Centennial-scale Climate Change from Decadally-paced Explosive Volcanism

Yafang Zhong and Gifford Miller
INSTAAR, University of Colorado at Boulder, USA

Bette Otto-Bliesner, Caspar Ammann, Marika Holland,
David Bailey and David Schneider
NCAR, USA

Aslaug Geirsdottir
University of Iceland, Iceland

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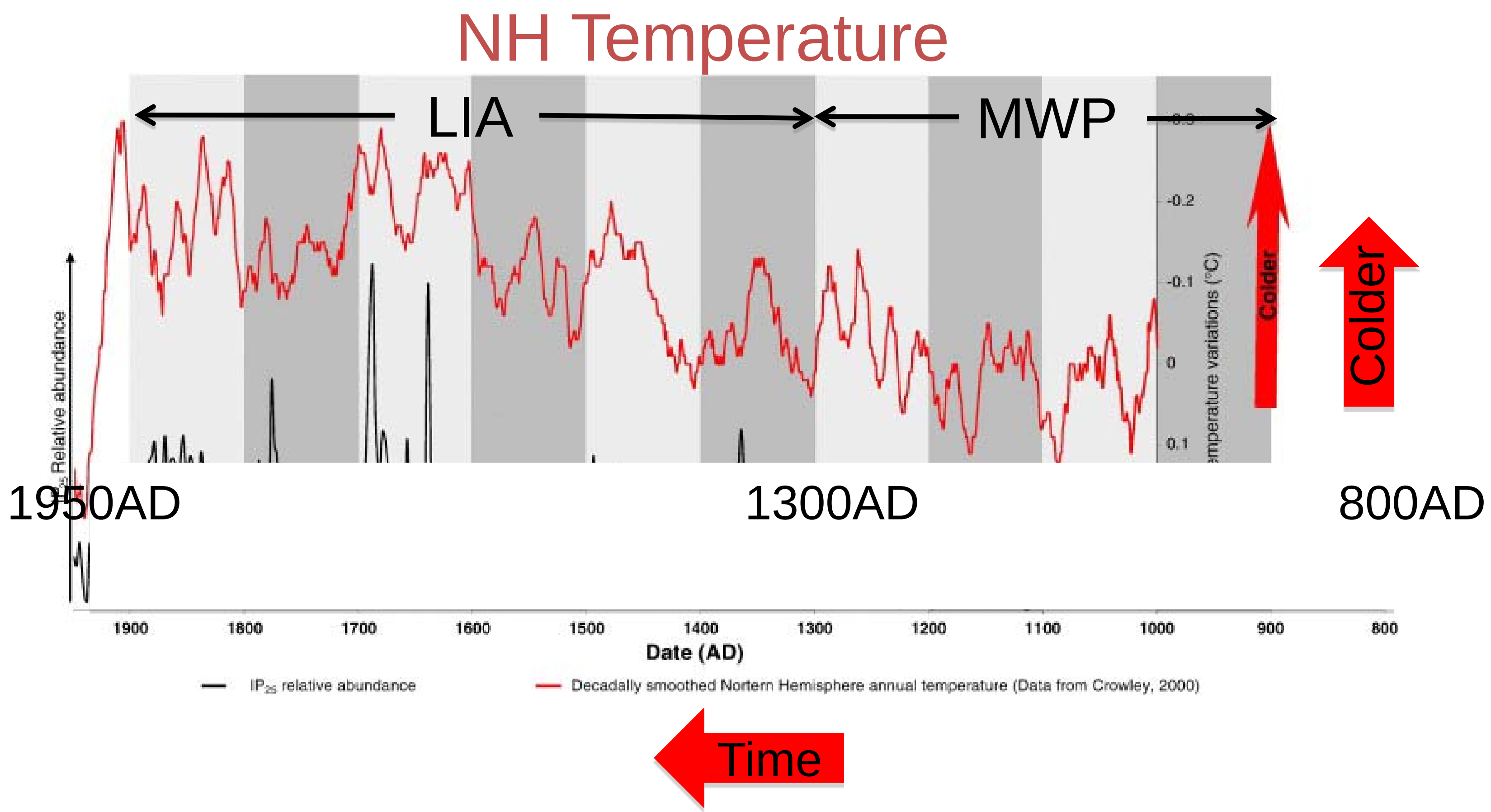
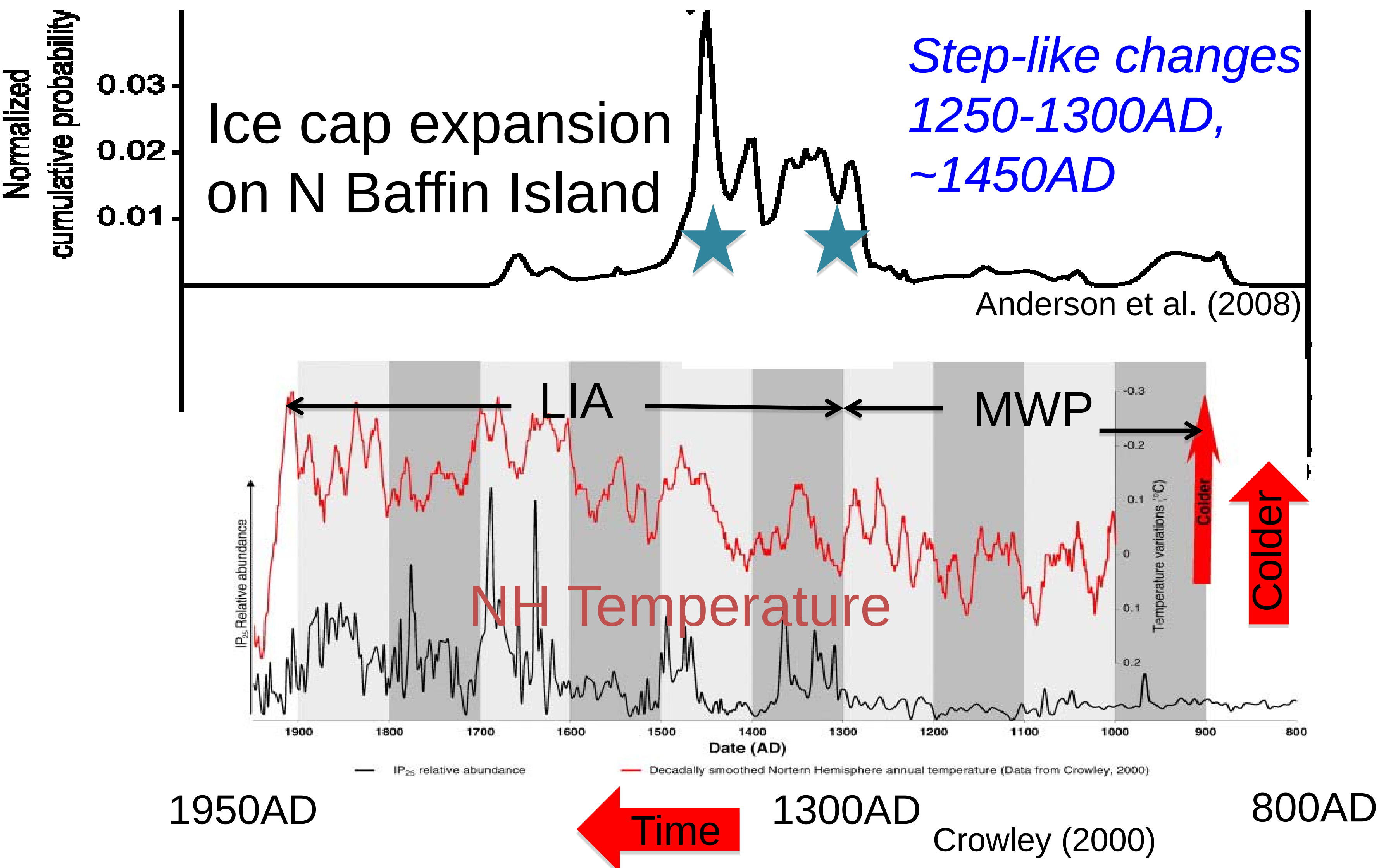
NH climate of the past millennium



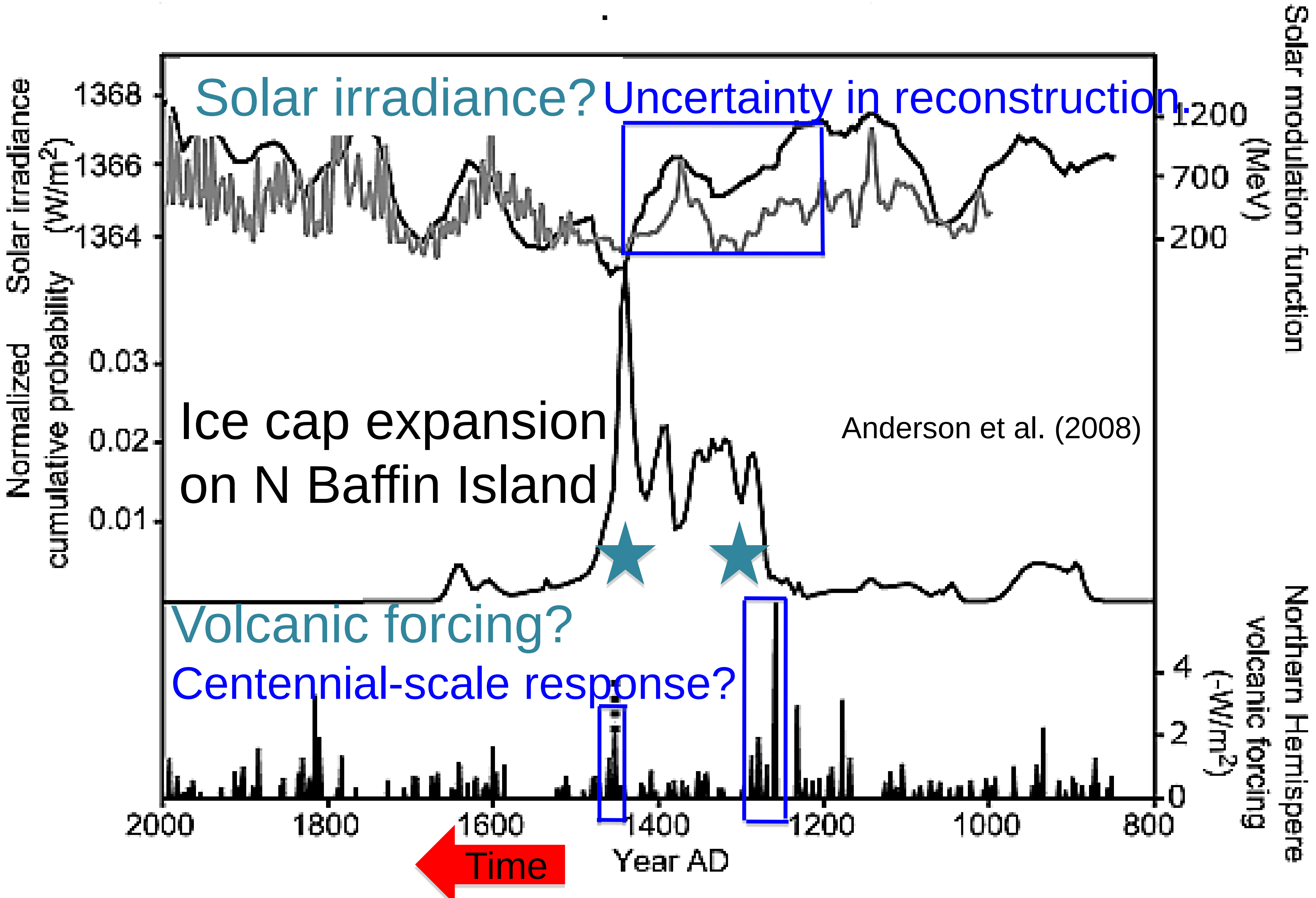
Crowley (2000)

The past millennium is characterized by Medieval Warm Period (MWP), Little Iage Age (LIA), and 20th century warming.

Step-like ice cap expansion during the cooling into the Little Ice Age

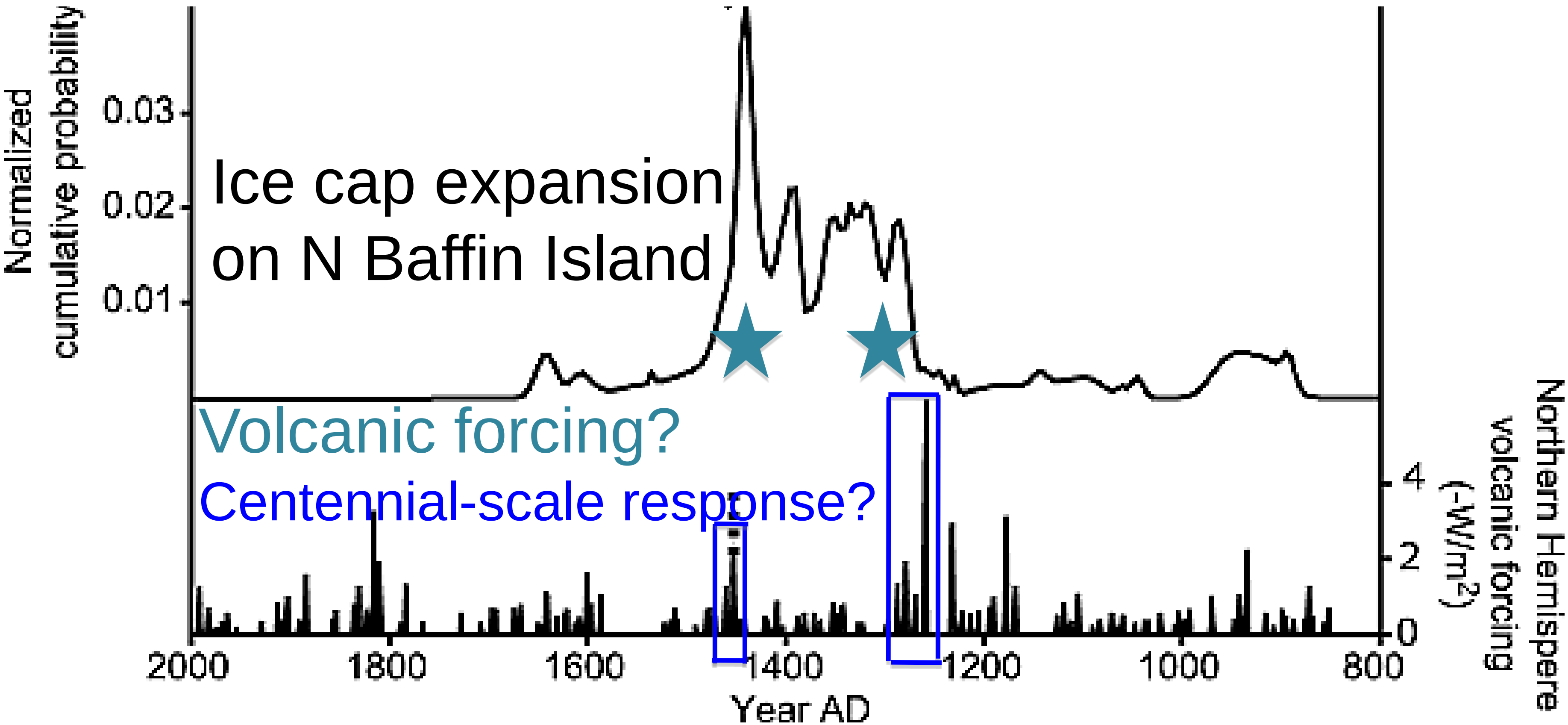


Possible causes of the Little Ice Age



Possible causes of the Little Ice Age

Question: Could the decadally sequenced volcanic eruptions cause centennial-scale response in NH sea ice?

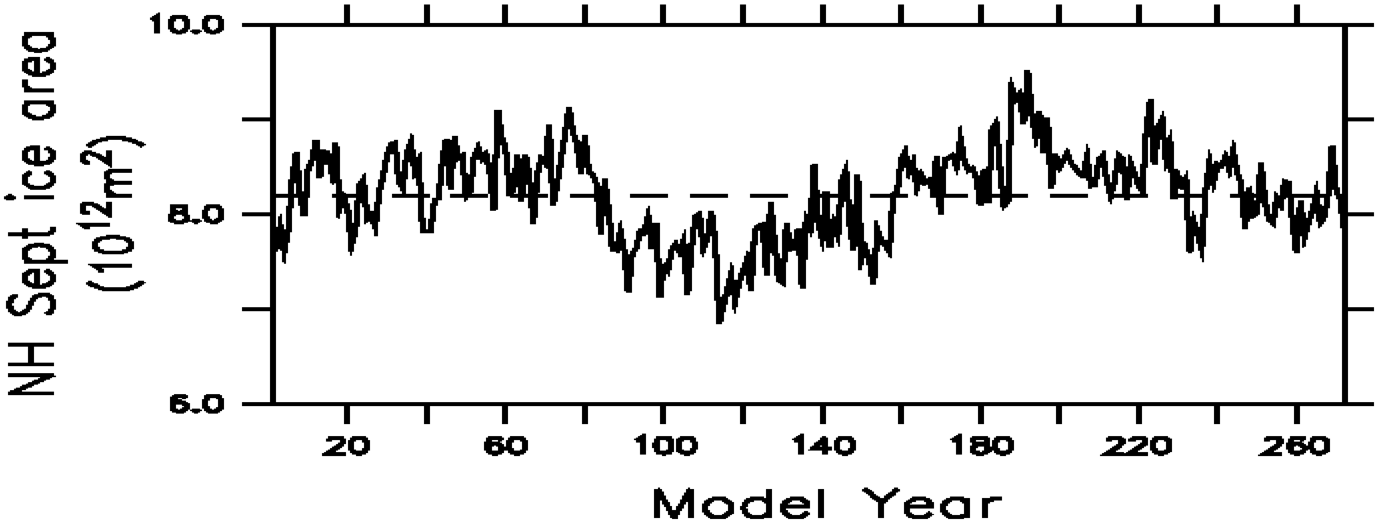


Experiments using the CCSM3

Medieval control run:

- 950AD orbital forcing
- Solar constant is 1365 W/m2
- 1000AD Greenhouse Gas level

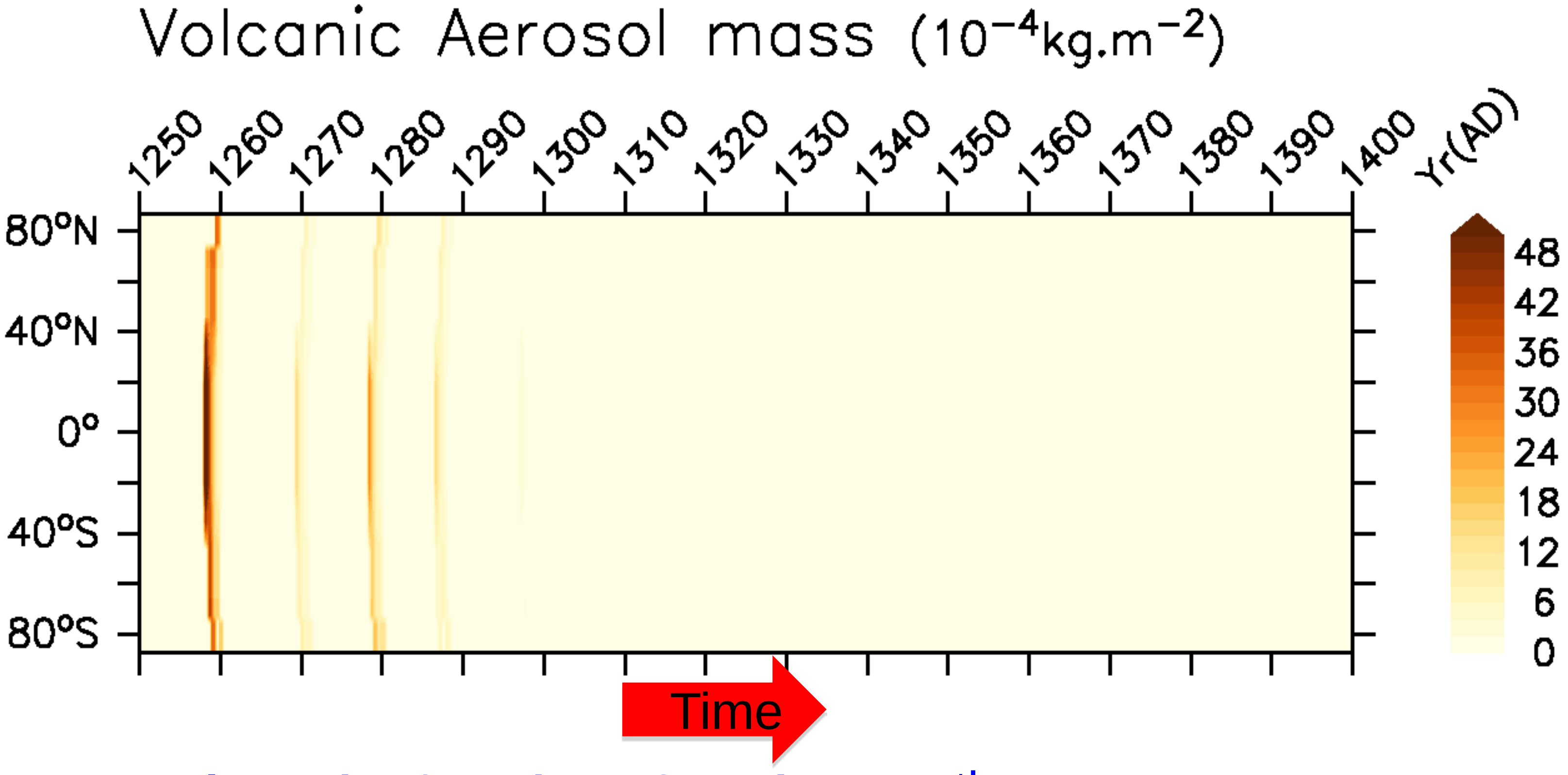
  280.6ppm CO_2, 684.3ppb CH_4, 264.5 ppb N_2O



Experiments using the CCSM3 (Cont)

Volcanism experiments

- Volcanic forcing: decadally sequenced tropical eruptions in the second half of the 13th century

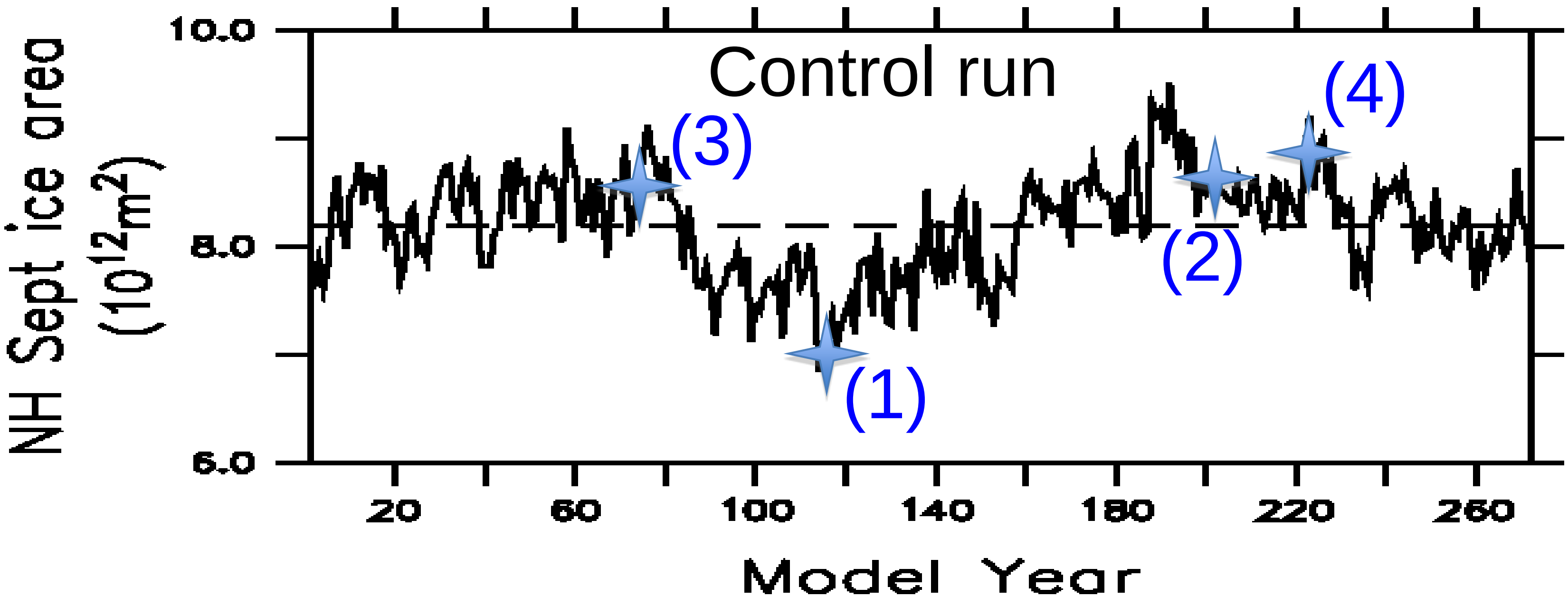


No volcanic forcing for the 14th century

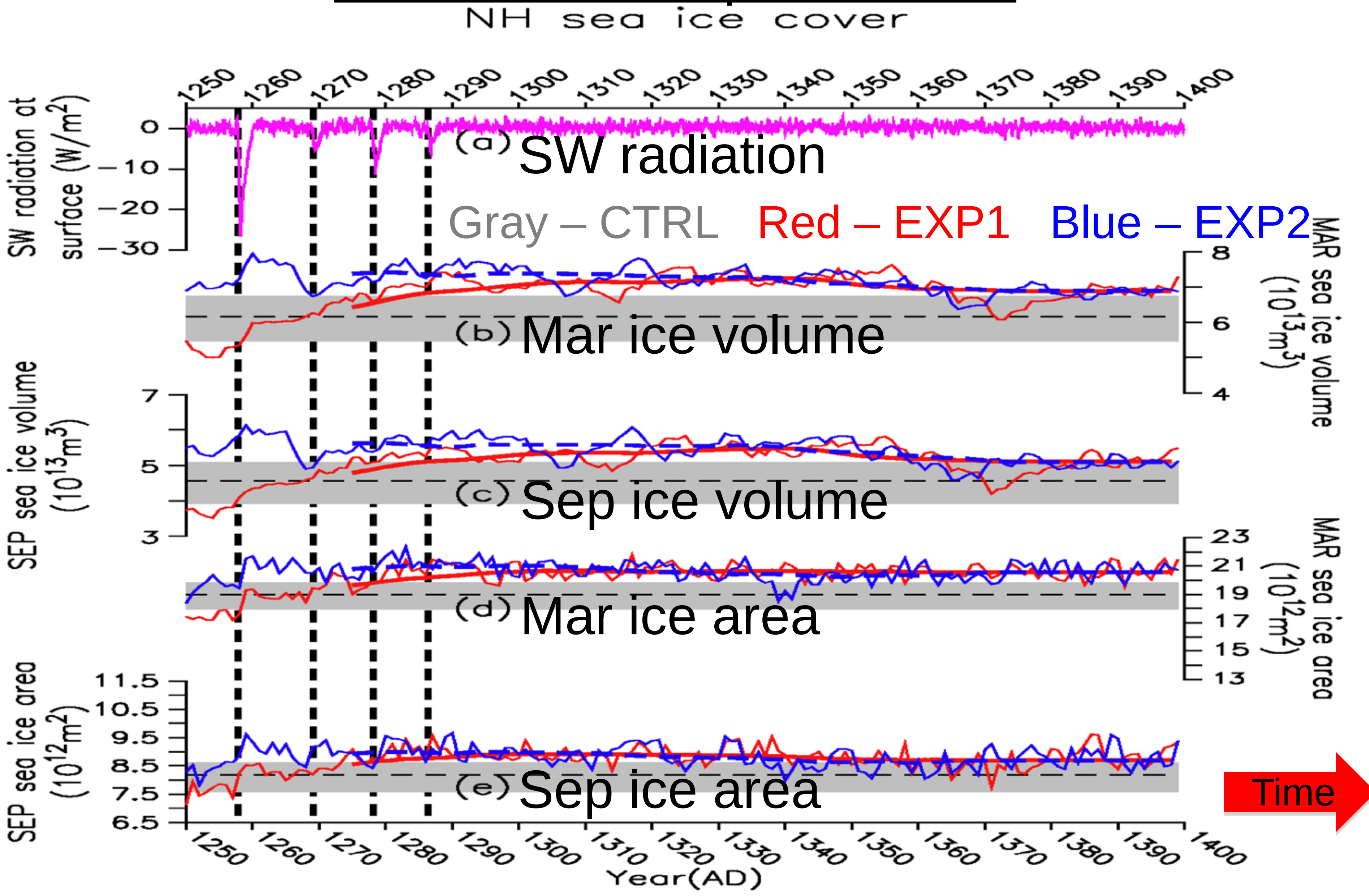
Experiments using the CCSM3 (Cont)

Volcanism experiments

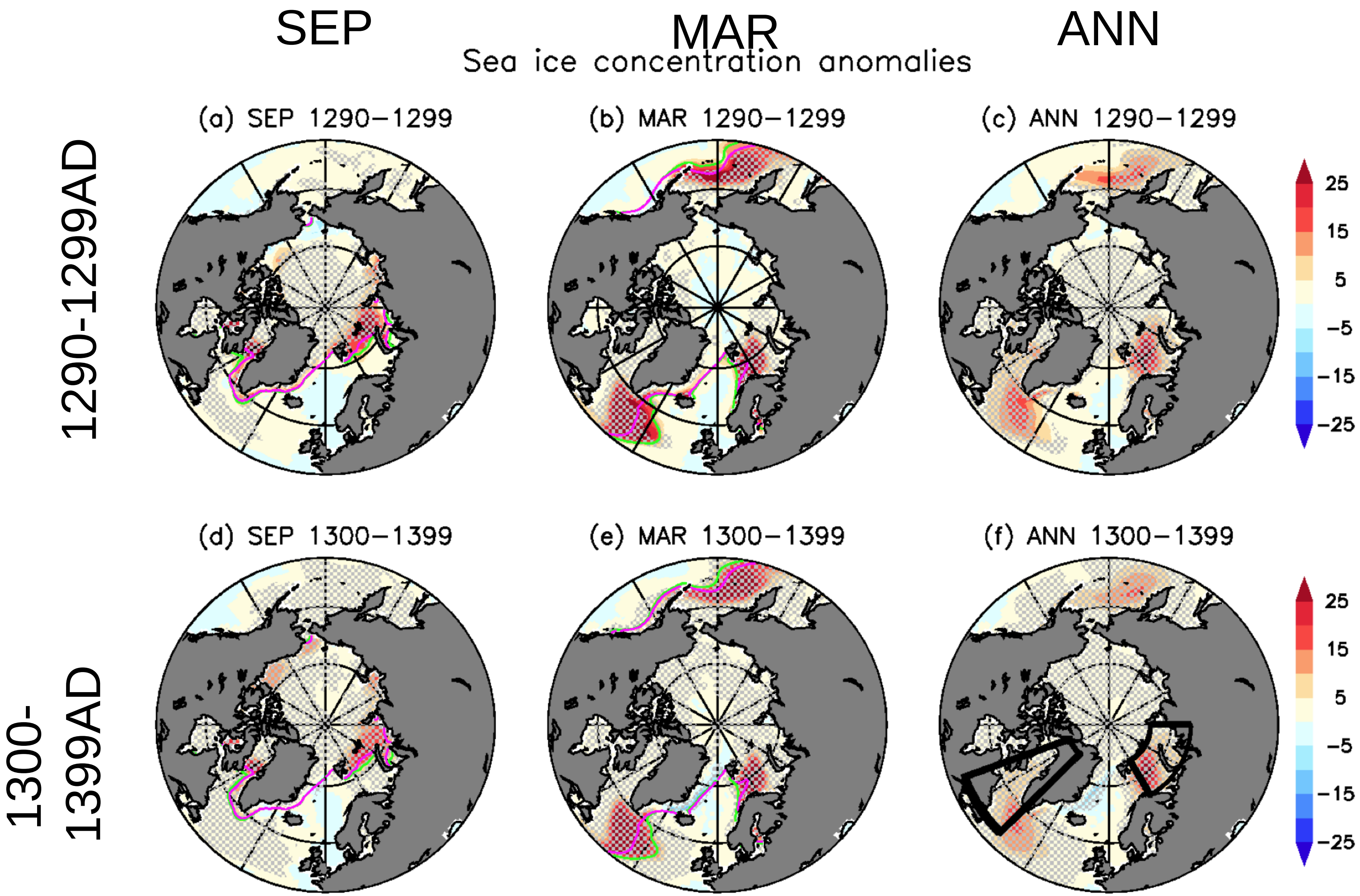
- Four runs, randomly selected initial states.



Centennial-scale response in NH sea ice in volcanism experiments

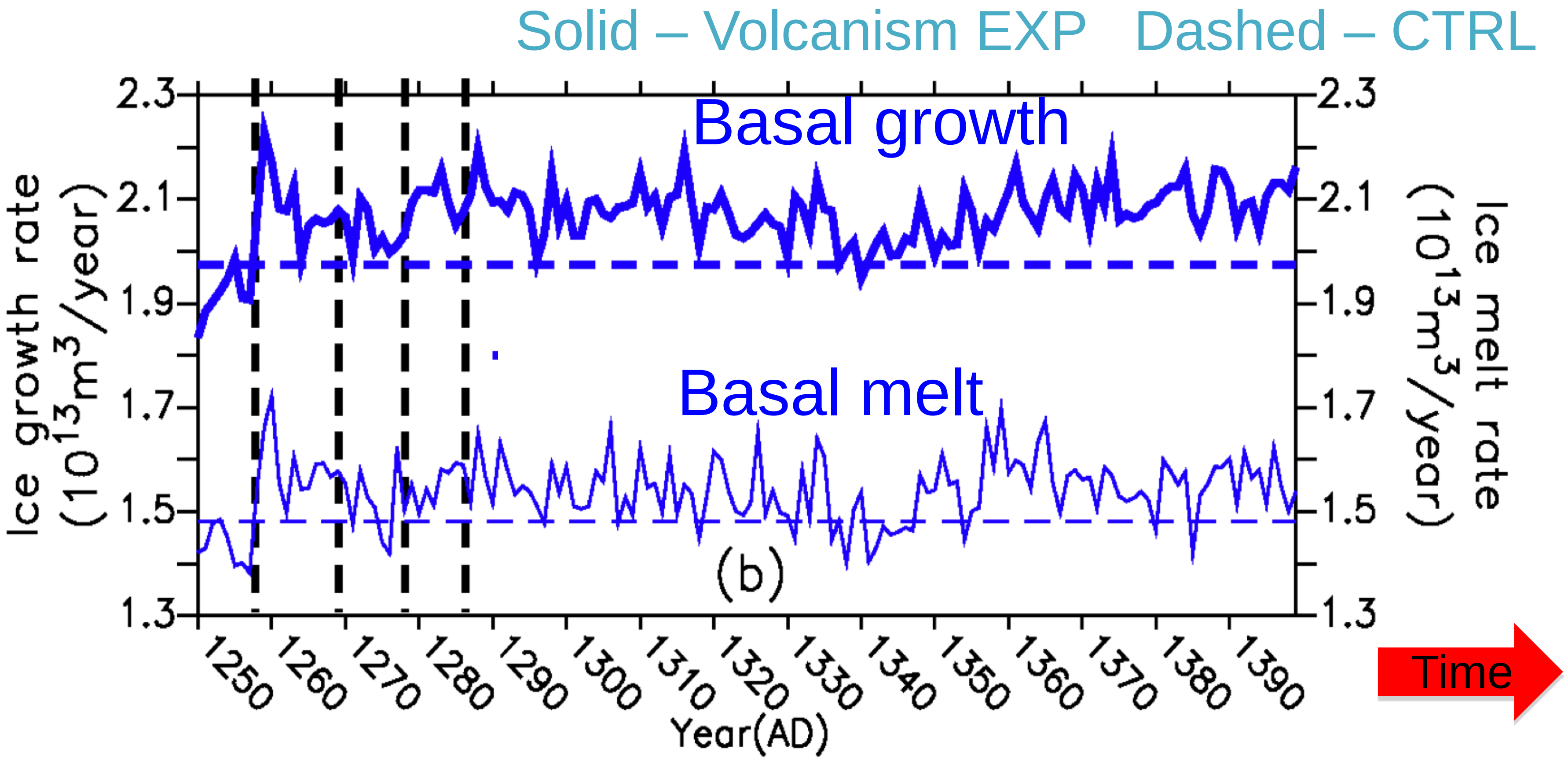


NH sea ice concentration anomalies



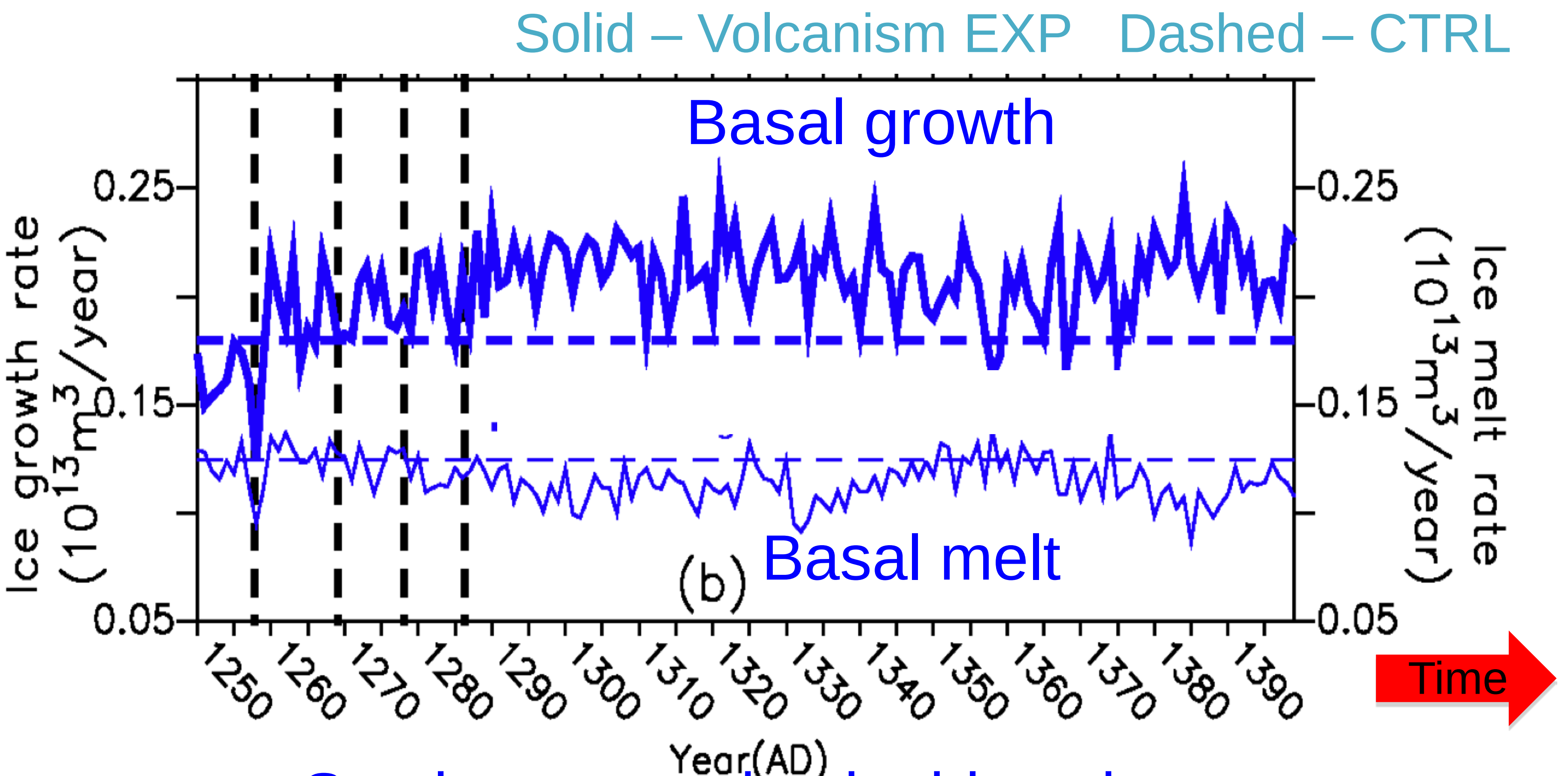
Largest anomalies in September occur in the Atlantic sector, which agrees with paleo reconstructions.

Mass budget of NH annual sea ice



Sea ice expansion is driven by decreased ice-ocean heat exchange.

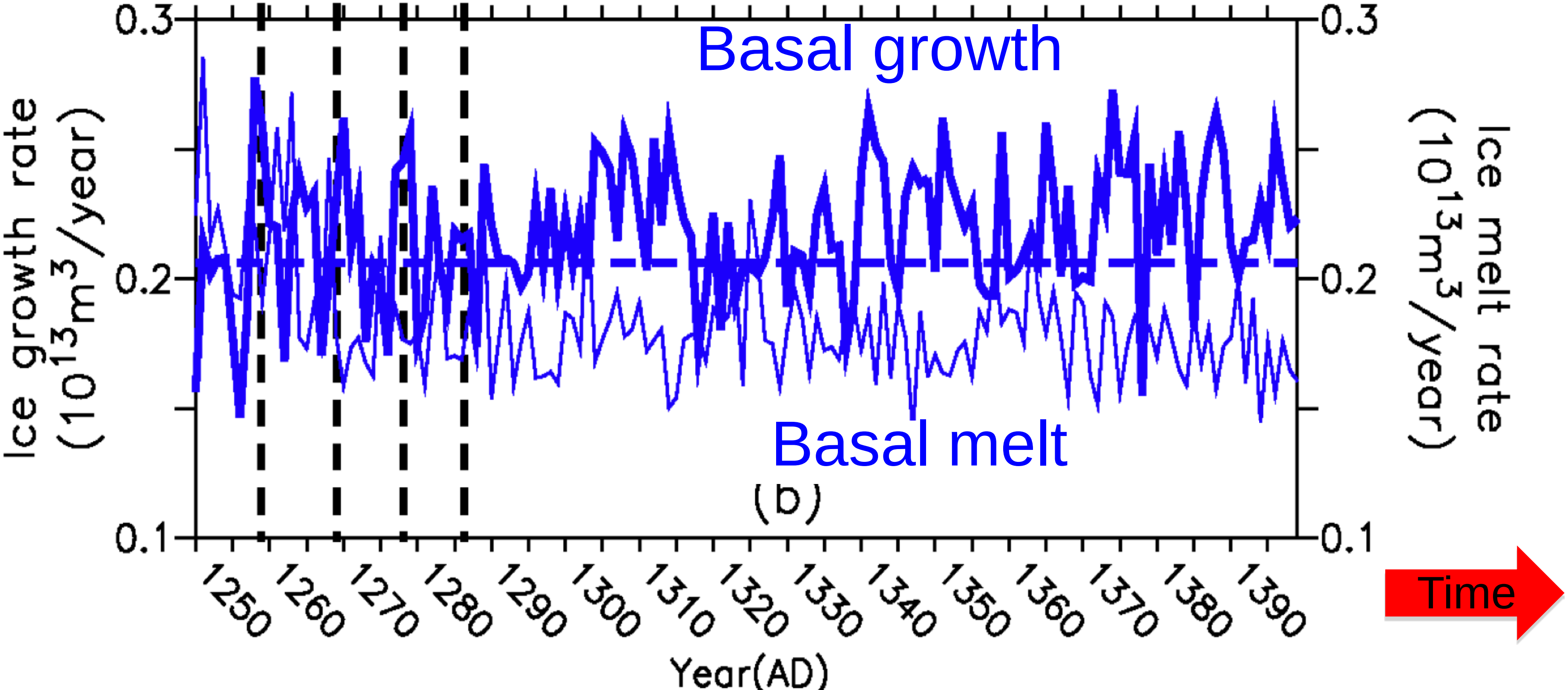
Ice mass budget for Barents Sea region



Sea ice expansion is driven by decreased ice-ocean heat exchange.

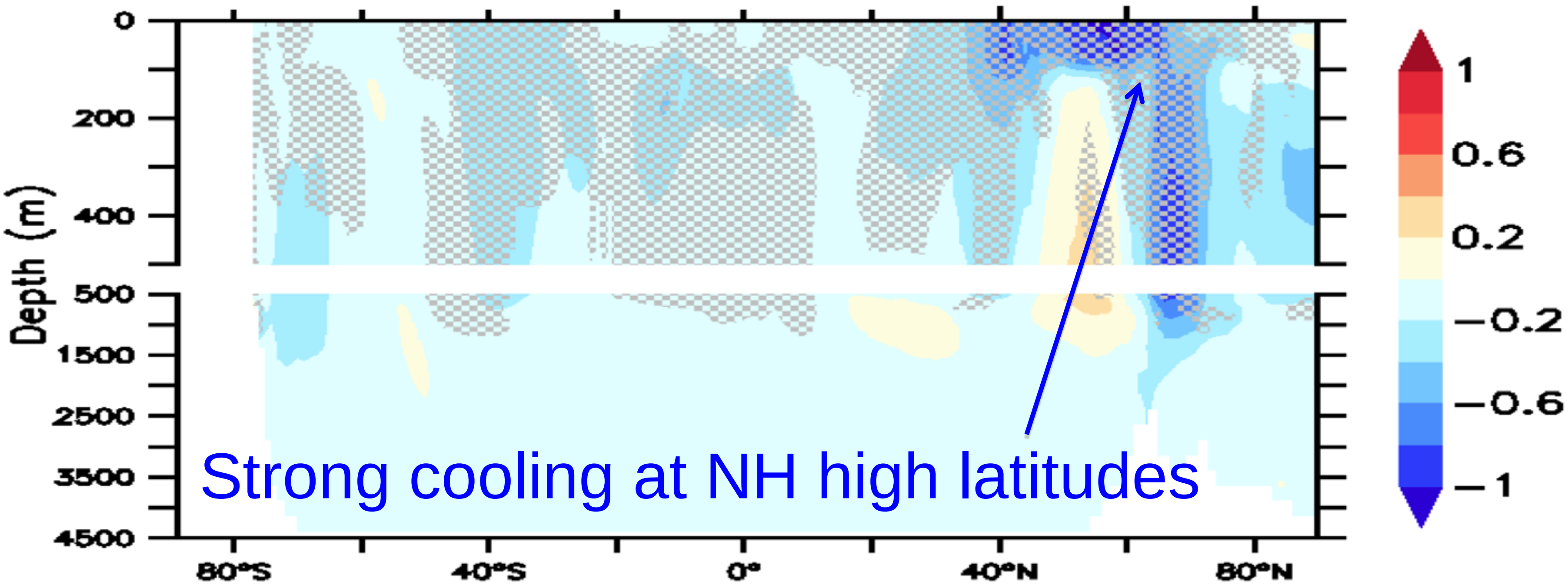
Sea ice mass budget for west of Greenland

Solid – Volcanism EXP   Dashed – CTRL



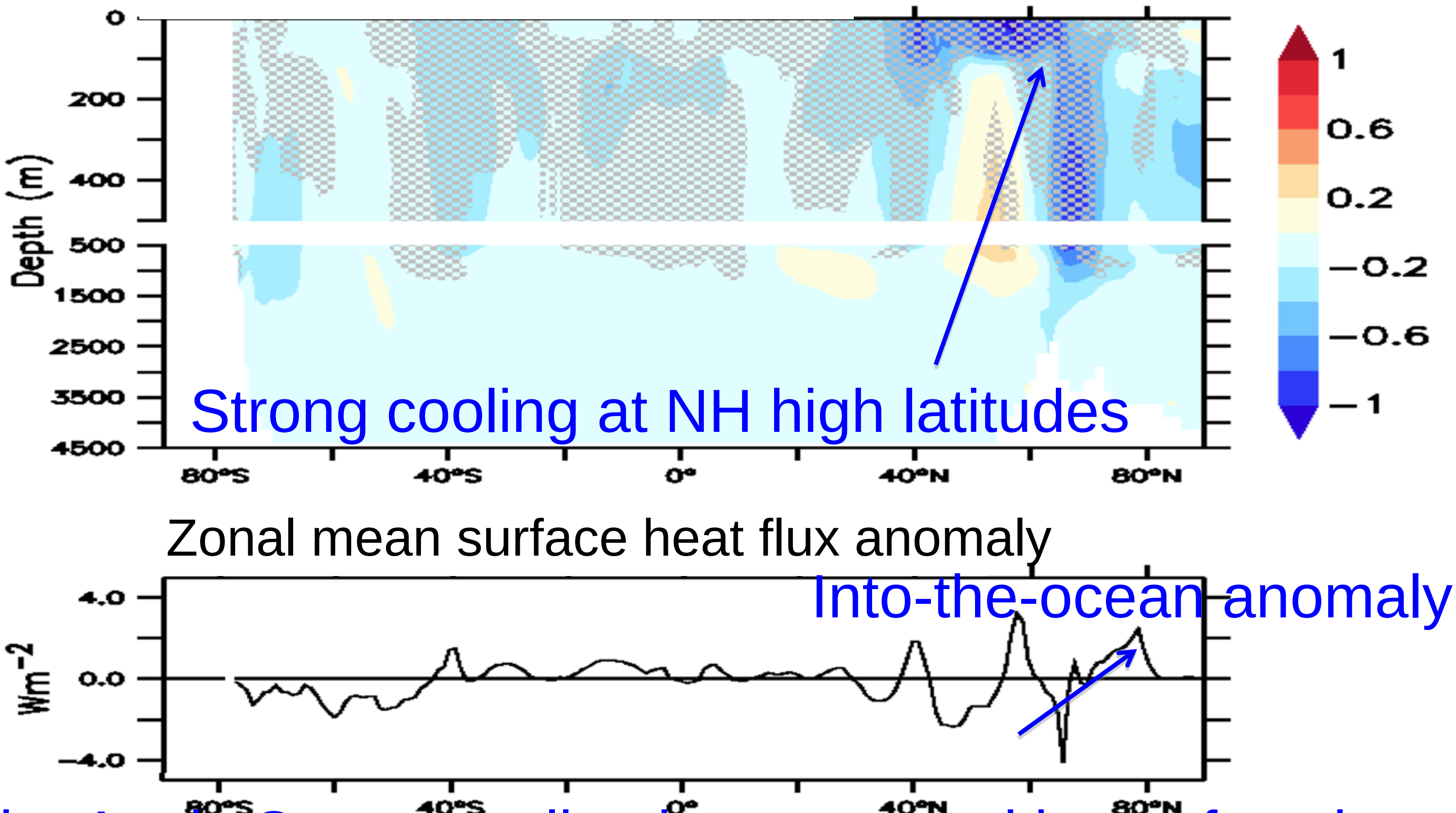
Sea ice expansion is driven by decreased ice-ocean heat exchange.

Surface cooling in the North Atlantic and Arctic oceans



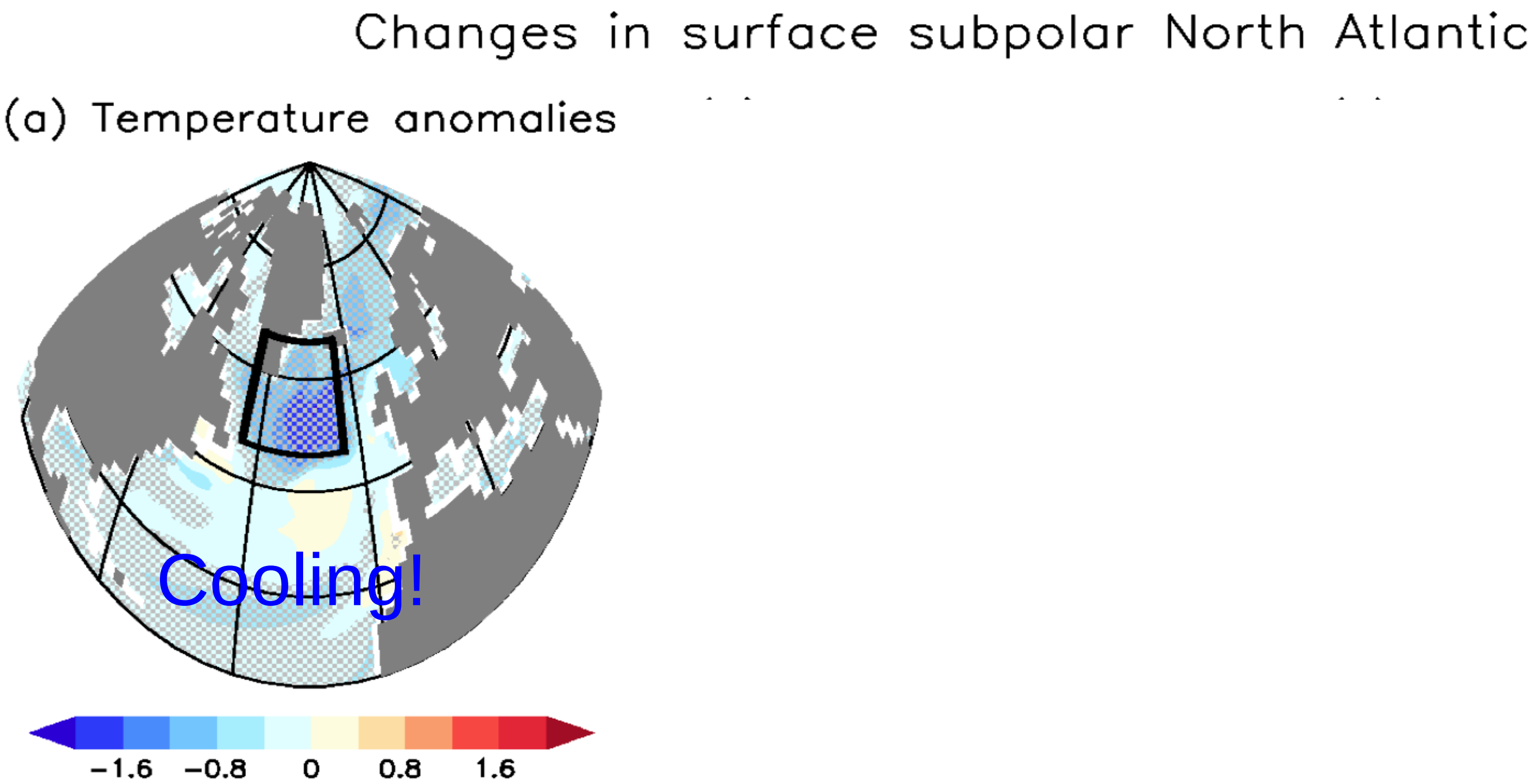
Zonal mean ocean temperature anomalies.
Shading: significant at 95% confidence level

Surface cooling in the NH high-latitude and Arctic oceans

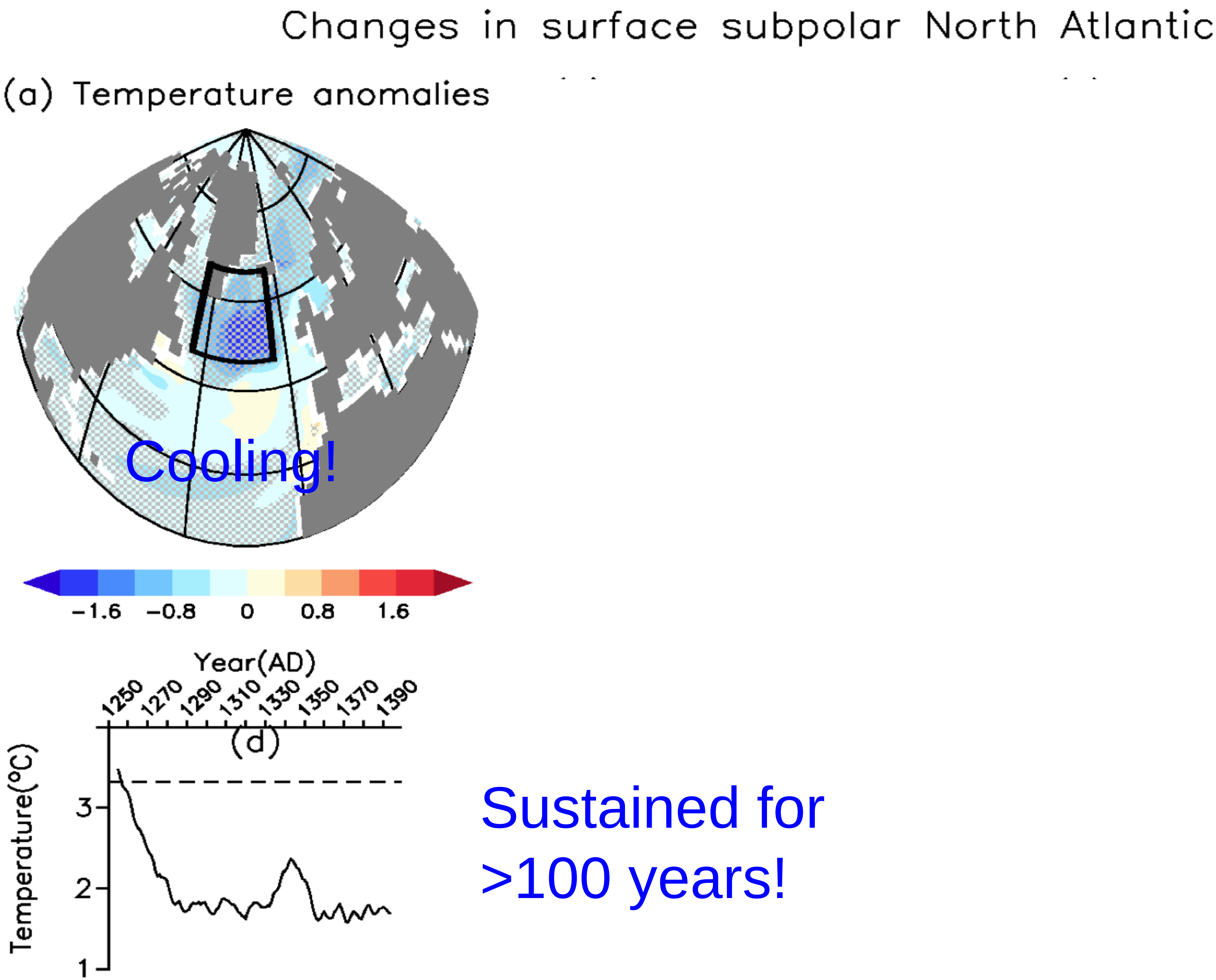


The Arctic Ocean cooling is not caused by surface heat flux changes, but rather by reduced ocean heat transport poleward.

Changes in the surface ocean



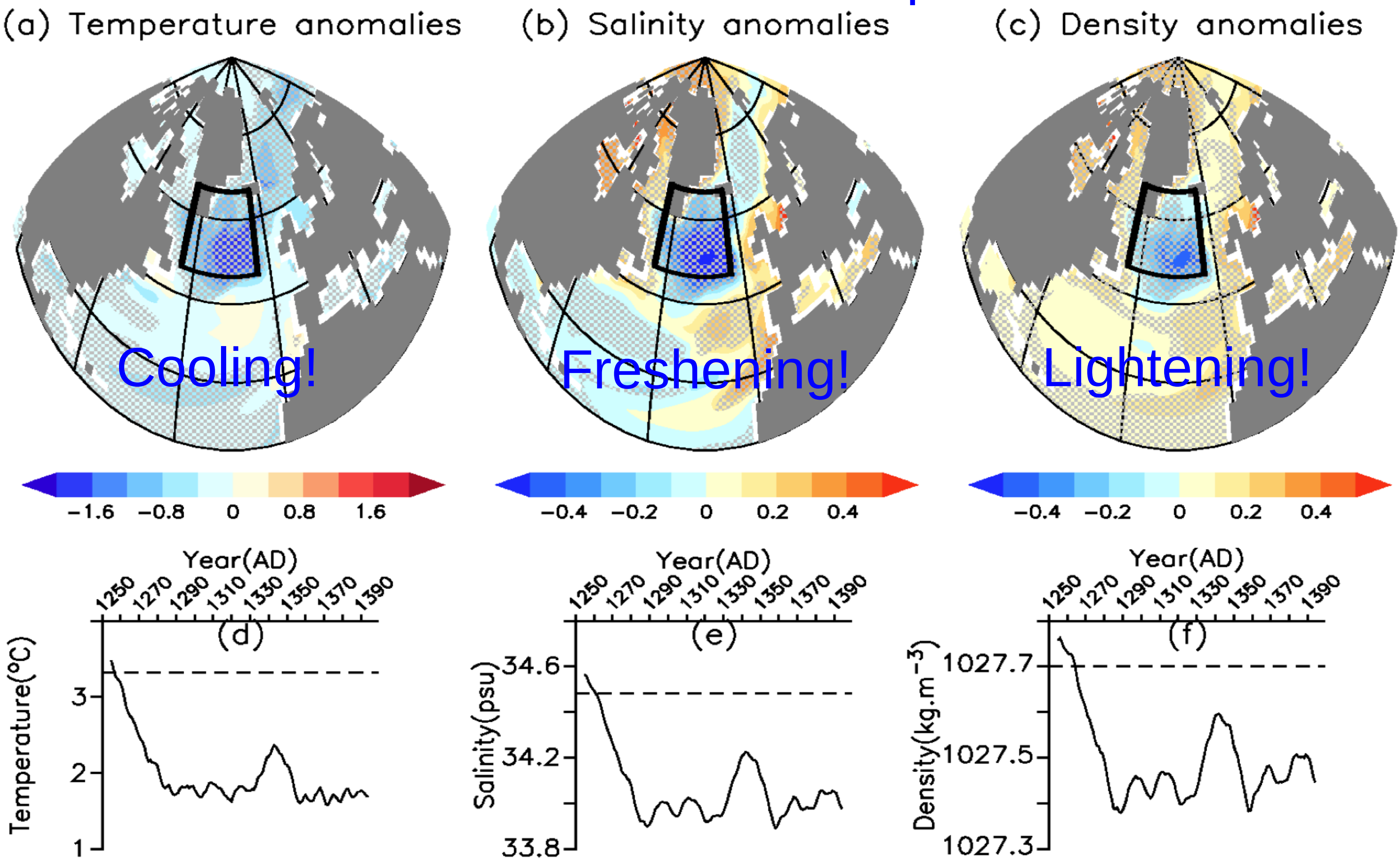
Changes in the surface ocean



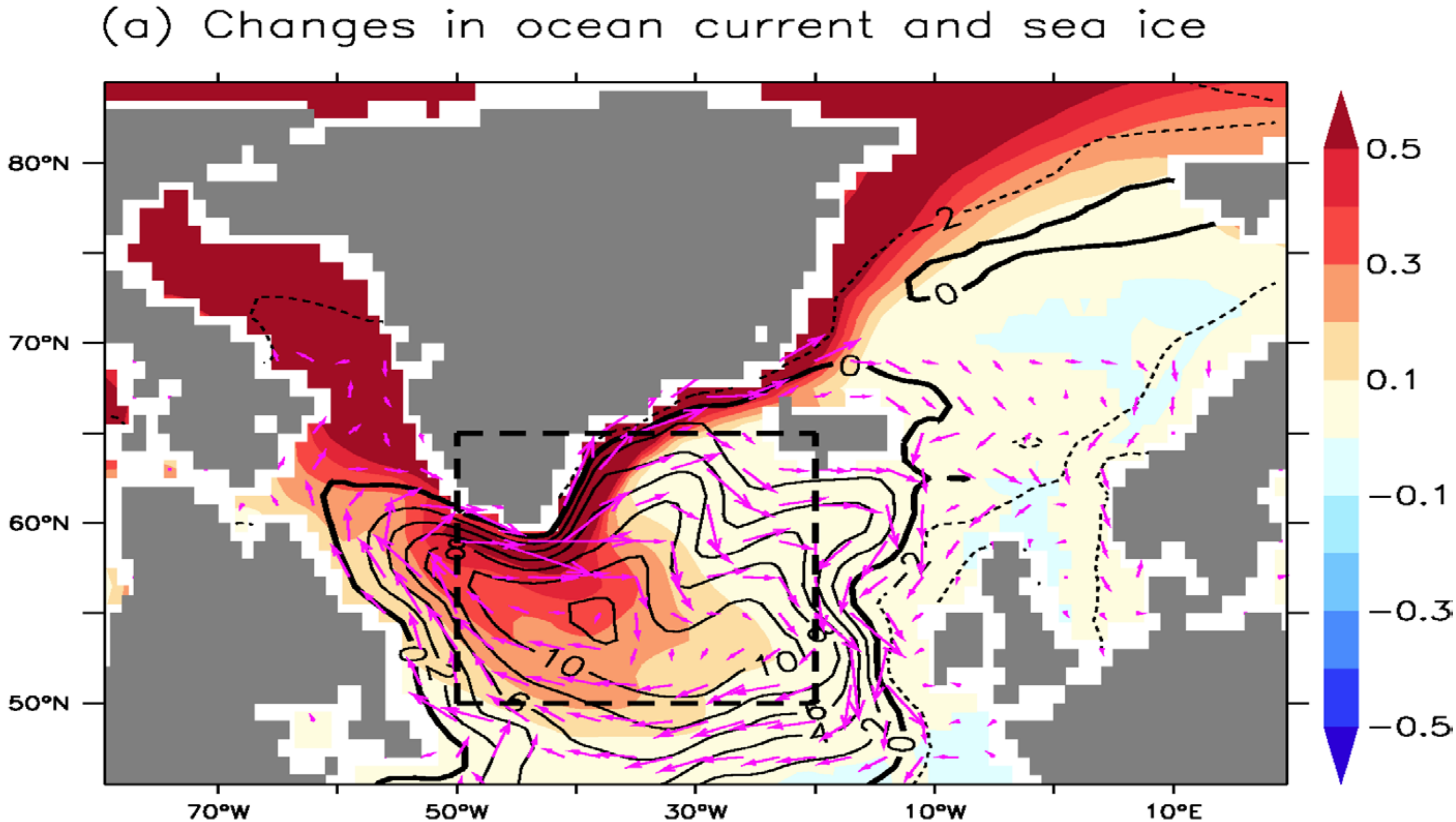
Sustained for >100 years!

Changes in the surface ocean

Increased sea ice export (freshwater flux) to and thus weakened convection in the subpolar N Atlantic!



Decreased heat/salt advection associated with the slowed-down subpolar gyre circulation



Color: ANN sea ice thickness anomaly
Contour: Sea surface height anomaly
Vector: Current anomaly

Summary

- The sequenced volcanism could produce an expanded NH sea ice that is sustainable for >100 years after the removal of volcanic aerosols from the stratosphere.

- A coupled sea ice-ocean mechanism:
  - Sea ice expands and thickens in response to volcanic aerosol radiative forcing
  - More ice is exported through Fram Strait and the Canadian Achipelago, and melts in the subpolar North Atlantic
  - Cooling and freshening of the surface water in the subpolar N Atlantic, in aid of weakened convection and decreased heat/salt advection
  - Anomalously cold water is advected into the Arctic Ocean and reduces ice-ocean heat exchange
  - Preserves the expanded sea ice

- The coupled sea ice-ocean mechanism may be sensitive to the pre-volcanic mean states, such as mixing layer depth in the subpolar N Atlantic.

Thank you!

Summary

•Sequenced volcanism produced an expanded NH sea ice that sustained for >100 years after the removal of volcanic aerosols from the stratosphere. The largest concentration anomalies occurred in the Atlantic sector of the Arctic, agreeing with paleo data.

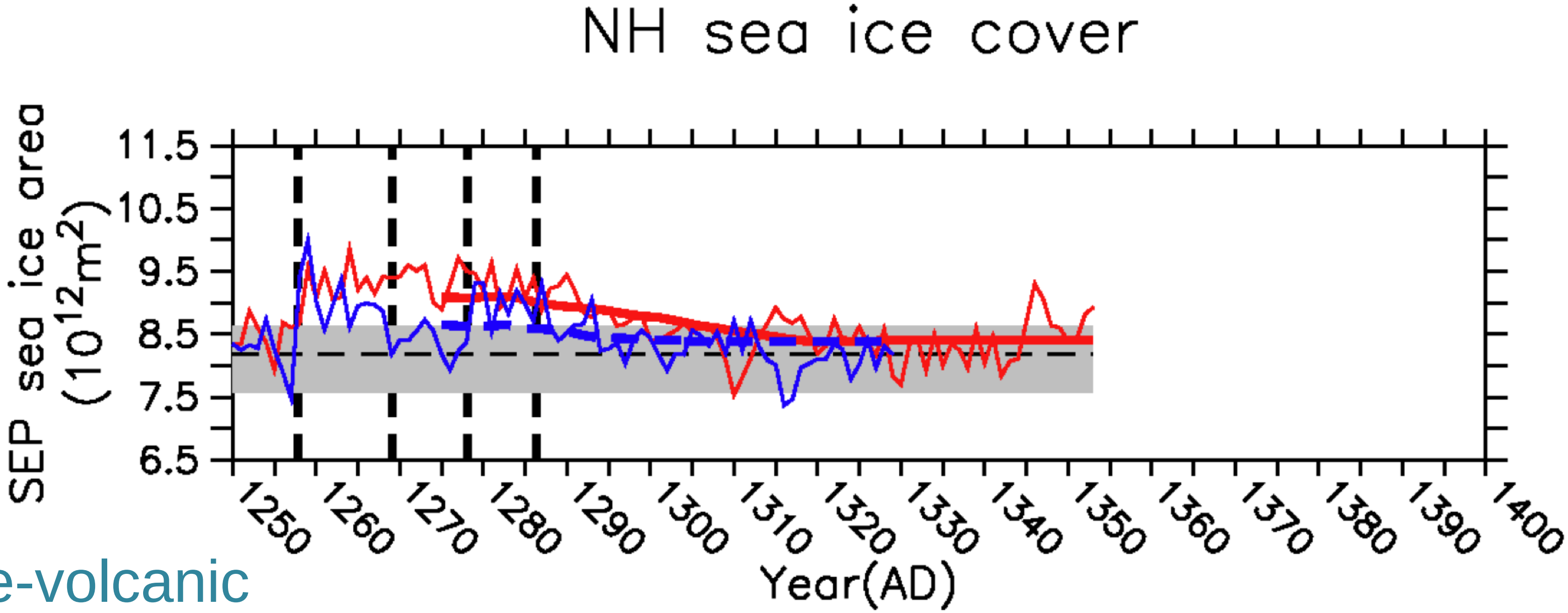
•A coupled sea ice-ocean mechanism:

Sea ice expands and thickens in response to volcanic aerosol radiative forcing

→More ice is exported and melts in the subpolar North Atlantic

→Cooling and freshening of the surface water in the subpolar N Atlantic, in aid of weakened convection and decreased heat/salt advection

The volcanism experiments showing no centennial-scale response



Pre-volcanic

- Shallow mixing layer depth in the subpolar N Atlantic, already weak convection

Post-volcanic

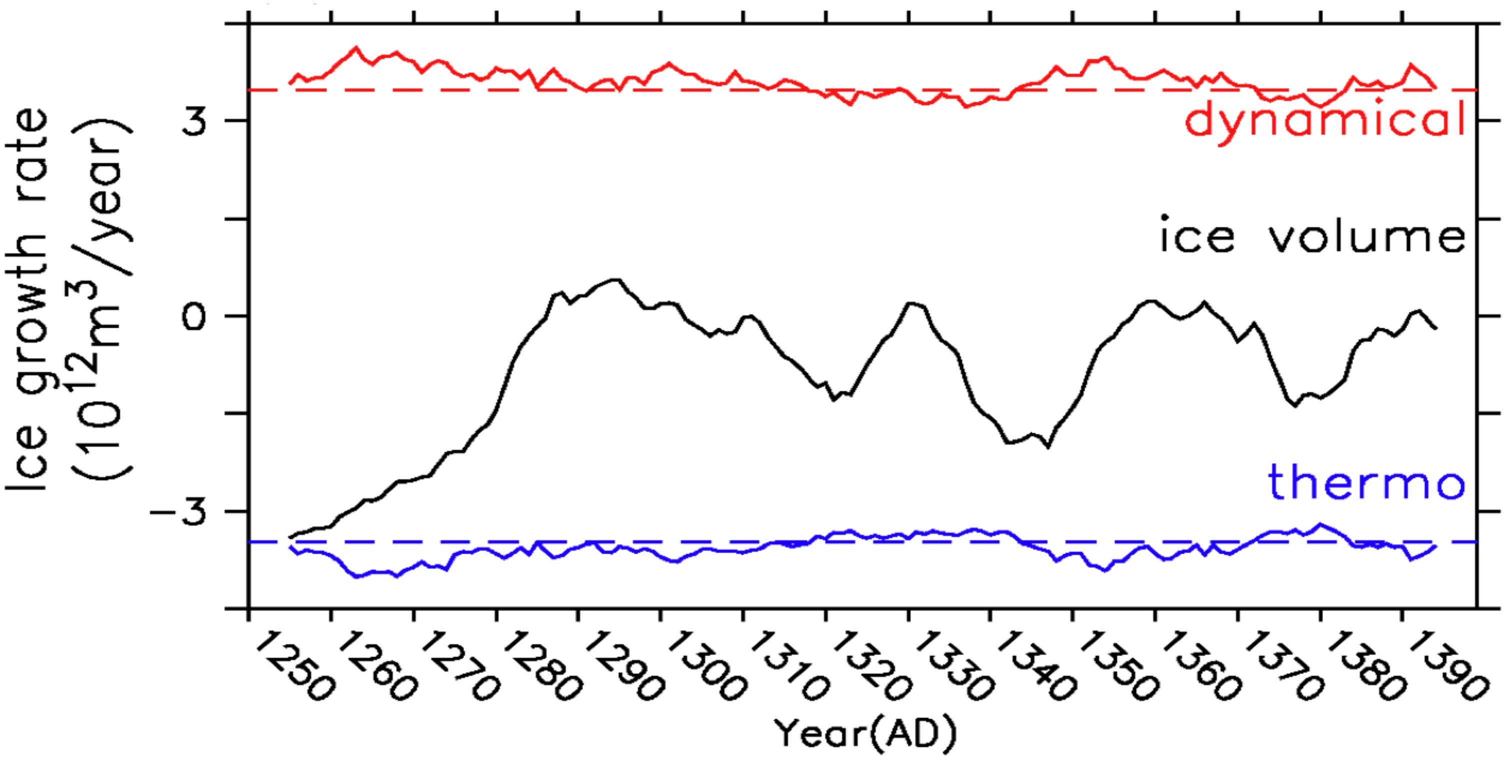
- Convective feedback ineffective in the subpolar N Atlantic.
- Rapid sea ice growth, increased brine rejection, positive density flux in marginal seas → strengthened Atlantic MOC, increased heat transport into the Arctic → Sea ice recedes

Summary

- Sequenced volcanism produced an expanded NH sea ice that sustained for >100 years after the removal of volcanic aerosols from the stratosphere. The largest concentration anomalies occurred in the Atlantic sector of the Arctic, agreeing with paleo data.

- A coupled sea ice-ocean mechanism

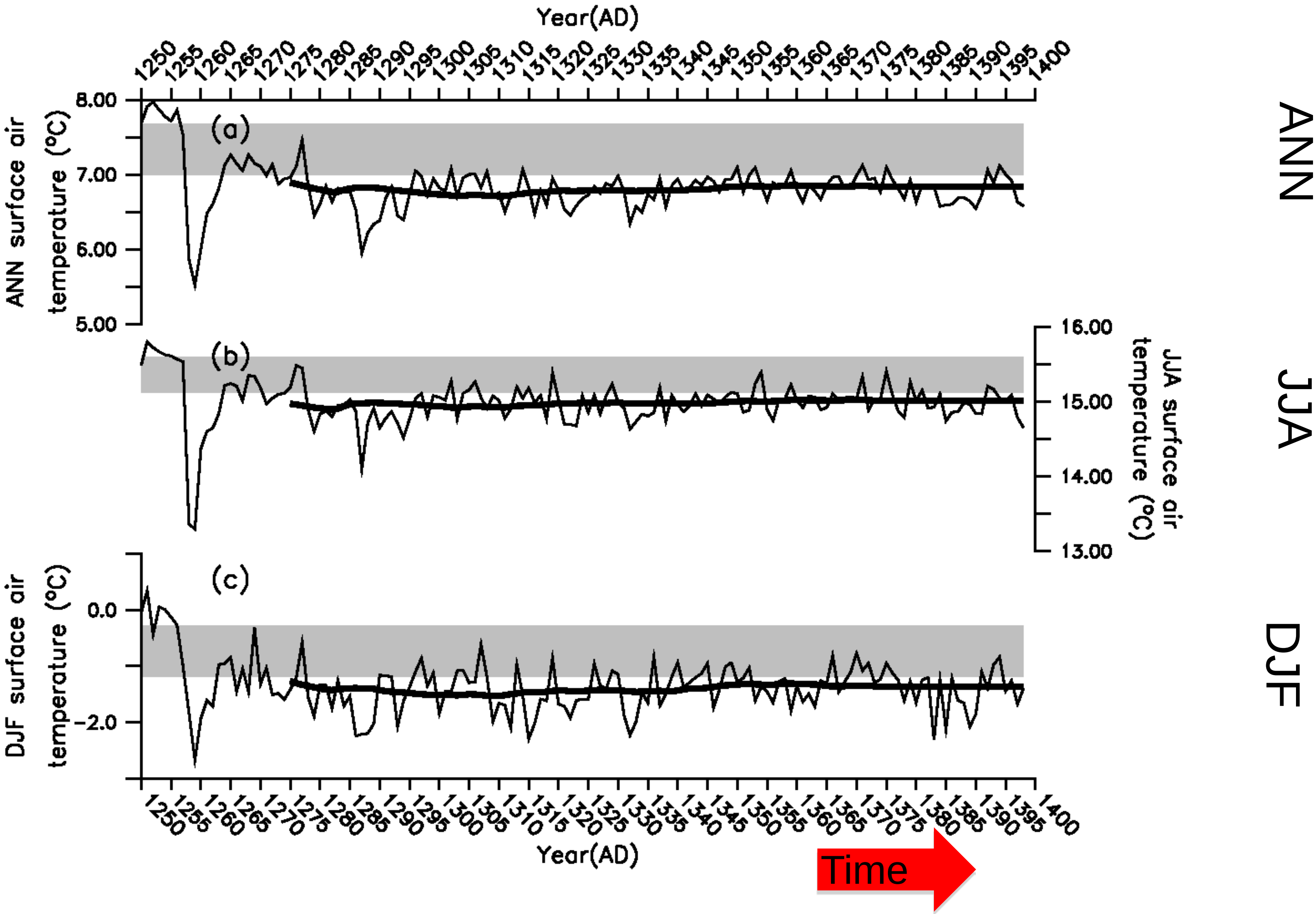
Increased sea ice export to subpolar N Atlantic

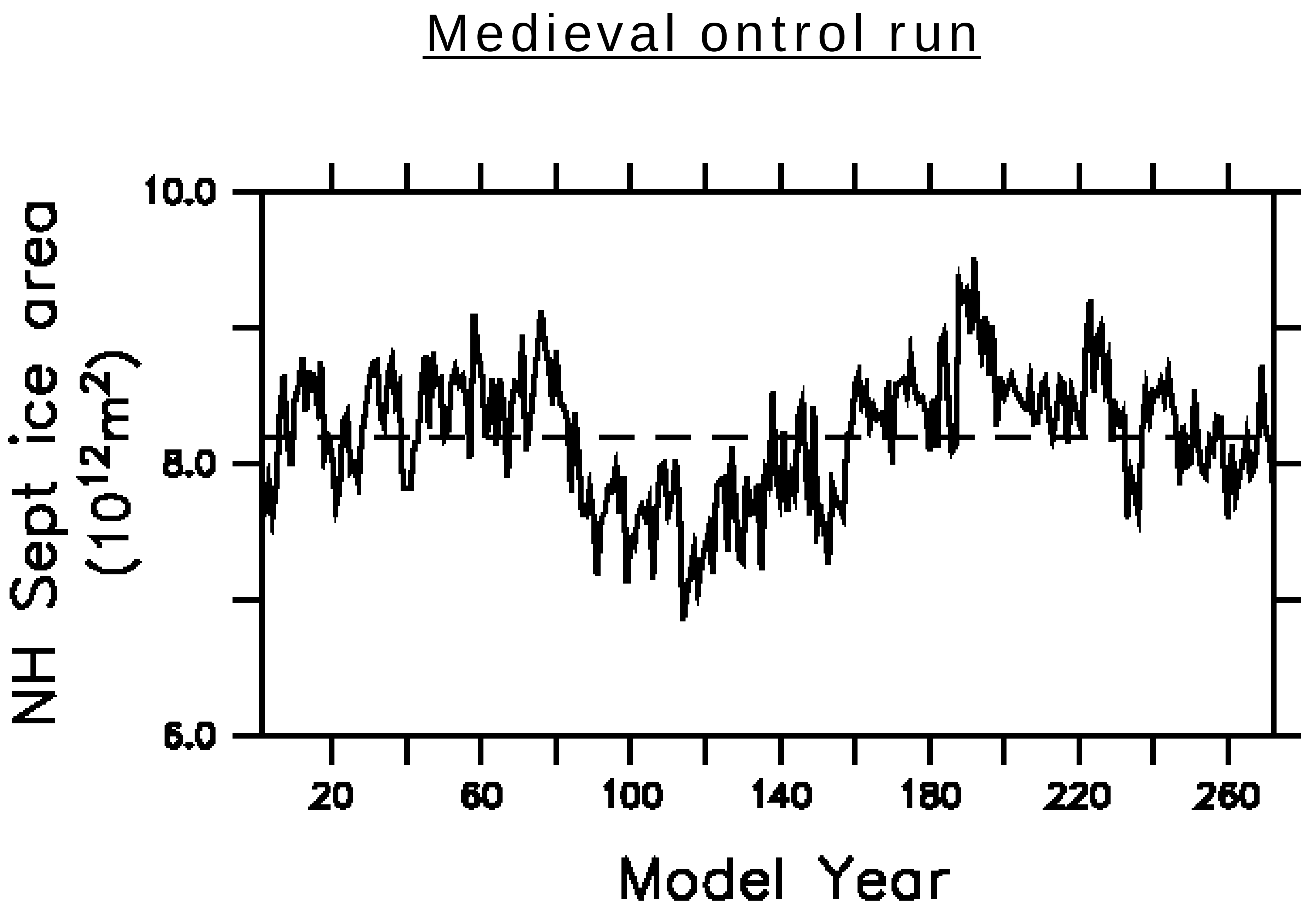


➔ Net freshwater flux

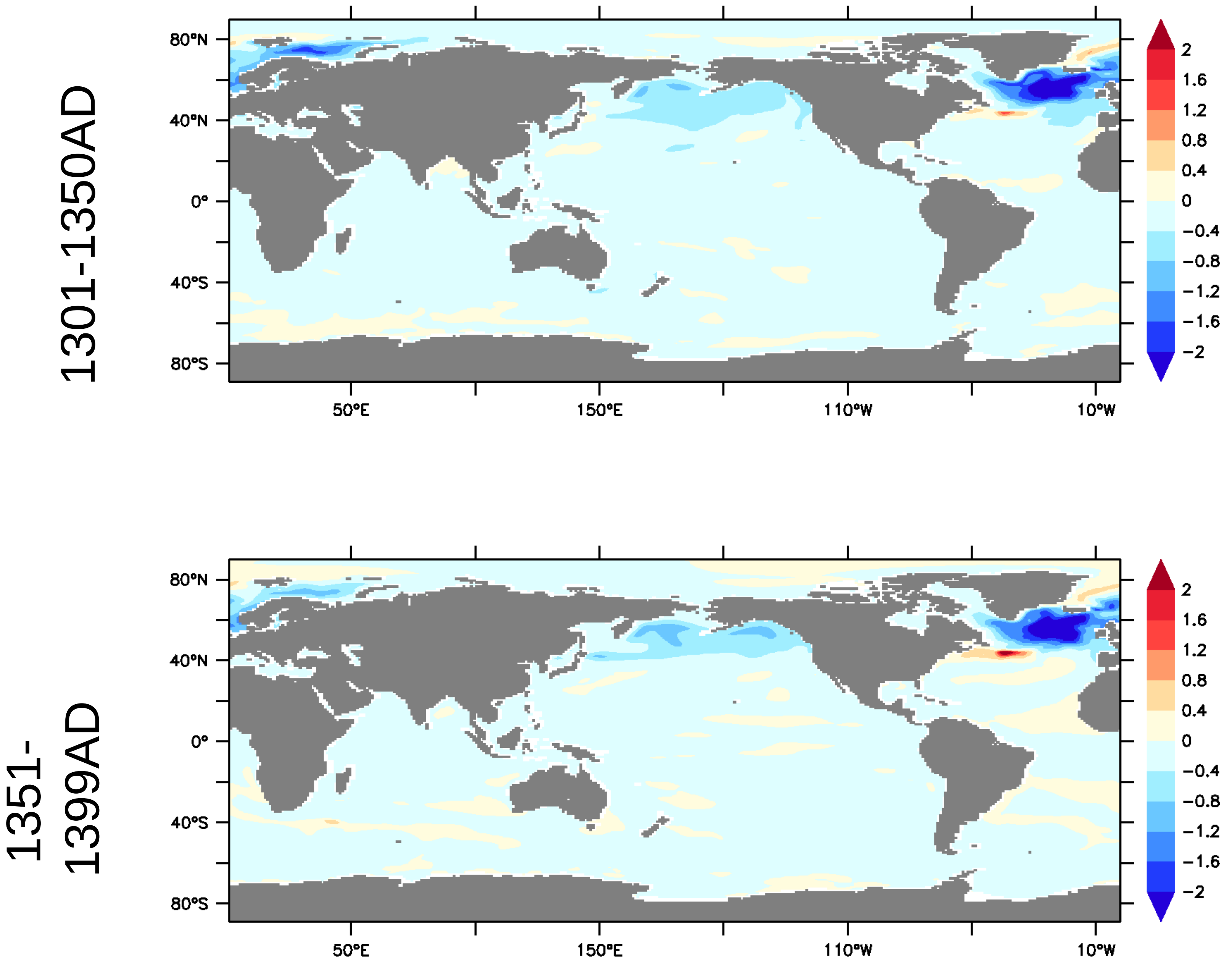
➔ Freshening effect on the subpolar North Atlantic!

Centennial-scale response in NH air temperature

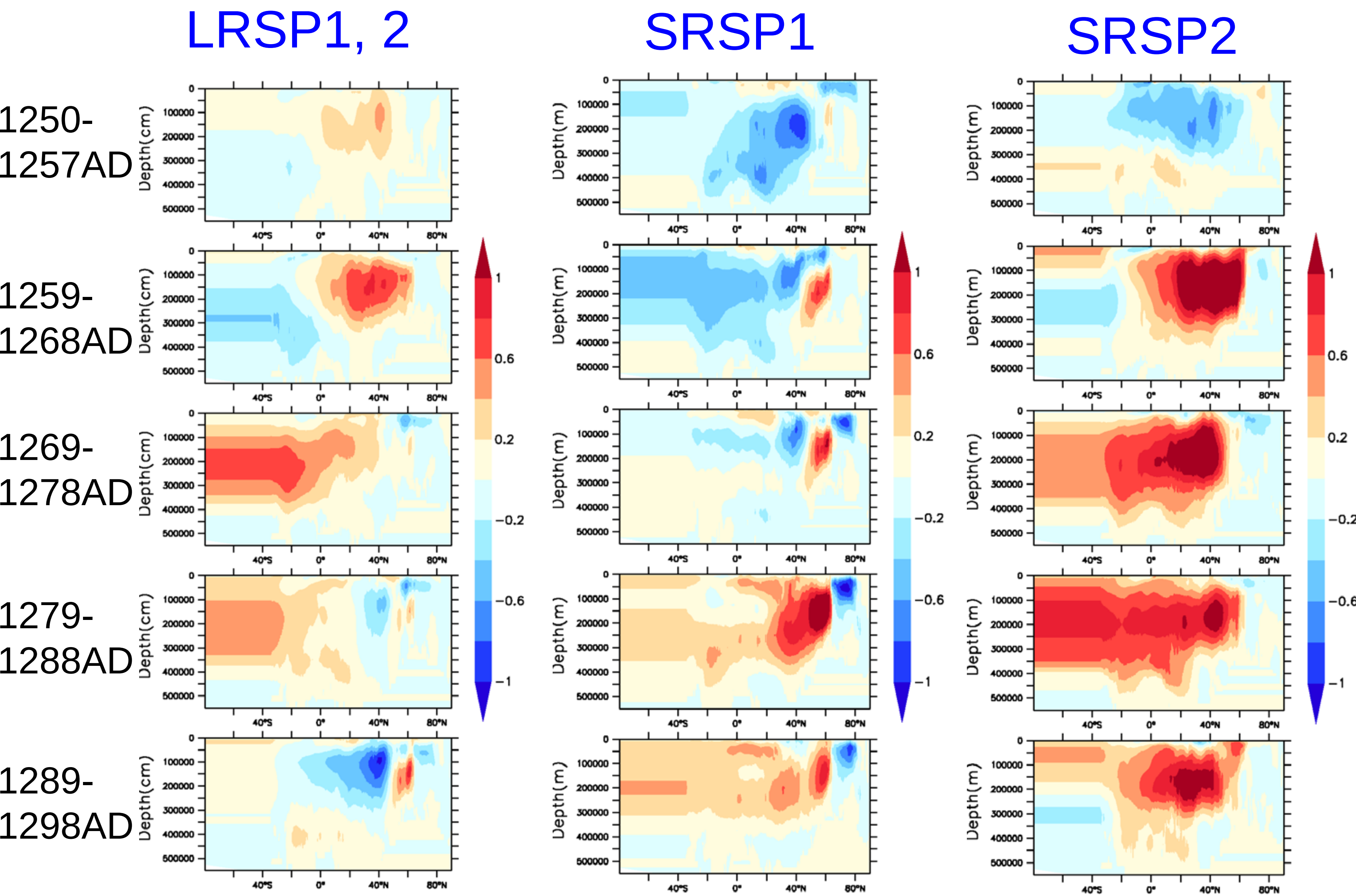



Medieval ontrol run
10.0
8.0
6.0
NH Sept ice area
(10^12m^2)
20
60
100
140
180
220
260
Model Year

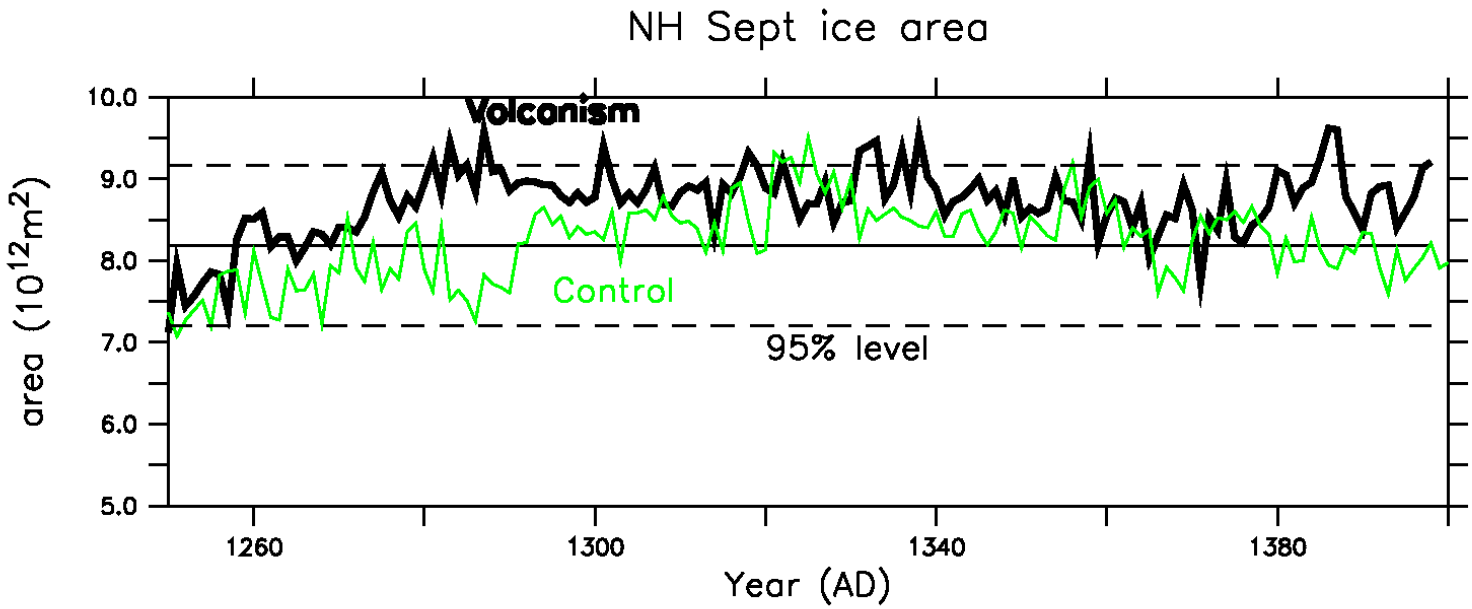
Ocean temperature anomaly

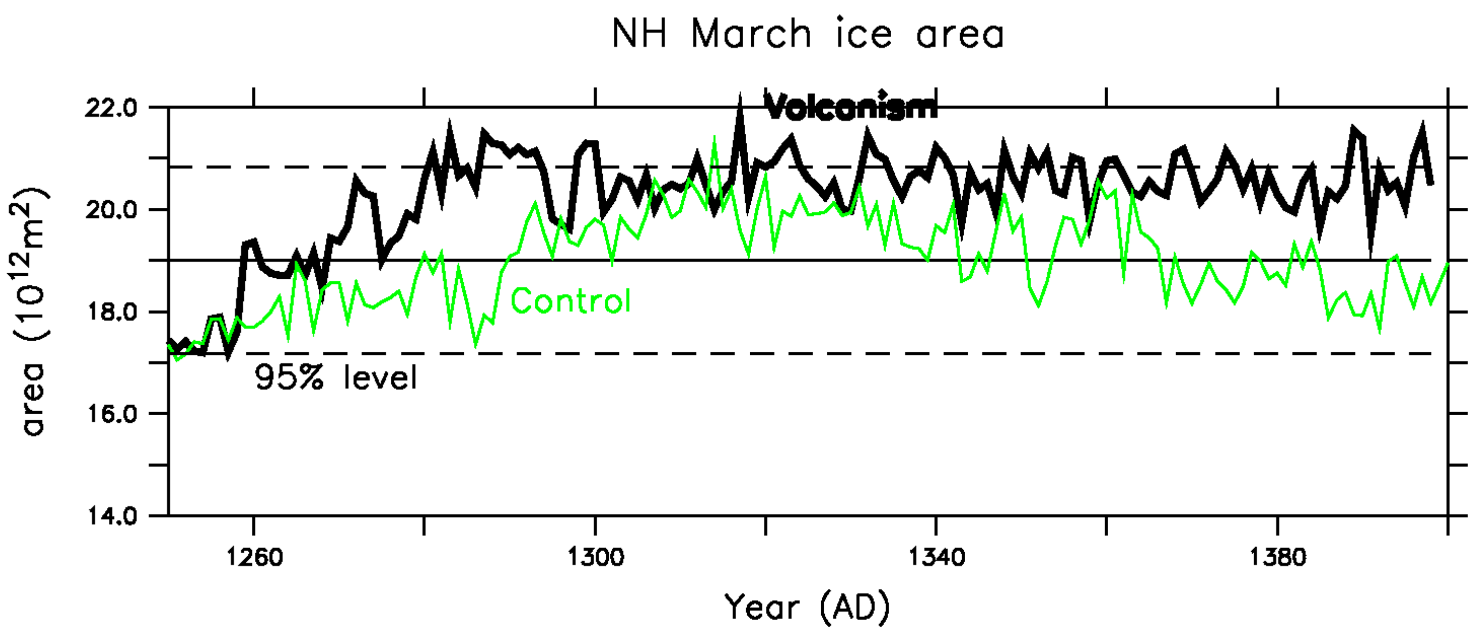


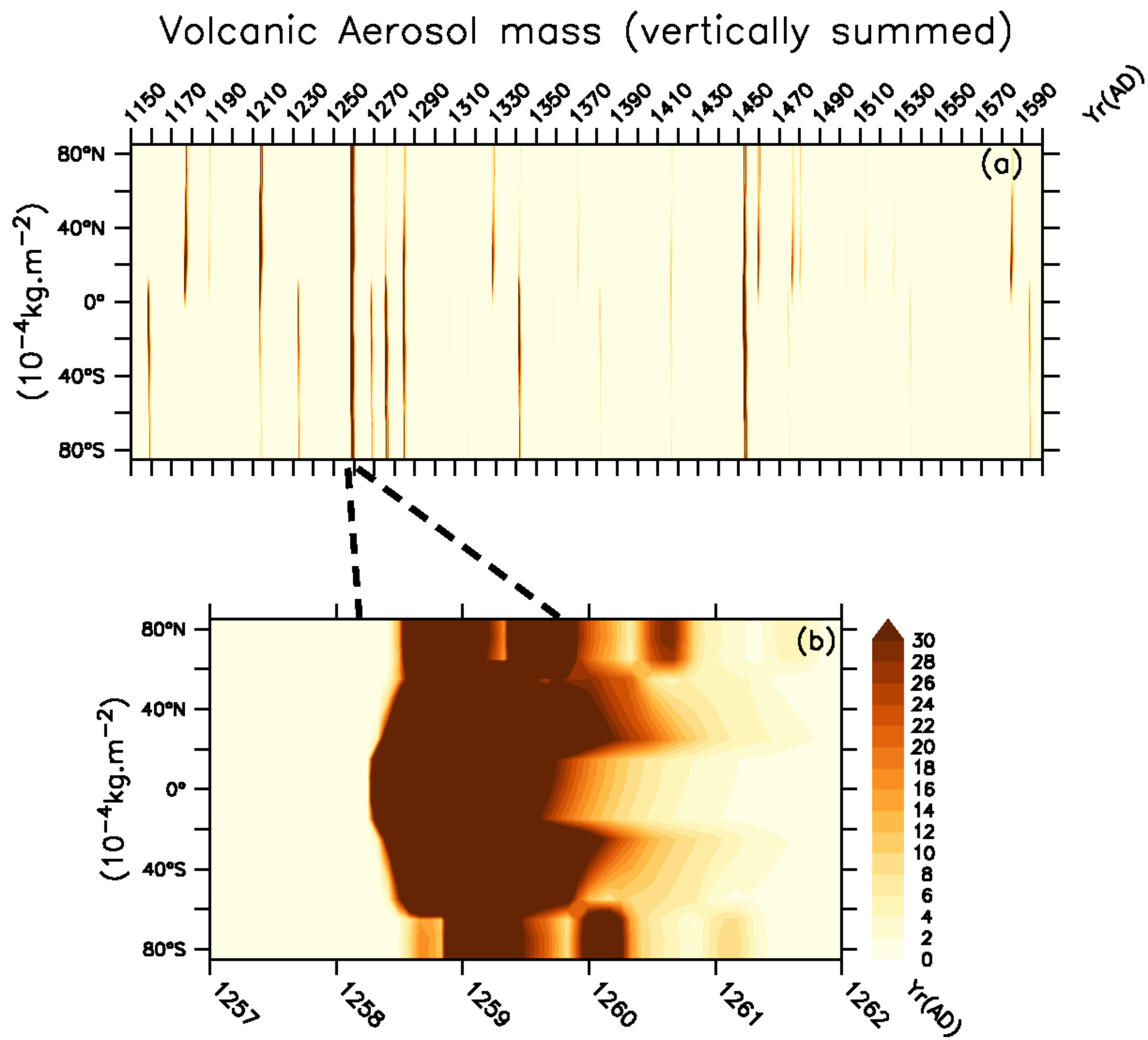
Atlantic MOC in volcanism exps

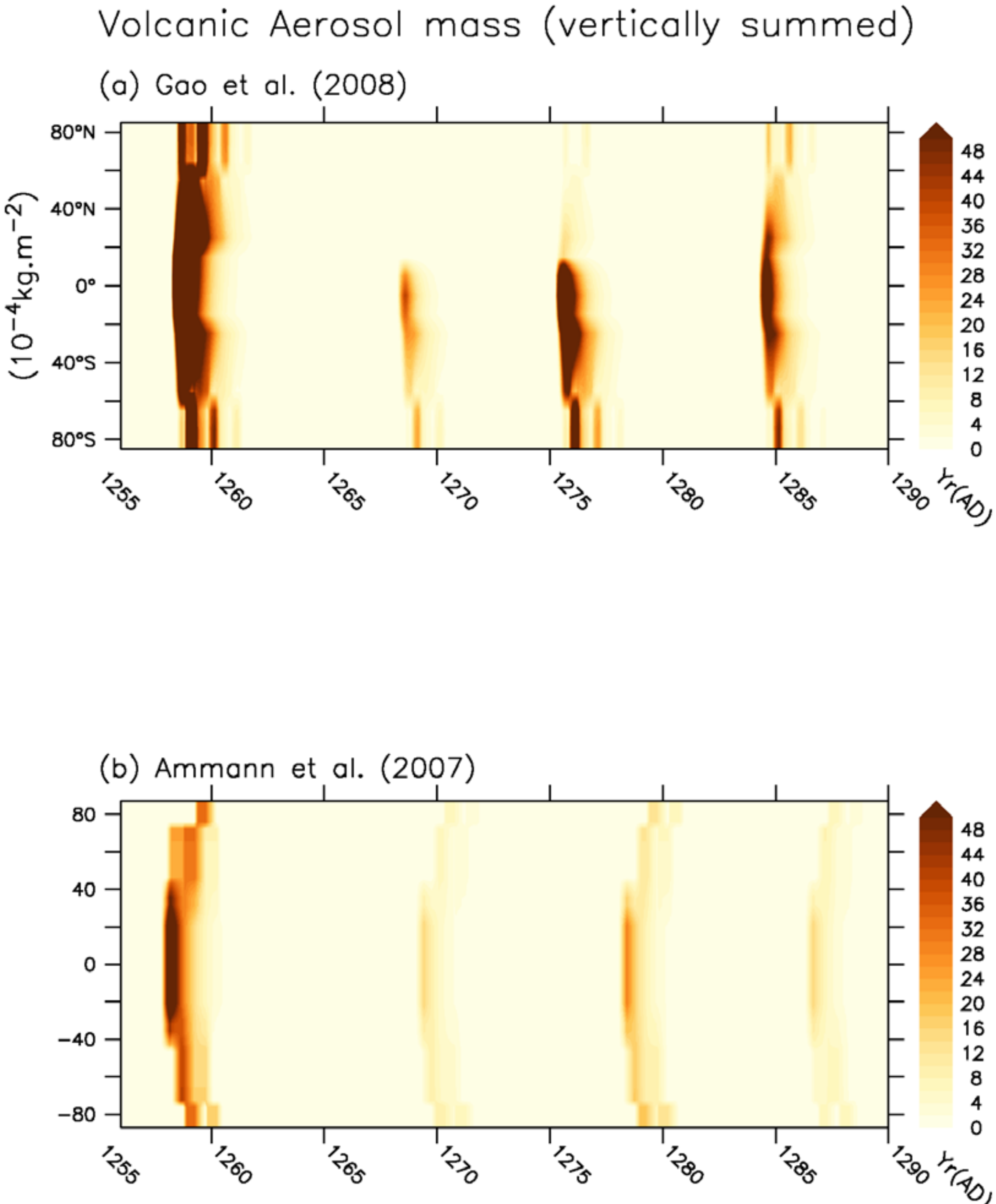


Control run Vs. LRSP1



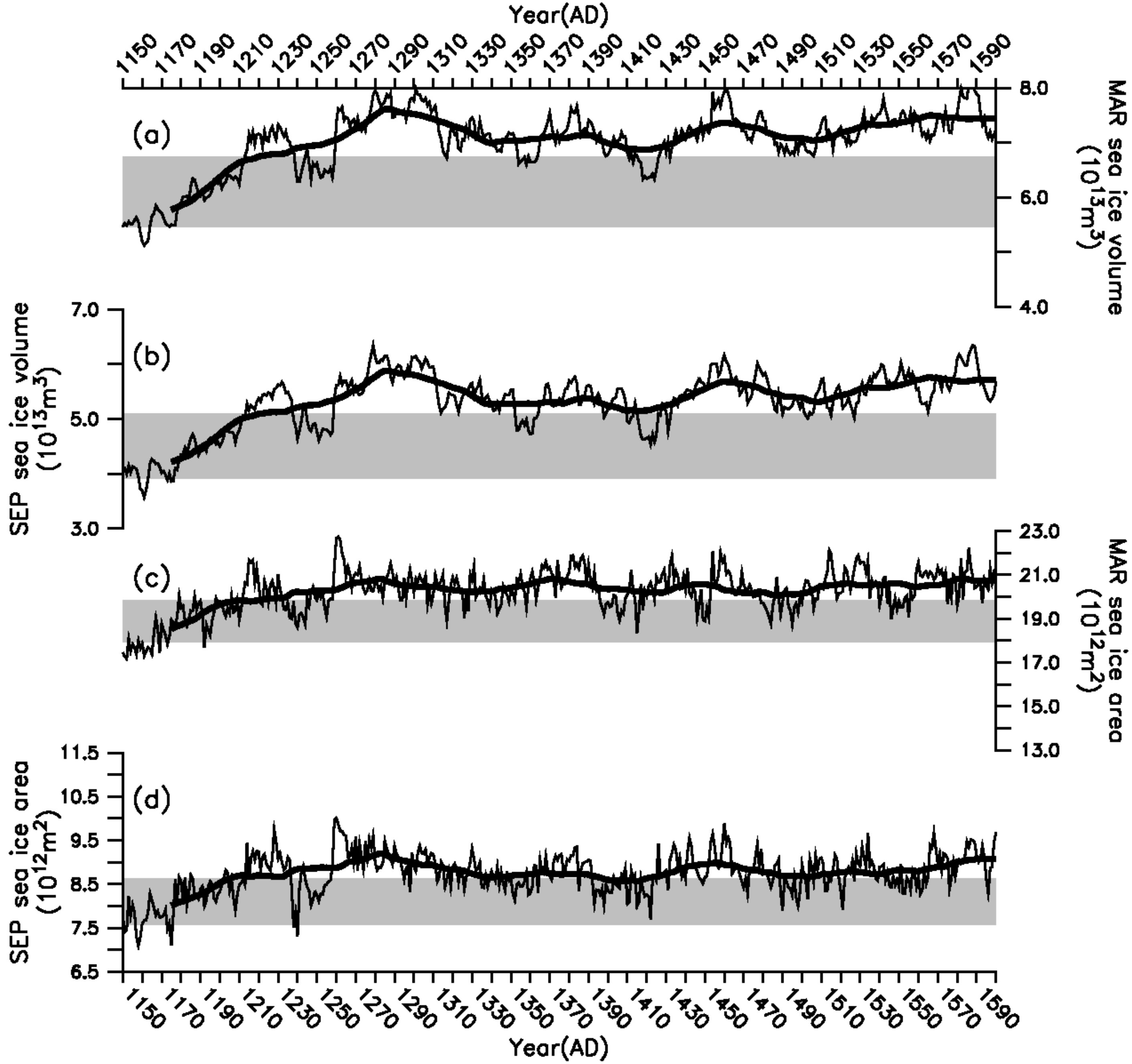


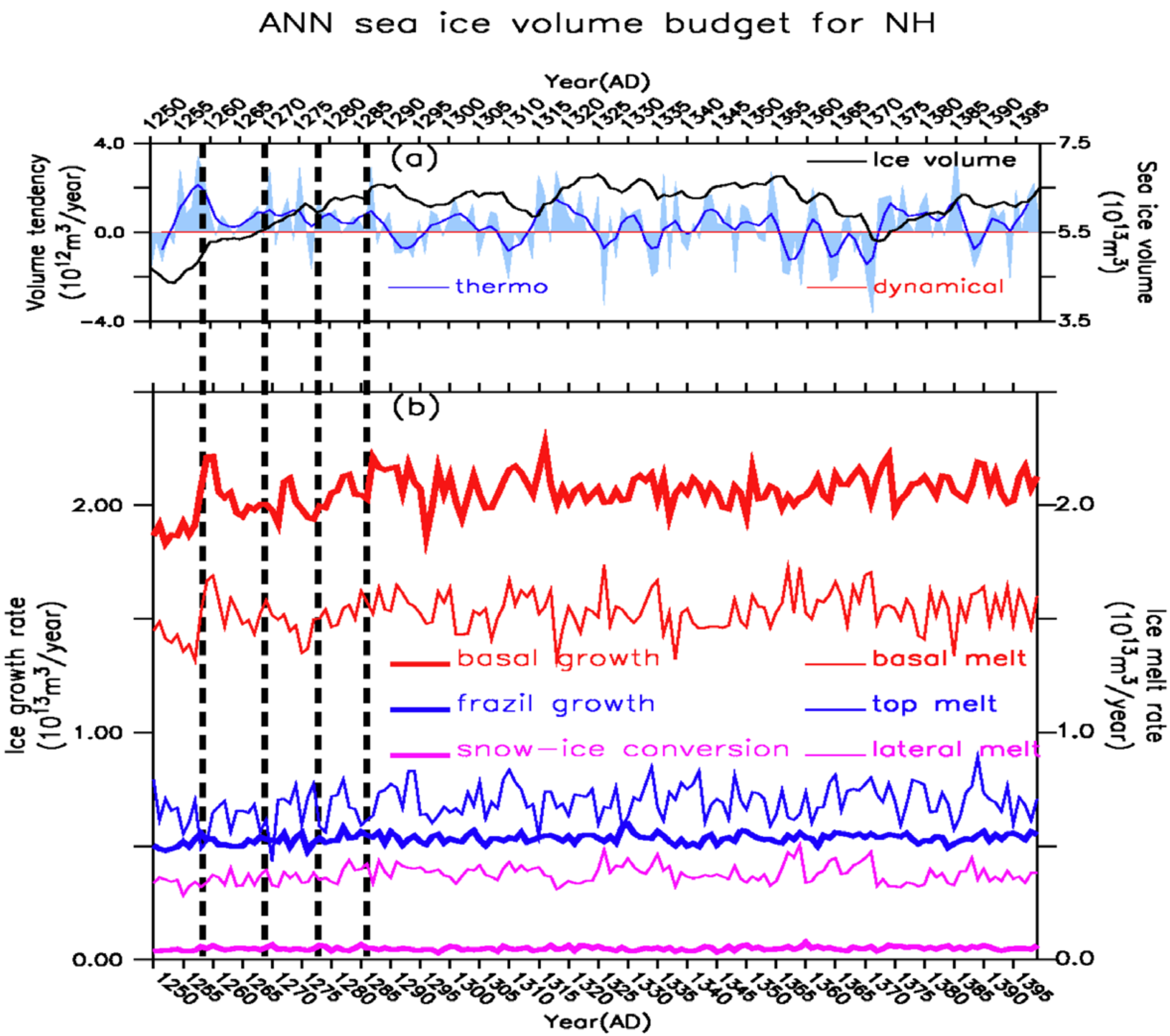

Volcanic Aerosol mass (vertically summed)
(a)
(b)
(10^{-4}kg.m^{-2})
80°N
40°N
0°
40°S
80°S
Yr(AD)
1150
1170
1190
1210
1230
1250
1270
1290
1310
1330
1350
1370
1390
1410
1430
1450
1470
1490
1510
1530
1550
1570
1590
1257
1258
1259
1260
1261
1262
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30



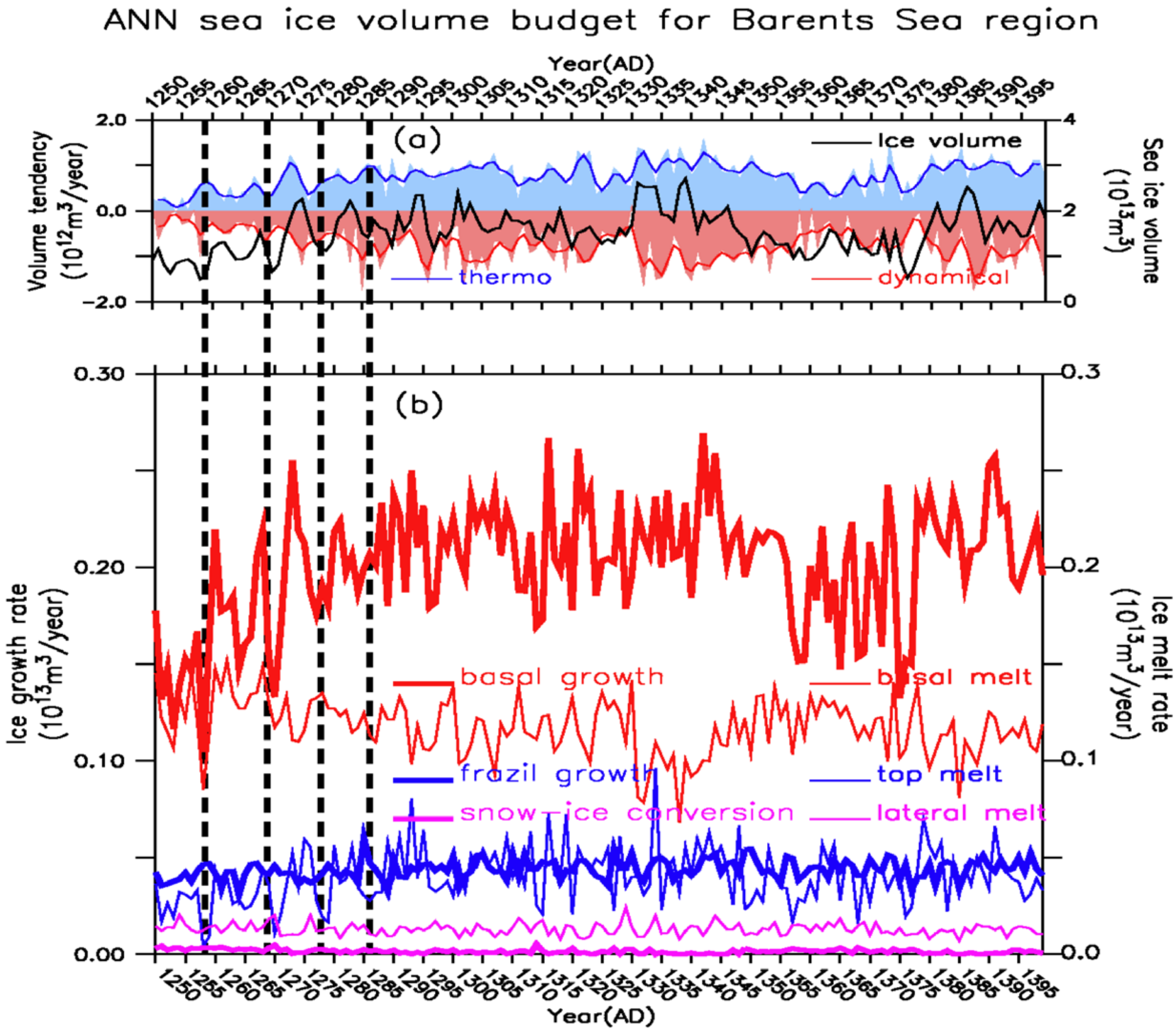
Volcanic Aerosol mass (vertically summed)
(a) Gao et al. (2008)
(b) Ammann et al. (2007)
(10^{-4}kg.m^{-2})
80°N
40°N
0°
40°S
80°S
80
40
0
−40
−80
1255
1260
1265
1270
1275
1280
1285
1290
Yr(AD)
48
44
40
36
32
28
24
20
16
12
8
4
0

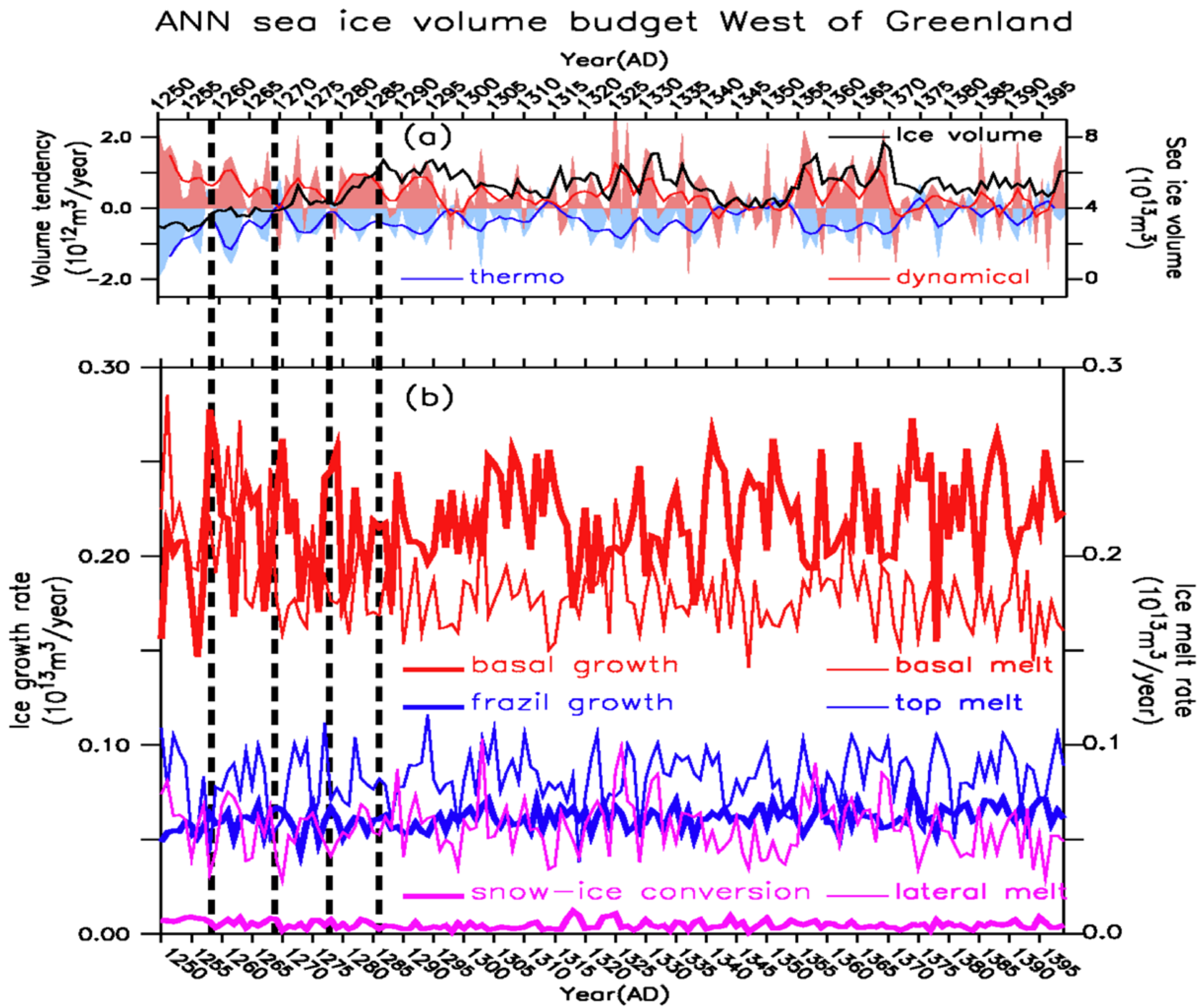
1150-1600AD realistic volcanic forcing





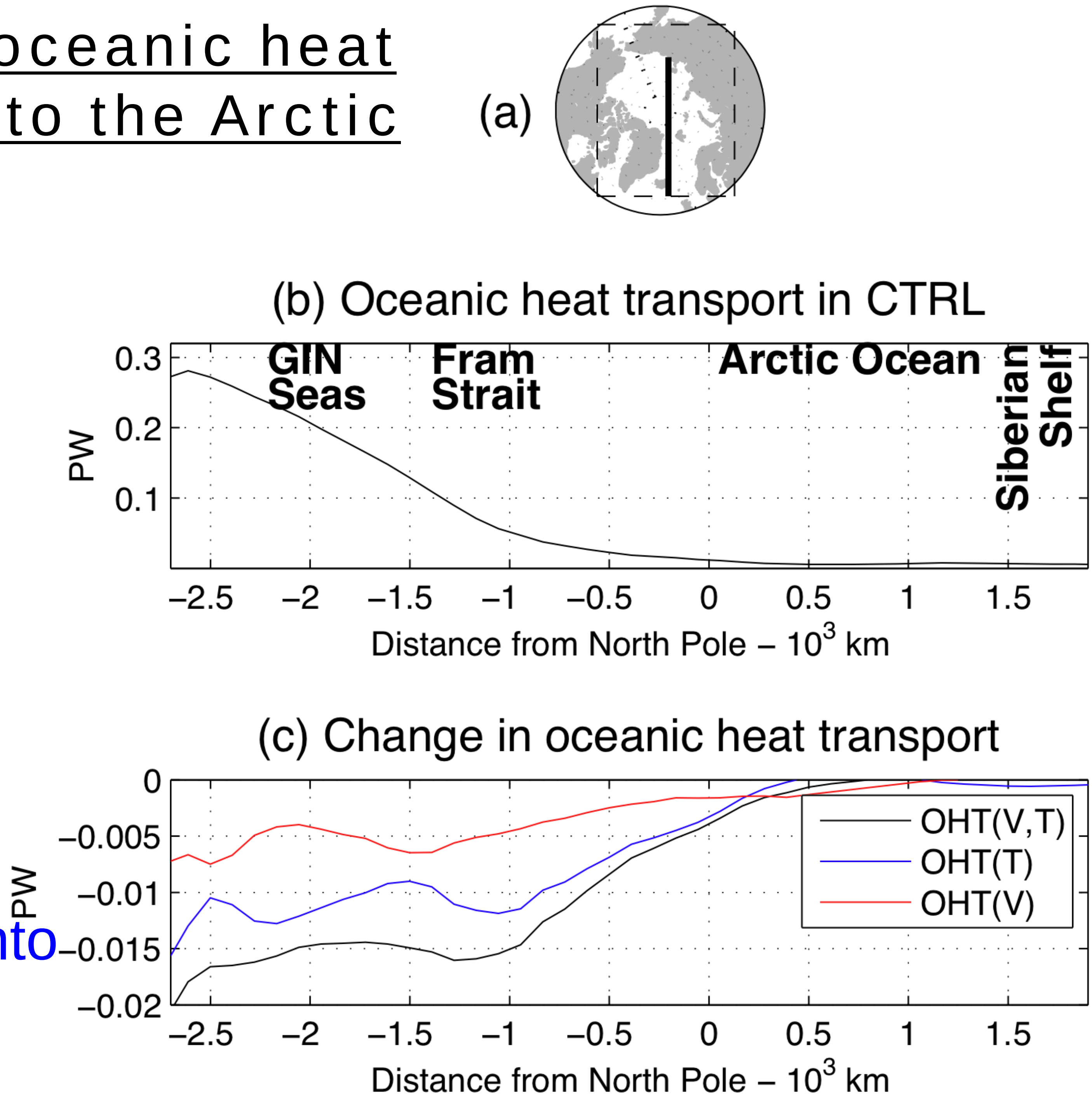
ANN sea ice volume budget for NH
Year(AD)
(a)
Ice volume
Volume tendency (10^12 m^3/year)
Sea ice volume (10^13 m^3)
thermo
dynamical
(b)
basal growth
basal melt
frazil growth
top melt
snow-ice conversion
lateral melt
Ice growth rate (10^13 m^3/year)
Ice melt rate (10^13 m^3/year)
Year(AD)


ANN sea ice volume budget for Barents Sea region
Year(AD)
(a)
Ice volume
thermo
dynamical
Volume tendency (10^12m^3/year)
Sea ice volume (10^13m^3)
(b)
basal growth
basal melt
frazil growth
top melt
snow-ice conversion
lateral melt
Ice growth rate (10^13m^3/year)
Ice melt rate (10^13m^3/year)
Year(AD)



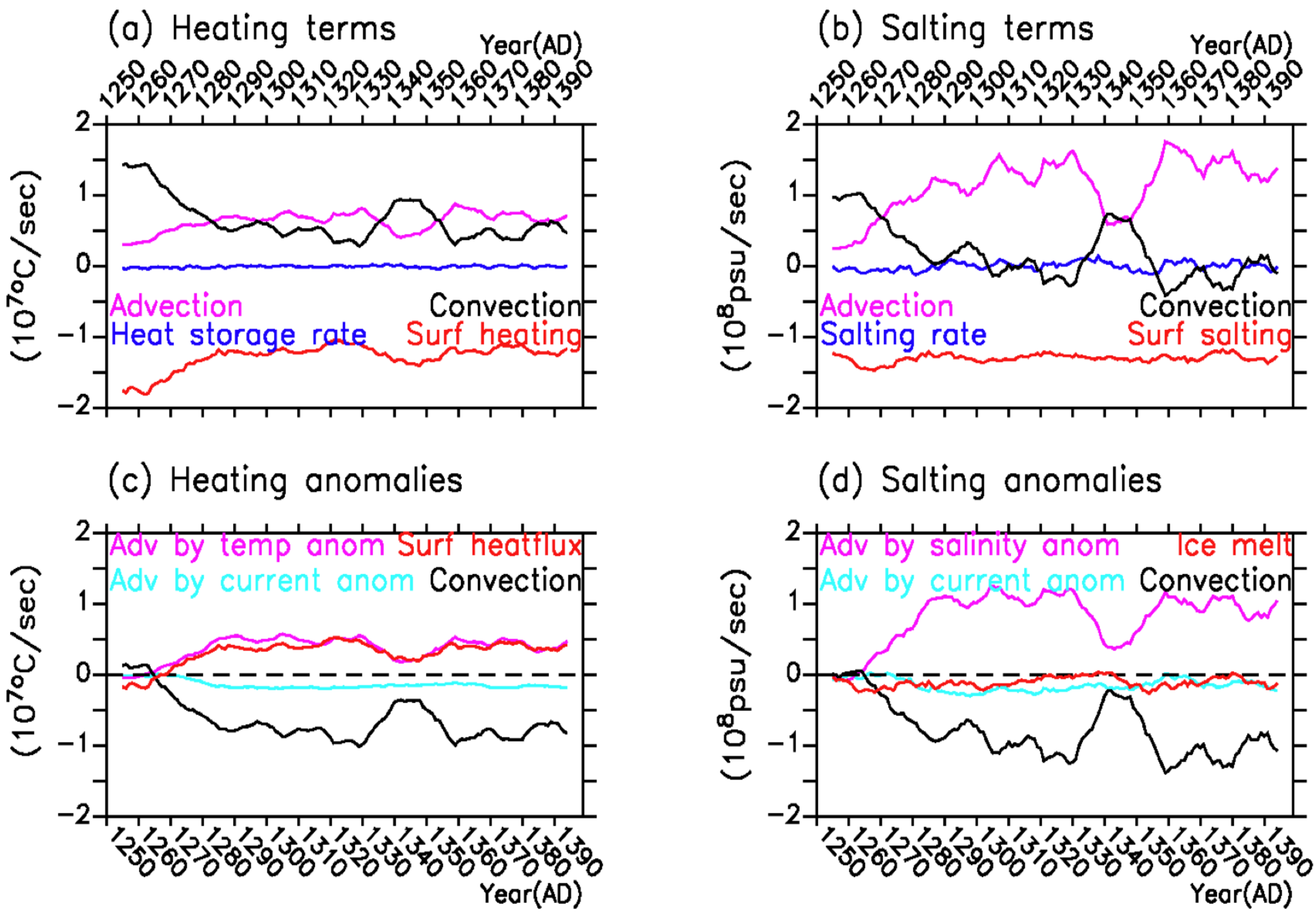
ANN sea ice volume budget West of Greenland
Year(AD)
1250 1255 1260 1265 1270 1275 1280 1285 1290 1295 1300 1305 1310 1315 1320 1325 1330 1335 1340 1345 1350 1355 1360 1365 1370 1375 1380 1385 1390 1395
(a)
Ice volume
thermo
dynamical
Volume tendency
($10^{12}m^3$/year)
2.0
0.0
−2.0
Sea ice volume
($10^{13}m^3$)
8
4
0
(b)
basal growth
basal melt
frazil growth
top melt
snow−ice conversion
lateral melt
Ice growth rate
($10^{13}m^3$/year)
0.30
0.20
0.10
0.00
Ice melt rate
($10^{13}m^3$/year)
0.3
0.2
0.1
0.0
Year(AD)

Decreased oceanic heat transport into the Arctic



Colder water into the Arctic!

Heat and salt budgets of surface subpolar North Atlantic



Weakend Atlantic Meridional Overturning Circulation