

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



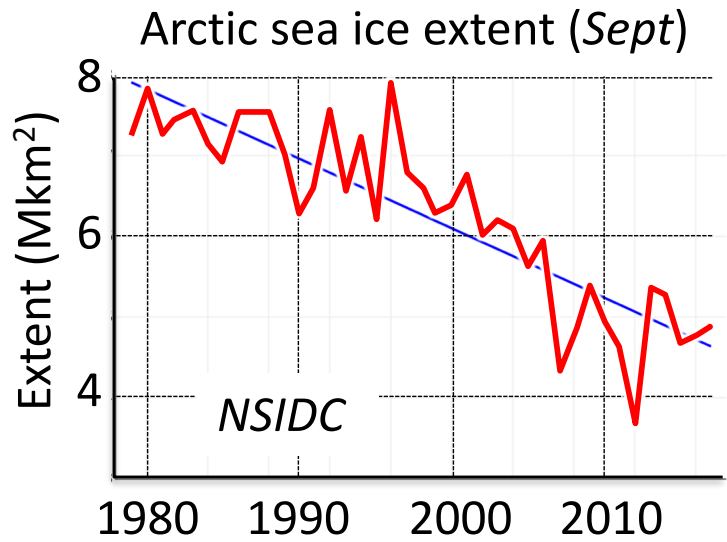
Michael Steele

***Wenli Zhong, J. Zhang, W. Ermold,
S. Dickinson, T. Martin, I. Rigor***

*Polar Science Center, Applied Physics Laboratory
University of Washington
Seattle, WA USA*



Sea ice is declining!

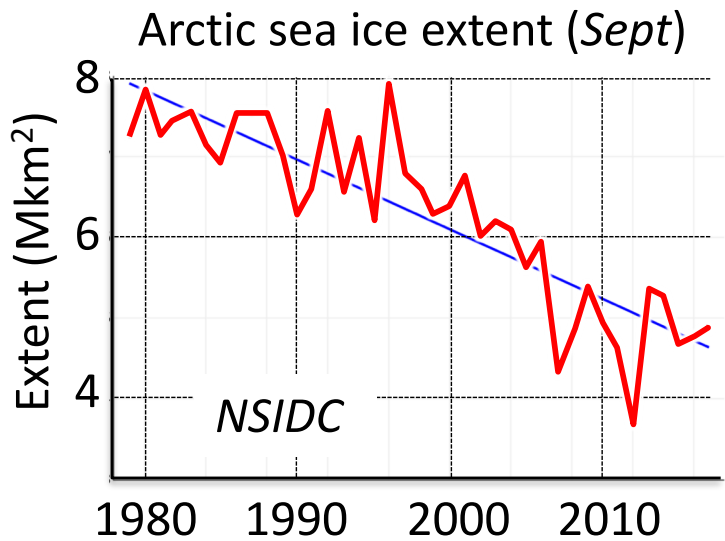




Sea ice is declining!

What about
T, S, V?

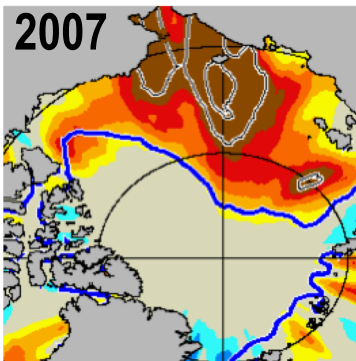
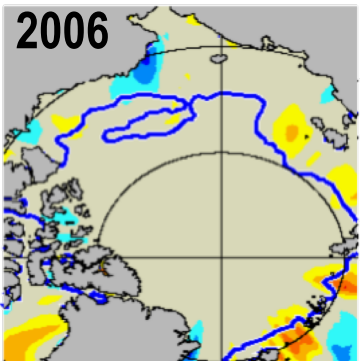
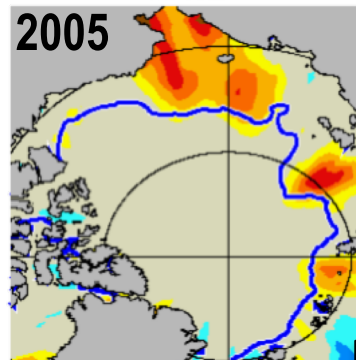
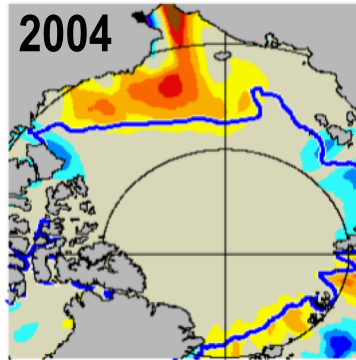
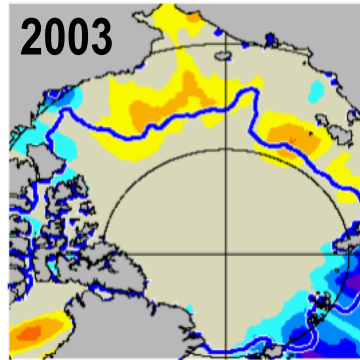
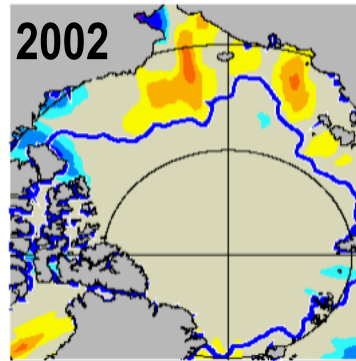
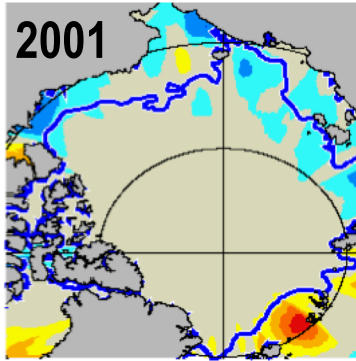
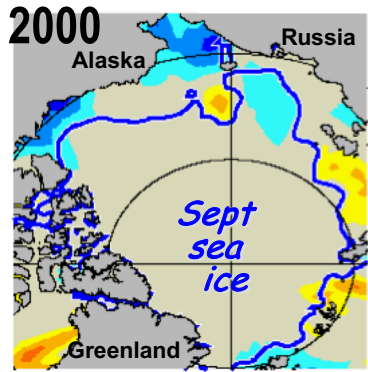
Temperature
Salinity
Velocity



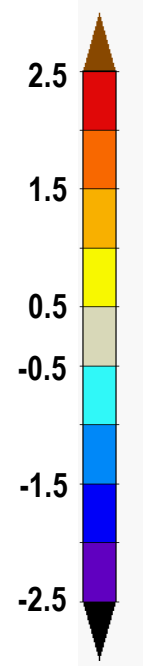
Physical
Oceanographer



Ice Retreat → Ocean Warming



Steele et al. (GRL, 2008)



Anomaly of Summer \equiv JAS
Sea Surface Temperature ($^{\circ}\text{C}$)
(relative to 1982-2007 mean)

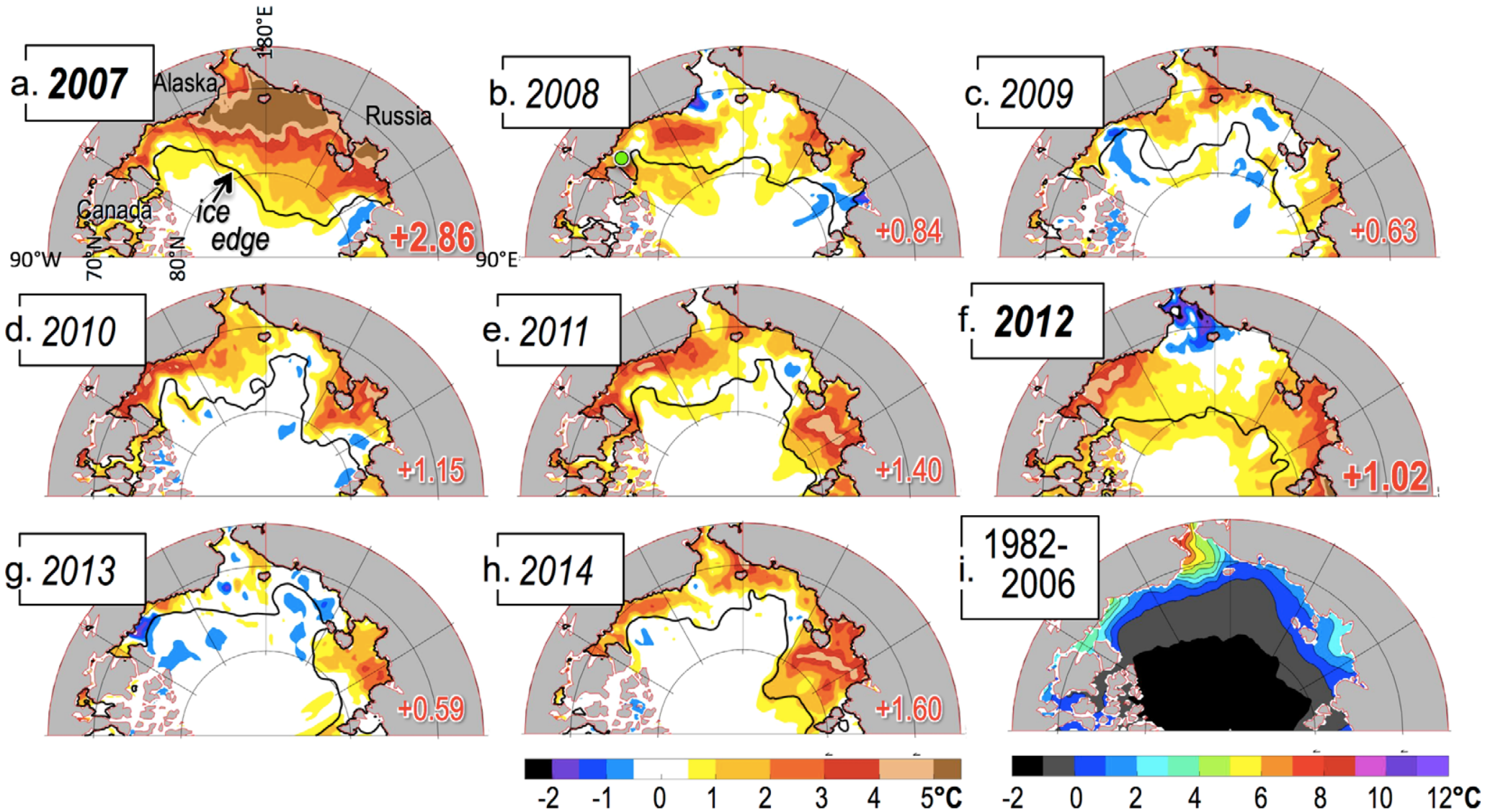
Most of this is **local solar input**
Steele et al. (JGR, 2010)



daily NOAA OISST
(satellite + some in situ obs)

More recently

Steele & Dickinson (2016)

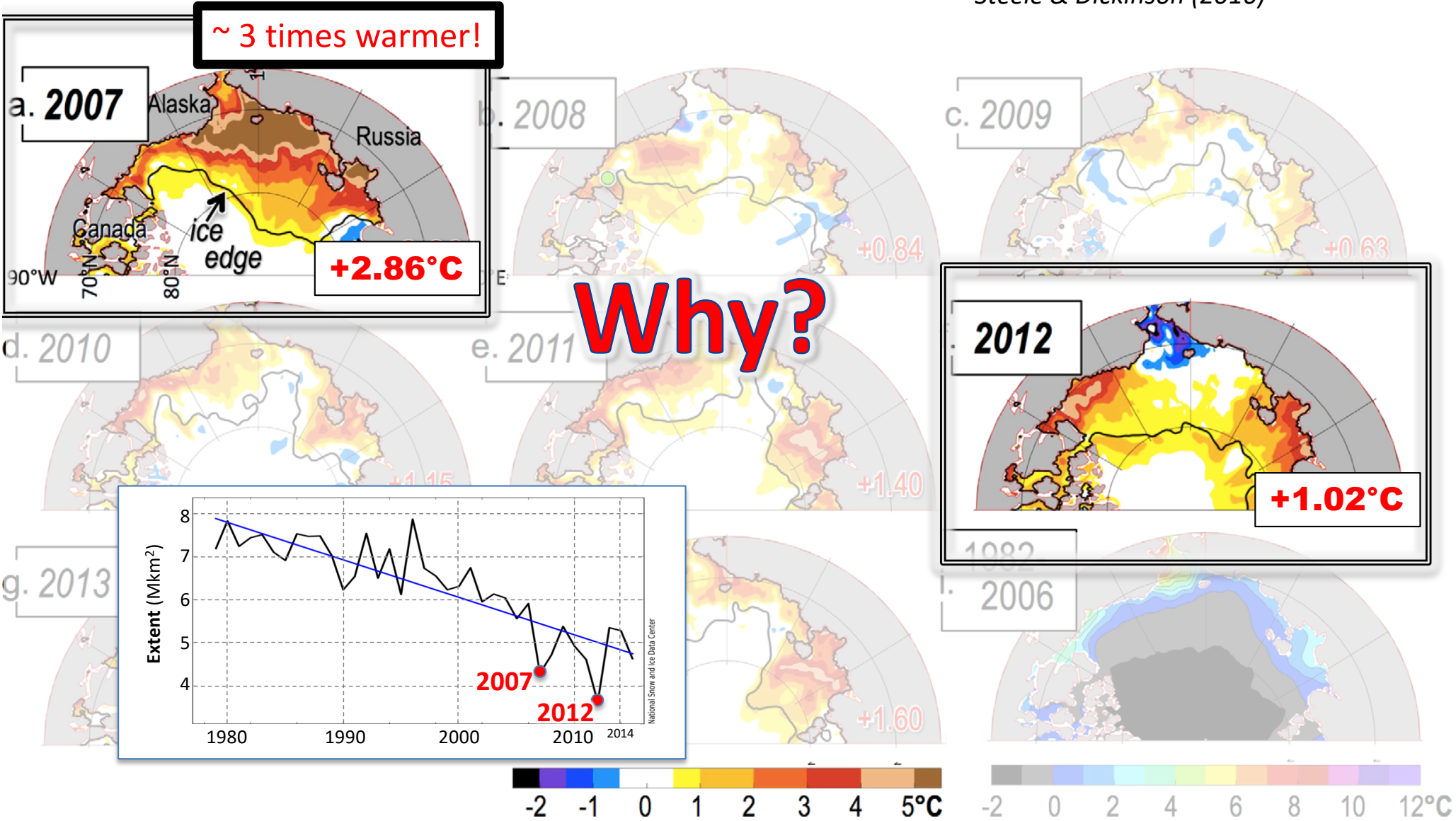


SST: dOISST (AVHRR only) July/Aug
Ice edge: 15% concentration (NASA Team1)

Mostly warm

More recently

Steele & Dickinson (2016)

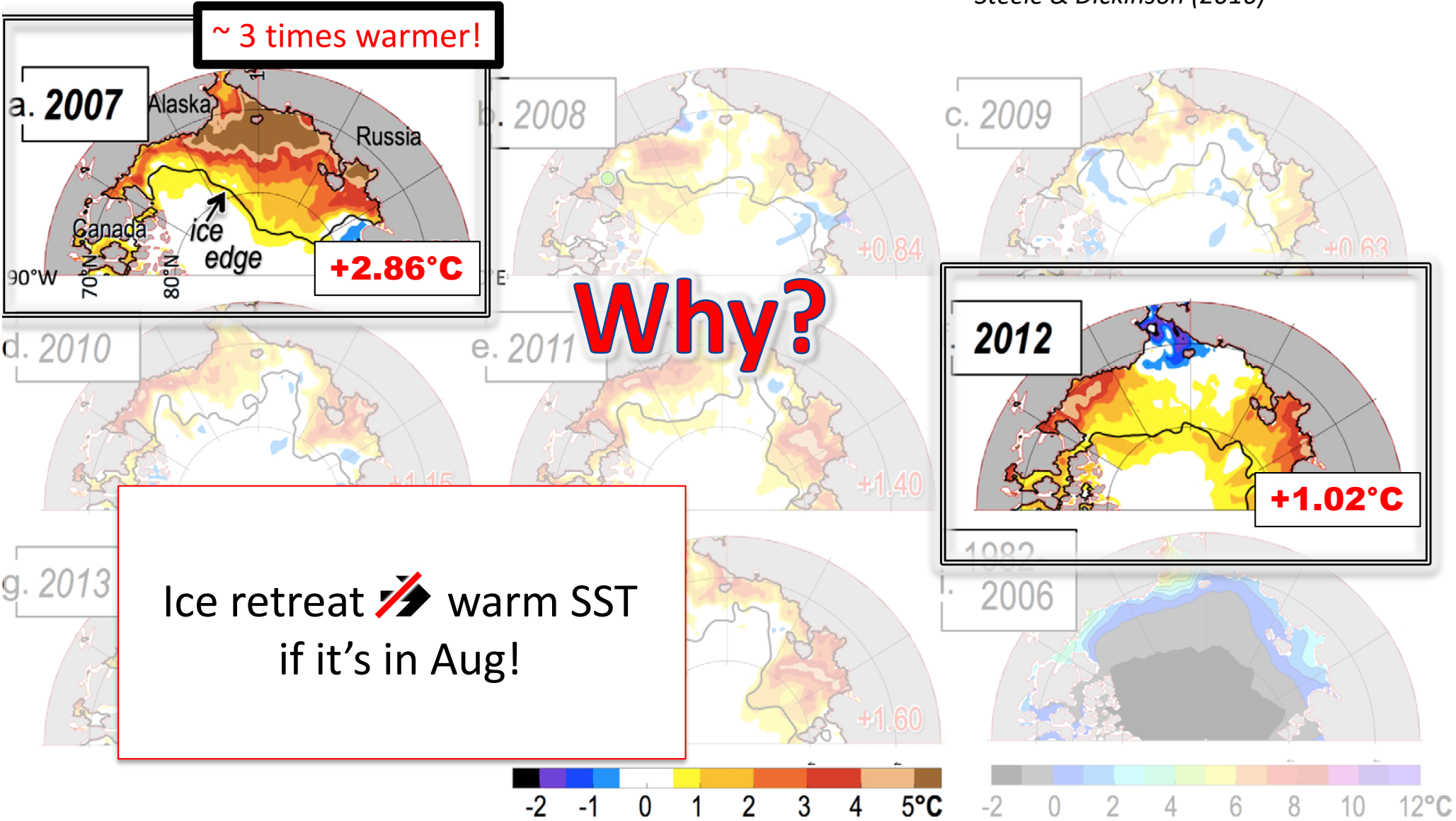


SST: dOISST (AVHRR only)

Ice edge: 15% concentration (NASA Team1)

More recently

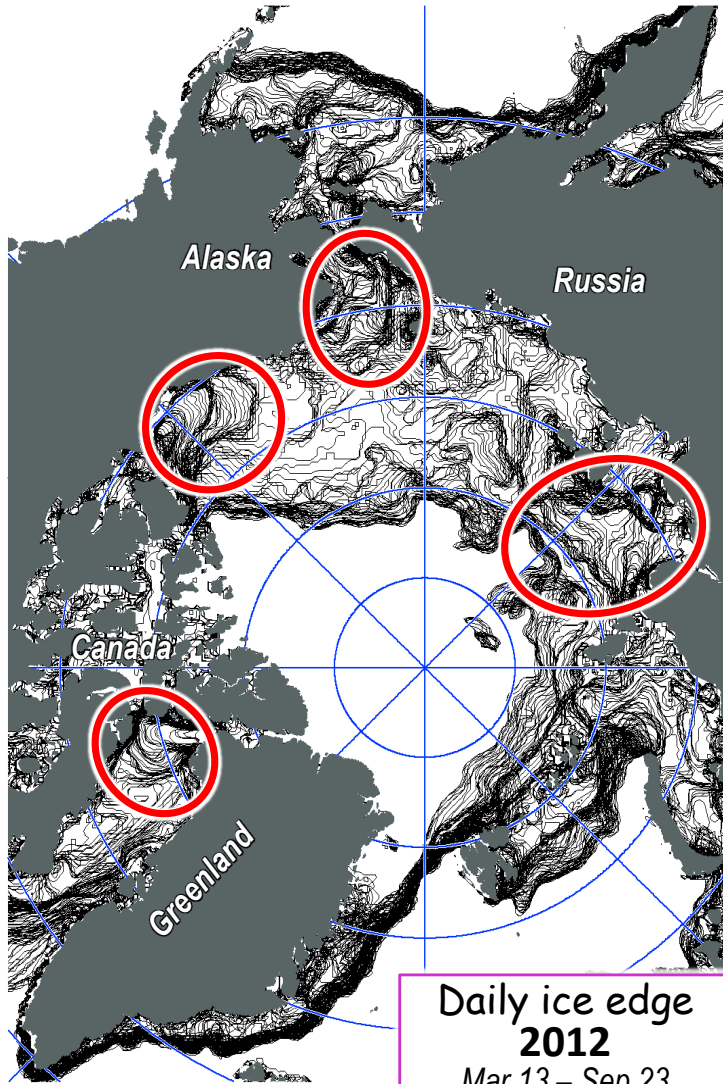
Steele & Dickinson (2016)



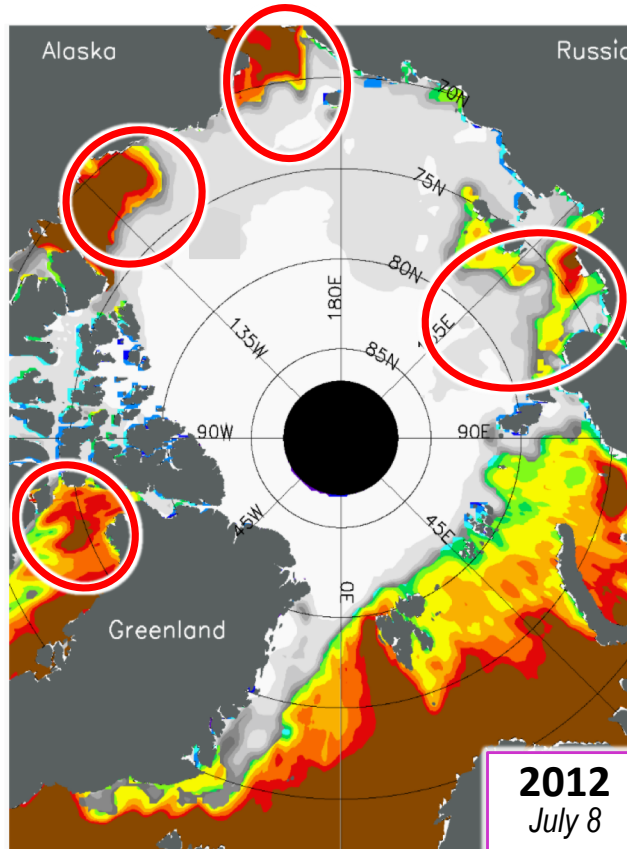
SST: dOISST (AVHRR only)

Ice edge: 15% concentration (NASA Team1)

Ice Retreat ← Ocean Warming



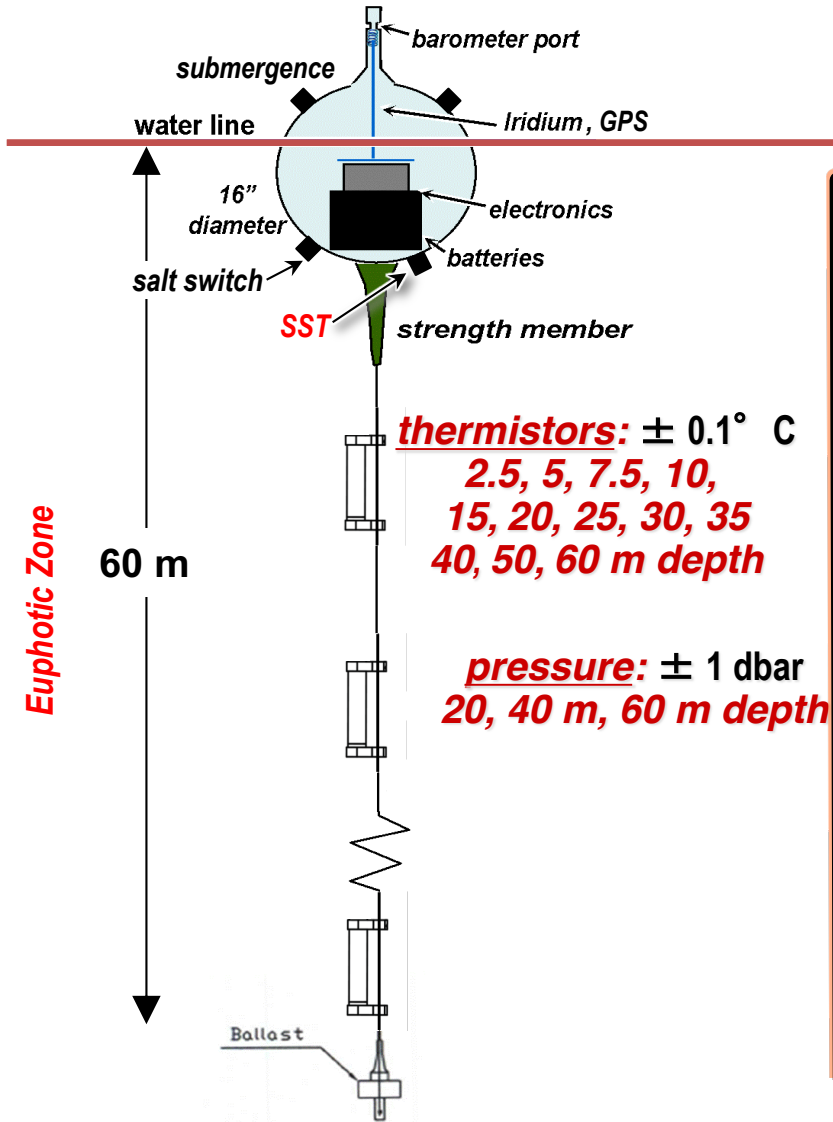
"Ice edge loitering"
Steele & Ermold (JGR, 2015)



Explanation?
Off-ice winds +
warm SSTs

The UpTempO buoy

Upper Temperature of the polar Oceans

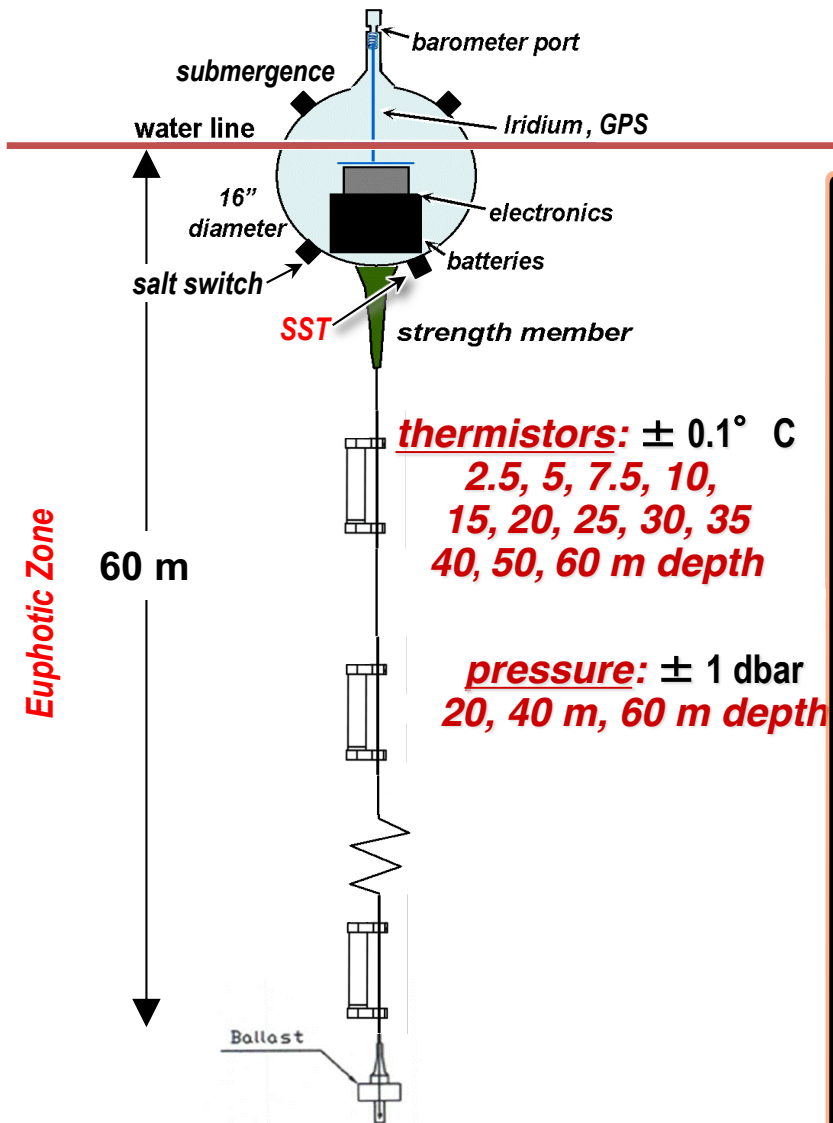


- Surface: SLP, **SST**, GPS, Iridium ...[anemometer]
- Cable: 12-16 x **T** ($\pm 0.1^\circ \text{C}$), 3 x **P** ($\pm 1 \text{ dbar}$) ...[S]
- 60 m (basin) or 25 m (shelves)

Google "uptempo arctic"

The UpTempO buoy

Upper Temperature of the polar Oceans



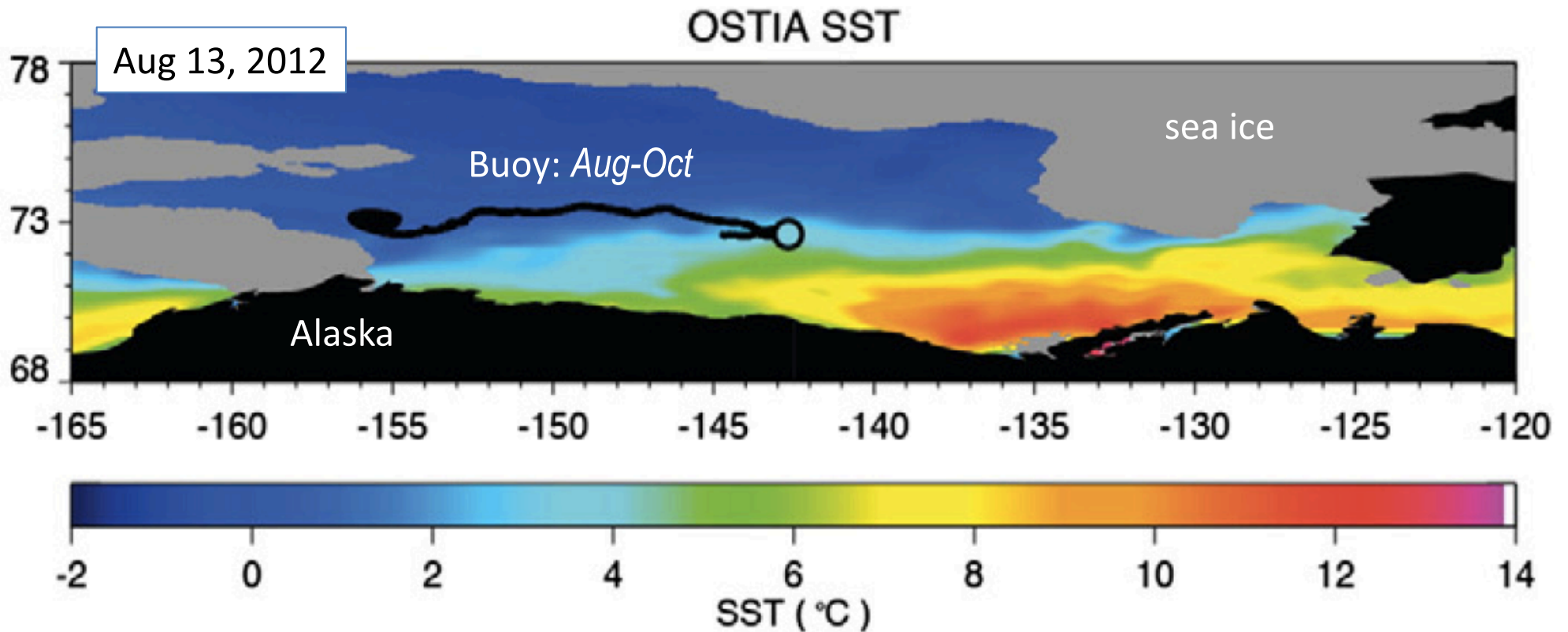
- Surface: SLP, **SST**, GPS, Iridium ...[anemometer]
- Cable: 12-16 x **T** ($\pm 0.1^\circ \text{C}$), 3 x **P** ($\pm 1 \text{ dbar}$) ...[S]
- 60 m (basin) or 25 m (shelves)
- Deploy: in ice or water by ship, ice camp, air



Google "uptempo arctic"

The UpTempO buoy

Upper Temperature of the polar Oceans



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

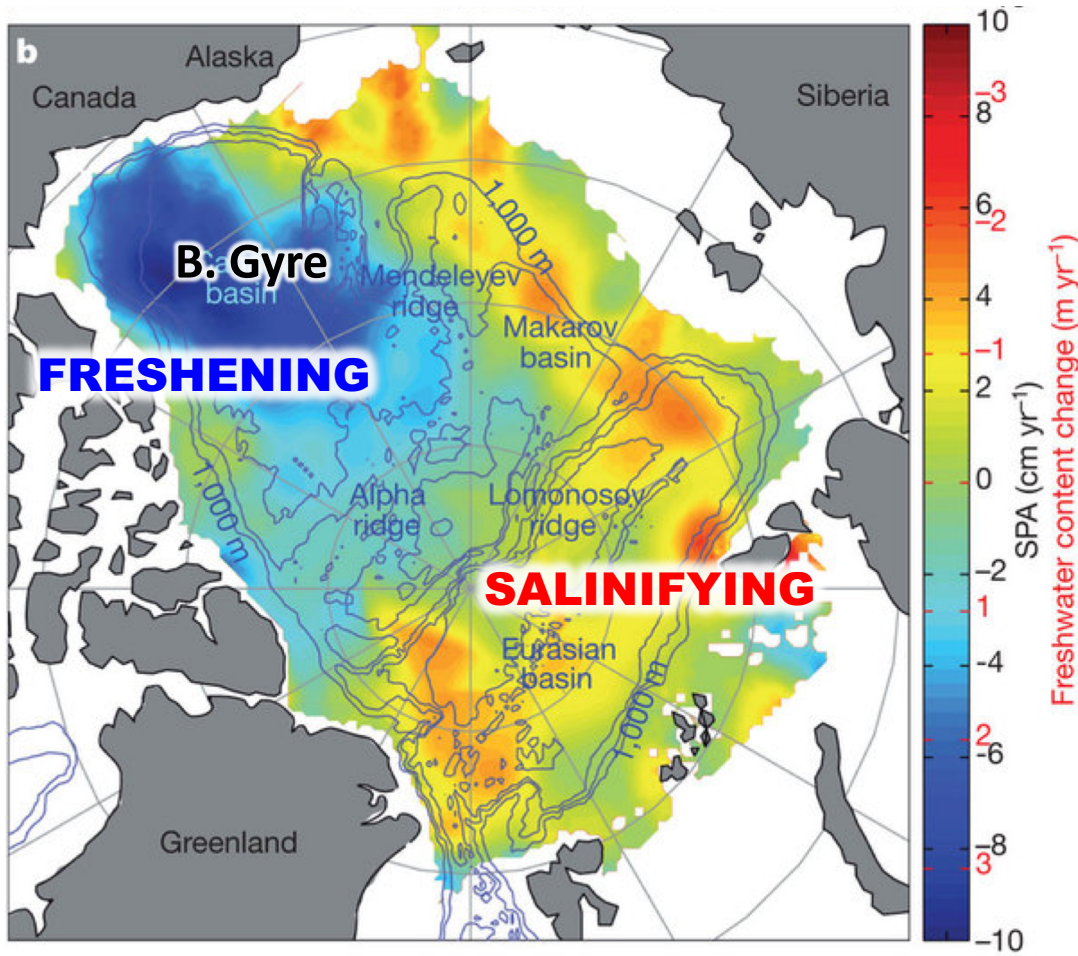


Castro et al. (*Rem. Sens. Environ.*, 2016)

What about salinity?



Trend in upper ocean "freshwater" = $\int_{\sim 250 \text{ m}} S dz$
 (2005 → 2008)



- **Strong regional trends**

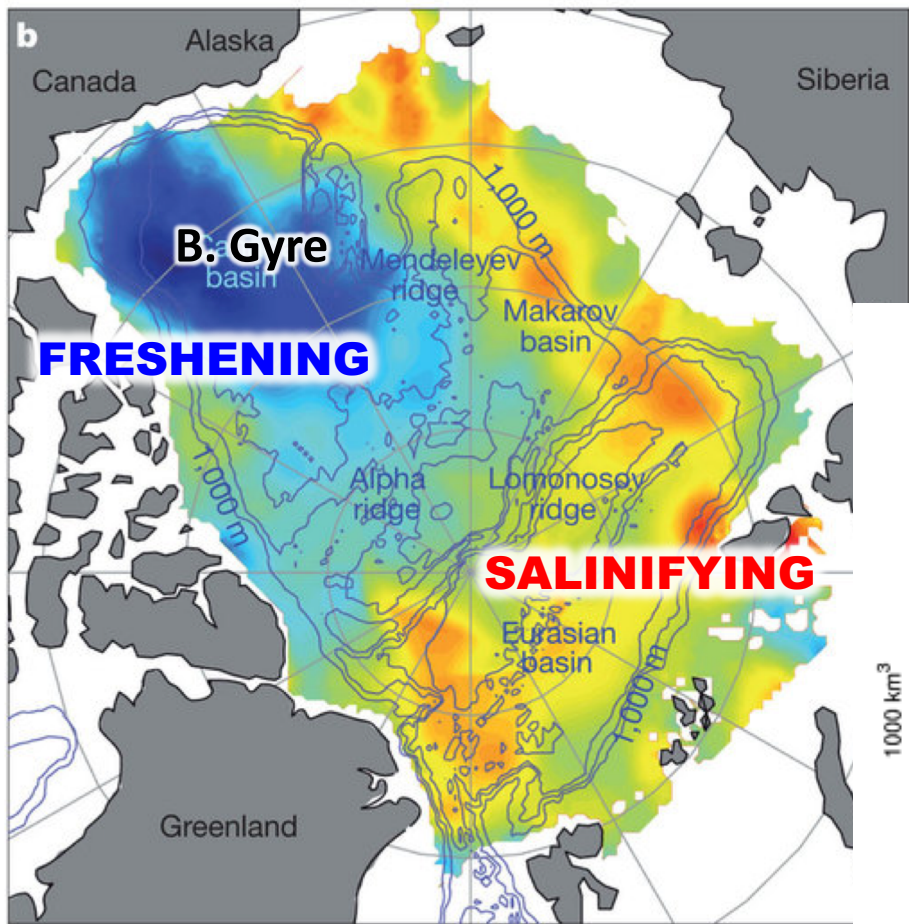
Beaufort Gyre freshening

(ice melt, PacWater, rivers)

Morison et al. (Nature, 2012)

...from satellite observations!

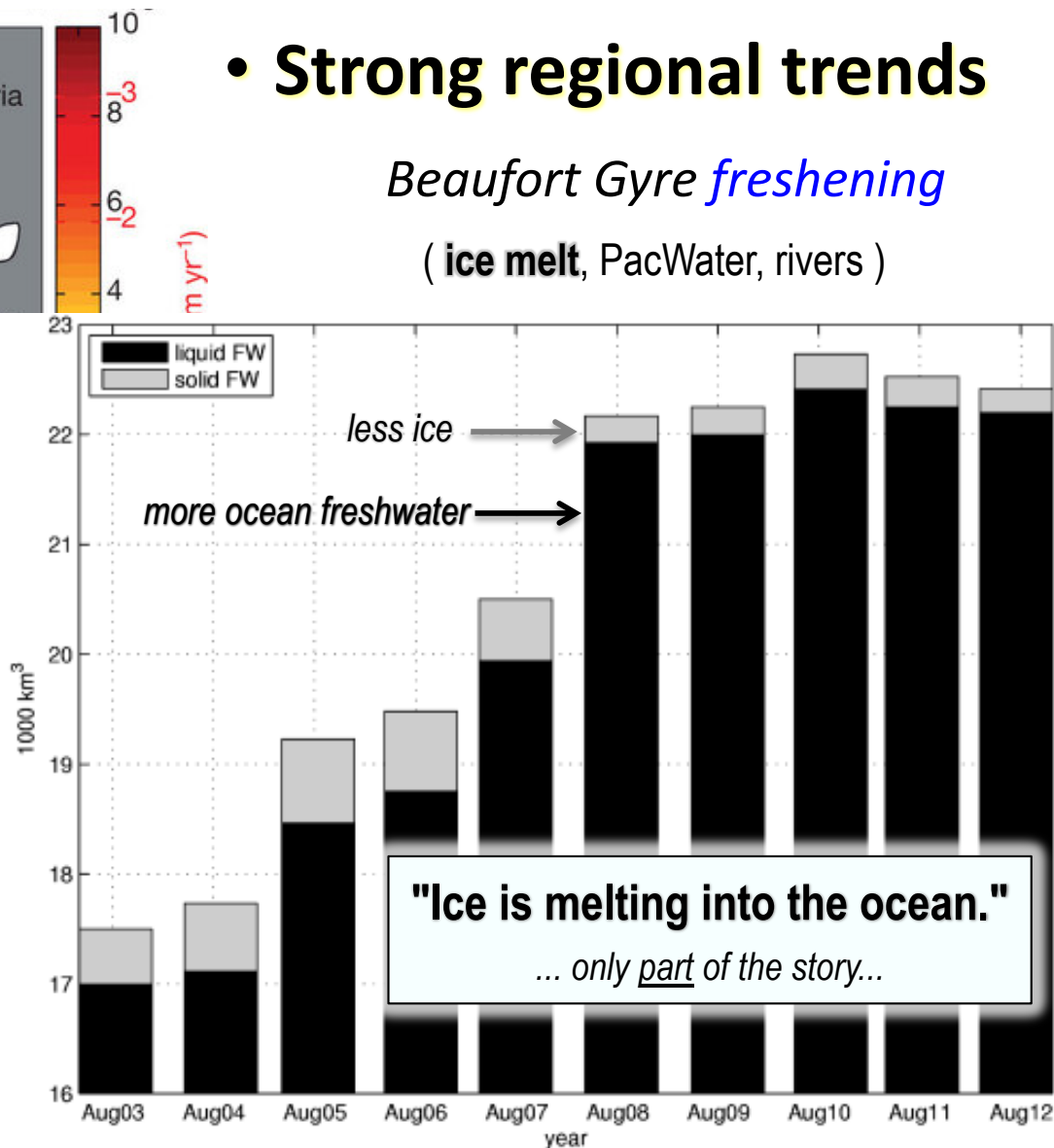
Trend in upper ocean "freshwater" = $\int_{\sim 250\text{ m}} S dz$ (2005 \rightarrow 2008)



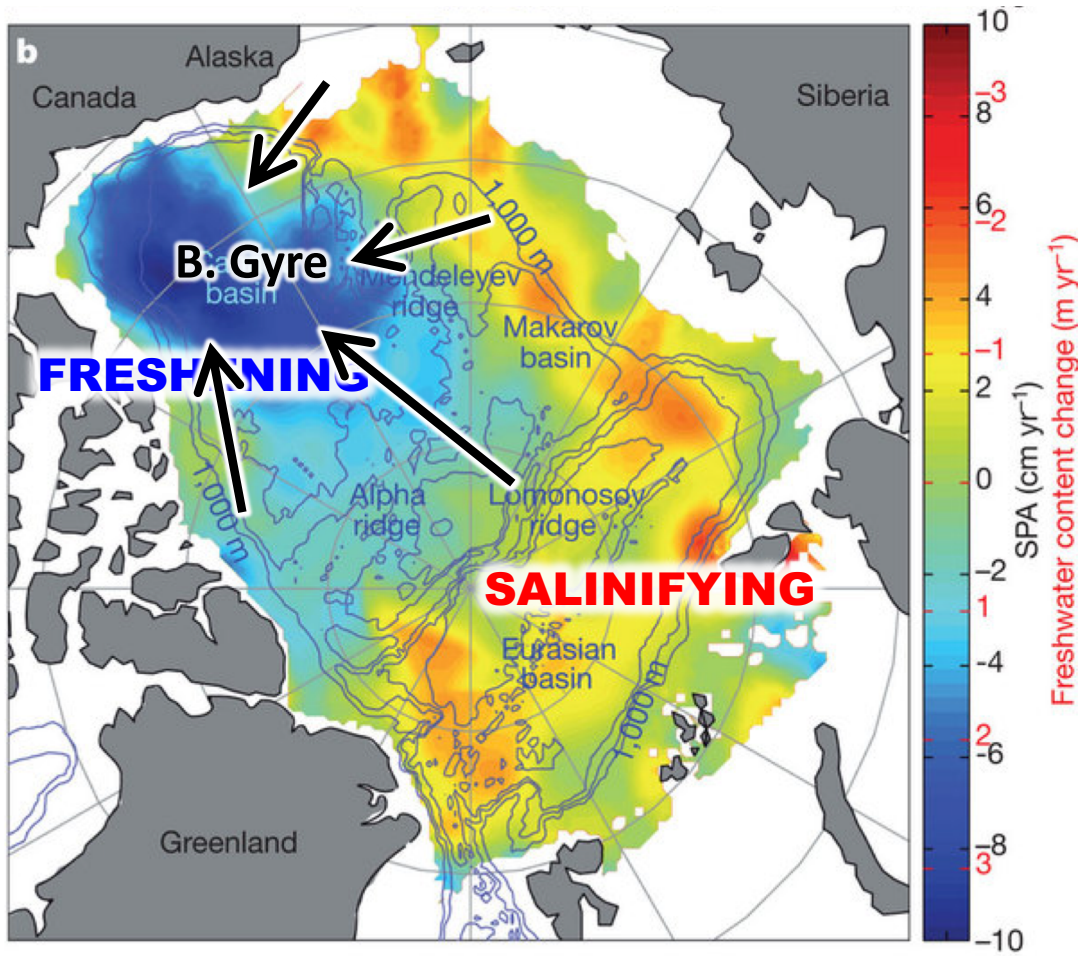
• Strong regional trends

Beaufort Gyre freshening

(ice melt, PacWater, rivers)



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 (2005 → 2008)



• Strong regional trends

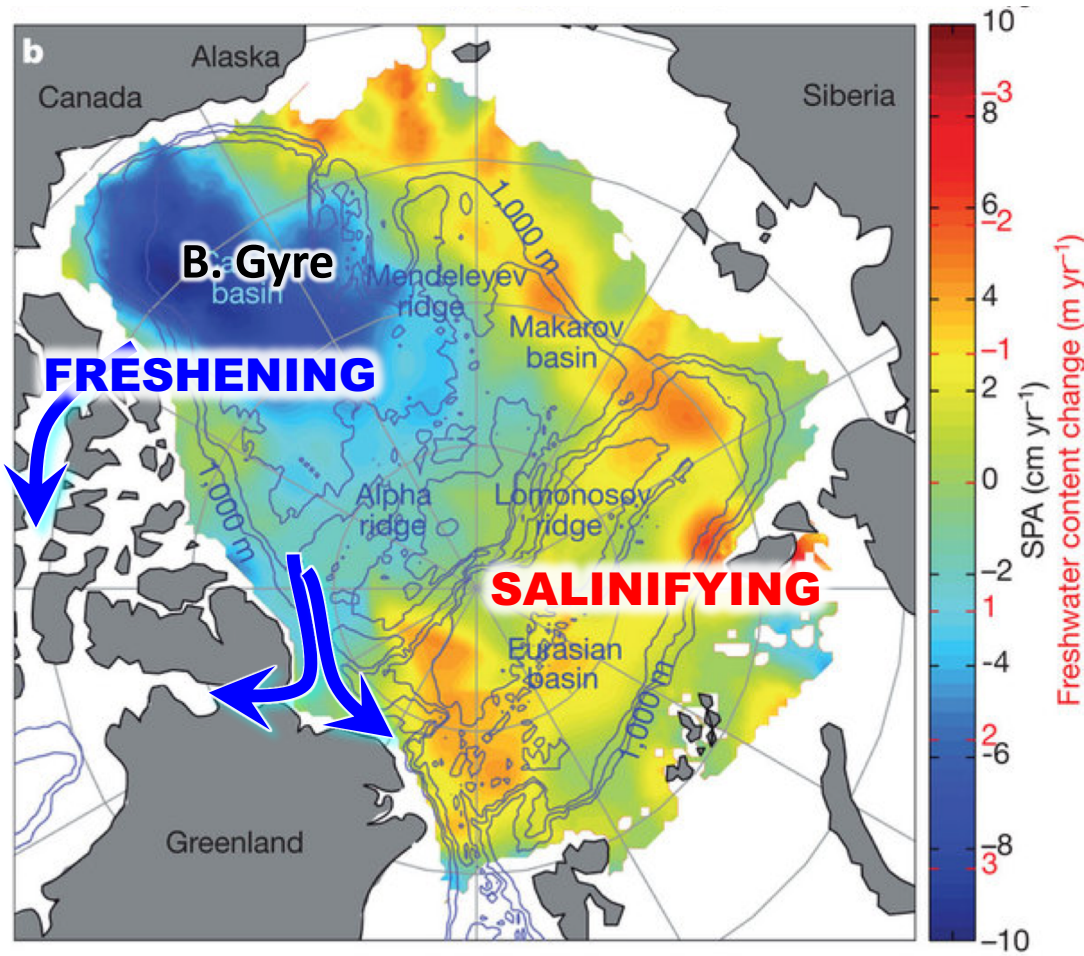
Beaufort Gyre *freshening*

(ice melt, PacWater, rivers)

Ocean circulation changes

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

Trend in upper ocean "freshwater" = $\int_{\sim 250 \text{ m}} S dz$
 (2005 → 2008)



• Strong regional trends

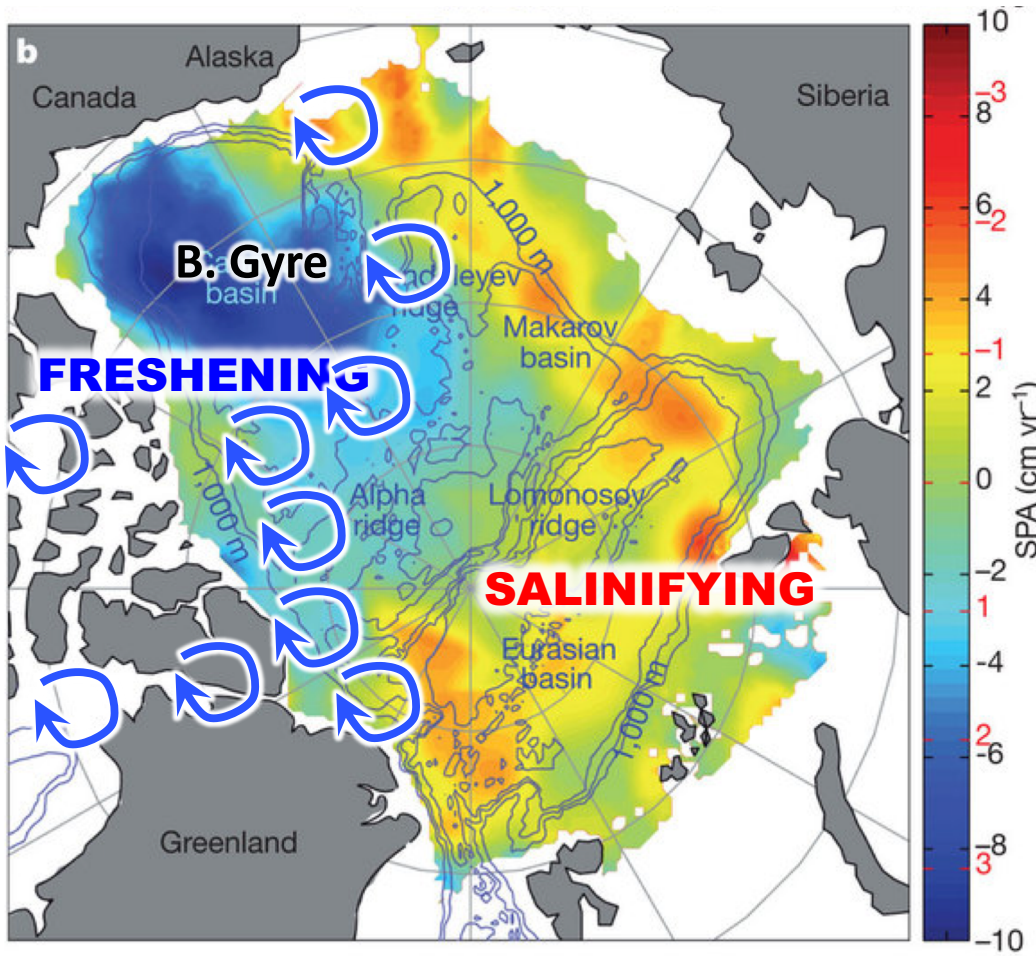
Beaufort Gyre freshening

(ice melt, PacWater, rivers)

...some leakage

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

Trend in upper ocean "freshwater" = $\int_{\sim 250 \text{ m}} S dz$
 (2005 → 2008)



• Strong regional trends

Beaufort Gyre freshening

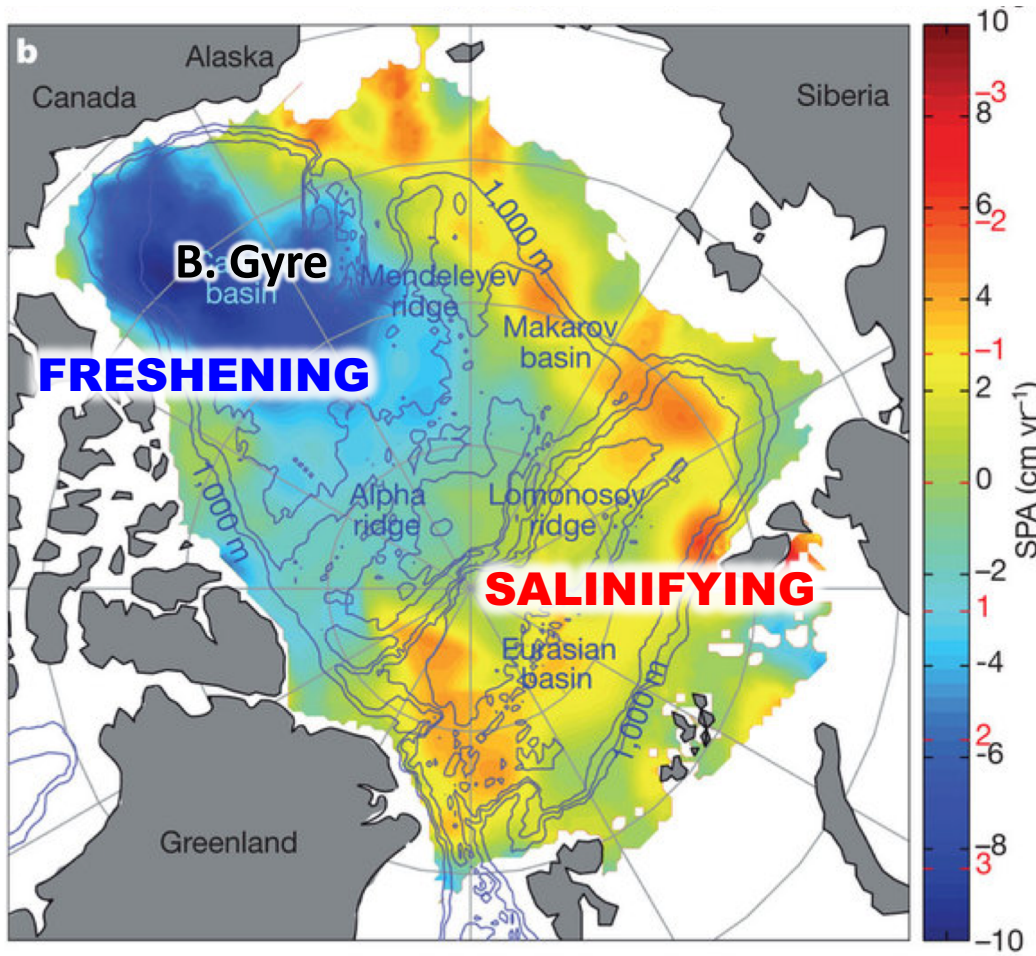
(ice melt, PacWater, rivers)

...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" = $\int_{\sim 250 \text{ m}} S dz$
 (2005 \rightarrow 2008)



- **Strong regional trends**

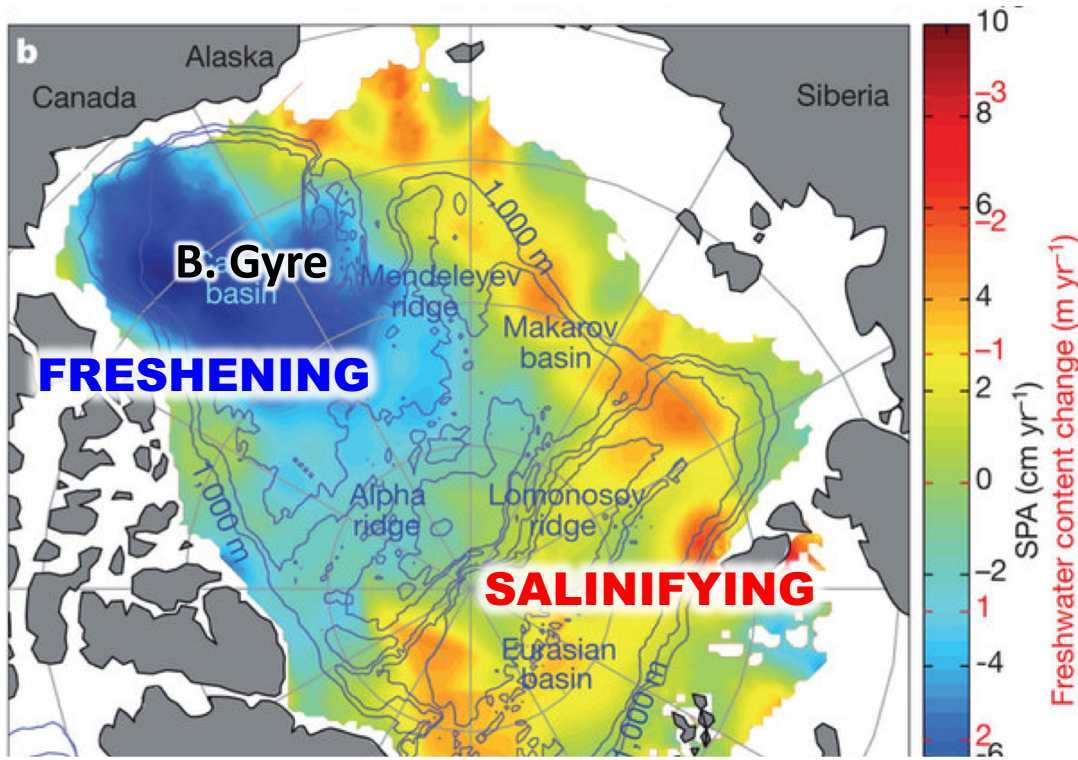
Beaufort Gyre freshening
 (ice melt, PacWater, rivers)

- **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" = $\int_{\sim 250 \text{ m}} S dz$
 (2005 → 2008)



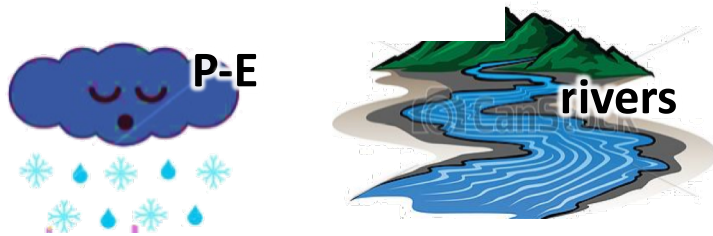
...small freshening...

Rabe et al. (GRL, 2014)

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

Peralta-Ferriz & Woodgate. (PiO, 2015)

(1) Incr. Hydrol. Cycle:



long-term...

(2) Sea ice melt:



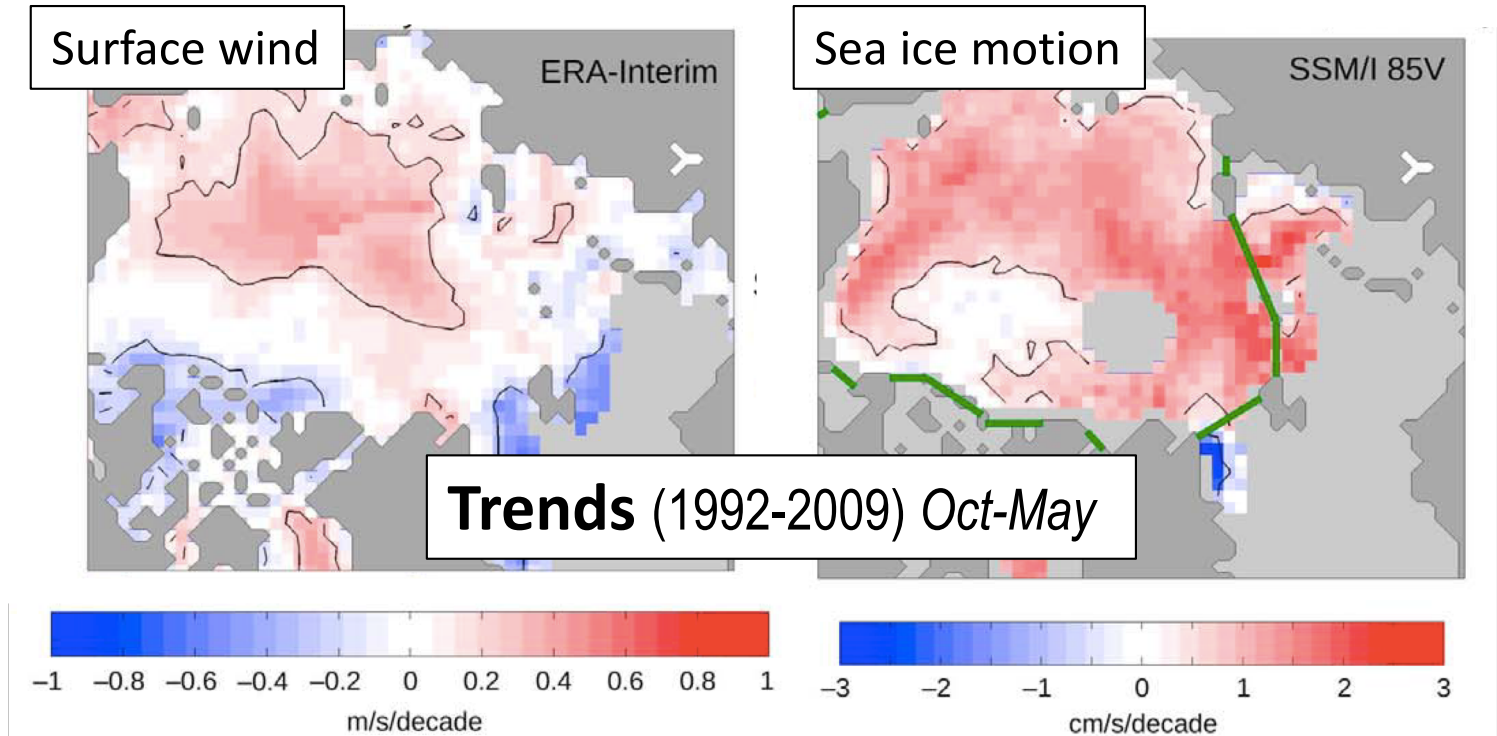
transient...

What about Kinetic Energy?



wind & ice motion trends

Spreen et al. (GRL, 2011)

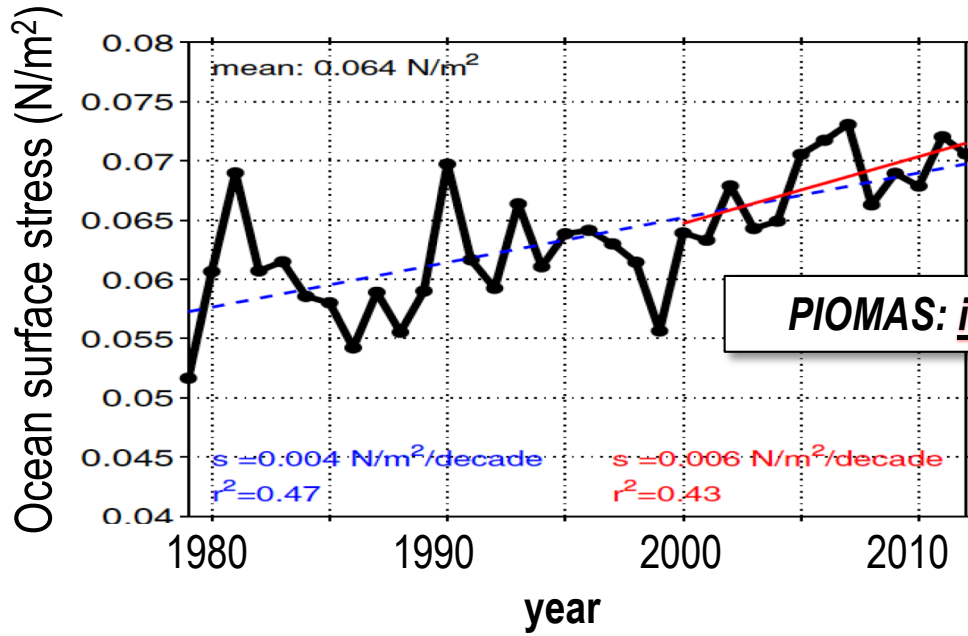


< 1 m/s over 20 years
..eh..

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

More KE -> ocean?

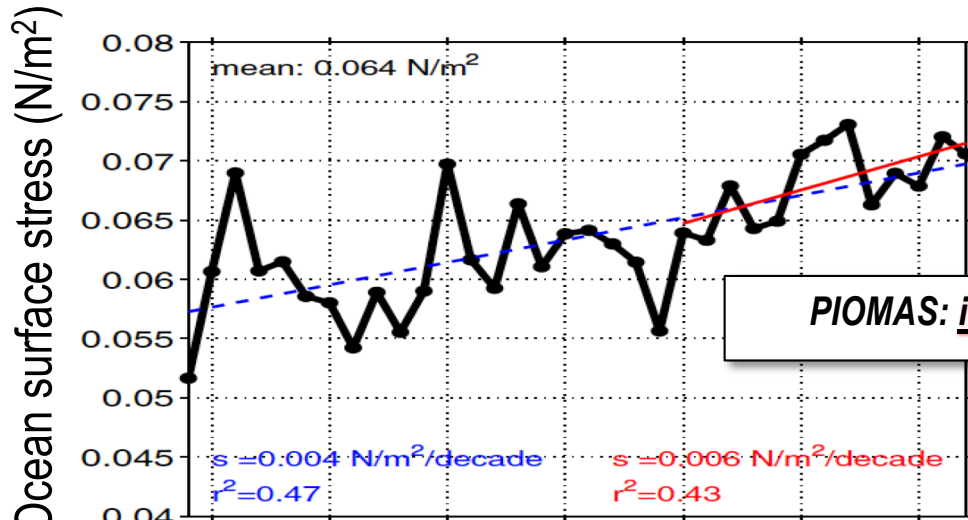
More KE -> ocean?



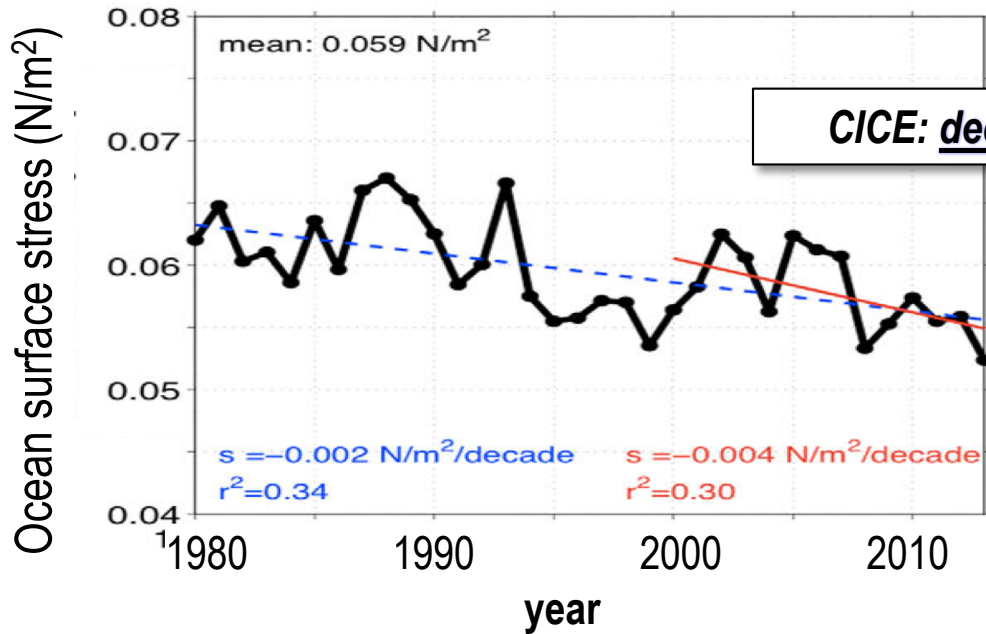
Martin et al. (JGR, 2014)

...faster ice

More KE -> ocean?



...faster ice

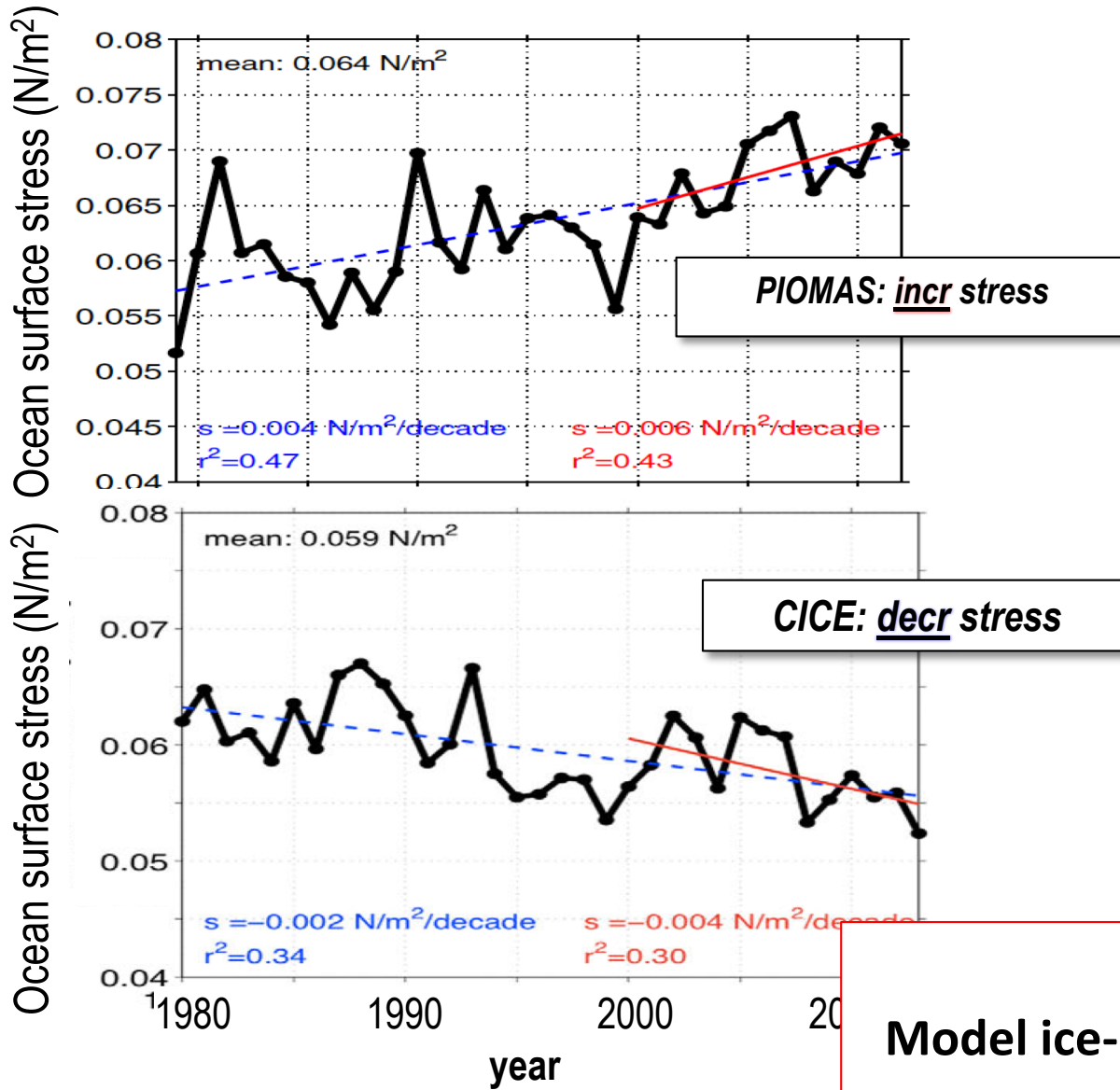


Martin et al. (JPO, 2016)

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



More KE -> ocean?

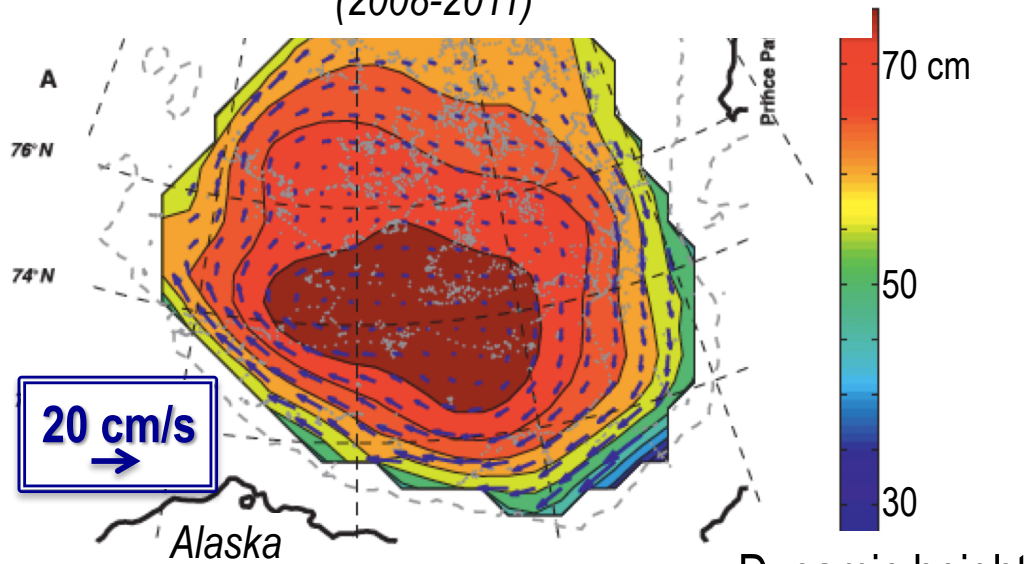


But:
Model ice-ocn boundary layer sucks
Cole et al. (Elementa, 2017)

So... is the ocean moving faster?

Geostrophic current (*in situ obs*)

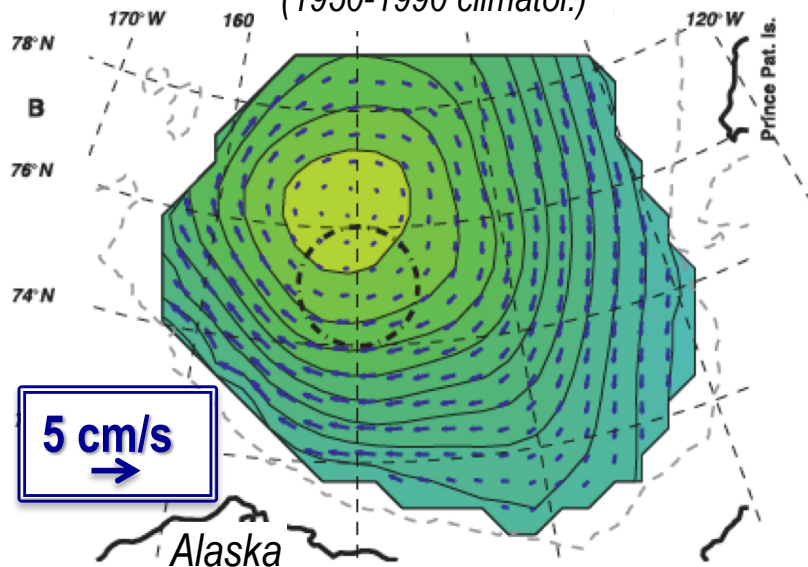
(2008-2011)



Beaufort Gyre: **Yup!**

(Elsewhere: ??!)

(1950-1990 climatol.)

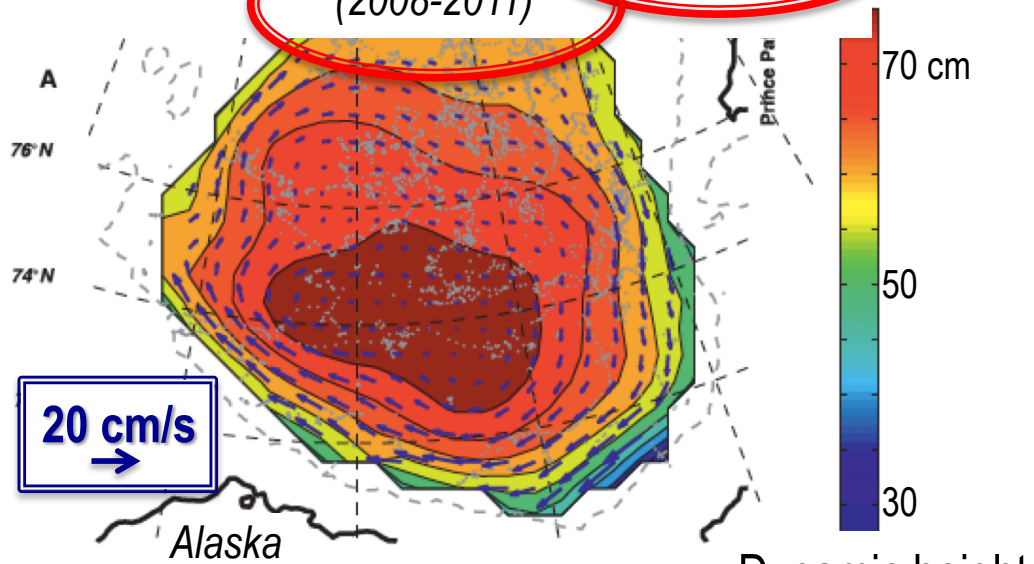


McPhee (GRL, 2012)

So... is the ocean moving faster?

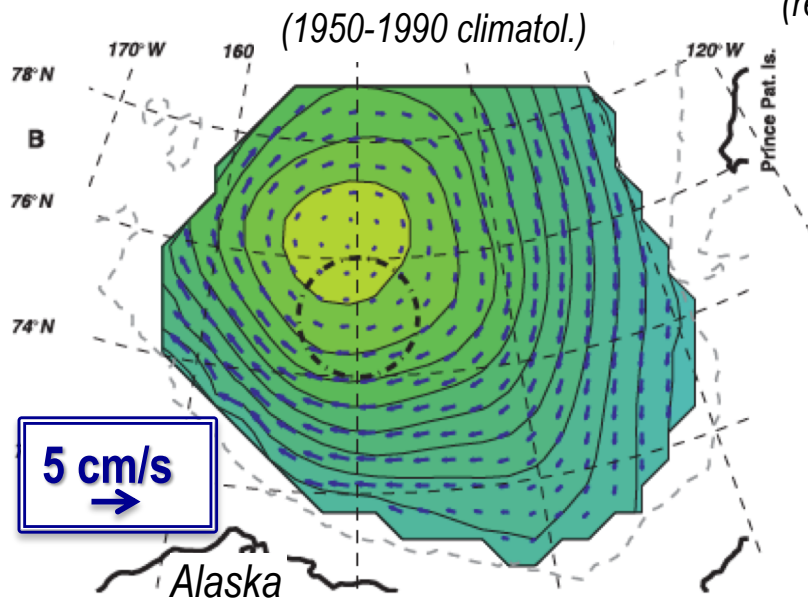
Geostrophic current (*in situ obs*)
(2008-2011)

ugh



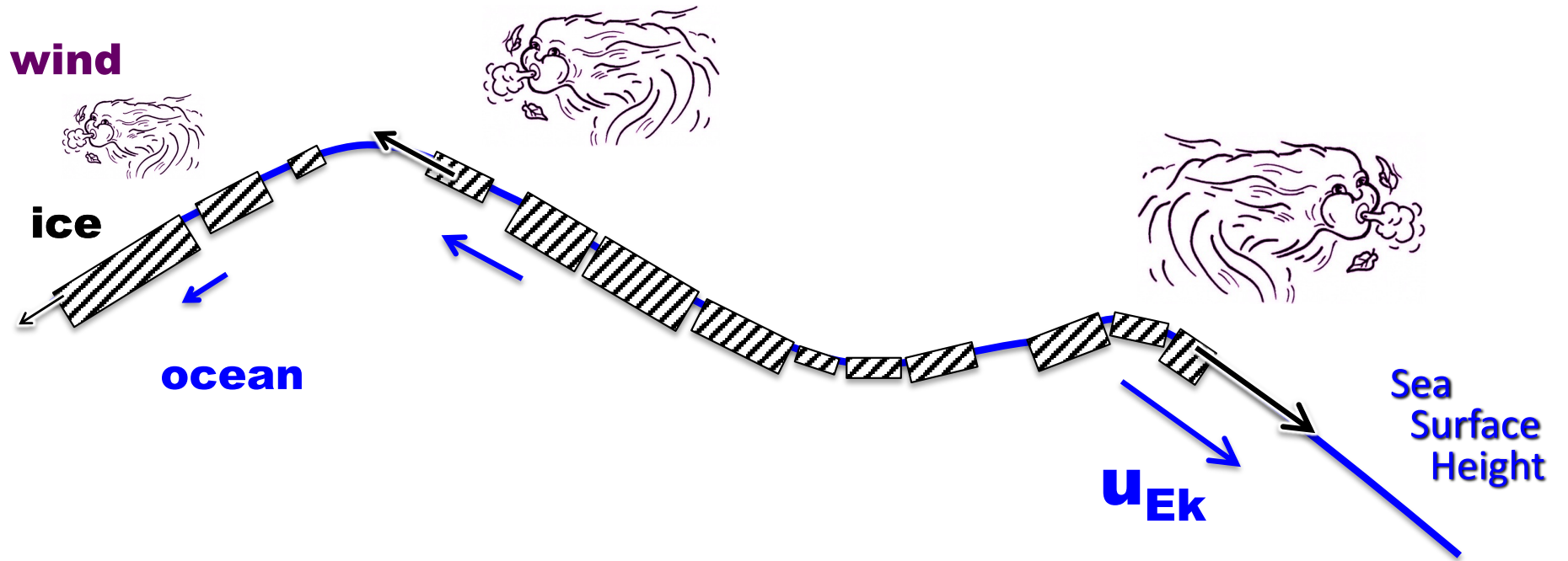
Beaufort Gyre: **Yup!**

(Elsewhere: ??!)



McPhee (GRL, 2012)

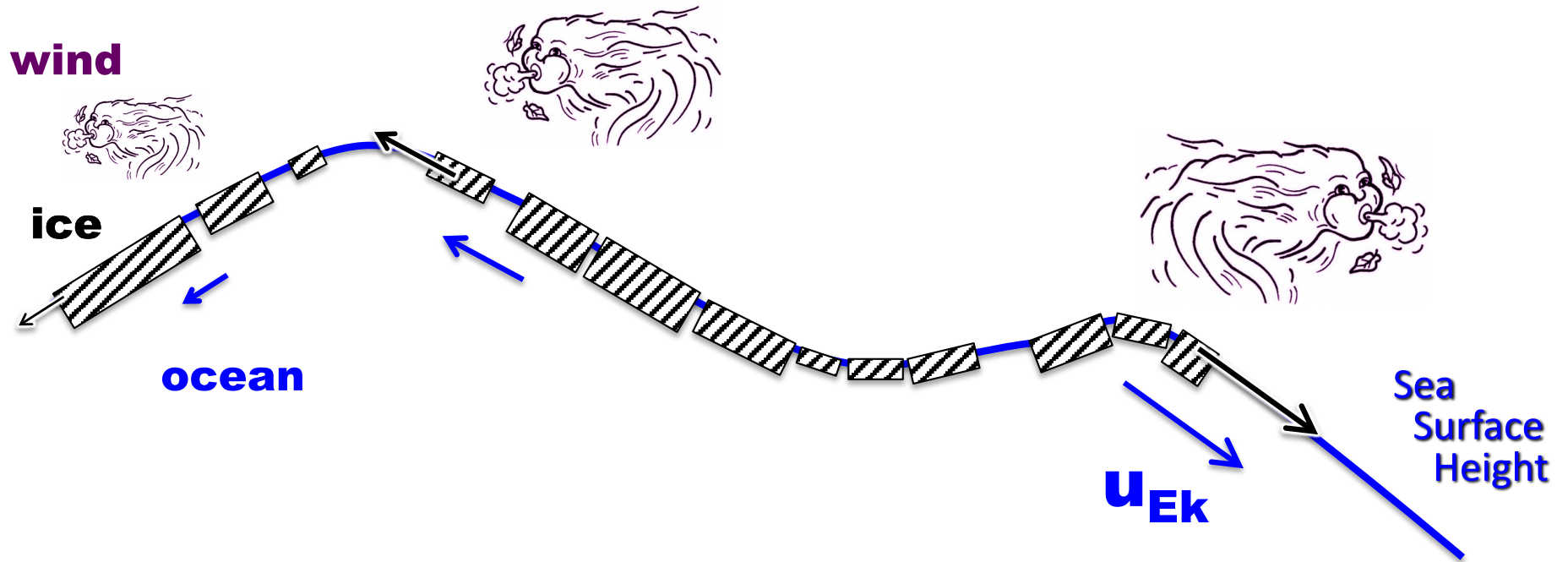
Surface currents ($u_{geo} + u_{Ek}$)



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

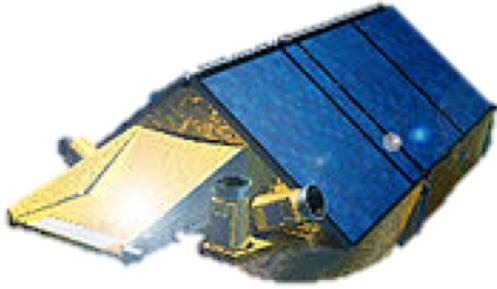
difficult

easy-ish

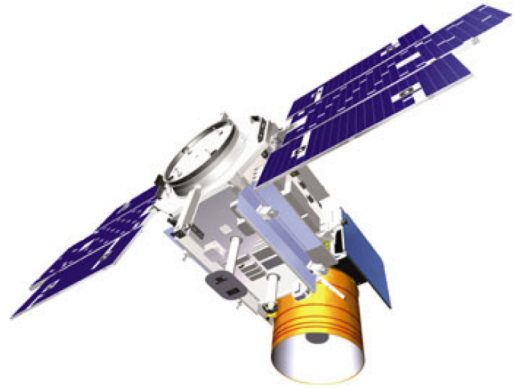


u_{geo} often ignored

u_{geo} from space!



Radar

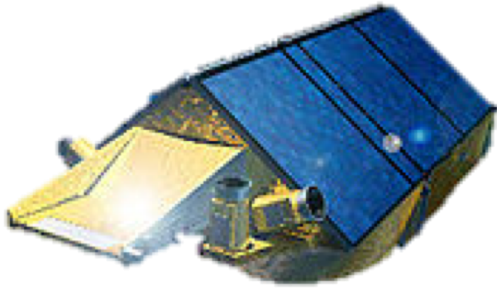


Laser

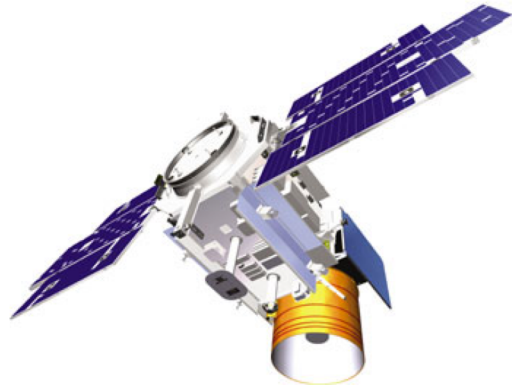
Satellite altimeters →
ocean surface height →

u_{geo}

u_{geo} from space!



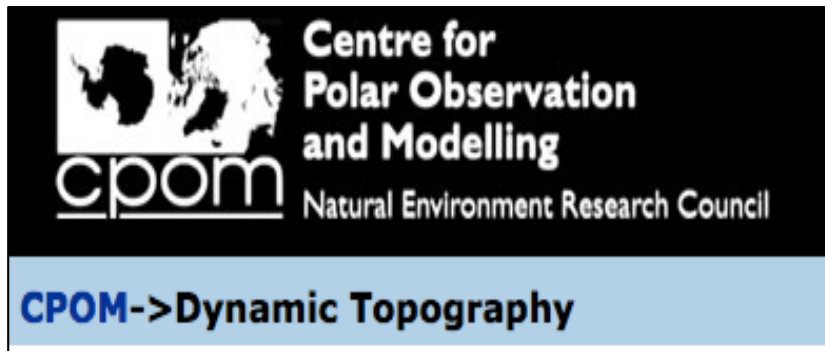
Radar



Laser

Satellite altimeters →
ocean surface height →

u_{geo}



Public data download (2003-2014)

Monthly, 100 km resolution

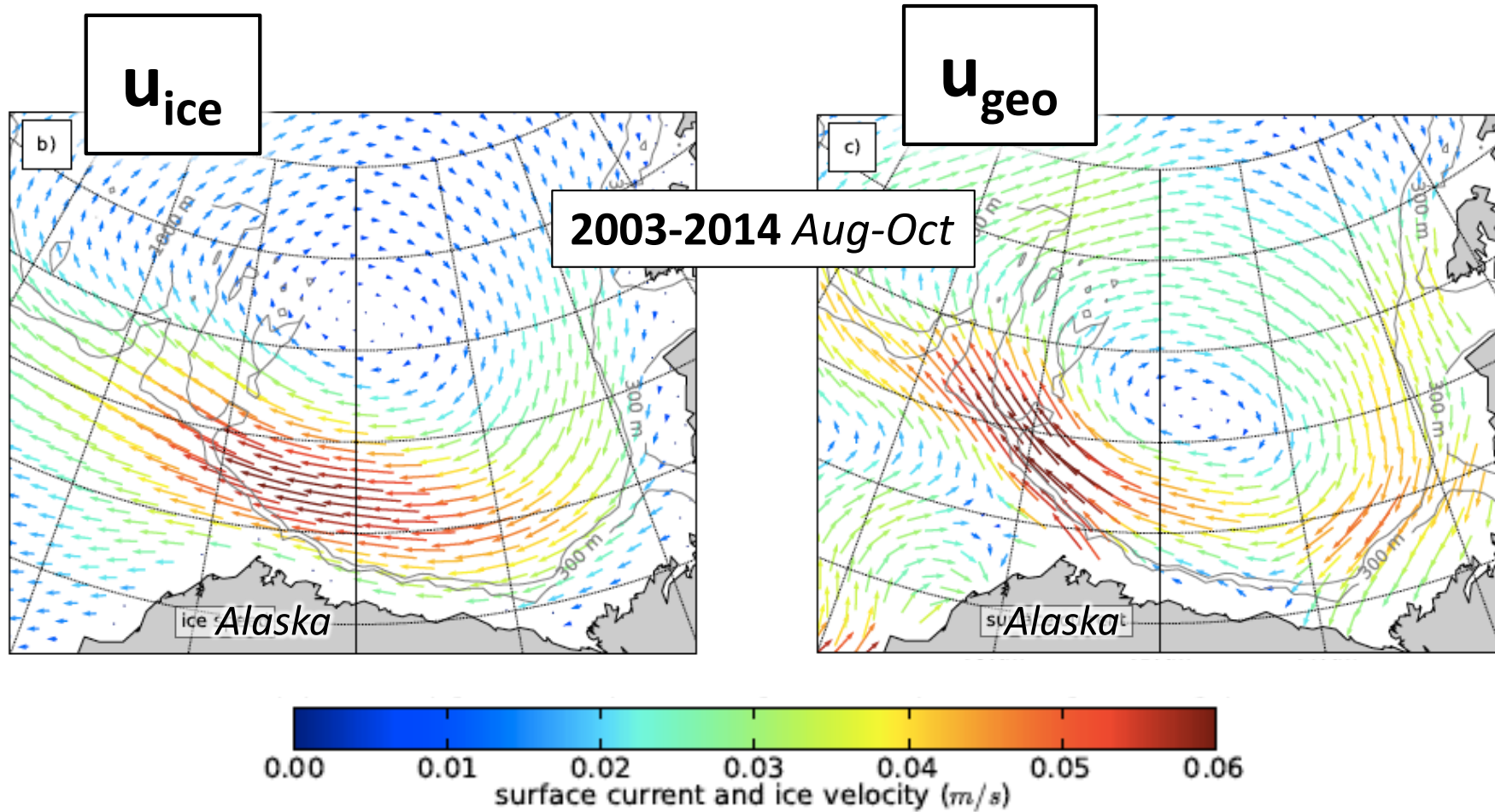
A revolution in
Arctic physical oceanography

...but endangered



Tom Armitage

Geostrophic circulation

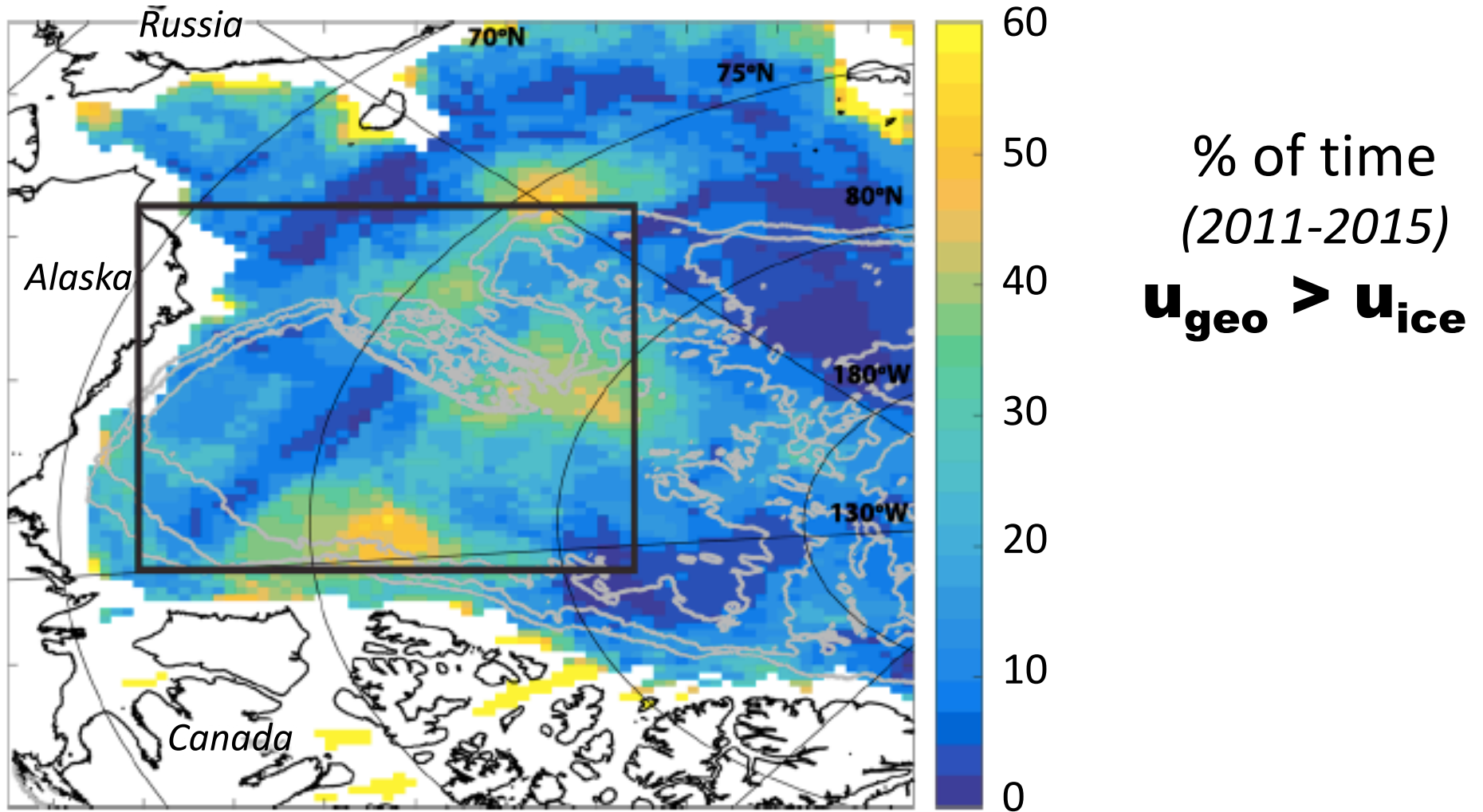


$$u_{geo} \approx u_{ice}$$

Meneghello et al. (JPO, 2018)

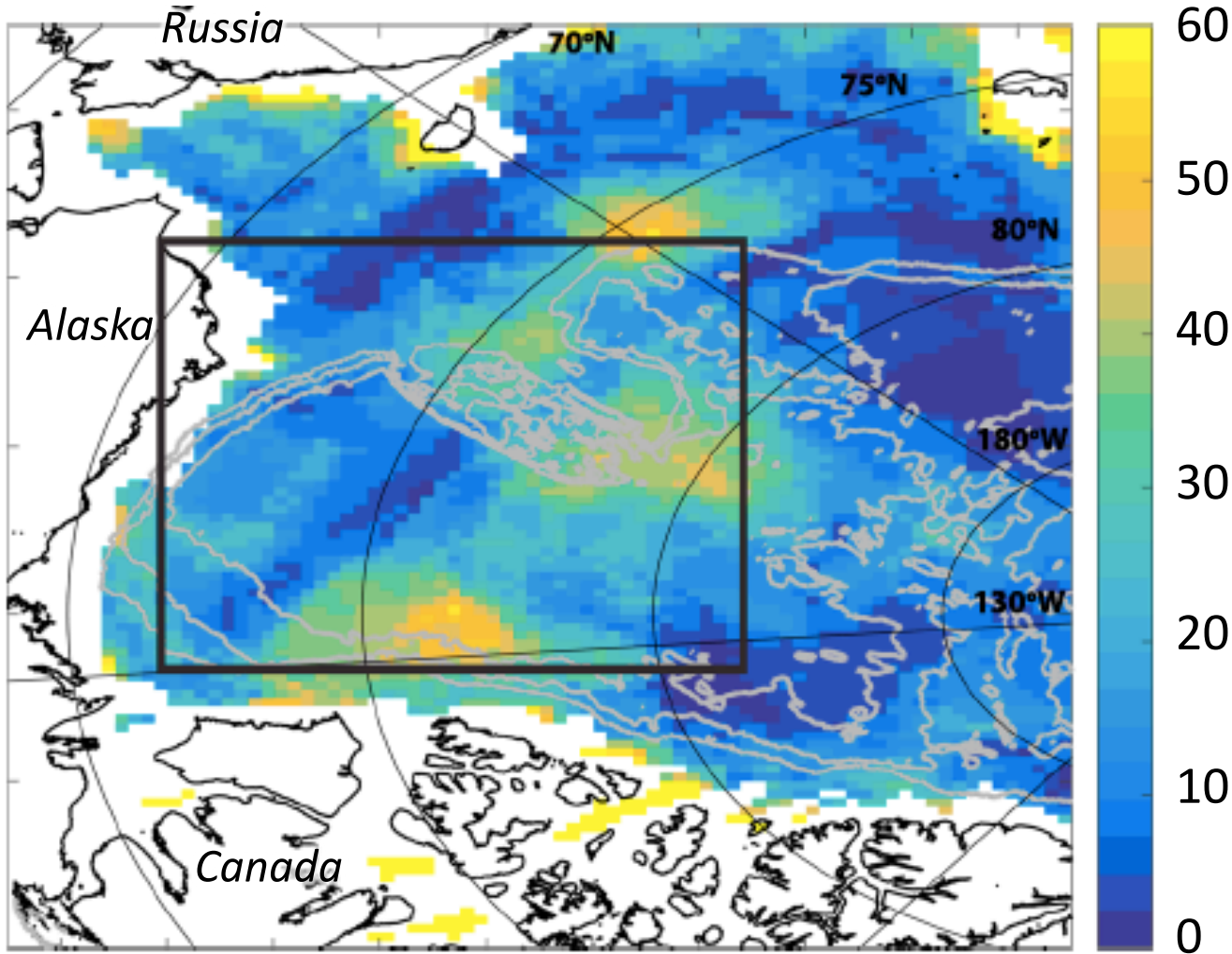
(also Armitage et al., The Cryosph., 2017)

Geostrophic circulation



Dewey et al. (GRL, 2018)

Geostrophic circulation



% of time
(2011-2015)
 $u_{geo} > u_{ice}$

**The ocean is
driving the ice!!**

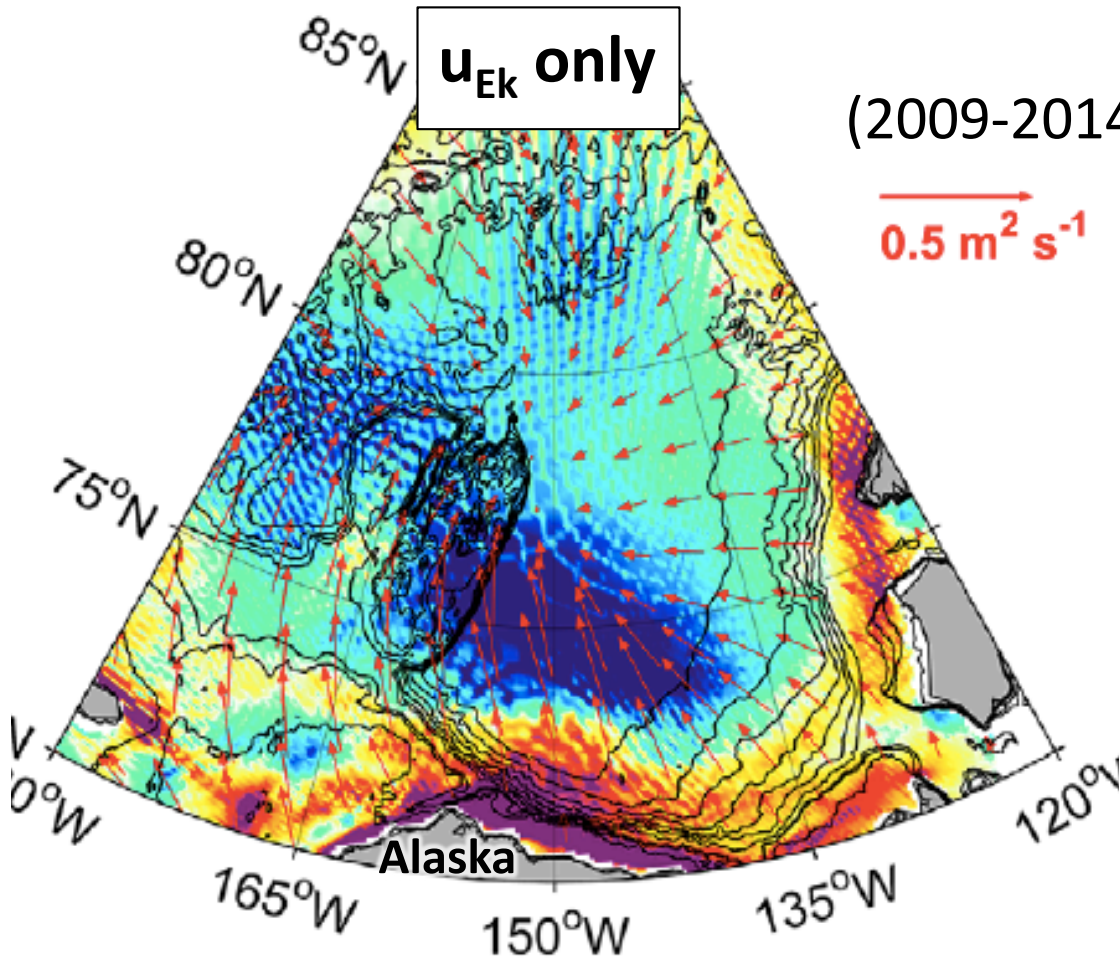
Dewey et al. (GRL, 2018)



Surface currents

$$\int_{20m} u dz$$

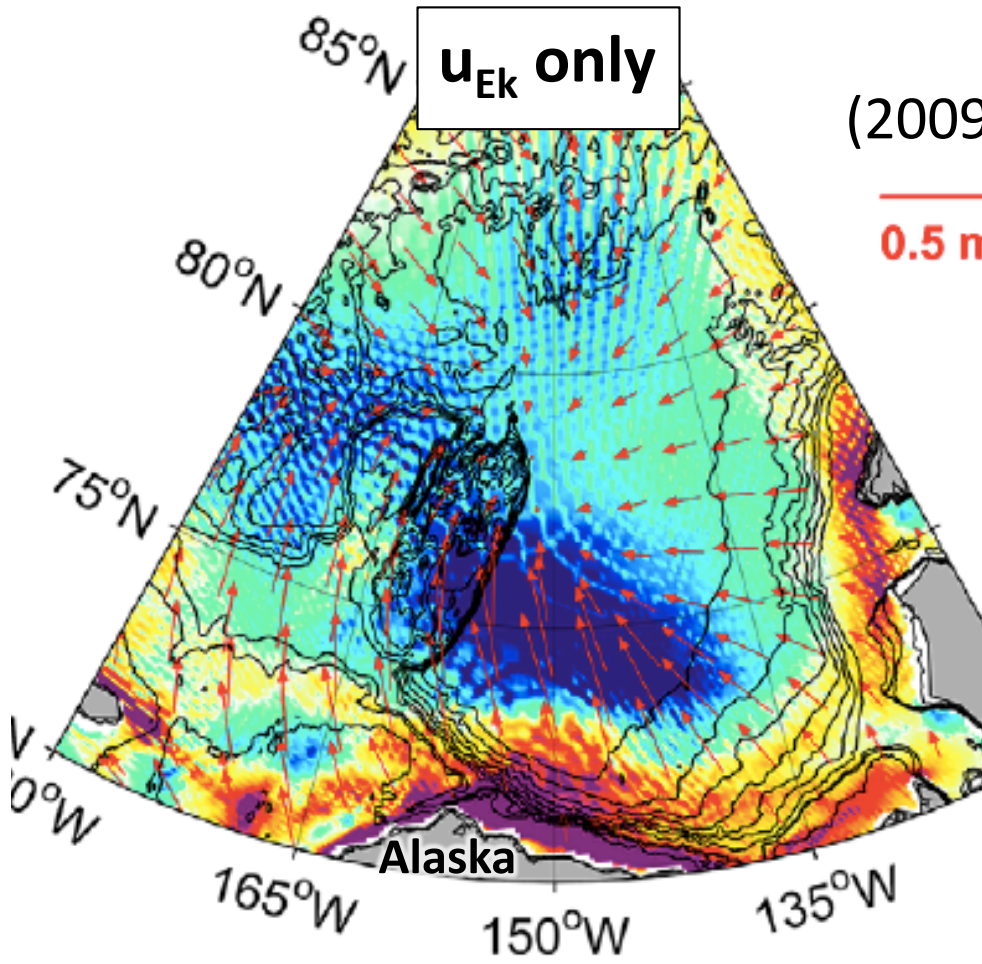
Zhong et al. (JGR, 2017)



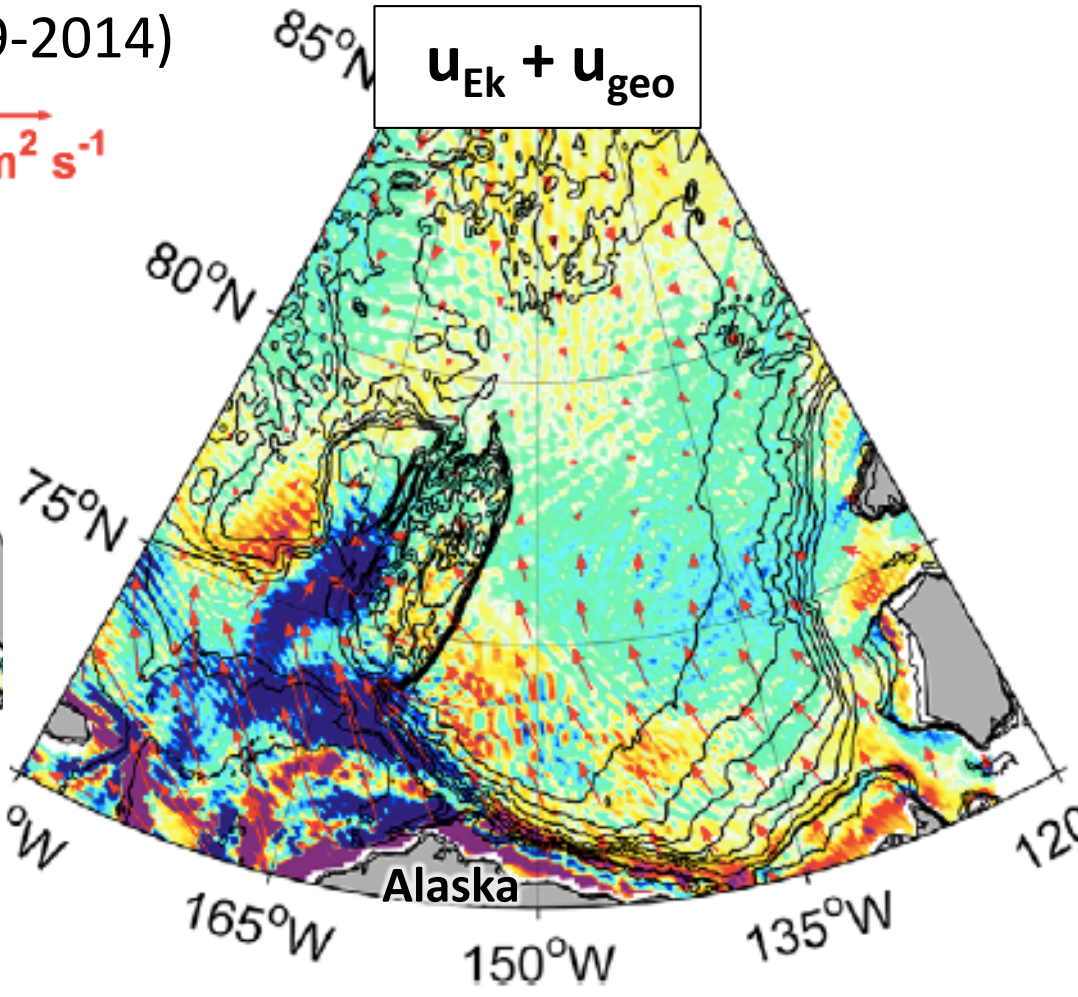
**Strong convergence
all around**

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

Zhong et al. (JGR, 2017)



**Strong convergence
all around**



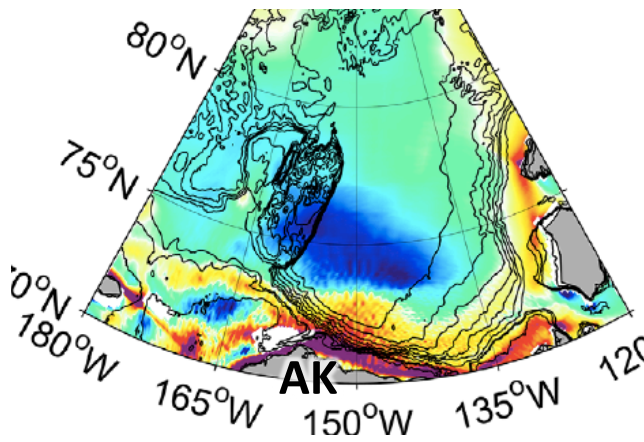
So different!

Ekman pumping

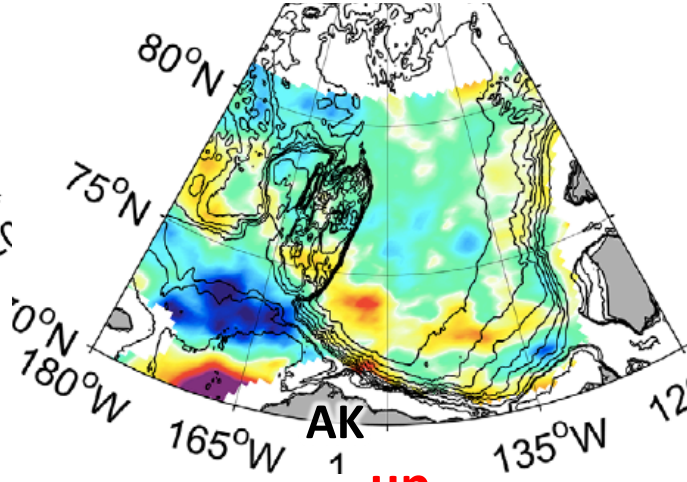
$$W_{Ek}$$

Zhong et al. (JGR, 2017)

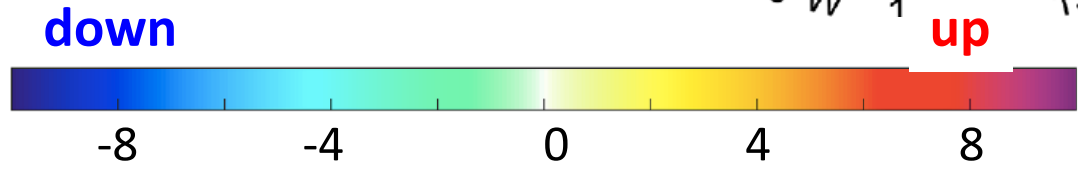
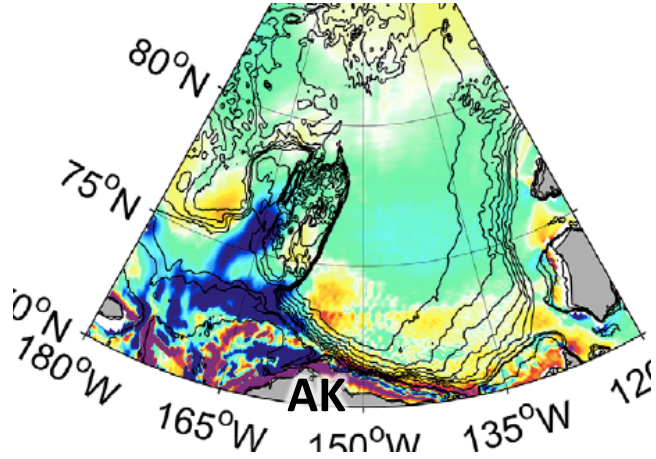
u_{Ek} only



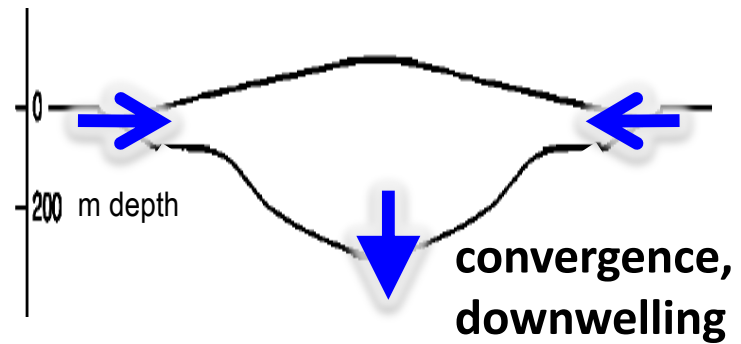
$u_{Ek} + u_{geo}$
(sat. obs)



$u_{Ek} + u_{geo}$
(PIOMAS model)



W_{ek} ($cm\ day^{-1}$)



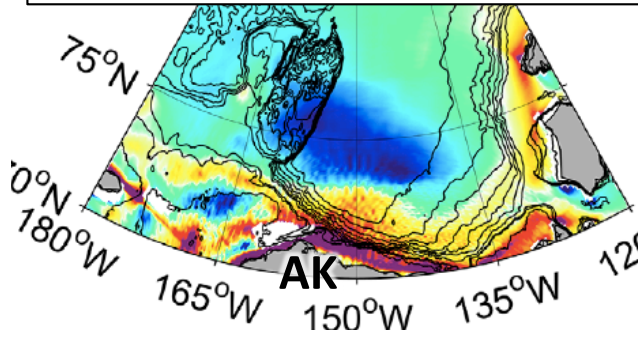
Ekman pumping

$$W_{Ek}$$

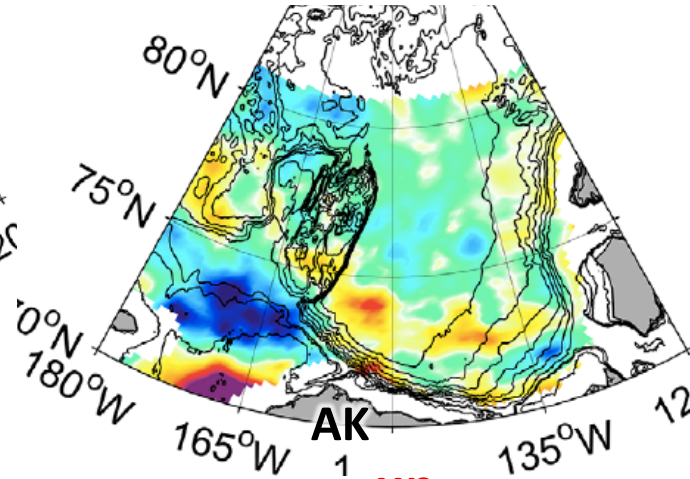
Zhong et al. (JGR, 2017)

u_{Ek} only

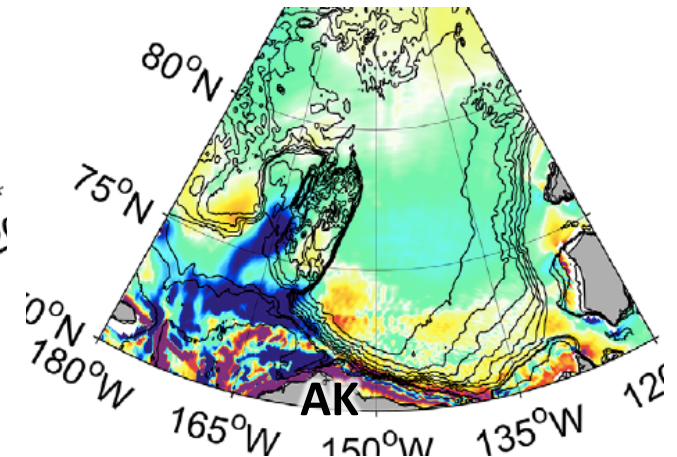
BGyre downwelling overestimated!



$u_{Ek} + u_{geo}$
(sat. obs)



$u_{Ek} + u_{geo}$
(PIOMAS model)



down

up

-8 -4 0 4 8

W_{ek} ($cm\ day^{-1}$)

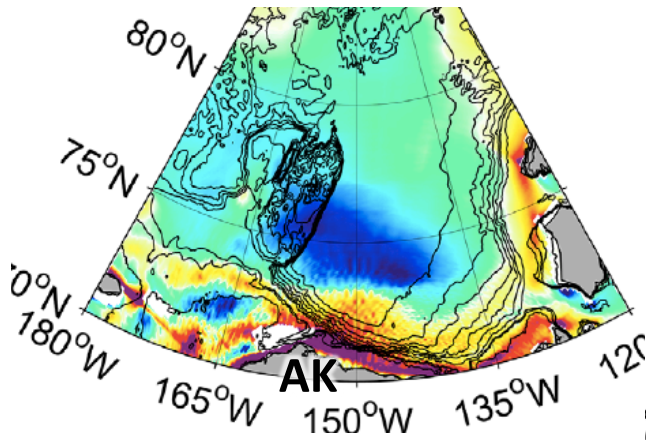
- Storage of freshwater in the Gyre
- Nutrient sink for productivity
- Etc.

Ekman pumping

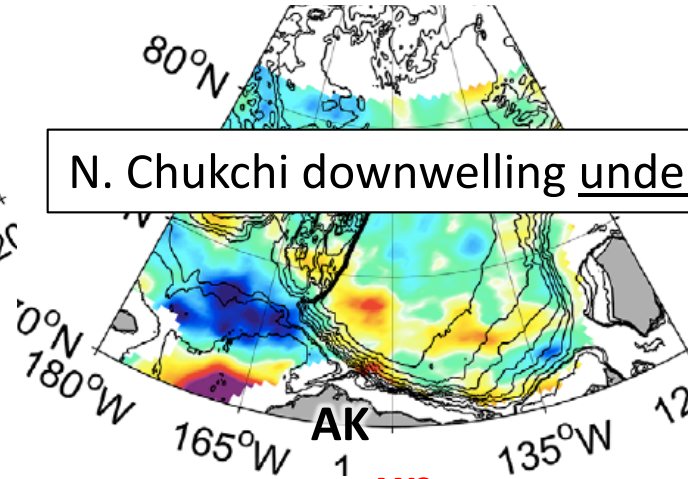
$$W_{Ek}$$

Zhong et al. (JGR, 2017)

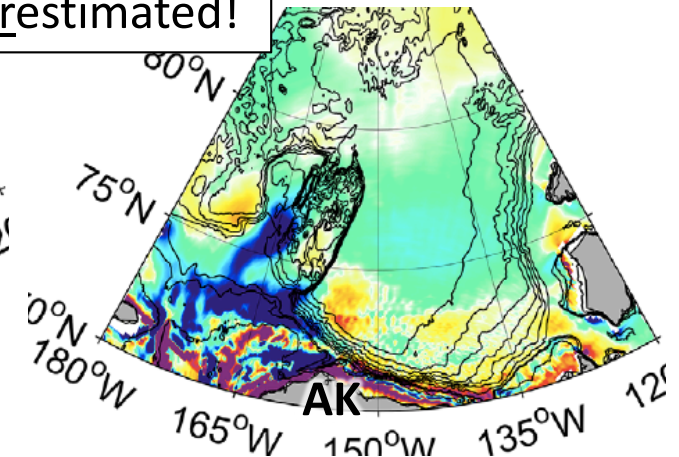
u_{Ek} only



$u_{Ek} + u_{geo}$
(sat. obs)



$u_{Ek} + u_{geo}$
(PIOMAS model)



down

up

-8 -4 0 4 8

W_{ek} ($cm\ day^{-1}$)

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

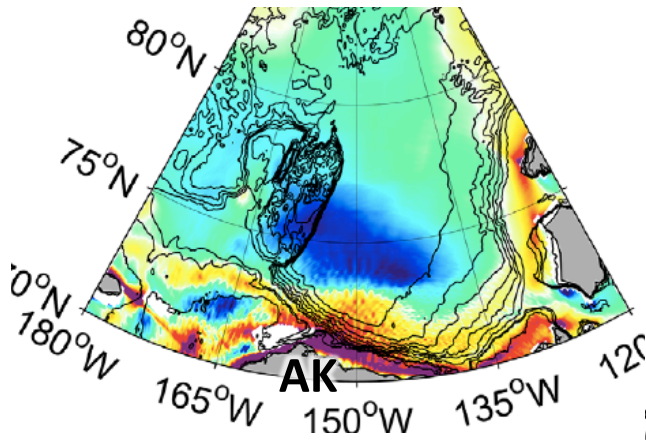
e.g., Timmermans et al. (2017)

Ekman pumping

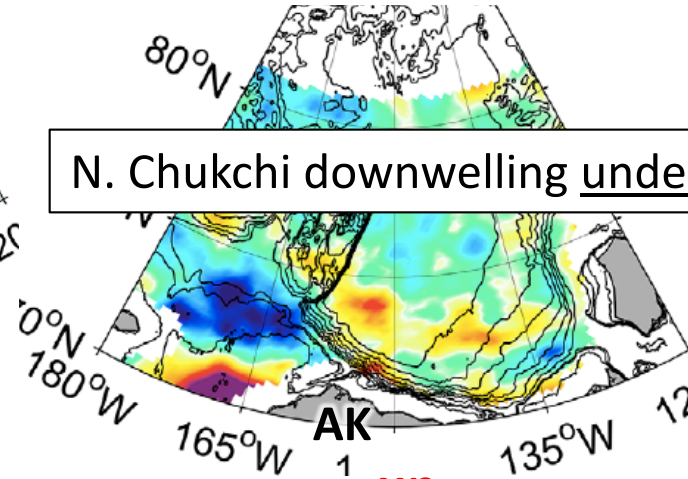
W_{Ek}

Zhong et al. (JGR, 2017)

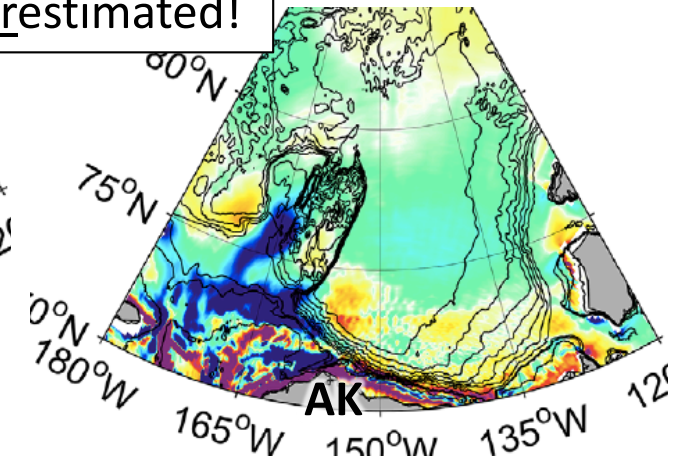
u_{Ek} only



$u_{Ek} + u_{geo}$
(sat. obs)



$u_{Ek} + u_{geo}$
(PIOMAS model)



down

up

-8 -4 0 4 8

W_{ek} ($cm\ day^{-1}$)

- **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:

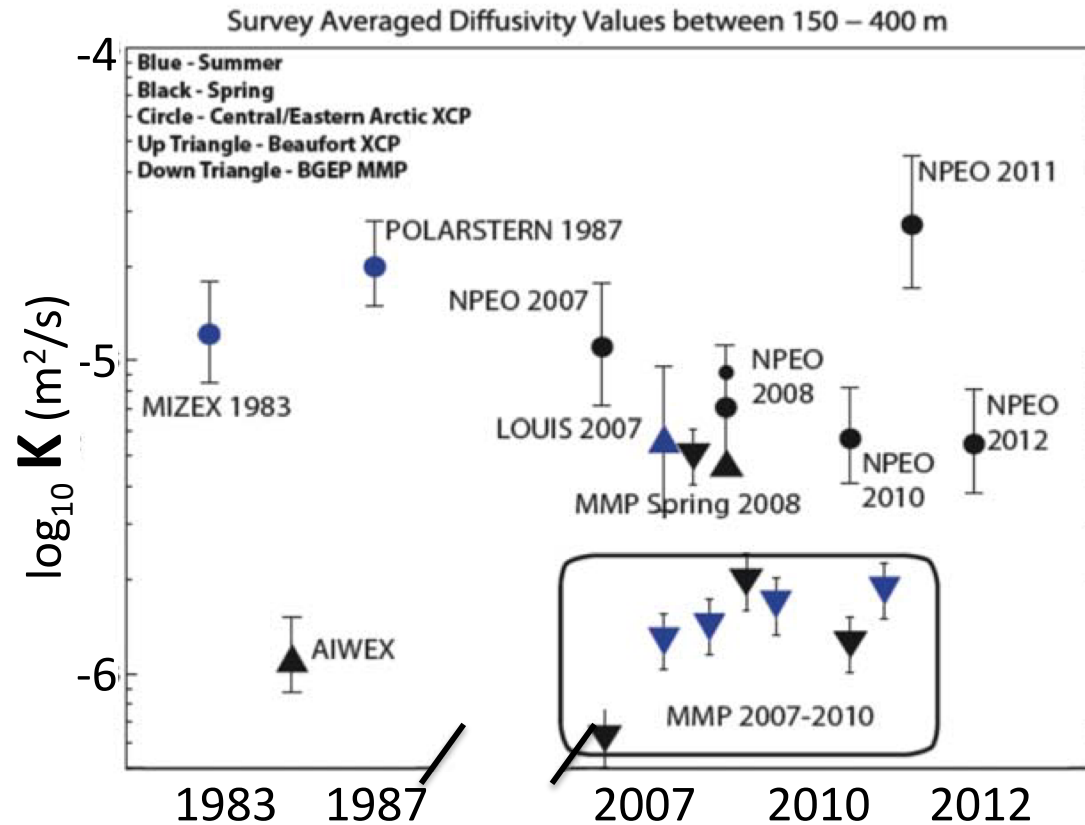
- Will a *freshening Arctic* affect the global circulation?

Ocean circulation:

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

Thank You

Also... is there more ocean mixing?

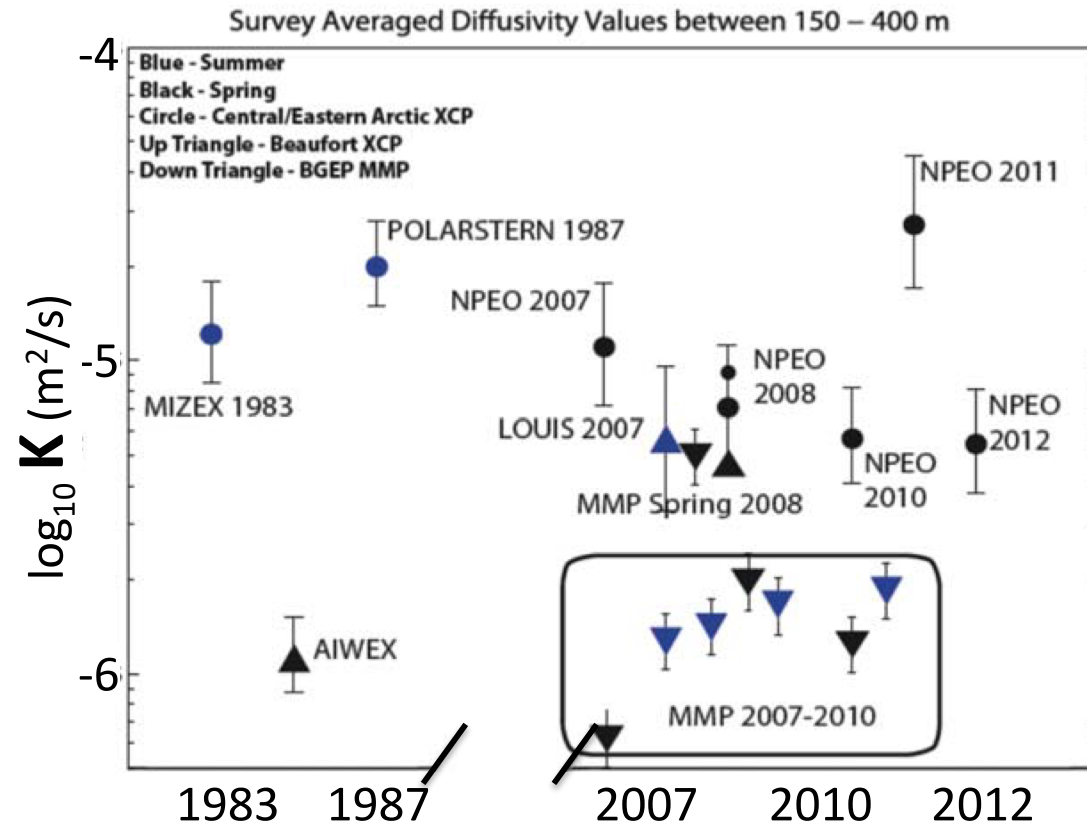


Guthrie et al. (JGR, 2013)

Amerasian Basin: **Nope!**

- incr surface stress but also incr stratification!

Also... is there more ocean mixing?



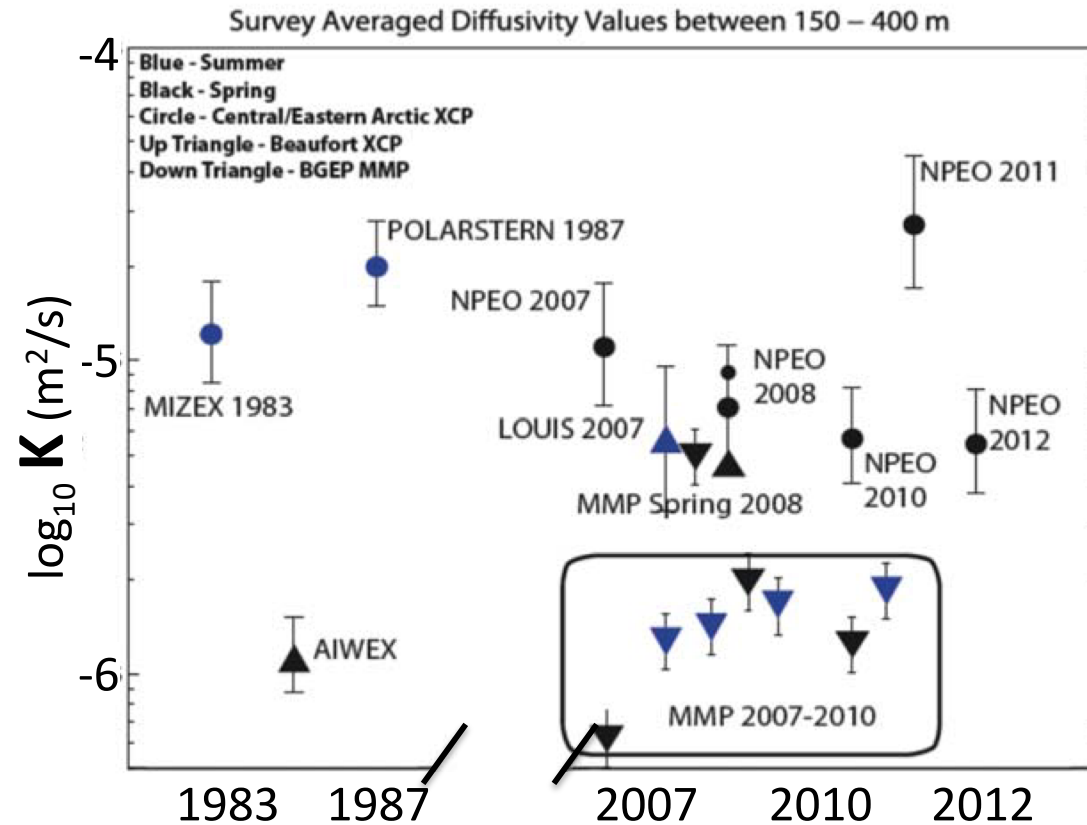
Guthrie et al. (JGR, 2013)

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**?



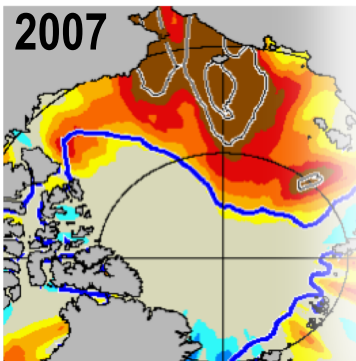
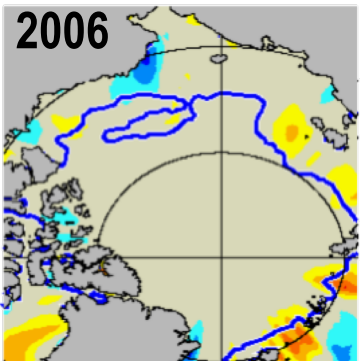
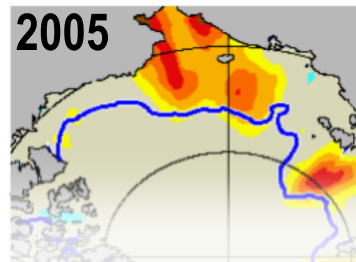
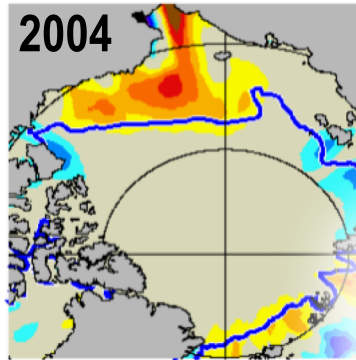
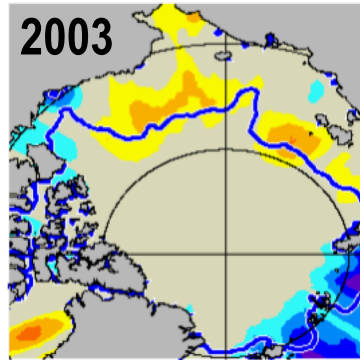
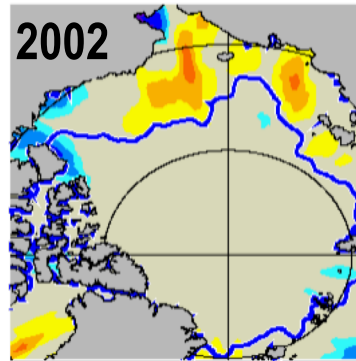
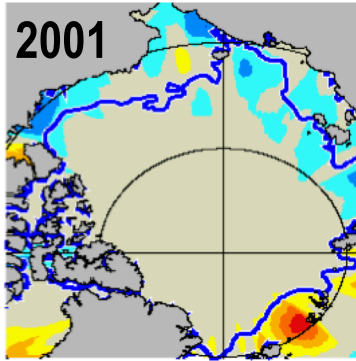
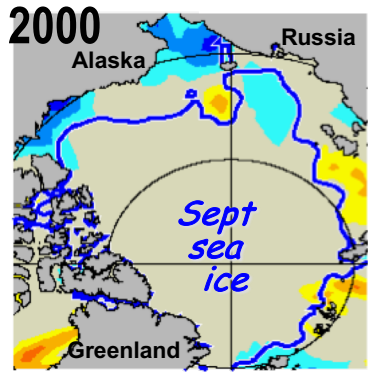
Guthrie et al. (JGR, 2013)

Amerasian Basin: **Nope!**

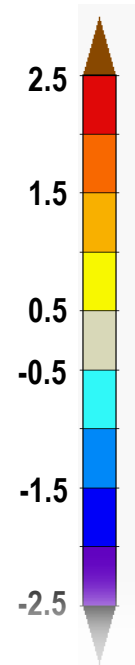
- incr surface stress but also incr **stratification!**

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

Ice Retreat → Ocean Warming



Steele et al. (2008)



Anomaly of Summer \equiv JAS
Sea **S**urface **T**emperature ($^{\circ}$ C)
(relative to 1982-2007 mean)

- So what?
- ecosystems
 - air-sea fluxes
 - sub-surface T_{\max} layers (*the "NSTM"*)
 - ice-albedo feedback