An internal atmospheric process determining summertime Arctic sea ice melting in the next three decades

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The subject of the presentation:

- The Arctic summer (JJA) circulation has been dominated by an atmospheric process resembling an anticyclone centered above Greenland and Northeast Canada for the past 4 decades (Fig.1.); a circulation driven process that warms and moistens the lower troposphere adiabatically, thus regulates downward long wave radiation that can cause sea ice melt (see Ding et al. 2017).

- How is this represented in future model simulations?

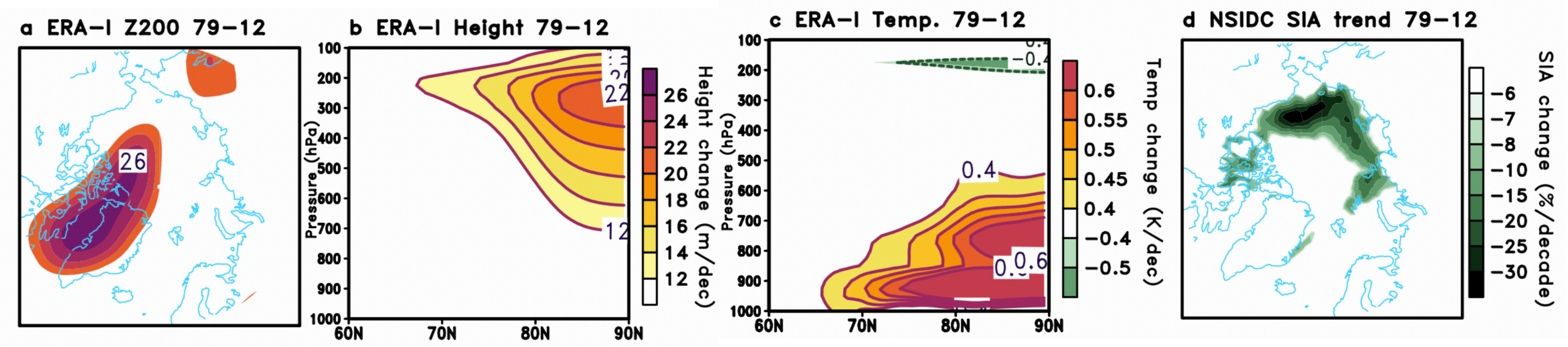


Fig.1. Observed (ERA-Interim Reanalysis/NSIDC) (a) Z200 (unit: m/decade), (b) zonal mean geopotential height (unit: m/decade), (c) zonal mean temperature (unit: K/decade) and (d) September sea ice area linear trends for JJA in 1979-2012.

Key points of the presentation

- In the next couple of slides we study how this atmospheric process is manifested in 5 large ensemble (LE) and 31 CMIP5 model simulations.
- We will show that models basically capture the observed mechanism (Fig.1.) albeit with limitations, which we propose to originate from a weaker simulated atmosphere-sea ice coupling mechanism:
    - All models show limitations in replicating the magnitude of the observed local atmosphere-sea ice coupling and its sensitivity to remote tropical SST variability in the past four decades.

MODELLING CENTER	MODEL VERSION	SHORT NAME	#MEMBERS	FORCING	REFERENCE
MPI	MPI-ESM-LR	MPI-GE	100	historical, RCP2.6, RCP4.5, RCP8.5	Maher et al. (2019)
CCCma	CanESM2	CanESM-LE	50	historical, RCP8.5	Kirchmeier-Young et al. (2017)
NCAR	CESM1	CESM-LE	40	historical, RCP8.5	Kay et al. (2015)
CSIRO	MK3.6	CSIRO-LE	30	historical, RCP8.5	Jeffrey et al. (2013)
GFDL	CM3	GFDL-LE	20	historical, RCP8.5	Sun et al. (2018)

The list of large ensemble of model simulations used in the presentation

How about past (1979-2012) sea ice changes in Obs. and models?

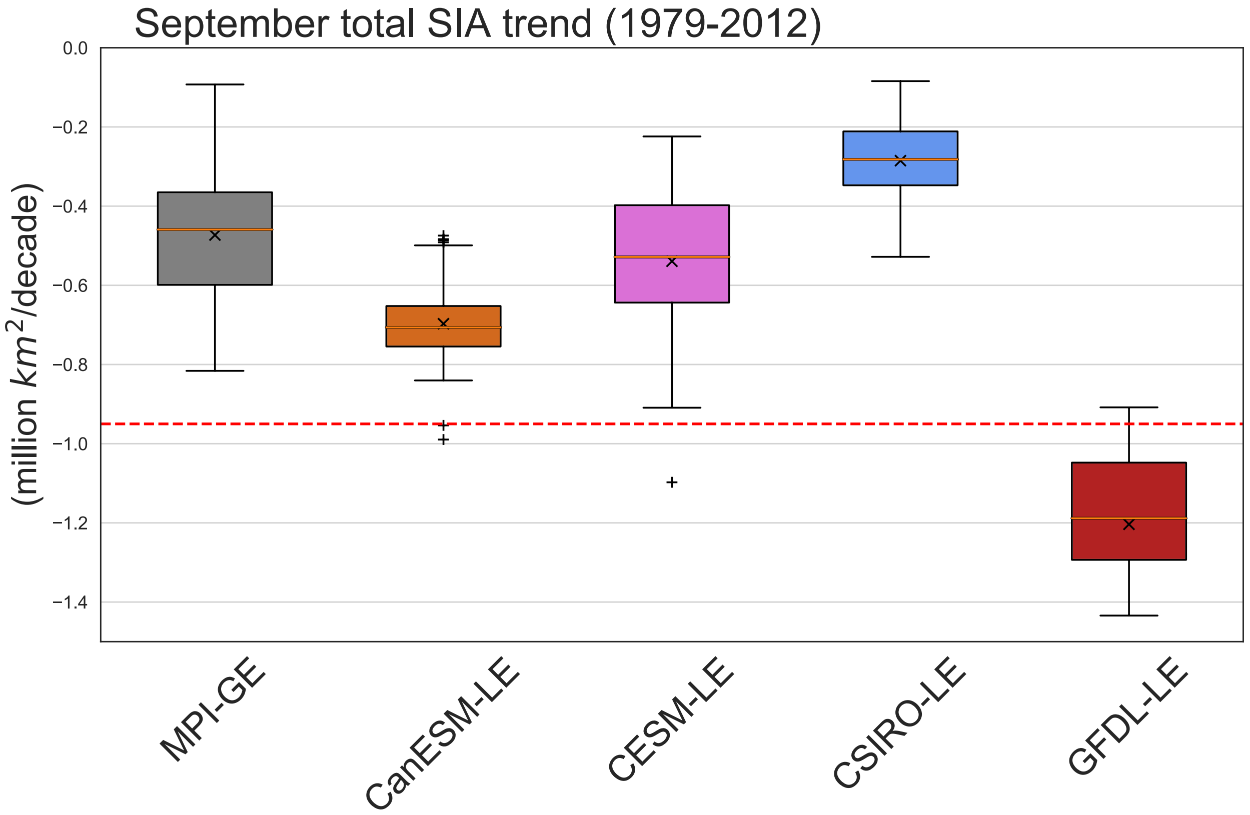


Fig.2. Box-Whiskers of September total sea ice area (SIA) index linear trends (1979-2012) in the 5 LE simulations (indicated below the x-axis) and the observed trend (red dashed line: -0.95*10^6 km^2/decade). The whiskers extend to the 90th and 10th percentiles and the box contains 75% of the data. Crosses mark average values, plus signs mark the outliers (1.5*IQR). The median is indicated with orange horizontal line.

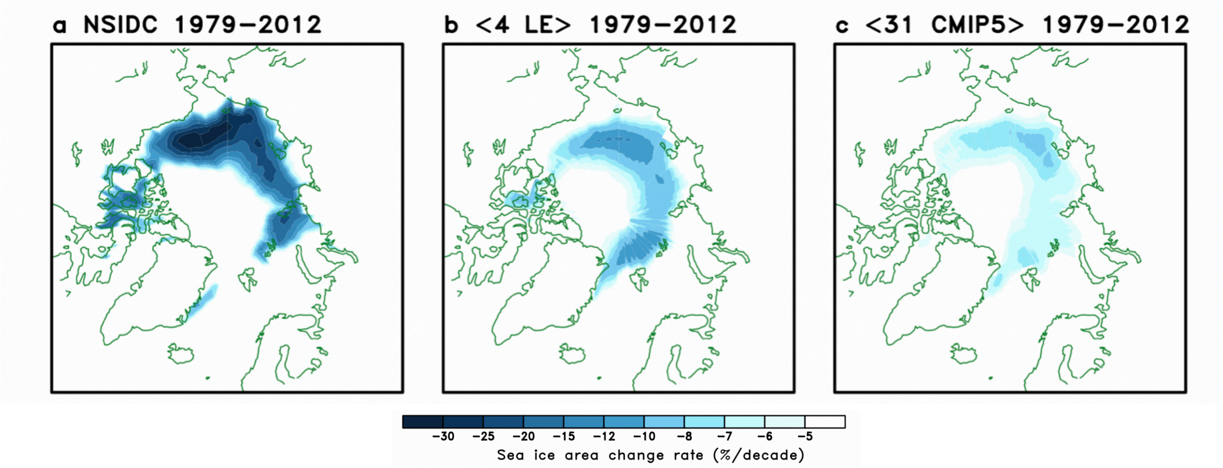


Fig.3. Linear trend of September sea ice area in: (a) observations (NSIDC), (b) the mean (denoted with < >) of the 4 LE's ensemble mean historical+RCP8.5 simulations (excluding CSIRO-LE) and (c) the mean of 31 CMIP5 historical+RCP8.5 simulations for 1979-2012.

1. **Spatial pattern is well reproduced in models!**
2. **Reasons behind the observed magnitude differences:**
   - lower sea ice sensitivity?
   - other inherent atmospheric processes?

Interannual atmosphere-sea ice coupling

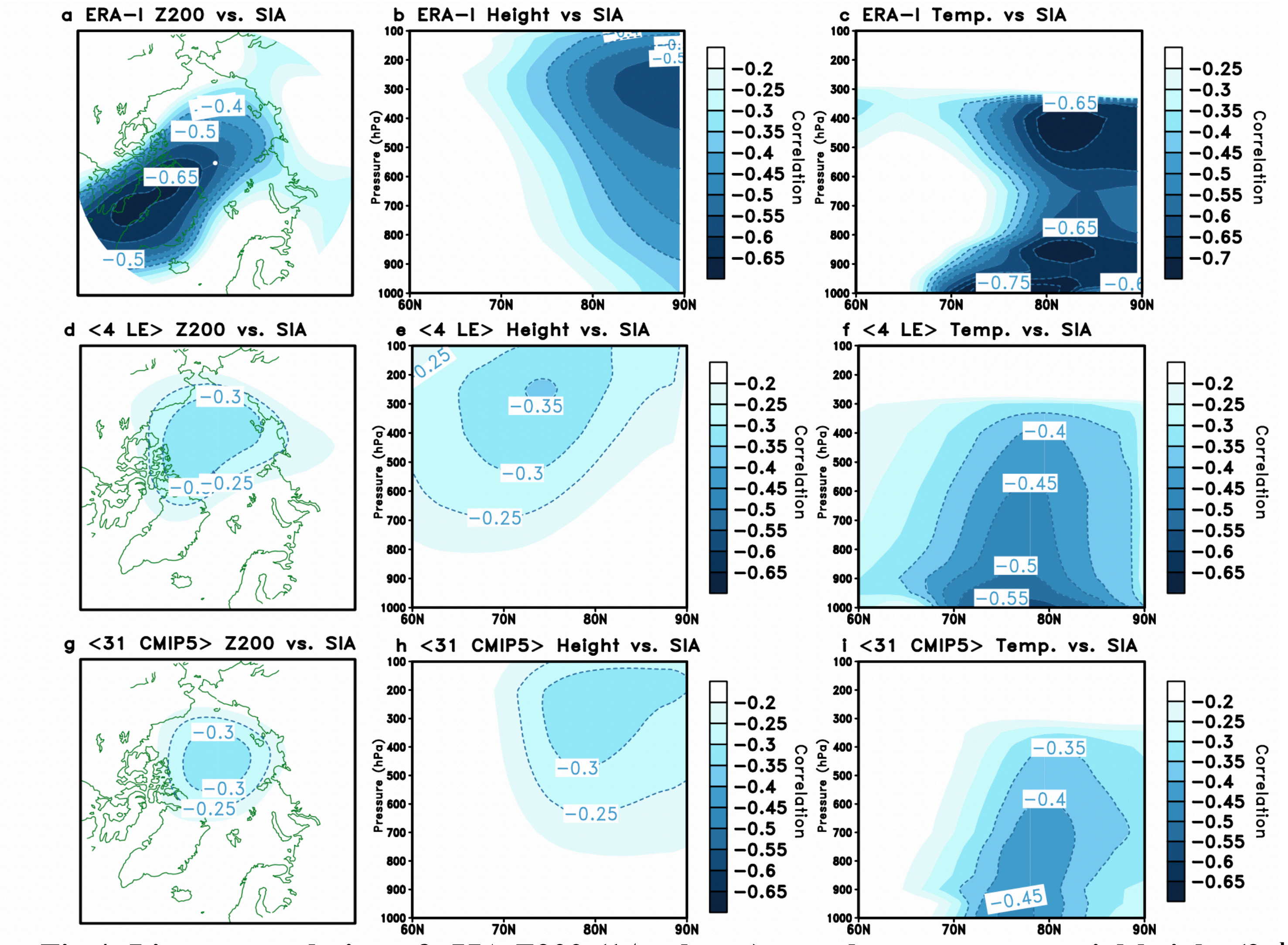


Fig.4. Linear correlation of: JJA Z200 (1st column), zonal mean geopotential height (2nd column) and temperature (3rd column) with September total sea ice area (SIA) index in ERA-I and the mean (< >) of 4 LE and 31 CMIP5 simulations (correlations are averaged after having been calculated in each members). All variables are detrended before correlation.

What to conclude?

- Observed correlations show a very similar pattern to the linear trends in the previous figure: **shared physical mechanism over the two timescales**
- Observed interannual correlations of the atmosphere with sea ice is more pronounced.
- **Observed correlations lie out of the IQR of all members (except for CESM-LE) – not shown**.
- Models may underestimate the coupling mechanism on the interannual time scales.

Now, let's see low-frequency timescales: →

Method to separate internal vs. forced trends

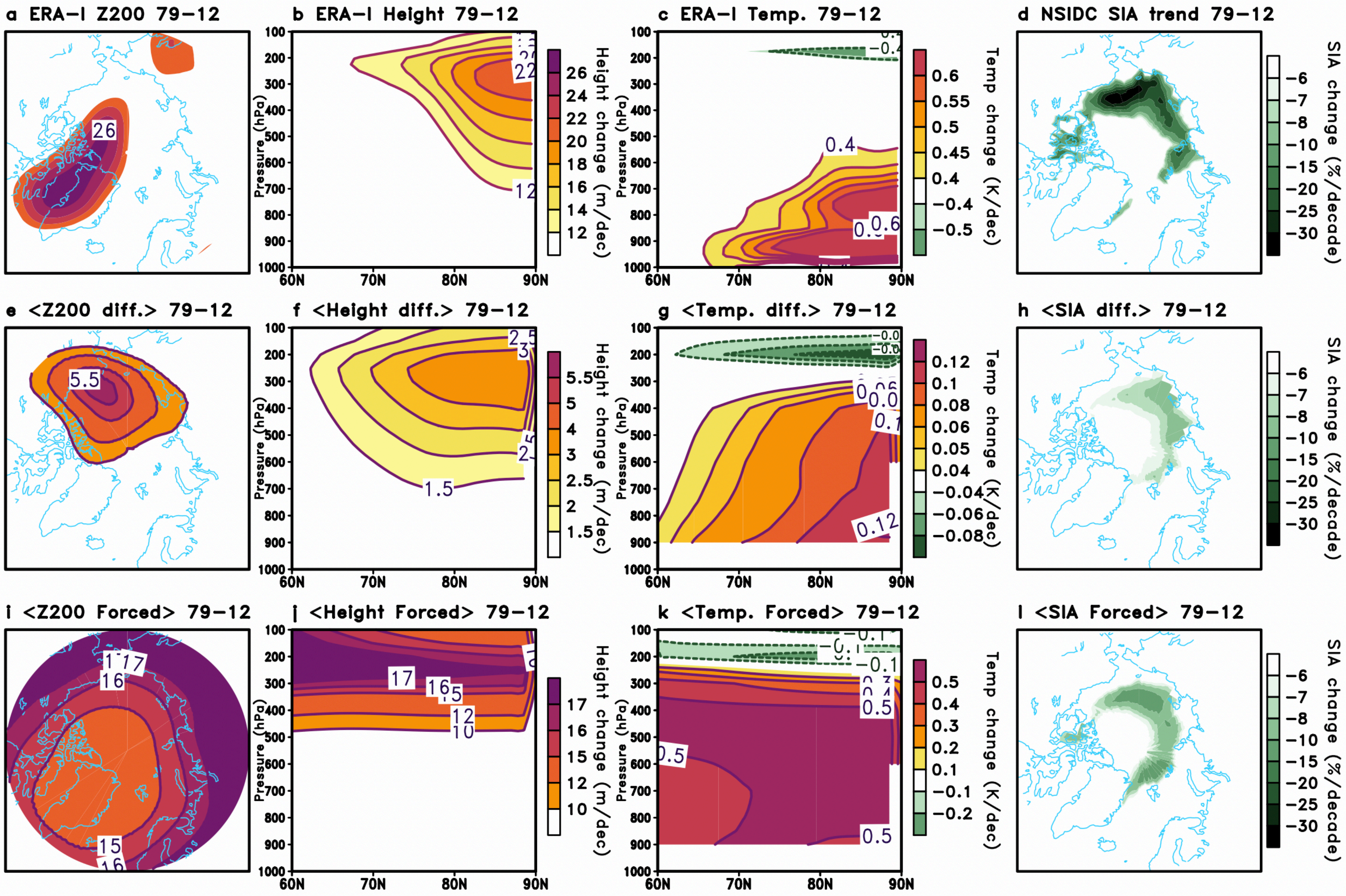
fast-minus-slow composite (COMPOSITE) for LE simulations:

- select the two tails of the September total SIA index trend distribution of each ensemble:
  - fast melting group (15% fastest out of the total ensemble)
  - slow melting group (15% slowest out of the total ensemble)
- average the corresponding members' Z200 trends to get a fast melting group Z200 trend and a slow melting group Z200 trend
- difference the Z200 trends belonging to the fast and slow groups = fast-minus-slow composite
- repeat for different variables e.g. zonal mean geop. height and temperature
- the composite is referred as (diff.) in the plot titles

What is it good for?

- Represents internal trends (the forced component is removed with the differencing)
- Represents atmospheric changes associated with sea ice changes
- Direction of the coupling is assumed based on to Ding et al. (2017) (top-down: atmosphere is the driver of sea ice variability)

Low-frequency atmosphere-sea ice coupling in LE simulations



→ **Observed linear trends**

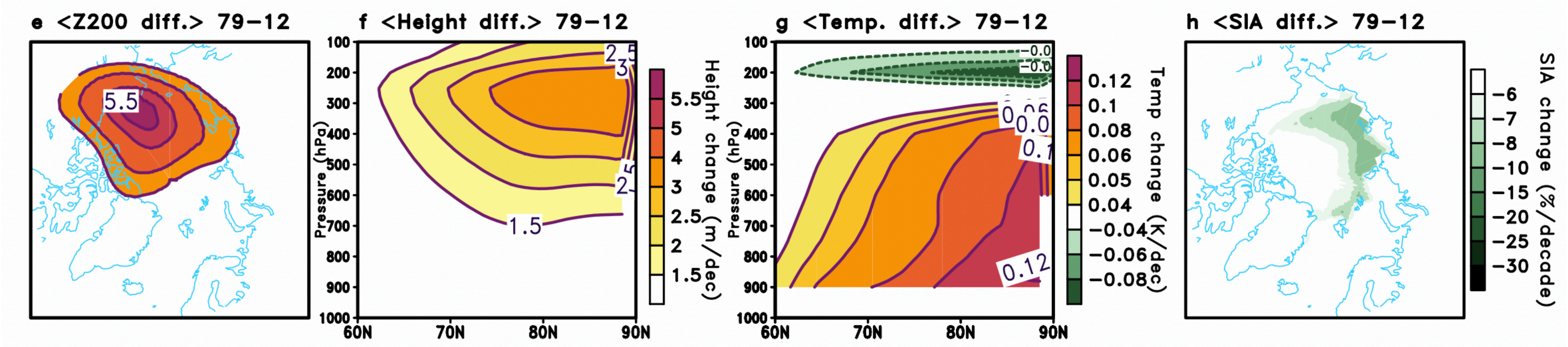
→ **Composite (internal) linear trends**

→ **Ensemble mean (forced) trends**

Fig.5. Observed (ERA-Interim Reanalysis/NSIDC) (a) Z200 (unit: m/decade), (b) zonal mean geopotential height (unit: m/decade), (c) zonal mean temperature (unit: K/decade) and (d) September sea ice area linear trends for 1979-2012. Historical (e) Z200, (f) zonal mean geopotential height, (g) zonal mean temperature and (h) September sea ice area fast-minus-slow composite trends and the ensemble mean (i) Z200, (j) zonal mean geopotential height, (k) zonal mean temperature and (l) September sea ice area trends averaged over the 4 LE historical+RCP8.5 experiments for 1979-2012 (excluding CSIRO-LE the mean of four Z200, height, temperature and sea ice either fast-minus-slow composite or ensemble mean (forced) trends are denoted with < >).

Low-frequency atmosphere-sea ice coupling in LE simulations

<u>Composite</u> (internal) linear trends <u>resemble</u> the observed atmospheric changes, while the <u>forced</u> trends do <u>not</u>!



→ Composite (internal) linear trends

- **composite magnitudes are smaller than the observed trends' → we refer to the underestimated interannual coupling, which might be the cause why (seen in previous Fig.4)**
- **the relative importance of internal component cannot be estimated due to model limitations**

Low-frequency atmosphere-sea ice coupling in CMIP5 simulations

- **we repeat the analysis on long (>200 years) pre-industrial control simulations from CMIP5:**
  - **select each consecutive 34-yr long period to create a *pseudo-ensemble* of each model**
  - **we do fast-minus-slow compositing on the pseudo-ensembles per model (total of 31)**
  - **then average the composite patterns belonging to each of the models →**

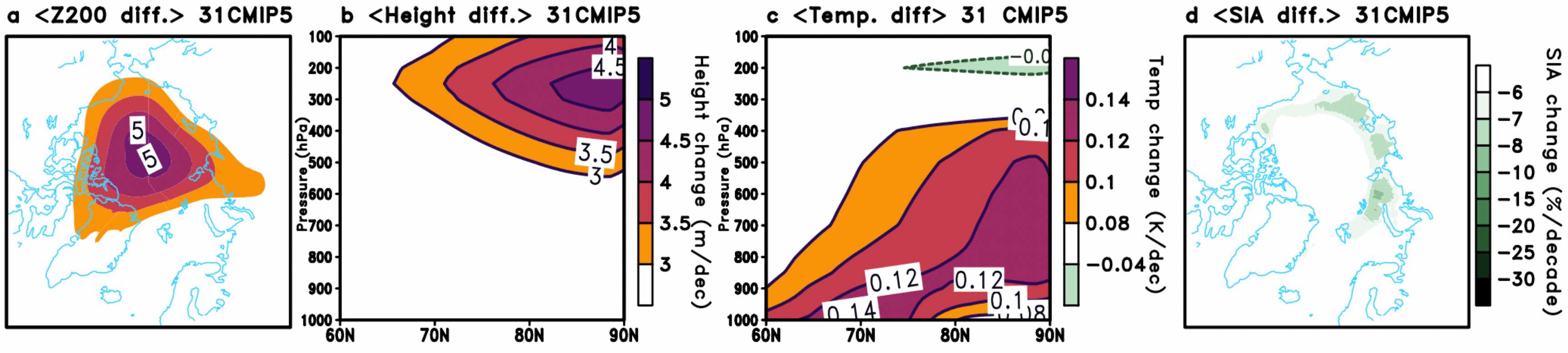
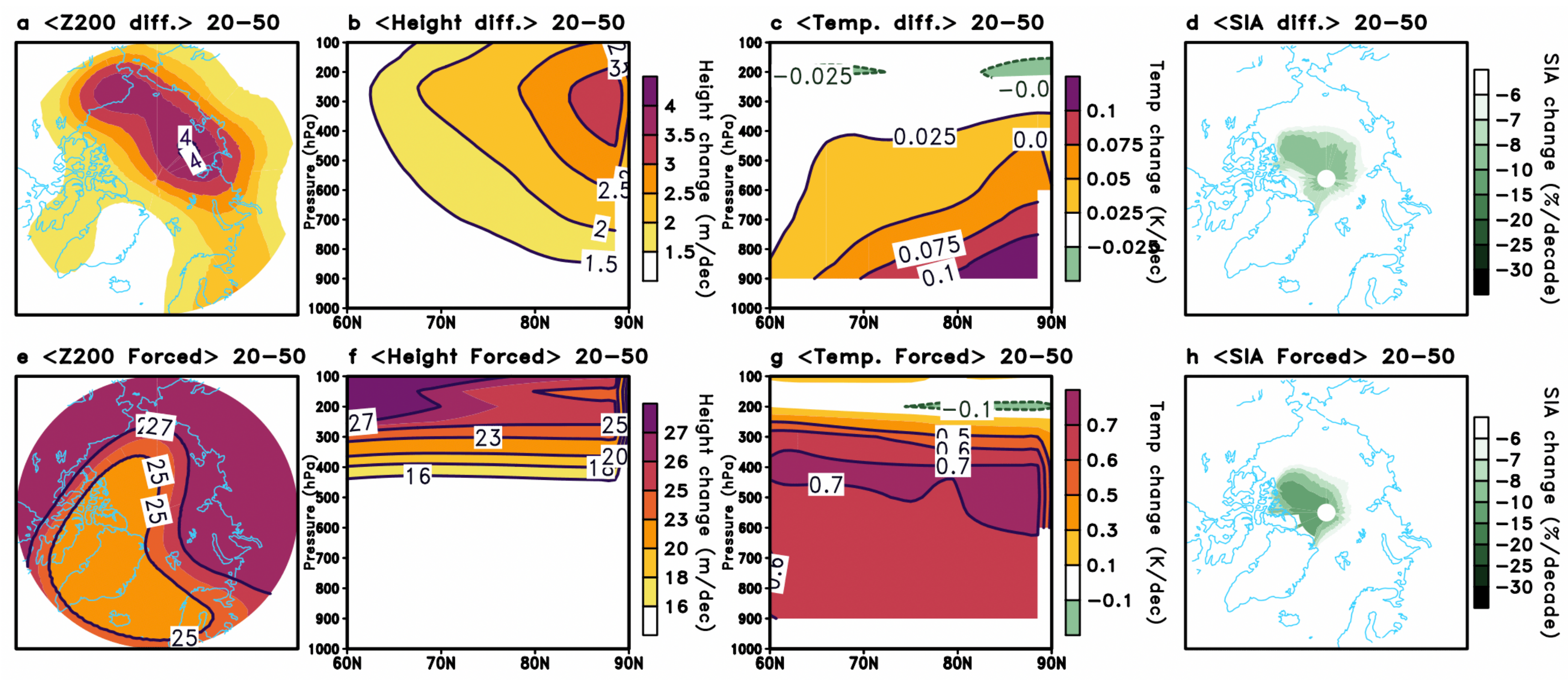


Fig.6.The mean (denoted with < >) of 31 fast-minus-slow (a) Z200, (b) zonal mean geopotential height, (c) zonal mean temperature and (d) September sea ice area composites constructed using each 34-yr long periods of long pre-industrial control integration of 31 individual CMIP5 models aka. the pseudo-ensemble method.

- **the pattern strongly resembles the one seen in observations and historical LE simulations → robust result**

How is this mechanism represented in future model simulations?

Low-frequency atmosphere-sea ice coupling 2020-2050

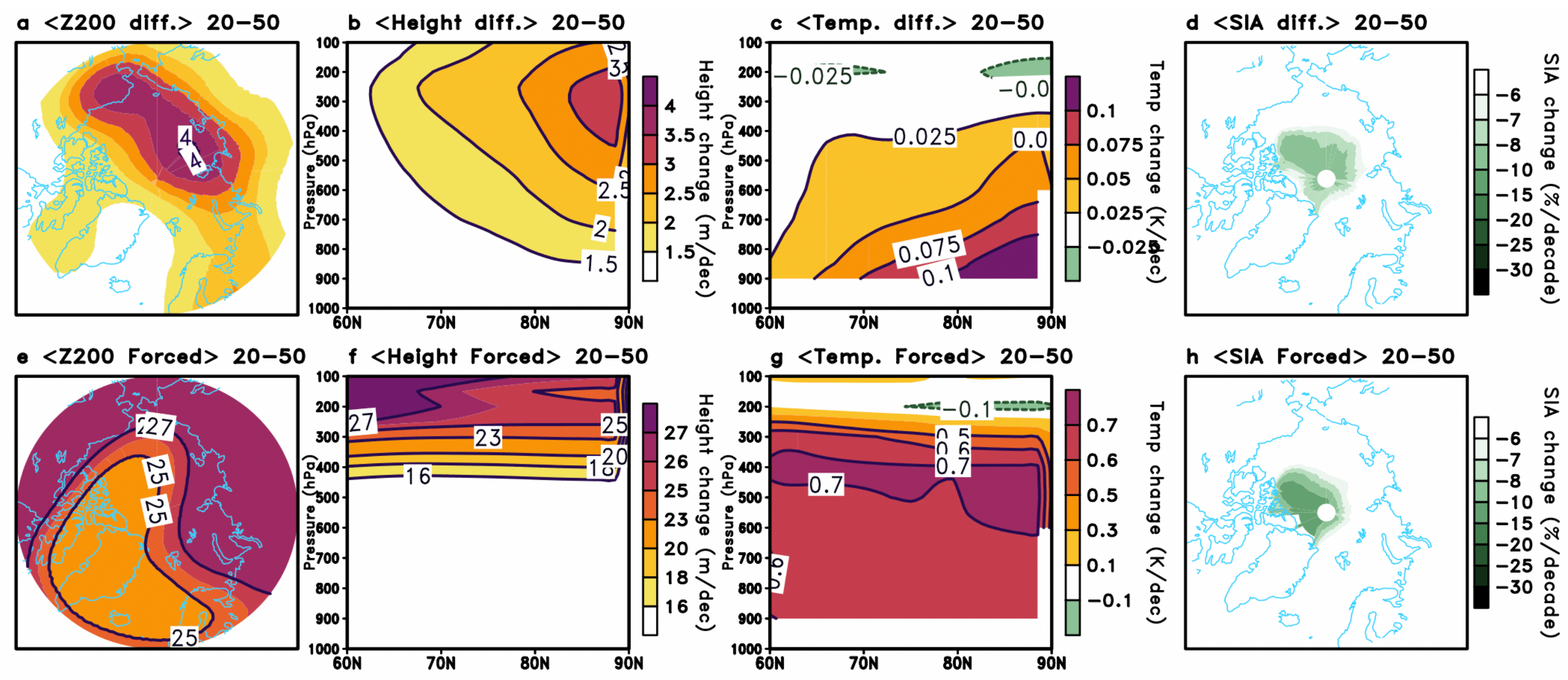


→ **Composite (internal) linear trends**

→ **Ensemble mean (forced) trends**

Fig.7. Future (a) Z200, (b) zonal mean geopotential height, (c) zonal mean temperature and (d) September sea ice area fast-minus-slow composite trends and the ensemble mean (e) Z200, (f) zonal mean geopotential height, (g) zonal mean temperature and (h) September sea ice area trends averaged over four large ensembles' RCP8.5 experiments for 2020-2050 (excluding CSIRO-LE the mean of each of the four Z200, height, temperature and sea ice either fast-minus-slow composite or ensemble mean (forced) trends are denoted with < >).

Low-frequency atmosphere-sea ice coupling 2020-2050



→ **Composite (internal) linear trends**

→ **Ensemble mean (forced) trends**

Composite trends are reminiscent of the ones seen in historical and pre-industrial simulations:

- high pressure in the Arctic upper troposphere along with surface warming concomitant to sea ice loss
- trend magnitudes are comparable to the small historical and pre-industrial composite magnitudes (might be rooted in the underestimated simulated coupling)
- models show discernible sea ice melt during 2020-2050 compared to 1979-2012, while the differences in the magnitude of sea ice associated atmospheric changes are not so pronounced between the two periods → circulation may be of key importance in driving future sea ice loss

What can drive the local coupling?

What can cause this local coupling?

- We study whether remote tropical Pacific SST changes can drive such an atmospheric pattern
- Previous work (Baxter et al. 2019) showed evidence for a Rossby-wave train connecting the Arctic to East Central Pacific SST variability

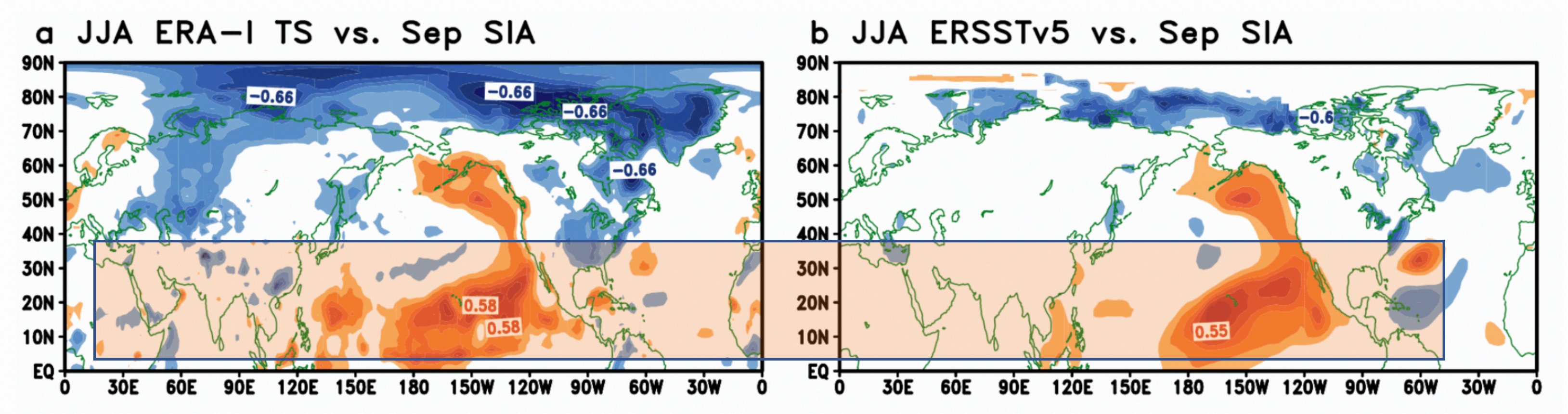


Fig.8. Observed correlation of (a) detrended JJA TS and (b) JJA SST with detrended September total SIA index for 1979-2012.

POSITIVE CORRELATION

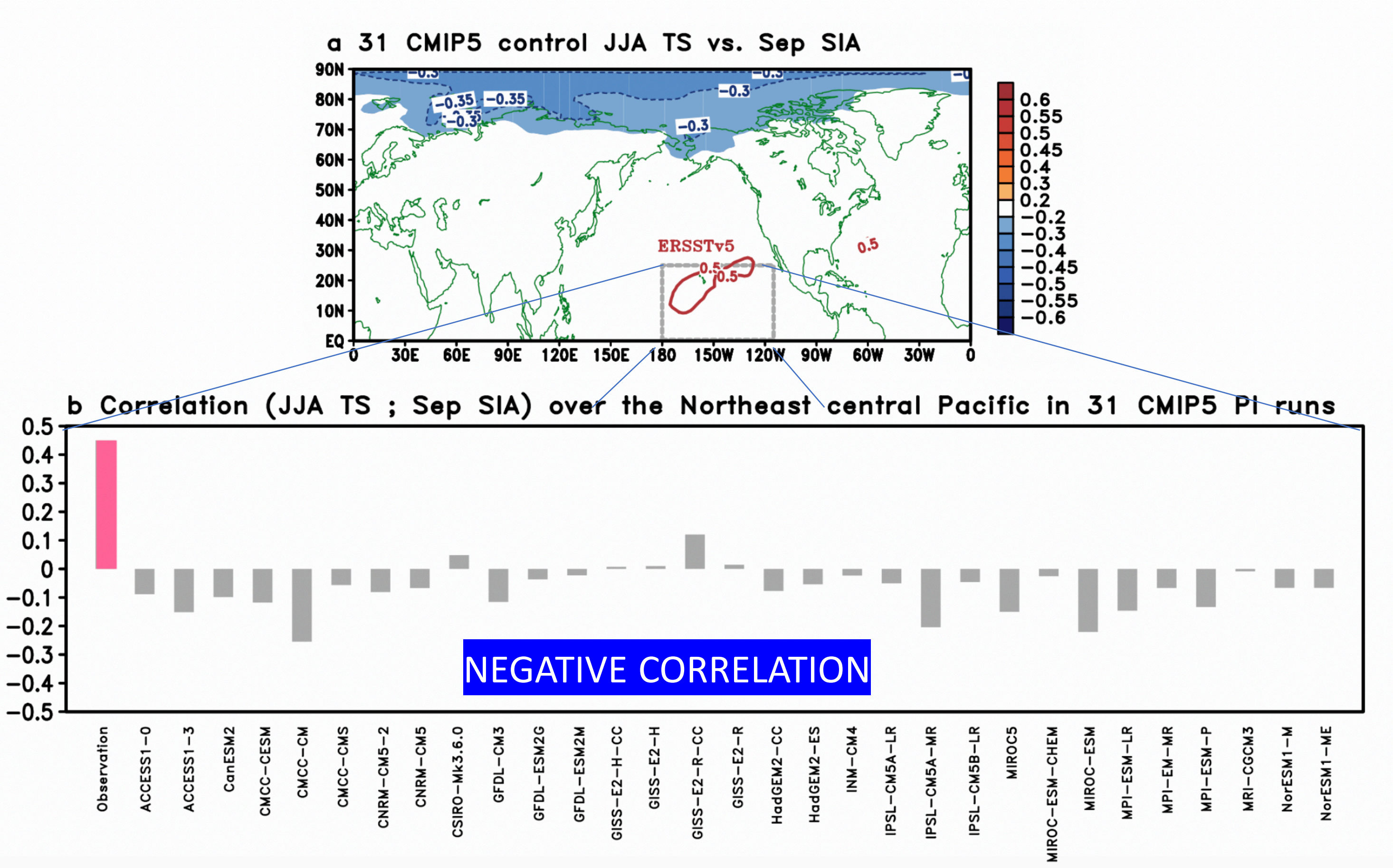


Fig.9. Correlation of detrended JJA TS with detrended September total SIA index in (a) mean of 31 CMIP5 model's pre-industrial simulations and (b) in each of simulations (JJA TS is averaged for the Northeast central Pacific grey box on (a)).

Conclusions:

- *not any CMIP5 model capture the observed positive correlations from the tropics connected to Arctic sea ice loss*

Let’s analyze trends, so we make use of the fast-minus-slow composite:

- to show summertime SST changes connected to September sea ice loss

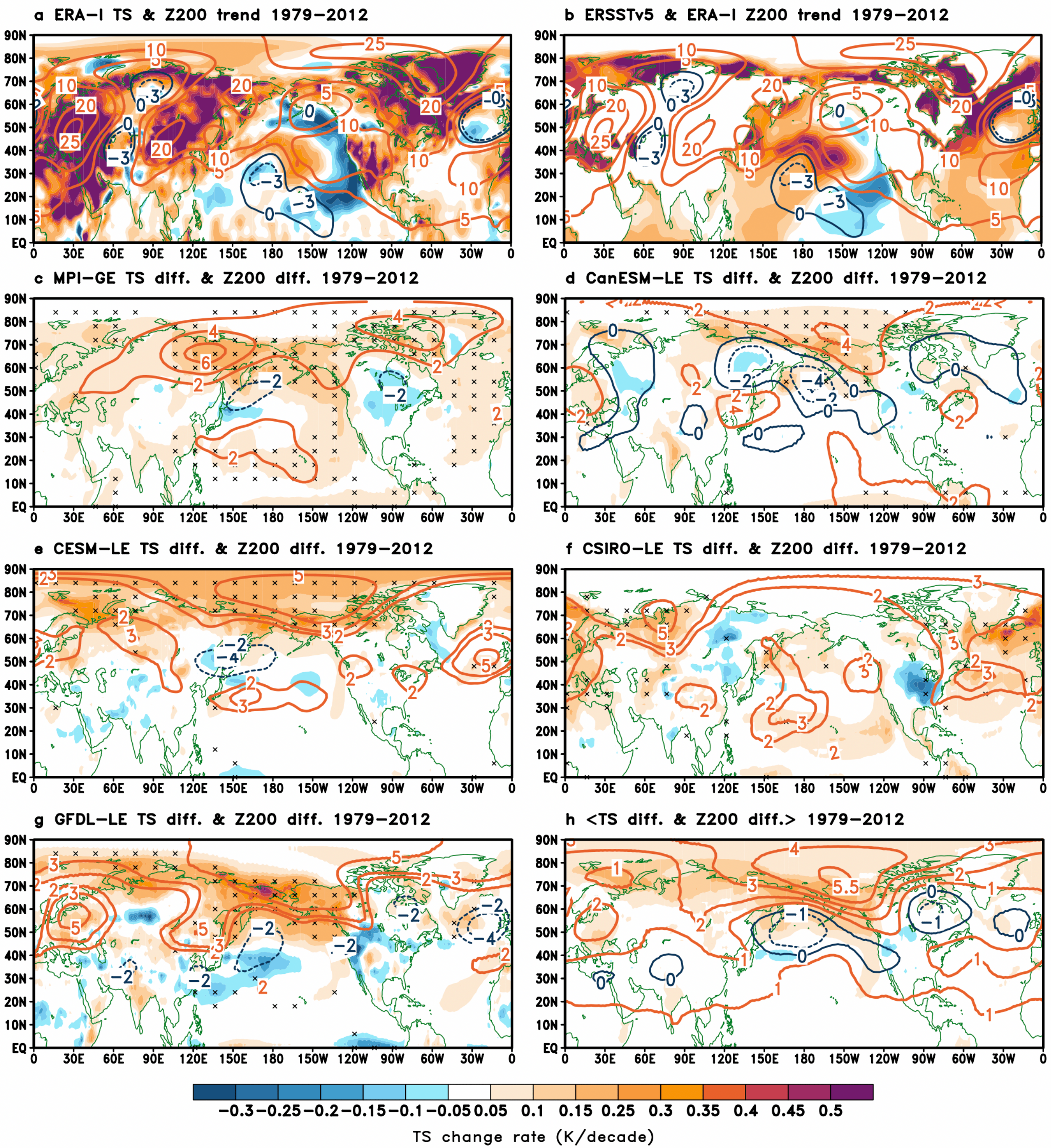


Fig.10. (a)-(b): Linear trends of JJA Z200 (contour) and (a) TS (ERA-I: shading) or (b) SST (ERSSTv5: shading) for 1979-2012 in observations.
(c)-(h): Historical fast-minus-slow composite trends of JJA Z200 (contour) and TS (shading) in the 5 LE's historical+RCP8.5 simulations for 1979-2012: (c) MPI-GE, (d) CanESM-LE, (e) CESM-LE, (f) CSIRO-LE , (g) GFDL-LE and (h) the average of 4 LE (excluding CSIRO-LE; denoted with < >). Crosses indicate significant TS composite values on the 95% level (two-sample t-test).

Conclusions:

- Models simulate the opposite sign relationship between JJA Arctic sea ice and tropical Pacific SST
- In Obs. we see a cold-Pacific-warm-Arctic pattern
- Models show warm-Pacific-warm-Arctic pattern

How about for 2020-2050?

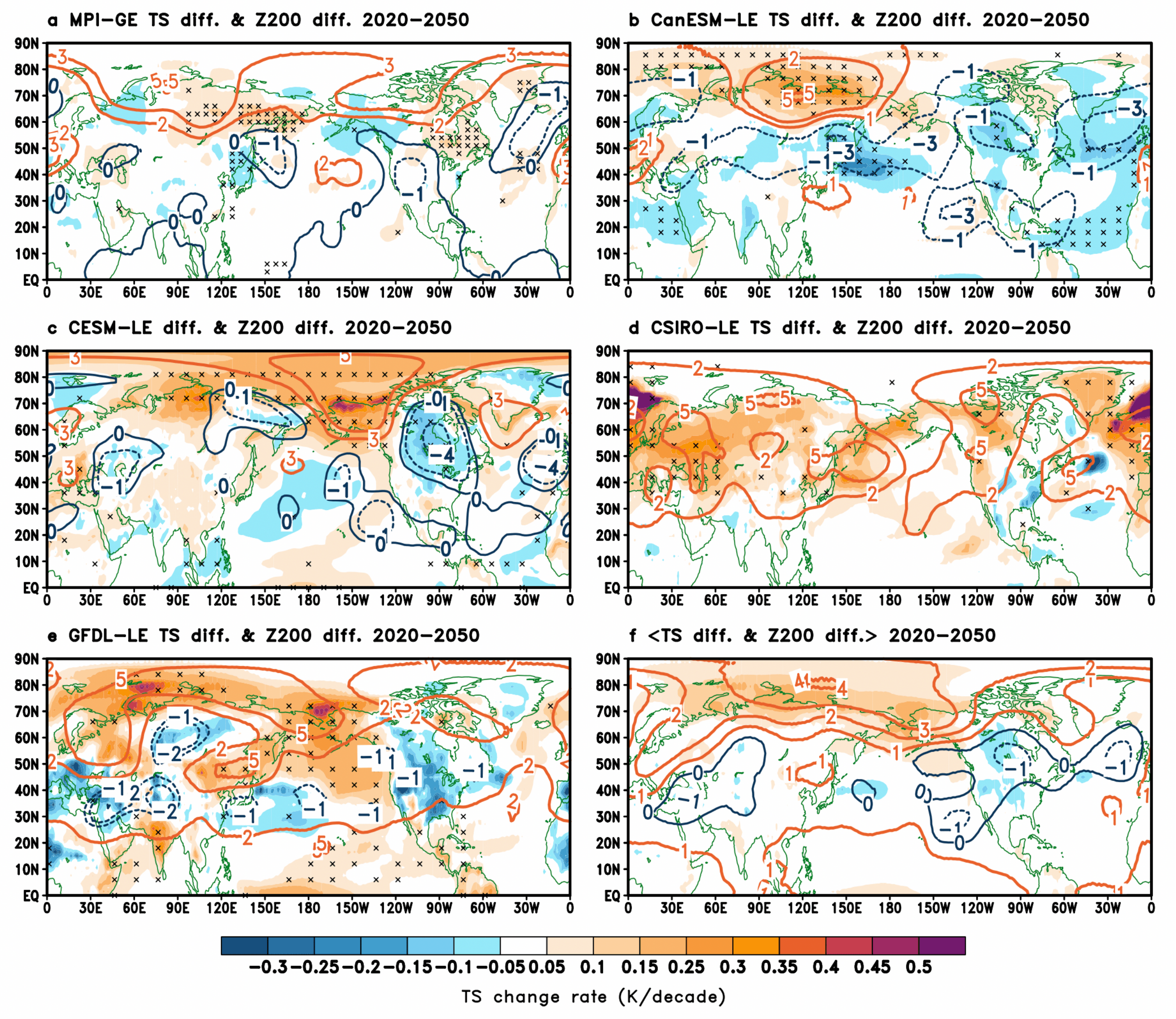


Fig.11. Future fast-minus-slow composite trends of JJA Z200 (contour) and TS (shading) in the 5 LE's RCP8.5 simulations for 2020-2050: (c) MPI-GE, (d) CanESM-LE, (e) CESM-LE, (f) CSIRO-LE, (g) GFDL-LE and (h) the average of 4 LE's (excluding CSIRO-LE). Crosses indicate significant TS composite values on the 95% level (two-sample t-test).

Conclusions:

- Models stick to simulating the opposite sign relationship between JJA Arctic sea ice and tropical Pacific SST
- warm-Pacific-warm-Arctic pattern for 2020-2050 too

Conclusions

- circulation-sea-ice coupling is underestimated in all models
- local physical mechanism is yet captured
- Lack of tropical signal might partially be responsible for the weak Arctic fast-minus-slow composite trend magnitudes
- Opposite sign simulated tropical-Arctic connections: caution for predictability

We call for caution in the interpretation of existing models' simulations and fresh thinking about models' credibility in simulating interactions of sea ice variability with the Arctic and global climate systems.

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