The Arctic Ocean Spices Up!

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The Arctic Ocean Spices Up

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ABSTRACT

The contemporary Arctic Ocean differs markedly from midlatitude, ice-free, and relatively warm oceans in the context of density-compensating temperature and salinity variations. These variations are invaluable tracers in the midlatitudes, revealing essential fundamental physical processes of the oceans, on scales from millimeters to thousands of kilometers. However, in the cold Arctic Ocean, temperature variations have little effect on density, and a measure of density-compensating variations in temperature and salinity (i.e., spiciness) is not appropriate. In general, temperature is simply a passive tracer, which implies that most of the heat transported in the Arctic Ocean relies entirely on the ocean dynamics determined by the salinity field. It is shown, however, that as the Arctic Ocean warms up, temperature will take on a new role in setting dynamical balances. Under continued warming, there exists the possibility for a regime shift in the mechanisms by which heat is transported in the Arctic Ocean. This may result in a cap on the storage of deep-ocean heat, having profound implications for future predictions of Arctic sea ice.

Spice

Changes in seawater temperature and salinity may be scaled by the coefficients of thermal expansion α and haline contraction β,

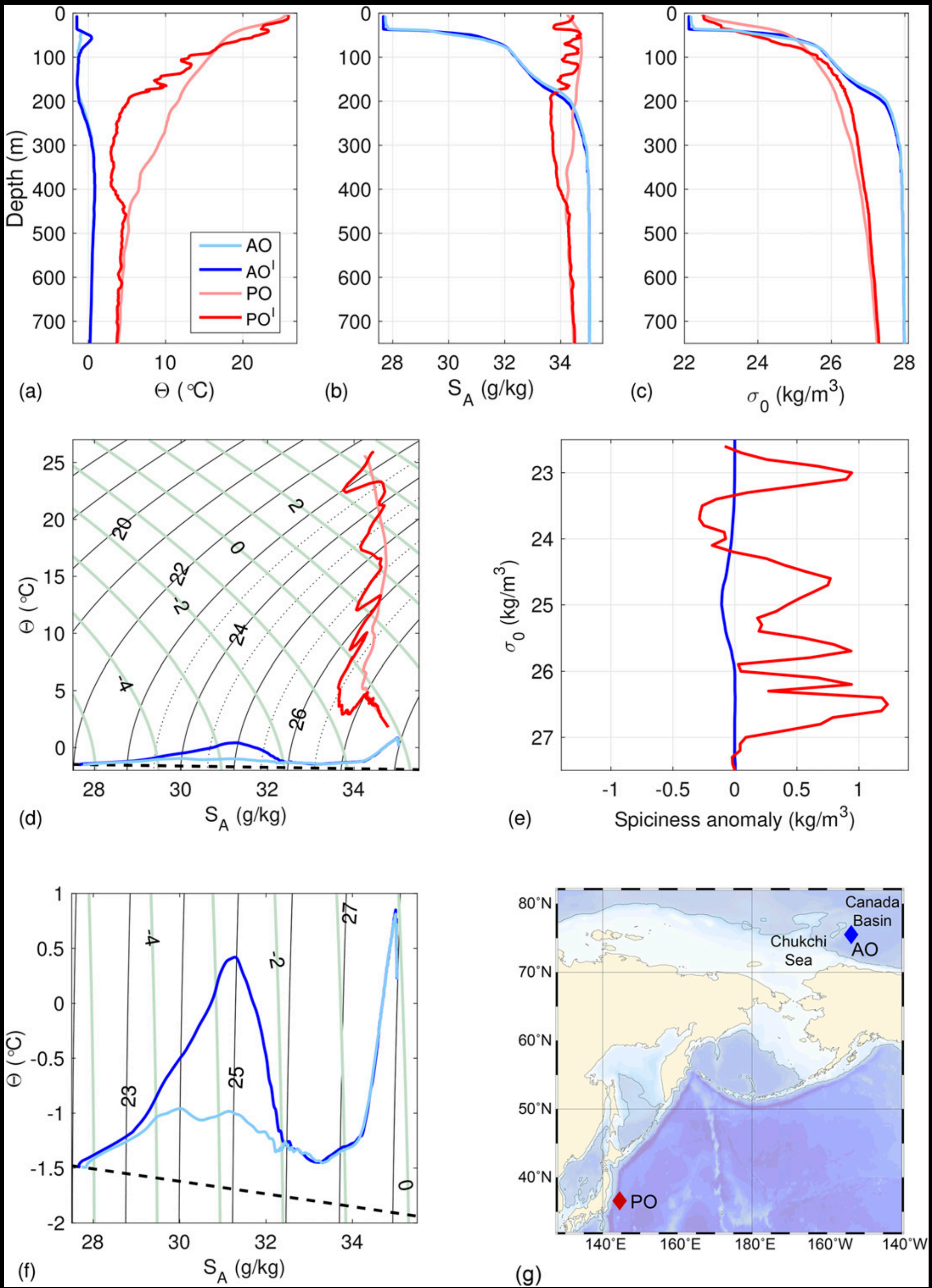
$$\alpha = -\frac{1}{\rho}\frac{\partial\rho}{\partial\Theta}\bigg|_{S_A,p} \qquad \beta = \frac{1}{\rho}\frac{\partial\rho}{\partial S_A}\bigg|_{\Theta,p},$$

to express the total differential in density ρ as

$$\frac{d\rho}{\rho} = -\alpha d\Theta + \beta dS_A,$$

$$\int_\sigma d\tau = \int_\sigma \sigma(\alpha d\Theta + \beta dS_A)$$

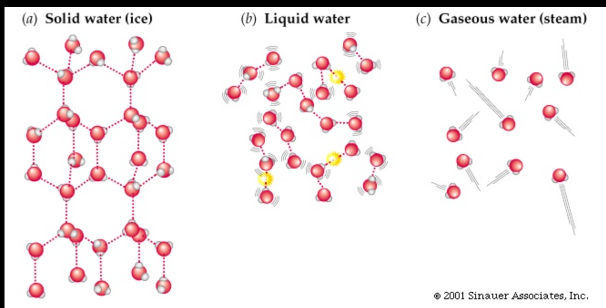
- On a single isopycnal, water can be warmer and saltier or colder and fresher
- “Spice” quantifies how warm and salty it is (spicy is hot and salty (thanks Walter!!)).
- Only makes sense when density is held constant

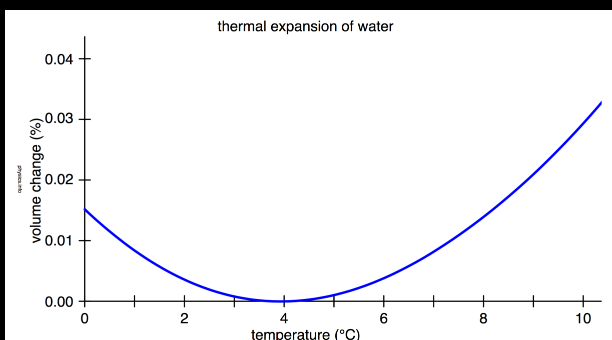


- Arctic Ocean is generally not spicy because it is very cold, which means α is very small.
- Even though there is often complex T-S structure, spice varies much less than in mid-latitude oceans
- Under a warming scenario, spice could become increasingly important since warmer water is spicier

Thermal Expansion

Freshwater





Saltwater

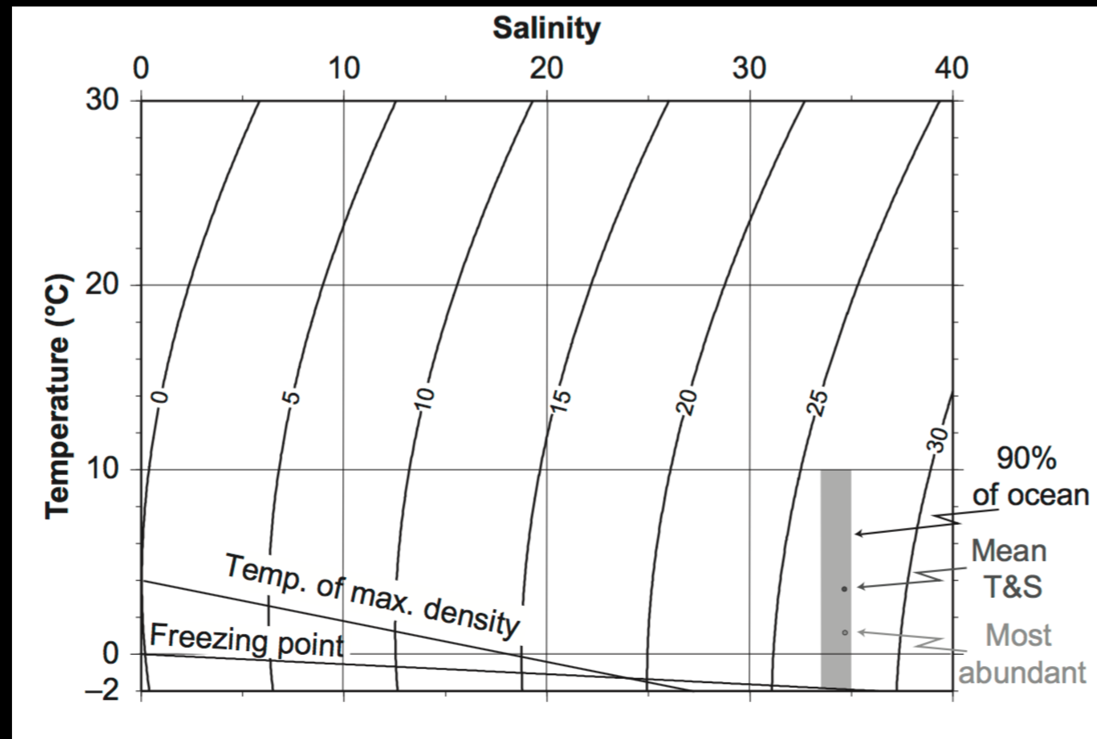
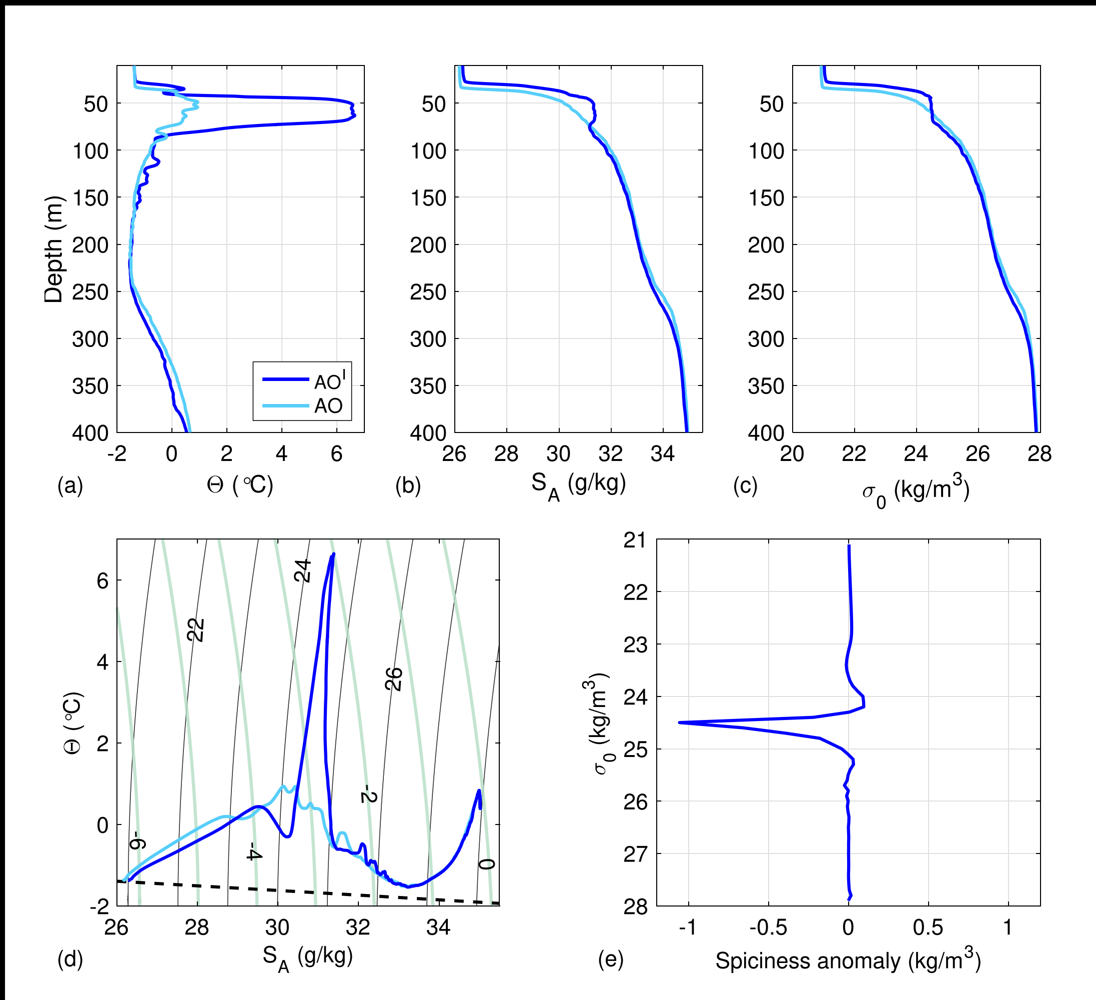


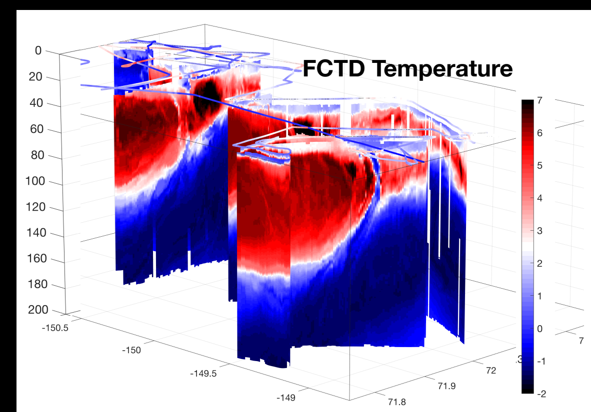
TABLE 3.2 Variation of Density ($\Delta\sigma_t$) with Variations of Temperature (ΔT) and of Salinity (ΔS) as Functions of Temperature and Salinity

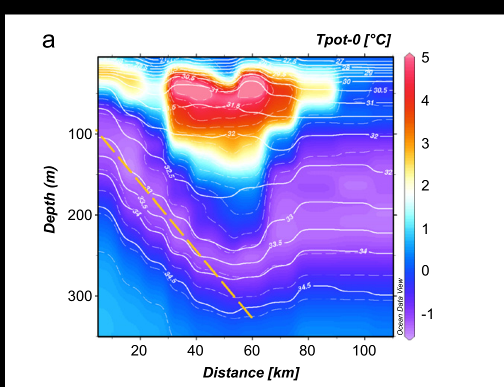
Salinity	0	20	35	40	0	20	35	40
Temperature (°C)		$\Delta\sigma_t$ for $\Delta T = +1$°C				$\Delta\sigma_t$ for $\Delta S = +0.5$		
30	−0.31	−0.33	−0.34	−0.35	0.38	0.37	0.37	0.38
20	−0.21	−0.24	−0.27	−0.27	0.38	0.38	0.38	0.38
10	−0.09	−0.14	−0.18	−0.18	0.39	0.39	0.39	0.39
0	+0.06	−0.01	−0.06	−0.07	0.41	0.40	0.40	0.40

(Talley et al. 2011)

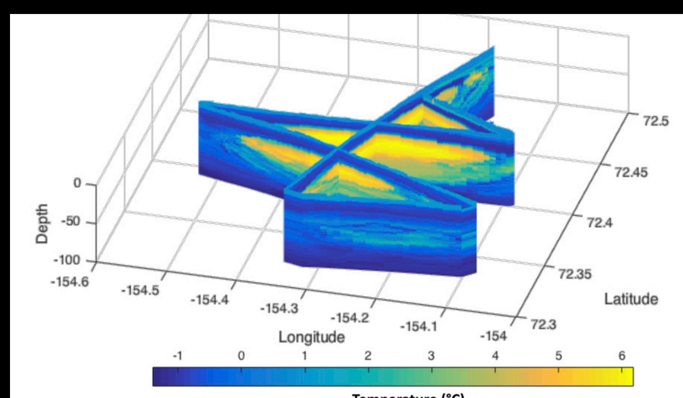


In fact, very warm intrusions have already been observed that show much more of a spice signature

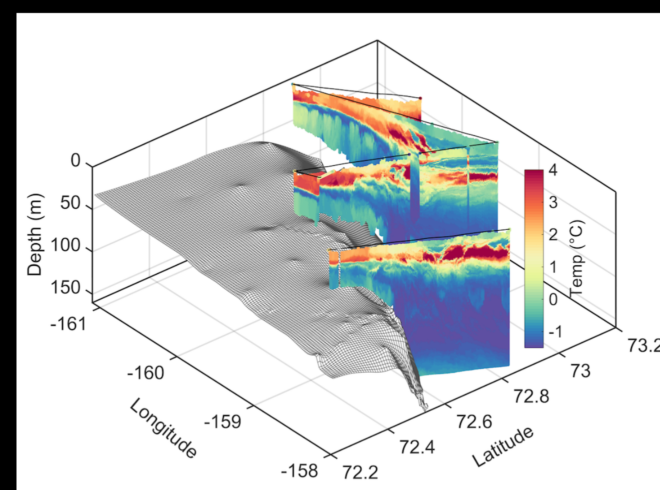




(Kawaguchi et al. 2012)

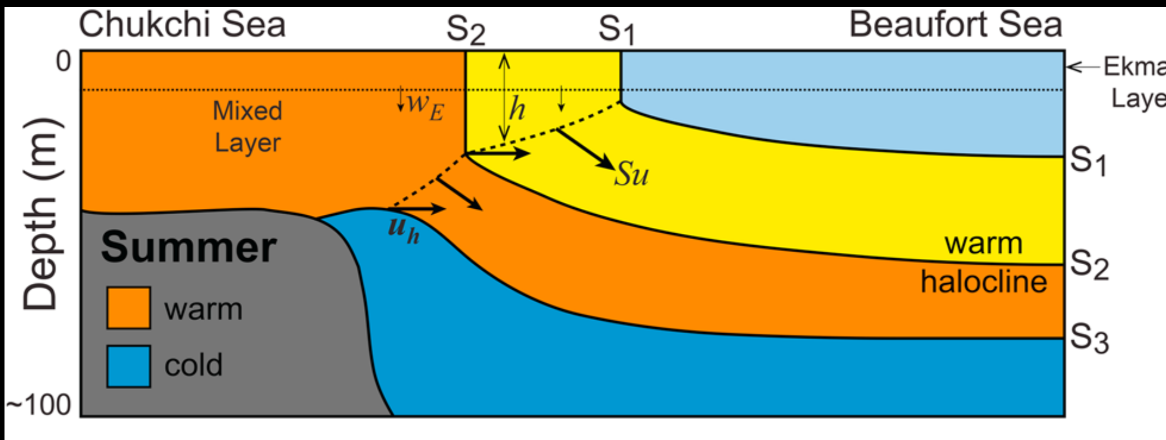


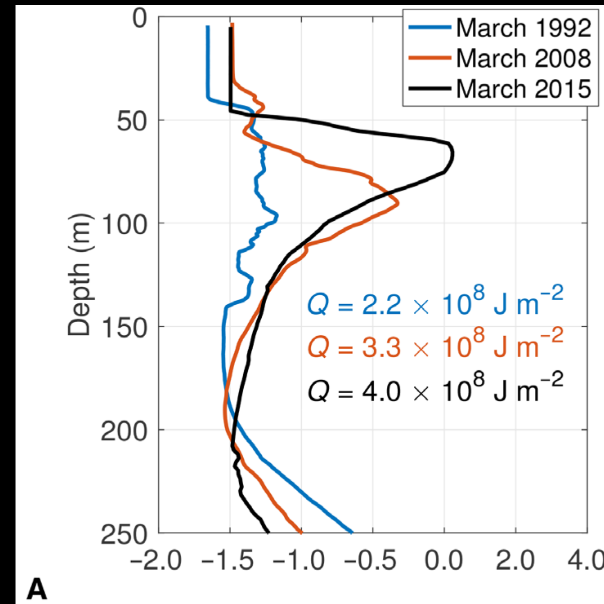
(Fine et al. 2018)

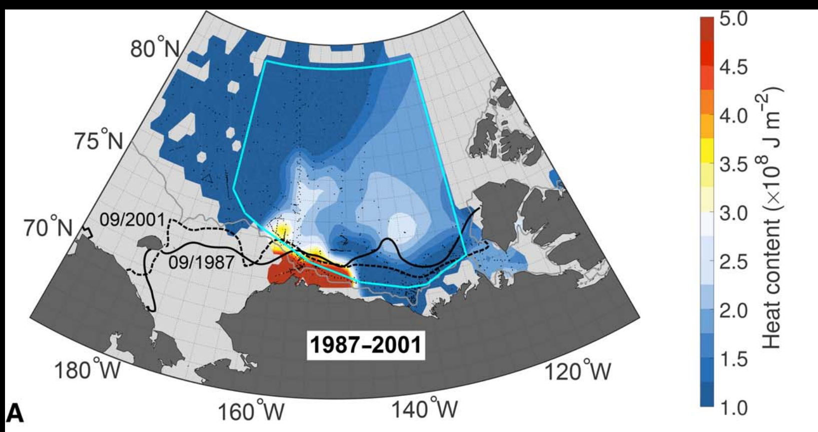


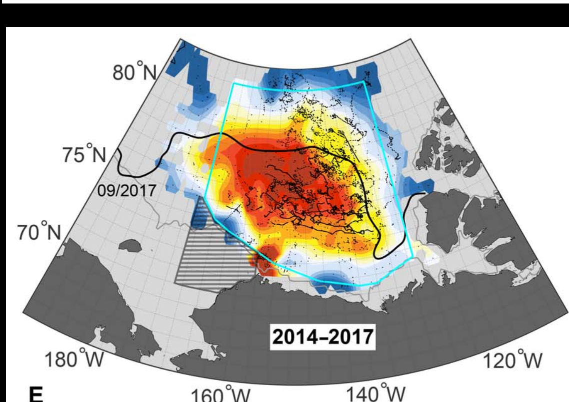
(SODA cruise report)

Implications: Ventilation





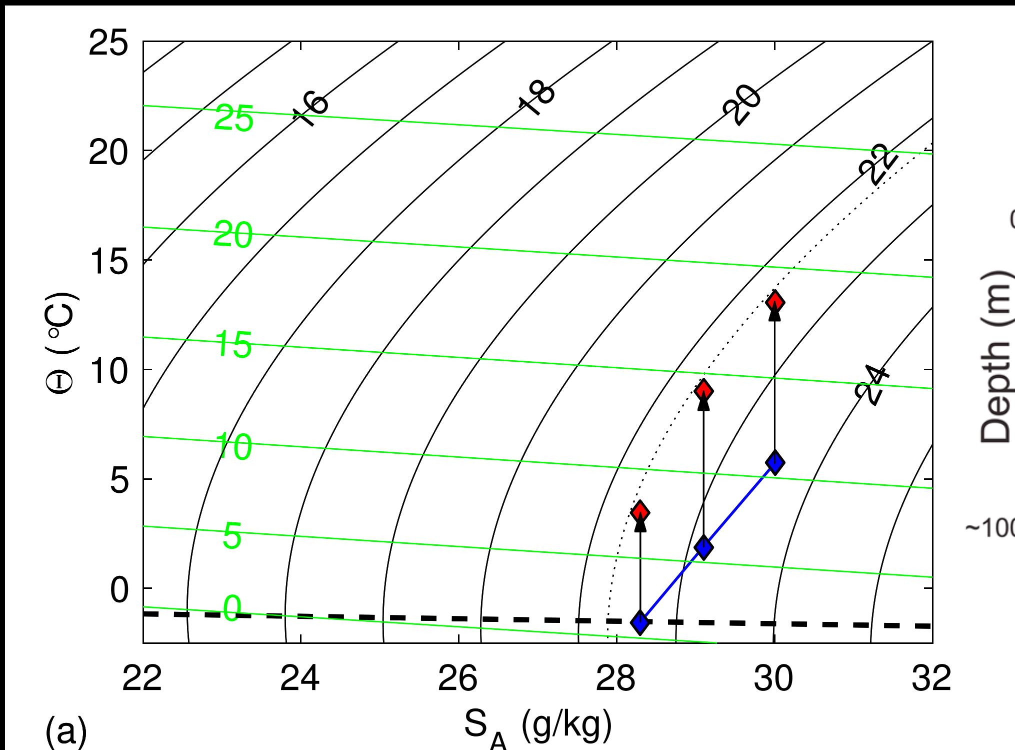


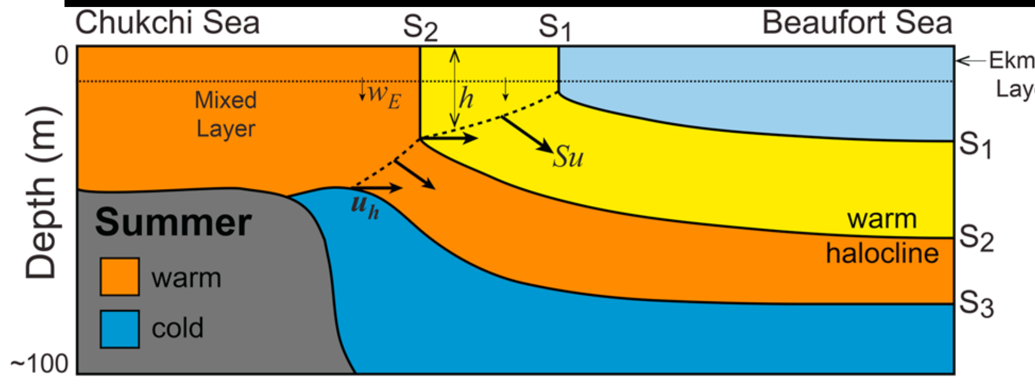


- In the western Arctic, the warm PSW halocline is ventilated during the summer as Chukchi Sea surface water subducts
- As this layer gets spicier, heat is subducted and archived in the halocline
- Stored heat may affect sea ice growth/ melt, etc.

(Timmermans et al. 2017, 2018)

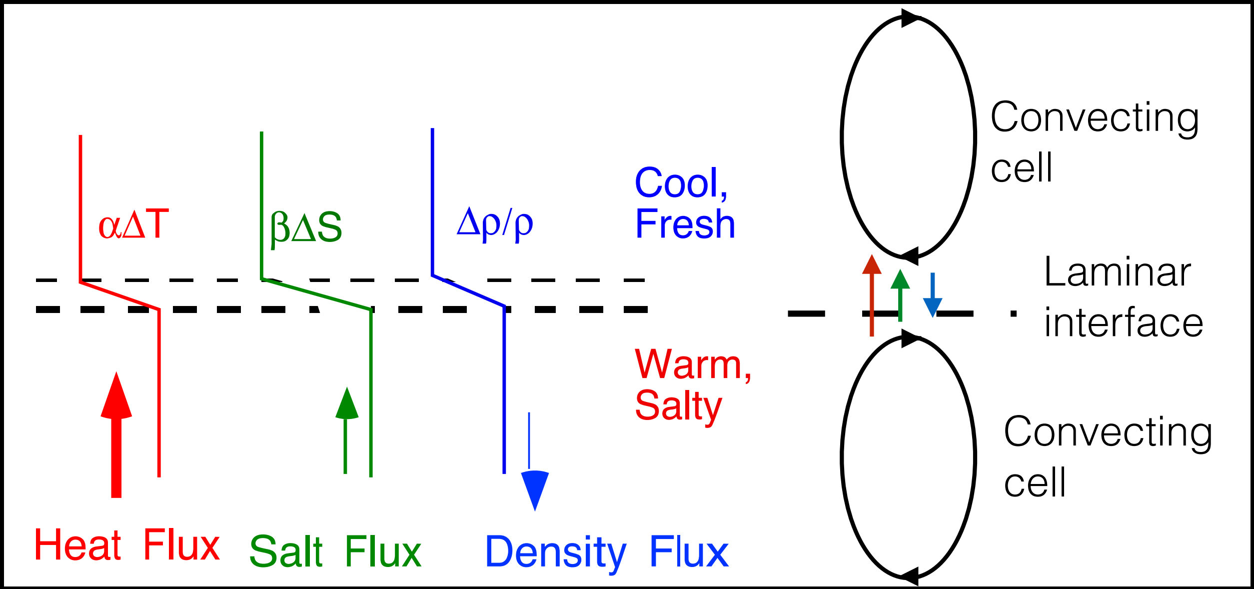
Implications: Ventilation





- If the Chukchi continues to warm, the lateral density gradient between the Chukchi and Beaufort Sea will decrease
- This changes the shape of the isopycnals, so that the deeper PSW isopycnal would no longer be ventilated in the height of summer
- The amount of warming needed is realistic with longer ice-free periods in the Chukchi (200 W/m^2 for 1.5 months)
- This would shut off the mechanism that's currently archiving much of the summer heat input

Implications: Double Diffusion

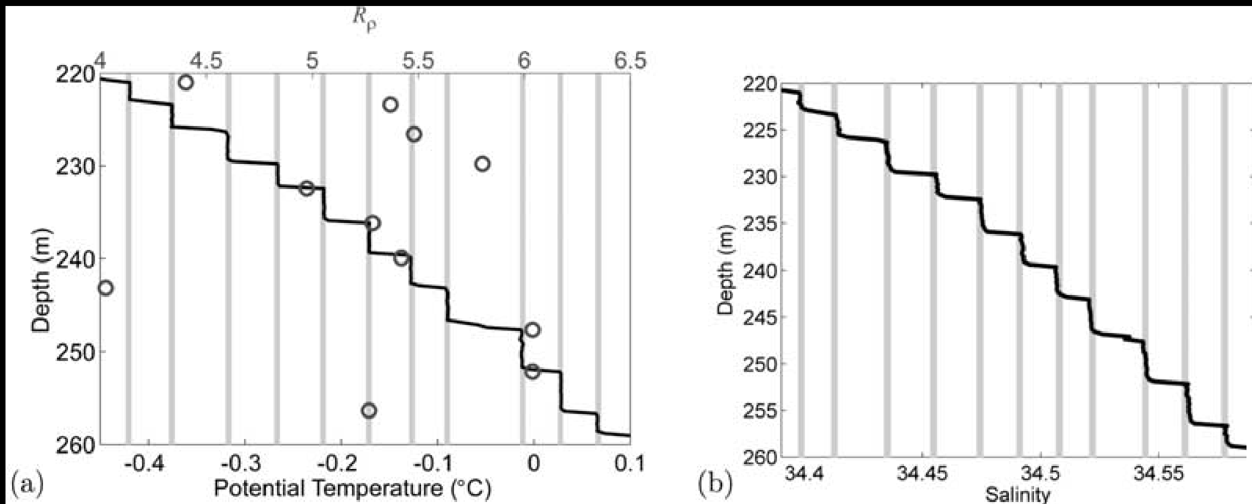


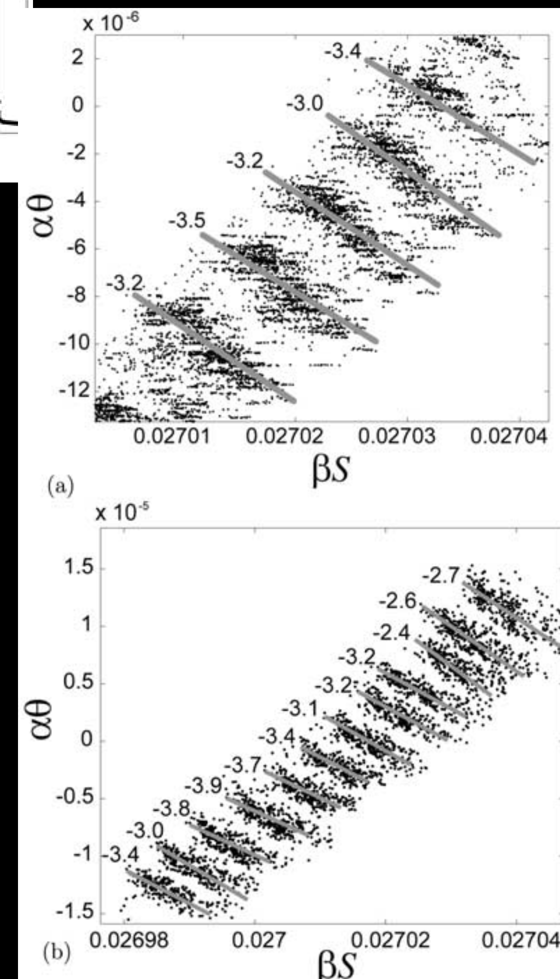
(Ruddick & Gargett 2003)

- The difference in molecular diffusion of heat and salt can create convective cells when cool fresh water lies above warm salty water

- Over time, this results in mixed layers separated by sharp interfaces creating a characteristic "step" structure
- Over the course of the staircase, both heat and salt rise. Heat rises faster than salt due to it's higher molecular diffusivity
- Density travels down the staircase, increasing stratification

Implications: Double Diffusion

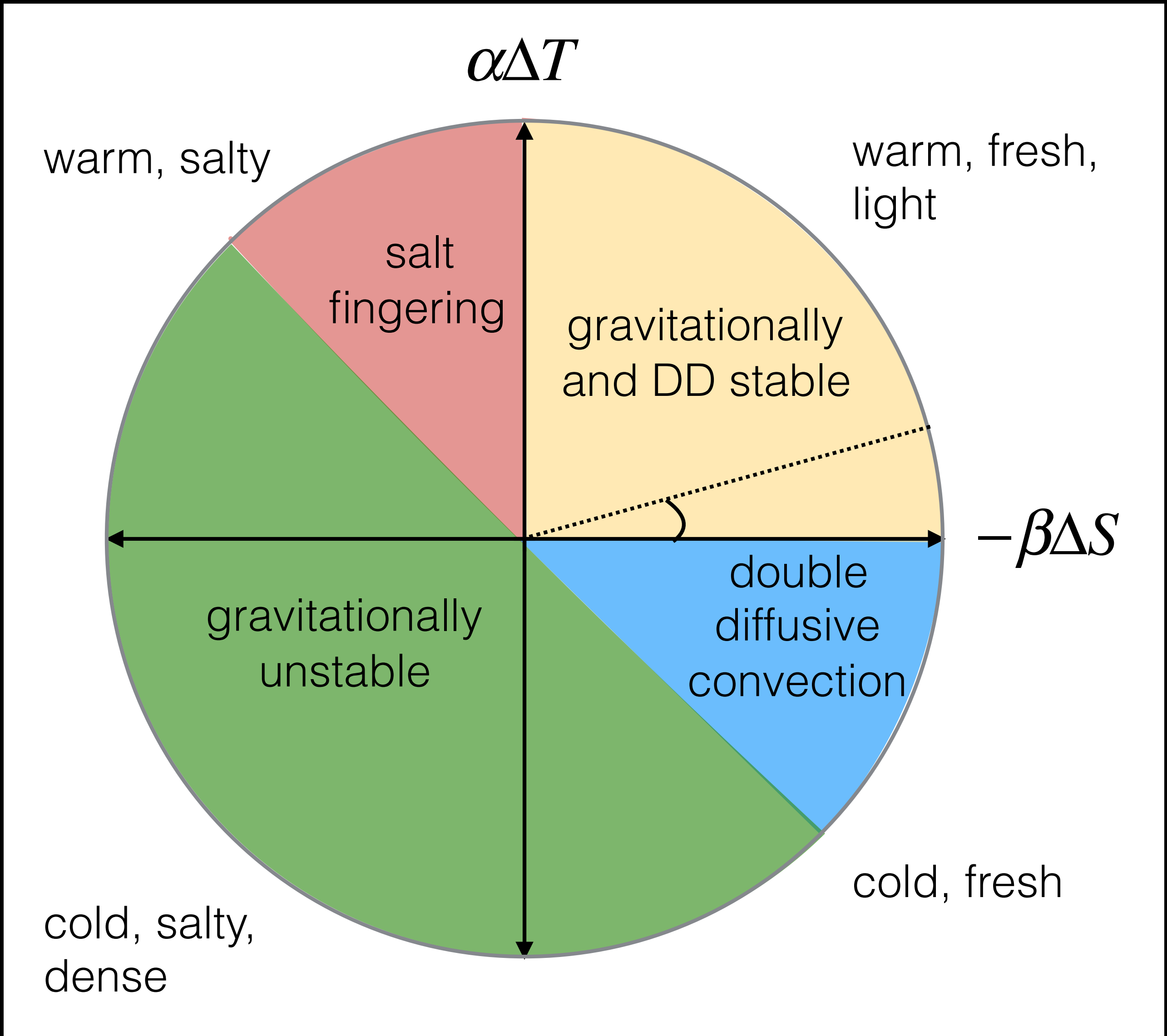




- DD Layers are ubiquitous above the Atlantic Water Layer in the Arctic
- They are extremely coherent and extend 100s of kilometers (!)
- Upward heat fluxes through them are persistent but small (0.05-0.3 W/m^2)
- Currently there is no persistent double diffusion above the PSW warm layer

(Timmermans et al. 2008)

Implications: Double Diffusion

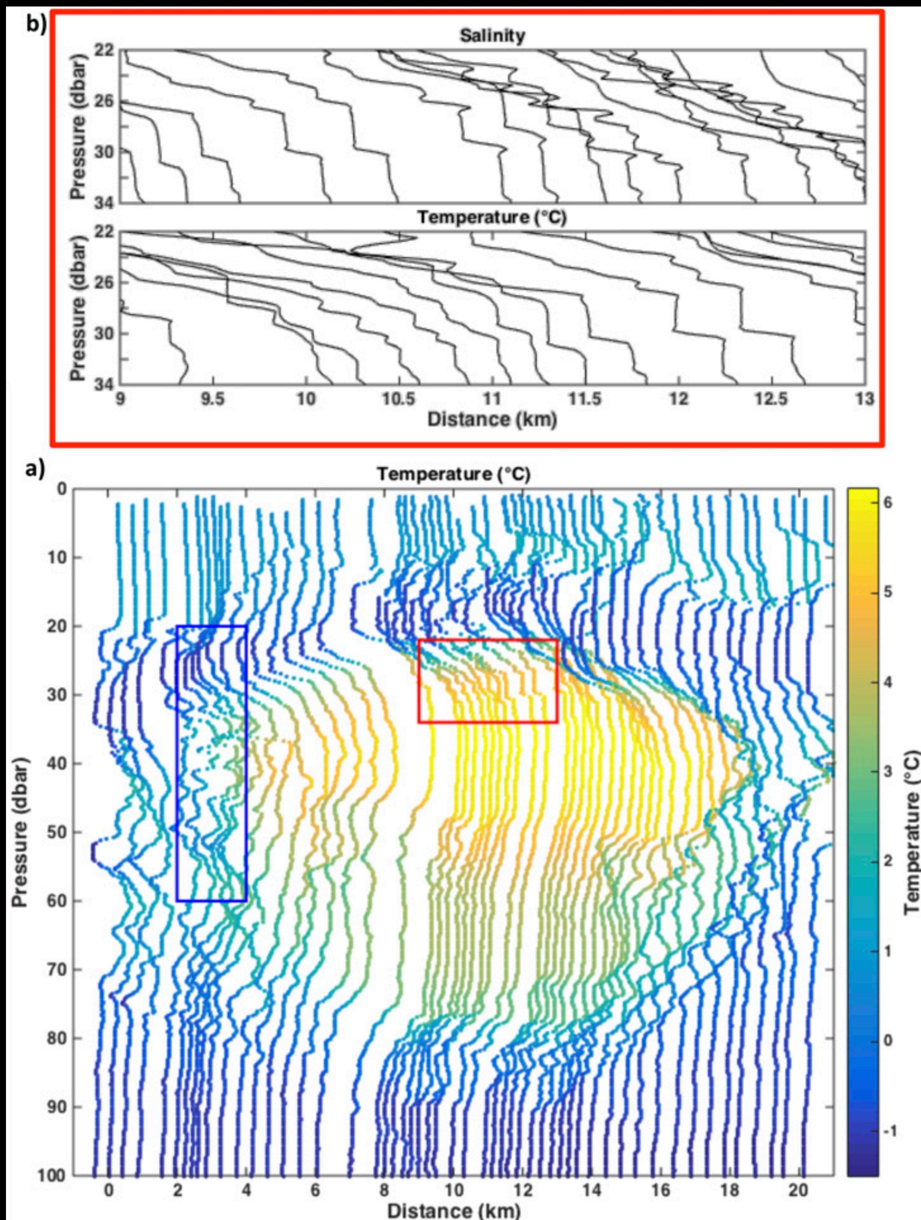


- The strength of double diffusion is controlled by how much temperature and salinity change within a profile
- As the temperature change gets larger, the double diffusion gets stronger
- Spicy intrusions represent a large change in temperature in the vertical, and can induce local double diffusive convection

$$\Delta\rho = -\alpha\Delta T + \beta\Delta S$$

$$Tu = \arctan(-\alpha\Delta T / \beta\Delta S) - 45^\circ$$

Implications: Double Diffusion



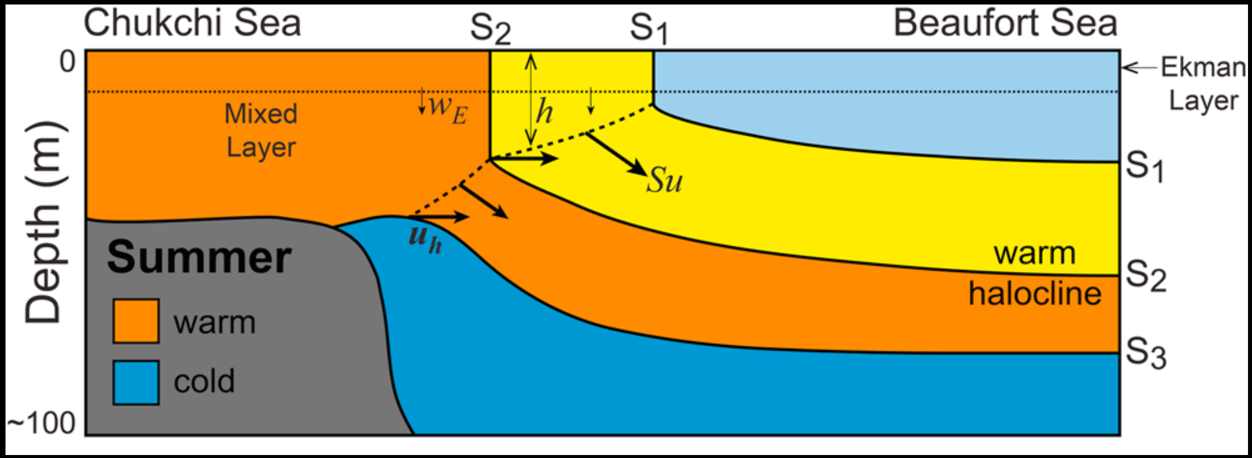
(Fine et al. 2018)

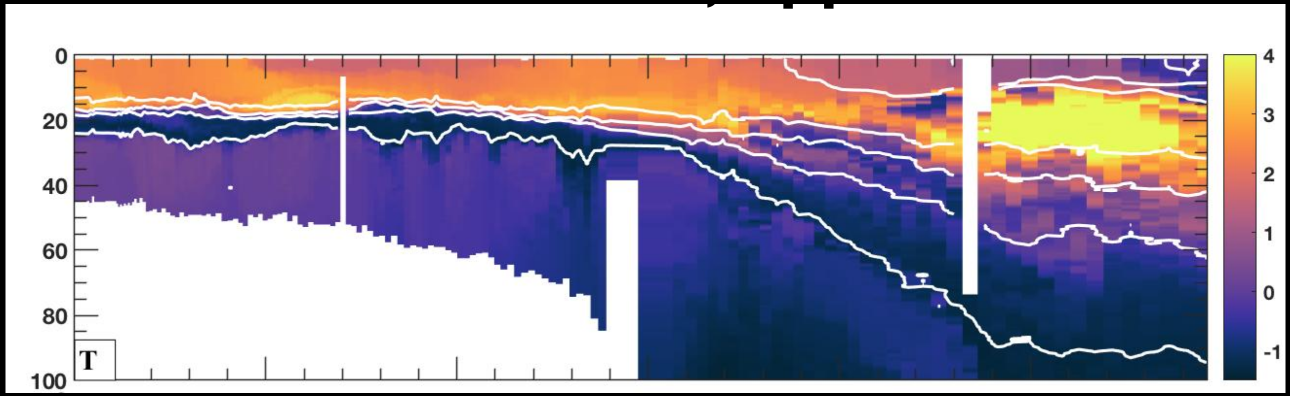
- ArcticMix eddy had double diffusive layers on top
- Vertical heatflux through these layers was ~5 W/m^2
- Increasingly spicy intrusions—or increasing frequency of spicy intrusions—will lead to more vertical double diffusive heat fluxes
- Implications for climate/sea ice…???

Conclusions

- Arctic has historically been a minty ocean, but as surface temperatures increase around the Arctic and warmer water subducts, it is becoming increasingly spicy
- In the short-term, this spice allows for the storage of intrathermocline heat
    - Possibly this heat is safely sequestered away?
    - Or possibly the subduction brings this heat from basin margins into the Central Arctic, where it can melt more sea ice?
- Spicy intrusions may also be susceptible to double diffusion, providing another pathway for subsurface heat to affect surface sea ice
- In the long-term, increasingly warm surface waters may not subduct at all in the summer, releasing more heat to the atmosphere

Thoughts for Discussion

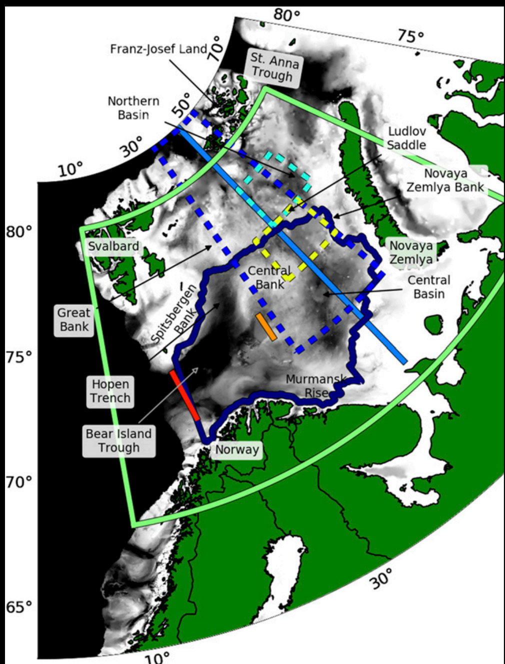


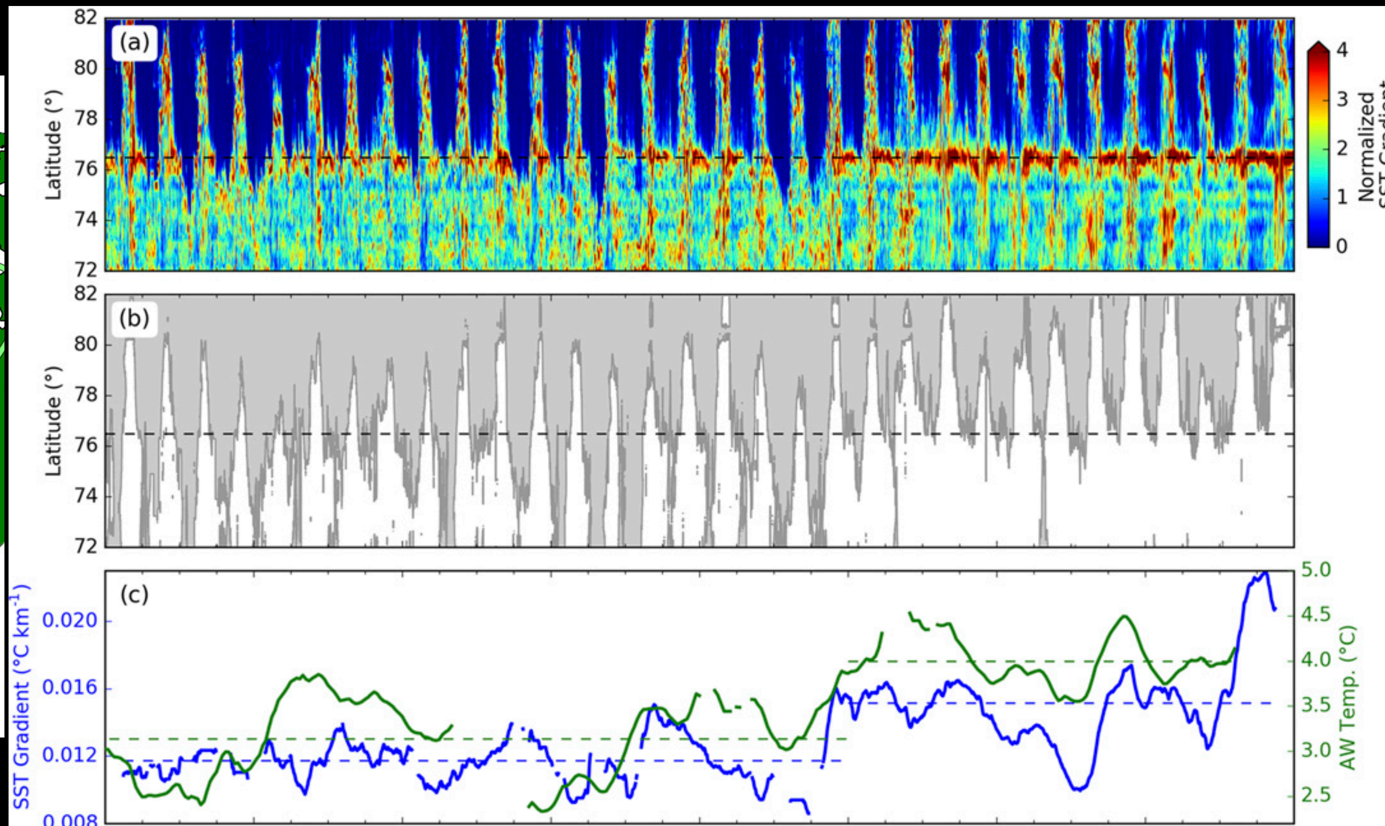


Actual Arctic is way more complicated than the cartoon. How does the patchiness of warm water and subduction locations affect this picture?

(SODA cruise report)

Thoughts for Discussion





- On the European side, the Polar Front between the Atlantic and the Arctic is deep but still linked to topography.
- Warmer Atlantic Water sharpens the front and prevents sea ice formation south of it

(Barton et al. 2018)

Thoughts for Discussion

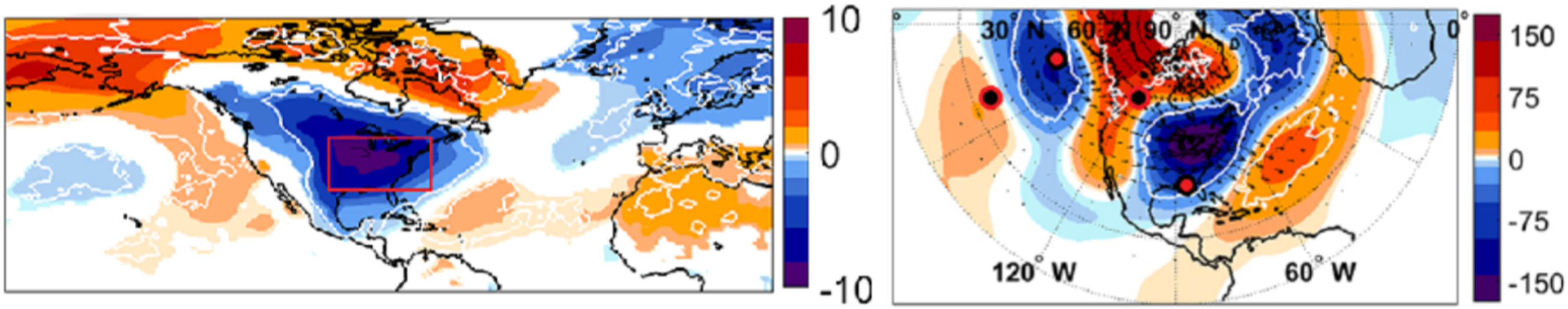


Figure 10. (left) Surface temperature anomalies (K) and (right) 250 hPa geopotential height anomalies (m, shading) during North American cold spells as determined in the red box region. Only anomalies exceeding the 95% confidence level derived from a random Monte Carlo sampling procedure are shown. The data covers ERA-20C DJFs over the period 1900–2010. (Figure from Messori et al. 2016).

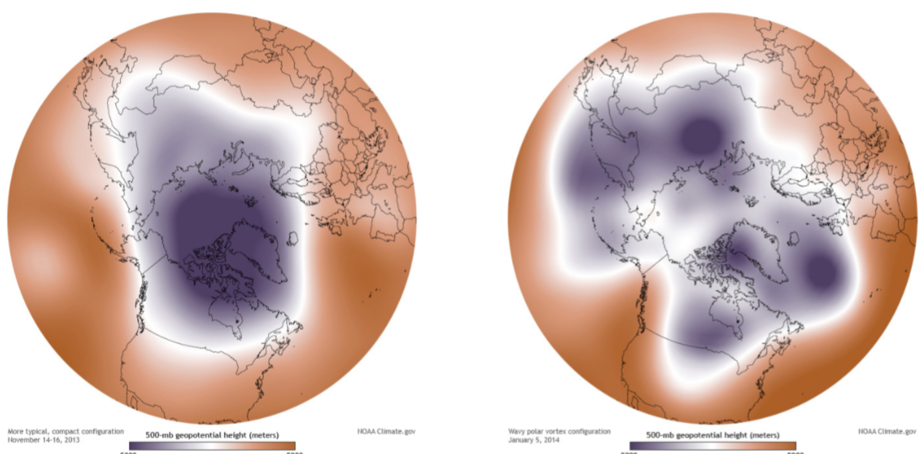


Figure 6. Sample geopotential height fields for 500 hPa with lower values in purple and the jet stream in white. (a) Contrasts a single, more zonal path encircling the tropospheric polar vortex versus a wavier configuration (b) with multiple low centers. (Figure from NOAA Climate.gov).

Atmospheric effects of more heat available in Chukchi may result in more extreme North American winter weather?

(Francis et al. 2017, Messori et al. 2016, NOAA)

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