

# *Changes in the Arctic Ocean:* **A story in T, S, & V**



***Michael Steele***

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***S. Dickinson, T. Martin, I. Rigor***

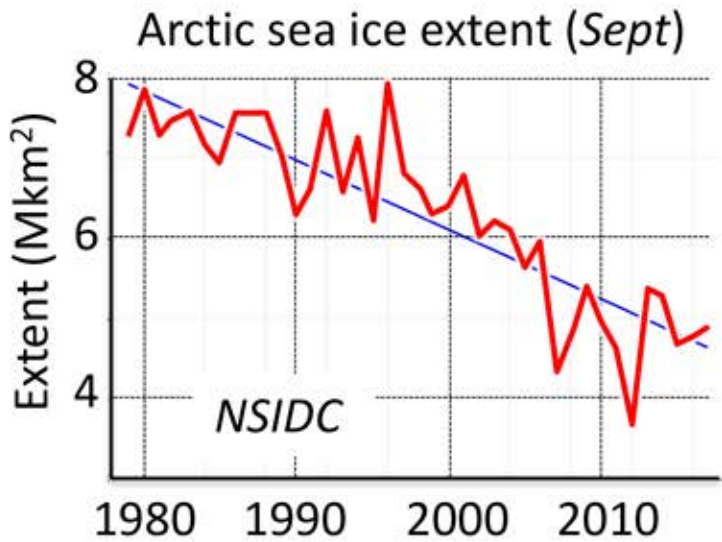
*Polar Science Center, Applied Physics Laboratory*

*University of Washington*

*Seattle, WA USA*



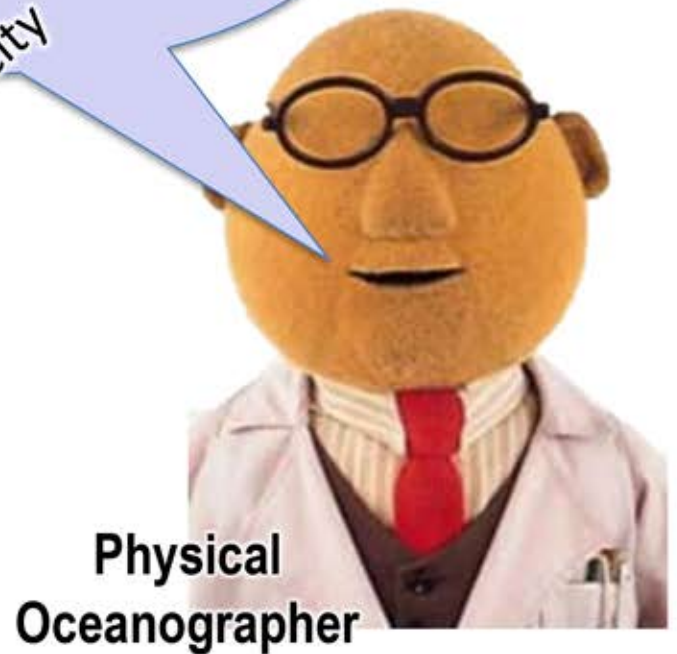
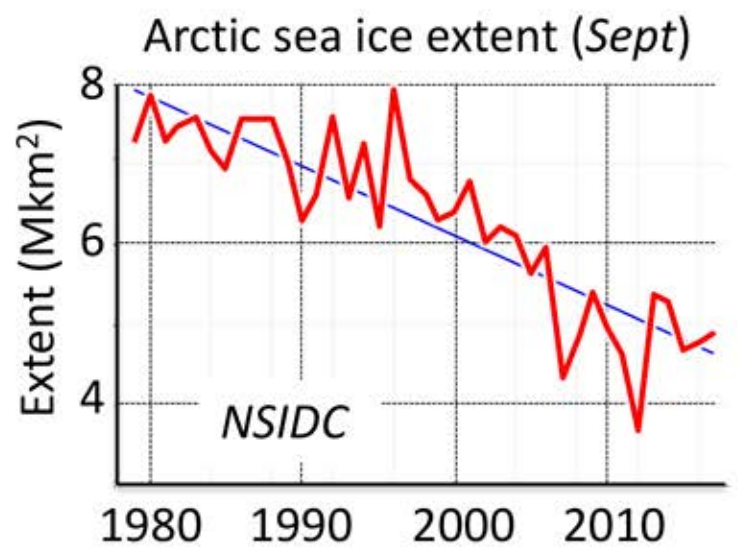
**Sea ice is declining!**





Sea ice is declining!

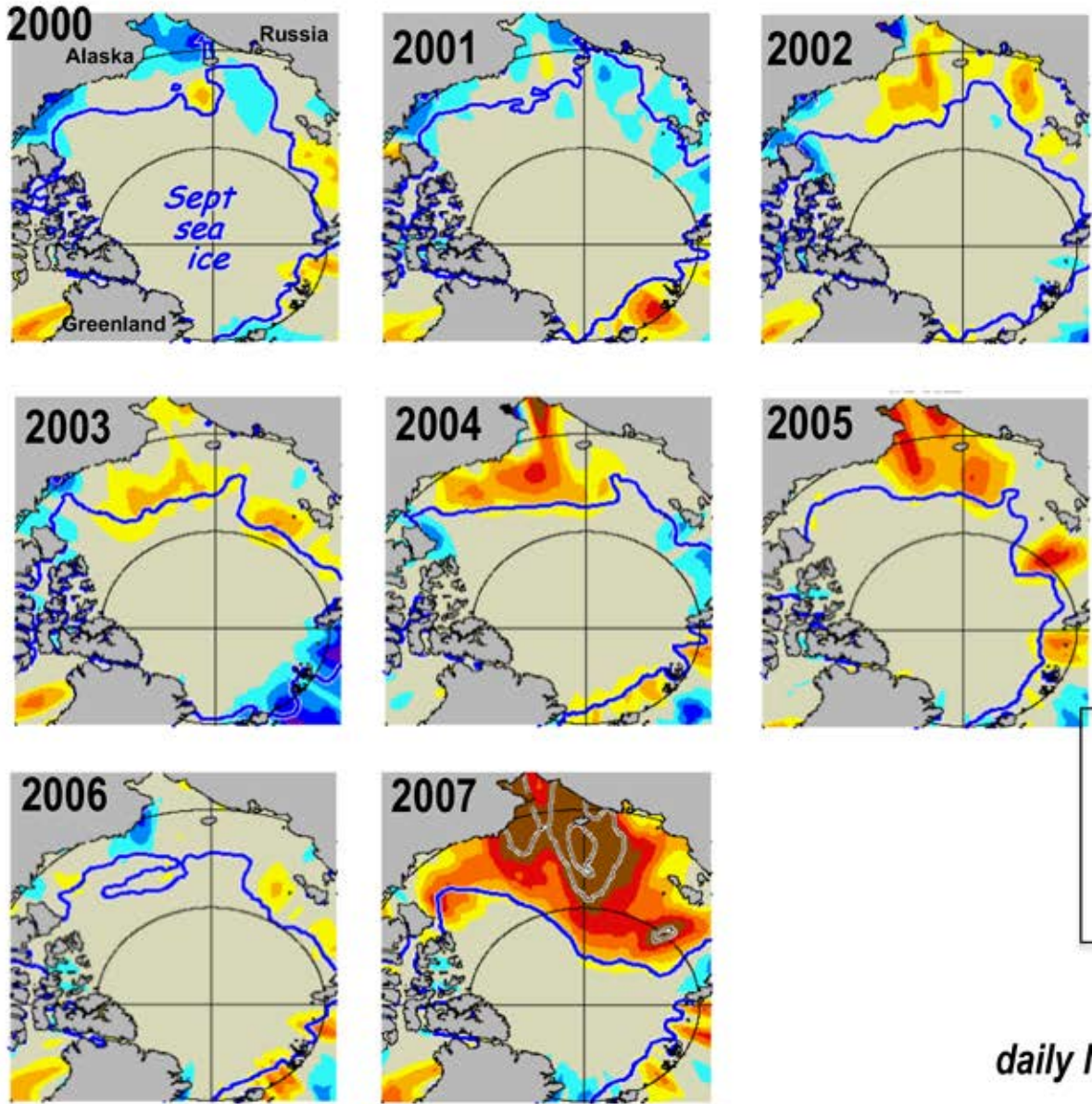
What about  
**T, S, V?**  
Temperature  
Salinity  
Velocity



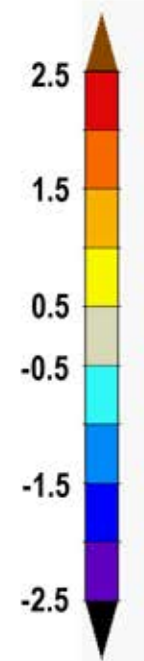
Physical  
Oceanographer



# Ice Retreat → Ocean Warming



Steele et al. (GRL, 2008)



Anomaly of Summer ≡ JAS  
**Sea Surface Temperature (°C)**  
(relative to 1982-2007 mean)

Most of this is **local solar input**  
Steele et al. (JGR, 2010)

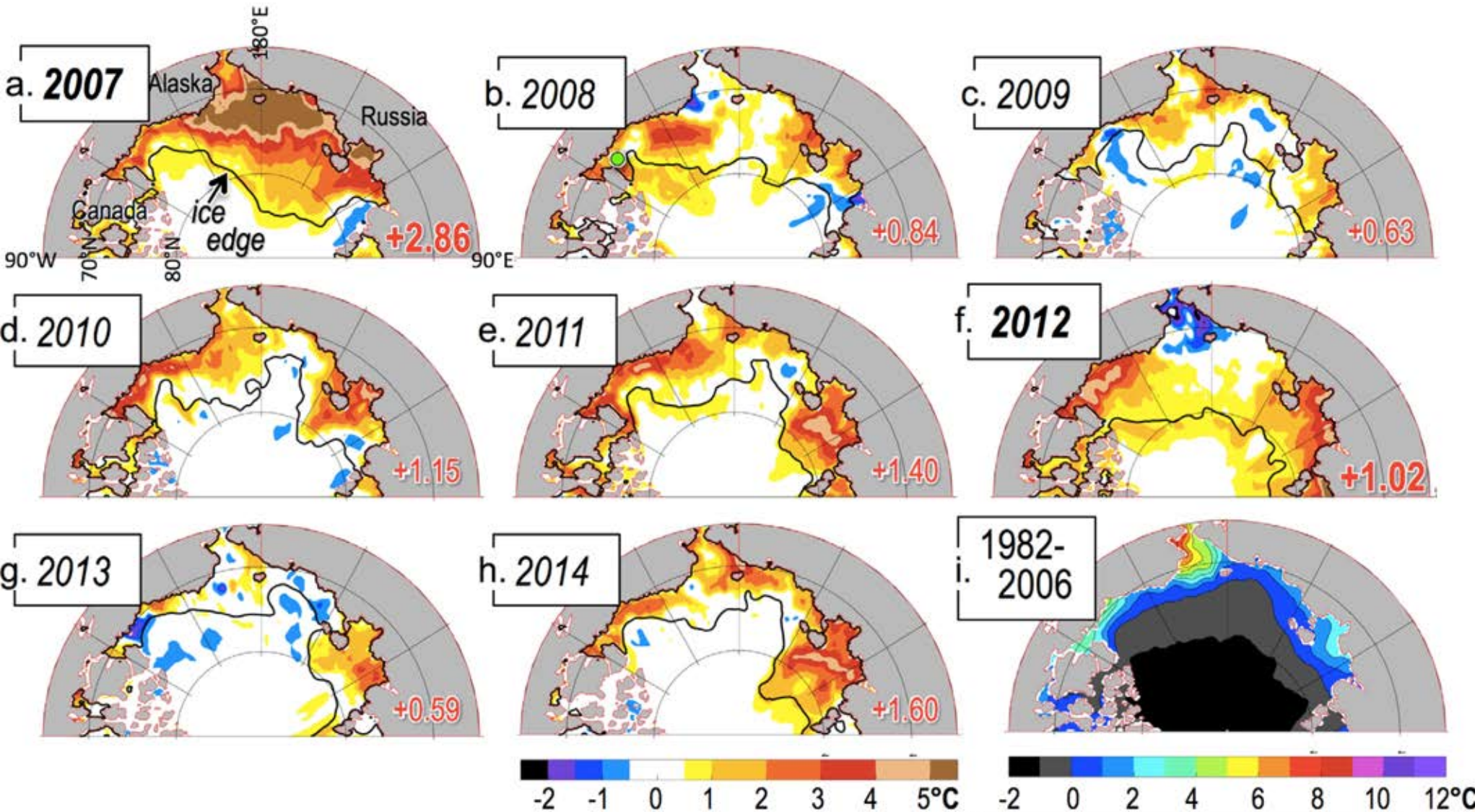


daily NOAA OISST  
(satellite + some in situ obs)



# More recently

Steele & Dickinson (2016)



**SST:** dOISST (AVHRR only) July/Aug

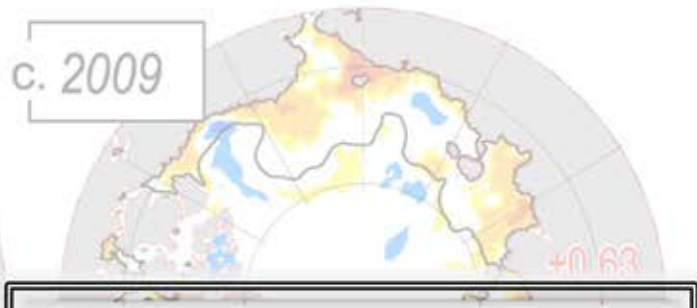
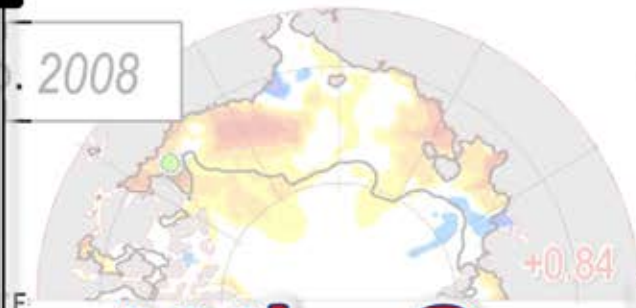
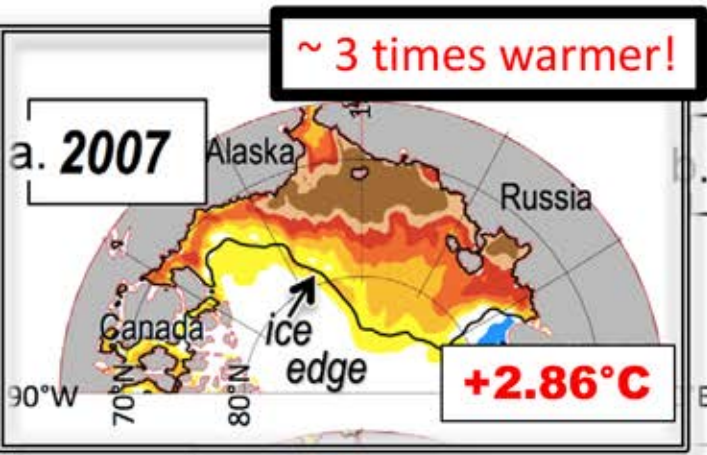
**Ice edge:** 15% concentration (NASA Team1)

**Mostly warm**

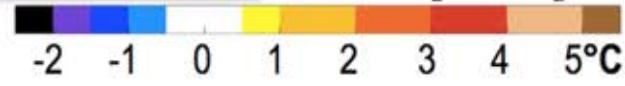
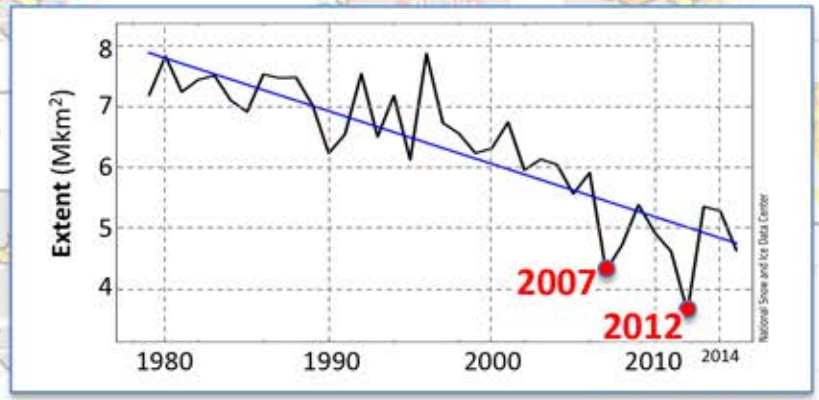
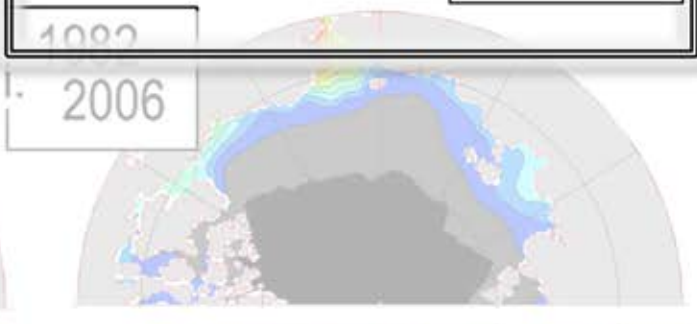
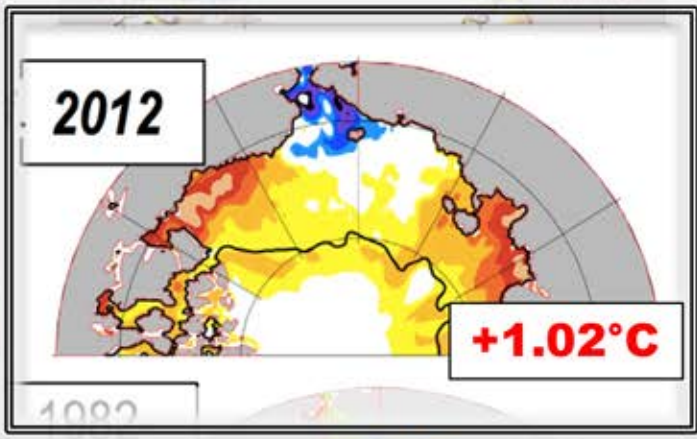
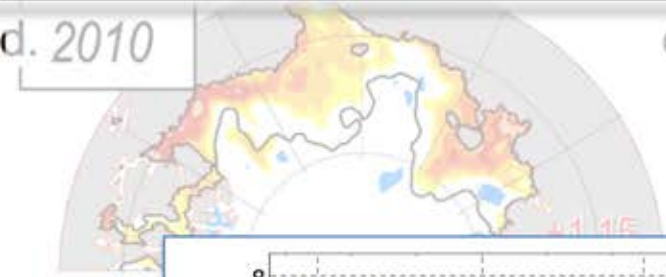


# More recently

Steele & Dickinson (2016)



# Why?

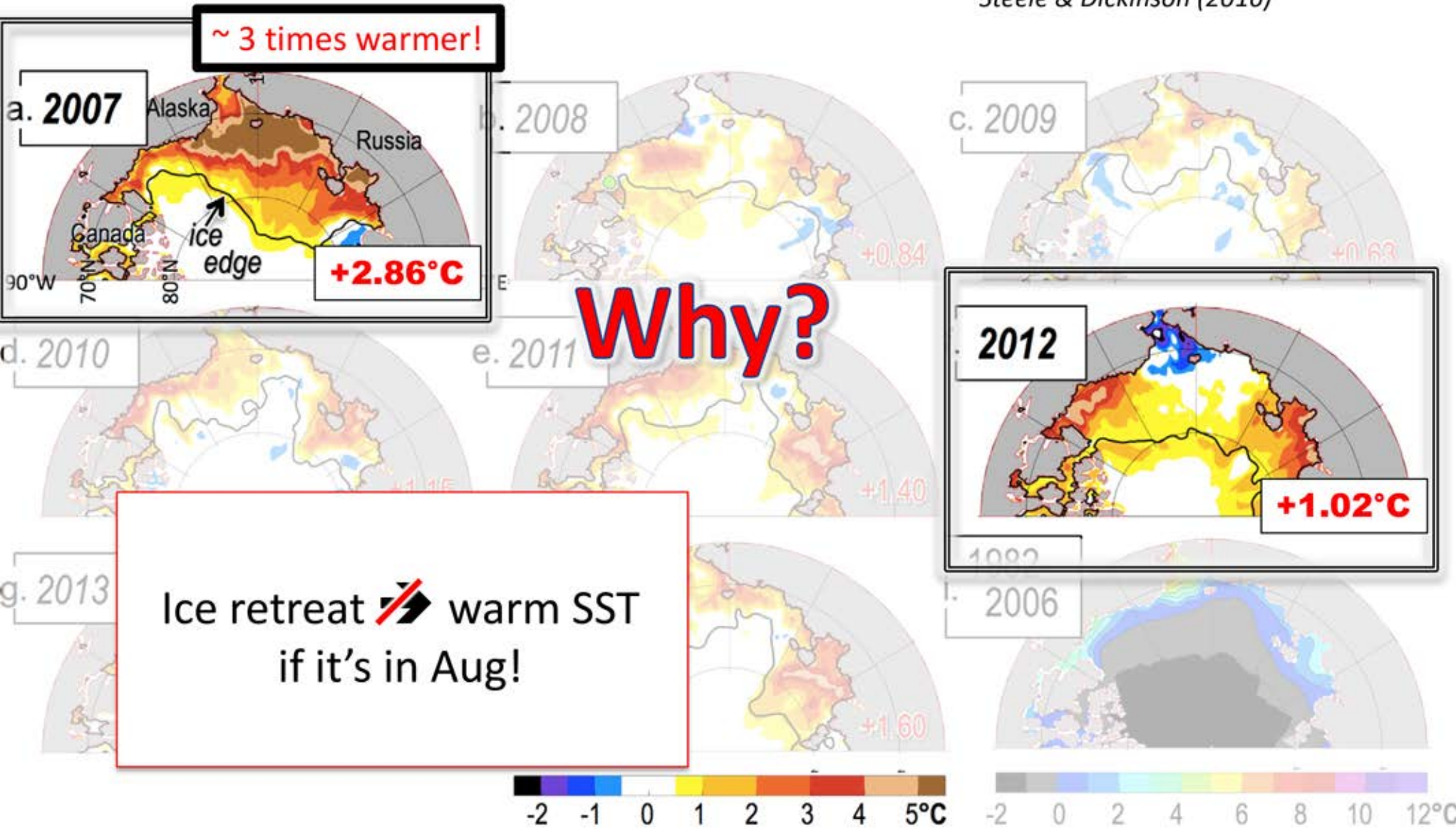


**SST:** dOISST (AVHRR only)

**Ice edge:** 15% concentration (NASA Team1)

# More recently

Steele & Dickinson (2016)

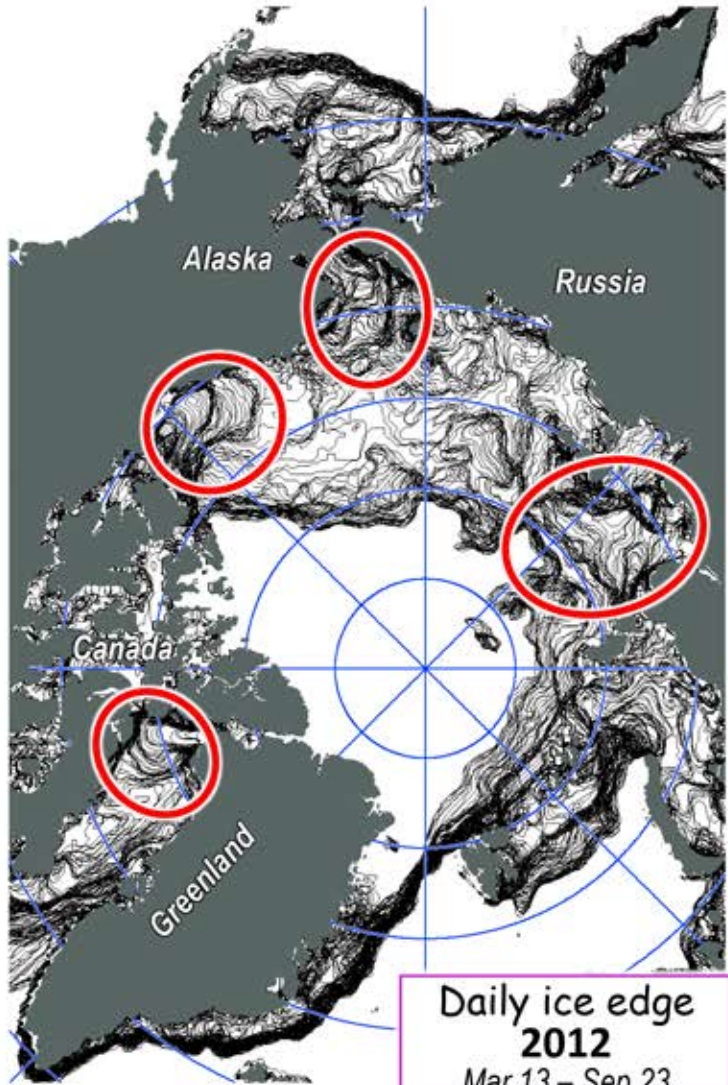


**SST:** dOISST (AVHRR only)

**Ice edge:** 15% concentration (NASA Team1)

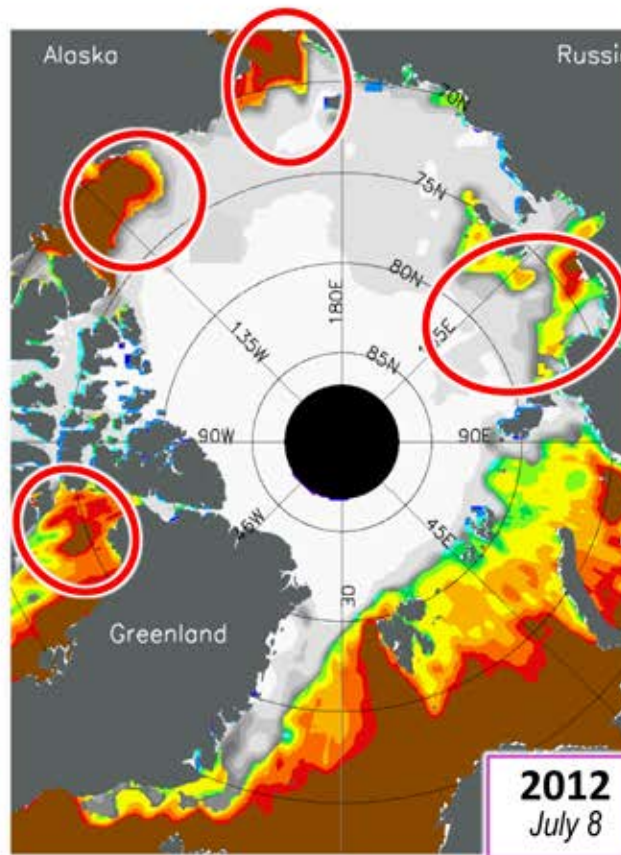


# Ice Retreat ← Ocean Warming



## "Ice edge loitering"

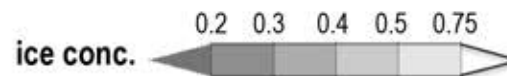
Steele & Ermold (JGR, 2015)



## Explanation?

Off-ice winds +

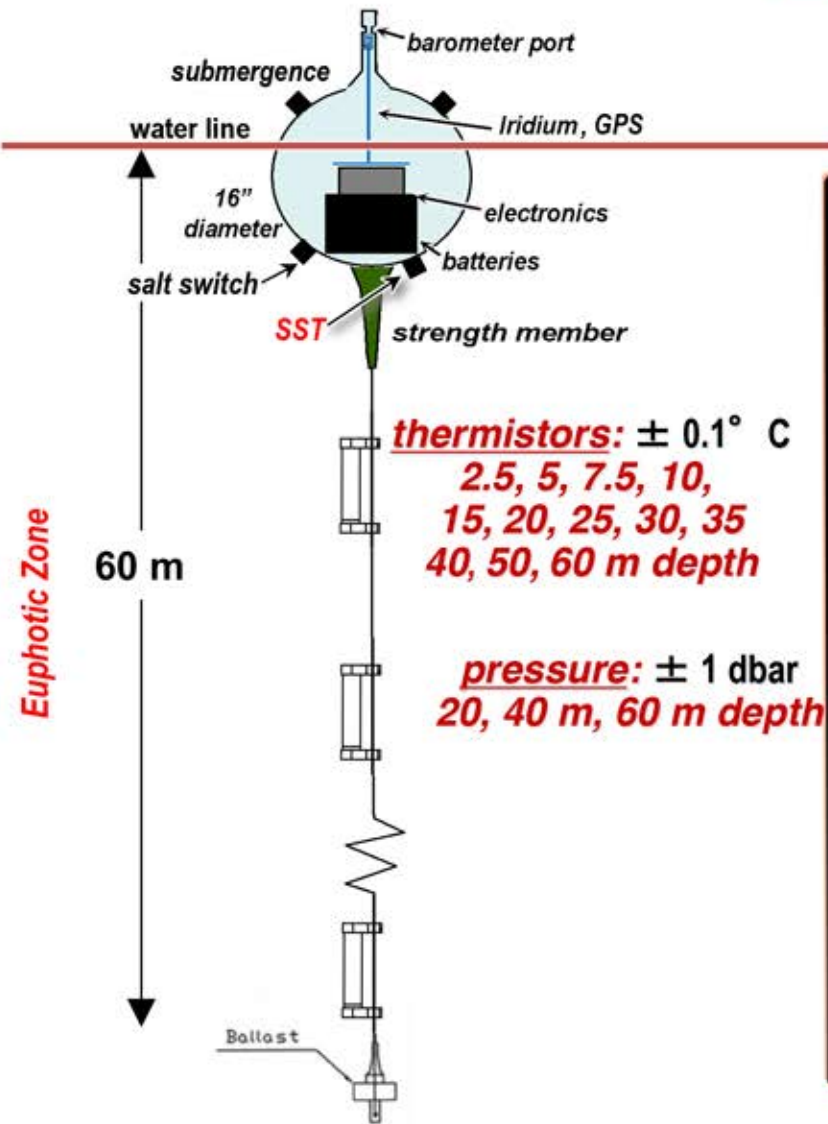
warm SSTs





# The UpTempO buoy

## Upper Temperature of the polar Oceans

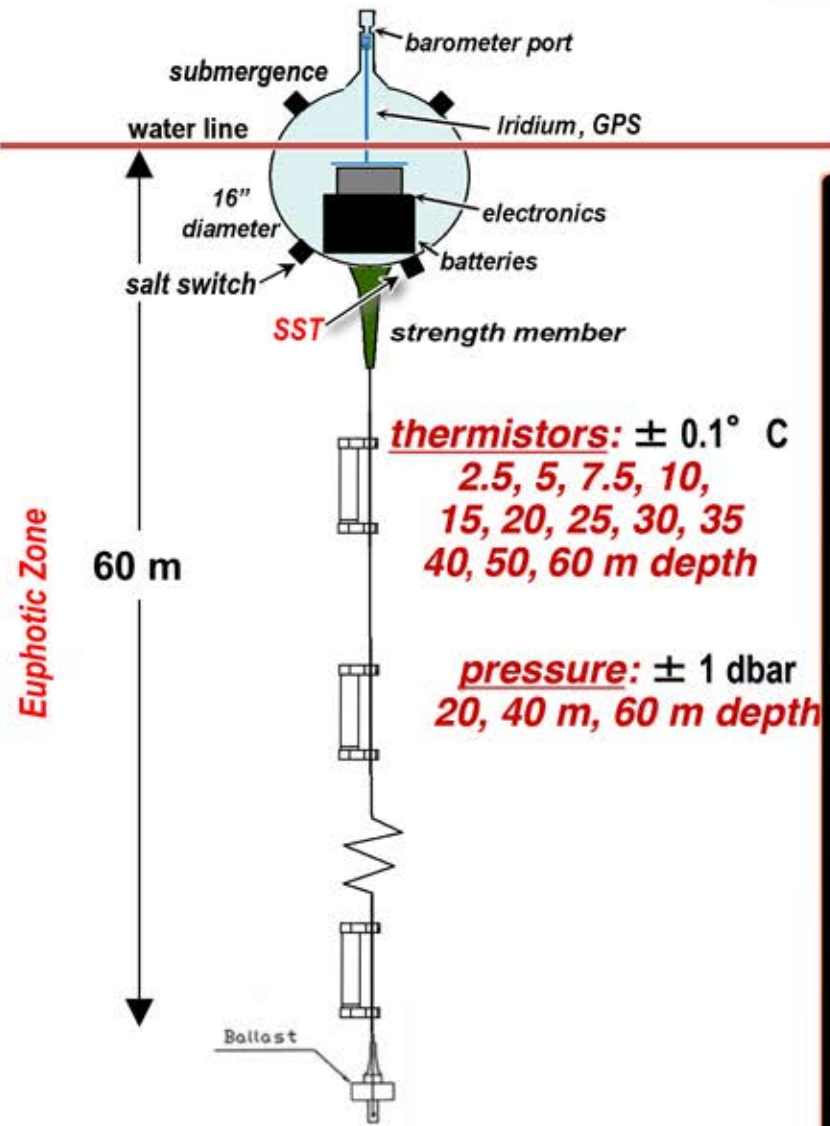


- Surface: SLP, **SST**, GPS, Iridium ...[anemometer]
- Cable: 12-16 x **T** ( $\pm 0.1^\circ \text{C}$ ), 3 x **P** ( $\pm 1 \text{ dbar}$ ) ...[S]
- 60 m (basin) or 25 m (shelves)

Google "uptempo arctic"

# The UpTempO buoy

Upper Temperature of the polar Oceans



- Surface: SLP, **SST**, GPS, Iridium ...[anemometer]
- Cable: 12-16 x **T** ( $\pm 0.1^\circ \text{C}$ ), 3 x **P** ( $\pm 1 \text{ dbar}$ ) ...[S]
- 60 m (basin) or 25 m (shelves)
- Deploy: in ice or water by **ship**, **ice camp**, **air**

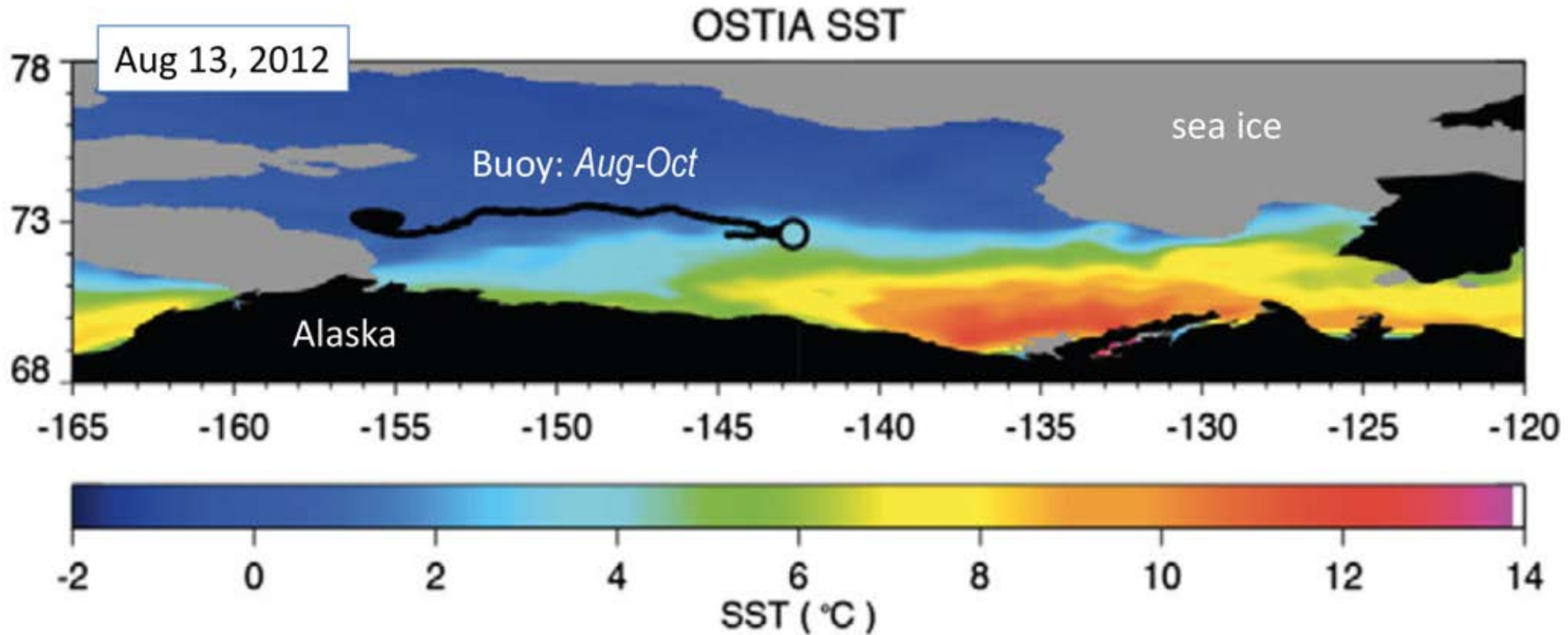


Google "uptempo arctic"



# The UpTempO buoy

Upper Temperature of the polar Oceans



SST validation: *OISST, CMC, GMPE overall best*

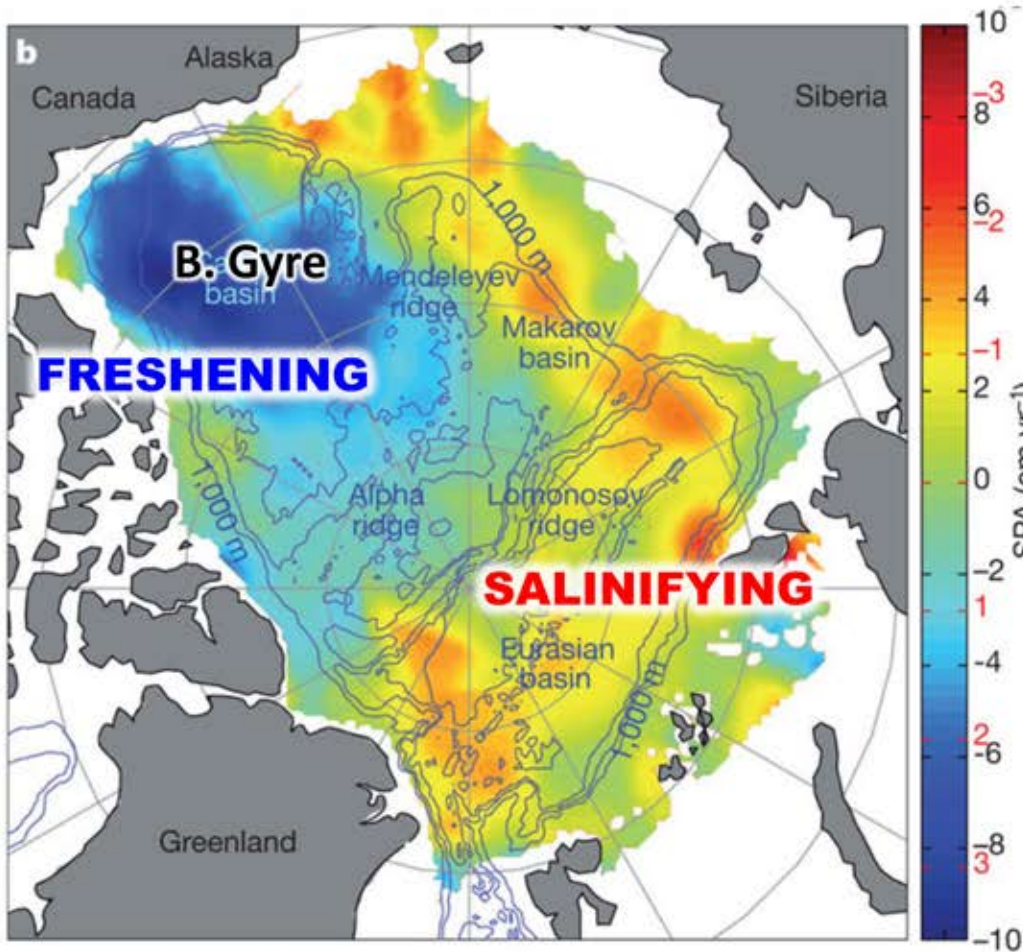


# What about salinity?





Trend in upper ocean "freshwater" =  $\int S dz$   
 ~250 m  
 (2005 → 2008)



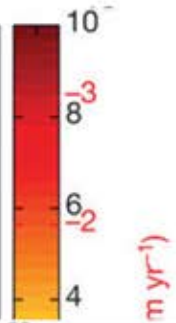
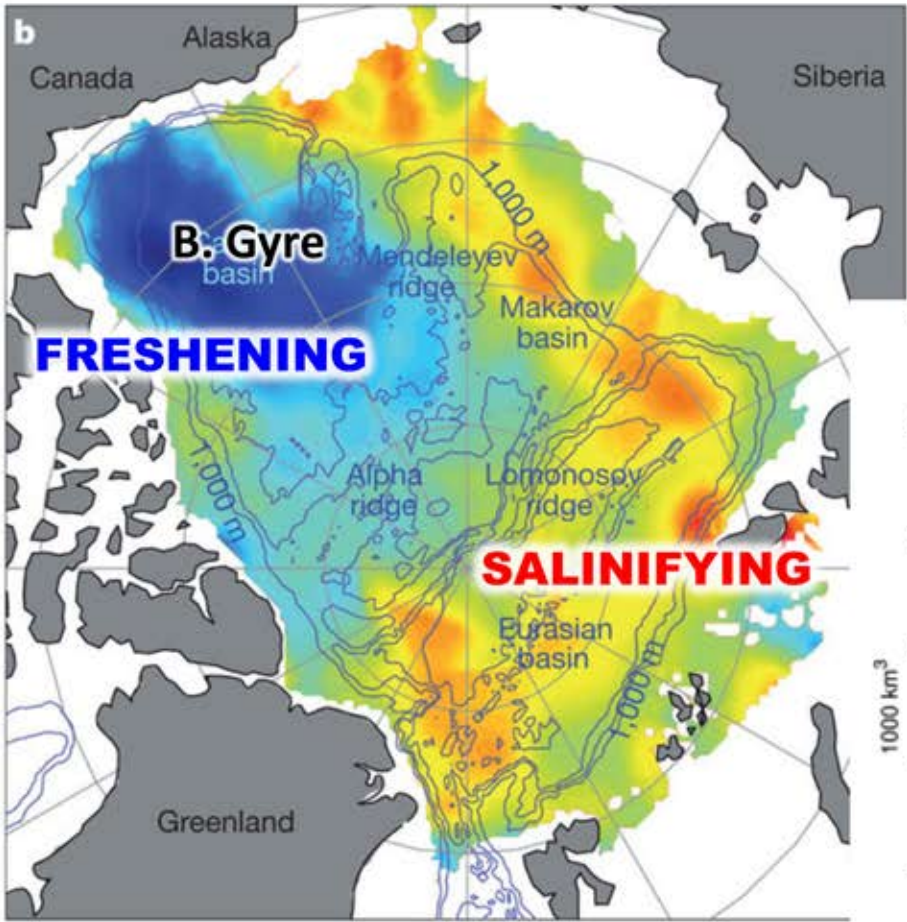
• **Strong regional trends**

*Beaufort Gyre freshening*  
 ( ice melt, PacWater, rivers )

Morison et al. (Nature, 2012)

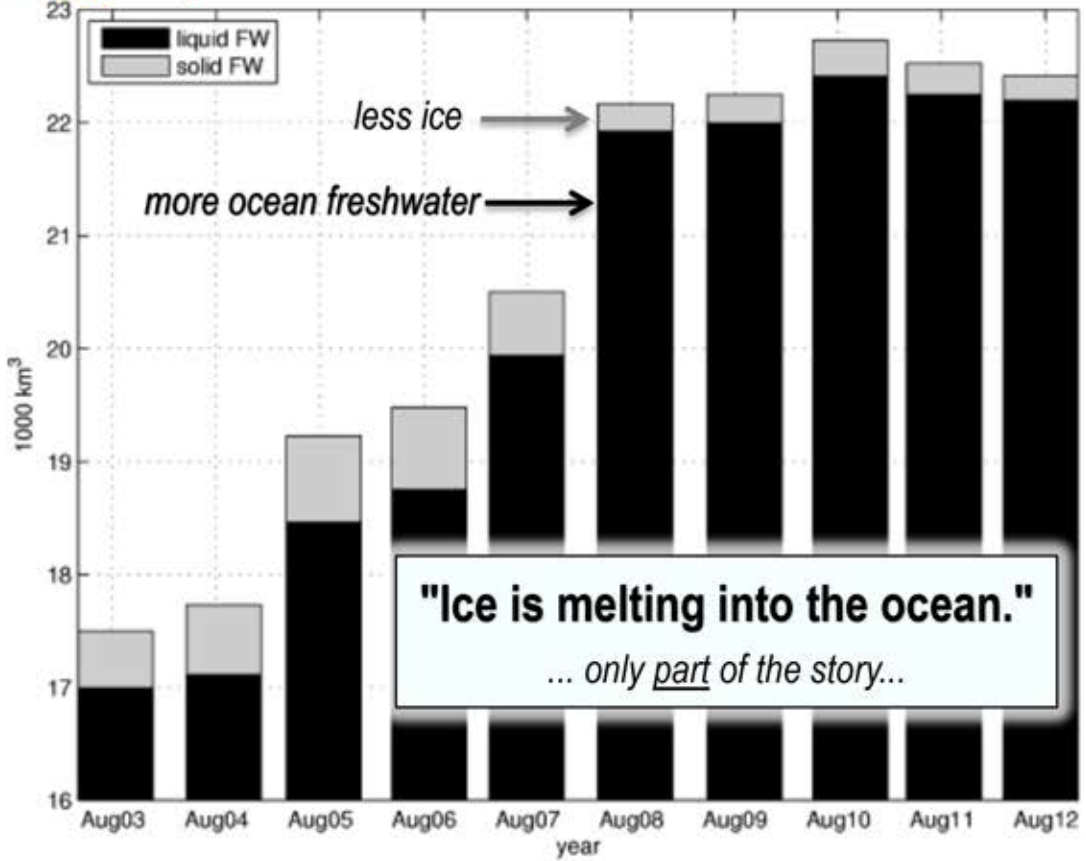
*...from satellite observations!*

Trend in upper ocean "freshwater" =  $\int Sdz$   
 (2005 → 2008) ~250 m



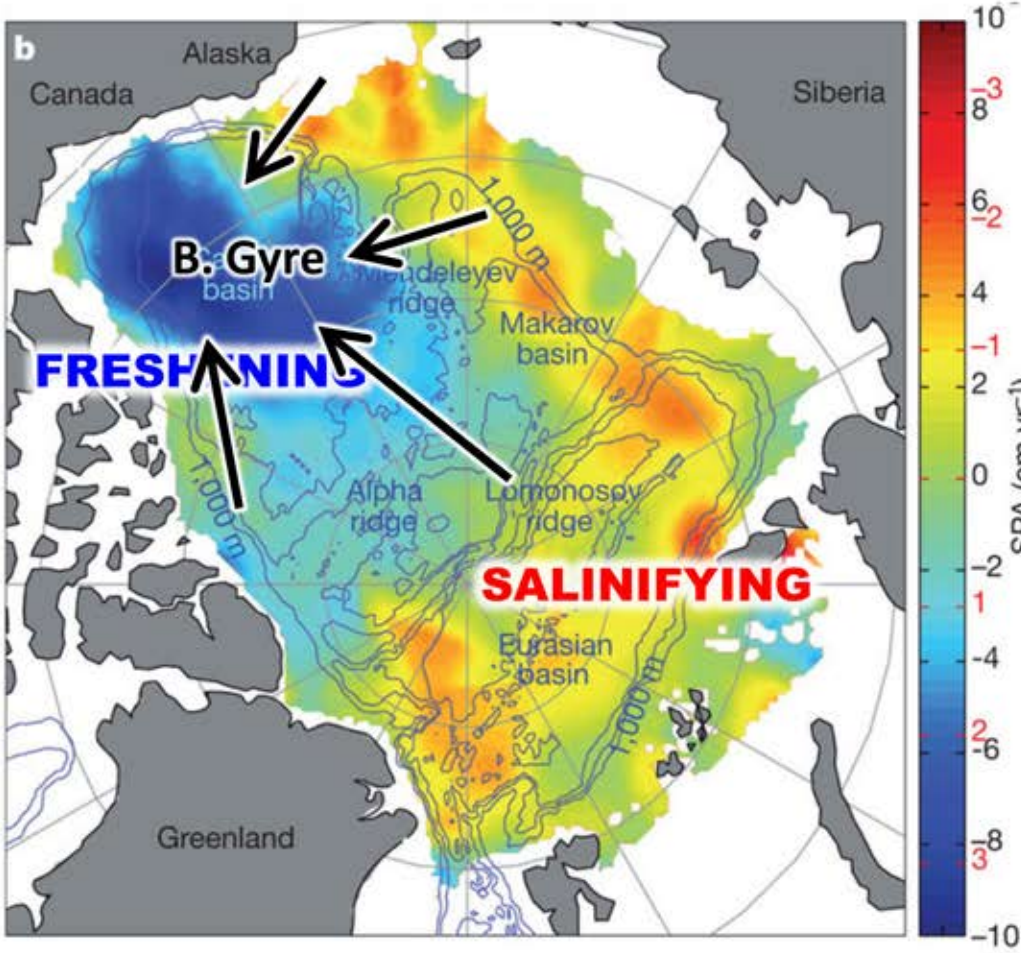
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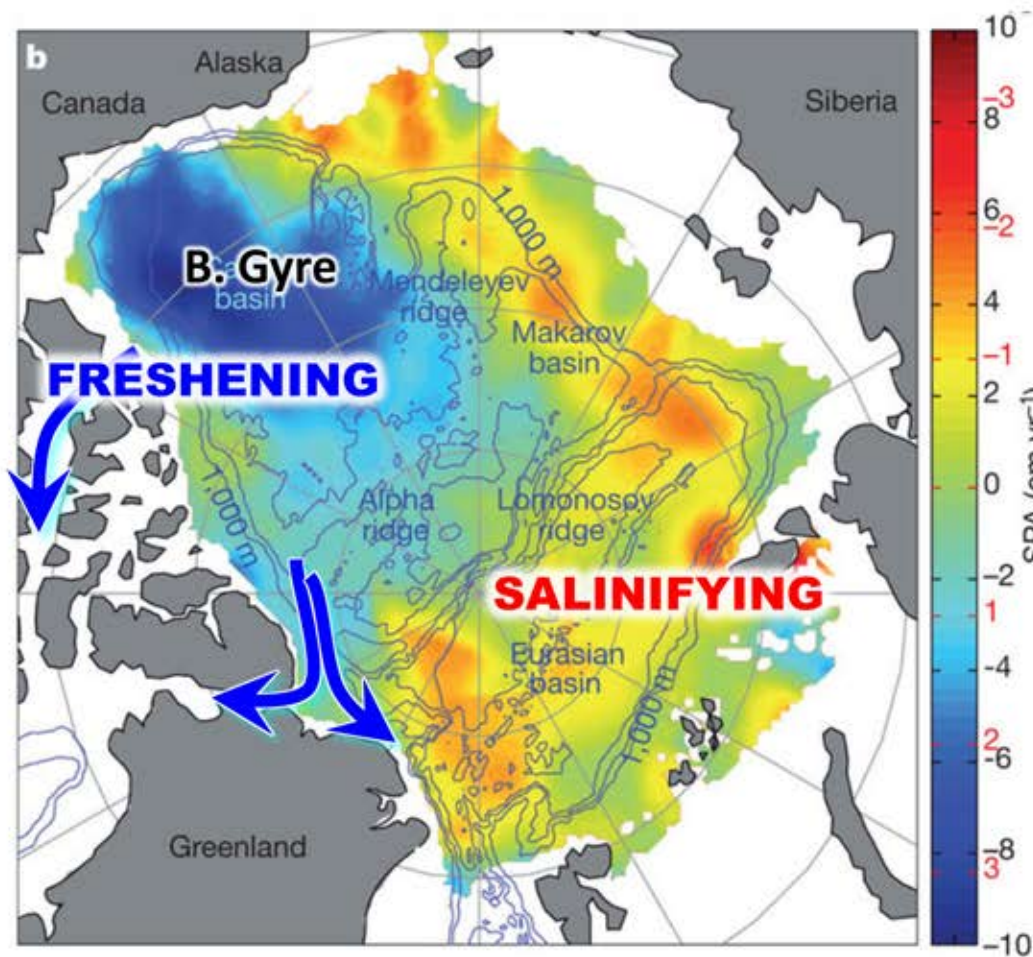
• Strong regional trends

Beaufort Gyre *freshening*  
 ( ice melt, PacWater, rivers )

Ocean circulation changes

Morison et al. (Nature, 2012)  
 Proshutinsky et al. (JGR, 2009)

Trend in upper ocean "freshwater" =  $\int S dz$   
 ~250 m  
 (2005 → 2008)



• Strong regional trends

Beaufort Gyre *freshening*

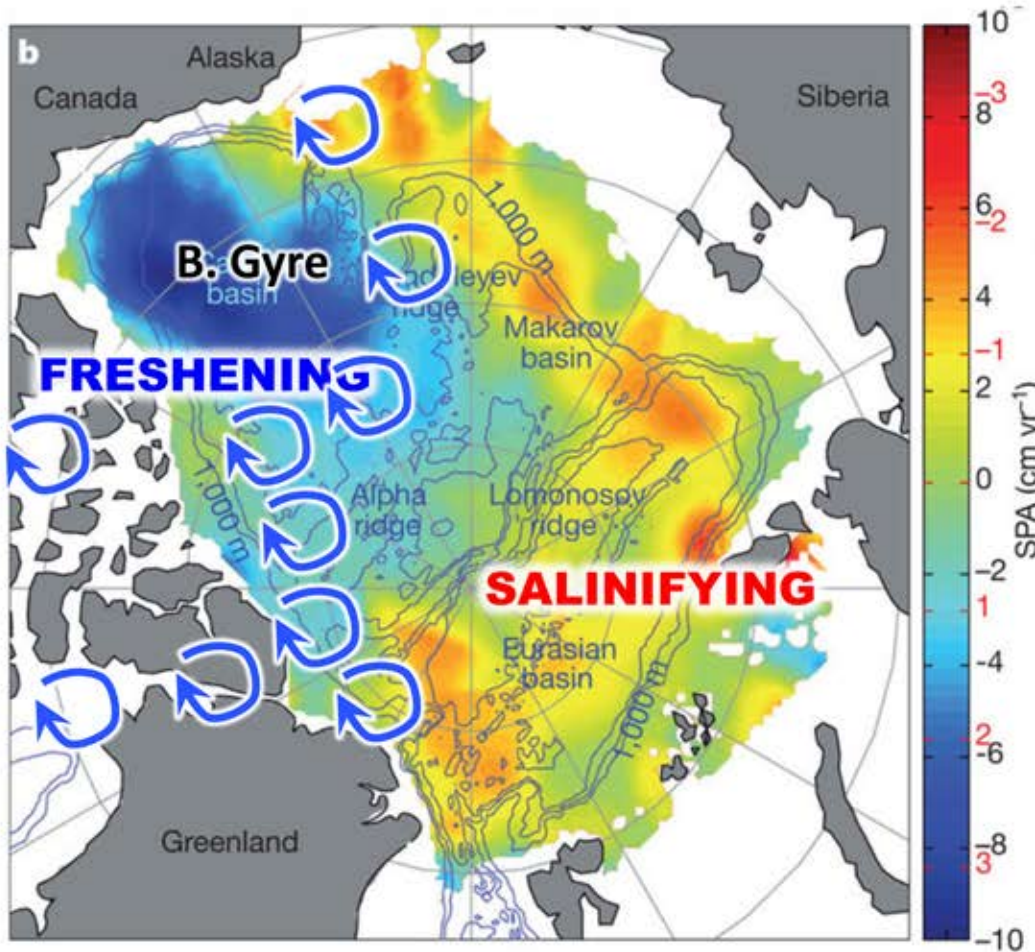
( ice melt, PacWater, rivers )

...some *leakage*

Curry et al. (JPO, 2014),  
 de Steur et al. (GRL, 2015)



Trend in upper ocean "freshwater" =  $\int S dz$   
 ~250 m  
 (2005 → 2008)



• **Strong regional trends**

*Beaufort Gyre freshening*

( ice melt, PacWater, rivers )

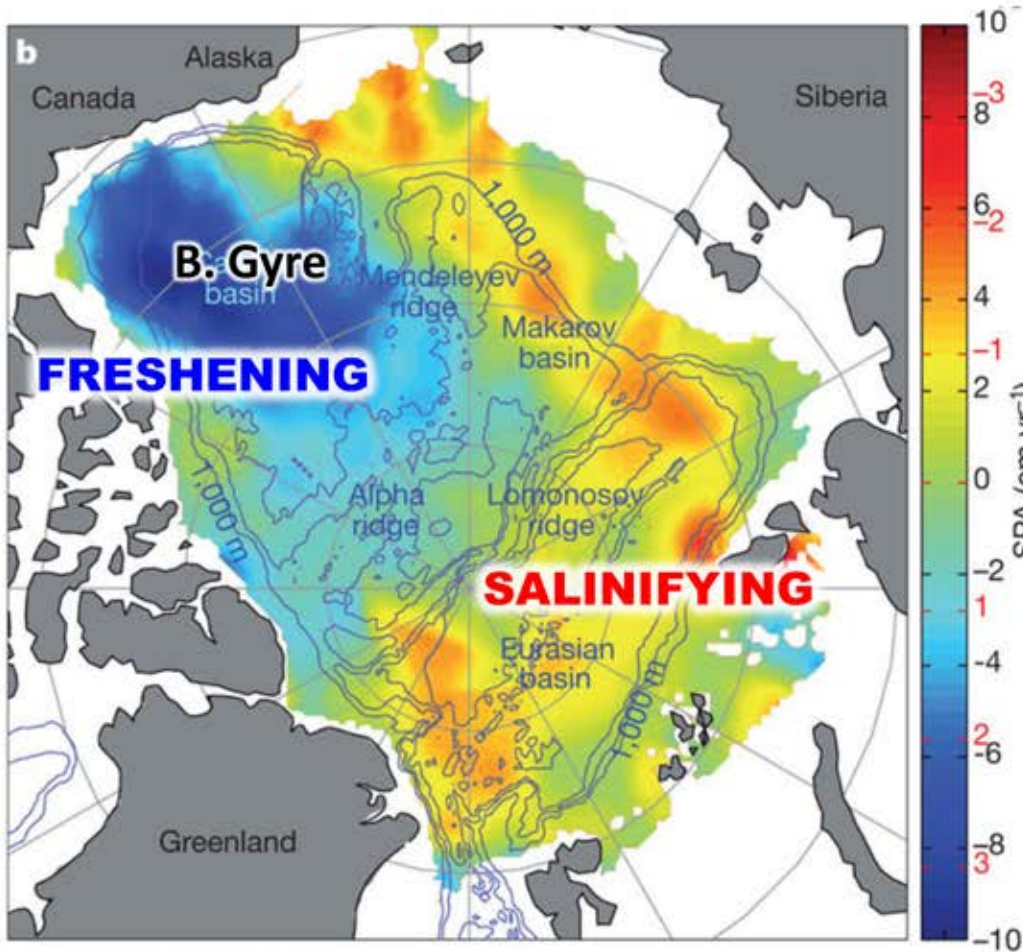
*...some leakage*

Curry et al. (JPO, 2014),  
 de Steur et al. (GRL, 2015)

Eddy leakage:

e.g., Manucharyan & Spall (GRL, 2016)

Trend in upper ocean "freshwater" =  $\int S dz$   
 ~250 m  
 (2005 → 2008)



• **Strong regional trends**

*Beaufort Gyre freshening*  
 ( ice melt, PacWater, rivers )

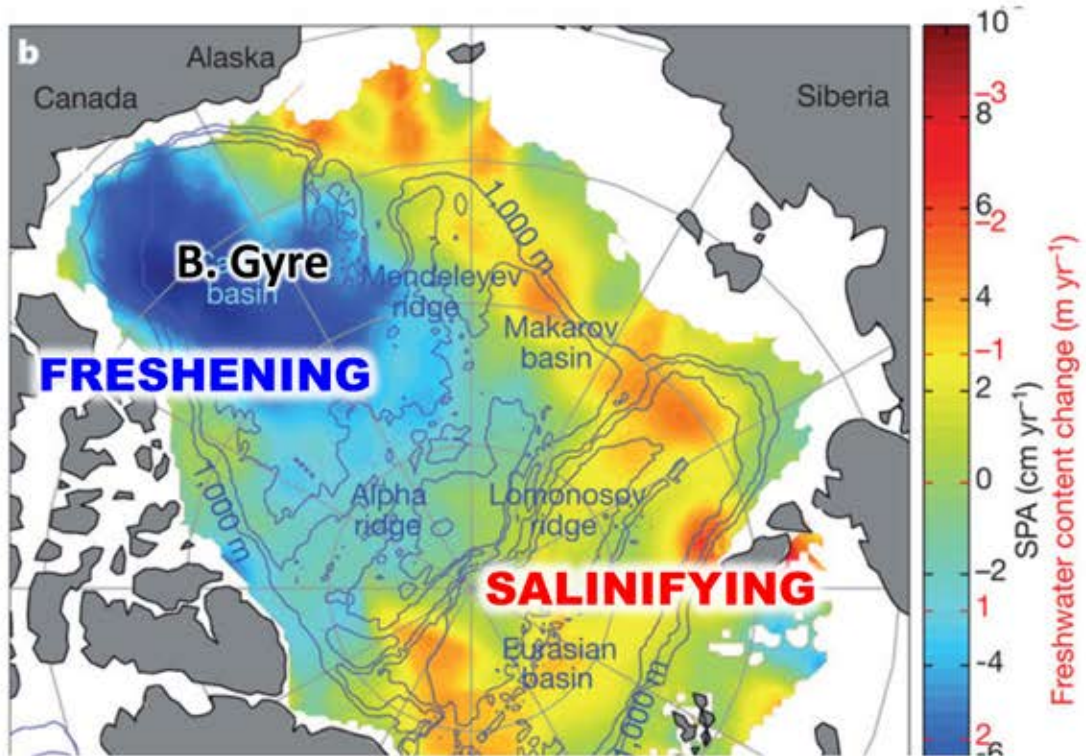
• **Overall? hmmm...**

**...small freshening...**

Rabe et al. (GRL, 2014)  
 Haine et al. (Global & Plan. Ch., 2015)  
 Peralta-Ferriz & Woodgate. (PiO, 2015)



Trend in upper ocean "freshwater" =  $\int S dz$   
 (2005 → 2008) ~250 m



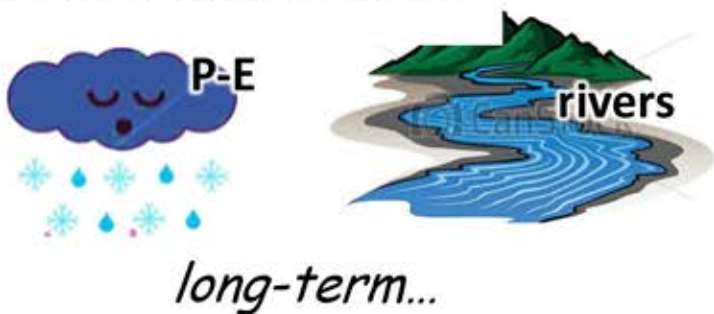
**...small freshening...**

*Rabe et al. (GRL, 2014)*

**Haine et al. (Global & Plan. Ch., 2015)**

*Peralta-Ferriz & Woodgate. (PiO, 2015)*

**(1) Incr. Hydrol. Cycle:**



**(2) Sea ice melt:**



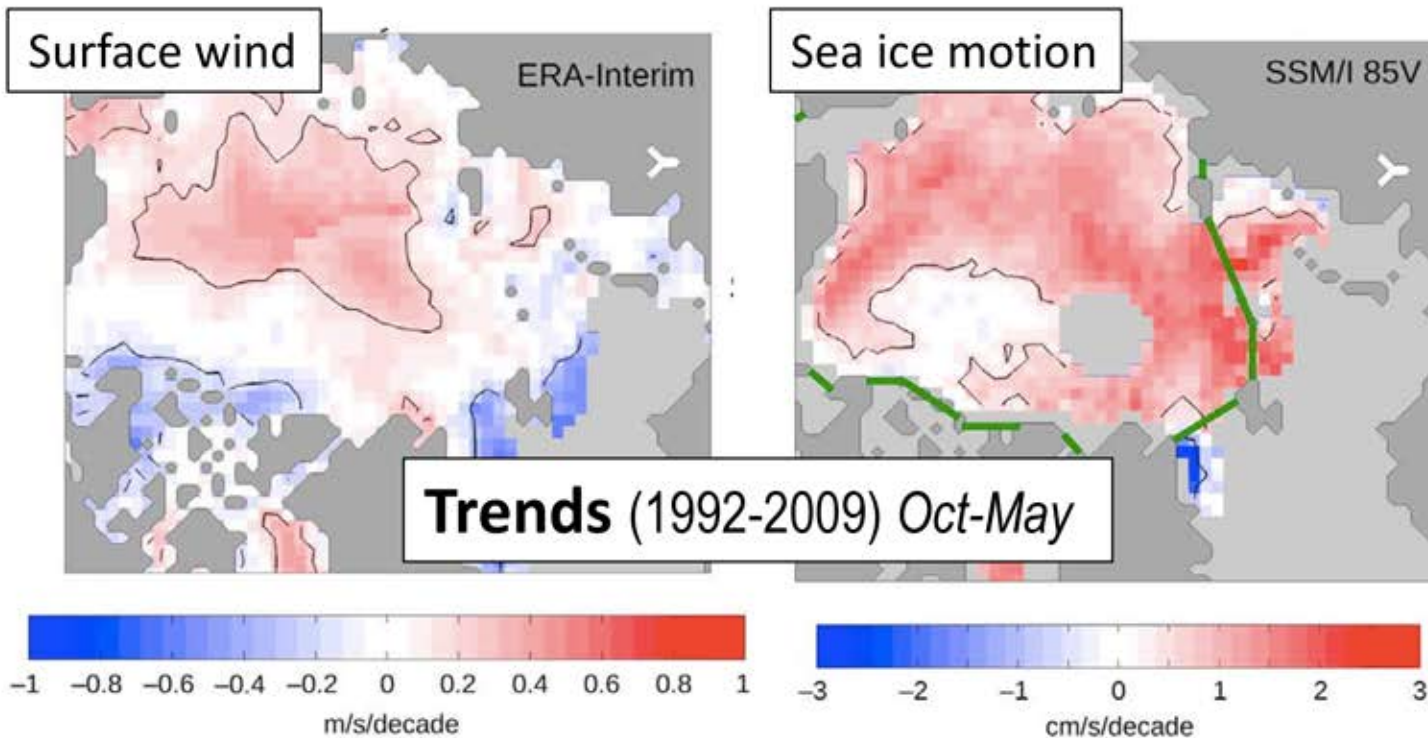
# What about Kinetic Energy?





# wind & ice motion trends

Spren et al. (GRL, 2011)

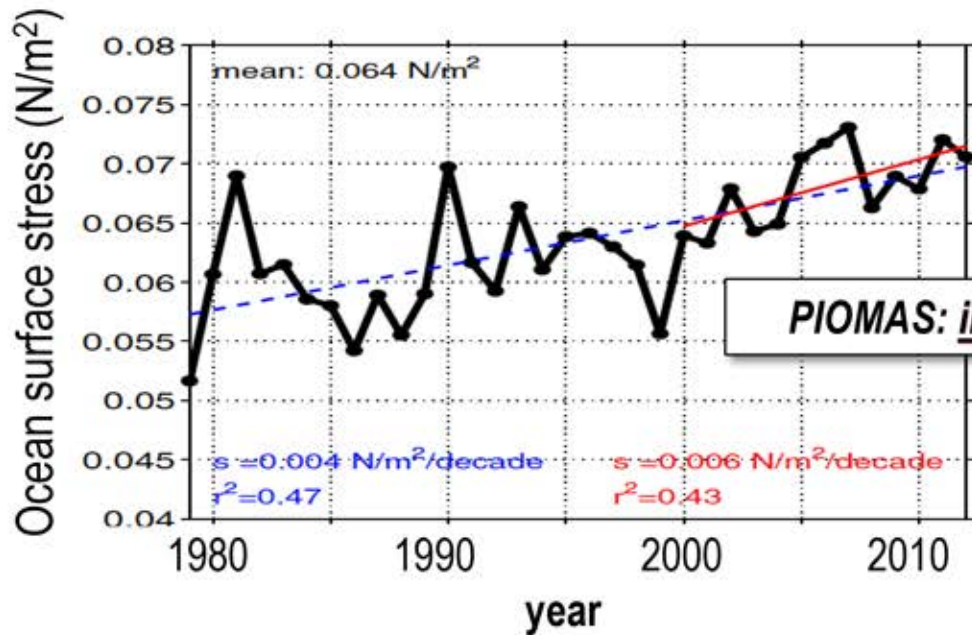


< 1 m/s over 20 years  
..eh..

up to 6 cm/s over 20 years  
..yowza..

More KE -> ocean?

# More KE -> ocean?

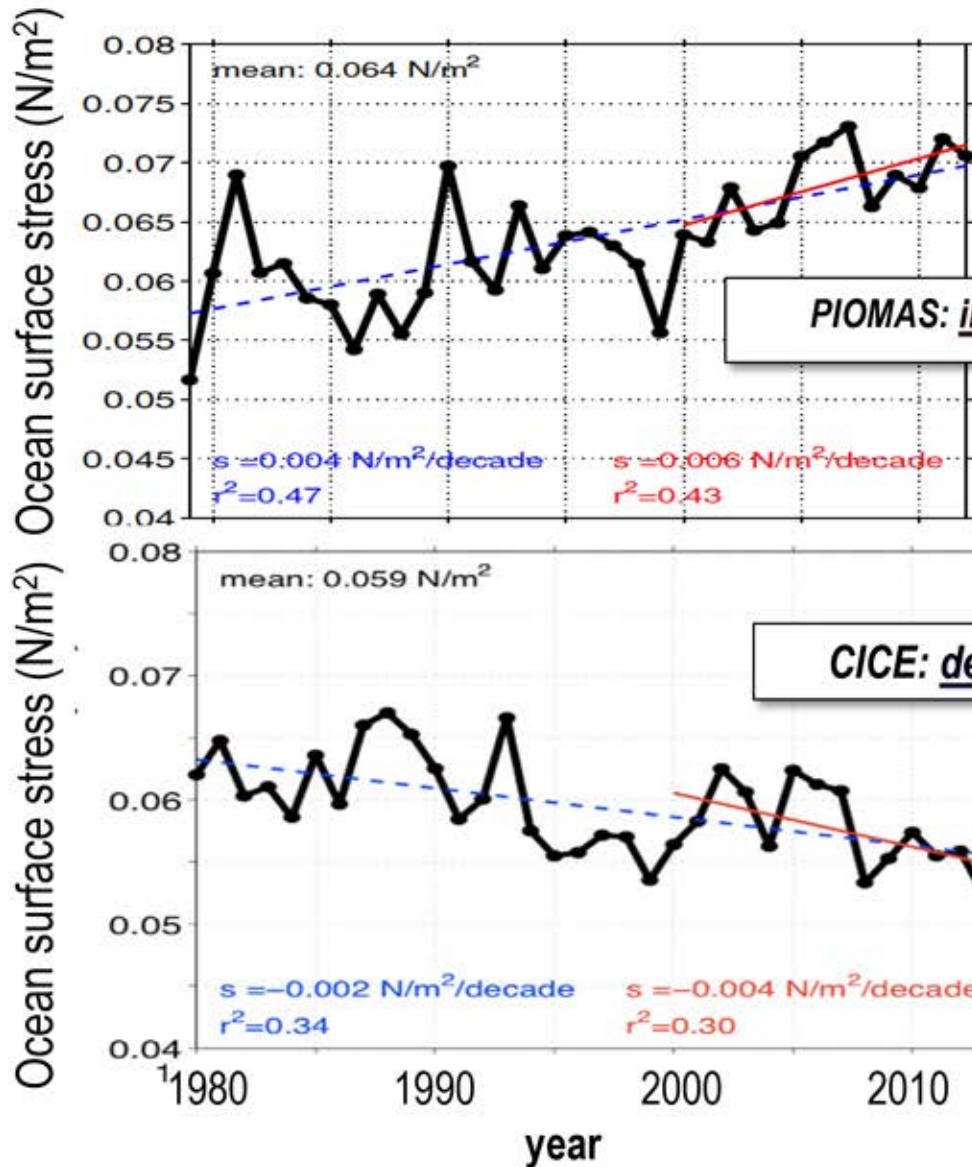


...faster ice

Martin et al. (JGR, 2014)



# More KE -> ocean?



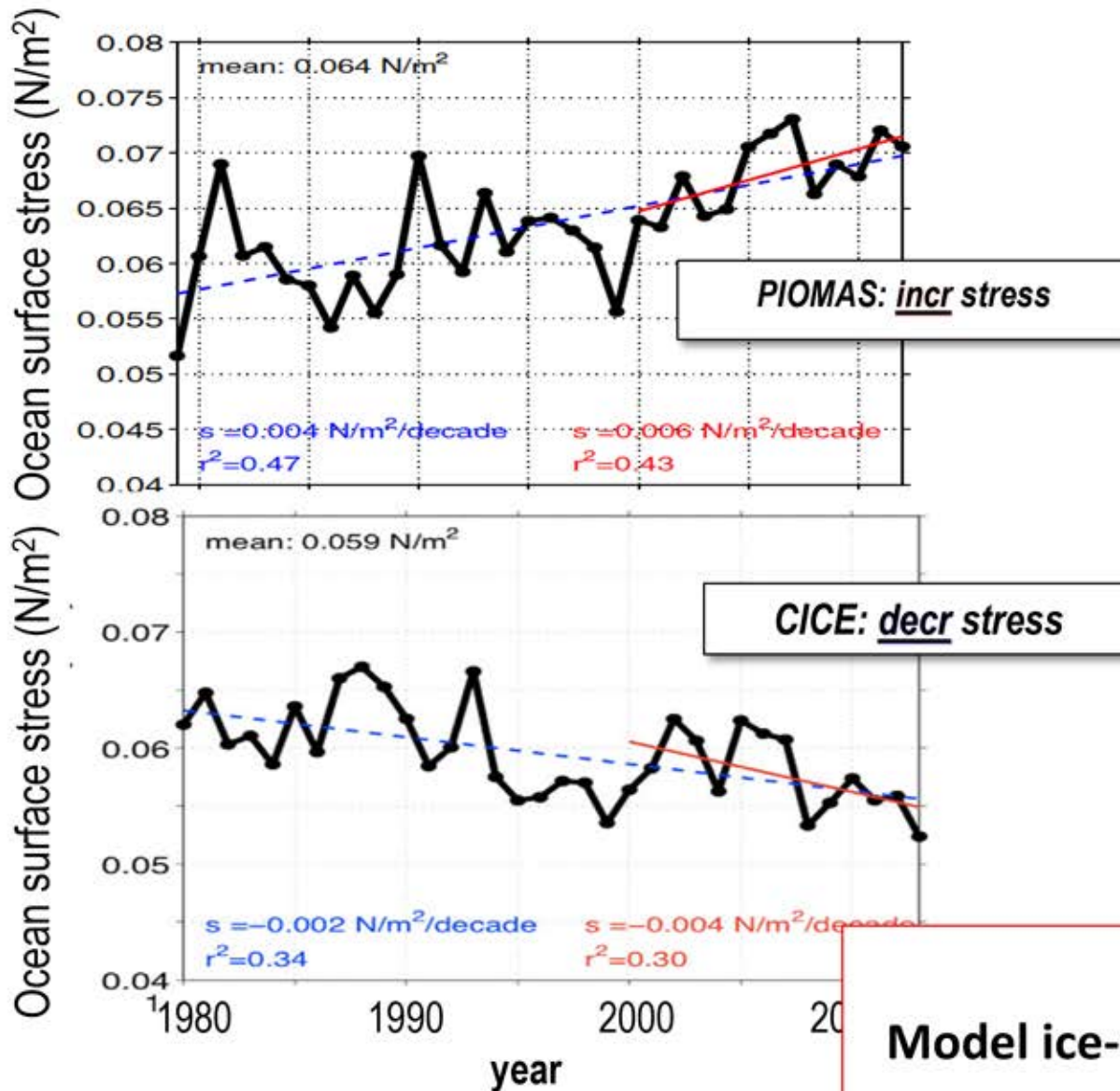
...faster ice

Martin et al. (JPO, 2016)

...faster ice,  
 but **thinner & smoother**



# More KE -> ocean?



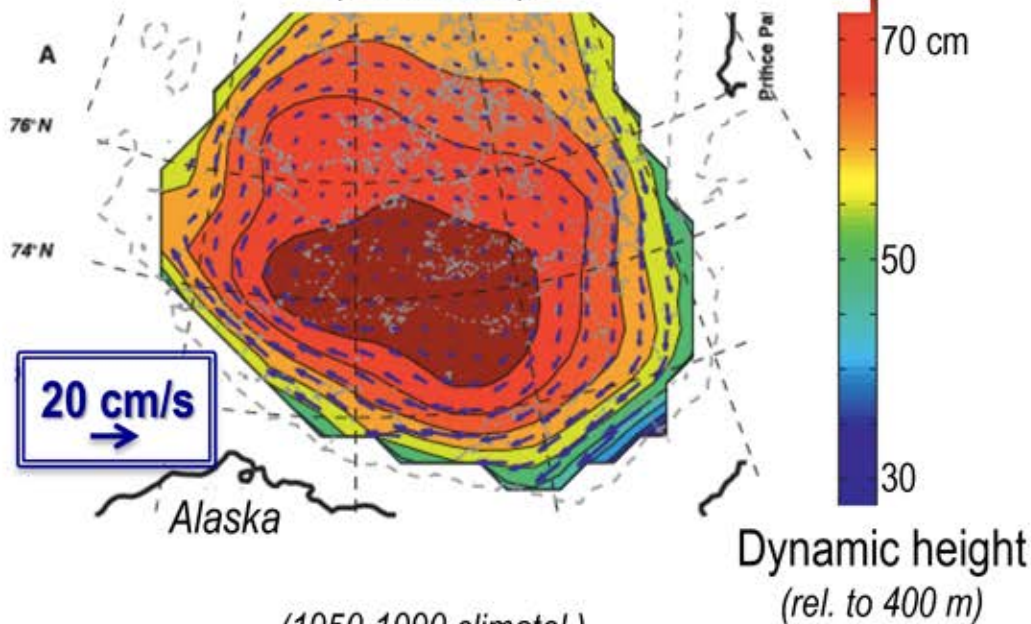
But:  
**Model ice-ocn boundary layer sucks**  
*Cole et al. (Elementa, 2017)*



# So... is the ocean moving faster?

## Geostrophic current (*in situ obs*)

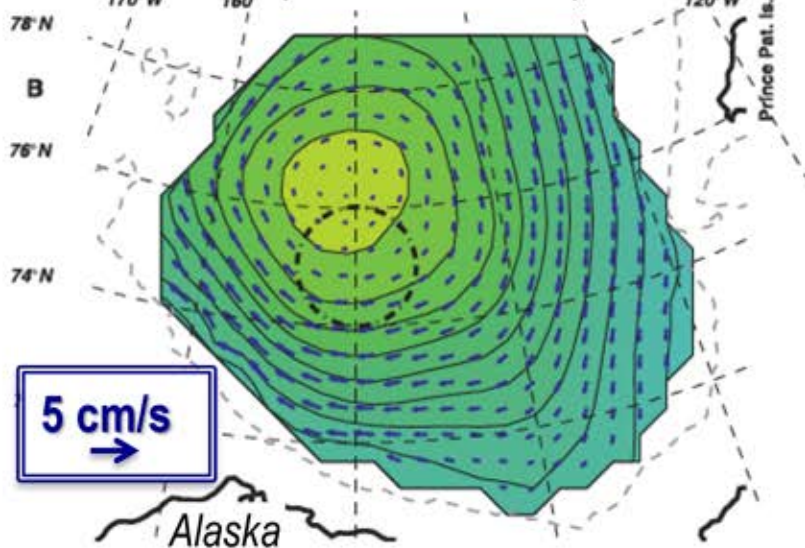
(2008-2011)



Beaufort Gyre: **Yup!**

(Elsewhere: ???)

(1950-1990 climatol.)



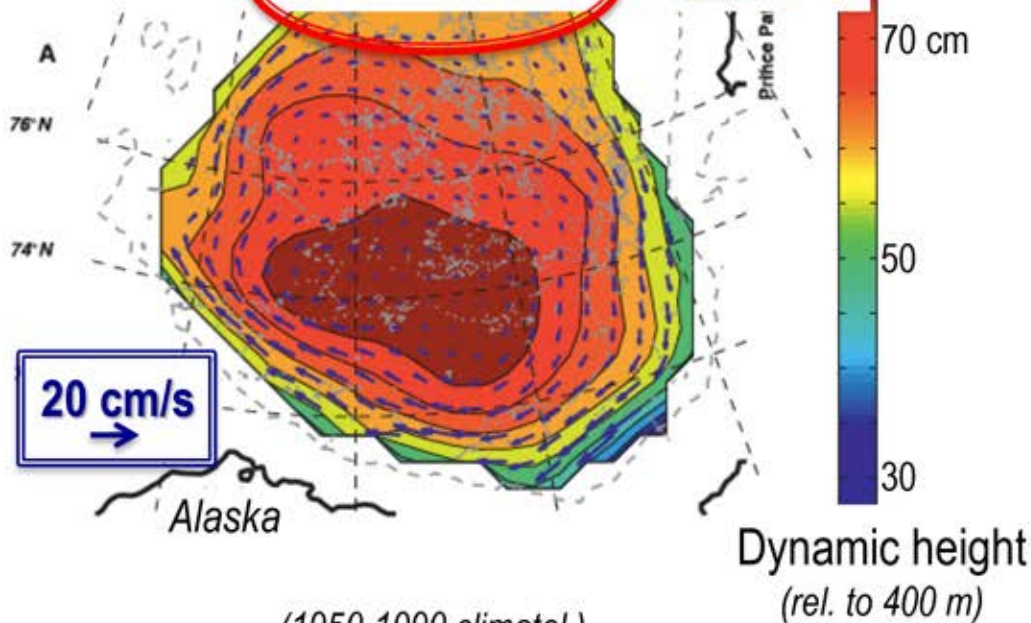
McPhee (GRL, 2012)

# So... is the ocean moving faster?

Geostrophic current (in situ obs)

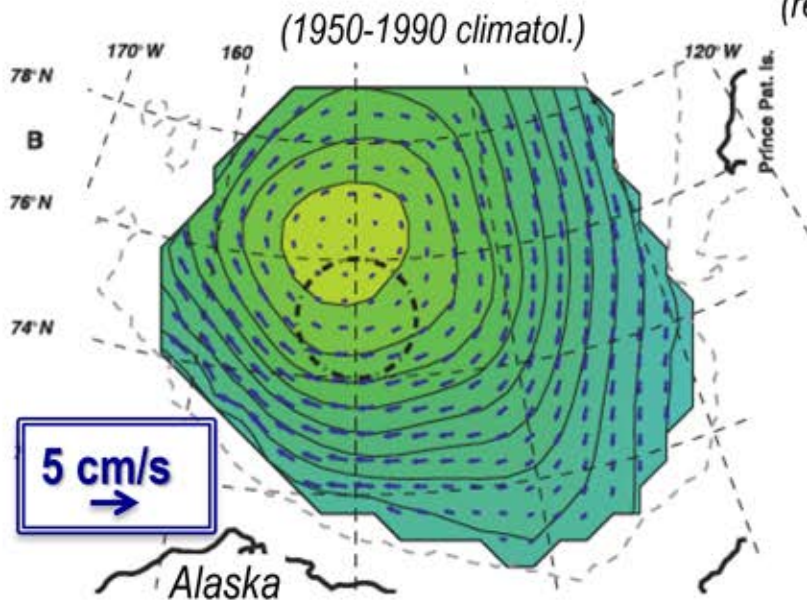
(2008-2011)

*ugh*



Beaufort Gyre: **Yup!**

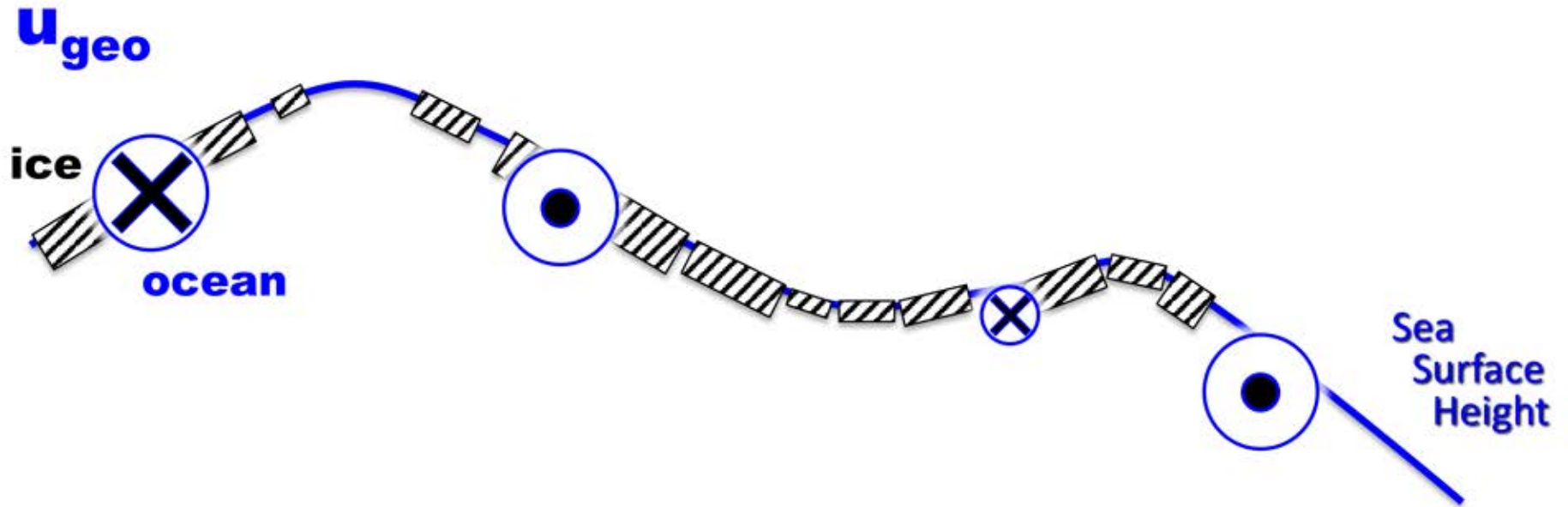
(Elsewhere: ???)



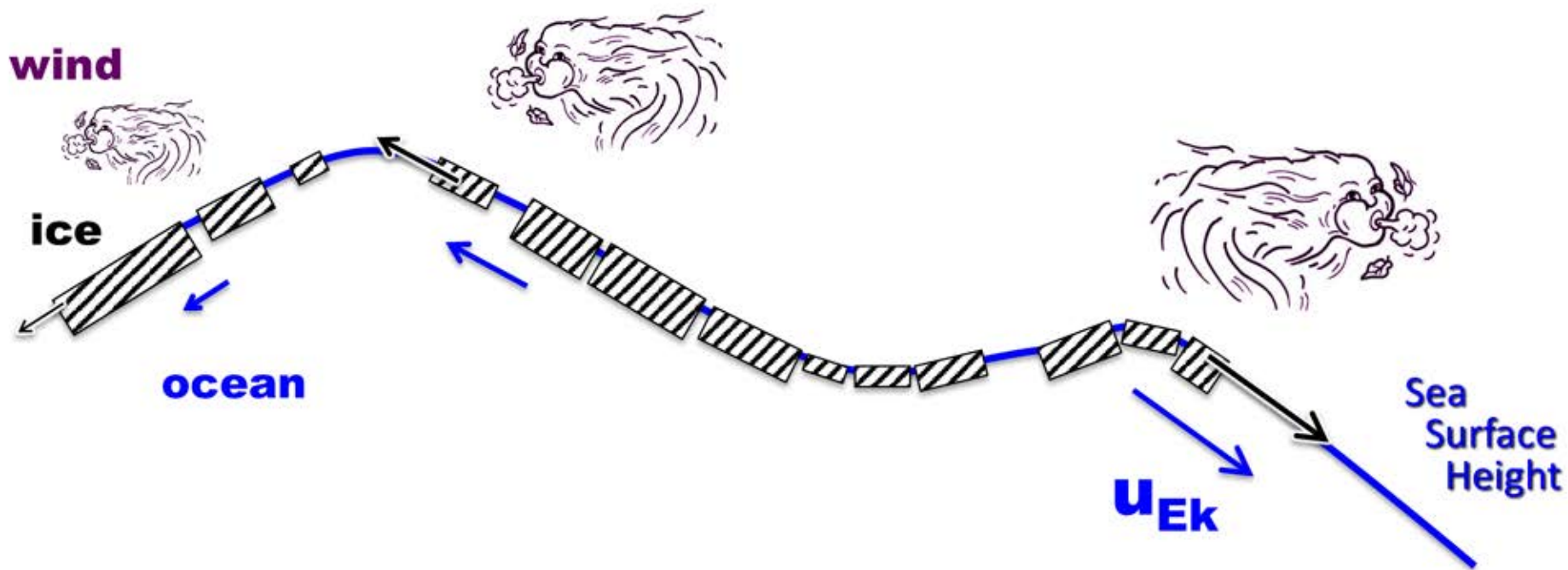
McPhee (GRL, 2012)



# Surface currents ( $\mathbf{u}_{geo} + \mathbf{u}_{Ek}$ )



# Surface currents ( $u_{geo} + u_{Ek}$ )

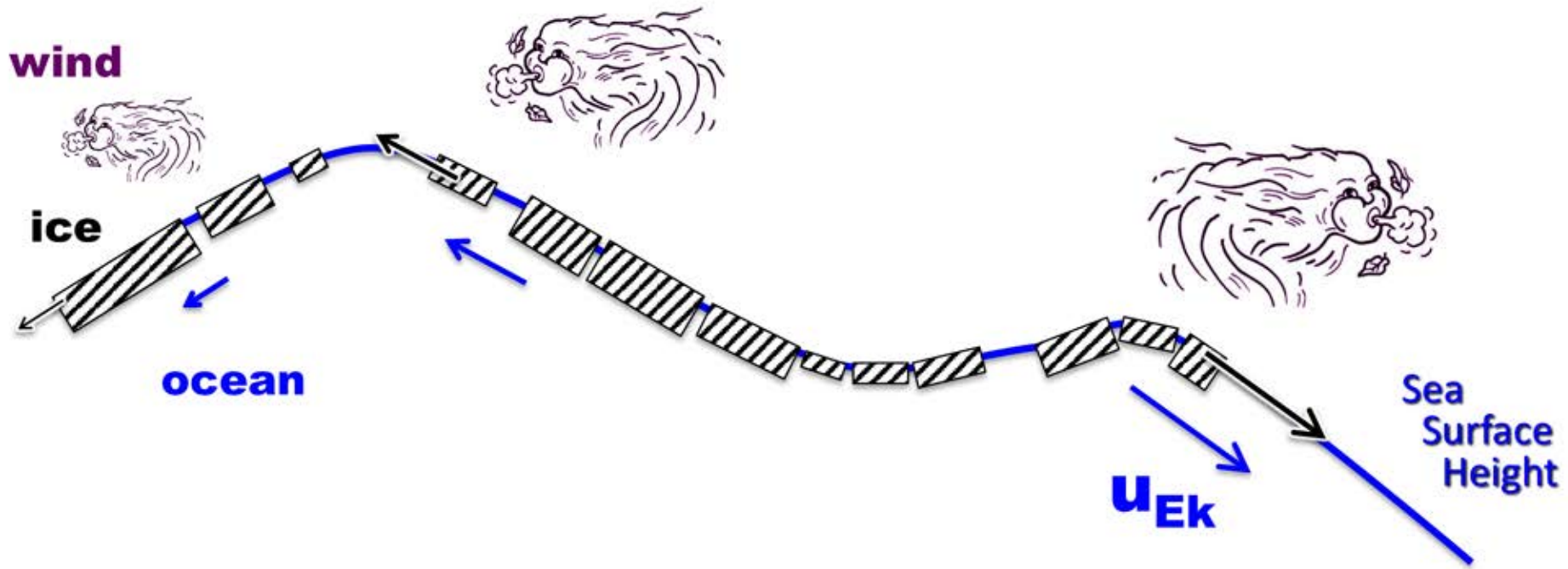




# Surface currents ( $u_{geo} + u_{Ek}$ )

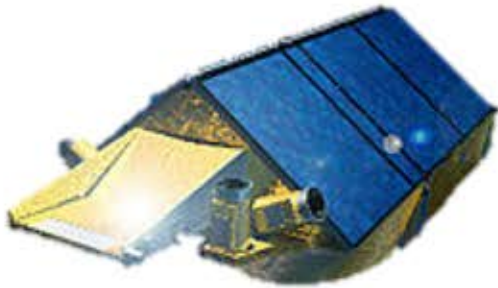
difficult

easy-ish



$u_{geo}$  often ignored

# $u_{geo}$ from space!



Radar



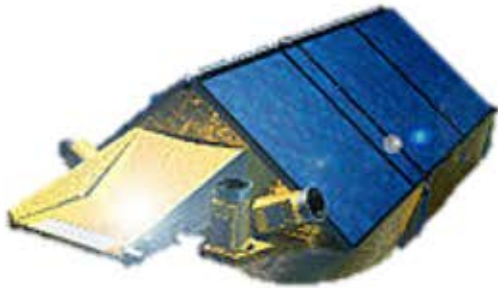
Laser

Satellite altimeters →  
*ocean surface height* →

$u_{geo}$



# $u_{geo}$ from space!




Radar



Laser

Satellite altimeters →  
*ocean surface height* →

$u_{geo}$



Centre for  
Polar Observation  
and Modelling  
cpom  
Natural Environment Research Council

**CPOM** → Dynamic Topography

Public data download (2003-2014)

*Monthly, 100 km resolution*

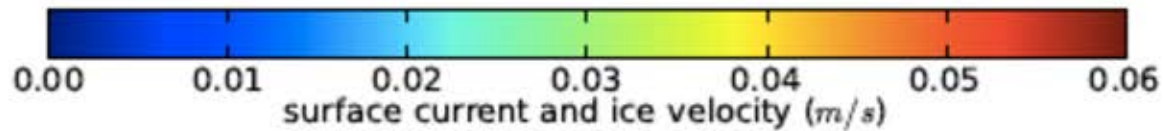
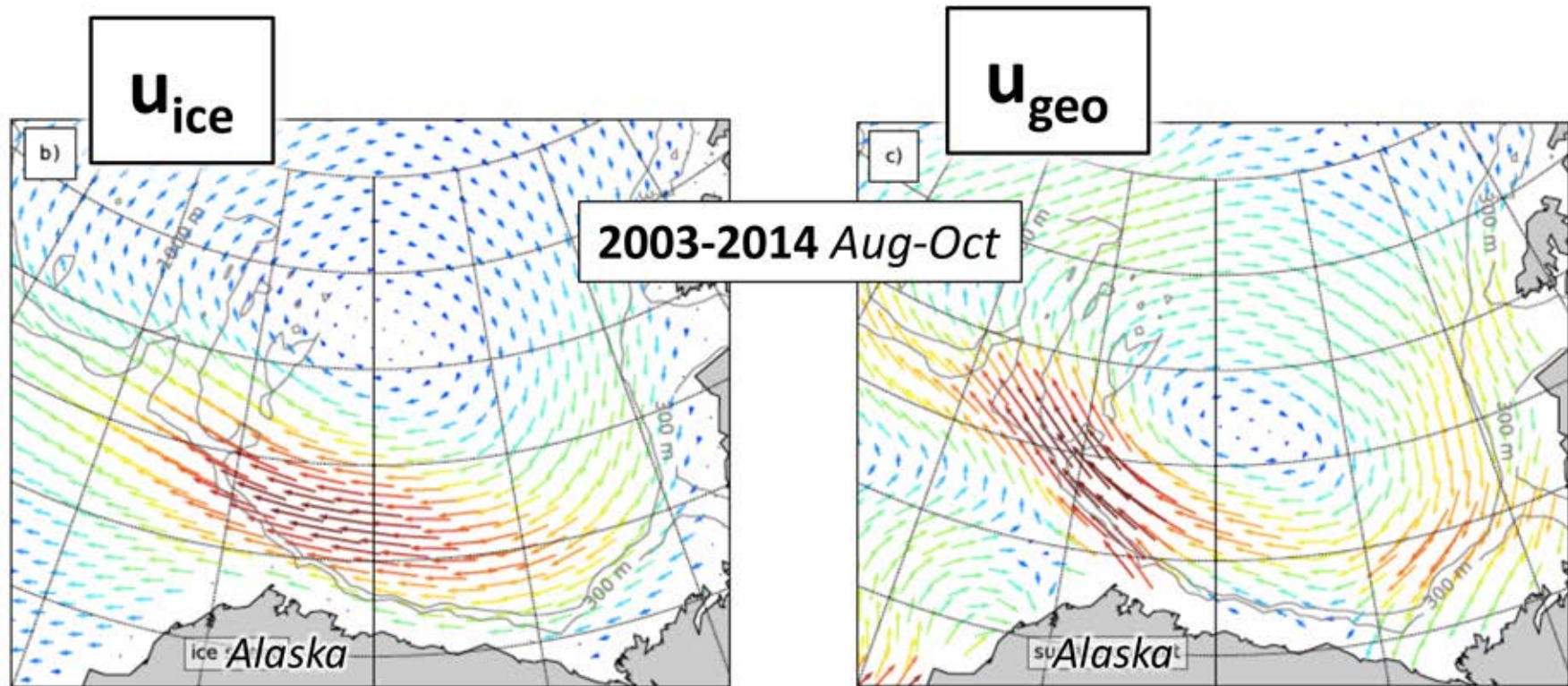


Tom Armitage

A revolution in  
Arctic physical oceanography

*...but endangered*

# Geostrophic circulation



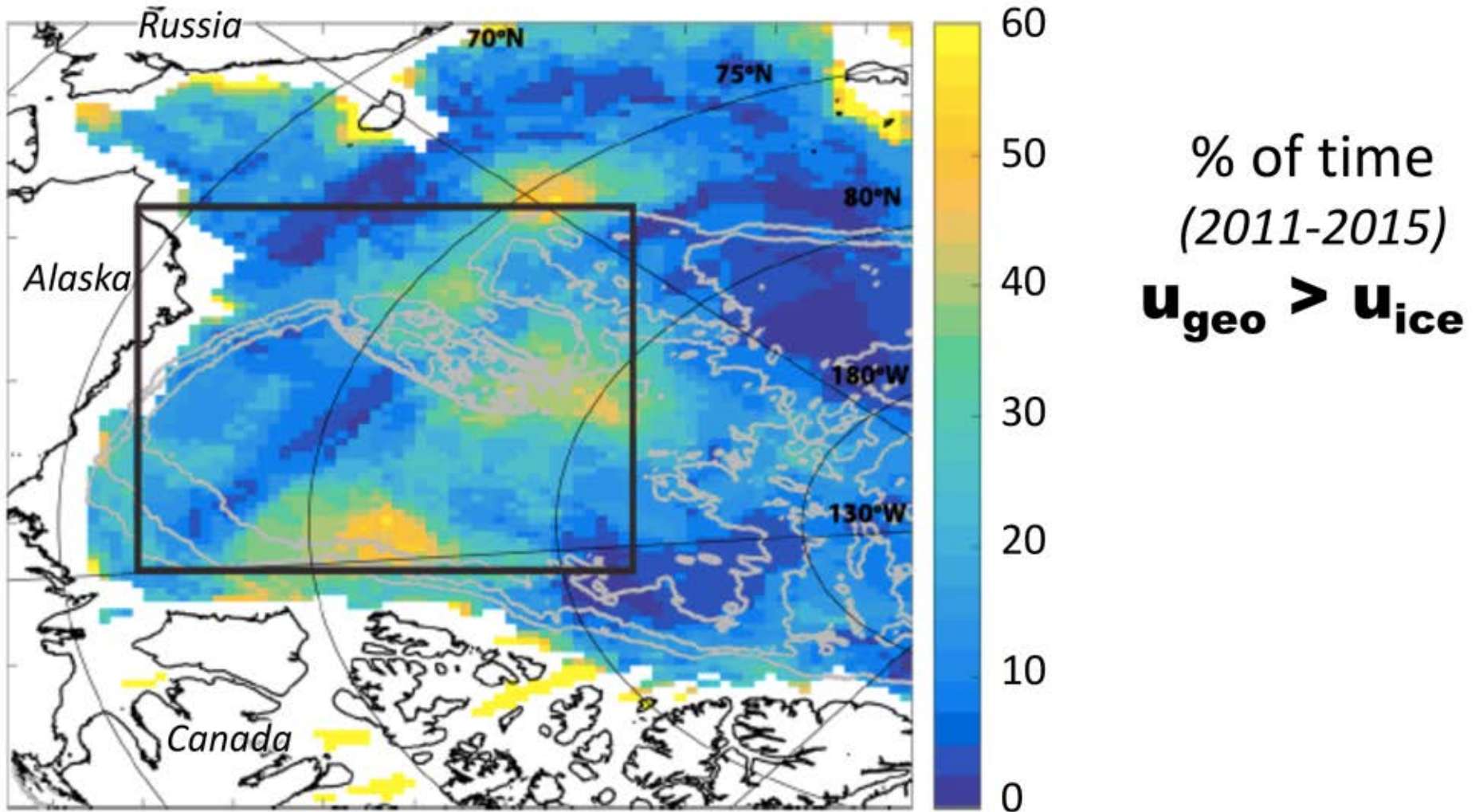
$$u_{geo} \approx u_{ice}$$

Meneghello et al. (JPO, 2018)

(also Armitage et al., *The Cryosph.*, 2017)



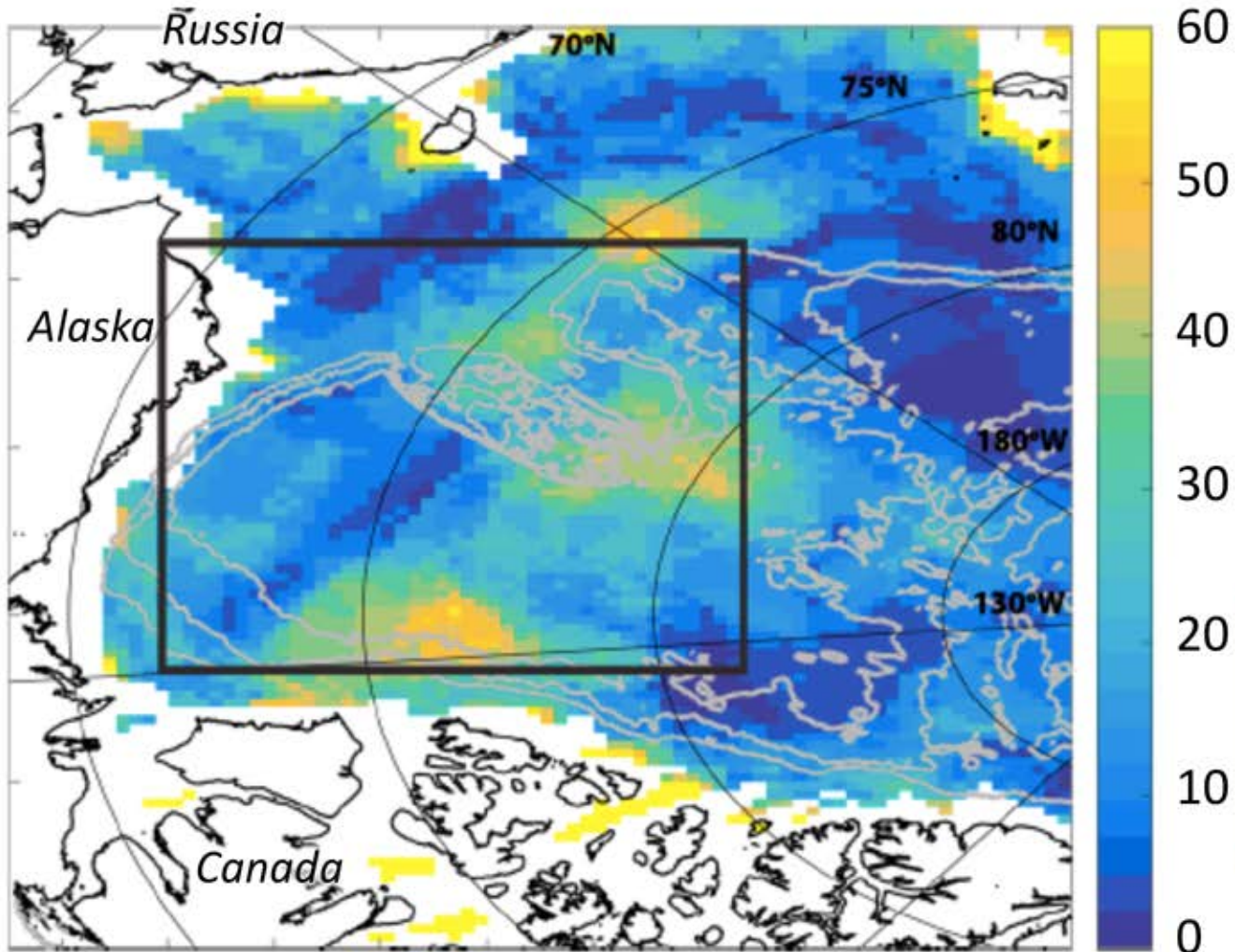
# Geostrophic circulation



Dewey et al. (GRL, 2018)



# Geostrophic circulation



% of time  
(2011-2015)

$$u_{\text{geo}} > u_{\text{ice}}$$

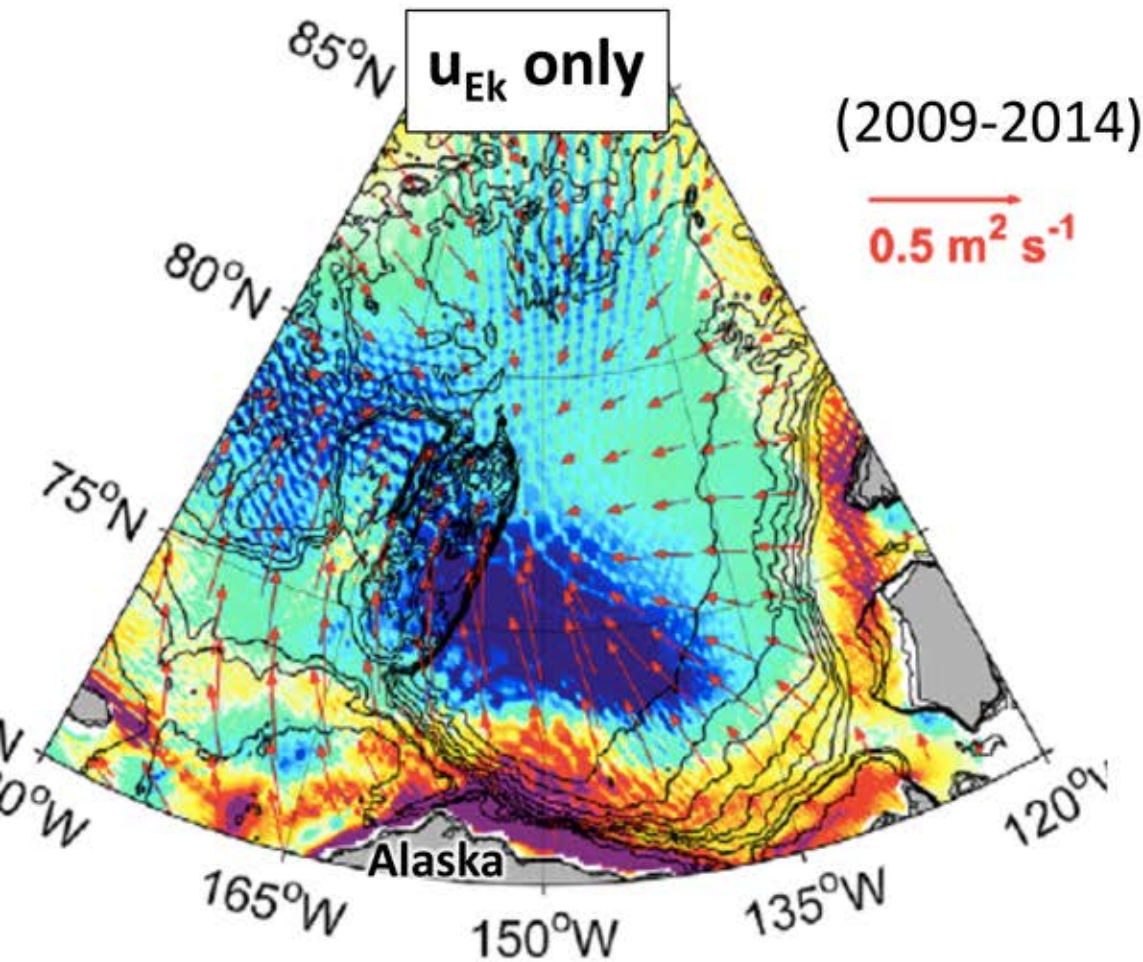
The ocean is  
driving the ice!!

Dewey et al. (GRL, 2018)



# Surface currents $\int_{20m} u dz$

Zhong et al. (JGR, 2017)

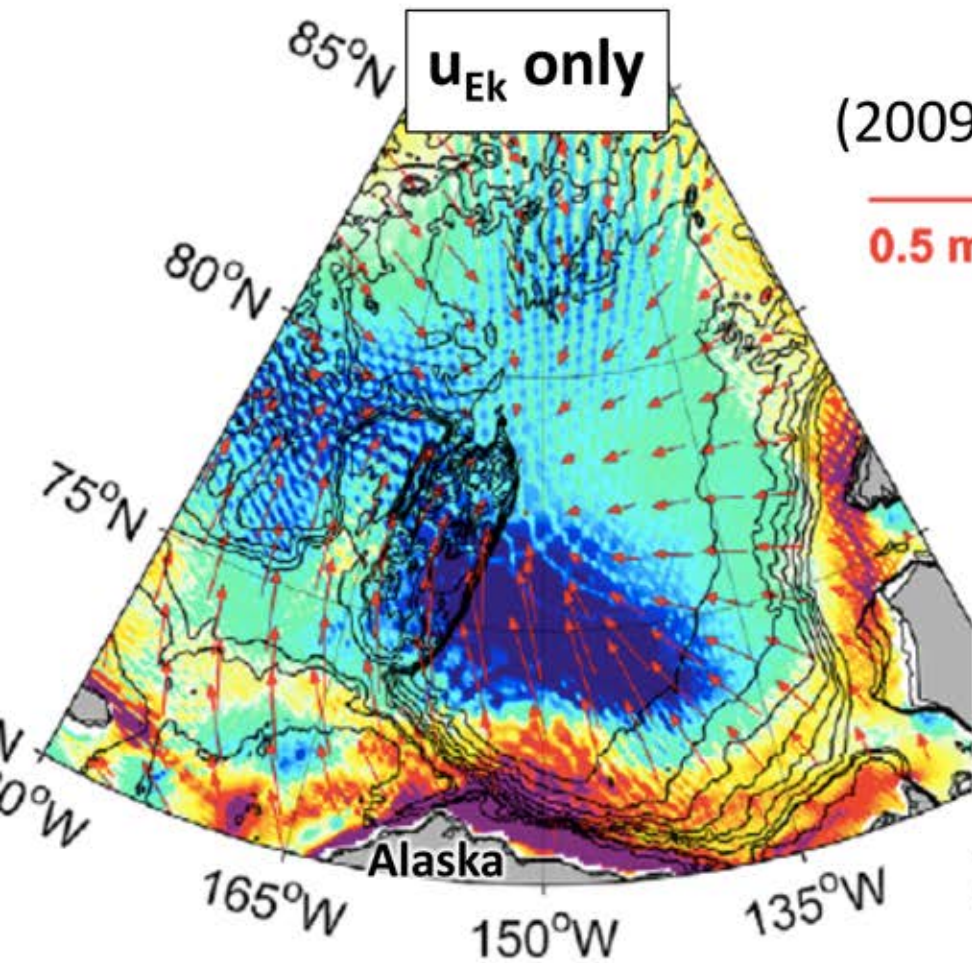


**Strong convergence  
all around**

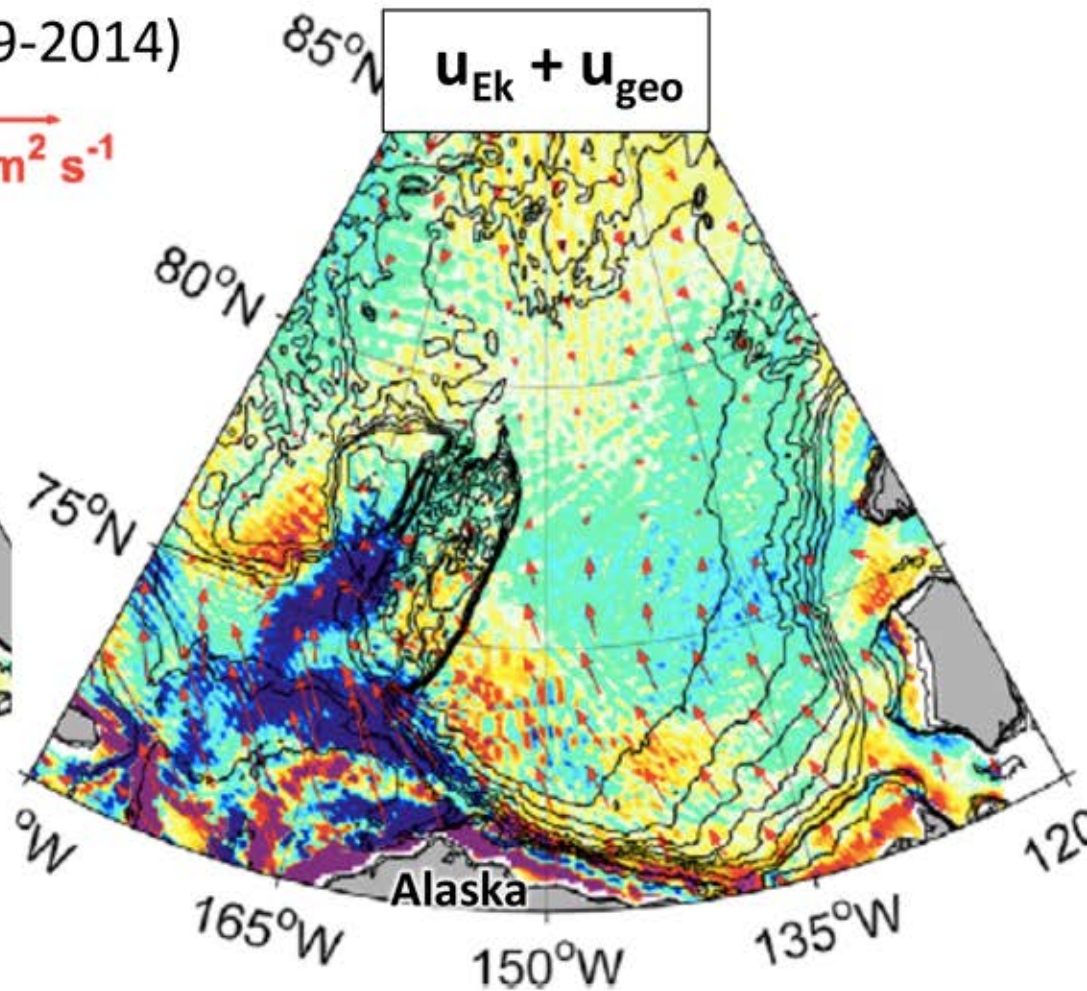


# Surface currents $\int_{20m} u dz$

Zhong et al. (JGR, 2017)



**Strong convergence  
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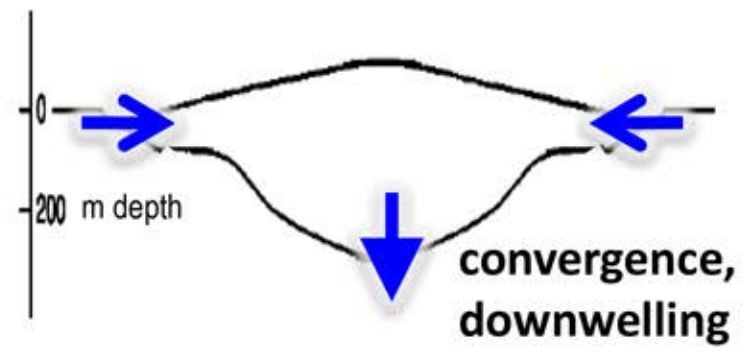
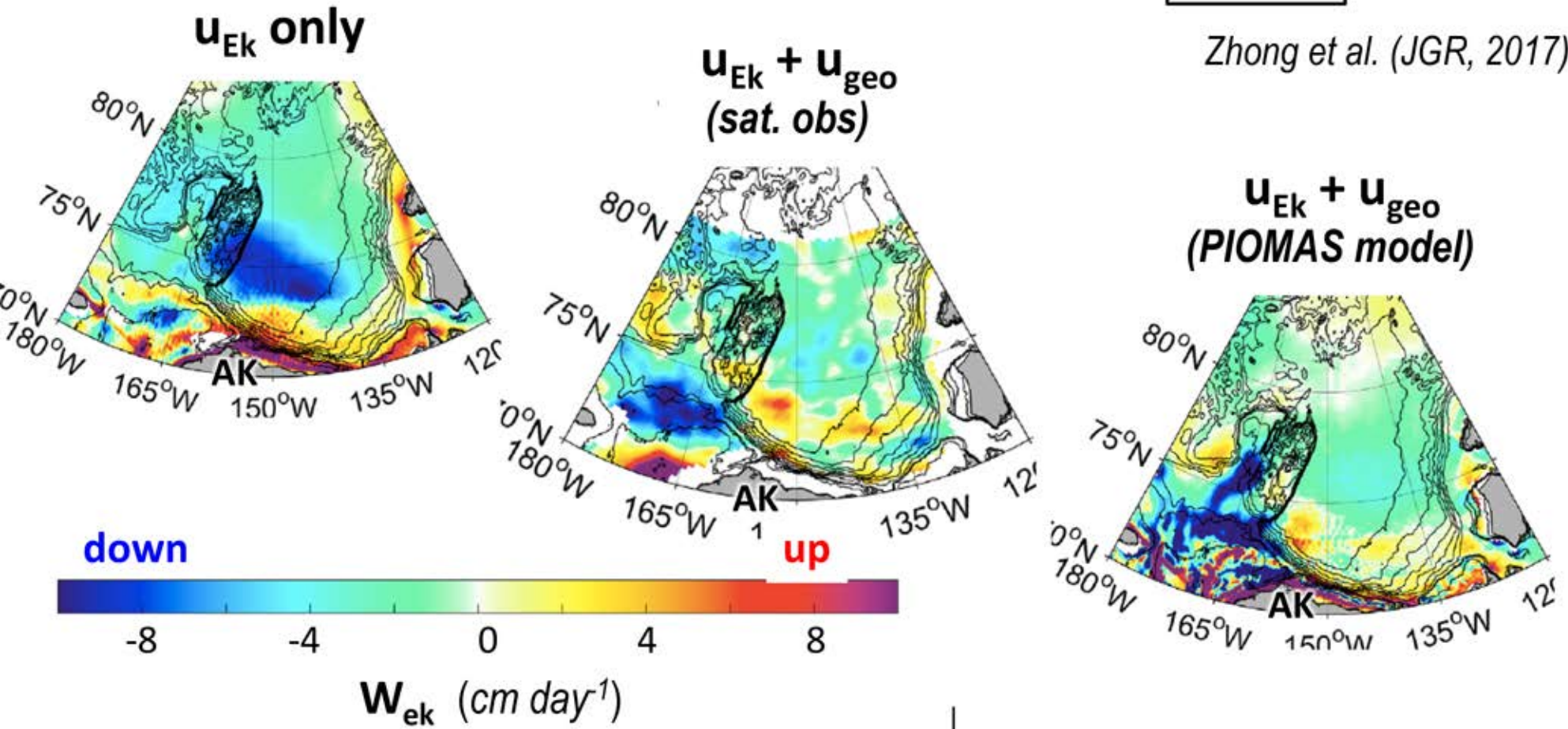
**So different!**



# Ekman pumping

$$W_{Ek}$$

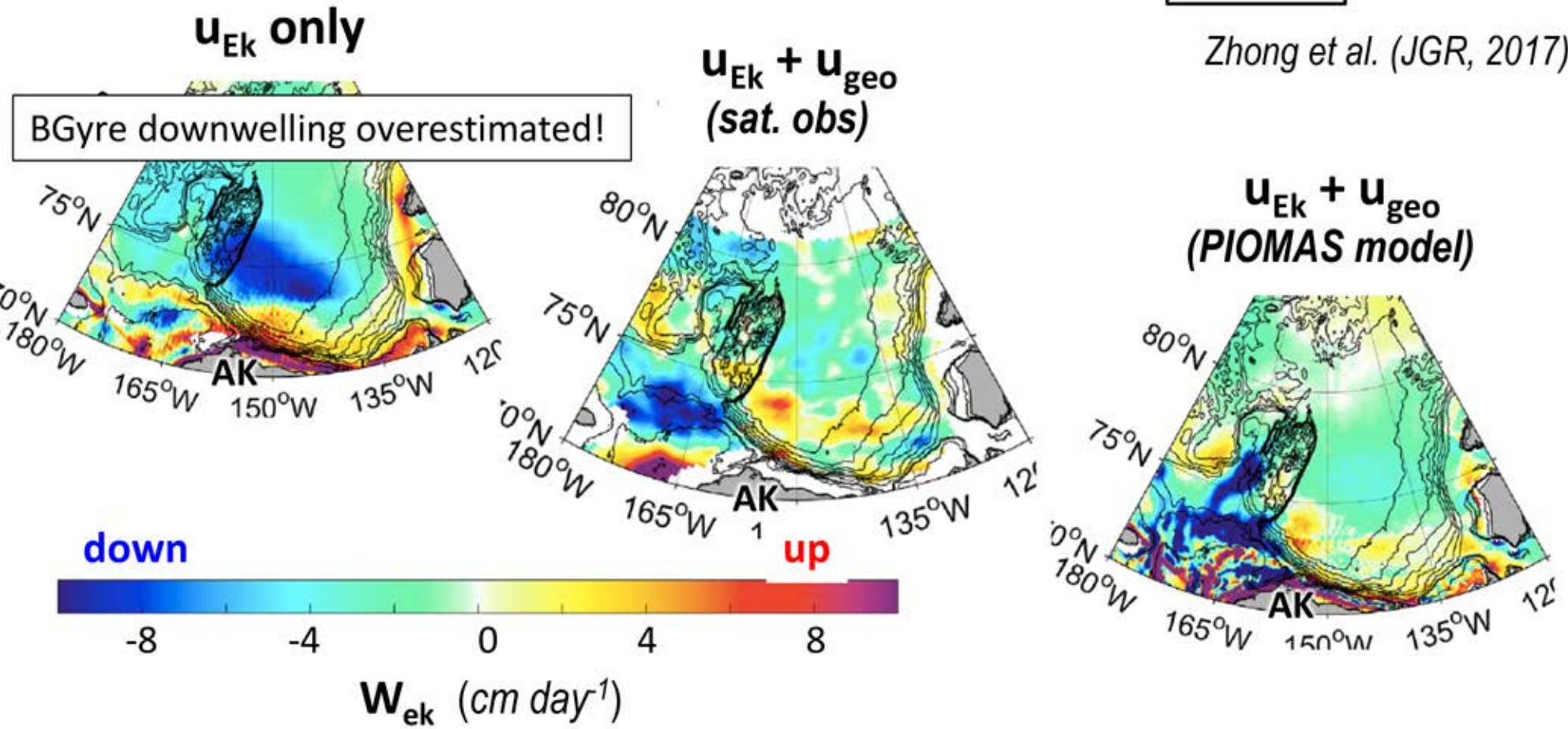
Zhong et al. (JGR, 2017)



# Ekman pumping

$$W_{Ek}$$

Zhong et al. (JGR, 2017)



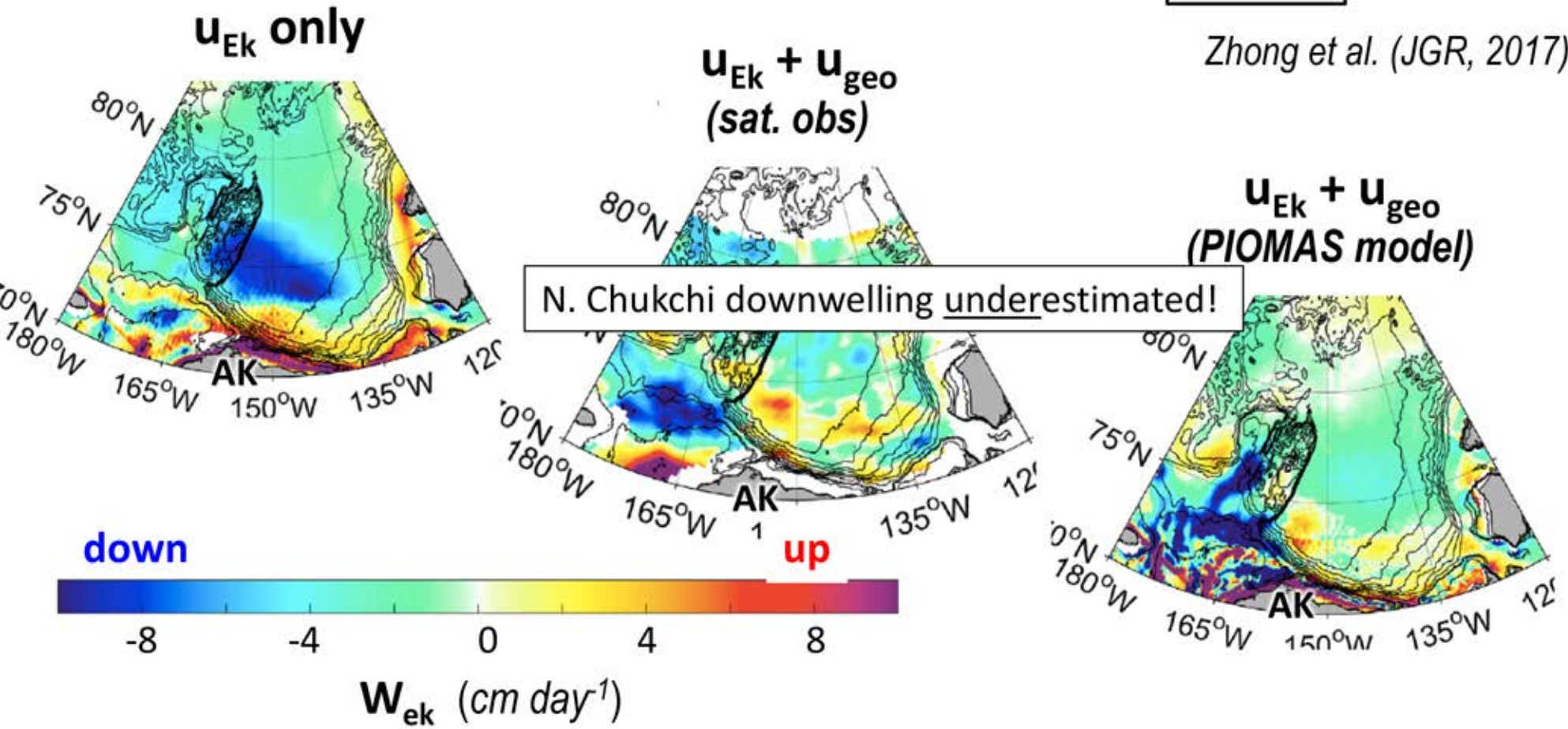
- Storage of freshwater in the Gyre
- Nutrient sink for productivity
- Etc.



# Ekman pumping

$$W_{Ek}$$

Zhong et al. (JGR, 2017)



- **Chukchi** downwelling > central **BGyre** downwelling!
- **Injection of Pacific waters** into the Arctic Ocean

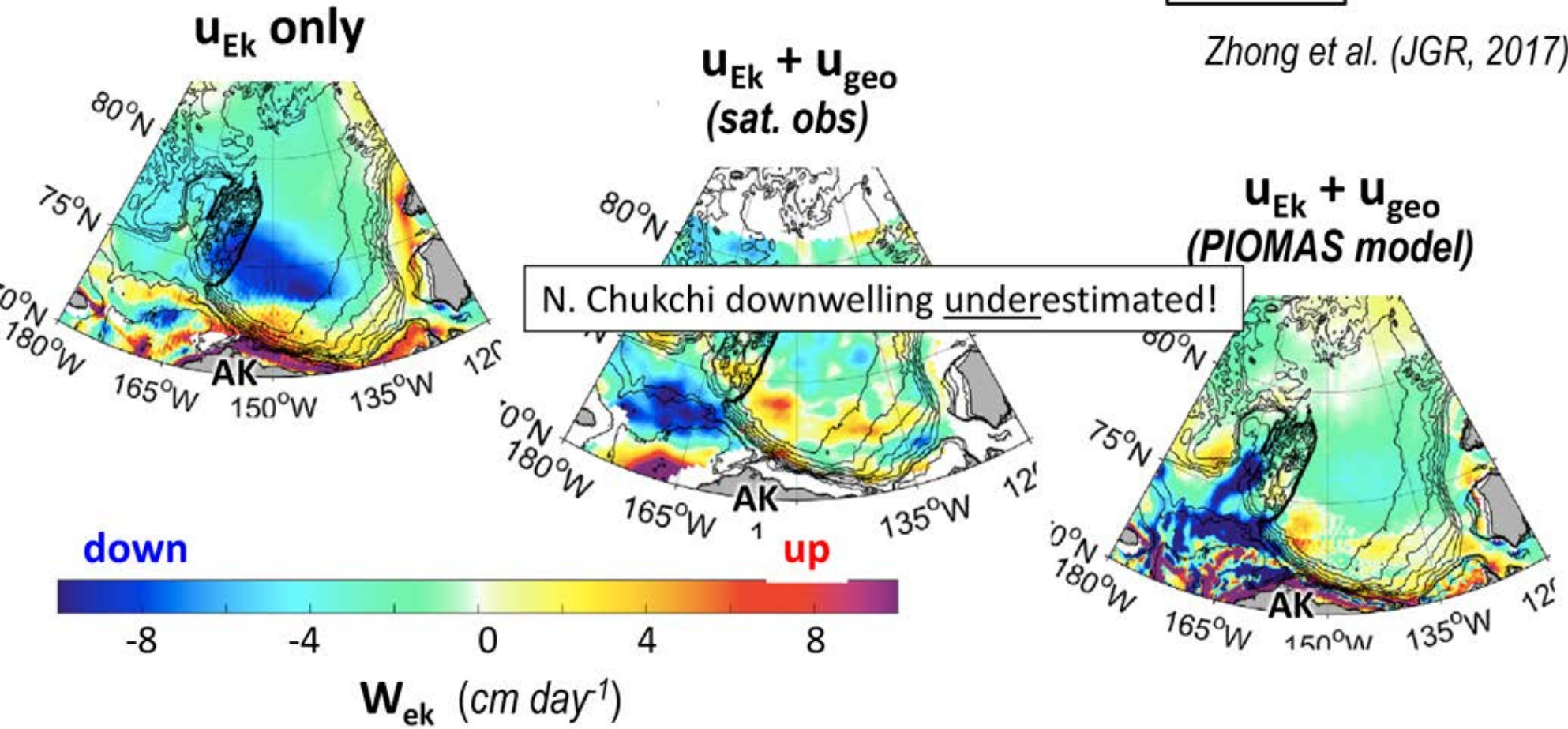
e.g., Timmermans et al. (2017)



# Ekman pumping

$$W_{Ek}$$

Zhong et al. (JGR, 2017)



- **Chukchi downwelling > central B Gyre downwelling!**
- **Injection of Pacific waters** into the Arctic Ocean
- **Stabilization** of Gyre “spin up”

# Cool Topix of the Future



## Ocean mixing:

- Will *subsurface heat* melt ice, warm the atmos?

## Freshwater:

- Will a *freshening Arctic* affect the global circulation?

## Ocean circulation:

- Just *speed* changes, or *direction*, too?

# Cool Topix of the Future



## Ocean mixing:

- Will *subsurface heat* melt ice, warm the atmos?

## Freshwater:

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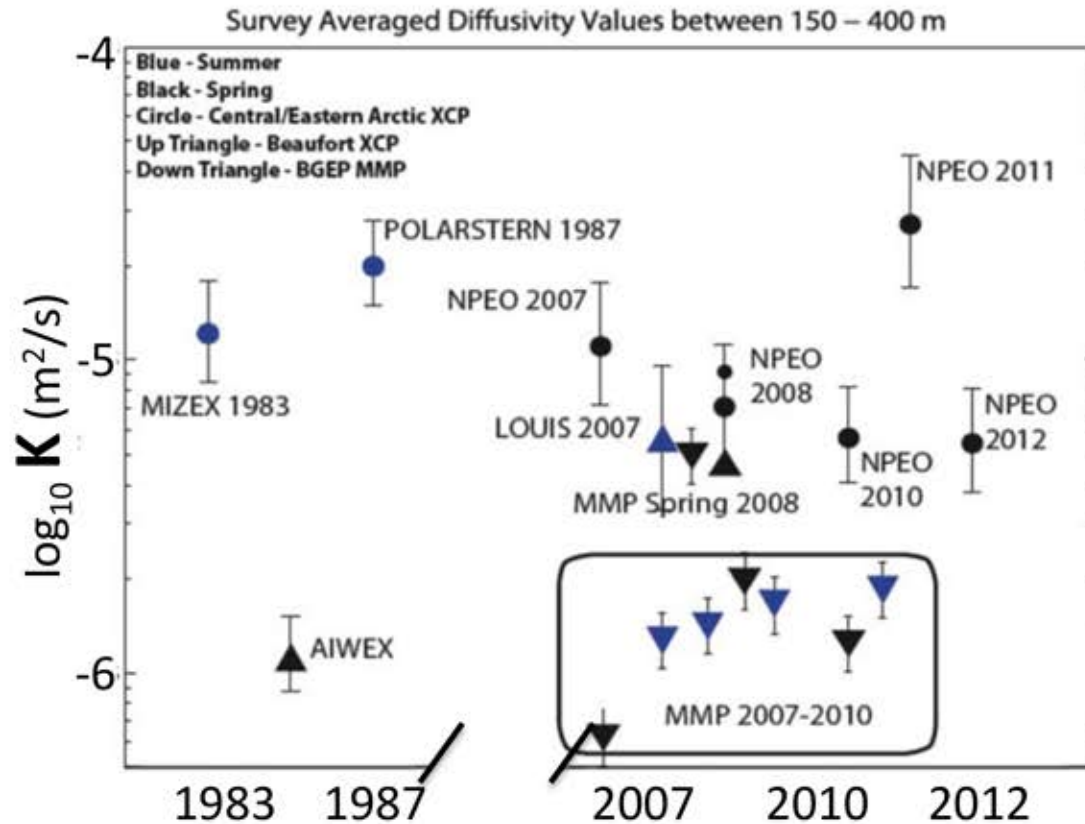
## Ocean circulation:

- Just *speed* changes, or *direction*, too?

Thank You



# Also... is there more ocean mixing?

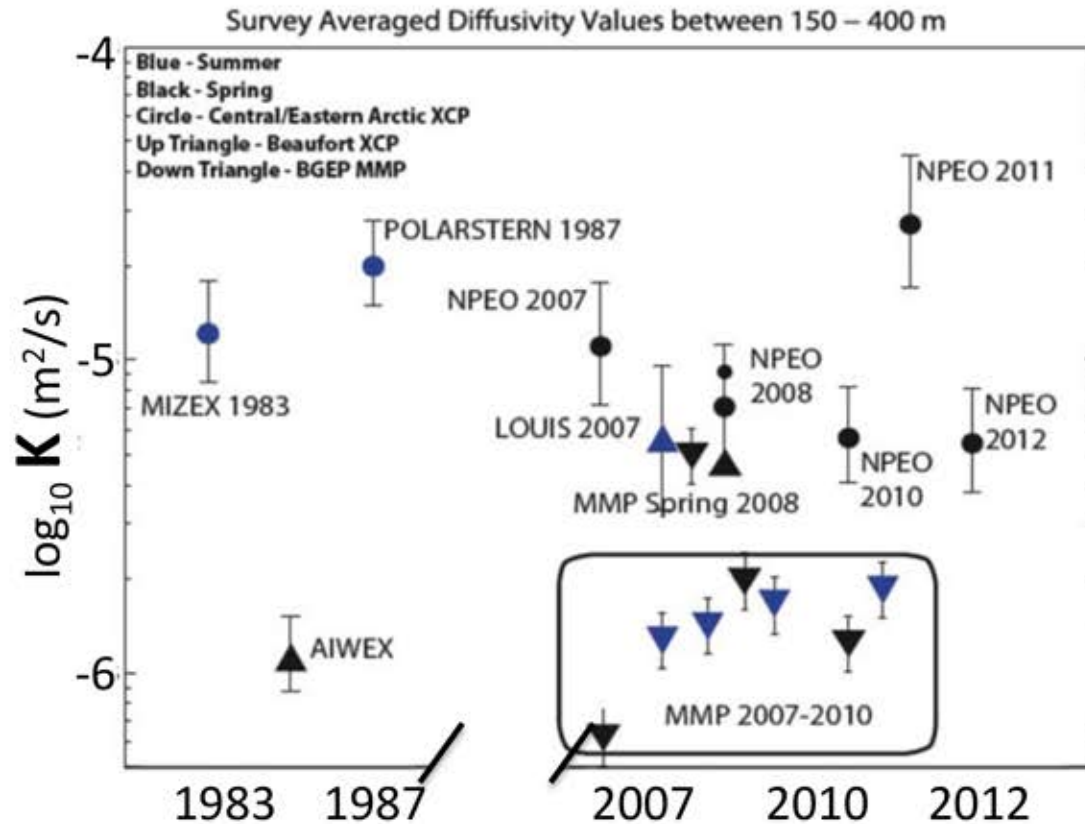


Guthrie et al. (JGR, 2013)

Amerasian Basin: **Nope!**

- incr surface stress but also incr stratification!

# Also... is there more ocean mixing?



Guthrie et al. (JGR, 2013)

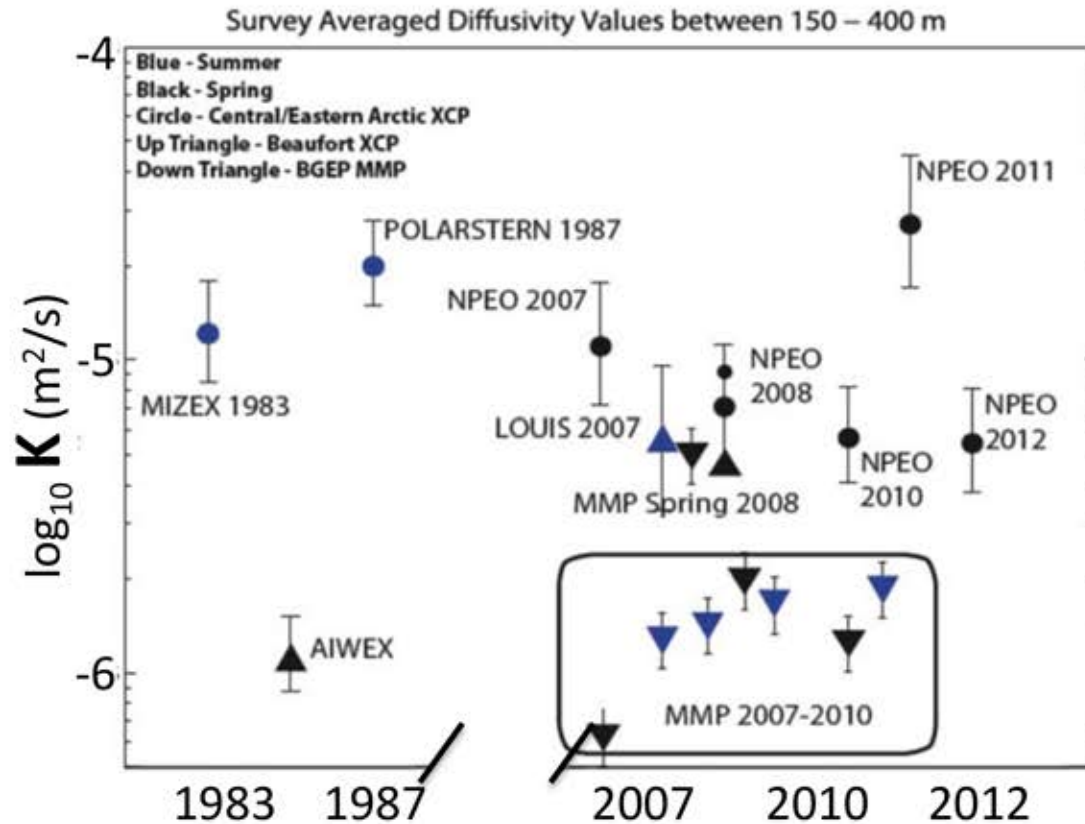
## Amerasian Basin: Nope!

- incr surface stress but also incr stratification!

A new genre of Arctic ocean mixing study: **“Guthrie, but...”**



# Also... is there more ocean **mixing**?



Guthrie et al. (JGR, 2013)

Amerasian Basin: **Nope!**

- incr surface stress but also incr **stratification!**

Eurasian Basin: **Yup** (maybe) Polyakov et al. (Science, 2017)

# Ice Retreat → Ocean Warming

