Atmospheric processes contributing to Bering Sea warming in the late 20th and early 21st century

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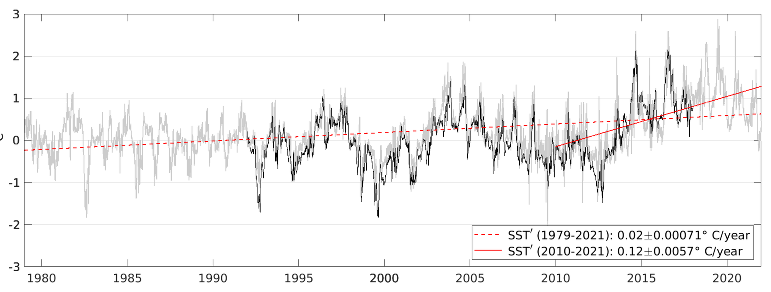
1. Bering Sea climate variability and the role of surface forcing

Recent **Bering Sea** climate **extremes**:

- Extreme low sea ice extent [6]
- Increased heat flux variability [2]
- Elevated sea surface temperature [7]

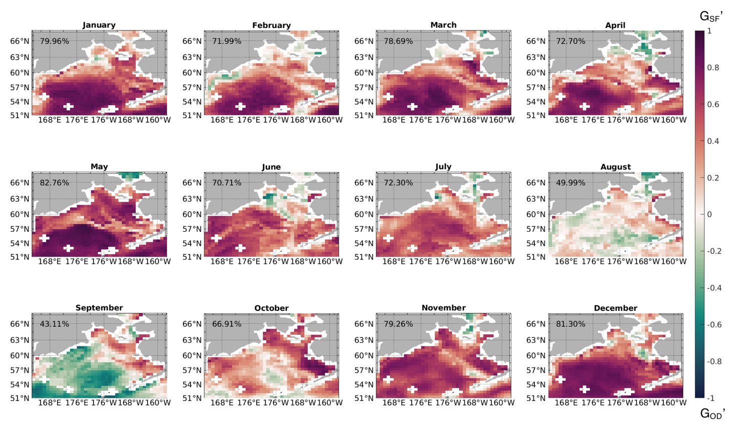
These extremes are difficult to predict…

→ Underlying physical mechanisms of the warming trend and subseasonal variability are not well understood



Spatially-averaged, daily SST anomalies (grey) and MLT anomalies (black). Linear trend for SST' has a slope of 0.02 ± 0.00071 °C/year over the full period (1979-2021) and increases to 0.12 ± 0.0057 °C/year, over 2010-2021 (ERA5 and ECCO Ocean State Estimate)

Surface forcing is a key driver of mixed layer temperature (MLT) **anomalies** on **subseasonal-to-seasonal** timescales [4]

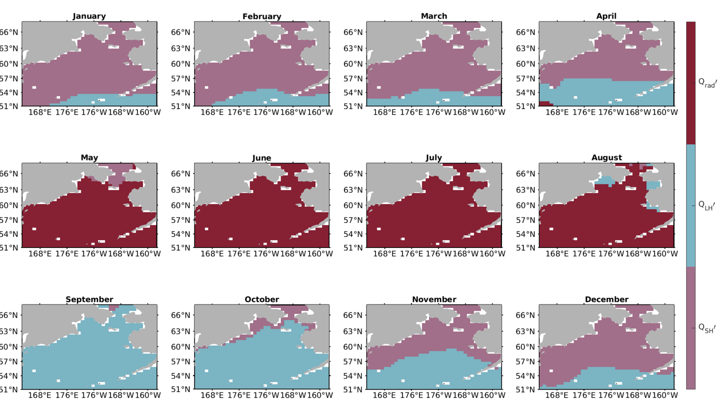


Balance Metric, M_B [3]:

- Describes relative importance of ocean dynamics (G_{OD}') to surface forcing (G_{SF}') in driving MLT tendency anomalies
  - G_{OD}= Advection + Diffusion
- $M_B \cong 1$: G_{SF}' drives majority of MLT variability
- $M_B \cong -1$: G_{OD}' drives majority of MLT variability

Balance metric computed for the period 1992-2017 from monthly ECCO anomalies (relative to 1992-2017 baseline). The heat budget terms used in the metric were computed over the depth of the mixed layer and thus describe the MLT tendency(ECCO Ocean State Estimate)

The **turbulent** components of the net heat flux dominate **surface forcing variability** in fall through early spring [4]



Dominance analysis (DA) [1] that describes the generally dominant term in the net air-sea heat flux anomalies over the Bering Sea. DA accounts for interactions/cross-correlations between component terms in the net air-sea heat flux (ERA-Interim)

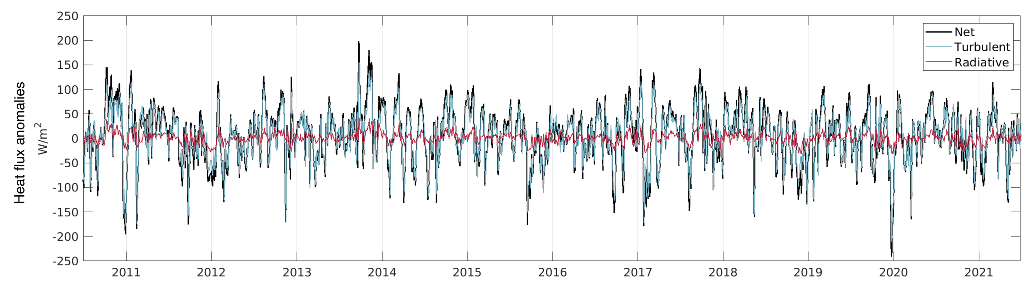
2. Wintertime warming forced by turbulent heat flux

Net Air-Sea Heat Flux = Radiative + Turbulent

Net Shortwave + Net Longwave | Latent = $\rho_a C_E L_V V_{10} \Delta q$ | Sensible = $\rho_a C_P C_H V_{10} \Delta T$

October-March, 2010-2021:

- > **2000 EJ** (10^{18} J) **excess heat** entered the Bering Sea due to anomalies in the net heat flux
- **Turbulent** fluxes accounted for ~**85%** of total excess heat
- **Total sensible** heat flux anomalies were an order of magnitude **greater** than **latent** heat flux anomalies



Daily, area-averaged air-sea heat flux anomalies over the ice-free Bering Sea, during the sea ice season (October –March, 2010-2021). Anomalies are computed relative to the 1979-2010 climatology (ERA5)

3. Air-mass anomalies drive warming fluxes

Decomposition of sensible (SHF) and latent (LHF) heat fluxes

→ Daily climatology ($\bar{x}$) and daily anomaly (x')

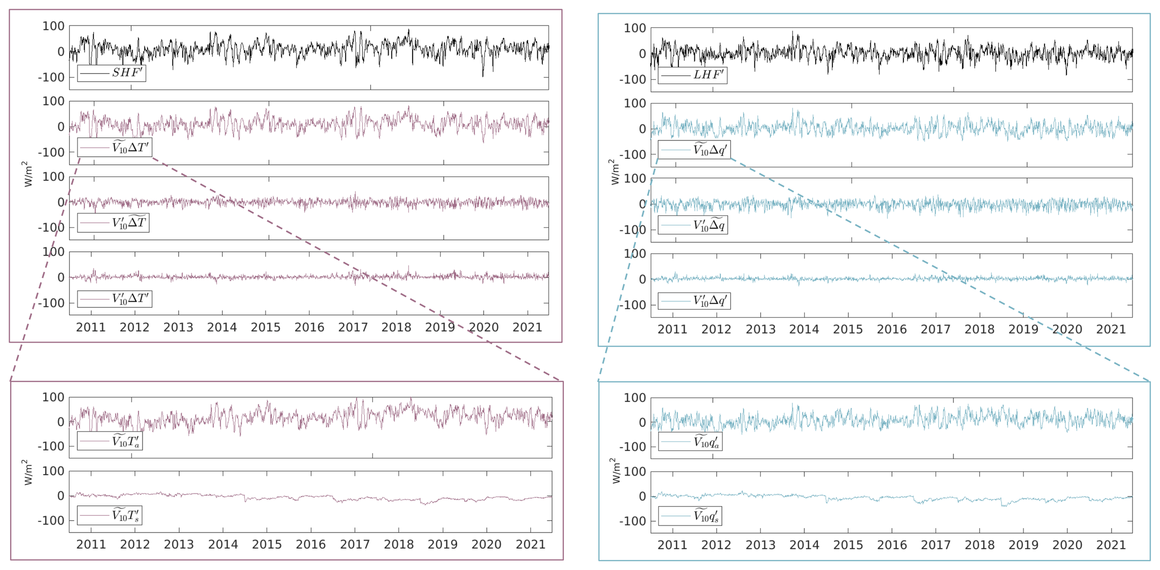
$$SHF' = \rho_a C_P C_H V_{10} \Delta T' \rightarrow \rho_a C_P C_H [\widetilde{V_{10}} \Delta T' + V_{10}' \widetilde{\Delta T} + V_{10}' \Delta T']$$
$$LHF' = \rho_a C_E L_V V_{10} \Delta q' \rightarrow \rho_a C_E L_V [\widetilde{V_{10}} \Delta q' + V_{10}' \widetilde{\Delta q} + V_{10}' \Delta q']$$

→ $\Delta T'$ describes **~93%** of **SHF' variance**

→ Air temperature anomaly (**T_a'**) dominates

→ $\Delta q'$ describes **~88%** of **LHF' variance**

→ Air specific humidity anomaly (**q_a'**) dominates

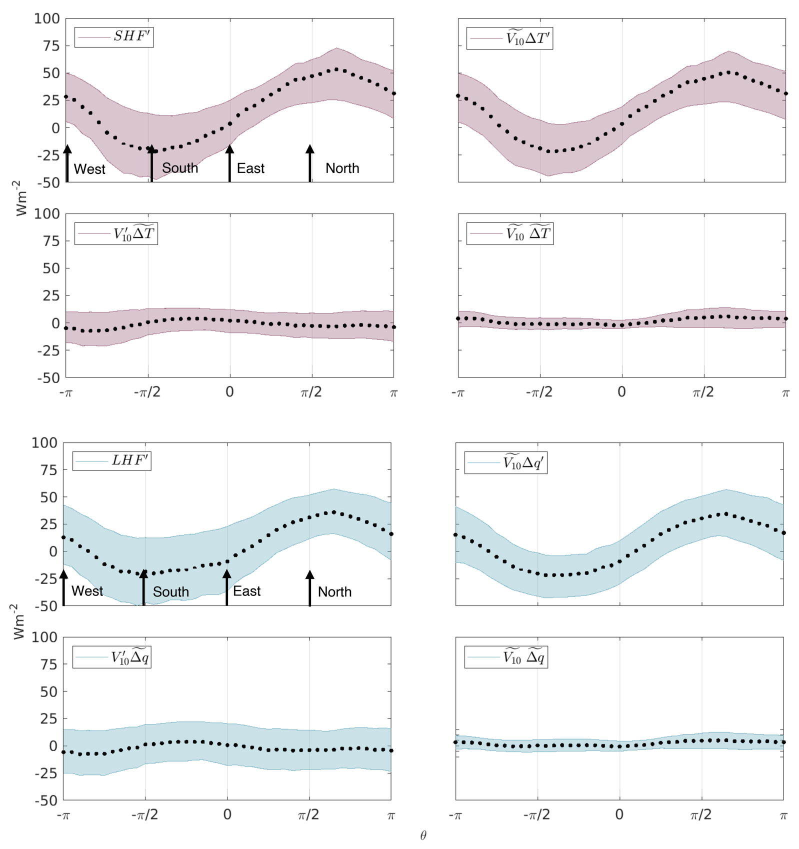


Daily, area-averaged turbulent heat flux anomalies and decomposition terms over the ice-free Bering Sea, during the sea ice season, October-March, 2010-2021 (ERA5)

4. Wind direction and air-mass anomalies

Sign and **magnitude** of turbulent flux and air-mass **anomalies** linked to wind direction (**θ**)

- **Northward** winds → **decreased** ocean heat loss
- **Southward** winds → **increased** ocean heat loss



Air-sea temperature difference anomalies proportional to **wind direction**

Air-sea specific humidity difference anomalies proportional to **wind direction**

Turbulent heat flux anomalies and decomposition terms bin averaged by wind direction, θ. Shaded regions depict 95% CI of means in each bin (ERA5)

Wind speed anomalies are ***NOT*** *driving turbulent heat flux anomalies*

→ Atmospheric circulation anomalies drive anomalous surface temperature and moisture

5. **Conclusions** and *Future Work*

Atmospheric variability is driving the majority of Bering Sea warming, and likely plays a dominant role in the initiation of MHW in the region

- **Surface forcing anomalies account for most of the mixed layer temperature tendency anomalies**
  - → *Assess spatial and temporal variability of the mixed layer heat budget dynamics*
- **Sensible heat flux anomalies are the dominant driver of ocean warming during the sea ice season**
  - → *Evaluate feedback mechanism between sea ice loss and increased turbulent heat flux*
- **Atmospheric variability (air temperature and specific humidity anomalies) drives ocean warming flux anomalies**
  - → *Determine the role of meridional heat and moisture convergence on intra-seasonal and synoptic-scales*

This work is part of two manuscripts in preparation

6. Implications

- (Sub)mesoscale air-sea coupled processes in the sub-Arctic and Arctic are poorly observed and understood, but appear to be a key driver of recent ocean warming and sea ice loss in the Bering Sea
- Our work supports the need for sustained, long-term surface air-sea heat flux measurements in the Bering Sea, which are crucial to monitoring climate change in the region and diagnosing their impacts
- Our turbulent heat flux decomposition may be a powerful tool for diagnosing air-sea coupling, and for assessing the role of the atmosphere in driving mesoscale ocean anomalies

References and Acknowledgements

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