Suppressed mid-latitude summer atmospheric warming by Arctic sea ice loss during 1979-2012

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Background and Methods

1. Since the 1980s, rapid Arctic warming, sea ice decline, and weakening summer circulation have coincided with an increasing number of extreme heatwaves and other destructive weather events in the Northern Hemisphere (NH) mid-latitudes in summer. **Recent papers disagree about whether such high-impact events are related to Arctic warming and/or ice loss.**

2. **Recent observational studies have hypothesized that in the summer, sea ice loss and Arctic amplification cause more frequent extreme mid-latitude heat events** by weakening the poleward temperature gradient, which induces circulation changes such as reduced zonal winds and increased wave amplitudes [Francis and Vavrus 2012, 2015; Petoukhov et al. 2013; Tang et al. 2014; Overland 2014; Coumou et al. 2014, 2015]. Such hypothesized linkage is based on the observed coincidence of events, trends or statistical correlations, so the chain of cause and effect is not clear.

3. **The hypothesis that Arctic sea ice loss remotely causes more frequent extreme hot mid-latitude summer weather is not confirmed in modeling studies, and has instead often been criticized** [Barnes, 2013; Barnes et al., 2014; Wallace et al., 2014; Trenberth et al., 2014].

4. We use atmospheric model ensemble simulations to attribute effects of sea ice loss and other factors (SST warming outside of the Arctic and anthropogenic increase of greenhouse gas (GHG) concentration) on observed summer climate trends during 1979-2012.

5. Two sets of AMIP simulations from two models provided by NOAA ERSL: (1) **AMIP_full** (prescribed observed monthly spatial fields of SST, sea ice and GHG); (2) **AMIP_noSIC** (prescribed observed monthly spatial fields of SST outside of polar regions and GHG, but climatological sea ice).

6. **The atmospheric response attributed to forcing from Arctic sea ice changes (AMIP_SIC) in two models is the AMIP_full minus AMIP_noSIC superensemble mean difference.**

Experiment	Forcings			No. of Runs	
	SST	Sea Ice (SIC)	Greenhouse Gas	CAM4	ECHAM5
AMIP_full	1979-2012	1979–2012	1979–2012	20 runs	30 runs
AMIP_noSIC	1979-2012	1979-1988 climatology	1979–2012	20 runs	10 runs

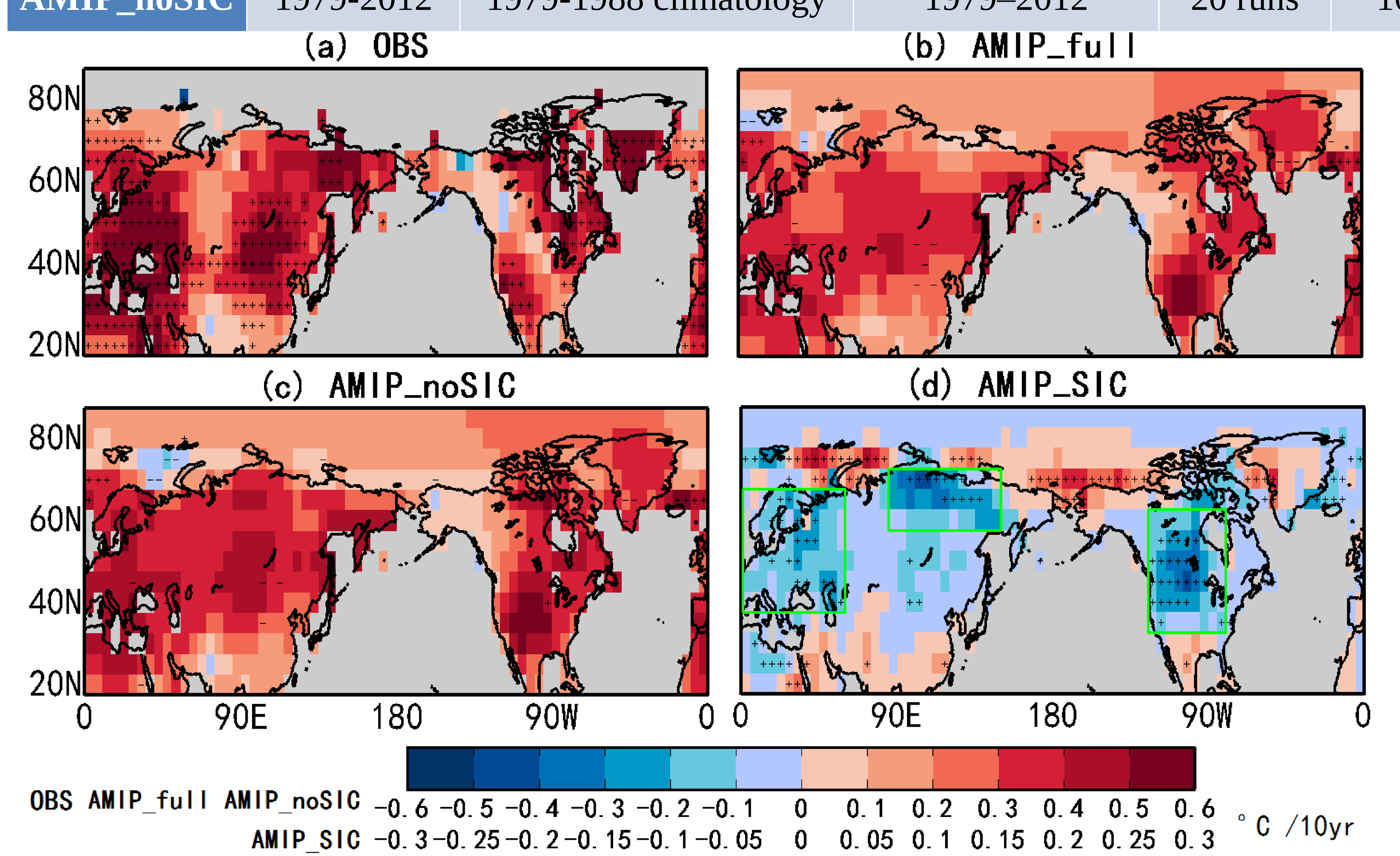

Figure 1. 1979-2012 summer (JJA) linear SAT trends [K (10 yr)$^{-1}$]. **(a)** From observed NOAA dataset. **(b, c, d)** Superensemble-mean (average of all CAM4 and ECHAM5 simulations) trends from (**b**) AMIP_full, (**c**) AMIP_noSIC runs, and (**d**) attributed to sea ice forcing, AMIP_SIC. Gray shaded areas indicate insufficient data in (**a**) and oceans outside the Arctic in all panels. Plus/minus symbols mark individual grid boxes with significant warming/cooling trends in (**a**), significantly larger/smaller forced trends than observations in (**b**, **c**), and significantly different forced trends between the AMIP_full and AMIP_noSIC experiments in (**d**), all at the 5% significance level. Three green rectangles in (**d**) outline areas with most significant cooling trends used in Fig. 2.

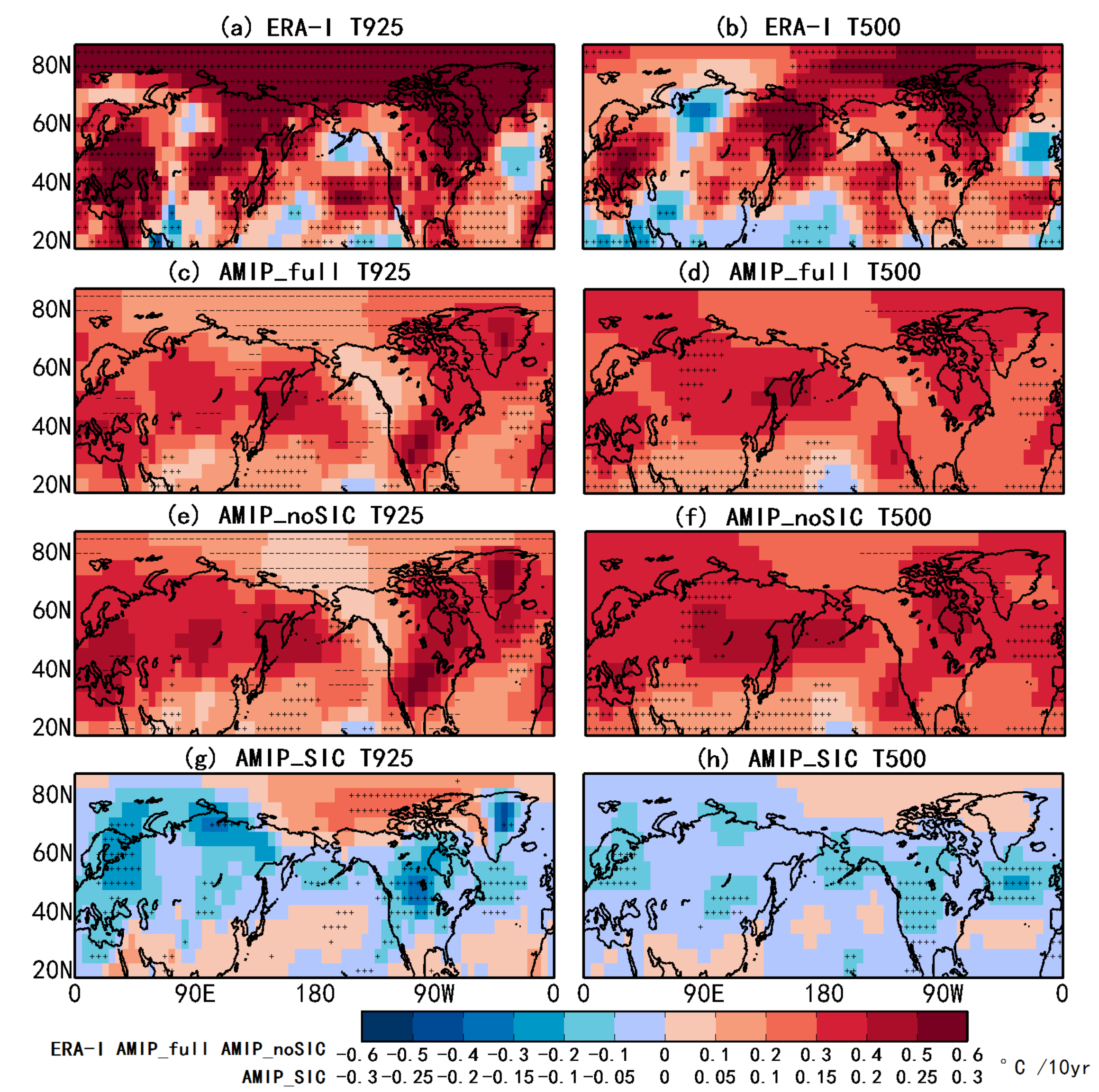

Figure 3. 1979-2012 linear trends of air temperature [K (10 yr)$^{-1}$] (left column) at 925 hPa and (right column) 500 hPa, in (**a, b**) observations (ERA Interim reanalysis) and superensemble-mean trends in the (**c, d**) AMIP_full and (**e, f**) AMIP_noSIC experiments, and (**g, h**) trend component attributed to sea ice forcing, AMIP_SIC. Plus/minus symbols mark individual grid boxes with significant warming/cooling trends in (**a**, **b**), and significantly larger/smaller forced trends than observations in (**c-f**), and significantly different forced trends between the AMIP_full and AMIP_noSIC experiments (**g, h**) at the 5% significance level.

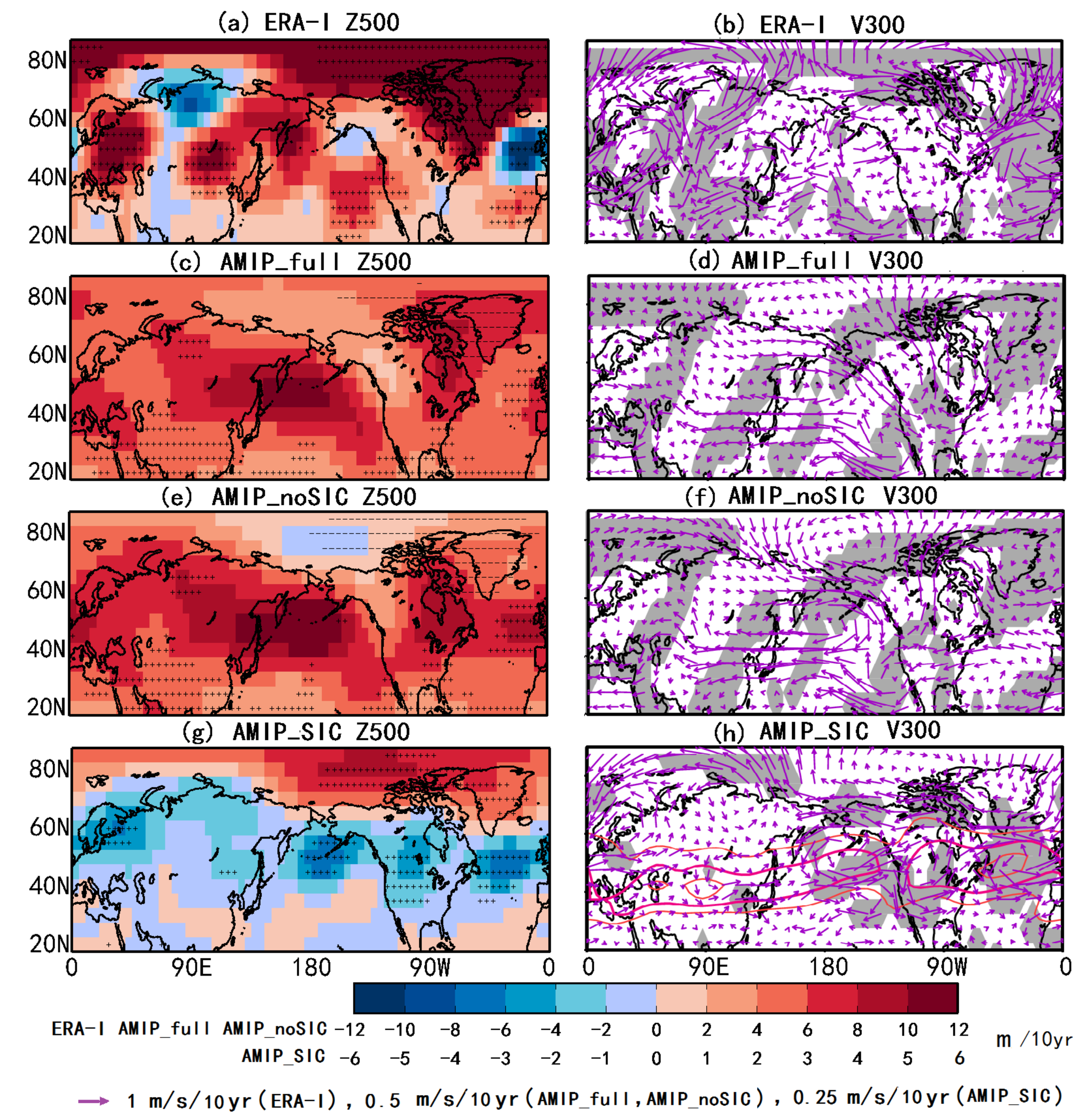

Figure 4. 1979-2012 linear trends of 500-hPa geopotential height [m (10 yr)$^{-1}$] (left column) and 300-hPa wind vectors [m s^{-1} (10 yr)$^{-1}$] (right column) in (**a, b**) observations, superensemble-mean trends in the (**c, d**) AMIP_full and (**e, f**) AMIP_noSIC experiments, and (**g, h**) trend component attributed to sea ice forcing. In (**h**), 300-hPa climatological zonal wind speed ≥10 m s^{-1} is overplotted (red, interval 5 m s^{-1}, thick contour is 15 m s^{-1}). Plus/minus symbols have the same meaning as in Fig. 3. Gray shaded areas in right panels have significant trends of 300-hPa zonal and/or meridional wind speed (**b, h**) and significantly different forced trends of 300-hPa zonal and/or meridional wind speed than observations in (**d**, **f**) at the 5% level.

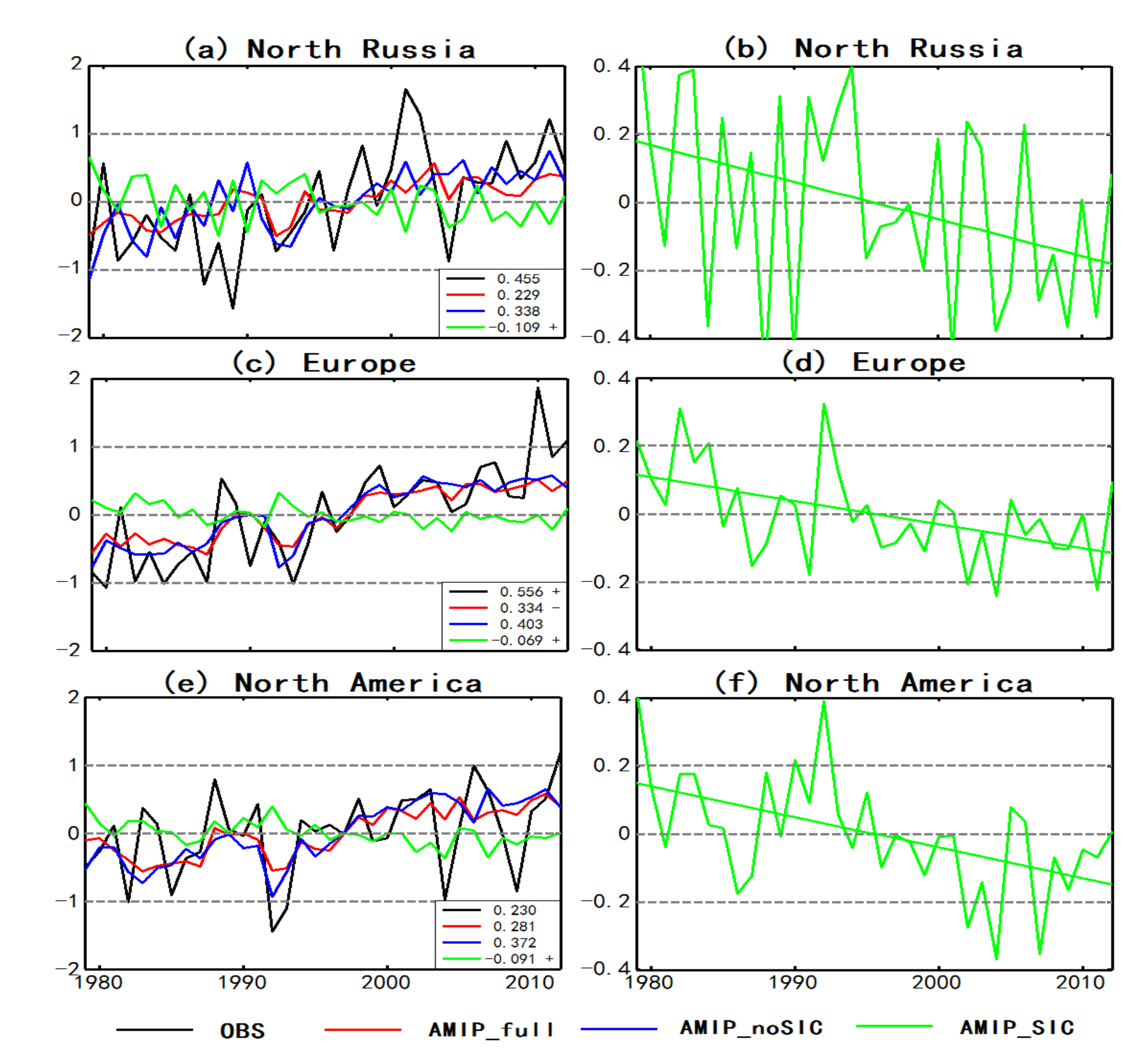

Figure 2. Time series of anomalous summer (JJA) areal averaged SAT and the corresponding linear trends [K (10 yr)$^{-1}$] for 1979-2012 over three regions indicated with green rectangles in Fig. 1(**d**) including (**a**, **b**) North Russia, (**c**, **d**) Europe and (**e**, **f**) North America in (thick black line) the observed dataset, the superensemble mean from the (red) AMIP_full or (blue) AMIP_noSIC experiments, and (green) attributed to sea ice forcing, AMIP_SIC. Time series attributed to sea ice forcing and their linear trends are expanded separately in the right panels.

Conclusions

(1) Sea ice loss has induced a negative Arctic Oscillation (AO)-type circulation with significant summer surface and tropospheric cooling trends over large portions of the NH mid-latitudes, which reduce the warming and might reduce the probability of regional severe hot summers.

(2) The hypothesized causality of extreme mid-latitude summer weather originating from Arctic sea ice loss is not supported in simulations.

(3) Widespread summer NH land and troposphere warming is predominantly driven by greenhouse gas radiative forcing and by SST changes outside the Arctic.

(4) The ongoing greenhouse gas buildup and resulting SST warming have significantly weakened mid-latitude zonal winds and might have dynamically contributed to more persistent heat waves.

(5) It is very likely that events such as heat waves in Europe in 2003, Russia in 2010 and the southern United States in 2011 became more extreme due to effects of rising greenhouse gas concentrations, but were not further prolonged and intensified by Arctic sea ice decline and resulting Arctic amplification.

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