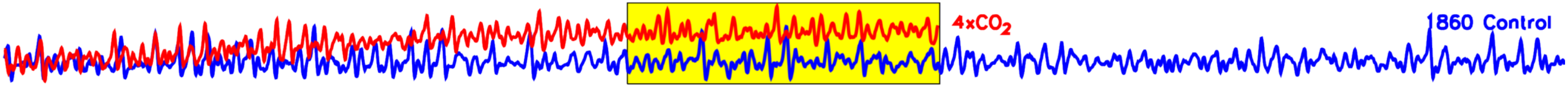
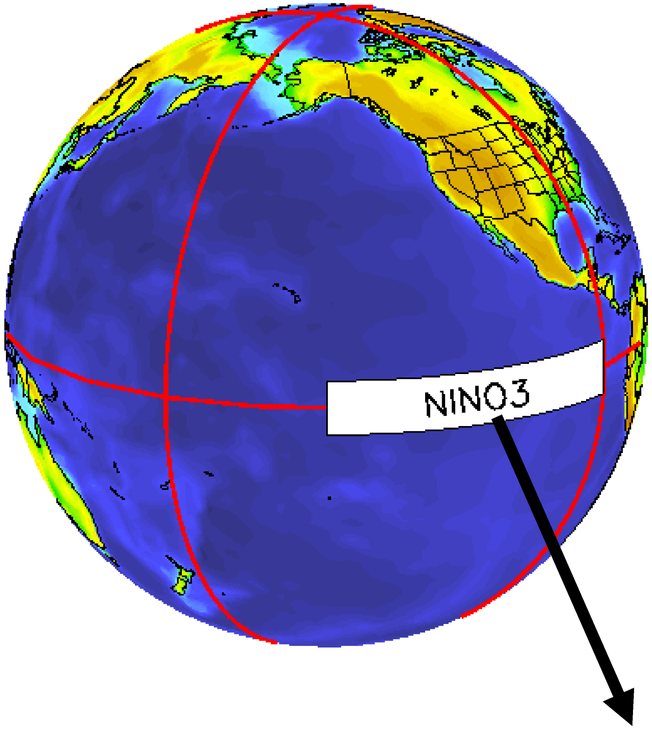
Model fidelity and ENSO change: signal vs. noise

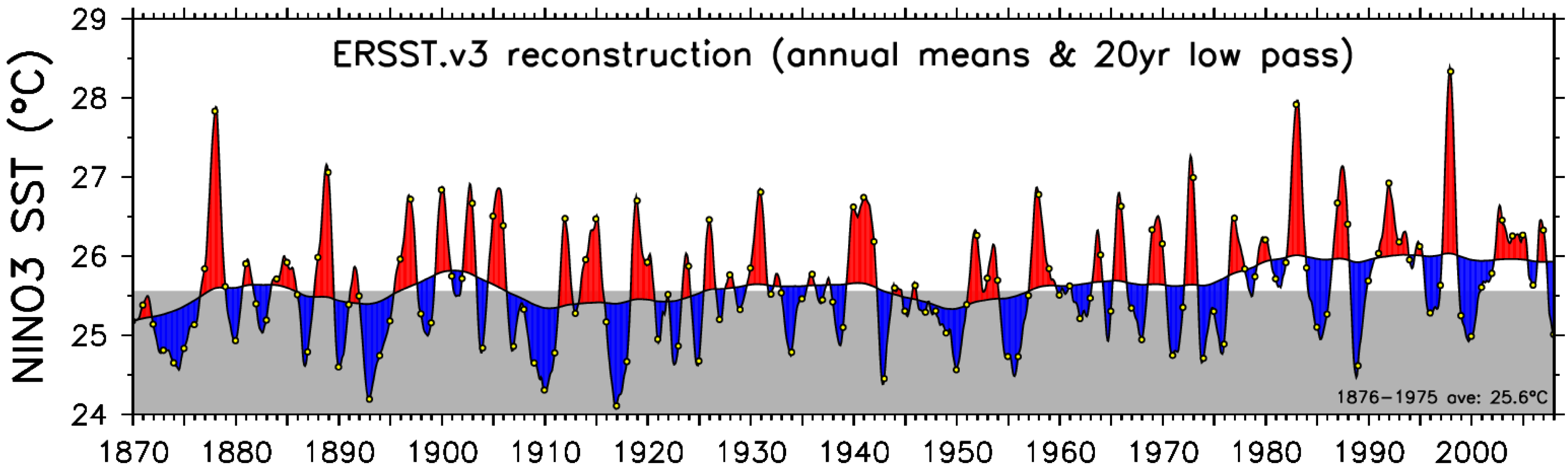


Andrew Wittenberg
NOAA/GFDL

Is ENSO changing?

- Variations in amplitude & period
- Short record, changing obs system
- Disparate AR4 model projections
- Which models to trust?
- How long to evaluate/distinguish?





Review of ENSO modulation

See also: Diaz & Markgraf (2000), esp. chapter by Kleeman & Power

1. ENSO modulation in historical records

Multidecadal variations in ENSO amplitude, frequency, SSTA propagation
coincident with apparent changes in background state

Enfield & Cid (JC 1991); Wang (JC 1995); Wang & Wang (JC 1996); Torrence & Compo (BAMS 1998);
Allan (Diaz & Markgraf 2000); An & Wang (JC 2000); Fedorov & Philander (Science 2000);
Wang & An (GRL 2001; CD 2002); Timmermann (GPC 2003); An & Jin (JC 2004);
Yeh & Kirtman (JGRO 2004); Fang et al. (GRL 2008); Sun & Yu (JC 2009); Vecchi & Wittenberg (WIREs 2010)

2. "Unusual" recent behavior of ENSO

1990s less predictable; "extended ENSO"; more central-Pacific events
However: "not previously observed" needn't imply "nonstationary"
(perhaps we simply haven't observed long enough)
And must account for mean-state changes in ENSO indices (how, for recent past?)

Harrison & Larkin (GRL 1997); Rajagopalan et al. (JC 1997); Trenberth & Hoar (GRL 1997)
Latif et al. (JC 1997); Power & Smith (GRL 2007); Yeh et al. (Nature 2009); Lee & McPhaden (GRL 2010)

Review of ENSO modulation (ctd.)

3. ENSO modulation in paleo proxies

ENSO weaker at 6ka?
sparse, often discontinuous records, sometimes hard to interpret
limited time resolution, some rely on teleconnections, or confound SST/precip
what if seasonal cycle / teleconnections differed in the past?

Sandweiss et al. (Science 1996); Rodbell et al. (Science 1999); Markgraf & Diaz (Diaz & Markgraf 2000); Cole (Science 2001); Tudhope et al. (Science 2001); Moy et al. (Nature 2002); Cobb et al. (Nature 2003); McGregor & Gagan (GRL 2004); D'Arrigo et al. (GRL 2005); Emile-Geay et al. (JC subm. 2010)

4. ENSO modulation in intermediate models and CGCMs

Cane et al. (NRC 1995); Knutson et al. (JC 1997); Collins et al. (CD 2001); Picaut (workshop 2003); Yukimoto & Kitamura (JMSJ 2003); Yeh et al. (JC 2004); Yeh & Kirtman (JGRO 2004, GRL 2005); Moon et al. (CD 2007); Burgman et al. (JC 2008); Vimont et al. (JC 2002); AchutaRao & Sperber (CD 2002); Lin (GRL 2007); Wittenberg (GRL 2009)

5. IPCC-AR4 model projections of ENSO over next century:

some stronger, some weaker, some unchanged

Meehl et al. (IPCC-AR4 2007), Guilyardi et al. (BAMS 2009), Collins et al. (NG 2010)

Review of ENSO modulation (ctd.)

6. Mechanisms for ENSO modulation

ENSO might generate its own irregularity, internal to tropical Pacific region.
Internal nonlinearity, seasonal resonance, intermittency, bursting.

Münnich et al. (JAS 1991); Jin et al. (Science 1994); Tziperman et al. (Science 1994); Kirtman & Schopf (JC 1998); Timmermann & Jin (GRL 2002); Timmermann et al. (JAS 2003); Timmermann (GPC 2003)

And modulation could arise from noise and/or intrinsic chaos alone.

Schopf & Suarez (JAS 1988); Battisti (JAS 1988); Zebiak & Cane (Elsevier 1991); Penland & Sardeshmukh (JC 1995); Eckert & Latif (JC 1997); Zhang et al. (GRL 2003); Newman et al. (JC 2003); Flugel et al. (JC 2004); Kirtman et al. (JAS 2005)

ENSO sensitive to mean state (trades, TC depth/intensity).
But ENSO asymmetry itself can alter mean state.

Wang (JC 1995); Fedorov and Philander (JC 2001); Wittenberg (Princeton 2002); Dong et al. (GRL 2006) Rodgers et al. (JC 2004); Schopf and Burgman (JC 2006)

Might ENSO act to regulate tropical temperatures?

Sun (JC 2003); Sun & Liu (Science 1996); Sun & Zhang (GRL 2006)

ENSO modulation links to extratropical changes; cause & effect?
A recent focus: seasonal footprinting & meridional mode physics.

Barnett et al. (GRL 1999); Kleeman et al. (GRL 1999); Liu & Yang (GRL 2003); Sun et al. (JC 2004); Matei et al. (JC 2008); Vimont et al. (GRL 2001); Vimont et al. (JC 2003); Chang et al. (GRL 2007); Di Lorenzo (NG 2010); Alexander et al. (JC 2010)

IPCC-AR4: GFDL CM2.1 global coupled GCM

atmos: 2°x2.5°xL24 finite volume
ocean: 1°x1°xL50 MOM4 (1/3° near equator)
2hr coupling; ocean color; no flux adjustments
ENSO & tropics rank among top AR4-class models
SI forecasts; parent of GFDL AR5 models

4000-year pre-industrial control run

1860 atmospheric composition, insolation, land cover
220yr spinup from 20th-century initial conditions
substantial investment: 2 years on 60 processors

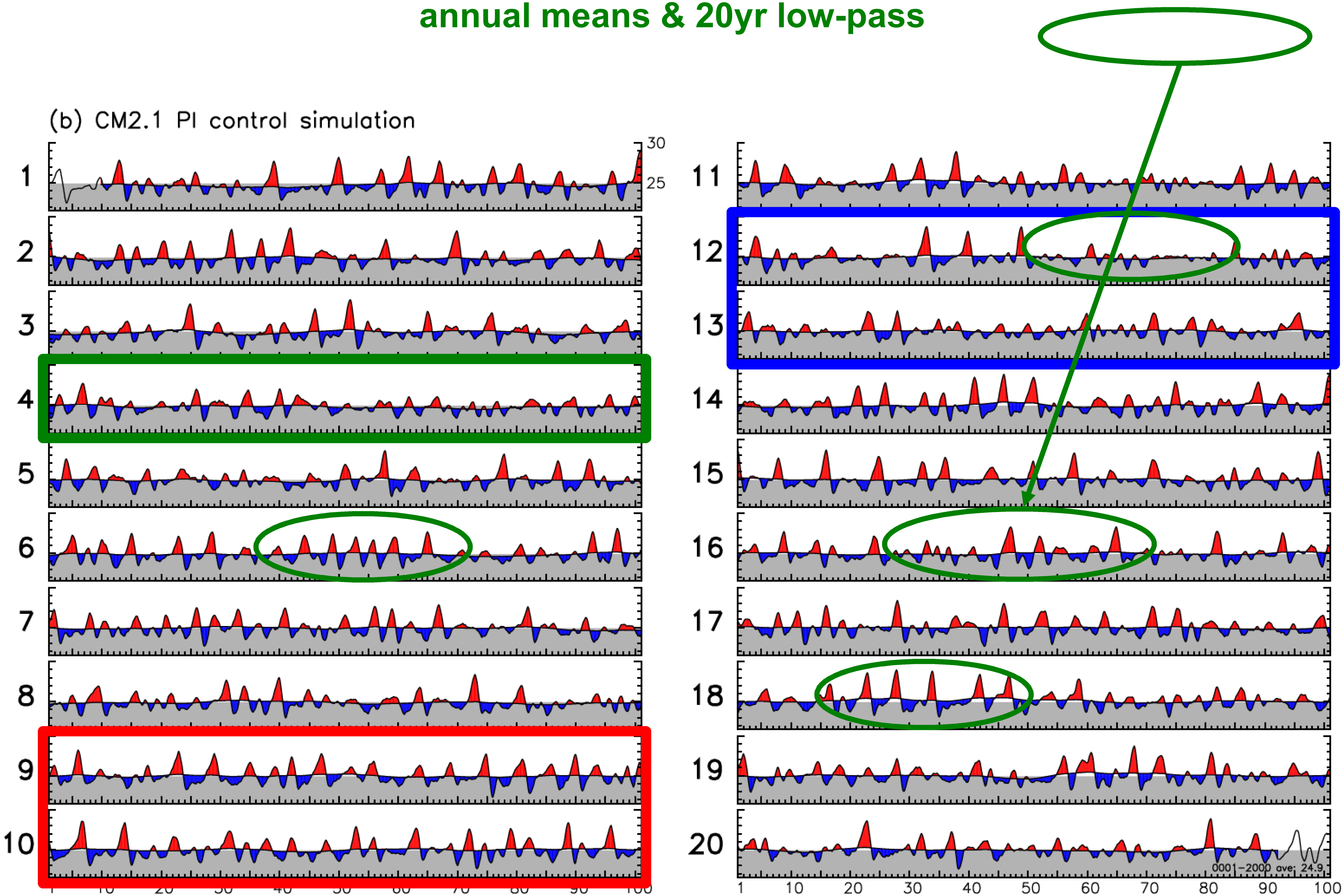
1990 control (300yr) **2xCO_2 (600yr)** **4xCO_2 (600yr)**

new AR5 models: **ESM2M** **ESM2G** **CM3**

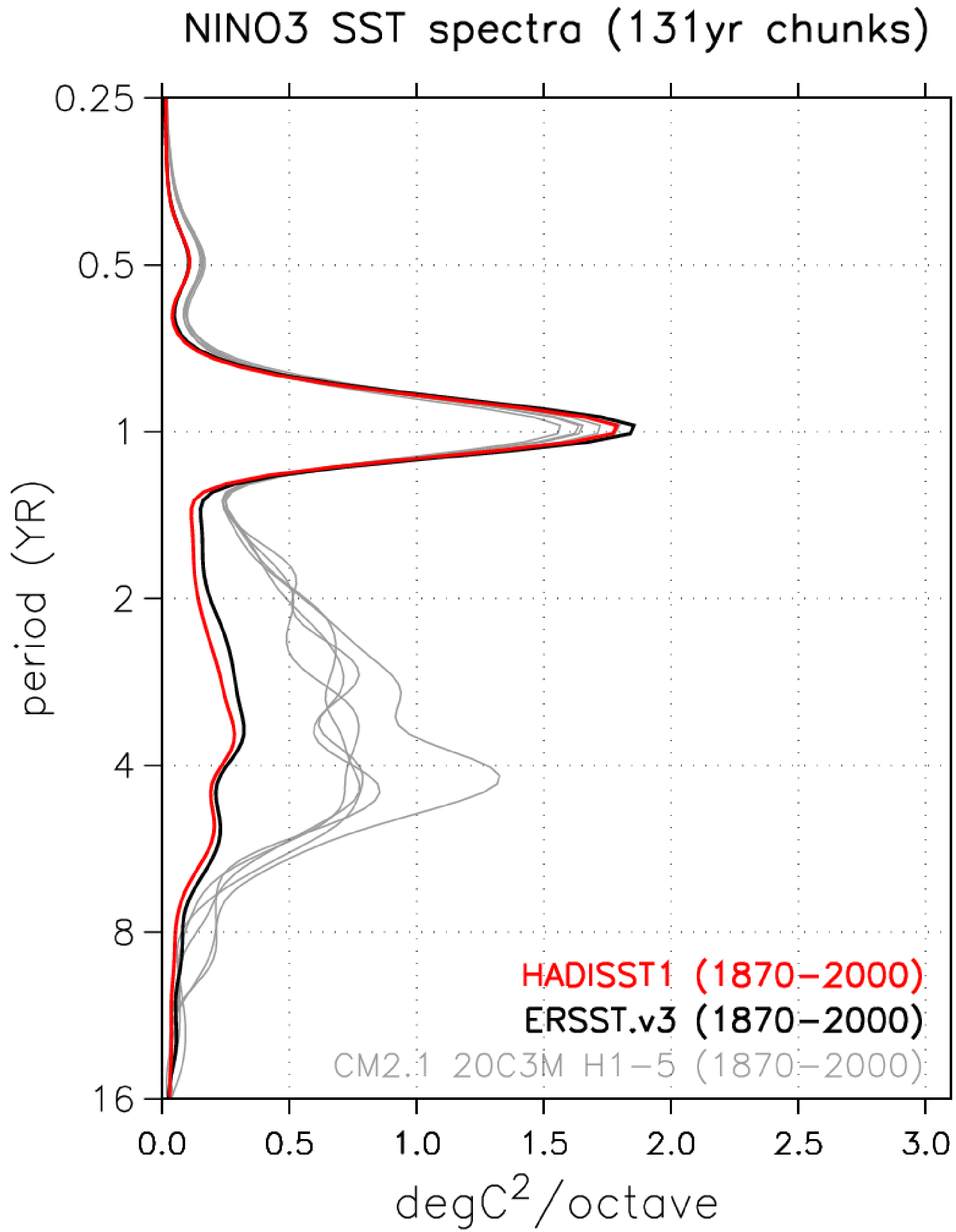
Delworth et al., Wittenberg et al., Merryfield et al., Joseph & Nigam (JC 2006), Wittenberg (GRL 2009)
Zhang et al. (MWR 2007); van Oldenborgh et al. (OS 2005); Guilyardi (CD 2006); Reichler & Kim (BAMS 2008)
Donner et al. (subm 2010), Griffies et al. (subm 2010); Stouffer et al. (in prep)

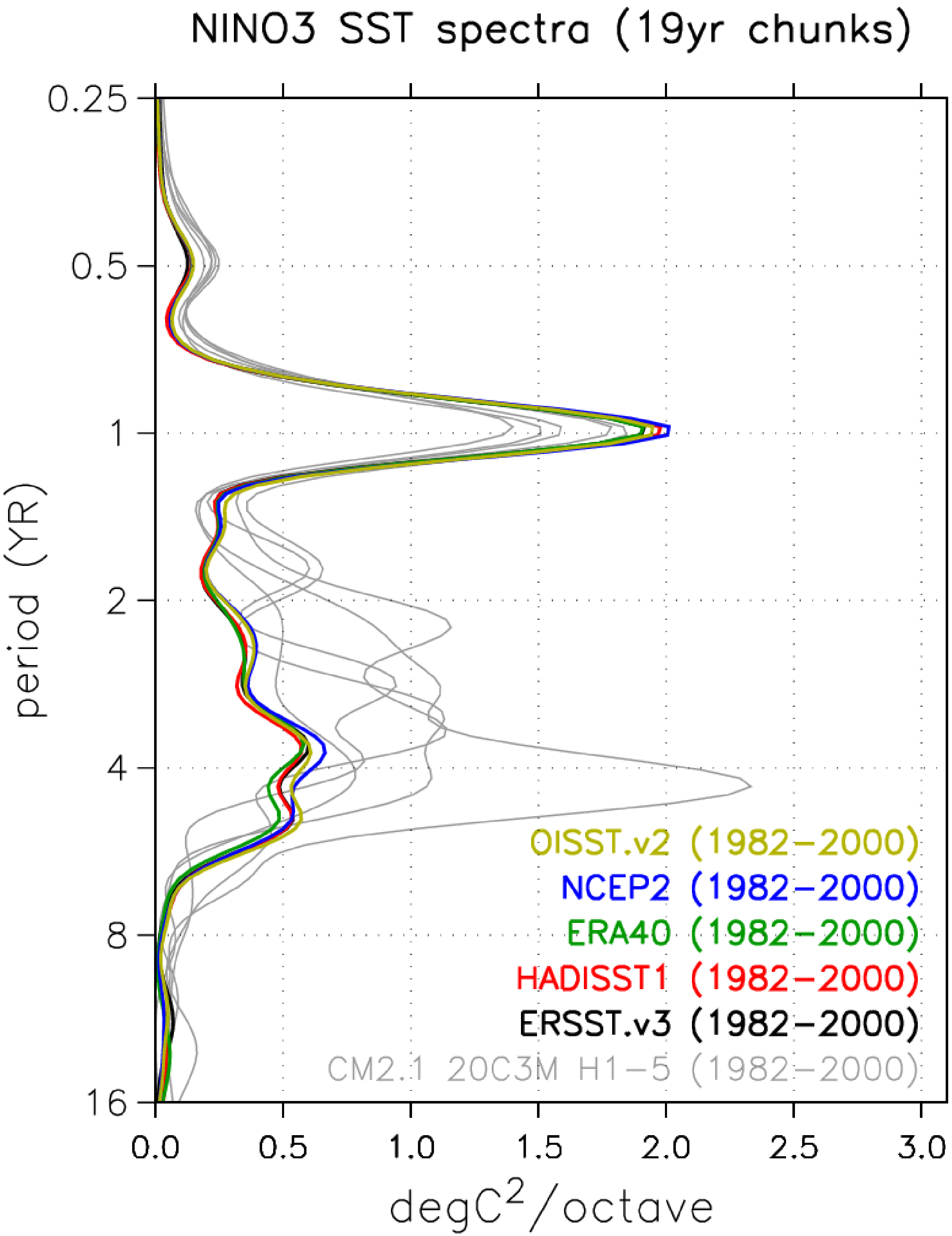
20 centuries of NINO3 SSTs

annual means & 20yr low-pass

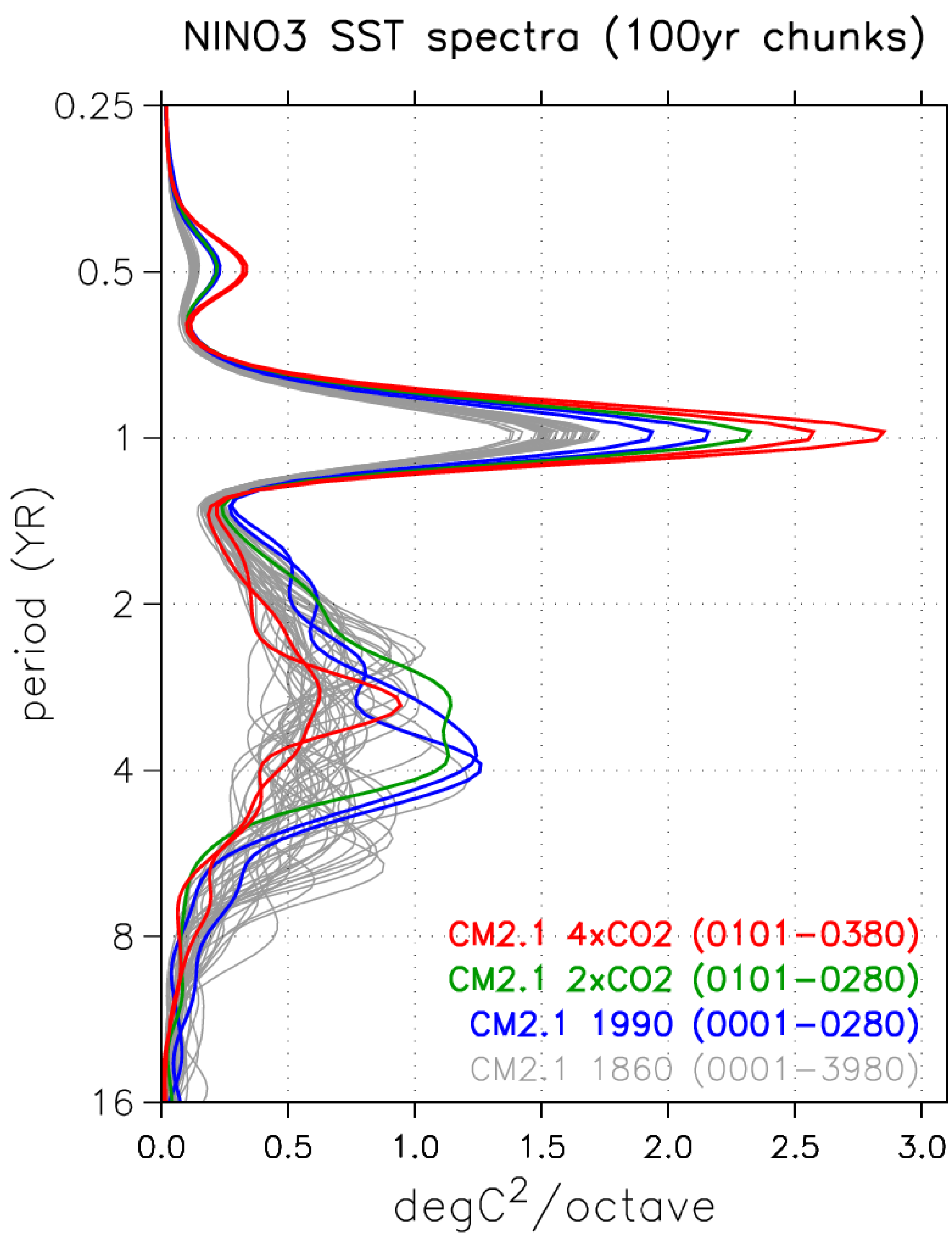


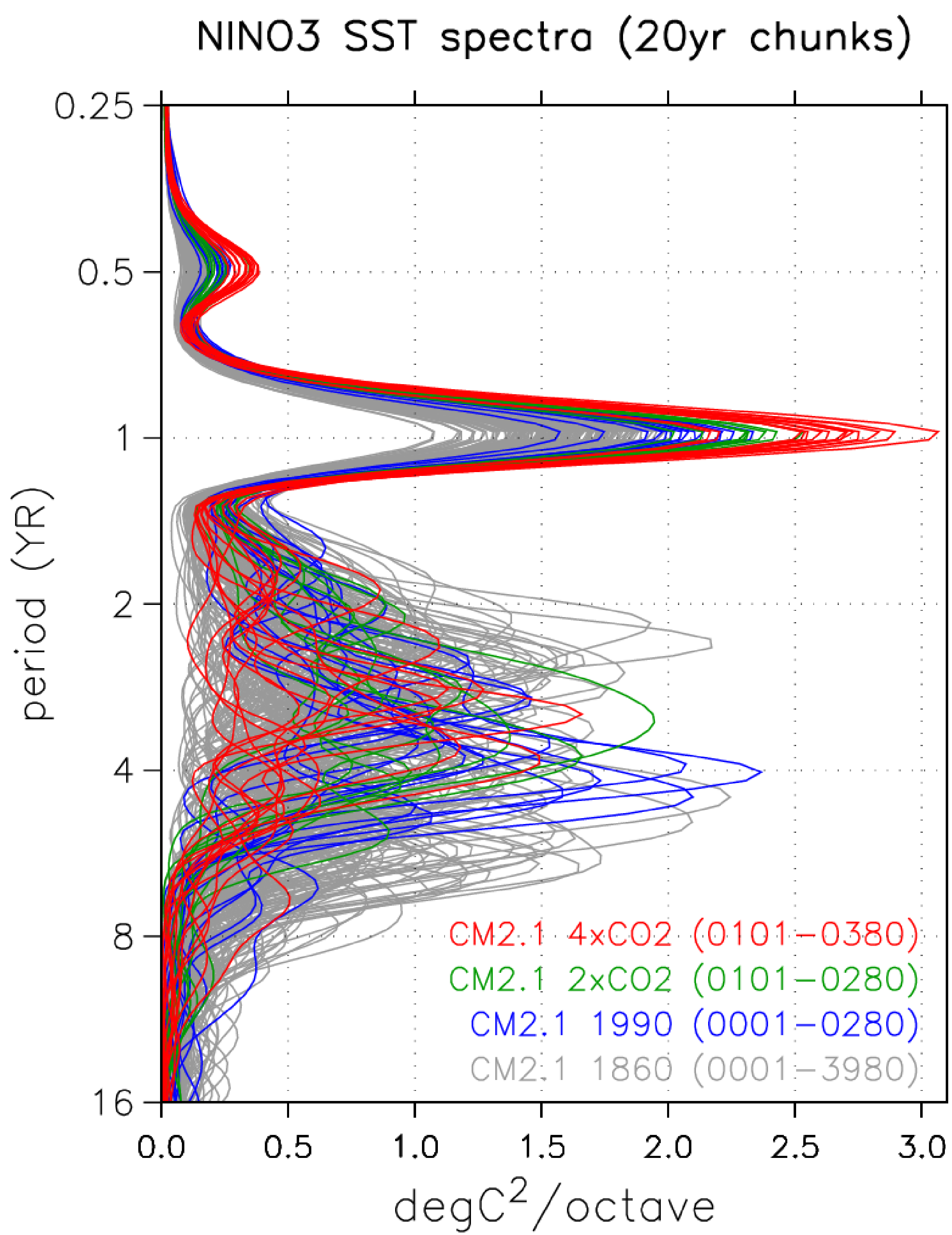
Spectrum of NINO3 SST


NINO3 SST spectra (131yr chunks)
0.25
0.5
1
2
4
8
16
period (YR)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
degC^2/octave
HADISST1 (1870–2000)
ERSST.v3 (1870–2000)
CM2.1 20C3M H1–5 (1870–2000)

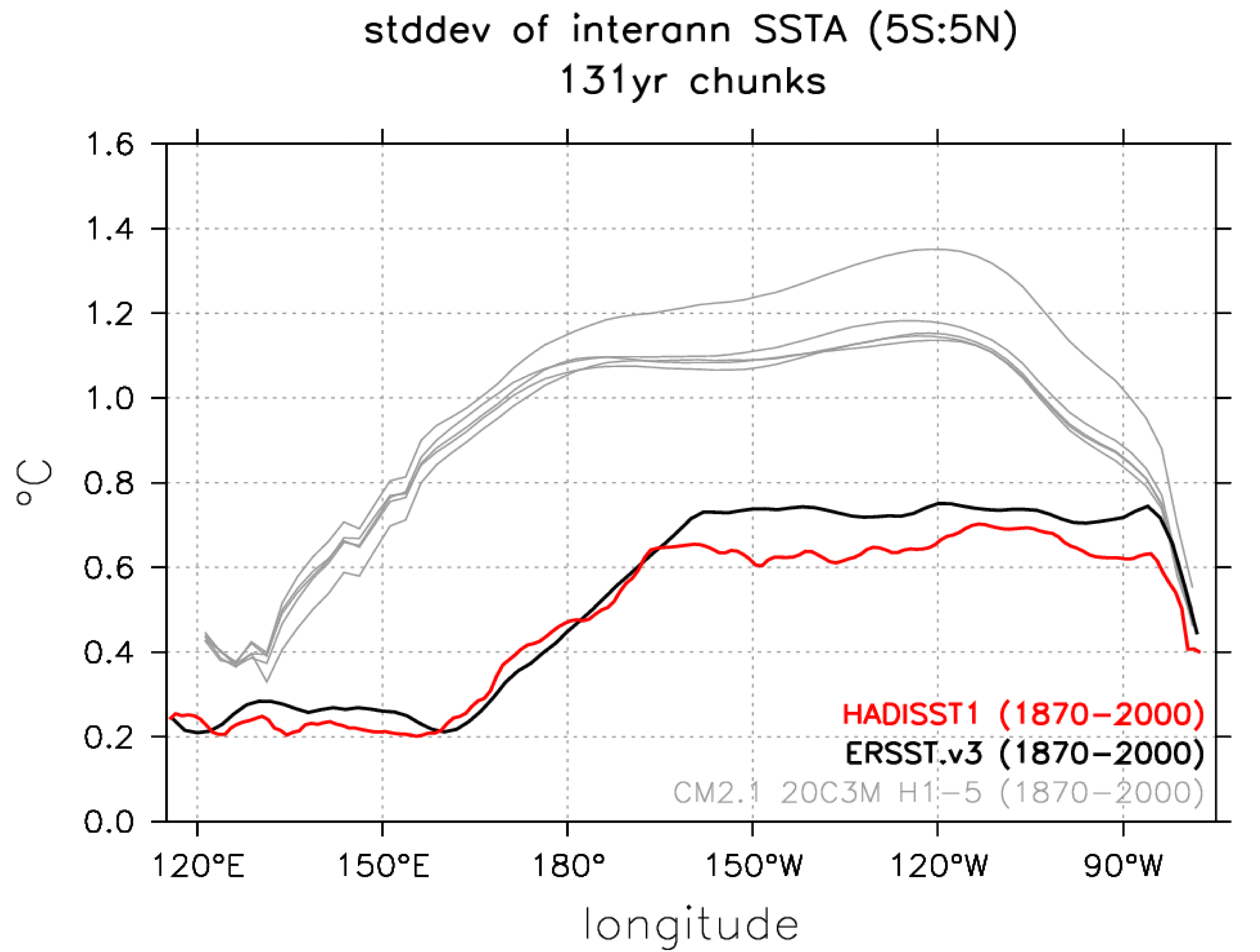


NINO3 SST spectra (19yr chunks)
period (YR)
0.25
0.5
1
2
4
8
16
0.0
0.5
1.0
1.5
2.0
2.5
3.0
degC^2/octave
OISST.v2 (1982–2000)
NCEP2 (1982–2000)
ERA40 (1982–2000)
HADISST1 (1982–2000)
ERSST.v3 (1982–2000)
CM2.1 20C3M H1–5 (1982–2000)

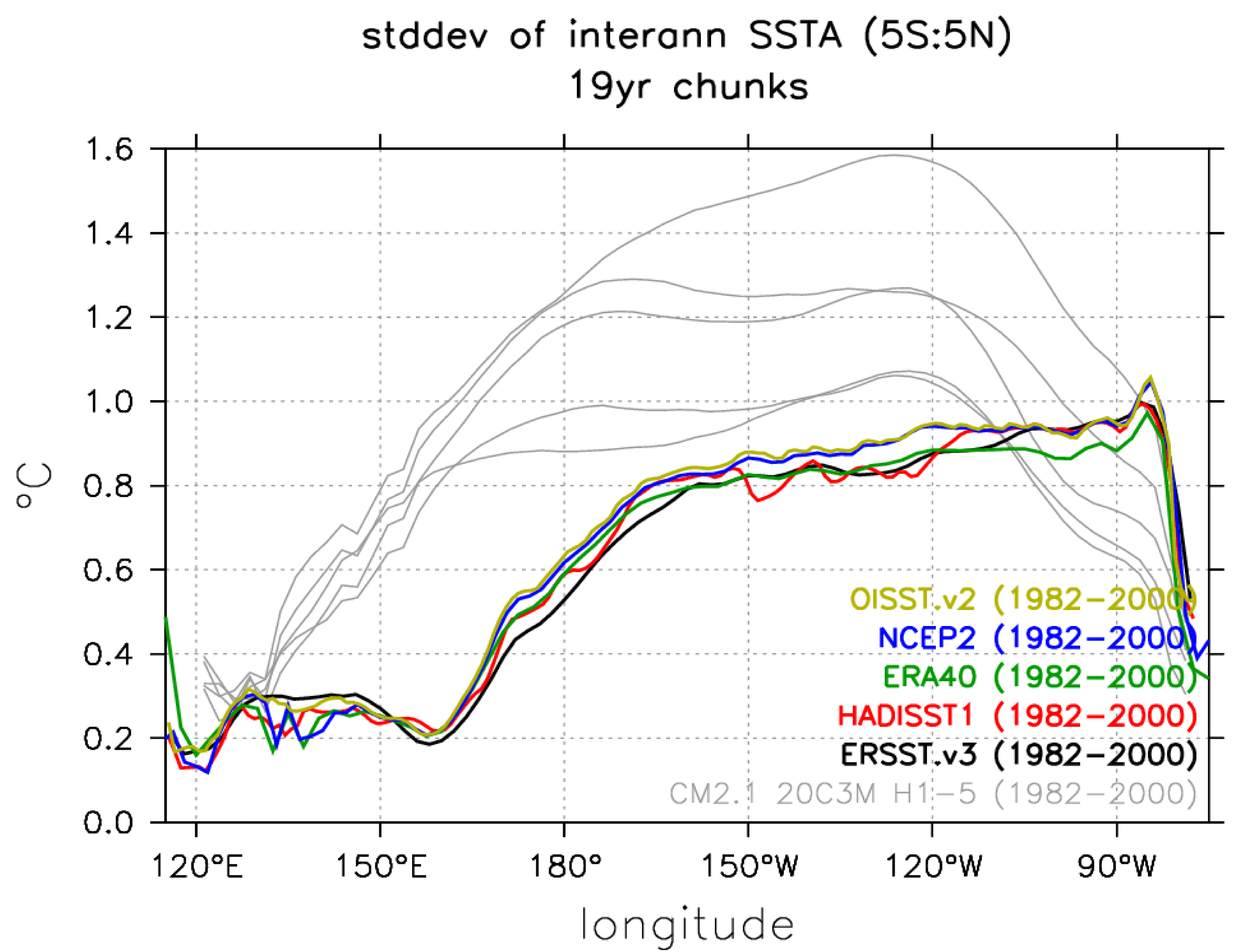

NINO3 SST spectra (100yr chunks)
0.25
0.5
1
2
4
8
16
period (YR)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
degC^2/octave
CM2.1 4xCO2 (0101–0380)
CM2.1 2xCO2 (0101–0280)
CM2.1 1990 (0001–0280)
CM2.1 1860 (0001–3980)

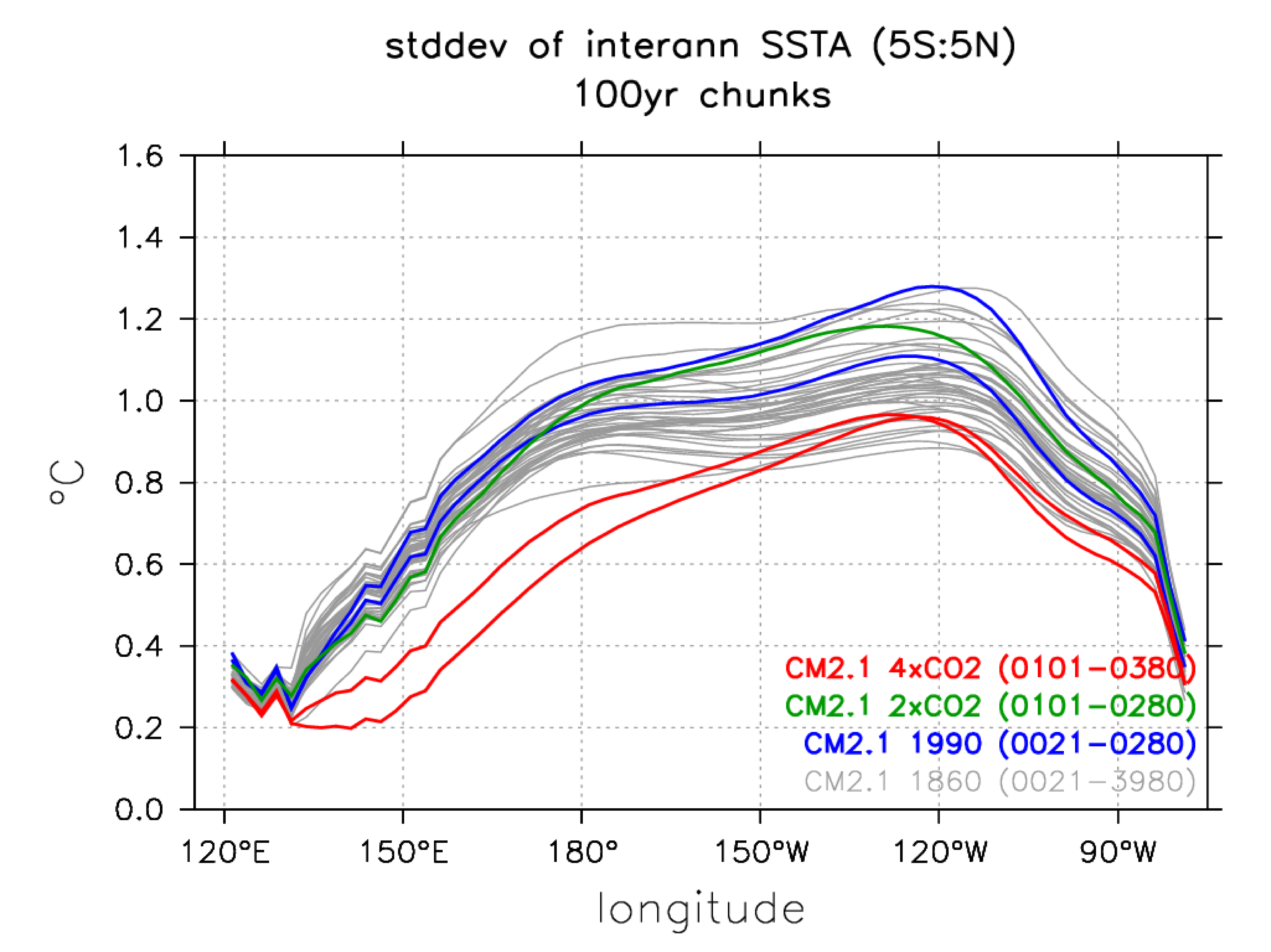

NINO3 SST spectra (20yr chunks)
period (YR)
0.25
0.5
1
2
4
8
16
0.0
0.5
1.0
1.5
2.0
2.5
3.0
degC^2/octave
CM2.1 4xCO2 (0101–0380)
CM2.1 2xCO2 (0101–0280)
CM2.1 1990 (0001–0280)
CM2.1 1860 (0001–3980)

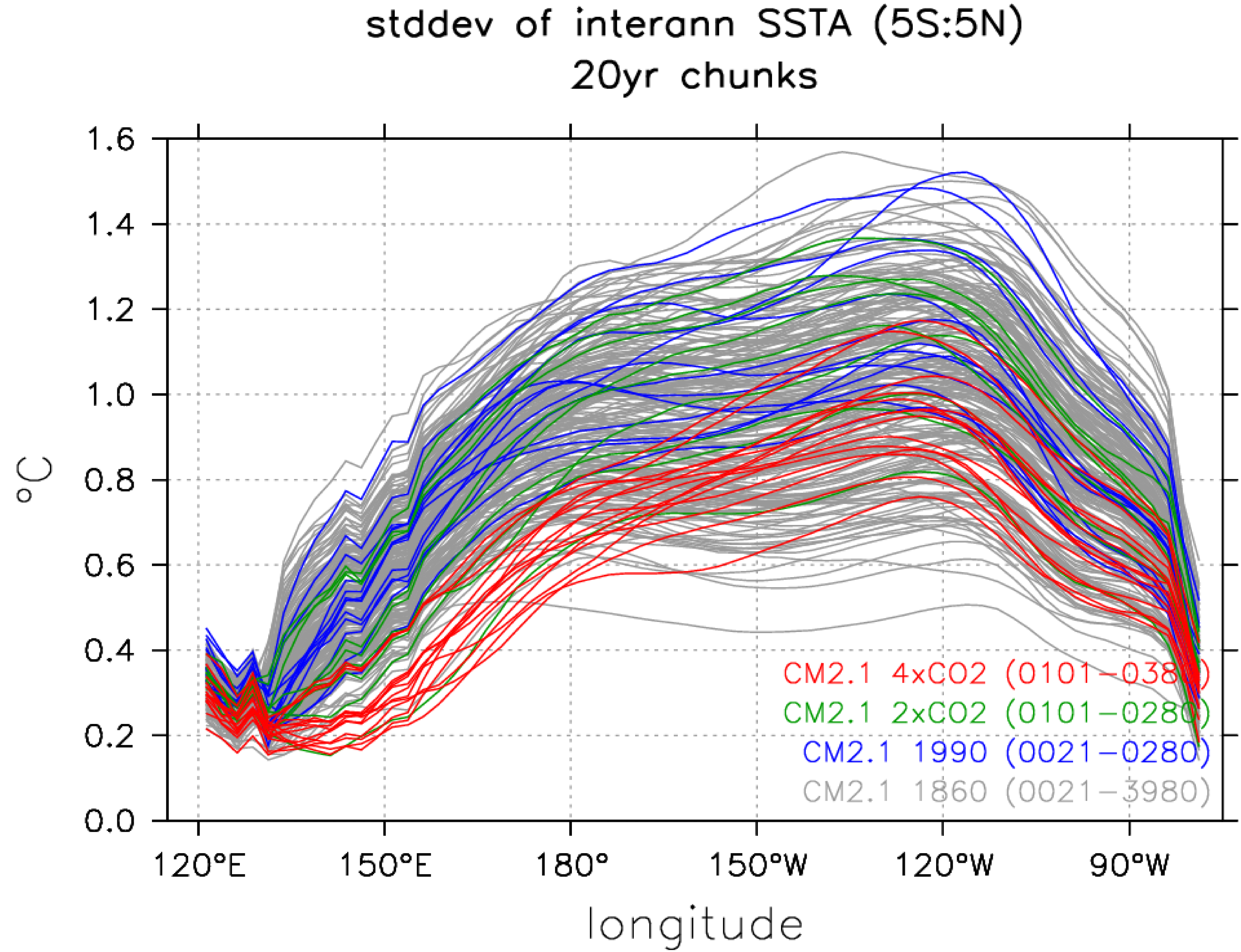
Equatorial SSTA standard deviation



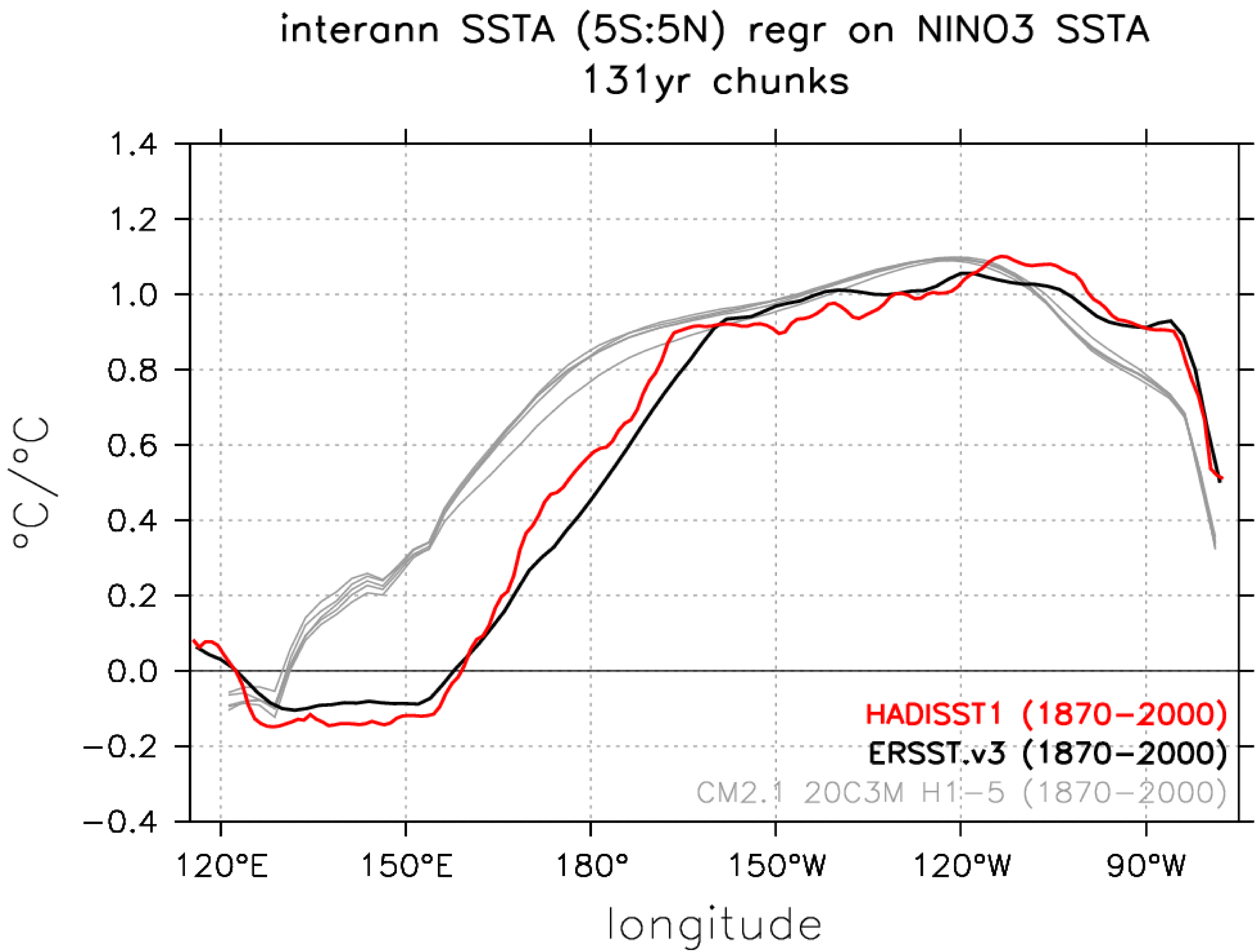
stddev of interann SSTA (5S:5N)
131yr chunks
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
°C
120°E
150°E
180°
150°W
120°W
90°W
longitude
HADISST1 (1870–2000)
ERSST.v3 (1870–2000)
CM2.1 20C3M H1–5 (1870–2000)


stddev of interann SSTA (5S:5N)
19yr chunks
°C
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
120°E
150°E
180°
150°W
120°W
90°W
longitude
OISST.v2 (1982-2000)
NCEP2 (1982-2000)
ERA40 (1982-2000)
HADISST1 (1982-2000)
ERSST.v3 (1982-2000)
CM2.1 20C3M H1-5 (1982-2000)

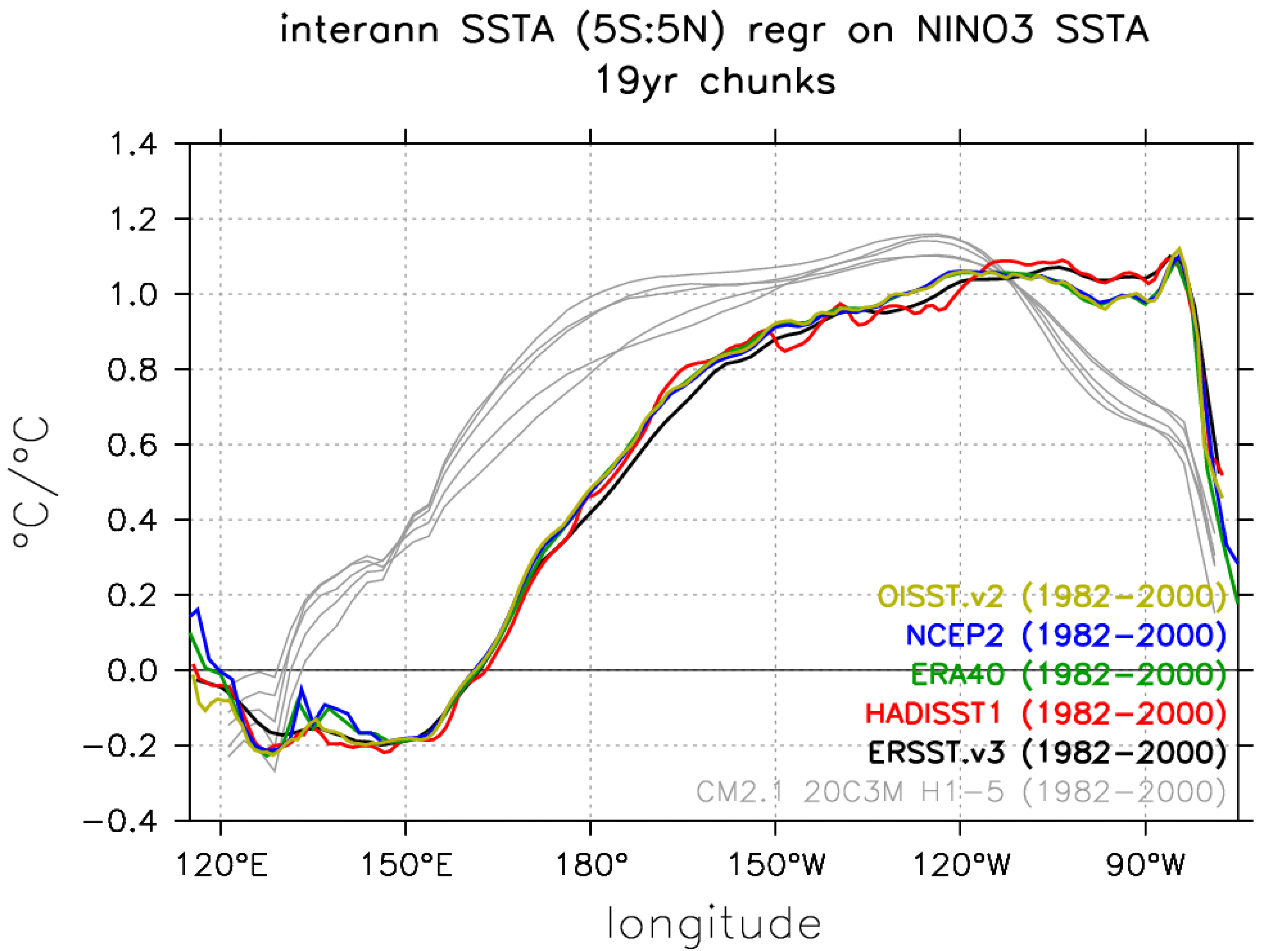

stddev of interann SSTA (5S:5N)
100yr chunks
°C
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
120°E
150°E
180°
150°W
120°W
90°W
longitude
CM2.1 4xCO2 (0101-0380)
CM2.1 2xCO2 (0101-0280)
CM2.1 1990 (0021-0280)
CM2.1 1860 (0021-3980)

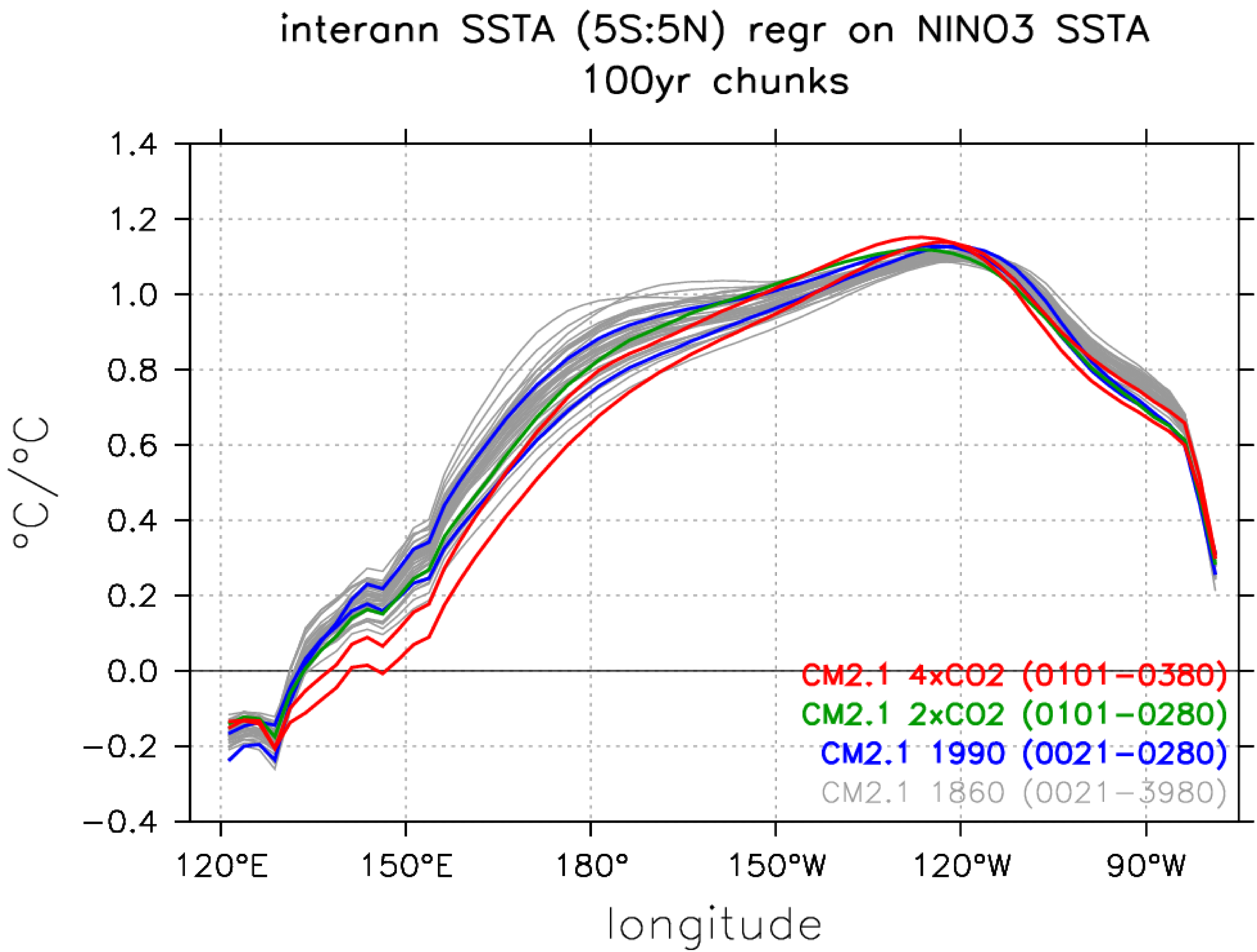

stddev of interann SSTA (5S:5N)
20yr chunks
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
°C
120°E
150°E
180°
150°W
120°W
90°W
longitude
CM2.1 4xCO2 (0101−038)
CM2.1 2xCO2 (0101−0280)
CM2.1 1990 (0021−0280)
CM2.1 1860 (0021−3980)

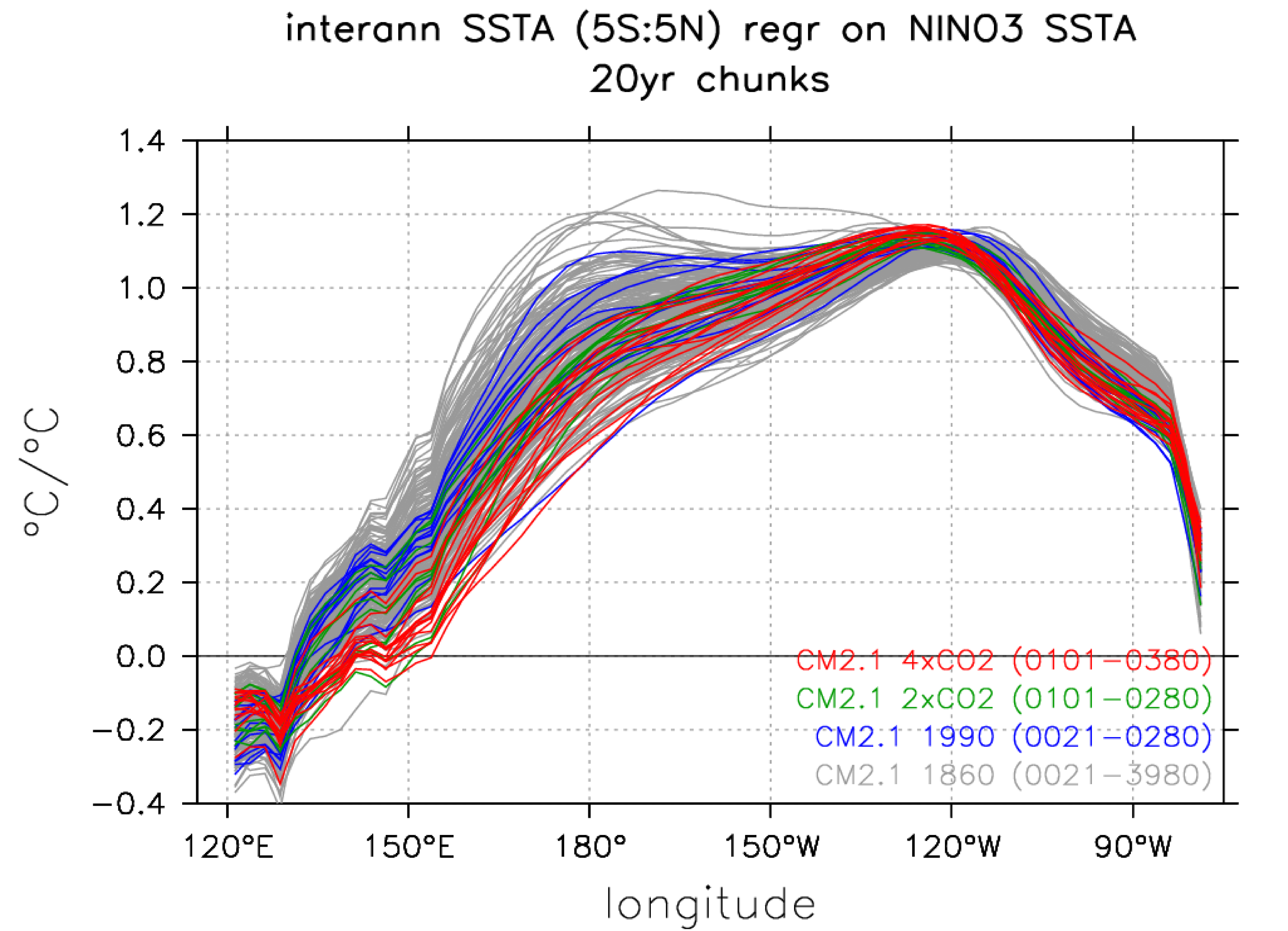
Equatorial SSTA regressed on NINO3 SSTA



interann SSTA (5S:5N) regr on NINO3 SSTA
131yr chunks
°C/°C
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
120°E
150°E
180°
150°W
120°W
90°W
longitude
HADISST1 (1870−2000)
ERSST.v3 (1870−2000)
CM2.1 20C3M H1−5 (1870−2000)

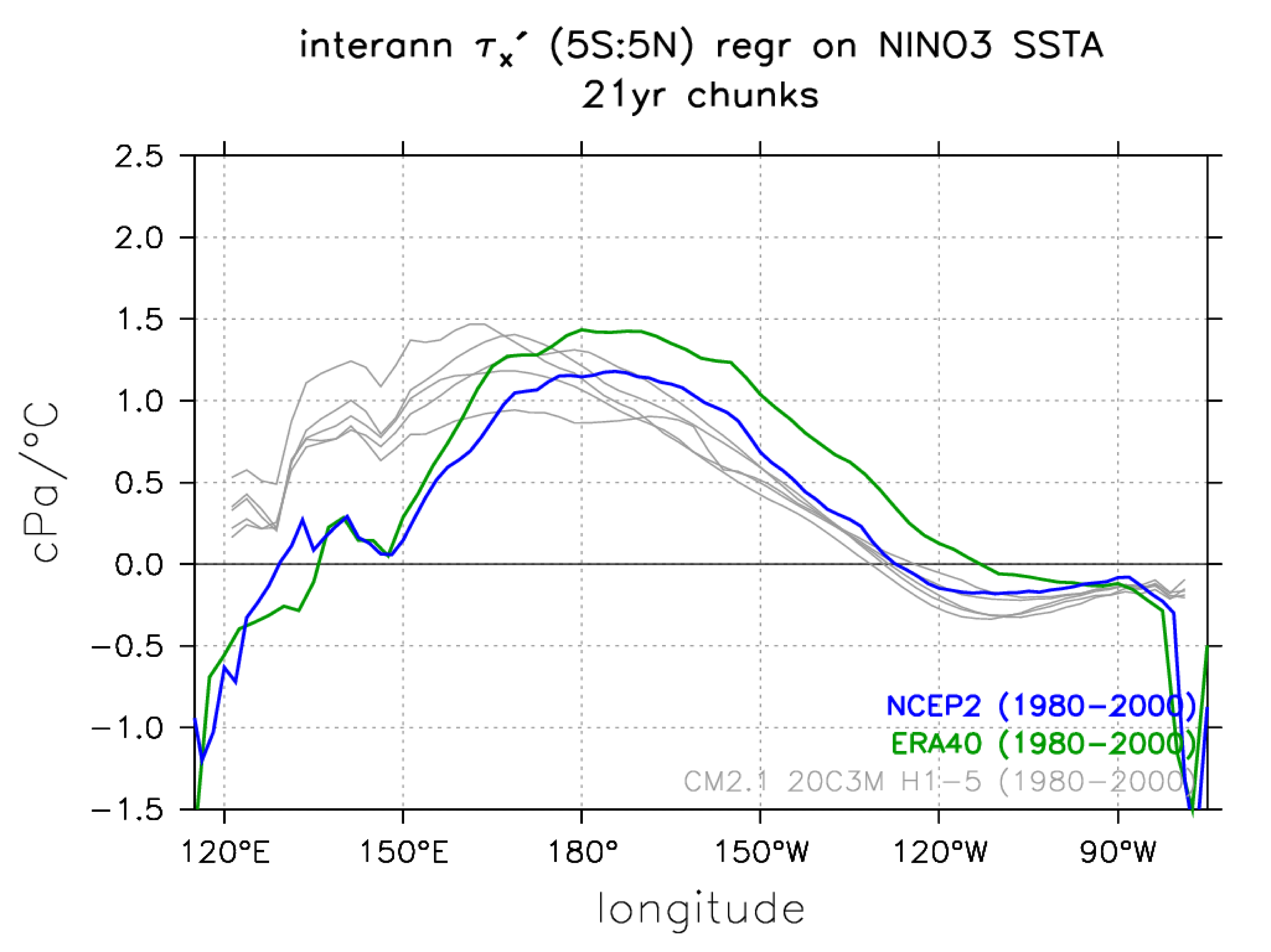

interann SSTA (5S:5N) regr on NINO3 SSTA
19yr chunks
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
°C/°C
120°E
150°E
180°
150°W
120°W
90°W
longitude
OISST.v2 (1982−2000)
NCEP2 (1982−2000)
ERA40 (1982−2000)
HADISST1 (1982−2000)
ERSST.v3 (1982−2000)
CM2.1 20C3M H1−5 (1982−2000)


interann SSTA (5S:5N) regr on NINO3 SSTA
100yr chunks
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
°C/°C
CM2.1 4xCO2 (0101−0380)
CM2.1 2xCO2 (0101−0280)
CM2.1 1990 (0021−0280)
CM2.1 1860 (0021−3980)
120°E
150°E
180°
150°W
120°W
90°W
longitude

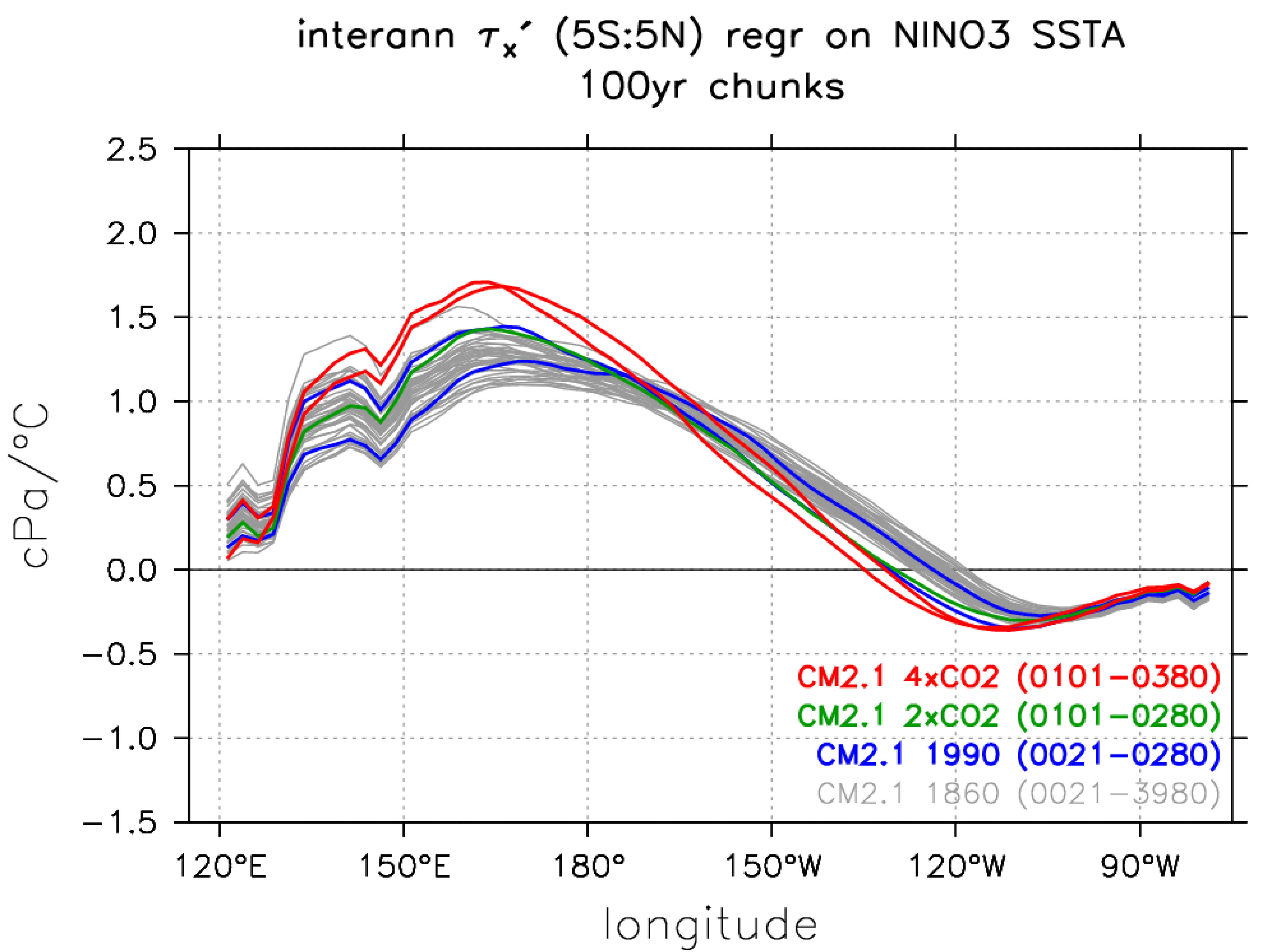


interann SSTA (5S:5N) regr on NINO3 SSTA
20yr chunks
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
°C/°C
120°E
150°E
180°
150°W
120°W
90°W
longitude
CM2.1 4xCO2 (0101−0380)
CM2.1 2xCO2 (0101−0280)
CM2.1 1990 (0021−0280)
CM2.1 1860 (0021−3980)

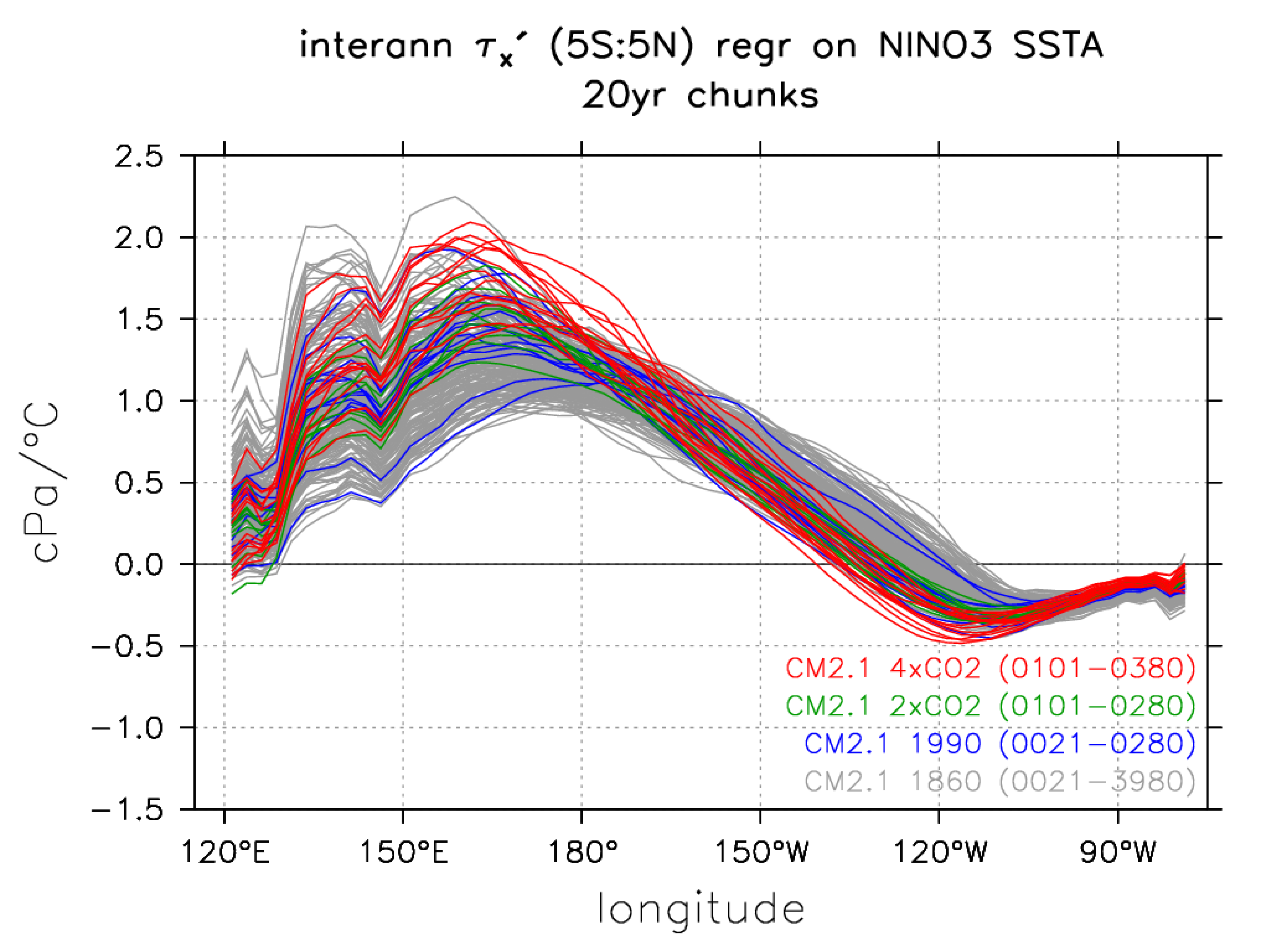
Equatorial zonal wind stress regressed on NINO3 SSTA



interann τ_x' (5S:5N) regr on NINO3 SSTA
21yr chunks
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
cPa/°C
120°E
150°E
180°
150°W
120°W
90°W
longitude
NCEP2 (1980−2000)
ERA40 (1980−2000)
CM2.1 20C3M H1−5 (1980−2000)

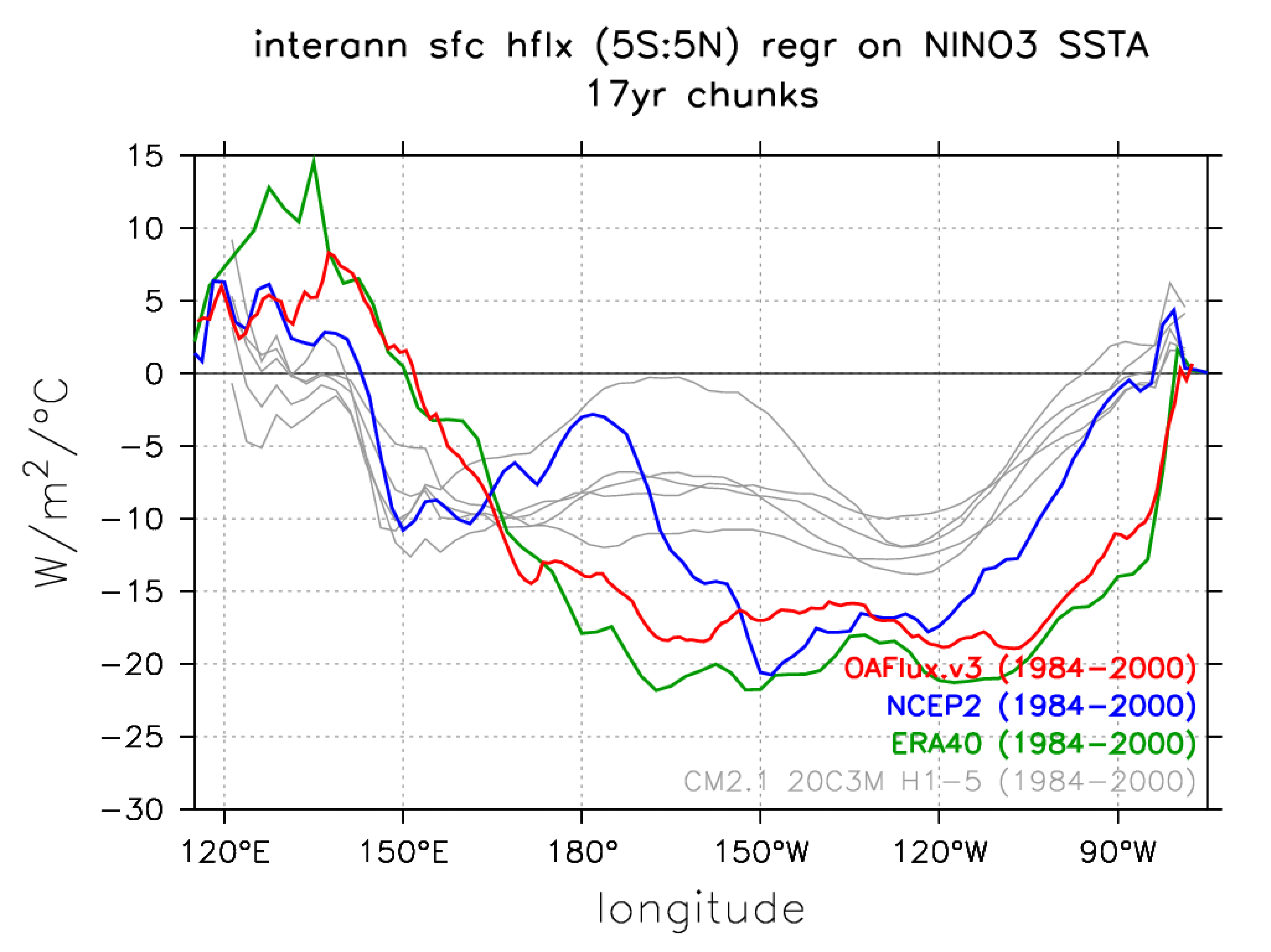


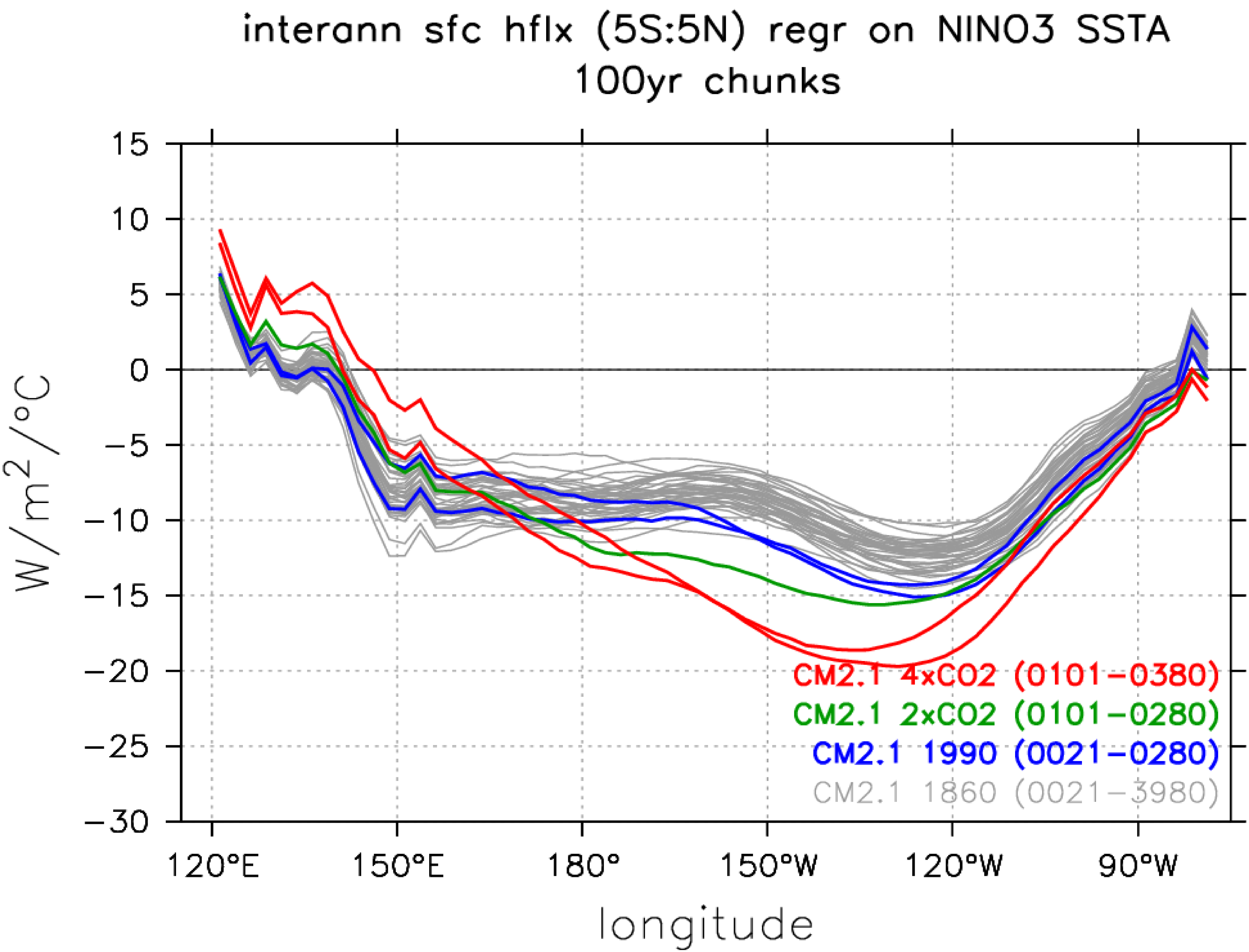
interann τ_x' (5S:5N) regr on NINO3 SSTA
100yr chunks
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
cPa/°C
120°E
150°E
180°
150°W
120°W
90°W
longitude
CM2.1 4xCO2 (0101−0380)
CM2.1 2xCO2 (0101−0280)
CM2.1 1990 (0021−0280)
CM2.1 1860 (0021−3980)

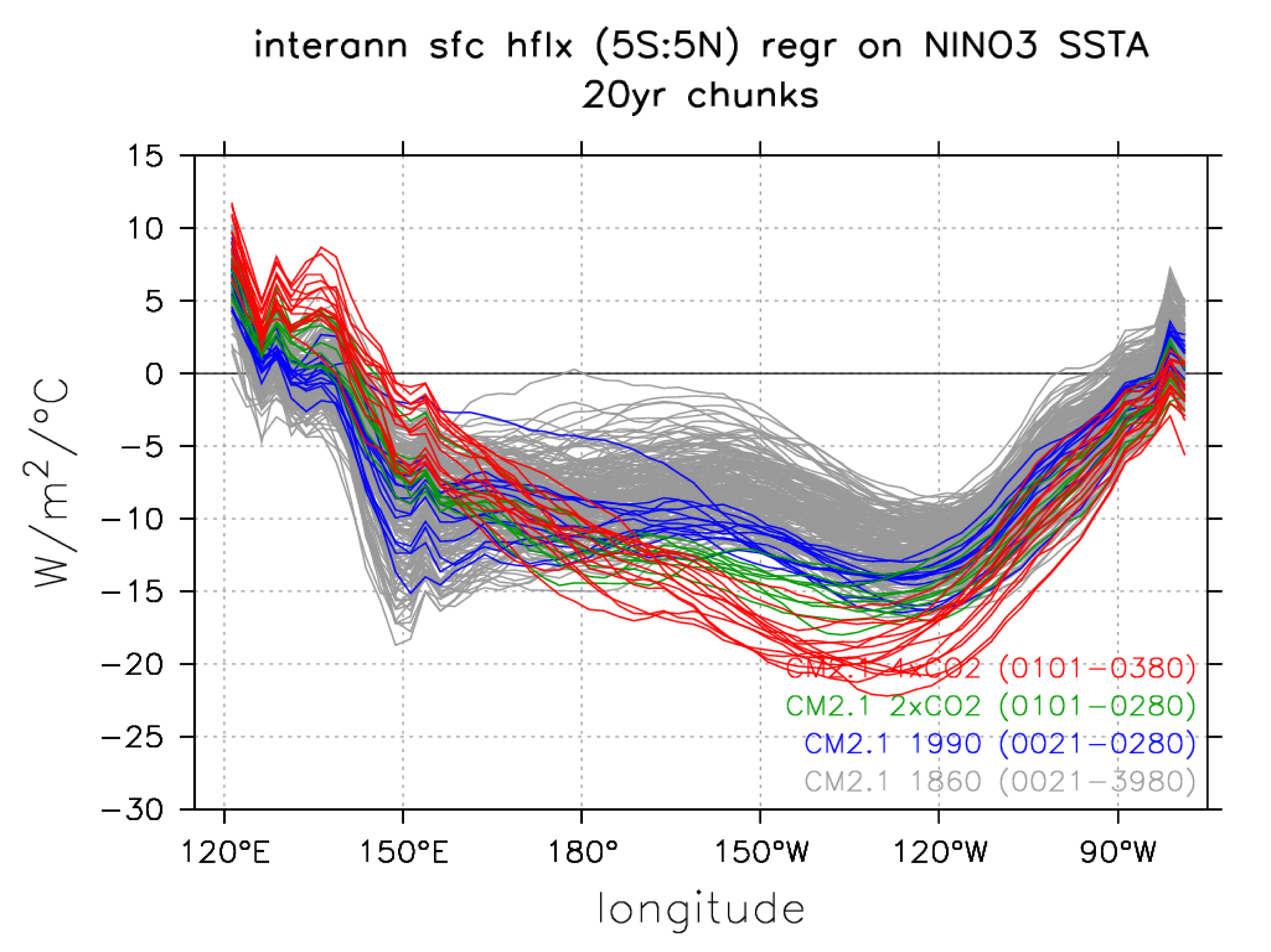


interann τ_x' (5S:5N) regr on NINO3 SSTA
20yr chunks
cPa/°C
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
120°E
150°E
180°
150°W
120°W
90°W
longitude
CM2.1 4xCO2 (0101−0380)
CM2.1 2xCO2 (0101−0280)
CM2.1 1990 (0021−0280)
CM2.1 1860 (0021−3980)

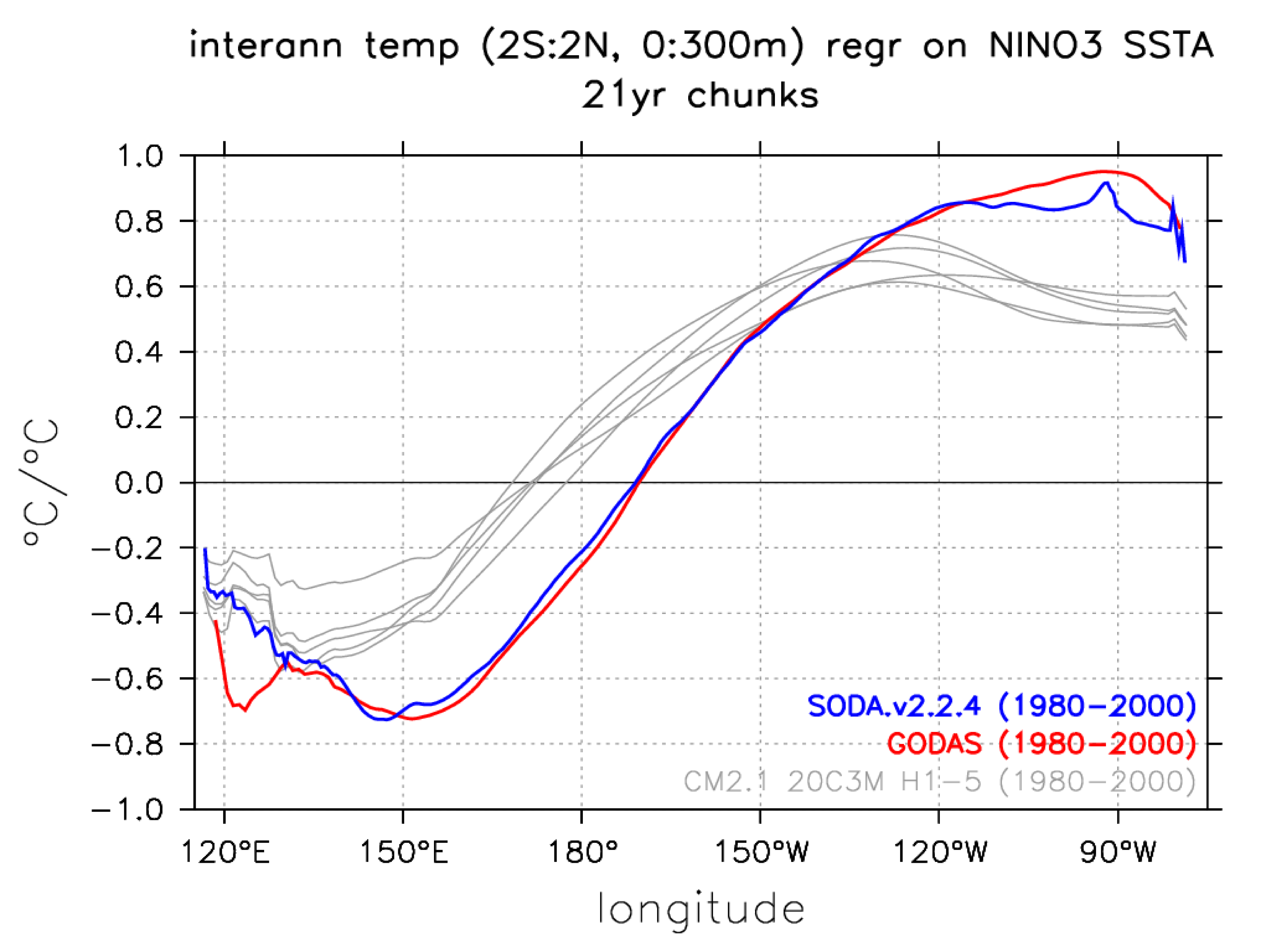
Equatorial net surface heat flux regressed on NINO3 SSTA

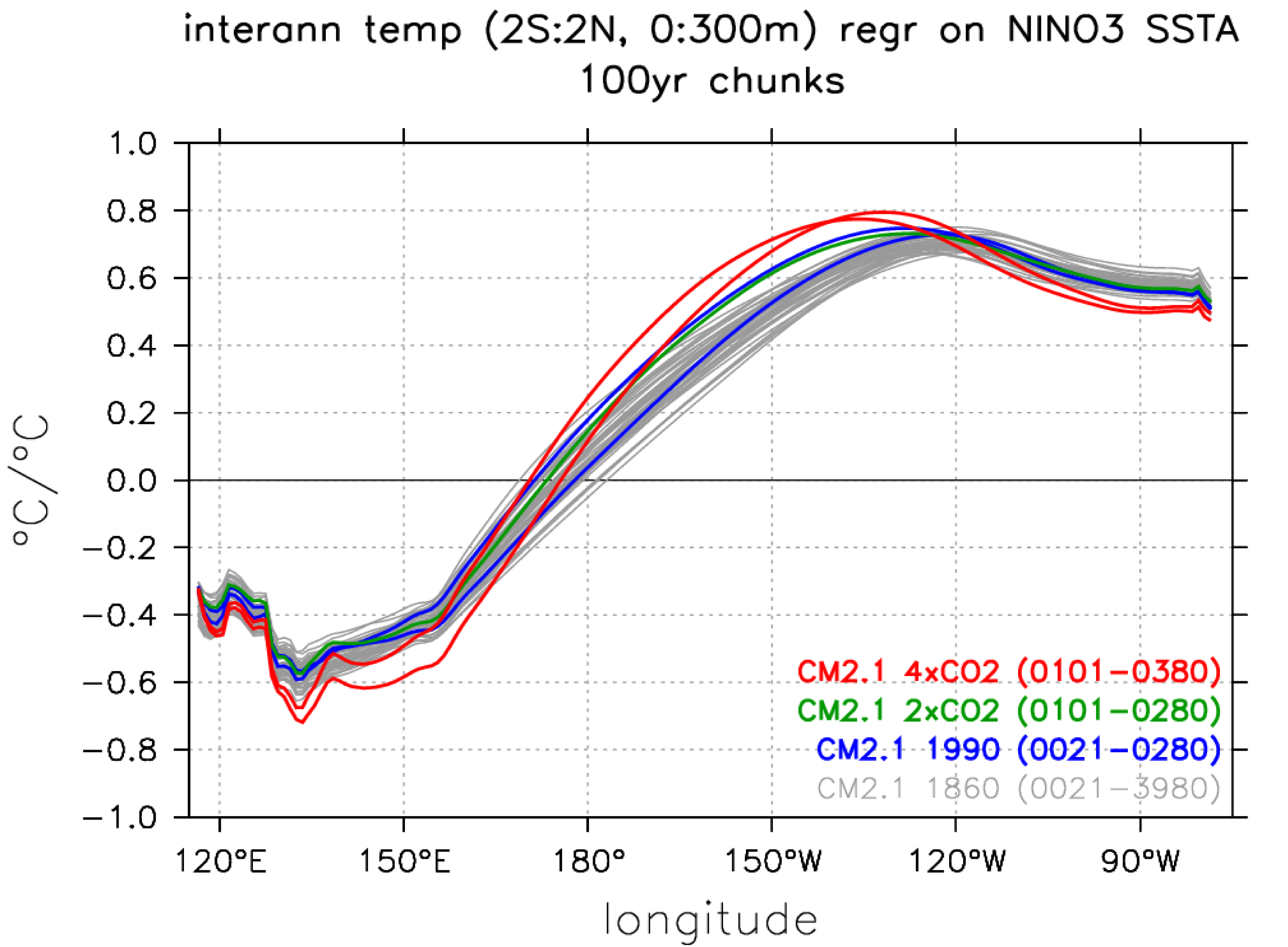

interann sfc hflx (5S:5N) regr on NINO3 SSTA
17yr chunks
15
10
5
0
−5
−10
−15
−20
−25
−30
W/m2/°C
120°E
150°E
180°
150°W
120°W
90°W
longitude
OAFlux.v3 (1984−2000)
NCEP2 (1984−2000)
ERA40 (1984−2000)
CM2.1 20C3M H1−5 (1984−2000)

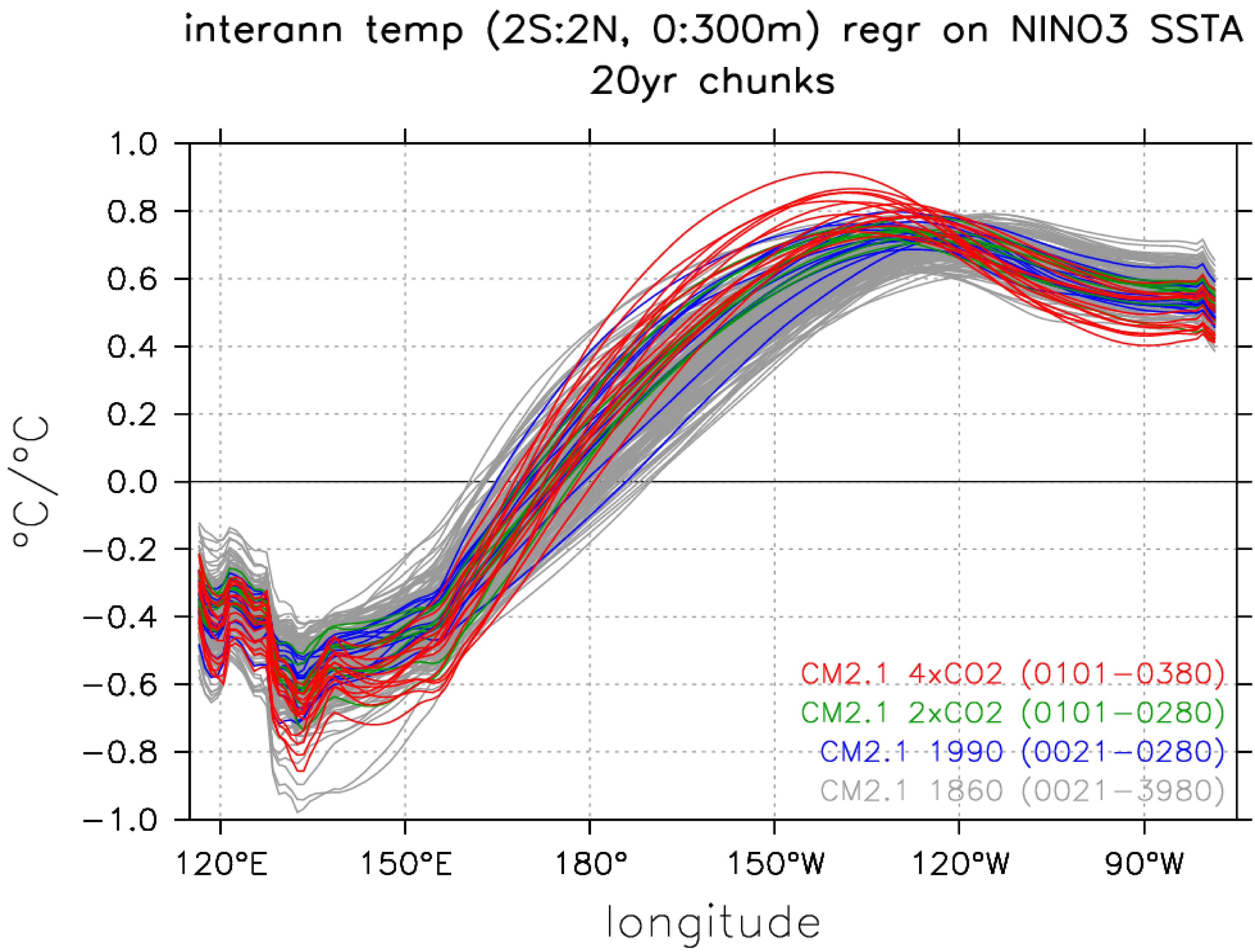

interann sfc hflx (5S:5N) regr on NINO3 SSTA
100yr chunks
15
10
5
0
−5
−10
−15
−20
−25
−30
W/m^2/°C
120°E
150°E
180°
150°W
120°W
90°W
longitude
CM2.1 4xCO2 (0101−0380)
CM2.1 2xCO2 (0101−0280)
CM2.1 1990 (0021−0280)
CM2.1 1860 (0021−3980)


interann sfc hflx (5S:5N) regr on NINO3 SSTA
20yr chunks
15
10
5
0
−5
−10
−15
−20
−25
−30
W/m2/°C
120°E
150°E
180°
150°W
120°W
90°W
longitude
CM2.1 4xCO2 (0101−0380)
CM2.1 2xCO2 (0101−0280)
CM2.1 1990 (0021−0280)
CM2.1 1860 (0021−3980)

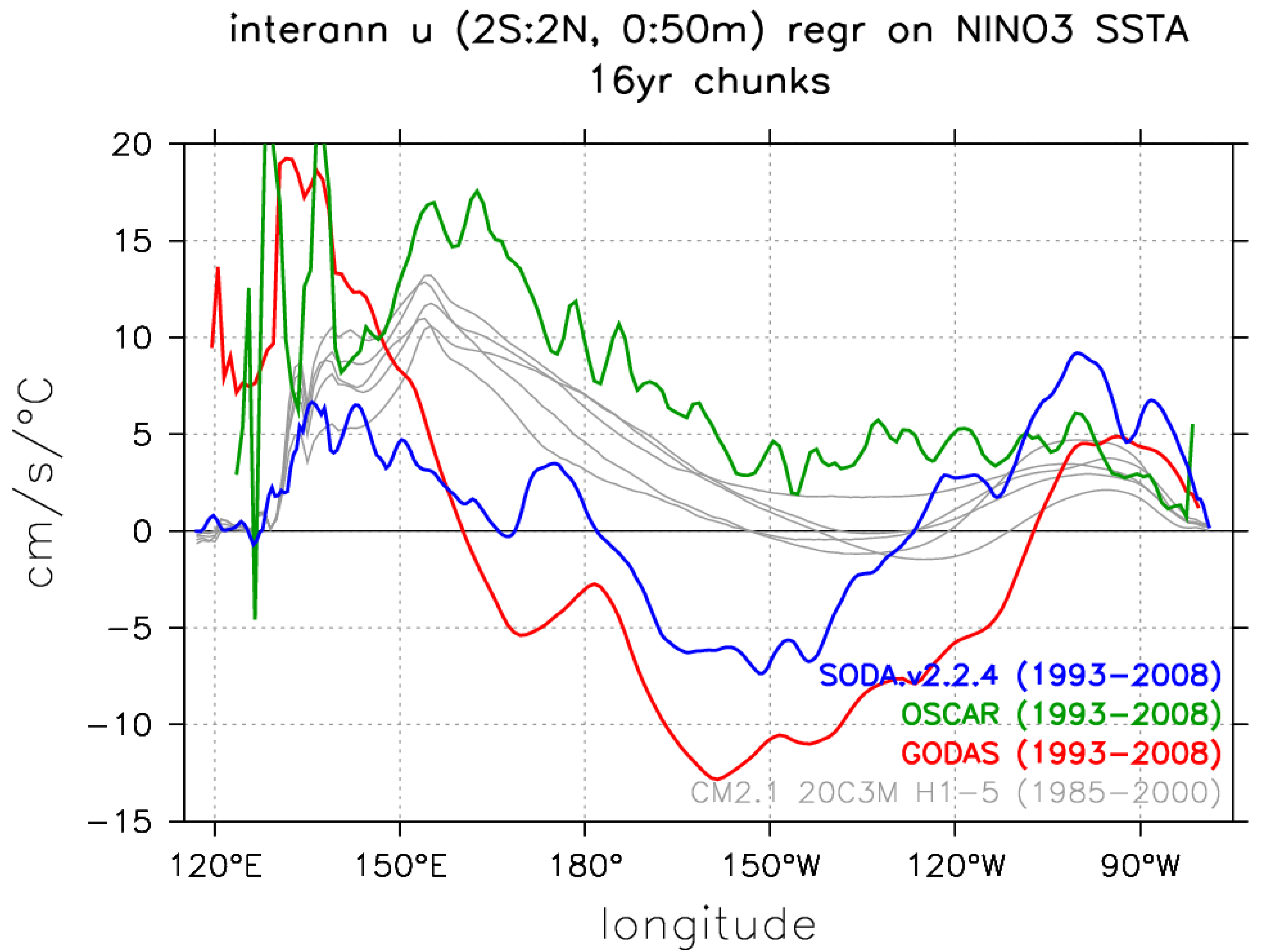
Equatorial 300m heat content regressed on NINO3 SSTA

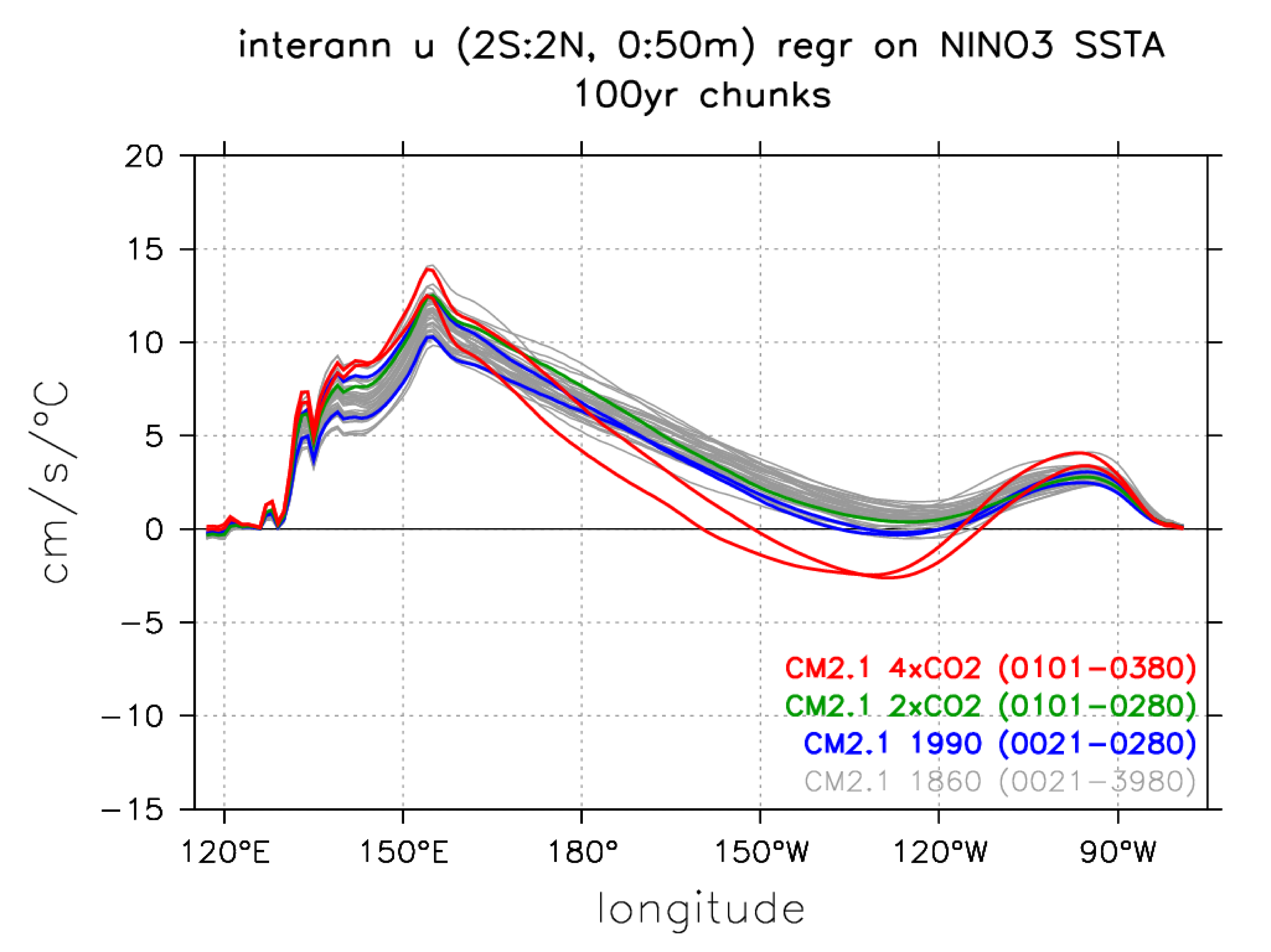

interann temp (2S:2N, 0:300m) regr on NINO3 SSTA
21yr chunks
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
−1.0
°C/°C
120°E
150°E
180°
150°W
120°W
90°W
longitude
SODA.v2.2.4 (1980−2000)
GODAS (1980−2000)
CM2.1 20C3M H1−5 (1980−2000)

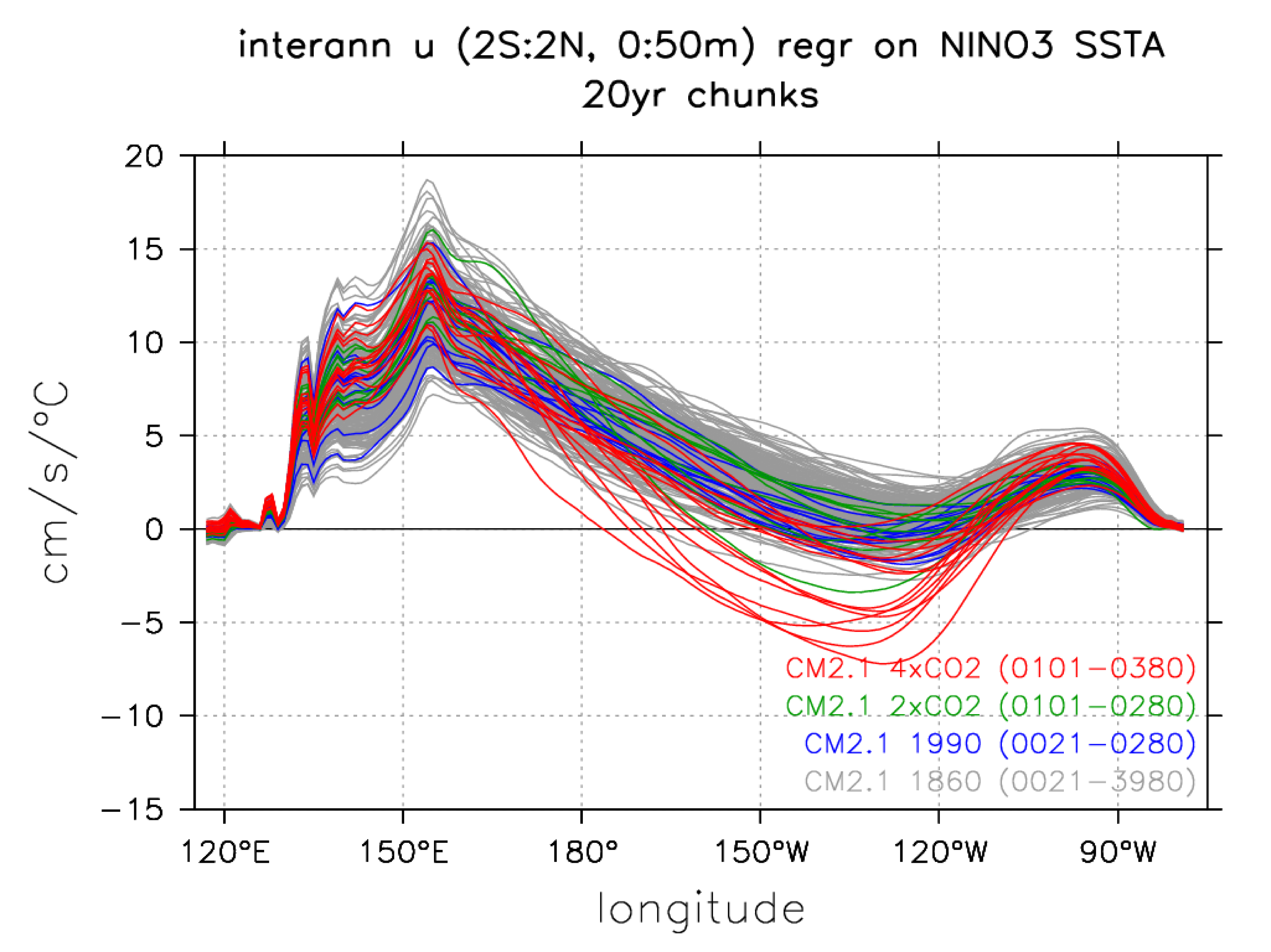

interann temp (2S:2N, 0:300m) regr on NINO3 SSTA
100yr chunks
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
−1.0
°C/°C
CM2.1 4xCO2 (0101−0380)
CM2.1 2xCO2 (0101−0280)
CM2.1 1990 (0021−0280)
CM2.1 1860 (0021−3980)
120°E
150°E
180°
150°W
120°W
90°W
longitude


interann temp (2S:2N, 0:300m) regr on NINO3 SSTA
20yr chunks
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
−1.0
°C/°C
120°E
150°E
180°
150°W
120°W
90°W
longitude
CM2.1 4xCO2 (0101−0380)
CM2.1 2xCO2 (0101−0280)
CM2.1 1990 (0021−0280)
CM2.1 1860 (0021−3980)

Equatorial surface zonal current regressed on NINO3 SSTA


interann u (2S:2N, 0:50m) regr on NINO3 SSTA
16yr chunks
cm/s/°C
20
15
10
5
0
−5
−10
−15
120°E
150°E
180°
150°W
120°W
90°W
longitude
SODA.v2.2.4 (1993−2008)
OSCAR (1993−2008)
GODAS (1993−2008)
CM2.1 20C3M H1−5 (1985−2000)


interann u (2S:2N, 0:50m) regr on NINO3 SSTA
100yr chunks
20
15
10
5
0
−5
−10
−15
cm/s/°C
120°E
150°E
180°
150°W
120°W
90°W
longitude
CM2.1 4xCO2 (0101−0380)
CM2.1 2xCO2 (0101−0280)
CM2.1 1990 (0021−0280)
CM2.1 1860 (0021−3980)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CM2.1 1860 (0021−3980)

Summary of GFDL model results

1. 4000yr run of pre-industrial CM2.1 shows strong **interdecadal & intercentennial modulation of ENSO**. AR5 models do too.

2. **Large uncertainties** for *some* ENSO metrics (e.g. spectra, stddevs) diagnosed from short time series. Regression (feedback) diagnostics are more robust.

3. For sub-century ENSO records, **model biases and intermodel differences** are much easier to distinguish than **impacts of CO2**. But the CM2.1 **ENSO optimum** near 2xCO2 is interesting.

4. **Intrinsic modulation might largely determine** the ENSO behavior we'll actually experience over our lifetimes.

5. **Both the ocean & atmosphere** model components still exert influence over the ENSO behavior, perhaps indirectly through the mean state.

Challenges & opportunities for ENSO research

1. Improve quality/utility of historical & paleo records

a. Obs of feedbacks are critical
  surface stress & heat flux; ocean currents, upwelling, mixing

b. Maintain the present ENSO observing system, with redundancy
  TAO, QSCAT

c. Uncertainty estimates -- particularly for reanalyses
  changing obs/analysis system

d. Obs intercomparisons
  e.g. of wind stress / heat flux products

e. Paleo synthesis/reanalysis

f. Provide obs in modeler-friendly form
  access: OPeNDAP (DODS) aggregations, NetCDF via FTP
  lon/lat gridded, monthly-means
  complete & correct metadata (grid info, units)
  references, contact for questions & bug reports

g. Community inventory of all ENSO-relevant obs products
  keep up-to-date
  advocate on behalf of modelers

Challenges & opportunities for ENSO research

2. Improve GCM simulations

a. Model intercomparisons
    shared problems, outlier behaviors (good & bad)

b. Identify/rank the “seeds & amplifiers” of model biases

c. Improve subgrid processes, coupled feedbacks
    atmos convection & clouds
    ocean vertical mixing & solar penetration

d. Auto-diagnostics (with summary metrics)

e. Auto-optimization (explicit cost function)
    constrained by other model aims: MOC, ice, carbon, MJO, hurricanes

f. In-house "obs data librarian" at modeling centers

g. Bigger computers
    longer runs, larger ensembles, higher-resolution
    more detail & comprehensiveness

h. Accelerate spinup, esp. for ESMs

Challenges & opportunities for ENSO research

3. Analyses & experiments

a. How has ENSO behaved in the past?
- could address with perfect-model studies
- what fraction of real-world ENSO attractor have we observed?
- representative/informative about rest of attractor?
- how to extrapolate full attractor, using models? and future changes in attractor?

b. Identify ensemble size / run length needed for detection
- depends on both model & metric
- what can we extrapolate from short runs/forecasts?

c. How do model biases affect:
- ENSO's sensitivity to climate change?
- ENSO teleconnections, and *their* sensitivity to climate change?

d. Extrapolating ENSO sensitivities from biased models to real world
- d(sensitivity) / d(metric) ?
- d(reliability) / d(metric) ?
- perfect-model and model-model interprediction

e. Prioritize useful metrics
- best constraints on simulations? (model tuning)
- best discriminants of ENSO response to climate change?

f. Paleo tests: bigger signal, but foggier "obs"
- test paleoreconstructions using pseudo-proxies

g. Increasing data volume: need parallel analysis tools

Challenges & opportunities for ENSO research

4. Understanding & theory

a. How to model the ENSO sampling problem?

- parameterize distributions of metrics

b. Map ENSO theory onto GCM fields & processes

- features shifted in space/time/seasonality
- continuous/parameterized processes
- diagnostic model hierarchy: fit to CGCMs
  - aim for efficient (but accurate) "knowledge-compression"
  - Poisson & ARMA models, LIMs & NLIMs
  - simple conceptual dynamical models
  - intermediate models
  - hybrid GCMs
  - atmos-only, ocean-only, nudged GCMs
- useful predictions of which knobs to turn?
- side-effects of those adjustments, e.g. on mean state?

c. Fundamental predictability

- sources/limits of predictability
- irreducible components of uncertainty
  - intrinsic variability/chaos
  - unpredictable forcings (volcanoes), and their leverage on ENSO

d. What sets maximum ENSO intensity?

- are we near an ENSO climate-optimum?

e. Changes in ENSO diversity?

- may first need to better sample & understand past diversity

Challenges & opportunities for ENSO research

5. Predictions & projections

a. ENSO CO2-optimum?

could help explain diversity of model sensitivities

b. How to improve predictions?

model: reduce biases
ensemble size & representativeness (internal variab)
initialization: more accurate, and consistent with model dynamics (to reduce shock)
- how best to correct for biases (a-priori corrections to dynamical equations?)

forcing scenario & components
- missing feedbacks/forcings (aerosols, land cover)

c. Communication to stakeholders

2-way street: what aspects of ENSO are most important to understand/simulate/predict?
- (e.g., do extremes matter most?)

small research community, rapidly growing list of stakeholders