How is decadal variability in the tropical Pacific linked to sea ice variations in the Arctic and Antarctic?

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Meehl et al, 2016: Antarctic sea ice expansion between 2000-2014 driven by tropical Pacific decadal climate variability. *Nature Geoscience*, DOI: 10.1038/NGEO2751.

Meehl et al., 2018: Tropical decadal variability and the rate of Arctic sea ice retreat, *Geophys. Res. Lett.*, 10.1029/2018GL079989.

Meehl et al., 2019: Recent sudden Antarctic sea ice retreat caused by connections to the tropics and sustained ocean changes around Antarctica, *Nature Comms*., **10**:14, https://doi.org/10.1038/s41467-018-07865-9

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High latitude tidbits:

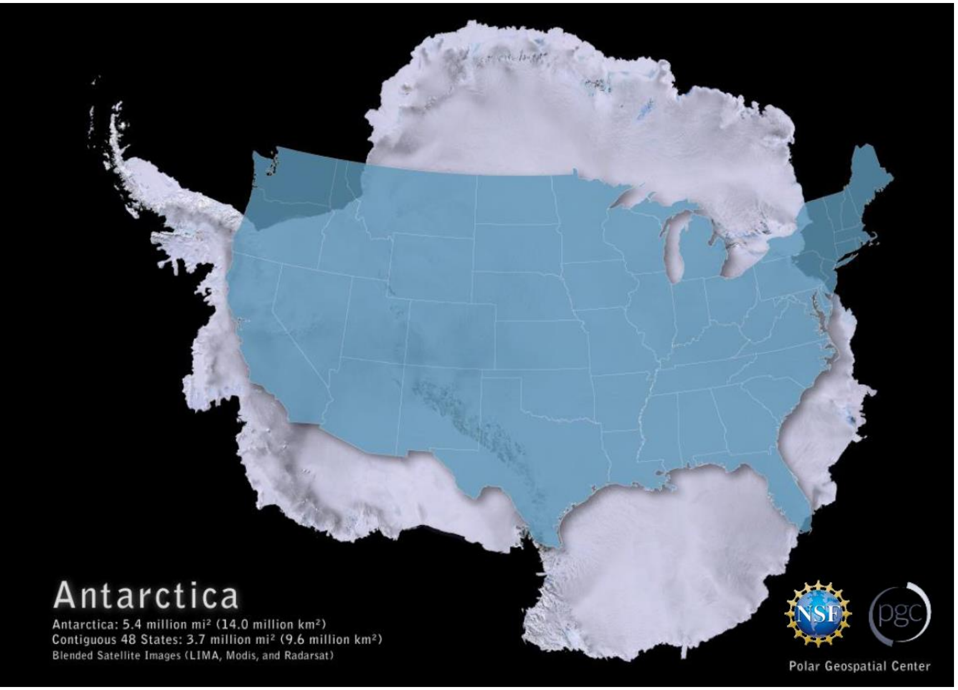
The Arctic is a polar ocean surrounded by land

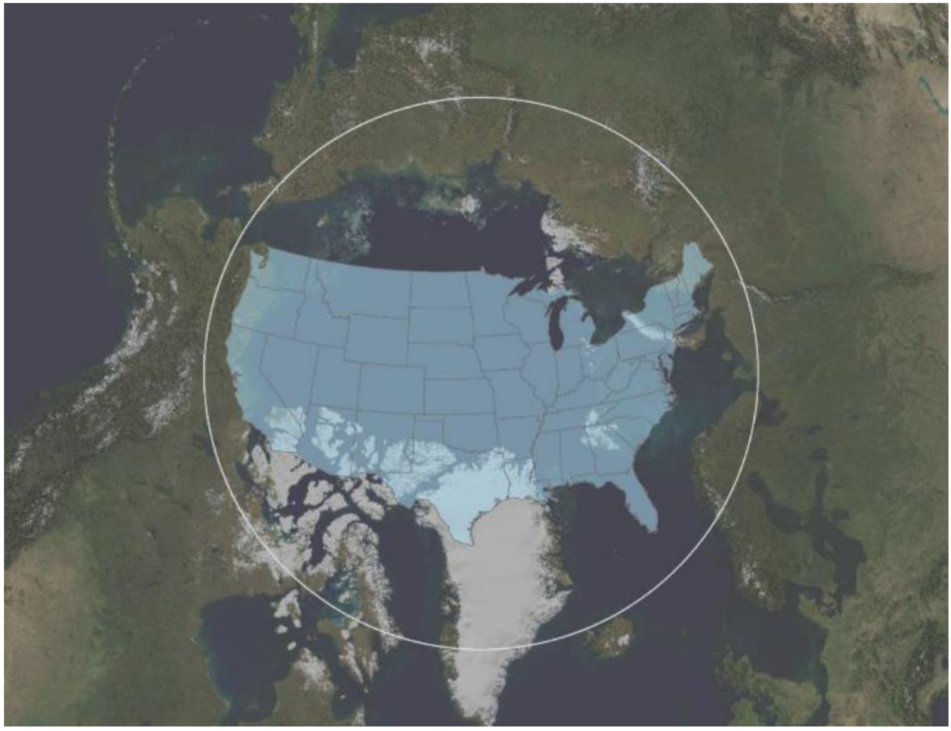
Antarctica is a polar continent surrounded by ocean

In the North Pacific and North Atlantic, the warmest water is near the surface and gets colder with depth

In the Southern Ocean around Antarctica, the coldest water is near the surface and gets warmer with depth

Both the Antarctic continent and the Arctic Ocean are a bit larger than the continental U.S.





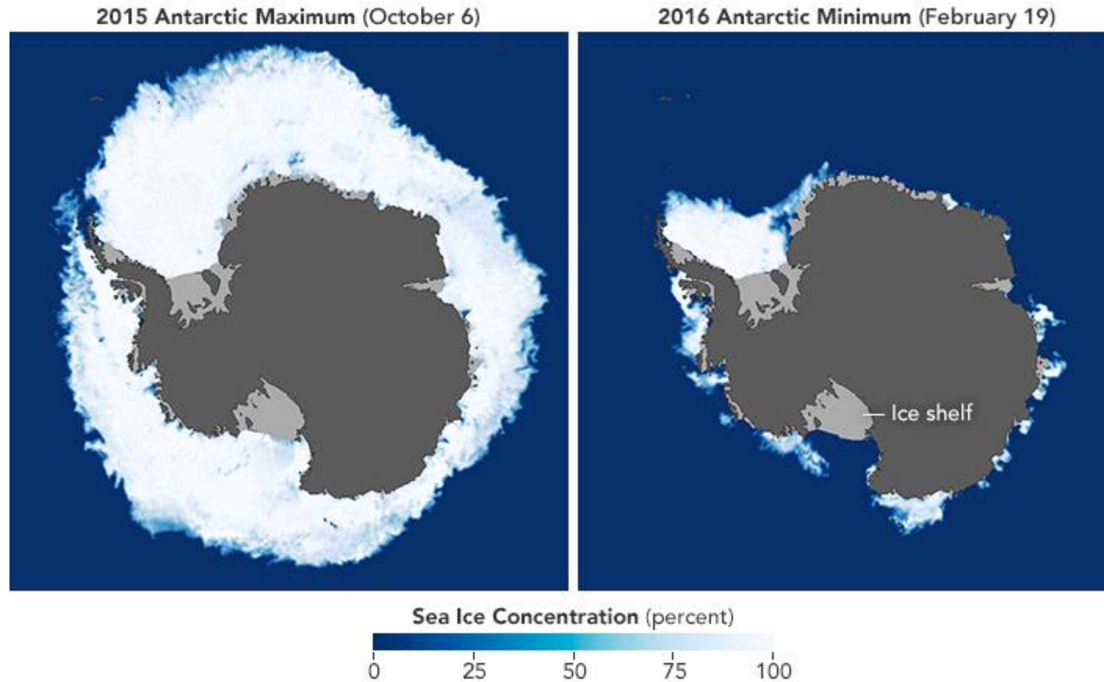
Antarctic and Arctic sea ice undergo large seasonal cycles

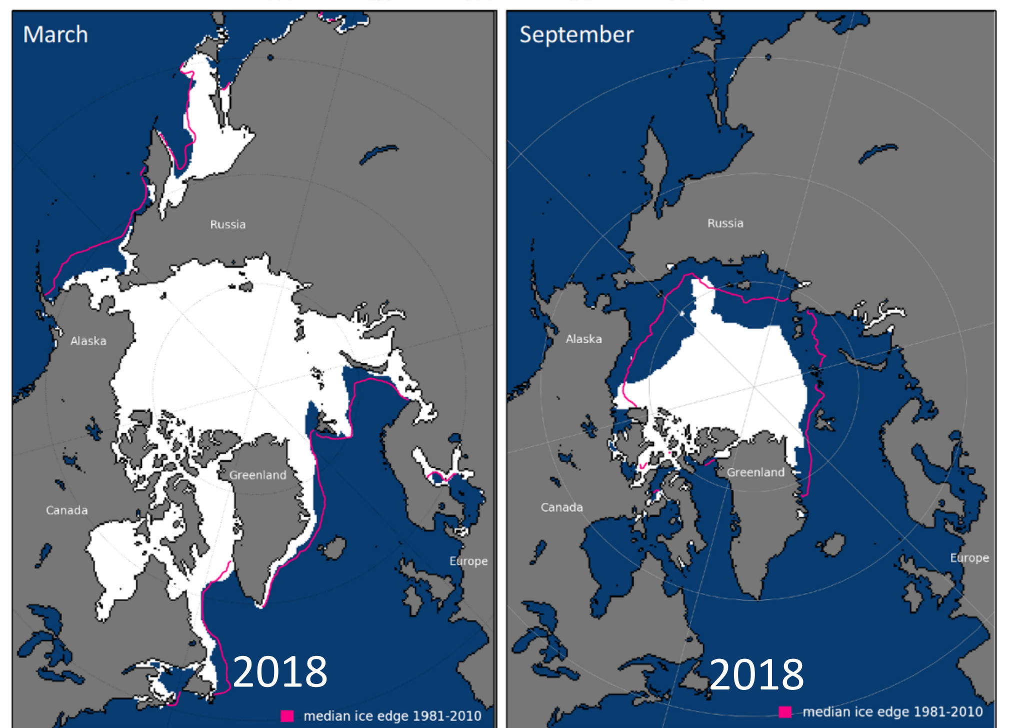
Antarctic: most of sea ice forms equatorward of 70S

Arctic: most of sea ice forms poleward of 70N

Nearly the entire Arctic still freezes over every winter (though the sea ice thickness has been decreasing)

There is interest in when the Arctic would become “ice free” in September, thus routinely opening up the Northwest Passage for commerce





Factors affecting distributions of Arctic and Antarctic sea ice from year to year and decade to decade

Because Antarctic sea ice is not constrained at the northern boundary, surface winds can push the ice either northward or southward and affect the sea ice extent (along with ocean and air temperatures)

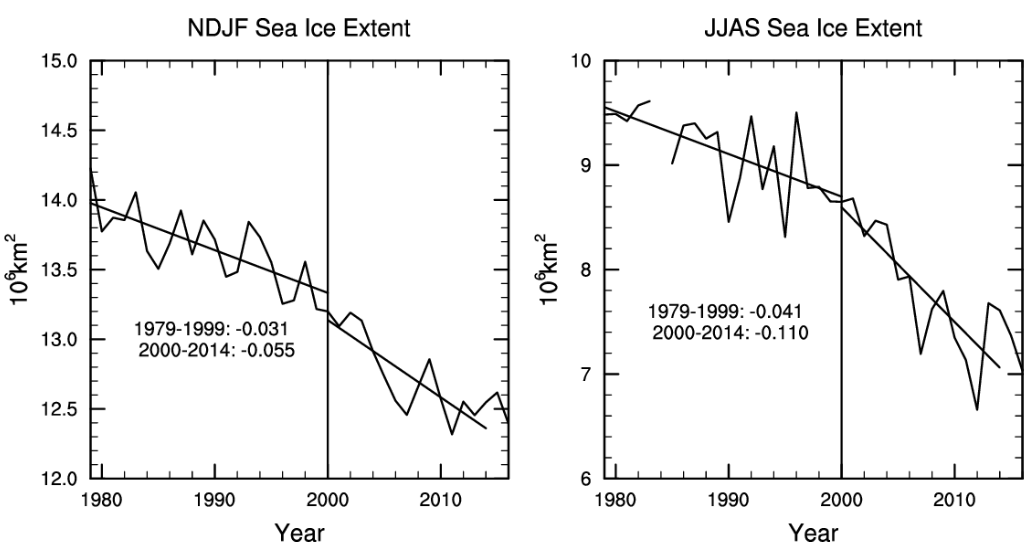
Because Arctic sea ice is constrained by land on all sides, surface winds can push the ice around within the Arctic, but sea ice extent is affected by the strength of the wind in opening leads to influence sea ice thickness and extent (along with ocean and air temperatures)

From 1979 to about 2015, Arctic sea ice extent decreased but Antarctic sea ice extent expanded

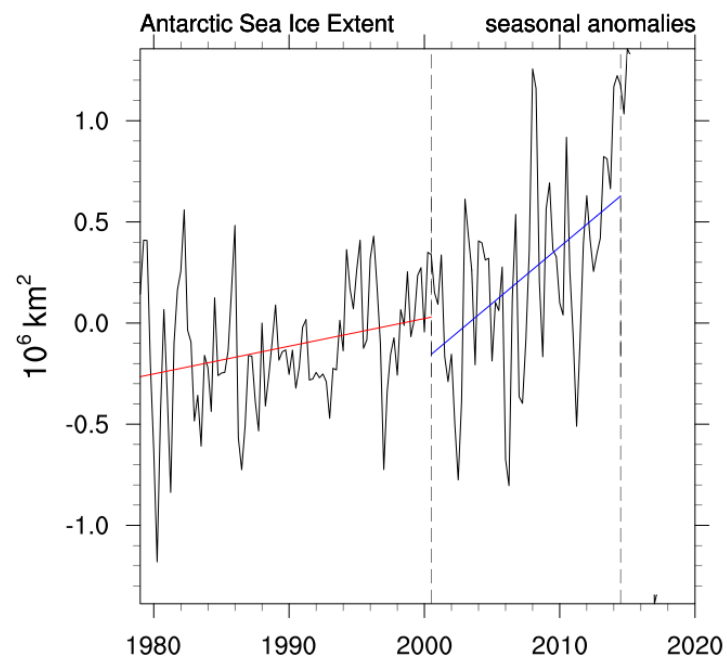
(spoiler alert: things changed in the Antarctic in 2016)

The average of all climate models showed sea ice extent decreasing in the Arctic and Antarctic

Arctic sea ice extent decreased



Antarctic sea ice extent increased



Concepts to explain how the tropics can affect high latitudes:

Teleconnection

(processes in one location can affect atmospheric circulation thousands of miles away)

Convective heating (diabatic heating)

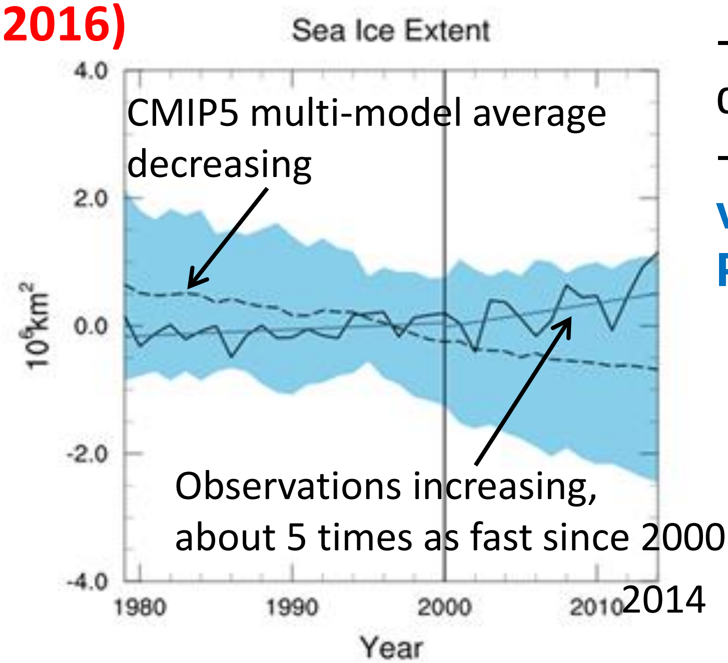
(convective heating anomaly in the tropics, produced by a precipitation anomaly usually associated with a sea surface temperature anomaly)

Rossby wave

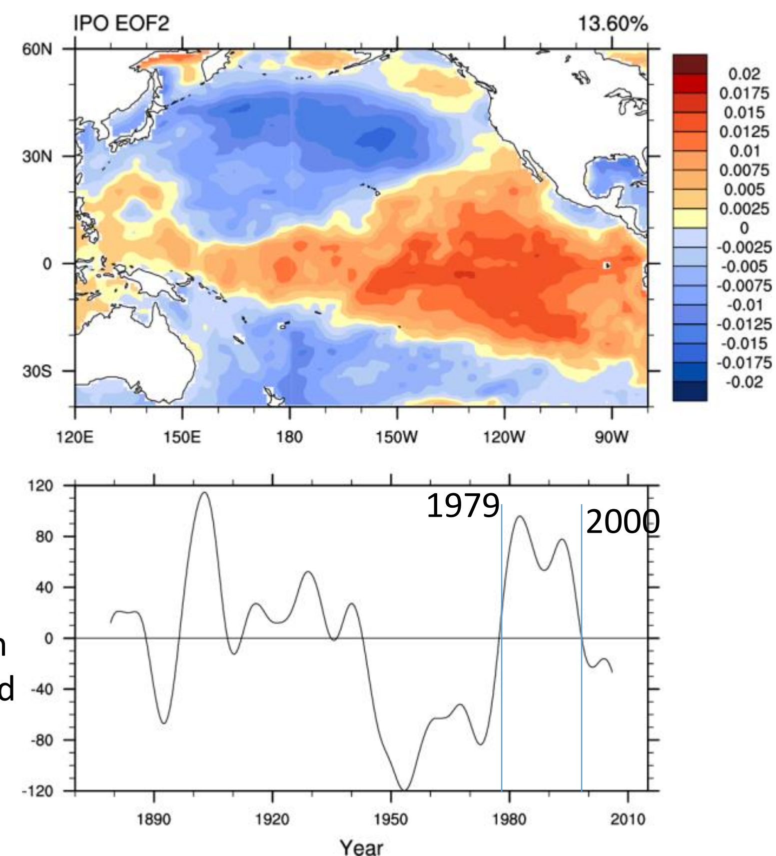
(large-scale standing wave in the atmosphere forced by a tropical convective heating anomaly; the mechanism of teleconnections from tropics to high latitudes)

Antarctic sea ice extent increased more rapidly after 2000…
(until 2016)

--Increases in observed Antarctic sea-ice extent accelerated after the late 1990s
--The average of all climate models shows a decline
--**Are the models wrong, or can natural variability associated with the Interdecadal Pacific Oscillation (IPO) be playing a role?**

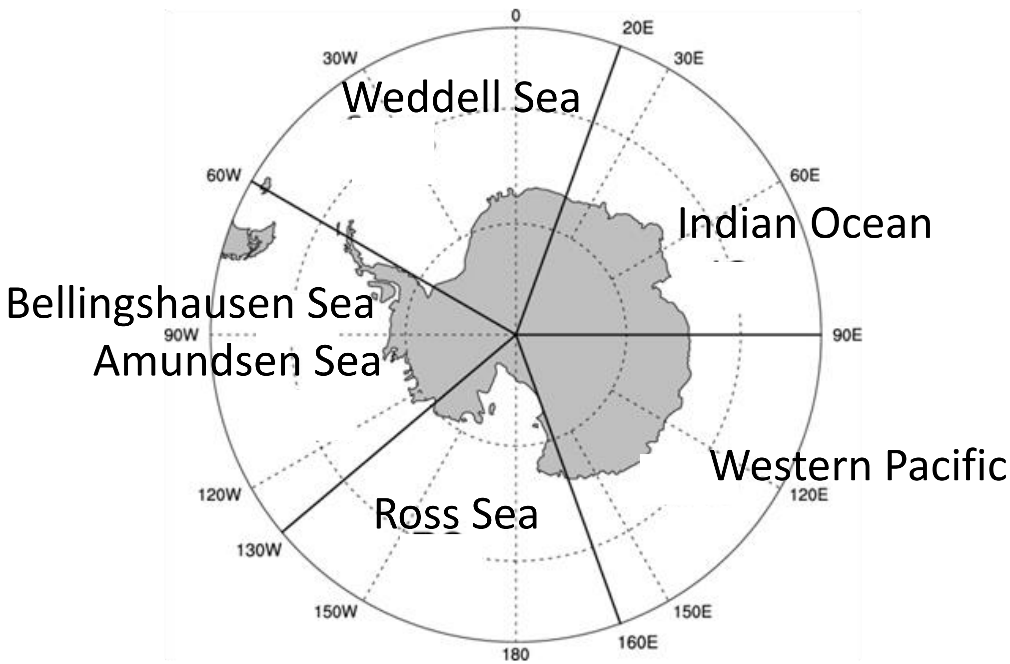


linear trend 1979-1999: $+0.12 \times 10^6$ km² decade^{-1}
2000-2014: $+0.57 \times 10^6$ km² decade^{-1}

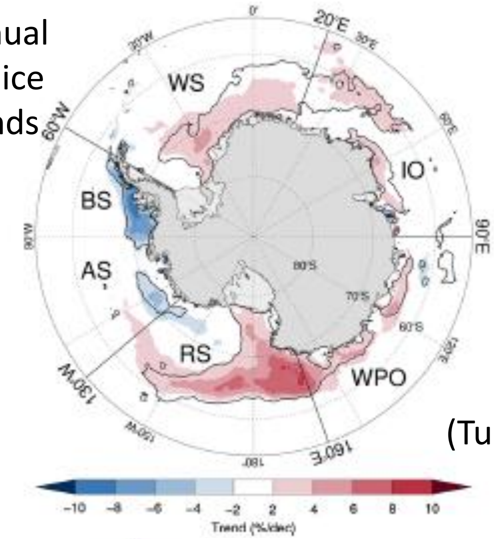


Observed IPO pattern (top, sign convention for positive IPO) and PC time series index (bottom)

(Meehl, G.A., J.M. Arblaster, C. Bitz, C.T.Y. Chung, and H. Teng, 2016: *Nature Geoscience*, DOI: 10.1038/NGEO2751.)


0
20E
30W
30E
Weddell Sea
60W
60E
Indian Ocean
Bellingshausen Sea
90W
90E
Amundsen Sea
Western Pacific
120W
120E
Ross Sea
130W
150W
150E
180
160E

Annual sea ice trends

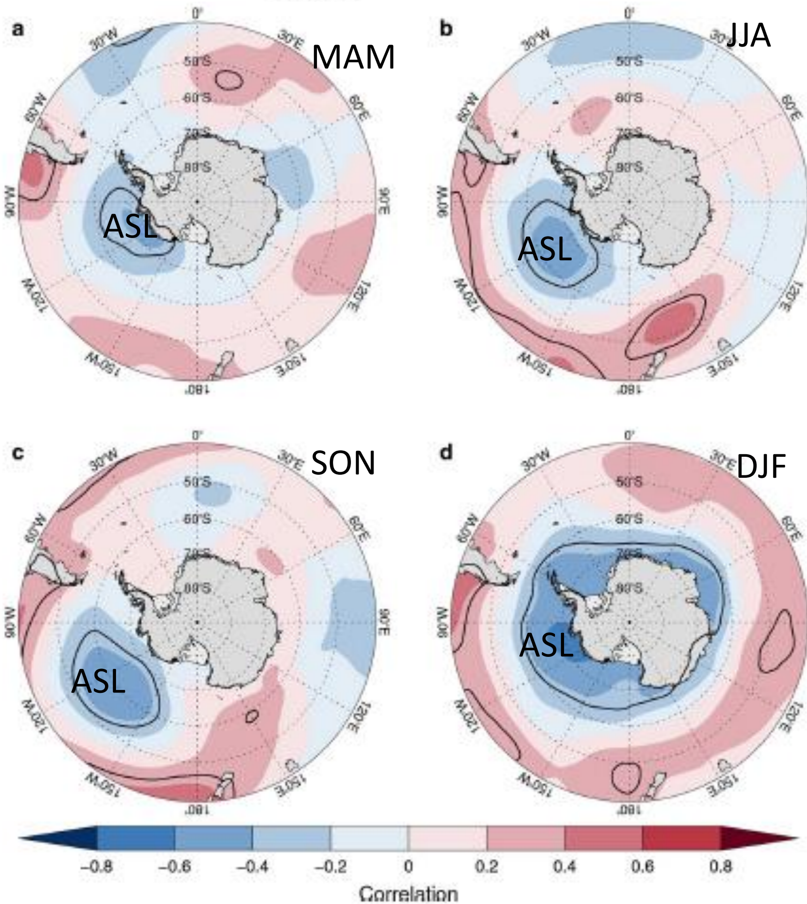


Largest trends for increasing sea ice since 1979 have been occurring in the Ross Sea region

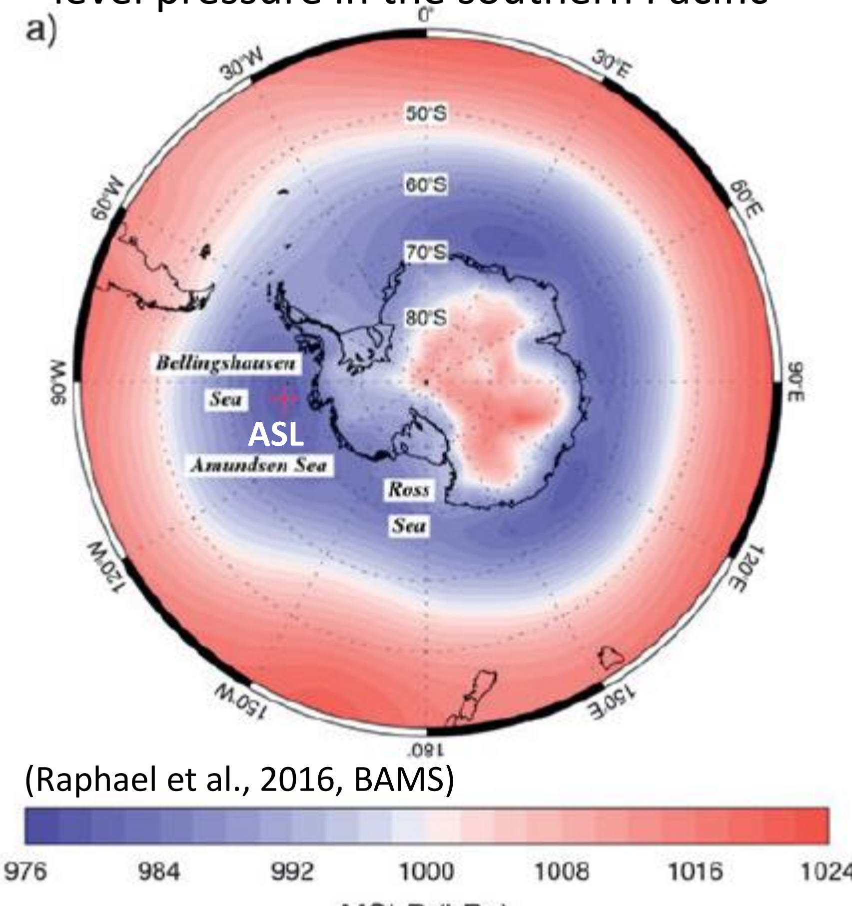
These increases are connecting to a deepening of the Amundsen Sea Low

(Turner et al., 2015, Clim. Dyn.)

The Amundsen Sea Low is a major feature of the mean climatology of sea level pressure in the southern Pacific



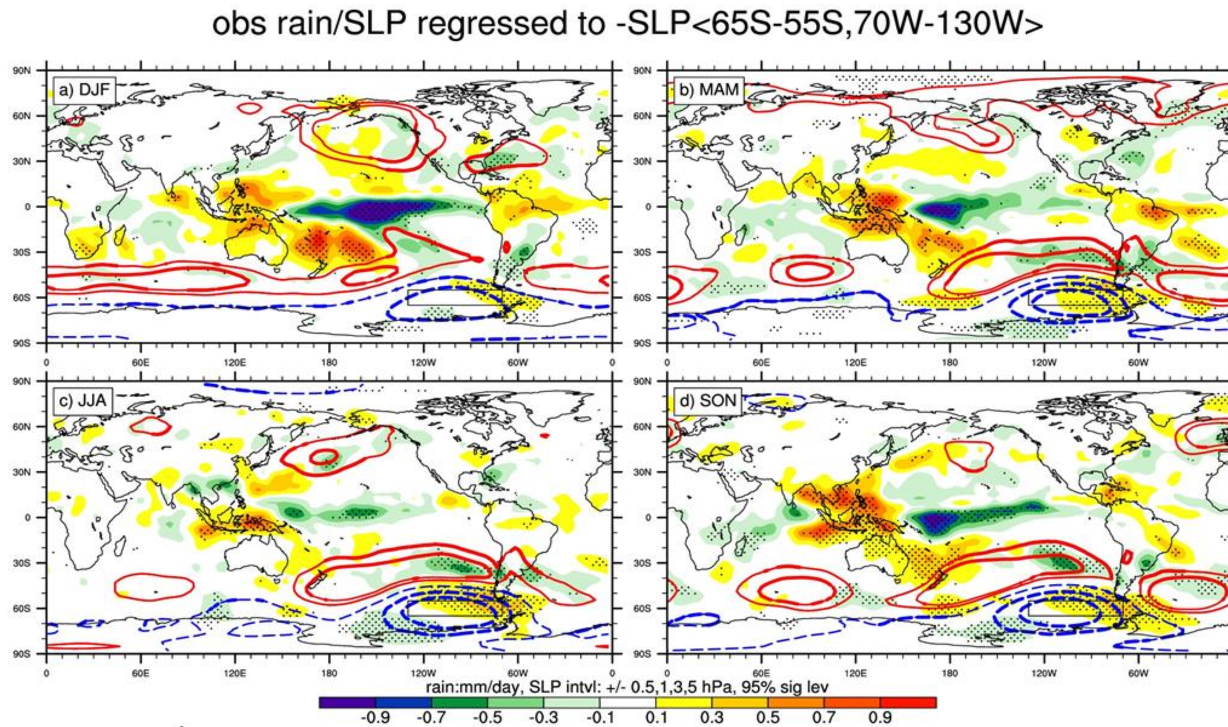
Correlation of sea ice extent in Ross Sea with SLP



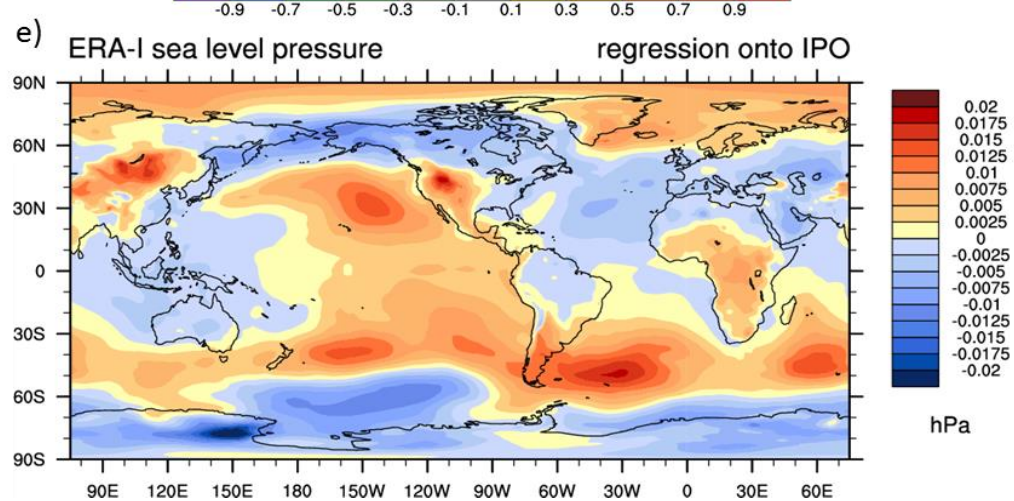
(Raphael et al., 2016, BAMS)

SLP in the Amundsen Sea Low is connected to rainfall in the tropics

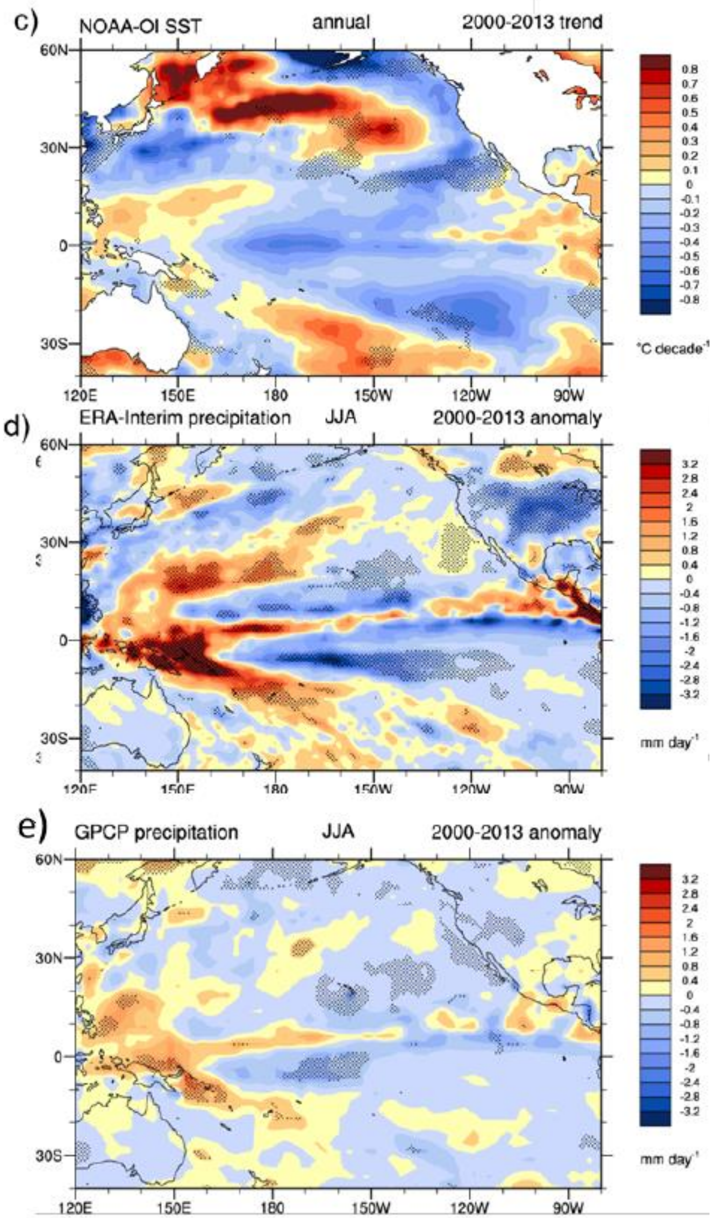
(also Ding et al., 2011, Nature Geo.; Schneider et al., 2012, J. Climate; Li et al., 2014, Nature; Clem and Renwick, 2015, J. Climate)



and the IPO

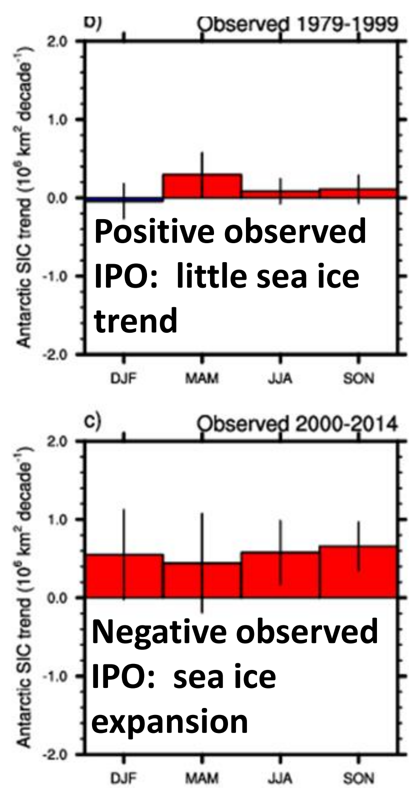


(Meehl, Arblaster, Bitz, Chung, and Teng, 2016, Nature Geo.)

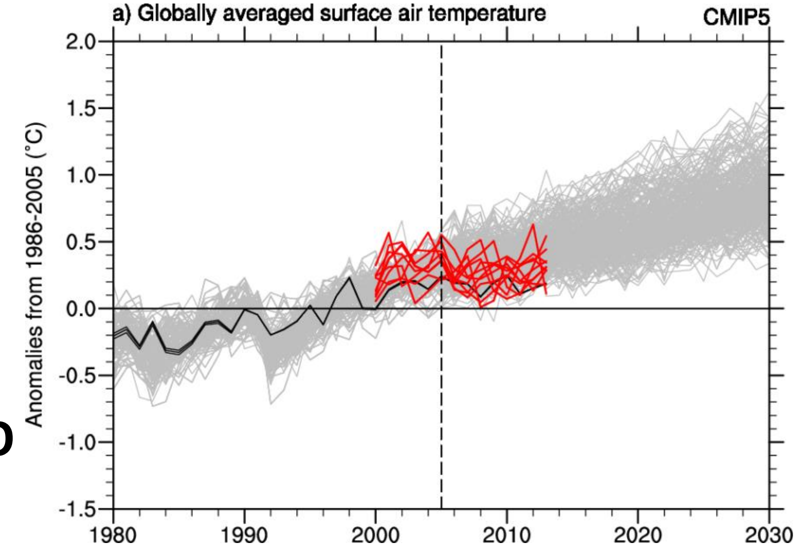


Observed SST trend, 2000-2013 (top) and two estimates of precipitation anomaly, 2000-2013 (middle and bottom)

Negative IPO: tropical Pacific SSTs cooler, negative precipitation and convective heating anomalies, and expanding Antarctic sea ice



Slowdown as observed from 2000-2013:
10 members out of 262 possible realizations

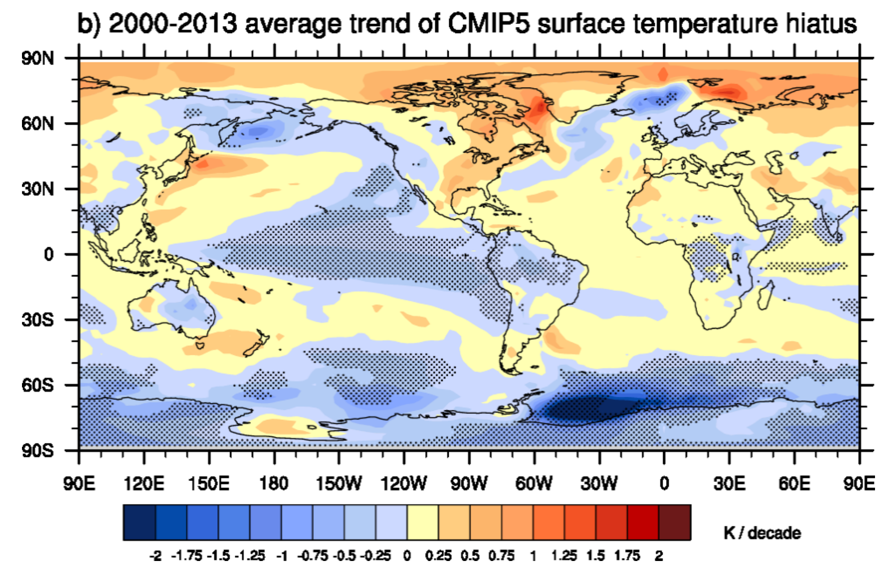


Some CMIP5 uninitialized models actually simulated the "early 2000s slowdown" (sometimes referred to as the "hiatus") as observed

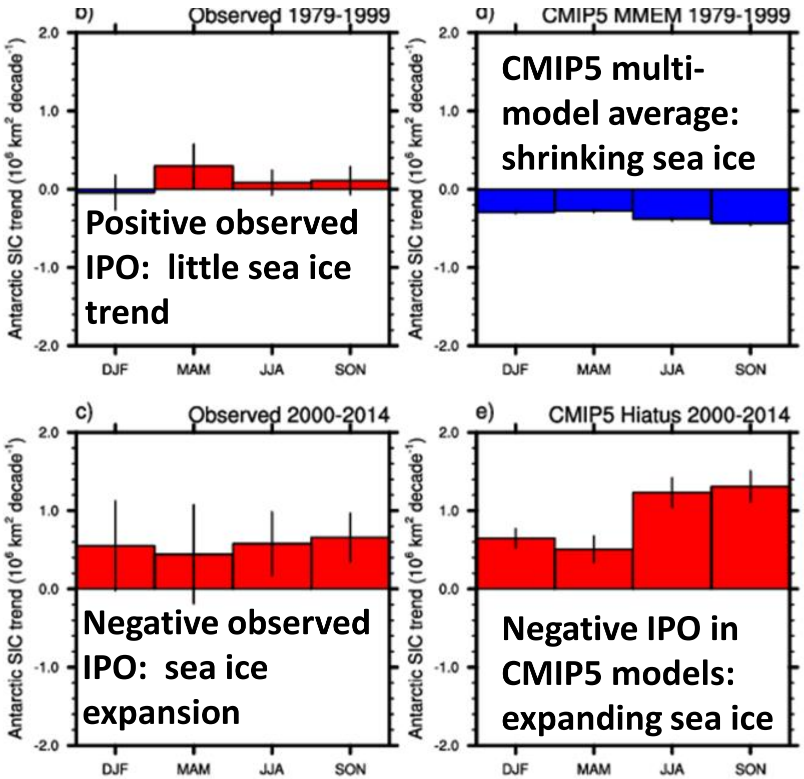
Characterized by a **negative phase of the IPO**

internally generated variability in those model simulations happened to sync with observed internally generated variability

(Meehl et al., 2014, Nature Climate Change)

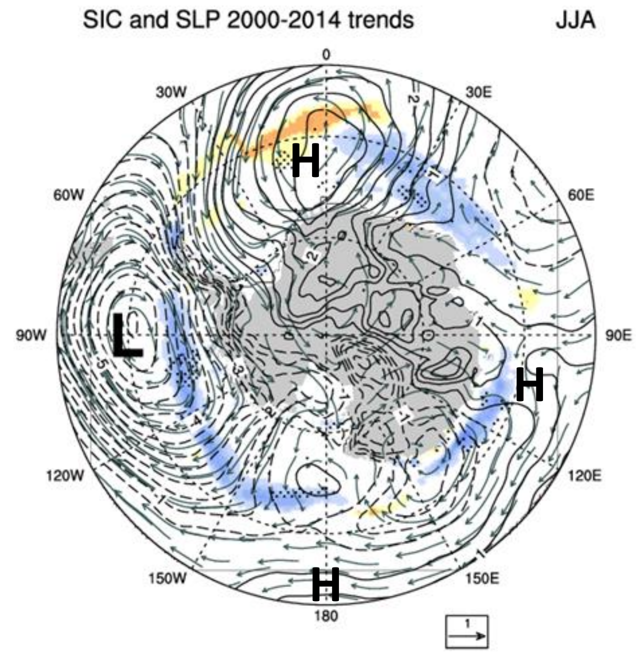


Negative IPO: tropical Pacific SSTs cooler, negative precipitation and convective heating anomalies, and expanding Antarctic sea ice



(Meehl et al., 2014, Nat. Clim. Chg.)

Negative IPO: observed deepening of Amundsen Sea Low, and expanding Antarctic sea ice since 2000 driven by equatorward surface winds



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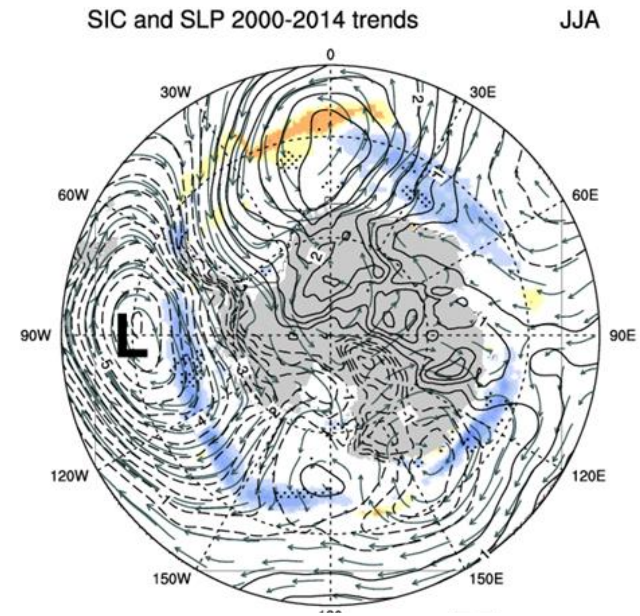
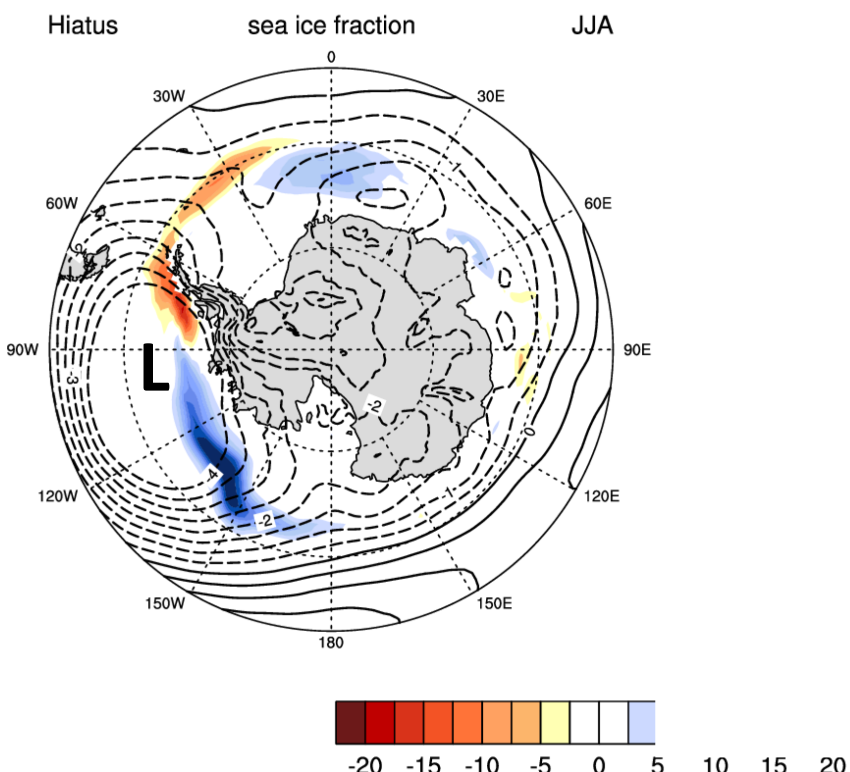
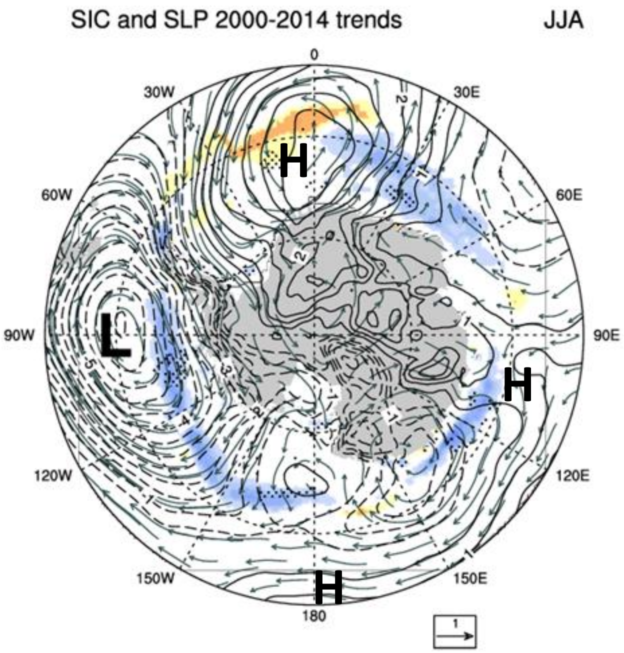


Model simulations with negative IPO 2000-2013

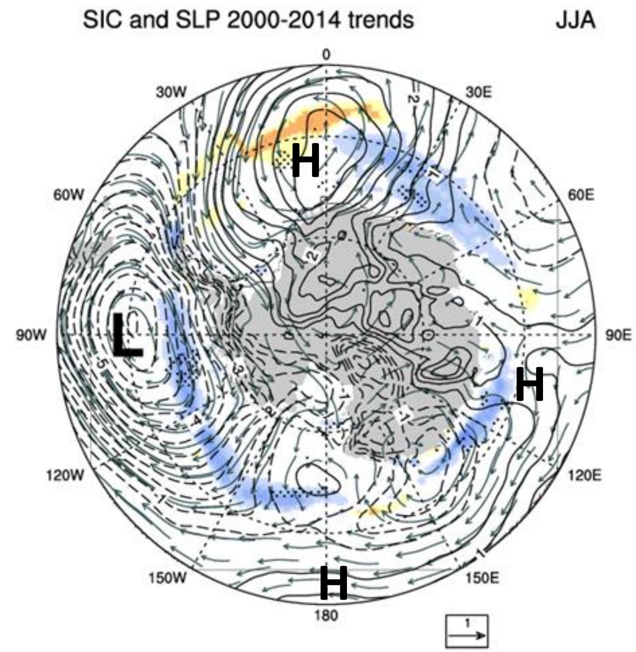


Negative IPO: observed deepening of Amundsen Sea Low from 2000-2014, and expanding Antarctic sea ice since 2000 driven by equatorward surface winds

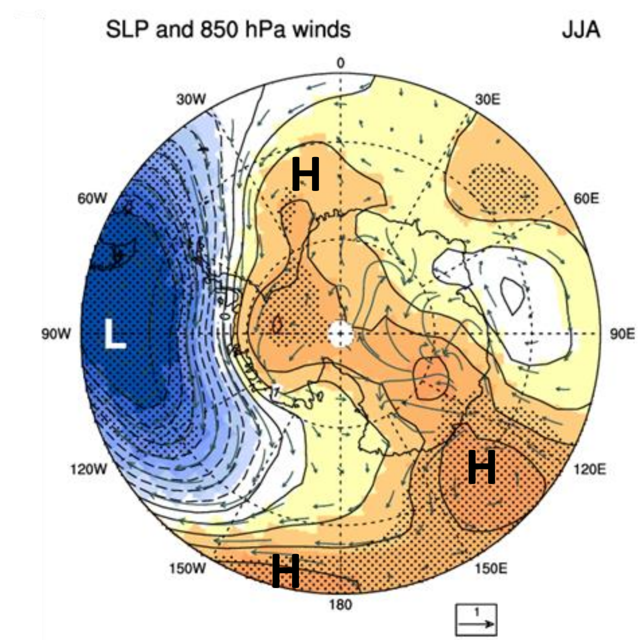


To pin down the connection between the IPO and Antarctic sea ice expansion, run an atmosphere model sensitivity experiment with a negative specified convective heating anomaly in the eastern equatorial Pacific (135W, Eq) to represent the negative precipitation anomalies associated with negative IPO that occurred from 2000-2014

Negative IPO: observed deepening of Amundsen Sea Low from 2000-2014, and expanding Antarctic sea ice since 2000 driven by equatorward surface winds



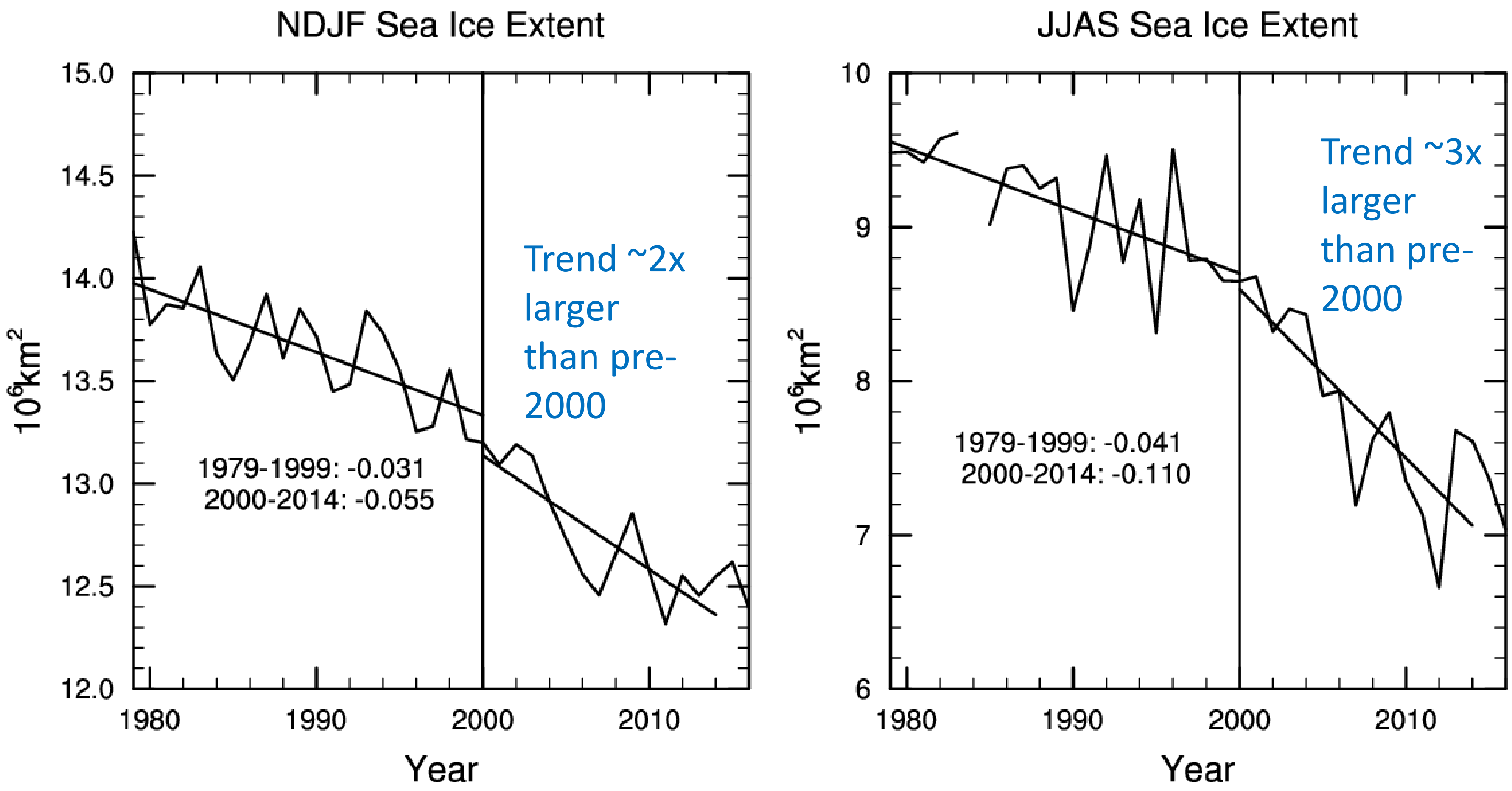
Model sensitivity experiment: IPO-related negative convective heating anomalies in eastern tropical Pacific (135W, Eq) produce and anomalous atmosphere Rossby wave response involving a deepened Amundsen Sea Low and preponderance of equatorward surface winds that expand Antarctic sea ice



(only JJA shown here, other seasons show similar results)

Meanwhile, in the Arctic…

At the IPO transition to negative around 2000, sea ice extent trends accelerate in both seasons (NDJF by nearly a factor of two, nearly a factor of three in JJAS)



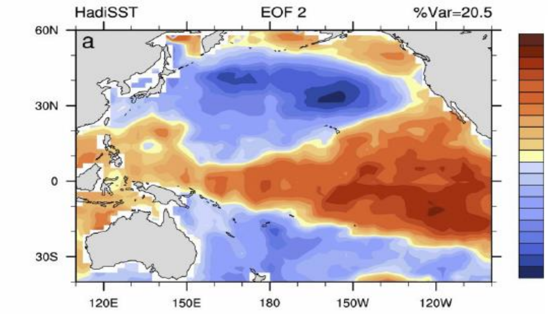
(Meehl et al., 2018: Tropical decadal variability and the rate of Arctic sea ice retreat, *Geophys. Res. Lett.*, 10.1029/2018GL079989.)

What is the nature of the connections between the tropics and the Arctic?

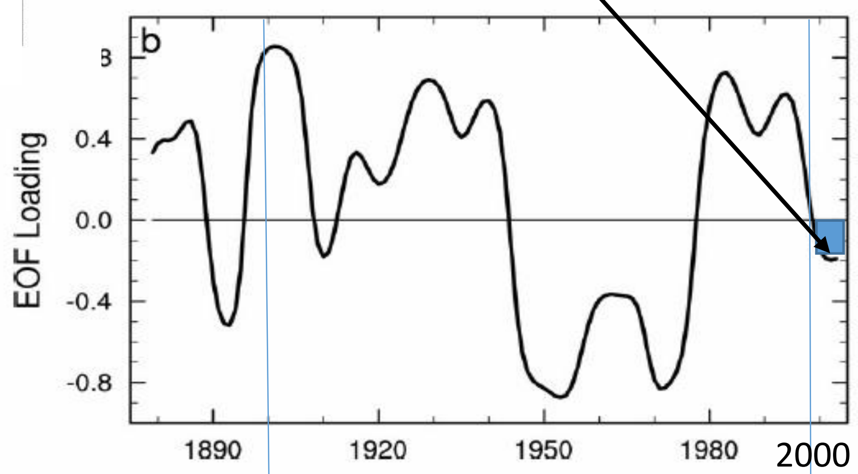
Tropics drive Arctic changes (Lee et al., 2011; Ding et al., 2014)

Arctic drives changes in lower latitudes (Cohen et al., 2018; Screen et al., 2018)

Two stage process—Arctic drives tropical changes which then feed back and drive Arctic changes (Cvijanovic et al., 2017)

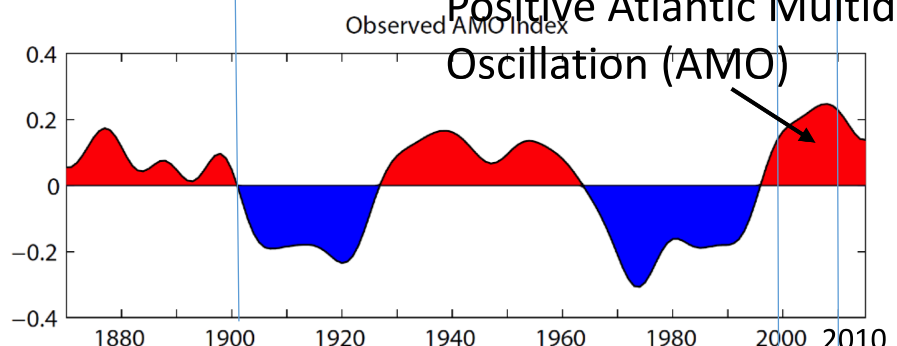


Negative IPO



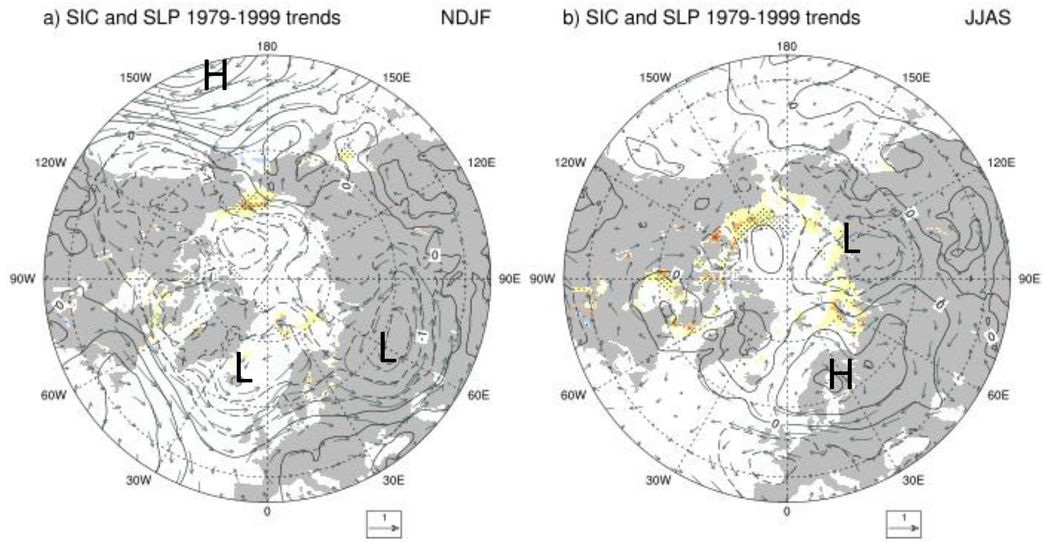
Second EOF of 13 year low pass filtered SSTs for Pacific 40S-60N (Meehl et al 2016)

Positive Atlantic Multidecadal Oscillation (AMO)



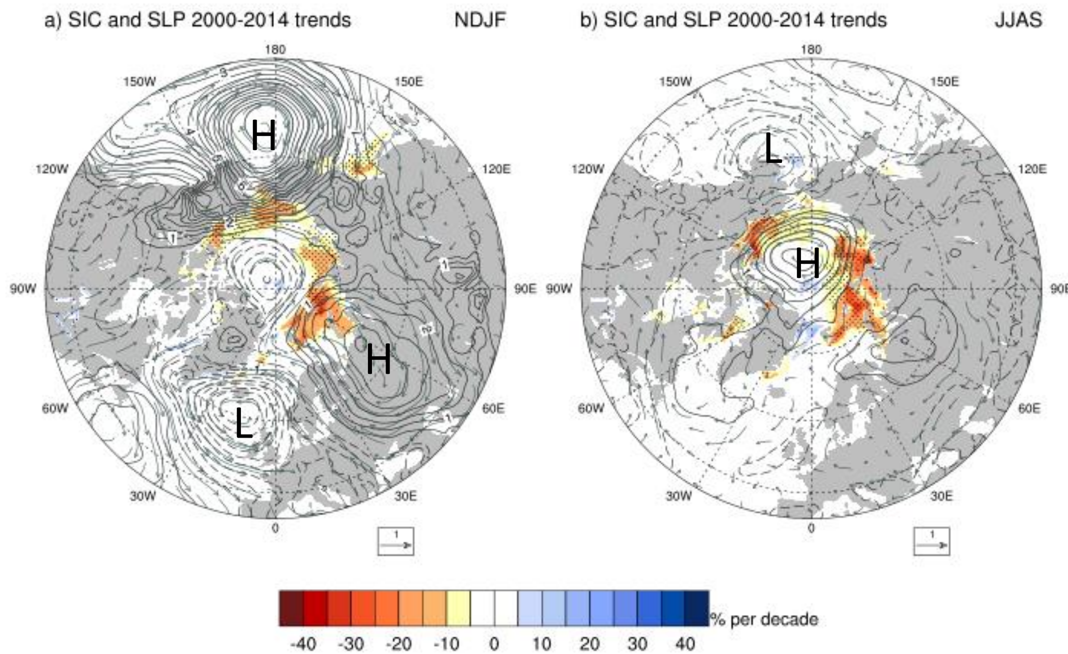
Detrended 10 year low pass filtered North Atlantic SSTs 0-60N, 1870-2015

Observed SLP and sea ice concentration trends 1979-1999

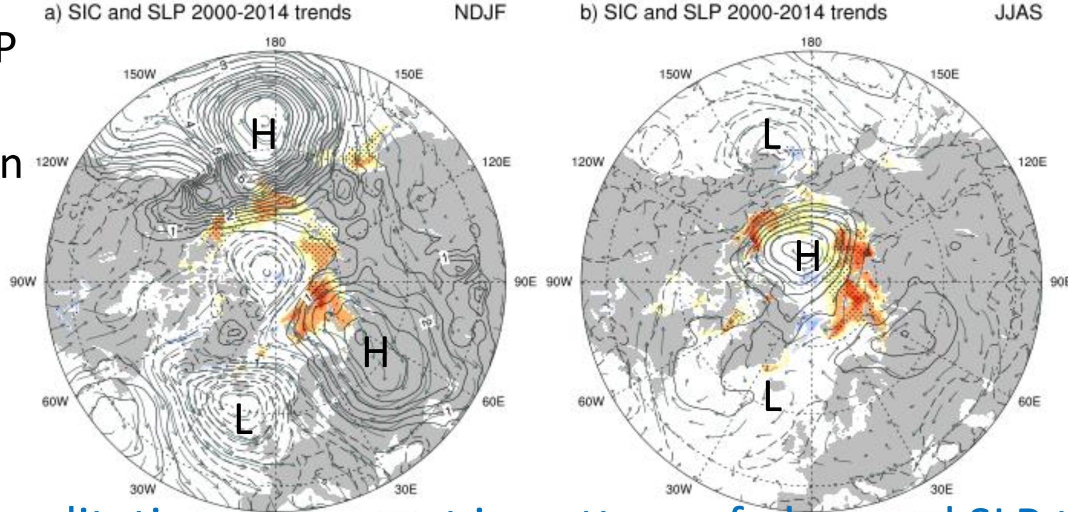


Marked difference in observed SLP trend patterns from 1979-99 (above) to 2000-2014 (below) in both seasons

Observed SLP and sea ice concentration trends 2000-2014



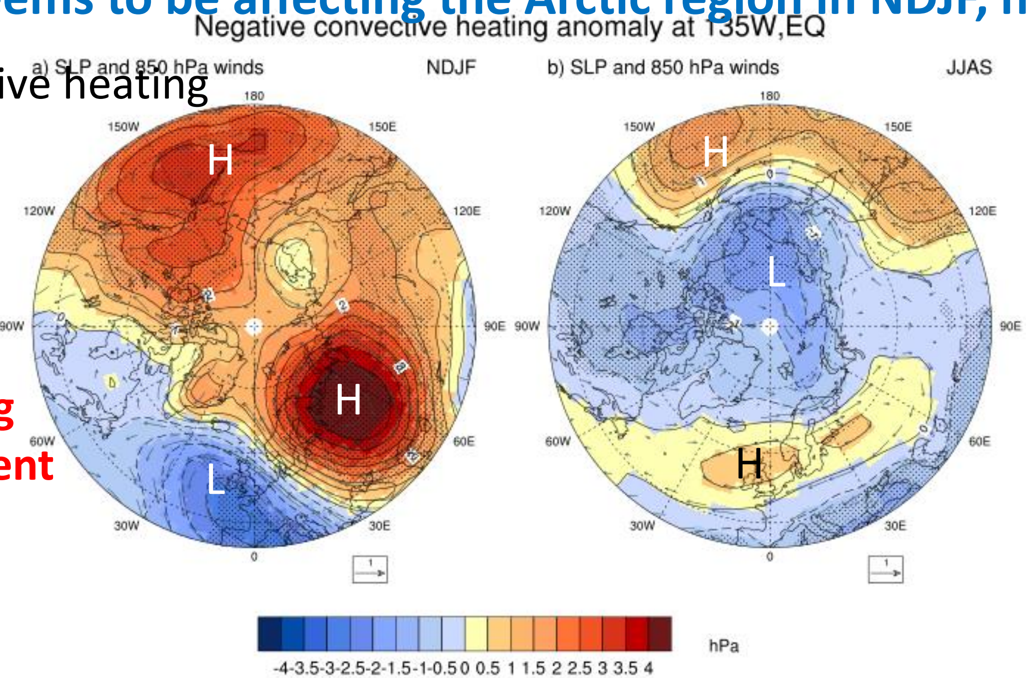
Observed SLP and sea ice concentration trends 2000-2014



2000-2014: qualitative agreement in pattern of observed SLP trends in NDJF for obs and negative IPO convective heating anomaly (left side); little agreement (actually opposite sign) of pattern from obs to model experiment in JJAS (right side); **forcing from Pacific seems to be affecting the Arctic region in NDJF, not JJAS**

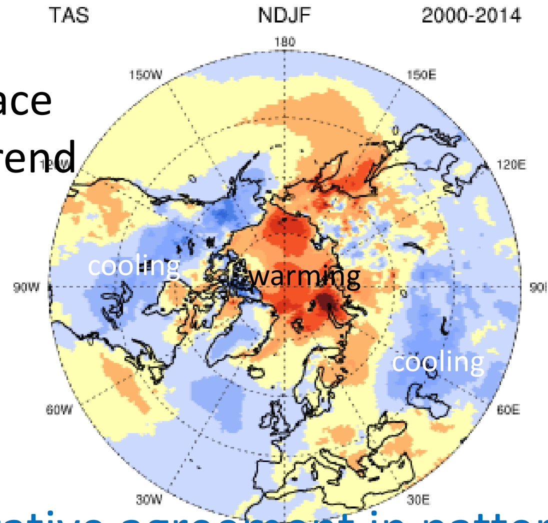
Negative convective heating anomaly Pacific (negative IPO) SLP

Negative Pacific convective heating anomaly experiment



Observed surface temperature trend 2000-2014

Surface temperature trends

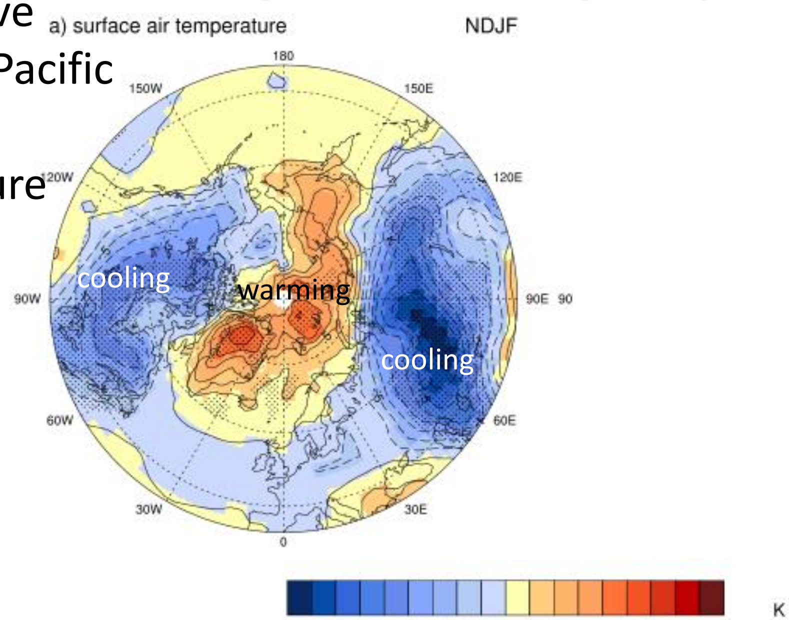


2000-2014: qualitative agreement in pattern of observed surface T trends in NDJF for obs and negative IPO convective heating anomaly (left side); little agreement in pattern from obs to model experiment in JJAS (right side). **Consistent with SLP, forcing from Pacific seems to be affecting the Arctic region in NDJF, not JJAS**

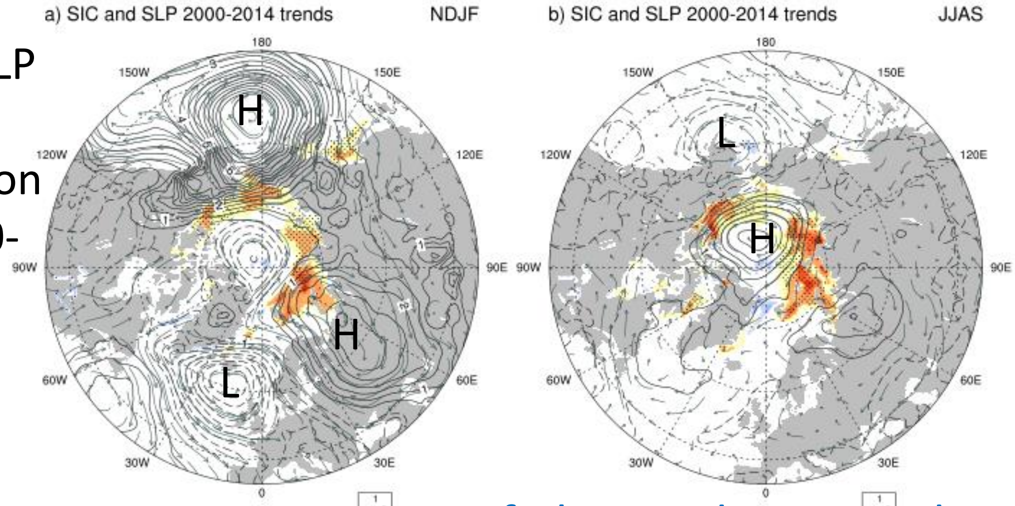
Negative convective heating anomaly at 135W,EQ

Negative convective heating anomaly, Pacific (negative IPO)

Surface temperature anomalies



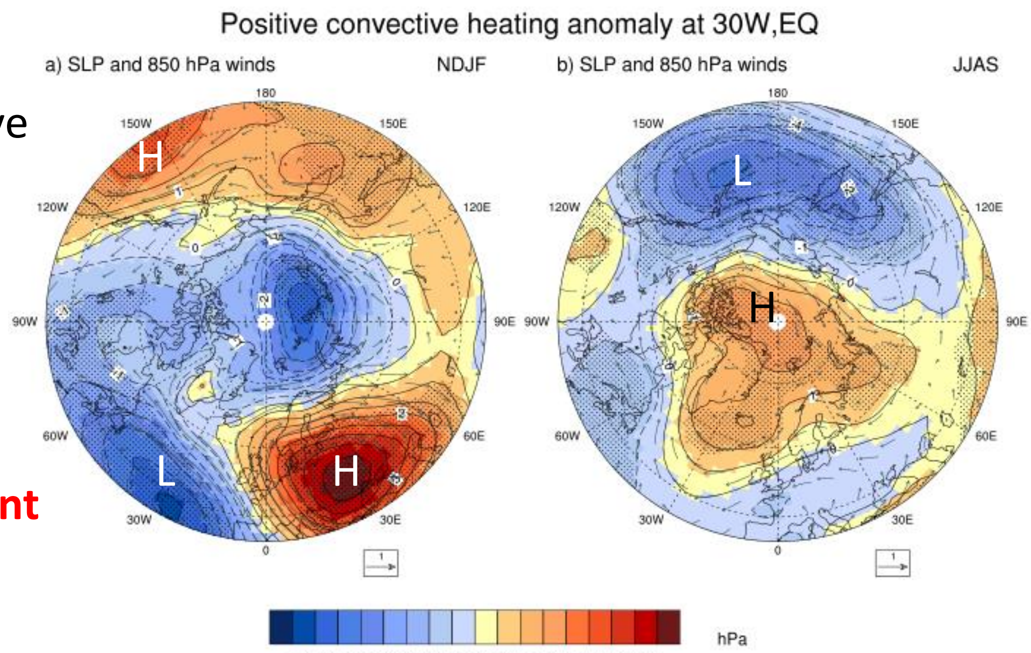
Observed SLP and sea ice concentration trends 2000-2014



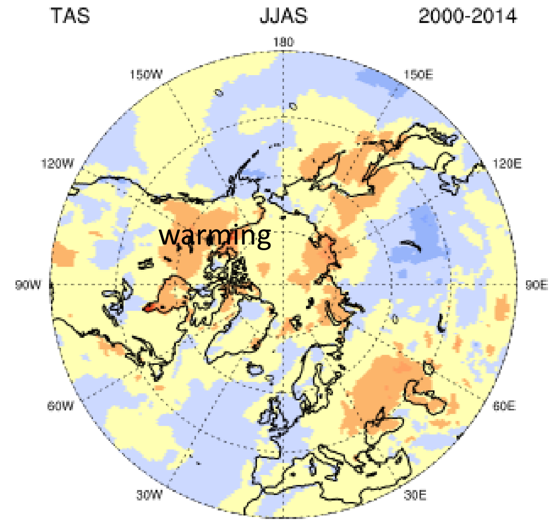
2000-2014: little agreement in pattern of observed SLP trends in NDJF for obs and positive Atlantic convective heating anomaly (left side); qualitative agreement in JJAS (right side); **forcing from Atlantic affecting the Arctic region JJAS, not NDJF**

Positive convective heating anomaly, Atlantic SLP

Positive Atlantic convective heating anomaly experiment



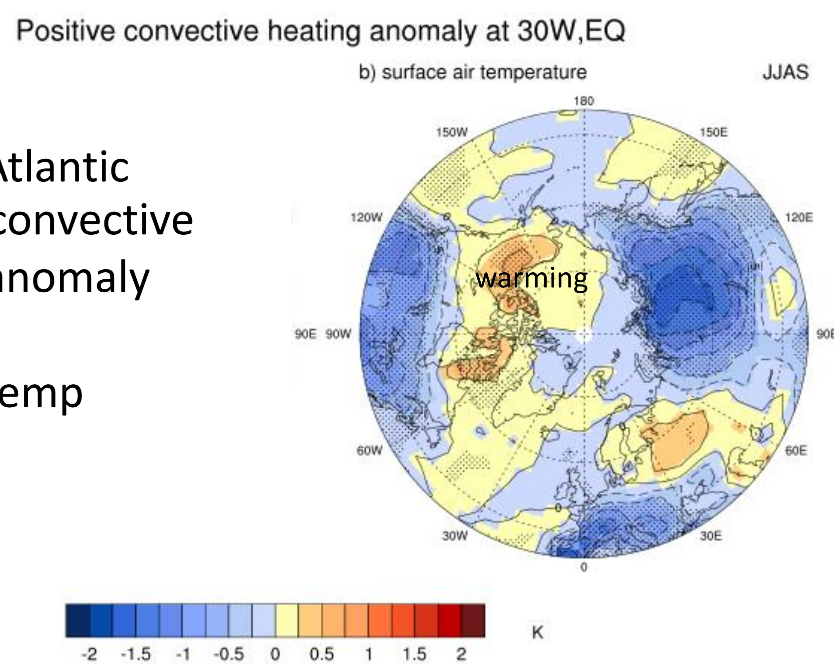
Observed surface temperature trend 2000-2014



2000-2014: **Consistent with SLP, forcing from Atlantic affecting the Arctic region JJAS**

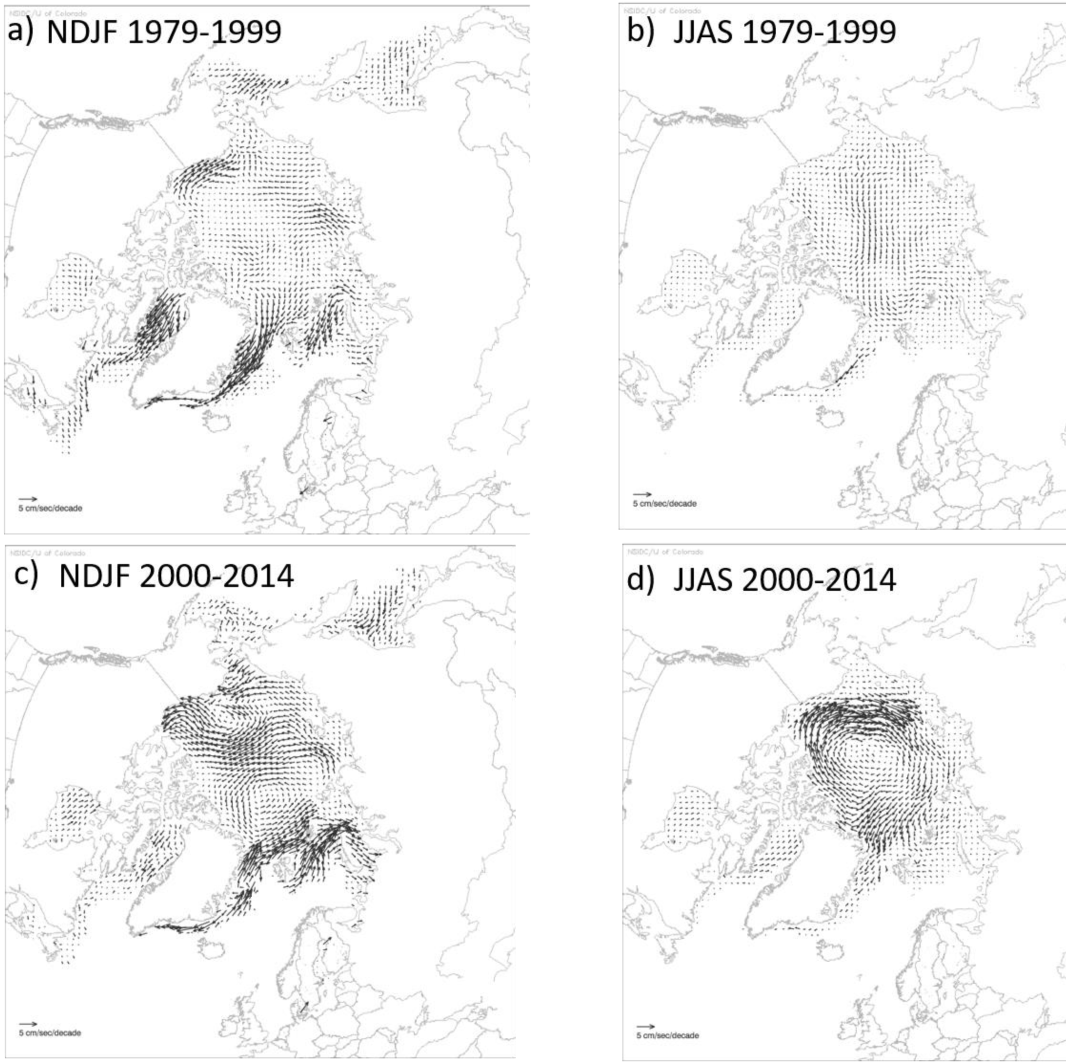
Tropical Atlantic
Positive convective heating anomaly

Surface temp

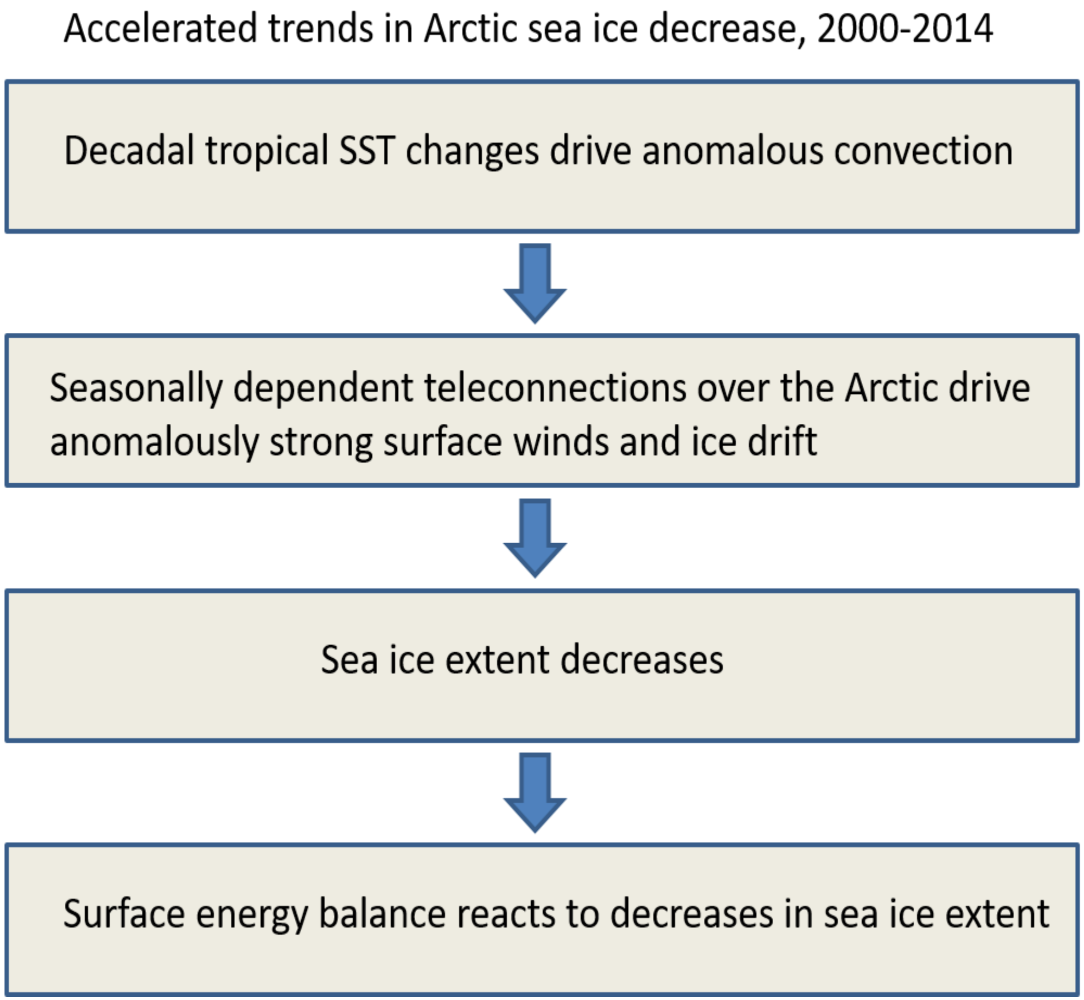


Larger amplitude SLP teleconnection patterns and thus stronger surface winds in the 2000-2014 period compared to 1979-99 are associated with increases in ice drift velocities (~factor of 3 in NDJF, ~factor of 10 in JJAS)

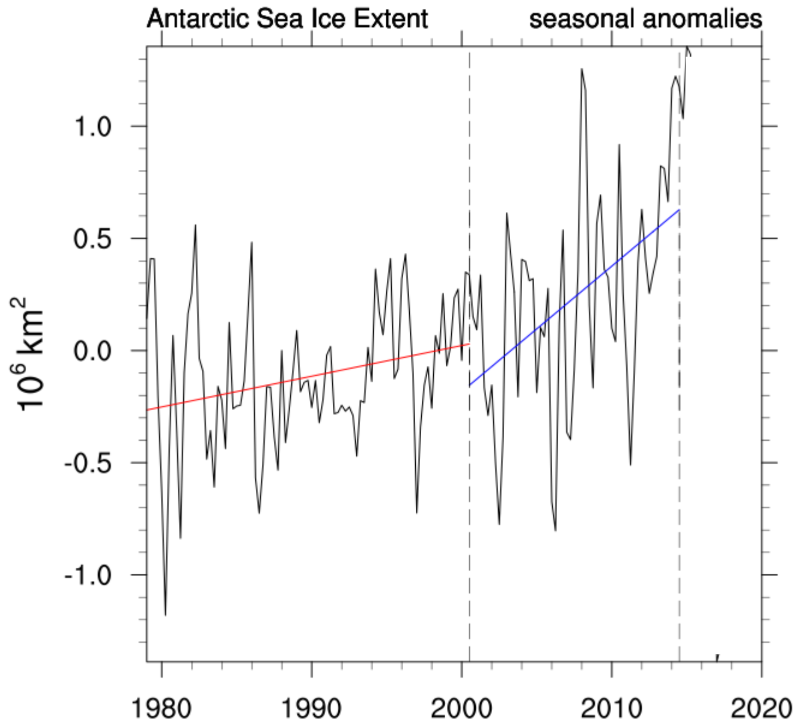
Stronger surface wind anomalies and ice drifts (Spreen et al., 2011) typically associated with reduced multiyear ice (Kwok et al., 2013) as seen in 2000-2014 compared to 1979-99



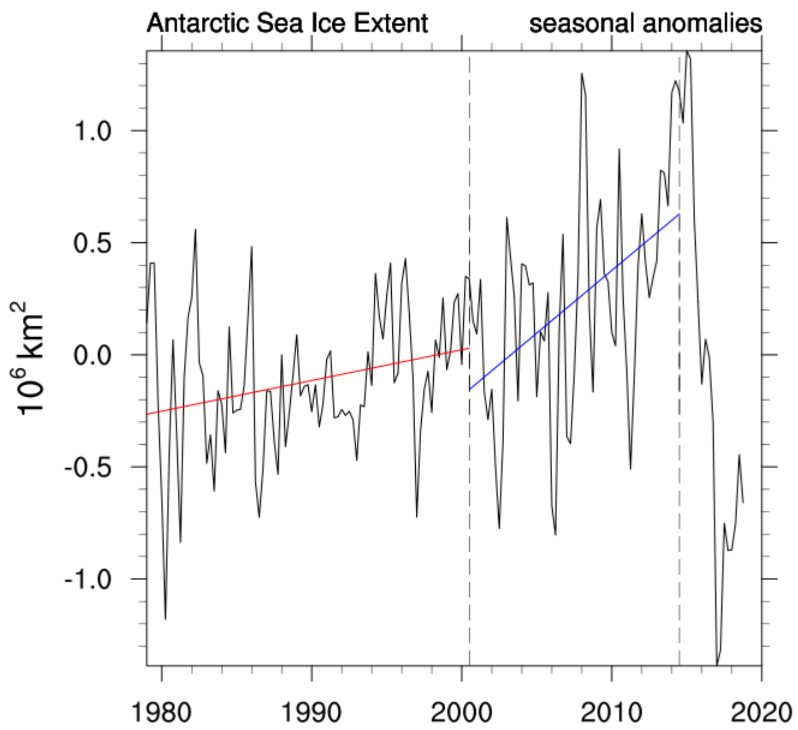
Ice drift trends (cm sec^{-1} decade^{-1})
(data source: Tschudi et al., 2016)


Accelerated trends in Arctic sea ice decrease, 2000-2014
Decadal tropical SST changes drive anomalous convection
Seasonally dependent teleconnections over the Arctic drive anomalously strong surface winds and ice drift
Sea ice extent decreases
Surface energy balance reacts to decreases in sea ice extent

Back to the Antarctic:

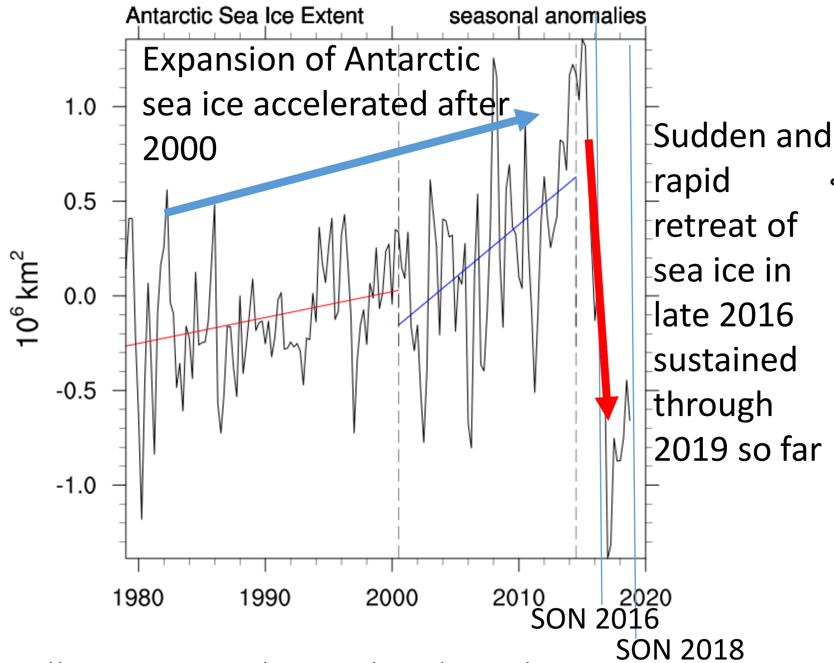


Back to the Antarctic:

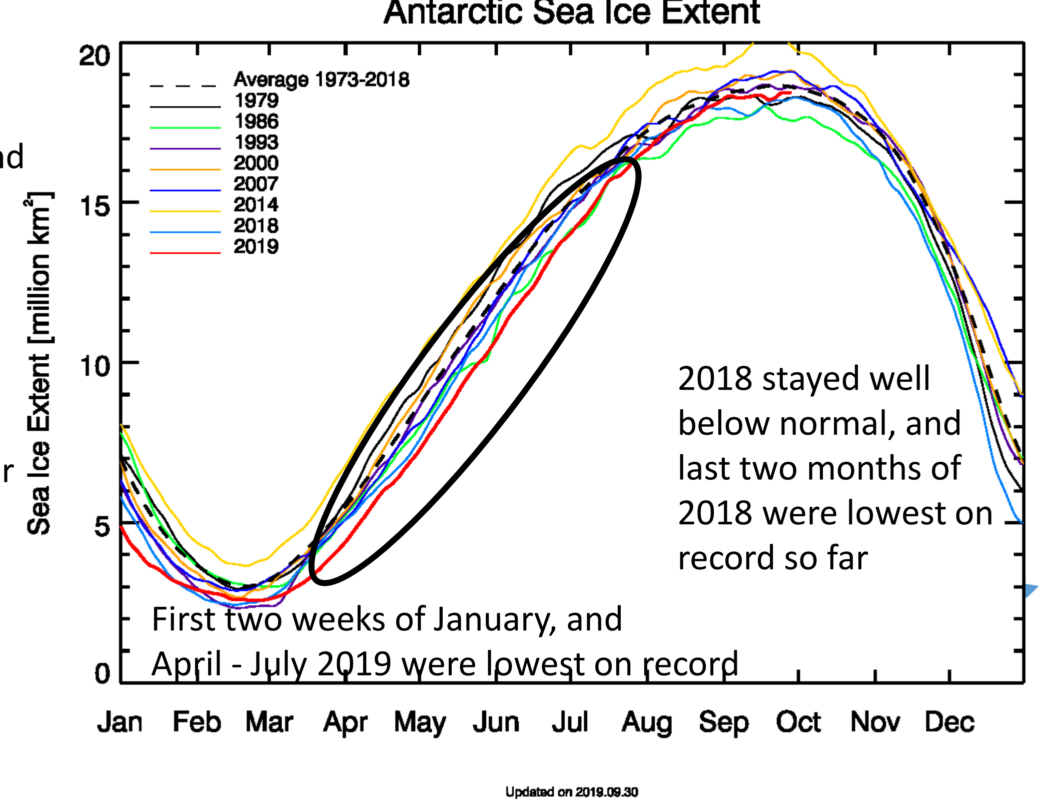


There was a sudden and dramatic *decrease* of Antarctic sea ice extent in late 2016 sustained through 2018 and into 2019

(Meehl et al., 2019: Recent sudden Antarctic sea ice retreat caused by connections to the tropics and sustained ocean changes around Antarctica, *Nature Comms*., **10**:14, https://doi.org/10.1038/s41467-018-07865-9)



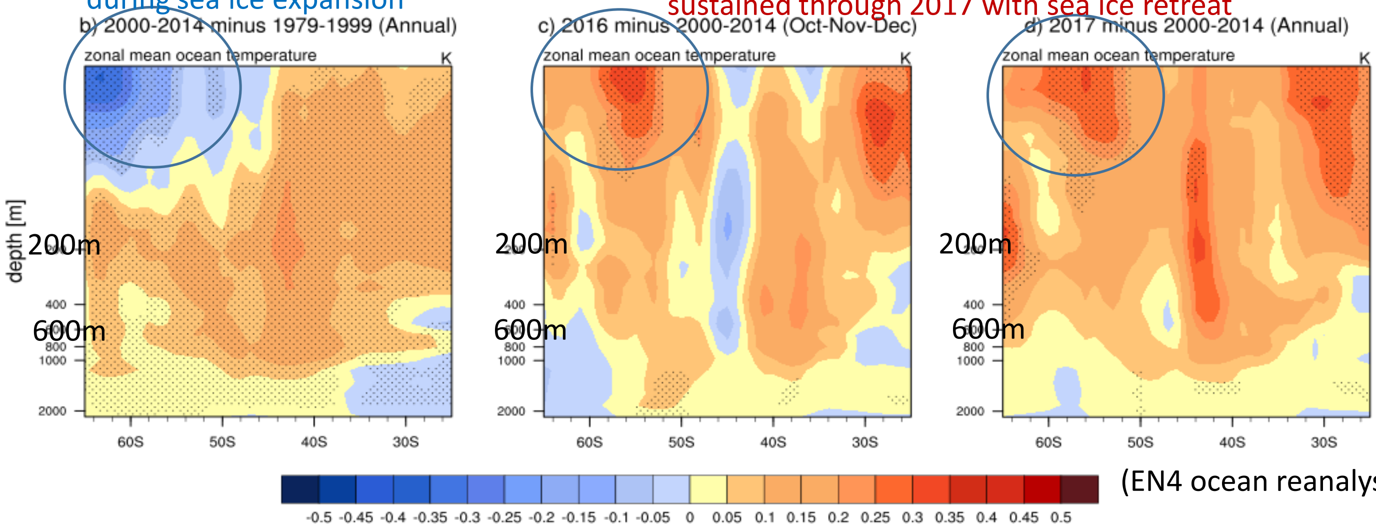
(ftp://sidads.colorado.edu/DATASETS/NOAA/G02135/)



Cold upper Southern Ocean during sea ice expansion

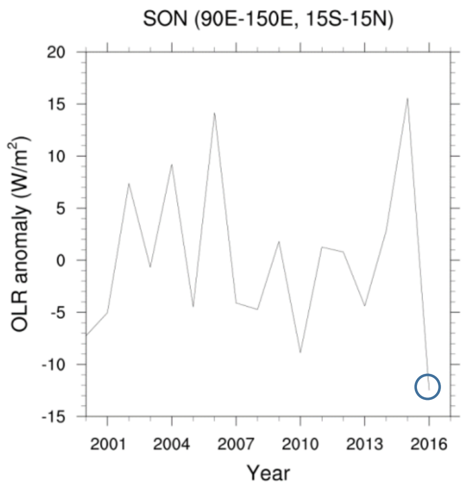
Warm upper Southern Ocean in 2016 sustained through 2017 with sea ice retreat

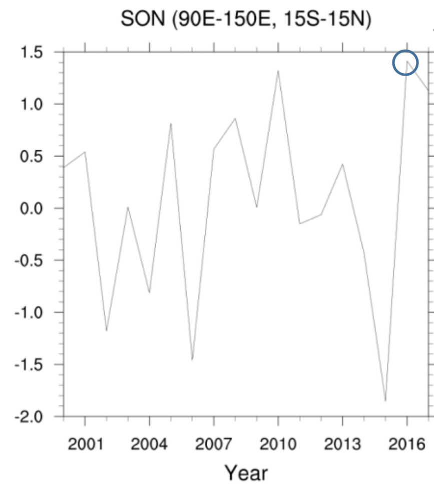
https://seaice.uni-bremen.de/sea-ice-concentration/time-series/



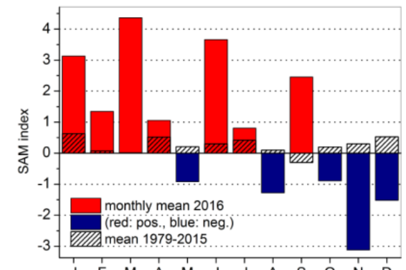
(EN4 ocean reanalysis data)

In late 2016, there were a lot of record anomalies that could have contributed





Record high precipitation in eastern Indian/western Pacific



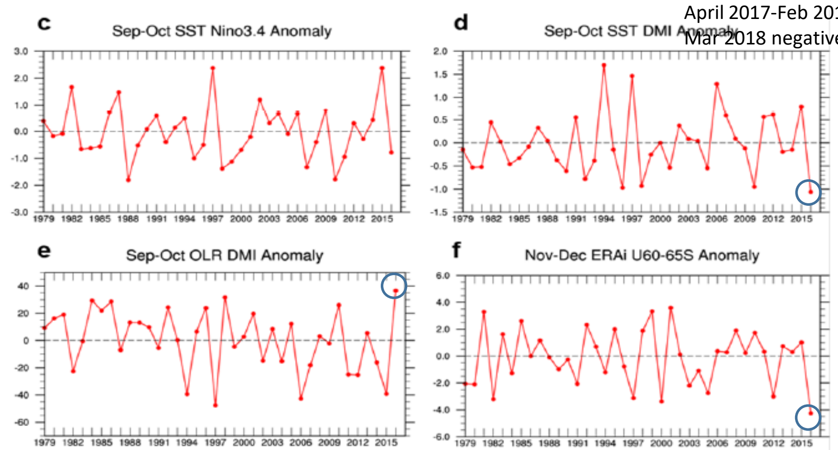
SAM index went from positive to negative (weaker westerlies) (Schlosser et al 2017)

http://www.nerc-bas.ac.uk/icd/gjma/sam.html

SAM negative Jan-Mar 2017; then positive April 2017-Feb 2018 with only Oct. 2017 and Mar 2018 negative

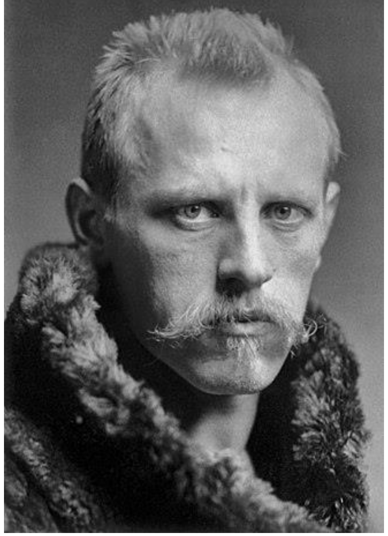
Records in the 2000s for SON:

--OLR in E. Indian
--precip in E. Indian
--negative DMI
--positive OLR-DMI
--negative SAM



(Wang et al., 2019, Nat. Comms.)

Record weak westerlies (easterly anomaly surface winds at 60-65S)



Fridtjof Nansen: Famous for reaching a record northern latitude of 86°14′ during his the Fram expedition of 1893–1896

Noticed that ice bergs and sea ice moved in a direction **to the right of the prevailing winds**

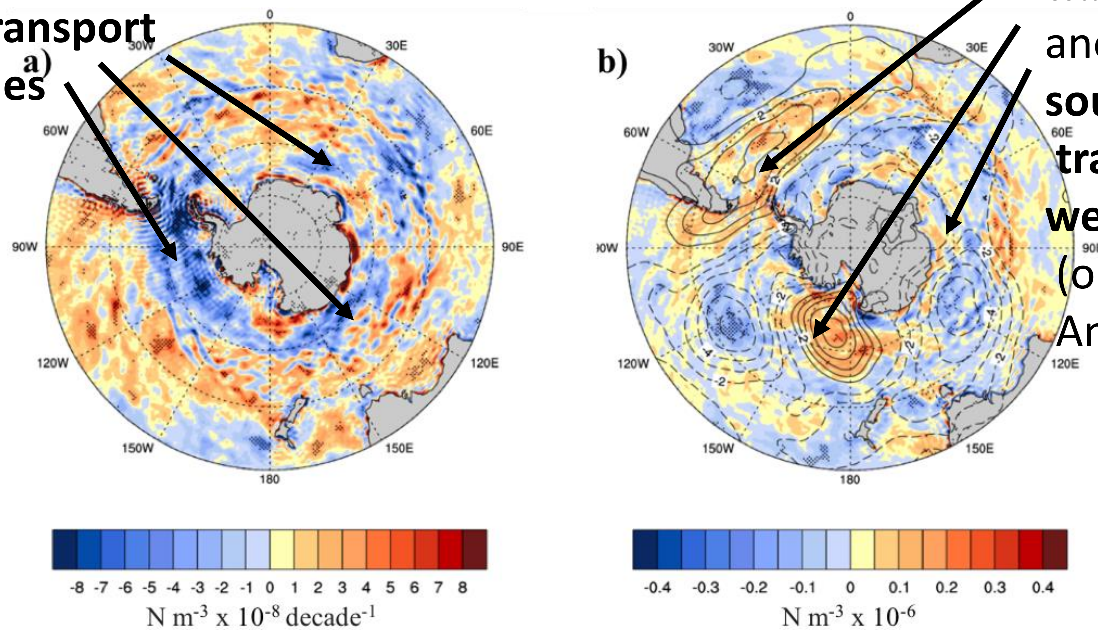
Ekman transport, part of Ekman motion theory first investigated in 1902 by Vagn Walfrid Ekman

As the wind blows it casts a friction force on the ocean surface that drags the upper 10-100m of the water column with it. Due to the influence of the Coriolis effect, the ocean water moves at a 90° angle from the direction of the surface wind (to the right in the NH, to the left in the SH)

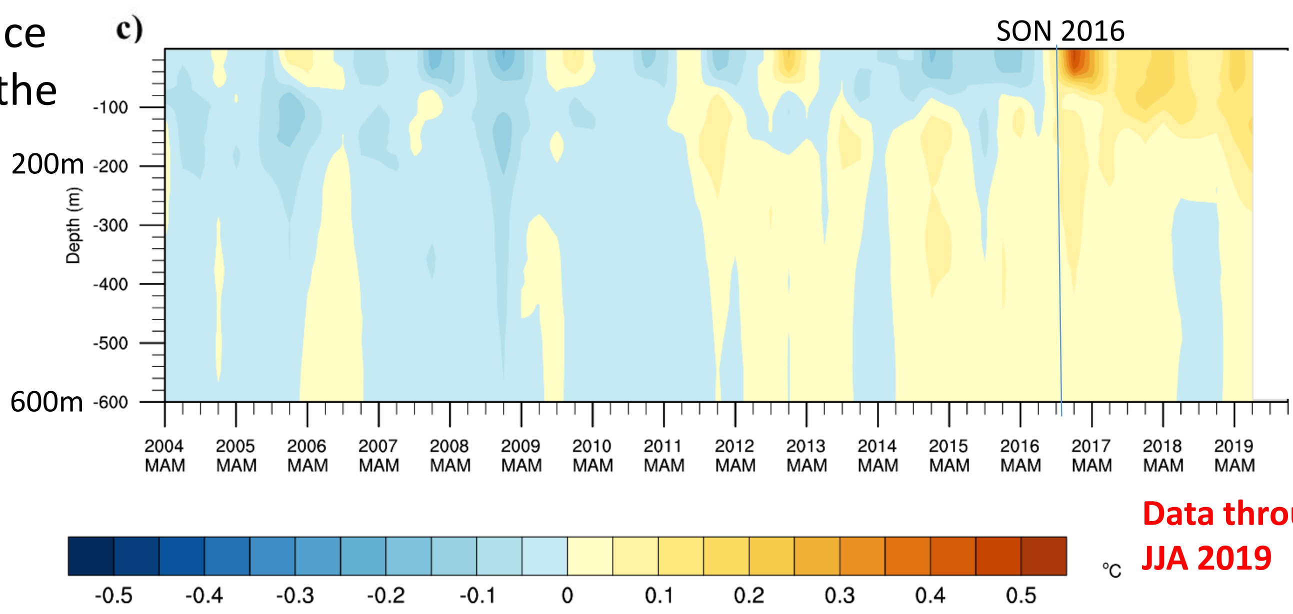
Strong westerly winds over the southern Ocean push surface water to the left, pulling up warmer subsurface water ("Ekman suction")

2000-2014 trend of negative wind stress curl anomalies and **northward Ekman transport** from **strong westerlies** (blue colors around Antarctica)

SON 2016 positive wind stress curl anomalies and **southward Ekman transport** from **weak westerlies** (orange colors near Antarctica)



Episodic movement of warm subsurface water upward in the water column (zonal mean temperature 50-65S)

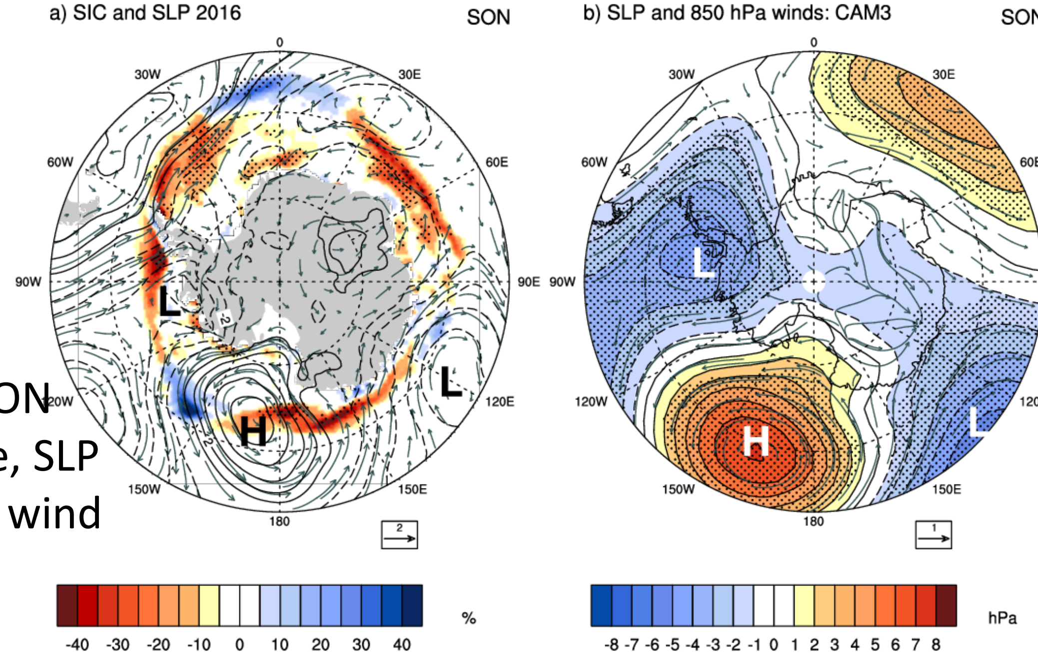


In SON 2016, entire zonal mean water column in upper 600m had positive temperature anomalies

Data through JJA 2019

Evidence that mid- and high latitude teleconnections with southward surface winds, which reduced sea ice extent, were driven from the tropics

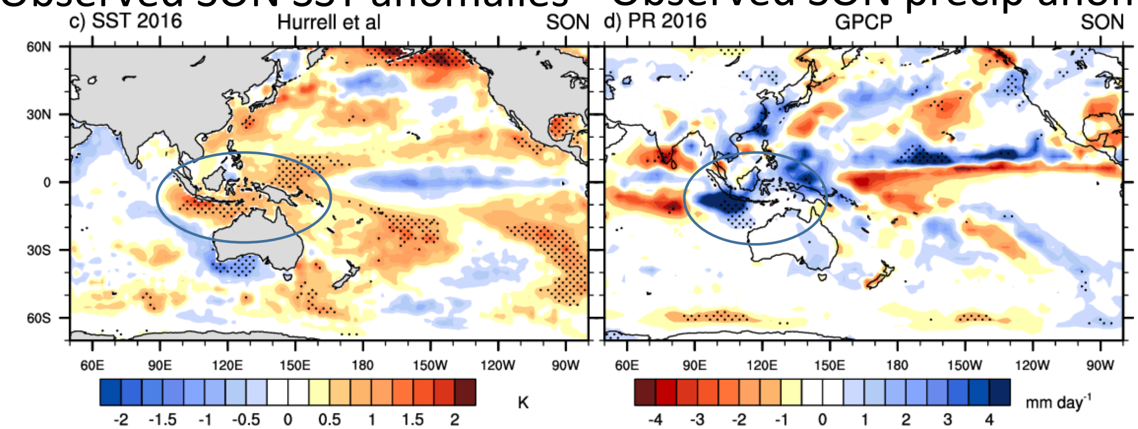
Observed SON 2016 sea ice, SLP and surface wind anomalies



Eastern Indian/western Pacific 120E,Eq positive convective heating anomaly experiment, SON SLP and surface wind anomalies

Observed SON SST anomalies

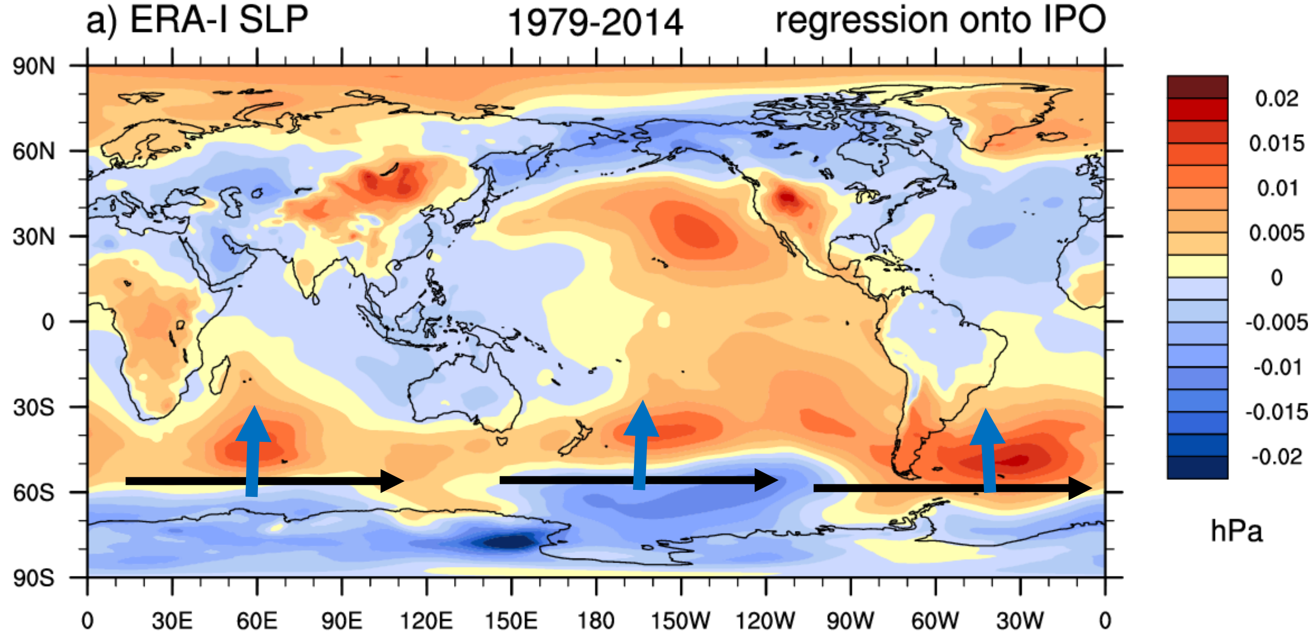
Observed SON precip anomalies



What could produce anomalously strong westerlies on the decadal timescale?

Negative IPO (shown here regressed onto sea level pressure) and positive SAM

Ekman transport to the left from strong westerlies slowly brings warm subsurface water nearer the surface

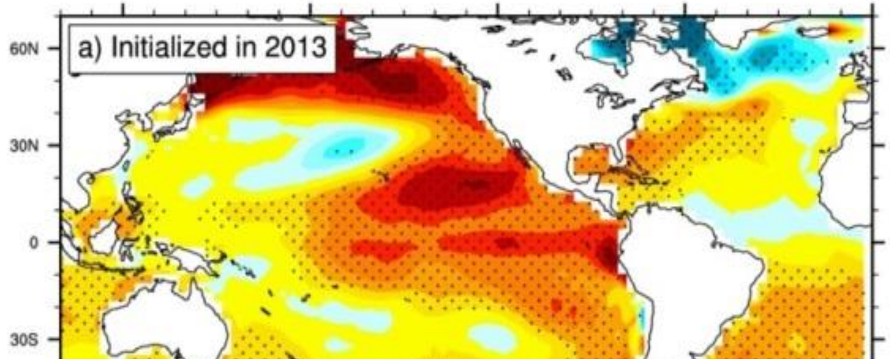


Anomalously strong westerlies on decadal timescale, northward Ekman transport of surface water; warm subsurface water move upward in column

What changed in 2015-2016?

The IPO was predicted to transition around 2016

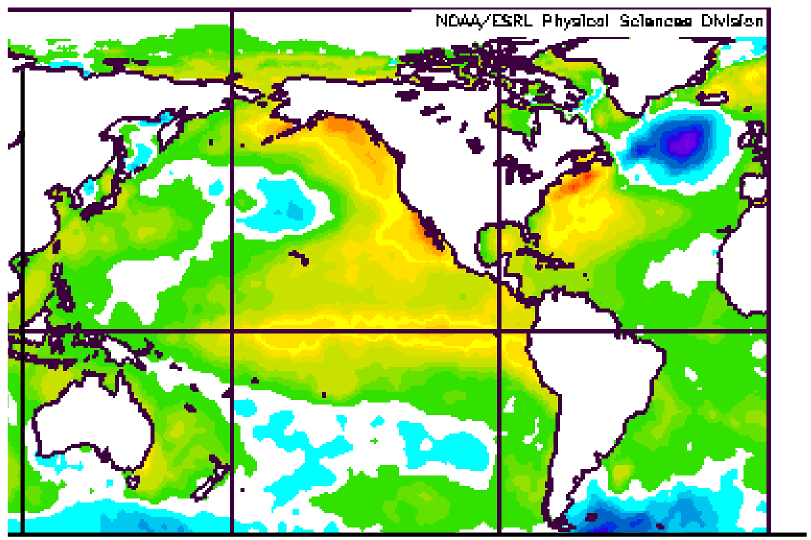
TAS 2015-2019 minus 1998-2012



Initialized prediction for 2015-2019 average

(Meehl, G.A., A. Hu, and H. Teng, 2016, *Nature Comms.*)

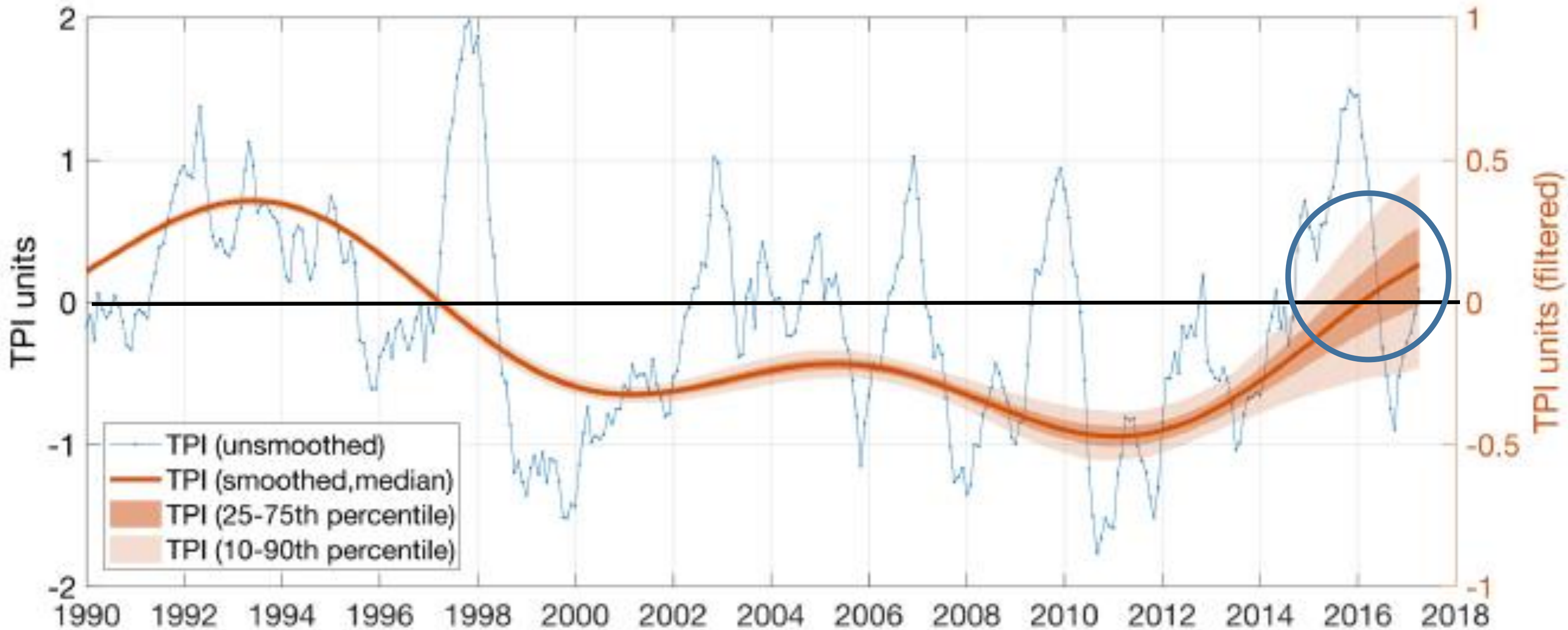
HadISST SST
Sea Surface Temperature (C) Composite Anomaly 1981-2010



Observed for ~2015-2019 average

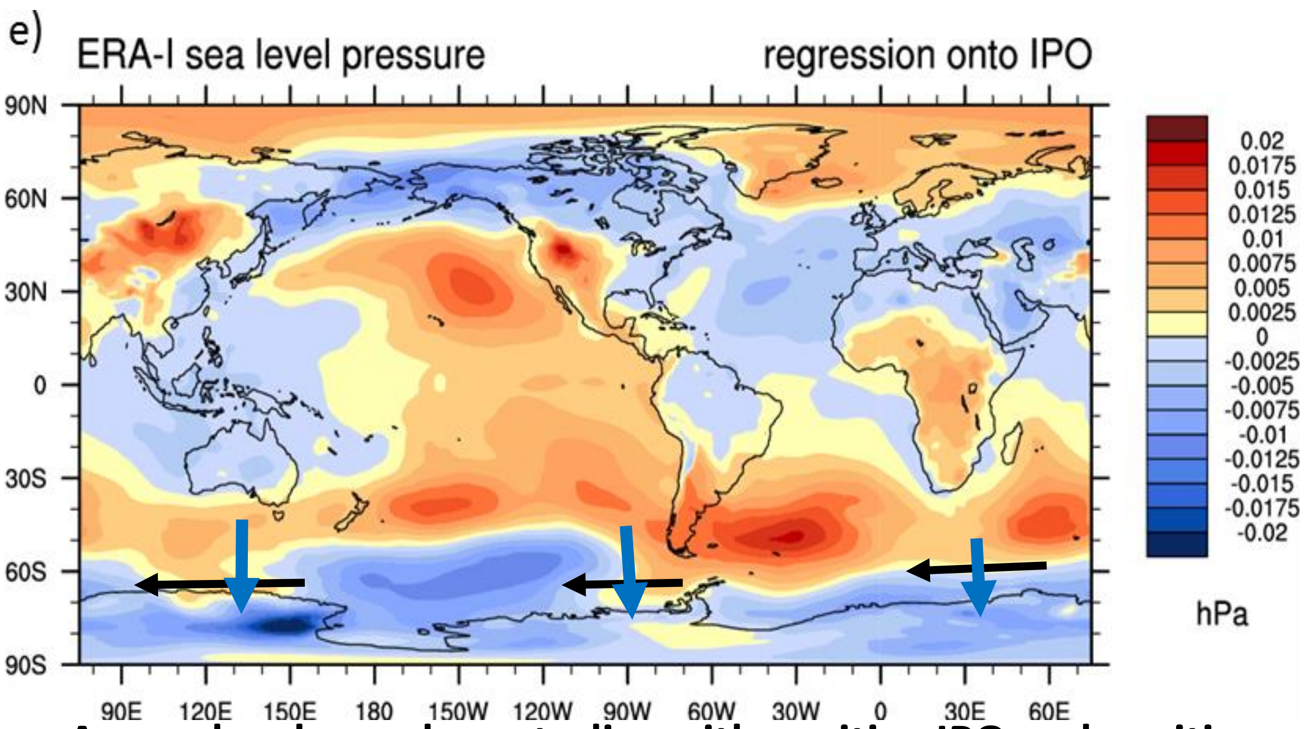
IPO transitioned to positive around 2015-2016

(Su et al., 2017, Sci. Rep.; Hu and Federov, 2017, GRL)



--Transition to positive IPO in 2015-2016 produced weak westerlies around Antarctica

--Ekman transport to the right brings warm surface water south to melt the ice; sustained due to decadal timescale of IPO



Anomalously weak westerlies with positive IPO and positive SAM, warm southward Ekman transport connects to warm subsurface water that had been moving upward for a decade, entire upper ocean now warm

Summary (part 1)

1. **Negative convective heating anomalies in the tropical Pacific from the negative phase of the IPO drove teleconnections and surface wind anomalies that contributed to the increasing Antarctic sea-ice extent from 2000-2014**

2. Decadal timescale convective heating anomalies from the tropics contributed to accelerated Arctic sea ice retreat in the 2000-2014 period (superimposed on long-term forcing from increasing greenhouse gases); negative IPO in the Pacific in the cold season, positive AMO in the Atlantic in the warm season

Summary (part 2)

3. What caused the sudden (and subsequently sustained) retreat of Antarctic sea ice starting in late 2016?

-- culmination of a decadal trend of strong westerlies around Antarctica with negative Interdecadal Pacific Oscillation that moved warmer water upward in the column closer to the surface around Antarctica

--a transition to positive Interdecadal Pacific Oscillation around 2015-2016, produced weaker westerlies and southward warm surface flow to complete the warming the entire upper ocean

--the trigger: Anomalous mid- and high latitude southward surface winds forced from the positive convective heating anomalies and record high SSTs in the tropical eastern Indian/western Pacific, southward warm surface winds and warmer water to the edge of the sea ice produced a warmer upper ocean from the surface to 200m depth and a sudden retreat of sea ice

What would it take to move warmer subsurface water upward?

Surface wind stress forcing can produce vertical motion in the water column (upward is "Ekman suction"):

$w_e = \frac{1}{\rho f} \nabla \times \tau \cdot \hat{k}$

w_e ~ curl of the wind stress

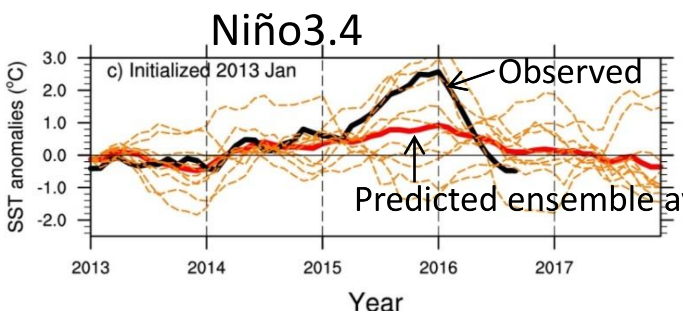
wind stress curl trend near 60˚S for the 2000s about 1×10^{-7} N m^{-3} yr^{-1},

average change of w_e over the last decade is about 0.5×10^{-6} m sec^{-1}.

-- about 15 m per year of upward vertical motion driven by the wind

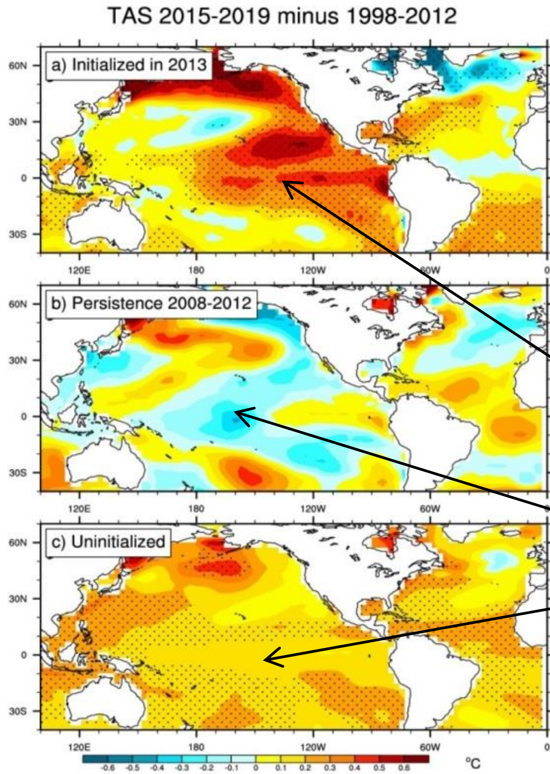
about 150 m of upward vertical motion if applied over 10 years.

Initialized prediction

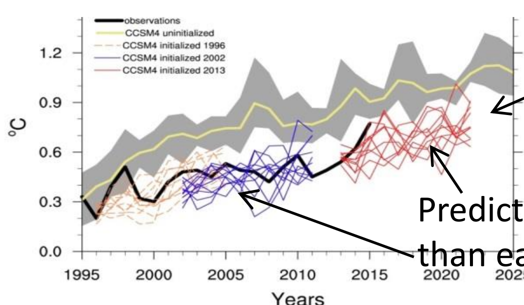


Model initialized in 2013 predicted small warming in 2014 followed by larger El Niño in 2015-2016

Physical basis for prediction skill: Initialized hindcasts show model qualitatively captures ENSO evolution in eastern equatorial Pacific that triggers decadal timescale IPO transitions associated with off-equatorial western Pacific ocean heat content anomalies



Prediction (initialized in 2013) for years 3-7 (2015-2019) shows transition to positive phase of the IPO different from persistence or uninitialized



Predicted transition to positive IPO produces global temperature trend for 2013-2022 of +0.22±0.13°C/decade, nearly 3 times larger than 2001-2014 trend of +0.08±0.05°C/decade during previous negative phase of IPO

(Meehl, G.A., A. Hu, and H. Teng, 2016, *Nature Comms.*)

In SON 2016, SSTs over much over much of the Southern Ocean warmed and mixed layer depth shallowed

(gridded Argo float data)