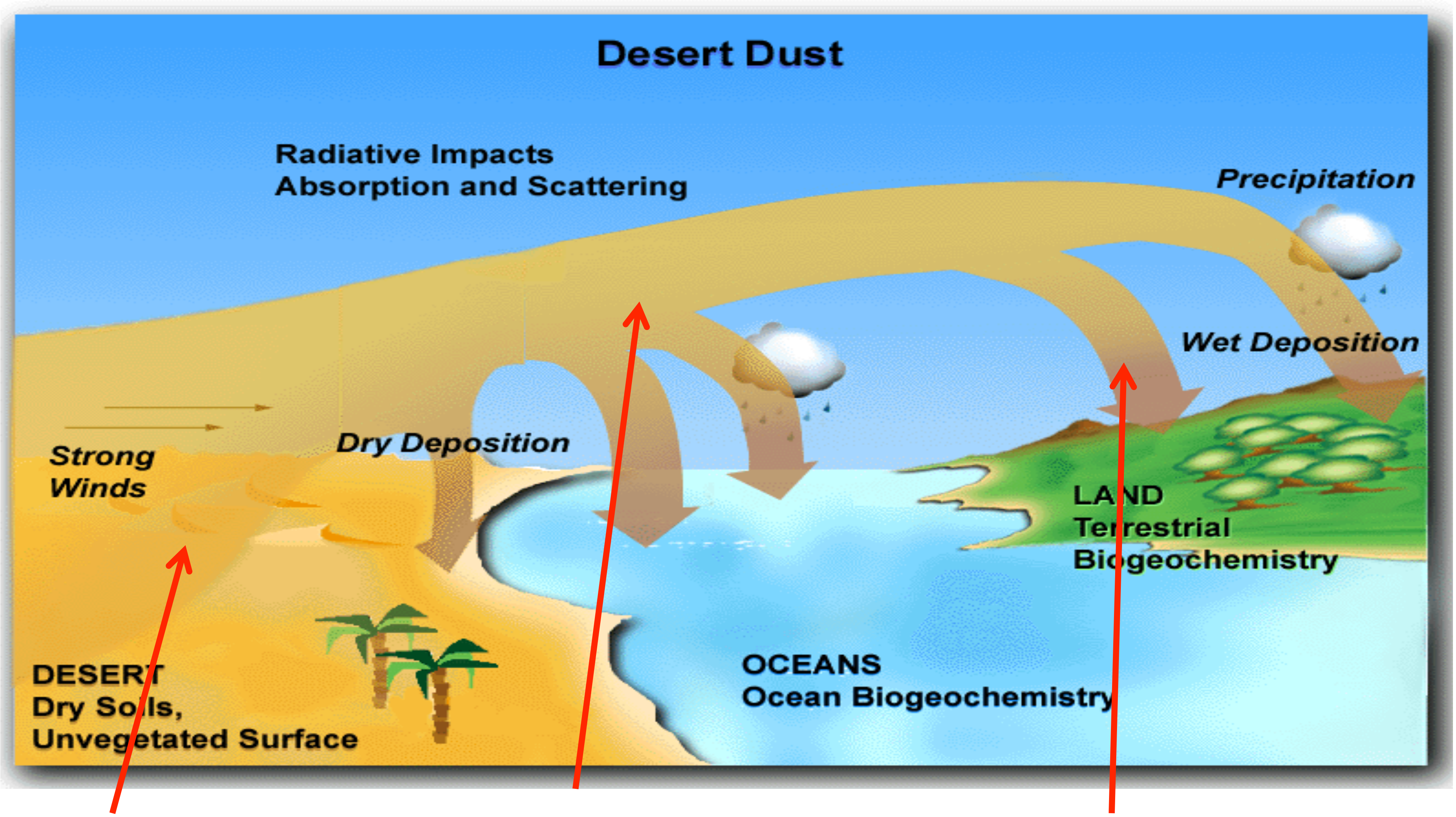
Transpacific transport of mineral dust: impact on aerosol in the United States

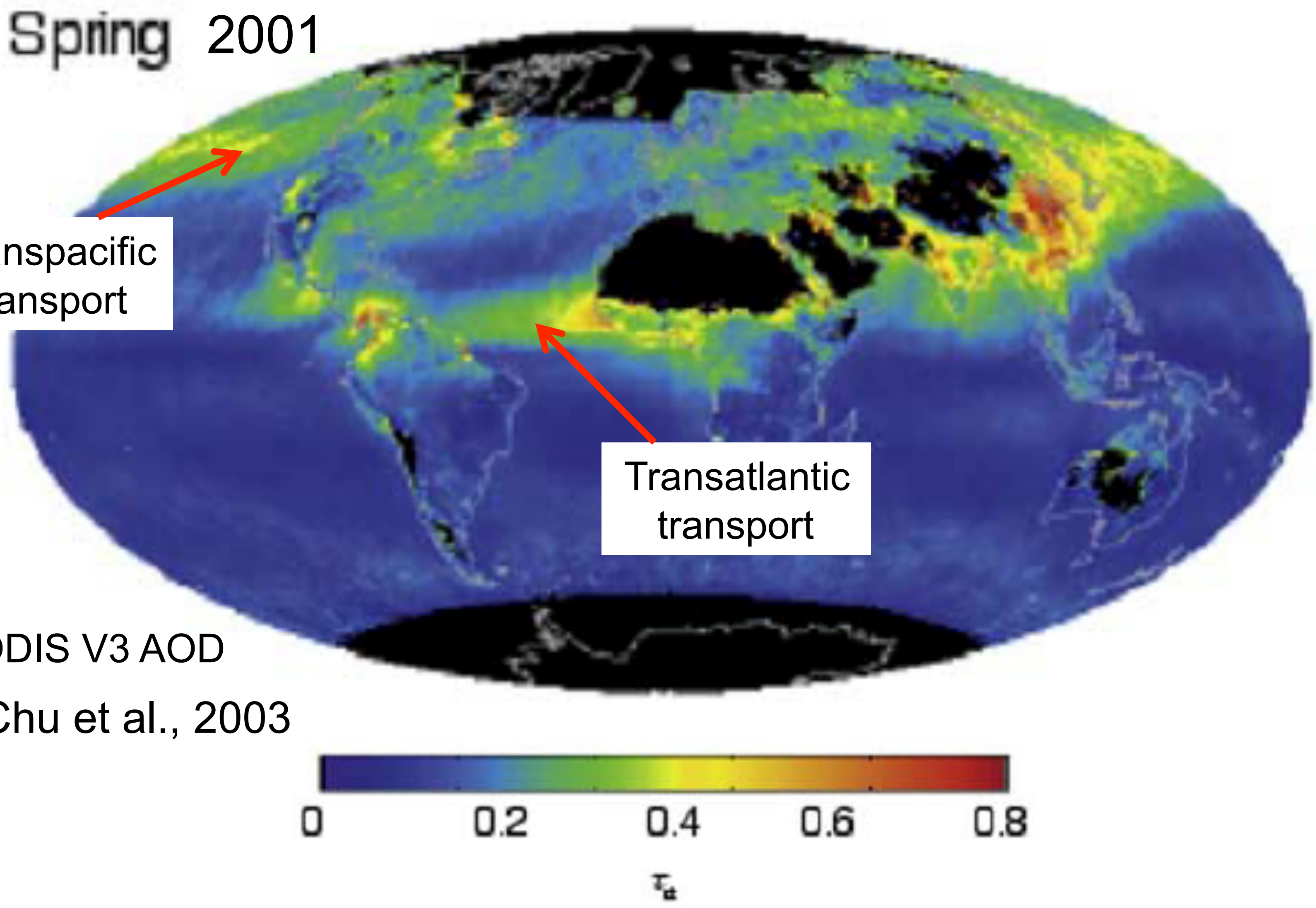


Mobilization

Long-range transport/ Chemical transformation

Deposition

Dust is a principal component of atmospheric aerosol



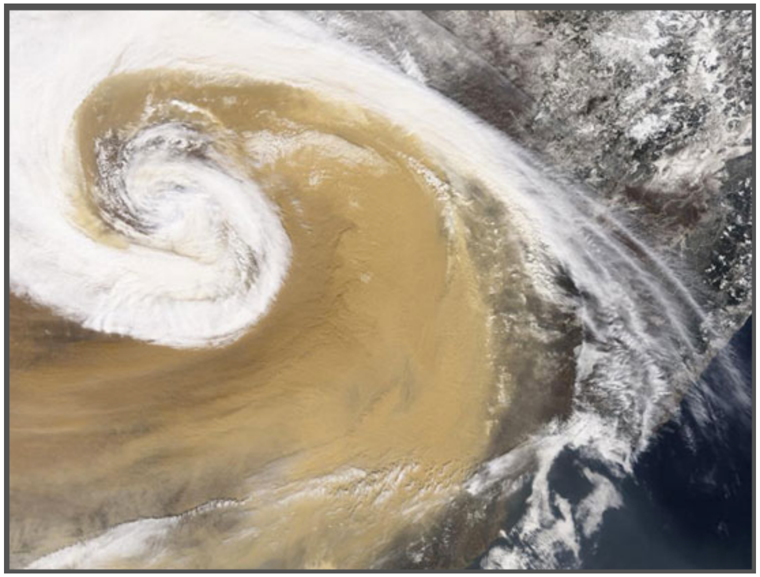
2001

Transpacific transport

Transatlantic transport

MODIS V3 AOD

From Chu et al., 2003



China dust storm, April 2001
SeaWifs

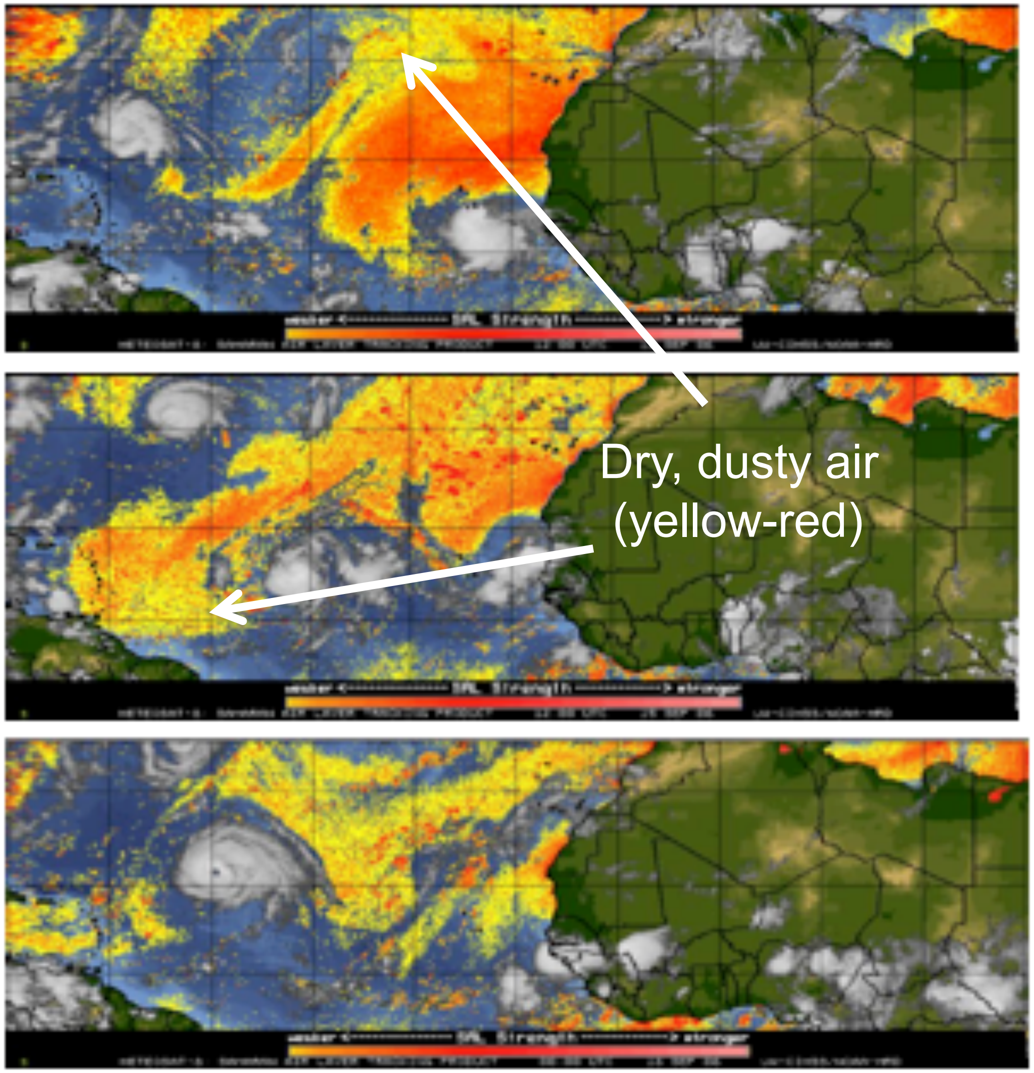
Beijing, March 29, 2004

Page, AZ, April, 2001

Riyadh, March, 2009

Helene's Interaction with the SAL

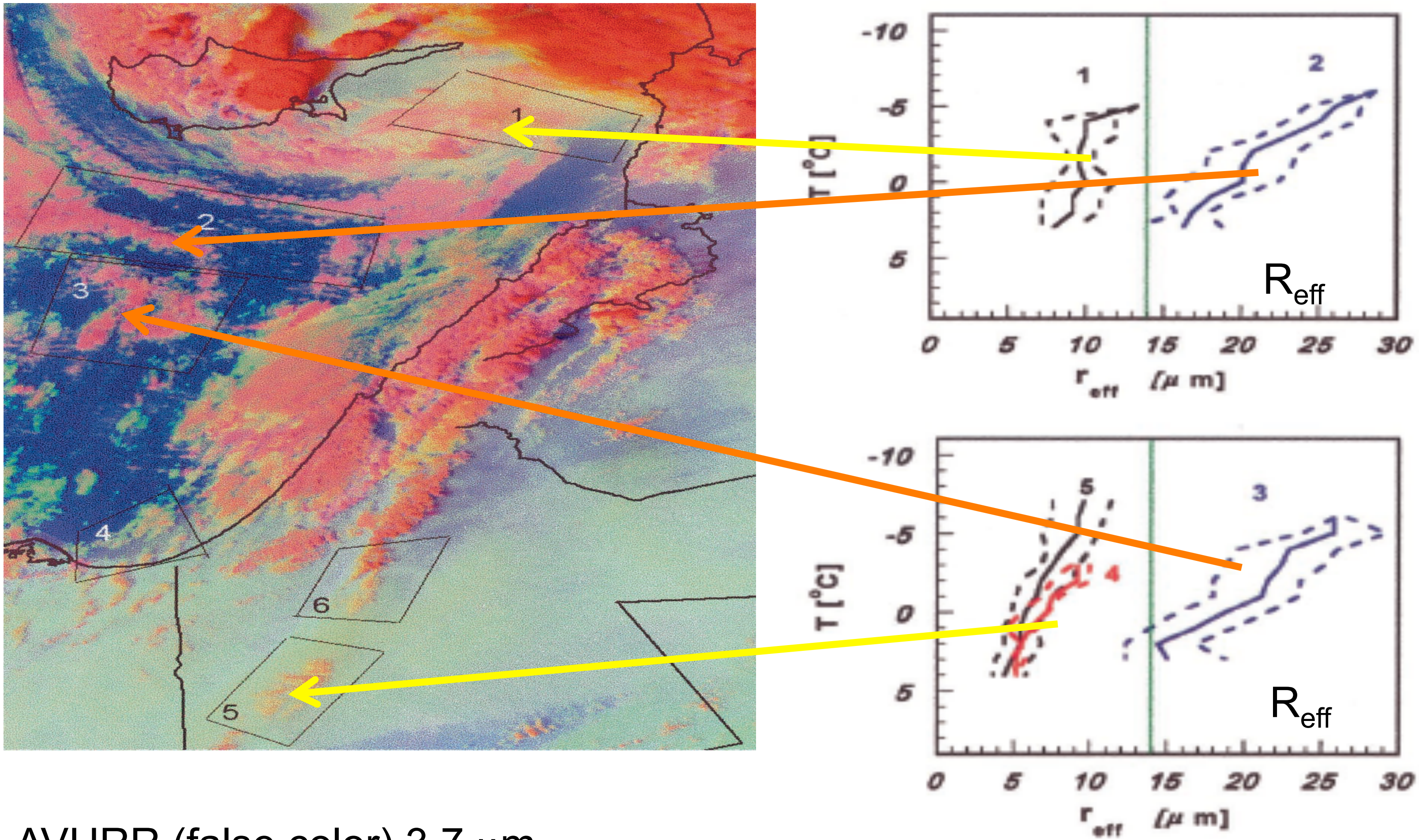
Helene became a tropical depression on September 12th 2006. Its path led it directly into the SAL. Its developments appears to be inhibited by the SAL for it was only able to develop an eye after it cleared the SAL on September 18th. Helene went on to became a hurricane and eventually dissipated September 24th.



Dry, dusty air
(yellow-red)

SAL METEOSAT product:
Courtesy:
UW-CIMSS/NOAA HRD

Dust can impact cloud droplet size, precipitation



AVHRR (false color) 3.7 μm
March, 1998
(from Rosenfeld et al., 2001)

Dusty (yellow-ish) clouds distinguished by R_{eff} < 14 μm, below threshold for precipitation

EPA Regional Haze Rule

EPA Regional Haze Rule: (i) “Natural visibility conditions” to be achieved by 2064 in federal class I areas; (ii) States to produce SIPs to reach those “natural visibility” goals; (iii) EPA provides default estimates of “natural concentrations” to define goals; (iv) States can propose refined estimates.

1. What effect does transpacific transport of mineral dust have on aerosol concentrations in the United States?
2. Does the impact extend beyond exceptional springtime episodes?
3. What are the implications for the EPA’s Regional Haze Rule?

Approach

1. Develop the mineral dust module for the GEOS-Chem global chemical transport model (CTM), (as part of a full suite of aerosol components).

2. Conduct global dust simulations; distinguish domestic from overseas contributions; use ground-based and airborne observations to interpret the model results.

Mineral dust in GEOS-Chem

GEOS-Chem is a global Chemical Transport Model (CTM); represents the sources, physical and photochemical processes that control the chemical composition of the troposphere.

The dust module represents the **mobilization**, **transport**, and **deposition** of mineral dust in the atmosphere.

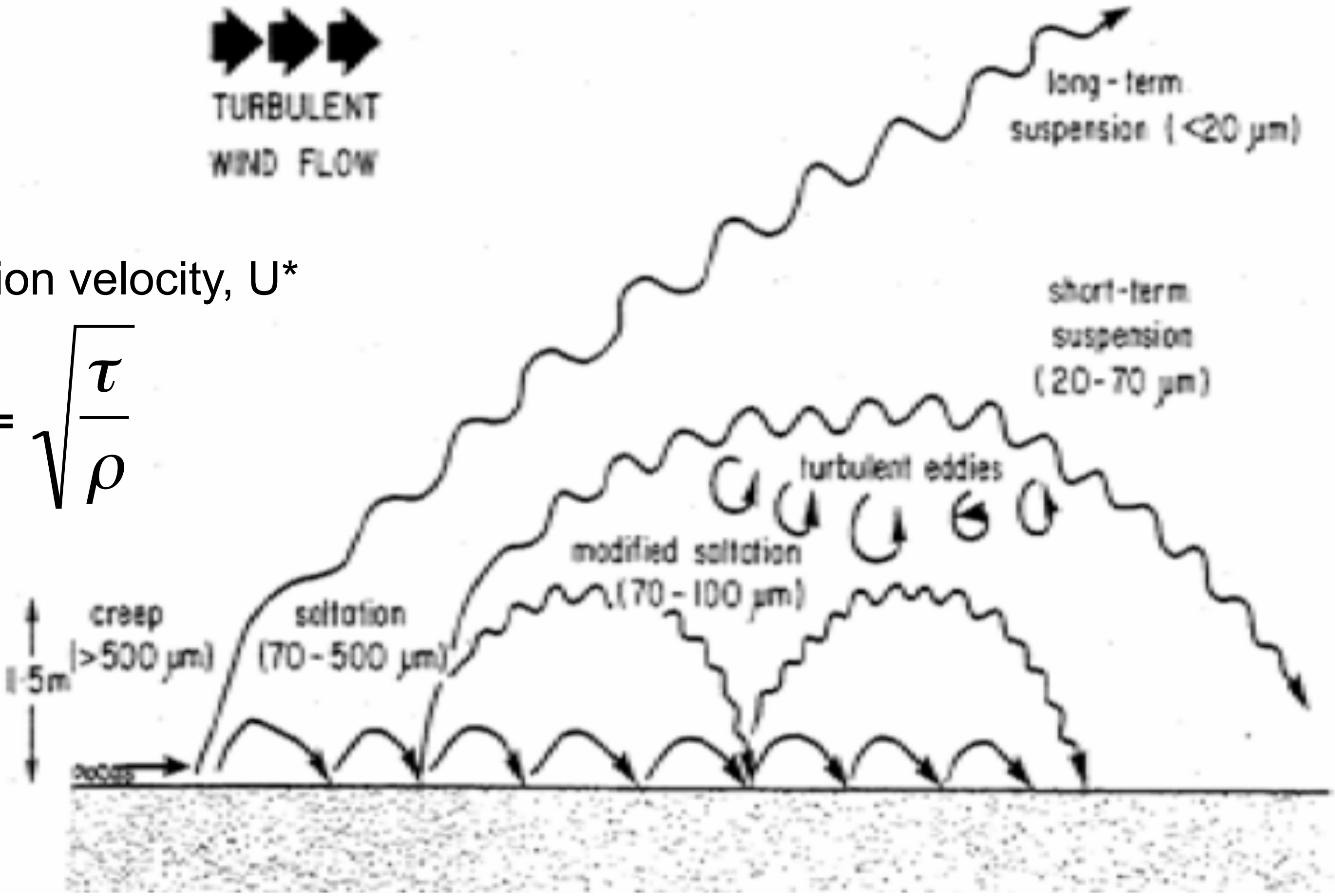
- Four size bins: 0.1-1.0, 1.0-1.8, 1.8-3.0, 3.0-6.0 μm radius (following Ginoux et al., 2001)

- Mobilization -- GOCART (Ginoux) and DEAD (Zender) schemes available)
- Dry deposition – gravitational settling, turbulent transfer, impaction, interception, Vd=Vd(D,ρ,sfc) (Zhang et al. 2001)
- Wet deposition – scavenging in convective updrafts; rainout and washout from large-scale and convective precipitation (Liu et al., 2001).

Dust mobilized indirectly by “saltating” sand particles

Define friction velocity, U*

$$U^{*} = \sqrt{\frac{\tau}{\rho}}$$



Mobilization inhibited by soil moisture, non-erodible elements, snow cover, vegetation. (cartoon from Pye et al., 1987)

Dust mobilization

Vertical dust flux, F_d, directly related to the horizontal saltation flux, Qs, i.e., $F_d \sim S\,Q_s$

$$Q_s \sim U*^3 \left(1 - \frac{U*_t}{U*}\right)\left(1 + \frac{U*_t}{U*}\right)^2$$ DEAD model

$$Q_s = U_{10}{}^2 (U_{10} - U*_t)$$ GOCART model

S – **source function** (defines potential dust source regions, includes vegetation, efficiency factors, e.g. topographic lows)

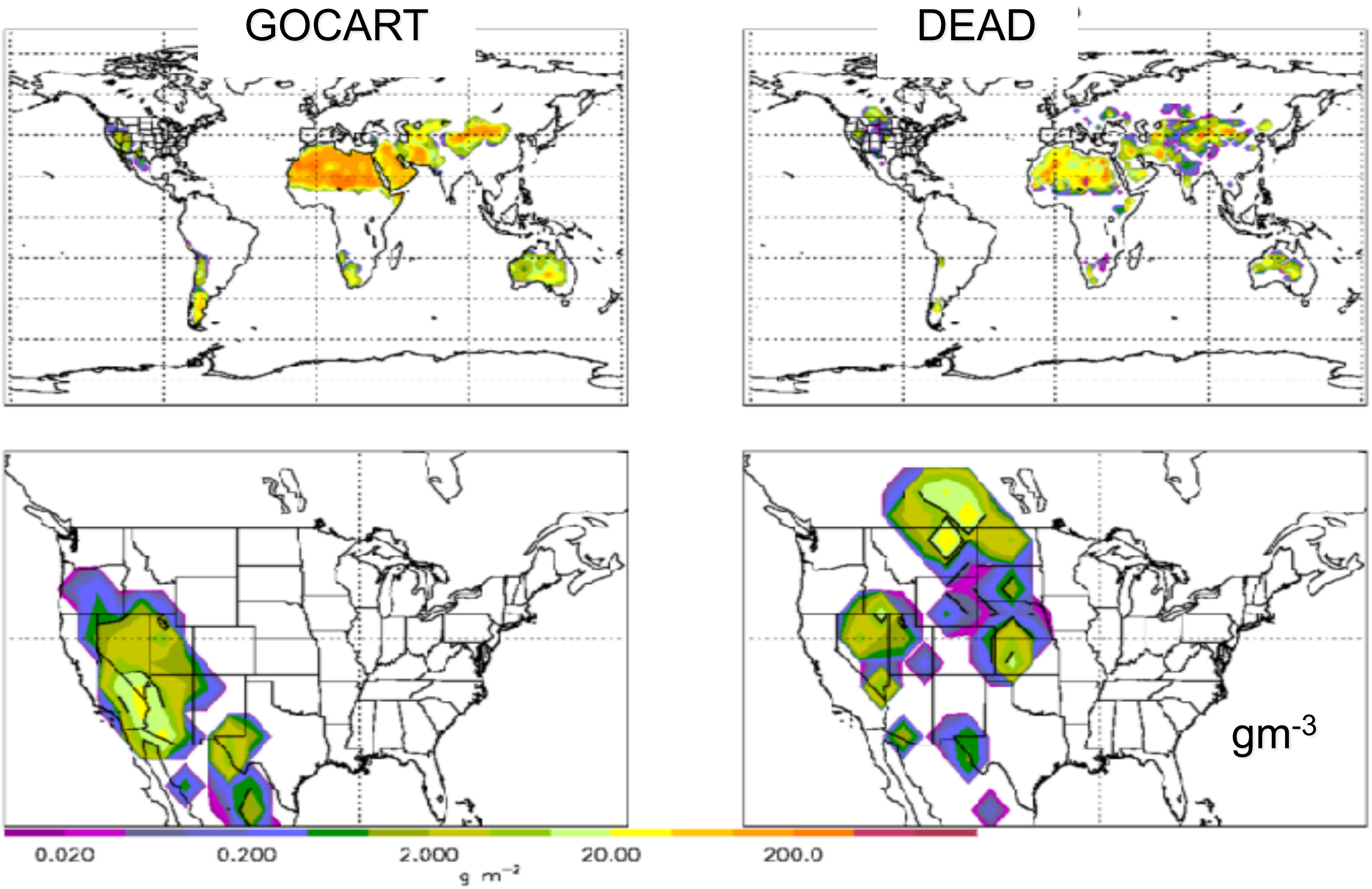
$U*_t$ – **threshold friction velocity** (particle size, density, modulated by **surface moisture**)

Essential difference, GOCART vs. DEAD, is in defining S.

DEAD lets **seasonal vegetation cover** control dust emission.

GOCART restricts emission to **permanent arid regions**.

2001 Annual dust emissions: GOCART vs. DEAD

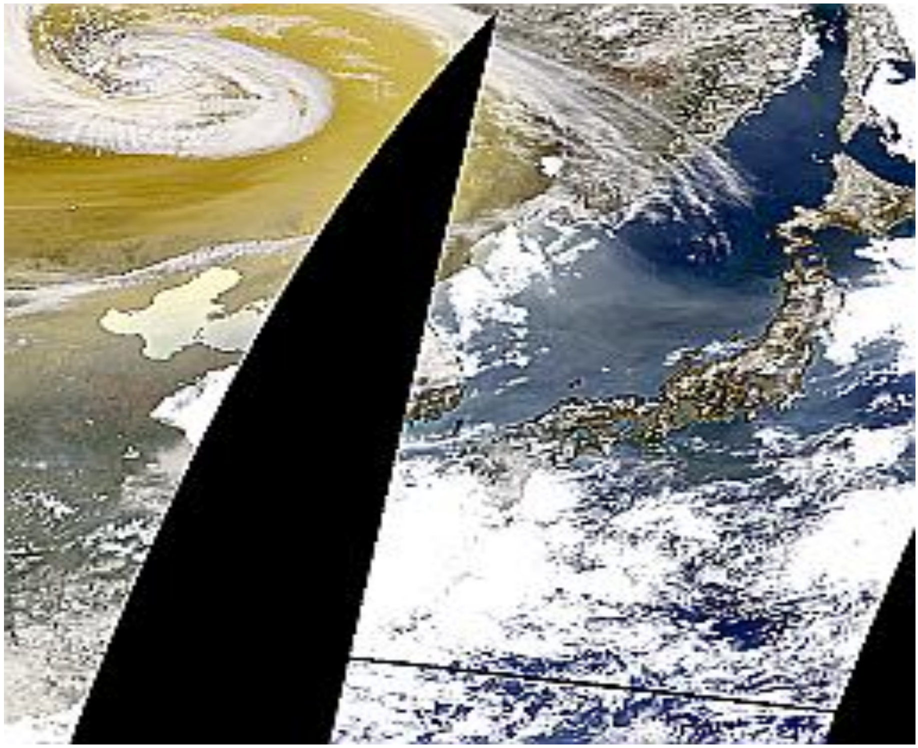


Globally, emissions distributions look similar, but large regional differences.

For North America, GOCART emissions restricted to arid west; DEAD emissions found in northern plains from seasonal changes in vegetation.

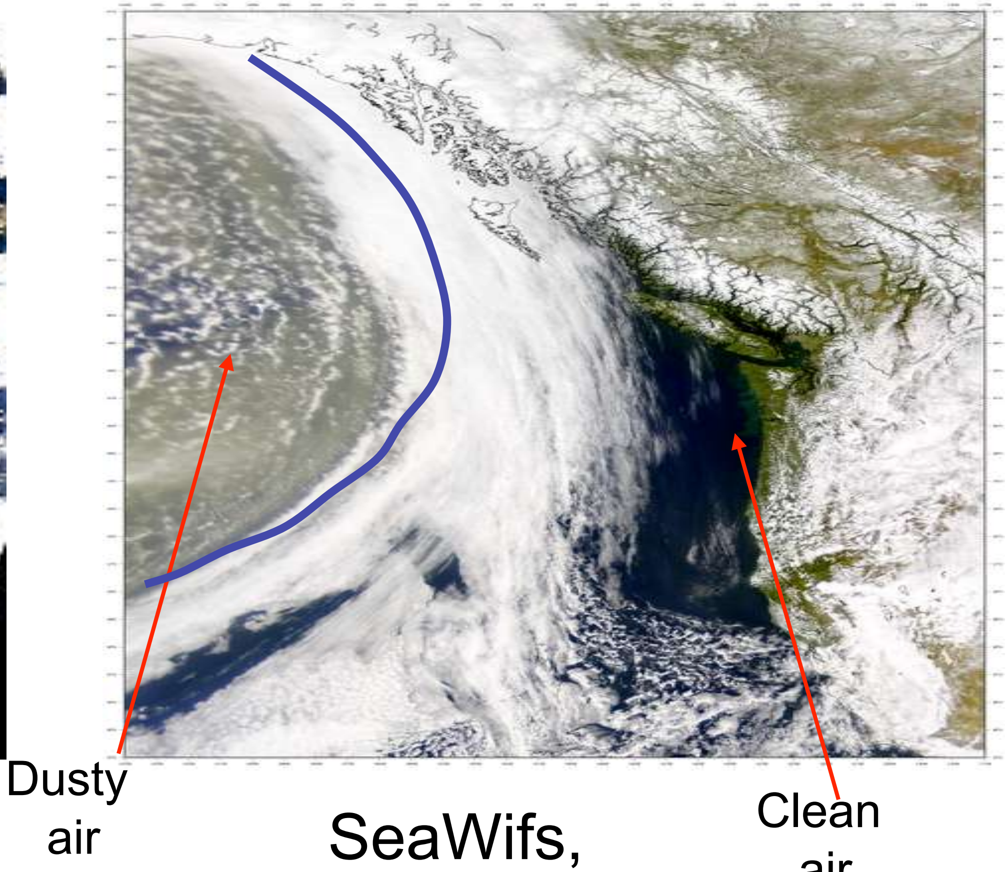
Transpacific transport, April, 2001

Dust storm Gobi Desert



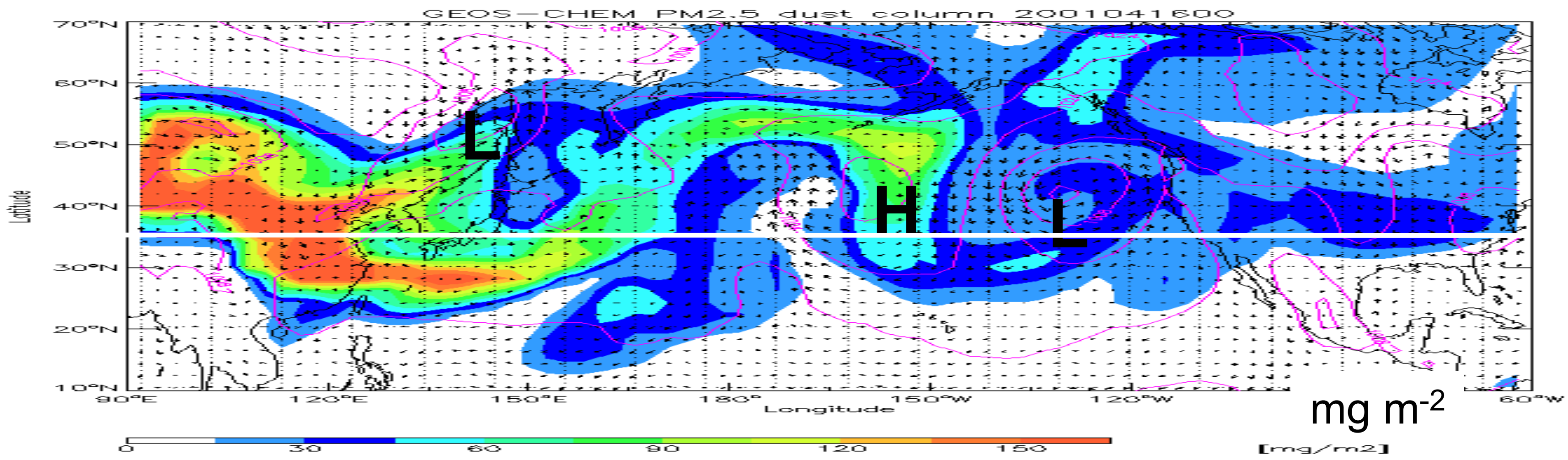
SeaWifs,
7 April 2001

Dust arrives behind front

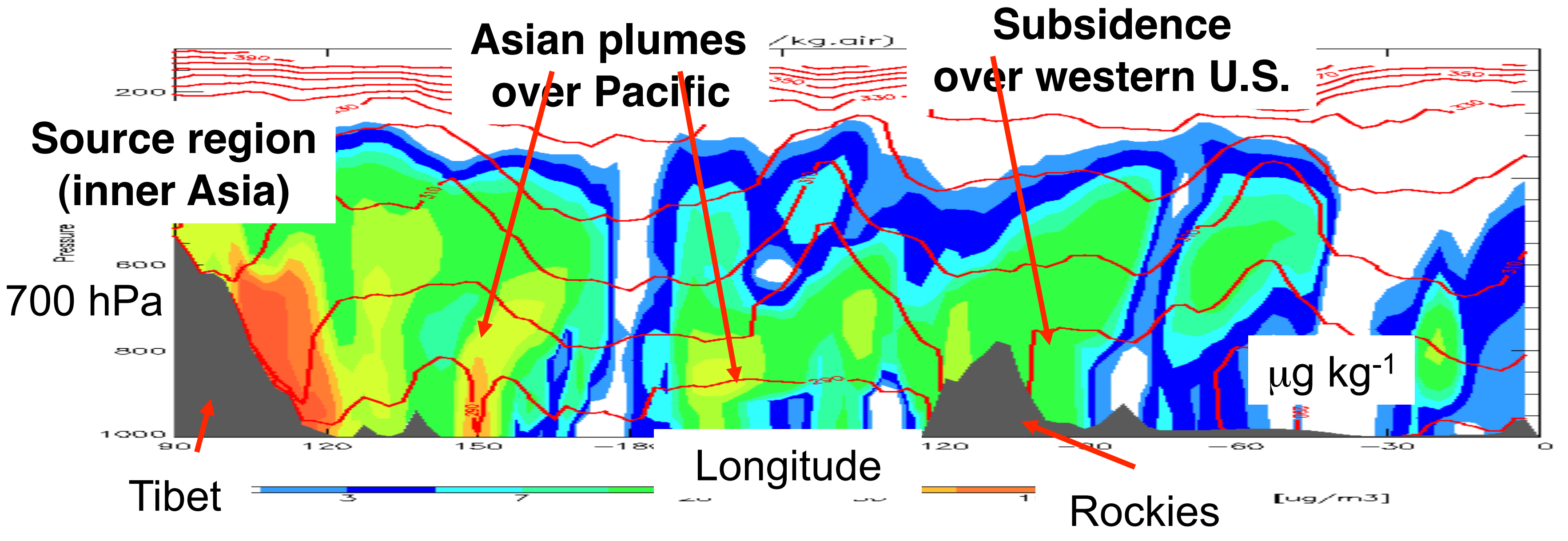


SeaWifs,
11 April 2001

GEOS-Chem Fine Dust Column, and mixing ratio
April 16, 2001



mg m^{-2}



Asian plumes over Pacific

Subsidence over western U.S.

Source region (inner Asia)

700 hPa

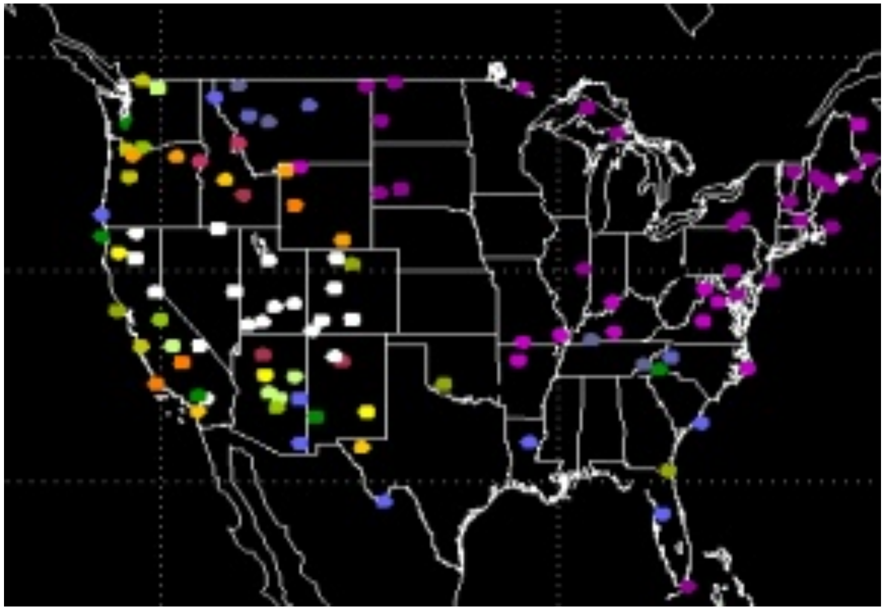
μg kg^{-1}

Tibet

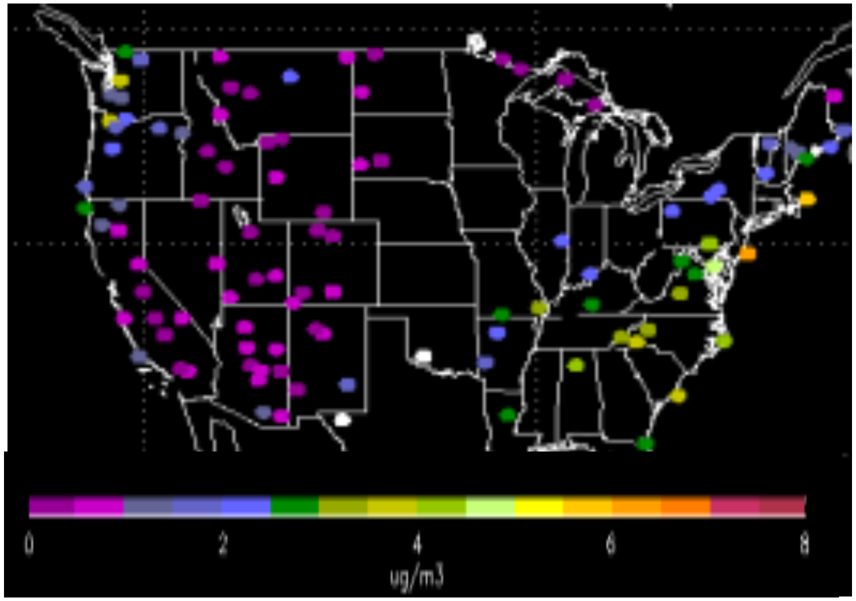
Longitude

Rockies

Asian dust observed at IMPROVE sites, April 2001



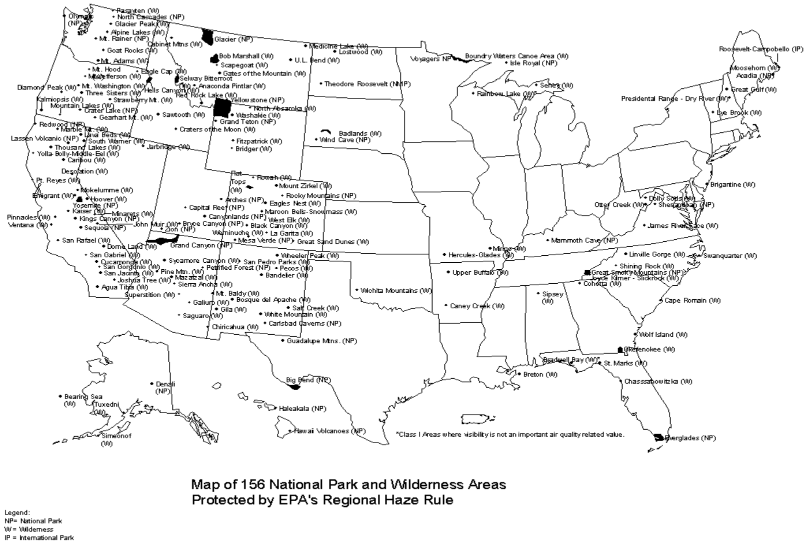
16 April, 2001



0 4 8 μg/m^3

22 April 2001

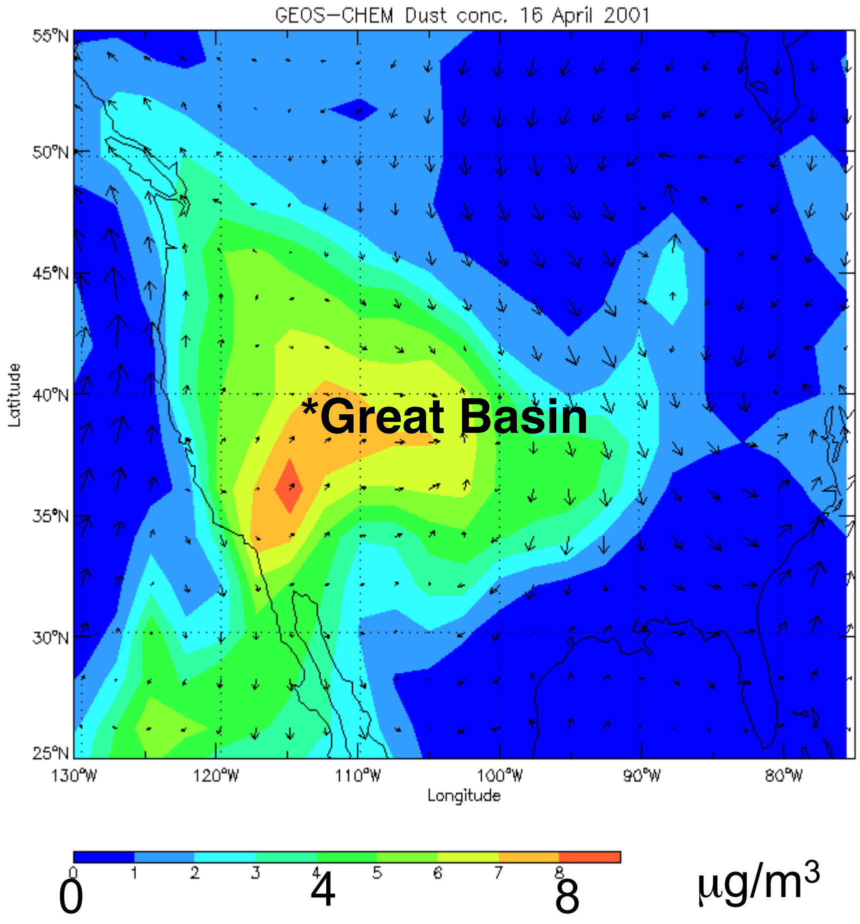
IMPROVE aerosol network:
sulfate, nitrate, ammonium, elemental carbon (EC), organic carbon (OC), fine and coarse dust, sea salt.



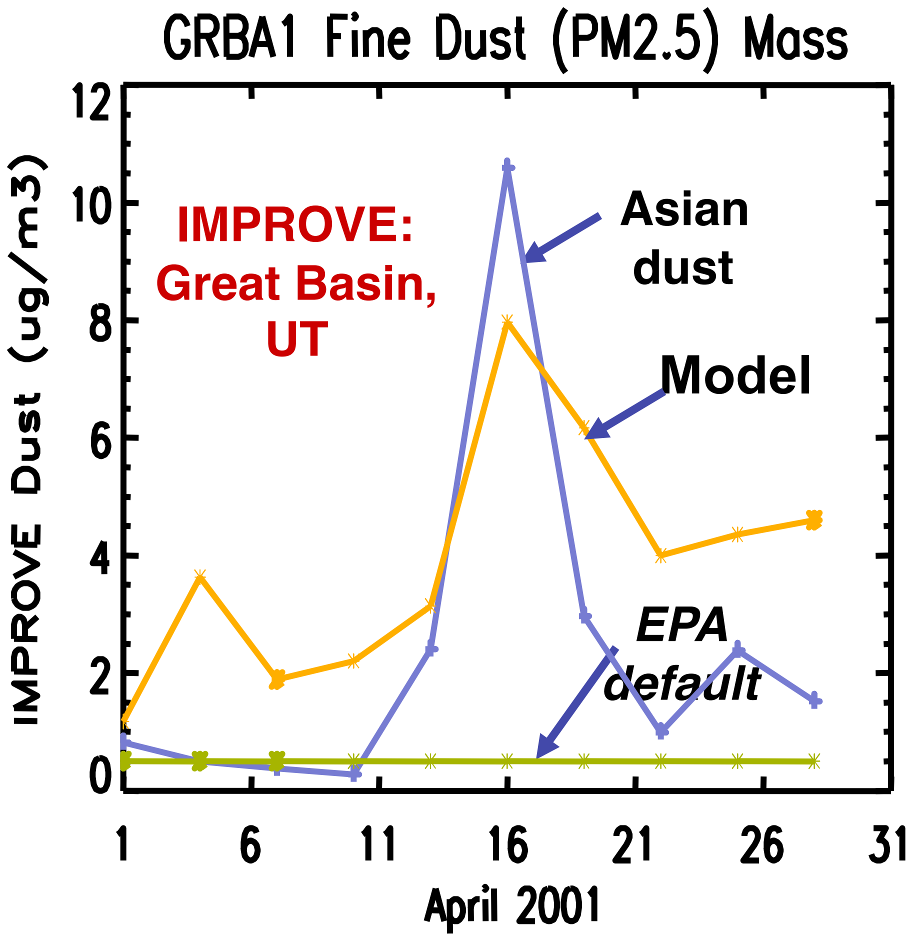
Fine dust (PM2.5) = 2.2*Al+2.49*Si+1.63*Ca +2.42*Fe+1.94*Ti (Malm et al., 1994)

Asian Dust Event in Western U.S., April 16, 2001

Simulated Asian dust

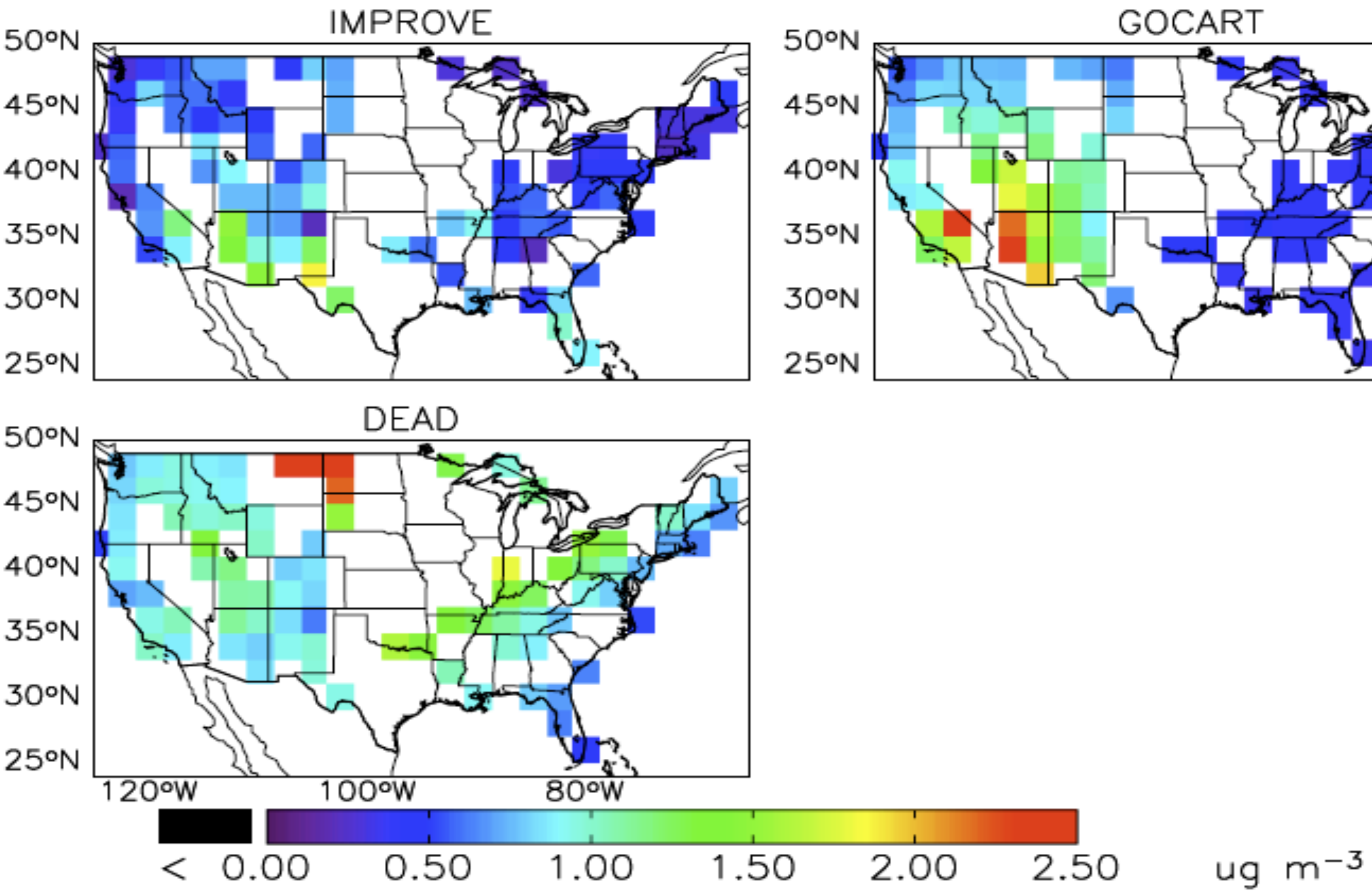


GOCART scheme

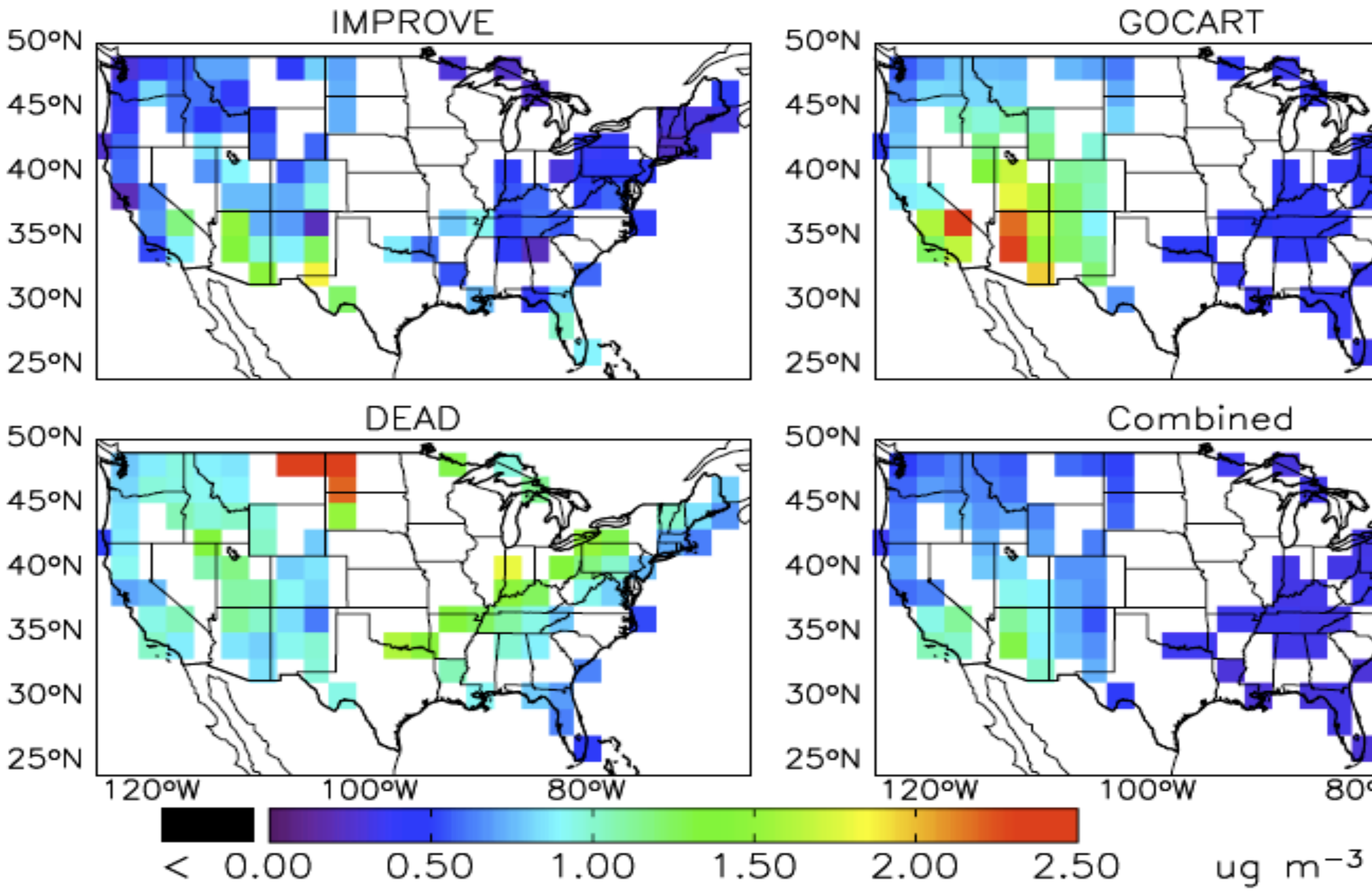


Note persistence of simulated Asian dust enhancement

Annual mean (2001) fine dust at IMPROVE sites

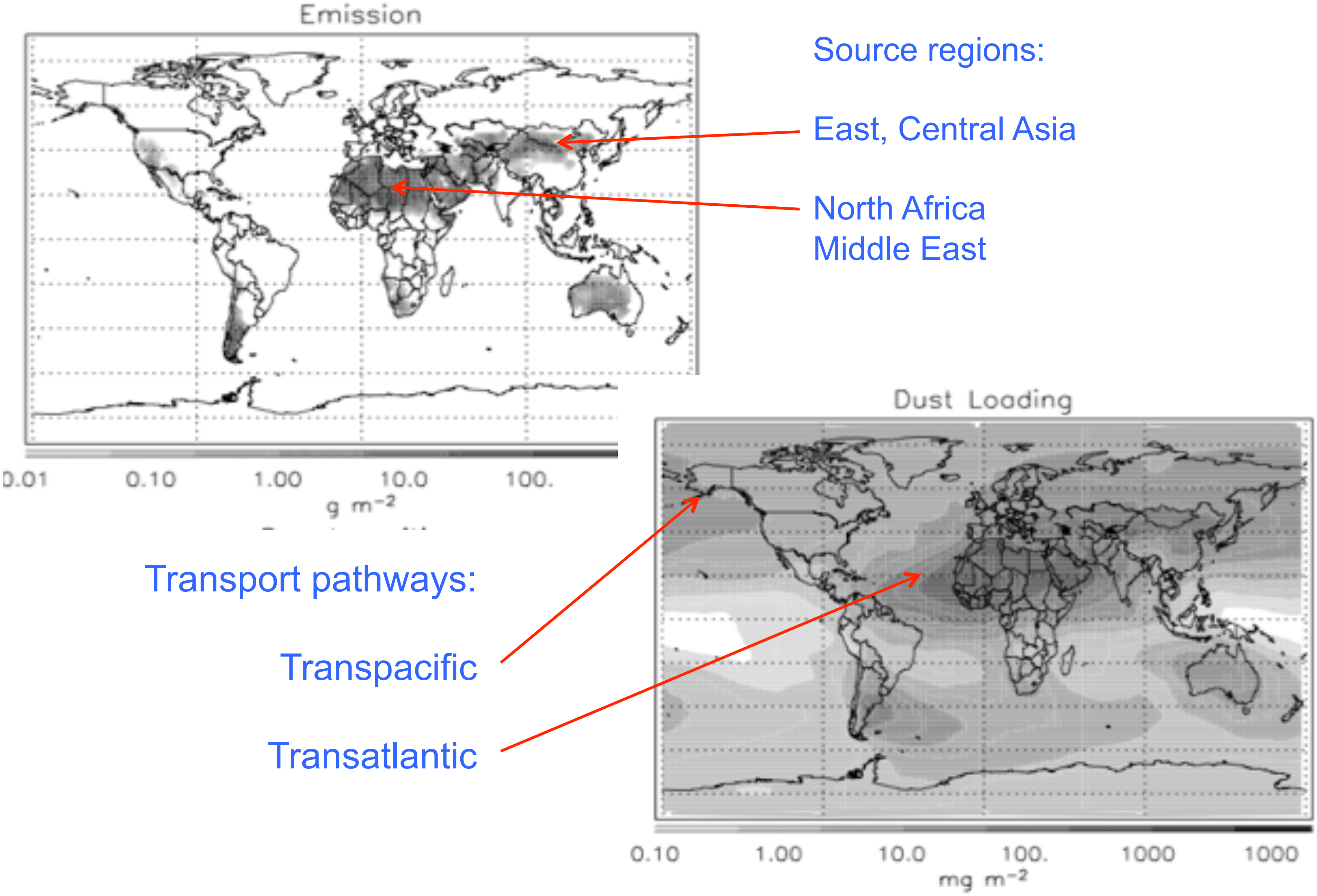


Annual mean (2001) fine dust at IMPROVE sites



“Combined” uses GOCART source function with DEAD formulation

GEOS-Chem dust simulation for 2001



Source regions:

East, Central Asia

North Africa
Middle East

Transport pathways:

Transpacific

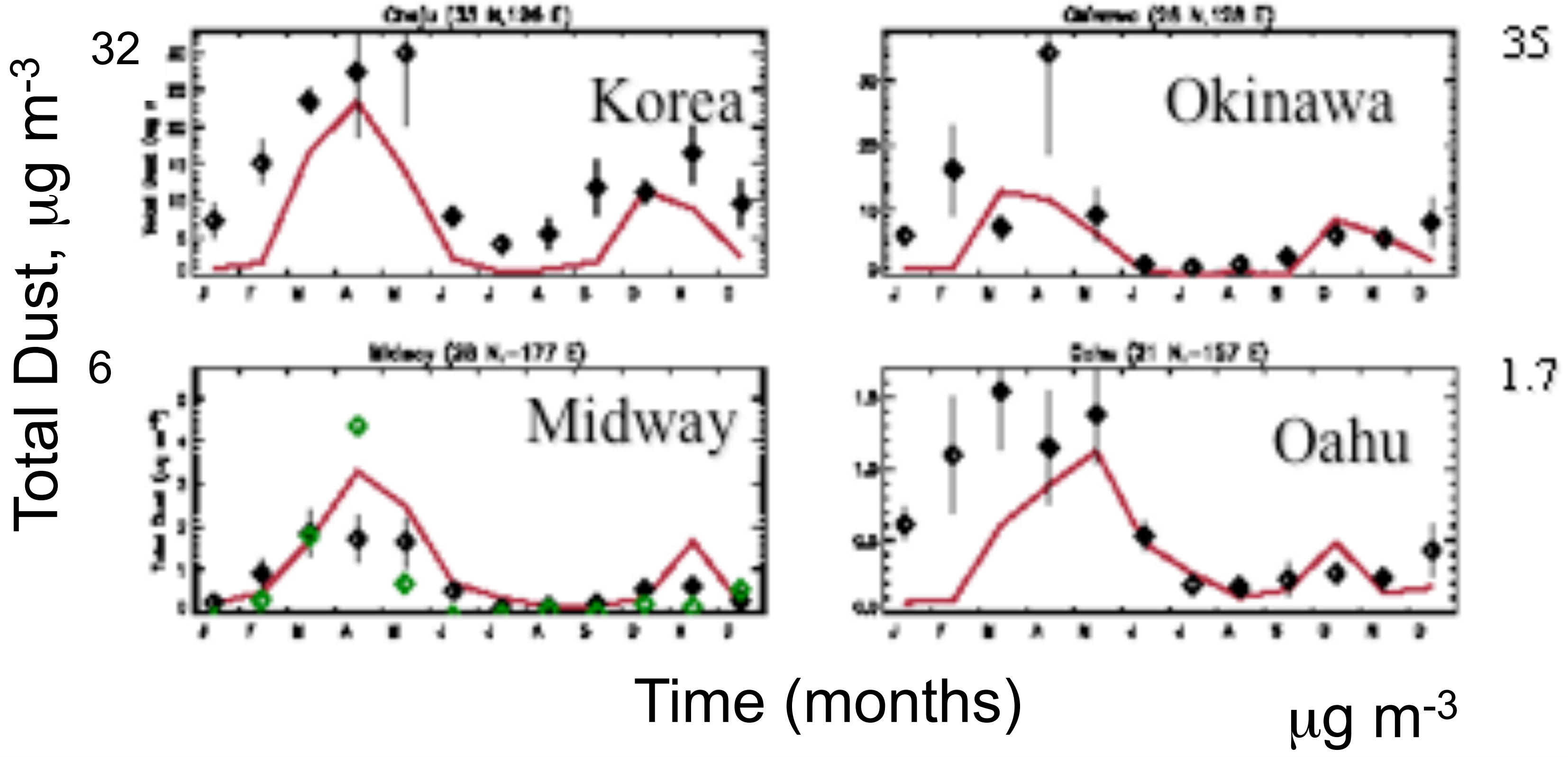
Transatlantic

Comparison with U. Miami bulk aerosol climatology (Prospero and Savoie)

◆ 2001 data

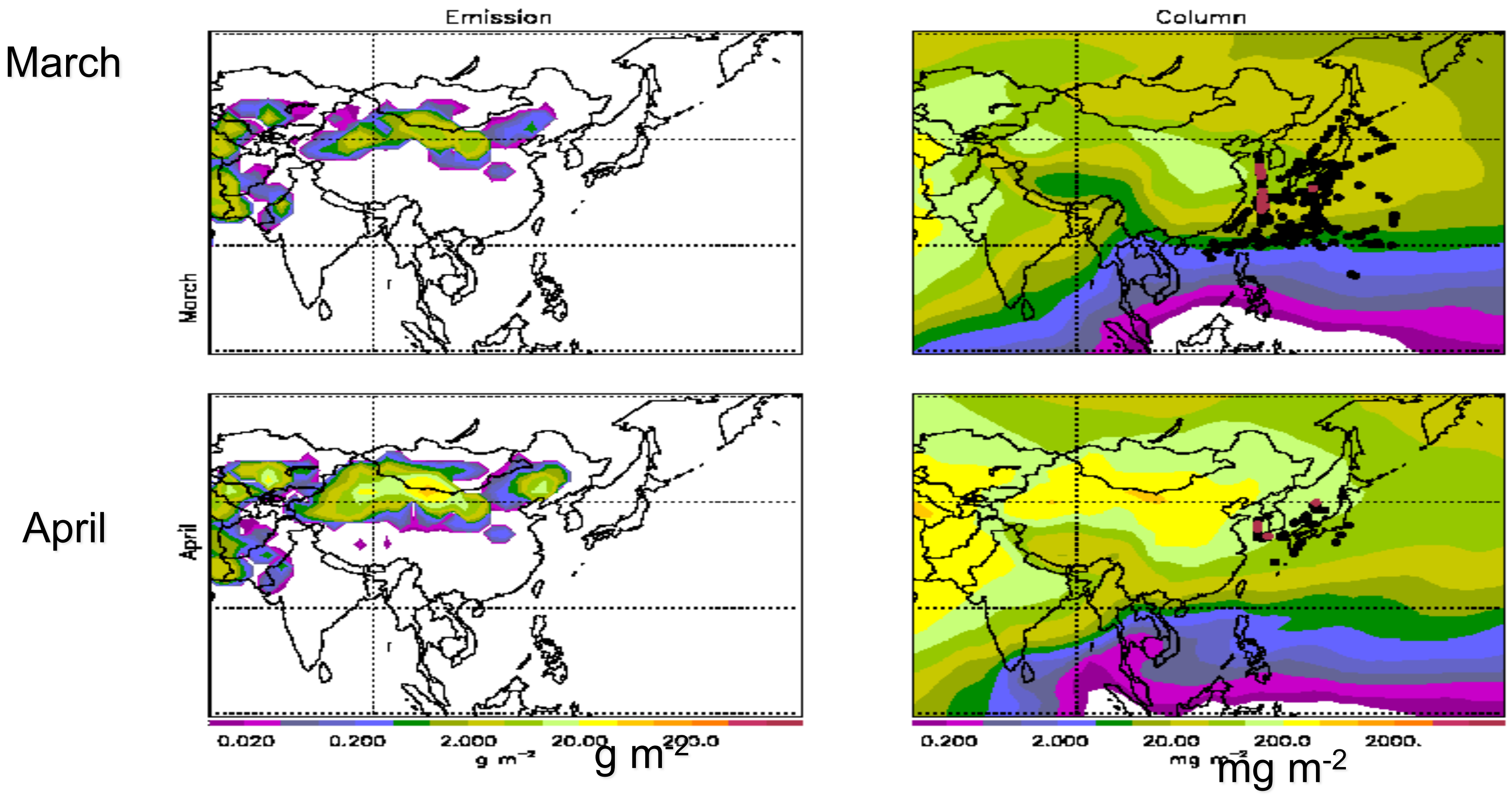
◆ climatology

— model



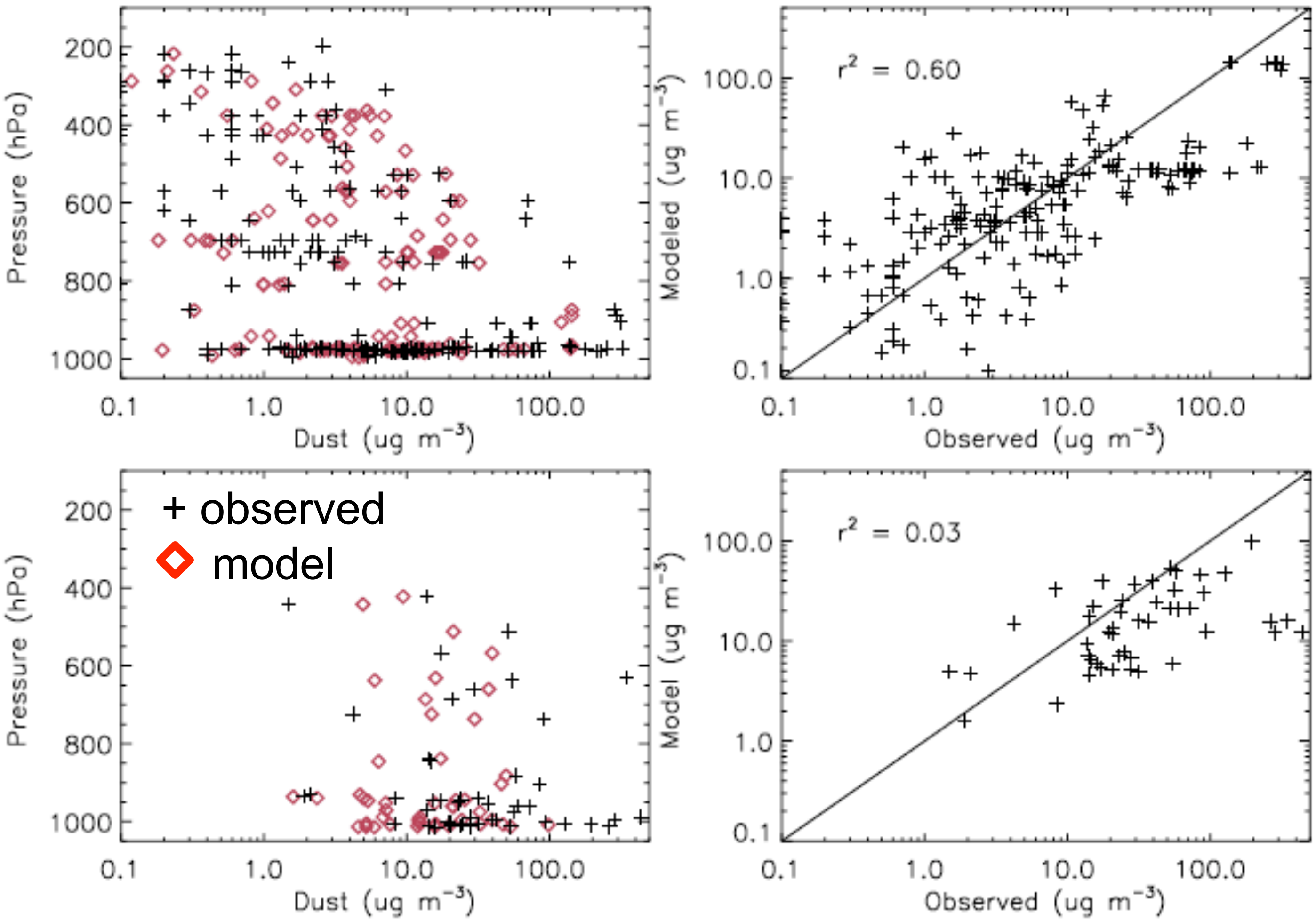
Model captures much of the magnitude and seasonal dust cycle over North Pacific. (note: different y-scales)

Monthly dust emissions and columns during TRACE-P (March) and ACE-Asia (April) field campaigns, 2001.



Model captures strong dust mobilization in East Asia, and outflow to the Pacific during TRACE-P and ACE-Asia.

Model comparison with TRACE-P and ACE-Asia obs.



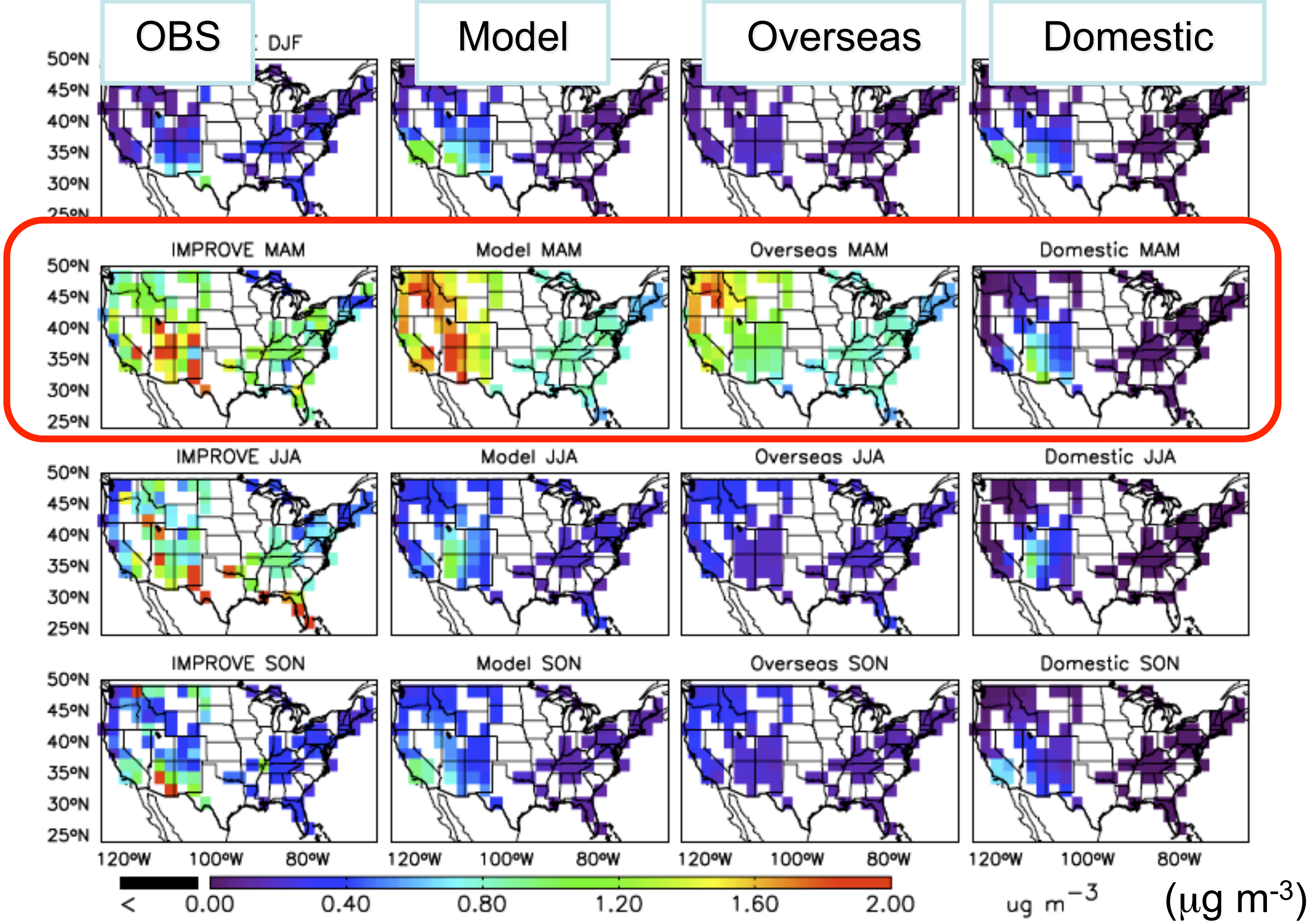
TRACE-P

ACE-Asia

(μg m^{-3})

Model generally unbiased in the free troposphere for TRACE-P; up to 70% low for ACE-Asia, when dust is 10 times as intense.

Seasonal comparison with IMPROVE fine dust



OBS

Model

Overseas

Domestic

DJF

MAM

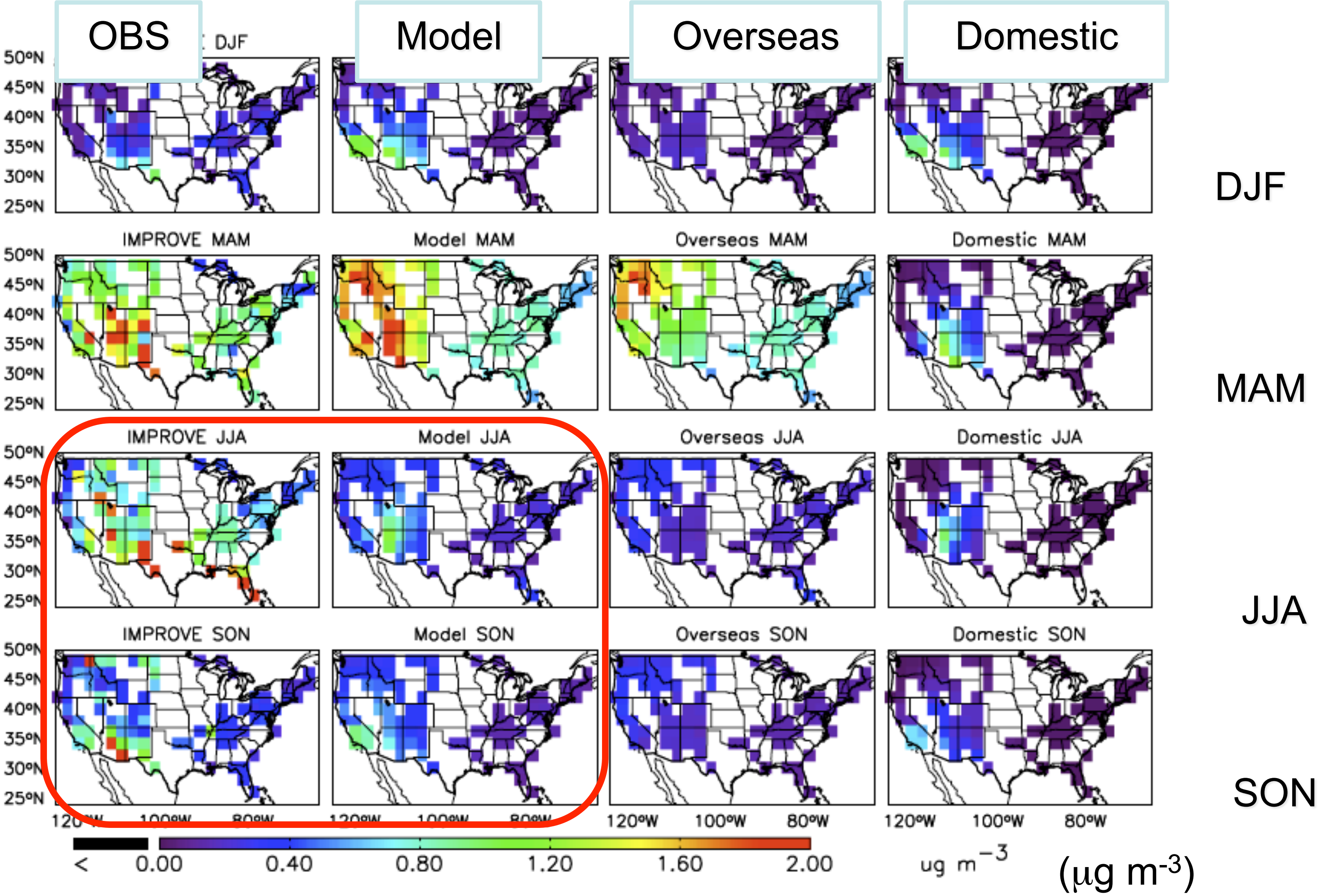
JJA

SON

(µg m^{-3})

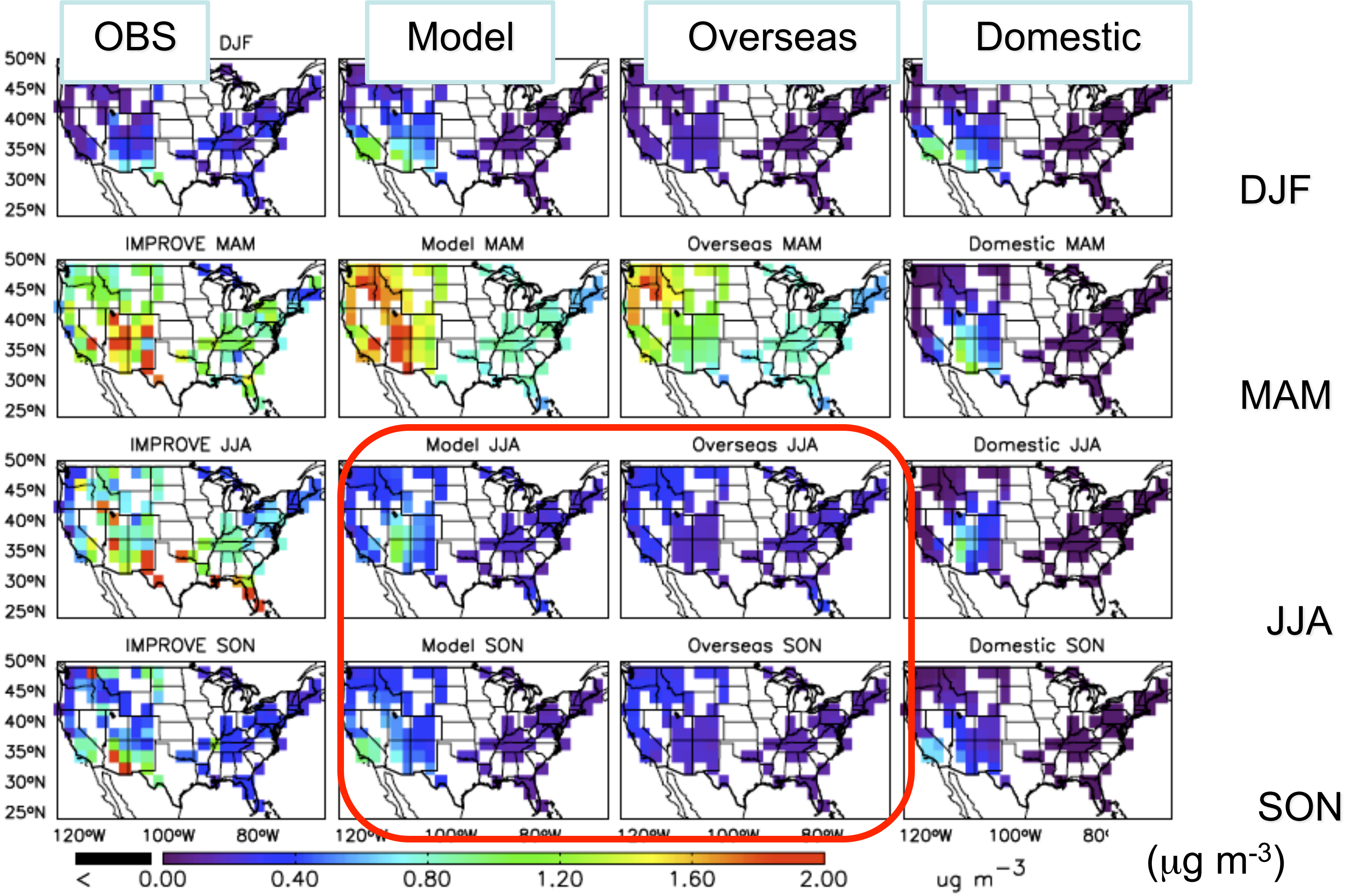
Model captures springtime nationwide peak in transpacific dust influence, mean (1.2 µg m^{-3} in west)

Seasonal comparison with IMPROVE fine dust



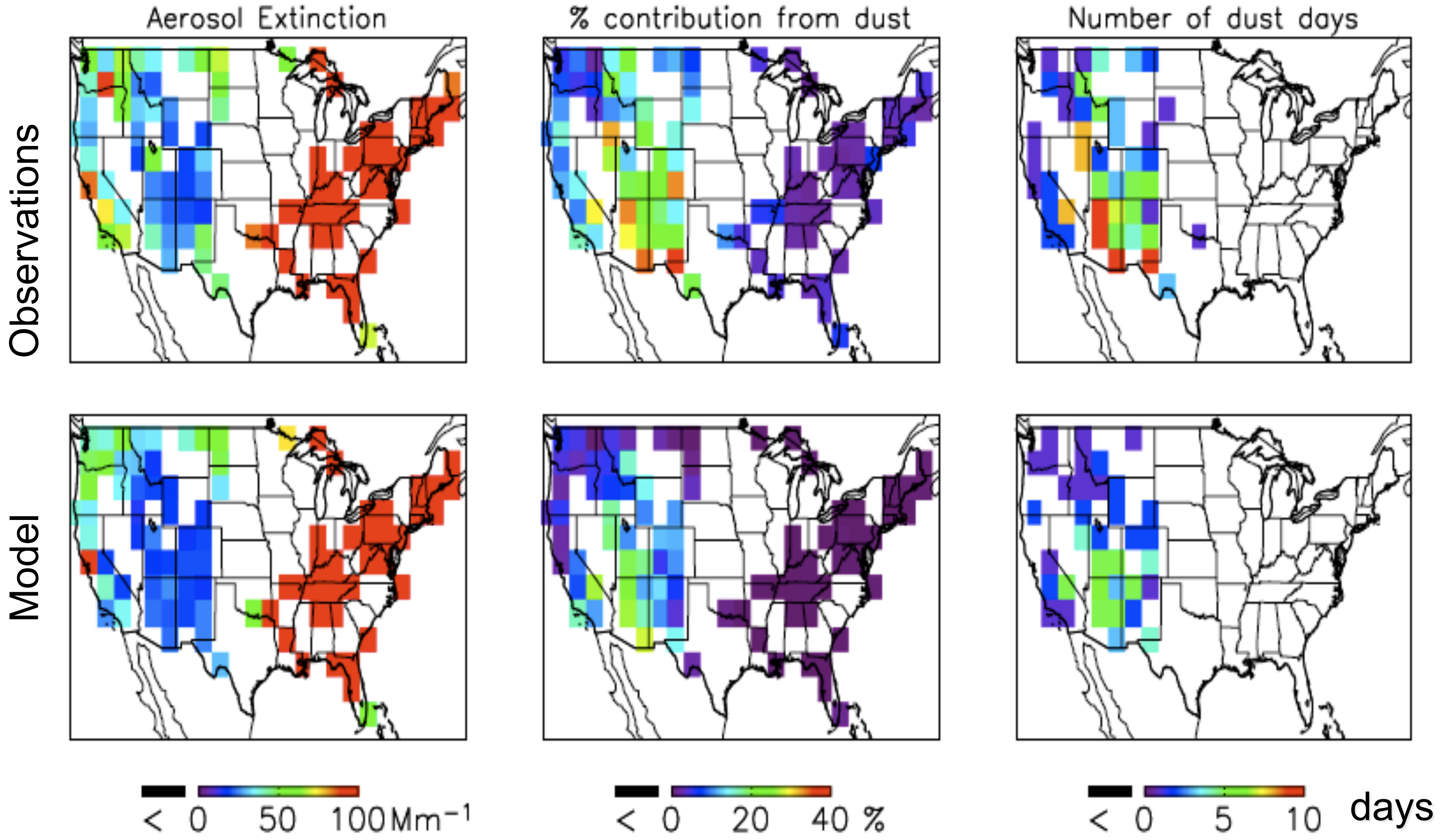
Domestic dust activity peaks in summer, due to meso-scale structures, e.g. dry convection, which the model underestimates.

Seasonal comparison with IMPROVE fine dust



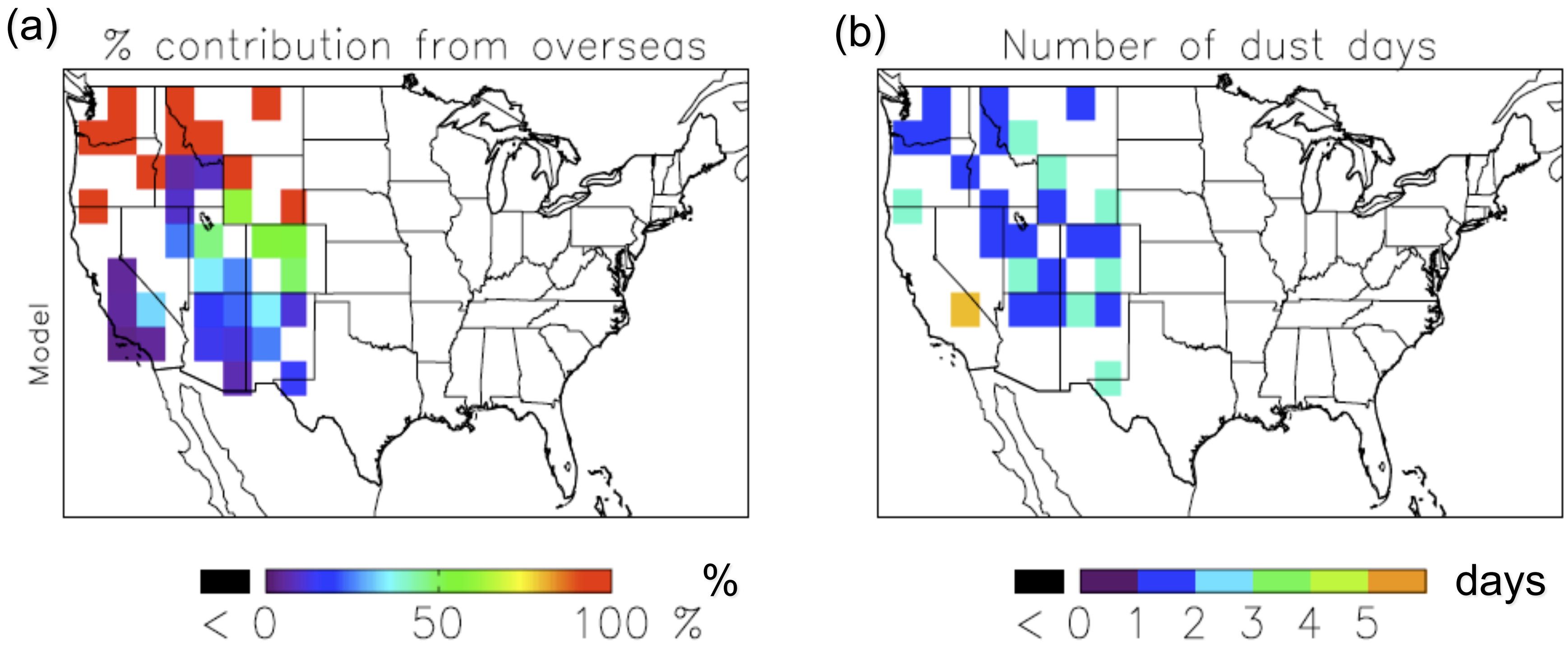
Model indicates small but persistent (0.2-0.4 μg m^{-3}) Asian dust presence in summer and fall (cf. EPA default for RHR 0.5 μgm^{-3})

The 20% worst visibility days in 2001: model vs. observed: and the contribution of dust



Dust contributes <10% in E, up to 50% in W to aerosol extinction. The model captures ~50% of the worst visibility days due to dust

Simulated transpacific contribution to dust extinction on **worst dust days**, and number of worst dust days due to transpacific sources



Transpacific sources contribute up to 100% to dust extinction in NW on worst dust days, and account for ~40% of worst dust days in the west. **States should account for Asian dust in setting realistic goals for regional haze.**

Principal findings

1. We find that Asian dust influence in the United States extends beyond springtime episodes. We attribute 0.12 (DJF), 1.2 (MAM), 0.25 (JJA), 0.25 (SON) $\mu g\ m^{-3}$ to Asian fine dust in the west (30-50% lower in the east)

2. We attribute ~40% of the worst dust days in 2001 to transpacific sources.

3. We conclude that states should account for Asian dust in setting attainable goals for regional haze.

Publications

1. The impact of transpacific transport of mineral dust in the United States

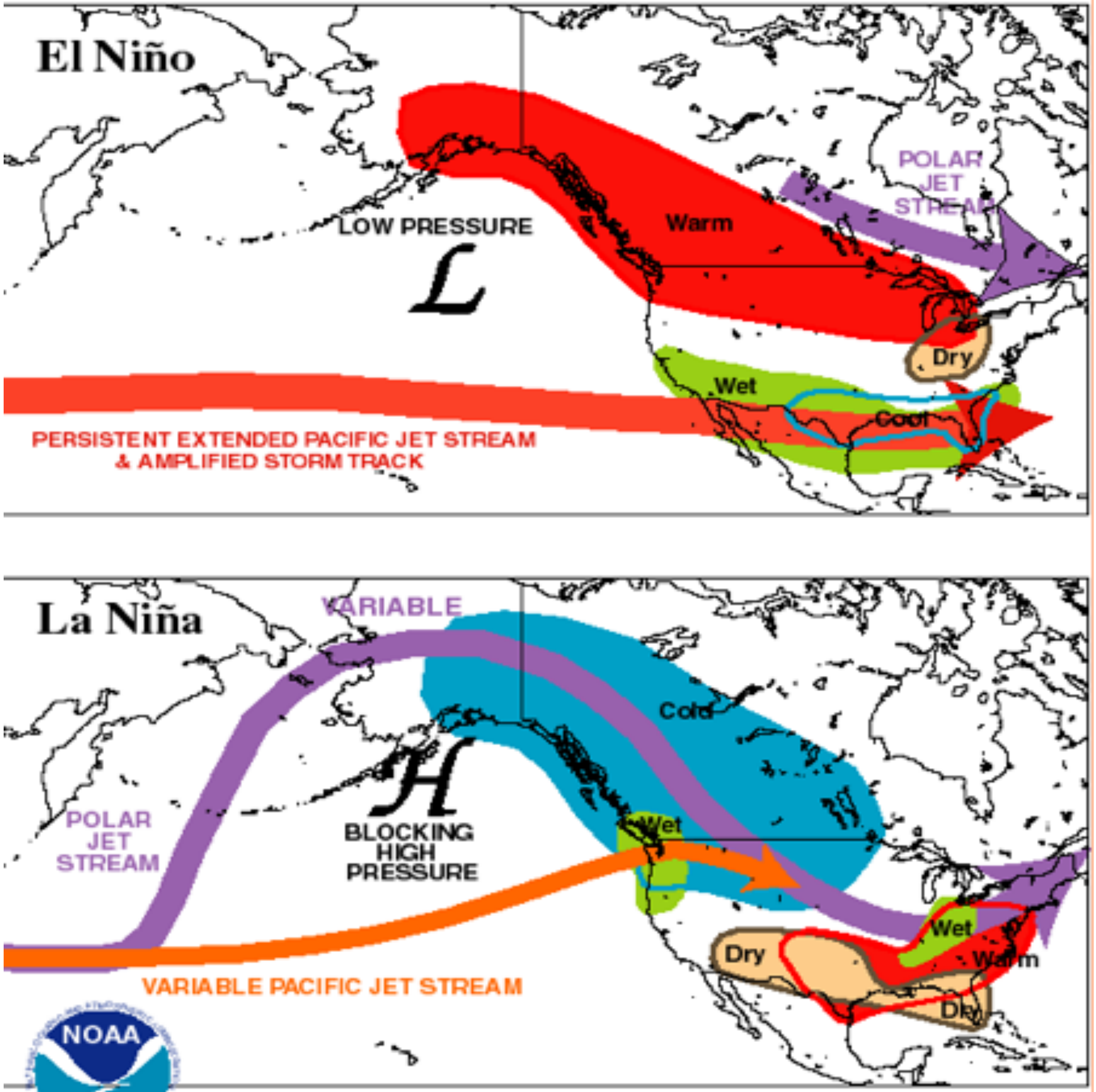
   [Fairlie, T.D., D.J. Jacob, R.J. Park, 2007, *Atmos. Env*. 41, 1251-1266]

2. The impact of mineral dust on nitrate, sulfate, and ozone in transpacific pollution plumes

   [Fairlie, T.D., D.J. Jacob, J.E. Dibb, B. Alexander, M.A. Avery, A. van Donkelaar, L. Zhang, 2010*, Atmos. Chem. Phys., 10, 3999-4012*]

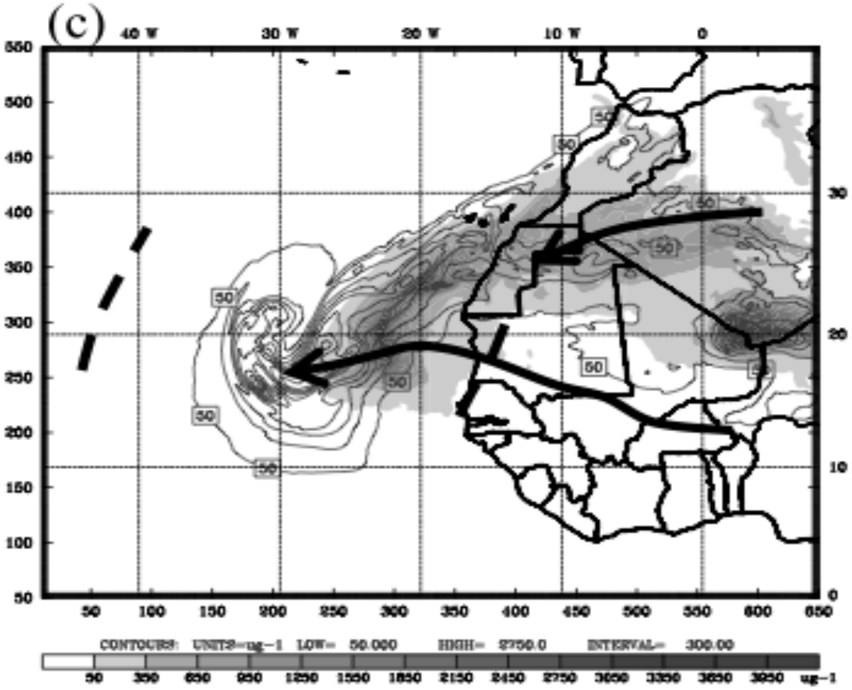
Questions

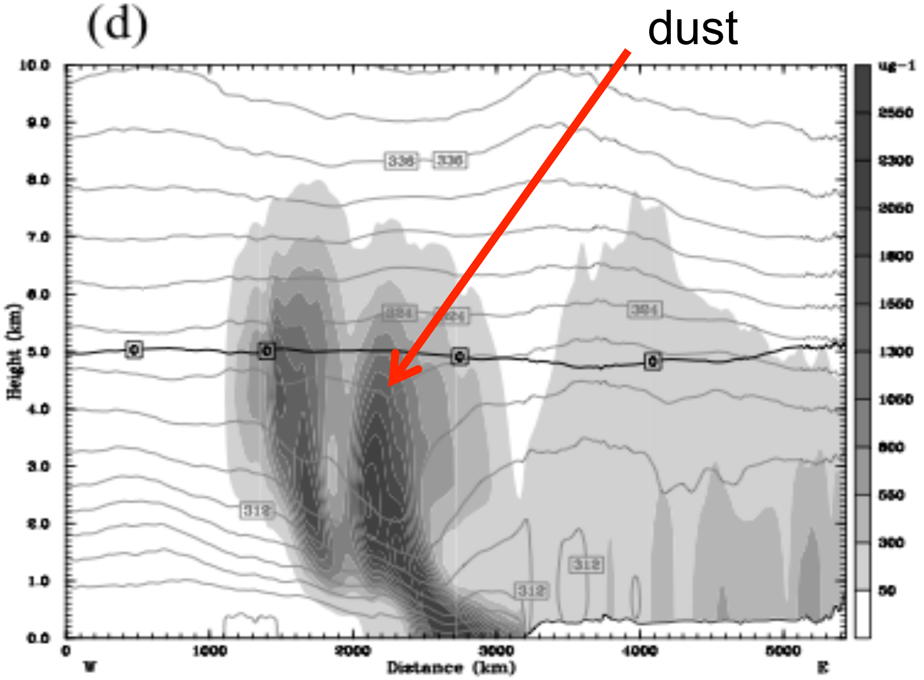
TYPICAL JANUARY-MARCH WEATHER ANOMALIES AND ATMOSPHERIC CIRCULATION DURING MODERATE TO STRONG EL NIÑO & LA NIÑA



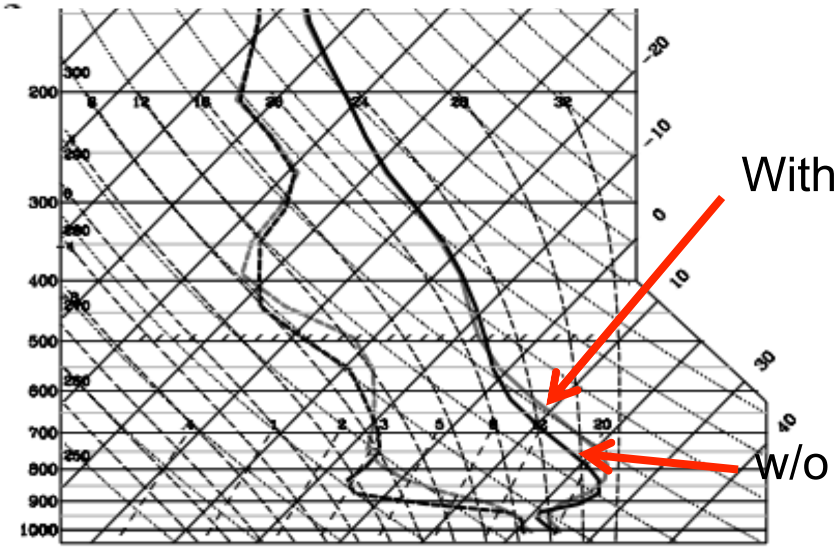
Climate Prediction Center/NCEP/NWS

Tropical Storm Development: Saharan Air Layer





dust



With

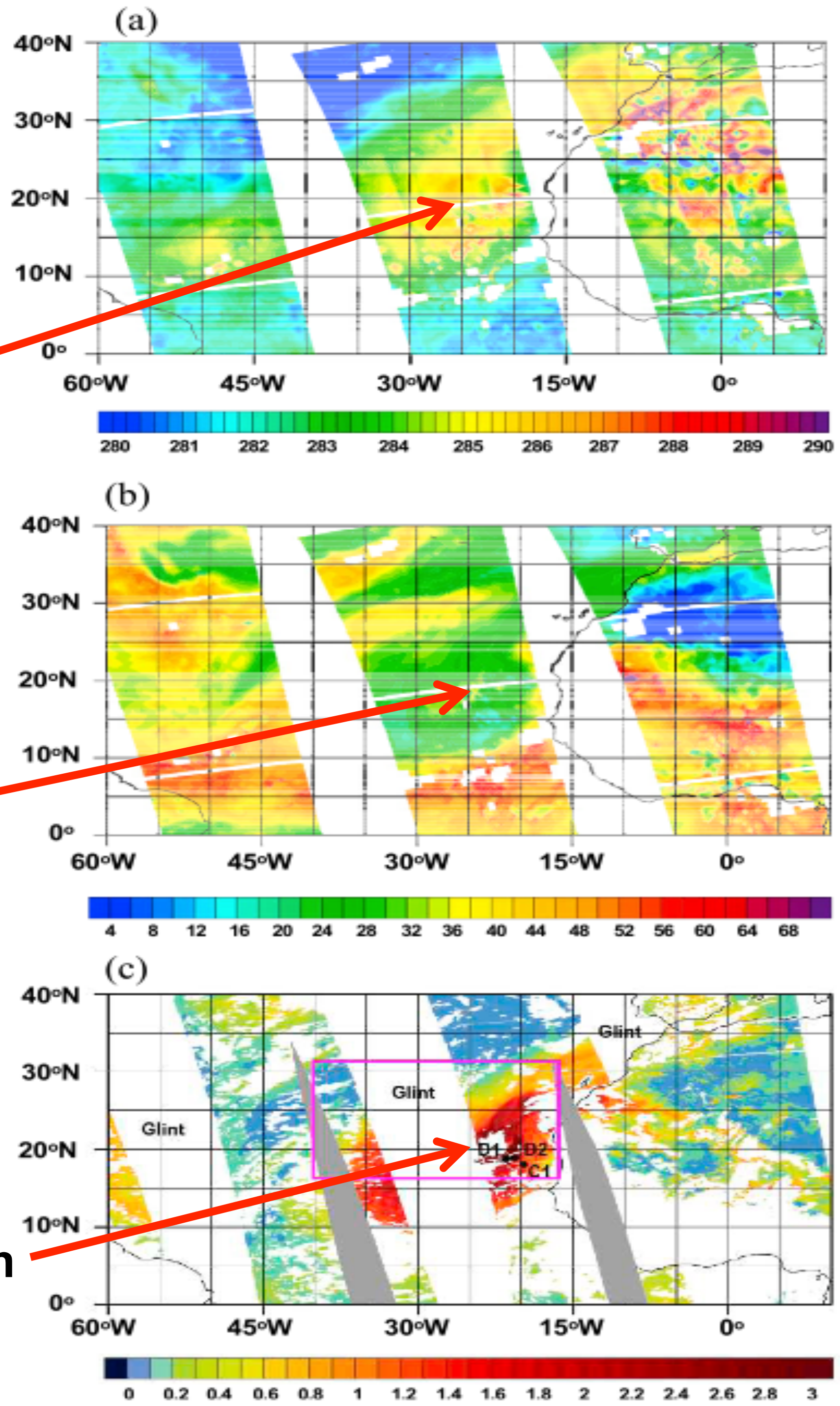
w/o

WRF simulation of SAL shows enhancement of trade wind inversion, warming, moistening, and self-lofting of the dust layer.

(gray line is with, black line is w/o radiative feedbacks from dust)
(from Chen et al., JGR, 2010)

Saharan Air Layer (SAL)

20 July 2005



700 mb Temperature
(AIRS, Aqua)

Warm

700 mb Total Precipitable Water
(AIRS, Aqua)

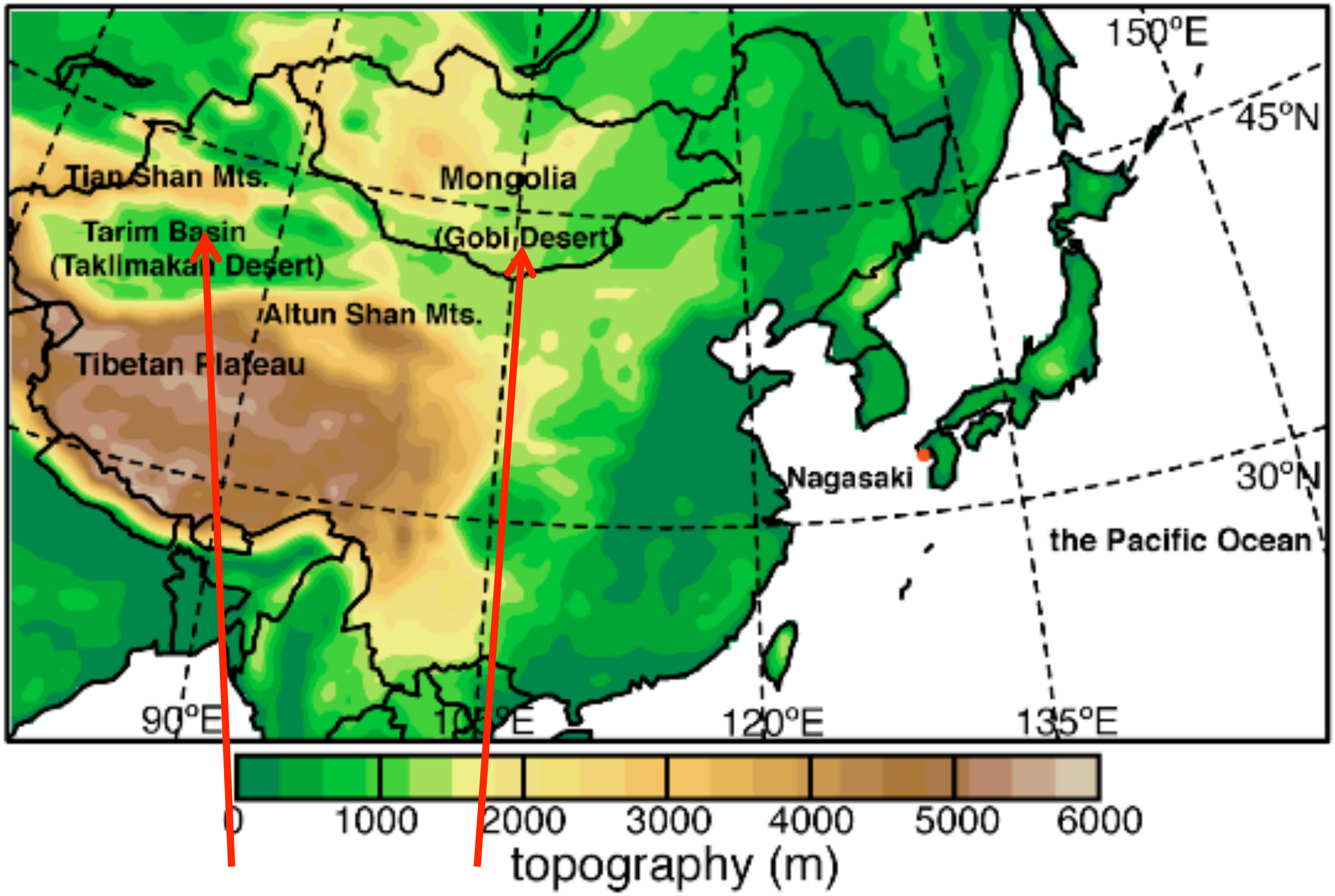
Dry

Aerosol Optical Depth (AOD)
(MODIS, Aqua)

Dust-laden

(from Chen et al., JGR, 2010)

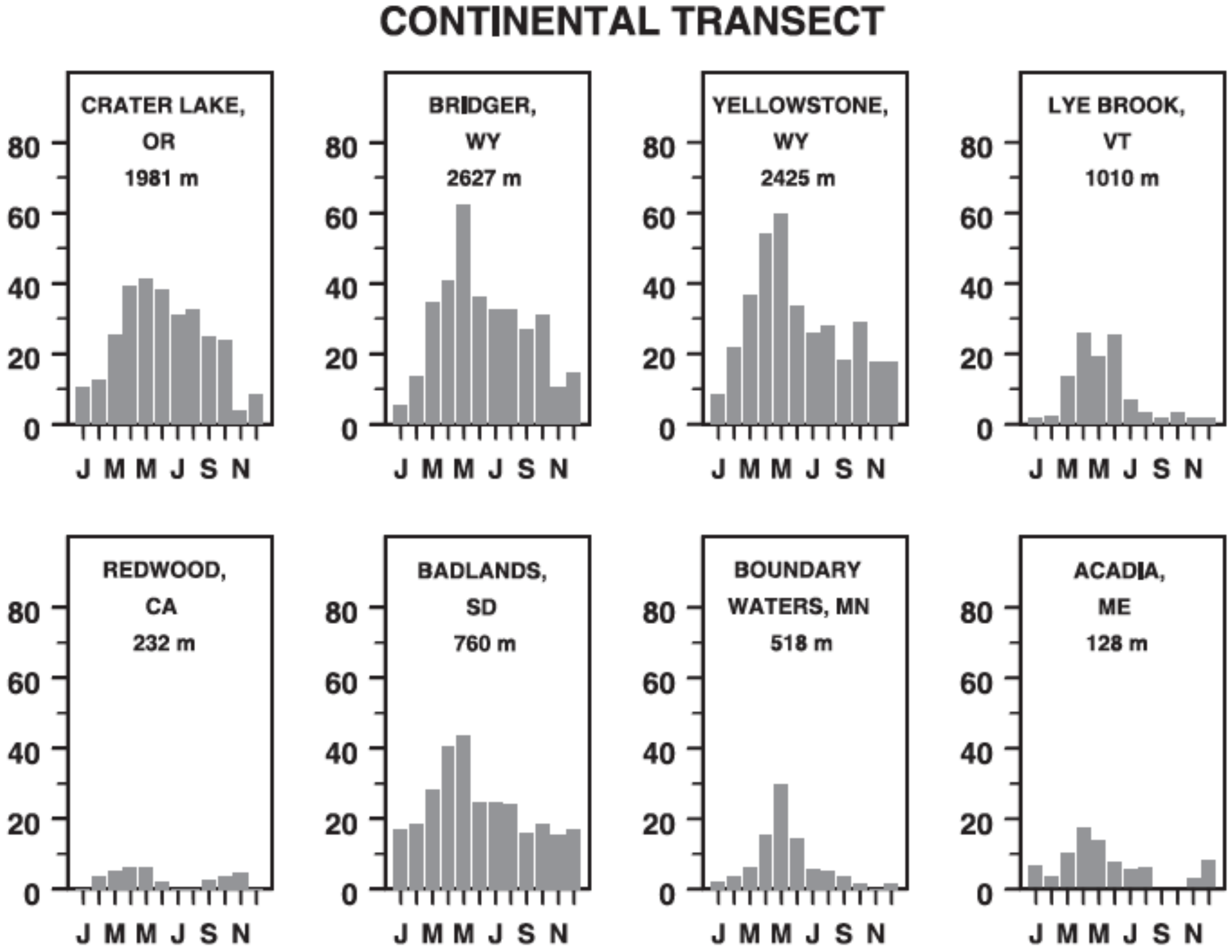
East Asian dust source regions



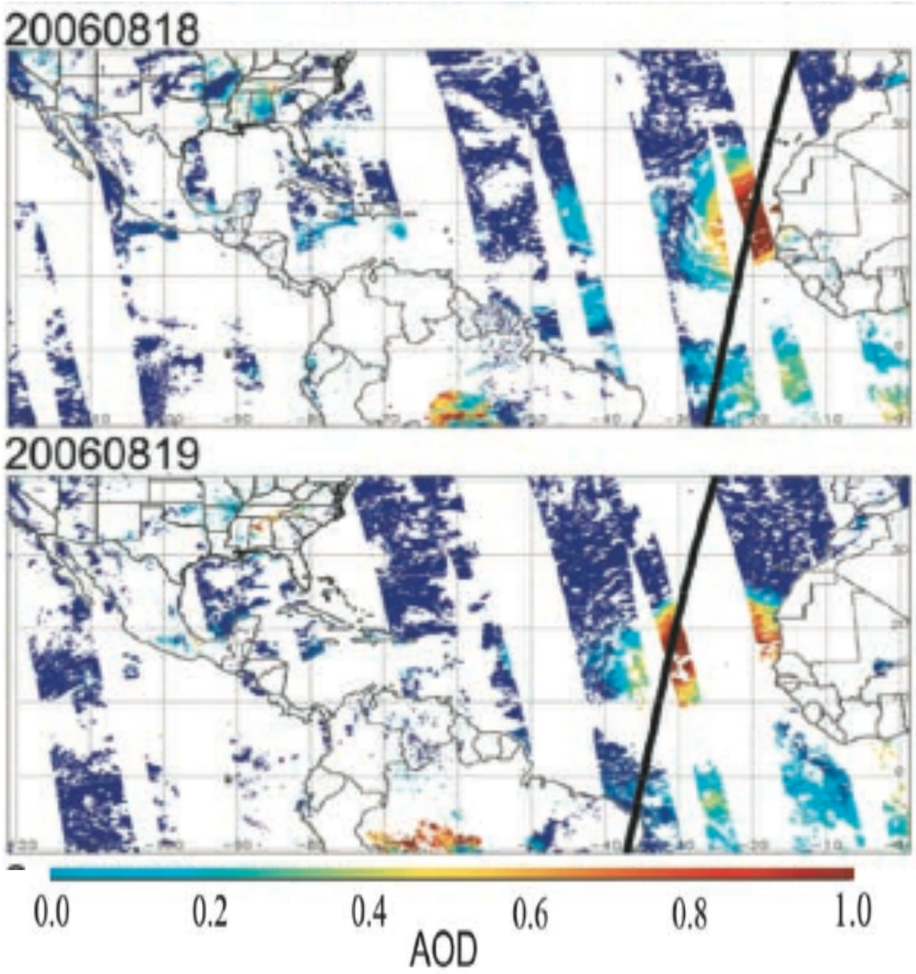
Taklimakan Gobi Desert
dust source regions

Yumimoto et al., 2009

Monthly Asian fine dust frequency at

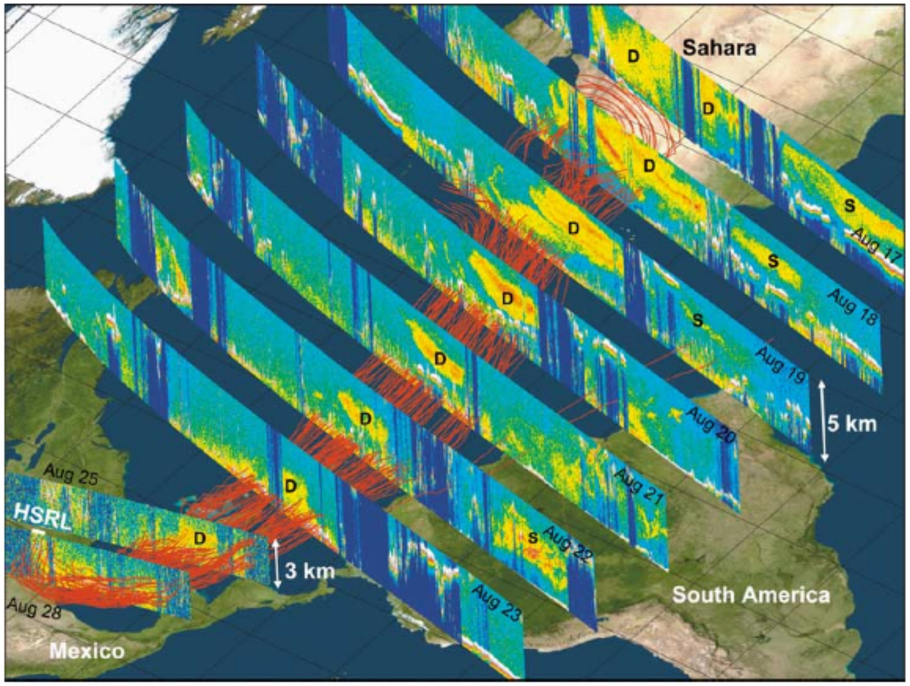


From van Curen and Cahill (2002)

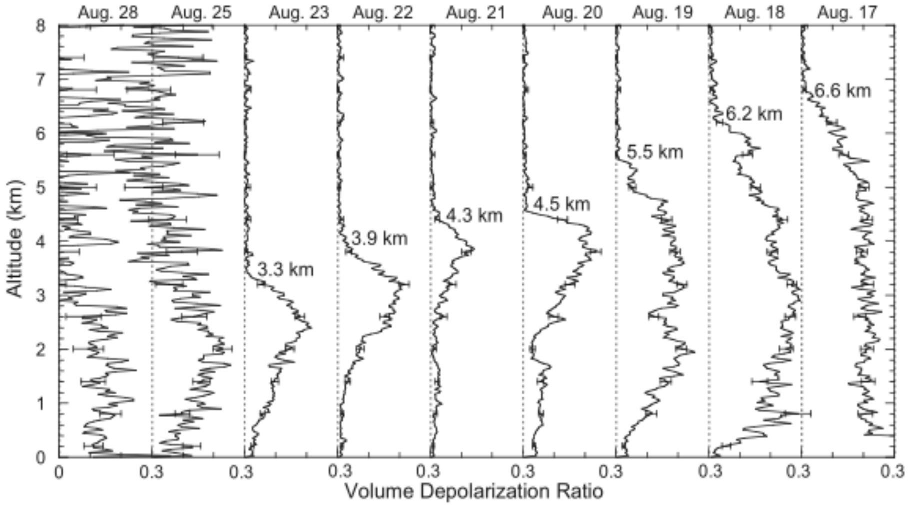


MODIS Aqua AOD shows dust outflow from N. Africa in August 2006

Top-right figure by Kurt Severance, NASA.
Figs. are from Zhaoyan. Liu et al., JGR, 2008



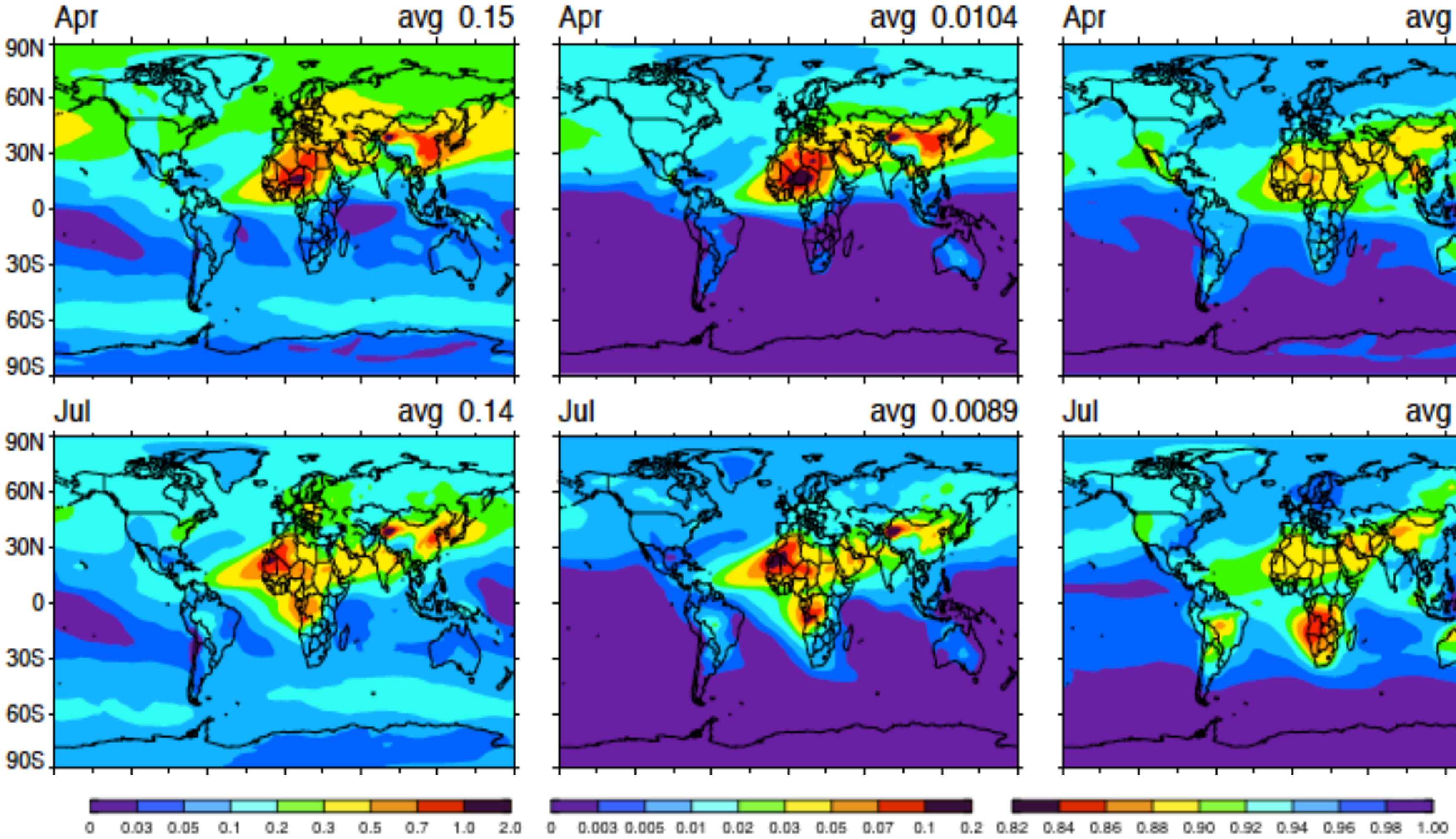
CALIOP 532 nm attenuated backscatter, with back trajectories, shows vertical structure in trans-Atlantic transport



Optical depth
550 nm

Optical Depth (Absorption)
550 nm

Single scattering Albedo
550 nm



GOCART model, 2000-2008, from Mian Chin et al., Ann. Geophys.,2009