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

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Sea ice is declining!

Arctic sea ice extent (Sept)

Extent (Mkm$^2$)

1980 1990 2000 2010

NSIDC
Sea ice is declining!

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

Arctic sea ice extent (Sept)

- Temperature
- Salinity
- Velocity

NSIDC

Extent (Mkm$^2$)

1980 1990 2000 2010

Physical Oceanographer
Ice Retreat $\rightarrow$ Ocean Warming

Steele et al. (GRL, 2008)

Anomaly of Summer = JAS Sea Surface Temperature ($^\circ$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

~ 3 times warmer!

Why?

Steele & Dickinson (2016)

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

~ 3 times warmer!

Why?

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

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

Daily ice edge 2012
Mar 13 – Sep 23

2012
July 8

SST (°C)

ice conc.
0.2 0.3 0.4 0.5 0.75
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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**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

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

**Upper Temperature of the polar Oceans**

Aug 13, 2012

Buoy: Aug-Oct

Alaska

Sea ice

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

![Flags](https://example.com/flags.png)

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

\textbullet \text{ Strong regional trends}

\textit{Beaufort Gyre freshening}

\text{(ice melt, PacWater, rivers)}

\textit{...from satellite observations!}
Trend in upper ocean "freshwater" = $\int Sdz$
(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 → 2008)
~250 m

• 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" = $\int S_dz$

(2005 → 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" = ∫Sdz
(2005 → 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 Sdz
(2005 \rightarrow 2008)
\sim 250 \text{ m}

- Strong regional trends
  - Beaufort Gyre freshening
    - (ice melt, PacWater, rivers)

- Overall? \textit{hmmm...}
  - \textit{small freshening...}

- \textit{Rabe et al. (GRL, 2014)}
- \textit{Haine et al. (Global \& Plan. Ch., 2015)}
- \textit{Peralta-Ferriz \& Woodgate. (PiO, 2015)}
Trend in upper ocean "freshwater" = $\int S dz$

$\text{(2005} \rightarrow \text{2008)}$

$\sim 250 \text{ m}$

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1. **Incr. Hydrol. Cycle:**
   - $P - E$
   - Rivers
   - Long-term...

2. **Sea ice melt:**
   - Ice
   - Transient...
What about Kinetic Energy?
wind & ice motion trends

Spreen et al. (GRL, 2011)

Surface wind

Sea ice motion


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

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

More KE -> ocean?
More KE -> ocean?

PIOMAS: incr stress

Martin et al. (JGR, 2014)

Ocean surface stress (N/m²)

year
More KE -> ocean?

PIOMAS: incr stress

...faster ice

CICE: decr stress

Martin et al. (JPO, 2016)

...faster ice, but thinner & smoother

???
More KE -> ocean?

PIOMAS: incr stress

CICE: decr 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!**

Dynamic height (rel. to 400 m)

(1950-1990 climatol.)

McPhee (GRL, 2012)

(Elsewhere: ??!)
So... is the ocean moving faster?

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

Beaufort Gyre: **Yup!**

(Elsewhere: ??!)

Dynamic height (rel. to 400 m)

McPhee (GRL, 2012)
Surface currents \((u_{geo} + u_{Ek})\)
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- \(u_{geo}\) often ignored

- wind
- ice
- ocean

- \(u_{Ek}\)

- Sea Surface Height
u_{geo} from space!

Satellite altimeters ➔

ocean surface height ➔

u_{geo}

Radar

Laser
$u_{geo}$ from space!

Satellite altimeters $\rightarrow$ ocean surface height $\rightarrow$ $u_{geo}$

Radar - Laser

A revolution in Arctic physical oceanography

Public data download (2003-2014)
Monthly, 100 km resolution

...but endangered

Tom Armitage
Geostrophic circulation

\[ u_{\text{ice}} \]

\[ u_{\text{geo}} \]

2003-2014 Aug-Oct

\[ u_{\text{geo}} \approx u_{\text{ice}} \]

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 $\int_{20m} udz$

Zhong et al. (JGR, 2017)

$\textbf{u}_{\text{Ek}}$ only (2009-2014)

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

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

Zhong et al. (JGR, 2017)

**$u_{Ek}$ only (2009-2014)**

- **Strong convergence all around**

**$u_{Ek} + u_{geo}$**

- **So different!**

0.5 m² s⁻¹
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

up

convergence, downwelling

200 m depth
Ekman pumping \( W_{Ek} \)

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

BGyre downwelling overestimated!

- Storage of freshwater in the Gyre
- Nutrient sink for productivity
- Etc.
Ekman pumping \( W_{ek} \)

- \( u_{ek} \) only
- \( u_{ek} + u_{geo} \) (sat. obs)
- \( u_{ek} + u_{geo} \) (PIOMAS model)

N. Chukchi downwelling underestimated!

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

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

*e.g., Timmermans et al. (2017)*
Ekman pumping $W_{Ek}$

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

N. Chukchi downwelling underestimated!

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

- 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?

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

Ocean circulation:
- Just *speed* changes, or *direction*, too?

Thank You
Also... is there more ocean mixing?

Survey Averaged Diffusivity Values between 150 – 400 m

Amerasian Basin: **Nope!**

- incr surface stress but also incr **stratification!**
Also... is there more ocean mixing?

\[ \text{Survey Averaged Diffusivity Values between 150 - 400 m} \]

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 $\rightarrow$ Ocean Warming

Steele et al. (2008)

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

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