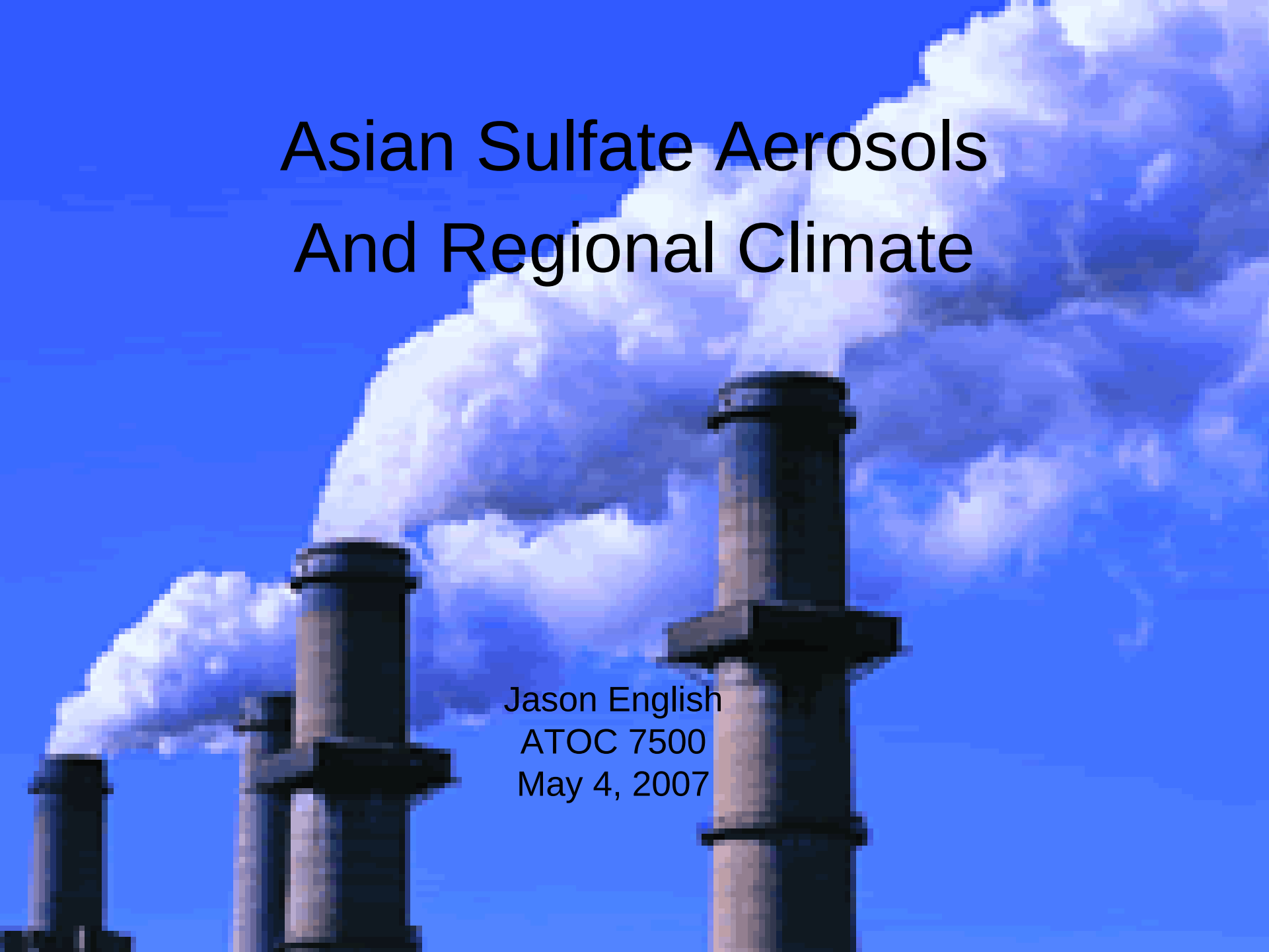


Asian Sulfate Aerosols And Regional Climate

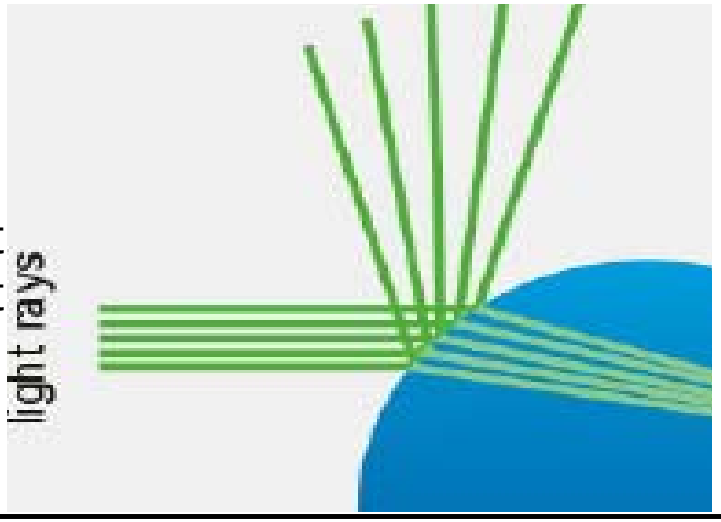
Jason English
ATOC 7500
May 4, 2007

Why are aerosols important?

Aerosols & Climate:

Global cooling effect, but spatially variable forcings may affect global circulation (e.g. regional warming or cooling)

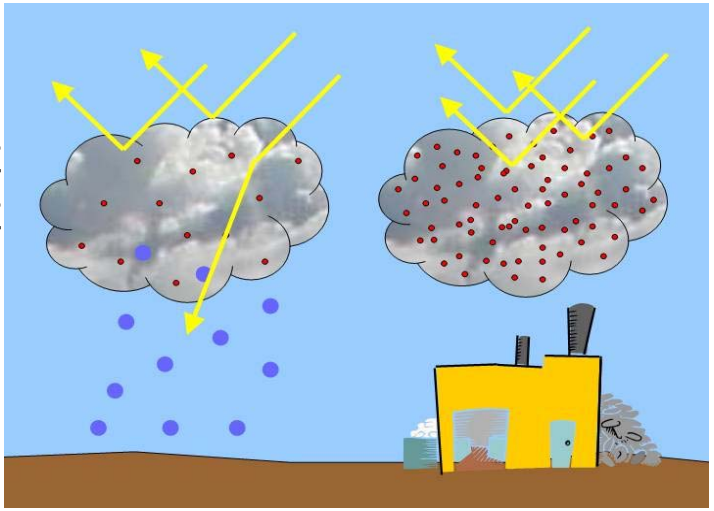
Direct effect



Direct (scattering):
albedo ↑
albedo ↓

Addressed in AR4

Indirect effect



1st indirect:
albedo ↑

2nd indirect:
cloud lifetime ↑

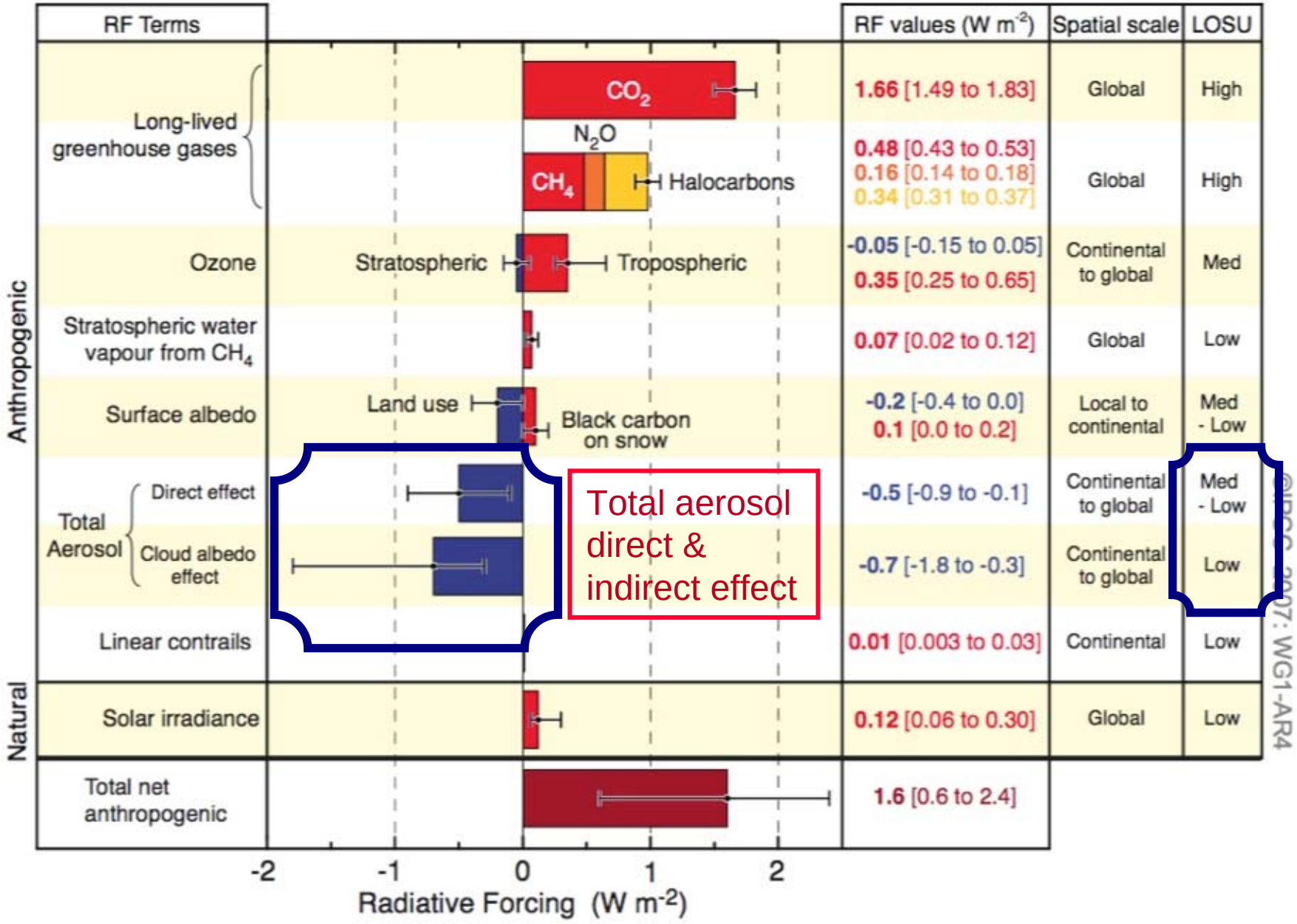
Semidirect:
cloud evap ↑

Glaciation:
ice nuclei (precip) ↑

Thermodynamic:
smaller, colder drops

Sfc energy budget:
heat flux, precip ↓

IPCC AR4 (2007)

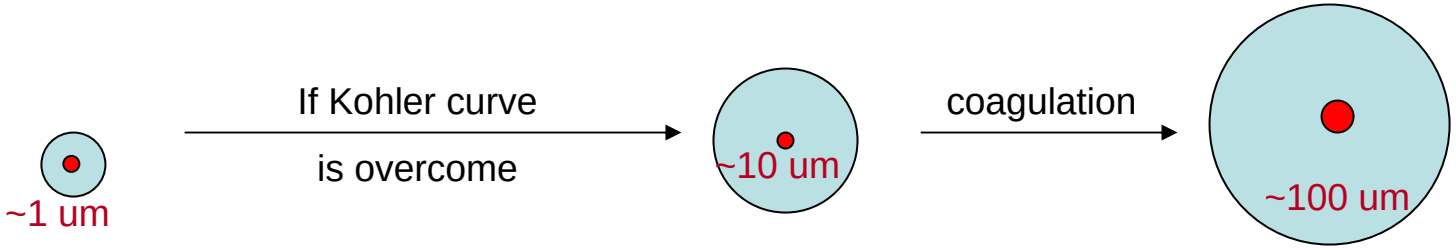


What are aerosols?

Tiny solid/liquid particles (mixture of key types below, plus water)

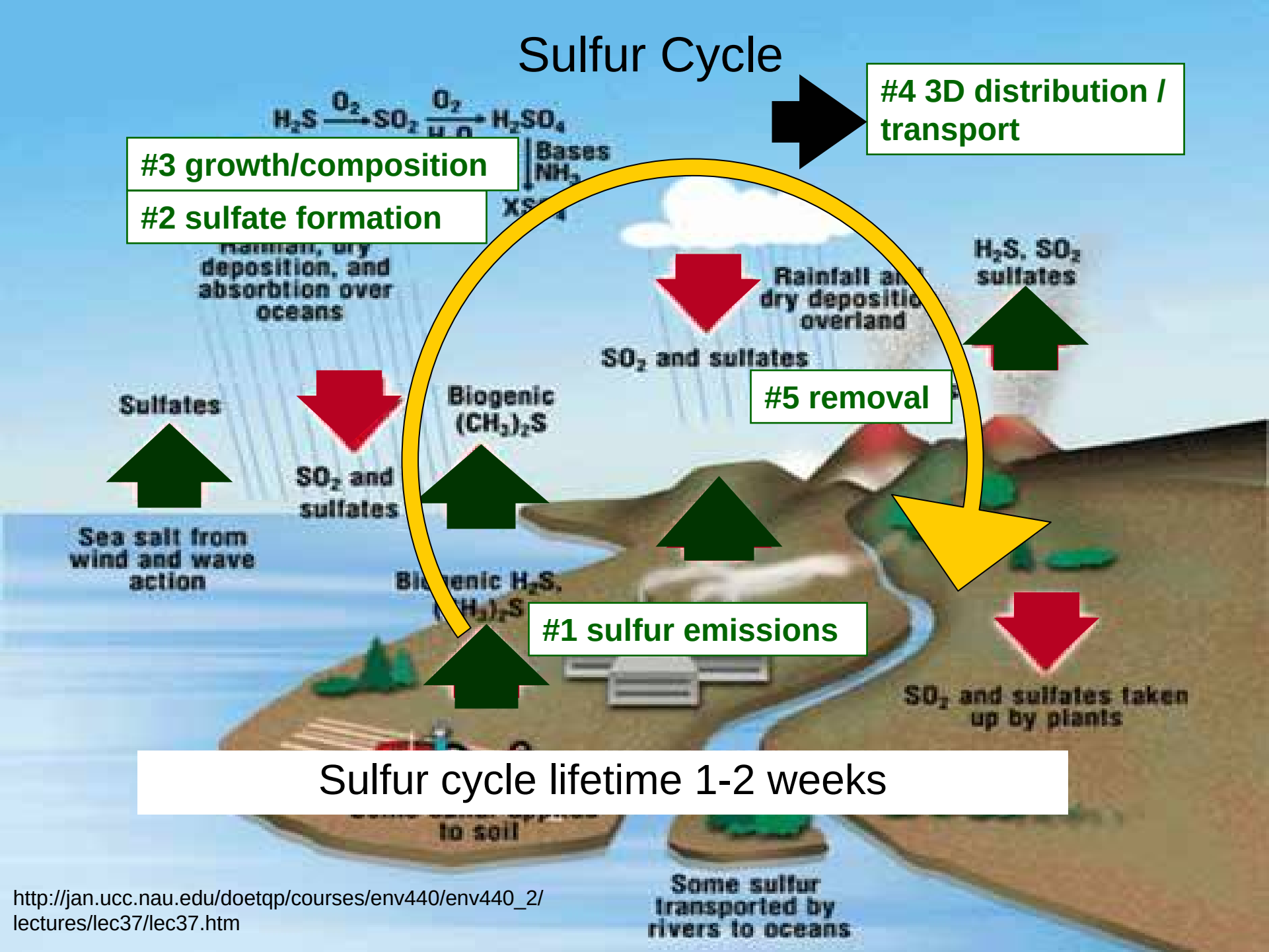
Type	Min. Size	Annual load	Anthro.	Key Source	RF (Wm^{-2})
Sulfate	0.01 um	110 Tg	75%	fossil fuels	-0.40
Black Carbon	0.01 um	22 Tg	100%	biomass	+0.20
Organic Carbon	0.01 um	130 Tg	80%	biomass	-0.10
Nitrate	0.01 um	50 Tg	50%	fossil fuels	-0.10
Dust	1 um	2000 Tg	40%	deserts	-0.10
Sea Salt	1 um	3000 Tg	0%	oceans	0
				Combined	-0.50

Human-influenced



Nucleation mode	Accumulation mode	Drizzle mode
CCN unactivated haze	GCCN cloud drops	drizzle

Sulfur Cycle

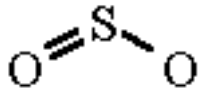


Sulfur cycle lifetime 1-2 weeks

http://jan.ucc.nau.edu/doetqp/courses/env440/env440_2/lectures/lec37/lec37.htm

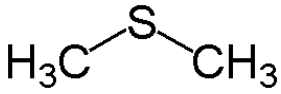
1. Sulfur emissions

combustion, industrial, volcanoes, biomass burning:

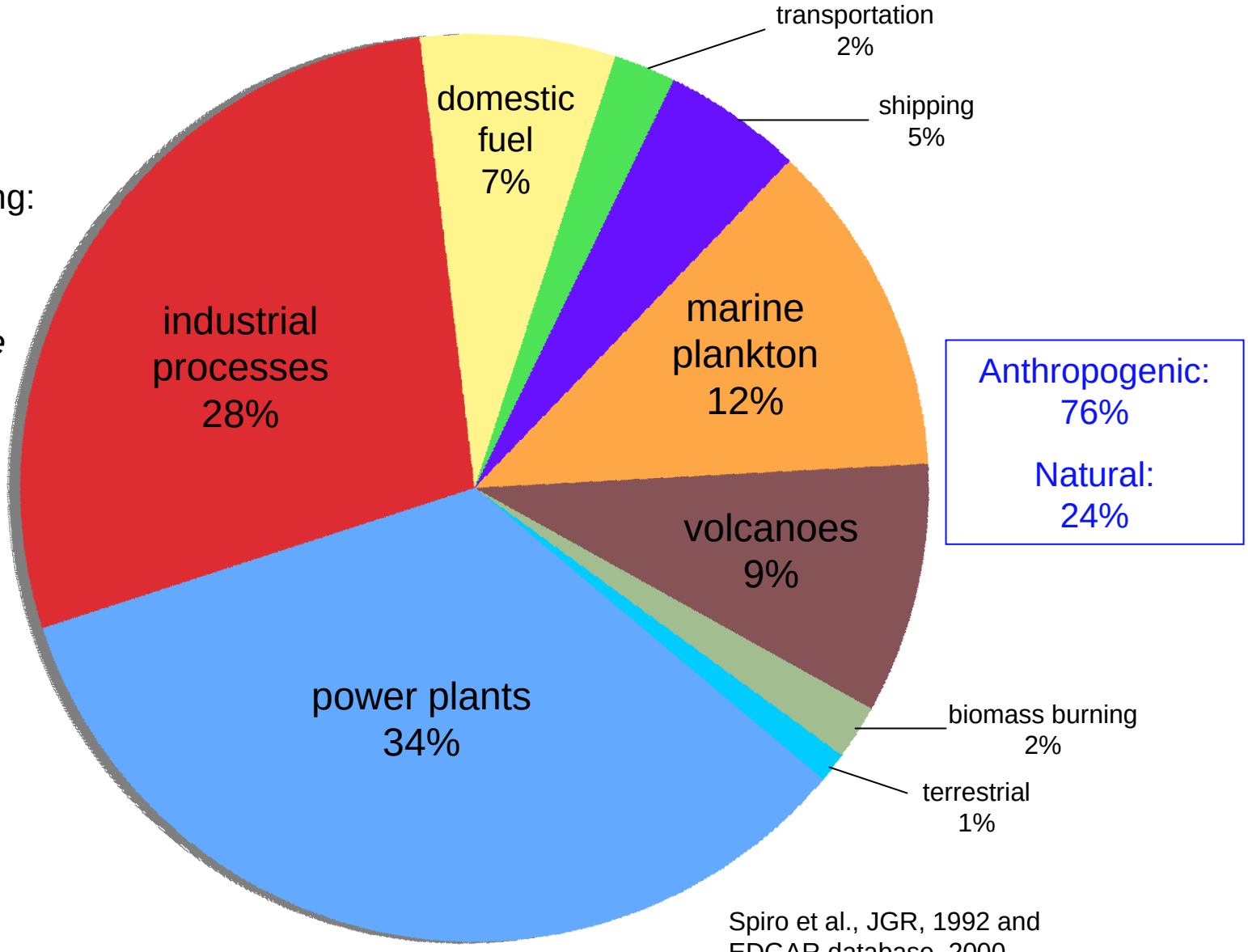


sulfur dioxide

Marine plankton:



dimethylsulfide



Anthropogenic: 76%

Natural: 24%

Spiro et al., JGR, 1992 and EDGAR database, 2000

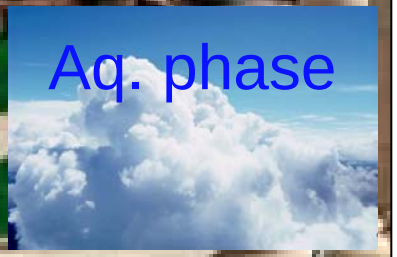
2. Sulfate Formation (Oxidation of SO_2)

Primary rxn: OH*

$$SO_2 + OH + M \rightarrow \underset{HOSO_2}{HSO_3} + M$$

$$\underset{HOSO_2}{HSO_3} + O_2 \rightarrow SO_3 + HO_2 \quad \text{(fast)}$$

$$SO_3 + H_2O + M \rightarrow H_2SO_4 + M \quad \text{(fast).}$$



Primary rxn: H_2O_2

$$SO_2(g) \leftrightarrow SO_2 \cdot H_2O$$

$$SO_2 \cdot H_2O \leftrightarrow HSO_3^- + H^+$$

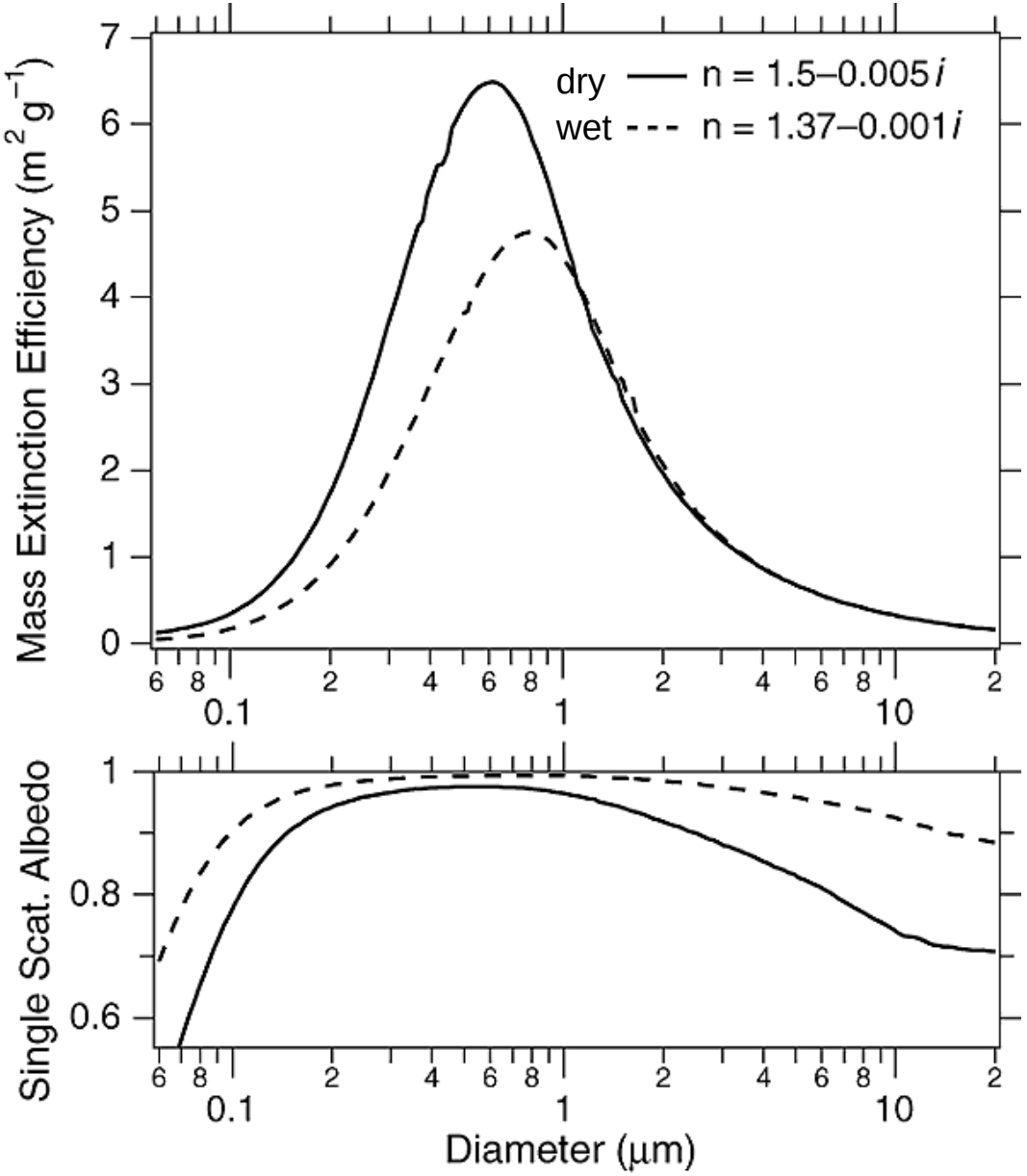
$$H_2O_2(g) \leftrightarrow H_2O_2(aq)$$

$$HSO_3^- + H_2O_2(aq) + H^+ \rightarrow SO_4^{2-} + 2H^+ + H_2O.$$

****OH involved with ~100 Trop. Rxns***

Barth et al, JGR 2000

Effect of size on RF



0.2 to 2 um diameters scatter the most light per unit mass

Hydration (dotted line) has higher SSA but less per unit aerosol mass

IPCC, 2001

How Models “deal with” Sulfates

	CAM3[a]	MOZART3	WACCM[b]	MOZART4[c]	CARMA in CAM
1. Emissions	SO_2, DMS	None	None	SO_2, DMS	SO_2, DMS
2. Formation (Reactions)	Full sulfur; limited OH*	None (106 non-sulfur)	None (106 non-sulfur)	Full sulfur; Full OH	Full sulfur; limited OH*
3. Growth, Composition	None	None	None	None	Yes (substeps)
4. Transport (Dynamics)	Built-in	Separate Driver (CAM, NCEP etc)	Separate Driver (CAM)	Separate Driver (CAM, NCEP etc)	Built-in
5. Removal	Dry,wet dep, layer scavenging	Dry, wet dep	Dry, wet dep	Dry, wet dep	Dry,wet dep, layer scavenging

[a]Described in Barth et al JGR 2000

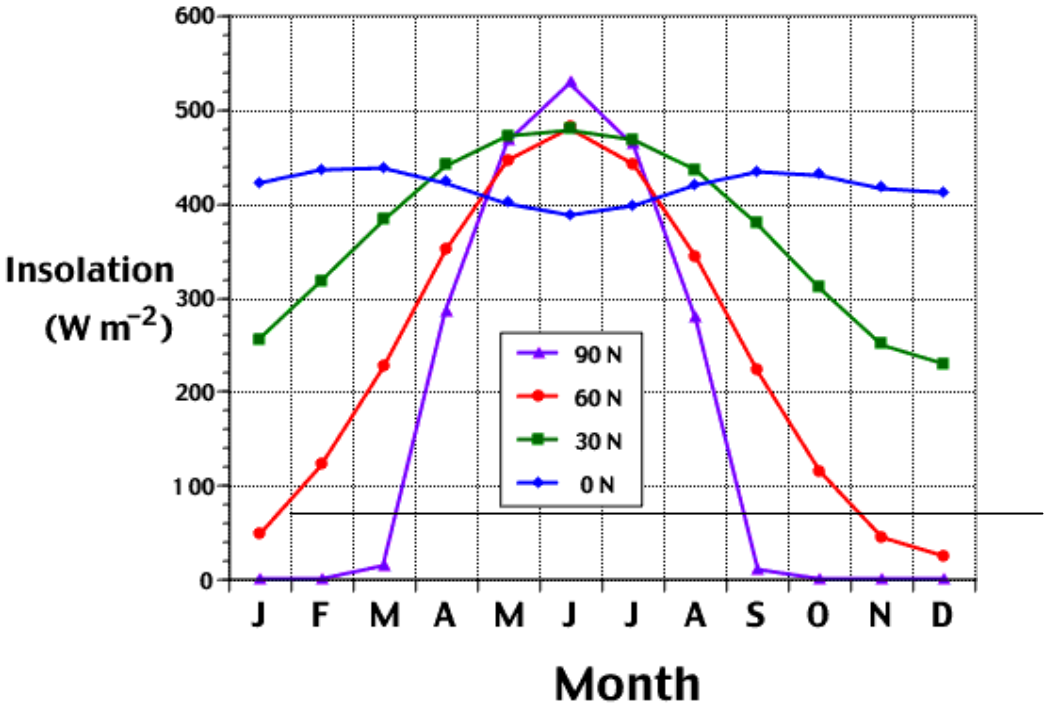
[b]Current WACCM uses MOZART3, CAM w/sulfur turned off

[c]MOZART4 is under development at NCAR (Loisa Emmons)

*CAM_CHEM is under development at NCAR (Francis Vitt)

Question to answer

- If regional aerosol RF is high enough, can it alter global circulation; causing climate change in other regions?



Global aerosol RF:
-0.5 W/m^2

Asia aerosol RF:
-10 to -50 W/m^2
(includes natural)

Sulfur Emissions Dataset

- Source: GEIA Emissions Dataset, 1990
  - Seasonal projections every 15 years (1990-2095)
  - 1°x 1° Flux resolution (kg / m^2 / s)
- CAM translates the data by
  - converting emissions data grid to simulation data grid (4x5)
  - Keeping emissions constant until next 15-year period
- SOx field : 4 dimension array
  1. Date field=32
     - Seasonal (4) emissions/year x 8 unique years
  2. Levels=2
     - 0 m, 100m
  3. Latitude=46
     - 4 degree increments; 180 degrees total
  4. Longitude=72
     - 5 degree increments; 360 degrees total

Scenario Designs

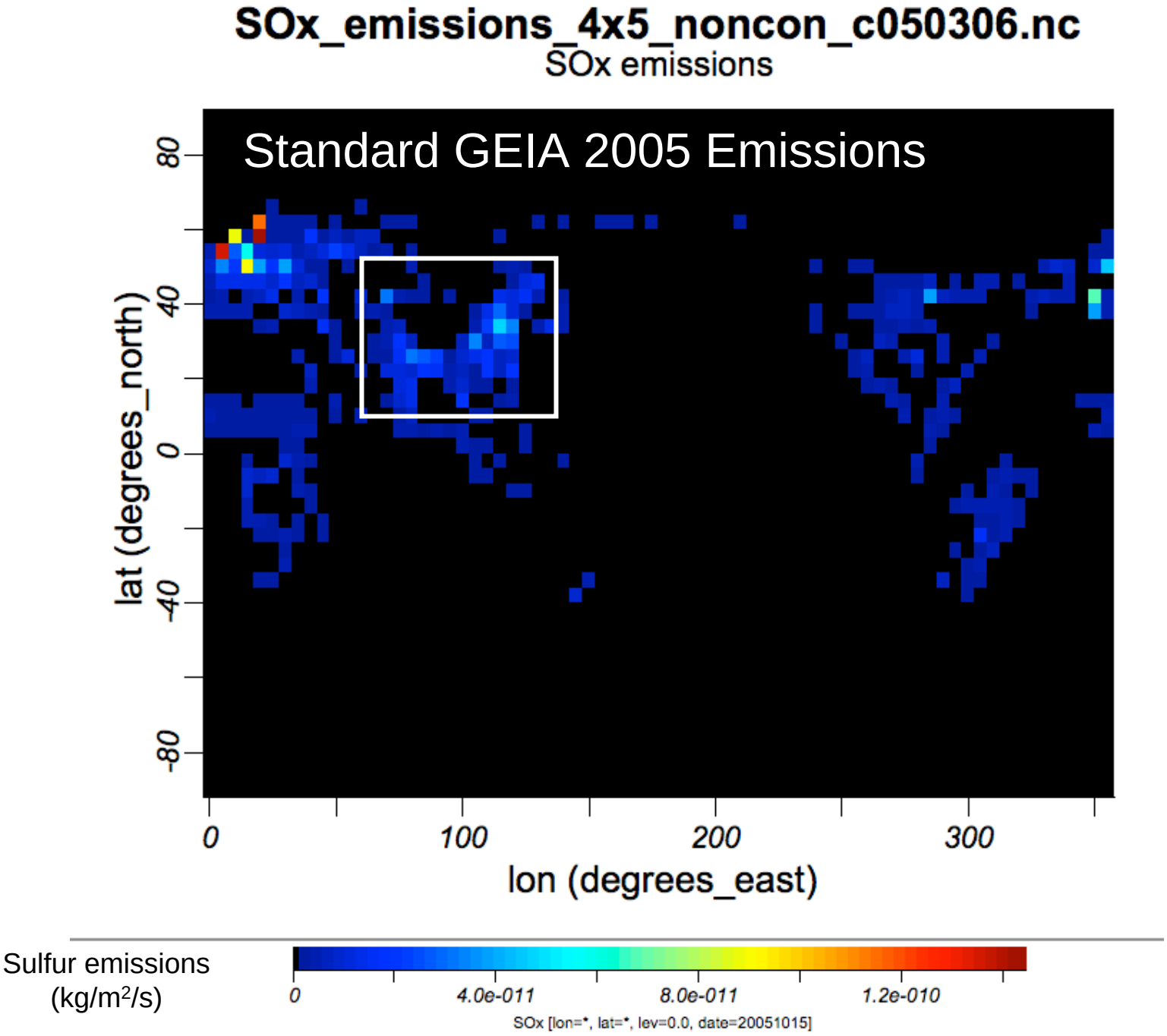
1. Base Case
   - 4°x 5° resolution
   - CO_2 1% increase/yr
   - Sulfur: Prognostic="Active"
   - 2005-2028; compared 14yr averages (2015-2028)

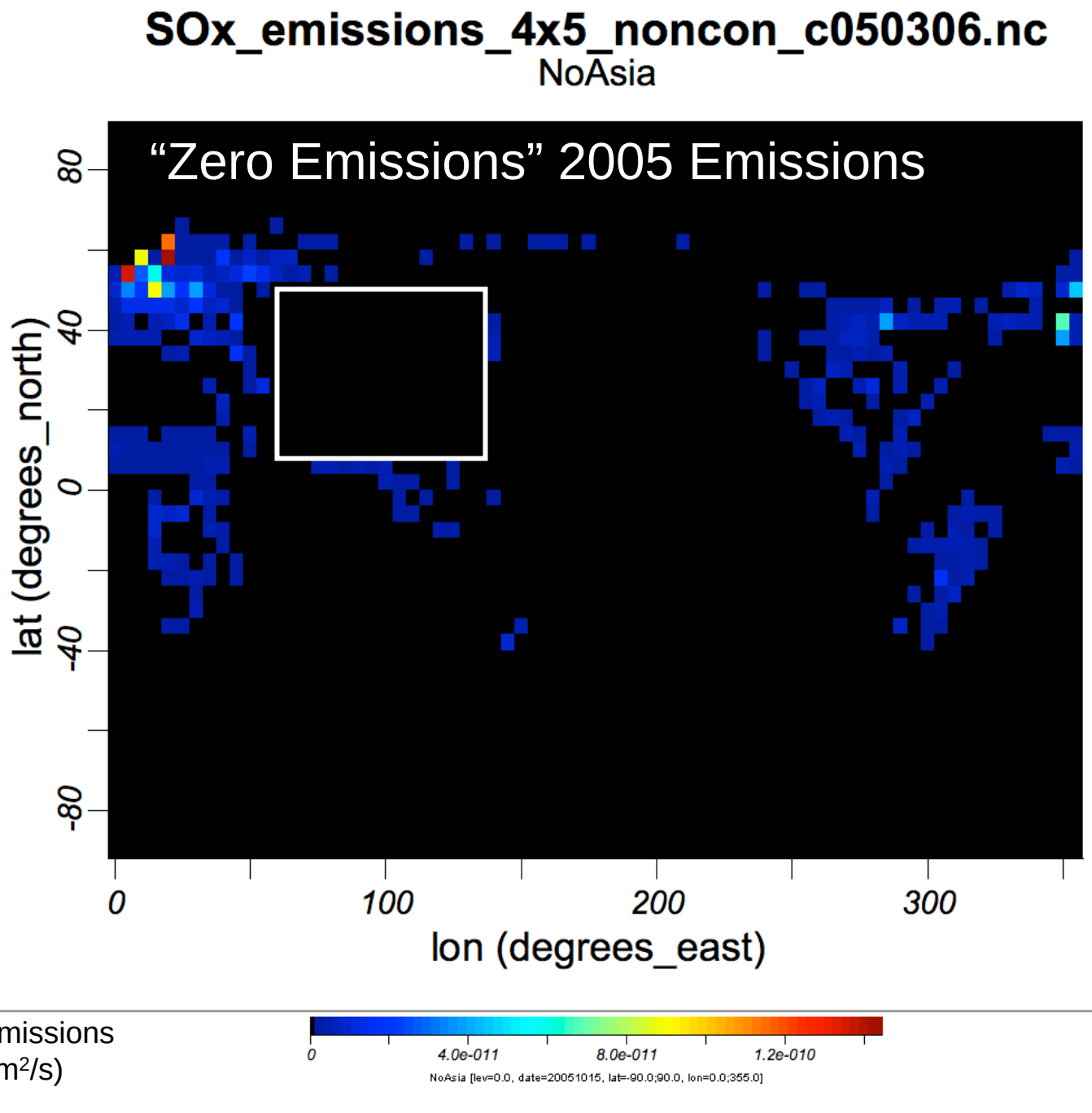
2. Zero Asian sulfur Emissions
   - Set emissions to zero for 8°-52° latitude; 60°-135° longitude

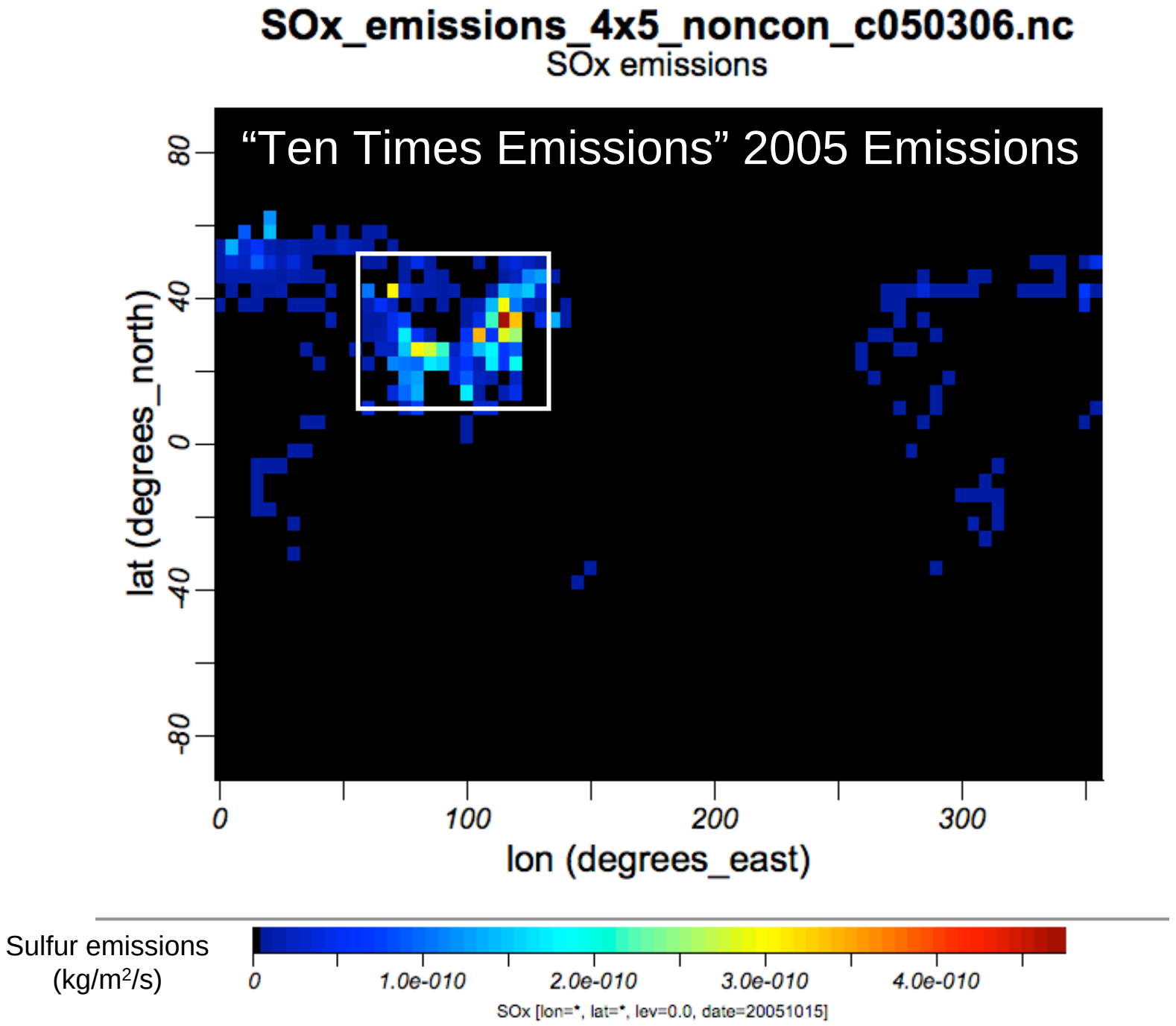
3. 10x Asian sulfur Emissions
   - Multiplied each grid box by 10 for 8°-52° latitude; 60°-135° longitude

Anthropogenic Sulfur Emissions by Scenario (Annual Average 2005-2025)

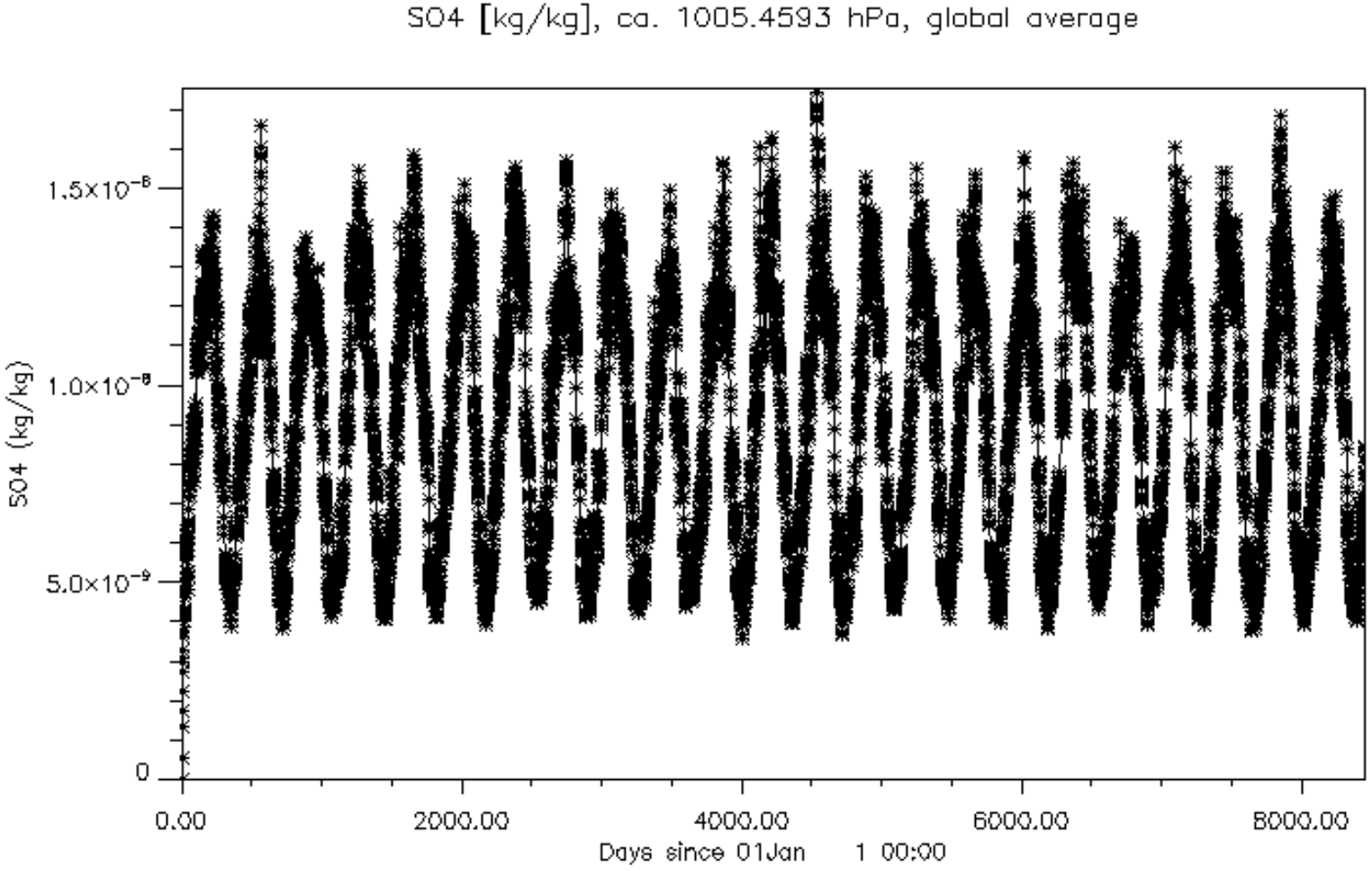
Scenario	Total Emissions	"Asian" Emissions 8°-52° latitude; 60°-135° longitude	
CAM Default	0 Tg	0 Tg	0% of total
Base Case	73 Tg	29 Tg	40% of total
Zero Asian	44 Tg	0 Tg	0% of total
10x Asian	335 Tg	290 Tg	87% of total


SOx_emissions_4x5_noncon_c050306.nc
SOx emissions
Standard GEIA 2005 Emissions
lat (degrees_north)
80
40
0
-40
-80
0
100
200
300
lon (degrees_east)
Sulfur emissions
(kg/m2/s)
0
4.0e-011
8.0e-011
1.2e-010
SOx [lon=*, lat=*, lev=0.0, date=20051015]


SOx_emissions_4x5_noncon_c050306.nc
NoAsia
“Zero Emissions” 2005 Emissions
lat (degrees_north)
80
40
0
-40
-80
0
100
200
300
lon (degrees_east)
Sulfur emissions
(kg/m2/s)
0
4.0e-011
8.0e-011
1.2e-010
NoAsia [lev=0.0, date=20051015, lat=-90.0;90.0, lon=0.0;355.0]

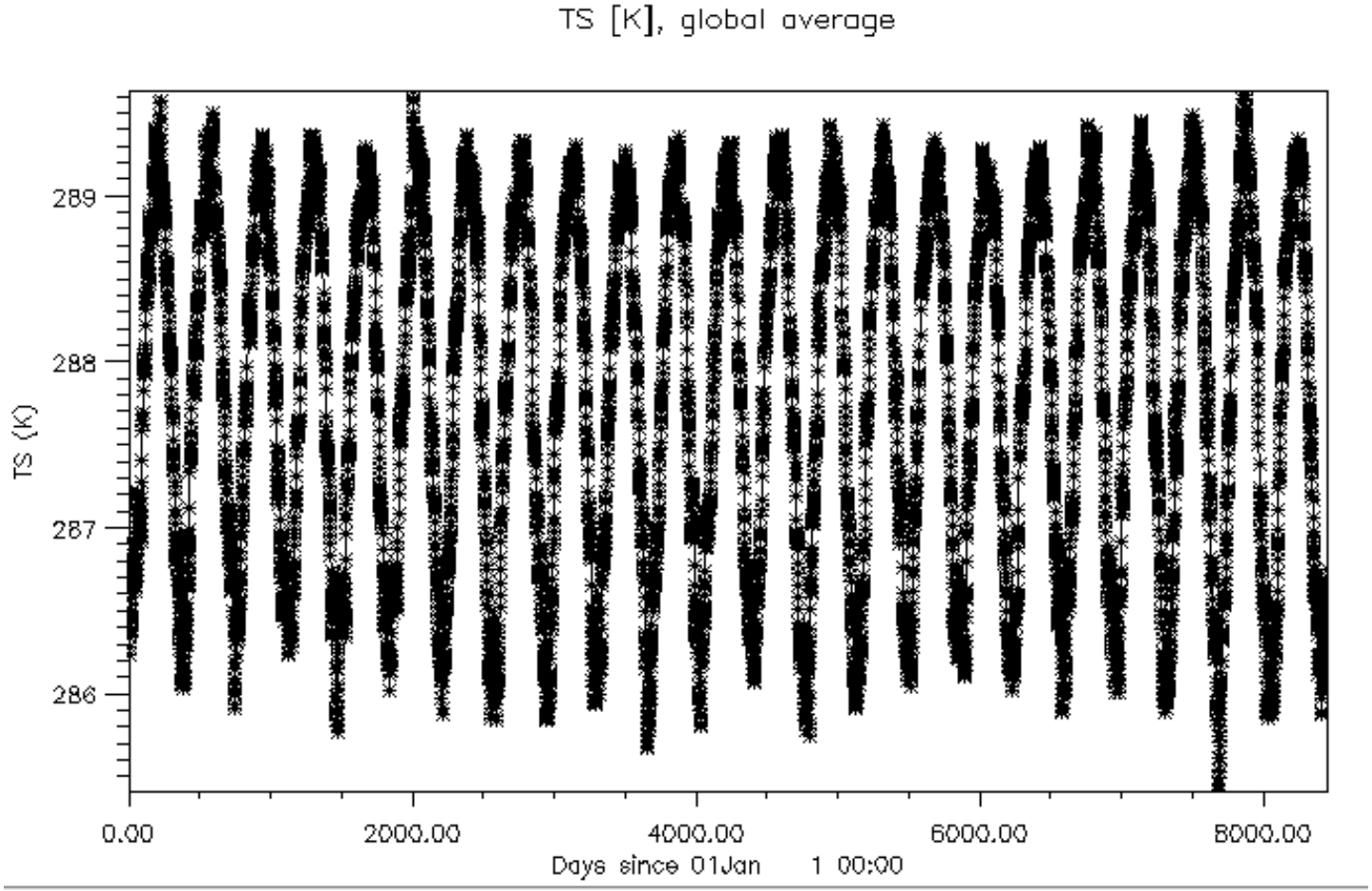

SOx_emissions_4x5_noncon_c050306.nc
SOx emissions
“Ten Times Emissions” 2005 Emissions
lat (degrees_north)
80
40
0
-40
-80
0
100
200
300
lon (degrees_east)
Sulfur emissions
(kg/m2/s)
0
1.0e-010
2.0e-010
3.0e-010
4.0e-010
SOx [lon=*, lat=*, lev=0.0, date=20051015]

SO4 load, base case 2005-2028



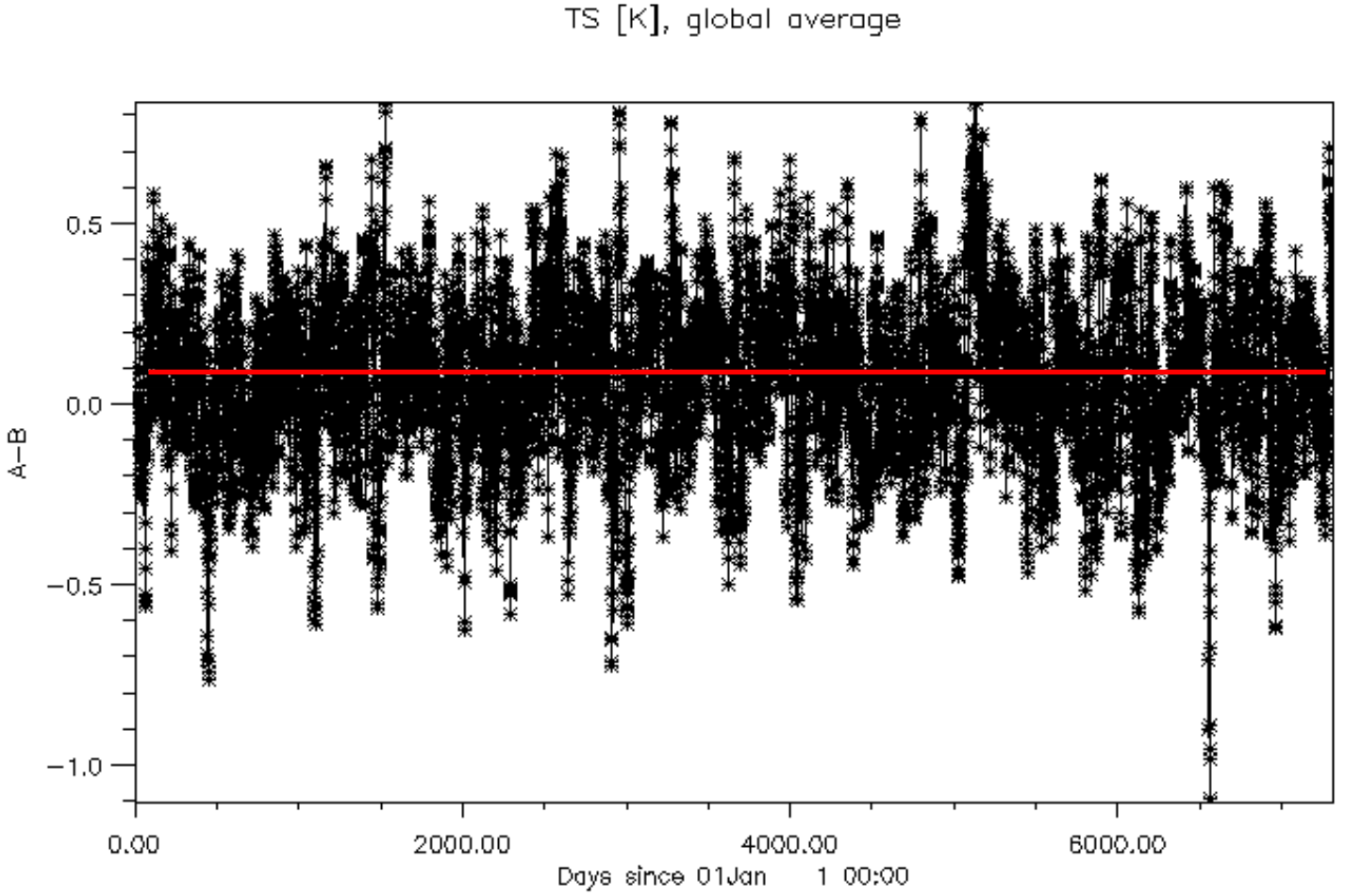
Global Atmospheric SO4 load is roughly constant from 2005-2025
Oscillation mirrors season emissions rate

Global Surface T, base case 2005-2028



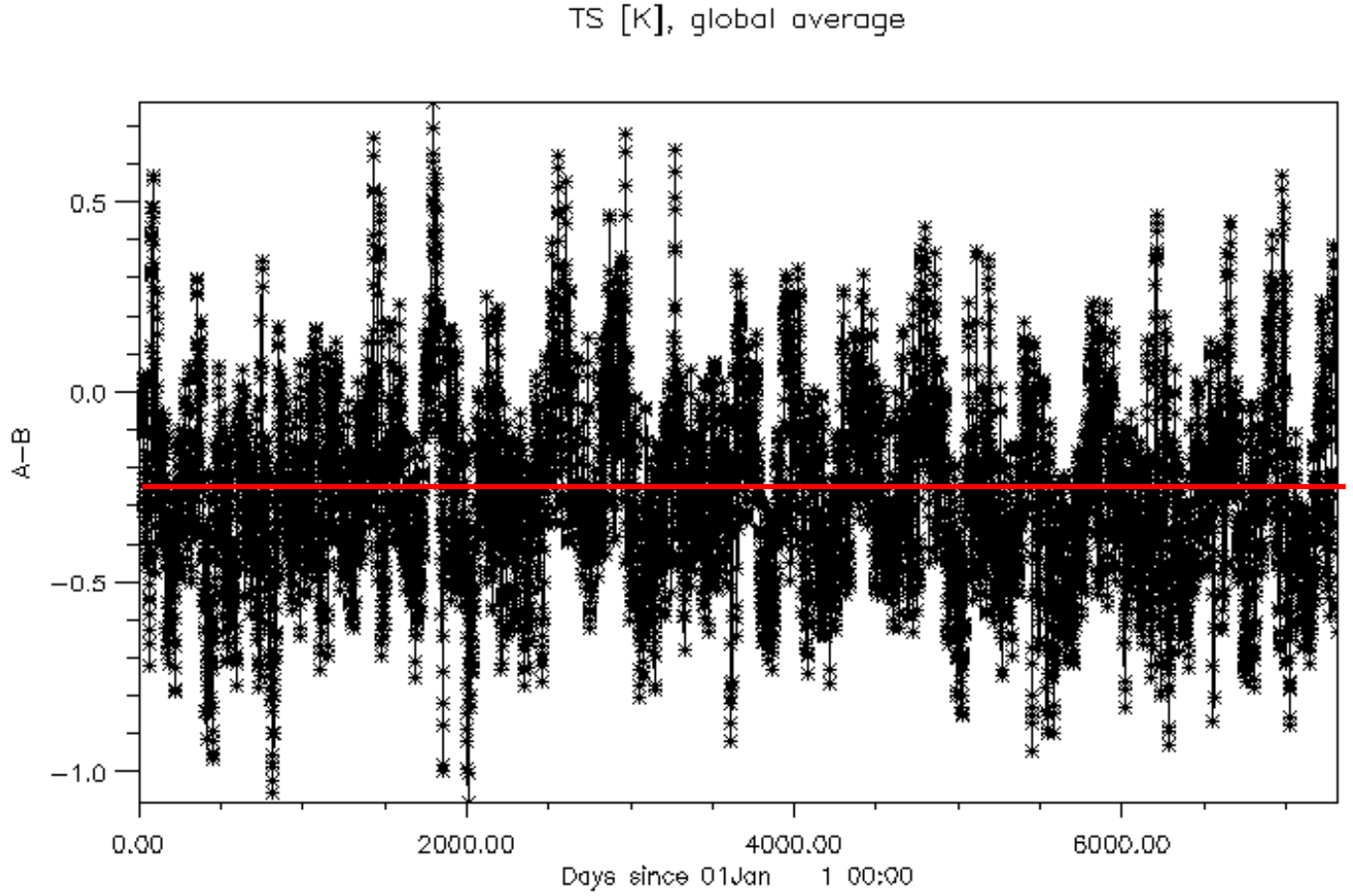
Global surface T roughly constant from 2005-2028 (aerosols cancel out +1% CO2)
Oscillation is due to seasonal emissions rate combined with difference in land area between N. and S. Hemisphere summer

Global Avg Surface Temp Change (Base Case - Zero emissions simulation)



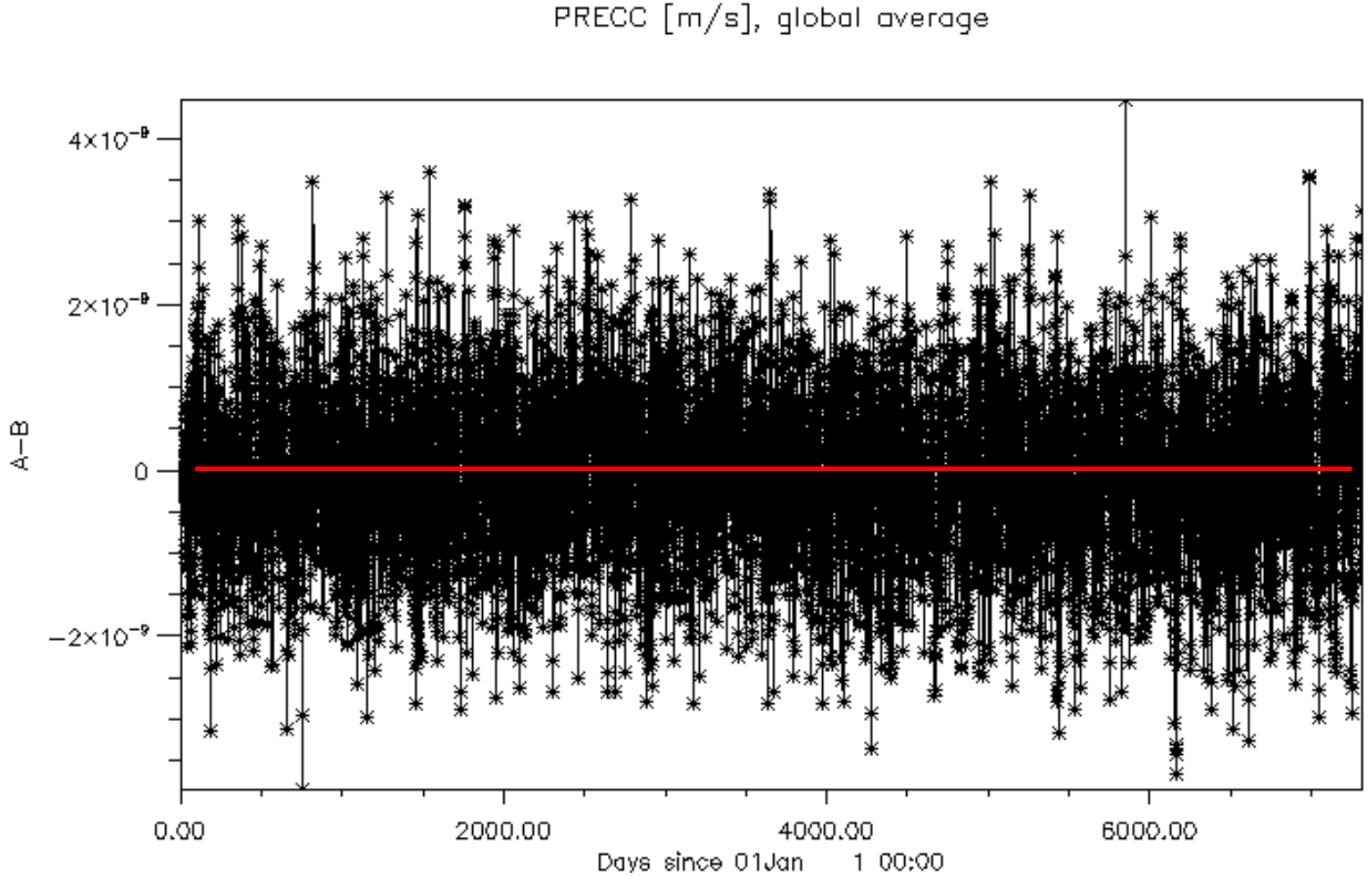
~0.1 deg C increase in global avg sfc Temperature

Global Avg Surface Temp Change (Base Case - 10x simulation)



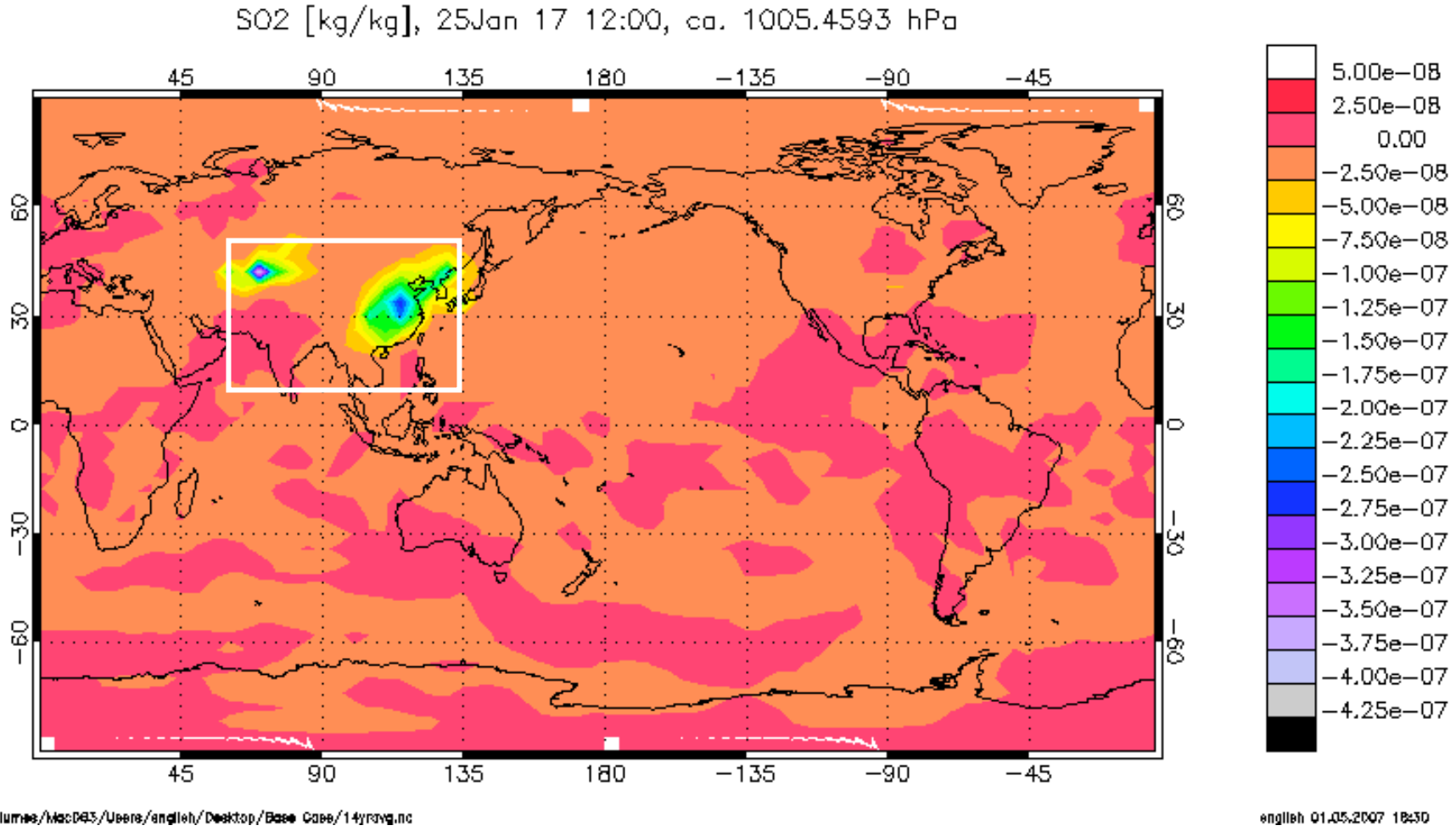
~0.3 deg C decrease in global avg sfc temp (why such a small difference? This is +300 Tg sulfur!)

Global Avg Convective Precip Change (Base Case - Zero emissions simulation)

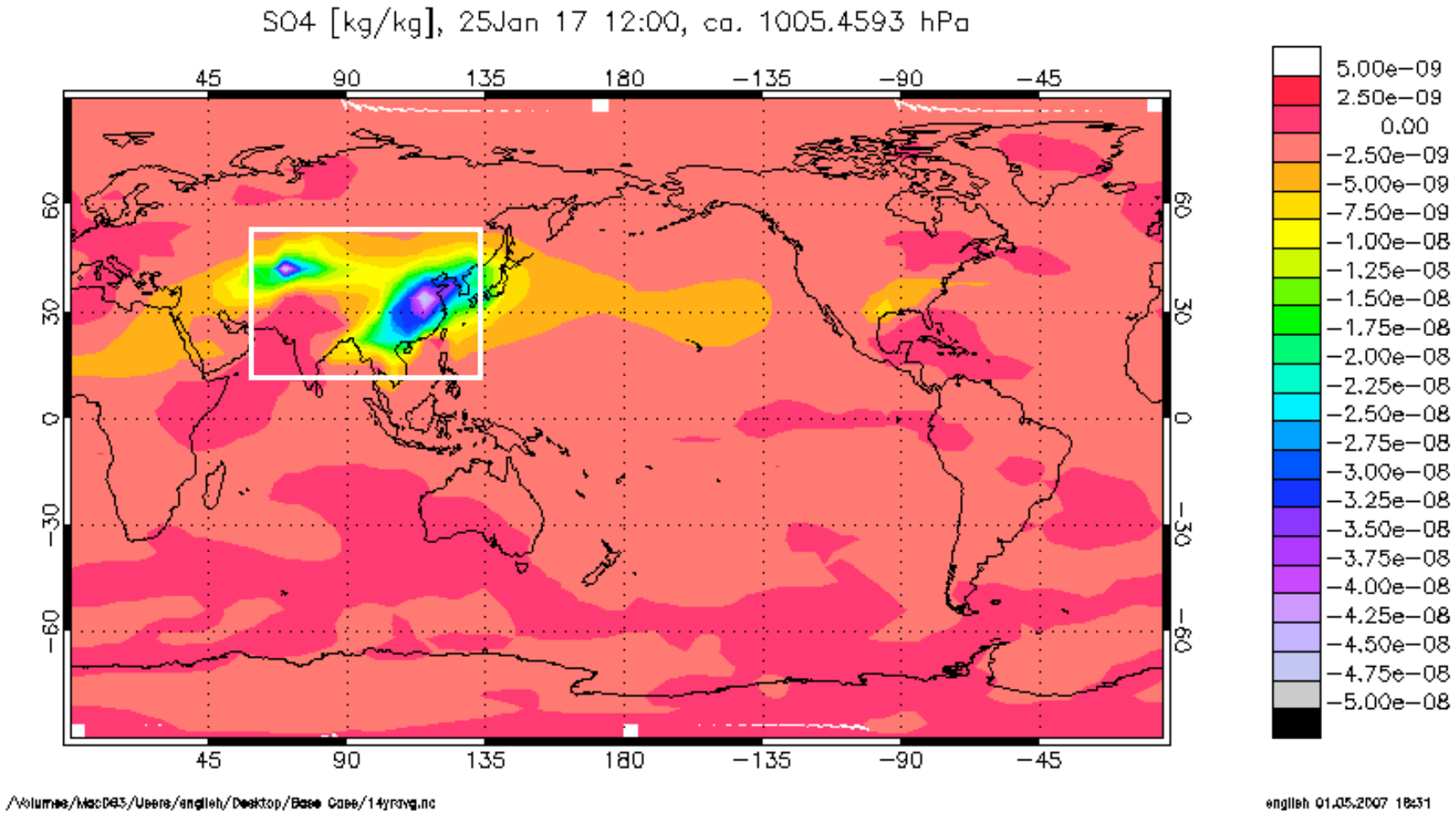


No change in global average Precip (why…? Poor atmosphere-ocean coupling? Decrease in Indian monsoon?)

Avg SO_2 change 2015-2028
Zero Emissions Scenario

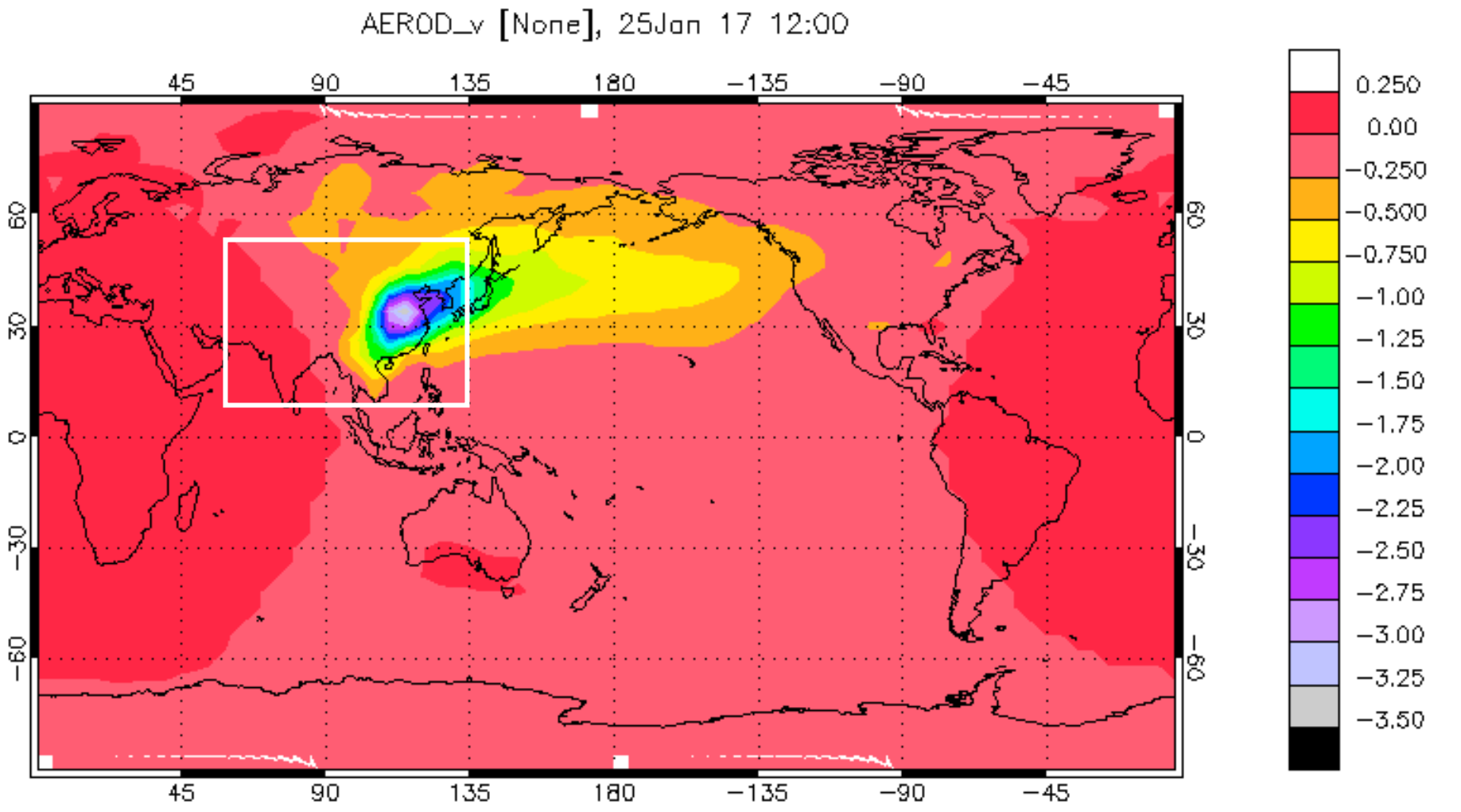


Avg SO_4 change 2015-2028
Zero Emissions Scenario



Optical Depth Decreases by 3.5 in formerly heavy emissions regions
Zonal Transport also decreases Optical depth across Pacific Ocean

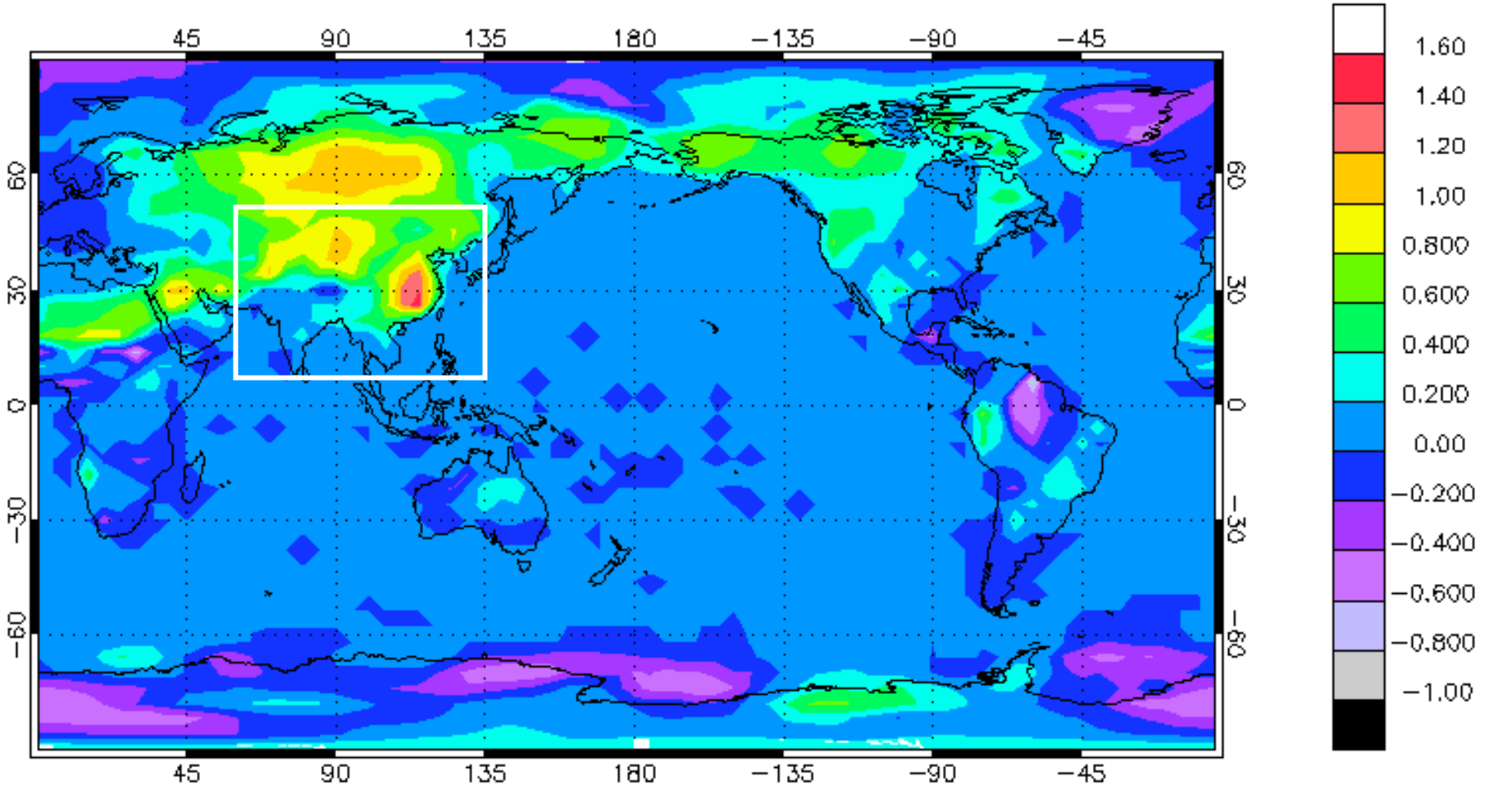
Avg O.D. change 2015-2028
Zero Emissions Scenario



Optical Depth Decreases by 3.5 in formerly heavy emissions regions
Zonal Transport also decreases Optical depth across Pacific Ocean
This seems too high by a factor of 10…. (averaging problem)

Avg Surface Temp Change 2015-2028
Zero Emissions Scenario

T change (K): (Zero scenario - base case)

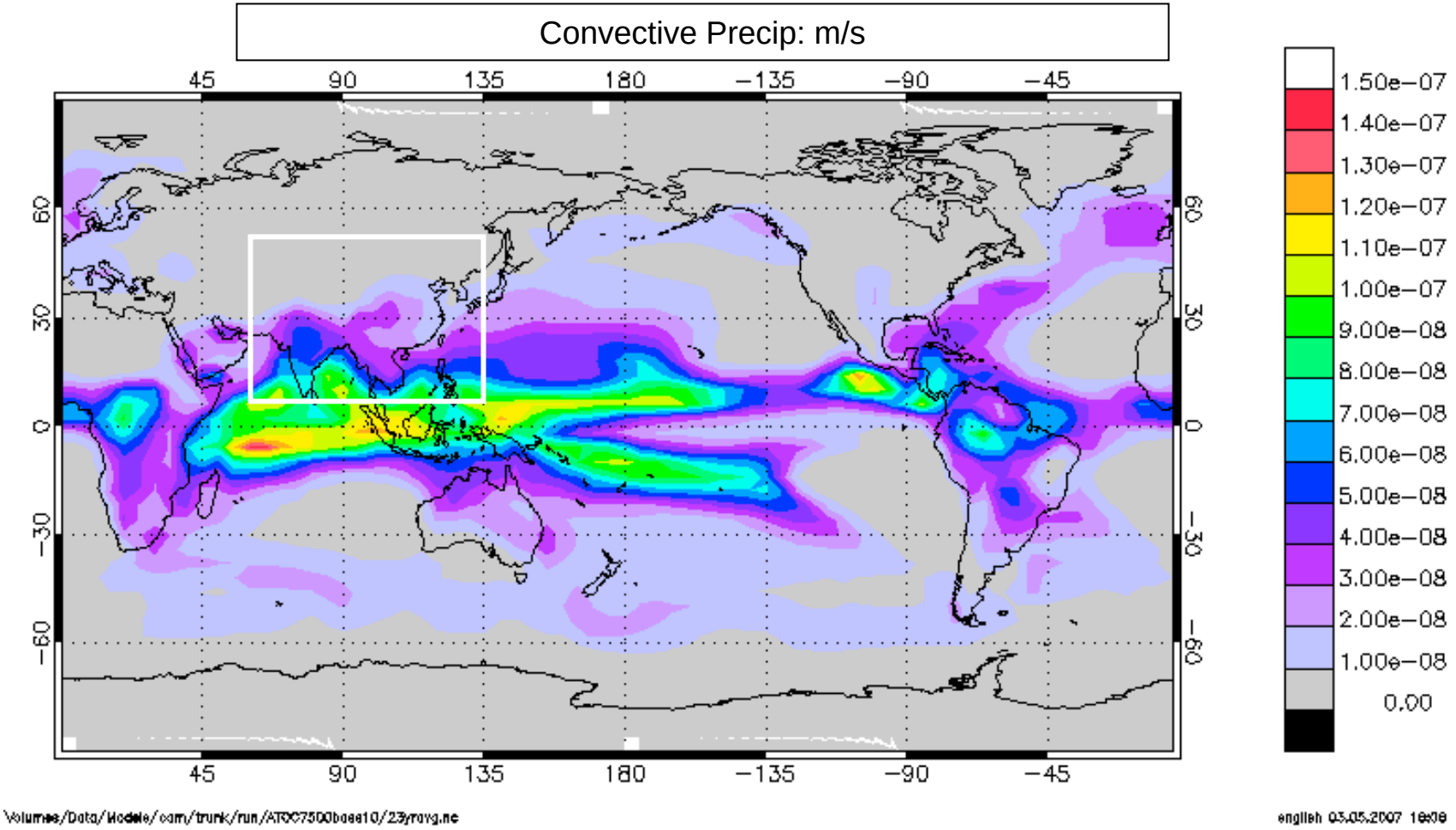


/Volumes/Dol

Warming where aerosols are removed
No change over oceans
Warming in Siberia, N.A., Cooling in Greenland, Brazil

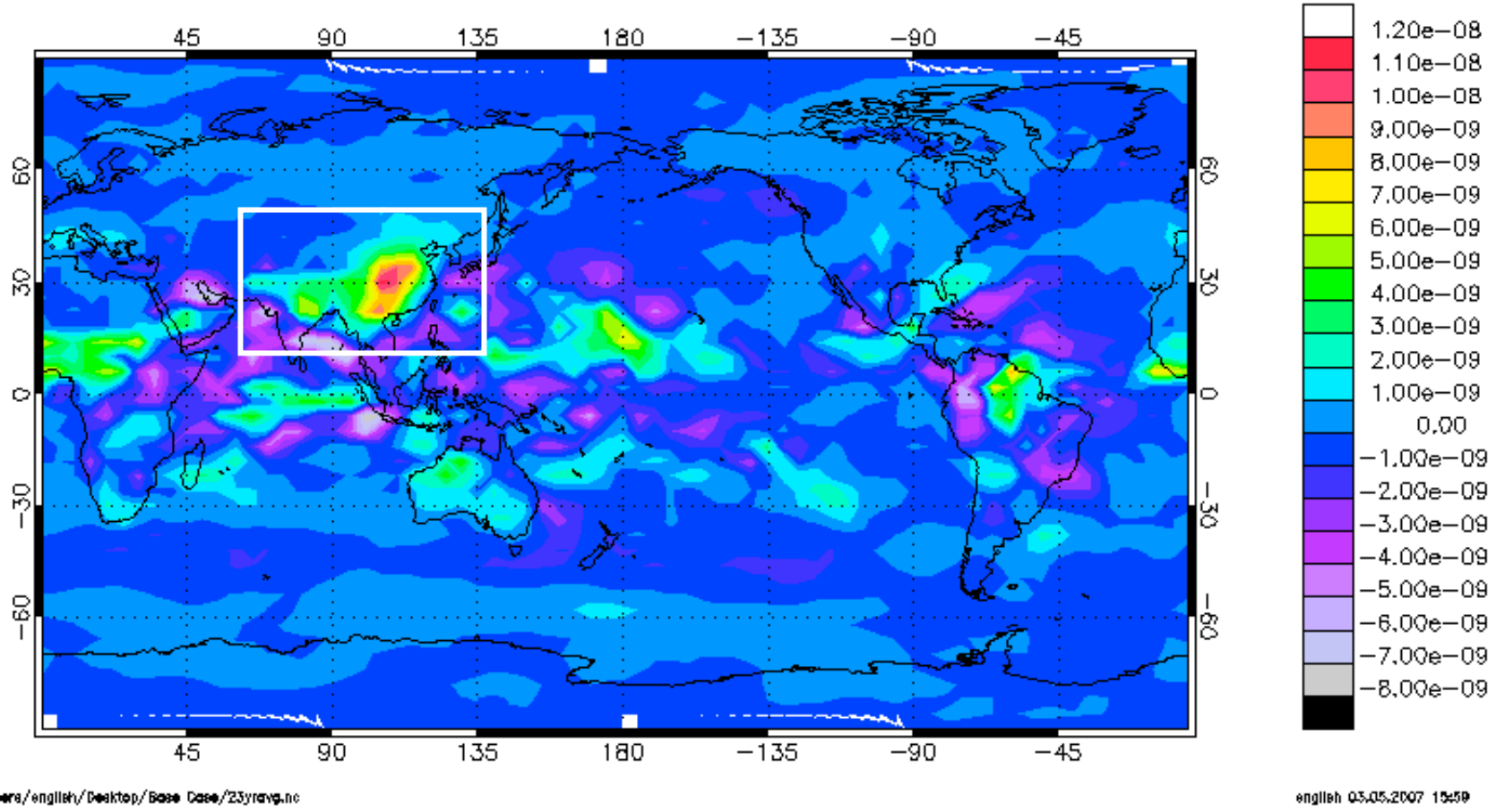
h 30.04.2007 16:55

Avg Convective Precip 2015-2028
Zero Emissions Scenario



Avg Convective Precip Change 2015-2028
Zero Emissions Scenario

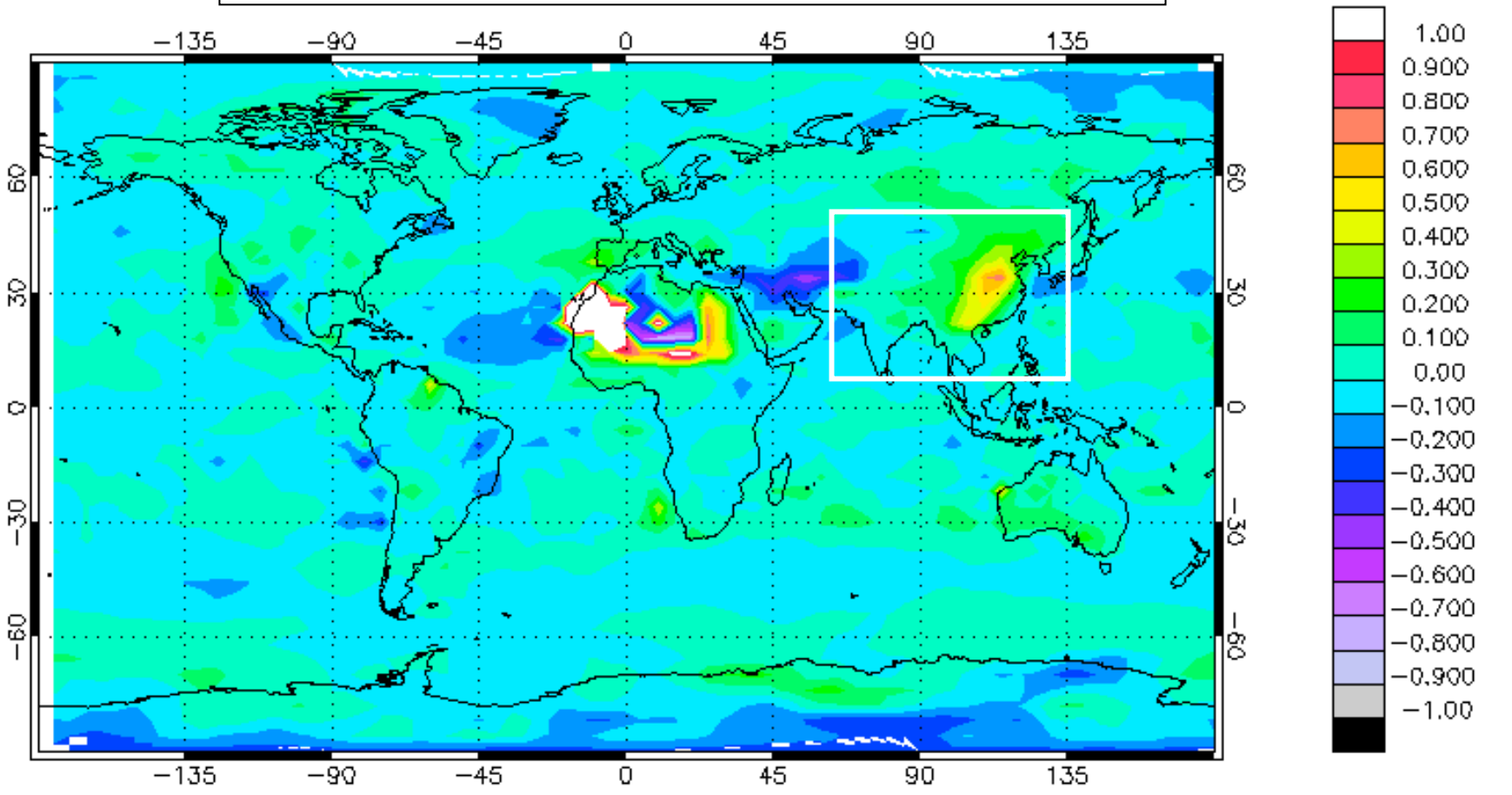
Precip change (m/s): (Zero scenario - base case)



Increase in convective precip over Asia (more RF, more vertical velocity)
Increase in ~10 deg N, decrease at the Equator (except near Asia)
Evidence of a northward shift of Asian Monsoon / ITCZ?

Avg Convective Precip Change 2015-2028
Zero Emissions Scenario

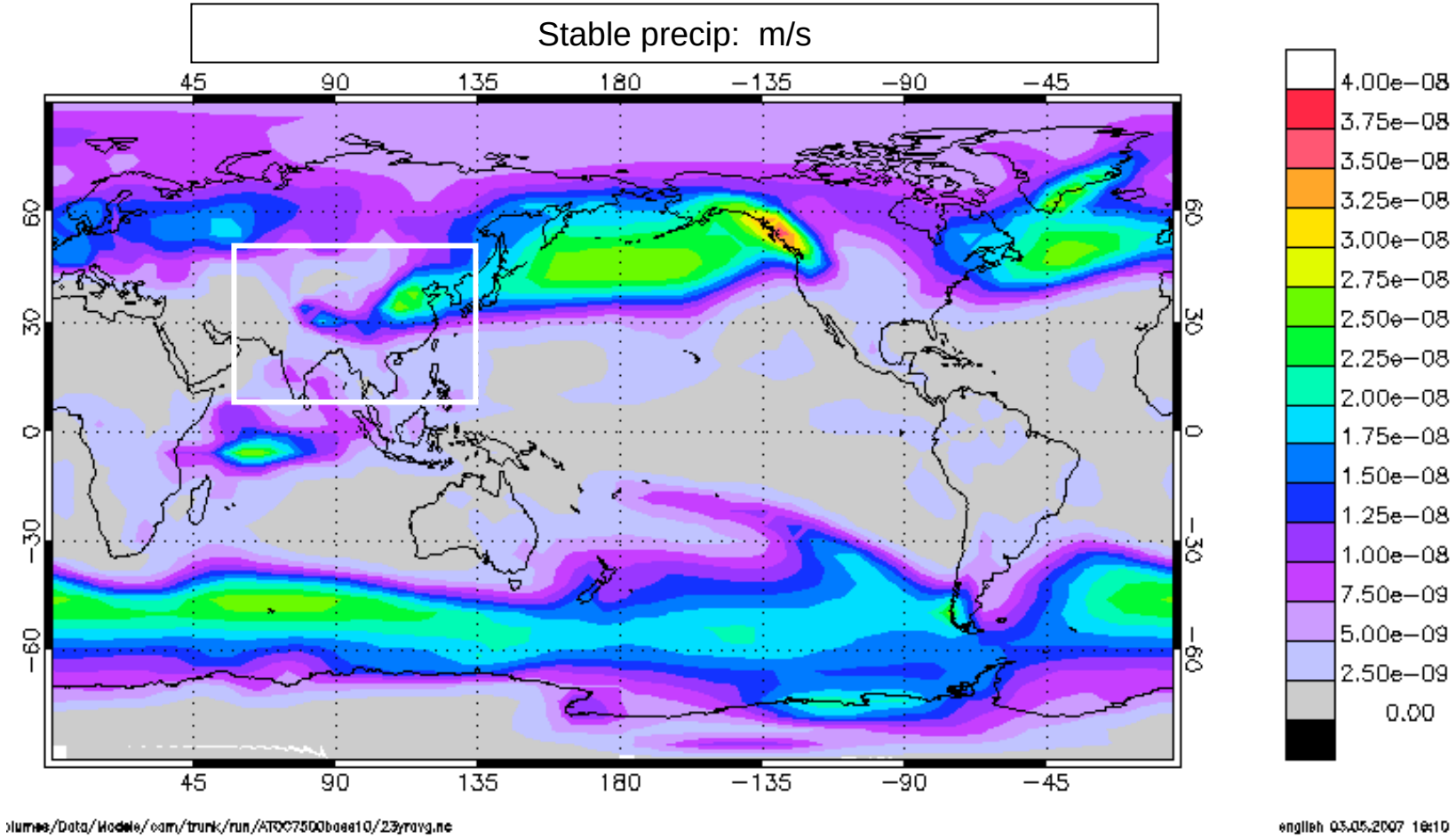
Frac.Precip.increase: (Zero scenario - base case) / base case



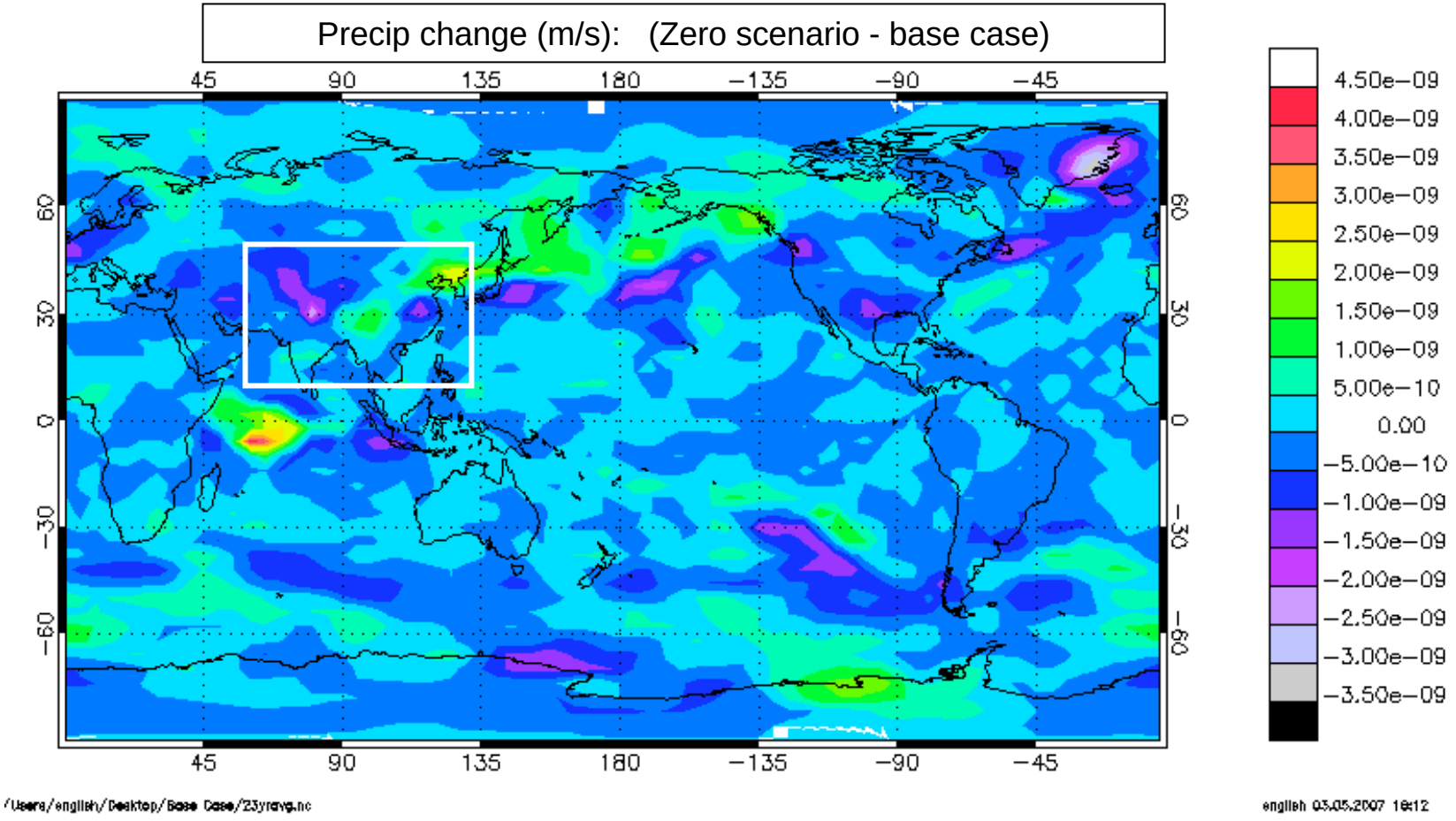
60% increase in convective precip over Asia (more RF, more vertical velocity)
10 fold increase in precip over Sahara (but tiny difference since it is so dry)
60% decrease over parts of Middle East
Evidence of a ITCZ shift?

1.05.2007 19:02

Avg Stable Precip 2015-2028
Zero Emissions Scenario



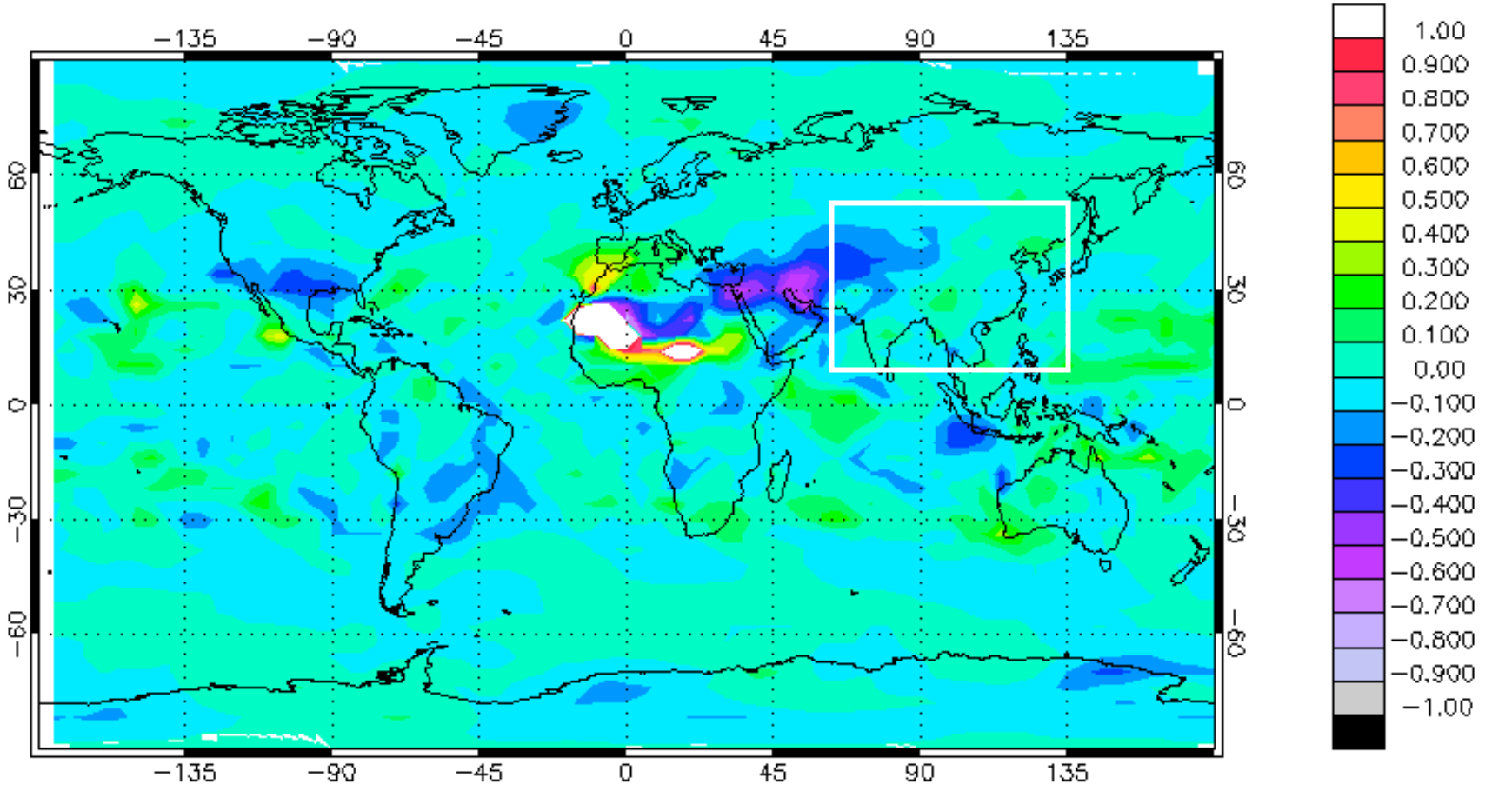
Avg Stable Precip Change 2015-2028
Zero Emissions Scenario



Decrease in stable precip around 30 deg N, increase just to the N and S of that
Evidence of a ITCZ shift to the North?

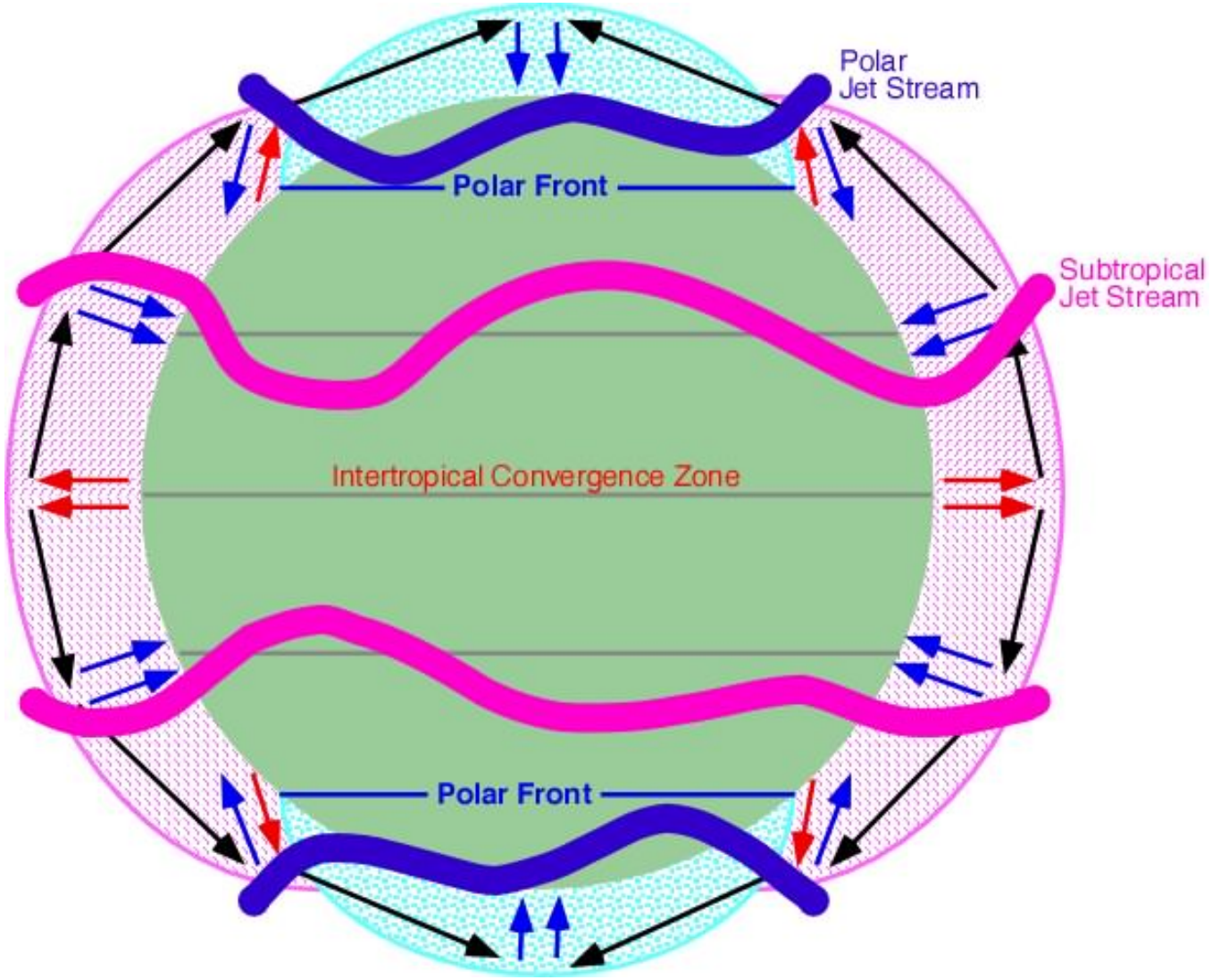
Avg Stable Precip Change 2015-2028
Zero Emissions Scenario

Frac.Precip.increase: (Zero scenario - base case) / base case



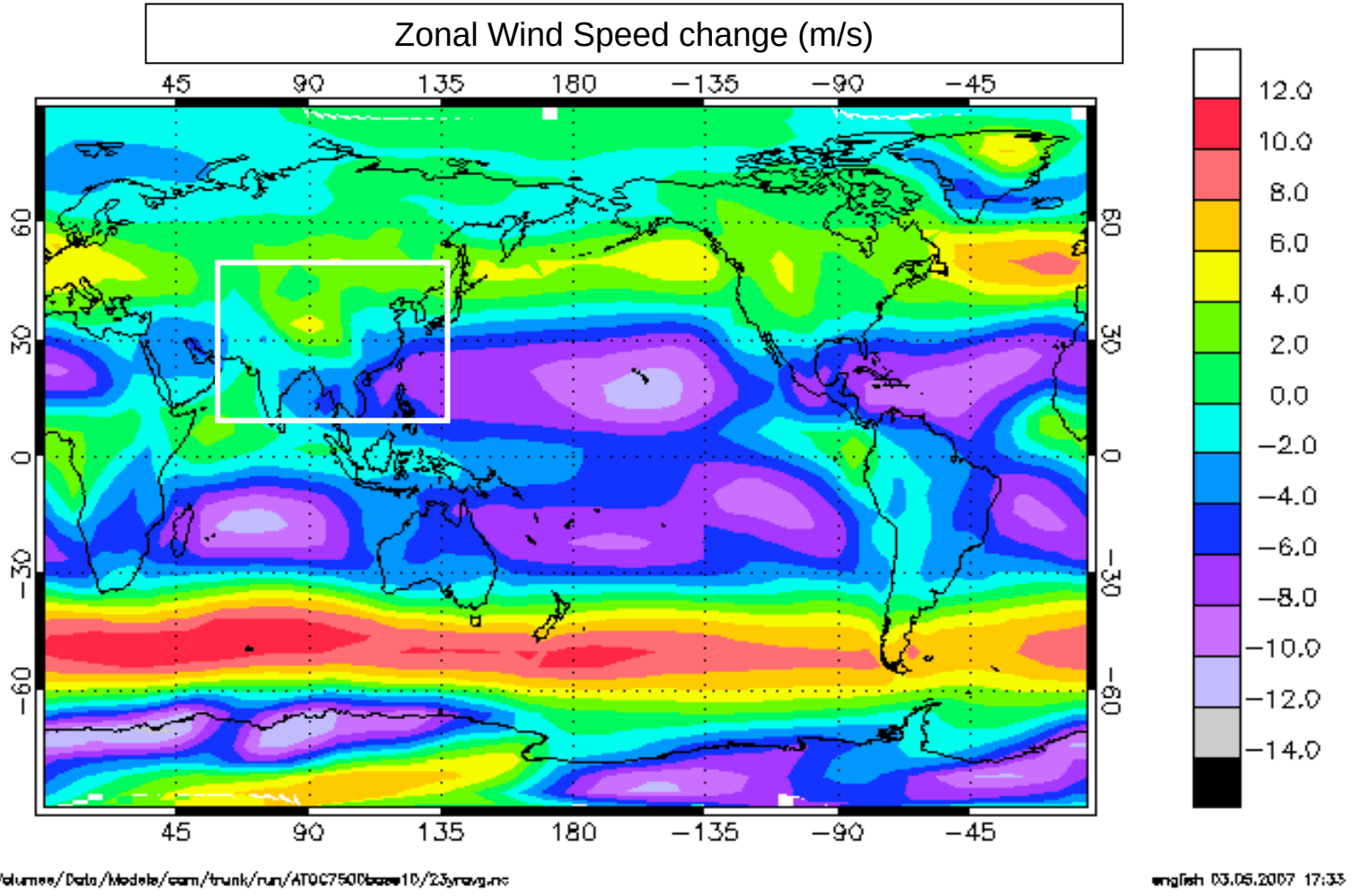
- No change in stable precip over Asia (no global circulation changes in this region)
  10 fold increase in precip over Sahara (but tiny difference since it is so dry)
  60% decrease over parts of Middle East
  Evidence of a ITCZ shift?

Zonal Circulation



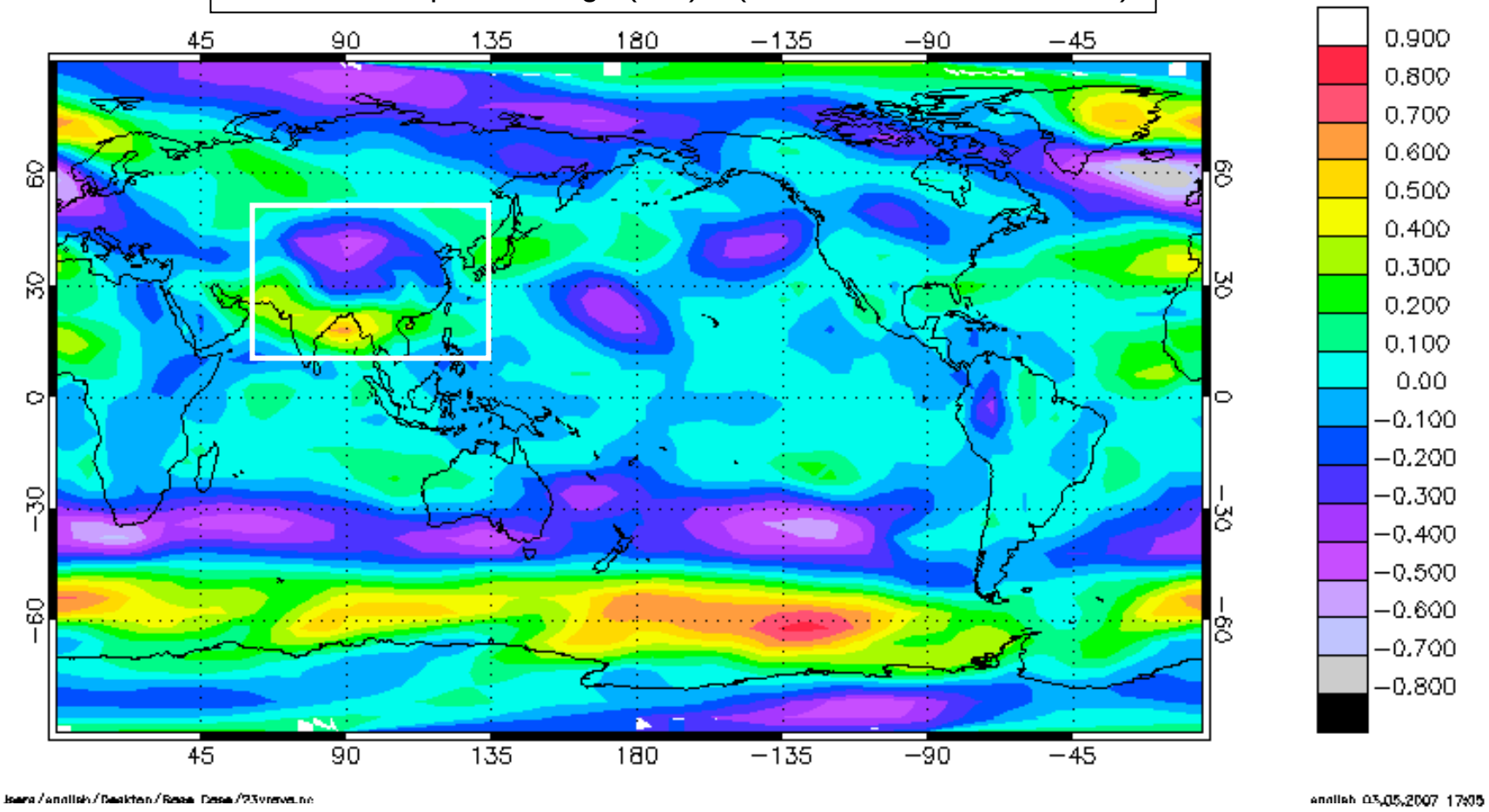
Zonal Winds - Zero Emissions 2015-2028

Zero Emissions Scenario



Change in Horizontal Winds 2015-2028
Zero Emissions Scenario

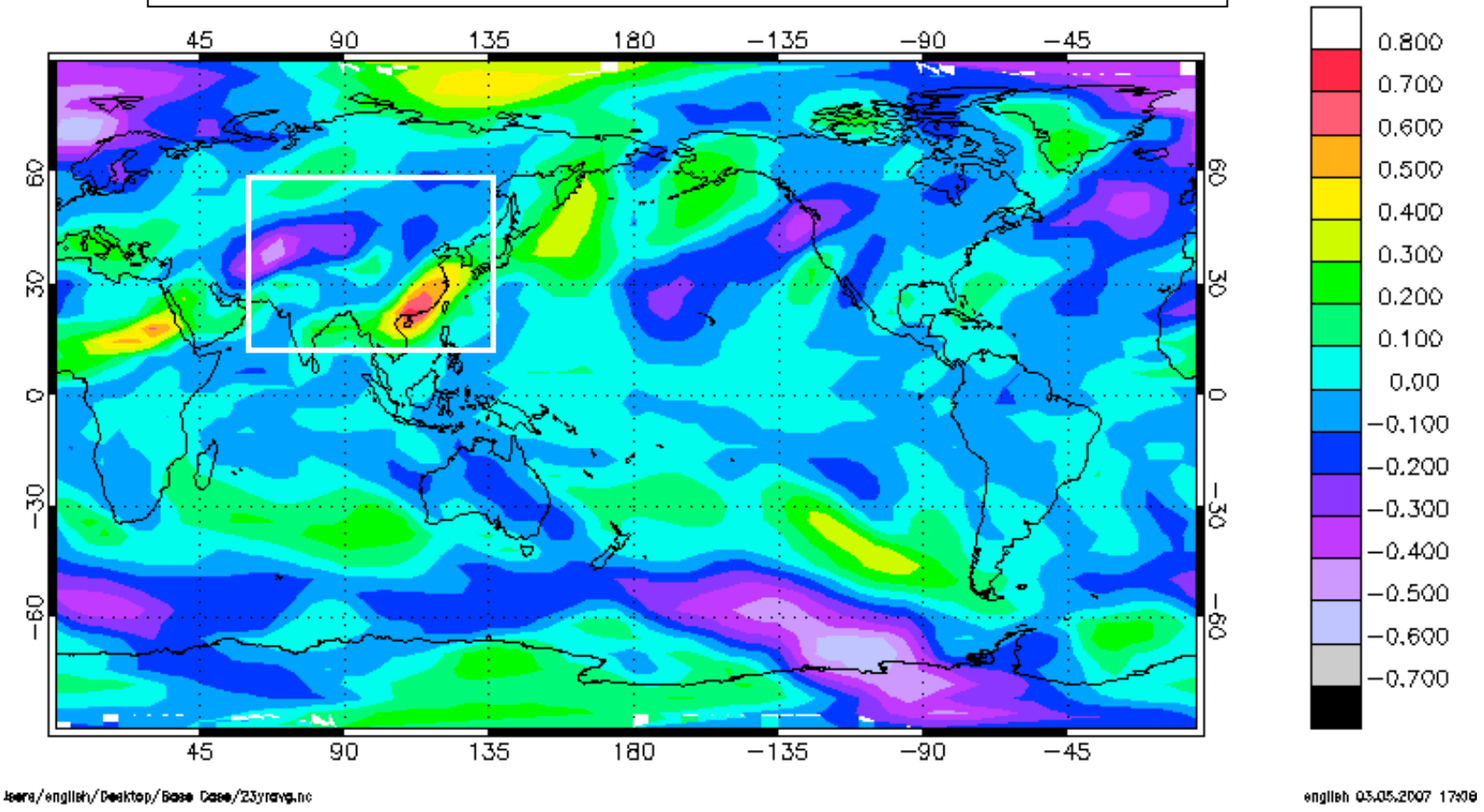
Zonal Wind Speed change (m/s): (Zero scenario - base case)



Shift in ITCZ, Subtropical Jet, Polar Jets !

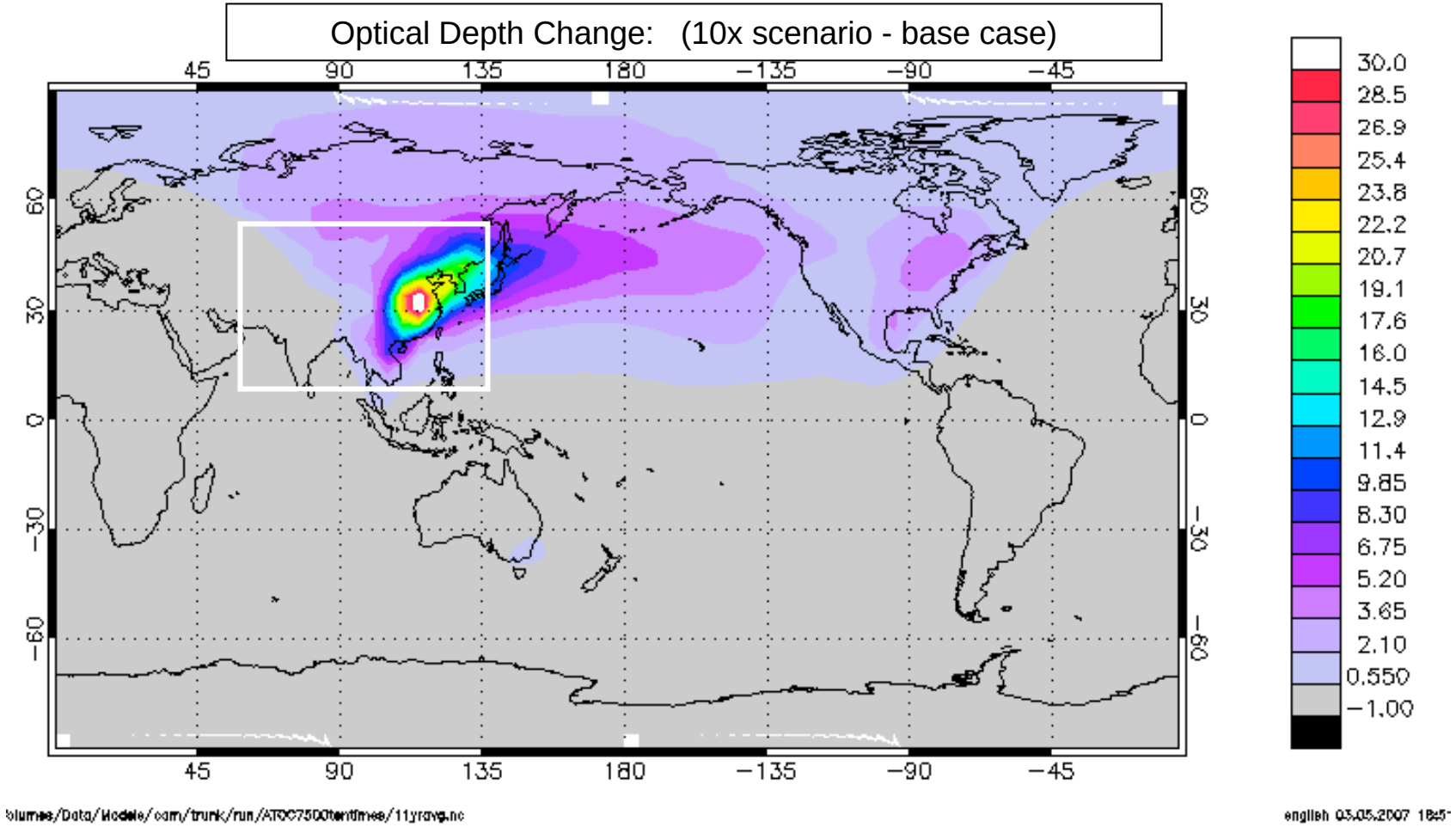
Change in Horizontal Winds 2015-2028
Zero Emissions Scenario

Meridional Wind Speed change (m/s): (10x scenario - base case)



Shift in ITCZ

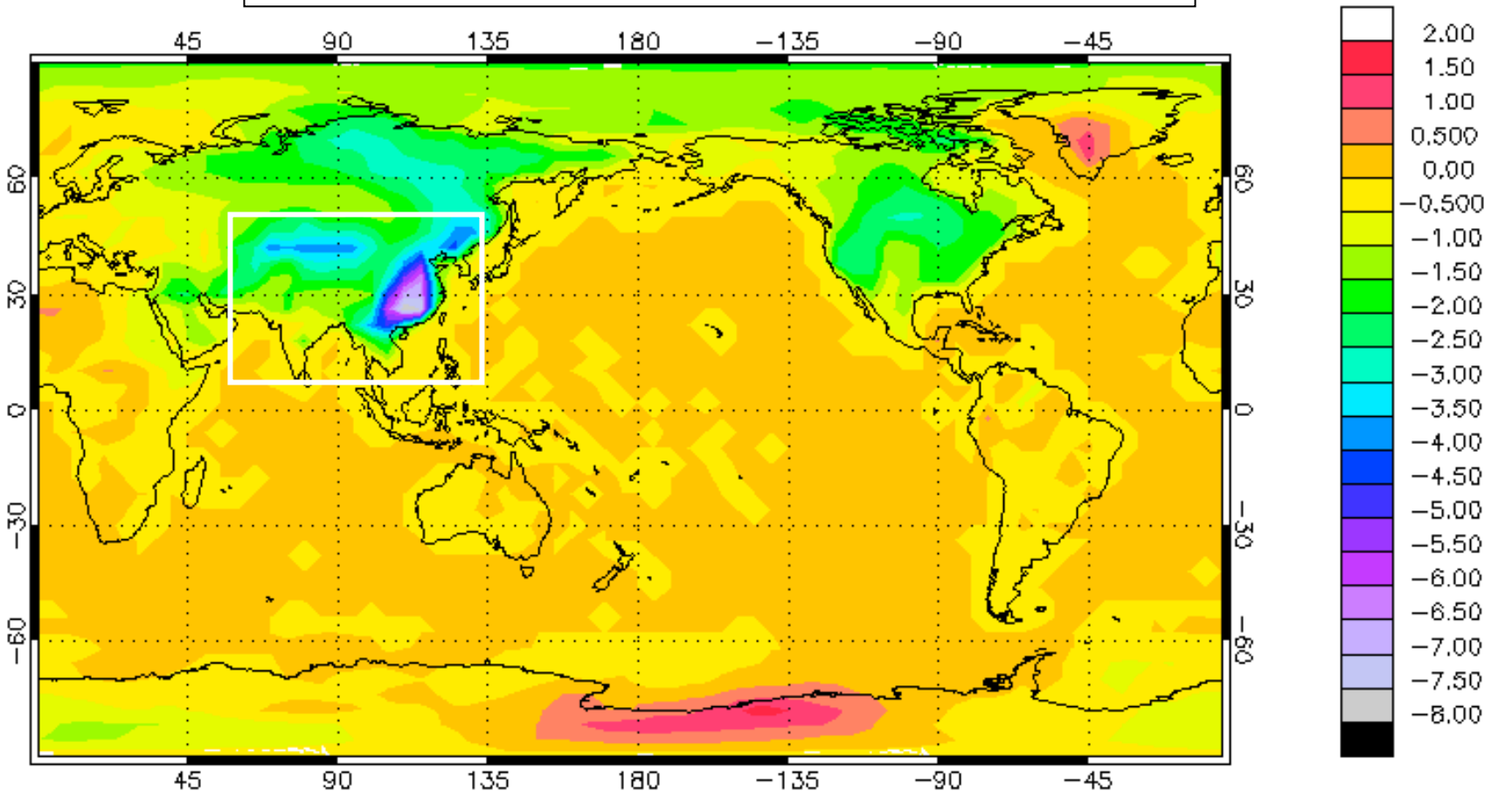
Avg O.D. Change 2015-2028
10x Emissions Scenario



10x the optical depth of base case
Optical depth continues to be suspiciously high…(averaging artifact?)

Avg Surface Temp Change 2015-2028
10x Emissions Scenario

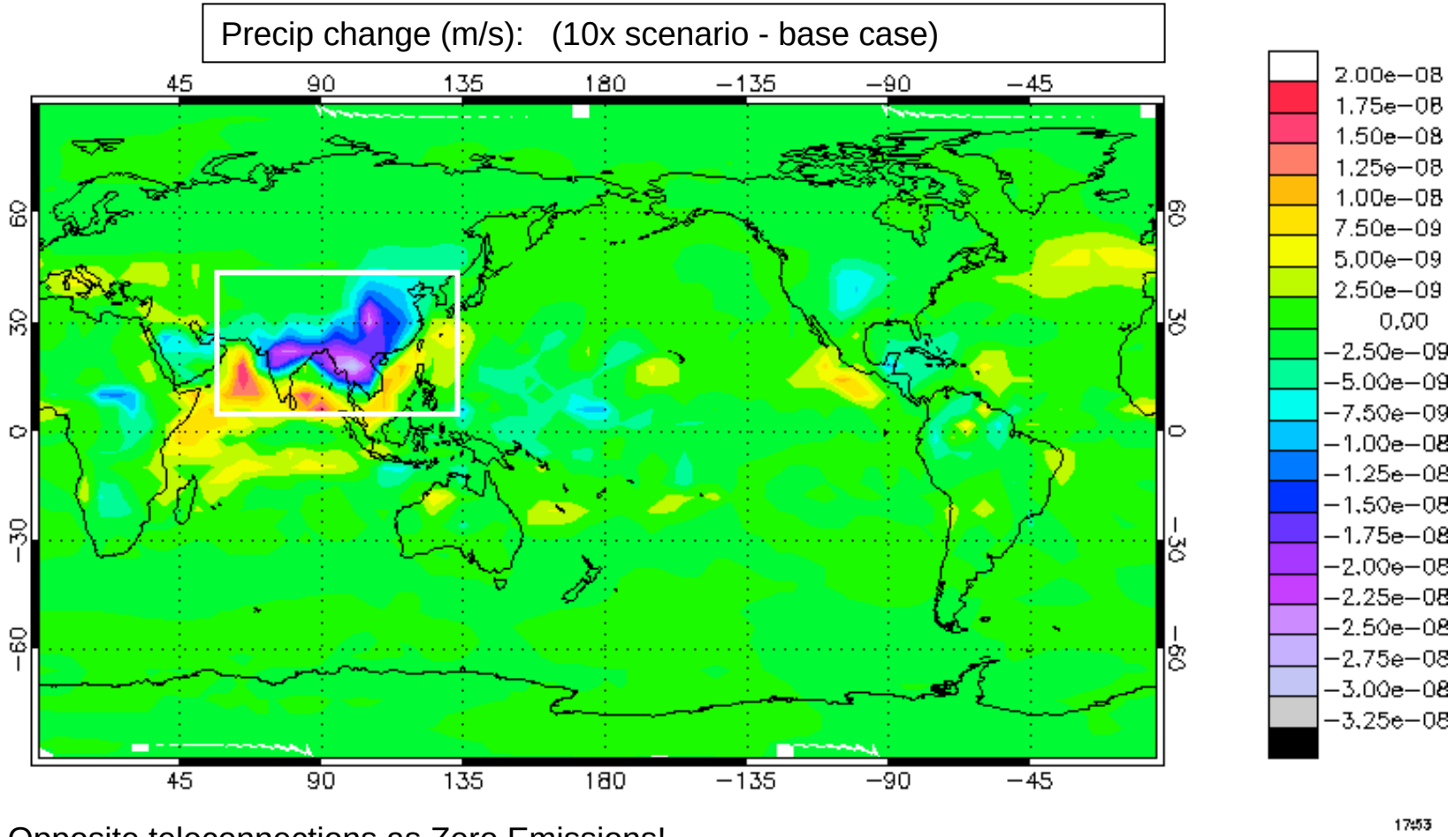
T change (K): (10x scenario - base case)



/Users/ Opposite teleconnections as Zero Emissions!
Cooling where 10x aerosols added
Cooling in Siberia, N.A., Warming in Greenland
No change over oceans

05.2007 17:4

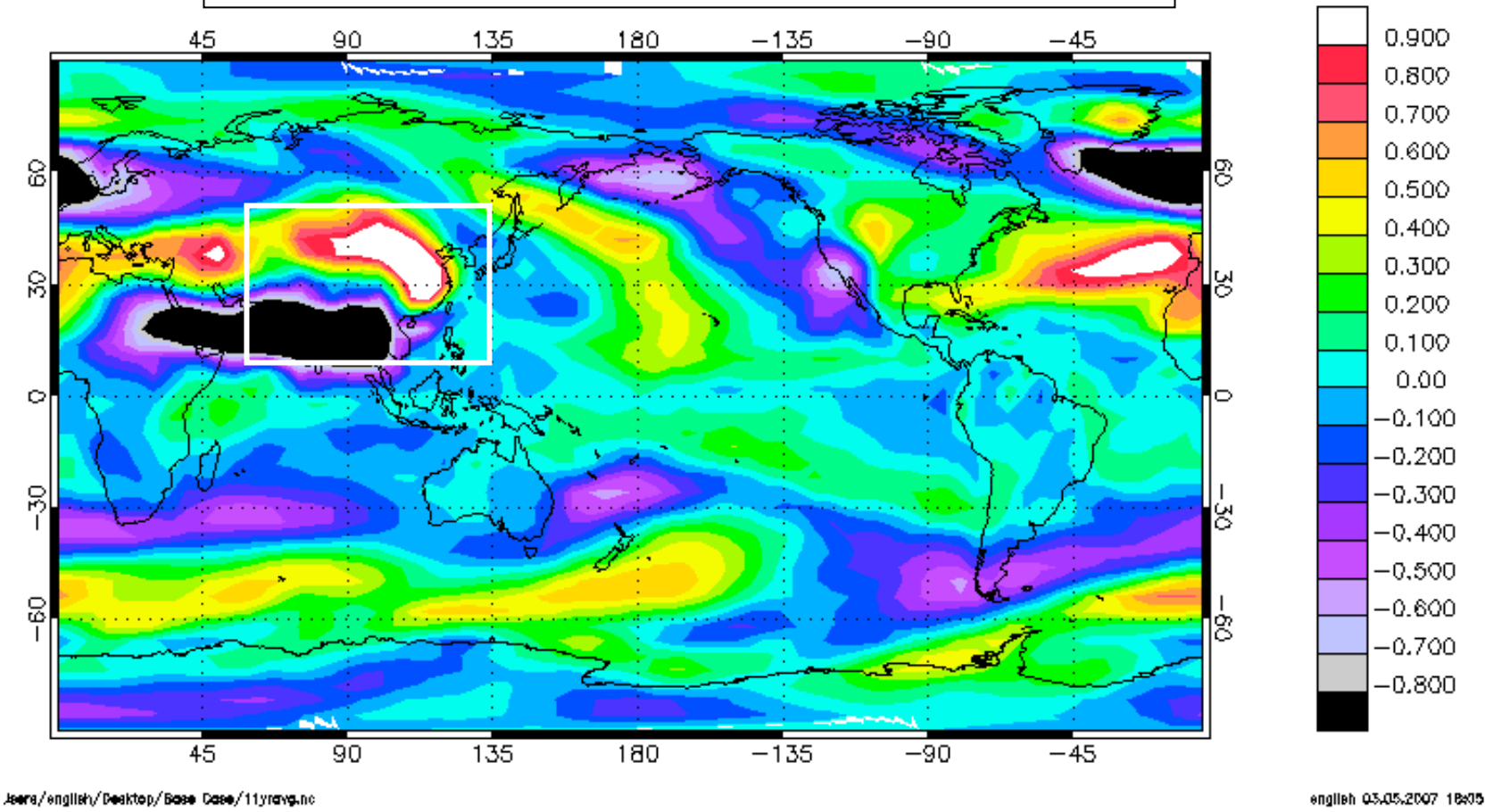
Avg Convective Precip Change 2015-2028
10x Emissions Scenario



Opposite teleconnections as Zero Emissions!
Decrease in convective precip over Asia (less RF, less vertical velocity)
Increase in ~10 deg N, decrease at the Equator (except near Asia)
Evidence of a southward shift of Asian Monsoon / ITCZ?

Change in Horizontal Winds 2015-2028
10x Emissions Scenario

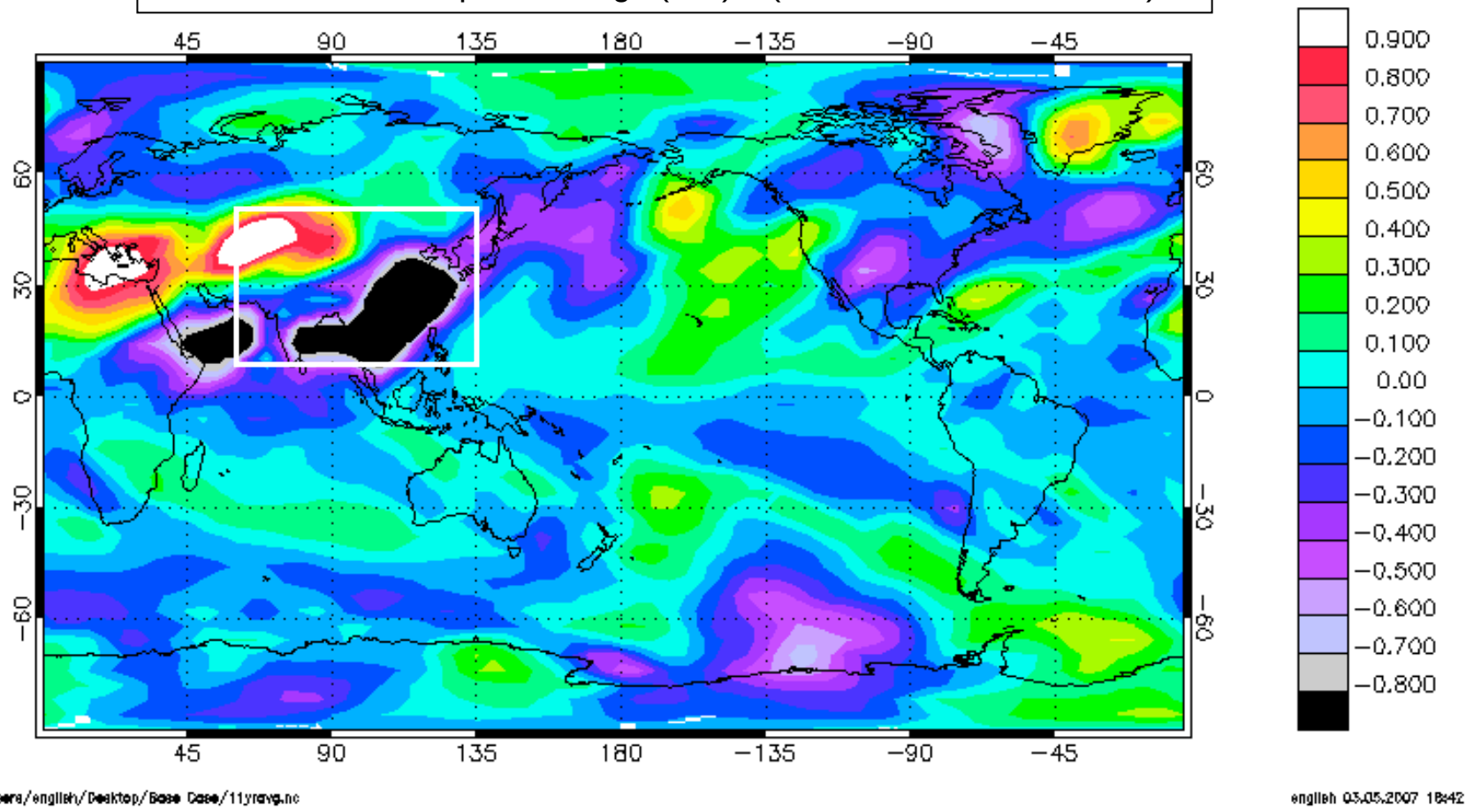
Zonal Wind Speed change (m/s): (10x scenario - base case)



Major wind shift in Asia - Giant High at 90 longitude / 30 Latitude

Change in Horizontal Winds 2015-2028
10x Emissions Scenario

Meridional Wind Speed change (m/s): (10x scenario - base case)



Major wind shift in Asia - Giant High at 90 longitude / 30 Latitude

Other Studies

- Kim et al (2006) - Dust and BC in Africa, Asia excite a planetary-scale teleconnection pattern in sea level pressure, temperature, and geopotential height spanning North Africa through Eurasia to the North Pacific.

- Gu et al (2006) - Aerosol RF causes cooling in China, reducing the T gradient to the North, reducing tropical convection

- Lau et al (2006) - Increased Asian aerosol loading increases the circulation of a High Pressure over the Tibetan continent

Summary

- Asia sulfur emissions inversely related to Asian surface temp & precip
- Global circulation (ITCZ, subtropical jets, polar jets) move 100's of km inducing significant changes to regional precipitation and temp
- Consistent with other simulations which suggest aerosol-induced circulation changes

Next Steps

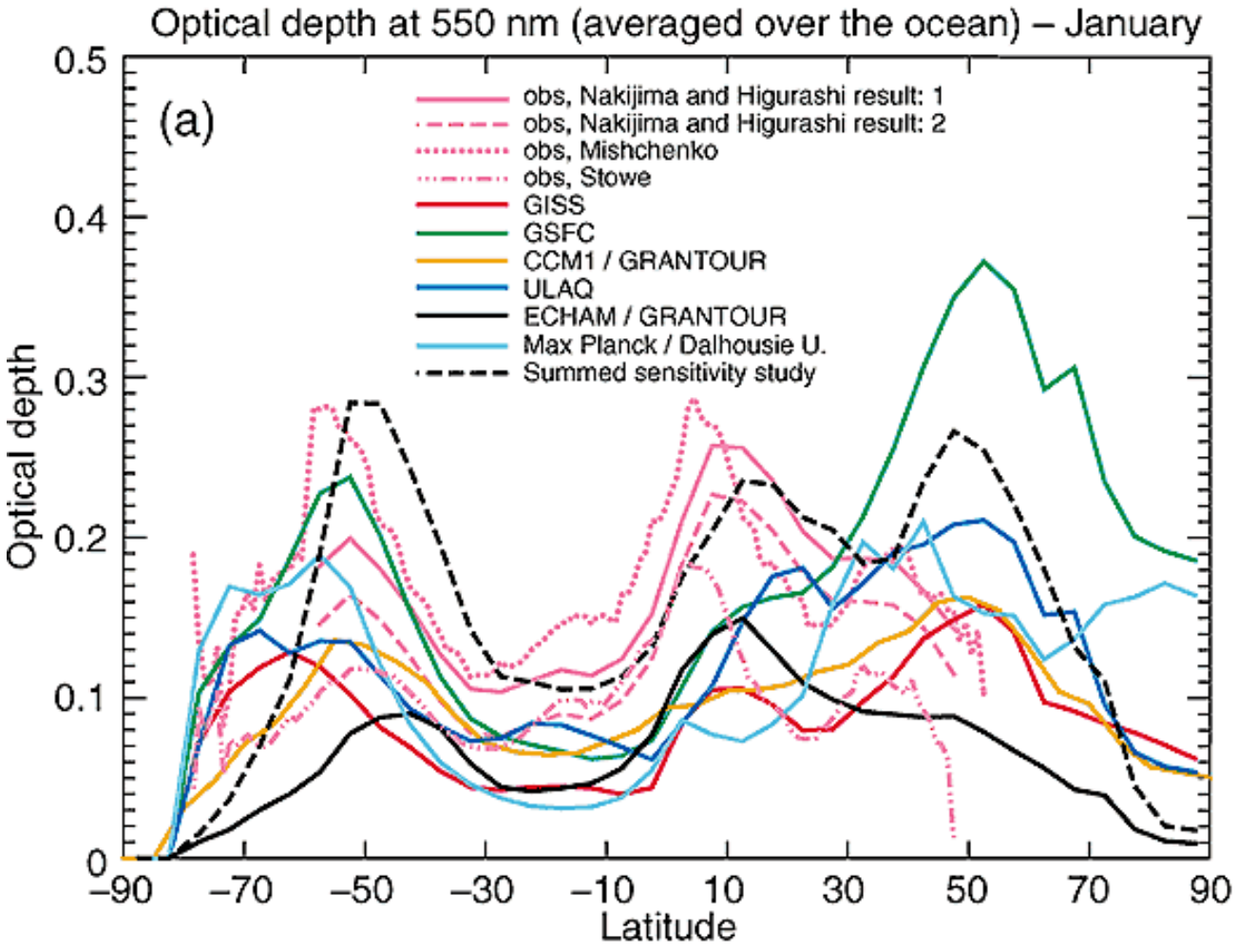
- Repeat base case with modified start date to quantify model variability
- Compare AOD to satellites; confirm that there was no error in simulation calculations
- Look into regional temp and precip changes over the past 50 years and compare to simulation results
- Investigate CAM’s ocean-atmosphere coupling and improvements to it

Quiz

What’s more reliable for quantifying aerosol RF:

Observations or Models ???

ANSWER: NEITHER!!!!



IPCC 2001

References

- Title: Atmospheric teleconnection over Eurasia induced by aerosol radiative forcing during boreal spring
- Author(s): Kim MK (Kim, Maeng-Ki), Lau WKM (Lau, William K. M.), Chin M (Chin, Mian), Kim KM (Kim, Kyu-Myong), Sud YC (Sud, Y. C.), Walker GK (Walker, Greg K.)
- Source: JOURNAL OF CLIMATE 19 (18): 4700-4718 SEP 2006
- Document Type: Article
- Language: English
- Cited References: 65 Times Cited: 0 Find Related Records Information
- Abstract: The direct effects of aerosols on global and regional climate during boreal spring are investigated based on numerical simulations with the NASA Global Modeling and Assimilation Office finite-volume general circulation model (fvGCM) with Microphyics of Clouds with the Relaxed-Arakawa Schubert Scheme (McRAS), using aerosol forcing functions derived from the Goddard Ozone Chemistry Aerosol Radiation and Transport model (GOCART).

- The authors find that anomalous atmospheric heat sources induced by absorbing aerosols (dust and black carbon) excite a planetary-scale teleconnection pattern in sea level pressure, temperature, and geopotential height spanning North Africa through Eurasia to the North Pacific. Surface cooling due to direct effects of aerosols is found in the vicinity and downstream of the aerosol source regions, that is, South Asia, East Asia, and northern and western Africa. Significant atmospheric heating is found in regions with large loading of dust (over northern Africa and the Middle East) and black carbon (over Southeast Asia). Paradoxically, the most pronounced feature in aerosol-induced surface temperature is an east-west dipole anomaly with strong cooling over the Caspian Sea and warming over central and northeastern Asia, where aerosol concentrations are low. Analyses of circulation anomalies show that the dipole anomaly is a part of an atmospheric teleconnection pattern driven by atmospheric heating anomalies induced by absorbing aerosols in the source regions, but the influence was conveyed globally through barotropic energy dispersion and sustained by feedback processes associated with the regional circulations.

- The surface temperature signature associated with the aerosol-induced teleconnection bears striking resemblance to the spatial pattern of observed long-term trend in surface temperature over Eurasia. Additionally, the boreal spring wave train pattern is similar to that reported by Fukutomi et al. associated with the boreal summer precipitation seesaw between eastern and western Siberia. The results of this study raise the possibility that global aerosol forcing during boreal spring may play an important role in spawning atmospheric teleconnections that affect regional and global climates.

References

- Title: Climatic effects of different aerosol types in China simulated by the UCLA general circulation model
- Author(s): Gu Y (Gu, Y.), Liou KN (Liou, K. N.), Xue Y (Xue, Y.), Mechoso CR (Mechoso, C. R.), Li W (Li, W.), Luo Y (Luo, Y.)
- Source: JOURNAL OF GEOPHYSICAL RESEARCH-ATMOSPHERES 111 (D15): Art. No. D15201 AUG 1 2006
- Document Type: Article
- Language: English
- Cited References: 57 Times Cited: 0 Find Related Records Information
- Abstract: The climatic effects of various types of aerosol in China have been investigated by using the atmospheric general circulation model (AGCM) developed at the University of California, Los Angeles (UCLA). The model includes an efficient and physically based radiation parameterization scheme specifically developed for application to clouds and aerosols. Simulation results show that inclusion of a background aerosol optical depth of 0.2 reduces the global mean net surface solar flux by about 5 W m(-2) and produces a decrease in precipitation in the tropics as a result of decreased temperature contrast between this area and the middle to high latitudes, which suppresses tropical convection. These decreases have partially corrected the overestimates in the surface solar flux and precipitation in the UCLA AGCM simulations without the aerosol effect. The experiment with increased aerosol optical depths in China shows a noticeable increase in precipitation in the southern part of China in July due to the cooling in the midlatitudes that leads to the strengthening of the Hadley circulation. Aerosol types play an important role in the determination of the global mean radiation budget and regional climate. While sulfates mainly reflect solar radiation and induce negative forcing at the surface, black carbon and large dust particles absorb substantial solar radiation and have a positive solar forcing at the top of the atmosphere, but reduce the solar radiation reaching the surface. Large dust particles also have a significant effect on thermal IR radiation under clear conditions, but this effect is largely masked by clouds generated from the model in AGCM simulations. Black carbon and large dust particles in China would heat the air column in the middle to high latitudes and tend to move the simulated precipitation inland, i.e., toward the Himalayas. The inclusion of black carbon in our simulations has not produced the "north drought/south flooding" precipitation pattern that has frequently occurred in China during

  the past 50 years.

References

- Title: Observational relationships between aerosol and Asian monsoon rainfall, and circulation
- Author(s): Lau KM (Lau, K. -M.), Kim KM (Kim, K. -M.)
- Source: GEOPHYSICAL RESEARCH LETTERS 33 (21): Art. No. L21810 NOV 8 2006
- Document Type: Article
- Language: English
- Cited References: 21 Times Cited: 0 Find Related Records Information
- Abstract: Preliminary observational evidences are presented showing that the Indian subcontinent and surrounding regions are subject to heavy loading of absorbing aerosols, i.e., dust and black carbon, which possess spatial and temporal variability that are closely linked to those of the Asian monsoon water cycle. Consistent with the Elevated Heat Pump hypothesis, we find that increased loading of absorbing aerosols over the Indo-Gangetic Plain in the pre-monsoon season is associated with a) increased heating of the upper troposphere, with the formation of a warm-core upper level anticyclone over the Tibetan Plateau in April May, b) an advance of the monsoon rainy season in northern India in May, and c) subsequent

  increased rainfall over the Indian subcontinent, and decreased rainfall over East Asia in June-July.

References

- Title: Global impacts of aerosols from particular source regions and sectors
- Author(s): Koch D (Koch, Dorothy), Bond TC (Bond, Tami C.), Streets D (Streets, David), Unger N (Unger, Nadine), van der Werf GR (van der Werf, Guido R.)
- Source: JOURNAL OF GEOPHYSICAL RESEARCH-ATMOSPHERES 112 (D2): Art. No. D02205 JAN 24 2007
- Document Type: Article
- Language: English
- Cited References: 49 Times Cited: 1 Find Related Records Information
- Abstract: [1] We study the impacts of present-day aerosols emitted from particular regions and from particular sectors, as predicted by the Goddard Institute for Space Studies GCM. We track the distribution and direct radiative forcing of aerosols, including sulfate and black and organic carbon, emitted from major source regions (North America, Europe, south Asia, Southeast Asia, South America, and Africa). We also partition the emissions by sector, including industrial, power, residential, transport, biomass burning, and natural. Southeast Asia produces 15% and 10% of the world's black carbon and sulfate and exports over 2/ 3 of this burden over the Northern Hemisphere. About 1/ 2 of the SO2 emitted by Southeast Asia and Europe is not converted to sulfate because of oxidant limitation. Although Africa has the largest biomass burning emissions, South America generates a larger (about 20% of the global carbonaceous) aerosol burden; about 1/ 2 of this burden is exported and dominates the carbonaceous aerosol load in the Southern Hemisphere. Calculated direct anthropogenic radiative forcings are -0.29, -0.06, and 0.24 W m(-2) for sulfate, organic, and black carbon, respectively. The largest BC radiative forcings are from residential (0.09 W m(-2)) and transport (0.06 W m(-2)) sectors, making these potential targets to counter global warming. However, scattering components within these sectors reduce these to 0.04 and 0.03 W m(-2), respectively. Most anthropogenic sulfate comes from power and industry sectors, and these sectors are responsible for the large negative aerosol forcings over the central Northern Hemisphere.
- KeyWords Plus: GENERAL-CIRCULATION MODEL; BLACK CARBON AEROSOL; ORGANIC-CARBON; 3-DIMENSIONAL MODEL; CLIMATE SENSITIVITY; GODDARD INSTITUTE; LIGHT-ABSORPTION; FUEL COMBUSTION; SULFUR CYCLE;

  ART.

References

- Title: Local and remote impacts of aerosol climate forcing on tropical precipitation
- Author(s): Chou C, Neelin JD, Lohmann U, Feichter J
- Source: JOURNAL OF CLIMATE 18 (22): 4621-4636 NOV 2005
- Document Type: Article
- Language: English
- Cited References: 33 Times Cited: 2 Find Related Records Information
- Abstract: Mechanisms that determine the direct and indirect effects of aerosols on the tropical climate involve moist dynamical processes and have local and remote impacts on regional tropical precipitation. These mechanisms are examined in a climate model of intermediate complexity [quasi-equilibrium tropical circulation model (QTCM)] forced by prescribed aerosol forcing, which is obtained from a general circulation model (ECHAM4). The aerosol reflection is the dominant aerosol forcing, while the aerosol absorption has complex but much weaker influences on the regional tropical precipitation based on the ECHAM4 aerosol forcing. The local effect associated with aerosols contributes negative precipitation anomalies over convective regions by affecting the net energy flux into the atmospheric column. This net energy flux is controlled by the radiative forcing at the top of the atmosphere on time scales where surface heat flux is near equilibrium, balancing anomalous solar radiation by evaporation, longwave radiation, and sensible heat. Considering the aerosol absorption effect alone, the associated precipitation anomalies are slightly negative but small when surface heat fluxes are near equilibrium. Two effects found in global warming, the uppedante mechanism and the anomalous gross moist stability mechanism, occur with opposite sign in the aerosol case. Both act as remote effects via the widespread cold tropospheric temperature anomalies induced by the aerosol forcing. In the upped-ante mechanism in global warming, a warm troposphere increases the low-level moisture "ante" required for convection, creating spatially varying moisture anomalies that disfavor precipitation on those margins of convective zones where the mean flow imports air from nonconvective regions. In the aerosol case here, a cool troposphere preferentially decreases moisture in convective regions, creating positive precipitation anomalies at inflow margins. In the anomalous gross moist stability mechanism for the aerosol case, the decrease in moisture in convective regions acts to enhance the gross moist stability, so convection and the associated precipitation are reduced. The partitioning between the aerosol local and remote effects on regional tropical precipitation differs spatially. Over convective regions that have high aerosol concentration, such as the South American region, the aerosol local effect contributes more negative precipitation anomalies than the anomalous gross moist stability mechanism in the QTCM simulations. On the other hand, the remote effect is more important over convective regions with small aerosol concentrations, such as the western Pacific Maritime Continent. Remote effects of midlatitude aerosol forcing have a substantial contribution to

tropical anomalies.

References

- Author(s): Ramanathan V, Crutzen PJ, Lelieveld J, Mitra AP, Althausen D, Anderson J, Andreae MO, Cantrell W, Cass GR, Chung CE, Clarke AD, Coakley JA, Collins WD, Conant WC, Dulac F, Heintzenberg J, Heymsfield AJ, Holben B, Howell S, Hudson J, Jayaraman A, Kiehl JT, Krishnamurti TN, Lubin D, McFarquhar G, Novakov T, Ogren JA, Podgorny IA, Prather K, Priestley K, Prospero JM, Quinn PK, Rajeev K, Rasch P, Rupert S, Sadourny R, Satheesh SK, Shaw GE, Sheridan P, Valero FPJ
- Source: JOURNAL OF GEOPHYSICAL RESEARCH-ATMOSPHERES 106 (D22): 28371-28398 NOV 27 2001
- Document Type: Article
- Language: English
- Cited References: 87 Times Cited: 248 Find Related Records Information
- Abstract: Every year, from December to April, anthropogenic haze spreads over most of the North Indian Ocean, and South and Southeast Asia. The Indian Ocean Experiment (INDOEX) documented this Indo-Asian haze at scales ranging from individual particles to its contribution to the regional climate forcing. This study integrates the multiplatform. observations (satellites, aircraft, ships, surface stations, and balloons) with one- and four-dimensional models to derive the regional aerosol forcing resulting from the direct, the semidirect and the two indirect effects. The haze particles consisted of several inorganic and carbonaceous species, including absorbing black carbon clusters, fly ash, and mineral dust. The most striking result was the large loading of aerosols over most of the South Asian region and the North Indian Ocean. The January to March 1999 visible optical depths were about 0.5 over most of the continent and reached values as large as 0.2 over the equatorial Indian ocean due to long-range transport. The aerosol layer extended as high as 3 km. Black carbon contributed about 14% to the fine particle mass and 11% to the visible optical depth. The single-scattering albedo estimated by several independent methods was consistently around 0.9 both inland and over the open ocean. Anthropogenic sources contributed as much as 80% (+/- 10%) to the aerosol loading and the optical depth. The in situ data, which clearly support the existence of the first indirect effect (increased aerosol concentration producing more cloud drops with smaller effective radii), are used to develop a composite indirect effect scheme. The Indo-Asian aerosols impact the radiative forcing through a complex set of heating (positive forcing) and cooling (negative forcing) processes. Clouds and black carbon emerge as the ma or players. The dominant factor, however, is the large negative forcing (-20 +/- 4 W m(-2)) at the surface and the comparably large atmospheric heating. Regionally, the absorbing haze decreased the surface solar radiation by an amount comparable to 50% of the total ocean heat flux and nearly doubled the lower tropospheric solar heating. We demonstrate with a general circulation model how this additional heating significantly perturbs the tropical rainfall patterns and

  the hydrological cycle with implications to global climate.