7	8	3	1	47
2018-2019	0	0	0	2	4	7	7	8	9	4	3	1	45
2019-2020	0	0	0	3	3	4	9	9	6	3	4	1	42
2020-2021	0	0	0	3	3	8	4	6	8	7	2	1	42
	0.1	0.1	0.4	1.4	4.0	4.3	8.3	8.9	8.7	5.8	1.9	0.6	44.9

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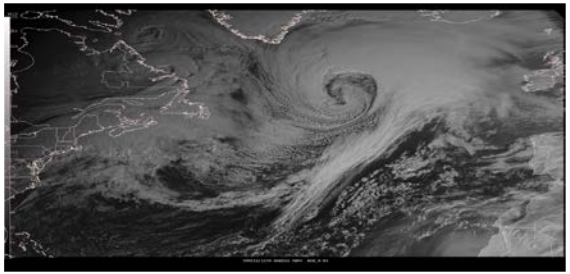
Hurricane-Force Lows



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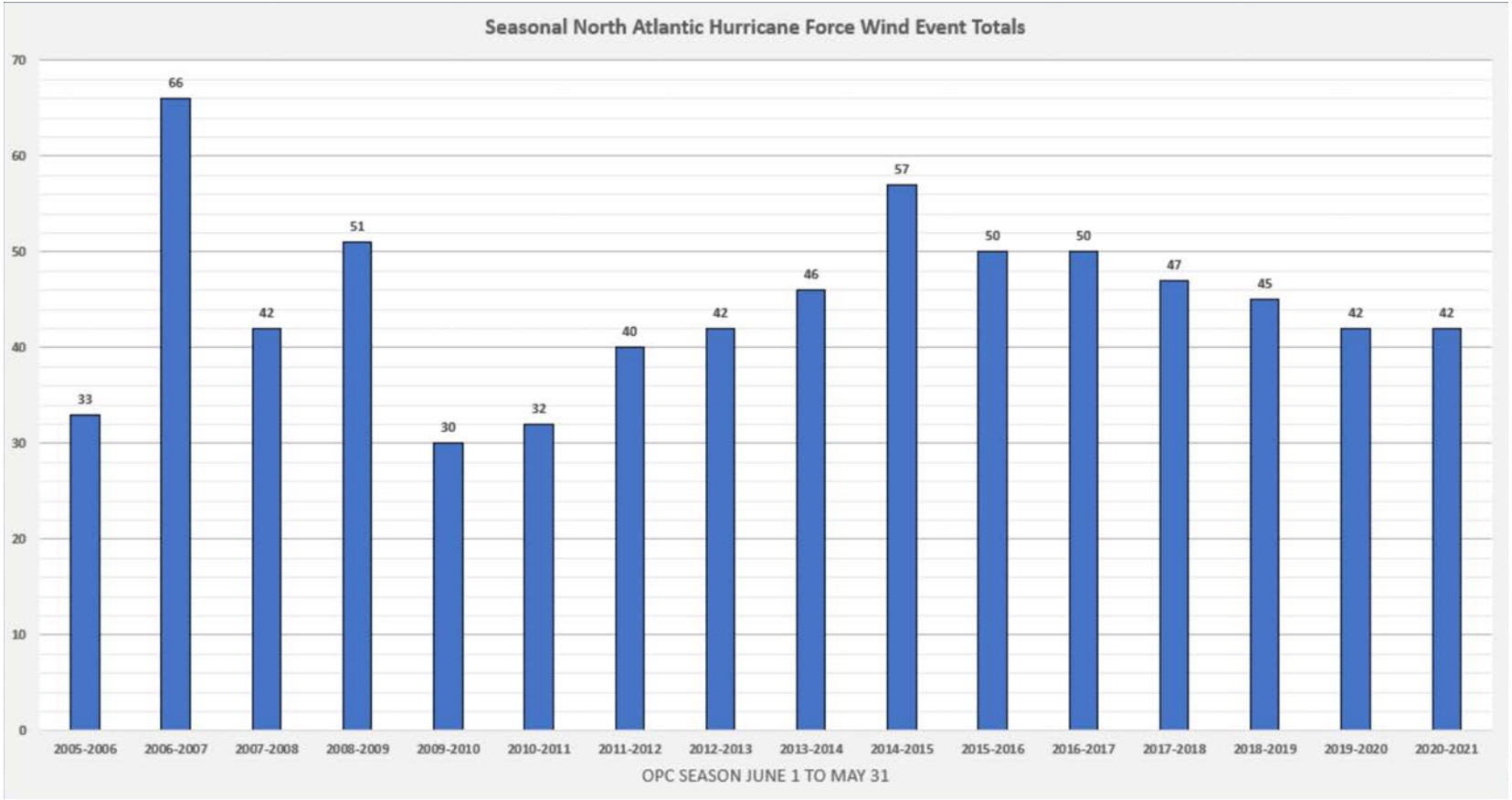
Hurricane-Force Lows



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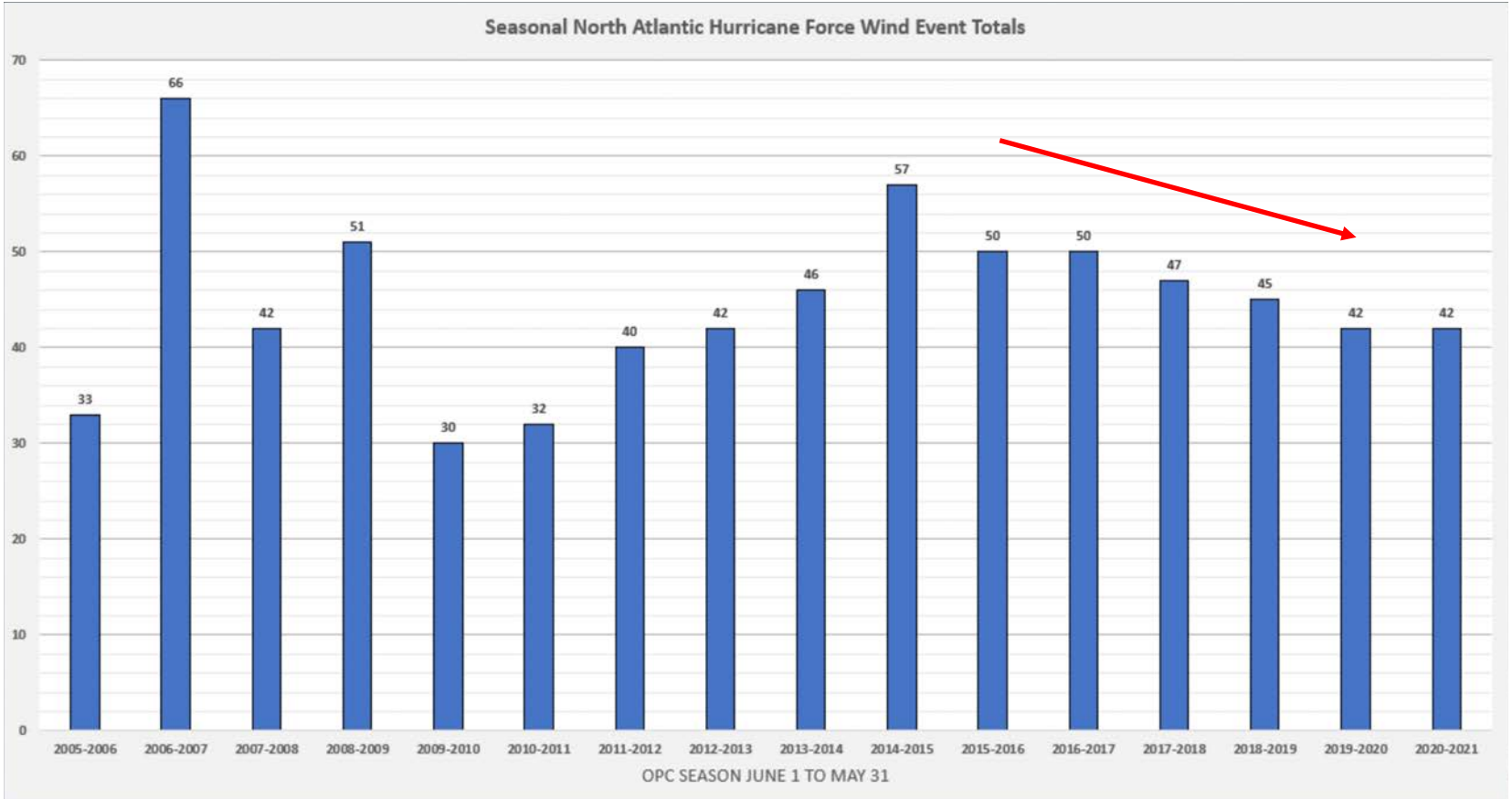
Hurricane-Force Lows



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