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

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Sea ice is declining!

Extent (Mkm$^2$)

Arctic sea ice extent (Sept)

NSIDC

1980 1990 2000 2010
Sea ice is declining!

What about $T$, $S$, $V$?

Arctic sea ice extent (Sept)

Temperature, Salinity, Velocity

Physical Oceanographer
Ice Retreat ➔ Ocean Warming

2000
Alaska
Russia
Greenland

2001

2002

2003

2004

2005

2006

2007

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)
More recently

Steele & Dickinson (2016)

~ 3 times warmer!

Why?

SST: dOISST (AVHRR only)
Ice edge: 15% concentration (NASA Team1)
More recently

Steele & Dickinson (2016)

Ice retreat ➔ warm SST if it’s in Aug!

SST: dOISST (AVHRR only)

Ice edge: 15% concentration (NASA Team1)
"Ice edge loitering"
Steele & Ermold (JGR, 2015)

Explaination?

Off-ice winds + warm SSTs

Daily ice edge
2012
Mar 13 – Sep 23

Ice Retreat 🡪 Ocean Warming
The **UpTempO** buoy

**Upper Temperature of the polar Oceans**

- **Surface**: SLP, SST, GPS, Iridium  ...[anemometer]
- **Cable**: 12-16 x T (± 0.1°C), 3 x P (± 1 dbar)  ...[S]
- 60 m (basin) or 25 m (shelves)

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**Euphotic Zone**

- **60 m**
  - **thermistors**: ± 0.1°C
    - 2.5, 5, 7.5, 10, 15, 20, 25, 30, 35, 40, 50, 60 m depth
  - **pressure**: ± 1 dbar
    - 20, 40 m, 60 m depth

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Google “uptempo arctic”
The **UpTempO** buoy

**Upper Temperature of the polar Oceans**

- **Surface:** SLP, SST, GPS, Iridium  …[anemometer]
- **Cable:** 12-16 x T (± 0.1° C), 3 x P (± 1 dbar)  …[S]
- **60 m (basin) or 25 m (shelves)**
- **Deploy:** in ice or water by ship, ice camp, air

**Euphotic Zone**

- **thermistors:** ± 0.1° C
  - 2.5, 5, 7.5, 10, 15, 20, 25, 30, 35, 40, 50, 60 m depth
- **pressure:** ± 1 dbar
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**60 m (basin) or 25 m (shelves)**

Google “uptempo arctic”

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**March, 2011**

**August, 2011**
The **UpTempO** buoy

Upper Temperature of the polar Oceans

Aug 13, 2012

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

Castro et al. (Rem. Sens. Environ., 2016)
What about salinity?
Trend in upper ocean "freshwater" = \(\int_{2005}^{2008} Sdz\) 
\(~250 \text{ m}\)

- Strong regional trends

Beaufort Gyre freshening

(ice melt, PacWater, rivers)

...from satellite observations!
Trend in upper ocean "freshwater" = ∫Sdz
(2005 ➔ 2008)

- Strong regional trends

Beaufort Gyre freshening
(ice melt, PacWater, rivers)

"Ice is melting into the ocean."
... only part of the story...

Krishfield et al. (JGR, 2014)
Trend in upper ocean "freshwater" = $\int Sdz$

(2005 $\rightarrow$ 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" = \( \int Sdz \)
(2005 \( \rightarrow \) 2008)

\(~250\) m

• 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" = \( \int Sdz \) 
(2005\( \Rightarrow \)2008) 
~250 m

• 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_{2005}^{2008} Sdz ~250 m

- 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"** = \( \int Sdz \)

(2005 ➔ 2008)

\( \sim 250 \text{ m} \)

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- **FRESHENING**
- **SALINIFYING**

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

- [Image of P-E balance and rivers]

- *long-term...*

(2) **Sea ice melt:**

- [Image of sea ice]

- *transient...*
What about Kinetic Energy?
wind & ice motion trends

Spreen et al. (GRL, 2011)

Surface wind

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

Sea ice motion

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

More KE -> ocean?
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PIOMAS: incr stress

...faster ice

Martin et al. (JGR, 2014)
More KE -> ocean?

PIOMAS: \textit{incr} stress

CICE: \textit{decr} stress

Martin et al. (JPO, 2016)

...faster ice,
but \textit{thinner} & \textit{smoother}
More KE -> ocean?

**PIOMAS:** incr stress

**CICE:** decre stress

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: ??!)

McPhee (GRL, 2012)
So... is the ocean moving faster?

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

Beaufort Gyre: **Yup!**

Dynamic height (rel. to 400 m)

(Elsewhere: ??!)

McPhee (GRL, 2012)
Surface currents ($u_{geo} + u_{Ek}$)
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Surface currents \( (u_{geo} + u_{Ek}) \)

\( u_{geo} \) often ignored

\( u_{Ek} \)

difficult

easy-ish
$u_{geo}$ from space!

Satellite altimeters $\rightarrow$ ocean surface height $\rightarrow$ $u_{geo}$
**u_{geo} from space!**

Satellite altimeters ➔ 
\[ \text{ocean surface height} \] ➔ \[ u_{geo} \]

Radar

Laser

A revolution in Arctic physical oceanography

Public data download (2003-2014)

Monthly, 100 km resolution

...but endangered
Geostrophic circulation

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

Meneghello et al. (JPO, 2018)
(also Armitage et al., The Cryosph., 2017)
Geostrophic circulation

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

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)

$u_{Ek}$ only

(2009-2014)

0.5 m$^2$ s$^{-1}$

Strong convergence all around
Surface currents $\int_{20m} u \, dz$

$u_{Ek}$ only

(2009-2014)

$u_{Ek} + u_{geo}$

Strong convergence all around

So different!

Zhong et al. (JGR, 2017)
Ekman pumping $W_{Ek}$

- $u_{Ek}$ only
- $u_{Ek} + u_{geo}$ (sat. obs)
- $u_{Ek} + u_{geo}$ (PIOMAS model)

Zhong et al. (JGR, 2017)

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

Down: $-8$ to $-4$
Up: $4$ to $8$

Convergence, downwelling

Northwest Pacific Ocean
Ekman pumping

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

BGyre downwelling overestimated!

Zhong et al. (JGR, 2017)

\[ W_{Ek} \]

\[ u_{Ek} \text{ only} \]

\[ u_{Ek} + u_{geo} \text{ (sat. obs)} \]

\[ u_{Ek} + u_{geo} \text{ (PIOMAS model)} \]
- Chukchi downwelling > central BGyre downwelling!
- Injection of Pacific waters into the Arctic Ocean

e.g., Timmermans et al. (2017)
- Chukchi downwelling > central BGYre 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 atmosphere?

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 atmosphere?

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?

Amerasian Basin: **Nope!**

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

Guthrie et al. (JGR, 2013)
Also... is there more ocean mixing?

Amerasian Basin: **Nope!**

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A new genre of Arctic ocean mixing study: “Guthrie, but…”
Also... is there more ocean mixing?

Amerasian Basin: **Nope!**
- incr surface stress but also incr **stratification!**

Eurasian Basin: **Yup (maybe)** Polyakov et al. *(Science, 2017)*
Ice Retreat ➔ Ocean Warming

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

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

**Steele et al. (2008)**