Developing the next version of the Community Earth System Model: Aerosol effects using CMIP5 and CMIP6 forcing data.

w/ Jean-François Lamarque, Andrew Gettelman, Richard Neale, Cecile Hannay, and many others

NCAR/CGD

WGNE, Exeter UK, October 12, 2017

Overview

- CESM2: New Physics
- Coupled model behavior with CMIP5 and CMIP6 emissions data

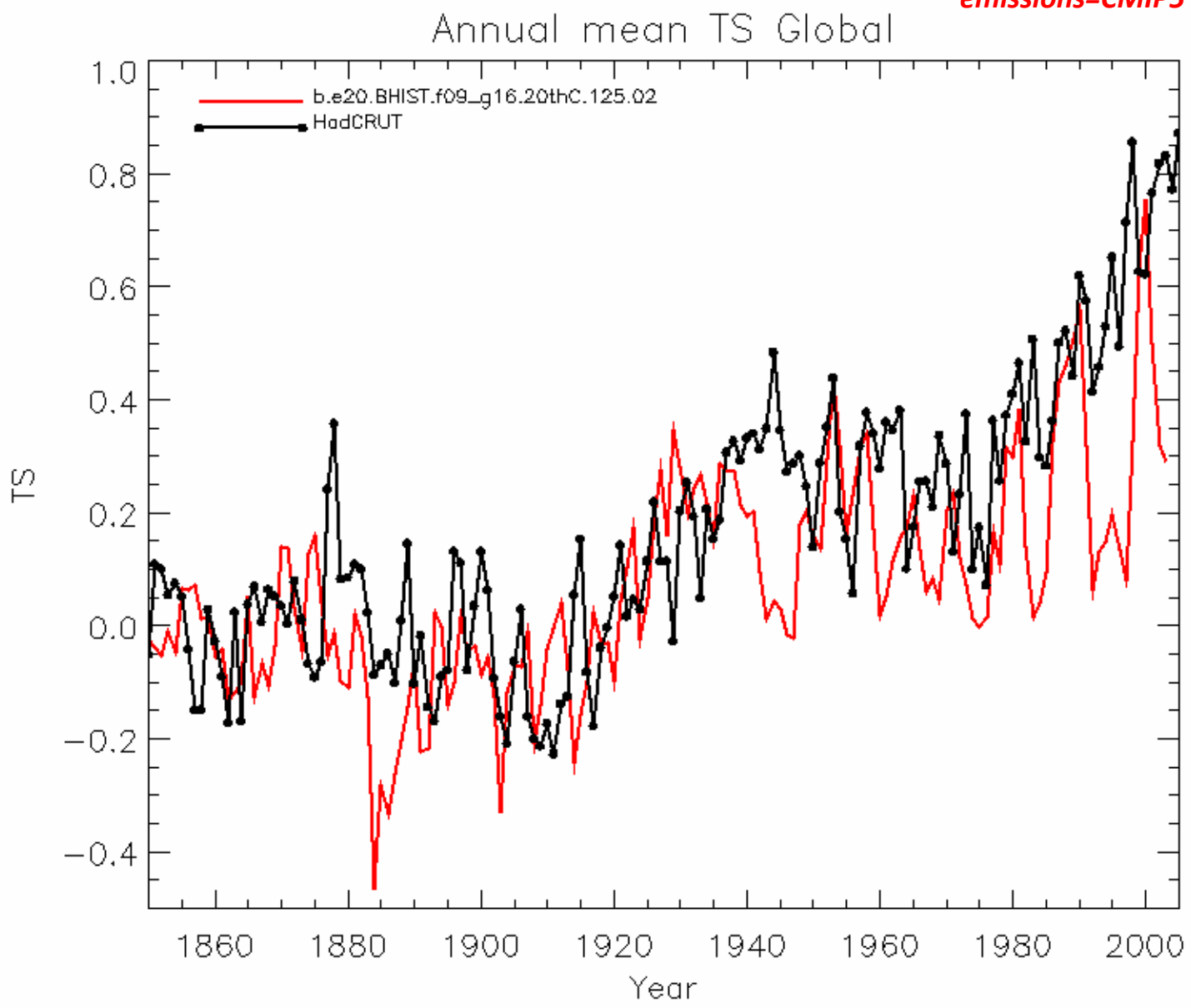
Evolution of CAM Model Physics

Model	CAM3 CCSM3	CAM4 CCSM4	CAM5 CESM1.0	CAM6 CESM2
Release	**Jun 2004**	**Apr 2010**	**Jun 2010**	**Sometime 2017**
PBL	Holtslag-Boville (1993)	Holtslag-Bovillle (1993)	Bretherton et al (2009)	CLUBB
Orographic form drag			Richter et al. (2010) "TMS"	Beljaars et al.2003
GW drag	McFarlane (1987)	McFarlane (1987)	McFarlane (1987) (non-orographic sources for WACCM)	Anisotropic/Low-level nonlinearities
Shallow Convection	Hack (1994)	Hack (1994)	Park et al. (2009)	CLUBB
Deep Convection	Zhang-McFarlane (1995)	Neale et al. (2008)	Neale et al. (2008)	Neale et al. (2008) Re-tuning
Microphysics	Rasch-Kristjansson (1998)	Rasch-Kristjansson (1998)	Morrison-Gettelman (2008)	Morrison-Gettelman v2 (2014)
Macrophysics	Rasch-Kristjansson (1998); Zhang et al (2003)	Rasch-Kristjansson (1998); Zhang et al (2003)	Park et al. (2011); Zhang et al (2003)	CLUBB
Radiation	Collins et al. (2001)	Collins et al. (2001)	Iacono et al. (2008)	Iacono et al. (2008)
Aerosols	Bulk Aerosol Model	Bulk Aerosol Model BAM	Modal Aerosol Model (MAM3, Ghan et al., 2011)	Modal Aerosol Model (MAM4, Liu et al., 2016)

= switch parameterization

= significant retuning/modification

Exp. 125 (Model ca. 3/2017; *emissions=CMIP5*



As of March 2017 development version CESM2 looked pretty good

- *Overall Taylor scores better than CESM1(LENS)*
- *Good El Niño*
- *Reasonable MJO*

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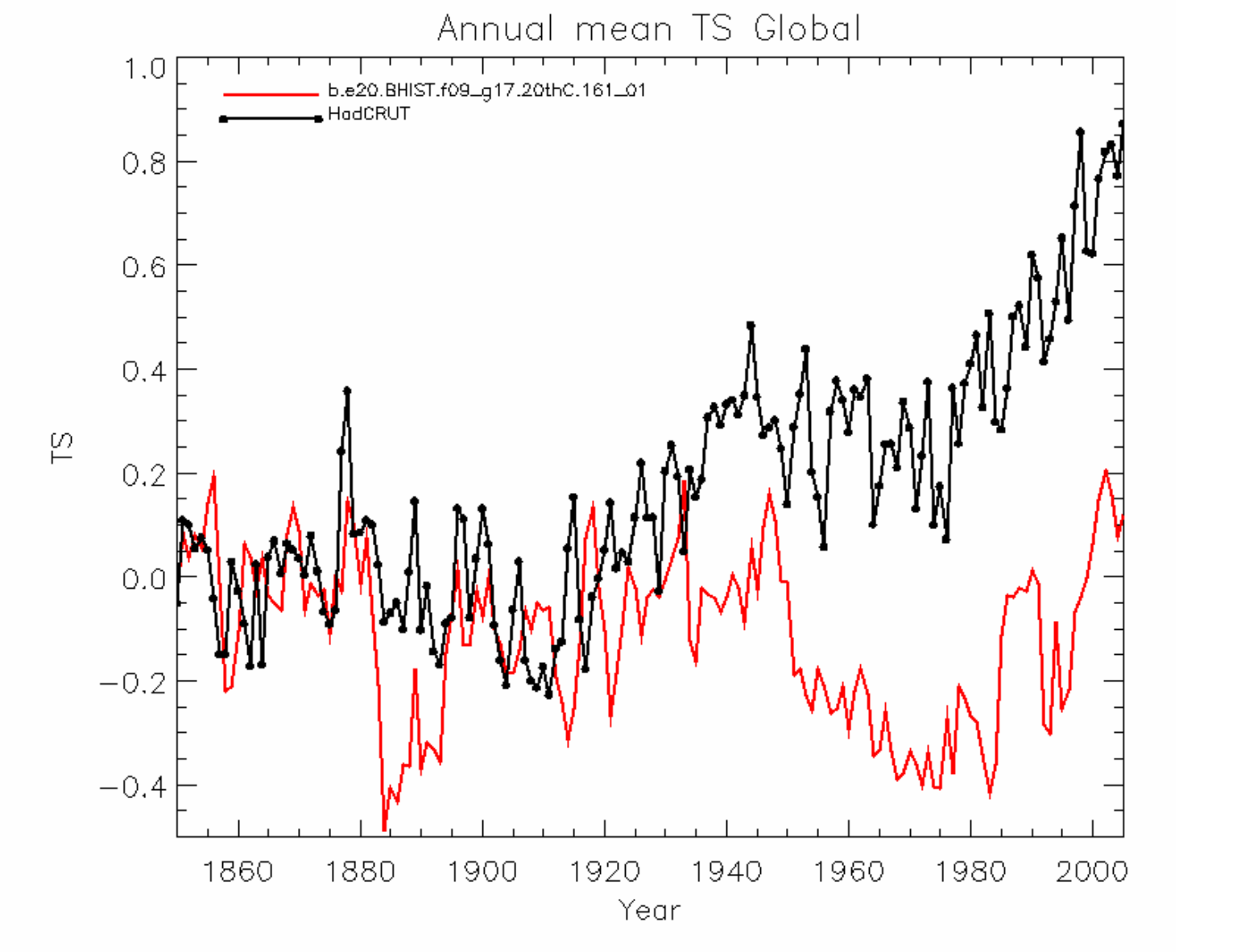
Next Steps:

- *Further development of land model*
- *Introduction of CMIP6 emissions*

Exp. 161 (Model ca. 5/2017;
emissions=CMIP6

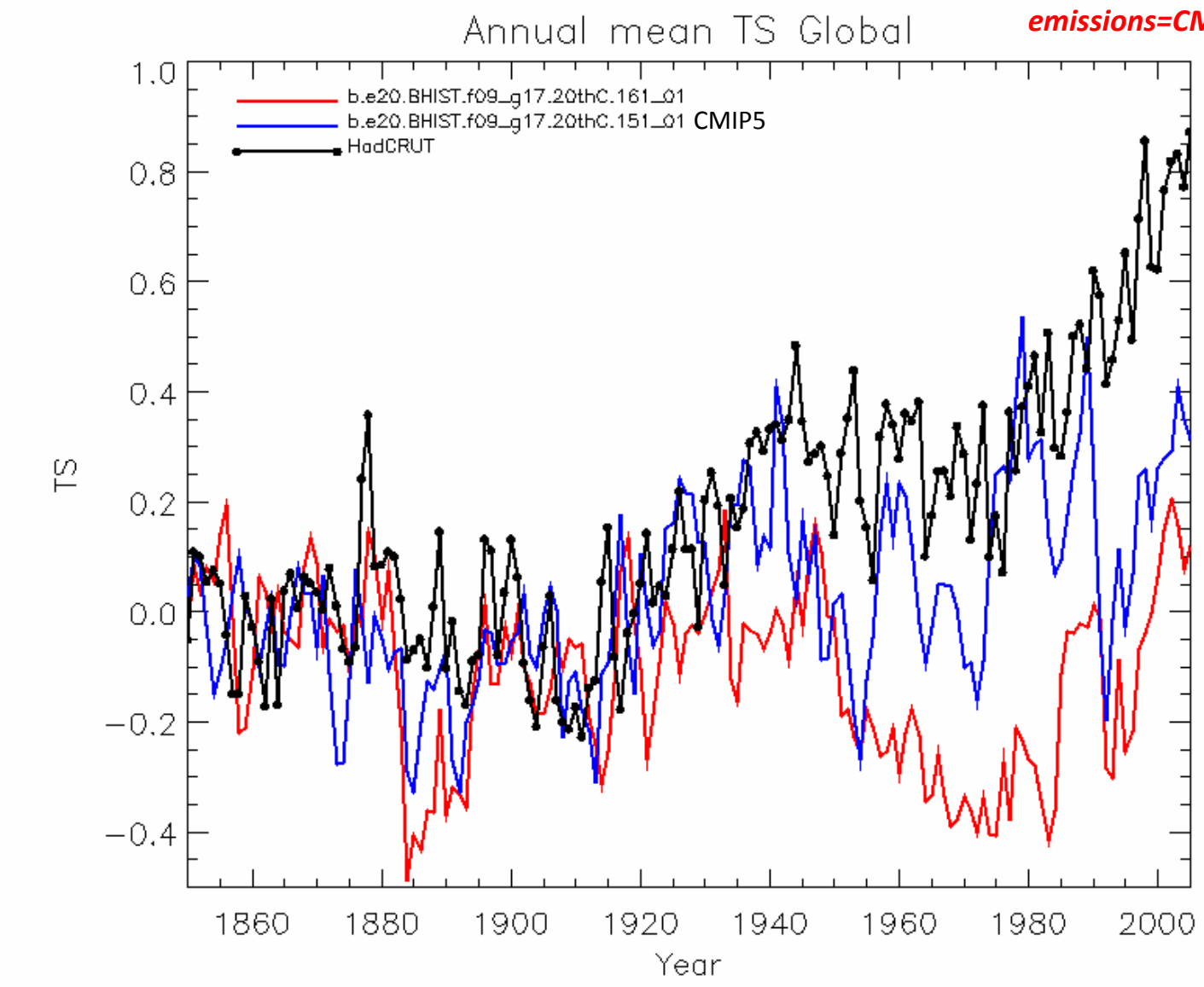


What happened???

- Dust tuning and land model changes led to significantly colder model. ***(these changes are not considered optional)***
- CMIP6 emissions ????

Exp. 151 (Model ca. 5/2017; *emissions=CMIP5*

Exp. 161 (Model ca. 5/2017; *emissions=CMIP6*



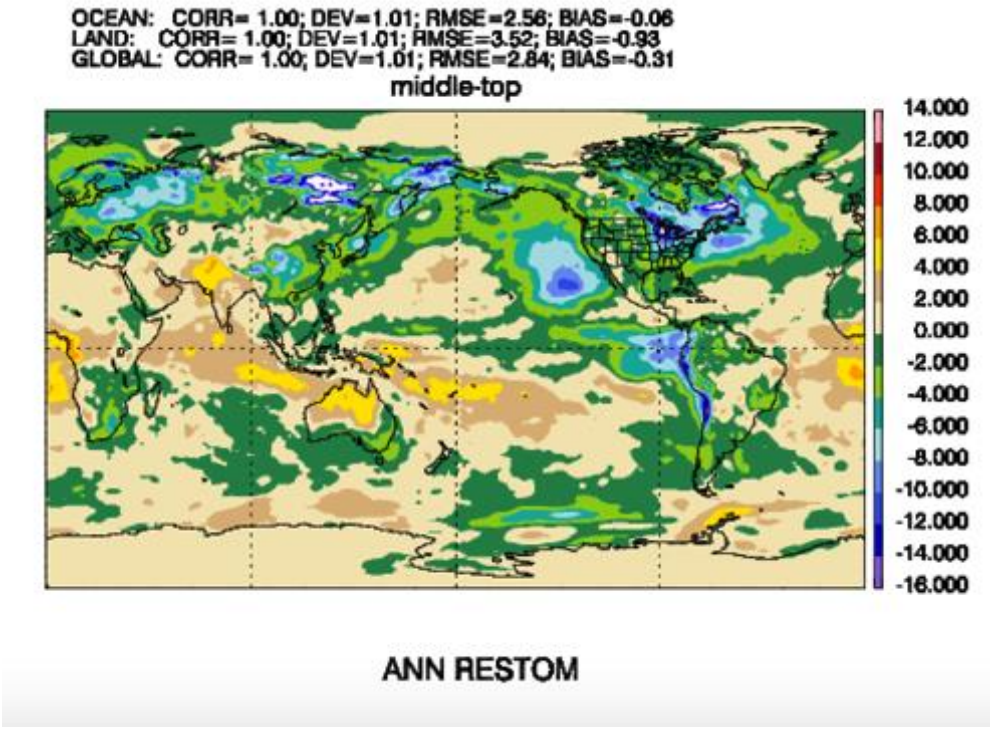
What happened???

- CMIP6 emissions contribute, but may not be the whole story

RESTOM* Change in 20thC run with CMIP6 emissions

PD *PI*

161 (1951-1970) – (1851-1870)



*RESTOM = Net SW – Net LW at “Top-of-model”

What else can we do???

- Patterns of RESTOM change suggestive of AIE

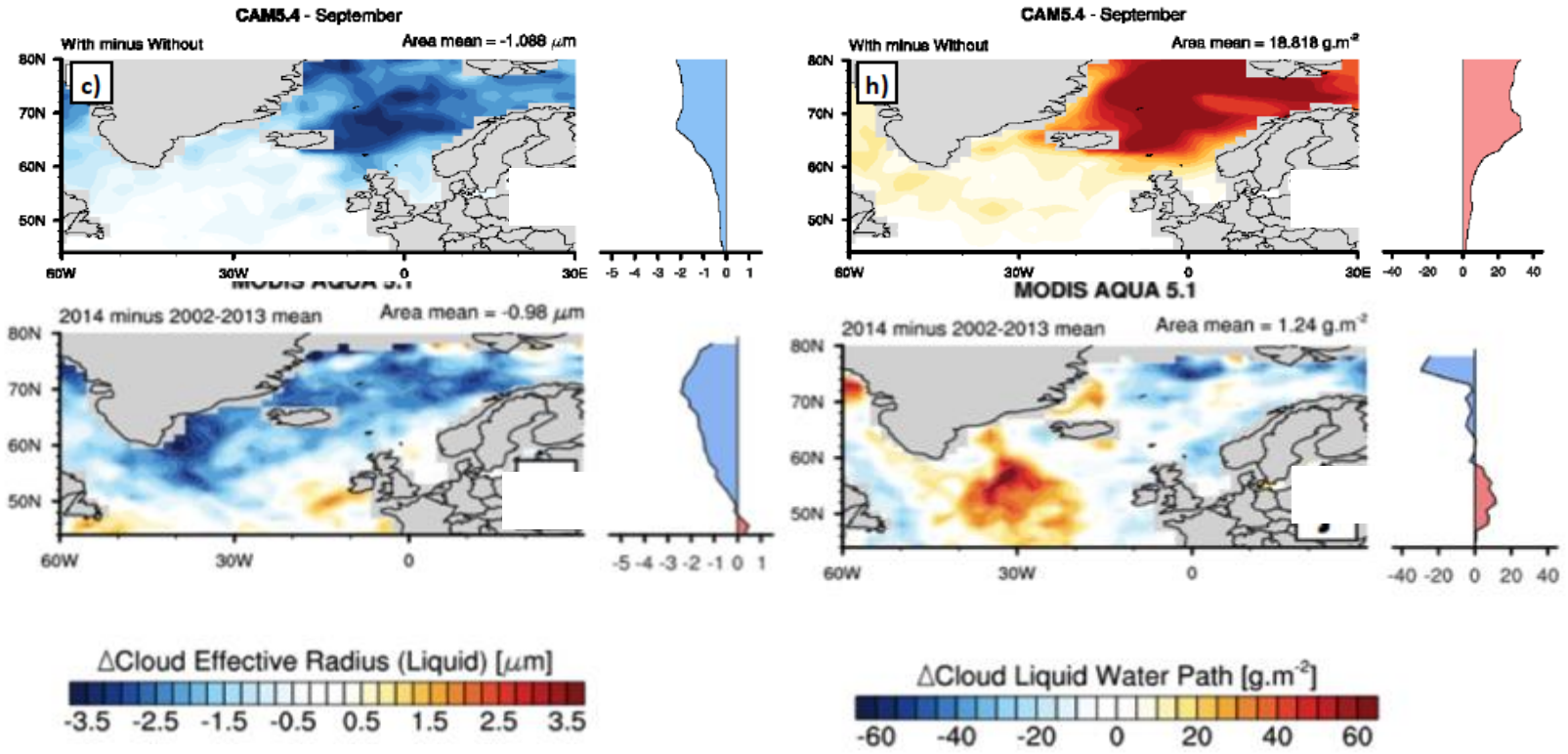
- ***2nd aerosol indirect effect (lifetime effect)***: more droplets➔ slower autoconversion➔thicker longer-lived clouds
  - Poorly constrained. Some obs (e.g. in volcanic plumes) suggest is not very big

Using Volcanic Plume to study Aersol-Cloud Interaction

CAM5.4 and CAM5.5 show big increases in cloud water with elevated aerosols.
Here: an example from the Holuhraun eruption in Iceland in 2014.
Smaller drops are seen, but no increase in cloud water from Satellites (MODIS)

Drop Size

Cloud Liquid Water Path



from A. Gettelman

Anomalies of Drop Size and Cloud Water for October 2014 from long term mean.

Malavelle et al 2017, Nature

2nd indirect effect (thicker clouds from reduced autoconversion) seems to large in CAM

$$Au = kL^a N^b$$

Au=autoconversion rate
L=cloud liquid (kg/kg)
N=droplet number (#/kg)

Seifert&Beheng*: a=4, b=-2*
Khairoudtinov&Kogan (KK)*; a=2.67, b=-1.79*

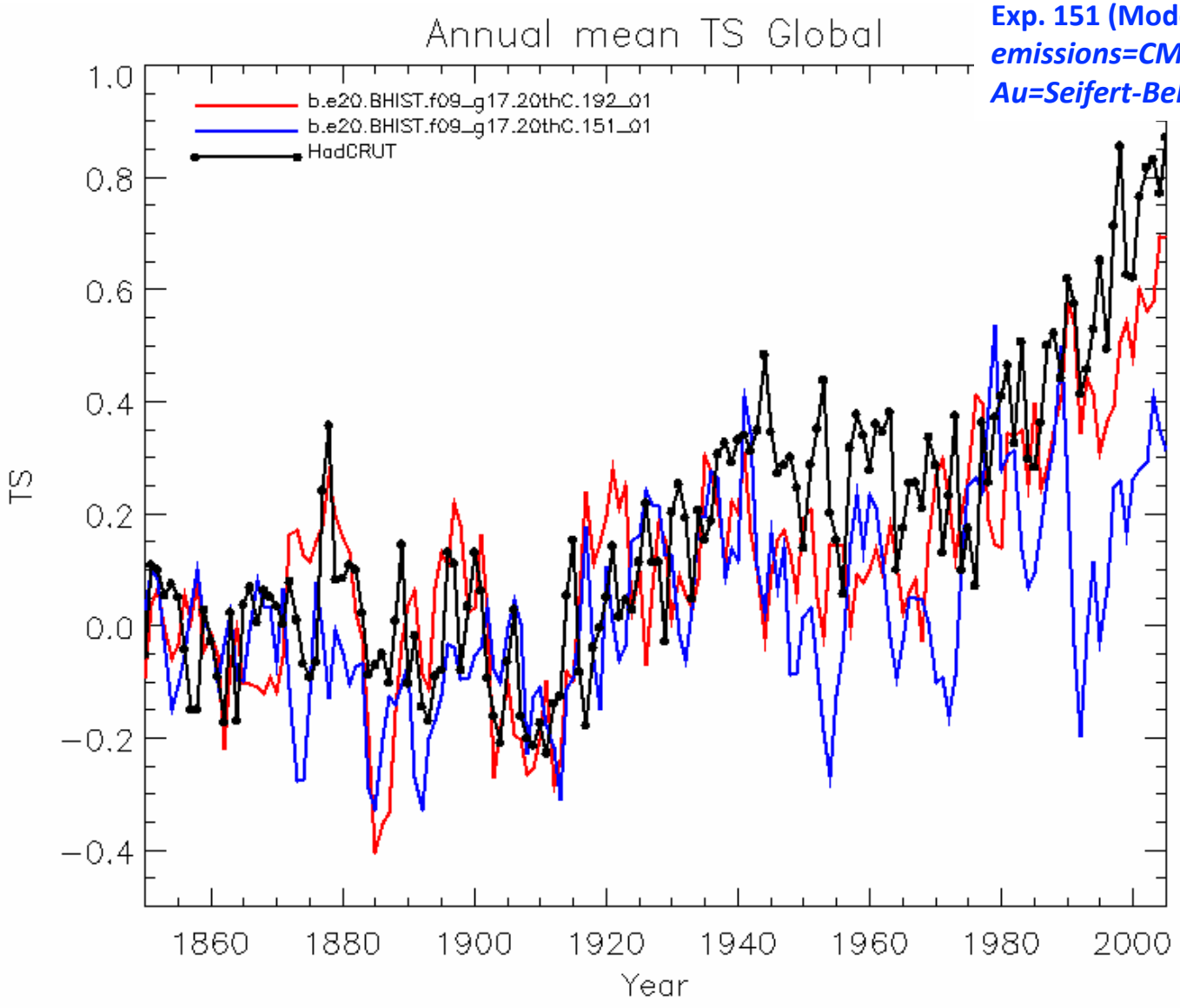
- ***R. Wood***: *b* in KK could be as weak as -0.9.
- compromise *b*=-1.1.

Other tunable numbers (KK)
$k=0.01k_0$, $k=0.02k_0$ (k_0=1350)
"relative dispersion" can affect *N* entering *Au* calculation

Reducing droplet dependence in autoconversion improves simulation (w/resp HadCRUT)

Exp. 192 (Model ca. 9/2017;
emissions=CMIP5
$Au = kL^a N^b$; with $b = -1.1$

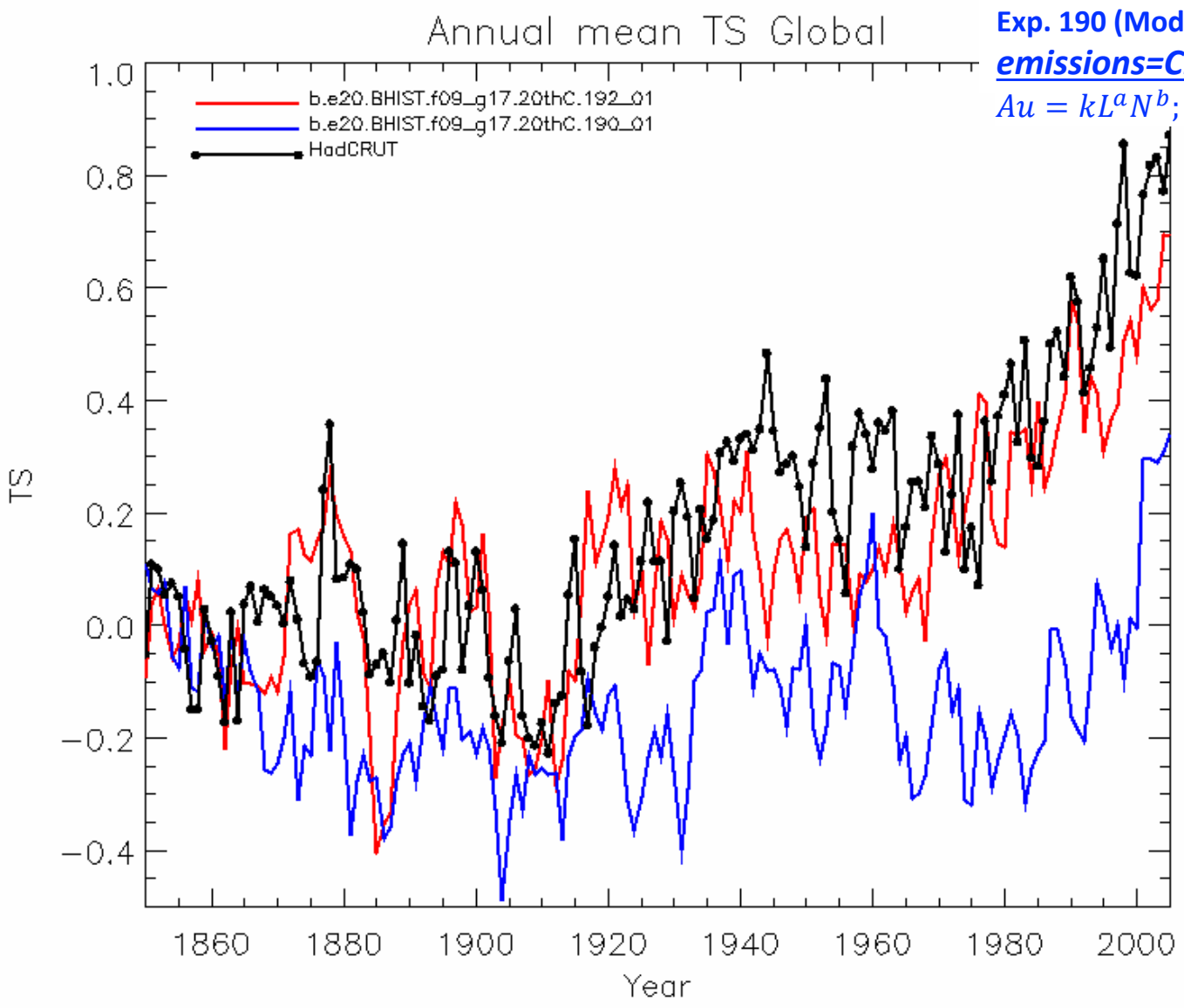
Exp. 151 (Model ca. 5/2017;
emissions=CMIP5
Au=Seifert-Beheng



… but simulation forced with CMIP6 emissions still doesn't warm enough (w/resp HadCRUT)

Exp. 192 (Model ca. 9/2017; *emissions=CMIP5*
$Au = kL^a N^b$; with $b = -1.1$

Exp. 190 (Model ca. 9/2017; *emissions=CMIP6*
$Au = kL^a N^b$; with $b = -1.1$



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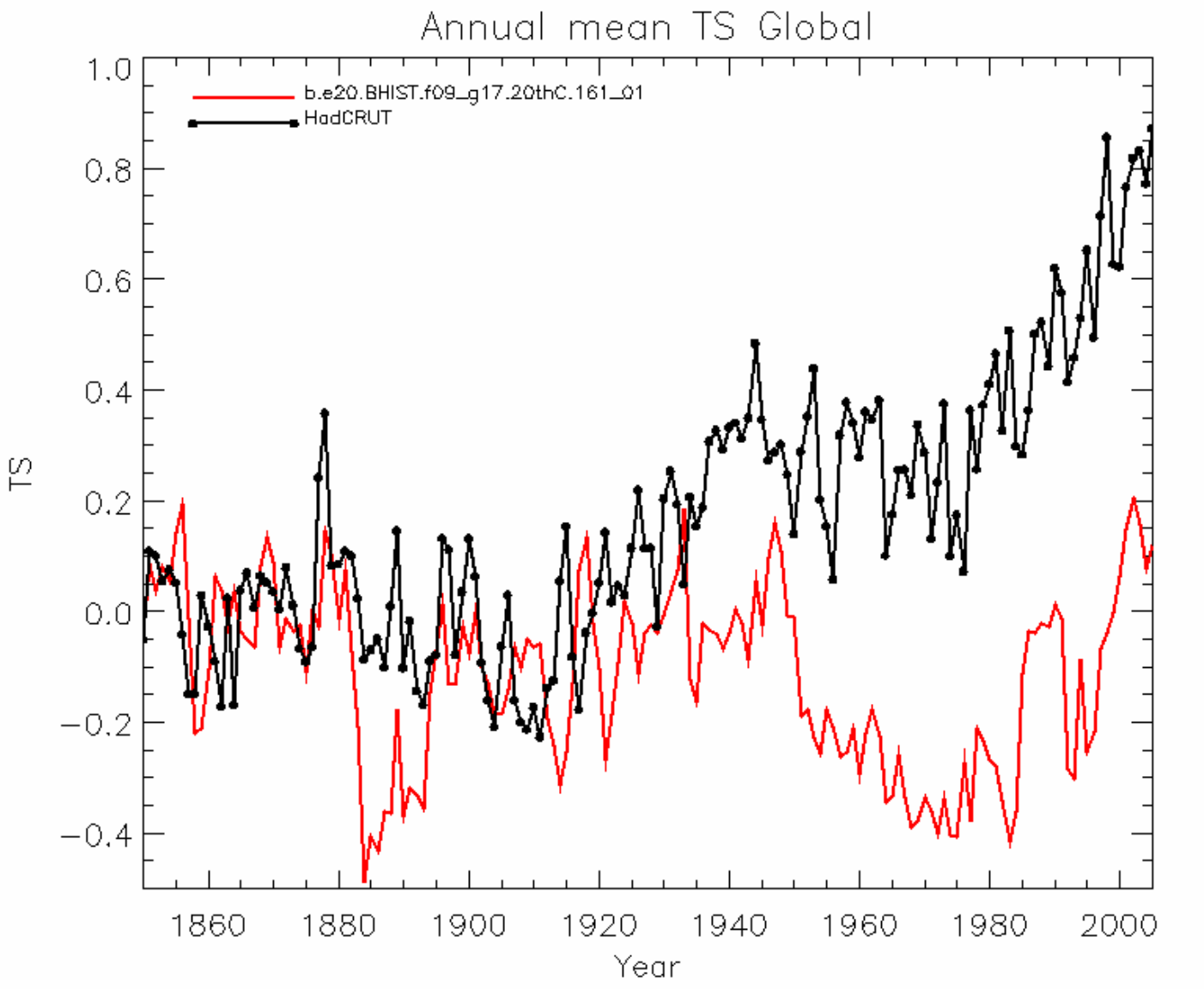

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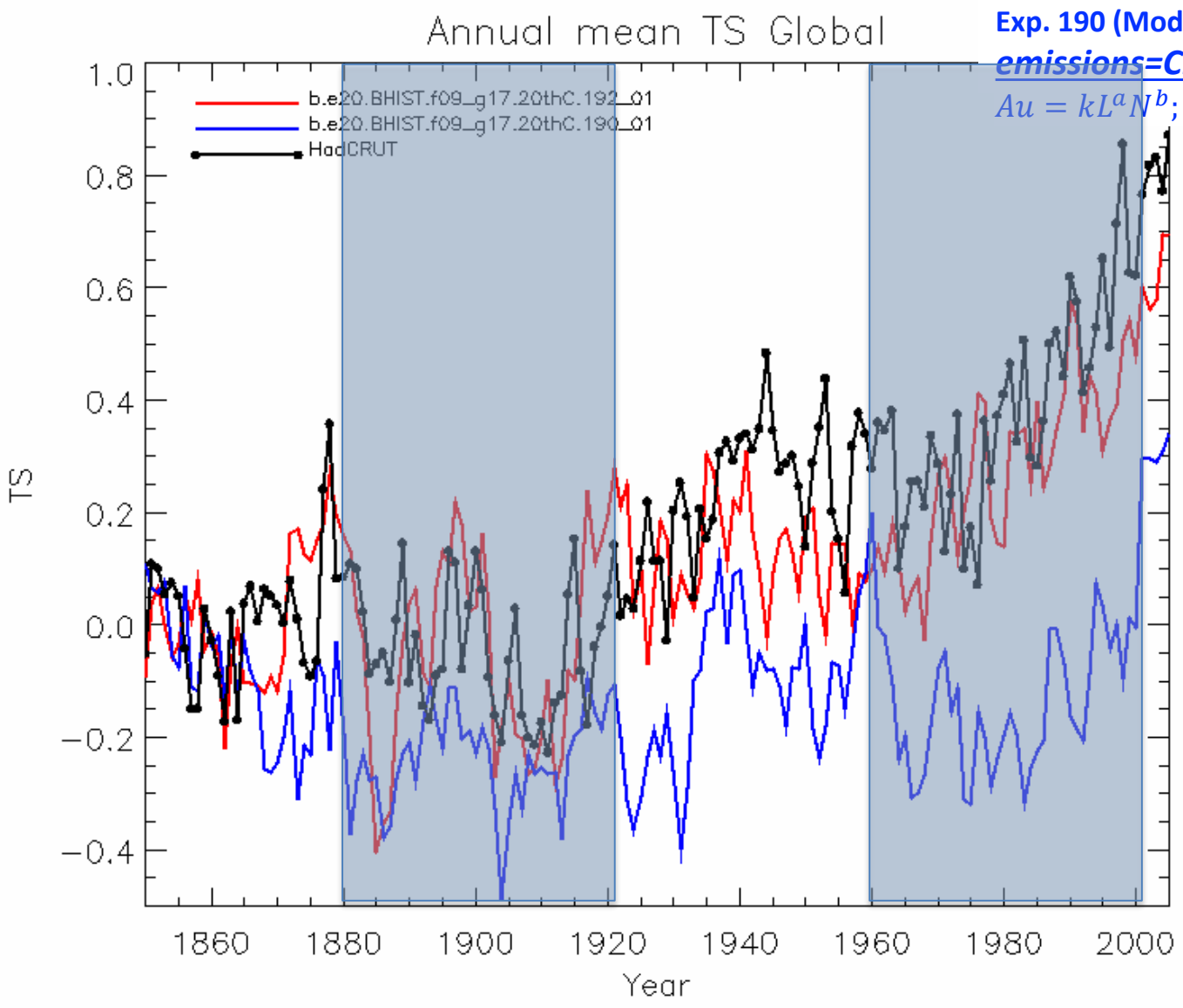
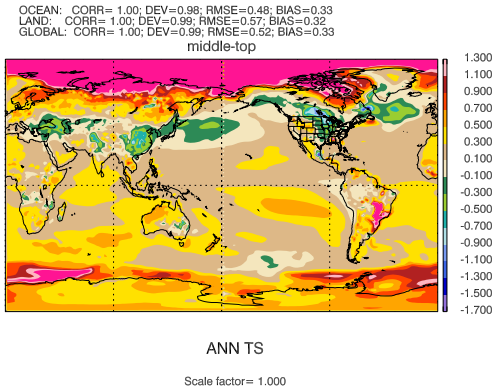
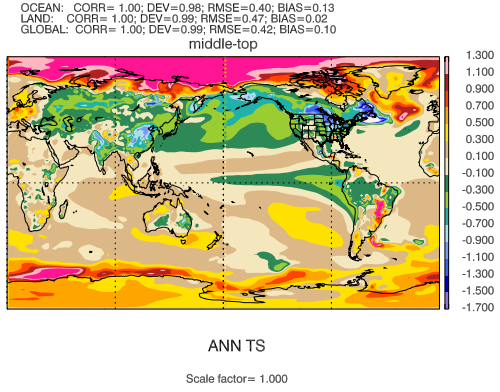


Warming 1880-1920 to 1960-2000

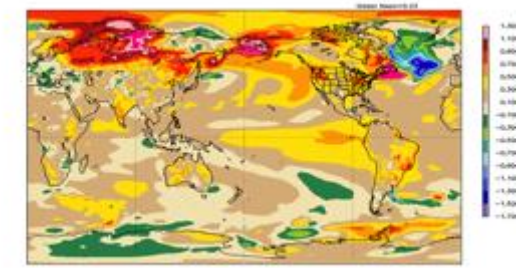
192(CMIP5)



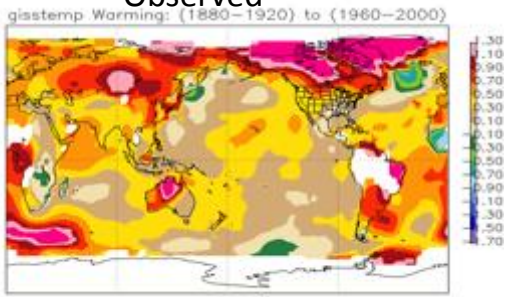
190(CMIP6)



192 minus 190



"Observed"

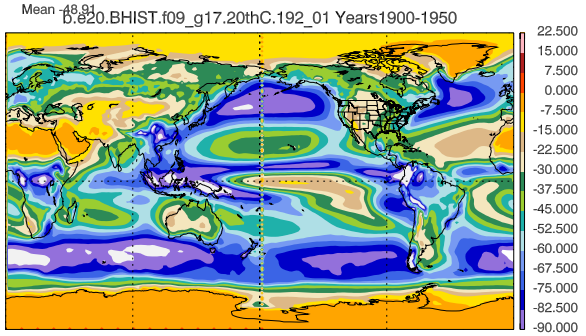


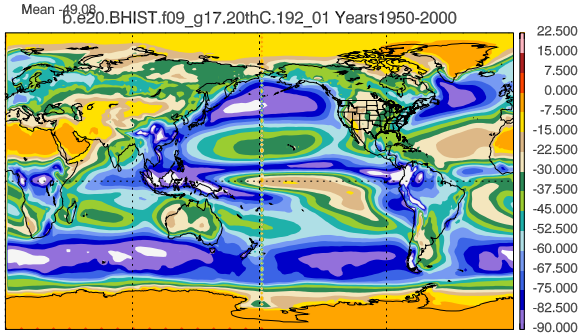
SWCF

1900-1950

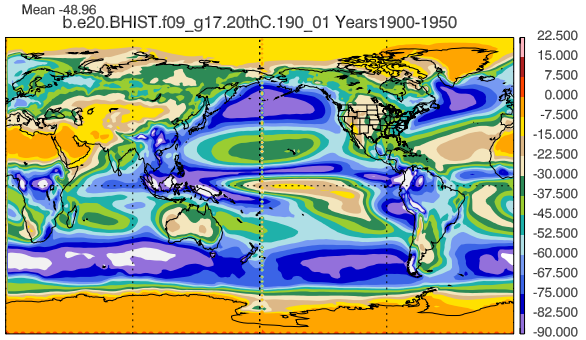
1950-2000

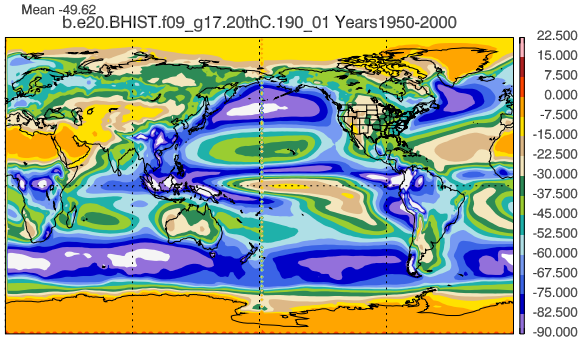
CMIP5



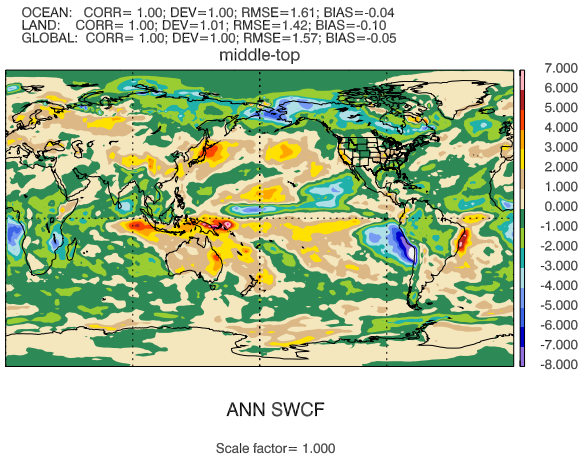


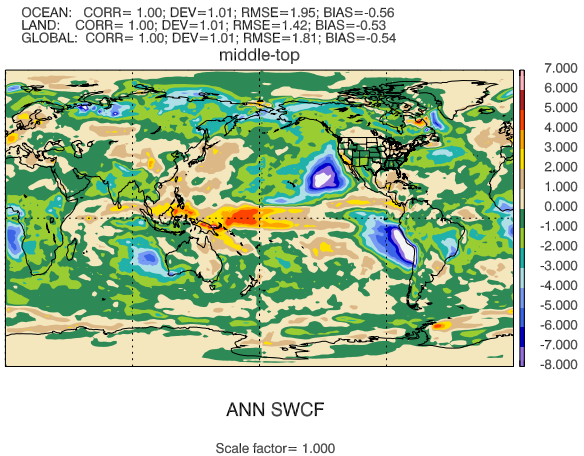
CMIP6





CMIP6 – CMIP5

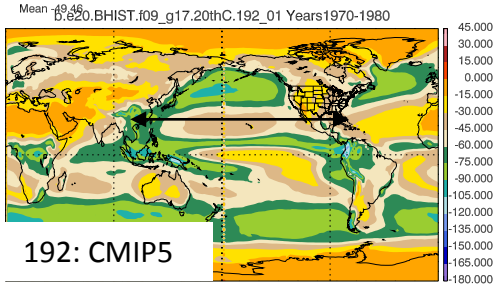




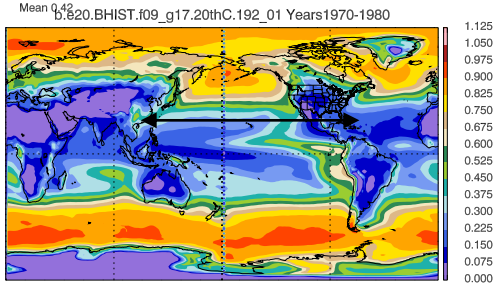
Differences in forcing CMIP5 -> CMIP6

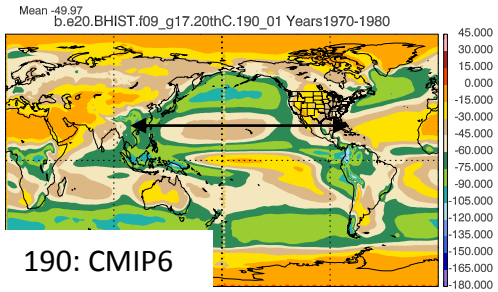
Period=1970-1980

Approximate location of cross-sections on following slide

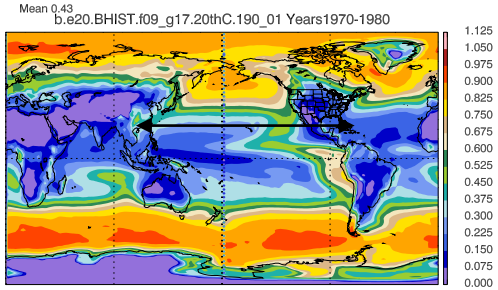


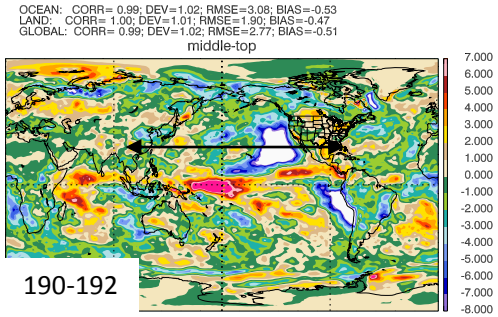
192: CMIP5



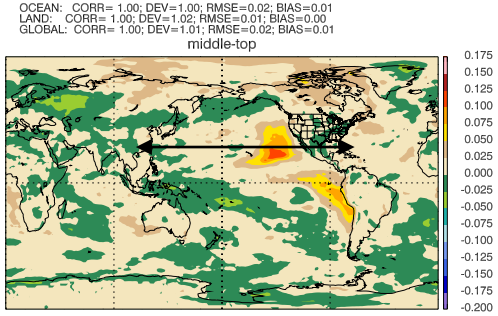


190: CMIP6





190-192

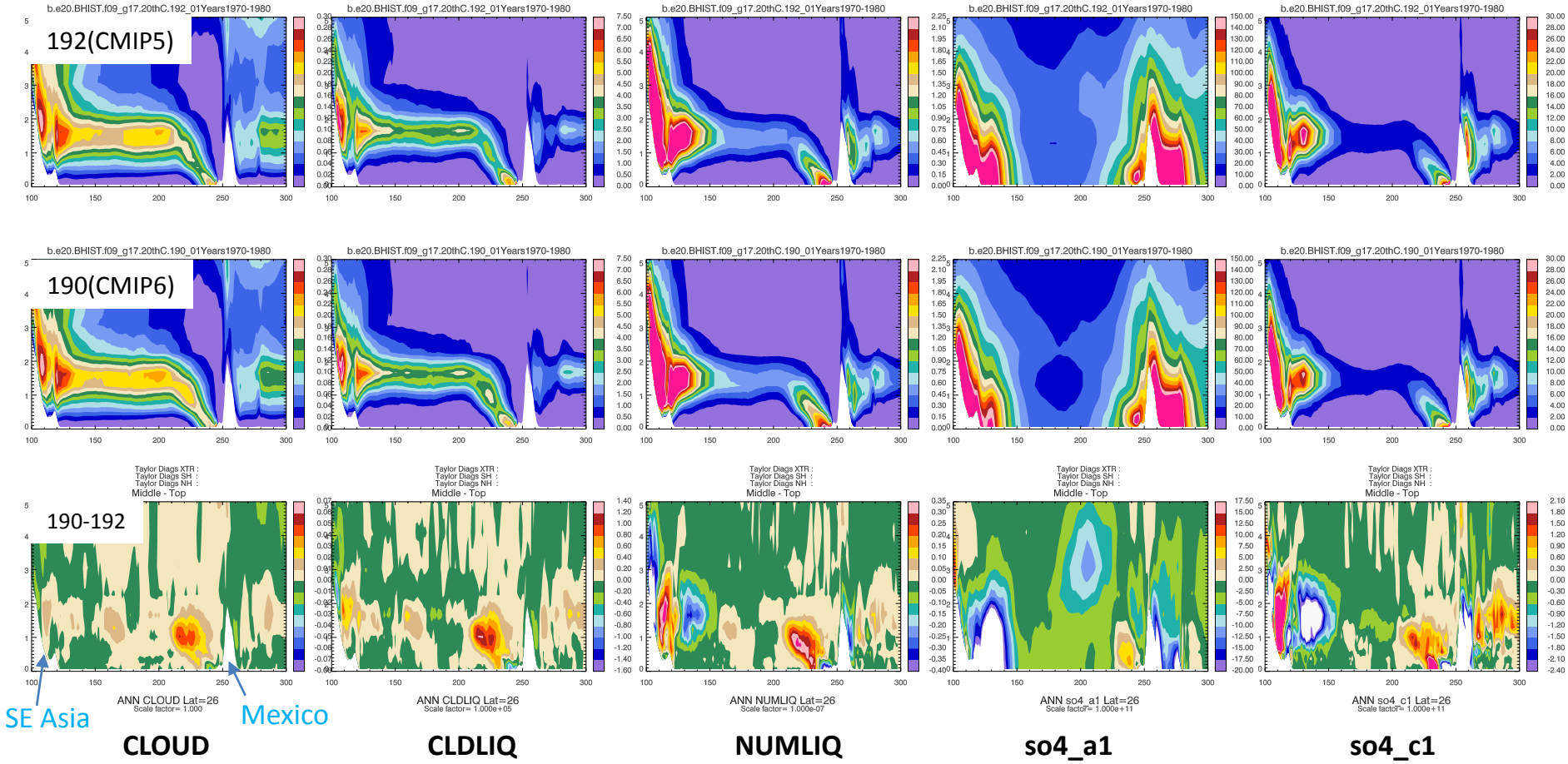


Annual SWCF (W/m^2)

Annual Low Clouds (%)

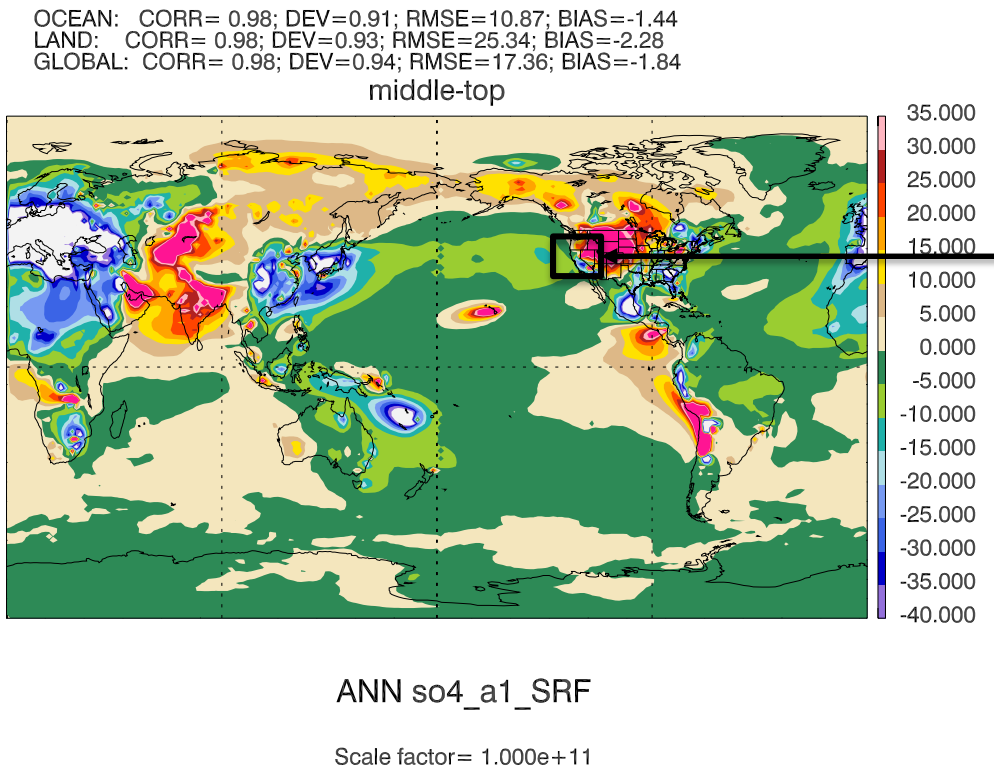
Differences in forcing CMIP5 -> CMIP6

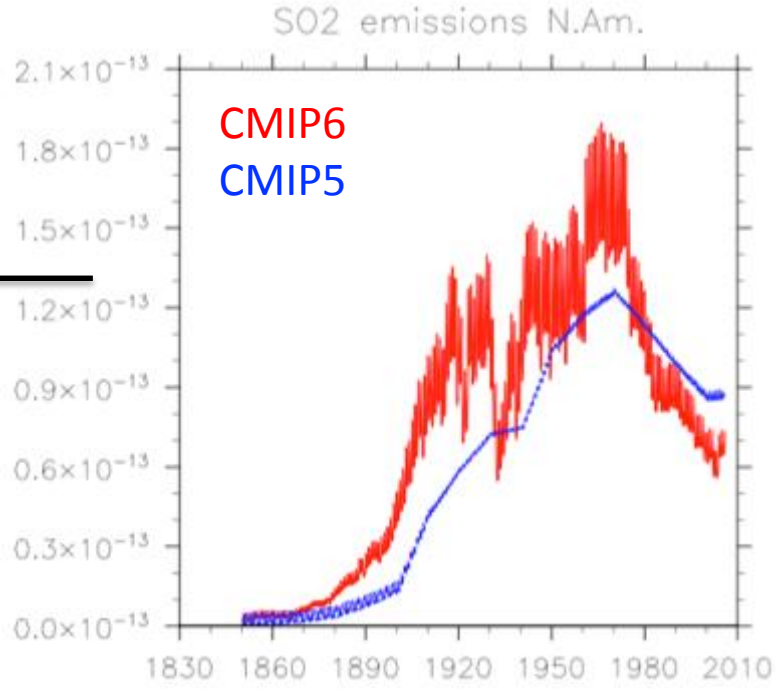
Longitude-height cross-sections along 26N (1970-1980 ann avg)



Differences in emissions

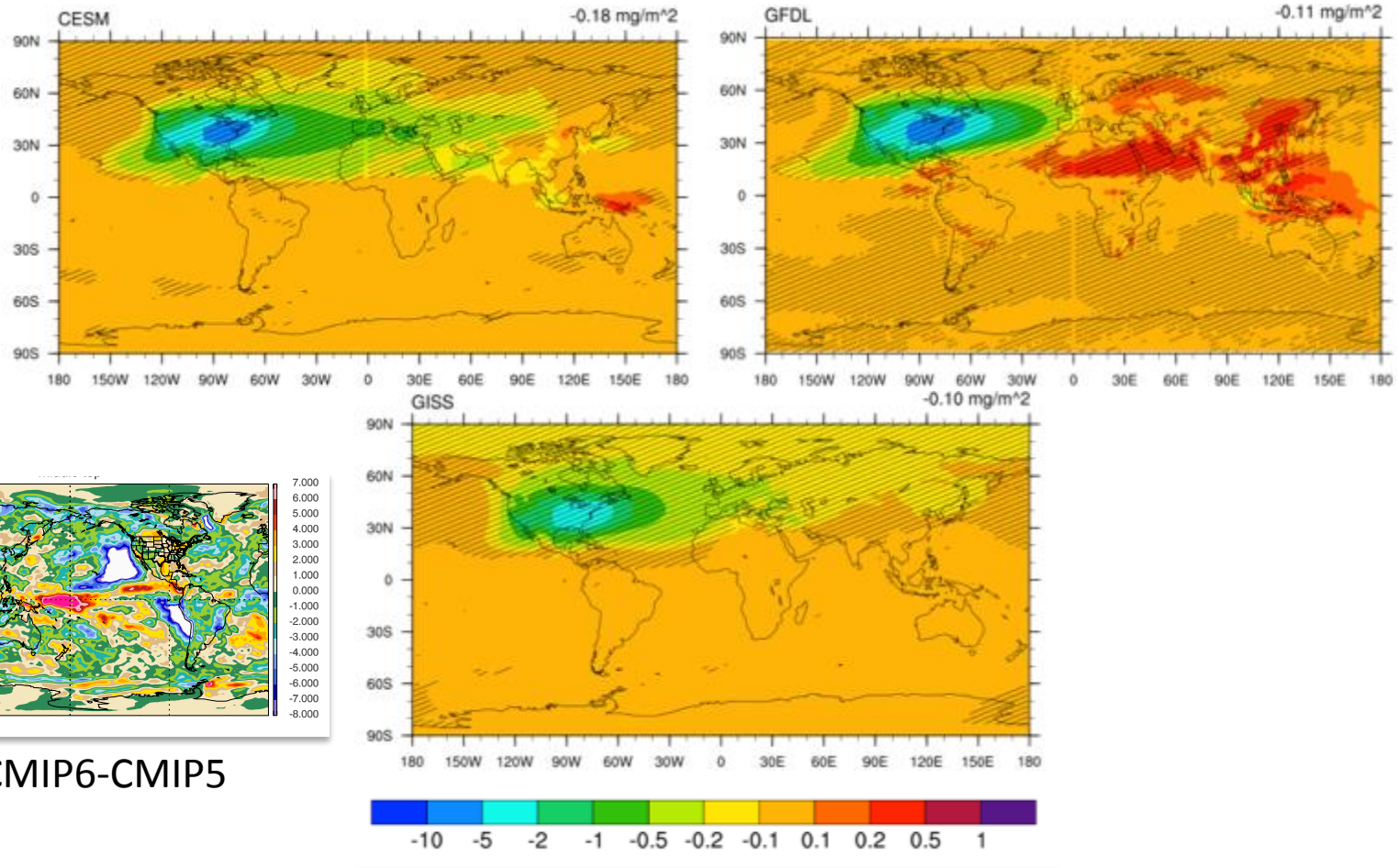
Surface SO_4 difference 1950-2000 CMIP6-CMIP5





from J.F.Lamarque

Transport of sulfate from US SO2 emissions

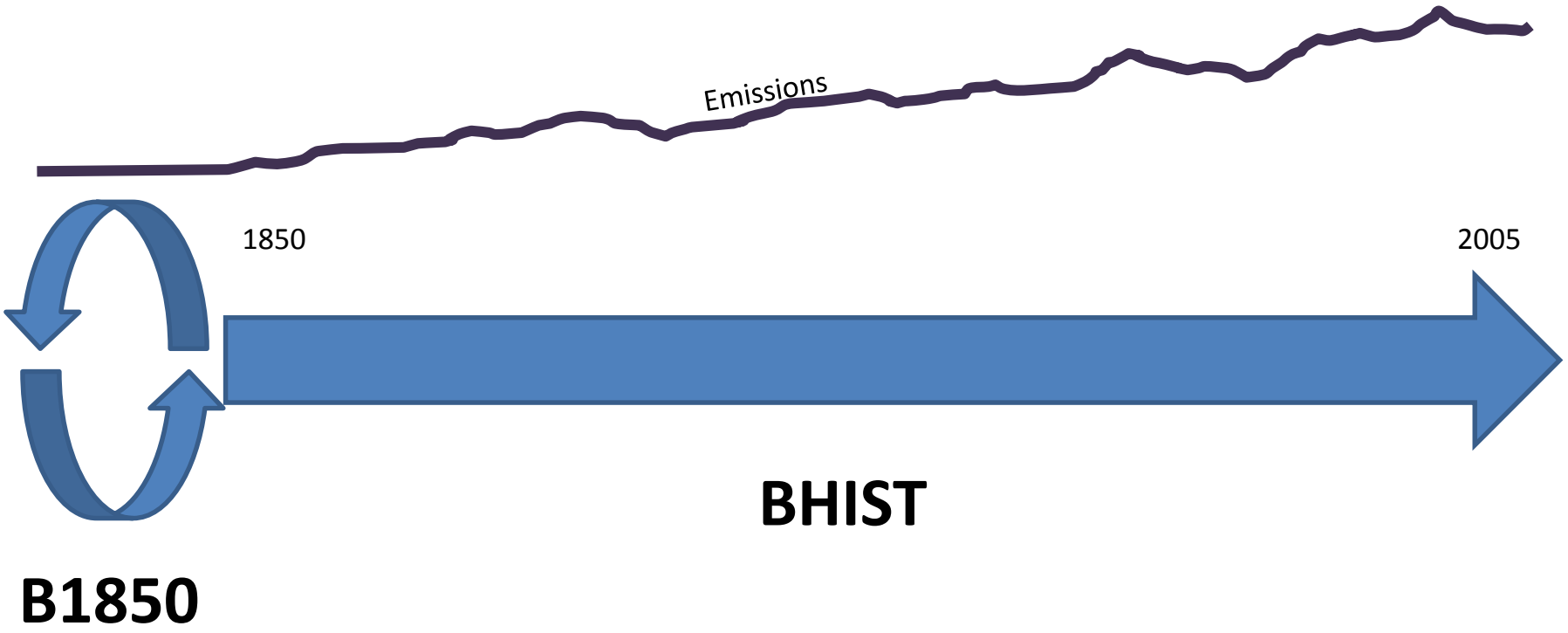


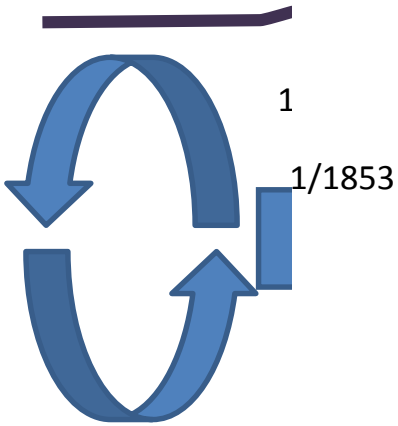
SWCF CMIP6-CMIP5

Conley et al., submitted, 2017

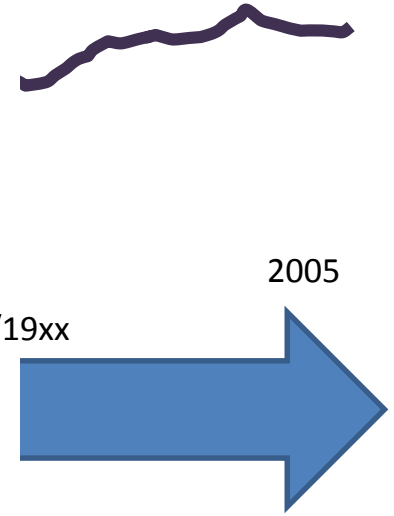
Slide from J.F. Lamarque

“Accelerated development” runs


Emissions
1850
2005
BHIST
B1850

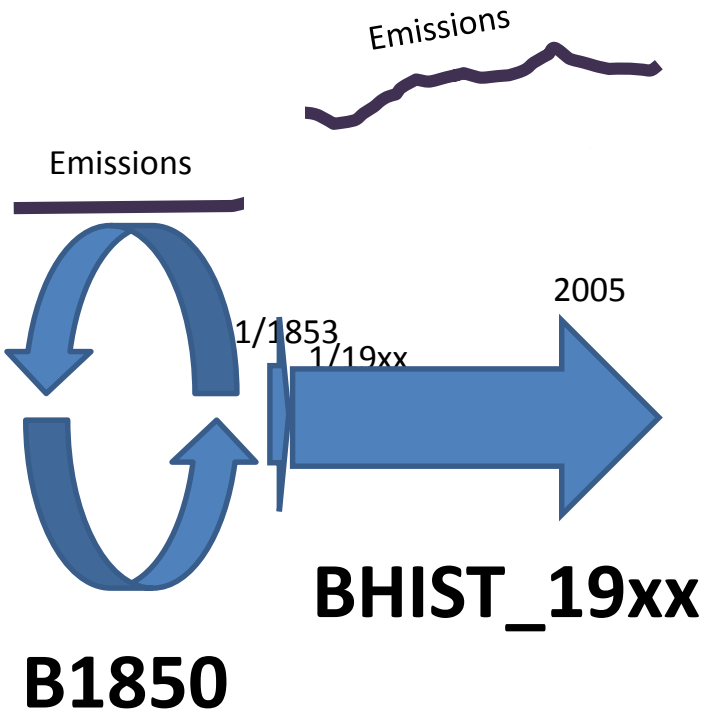


B1850



BHIST

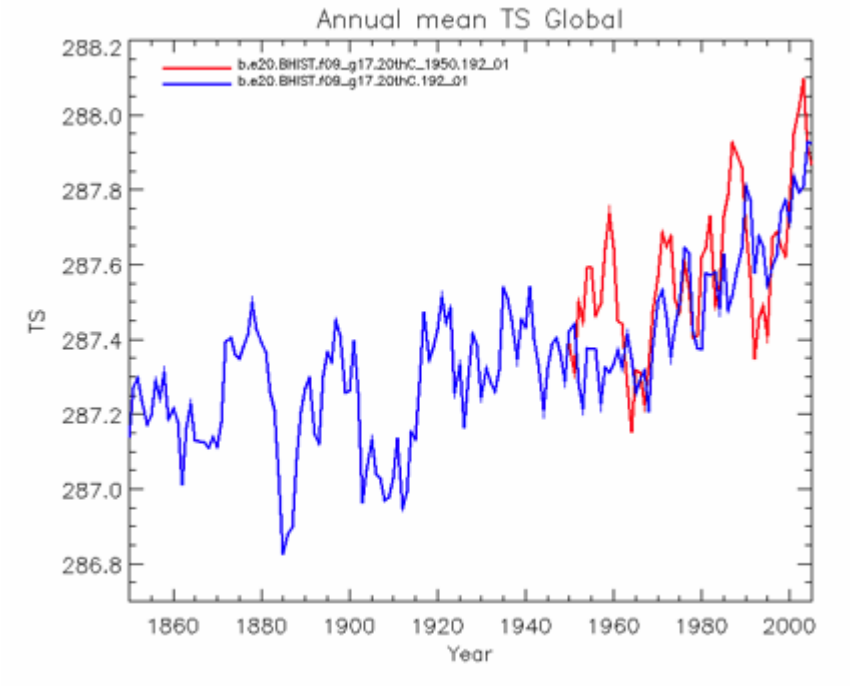
19xx = 1930, 1950 …



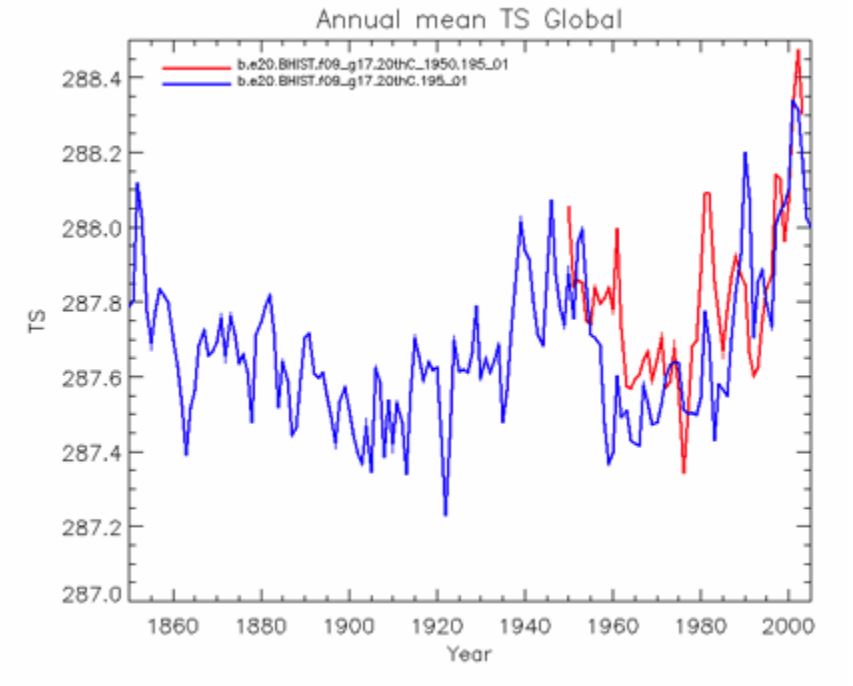
19xx = 1930, 1950 …

1950 Starts vs 1850 Starts

CMIP5 emiss.

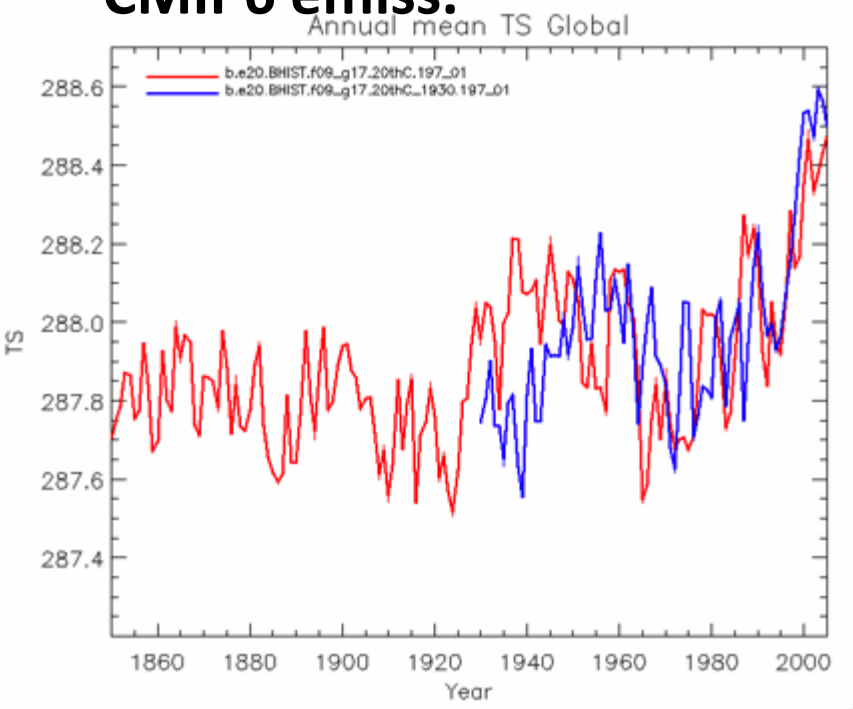


CMIP6 emiss.

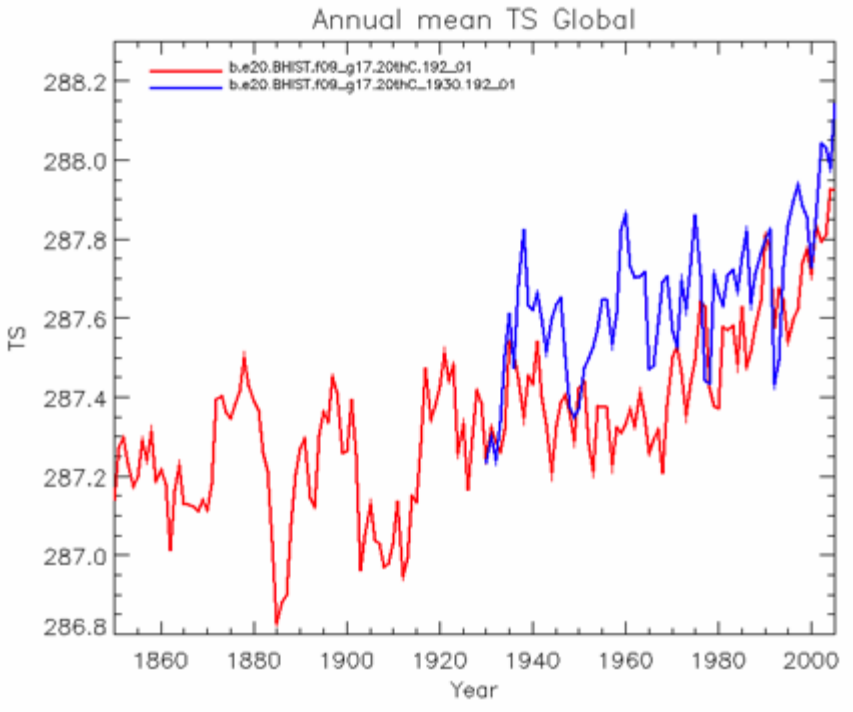


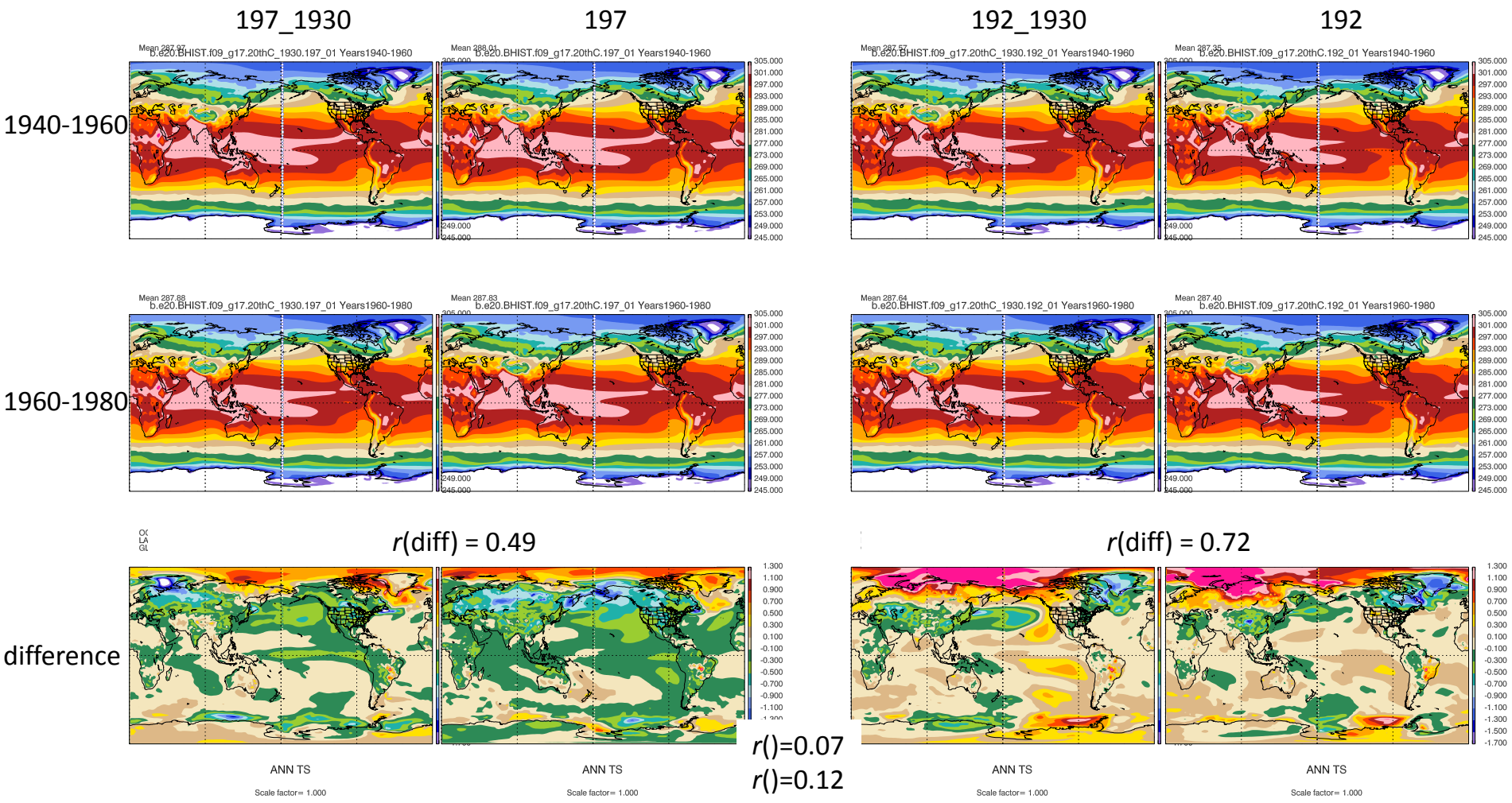
1930 Starts vs 1850 Starts

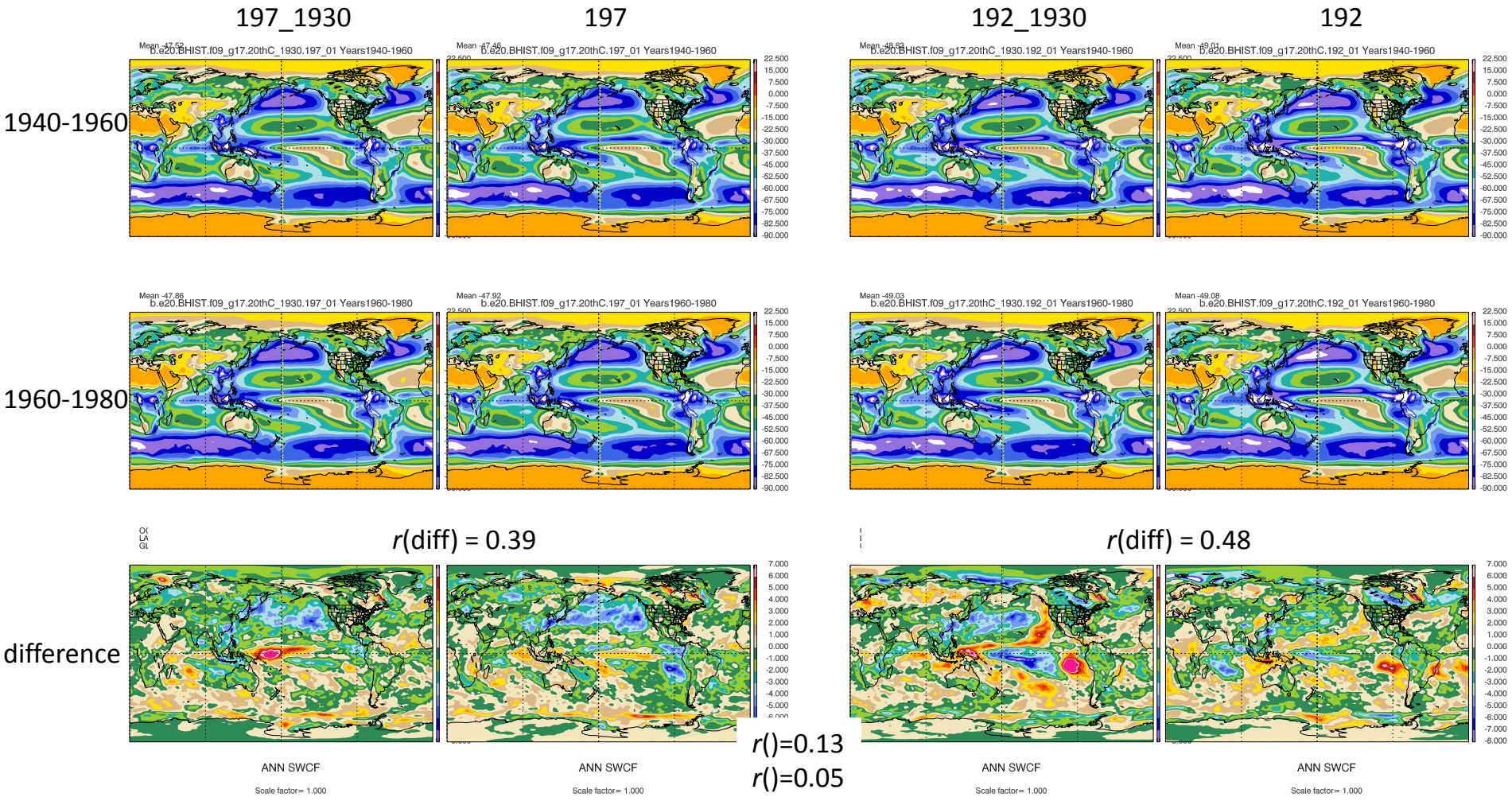
Latest (last week) model w/ CMIP6 emiss.



CMIP5 emiss.




197_1930
197
192_1930
192
1940-1960
1960-1980
difference
b.e20.BHIST.f09_g17.20thC_1930.197_01 Years1940-1960
b.e20.BHIST.f09_g17.20thC.197_01 Years1940-1960
b.e20.BHIST.f09_g17.20thC_1930.192_01 Years1940-1960
b.e20.BHIST.f09_g17.20thC.192_01 Years1940-1960
b.e20.BHIST.f09_g17.20thC_1930.197_01 Years1960-1980
b.e20.BHIST.f09_g17.20thC.197_01 Years1960-1980
b.e20.BHIST.f09_g17.20thC_1930.192_01 Years1960-1980
b.e20.BHIST.f09_g17.20thC.192_01 Years1960-1980
r(diff) = 0.49
r(diff) = 0.72
r()=0.07
r()=0.12
ANN TS
Scale factor= 1.000


197_1930
197
192_1930
192
1940-1960
1960-1980
difference
b.e20.BHIST.f09_g17.20thC_1930.197_01 Years1940-1960
b.e20.BHIST.f09_g17.20thC.197_01 Years1940-1960
b.e20.BHIST.f09_g17.20thC_1930.192_01 Years1940-1960
b.e20.BHIST.f09_g17.20thC.192_01 Years1940-1960
b.e20.BHIST.f09_g17.20thC_1930.197_01 Years1960-1980
b.e20.BHIST.f09_g17.20thC.197_01 Years1960-1980
b.e20.BHIST.f09_g17.20thC_1930.192_01 Years1960-1980
b.e20.BHIST.f09_g17.20thC.192_01 Years1960-1980
r(diff) = 0.39
r(diff) = 0.48
r()=0.13
r()=0.05
ANN SWCF
Scale factor= 1.000
ANN SWCF
Scale factor= 1.000
ANN SWCF
Scale factor= 1.000
ANN SWCF
Scale factor= 1.000

Possibilities

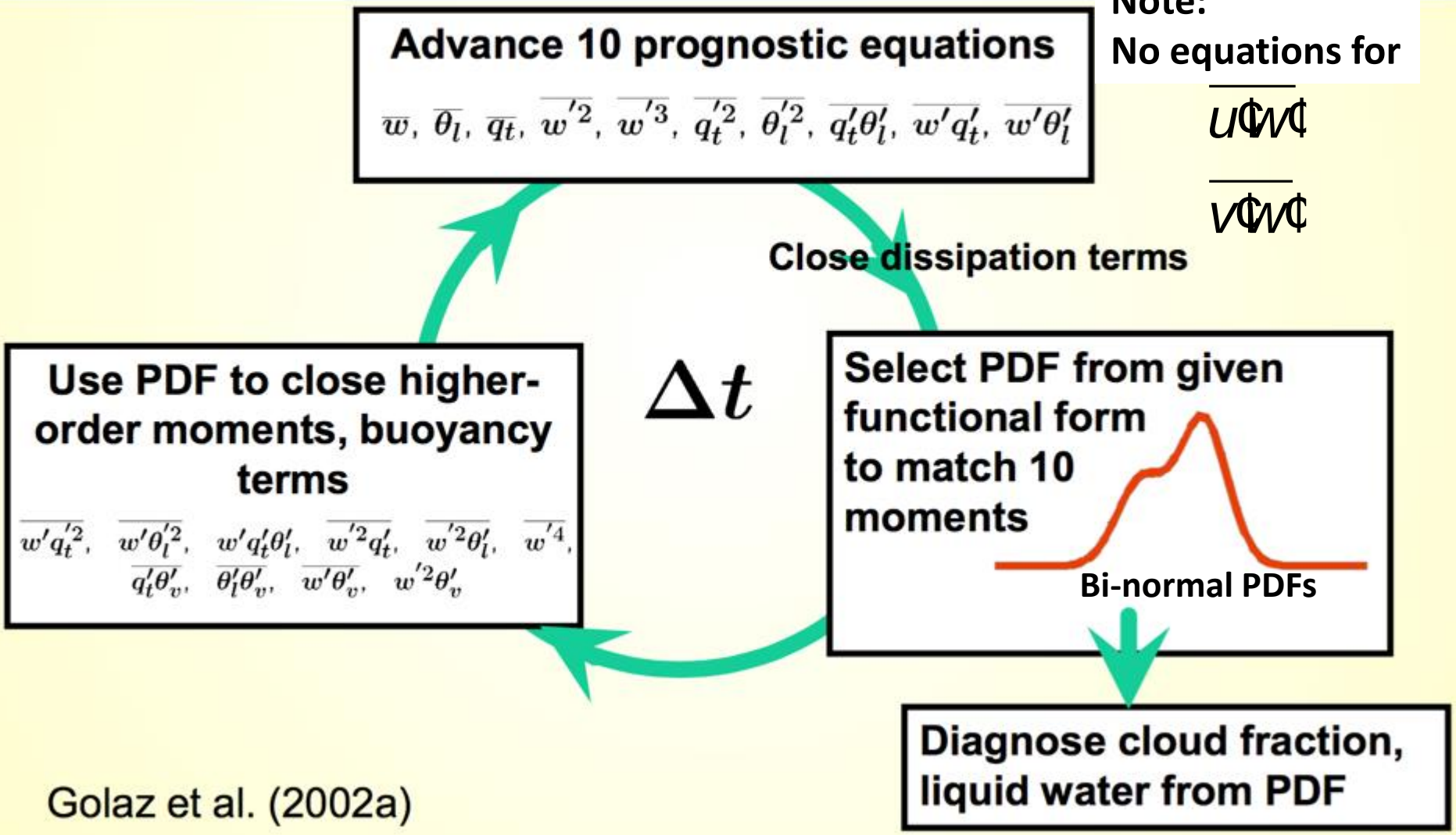
- Model is too sensitive to aerosol details
- Problem with CMIP5 (and CESM2) or CMIP6 emissions

Summary and Plans

- Current CESM2 performs well when forced with CMIP5 emission data, not so with CMIP6 emissions
- East Pacific feedbacks may play a role in cooling later 20th Century in CMIP6 - mechanism unclear.
- Beginning more intensive assessment of individual CMIP6 aerosol components
- Beginning physics “swaps”, e.g., PBL, ShCu schemes
- Examining changes to aerosol activation parameterizations

Thank You

Overview of CLUBB's solution procedure



Note:
No equations for

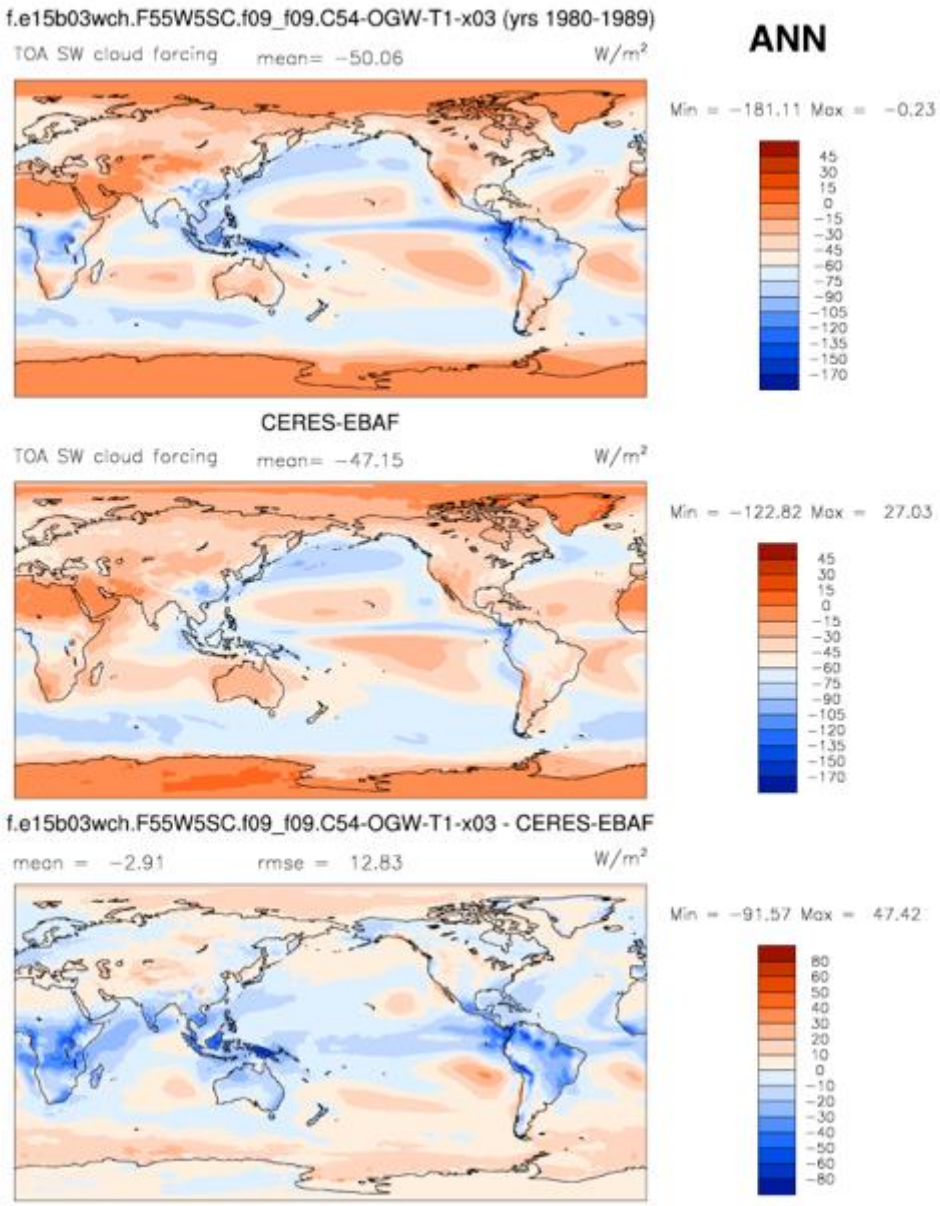
$\overline{u¢w¢}$

$\overline{v¢w¢}$

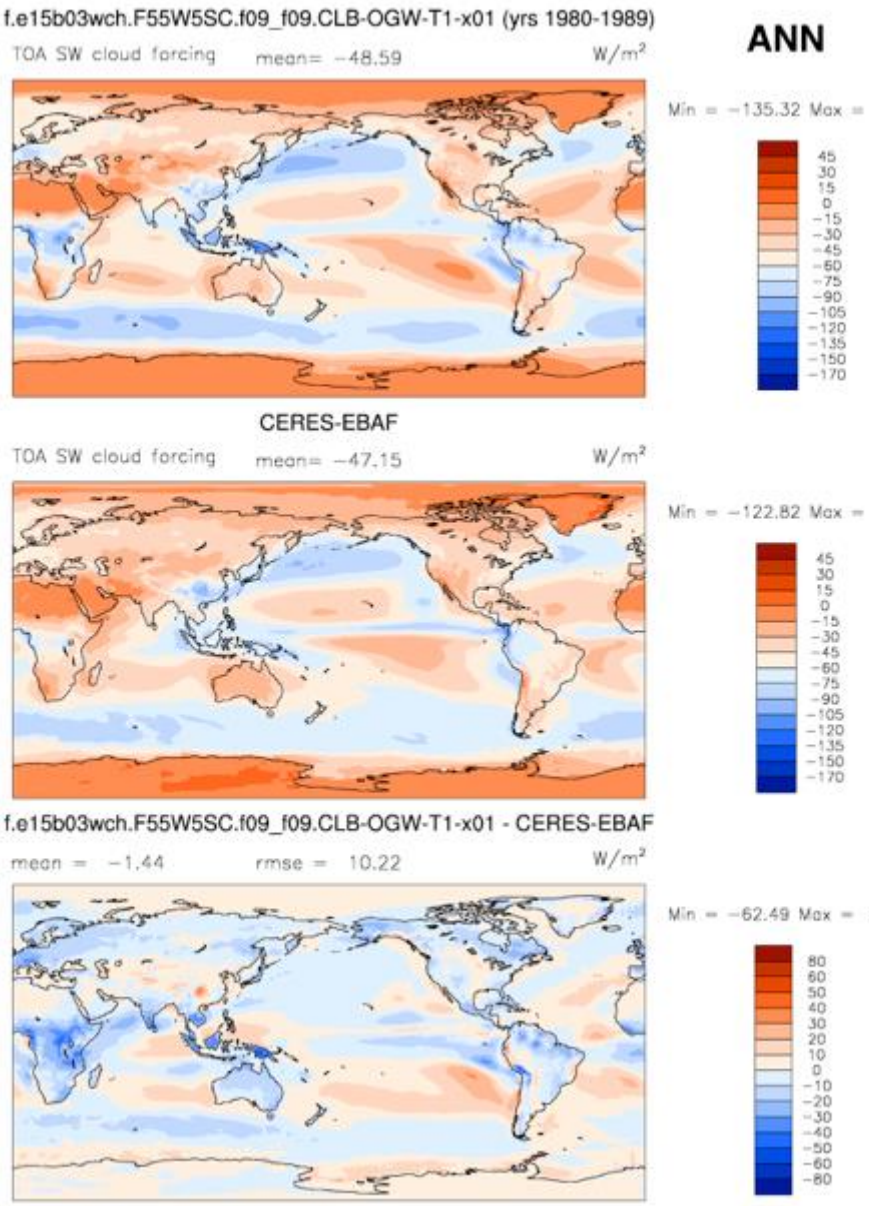
Golaz et al. (2002a)

Annual mean shortwave cloud forcing

CAM5.4 (before CLUBB)

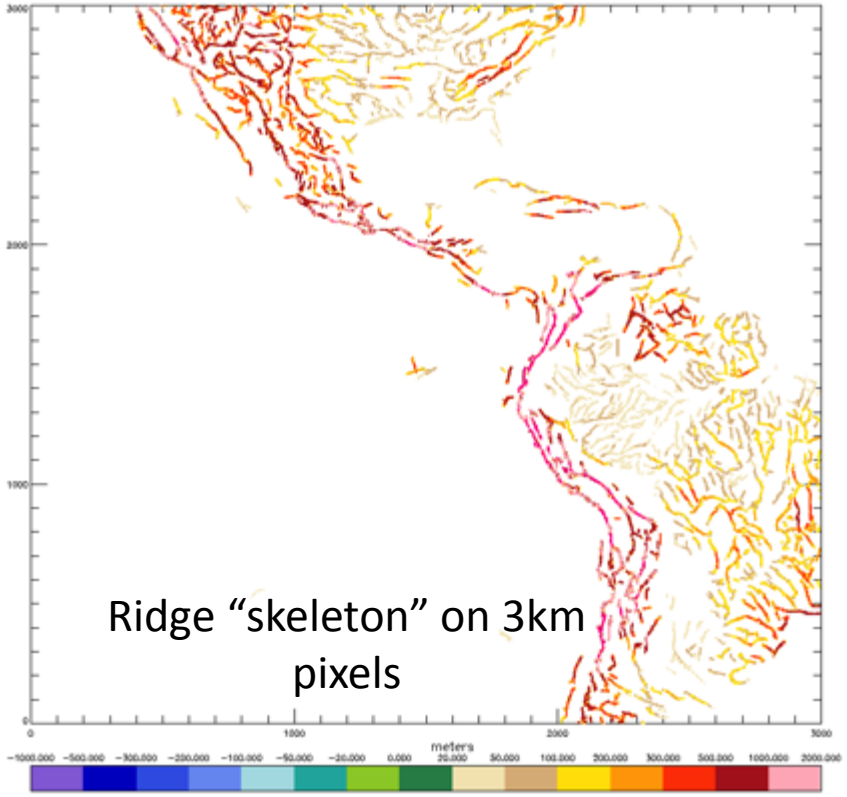


CAM5.5 (uses CLUBB)



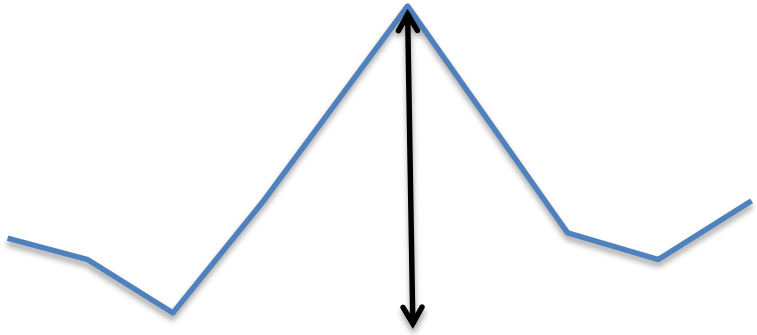
Anisotropic Orographic Gravity Wave Drag (scales~>10km)

Ridge orientation determines wave orientation and direction of drag force not low-level wind.

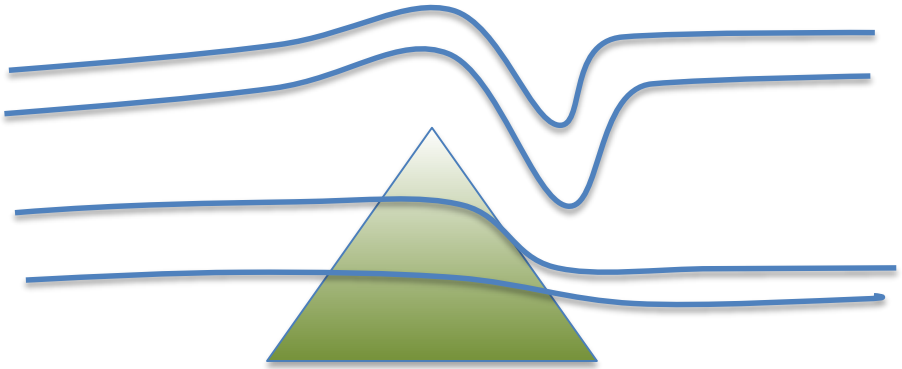


Ridge "skeleton" on 3km pixels

Ridge height estimate is based on min and max elevations of mean ridge profile not based on subgrid variance



Parameterization allows flow around obstacles – *form drag* - as well as "downslope wind" high-drag dynamics (e.g. Scinocca&McFarlane 2000)

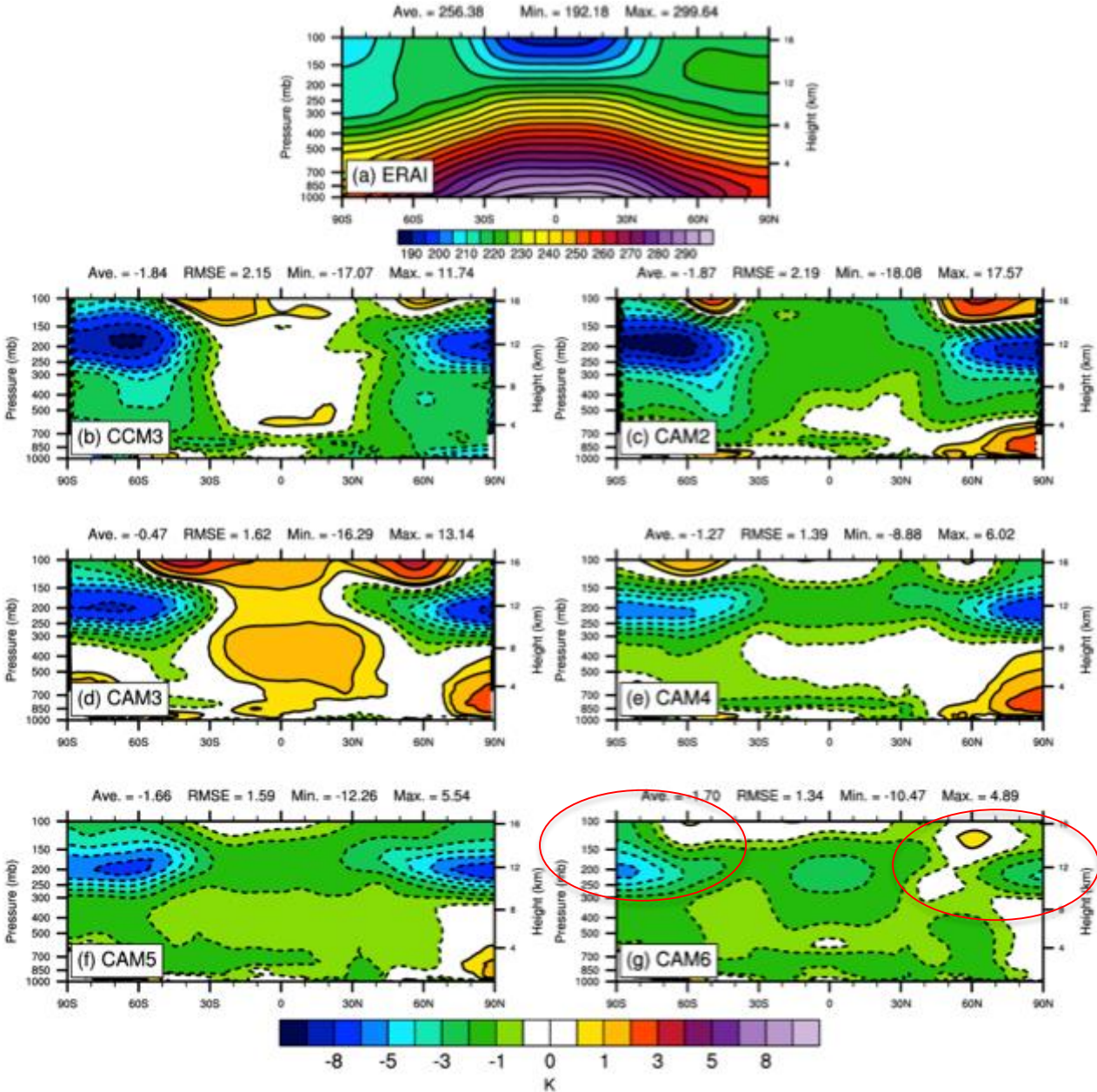


Generation of ancillary topography files

- No traceable process for generating topography forcing data existed for CESM1 or earlier versions.
  - Derivation of subgrid variables and smoothing of mean elevations left up to dycore developers. ***Note: <u>all</u> dycores employ additional smoothing beyond binning to grid.***
- New procedure starts from 1km GMTED2010 data (or GTOPO30) mapped to 3km cubed sphere grid. Further processing follows from 3km cubed sphere topo (*Lauritzen et al. GMD 2015*)

Temperature (Annual) - AMIP

- ***Lower stratospheric 'cold-pole' problems see significant decrease***
- Polar near-surface, improved stable PBLs
- Tropics go warm, cold, warm, cold, colder, cold
- A response to continued changes to deep convection
- Trade-off for climate mean and variability



Slide from Rich Neale

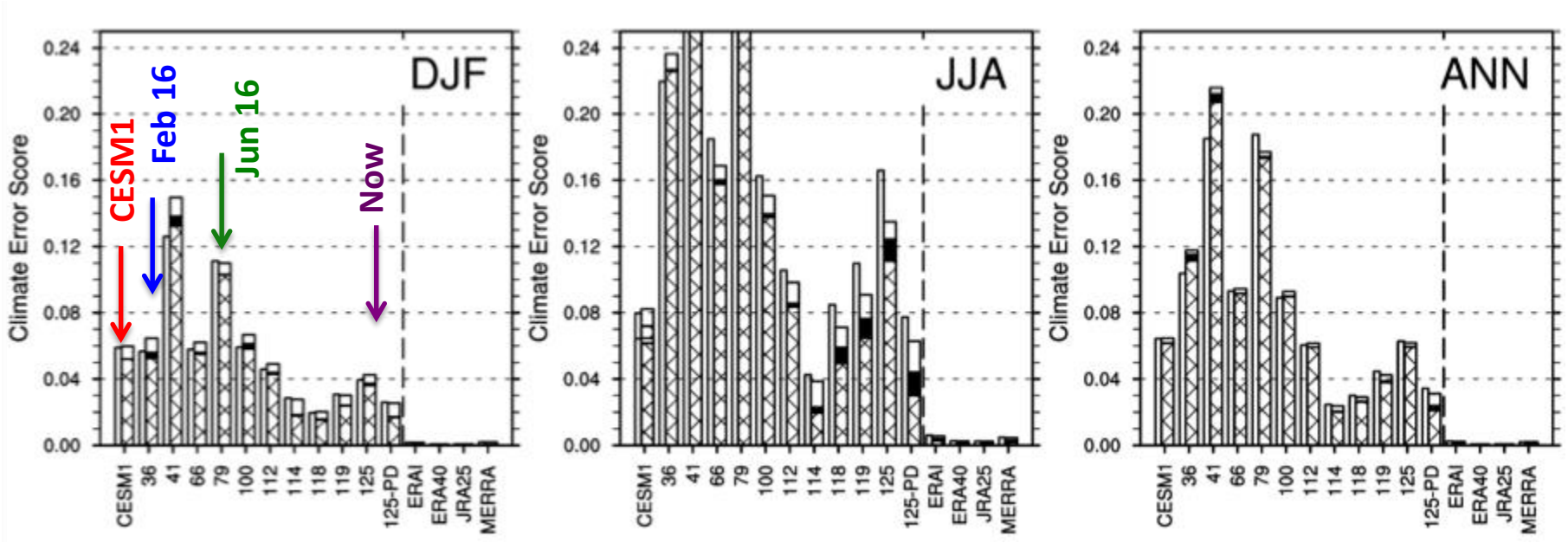
MG2 and MAM4

- Prognostic precipitation species (*rain and snow*)
- Additional carbon aerosol mode with longer residence time *(increases transport to high-latitudes)*

Coupled system (CESM)

Description of progress through ~March 2017 (***configuration 125***)

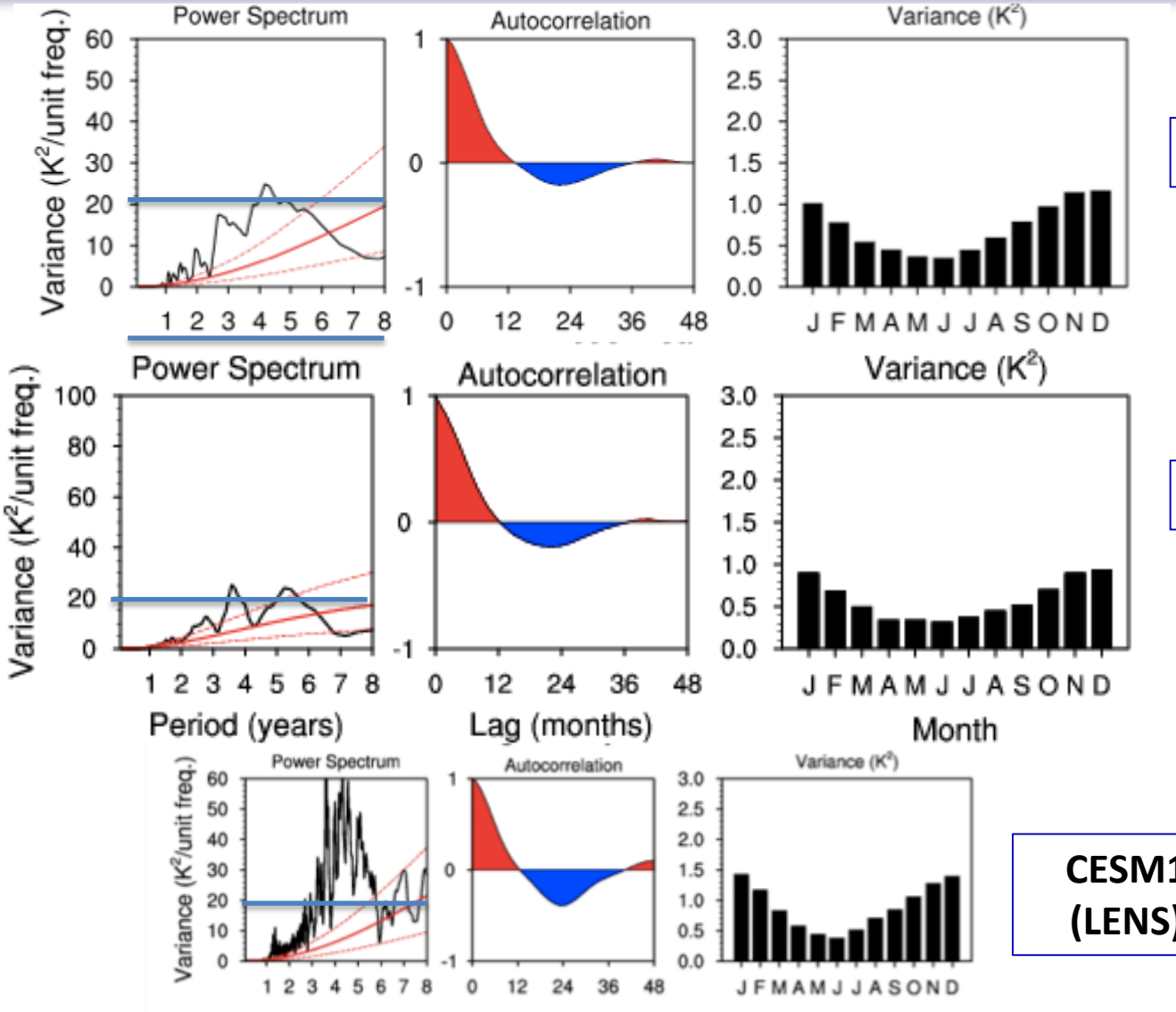
Skill Score (current simulation:#125)



NMSE = (a)+(b)+(c)

- General monotonic improvement from CESM1 (DJF/ANN)
- Large initial degradation in JJA mostly recovered
- Removing super-saturation -> improved skill, but high climate sensitivity
- Land model strongly impacts JJA score (new land at 118).

ENSO in CESM2

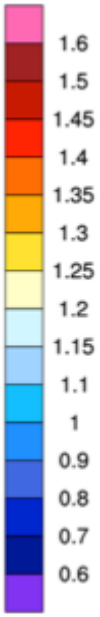


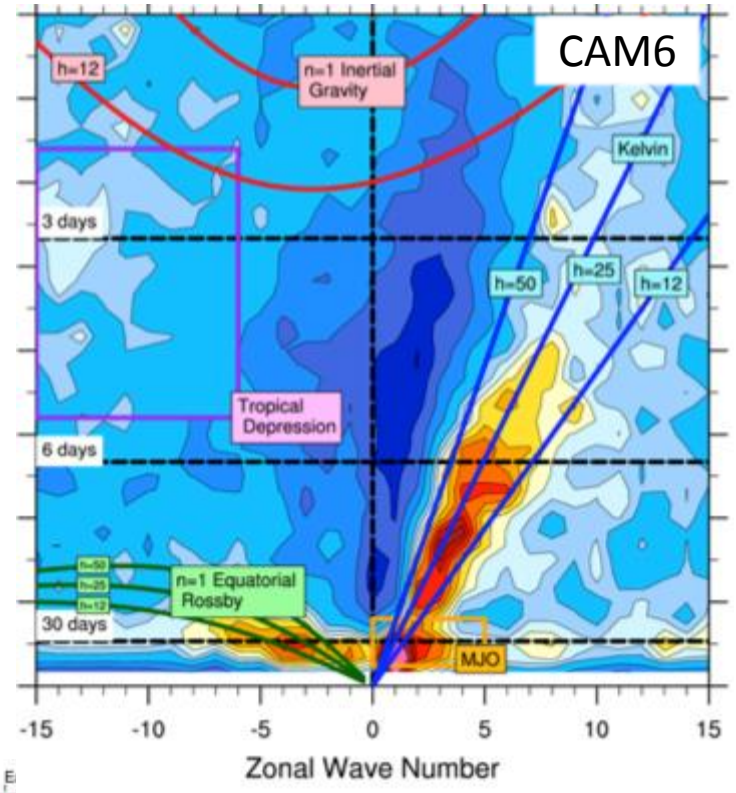
CESM2

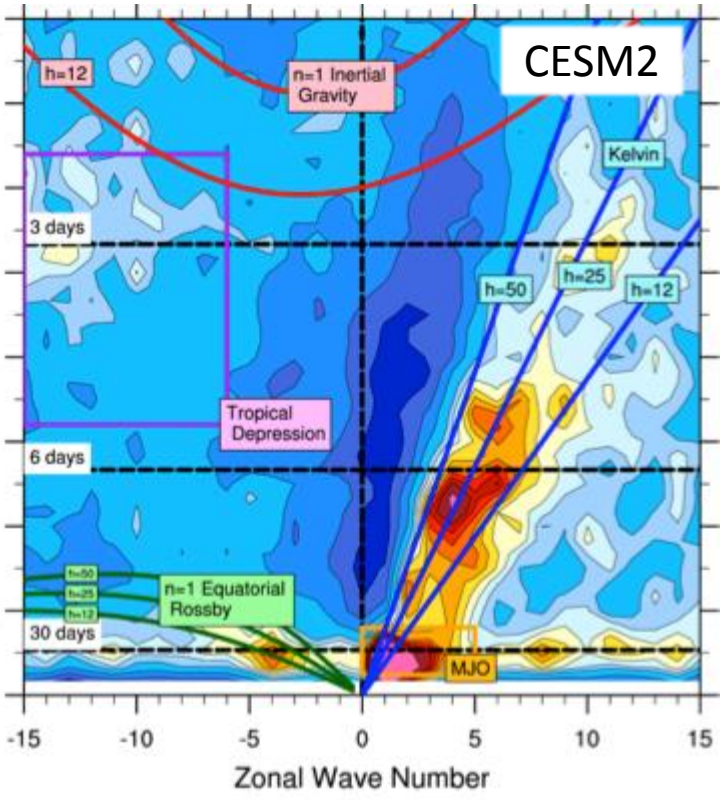
Obs.

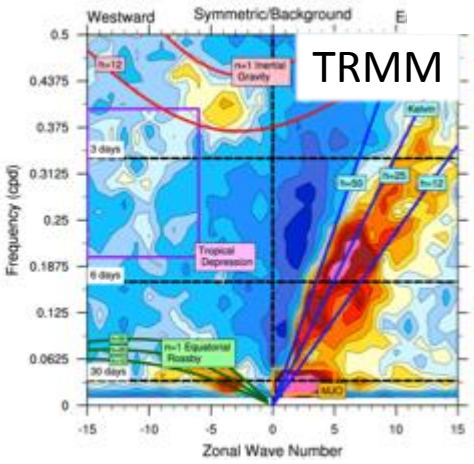
CESM1 (LENS)

Tropical Variability (Precipitation) - CESM







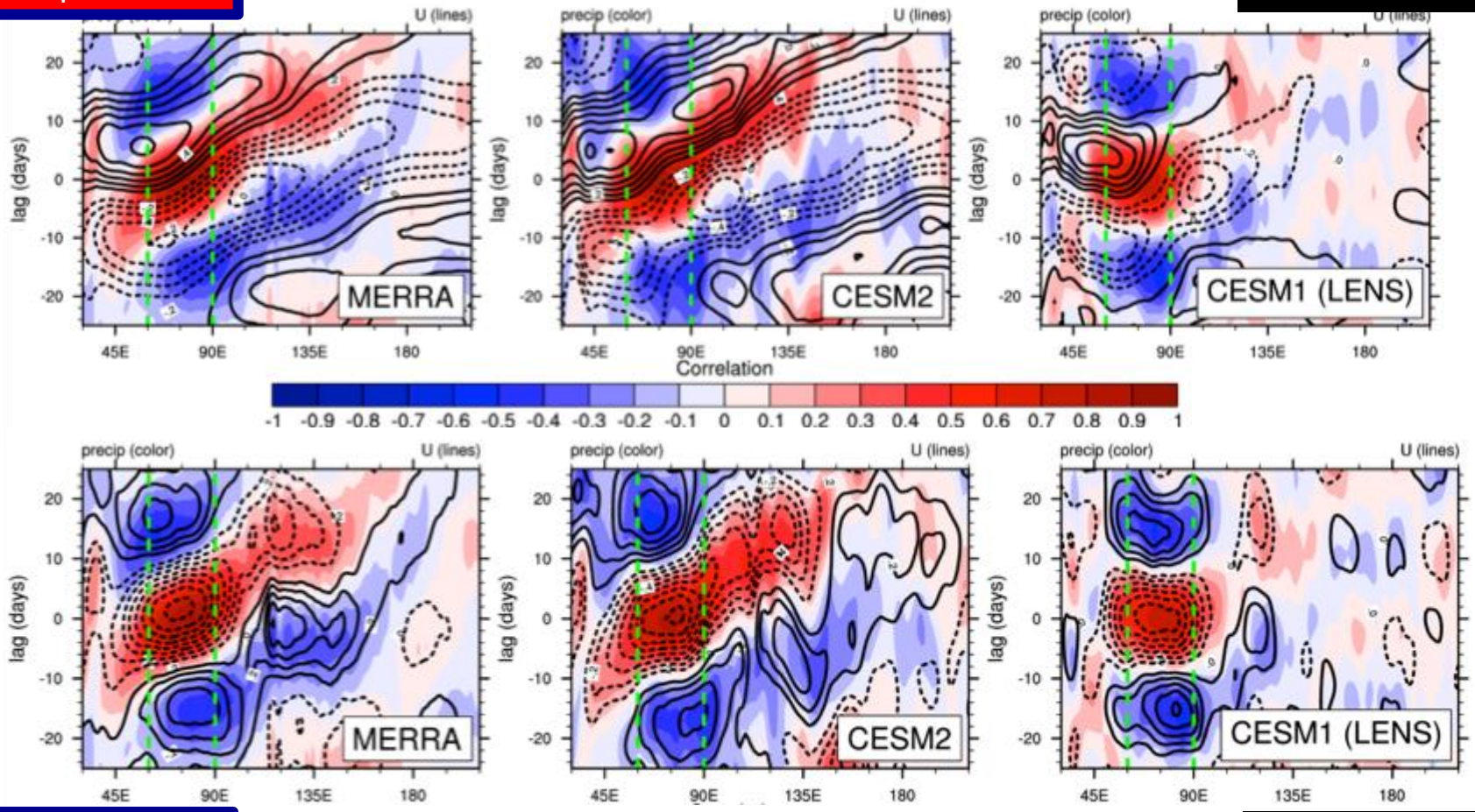


- Largest variation in MJO power
- Increased power and zonal wavenumber extent

Madden Julian Oscillation (MJO)

Precipitation

850-mb U

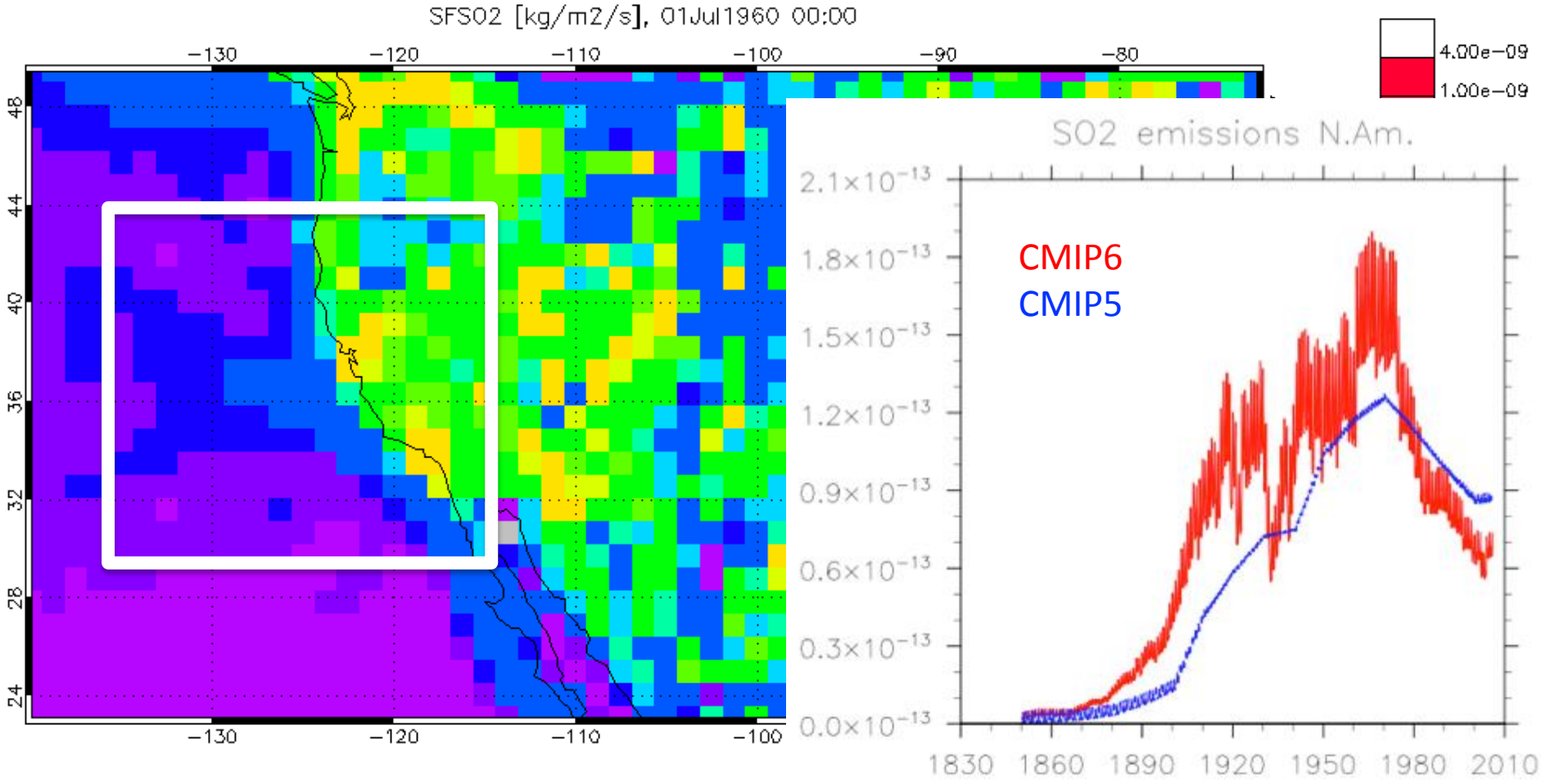


Precipitation

OLR

- Lag correlation with Indian-Ocean precip
- 20-100day band pass filter, 10S-10N
- 9 years, DJFMAM

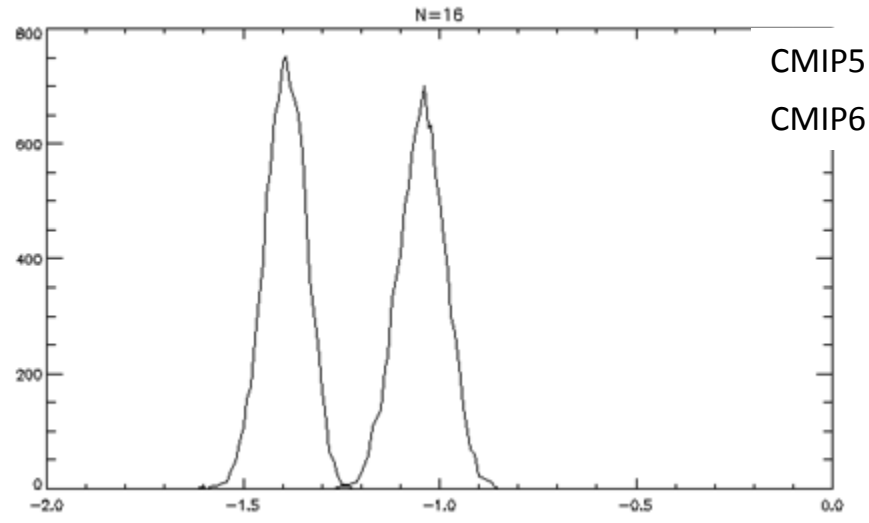
Differences in emissions



Slide from J.F. Lamarque

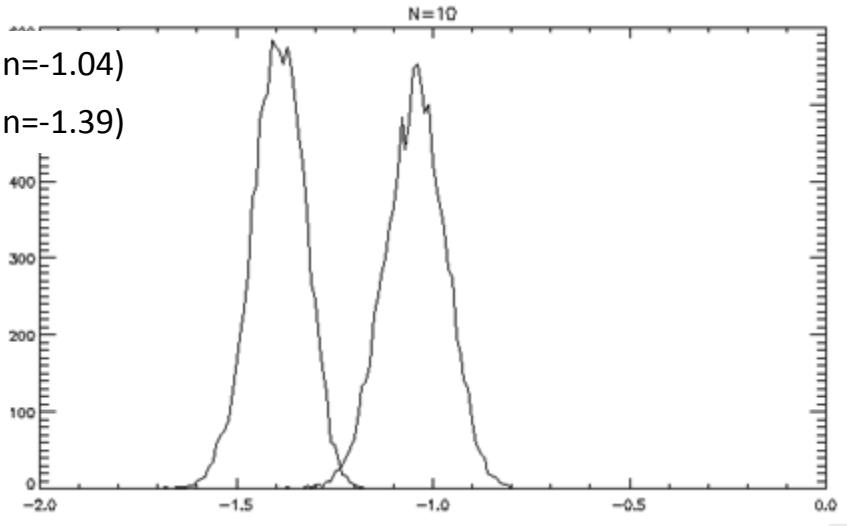
Bootstrap analysis of ΔSWCF

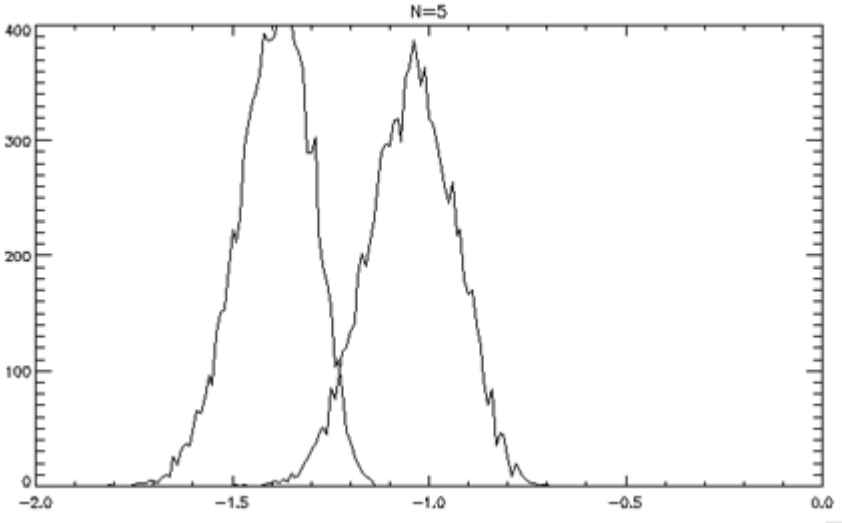
10000 artificial timeseries generated from 20 year 195.001 and 195.011(CMIP5). Random sampling w/ replacement: 3yr, 5yr, 10yr and 16yr artificial timeseries

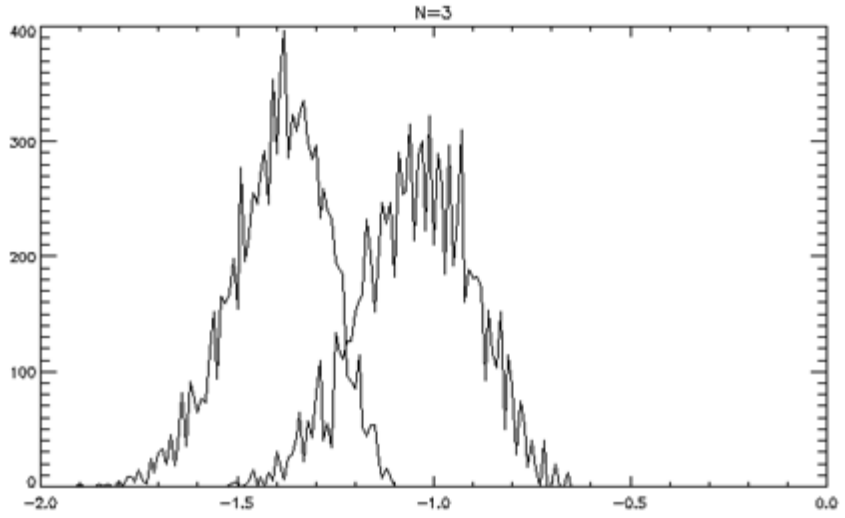


CMIP5 (mean=-1.04)

CMIP6 (mean=-1.39)

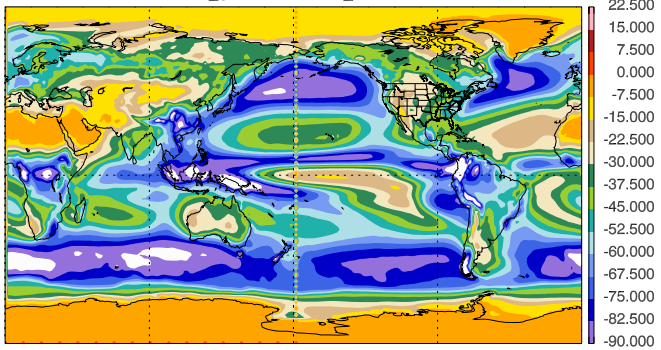






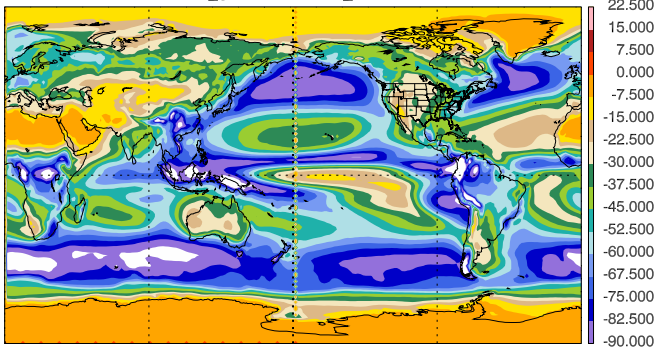
Mean -48.91

b.e20.BHIST.f09_g17.20thC.192_01 Years1900-1950



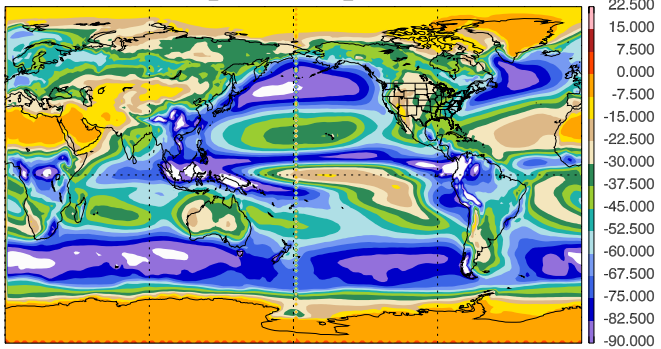
Mean -48.96

b.e20.BHIST.f09_g17.20thC.190_01 Years1900-1950



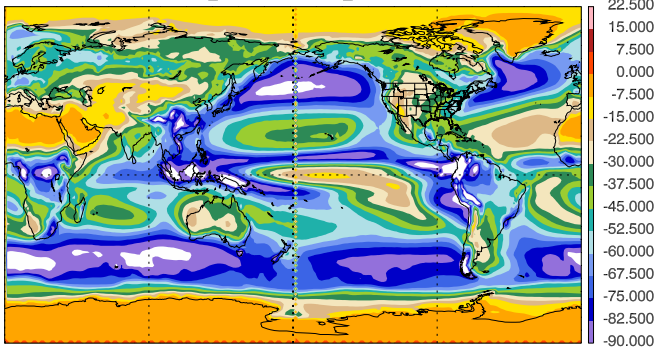
Mean -49.08

b.e20.BHIST.f09_g17.20thC.192_01 Years1950-2000



Mean -49.62

b.e20.BHIST.f09_g17.20thC.190_01 Years1950-2000



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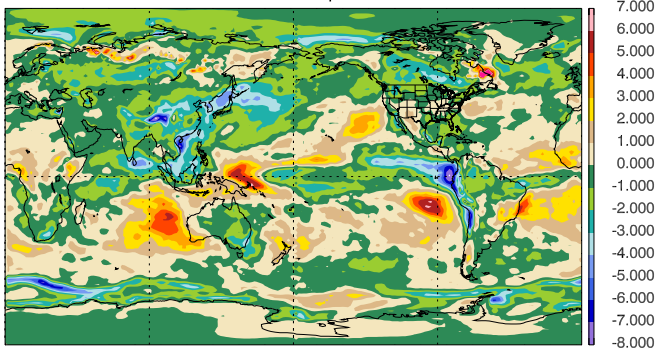
LAND: CORR= 1.00; DEV=1.01; RMSE=1.48; BIAS=-0.41
GLOBAL: CORR= 1.00; DEV=1.00; RMSE=1.63; BIAS=-0.16

middle-top

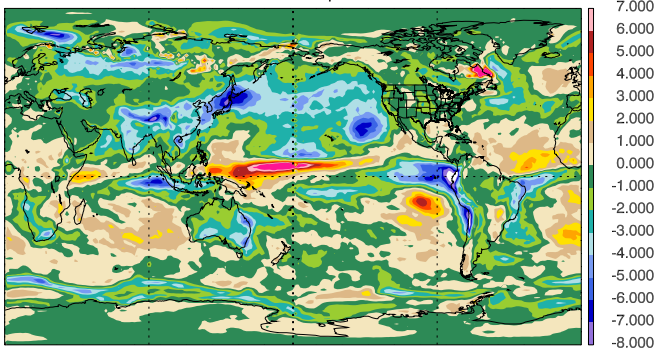


ANN SWCF

Scale factor= 1.000

OCEAN: CORR= 1.00; DEV=1.00; RMSE=2.06; BIAS=-0.57
LAND: CORR= 1.00; DEV=1.01; RMSE=1.81; BIAS=-0.85
GLOBAL: CORR= 1.00; DEV=1.00; RMSE=1.99; BIAS=-0.65

middle-top



ANN SWCF

Scale factor= 1.000

PBL Form Drag (from smooth small obstacles)

TMS:

$$\mathbf{F}_x = C_D |\mathbf{U}| U(z_{LM}), \quad C_D = k \left(\ln \frac{z_{LM}}{z_0} \right)^{-2}, \quad z_0 \propto \sqrt{\langle h_d'^2 \rangle}$$

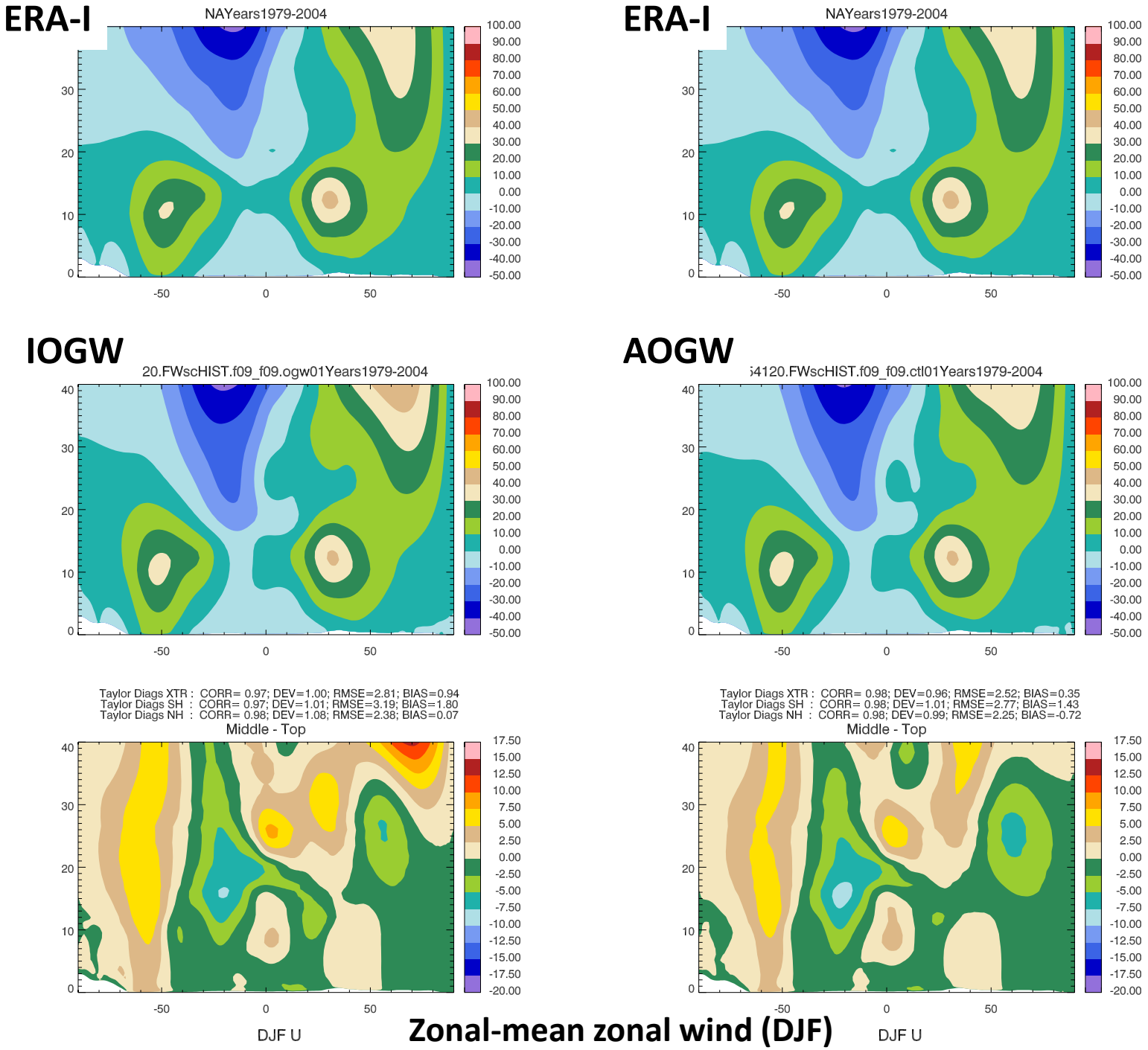
- Logarithmic in h'_δ. Only applied in lowest model layer.

Beljaars et al. (2004):

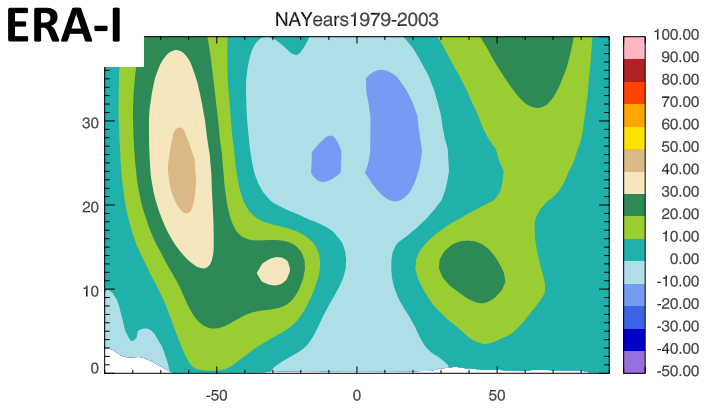
$$\mathbf{F}_x = -\alpha \beta C_{md} C_{corr} |\vec{U}(z)| \vec{U}(z) 2.109 e^{-(z/1500)^{1.5}} a_2 z^{-1.2}, \quad a_2 \propto \langle h_d'^2 \rangle$$

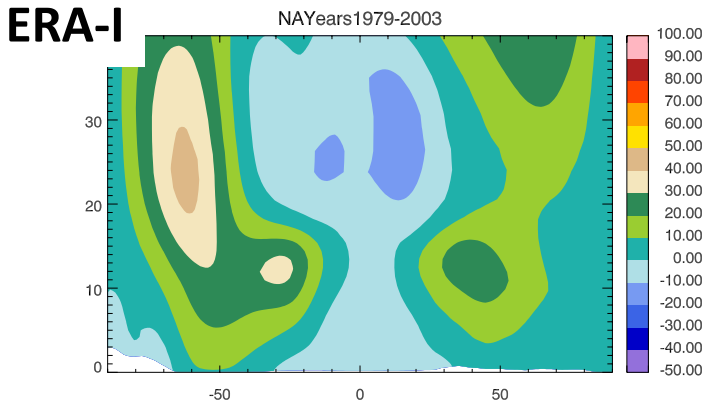
- Proportional to h'^2_δ. Applied over physically based vertical profile.

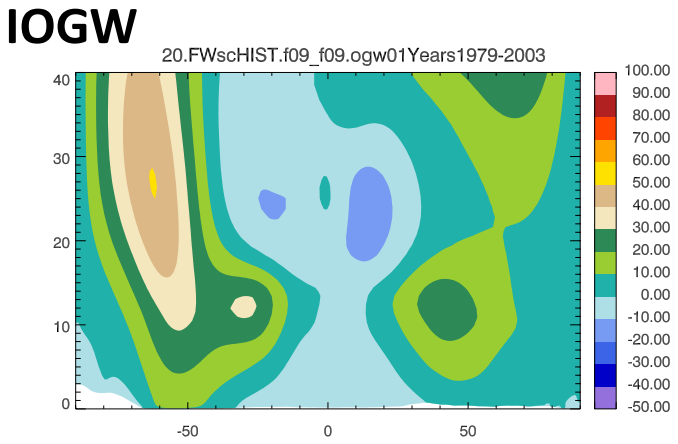
h_d' are topographic perturbations with scales below 3km derived from GMTED data. < > represents averaging to model grid.

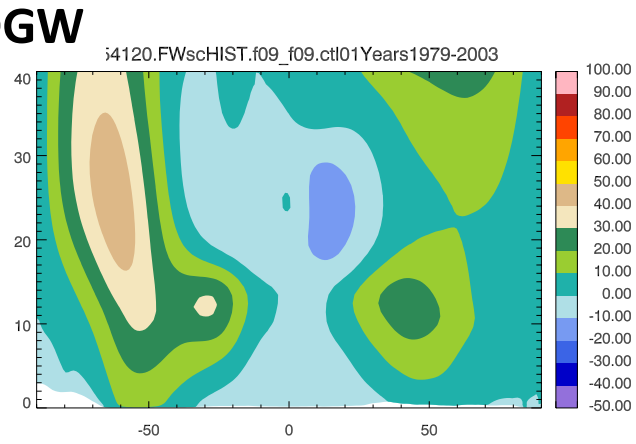


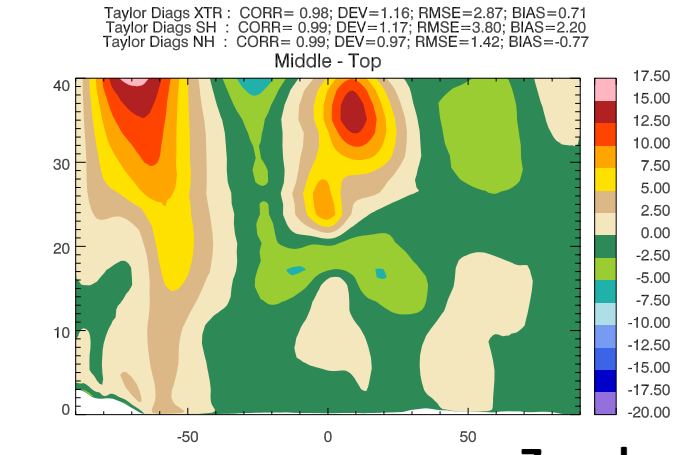
Zonal-mean zonal wind (DJF)

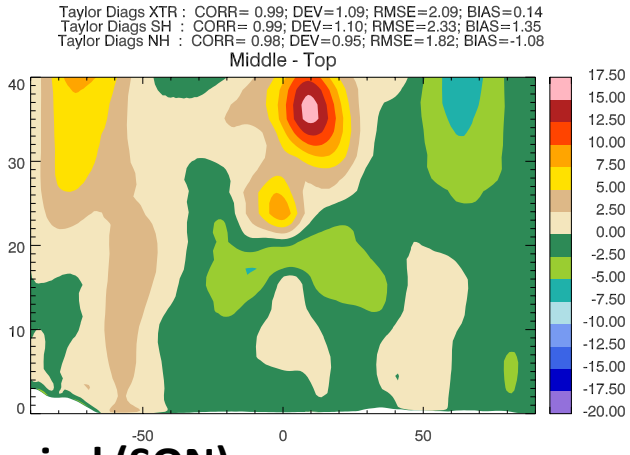












Zonal-mean zonal wind (SON)

Short cuts ???

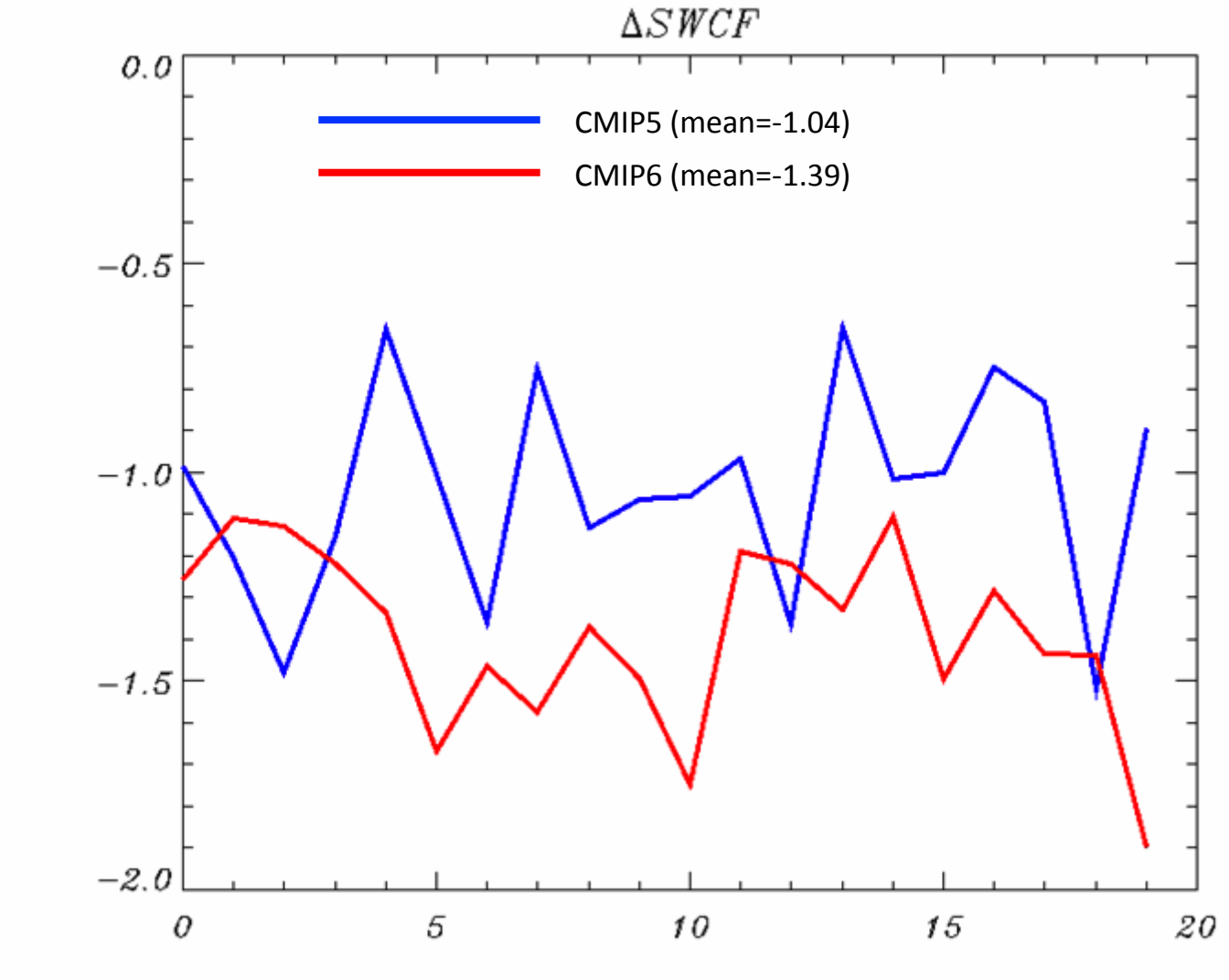
- Full 20th century coupled runs long time: ~8-10 days to go from 1850 to 2005

Climatological year 2000 runs

20 year runs with PD (year 2000)and PI(year 1850) aerosols

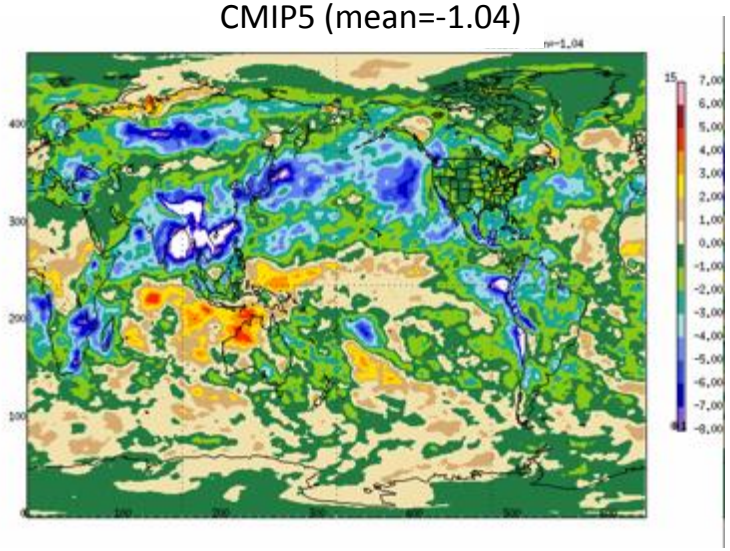
All other forcings, e.g. GHG, SSTs etc. are for year 2000

Change in SWCF from PI to PD



Mean change in SWCF from PI to PD

CMIP5 (mean=-1.04)



CMIP6 (mean=-1.39)