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Causes of the Little Ice Age

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Did volcanic eruptions at the end of the 13th Century produce the Little Ice Age?

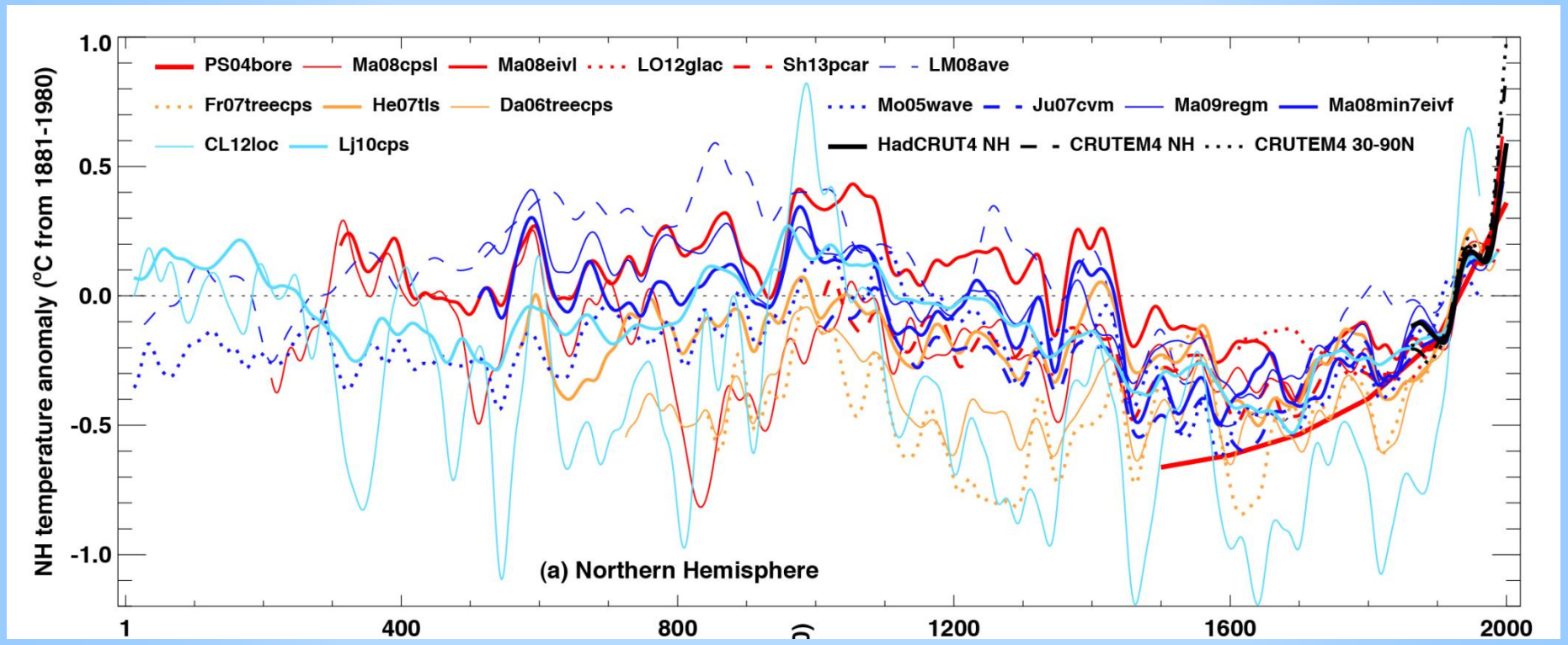

Figure 5.7: Reconstructed Northern Hemisphere annual temperatures during the last 2000 years. Individual reconstructions grouped by colour according to their spatial representation (red: land-only all latitudes; orange: land-only extra-tropical latitudes; light blue: land and sea extra-tropical latitudes; dark blue: land and sea all latitudes), anomalies (°C) from the 1881–1980 mean (horizontal dashed line), smoothed with a filter that reduces variations on timescales less than ~50 years. (IPCC AR5 WG I)

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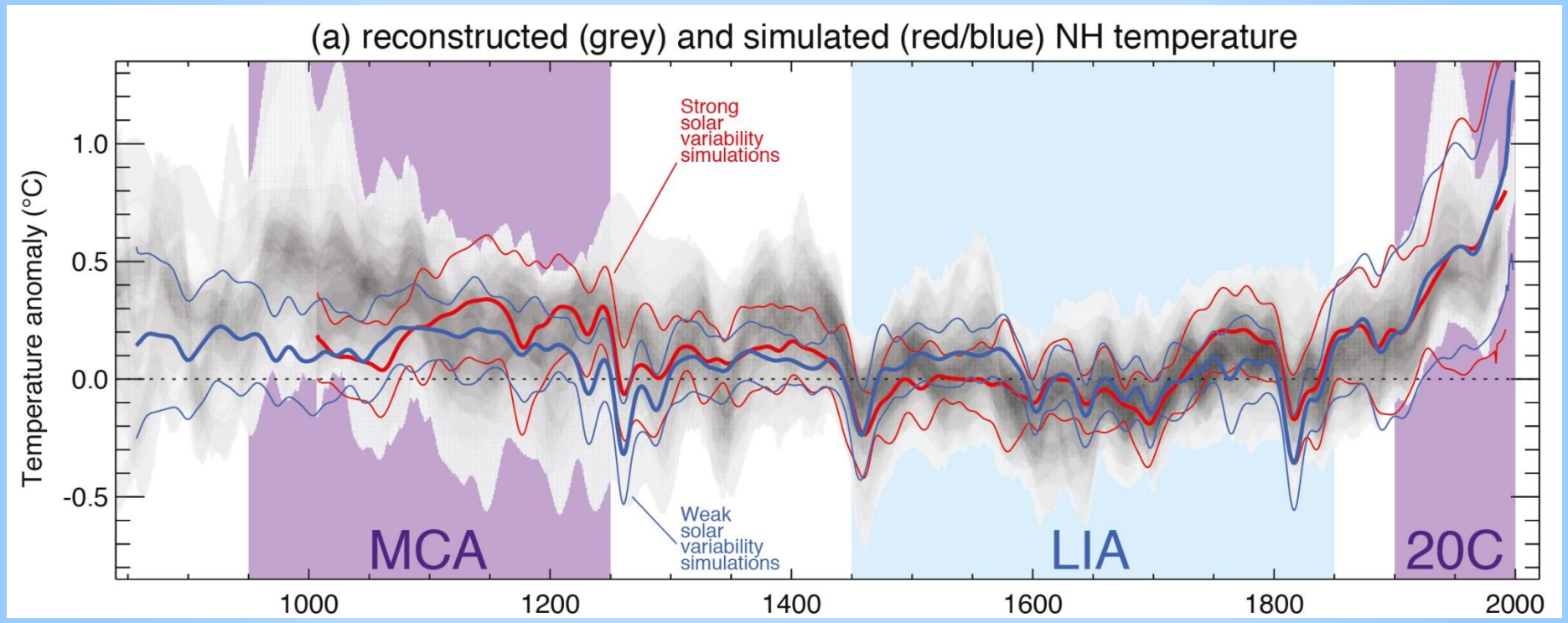

Figure 5.8: Comparisons of simulated and reconstructed NH temperature changes. (a) Changes over the last millennium. (IPCC AR5 WG I)

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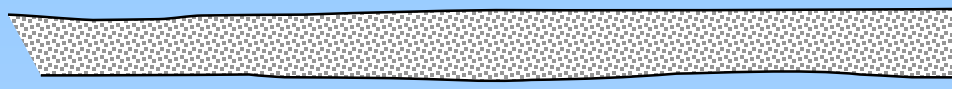


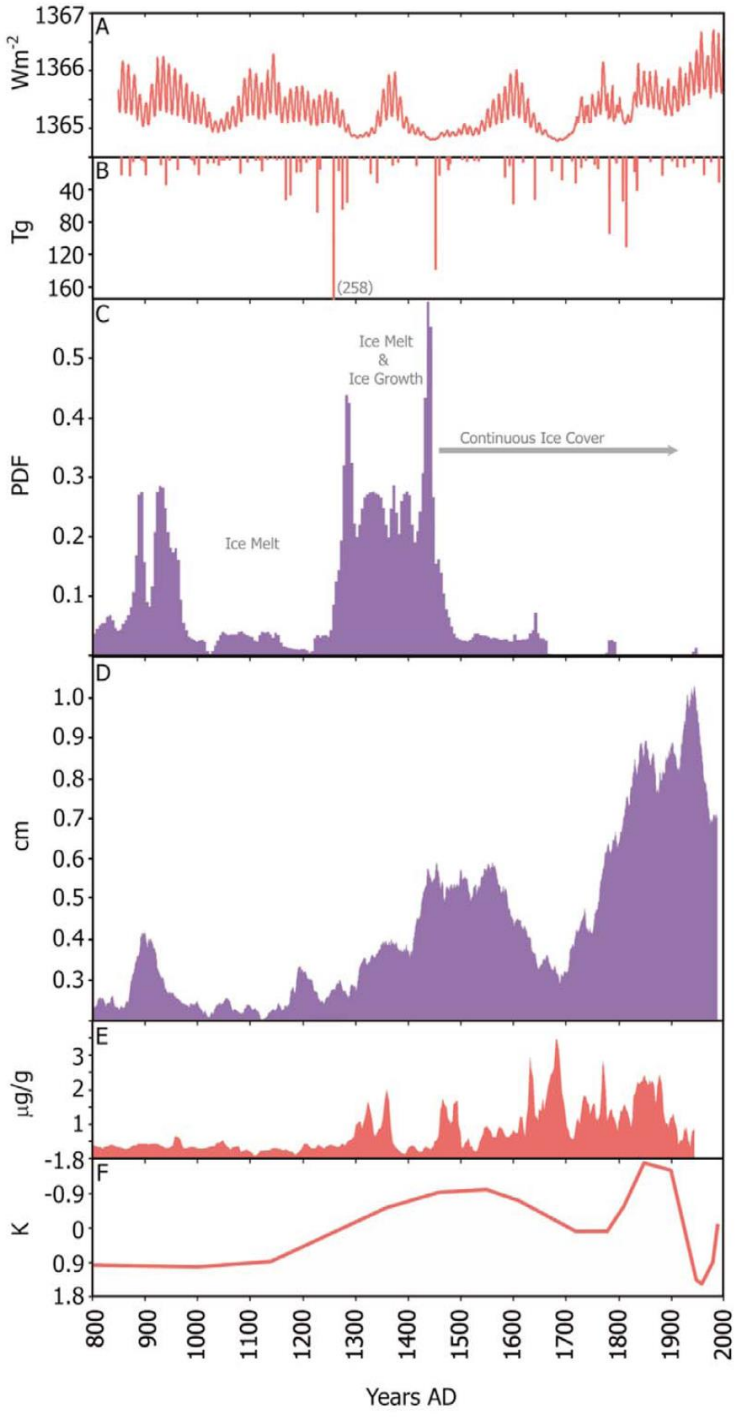
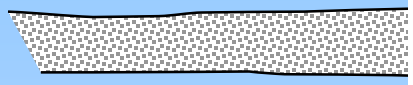


Figure 2. (a) Total solar irradiance (VSK [*Schmidt et al.*, 2011]). (b) Global stratospheric sulfate aerosol loadings [*Gao et al.*, 2008]. (c) Ice cap expansion dates based on a composite of 94 Arctic Canada calibrated ^{14}C PDFs. (d) 30-year running mean varve thickness in Hvítárvatn sediment core HVT03-2 [*Larsen et al.*, 2011]. (e) Arctic Ocean sea ice recorded in a sediment core on the north Iceland shelf [*Massé et al.*, 2008]; heavy sea ice years correlate with anomalously cold summers across Iceland. (f) Temperature anomalies over southern Greenland (wrt 1881–1980 AD mean) from the borehole temperature inversion at DYE-3 [*Dahl-Jensen et al.*, 1998].

Miller, Gifford H., et al., 2012: Abrupt onset of the Little Ice Age triggered by volcanism and sustained by sea-ice/ocean feedbacks. *Geophys. Res. Lett.*, **39**, L02708, doi:10.1029/2011GL050168.



Volcanic forcing

Arctic sea ice

Atlantic northward heat transport

North Atlantic land summer temperature

Miller et al. (2012)

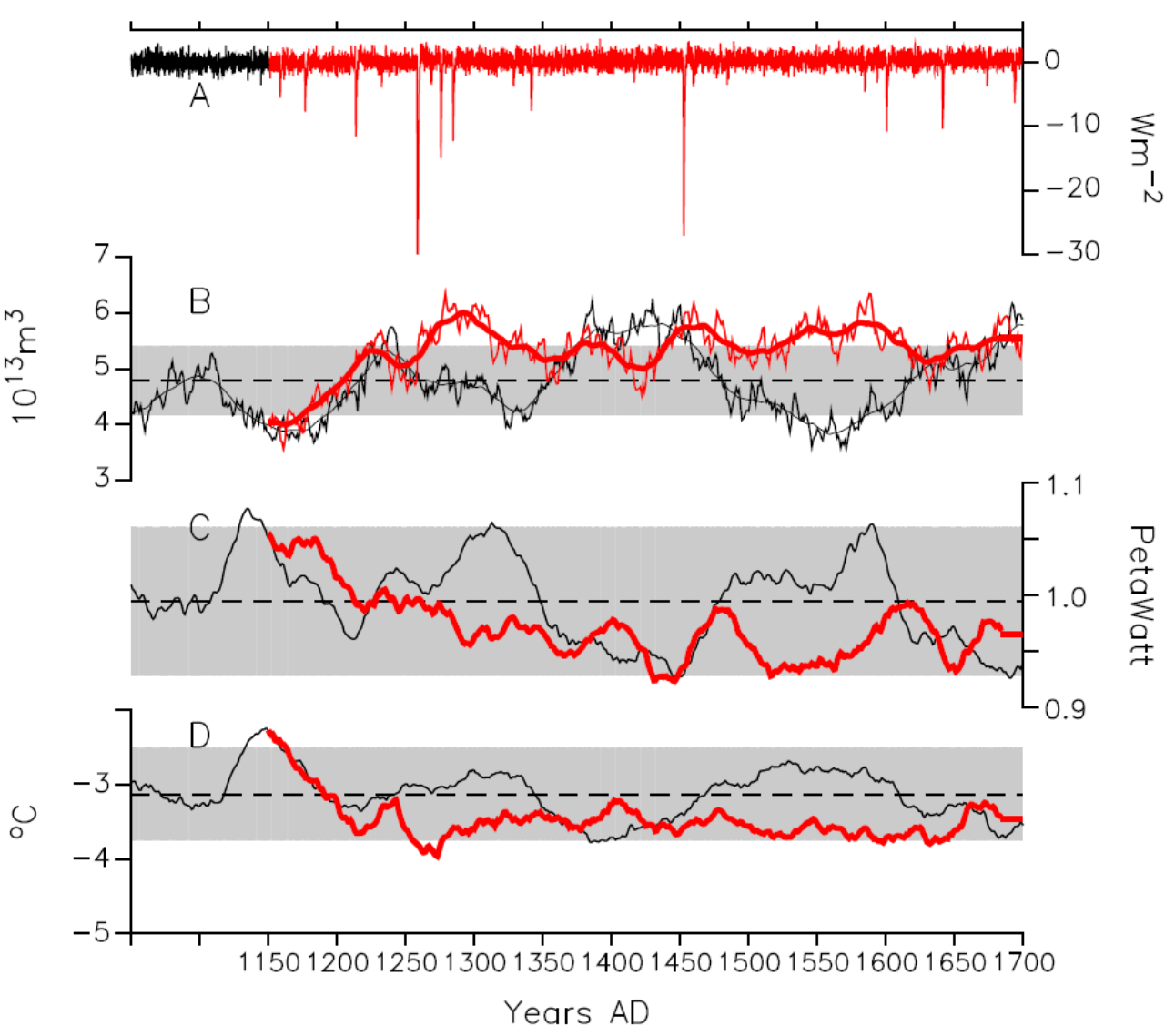
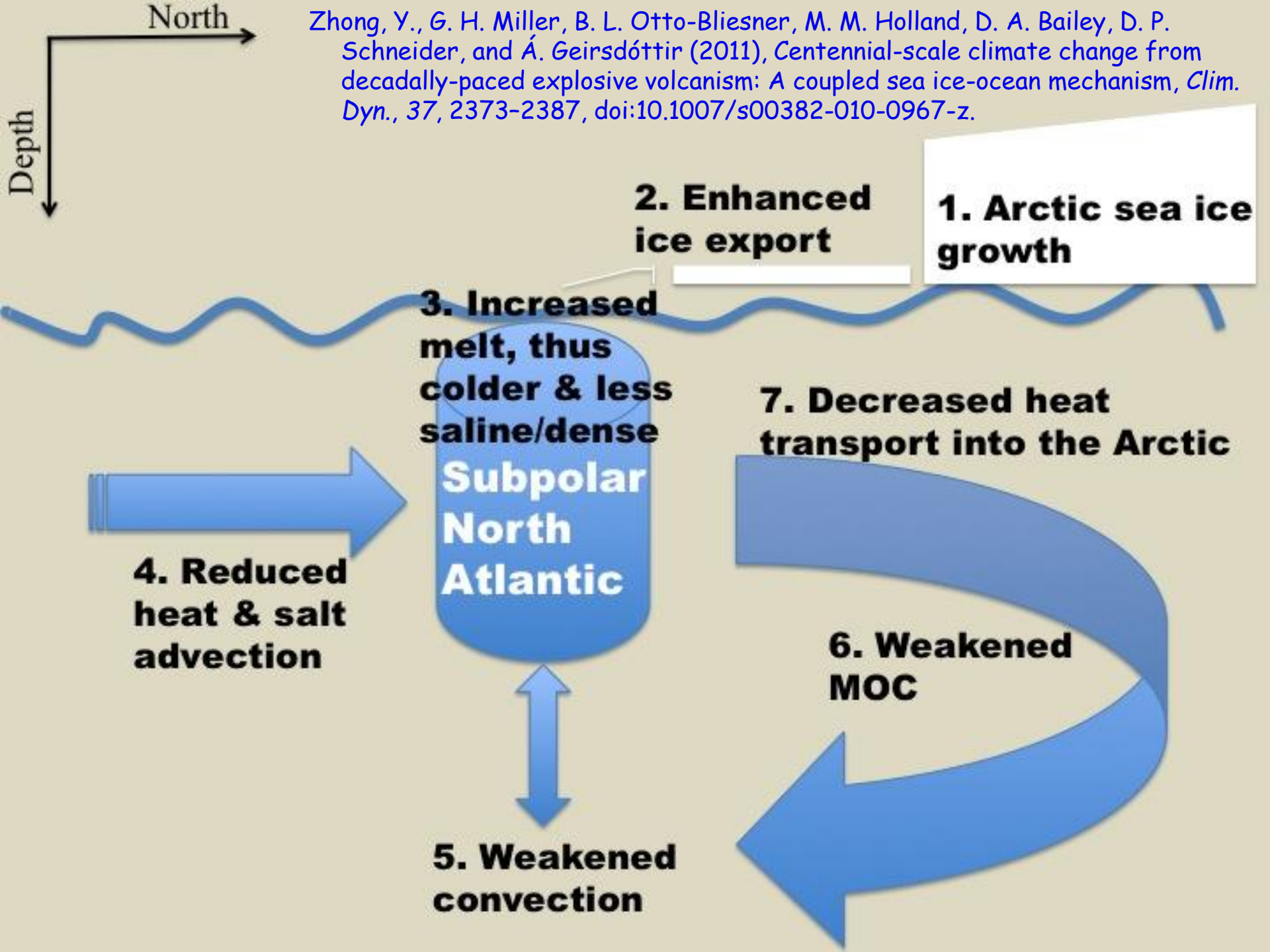
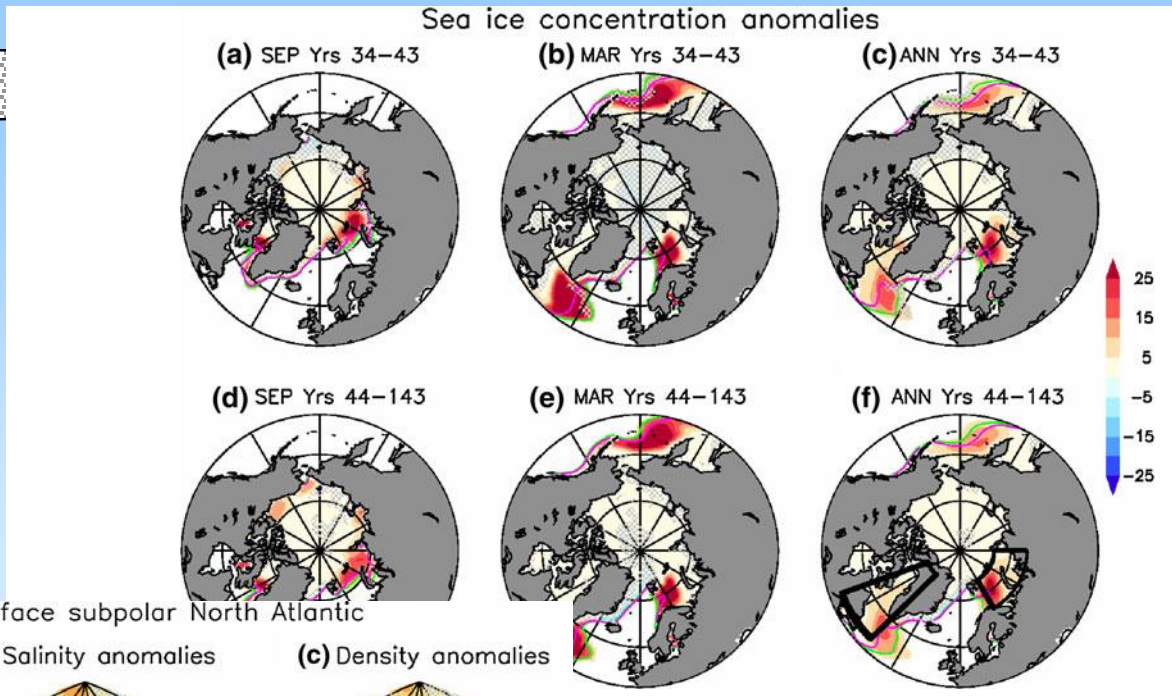


Figure 3. Climate model results for 1000 AD control (black), and volcanically perturbed transient beginning 1150 AD (red). Black dashed lines and gray bars represent mean and standard deviation of the control. (a) Monthly global downwelling surface shortwave radiation anomalies forced by aerosol loadings [*Gao et al.*, 2008] after 1150 AD; earlier portion is unforced control. (b) Yearly and 30-year running mean of NH sea ice volume in Sept. from perturbed transient compared to control from its branching point. (c) 30-year running mean of the northward heat transport in the North Atlantic at 26°N. (d) 30-year running mean of average summer (JJA) surface air temperature over North Atlantic Arctic land (>60°N and 90°W to 30°E).


North
Depth
Zhong, Y., G. H. Miller, B. L. Otto-Bliesner, M. M. Holland, D. A. Bailey, D. P. Schneider, and Á. Geirsdóttir (2011), Centennial-scale climate change from decadally-paced explosive volcanism: A coupled sea ice-ocean mechanism, Clim. Dyn., 37, 2373–2387, doi:10.1007/s00382-010-0967-z.
2. Enhanced ice export
1. Arctic sea ice growth
3. Increased melt, thus colder & less saline/dense
7. Decreased heat transport into the Arctic
Subpolar North Atlantic
4. Reduced heat & salt advection
6. Weakened MOC
5. Weakened convection



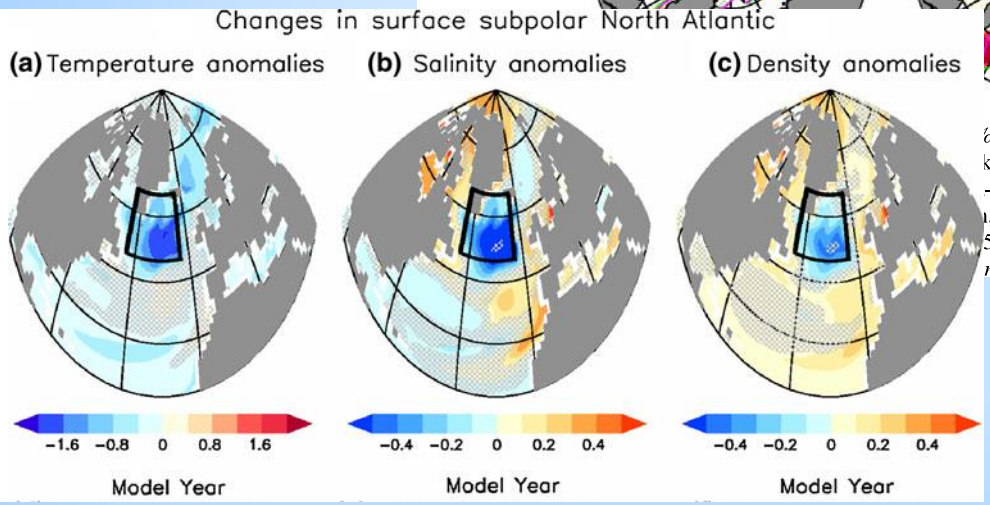


Fig. 9 Changes in upper 100 meters of subpolar North Atlantic Ocean. In upper panel is spatial pattern of the change for **a** temperature (°C), **b** salinity (psu) and **c** density (kg/m^3) for model years 34–43 compared to mean of the control run. In lower panel is the time series of **d** temperature, **e** salinity and **f** density in central subpolar North Atlantic (50°W–20°W, 50°N–65°N), as outlined with *thick lines*. *Solid*: average of experiments WARMNA and NORMNA1 in 11-year running mean; *dashed*: mean of the control run. *Stippled in gray* in (**a**–**c**) are

%, color
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–**c**) and
, **c** and
5% ice
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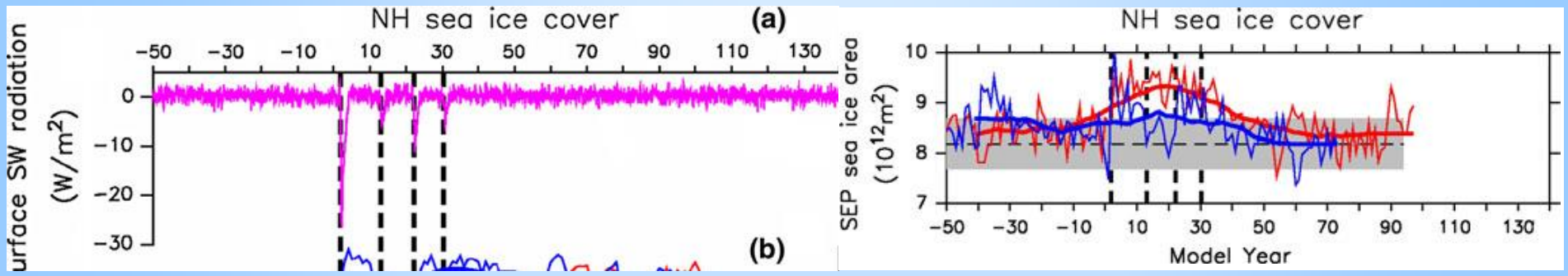
for model years after eruptions (*green line*). *Stipp*
anomalies that are insignificant at 95% level, base
T tests with serial autocorrelation taken into acco
obtained as the average of experiments WARMNA a
Barents Sea (30°E–90°E, 70°N–80°N) and west of Gr
45°W, 50°N–80°N) are outlined in (**f**) with *thick lin*

Zhong, Y., G. H. Miller, B. L. Otto-Bliesner, M. M. Holland, D. A. Bailey, D. P. Schneider, and Á. Geirsdóttir (2011), Centennial-scale climate change from decadally-paced explosive volcanism: A coupled sea ice-ocean mechanism, *Clim. Dyn.*, *37*, 2373–2387, doi:10.1007/s00382-010-0967-z.

Was the Little Ice Age just by chance?

Zhong et al. (2011) did four simulations with the NCAR CCSM3 climate model, and two of them produced a long-term cold Arctic and two did not.

Was it the model? Did it depend on initial conditions?



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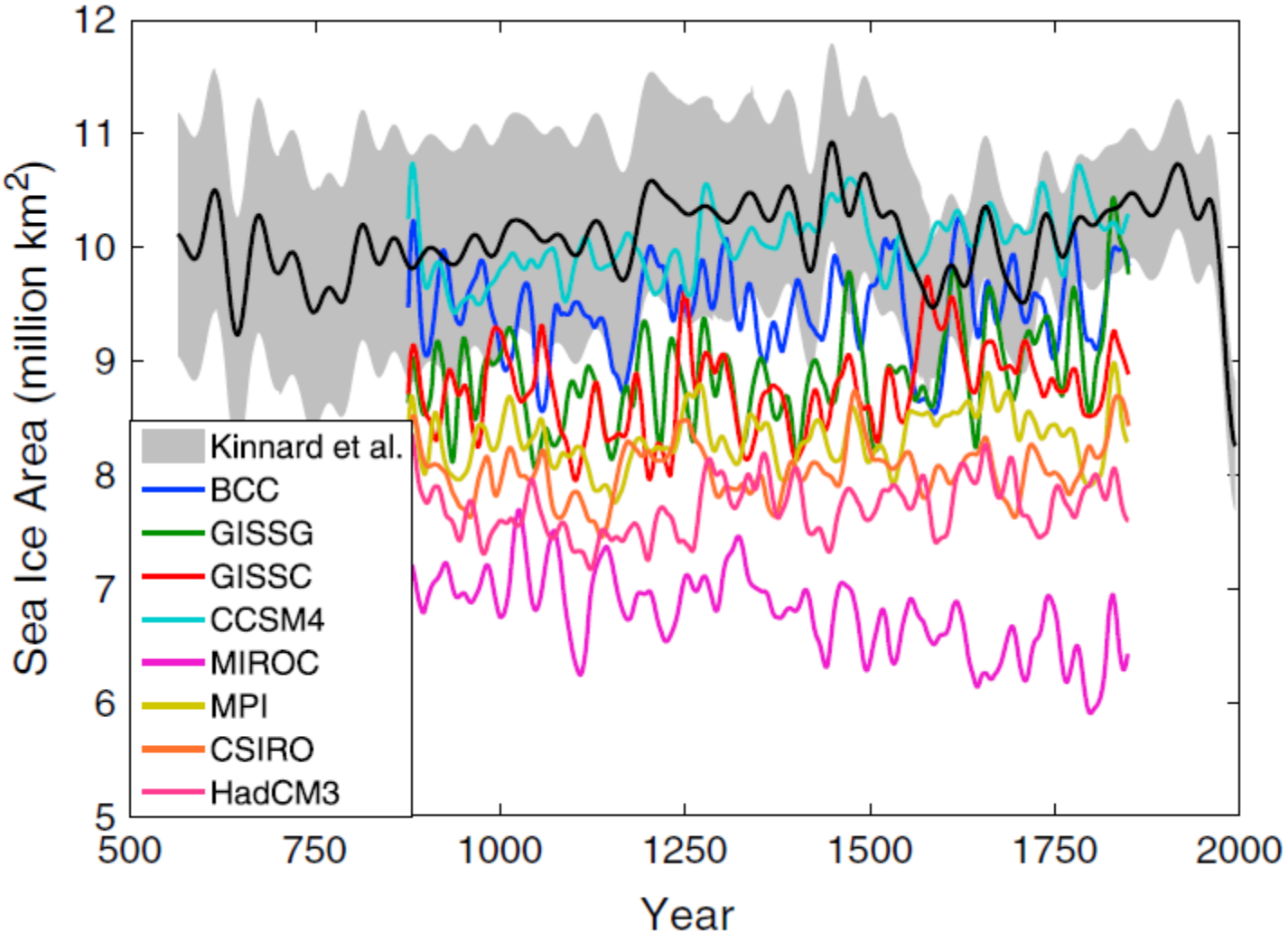
Many climate models have the Arctic climate wrong, with too little sea ice.



Berdahl, Mira, and Alan Robock, 2013: Cryospheric response to volcanic eruptions in the Paleoclimate Model Intercomparison Project 3 last millennium simulations. *J. Geophys. Res. Atmos.*, **118**, 12,359-12,370, doi:10.1002/2013JD019914.

NCAR CESM Last Millennium Ensemble (Otto-Bliesner et al. 2016)

Simulations for the period 850-1850 CE with different sets of prescribed external forcing:

- one control run (850 yr climatology)
- 5 ensemble members with volcanic forcing only
- 4 ensemble members with solar irradiance forcing only
- 3 ensemble members with orbital perturbation forcing only
- 3 ensemble members with greenhouse gas forcing only
- 3 ensemble members with land cover forcing only
- 10 ensemble members with all the forcings

Slawinska, Joanna, and Alan Robock, 2018: Impact of volcanic eruptions on decadal to centennial fluctuations of Arctic sea ice extent during the last millennium and on initiation of the Little Ice Age. *J. Climate*, 31, 2145-2167, doi:10.1175/JCLI-D-16-0498.1.

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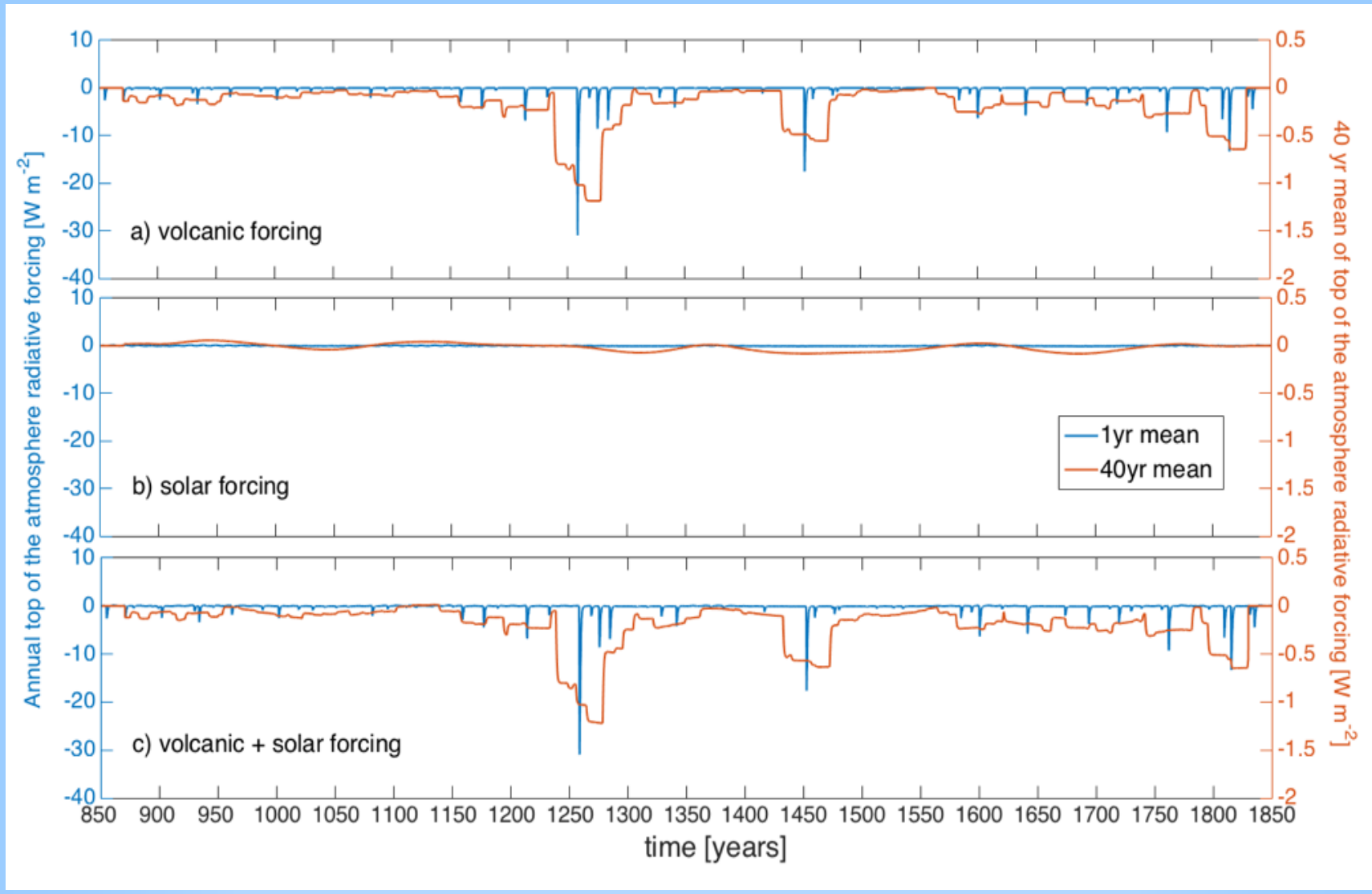

Volcanic and solar top of atmosphere radiative forcing (W m^{-2}) applied during the LME runs

Slawinska, Joanna, and Alan Robock, 2018: Impact of volcanic eruptions on decadal to centennial fluctuations of Arctic sea ice extent during the last millennium and on initiation of the Little Ice Age. J. Climate, 31, 2145-2167, doi:10.1175/JCLI-D-16-0498.1.

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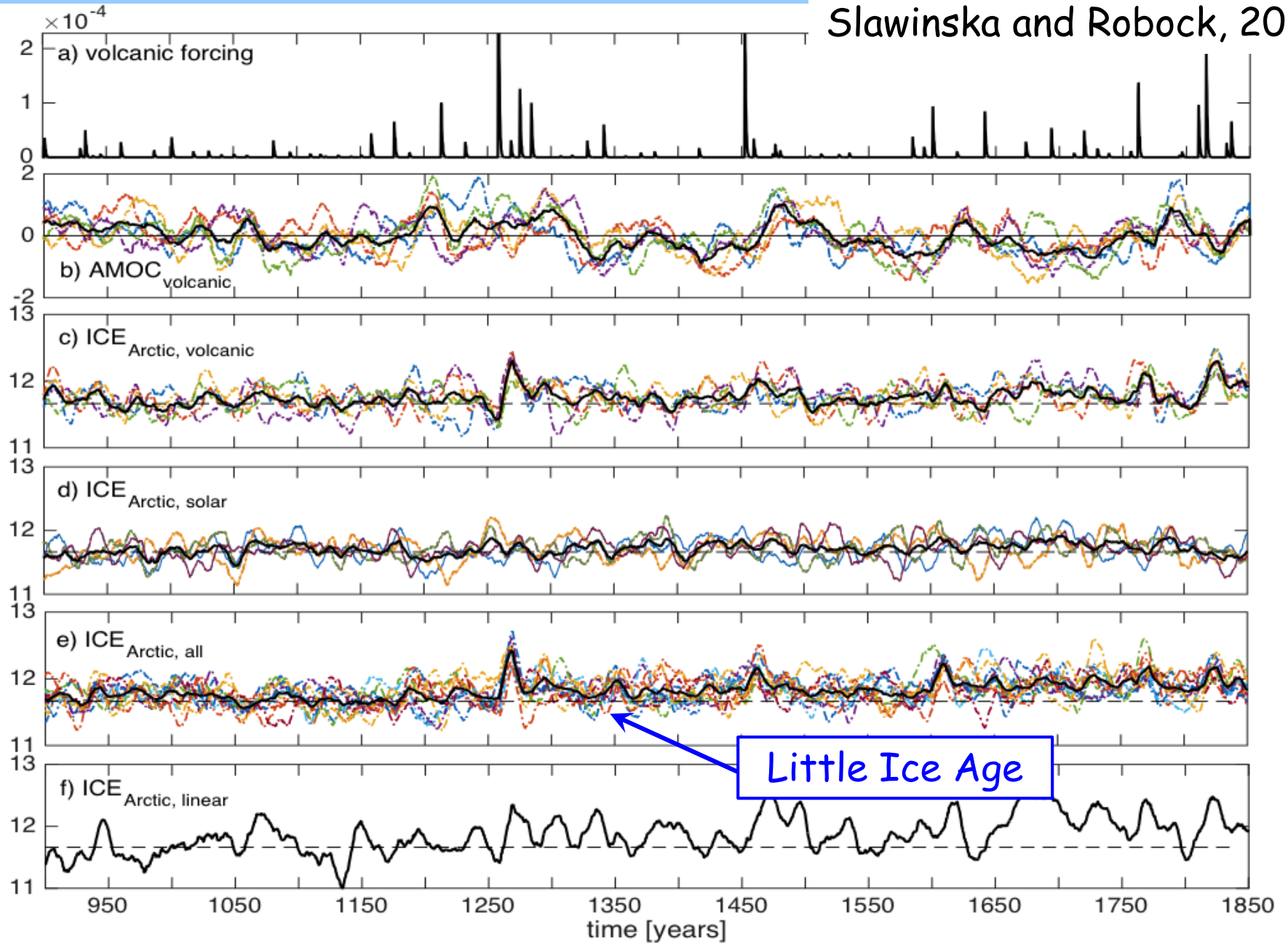
Slawinska and Robock, 2018



c)-f): NH sea ice area (x 10^6 km^2)

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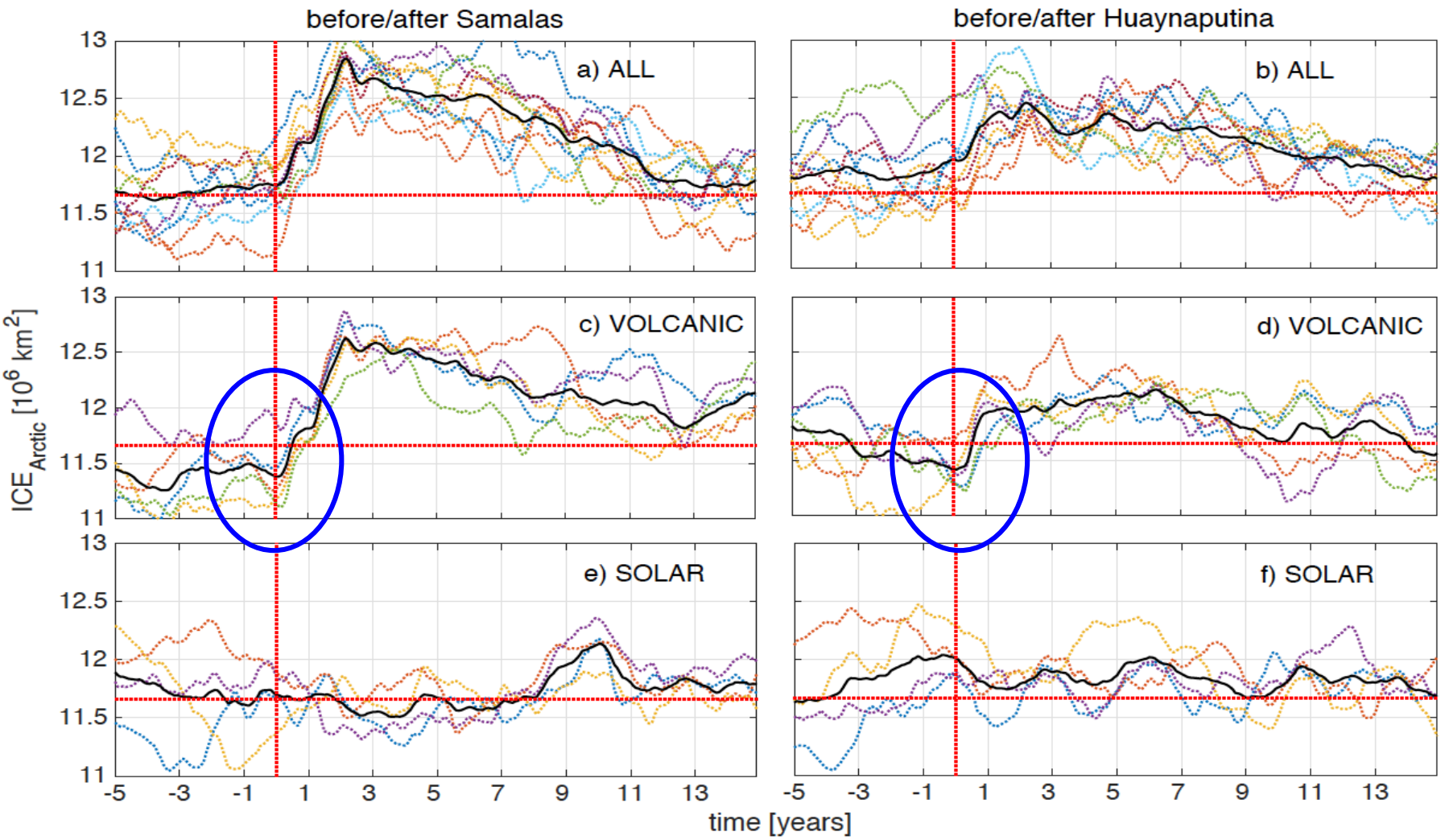
Slawinska and Robock, 2018

Volcanic forcing runs have warmer climate



NH sea ice area (x 10^6 km^2)

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Did volcanic eruptions cause the Little Ice Age?

1. If large volcanic eruptions cooled the Arctic, why did it stay cold long after the volcanic aerosols fell out of the atmosphere?
2. Did what happened at the end of the 13th Century depend on the state of the climate system at the time?
3. Was one large eruption enough, or did the forcing depend on a sequence of eruptions?
4. Did solar variations contribute to the Little Ice Age, or were volcanic eruptions enough?

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New simulations to understand the NCAR CESM Last Millennium Ensemble

100-year simulations (1255-1355 CE) for the period with different sets of prescribed external forcing, with cold, normal, and warm initial conditions:

- 1258 Samalas only
- Full volcanic forcing for 1258-1300 (4 Volcanoes)
- 1258 reduction of total solar irradiance by 2 W m^{-2} (-0.35 W m^{-2} radiative forcing) (Solar)
- Samalas + Solar
- 4 Volcanoes + Solar

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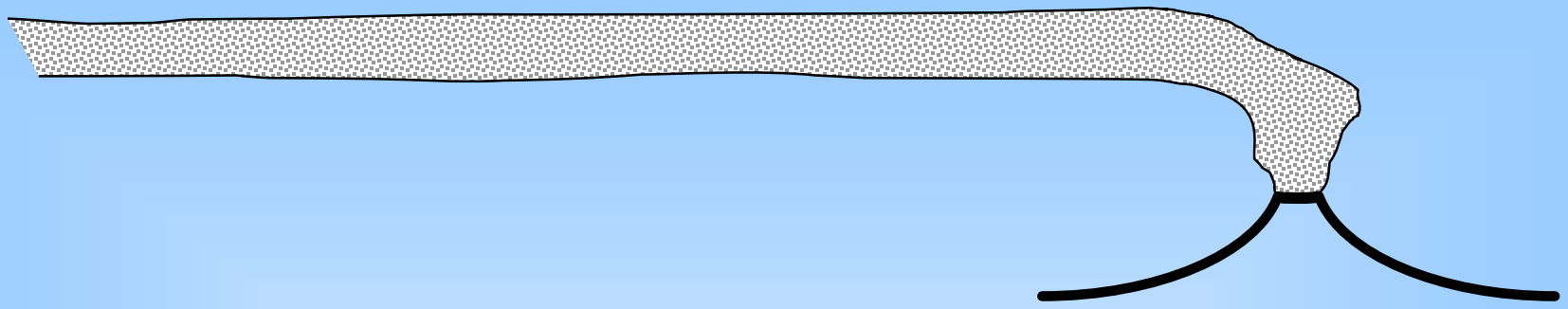

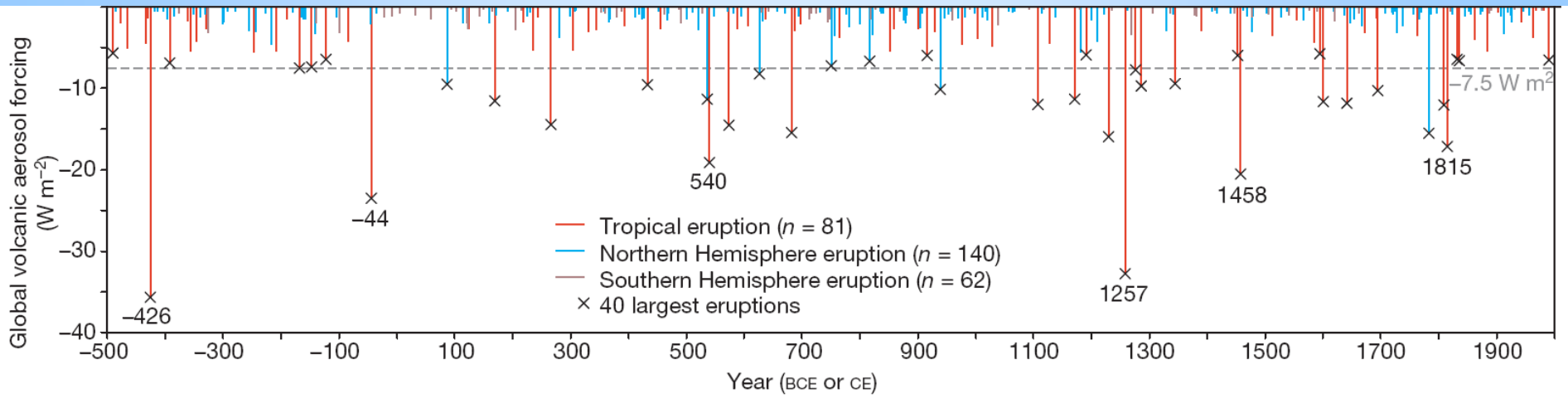

Sigl, M., et al., 2015: Timing and climate forcing of volcanic eruptions for the past 2,500 years. *Nature*, **523**, 543-549, doi:10.1038/nature14565.

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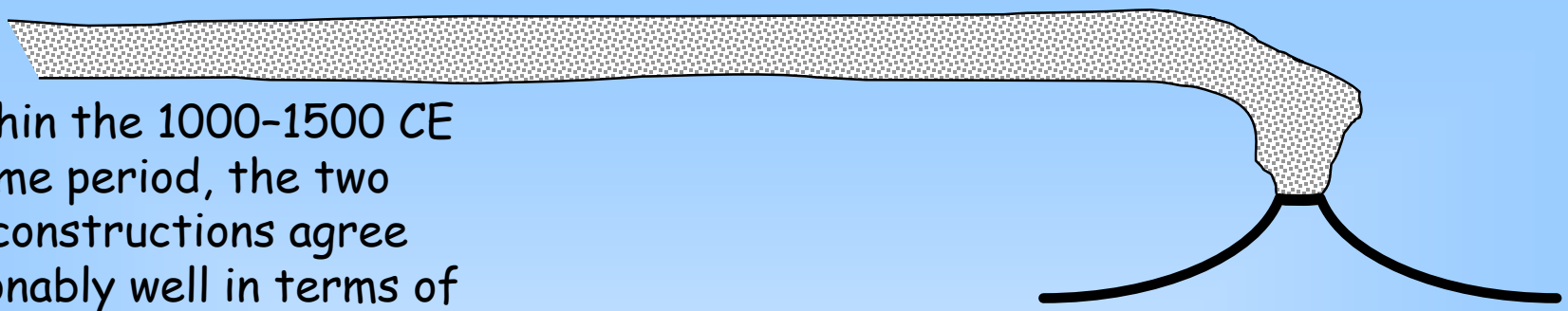
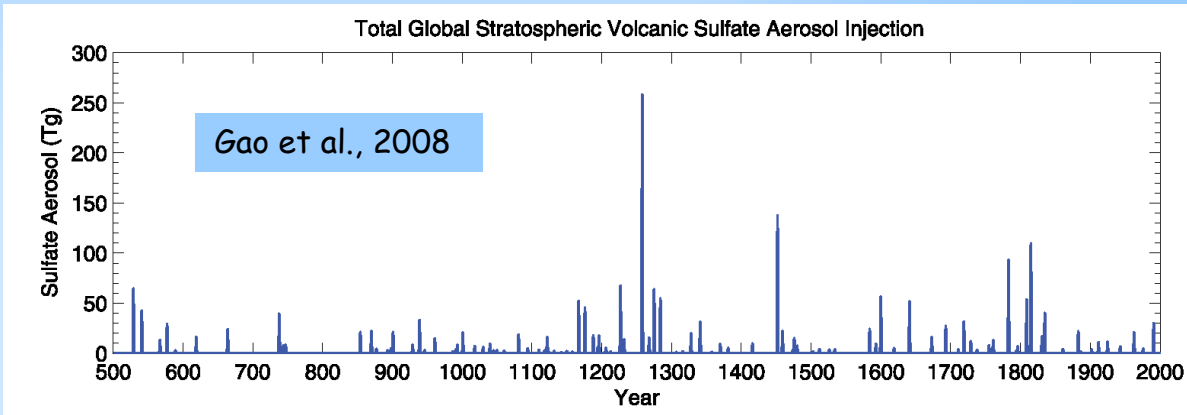
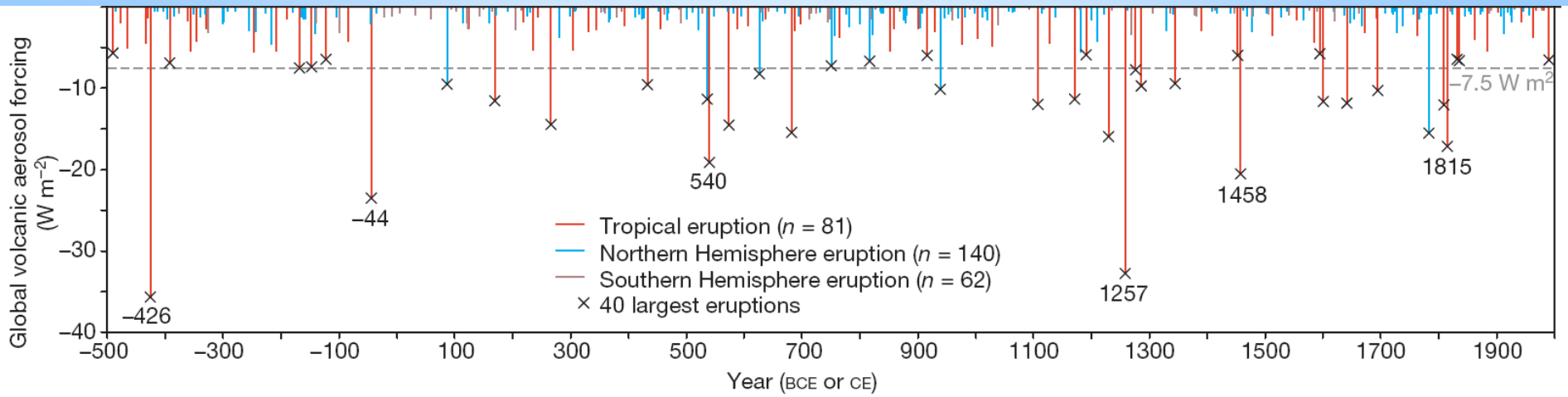


"Within the 1000–1500 CE time period, the two reconstructions agree reasonably well in terms of the timing and magnitude of the great 1257 Samalas eruption and the eruptions of 1276 and 1286."

Toohey and Sigl, 2017





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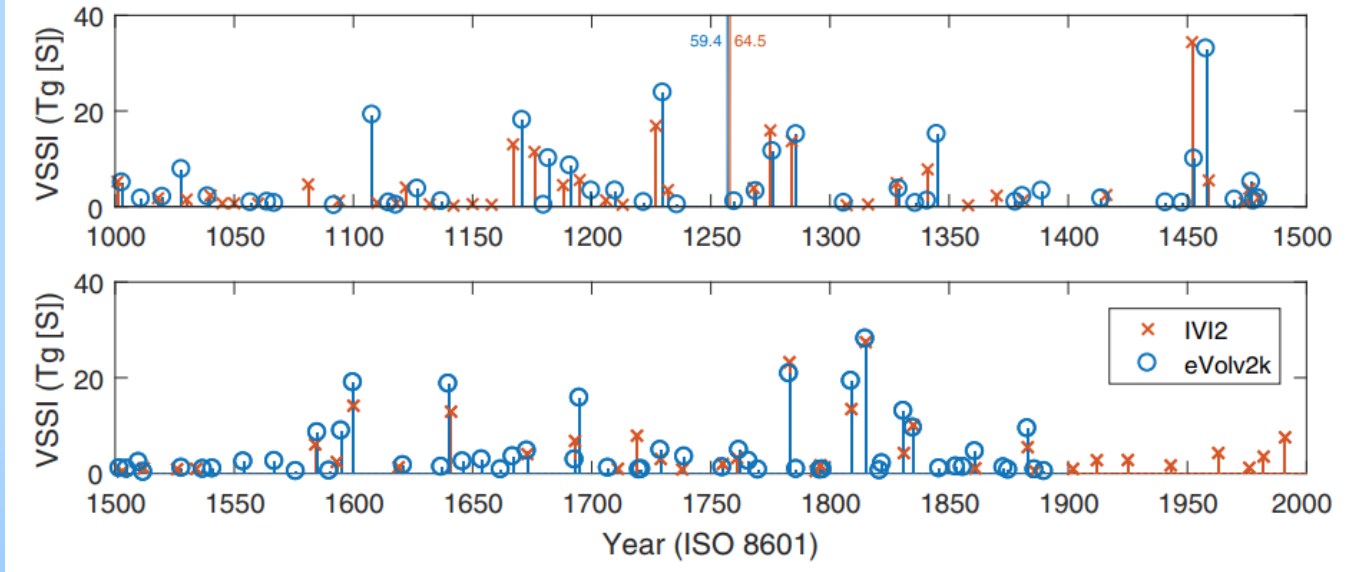

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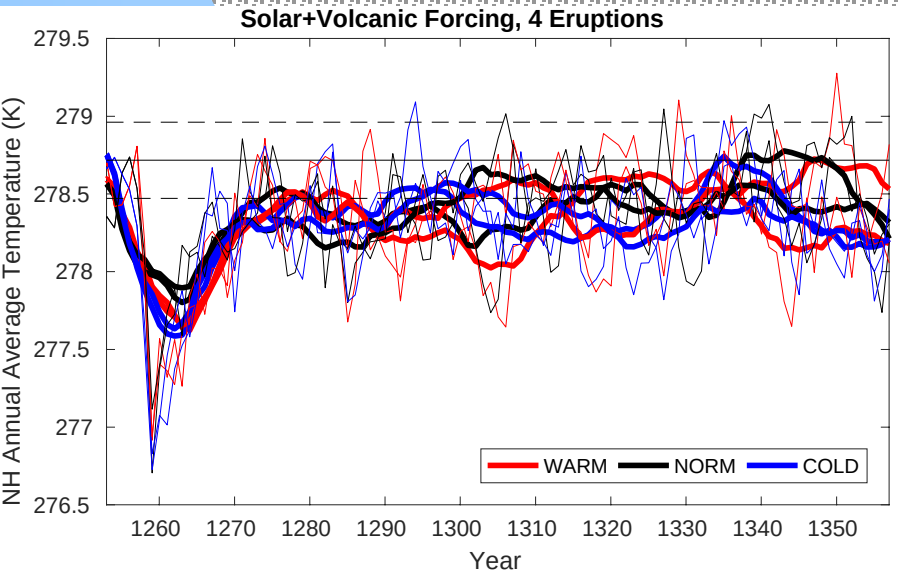

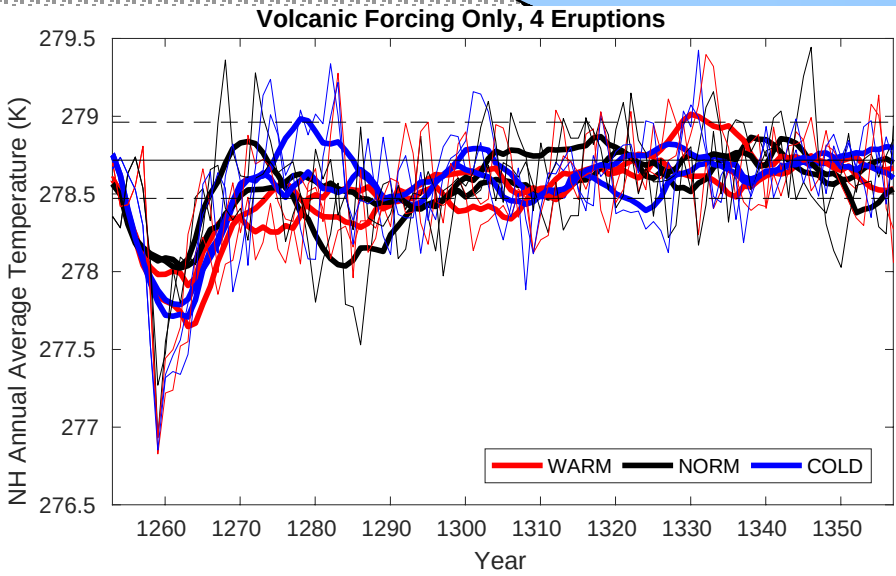

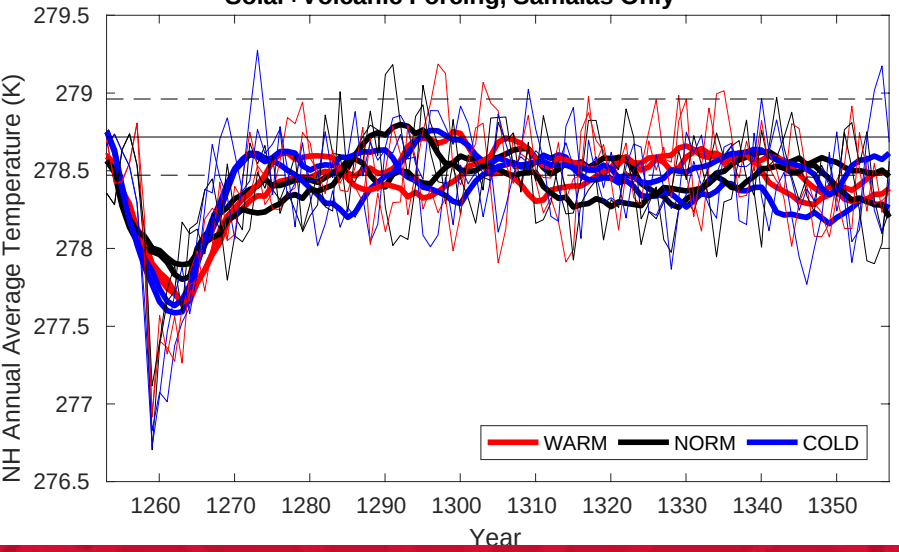

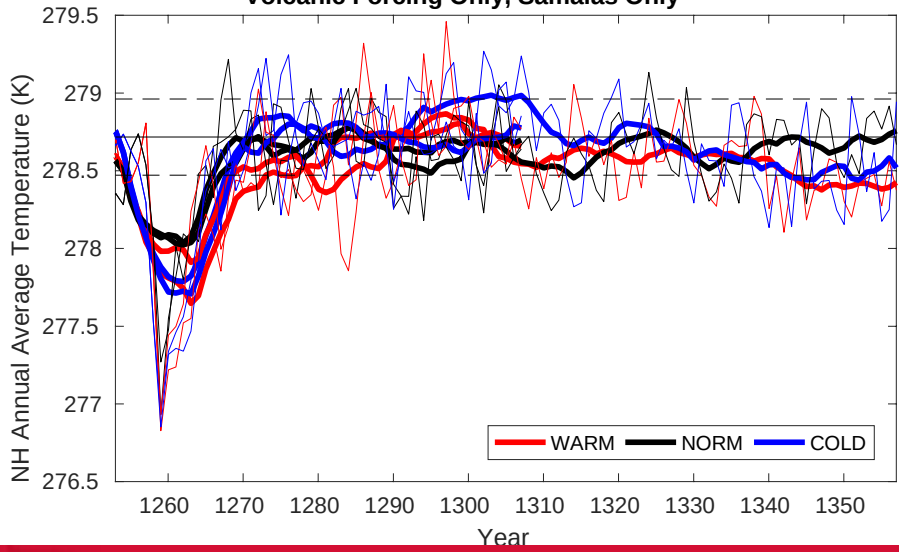

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All ensemble members

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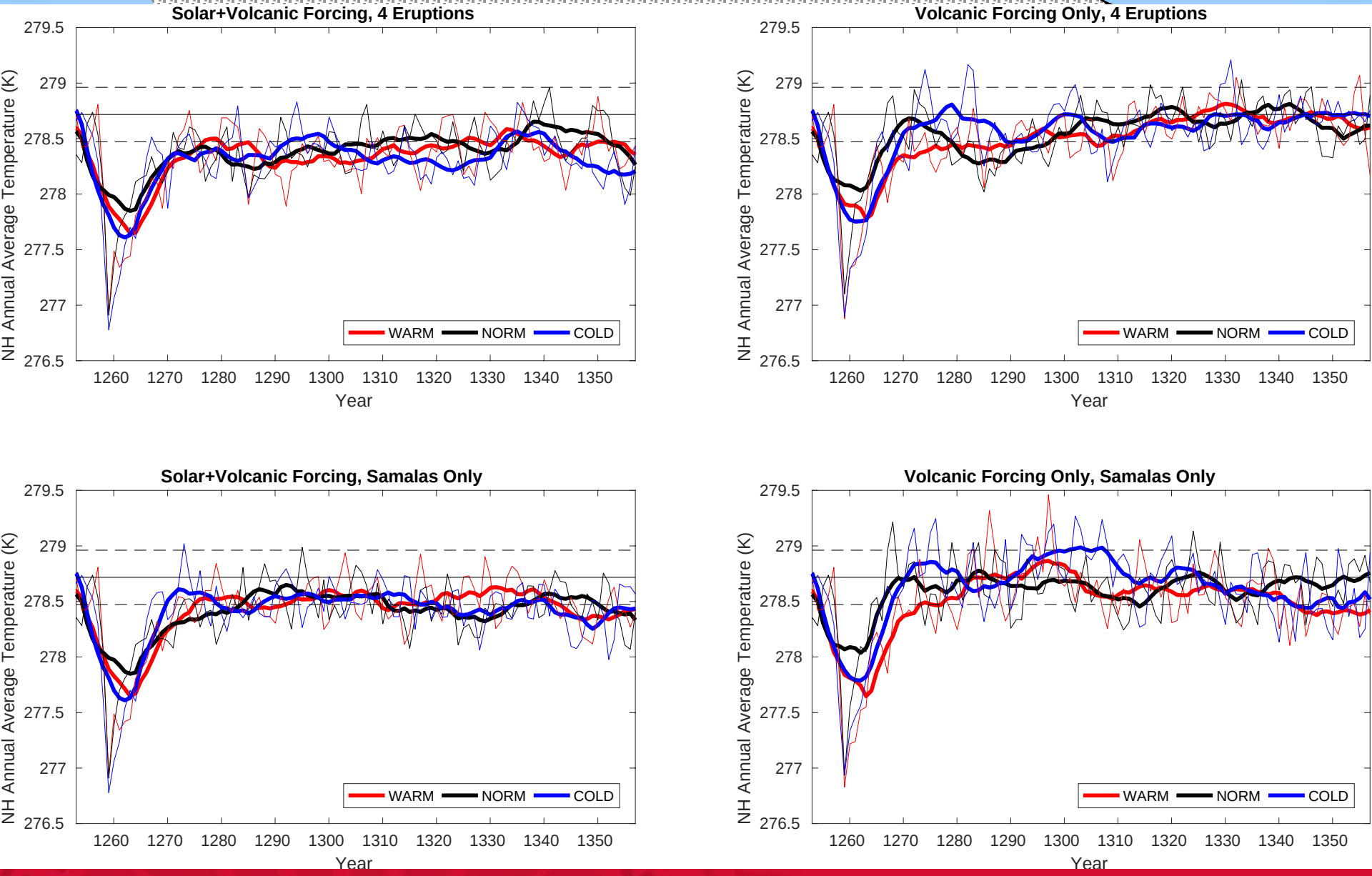

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2-member average

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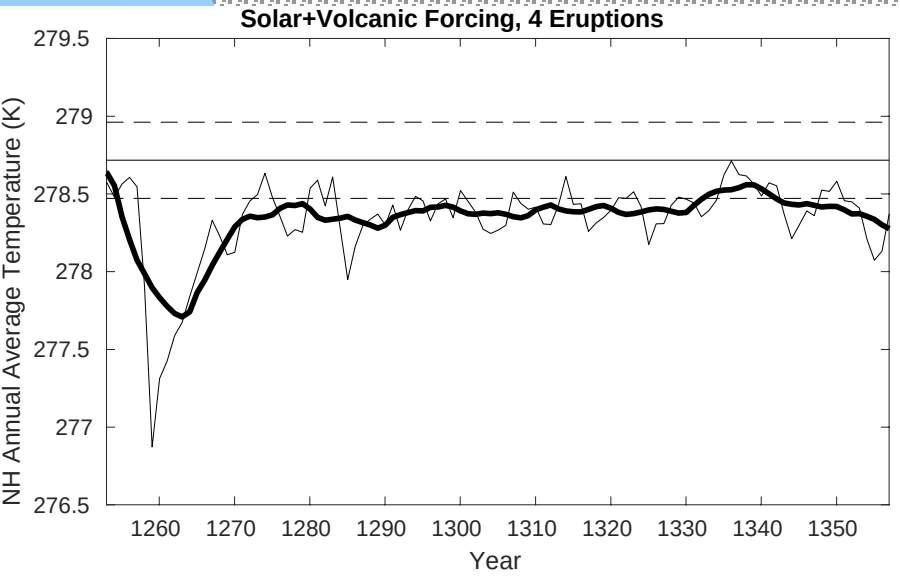

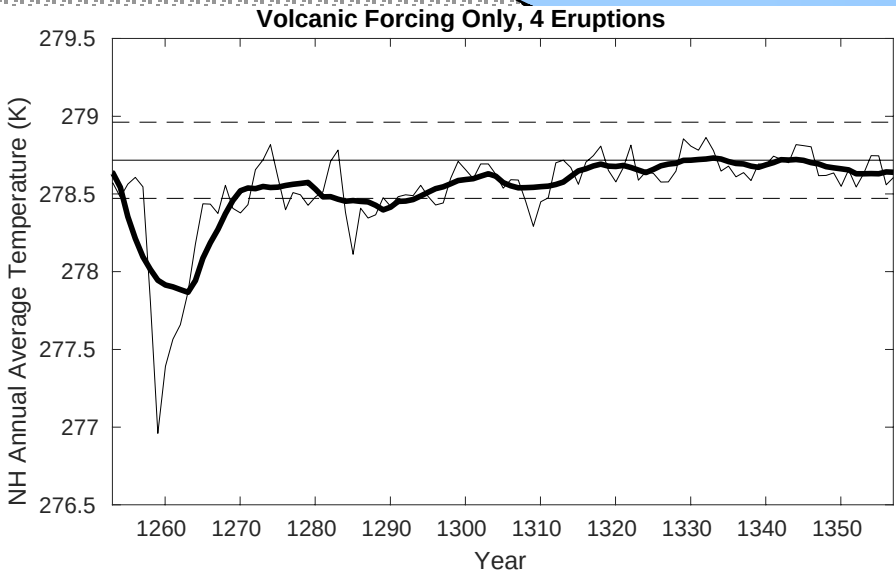

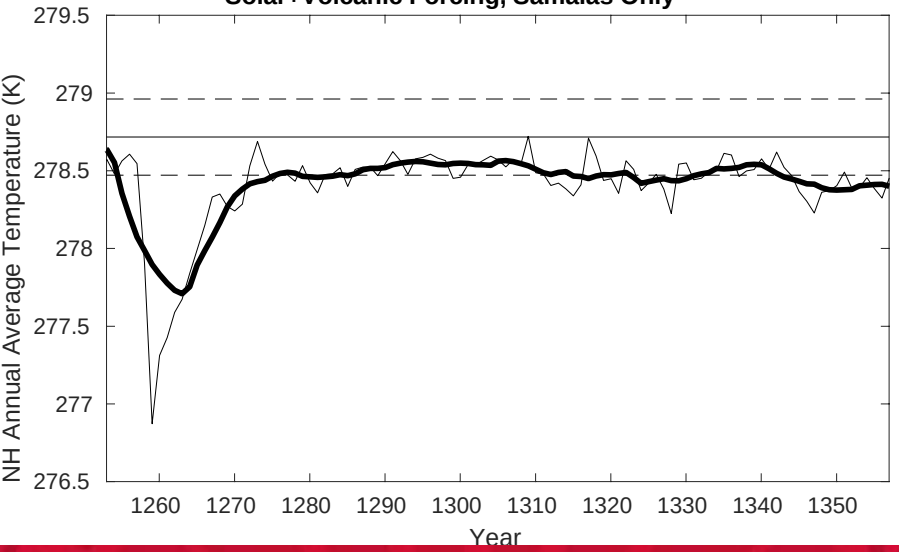

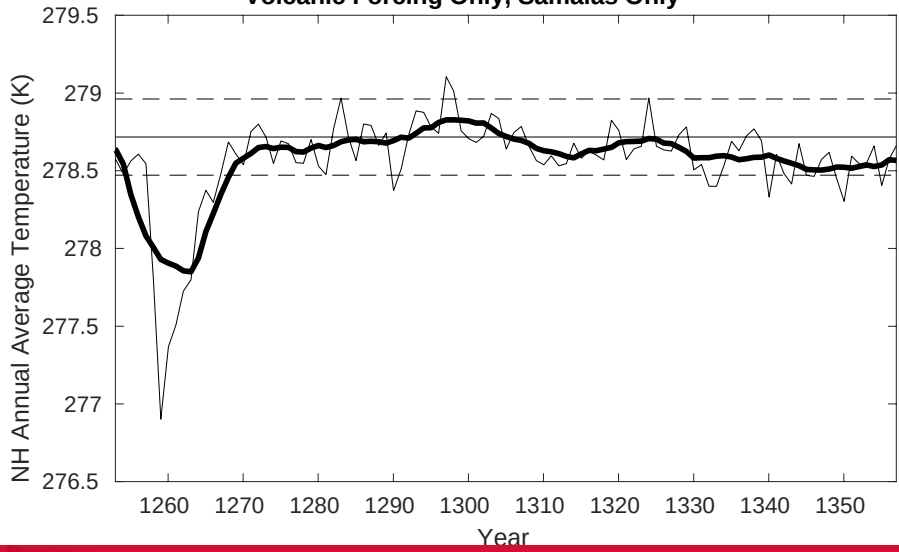

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Average over all initial conditions

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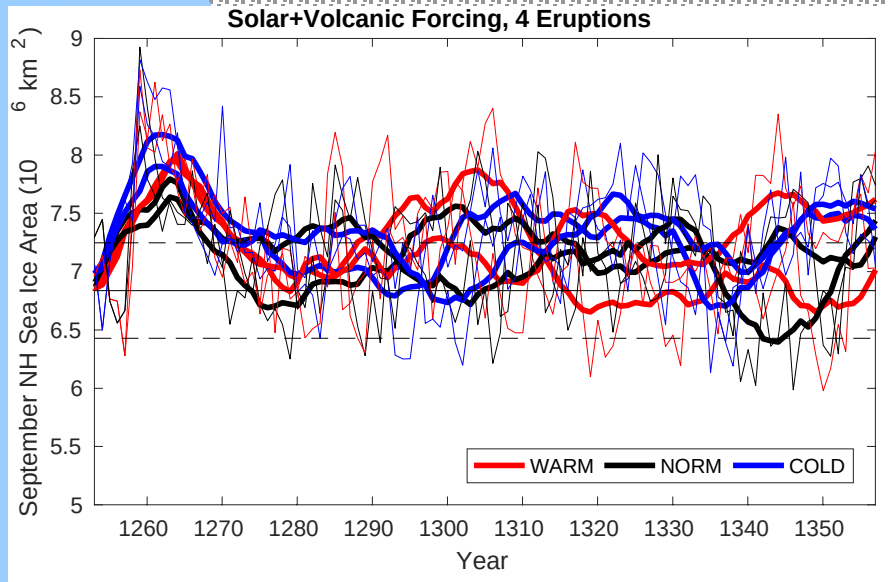

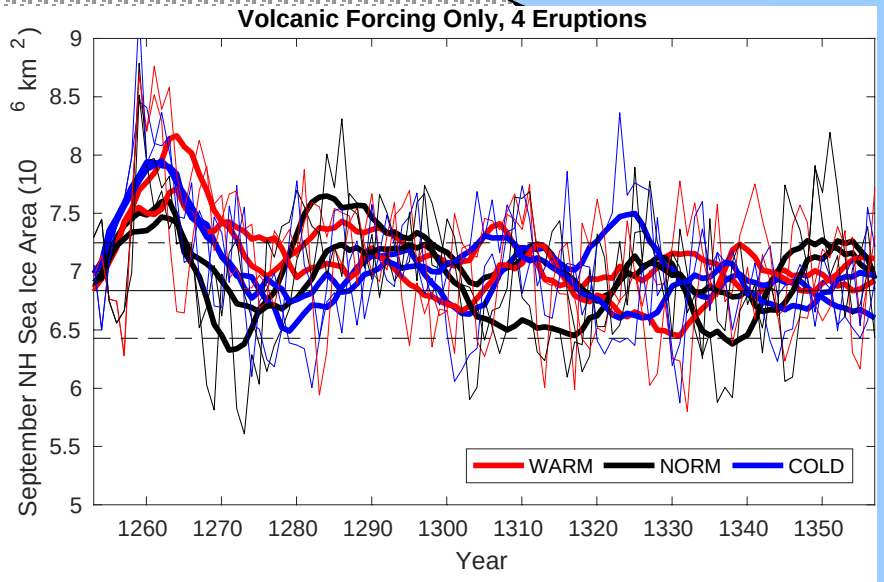

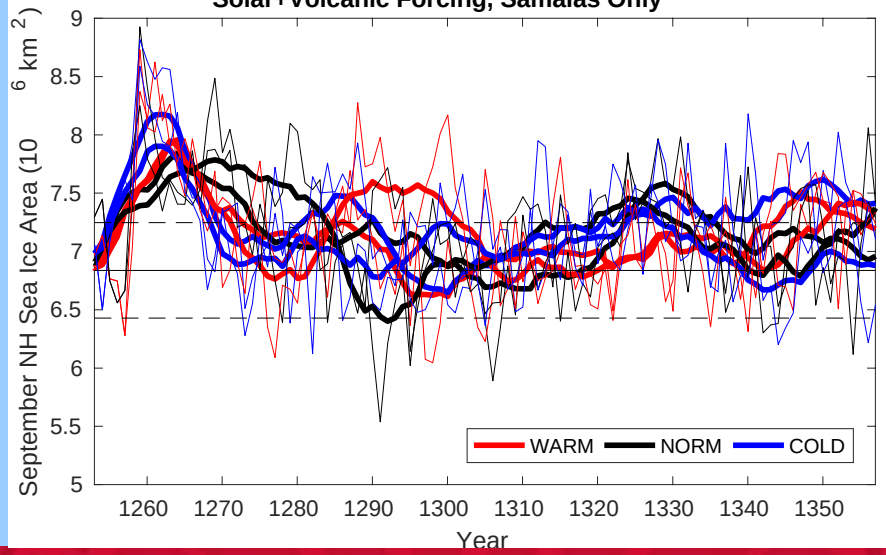

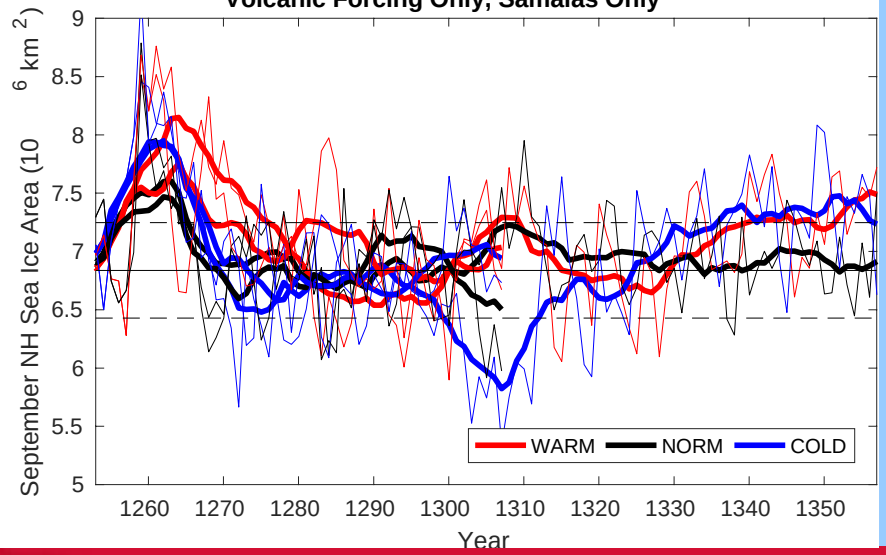

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All ensemble members

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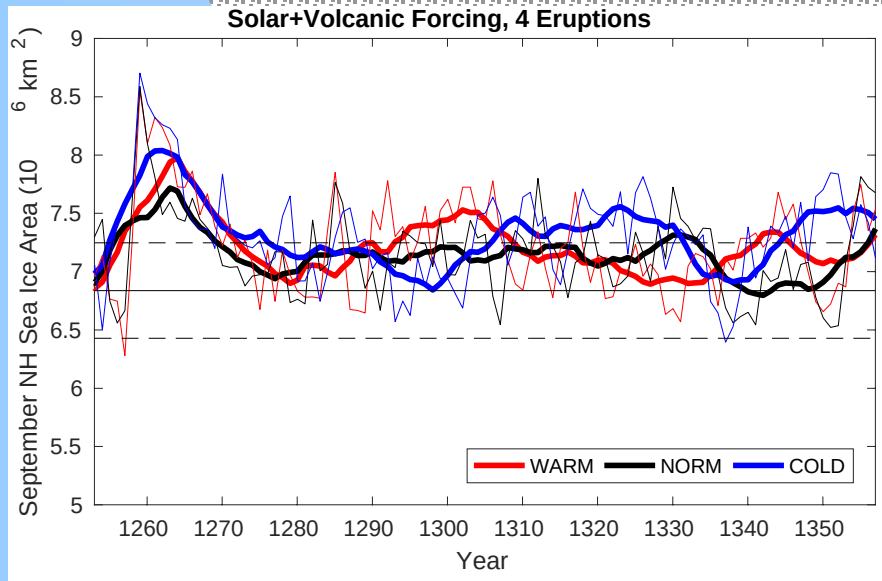

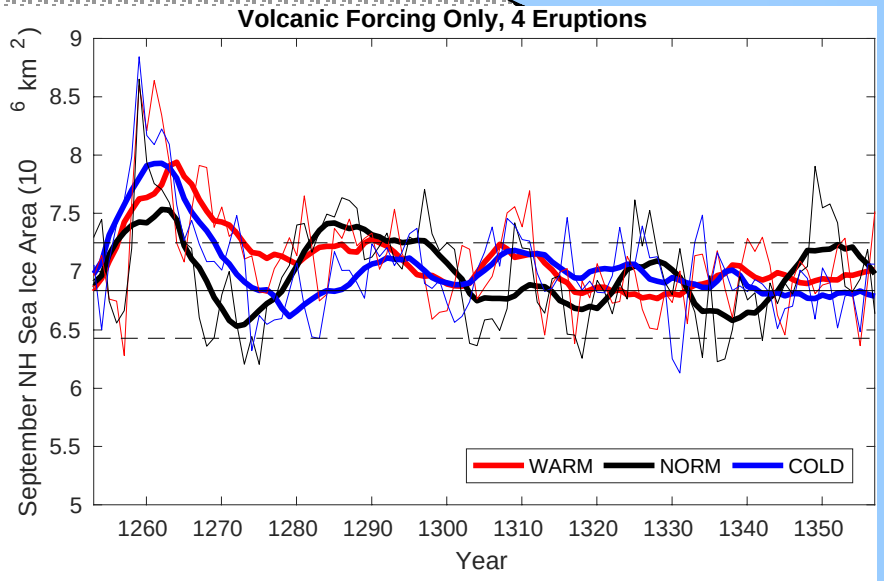

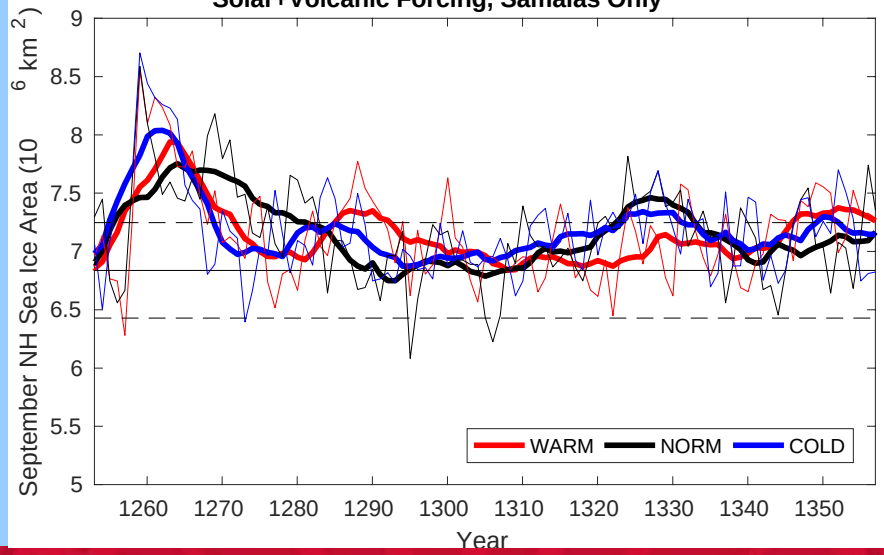

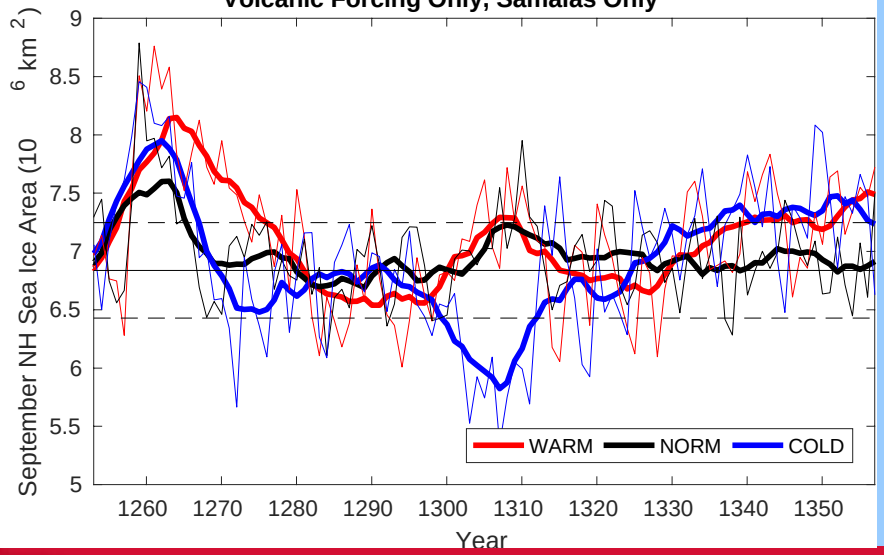

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2-member average

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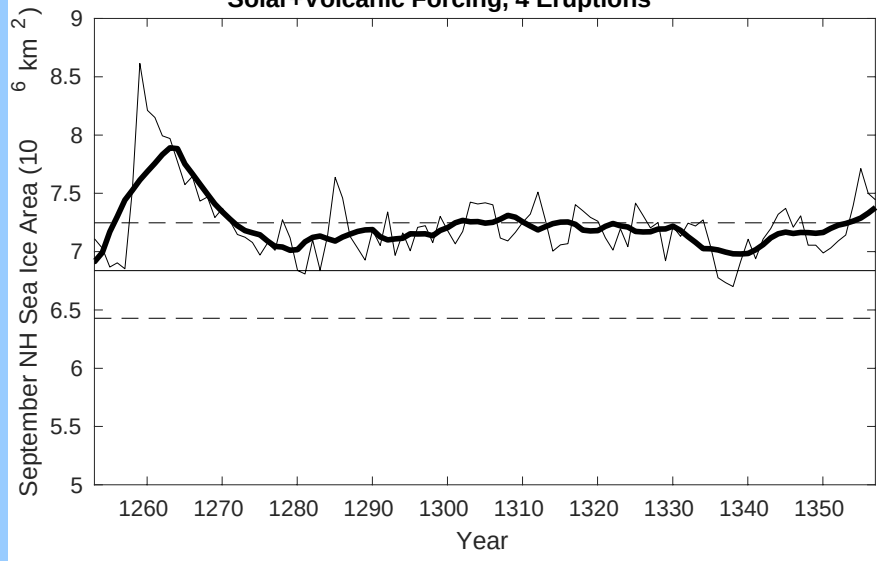

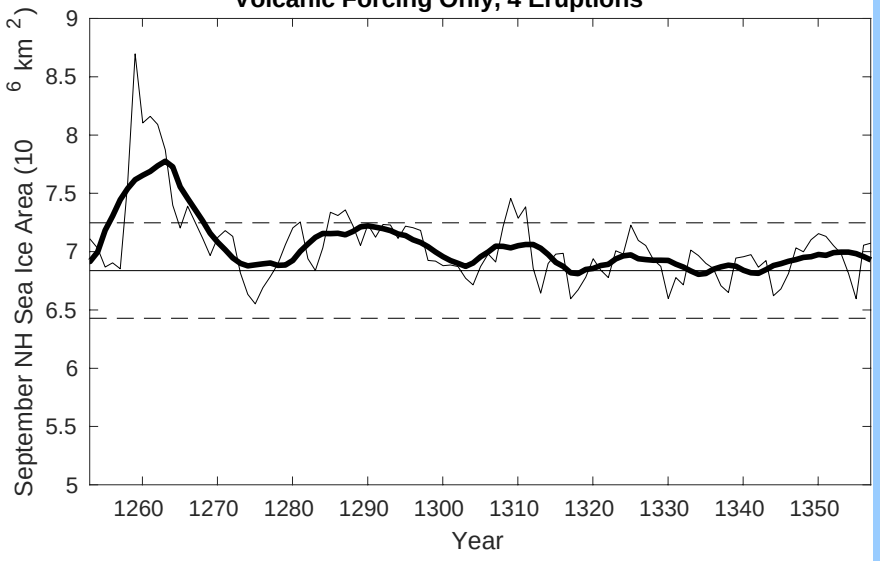

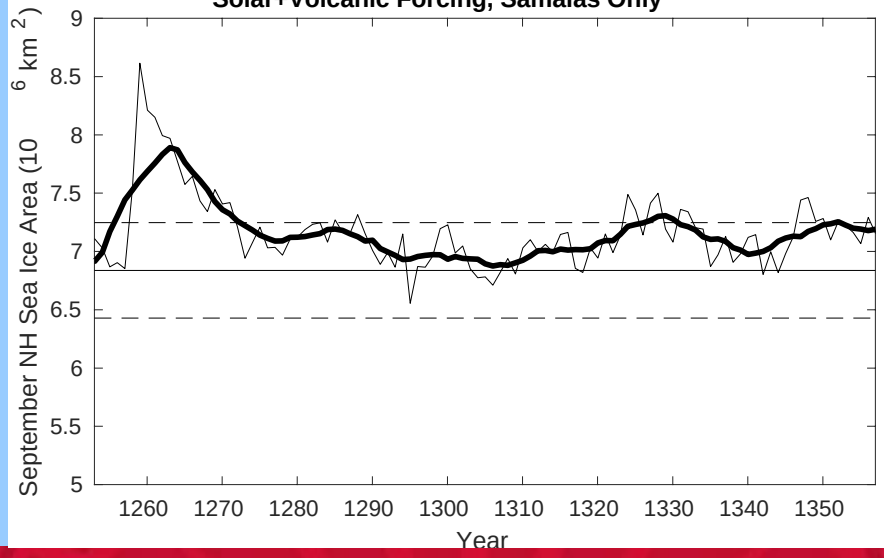

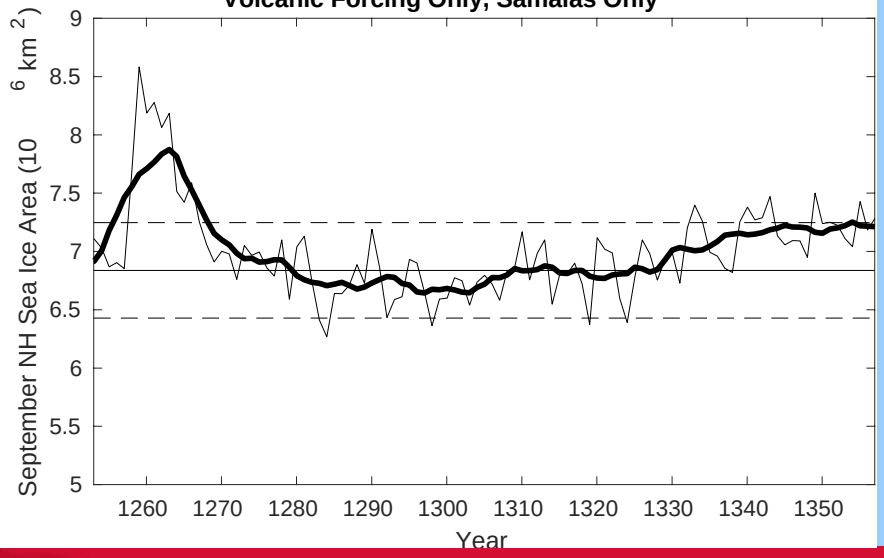

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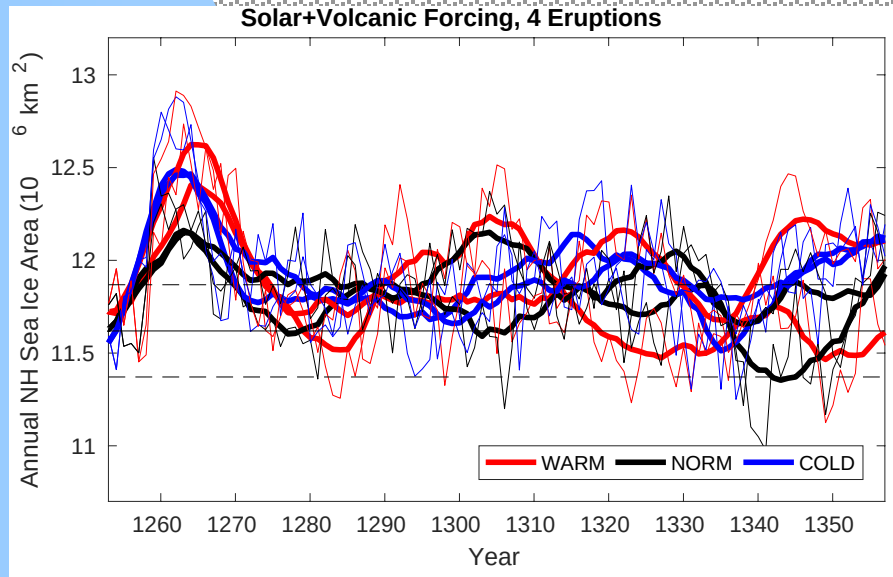

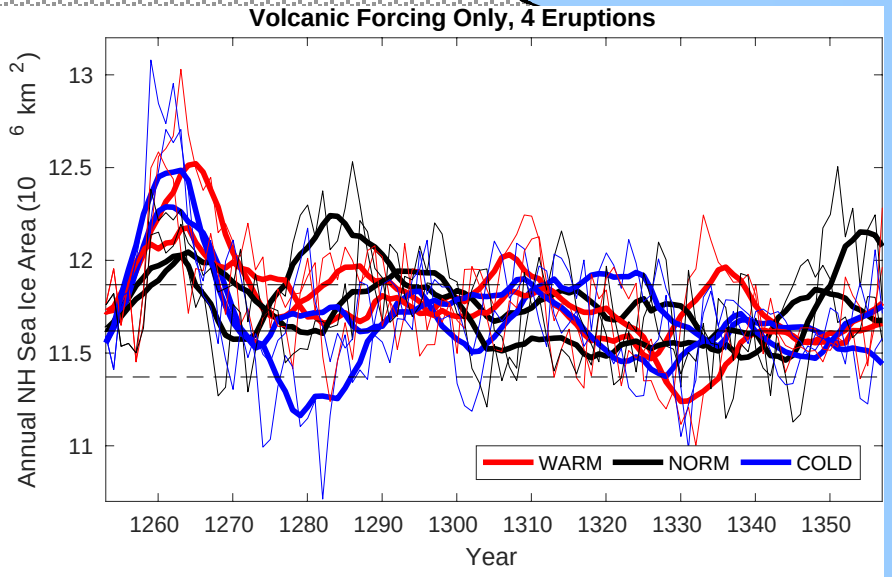

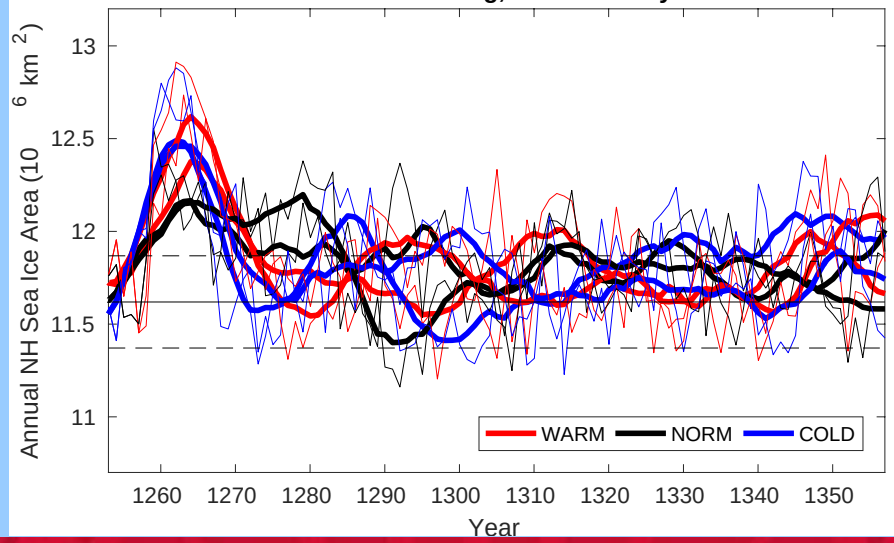

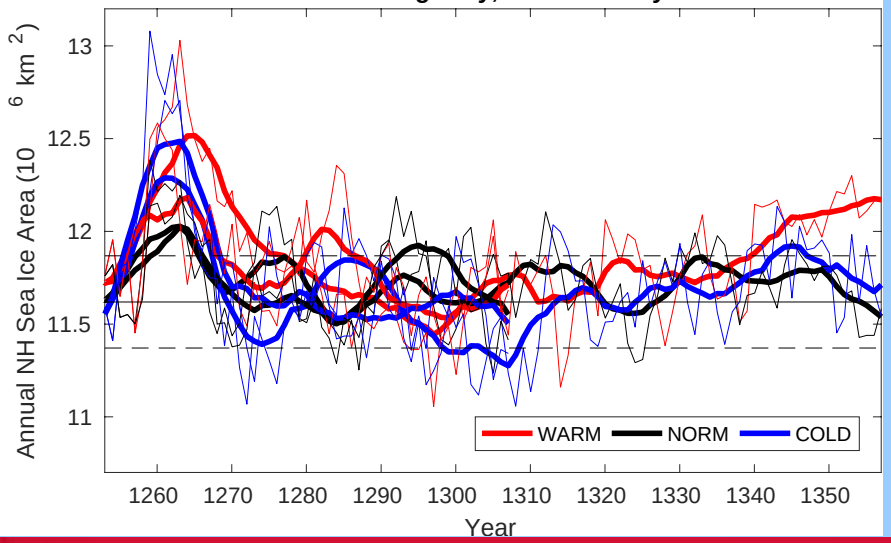

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All ensemble members

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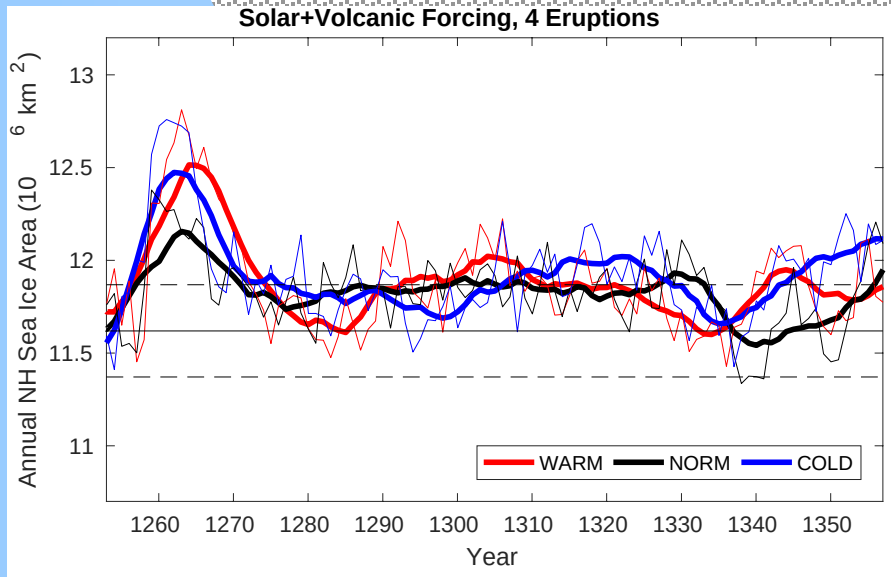

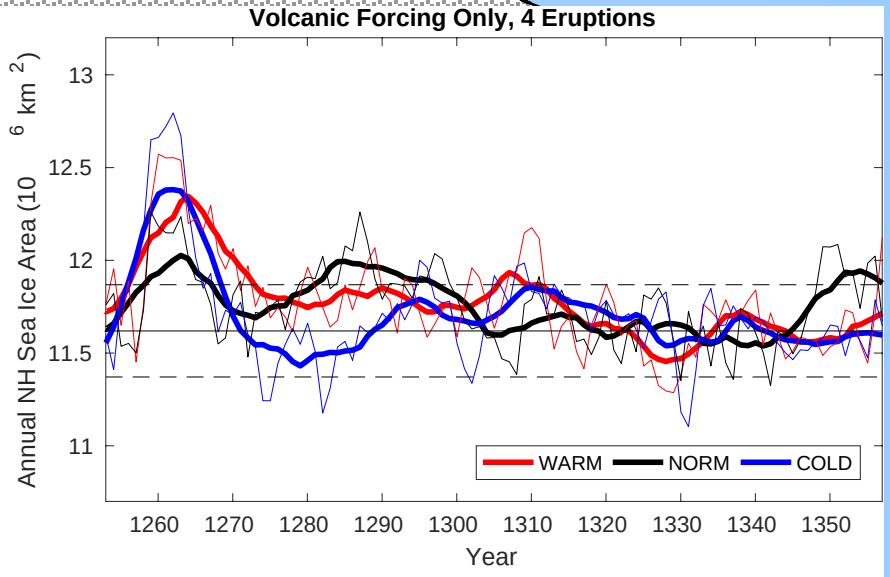

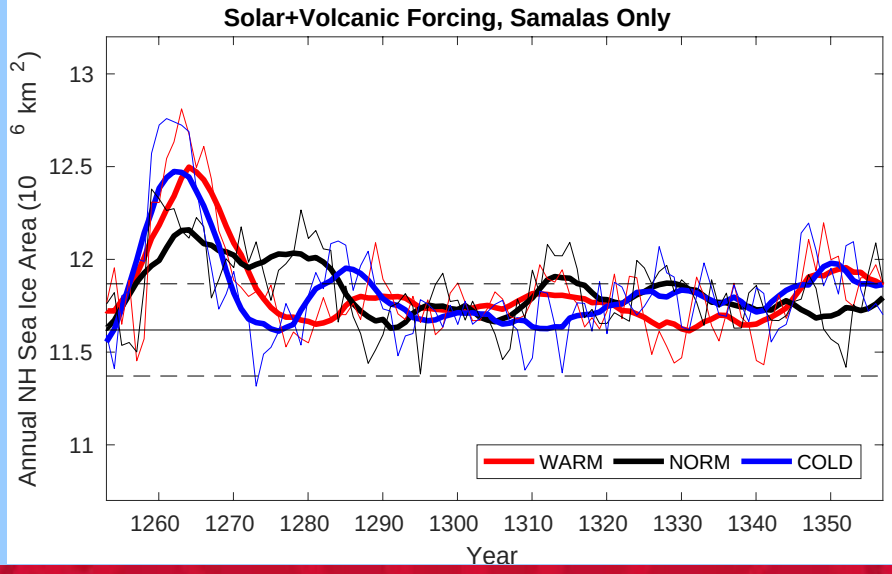

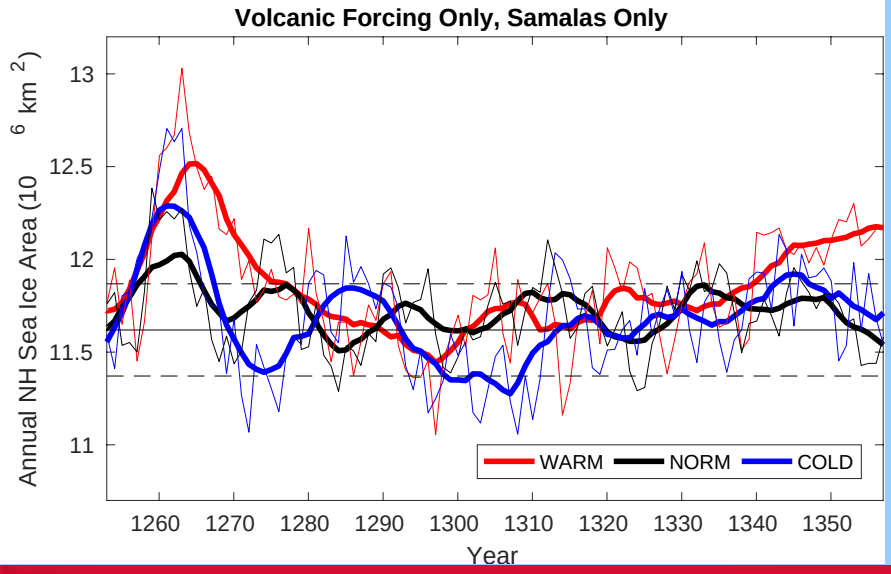

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2-member average

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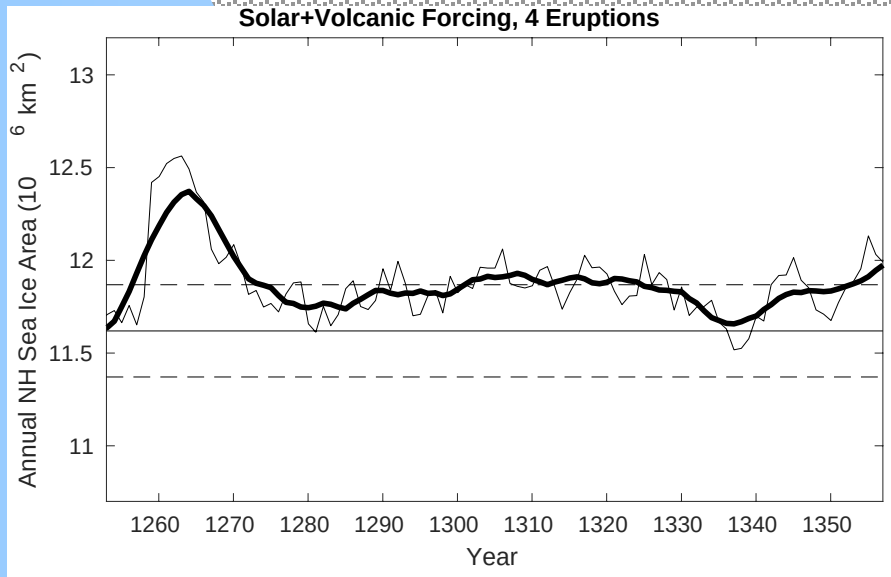

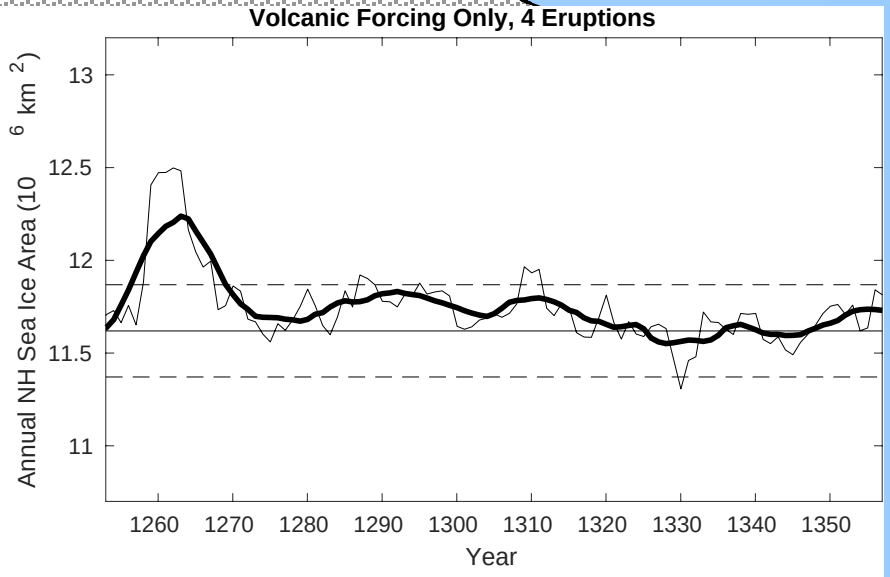

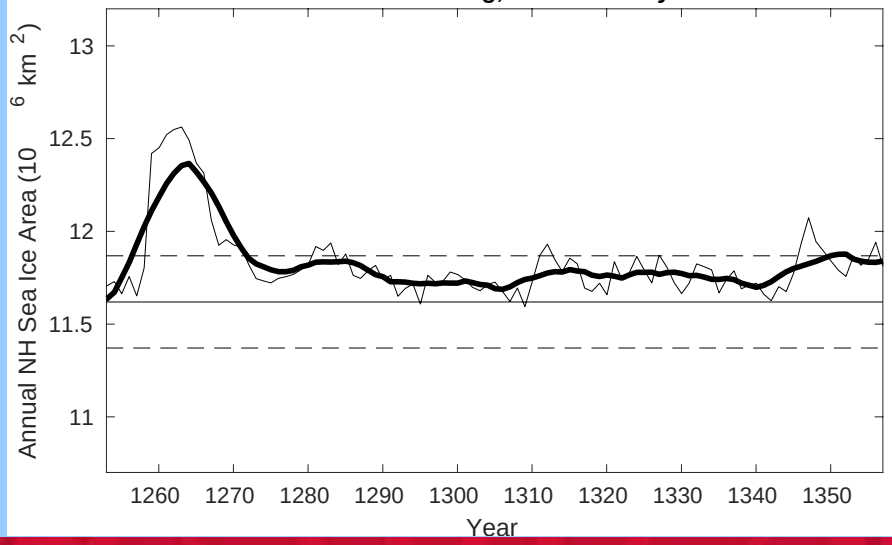

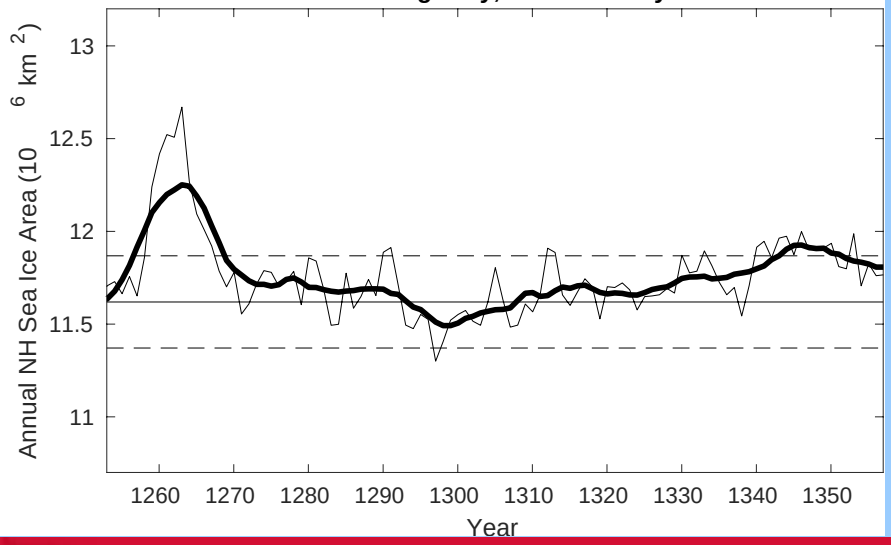

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Average over all initial conditions

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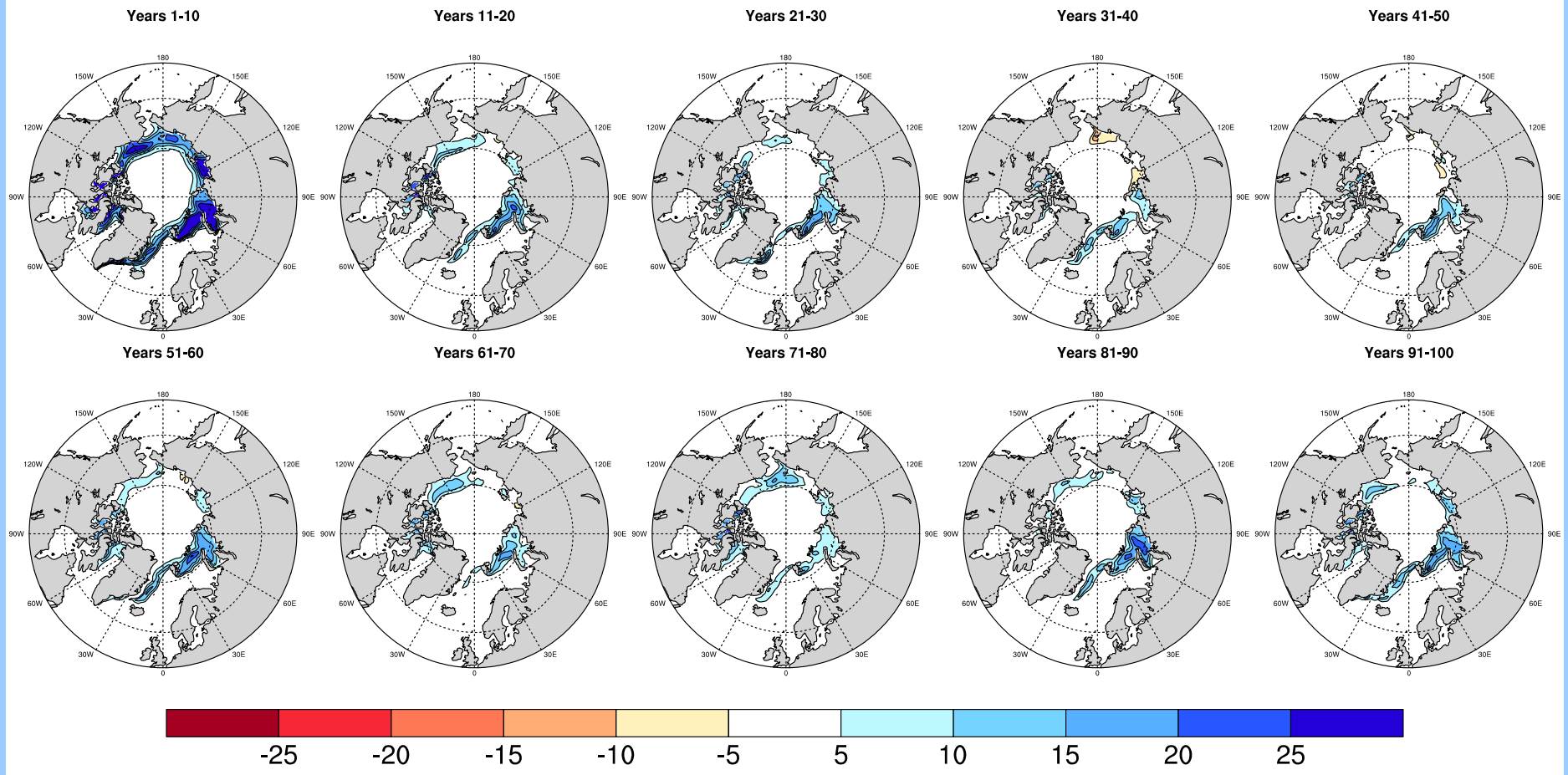
September Sea Ice Area Anomaly (%), Cold Runs



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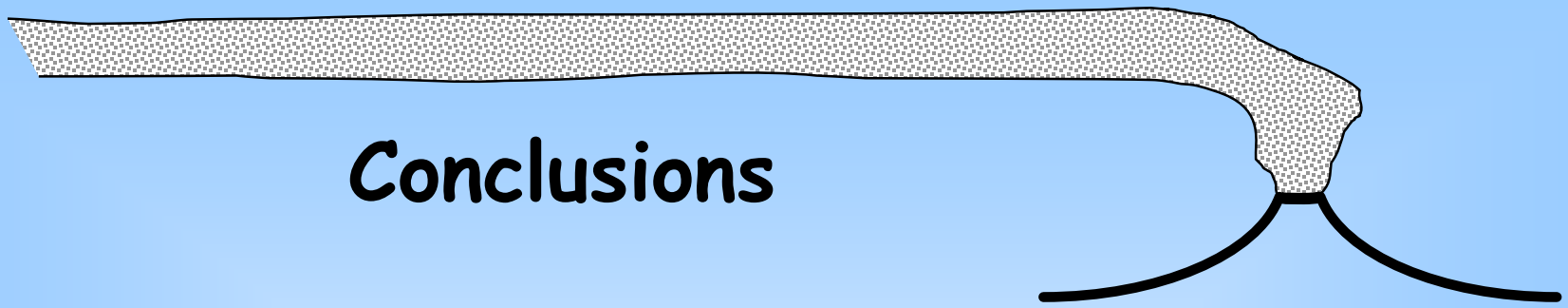

Conclusions

- Large volcanic forcings are necessary to explain the origin and duration of Little-Ice-Age-like perturbations.
- Prolonged reductions in solar irradiance enhance the magnitude of volcanically-triggered anomalies of Arctic sea ice extent.
- Results and mechanism model-dependent (~20% more ice in Zhong et al. mean)
- Model with more ice might not require solar forcing/multiple volcanic eruptions

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