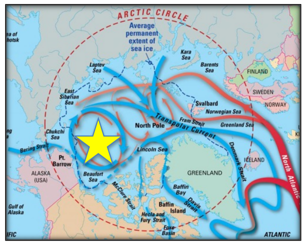
"Causal Mechanism of Sea Level Change in the Beaufort Sea"



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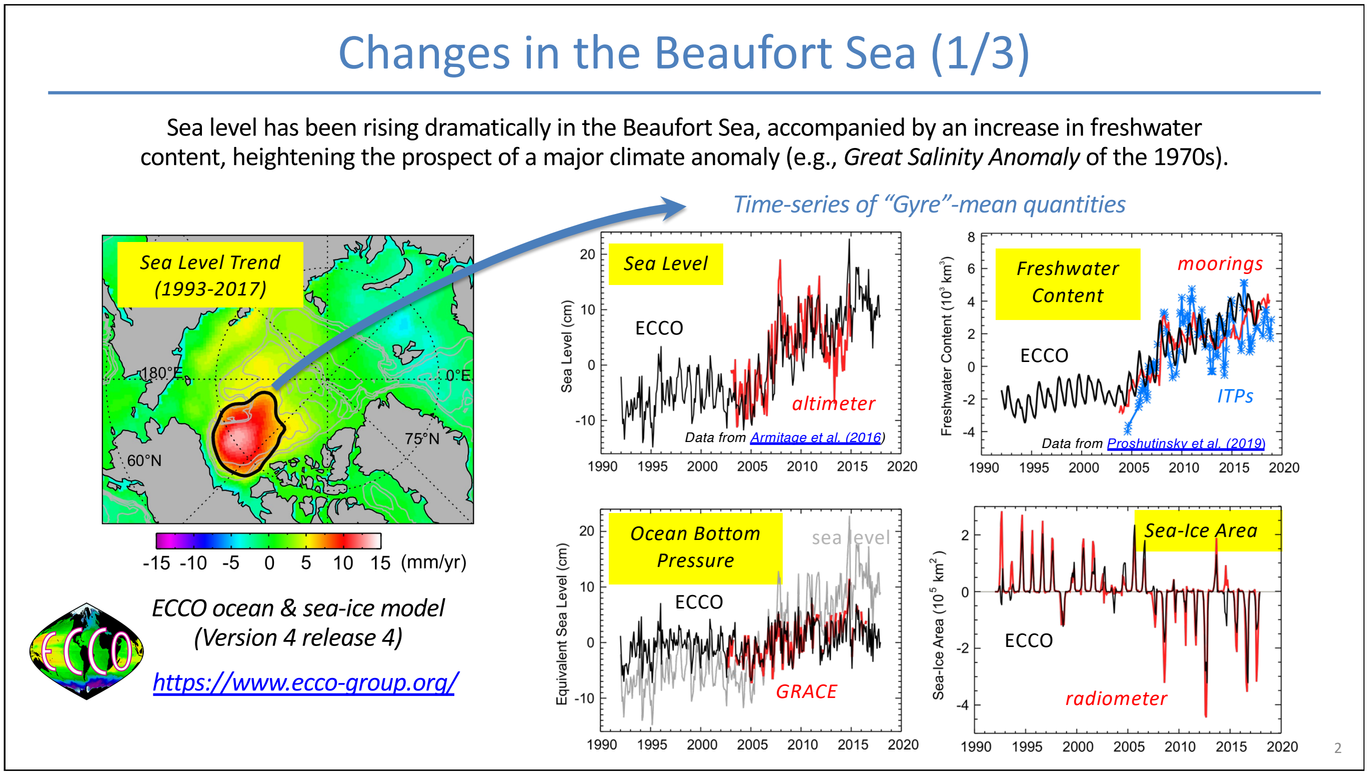
Fukumori, I., O. Wang, and I. Fenty, 2021: Causal Mechanisms of Sea-level and Freshwater Content Change in the Beaufort Sea. *J. Phys. Oceanogr.*, **51**, 3217–3234, https://doi.org/10.1175/jpo-d-21-0069.1.

Sea level in the Arctic's Beaufort Sea (yellow star on map with clockwise Beaufort Gyre circulation in blue) has been rising (> 1 cm/yr) faster than anywhere else on the globe.

Here we show that this change is jointly due to **wind** and **sea-ice melt**.

The study is based on a recent paper listed at the bottom of this slide.



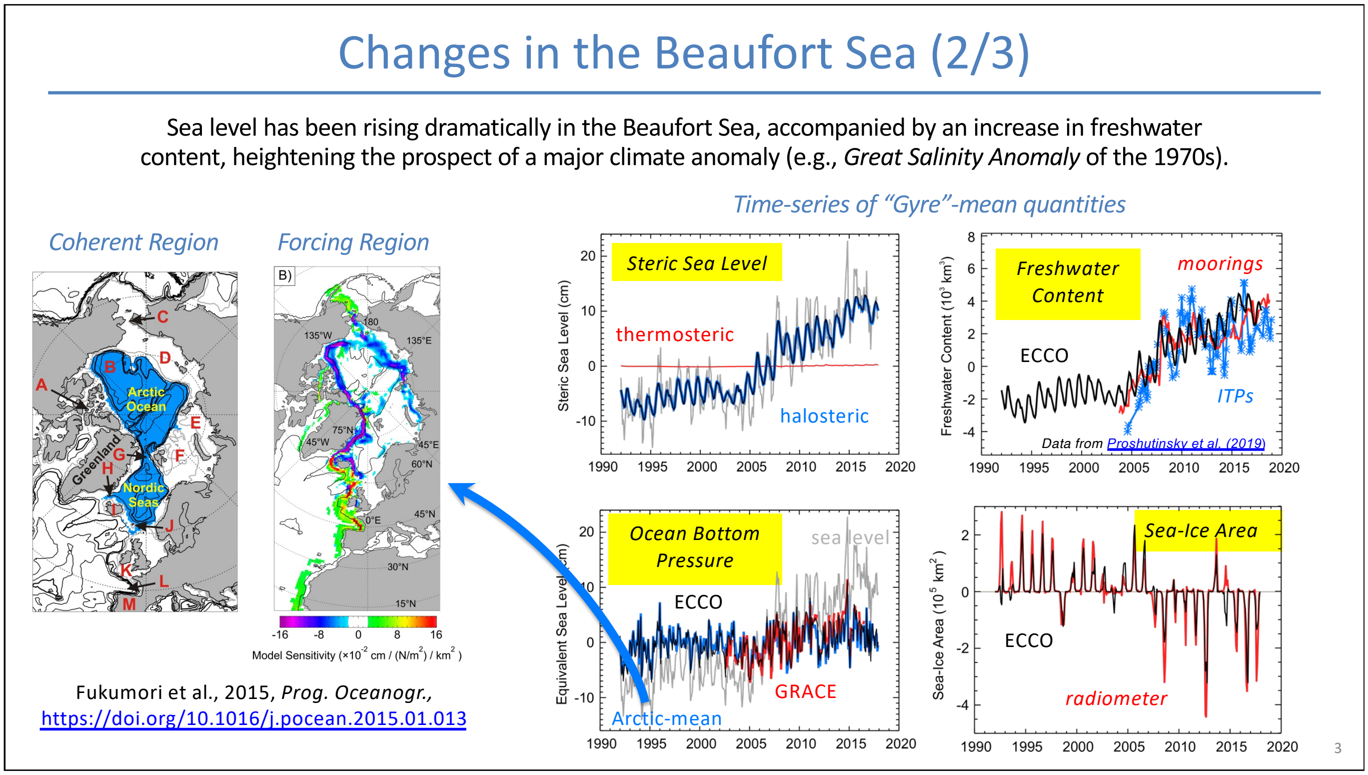
The next 3 slides illustrate the nature of Beaufort Sea's change, in terms of **sea level, freshwater content (salinity), ocean bottom pressure, and sea-ice area.**

Left map: Sea level trend (1993-2017) from ECCO's model-data synthesis shows Beaufort Sea's sea level rising faster than 1 cm/yr (red region). Black contour is 6 mm/yr, outlining the "Gyre" region (Beaufort Gyre, cf slide 1) analyzed in the study.

Right panel: Anomaly time-series (1992-2017) averaged across the "Gyre" region illustrating Beaufort Sea's change; sea level (top left), freshwater content (top right), ocean bottom pressure (bottom left), and sea-ice area (bottom right). All variables except bottom pressure display prominent decadal increase/decrease after 2007. The freshwater increase rivals that of the 1970s' Great Salinity Anomaly. In each panel, black is ECCO and red & cyan are observations; Note consistency between ECCO and data.

Takeaway;

- ✓ Sea level has been rising rapidly in the Beaufort Sea from 2007, accompanied by an increase in freshwater content and a decrease in sea-ice cover,
- ✓ Ocean bottom pressure lacks the multi-decadal change,
- ✓ ECCO's estimate and therefore its model's physics (owing to the analysis being a smoothed estimate) are consistent with observations.



Here we take a closer look at **sea level** and **ocean bottom pressure** from the previous slide. (Flip back and forth with previous slide, focusing on left figures of right panel.)

Right panel, top left: Steric sea level (black), which accounts for most of sea level’s (gray) seasonal to decadal change, is almost entirely halosteric (cyan) with negligible thermosteric contribution (red).

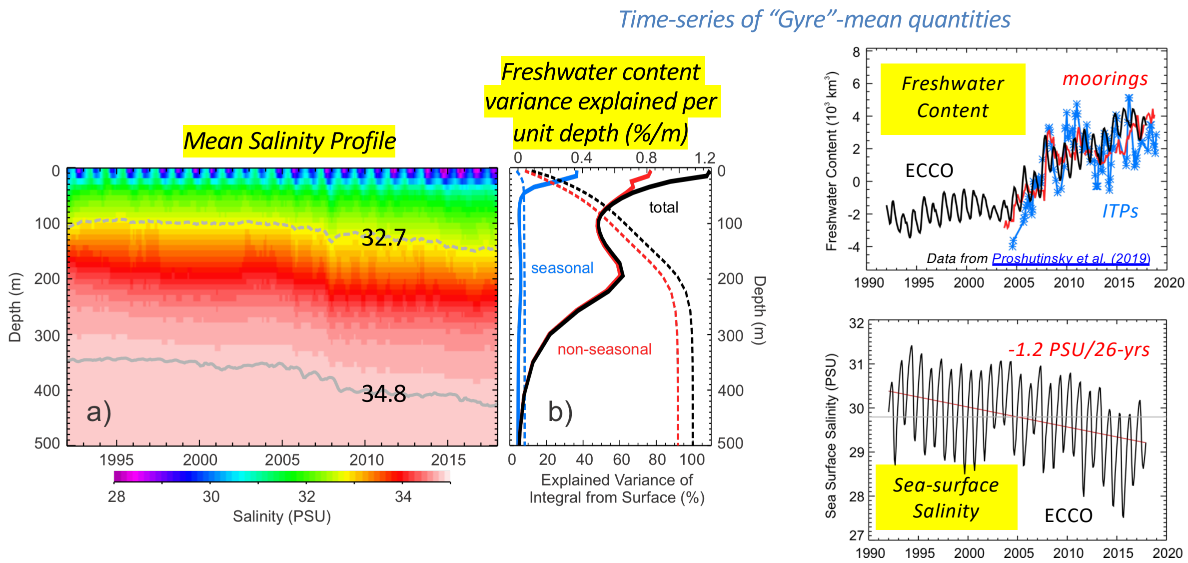
Right panel, bottom left: Ocean bottom pressure (black), which accounts for the difference between sea level and steric sea level (see “Right panel, top left” above), is practically the same as that averaged across the interconnected deep-ocean basins of the Arctic Mediterranean (cyan curve; region in blue in far left map). This pan-Arctic oscillation was a subject of another study (reference in bottom left) that showed it to be spatially near-uniform and driven by along-bathymetry winds along the region’s continental slope (colored region in left panel, right map); i.e., bottom pressure variation is unrelated to Beaufort Sea-specific change that is the subject of the present study.

Takeaway;

- ✓ Region’s sea level rise is entirely halosteric,
- ✓ Bottom pressure variation (manometric sea level) is unrelated to Beaufort Sea’s decadal change.

Changes in the Beaufort Sea (3/3)

Sea level has been rising dramatically in the Beaufort Sea, accompanied by an increase in freshwater content, heightening the prospect of a major climate anomaly (e.g., *Great Salinity Anomaly* of the 1970s).



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This slide examines **salinity** change underlying Beaufort Sea's halosteric sea level and **freshwater content** changes (right panel, top figure from previous 2 slides).

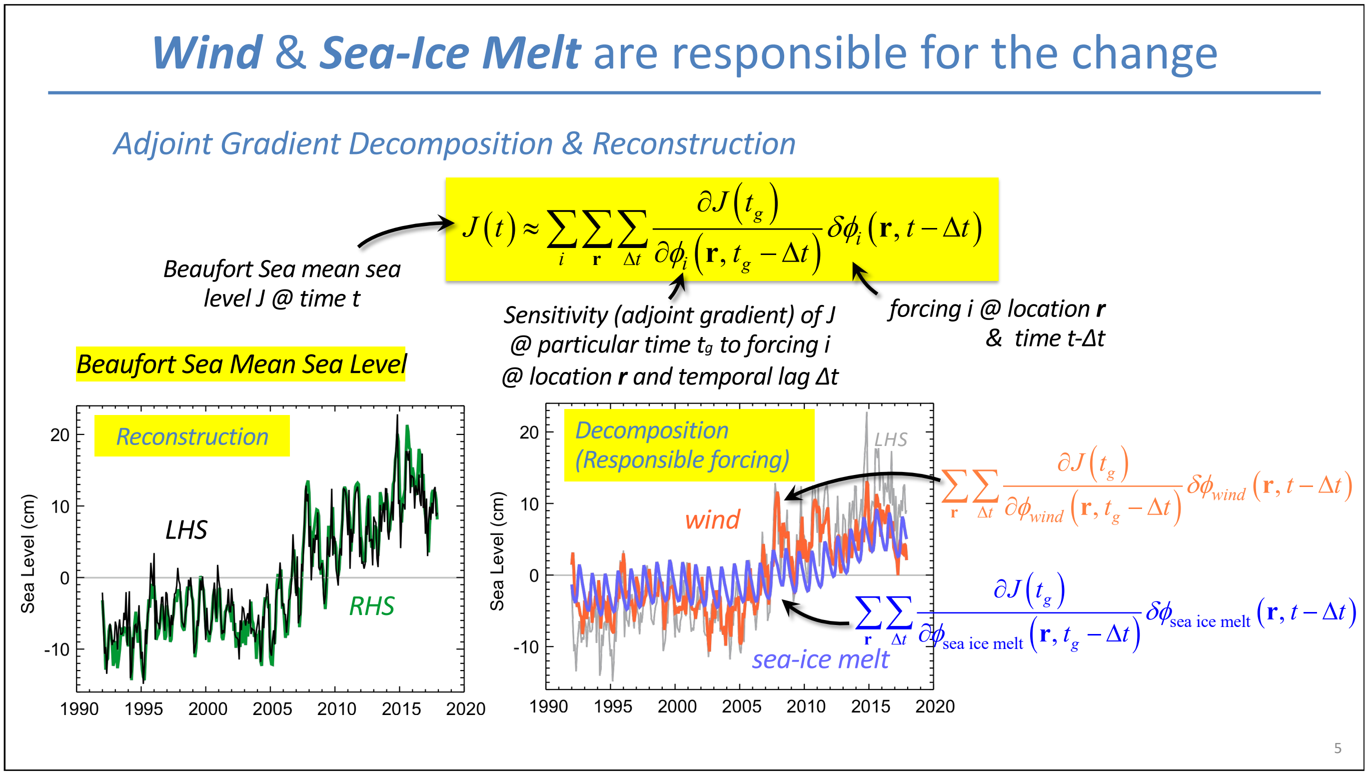
Left figure: Mean salinity profile vs time. Note deepening isohalines, indicating freshening. Dash and solid gray curves are 32.7 and 34.8 PSU isohalines, respectively. (Latter is used as reference salinity for freshwater content computation.)

Middle figure: Freshwater content profile shown as variance of net change explained as a function of depth (solid black with axis at top) and integral from surface (dashed black with axis at bottom). Cyan and red are the same but for seasonal and non-seasonal components. Note shallow seasonal change (<55m) and deeper near-uniform interannual change (<220m).

Right panel, bottom figure: Time-series of sea surface salinity. The multi-decadal change amounts to a 1.2 PSU decrease over 1992-2017.

Takeaway;

- ✓ Salinity is decreasing near uniformly to 220m,
- ✓ Seasonal salinity change is shallower, extending to only 55m.



We analyze **causal mechanisms** of the change in the <u>next 4 slides</u>.

Here we examine the responsible forcing by (equation) decomposing Beaufort Sea's mean sea level J into contributions from different forcing phi (variable, location, time) using gradients computed by ECCO's adjoint model. The equation approximates a first-order Taylor Series expansion with a particular set of gradients. Unlike correlation, the equation quantifies the causal relation between quantity J (sea level) on the left-hand-side and its forcing (phi) on the right-hand-side.

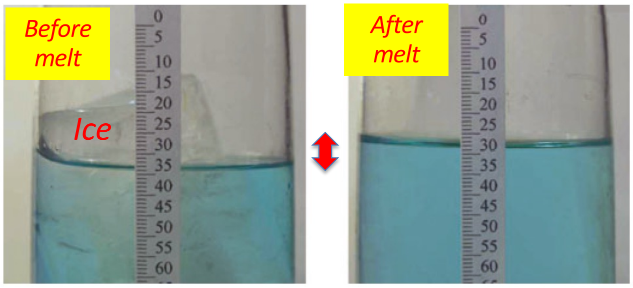
Left figure: Compares time-series of the region's sea level (black; LHS) with the sum of terms on the right-hand-side of the expansion (green; RHS). Agreement between the two demonstrates the fidelity of the decomposition.

Right figure: Same time-series as above but compares individual contributions from wind (orange) and sea-ice melt (blue) that dominate the overall change (gray; LHS). Sea-ice melt explains the seasonal cycle. Wind accounts for intra-seasonal to interannual change. Both contribute equally to decadal change.

Takeaway;

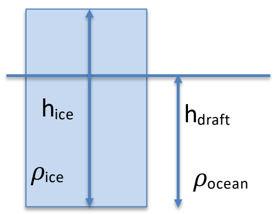
- ✓ Wind and sea-ice melt contribute equally to Beaufort Sea's decadal sea level change.

Sea-Level Rise by Sea-Ice Melt



[Noerdlinger & Brower (2007)]

Sea-level rises when floating sea-ice melts because melt-water is less dense, and therefore occupies a larger volume, than the sea-water displaced by ice.



Archimedes' Principle   Mass Conservation

$$\rho_{ocean} h_{draft} = \rho_{ice} h_{ice} = \rho_{fresh} h_{melt}$$

Therefore, $h_{melt} = \frac{\rho_{ocean}}{\rho_{fresh}} h_{draft} > h_{draft}$

because $\frac{\rho_{ocean}}{\rho_{fresh}} \approx \frac{1026}{1000} \approx 2.6\%$ increase

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This slide describes how sea-ice melt affects sea level.

Melt from sea-ice is often ignored in sea level change because floating ice already displaces sea water based on Archimedes' Principle. However, sea-ice melt is fresher than sea water and occupies a larger volume than what floating ice displaces, resulting in sea level rise as shown by (picture) *Noerdlinger and Brower (2007).* The amount of sea level rise equals 2.6% of sea-ice draft as illustrated mathematically.

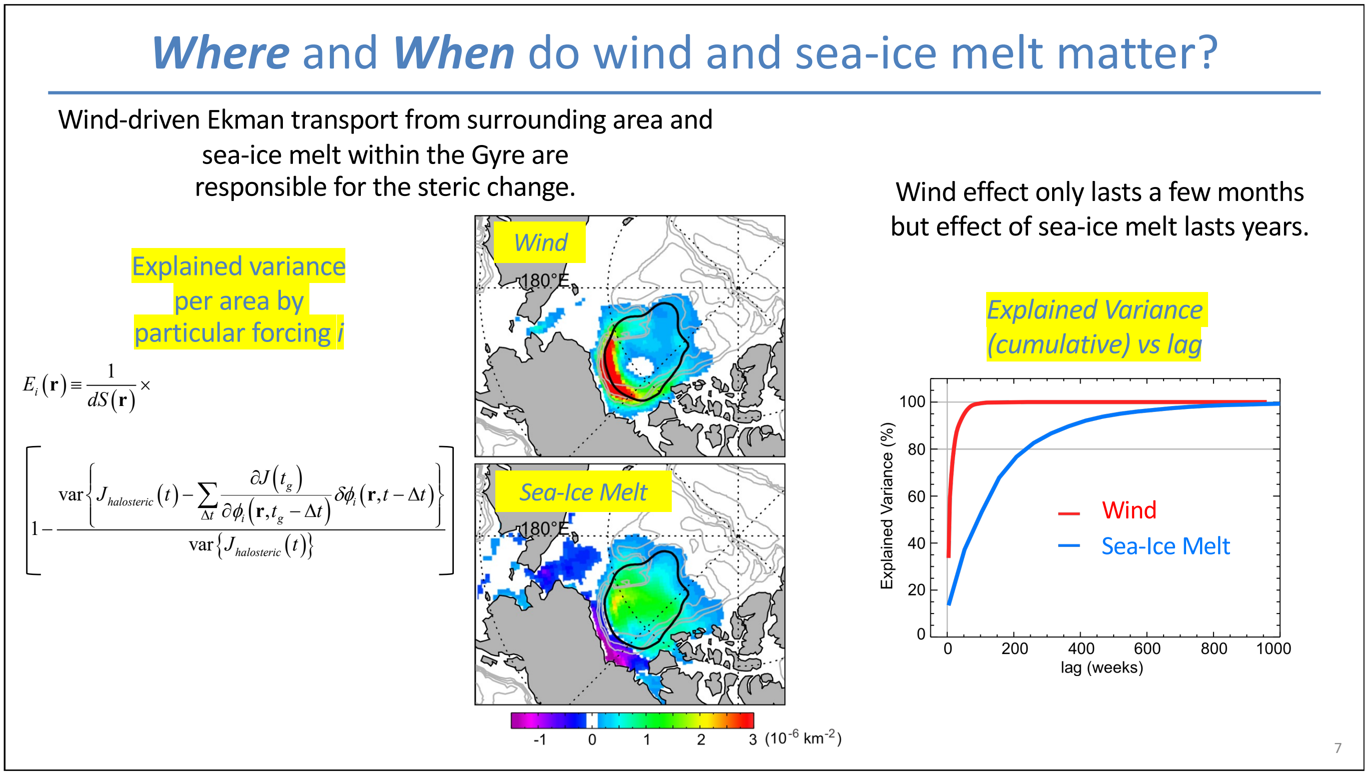
Takeaway;

✓ Sea-ice melt can cause sea level rise.

Note;

There are 2 additional reasons why sea-ice melt matters in the Beaufort Sea ("sea-ice reason"), which will be addressed in the next 2 slides. Issues are,

1) Why doesn't melt water simply spread away? (*Answer: Because of the region's semi-closed gyre circulation.*)
2) Does observed sea-ice loss account for the melt responsible for sea level rise? (*Answer: No, the melting sea-ice originates elsewhere and is a lot more than the apparent loss.*)



Here we examine how wind and sea-ice melt affect Beaufort Sea's sea level.

Utilizing the decomposition from 2 slides prior, and using as measure (equation) the explained variance of halosteric sea level, this slide quantifies where the respective forcing takes place (maps) and at what temporal lag (right figure).

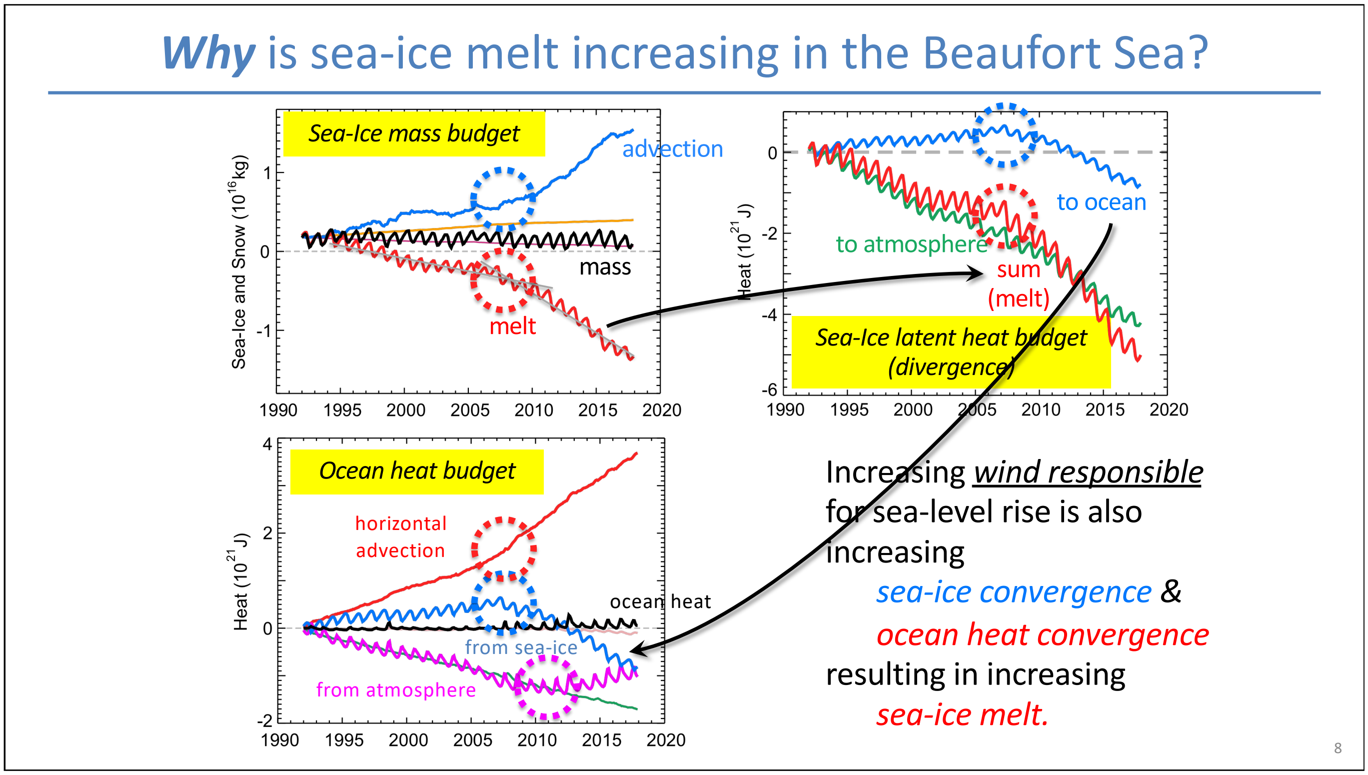
Top map: Winds surrounding the region are responsible, reflecting strengthening wind-driven lateral Ekman convergence of relatively fresh near-surface water.

Bottom map: Sea-ice melt contributes mainly over Beaufort Sea itself, reflecting effects of increasing direct freshwater input over the region.

Right figure: Although wind (red) only matters up to a few months, effect of sea-ice melt (cyan) lasts for years due to the semi-closed nature of Beaufort Sea's gyre circulation. (Figure is based on an equation similar to the one on the slide but one that is a function of lag "delta_t" instead of space "r".)

Takeaway;

- ✓ Increasing wind drives increasing Ekman convergence of fresh water,
- ✓ Water from increasing sea-ice melt stays in the region for years due to ocean circulation (“sea-ice reason” #1/2; cf slide 6).



Finally, we examine why sea-ice melt is increasing.

Here we analyze property budgets, focusing on decadal change (dashed circles) in the slope of time-integrated fluxes (colored curves). (Black arrows point to same quantities that appear in different budgets.)

Top left: Sea-ice mass budget (flux convergence). Melt (red) increases around 2007 resulting from increasing wind-driven advective convergence (blue), not change in the region's sea-ice itself (black). ("sea-ice reason" #2/2; cf slide 6)

Top right: Sea-ice latent heat budget (flux divergence). Heat responsible for increasing melt (red) comes from the ocean (blue) not atmosphere (green; includes radiative fluxes).

Bottom figure: Ocean heat budget (top 80m, flux convergence). Heat responsible for increasing sea-ice melt (cyan) results from wind-driven convergence (red) and subsequent increase in radiative convergence (magenta), not change in ocean heat content itself (black).

Takeaway;

- ✓ Sea-ice melt is increasing because of increasing wind-driven convergence of sea-ice and ocean heat,
- ✓ Controlling processes are not obvious from the state alone.

Summary

Sea-ice melt and **wind** are jointly responsible for
Beaufort Sea's seasonal-to-decadal sea level change;

1) *Seasonal* change reflects **sea-ice melt**,
2) *Inter-annual* variations are due to **wind** (Ekman transport),
3) At *decadal* time-scales, **sea-ice melt** is as important as direct **wind** effects,
4) **Sea-ice melt** at decadal time-scales is itself due to **wind** (increasing wind-driven convergence of both heat and sea-ice resulting in larger melt),
5) **Sea-ice melt**-driven change will last longer (years) than **wind**-driven change (months) (due to semi-closed nature of Beaufort Sea's gyre circulation).

Takeaway;

- ✓ Sea-ice melt is equally important as wind in causing Beaufort Sea's sea level rise.

Significance;

- ✓ This is the first example we are aware of that sea-ice melt is found to play a major role in observed sea level change.