Variability in atmospheric circulation over the Bering Sea and its impact on air-sea heat fluxes

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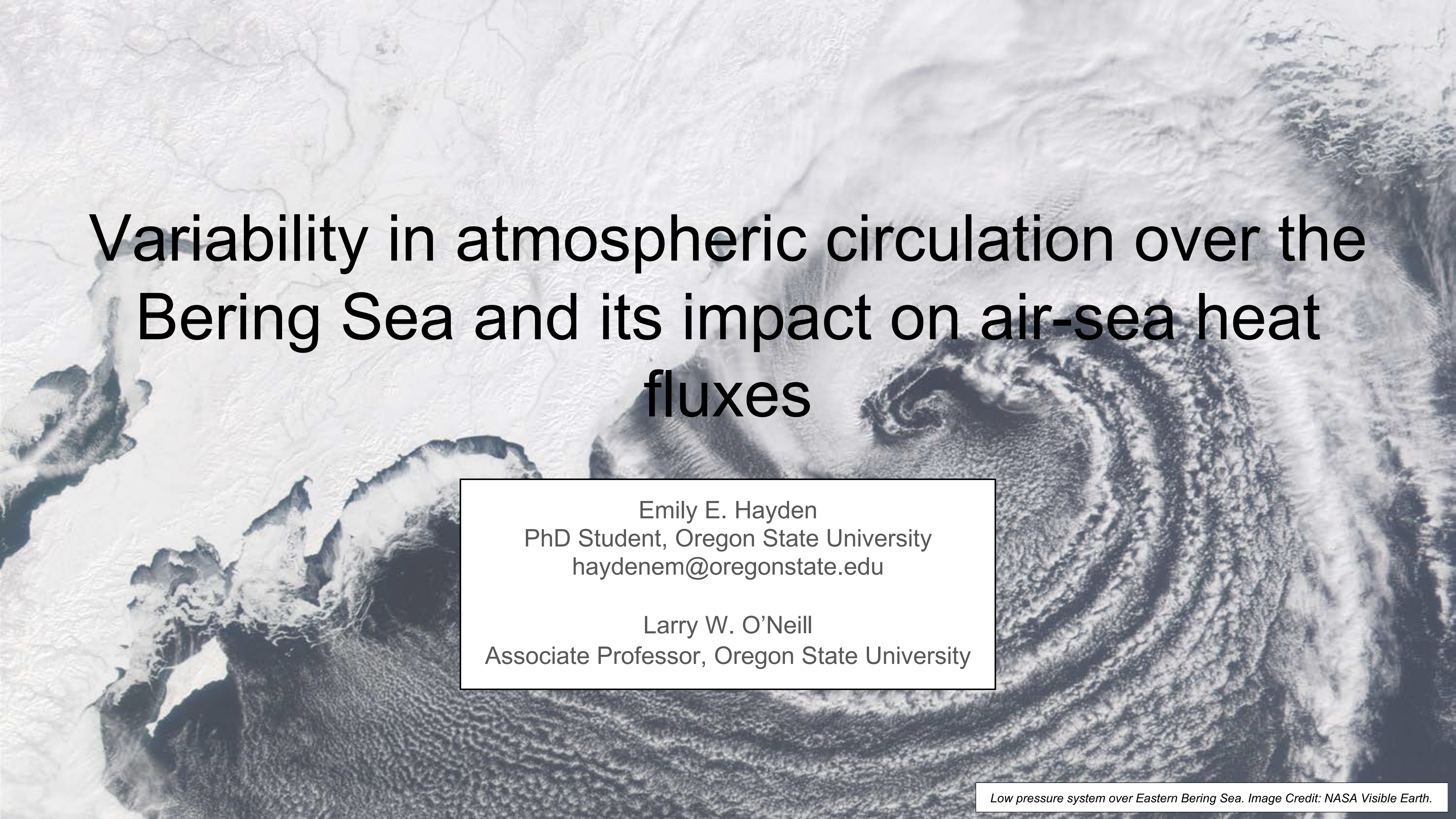


Low pressure system over Eastern Bering Sea. Image Credit: NASA Visible Earth.

Air-Sea Interactions in a Changing Climate

Important to understand…

- Especially at high-latitudes due to accelerated rates of change
- Because of severe and long-lasting ecosystem impacts
  - Marine Species Mortality
  - Altered Marine biodiversity
  - Large-scale species disturbance/migration
  - …Which have adverse effects on subsistence and commercial fishing

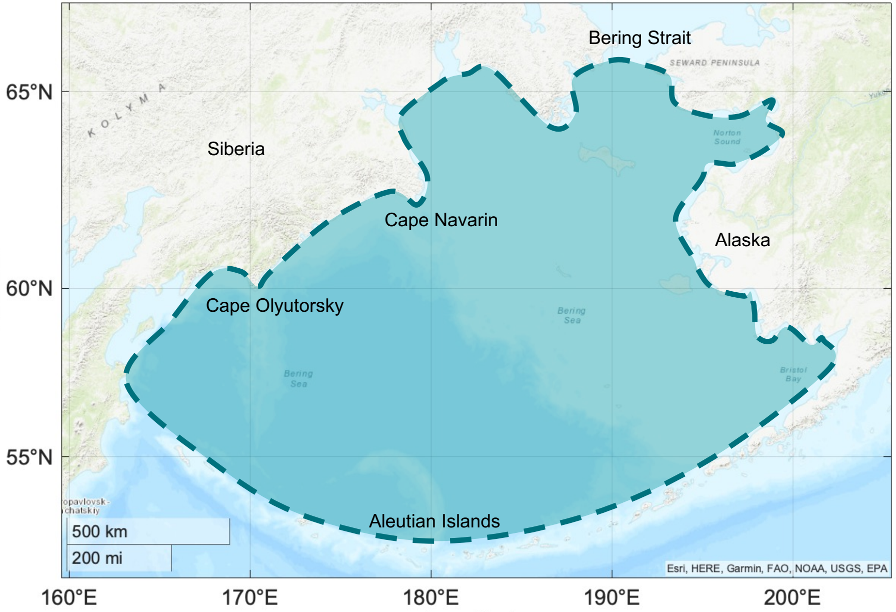
Study Region

Bering Sea

- Latitude: [51, 67] °N
- Longitude: [162, 203] °E

Regional, Coupled Air-Sea Interactions

- Sea ice formation driven by atmospheric forcing
- Wind-driven ocean circulation variability
- Ice cover sustains presence of cold Arctic air

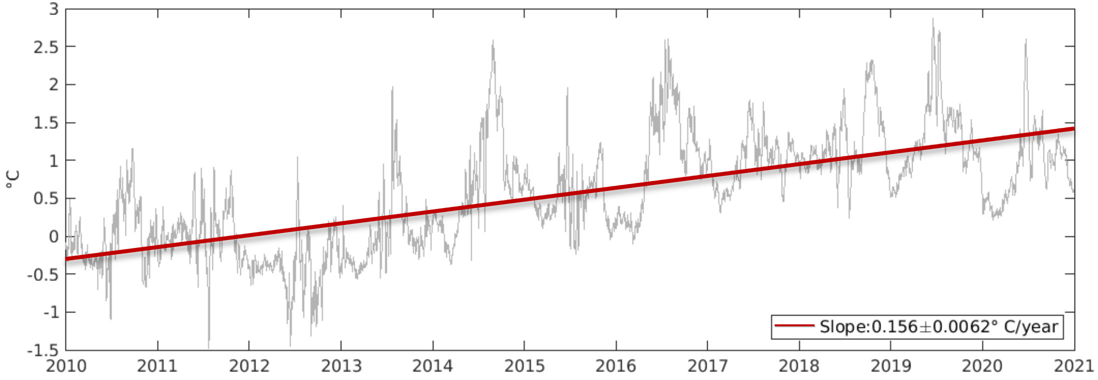


Bering Sea study area (shaded region). Key geographic locations noted.

Recent Bering Sea Extremes

Ocean-Atmosphere-Sea Ice Anomalies (2010-present)

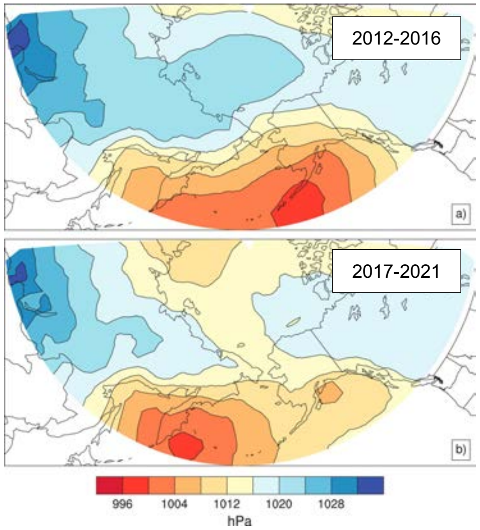
- Extreme low sea ice
- Elevated sea surface temperature (SST)
- Increased heat flux (HF) variability



Spatially-averaged, daily SST anomalies over the ice-free Bering Sea, 2010-2020 (ERA5). Slope of line is 0.156 ± 0.0062 °C/year.

Regime Shift

- 2017: Beginning of system-wide transformation
- Position/Magnitude of anomalies



Mean JFM SLP. Figure Credit: Ballinger, T. J., & Overland, J. E. (2022).

Research Questions

i. What is driving the observed heat flux anomalies? How are they affecting the coupled ocean-atmosphere system?

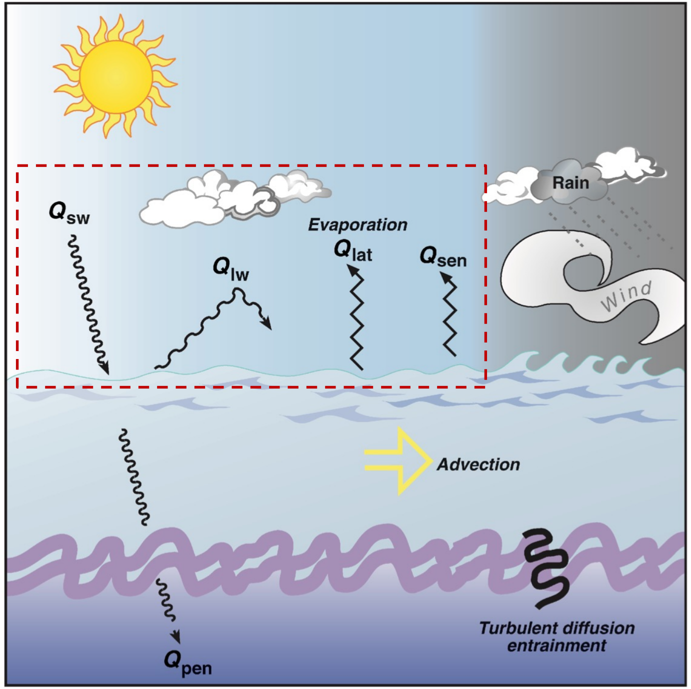
ii. What is the role of intra-seasonal and synoptic (storm-scale) atmospheric circulation in driving heat flux variability and temperature distributions in the ocean and the atmosphere?

iii. Are anomalies in the ocean driving anomalies in atmospheric circulation, or are atmospheric circulation anomalies driving anomalies in the ocean?

Air-Sea Heat Fluxes

$Q_{net} = Q_{SH} + Q_{LH} + Q_{SW} + Q_{LW}$

- Q_{LH}: Latent Heat Flux (Condensation/Evaporation)
- Q_{SH}: Sensible Heat Flux (Conduction)
- Q_{SW}: Net Shortwave Radiation
- Q_{LW}: Net Longwave Radiation
- **Positive**: into the ocean (**warming**) flux
- **Negative**: out of the ocean (**cooling**) flux



Air-Sea heat flux schematic. Figure Credit: Cronin, M.F. and J. Sprintall, 2001.

Data

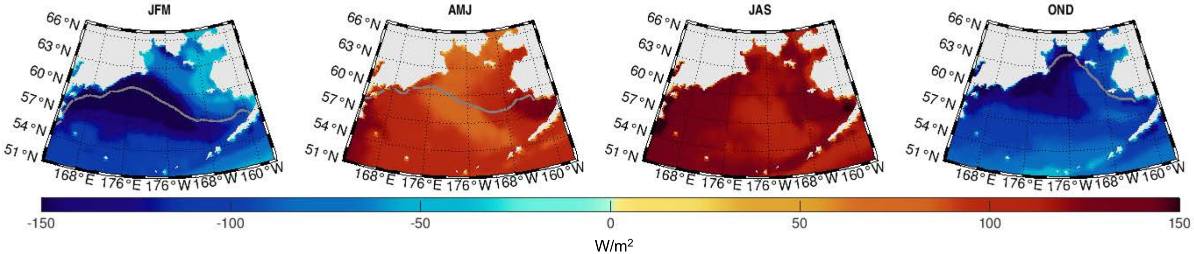
Goal: Analyze drivers of observed heat flux anomalies (emphasis on wind variability)

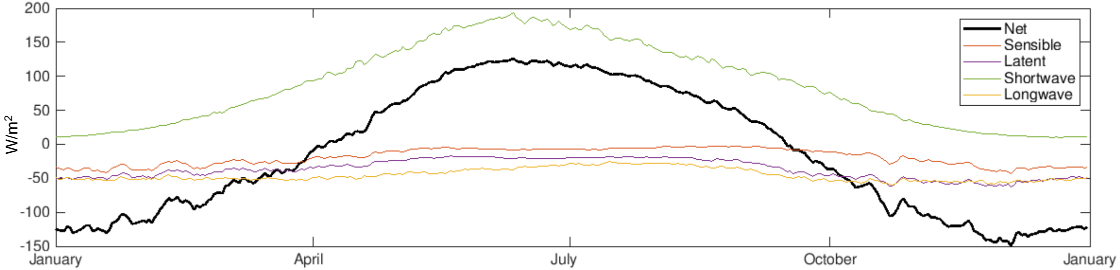
ECMWF ERA5: European Centre for Medium-Range Weather Forecasting Reanalysis (5th Generation)

- Global estimates at hourly-monthly intervals on a uniform 0.25° spatial grid
- Variables of interest (daily averages):
  - Air-sea heat flux components
  - Sea ice extent
  - 10m wind
  - SST
  - 2m air temperature
  - 2m dewpoint temperature

Climatological Net Air-Sea Heat Flux

- Climatology Period: 1981-2010
- Net Air-Sea HF: distinct seasonal cycle
    - Spring (AMJ) and Summer (JAS): Heat Sink
    - Fall(OND) and Winter (JFM): Heat Source





Upper: Seasonal mean net-air HF climatology (W/m²), climatological average sea ice extent shown in grey.
Lower: Spatially-averaged daily mean net air-sea HF climatology (W/m²).

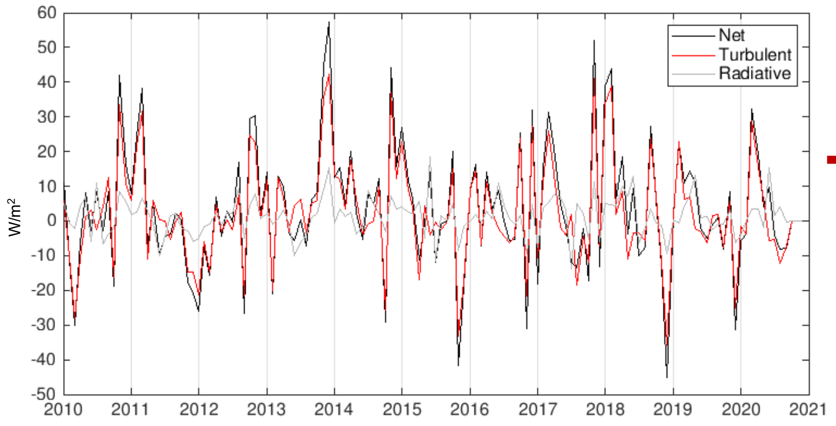
Heat Flux Anomalies

Strongest Net Air-Sea HF Anomalies occur in the Fall (OND) and Winter (JFM)

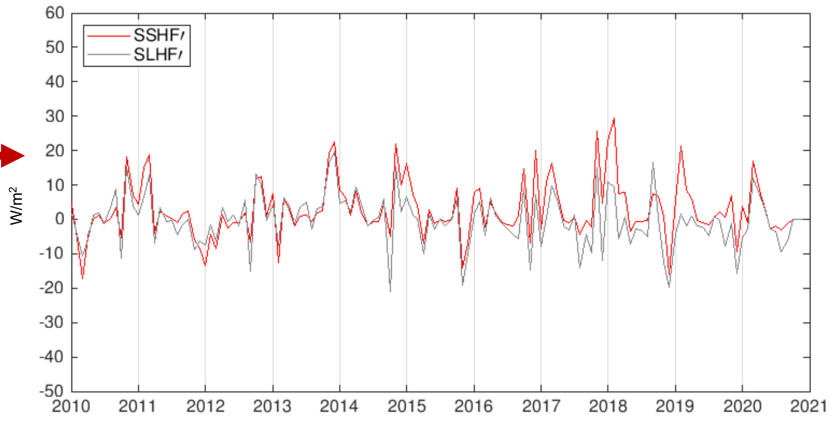
Net HF Anomalies dominated by turbulent (THF'):

$$Q'_{net} = \boxed{Q'_{SH} + Q'_{LH}} + Q'_{SW} + Q'_{LW}$$

Sensible HF Anom. (SSHF') > Latent HF Anom. (SLHF')



Spatially-averaged monthly HF anomalies (net, turbulent, and radiative) over ice-free Bering Sea (W/m²).



Spatially-averaged monthly Sensible (red) and Latent (grey) HF anomalies over the same ice-free area.

Heat Flux Decomposition

Bulk Flux Algorithm Turbulent Heat Fluxes:

$$SSHF = \rho_a C_P C_H V_{10}(T_a - SST) = \rho_a C_P C_H V_{10} \Delta T$$

$$SLHF = \rho_a C_E L_V V_{10}(q_a - q_s) = \rho_a C_E L_V V_{10} \Delta q$$

Decomposition of THF anomalies in terms of:

- Wind-Magnitude: V_{10}
- Air-Sea Temperature Difference (SSHF'): ΔT
- Air-Sea Specific Humidity Difference (SLHF'): Δq

$$SSHF' = [\rho_a C_P C_H V_{10} \Delta T]' \rightarrow \rho_a C_P C_H [\overbrace{\overline{V_{10}} \Delta T'}^{term\ 1} + \overbrace{V_{10}' \overline{\Delta T}}^{term\ 2} + \overbrace{V_{10}' \Delta T'}^{term\ 3}]$$

$$SLHF' = [\rho_a C_E L_V V_{10} \Delta q]' \rightarrow \rho_a C_E L_V [\overline{V_{10}} \Delta q' + V_{10}' \overline{\Delta q} + V_{10}' \Delta q']$$

Atmospheric Forcing of SSHF’

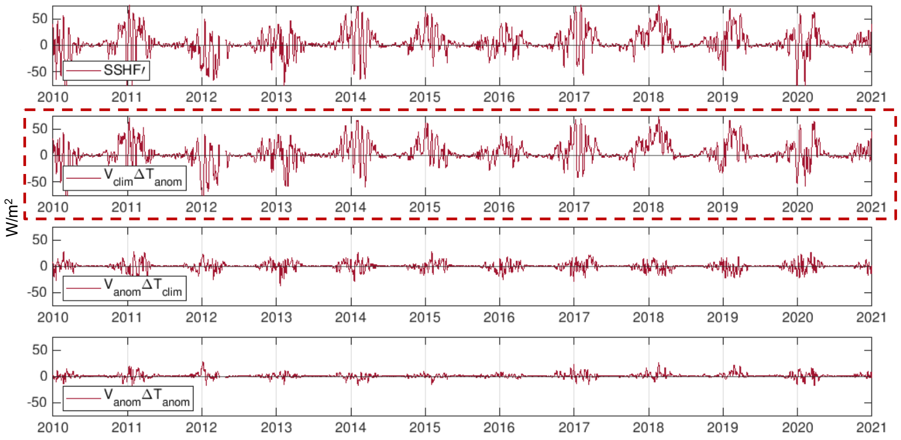
SSHF’ (2014-2020) are warming the ocean

- Positive (into the ocean) flux

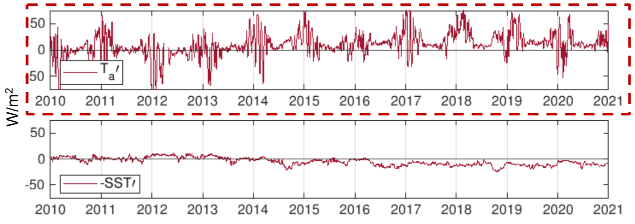
SSHF’ (2010-2020) are driven by anomalies in the air-sea temperature difference (ΔT_{anom})

Warm, moist air anomalies drive majority of observed wintertime (2014-2020) SSHF’

- T_a’ dominates SSHF’



Spatially-averaged daily SSHF’ and decomposition terms over the ice-free Bering Sea, 2010-2020.



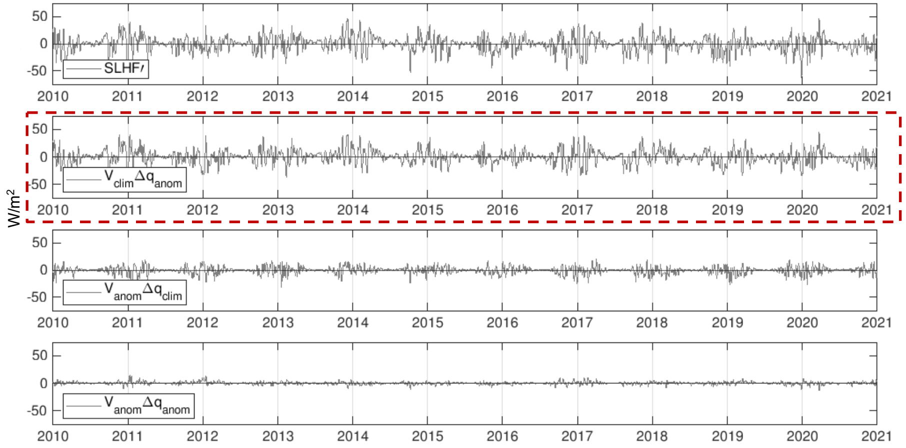
Decomposition of dominant term (∝ΔT_{anom}), in terms of T_a’ (above) and -SST’ (below).

Atmospheric Forcing of SLHF’

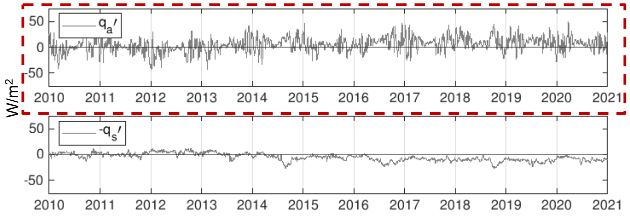
SLHF’ (2010-2020) are driven by anomalies in the air-sea specific humidity difference (Δq_{anom})

Warm, moist air anomalies drive majority of observed wintertime (2014-2020) SLHF’

- q_a’ dominates SLHF’



Spatially-averaged daily SLHF’ and decomposition terms over the ice-free Bering Sea, 2010-2020.

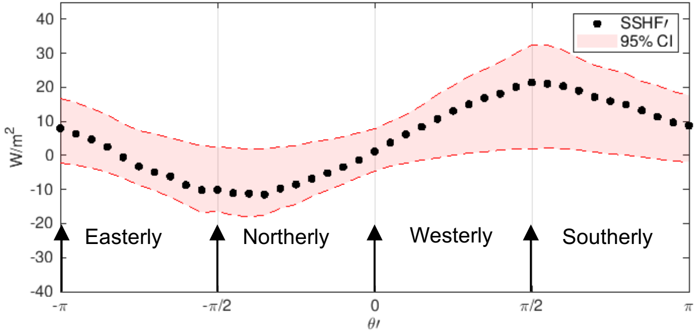


Decomposition of dominant term ($\propto \boldsymbol{\Delta} q_{anom}$), in terms of q_a’ (above) and -q_s’ (below).

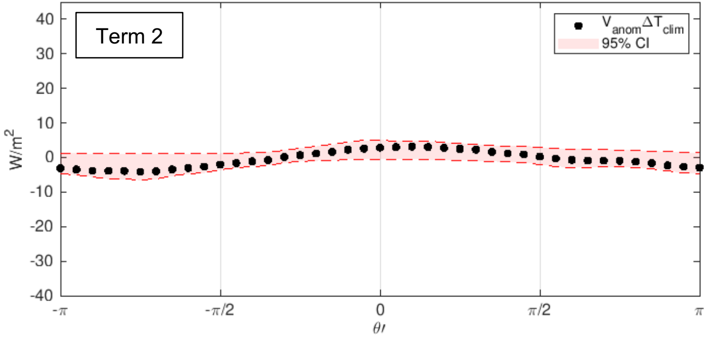
Wind Direction and SSHF’

Direction of anomalous wind (θ’) is linked to sign and magnitude of SSHF’ and T_a’

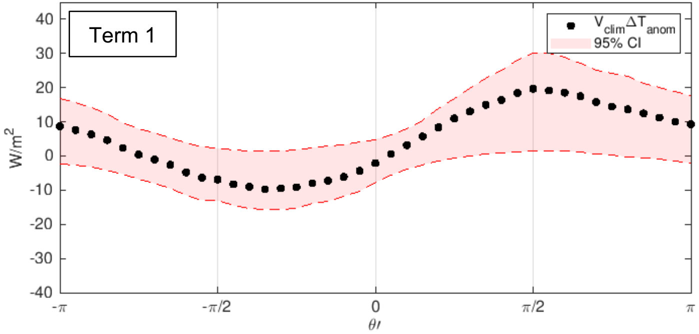
- Southerly winds → less ocean heat loss/ocean warming
- Northerly winds → more ocean heat loss/ocean cooling



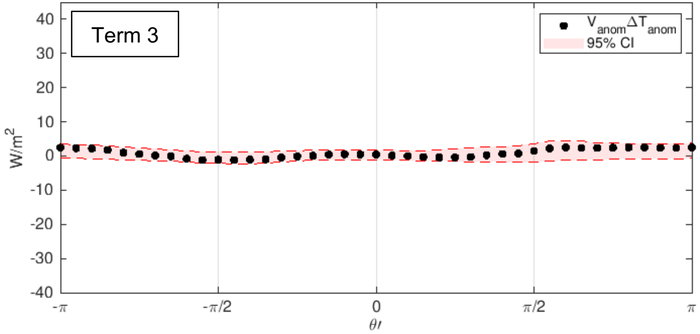
SSHF’ bin averaged by anomalous wind direction (θ’). Red lines: 95% CI of means in each bin.



SSHF’ decomposition term 2 ($\propto V_{anom}\Delta T_{clim}$) bin averaged by θ’.



SSHF’ decomposition term 1 ($\propto V_{clim}\Delta T_{anom}$) bin averaged by θ’.

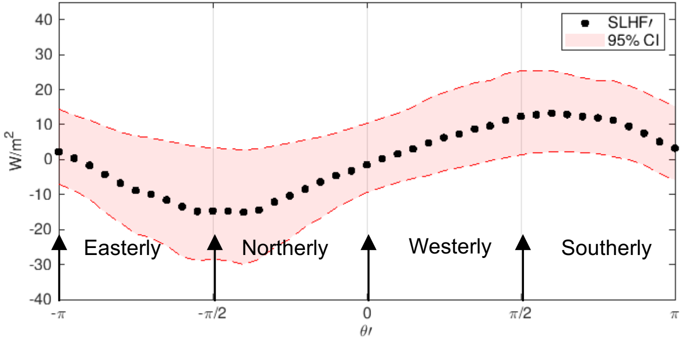


SSHF’ decomposition term 3 ($\propto V_{anom}\Delta T_{anom}$) bin averaged by θ’.

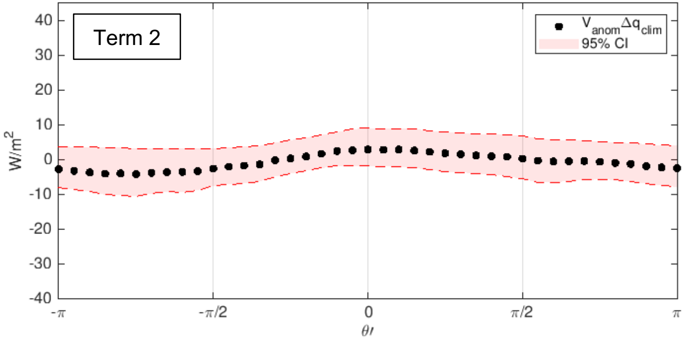
Wind Direction and SLHF’

Direction of anomalous wind (θ’) is linked to sign and magnitude of SLHF’ and q_a’

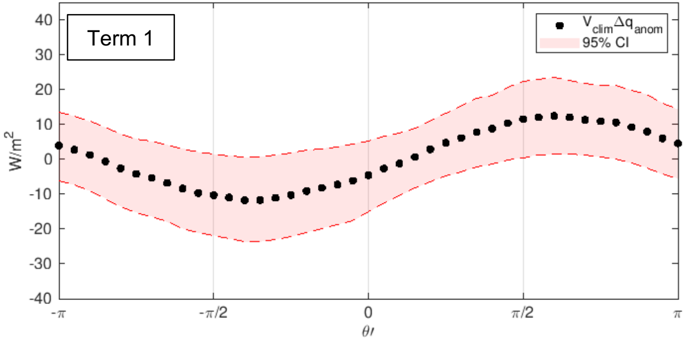
- Southerly winds → less ocean heat loss/ocean warming
- Northerly winds → more ocean heat loss/ocean cooling



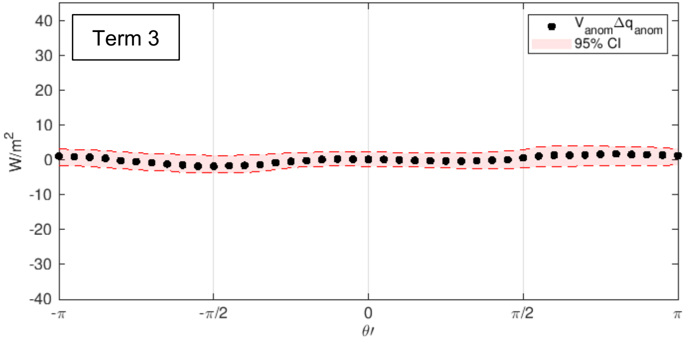
SLHF’ bin averaged by anomalous wind direction (θ’). Red lines: 95% CI of means in each bin.



SLHF’ decomposition term 2 (∝ $V_{anom}\Delta q_{clim}$) bin averaged by θ’.



SLHF’ decomposition term 1 (∝ $V_{clim}\Delta q_{anom}$) bin averaged by θ’.



SLHF’ decomposition term 3 (∝ $V_{anom}\Delta q_{anom}$) bin averaged by θ’.

Preliminary Results

1) Wintertime HF anomalies are dominated by turbulent components of the net heat flux (SSHF' > SLHF')
2) Warm, moist air anomalies are responsible for THF anomalies that are contributing to ocean heating.
3) Wind direction plays a key role in driving THF anomalies – positive anomalies associated with southerly wind.

Future Work

1) What role do they play in sea ice loss?
2) How much of the observed warming are they responsible for?
3) How are these anomalies related to intra-seasonal and synoptic-scale atmospheric events?

Acknowledgements and References

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