Decadal variability, predictability, and predictions (or…how one thing leads to another in a research path)

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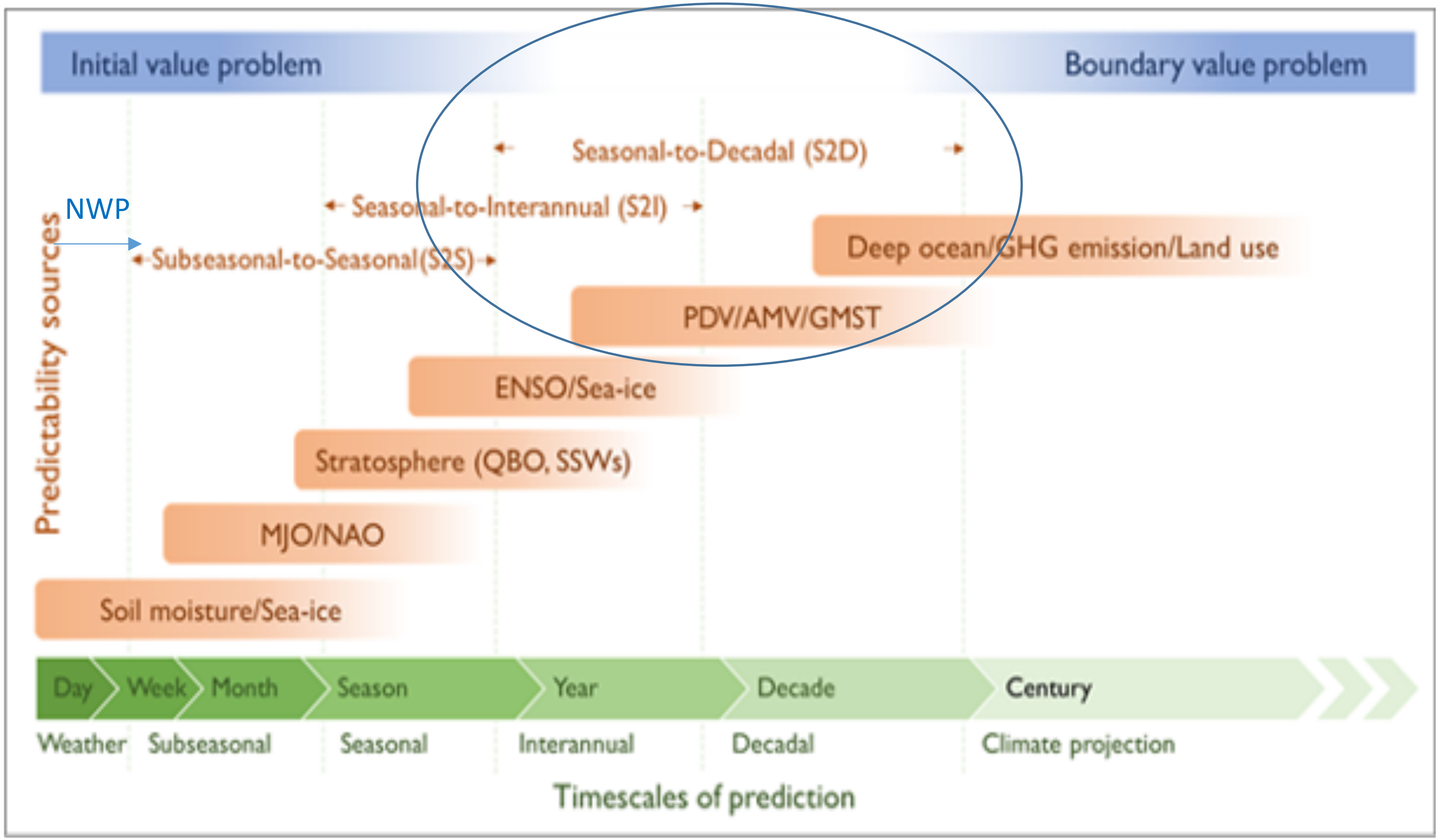
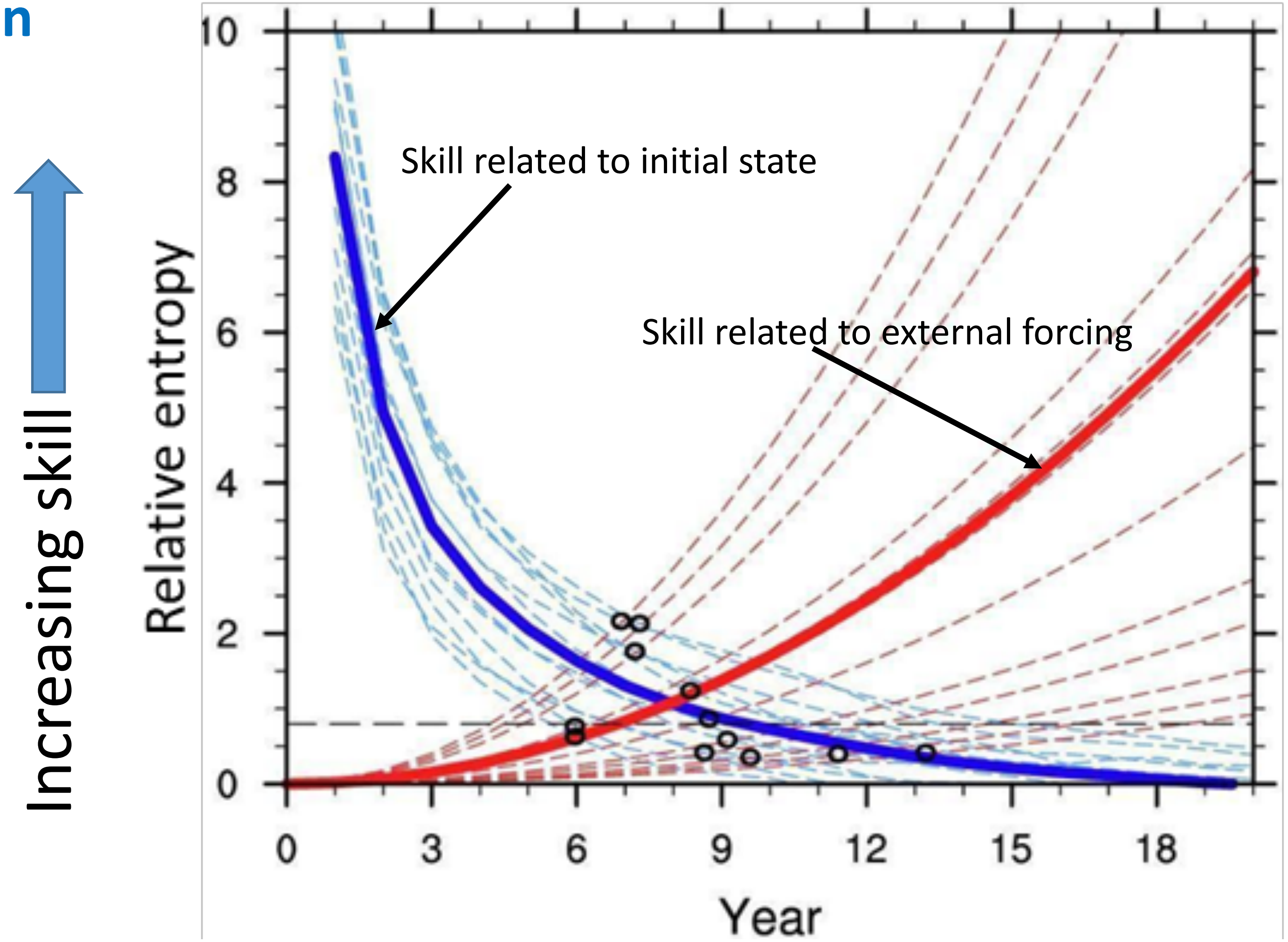
The initialized prediction landscape



(Meehl et al., 2021, *Nature Reviews Earth and Environment*, https://doi.org/10.1038/s43017-021-00155- x)

S2S timescale (~ 2 weeks to 2 months),
S2I timescale (~2 to 12 months), S2D timescale (~ 3 months to ten years)

Prediction skill can come from the initial state or external forcing, and depends on the time scale and region



(dashed lines indicate uncertainty measured from 12 CMIP5 models; black circles indicate when decreasing skill from the initial state crosses over increasing skill from external forcing, for upper 300m ocean layer, North Atlantic, horizontal black dashed line indicates 90% significance level) (Branstator and Teng, 2012).

Decadal climate variability related to initialized prediction presumes:

--there are relevant decadal timescale processes and mechanisms that arise from coupled processes with the ocean playing a major role (Atlantic Multidecadal Variability—AMV (AMO) and Pacific Decadal Variability—PDV (IPO) are major candidates)

-- if initialized properly, these processes and mechanisms could provide predictive skill beyond the first year or two

Major issue for studying/understanding/predicting decadal climate variability:

--the observational record is short relative to the timescales of decadal climate variability, and external forcing is a complicating factor

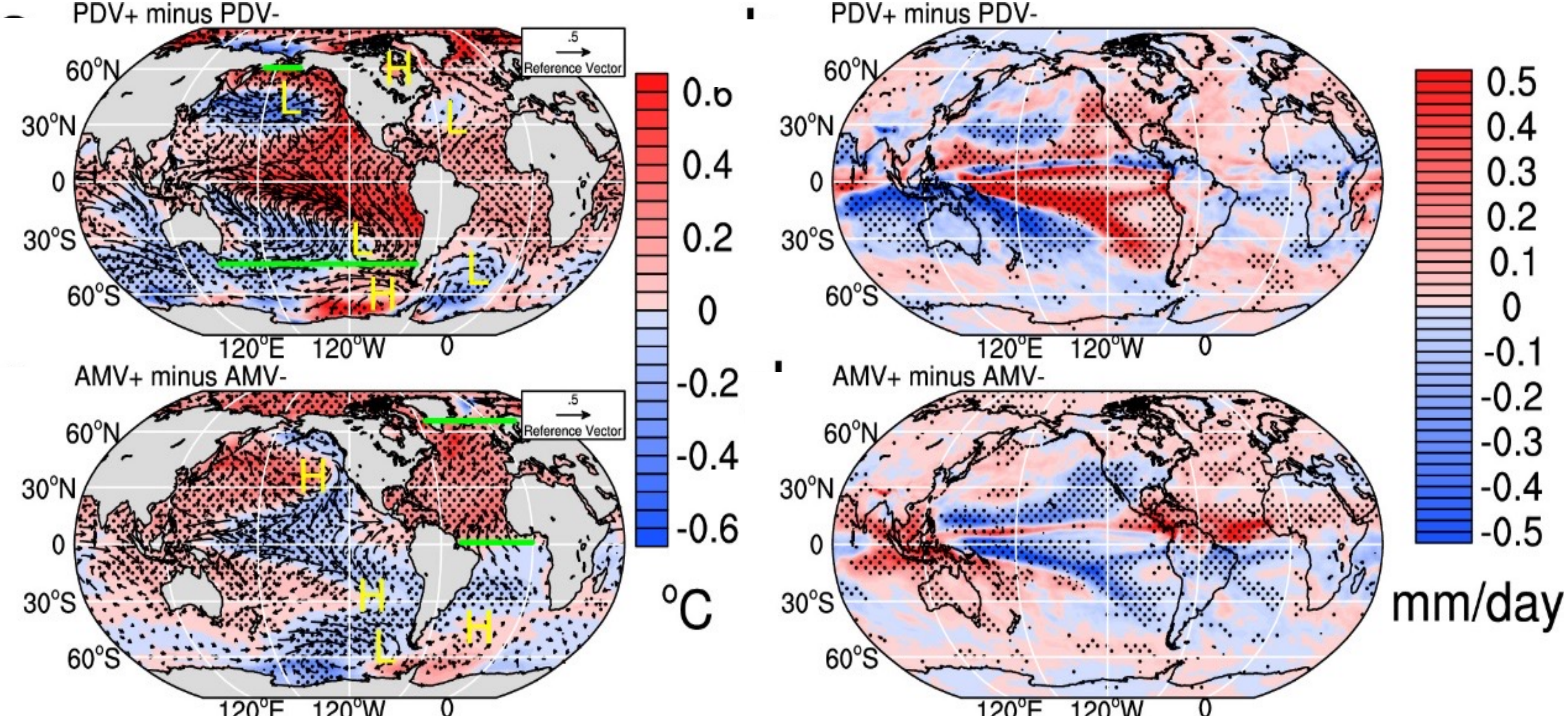
-- must rely on a hierarchy of climate models:

- **fully coupled unforced long control runs and historical simulations**
- **pacemaker model configurations (specify observed SSTs in one region while the rest of the model is fully coupled)**
- **atmospheric model with specified convective heating anomalies to test teleconnections**

How are AMV (AMO) and PDV (IPO) related?

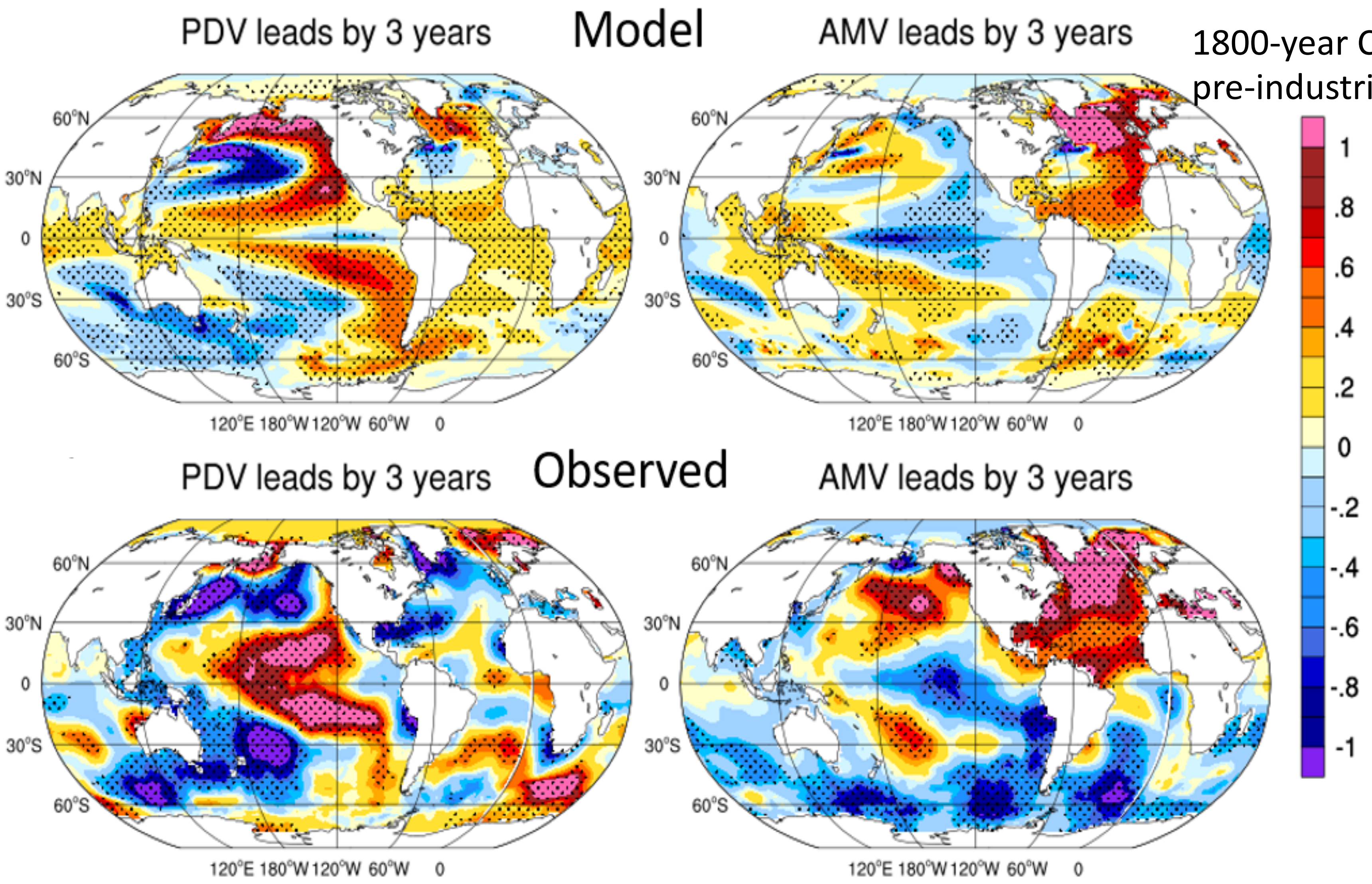
Perhaps if one was driving the other, then a skillful prediction of decadal variability in one basin would drive the other; the resulting predicted SST and teleconnections would then simplify the decadal climate prediction problem

Idealized pacemakers: specified PDV SSTs produce same-sign SST response in tropical Atlantic
specified AMV SSTs produce opposite-sign SST response in tropical Pacific



(Meehl et al., 2020, *Nature Geo.,* doi:10.1038/s41561-020-00669-x)

Lagged regression winter (DJFM) SST on AMV and PDV indices


Model

PDV leads by 3 years

AMV leads by 3 years

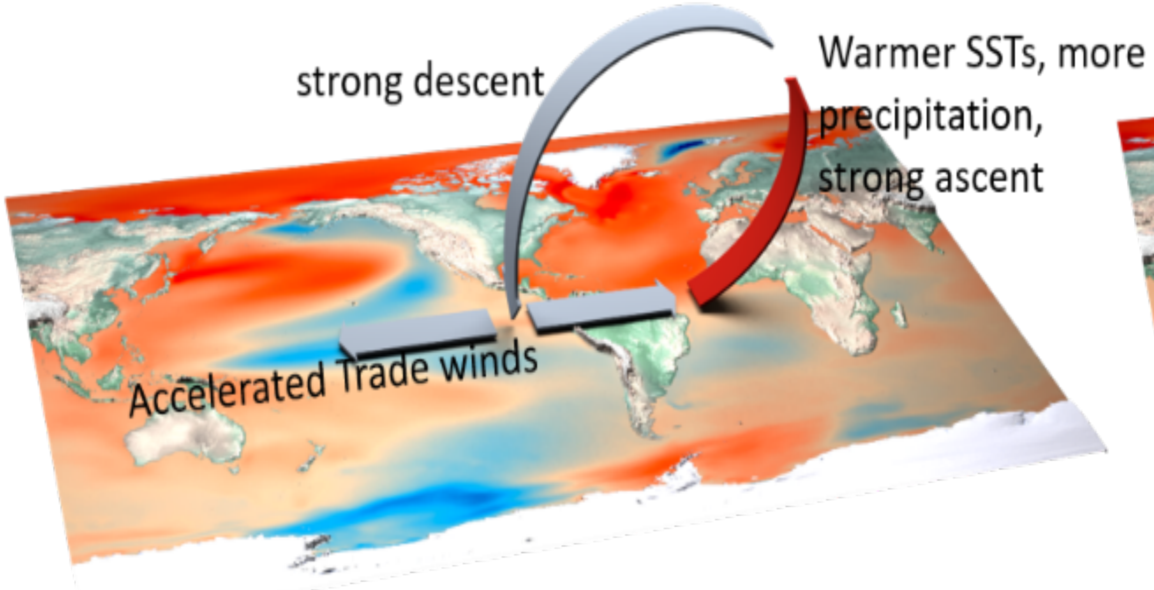
Observed

PDV leads by 3 years

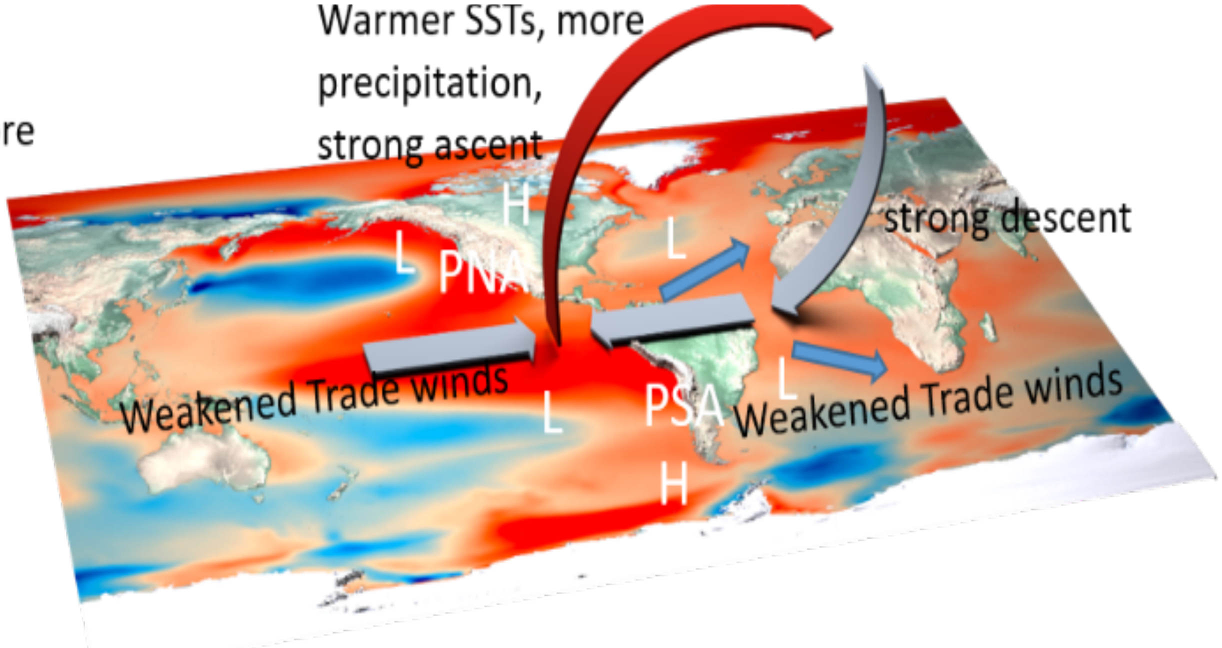
AMV leads by 3 years

1800-year CESM1 large ensemble
pre-industrial control

(Meehl et al., 2020, *Nature Geo.*, doi:10.1038/s41561-020-00669-x)



Tropical Atlantic drives opposite sign tropical Pacific



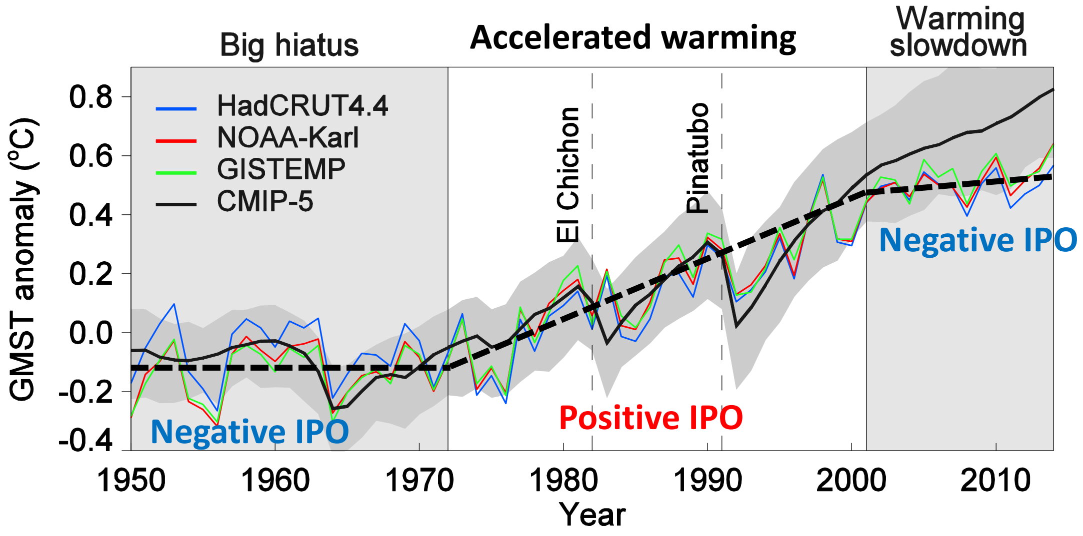
Tropical Pacific drives same sign tropical Atlantic

A new paradigm for understanding decadal timescale variability: processes in the Pacific and Atlantic are mutually and sequentially interactive mainly through the atmospheric Walker Circulation along with contributions from midlatitude teleconnections for the Atlantic response to the Pacific.

(Meehl et al., 2020, *Nature Geo.,* doi:10.1038/s41561-020-00669-x)

Focus on the IPO in the Pacific:

If we could predict the IPO (in terms of Pacific basin SSTs), what additional climate effects could then be predicted?



Phase of the IPO connected to magnitude of the global mean surface temperature trend:

Negative IPO = slower warming trend

Positive IPO = faster warming trend

(Fyfe, J.C., G.A. Meehl, M.H. England, M.E. Mann, B.D. Santer, G.M. Flato, E. Hawkins, N.P. Gillett, S.-P. Xie, Y. Kosaka, and N.C. Swart, 2016, *Nature Climate Change*, **6**, 224—228, doi:10.1038/nclimate2938).

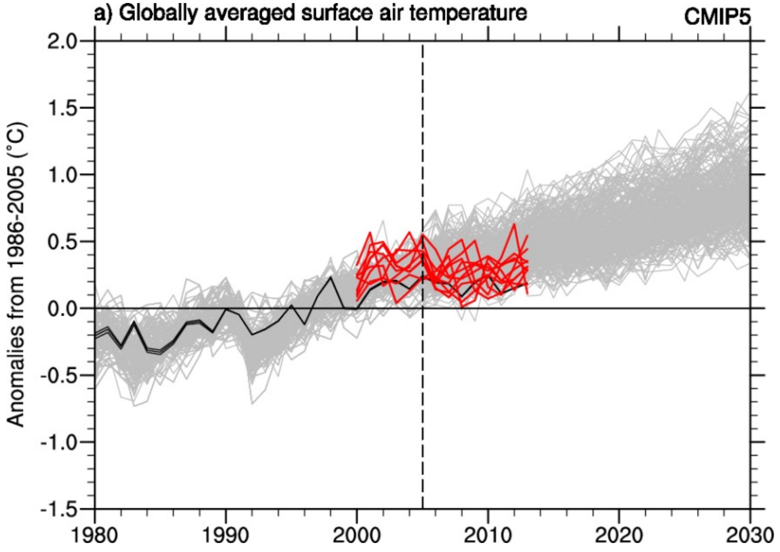
Did any CMIP5 models simulation the early 2000s slowdown?

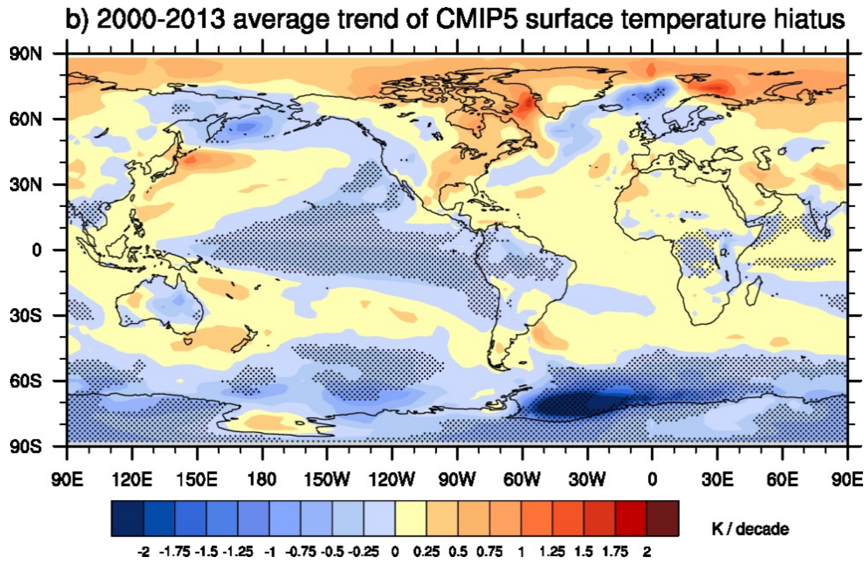
Slowdown as observed from 2000-2013:
10 members out of 262 possible realizations

Some CMIP5 uninitialized models actually simulated the slowdown as observed

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

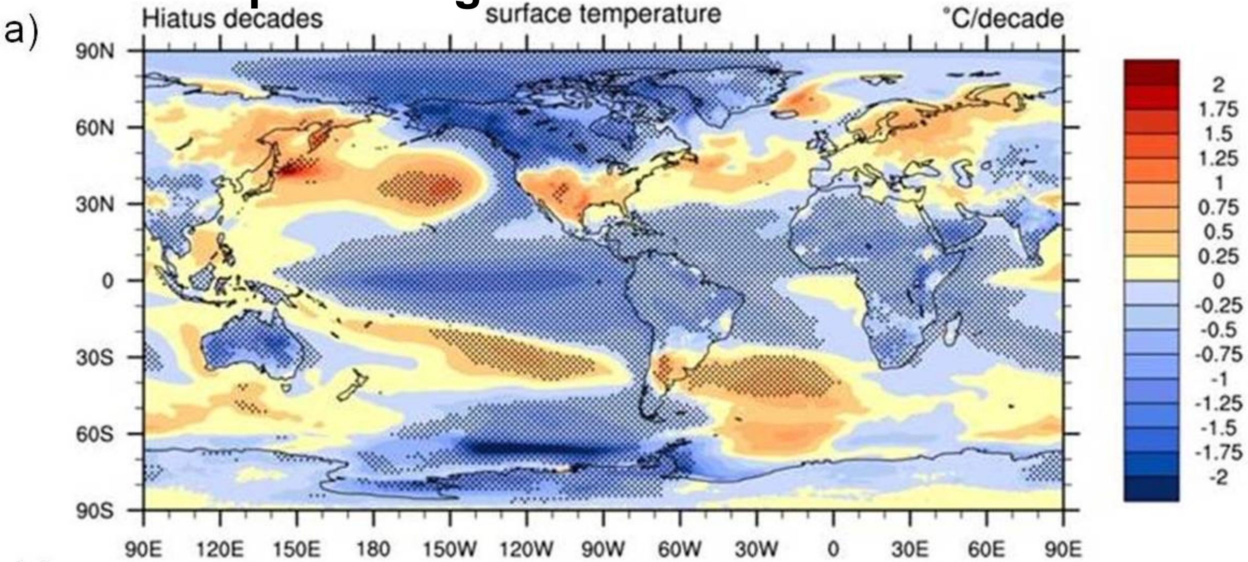
internally generated variability in those model simulations happened to sync with observed internally generated variability

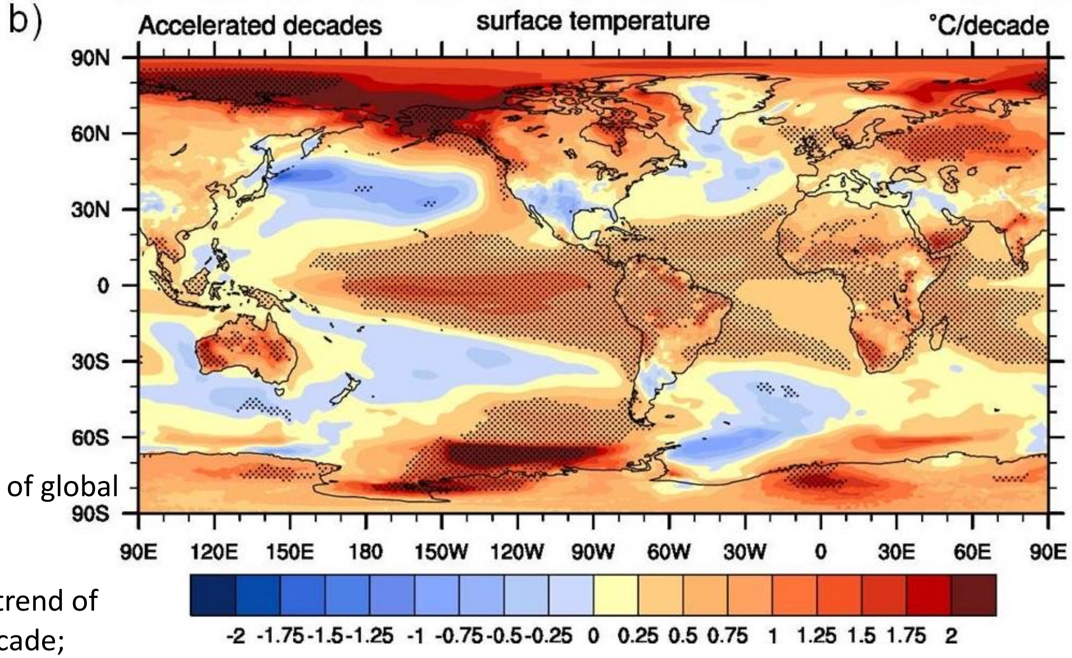




(Meehl et al., 2014, Nature Climate Change)

Is the IPO producing slowdown and accelerated warming decades?





(hiatus=linear trend of global T <-0.10K/decade;
8 hiatus decades
Accelerated=linear trend of global T>+0.41K/decade;
7 accelerated warming decades)

(Meehl et al., 2011, Nature Climate Change; Meehl et al., 2013, J. Climate)

Five CCSM4 21st century simulations with RCP4.5 (uniform increase in GHGs, no volcanoes):

Composites of decades with near-zero global warming trend (hiatus or slowdown decades) show negative IPO

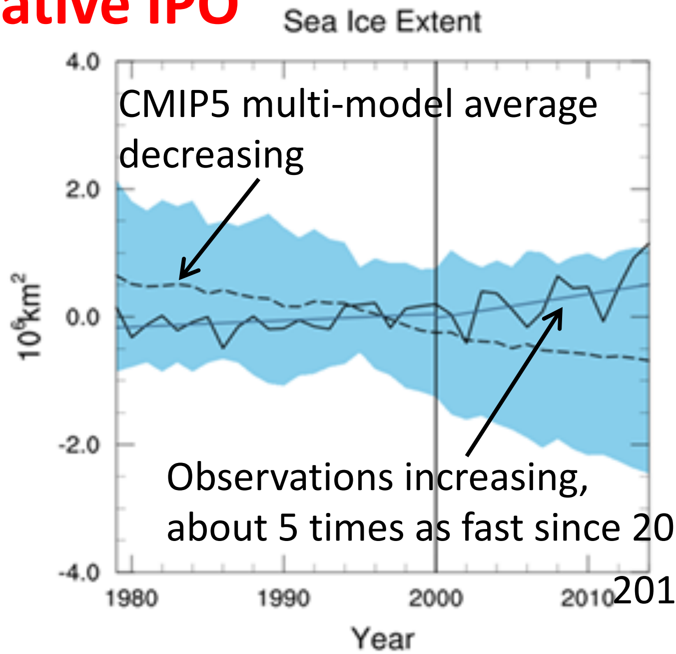
Decades with rapid global warming (accelerated warming decades) show positive IPO in the Pacific

Why? Negative IPO and slowdown in global T trend due to a cooler ocean surface layer due to more heat being put into deeper ocean through stronger STCs in Pacific, stronger AMOC, and weaker Antarctic bottom water formation (and vice versa for positive IPO and more rapid global warming)

IPO connections to Antarctic sea ice

extent increased more rapidly after 2000 during negative IPO (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?**

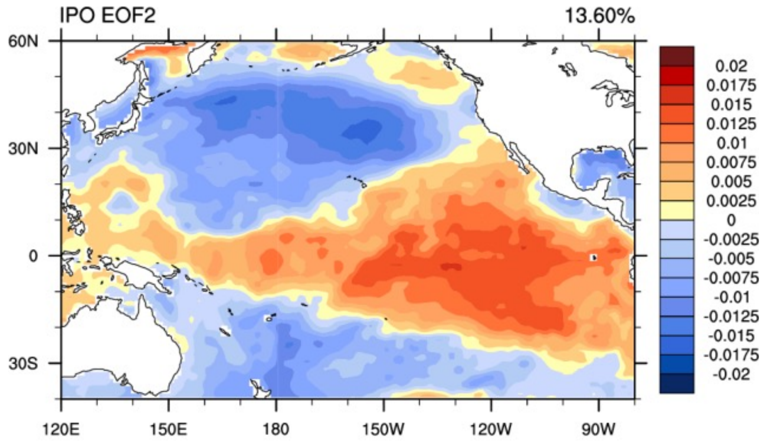


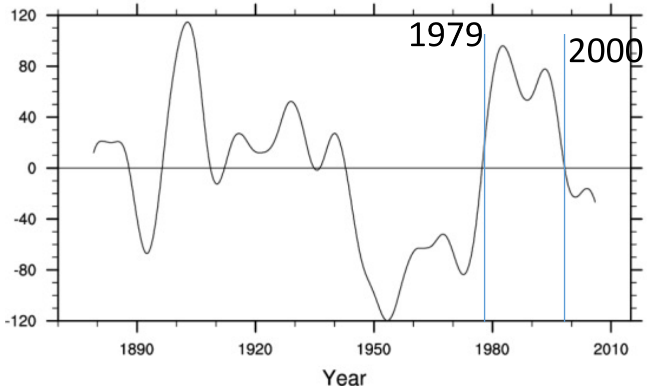
CMIP5 multi-model average decreasing

Observations increasing, about 5 times as fast since 2000

2014

linear trend 1979-1999: +0.12 x 10^6 km^2 decade^{-1}
2000-2014: +0.57 x 10^6 km^2 decade^{-1}



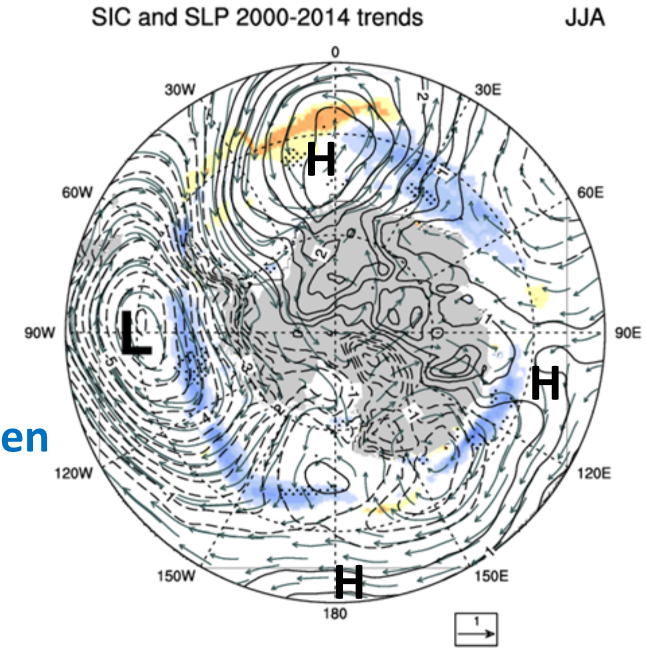


(Meehl, Arblaster, Bitz, Chung, and Teng, 2016: *Nature Geoscience*, DOI: 10.1038/NGEO2751.)

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

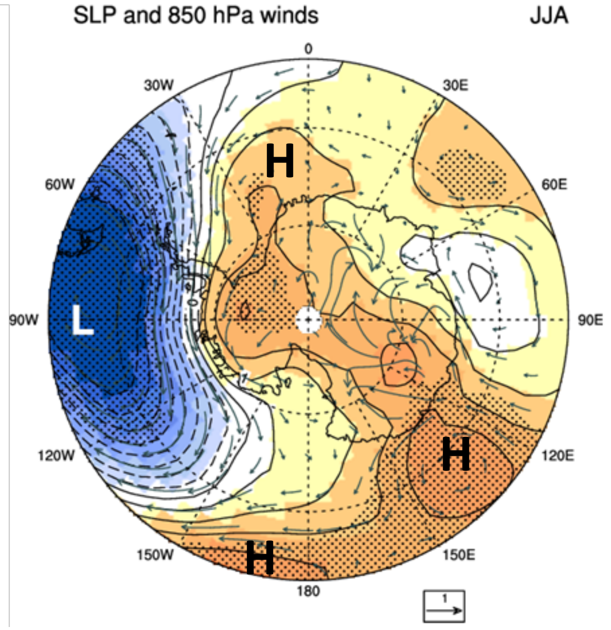
Specified convective heating anomaly experiments with CAM showed that the negative phase of the IPO contributed to anomalous surface winds near Antarctica that expanded Antarctic sea ice

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


SIC and SLP 2000-2014 trends JJA

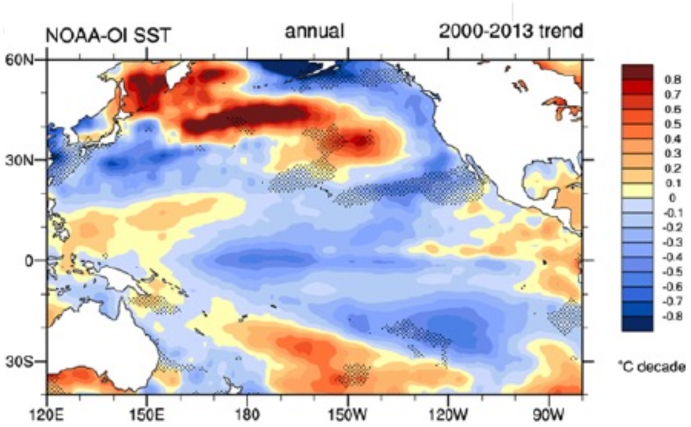
Model sensitivity experiment: IPO-related negative convective heating anomalies in eastern tropical Pacific (135W, Eq) produce and anomalous atmosphere Rossby wave response involving a deepened Amundsen Sea Low and preponderance of equatorward surface winds that expand Antarctic sea ice

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

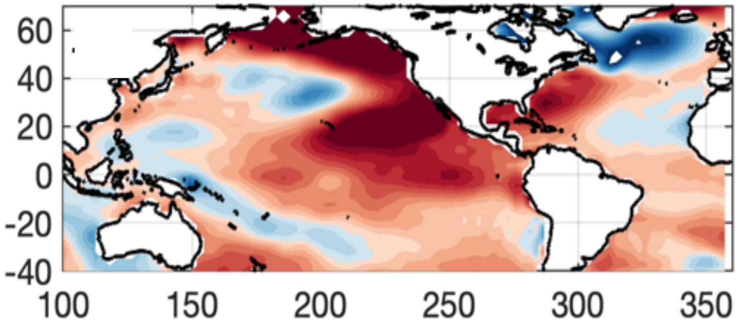

SLP and 850 hPa winds JJA

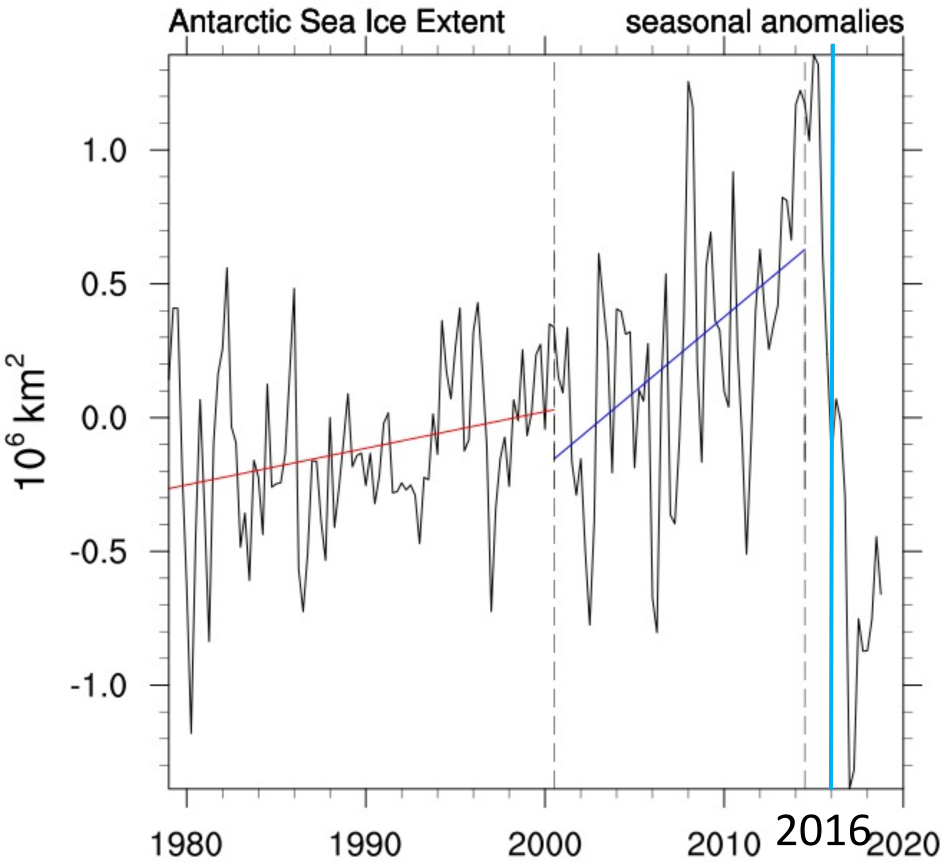
(Meehl, Arblaster, Bitz, Chung, and Teng, 2016: *Nature Geoscience*, DOI: 10.1038/NGEO2751.)

Negative IPO, 2000-2013



Positive IPO, 2015-2019





There was a sudden and dramatic *decrease* of Antarctic sea ice extent in late 2016 sustained through 2018 and 2019 associated with transition from negative to positive IPO

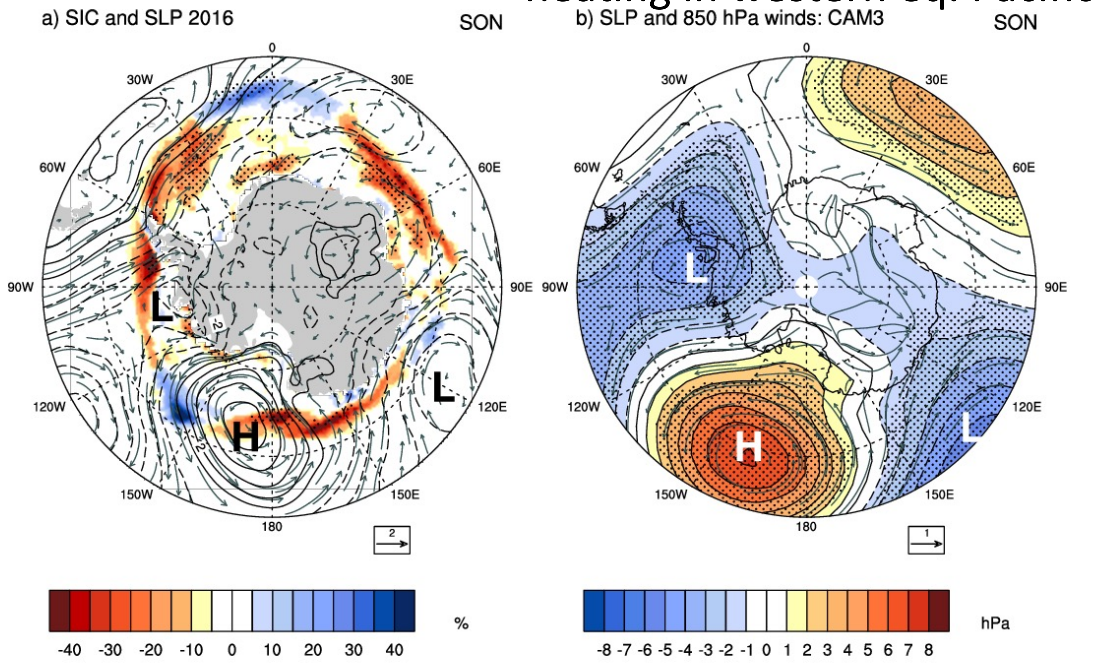
(Meehl et al., 2019, *Nature Comms.*, **10**:14, https://doi.org/10.1038/s41467-018-07865-9)

-- 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

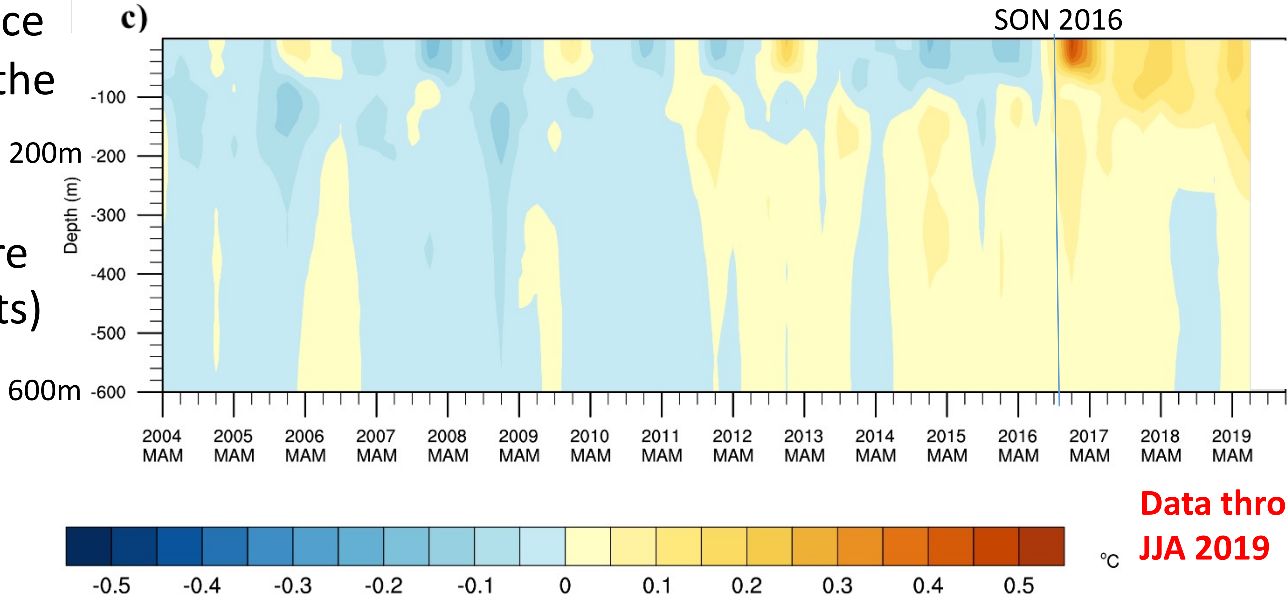
--a transition to positive Interdecadal Pacific Oscillation around 2015-2016, produced weaker westerlies and southward warm surface flow to complete the warming the entire upper ocean (and negative SAM)

Observations 2016

CAM positive convective heating in western eq. Pacific



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

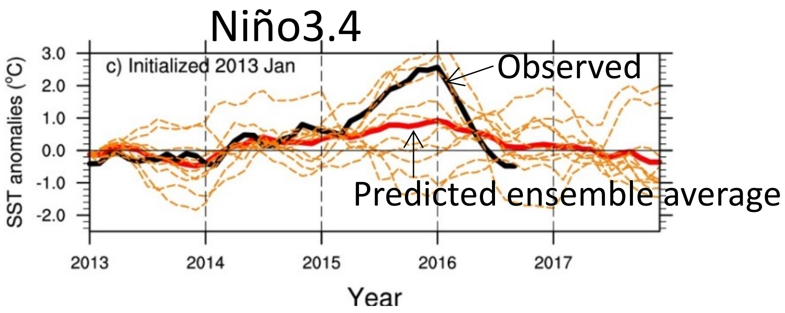


In SON 2016, entire zonal mean water column in upper 600m had positive temperature anomalies

Data through JJA 2019

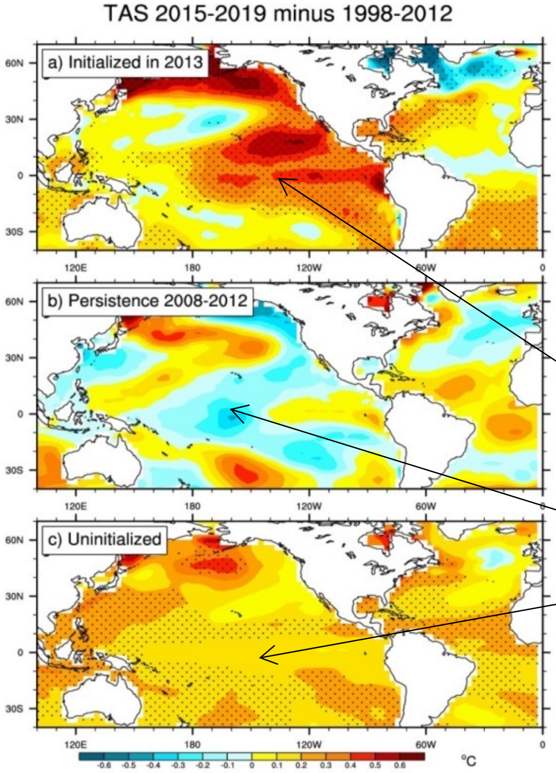
(Meehl et al., 2019, *Nature Comms.*, **10**:14, https://doi.org/10.1038/s41467-018-07865-9)

Published initialized prediction for IPO transition to positive ~2015 using CCSM4



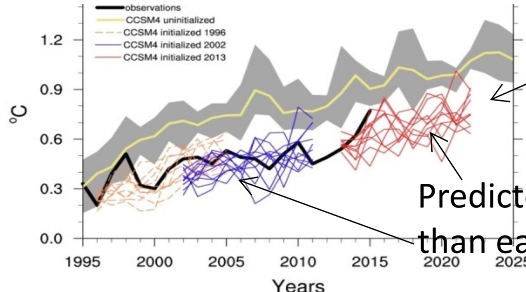
Model initialized in 2013 predicted small warming in 2014 followed by larger El Niño in 2015-2016

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



Predicted trend nearly 3 times larger than early 2000s

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

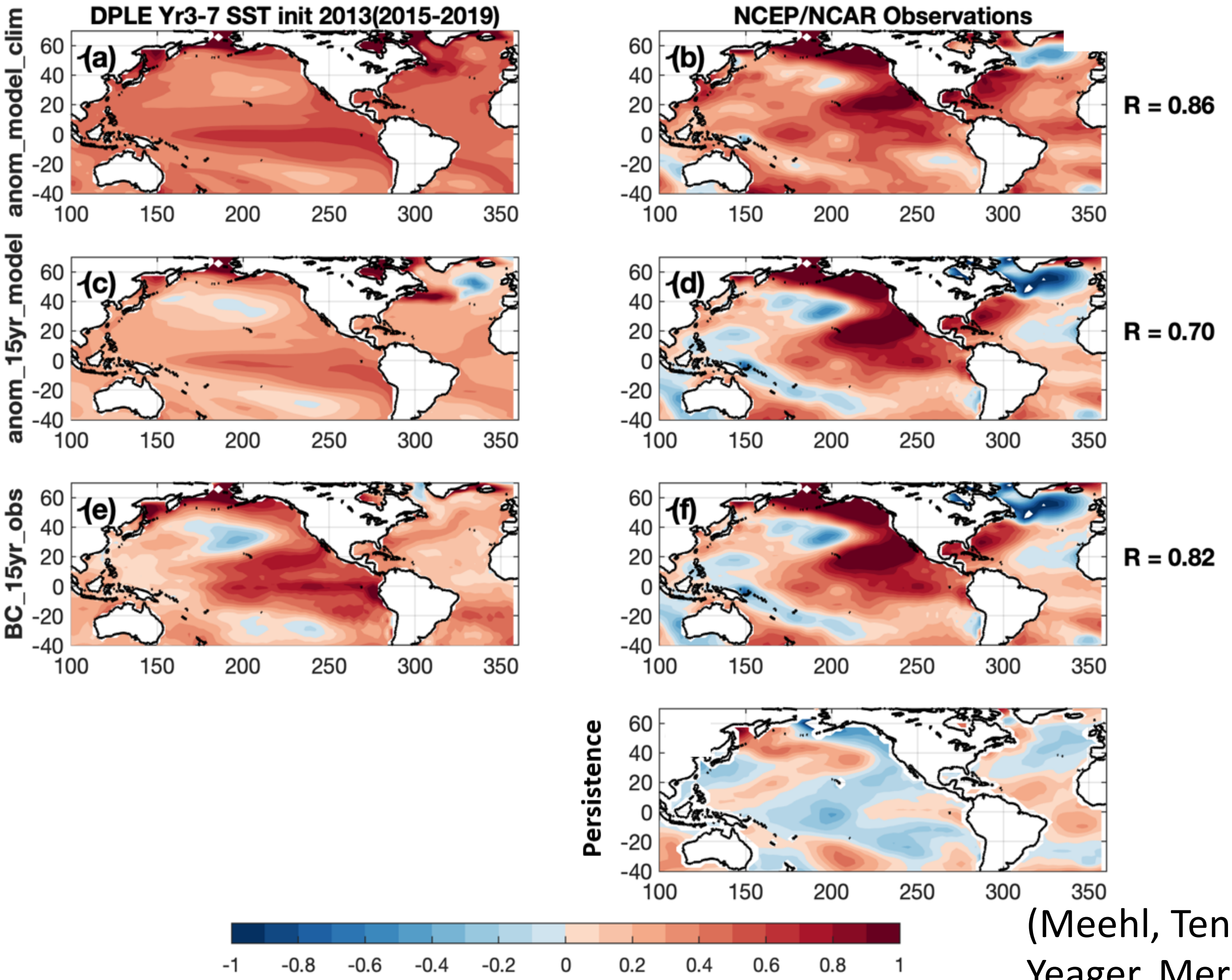
Similar result for positive IPO transition with CESM1, and verification with what ended up happening after 2015

CESM1 DPLE prediction initialized in 2013 for IPO transition in 2015-2019 (after Meehl et al., 2016)

Anomalies computed relative to entire climatology

Anomalies computed relative to previous 15 model years

Bias corrected anomalies computed relative to previous 15 observed years



(Meehl, Teng, Smith, Yeager, Merryfield, Doblas-Reyes, and Glanville, 2021, Cli. Dyn.)

ENSO activity on the interannual timescale can affect IPO transitions on the decadal timescale

(1800 year CESM1 pre-industrial control run)

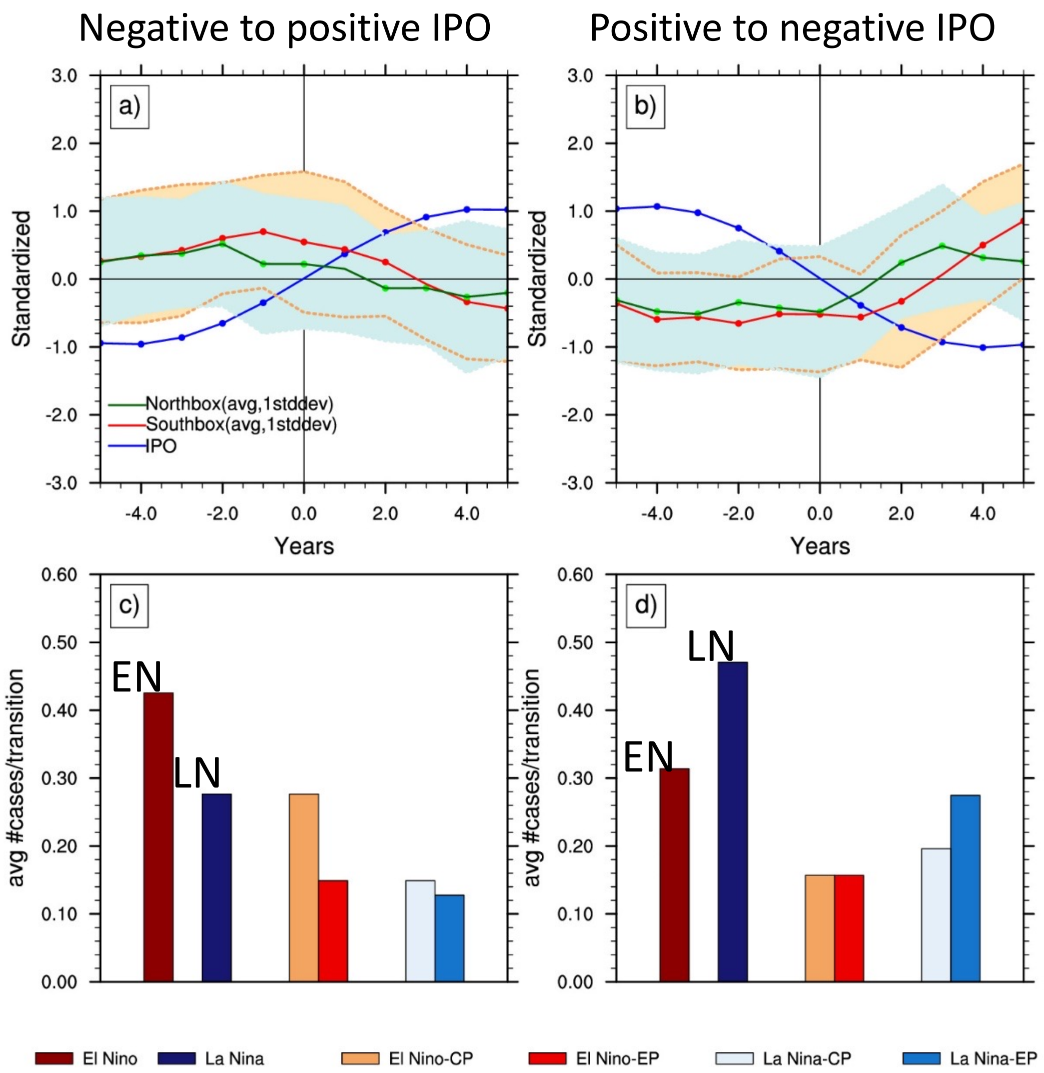
Off-equatorial ocean heat content reaches a necessary (but not sufficient) threshold (~0.5 standard deviations) prior to an ENSO event that provides the sufficient condition for a transition

In the year of an IPO transition from negative to positive, there is a better chance of an El Niño event

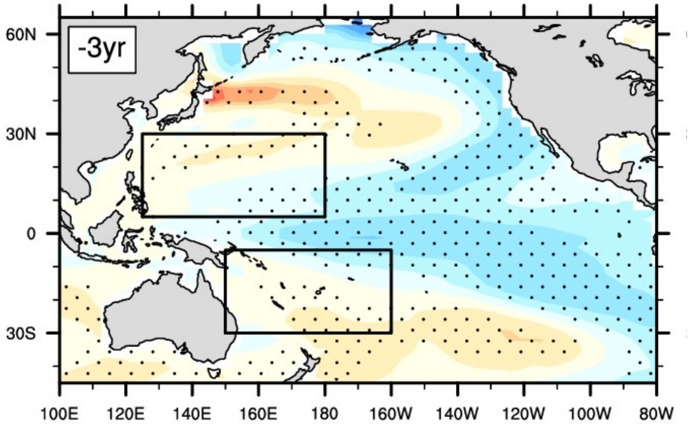
(and better chance of a La Niña event from positive to negative IPO)

1800 year CESM1 pre-industrial control run; Compute IPO index as the first EOF of low pass filtered SSTs for the Pacific basin; Select IPO transitions from positive to negative, and negative to positive; 47 cases of IPO negative to positive transition; 51 cases of IPO positive to negative transition

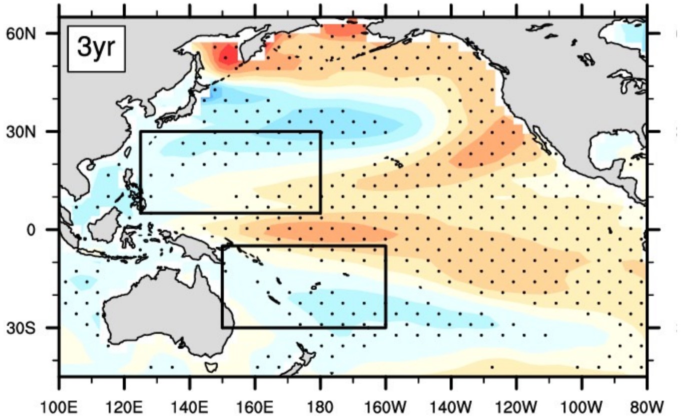
(Meehl, Teng, Capotondi, and Hu, 2021, Cli. Dyn.)



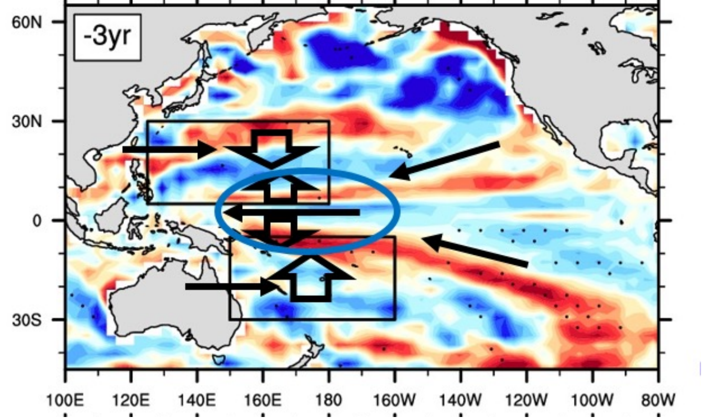
(El Niño: April-March Niño3.4 > +0.5°C for 5 consecutive overlapping 3 month seasons, events per IPO transition)



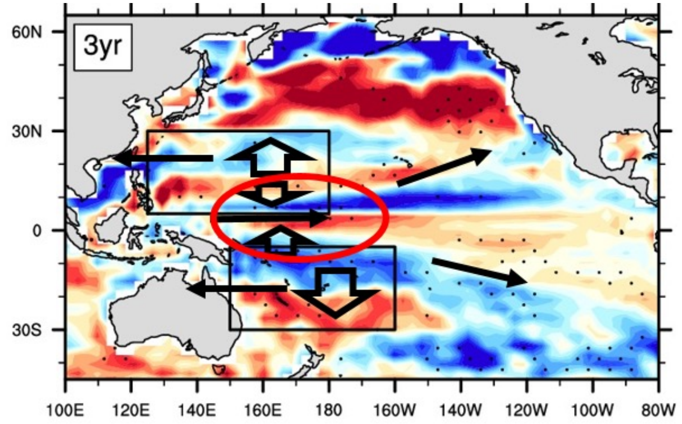
Negative IPO SST anomalies prior to transition



Positive IPO SST anomalies after transition



Wind stress curl anoms prior to transition



Wind stress curl anoms after transition

Composites from CESM1 long PI control run

(Meehl, Teng, Capotondi, and Hu, 2021, Cli. Dyn.)

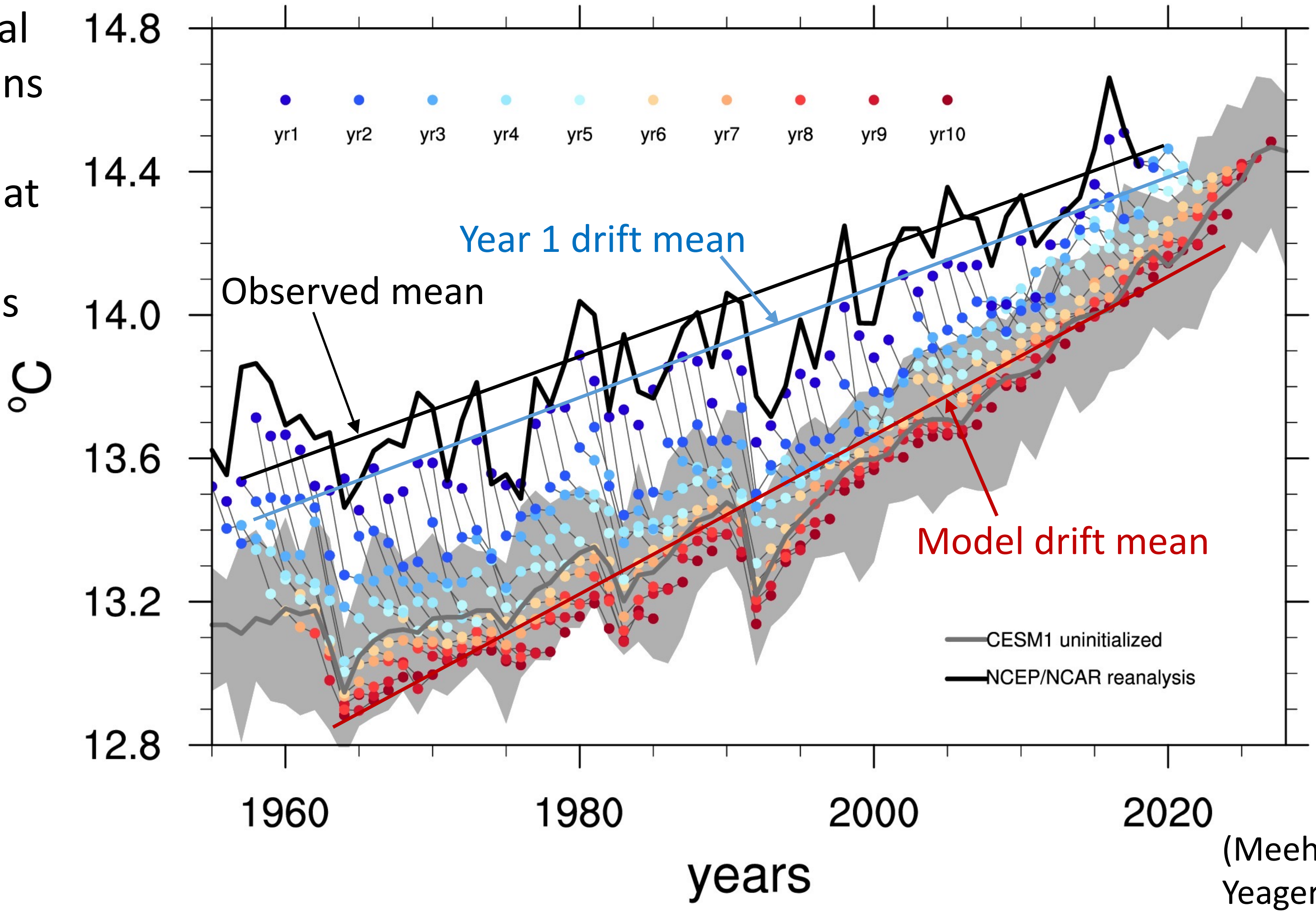
The build-up of decadal timescale upper ocean heat content in the off-equatorial western tropical Pacific from ocean heat divergence from equatorial western Pacific maintained by convective heating anomalies and off-equatorial surface winds from a Gill-type response

Ocean heat convergence into western equatorial Pacific from westerly anomaly near-equatorial surface winds associated with El Niño activity then sustain anomalously warm western and central Pacific SSTs from positive precipitation and convective heating anomalies, a Gill-type response and wind stress curl anomalies that continue to feed warm water into the near-equatorial western Pacific.

Remaining challenges: Model error, bias and drift

Bias: difference between model initial state and observations

Drift: Differences that develop between initialized predictions and observations as simulations evolve



Year 1 drift mean

Observed mean

Model drift mean

CESM1 LE and DPLE global surface temperature

Trends in climatology are less of a problem for shorter timescales:

S2S: 1999-2016 (18 yrs)

S2I (NMME): 1981-2010 (30 yrs)

S2D (DPLE): 1954-2015 (62 yrs)

(Meehl, Teng, Smith, Yeager, Merryfield, Doblas-Reyes, and Glanville, 2021, Cli. Dyn.)

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--Short observational record makes it difficult to understand decadal climate variability—indicates the need to use a hierarchy of model simulations, but what phenomena are we trying to understand?

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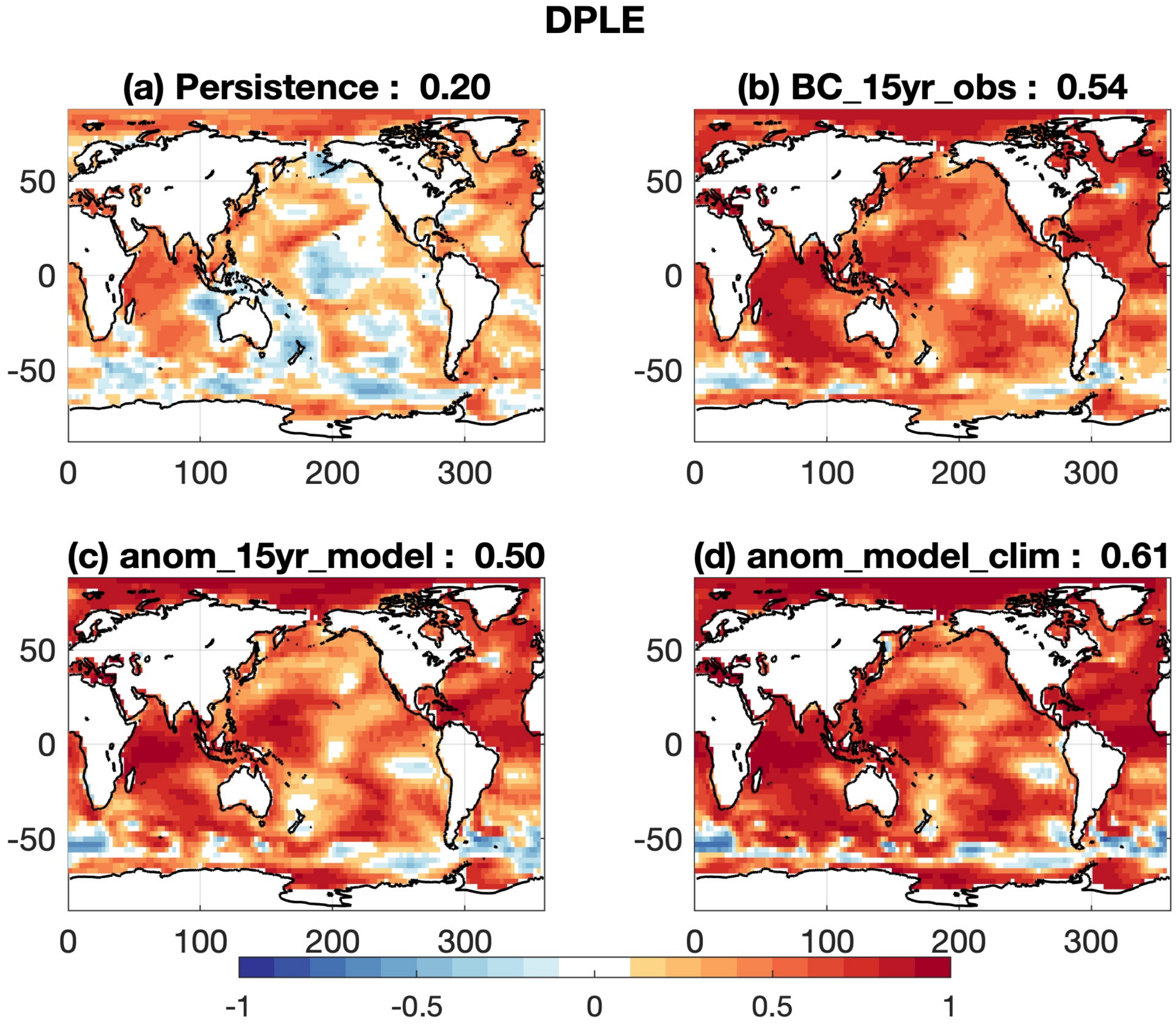
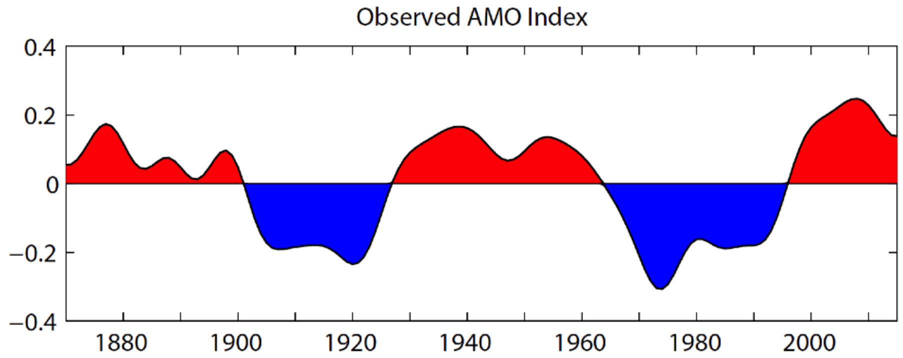
Less skill in the tropical Pacific in temporal correlations due in part to complicating effects of volcanic eruptions

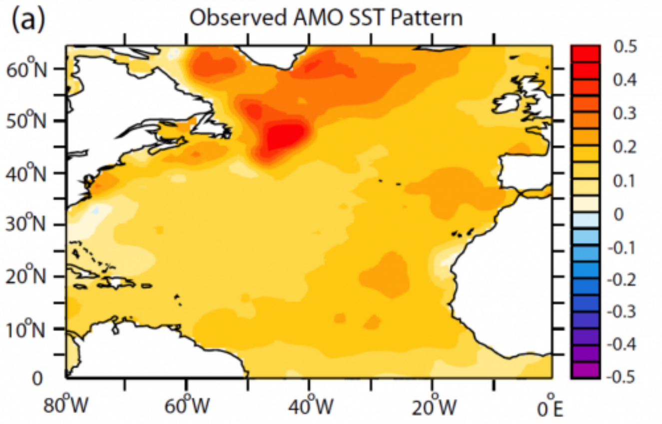


(Meehl, Teng, Smith, Yeager, Merryfield, Doblas-Reyes, and Glanville, 2021, Cli. Dyn.)

Chief candidates for decadal timescales processes and mechanisms:

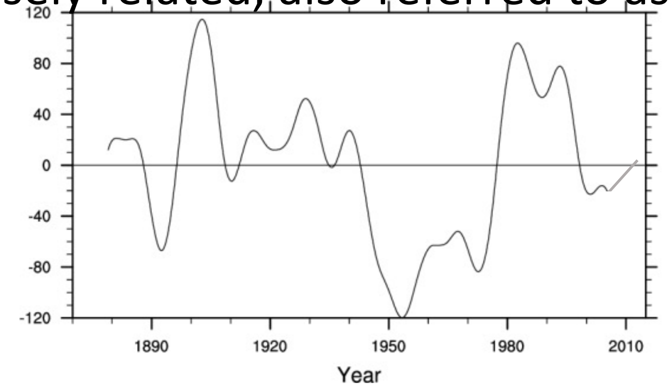
For the Atlantic: the Atlantic Multidecadal Oscillation (AMO) also referred to as Atlantic Multidecadal Variability (AMV)

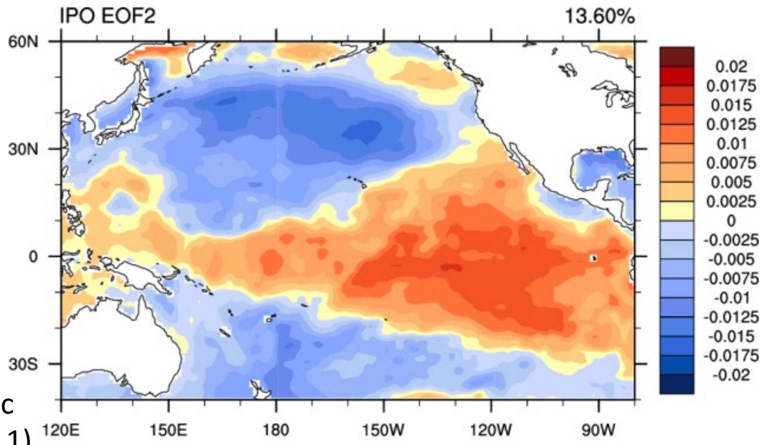




detrended 10-year low-pass filtered annual mean area-averaged SST anomalies over the North Atlantic basin (0N-65N, 80W-0E), using HadISST 1870-2015 (e.g. Trenberth and Shea, 2006)

For the Pacific: the Interdecadal Pacific Oscillation (IPO) and Pacific Decadal Oscillation (PDO); both are very closely related, also referred to as Pacific Decadal Variability (PDV)

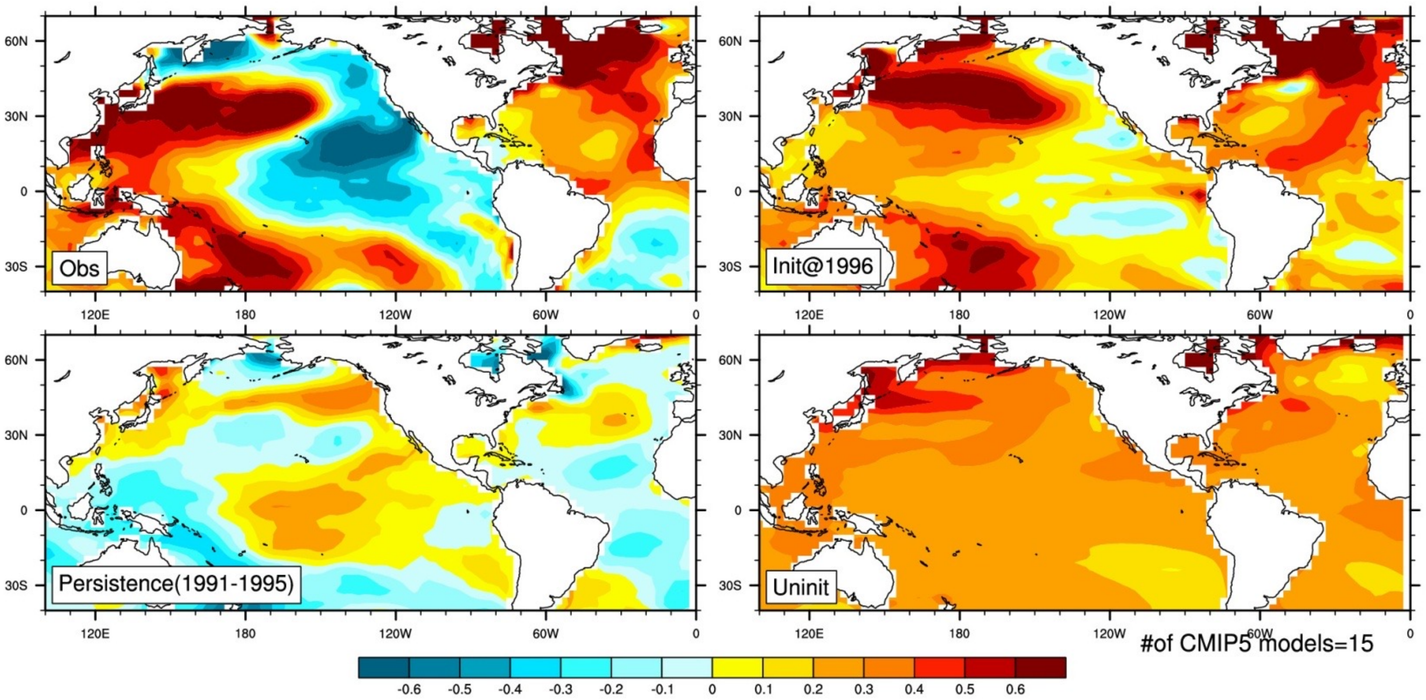




2nd EOF of low-pass filtered annual mean area-averaged SST anomalies over the Pacific basin (40S-60N, 120E-80W), using HadISST 1870-2015, (e.g. Meehl and Arblaster, 2011)

make a prediction in 1996 for years 1998-2002

TAS 1998-2002 minus 1981-1995



Change in net surface heat flux over global oceans, and Pacific wind stress index for CCSM4 DART (D) and Hindcast (H) runs

Indicates negative IPO

(positive heat flux means more heat going into deeper ocean; negative wind stress index means stronger trades)