CHAPTER 3

EARTH MEASUREMENTS & MODELING

Measurements and Modeling

- ✓ **Studies of the Earth system are based on measurements and numerical models.**

- ✓ **In different fields of geophysical sciences, fundamental information is often obtained first through measurements:**
  - **Weather, climate**
  - **Oceanography**
  - **Cryosphere**
  - **Biosphere**
  - **Chemistry**

- ✓ **Types of measurements: ground, sounding, remote sensing, aircraft, drone, campaign?**

Surface Meteorological Measurement Stations

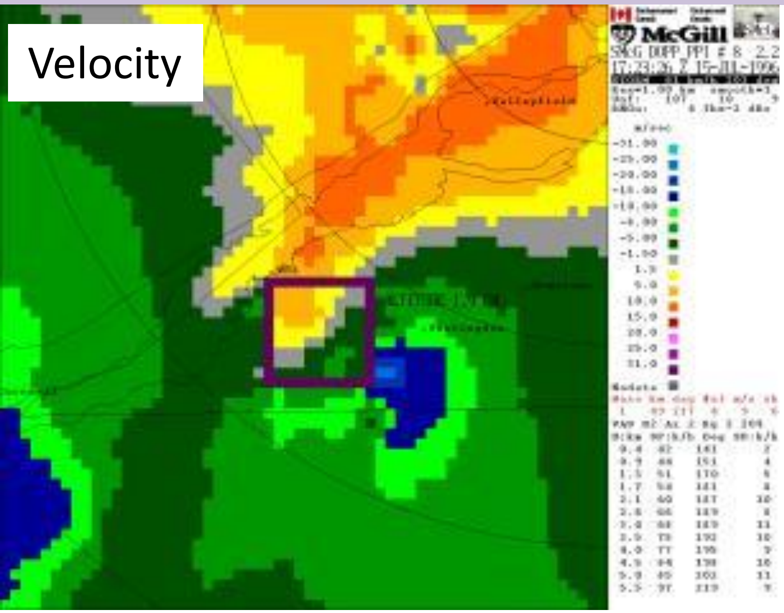
Measurements of meteorological parameters:
Temperature, humidity, pressure, winds, visibility, cloud, precipitation, solar radiation, etc.

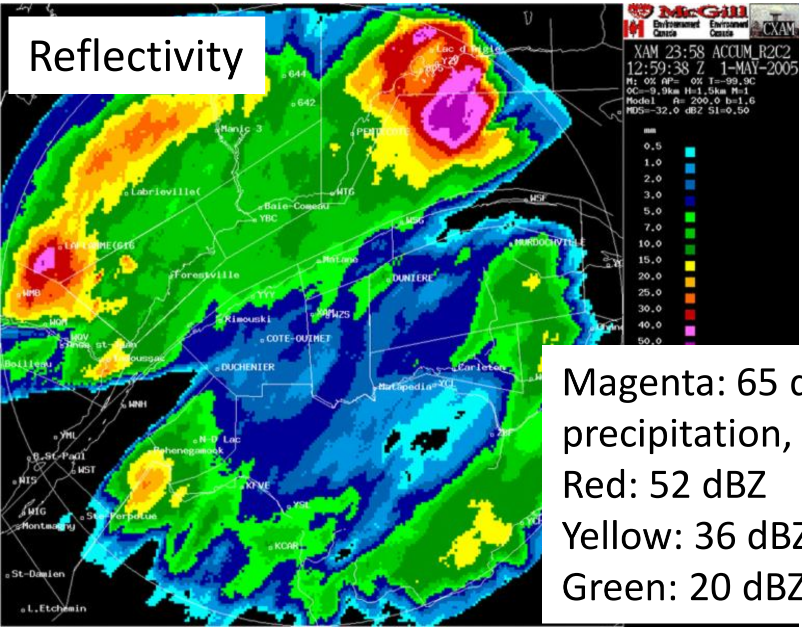
Visibility as Measurement of Meteorology and Pollution

Visibility = K / extinction_coefficient

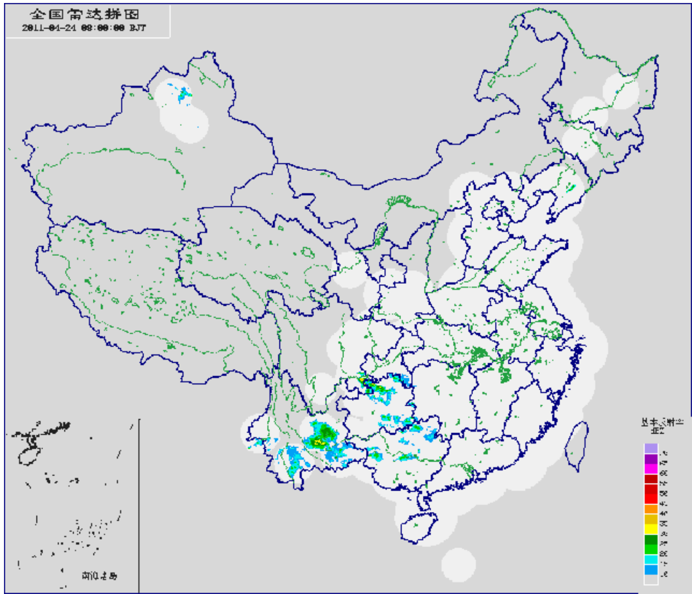
Used traditionally as a meteorological indicator, but employed more and more to study particulate air pollution

Radar Measurements

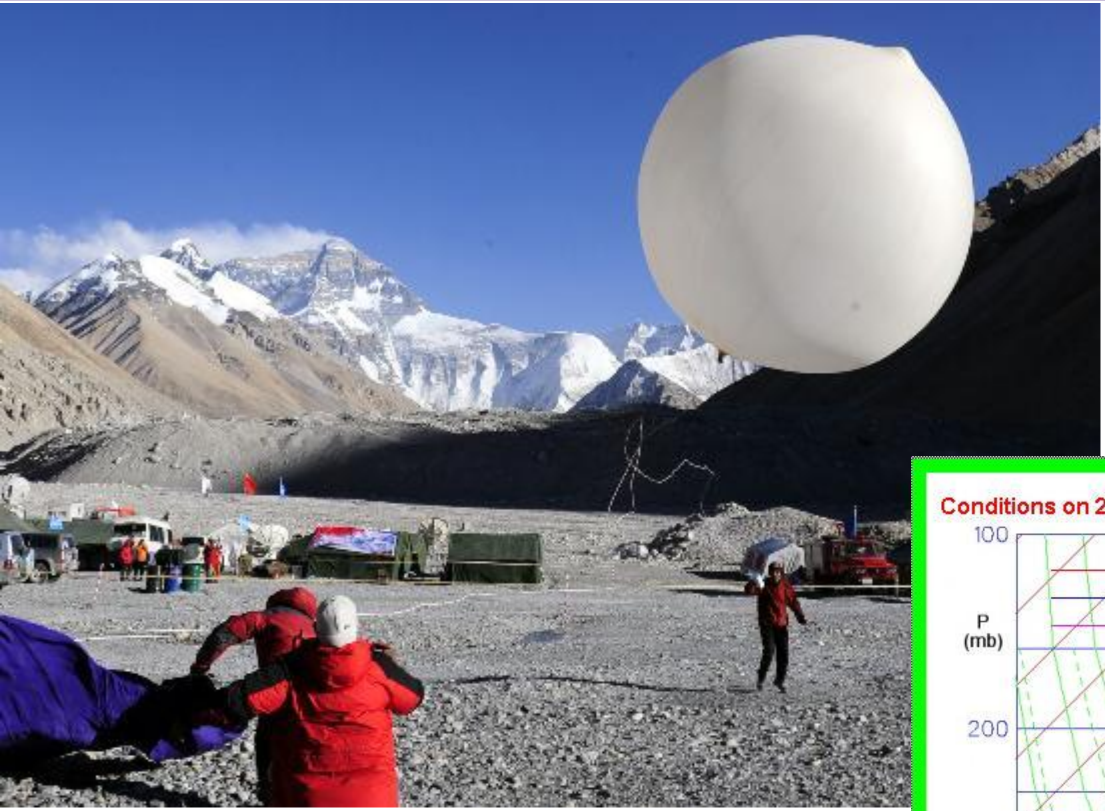


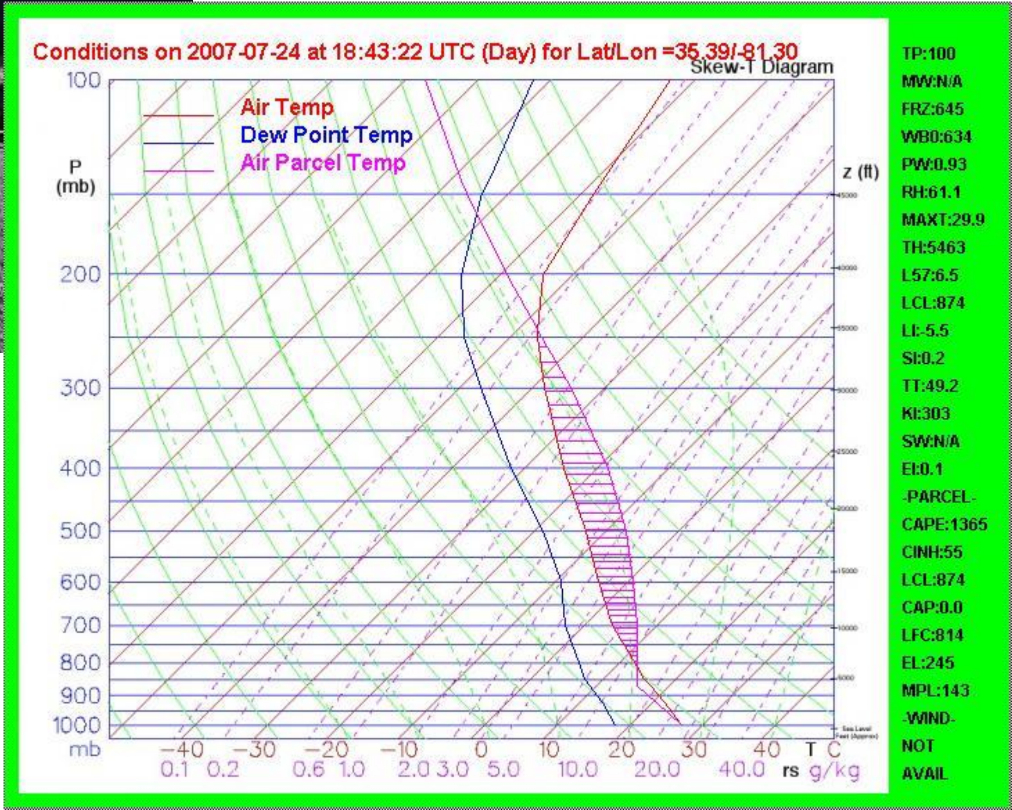


Magenta: 65 dBZ (extremely heavy precipitation, possible hail)
Red: 52 dBZ
Yellow: 36 dBZ
Green: 20 dBZ (light precipitation)



Sounding





Temperature, humidity, pressure, winds

Sounding: "Big Fish" over Tibetan Plateau

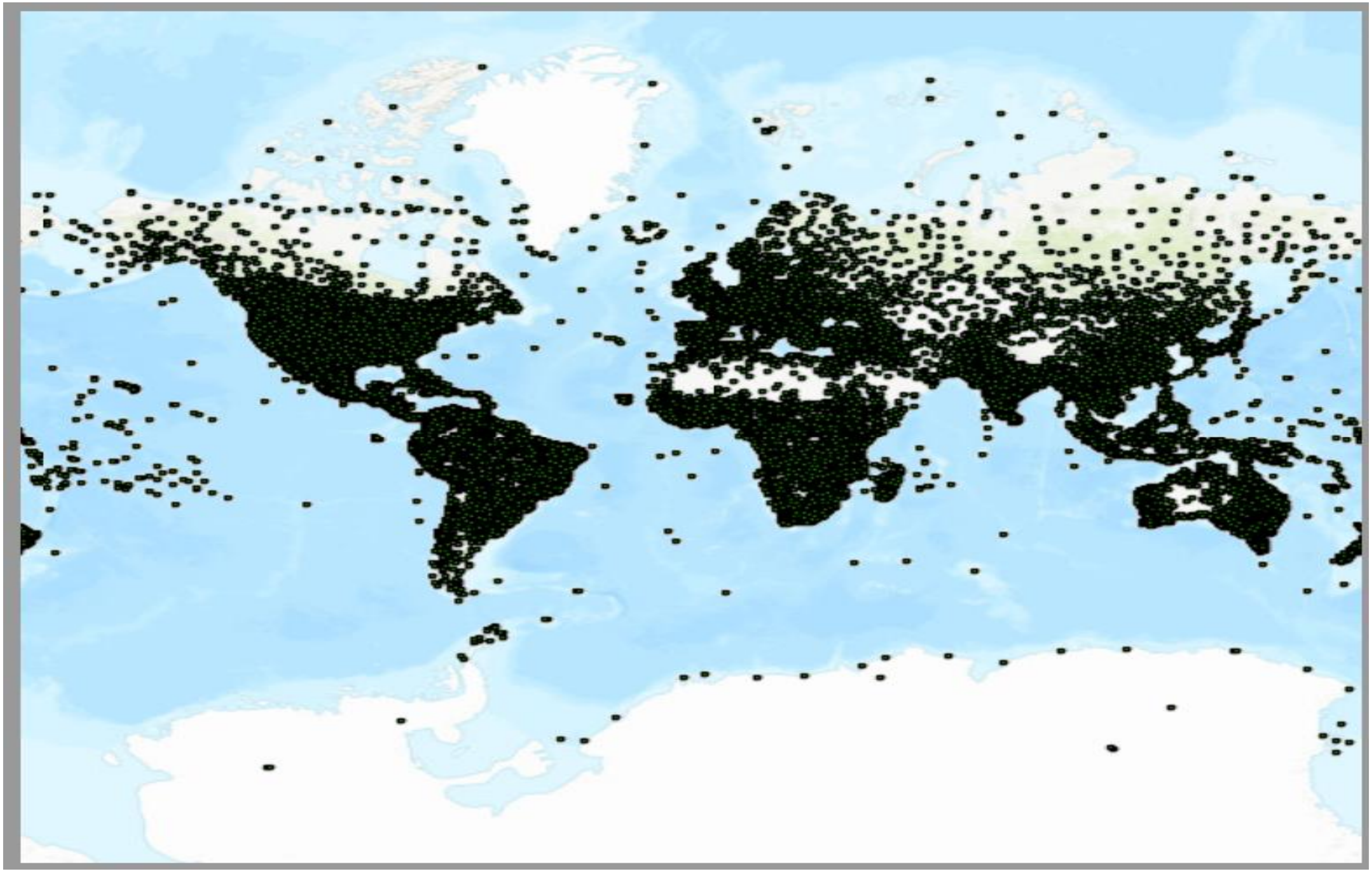
Zhaoze Deng

第二次青藏高原综合科学考察研究
"大气成分垂直结构及其气候影响"
科考分队"系留气艇探空观测实验"

Pictures taken in Lhasa in August 2020

Guiqian Tang

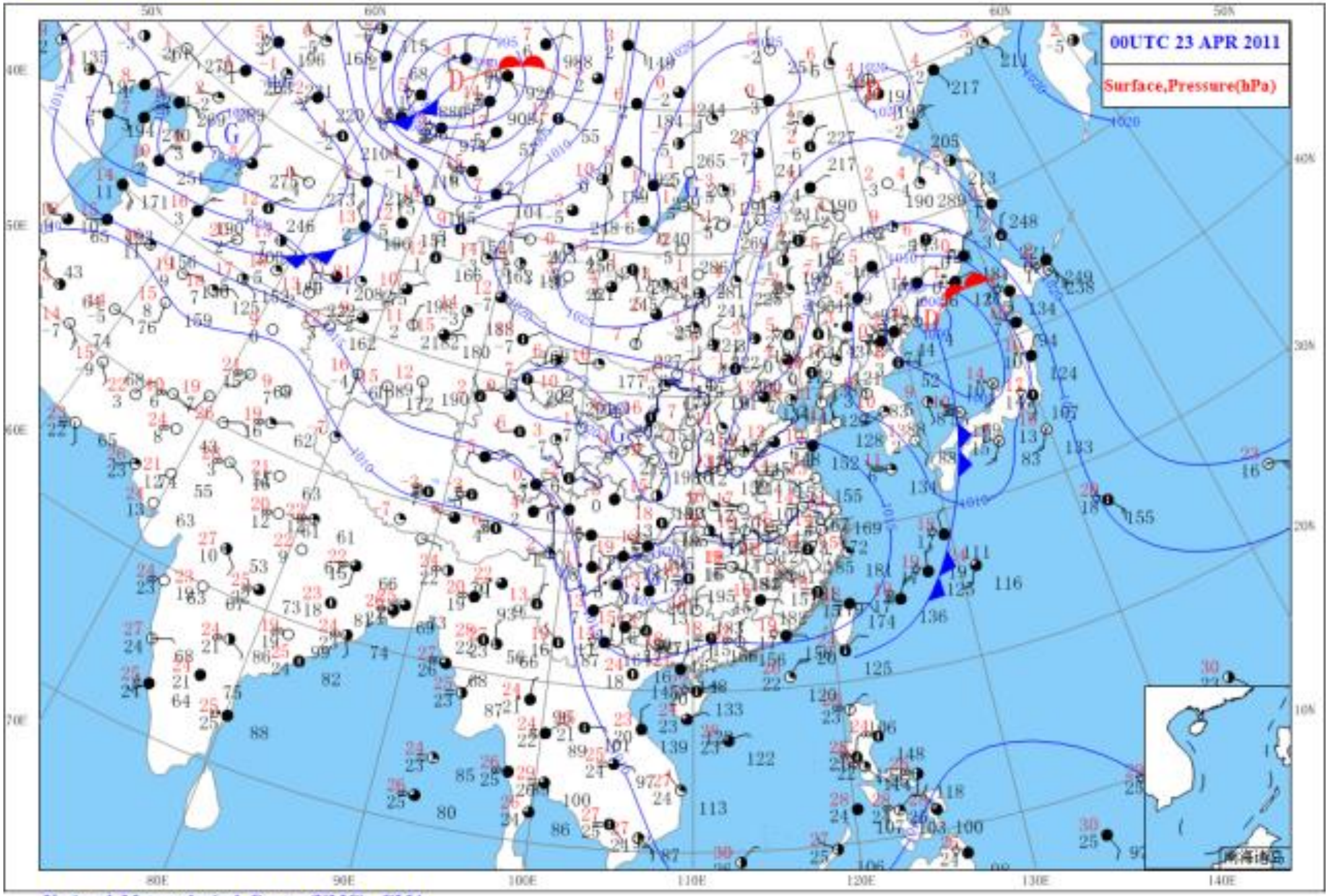
Surface Meteorological Measurement Stations



Source: WorldClim

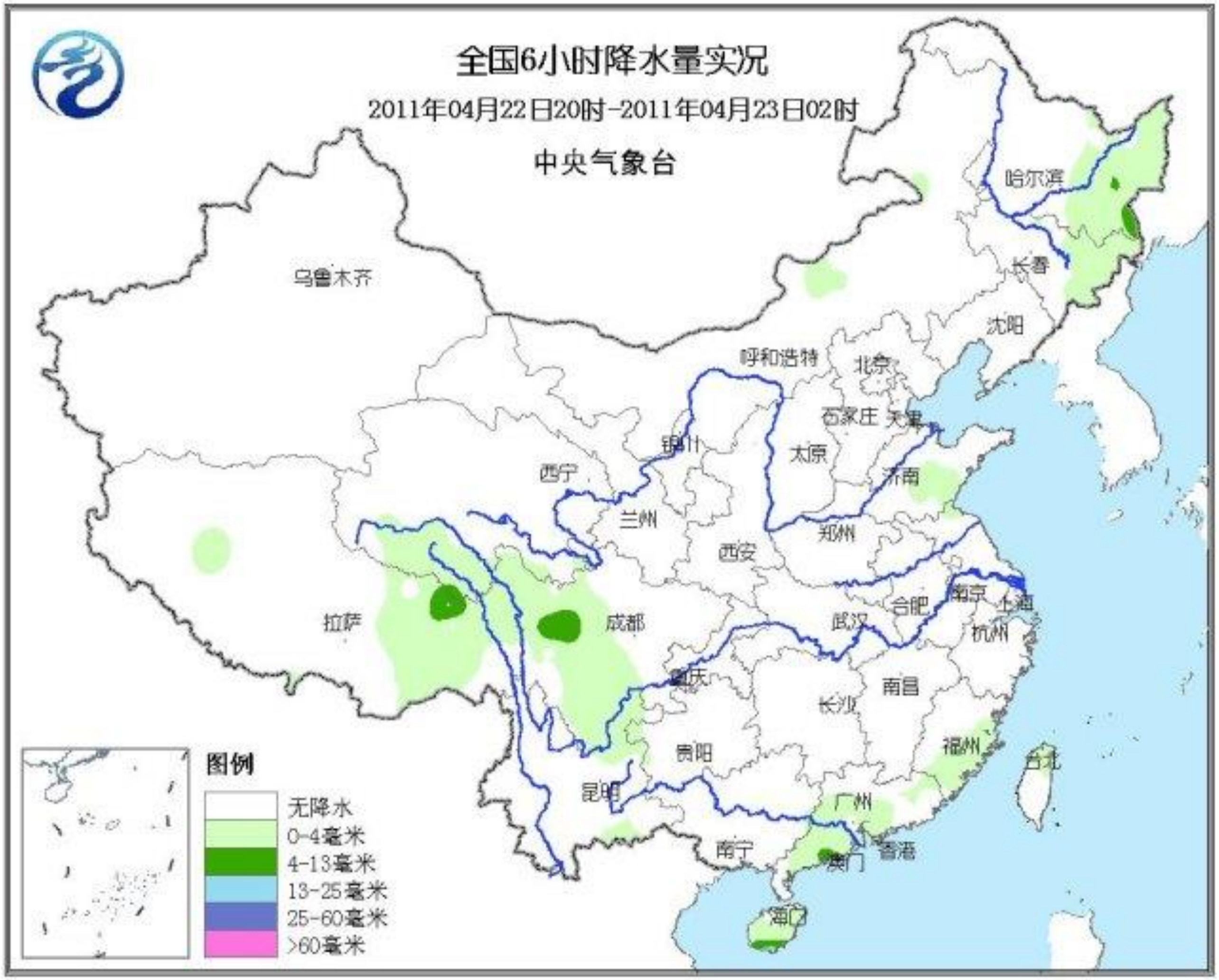
Weather Chart

00UTC 23 APR 2011(08BJT 23 APR 2011)

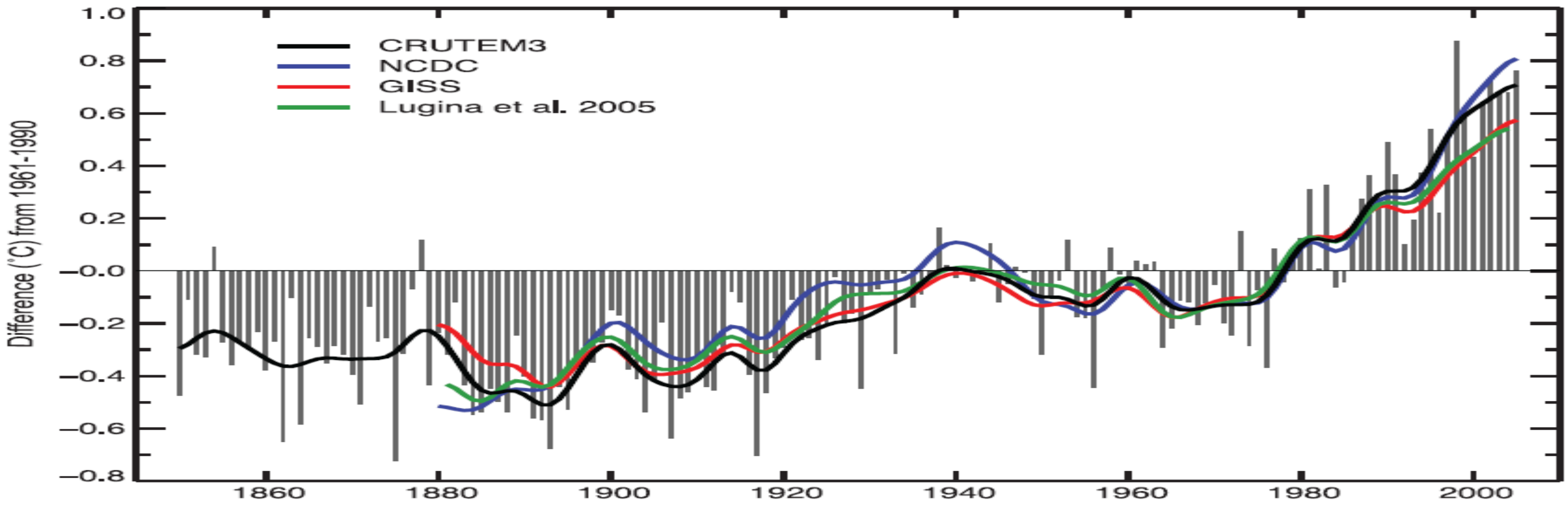


National Meteorological Center (NMC), CMA

Weather Chart

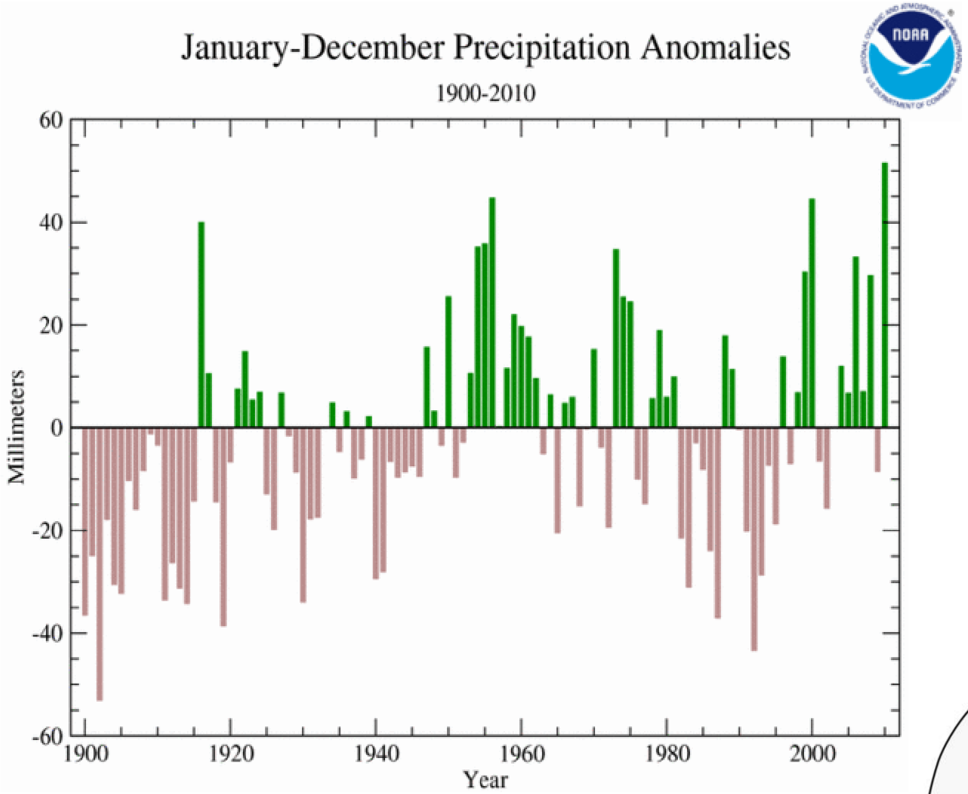


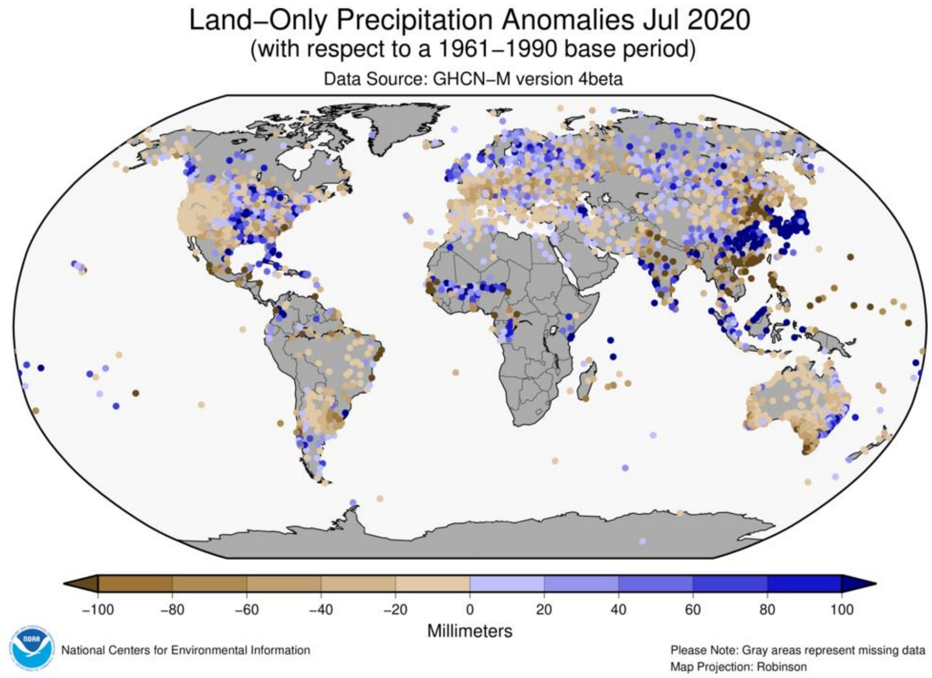
Global Warming in the Past 150 Years



- Spatial averaging:
  - CRUTEM3: land-area weighted sum (0.68 × NH + 0.32 × SH)
  - NCDC: area-weighted average of the grid-box anomalies
  - GISS: area-weighted average for three latitudinal zones
  - Lugina et al. (2005): (NH + 0.866 × SH) / 1.866 (excluding latitudes south of 60°S)
- Treatment of gaps in the data:
  - NCDC: anomalies are interpolated to be spatially complete
  - GISS: favors isolated island and coastal sites
  - Lugina et al. (2005): optimal interpolation adjusting anomalies towards zero where there are few observations nearby
- Numbers of stations: CRUTEM3, NCDC and GISS differ (4,349, 7,230 and >7,200)

Global Precipitation Anomaly



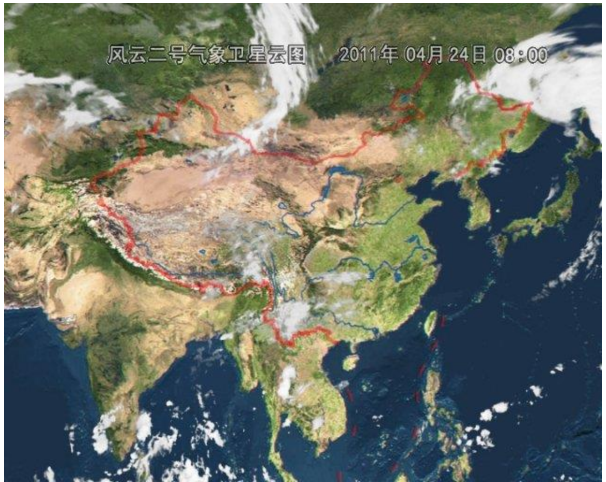


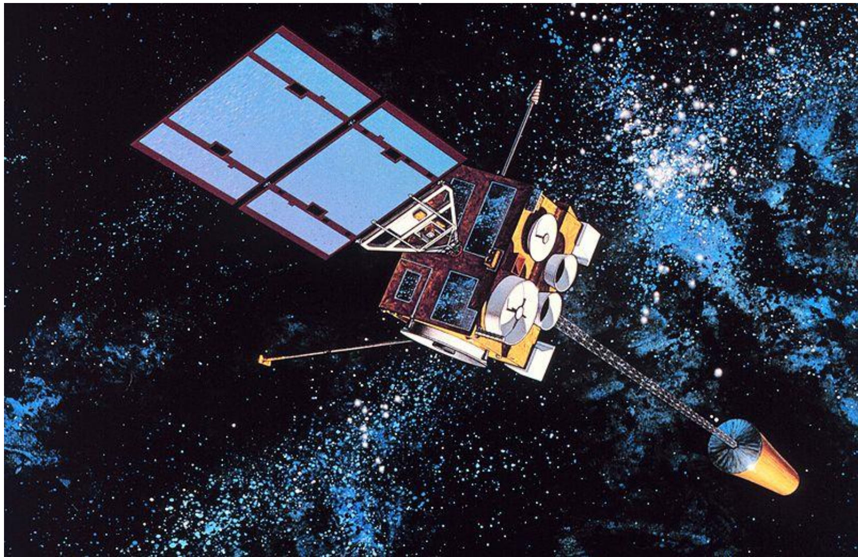
Meteorological Satellites

Sputnik 1: Oct 4, 1957
Sputnik 2: Nov 3, 1957

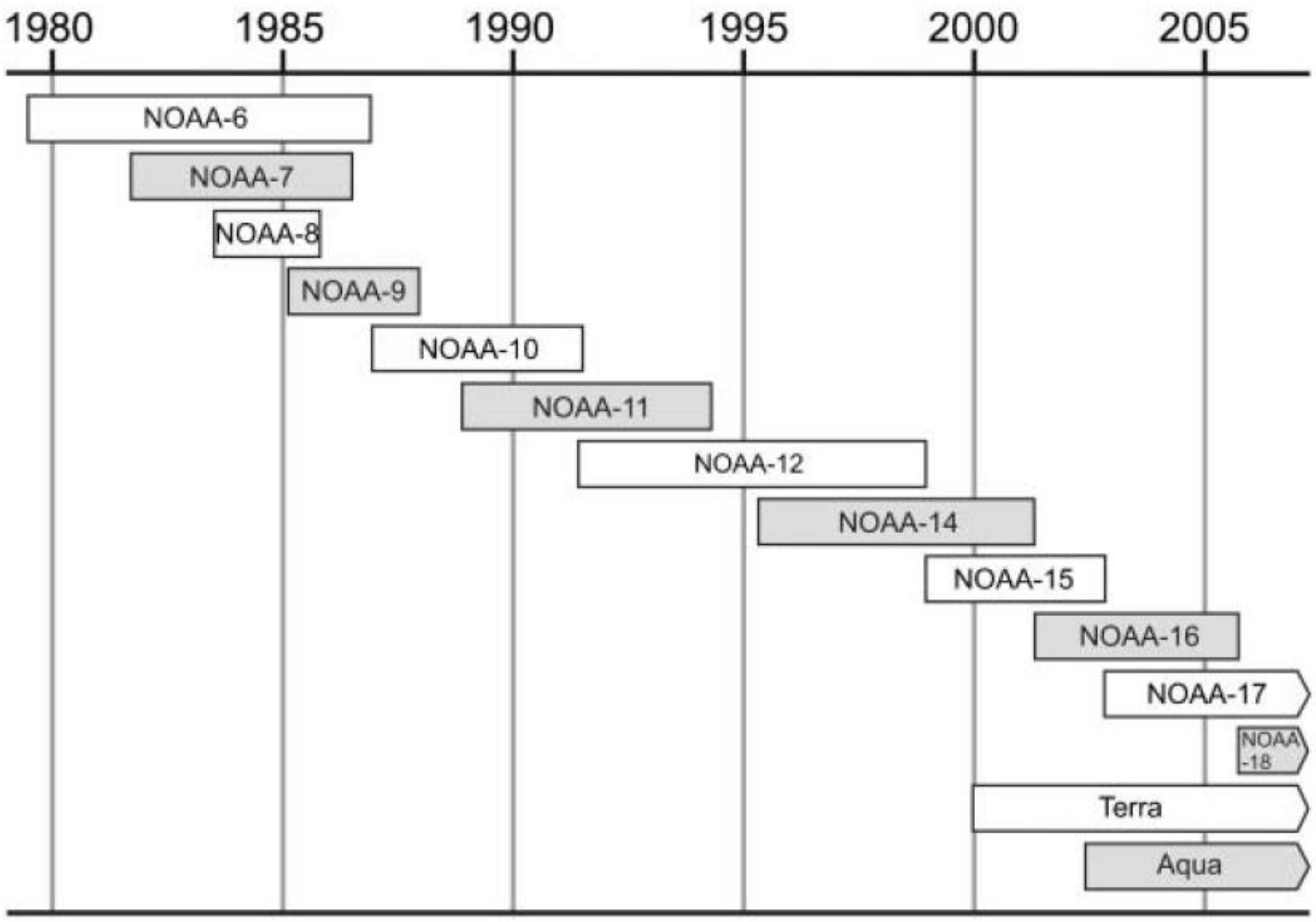
Weather Satellites

- Polar Orbiting Satellites
- Geostationary Satellites

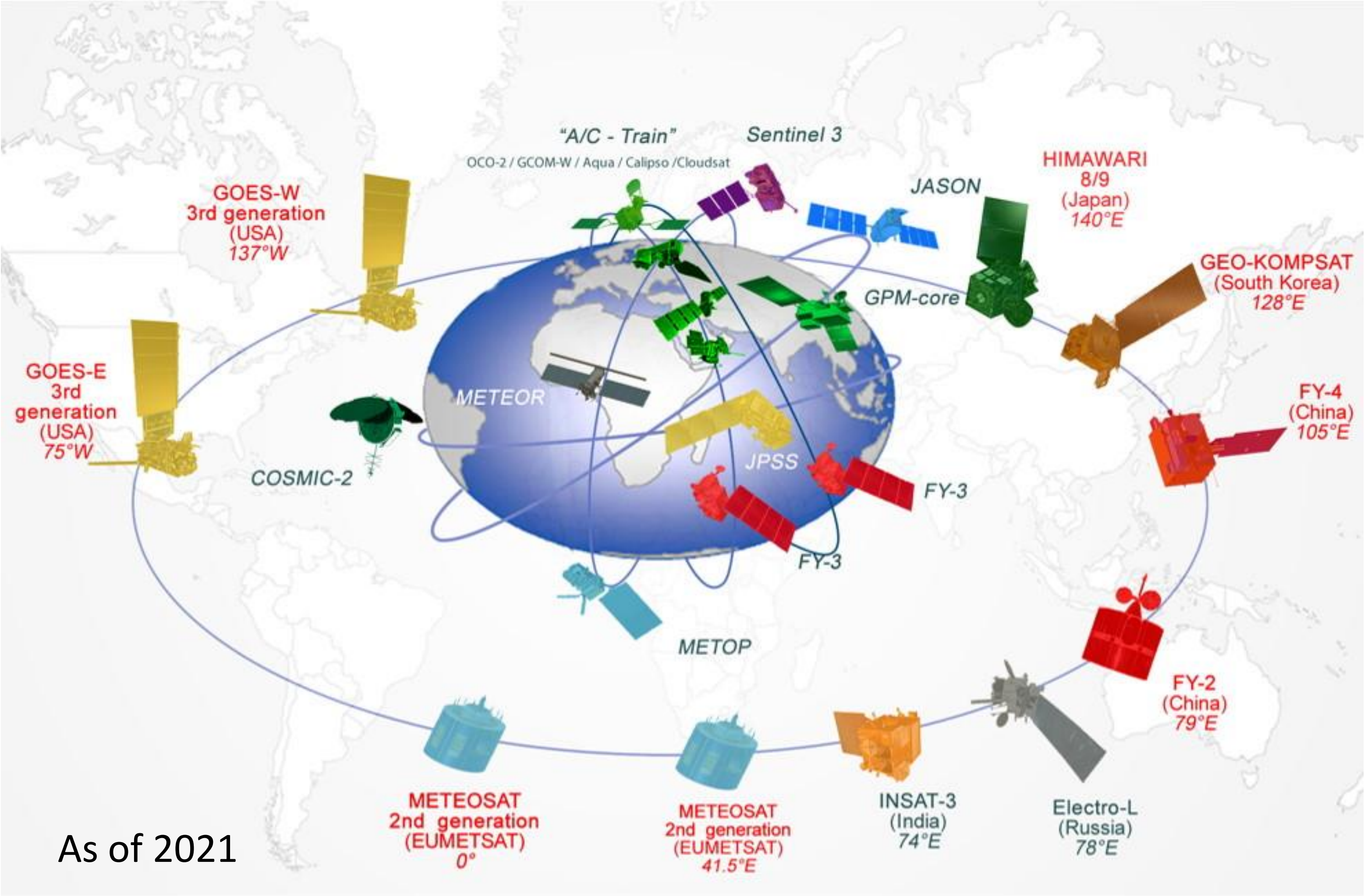




Weather Satellites: NOAA

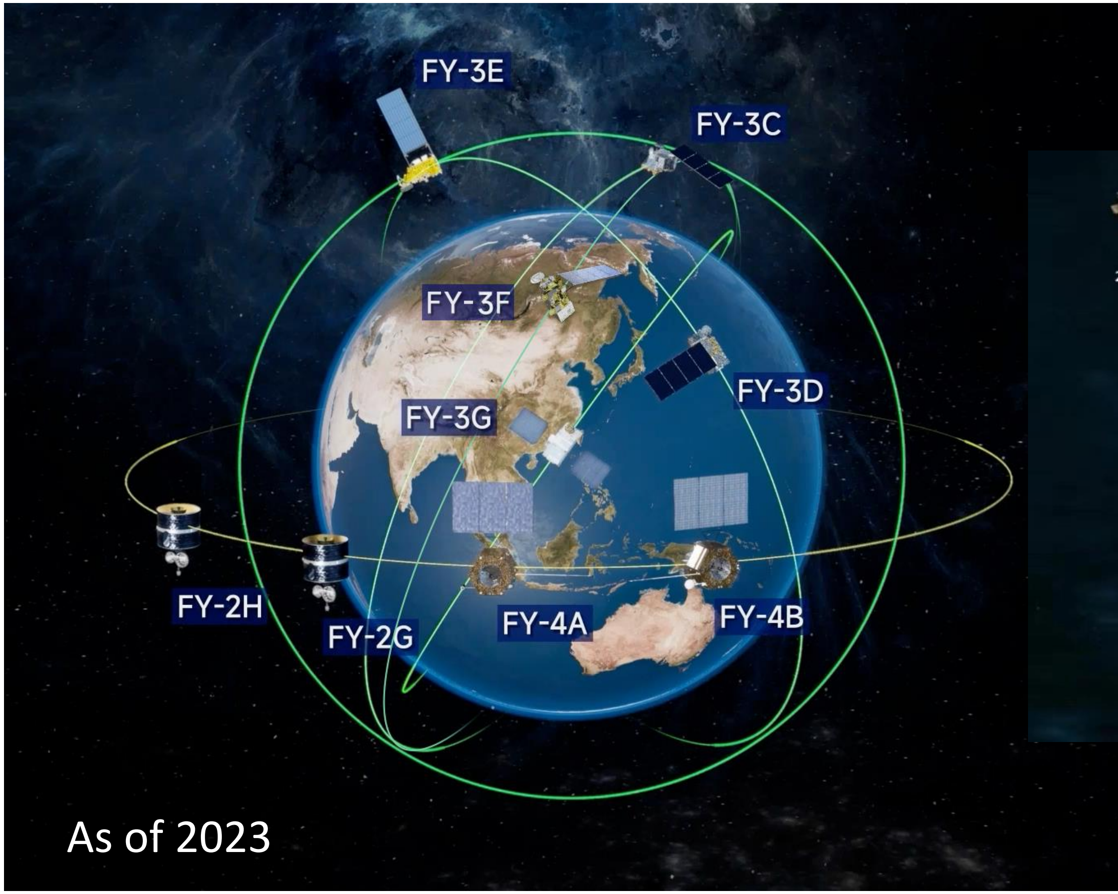


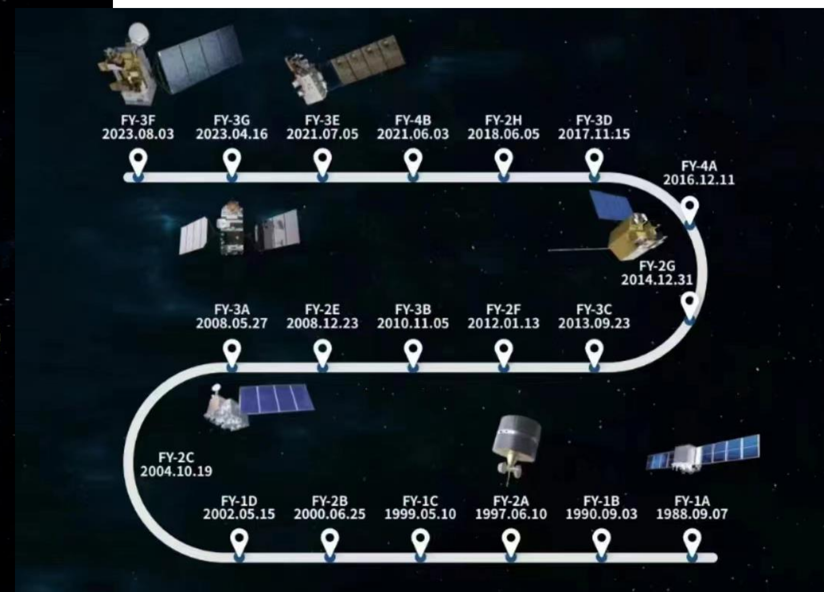
Global Operational Weather Satellites



Source: http://www.nsmc.org.cn/nsmc/cn/satellite/index.html

China's Operational Weather Satellites





Source: http://www.nsmc.org.cn/nsmc/cn/satellite/index.html

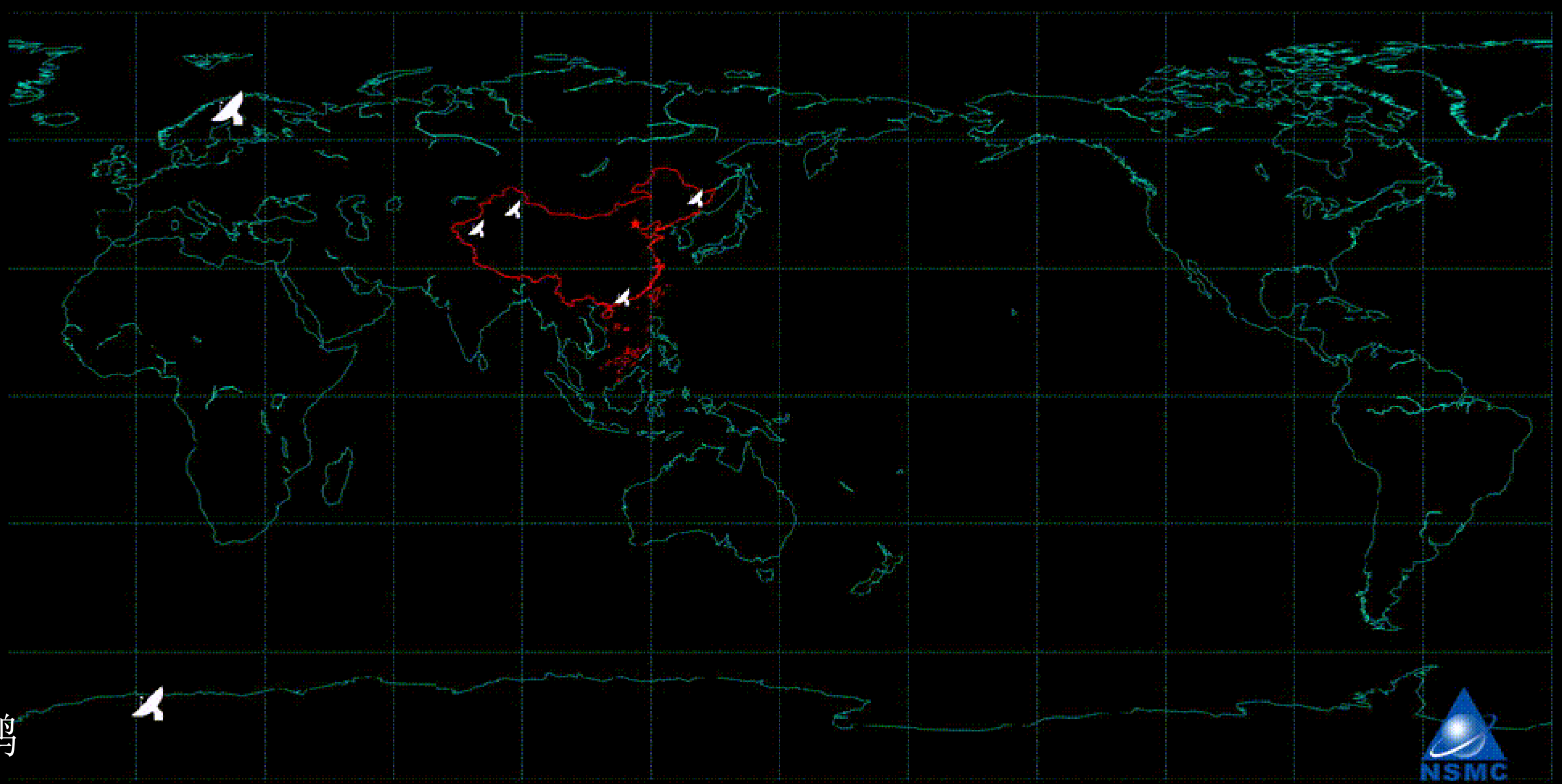
Polar Orbiting Satellite: FY-3

极轨气象卫星

观测特点：

1. 在约800公里轨道高度绕地球南北极飞行，每12小时无缝隙覆盖全球
2. 搭载多种遥感仪器，获取大气和地球环境综合探测信息

2018 年 9 月 15 日 风云三号D星 中分辨率光谱成像仪II



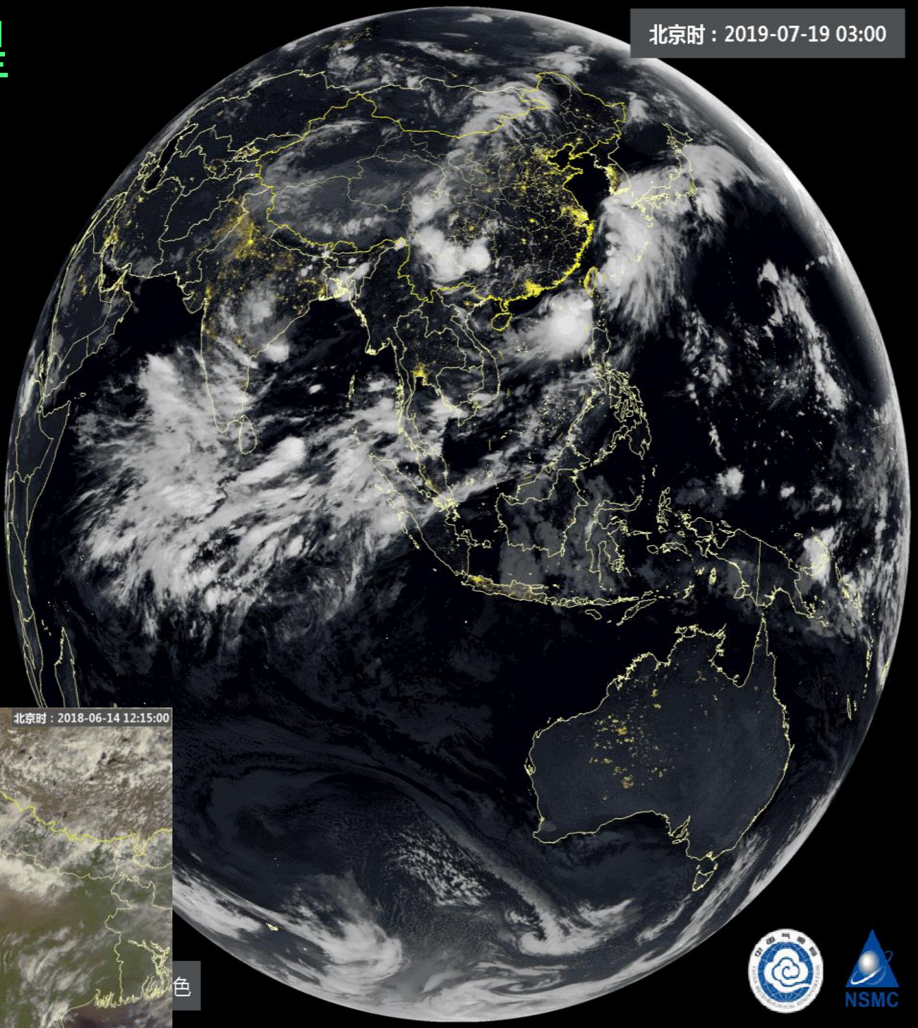
张鹏

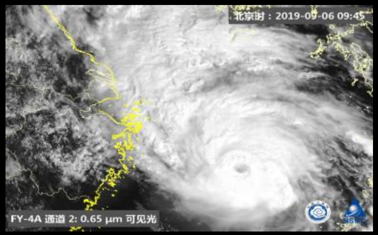
Geostationary Satellite: FY-4A

静止气象卫星

气象卫星作用和优势：

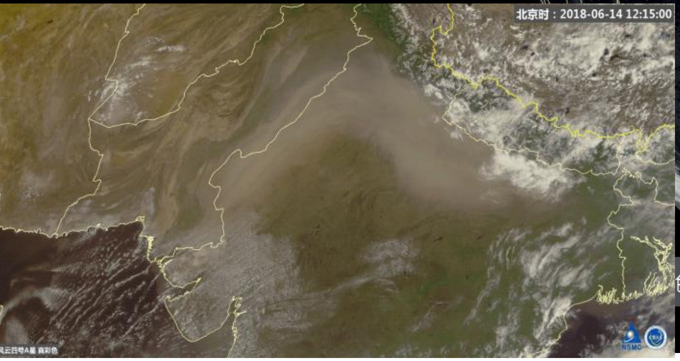
1. 全球全天候无缝隙观测，实现对地球大气和环境综合探测
2. 局地高频次观测，实现对自然灾害和环境事件的动态观测





观测特点：

1. 轨道高度约35800公里，与地球自转同步，观测区域相对固定
2. 可每15分钟获取地球全圆盘图像；每5分钟对中国区域进行高频扫描。



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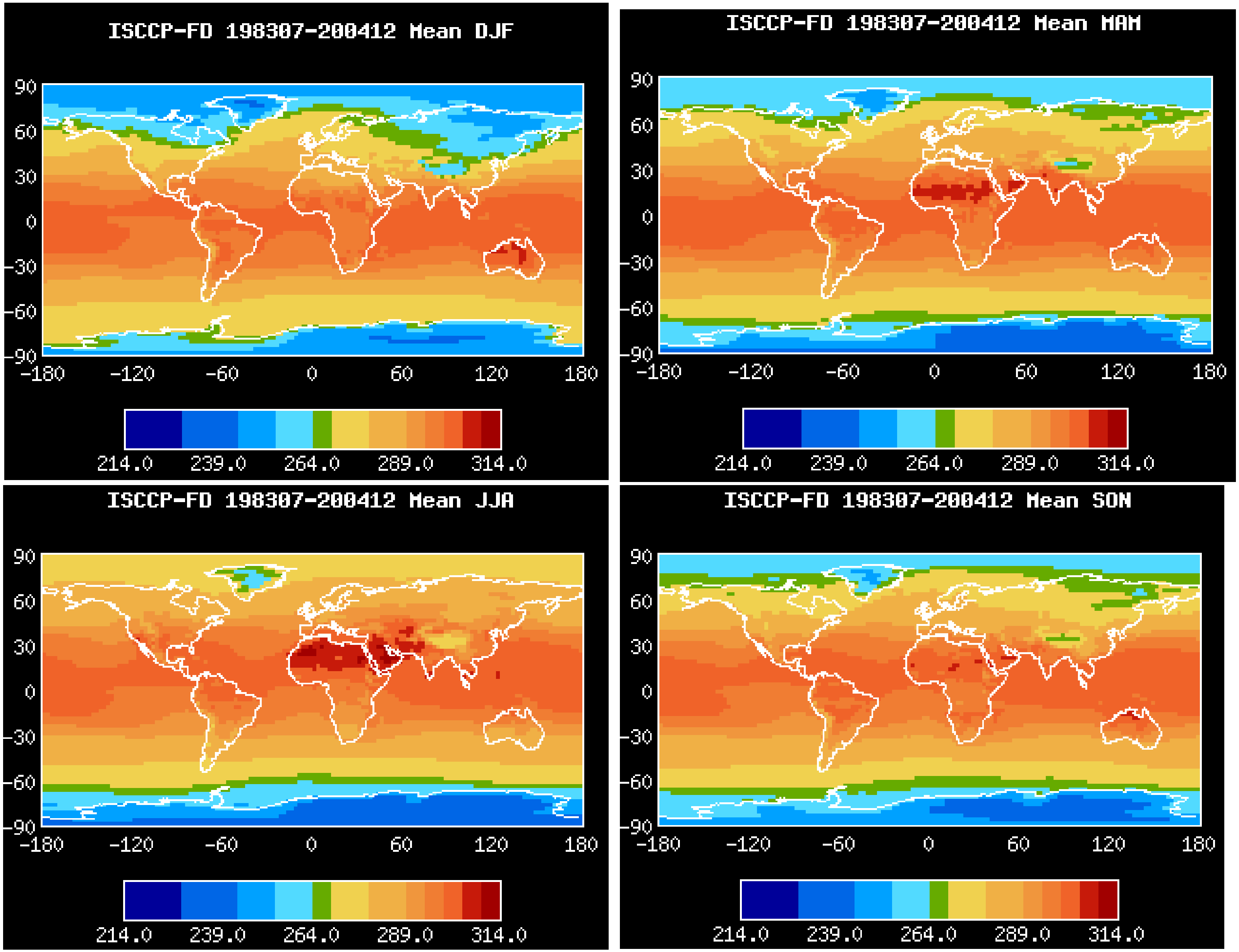
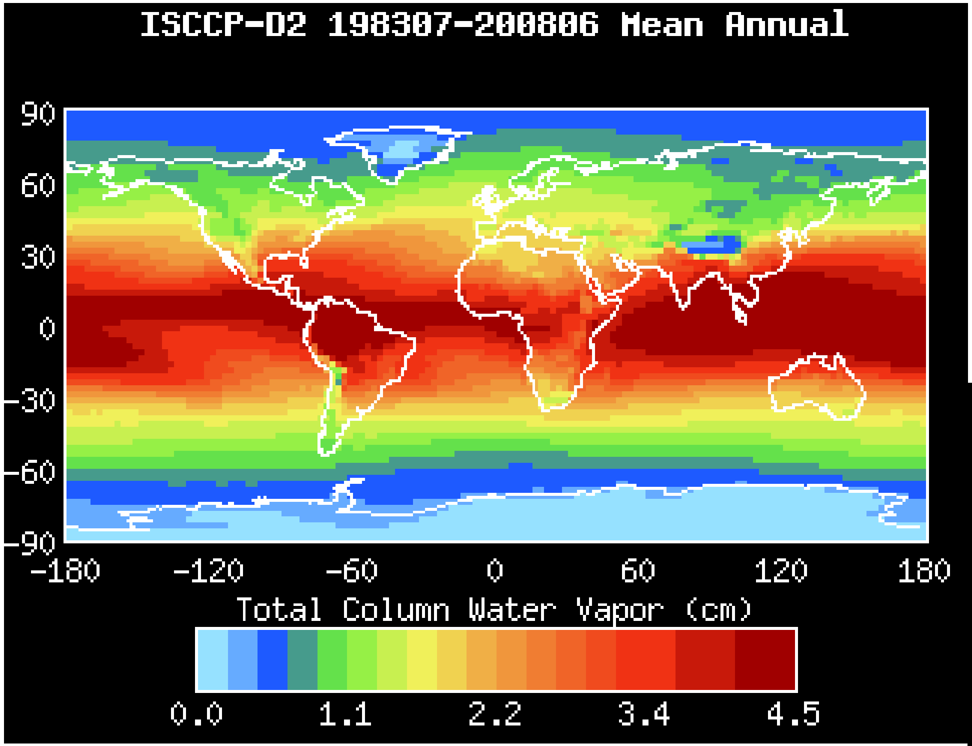
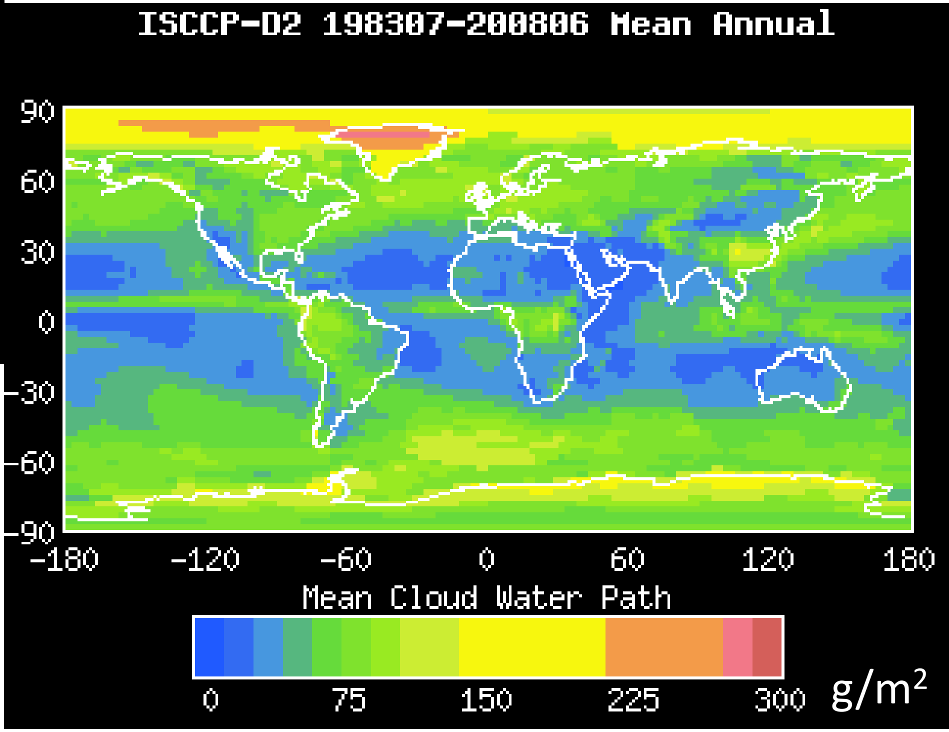
Global Seasonal Surface Air Temperature: 1983-2004

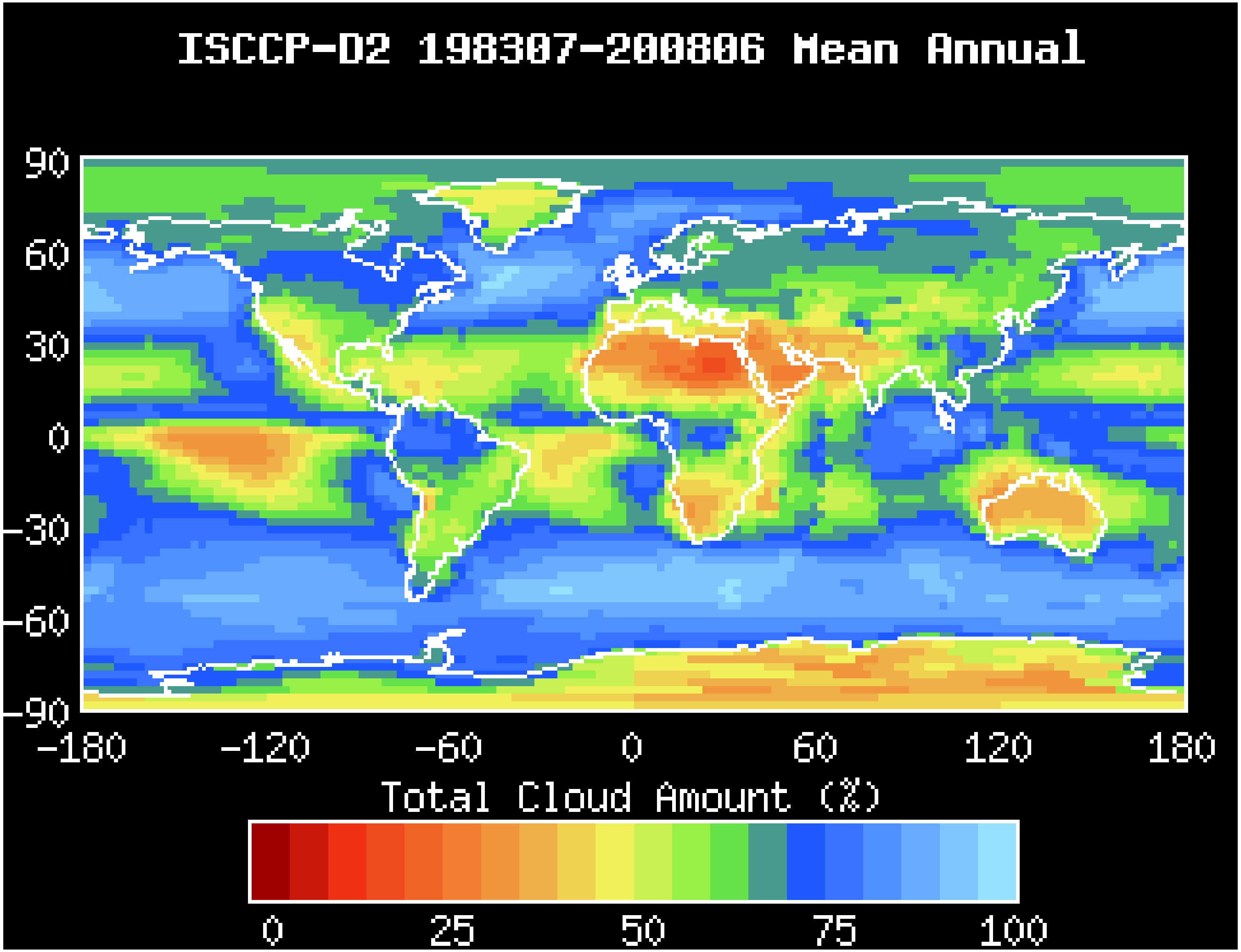


Global Water Content: 1983-2008

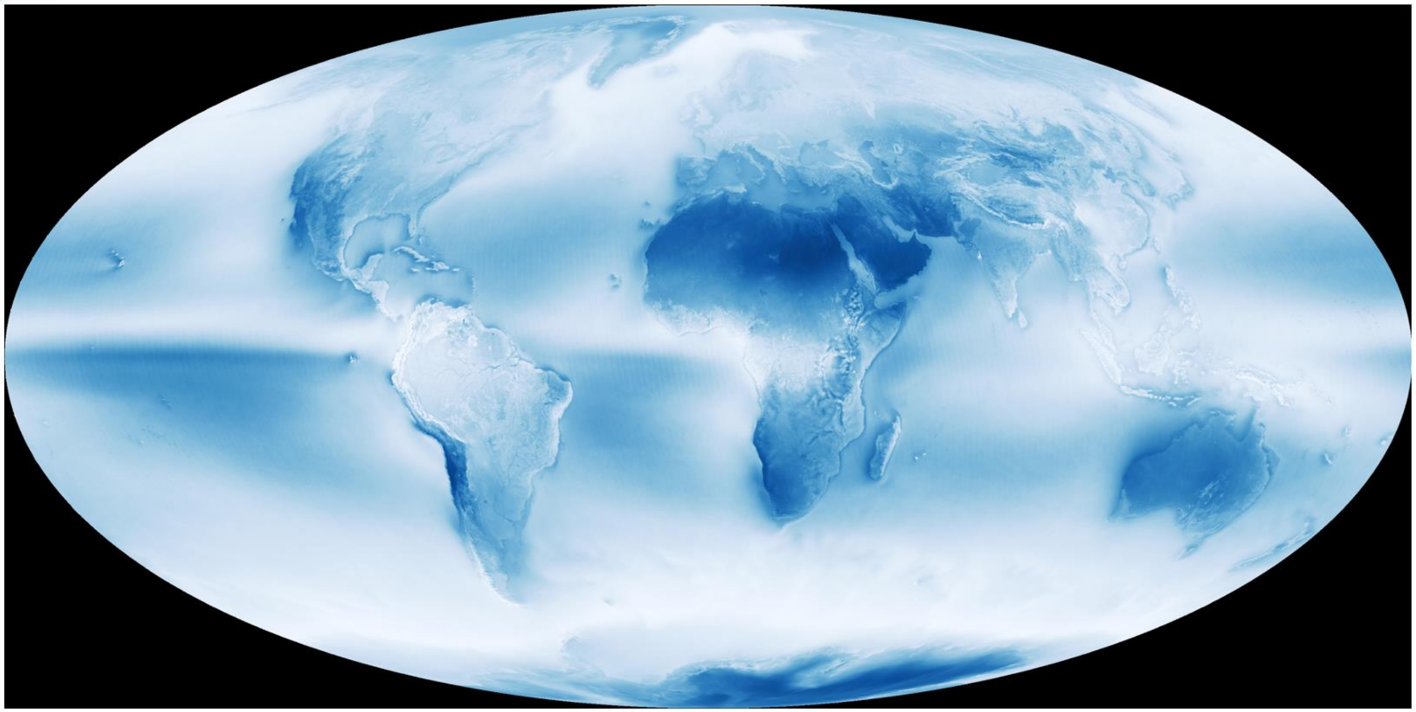




Global Cloud Cover: 1983-2008

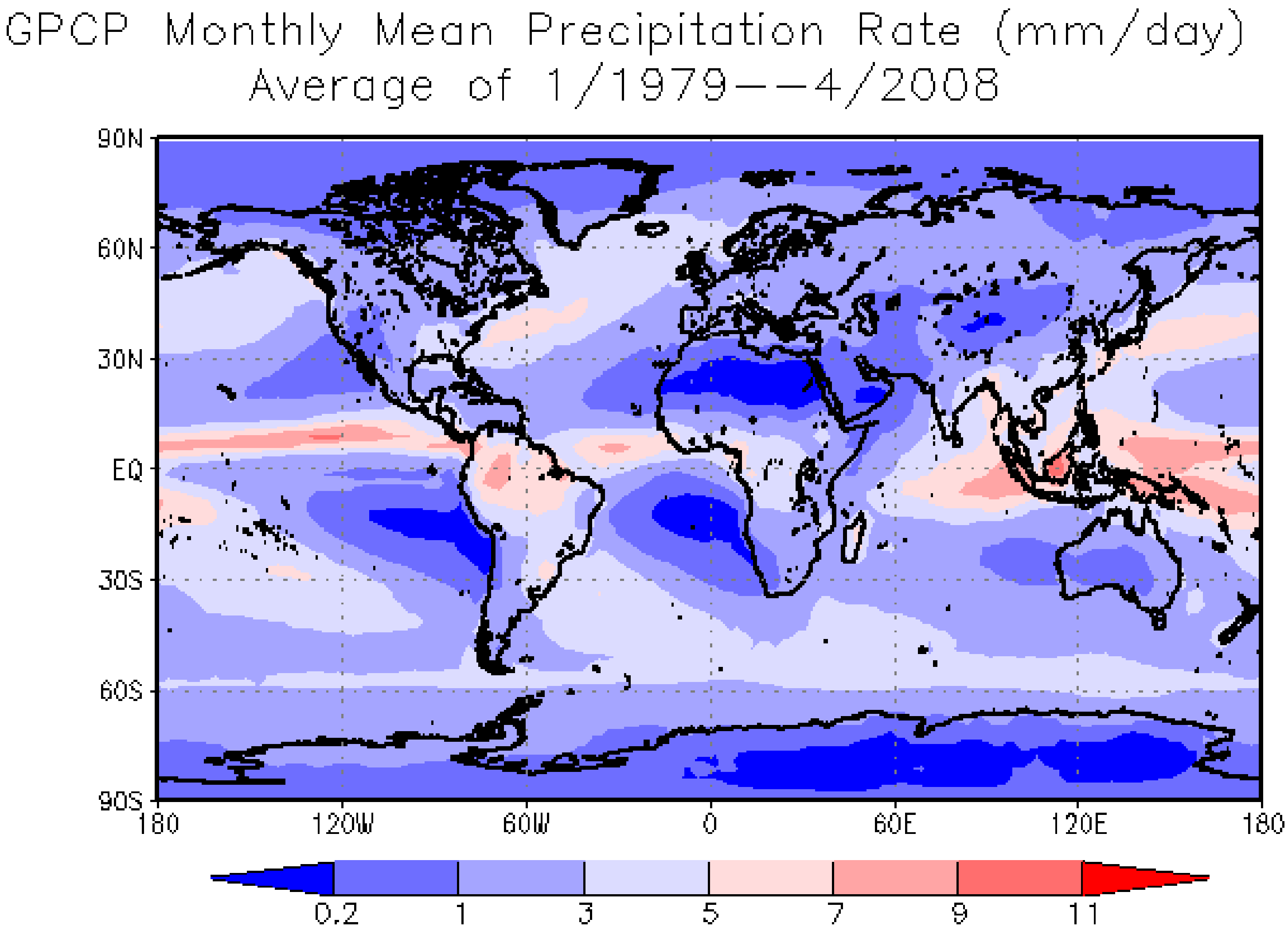


Global Cloud Coverage: 2002-2015



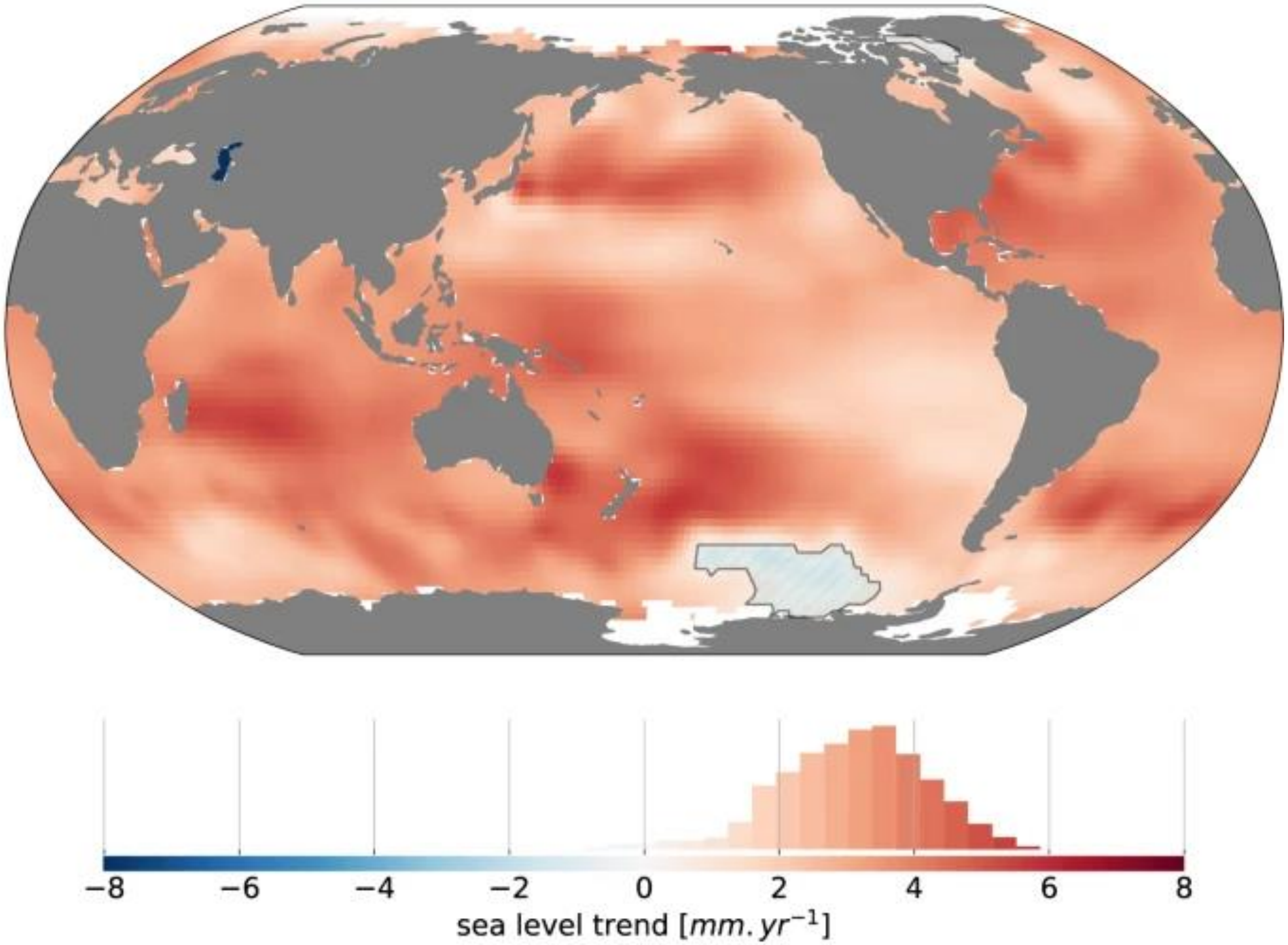
Credit: NASA Earth Observatory image by Jesse Allen and Kevin Ward, using data provided by the MODIS between July 2002 and April 2015. Colors range from dark blue (no clouds) to light blue (some clouds) to white (frequent clouds).

Global Precipitation: 1979-2008



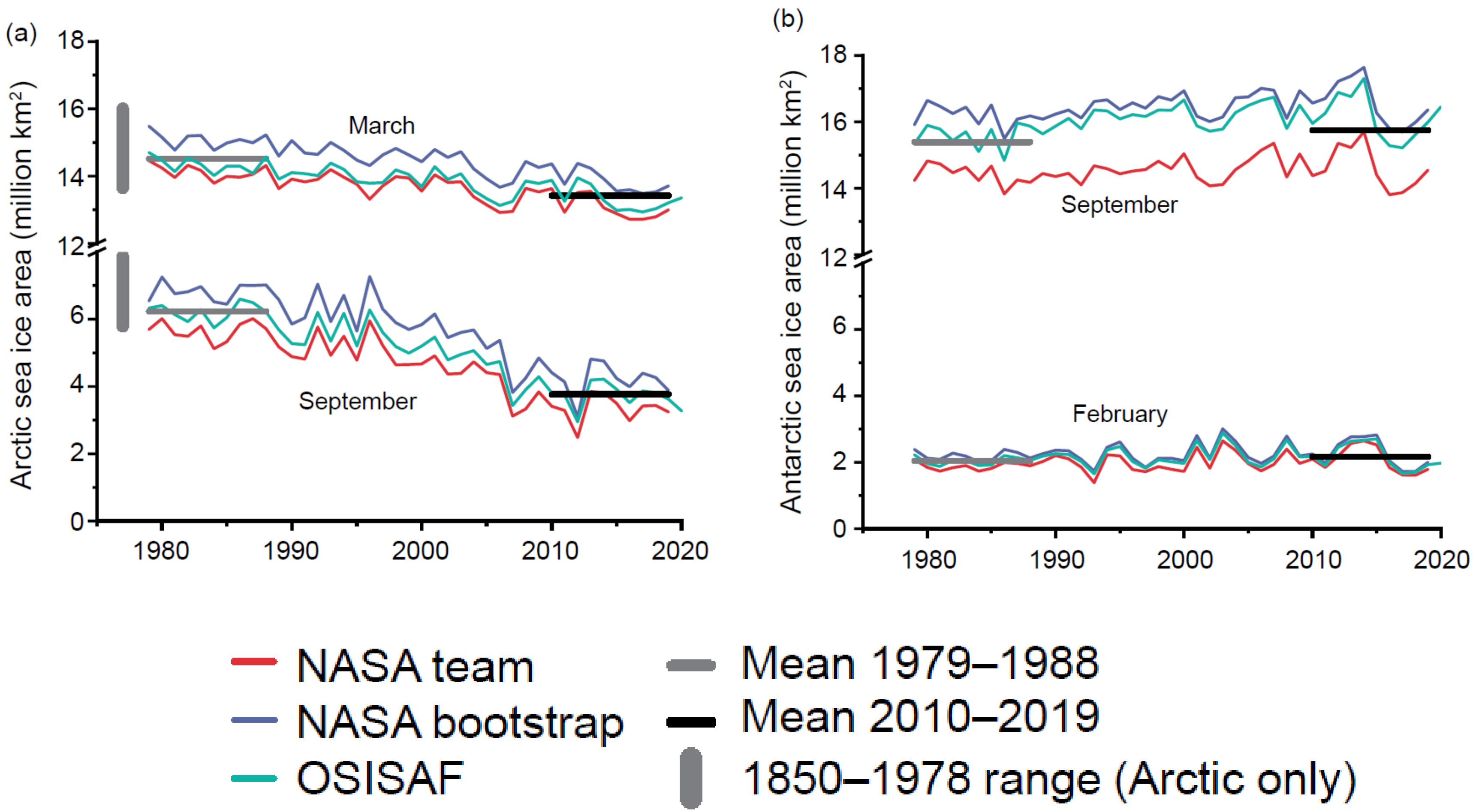
Observed Sea Level Rise: 1993–2019

Sea level trend



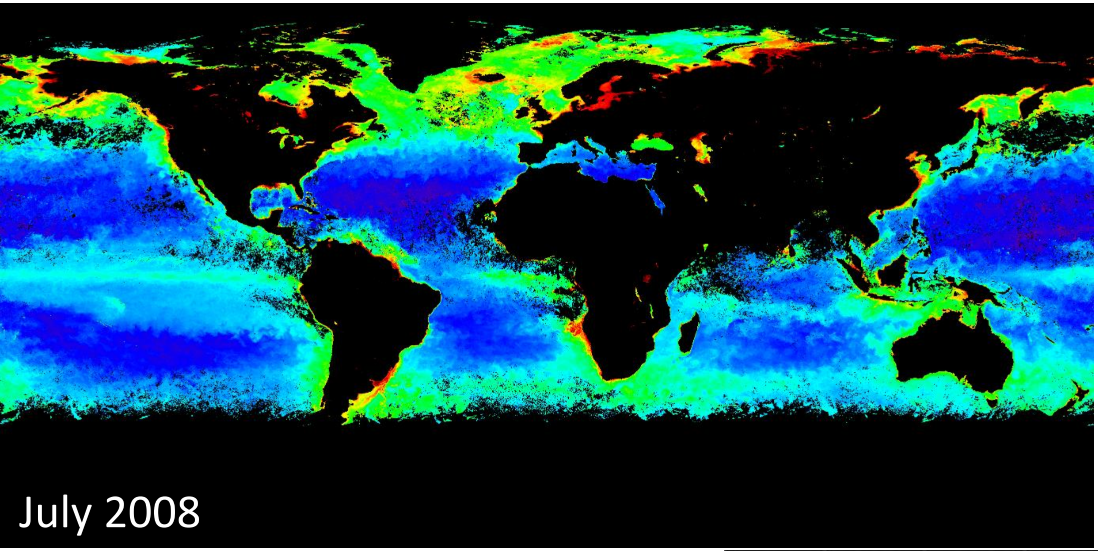
Prandi et al., 2021, Scientific Data

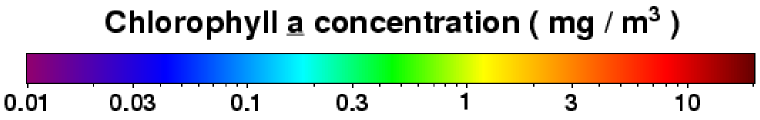
Snow and Ice Change: 1979–2020

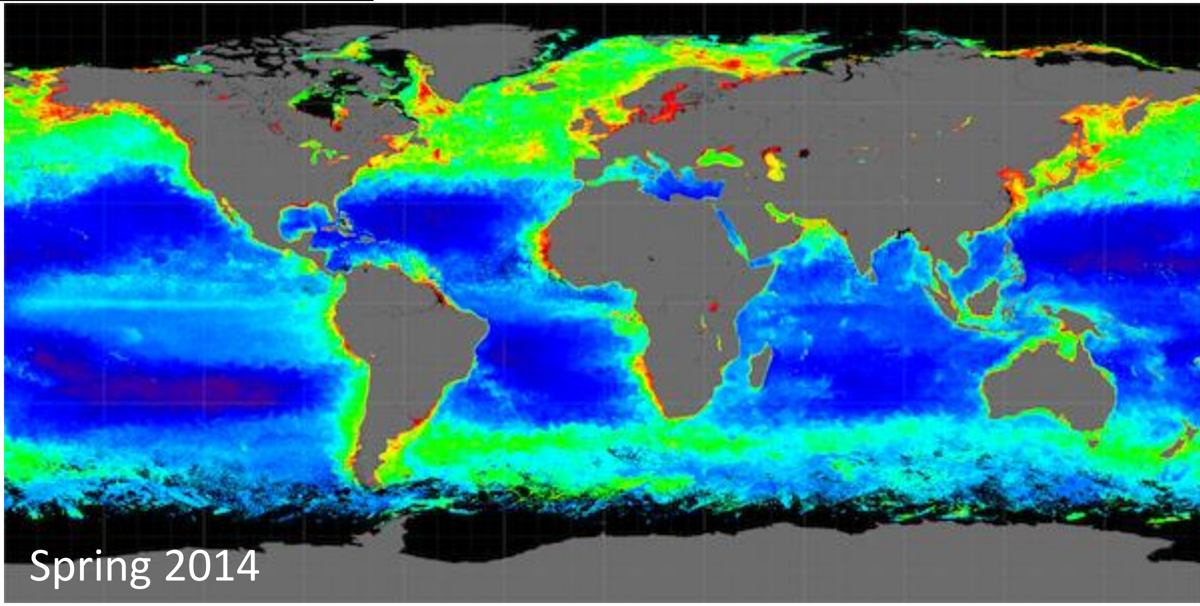


IPCC, 2013

Ocean Color: Concentration of Chlorophyll





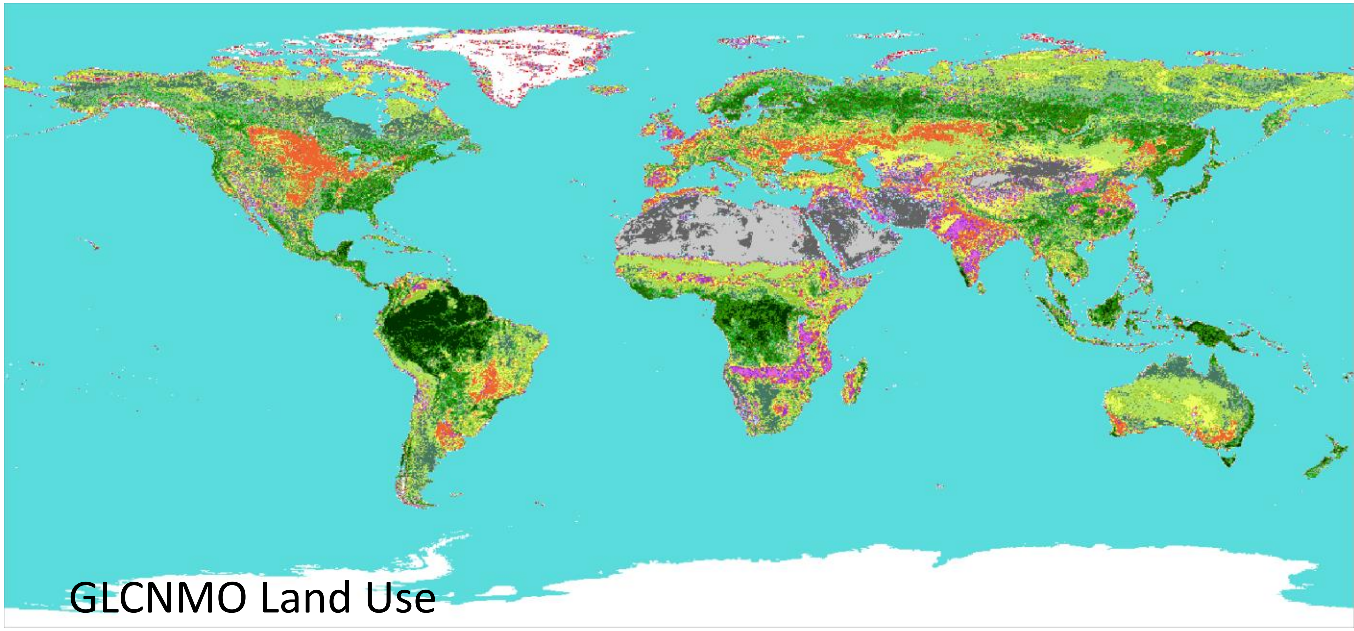


https://oceancolor.gsfc.nasa.gov/atbd/chlor_a/

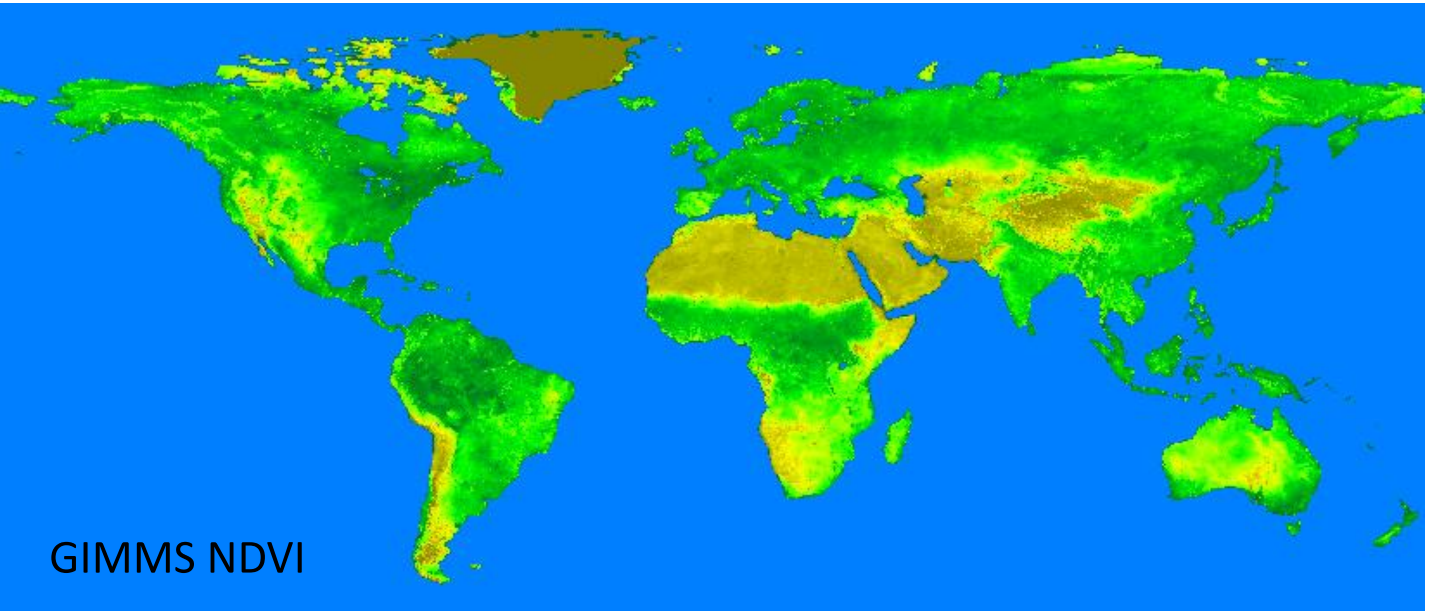
Land Surface Data

Surface products:

- Reflectance
- LAI
- NDVI
- Land Use Type



GLCNMO Land Use



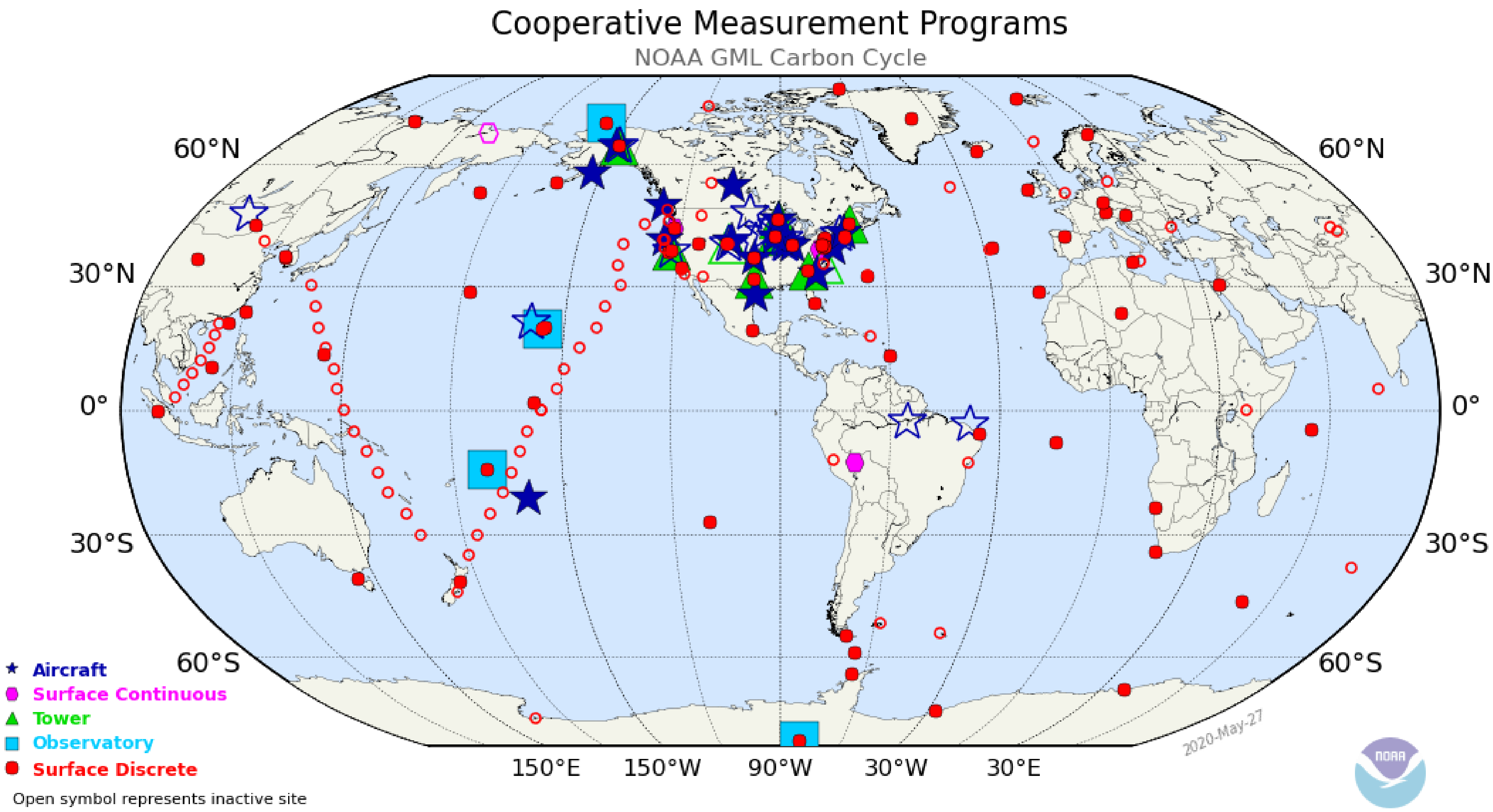
GIMMS NDVI

Measurements of Compositions of the Atmosphere

- Greenhouse Gases: CO_2, CH_4, N_2O
- Gaseous pollutants: Ozone, NOx, VOC, CO, SO_2
- Radicals: OH, HO_2, RO_2
- Aerosols: PM_{10}, $PM_{2.5}$, compositions, optical properties

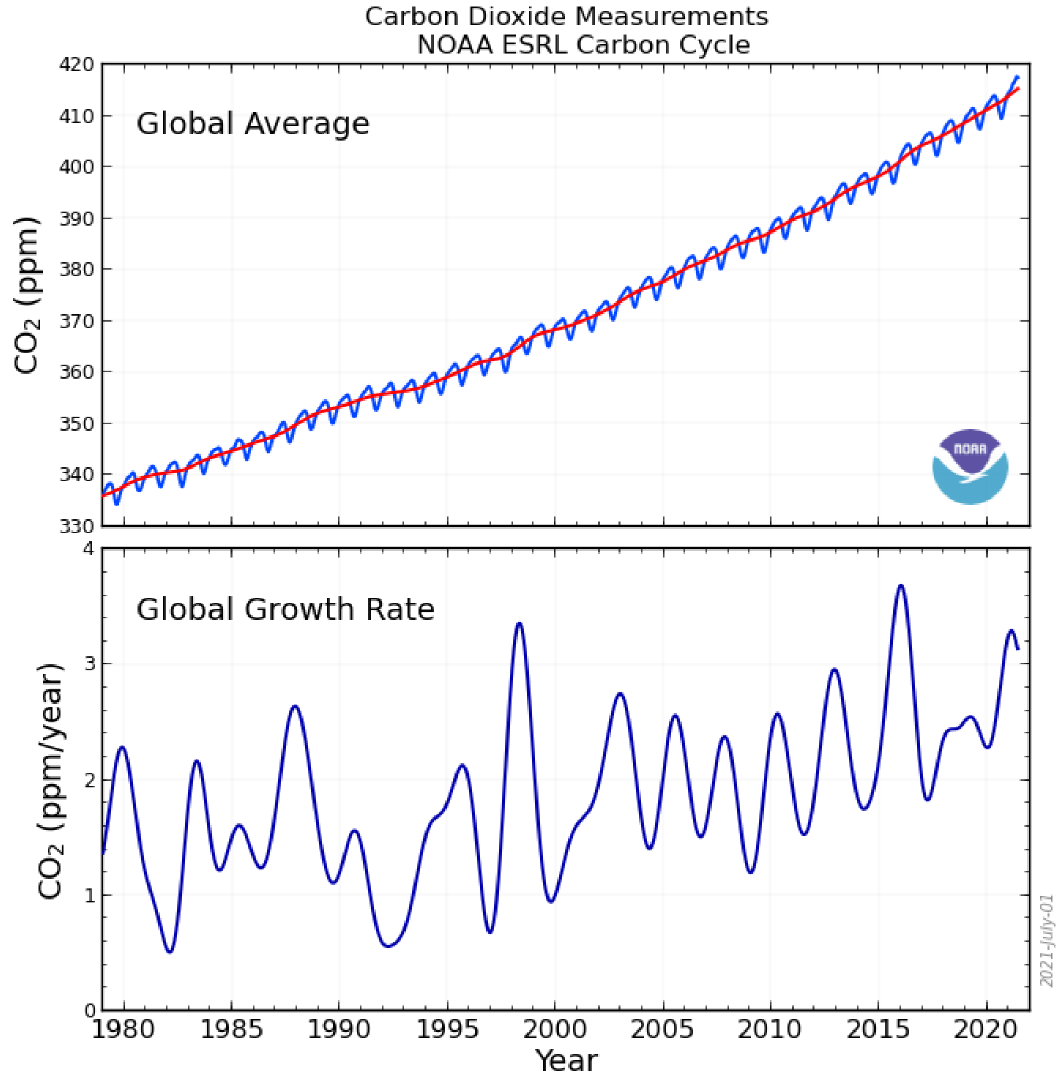
- Measurement methods:
  - Ground-based
  - Space-based
  - Aircraft, drone
  - Sounding
  - Proxy

Cooperative Measurement Programs



NOAA GML Carbon Cycle operates several measurement programs. Semi-continuous measurements are made at 4 baseline observatories, a few surface sites and from tall towers. Discrete surface and aircraft samples are measured in Boulder, CO. Presently, atmospheric carbon dioxide, methane, carbon monoxide, hydrogen, nitrous oxide, sulfur hexafluoride, the stable isotopes of carbon dioxide and methane, and halocarbon and volatile organic compounds are measured. Contact: Dr. Arlyn Andrews, NOAA ESRL Carbon Cycle, Boulder, Colorado, (303) 497-6773, arlyn.andrews@noaa.gov, http://www.esrl.noaa.gov/gmd/ccgg/.

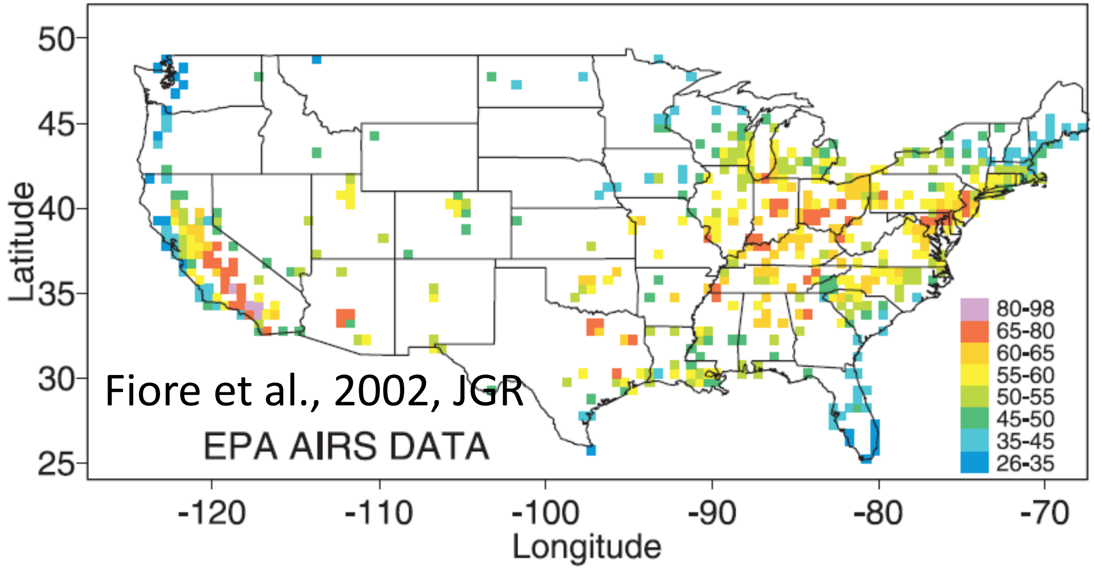
Observed Growth in Background CO_2

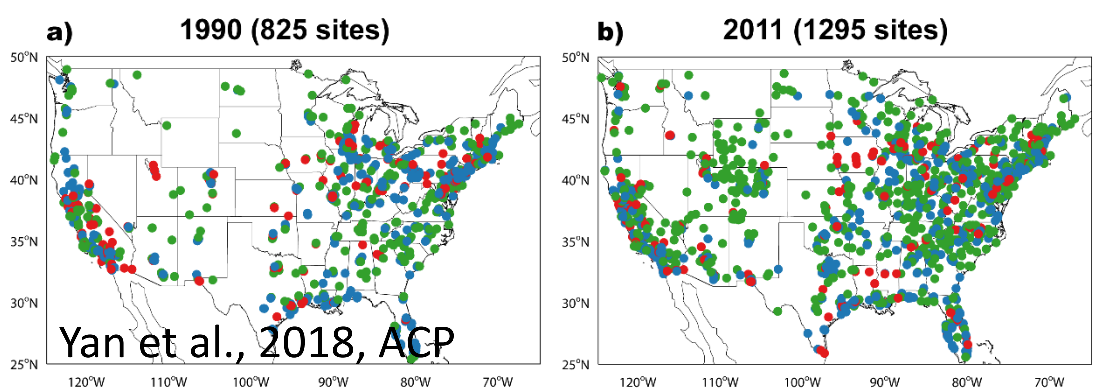


Top: Global average atmospheric carbon dioxide mixing ratios (blue line) determined using measurements from the Carbon Cycle cooperative air sampling network. The red line represents the long-term trend. Bottom: Global average growth rate for carbon dioxide. Contact: Dr. Arlyn Andrews, NOAA ESRL Carbon Cycle, Boulder, Colorado, (303) 497-6773, arlyn.andrews@noaa.gov, http://www.esrl.noaa.gov/gmd/ccgg/.

Surface Measurement Network in the U.S.

- Lots of pollutants: ozone, NOx, VOC, CO, $PM_{2.5}$, PM constituents, etc.
- 800+ sites since 1990; currently about 1200 sites





Surface Measurements: The Chinese Case

- Before 2013: API, PM_{10}, NO_2, SO_2. Regular measurements are available in 86 cities
- Since 2013: AQI, $PM_{2.5}$ & other gases; 300+ cities, 1500+ sites

http://www.cnemc.cn/

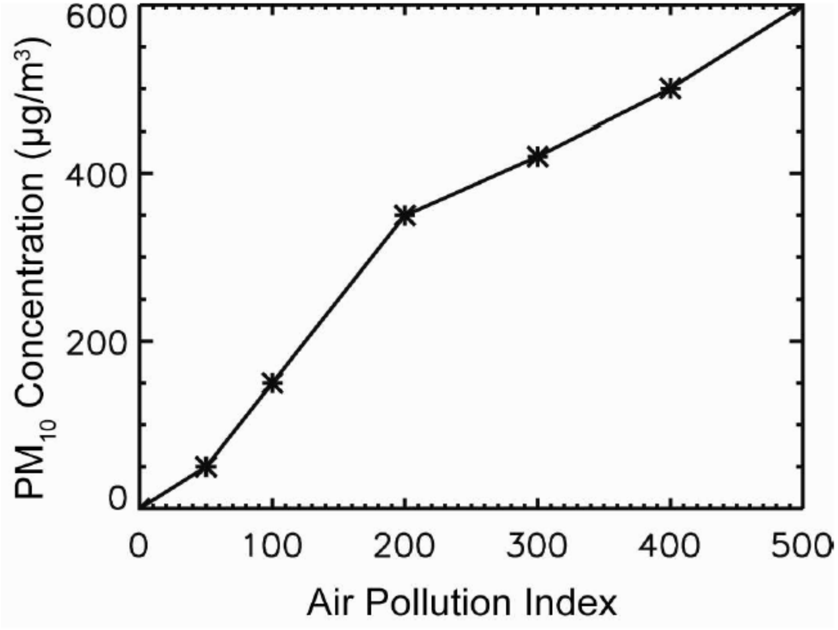
Exc. Good S.P. M.P. H.P. E.P.

https://www.aqistudy.cn/

Surface Measurements: The Chinese Case

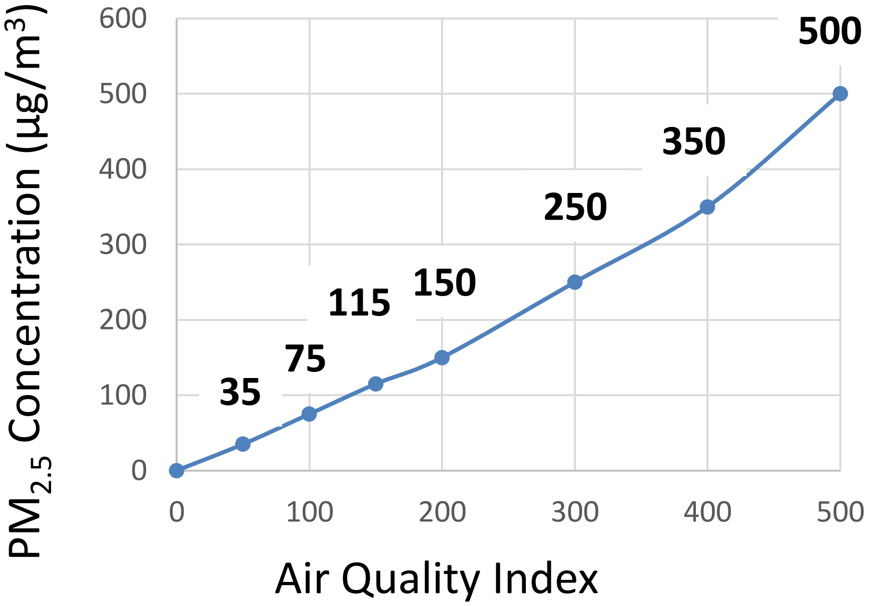
API for PM_{10}

Prior to 2013

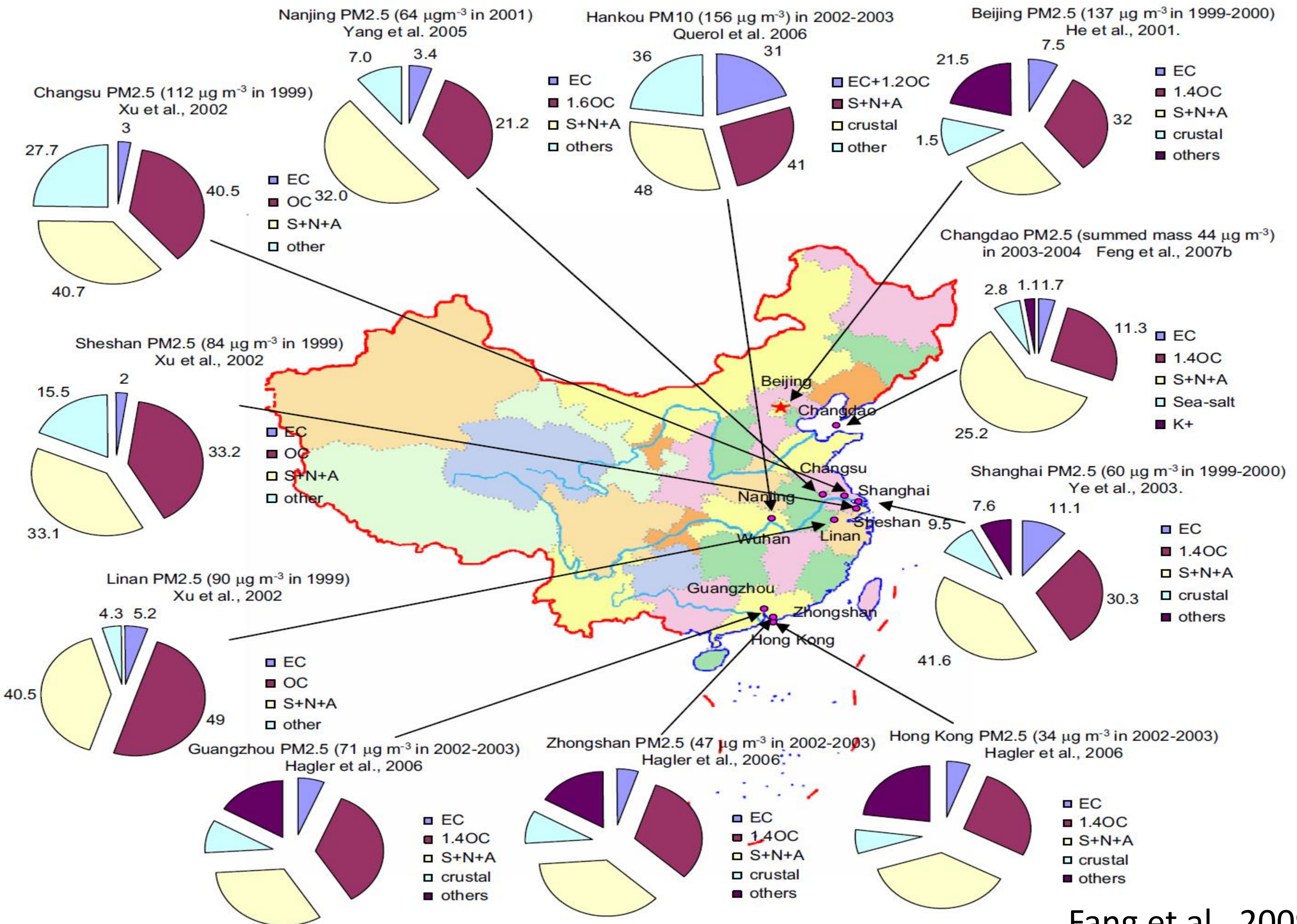


AQI for $PM_{2.5}$

In effect since 2013



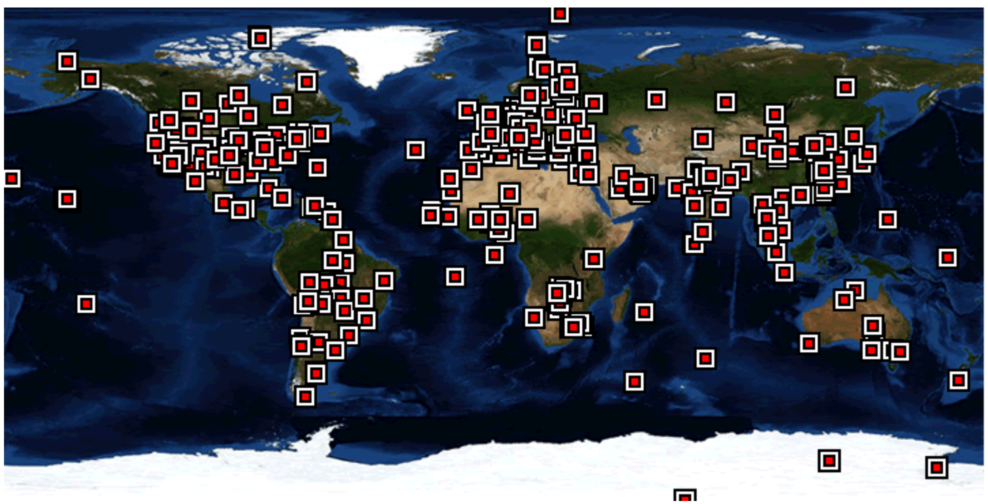
$PM_{2.5}$ Compositions Measurements



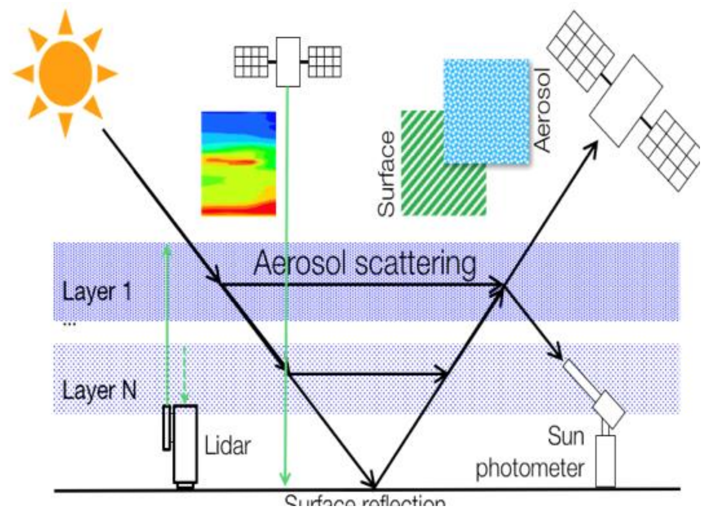
Fang et al., 2009

地基气溶胶光学观测：AERONET网络

- 自动跟踪太阳光度计（CIMEL 318）
- 中国目前只有少数几点进行连续观测并且共享数据，如北京、香河、太湖等。



NASA



Huizheng Che

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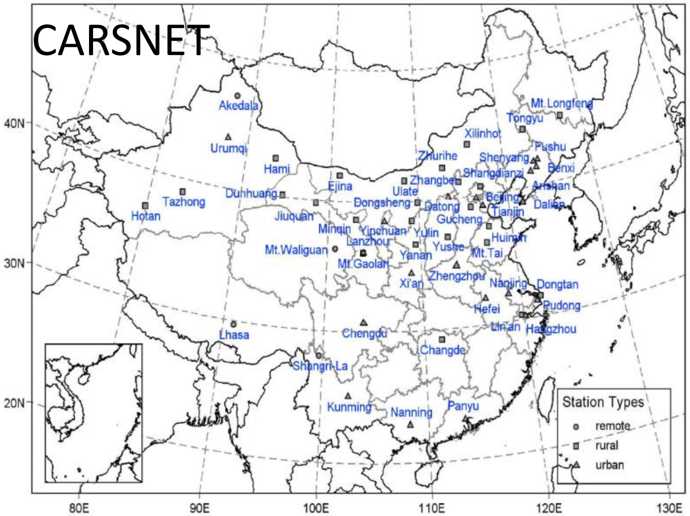
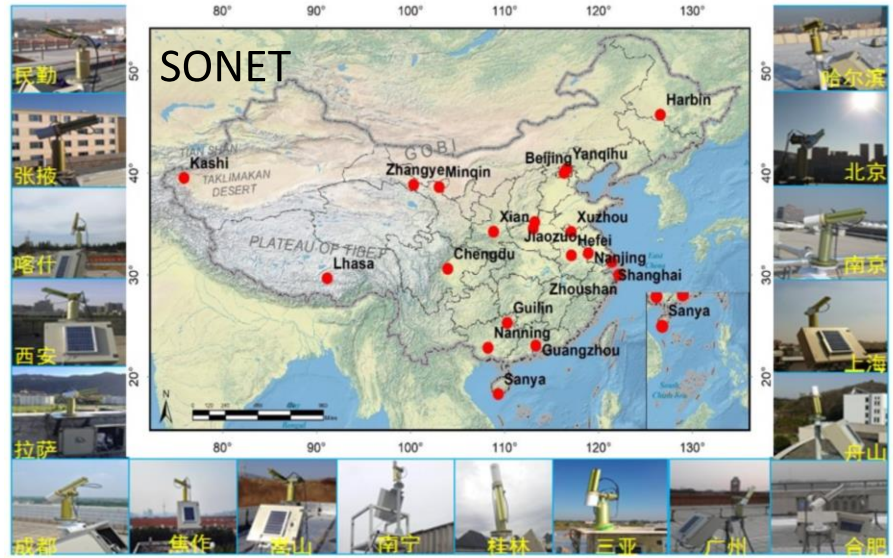
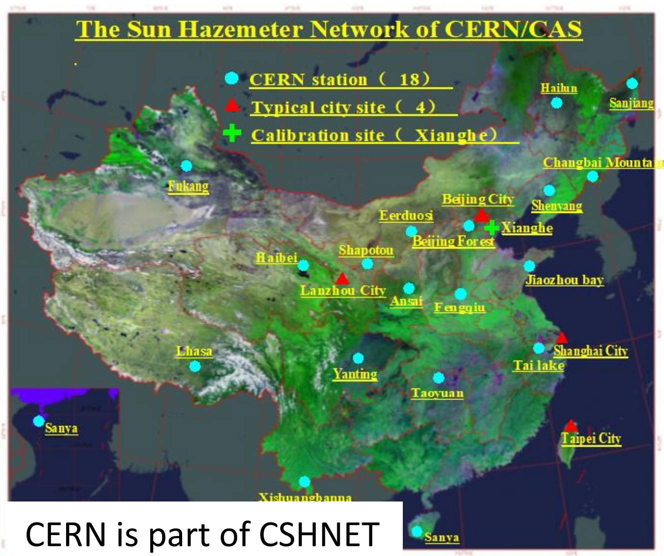
中国地基气溶胶光学观测
（AERONET、CARSNET、CSHNET、SONET等）

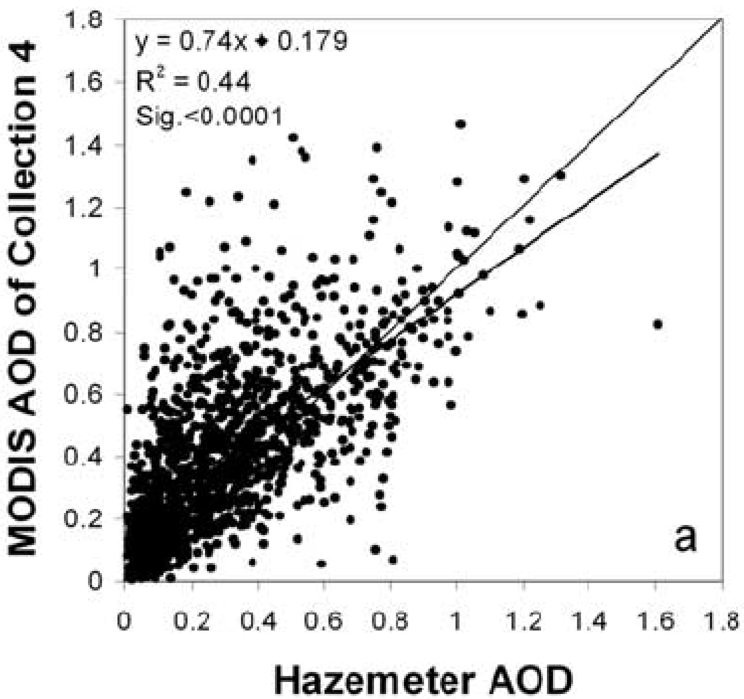


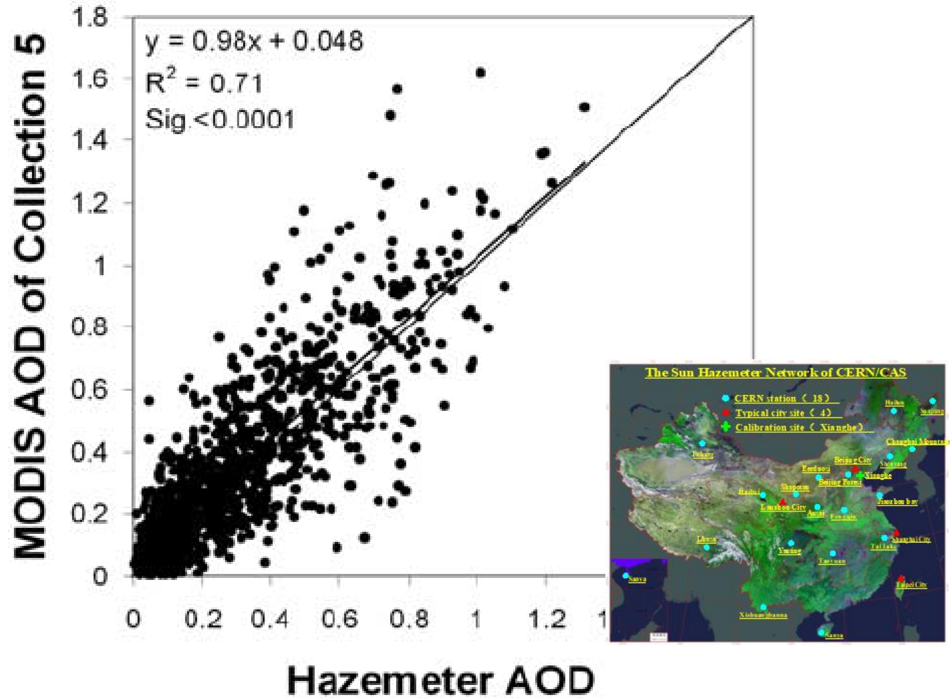




区域大气本底站观测到的AOD变化

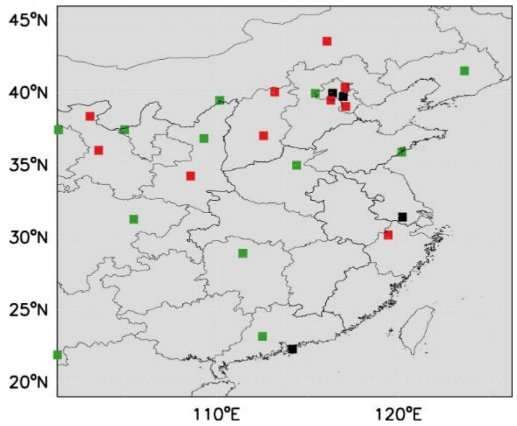
Using Ground-based AOD Measurements to Evaluate Satellite Data





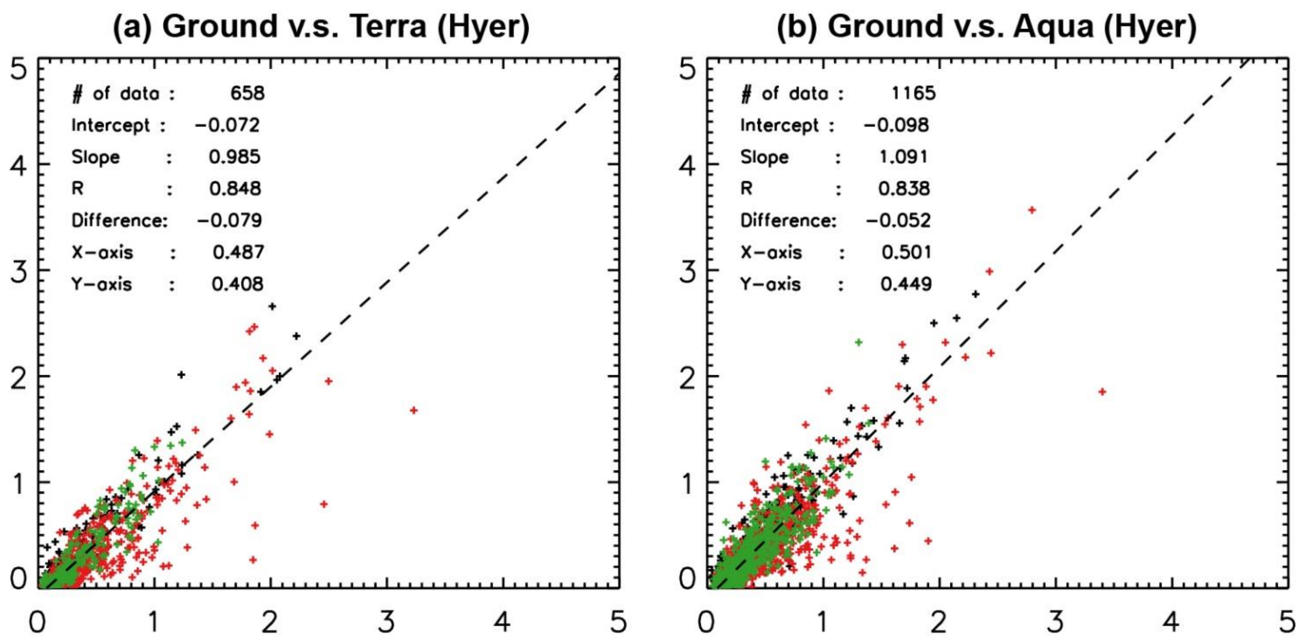
Xin Jinyuan et al.

Using Ground-based AOD Measurements to Evaluate Satellite Data

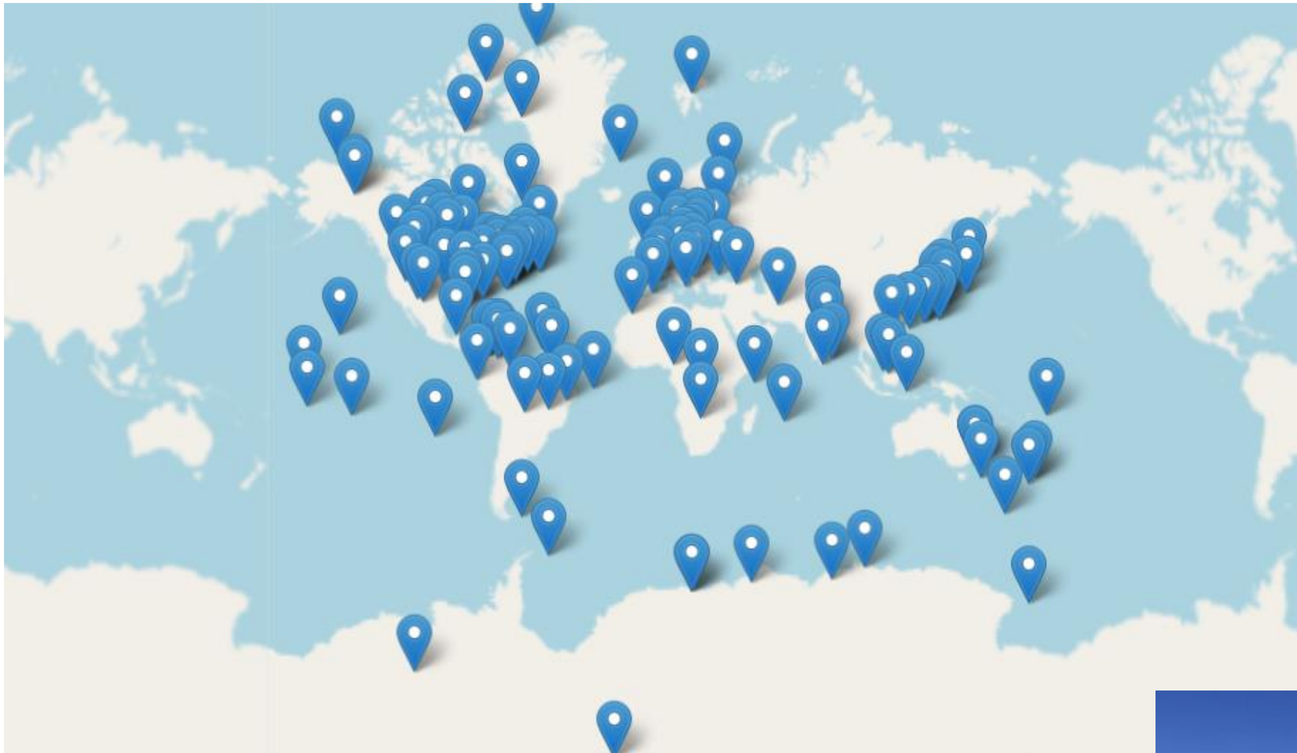


AERONET
CARSNET
CSHNET

Lin et al., 2014 AE

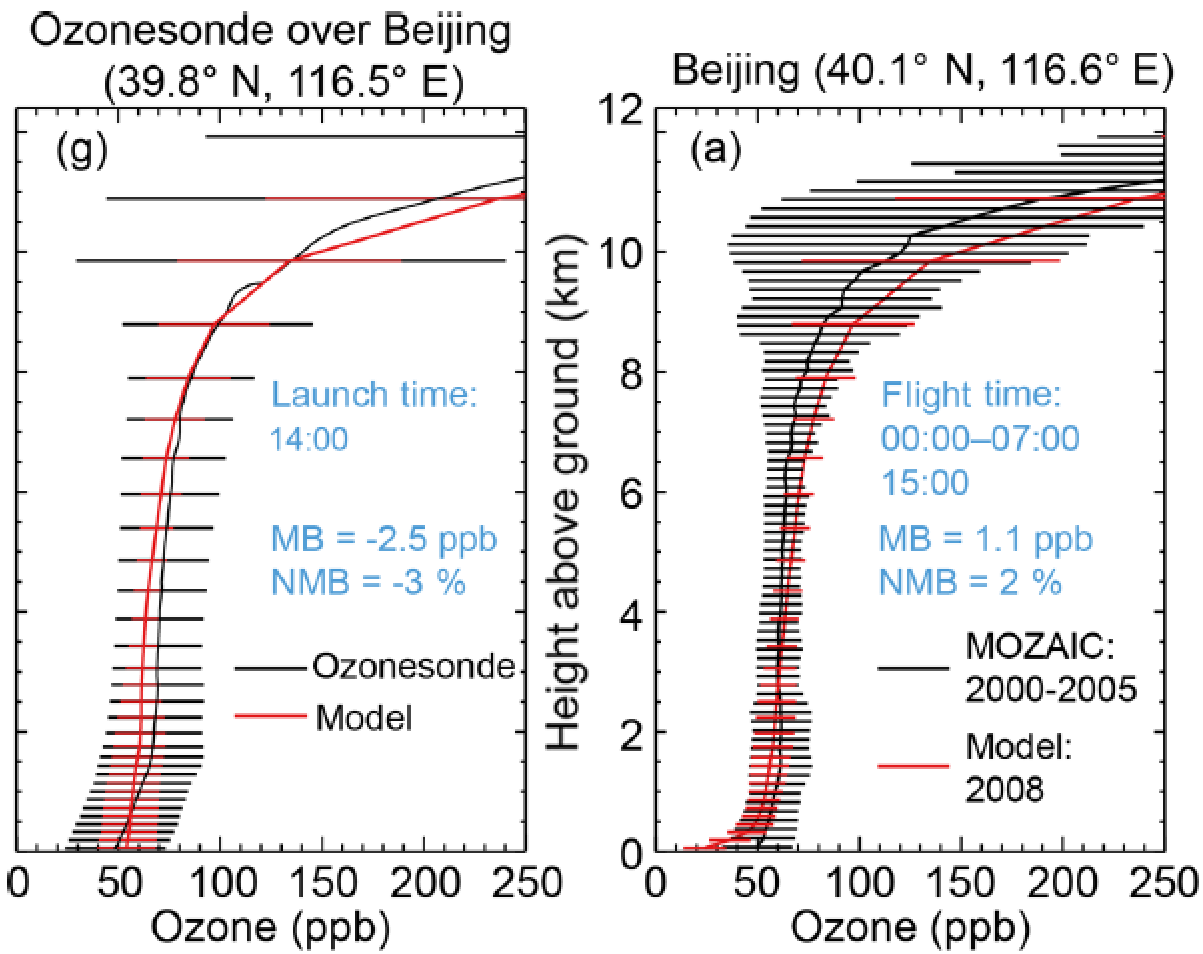


WOUDC Ozonesonde Network



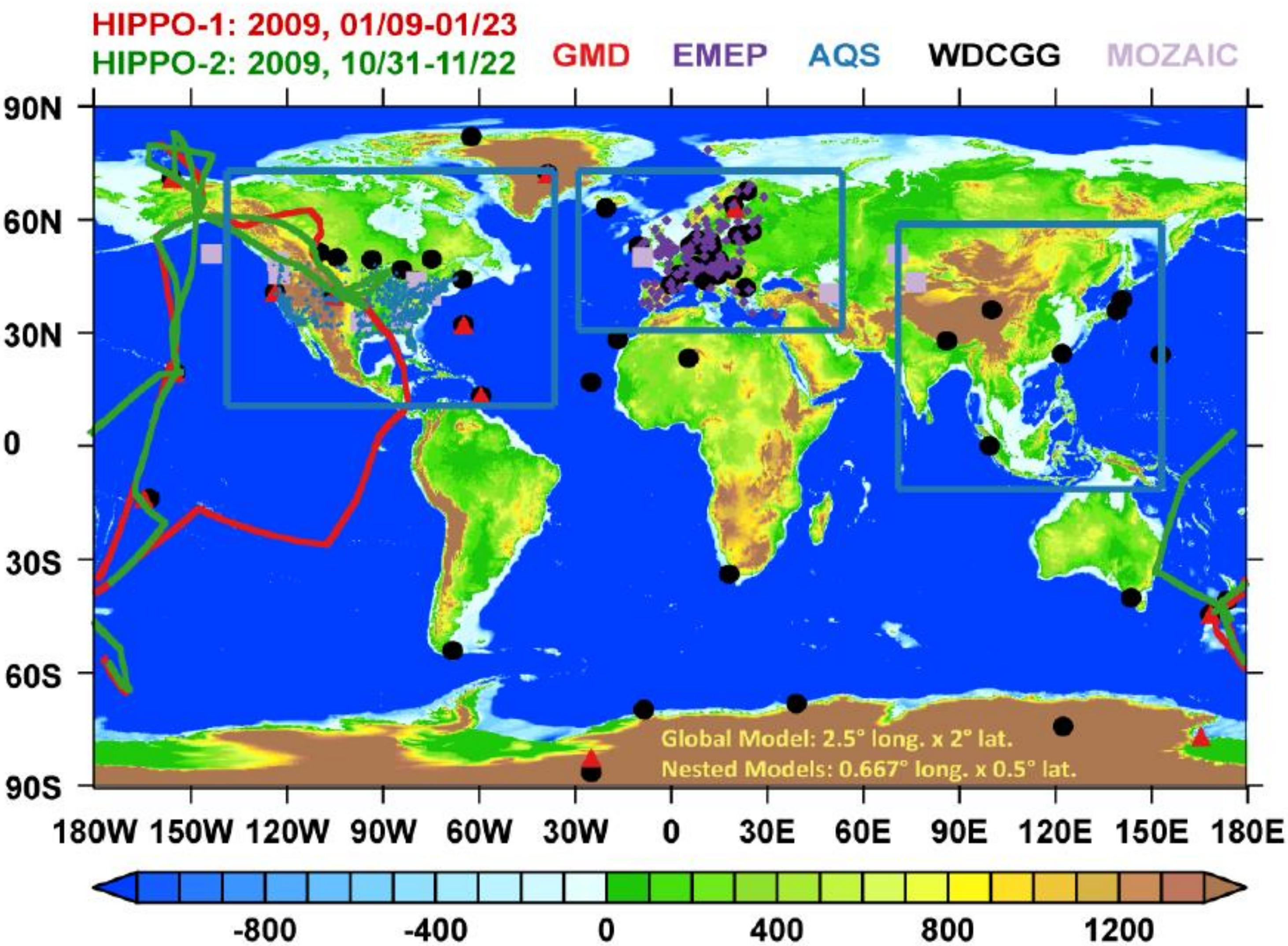
https://woudc.org/data/dataset_info.php?id=ozonesonde

Ozone Profiles over Beijing



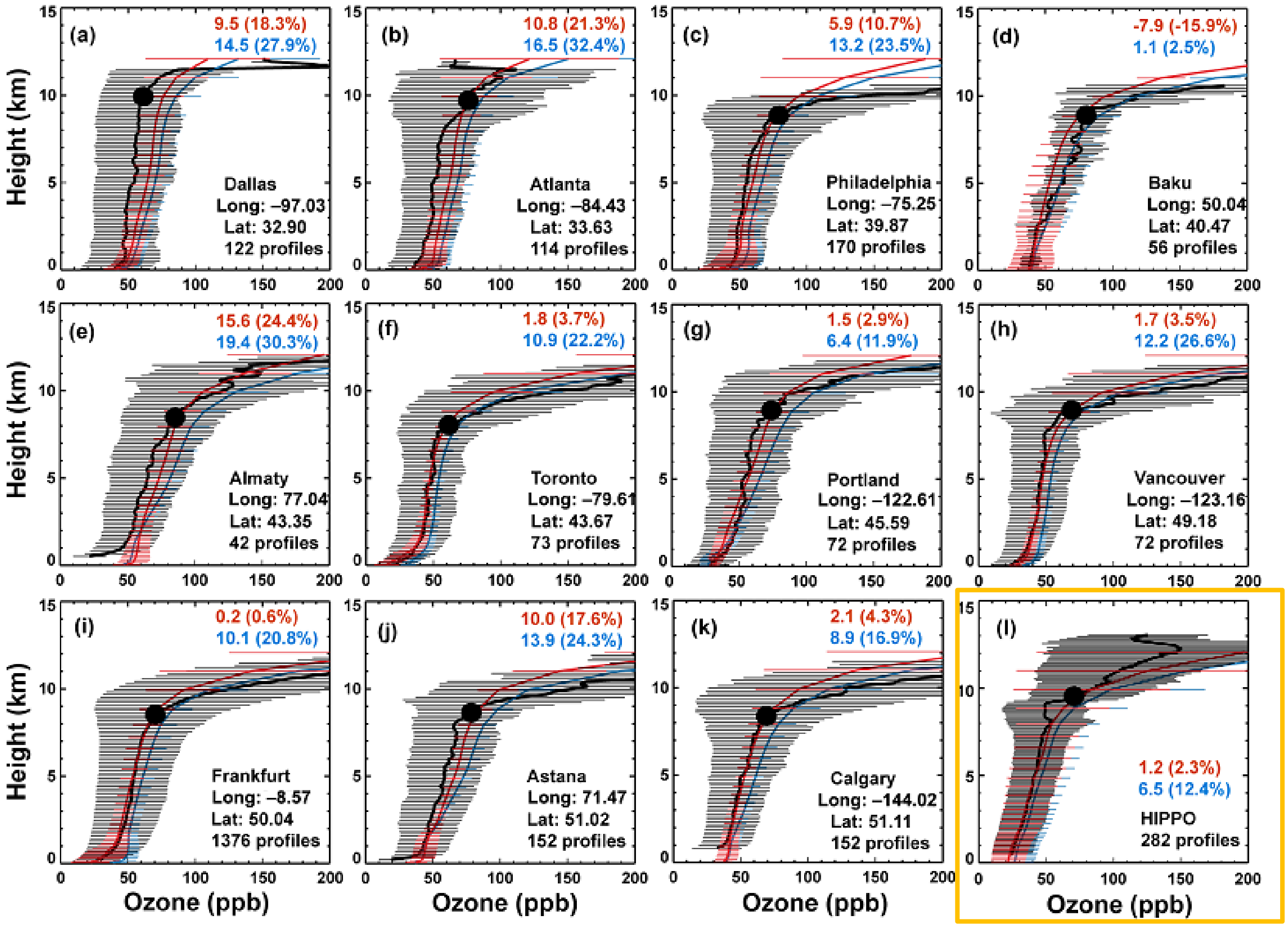
Ni et al., 2018, ACP

Pole-to-Pole Aircraft Measurements Over the Pacific



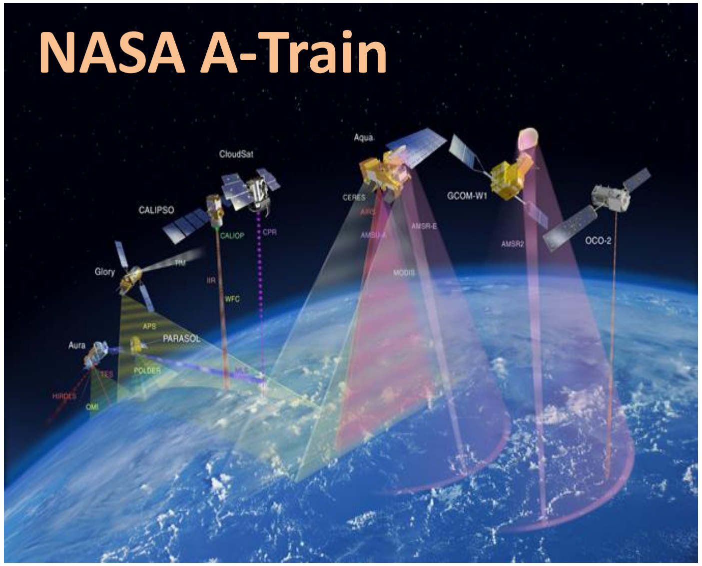
Wofsy et al., 2011 PTRS; Yan et al., 2014 ACP; 2016 ACP

Aircraft Measurements of Ozone



Yan et al., 2014 ACP; 2016 ACP

Modern Satellite Remote Sensing of Air Pollutants

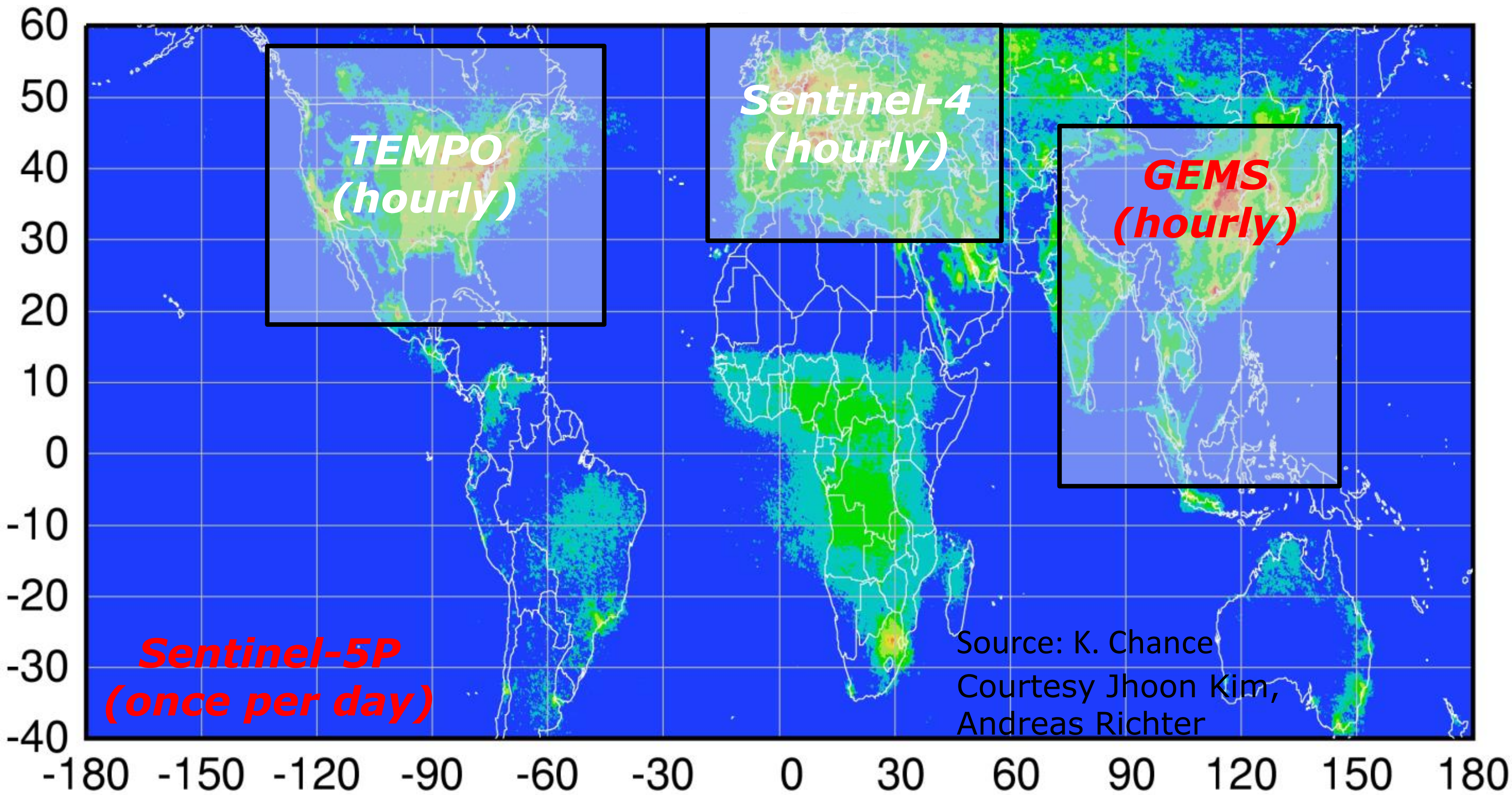


Advantages:

- Multiple species
- Excellent spatial coverage
- Long-term data
- High resolution data
- Easily accessible & verifiable

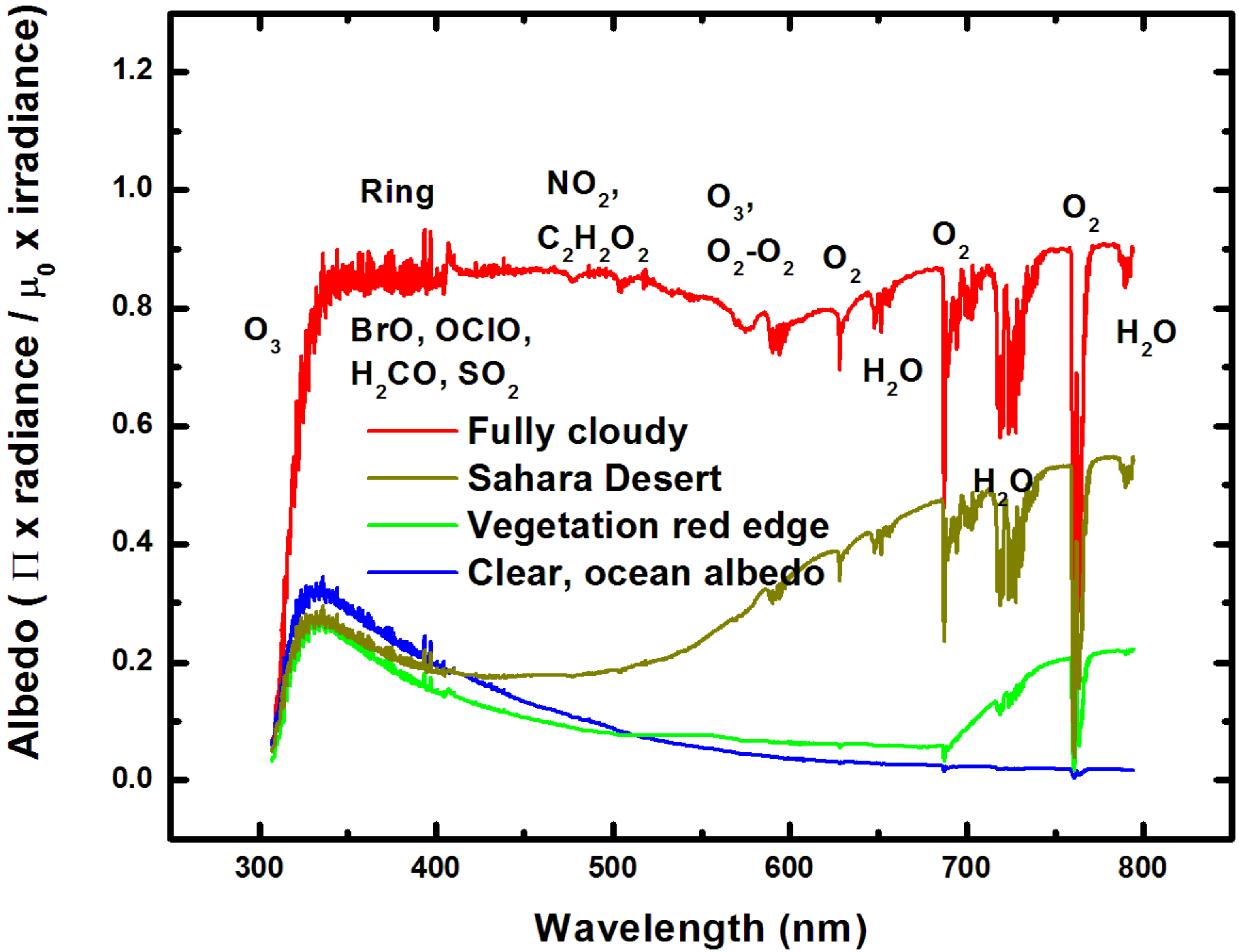
- ➢ Aerosols: MODIS, CALIOP, H-8, FY-4
- O_3: OMI, TES, AIRS, TropOMI, GF-5
- CO: TES, MOPITT, IASI
- NH_3: TES, IASI, CrIS
- ✓ NO_2: OMI, GOME-2, TropOMI, GF-5
- ✓ SO_2: OMI, GOME-2, TropOMI, GF-5
- ✓ HCHO: OMI, GOME-2, TropOMI, GF-5

High-Resolution Geostationary and Polar Orbiting Satellite Measurements of NO_2 and Other Tracers

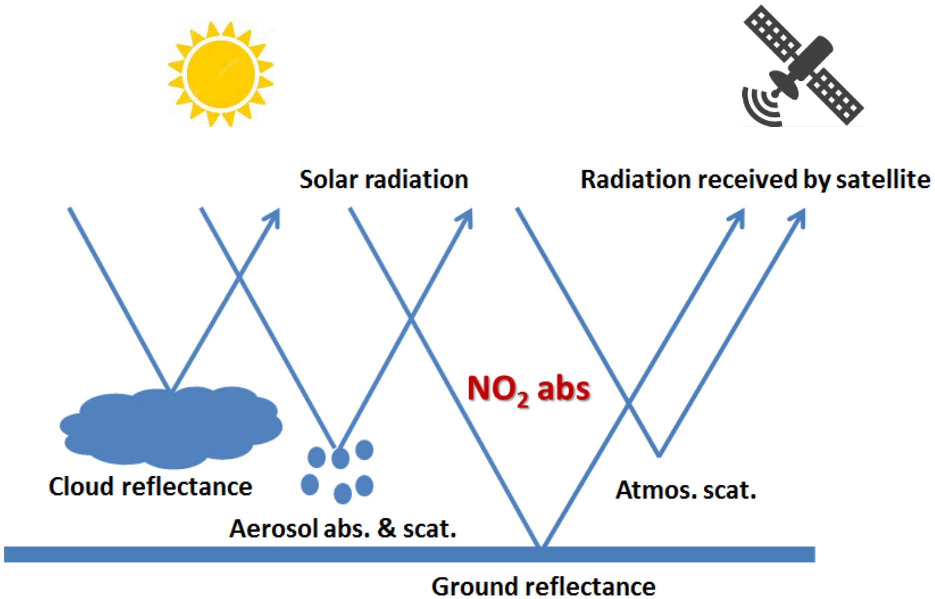


NO_2 sensors so far: GOME, SCIAMACHY, OMI, GOME-2A/B, GF-5, TropOMI, GEMS…

Reflectance Spectra at VIS-NI from ESA GOME-1



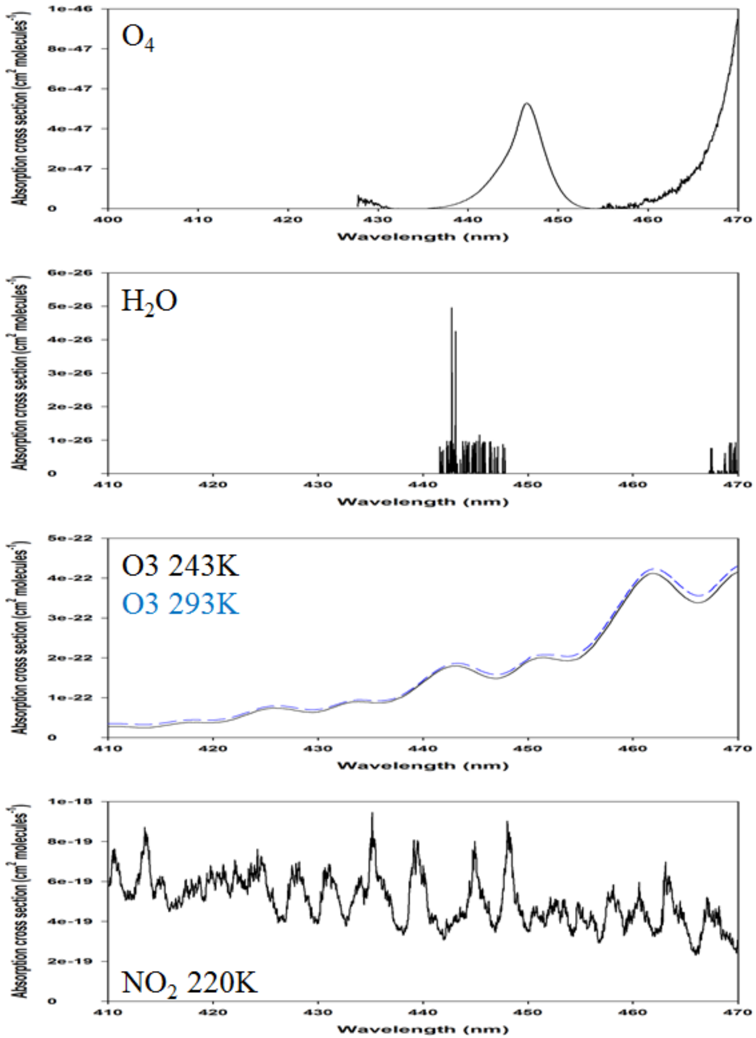
DOAS Approach to Retrieving NO_2, SO_2, HCHO, CHOCHO from Satellite Remote Sensing



DOAS

$$I(\lambda) = I_0(\lambda)e^{-\sum_i \sigma_i(\lambda)N_{s,i} + \sum_j a_j\lambda^j}$$

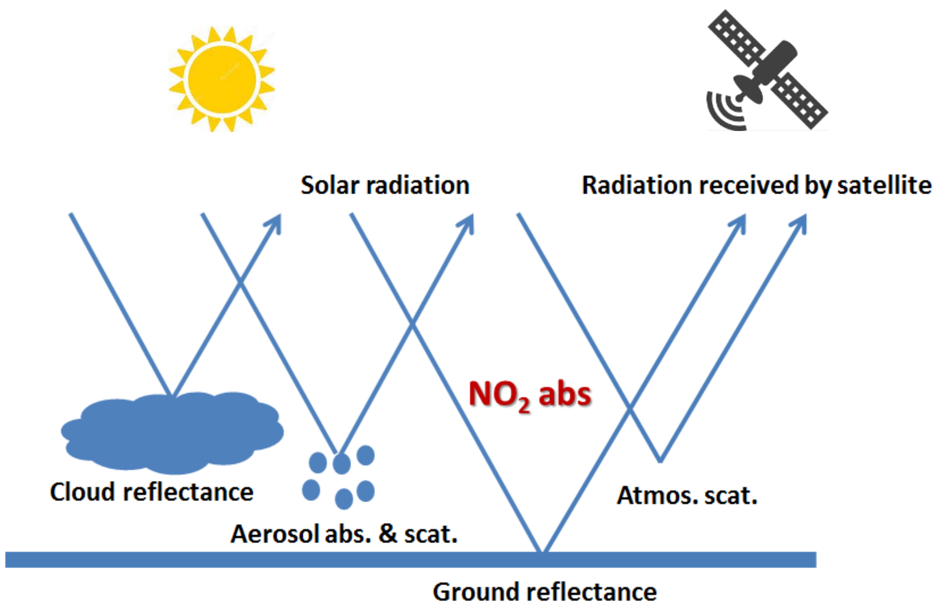
$$\ln\left(\frac{I(\lambda)}{I_0(\lambda)}\right) = -\sum_i \sigma_i(\lambda)N_{s,i} + \sum_j a_j\lambda^j$$



Retrieving NO_2 from Satellite Remote Sensing

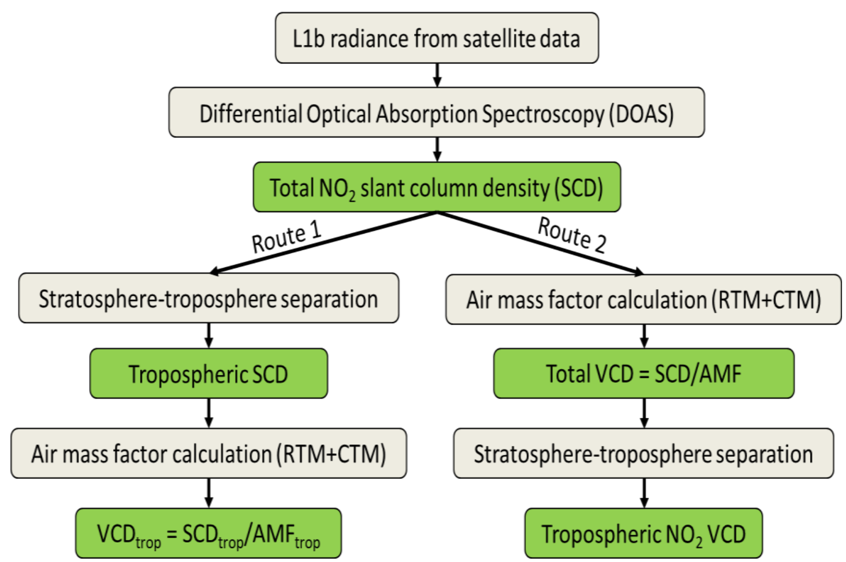
DOAS method to derive total SCD:

$$I(\lambda) = I_0(\lambda) e^{-\sum_i \sigma_i(\lambda) S_i + \sum_j a_j \lambda^j}$$

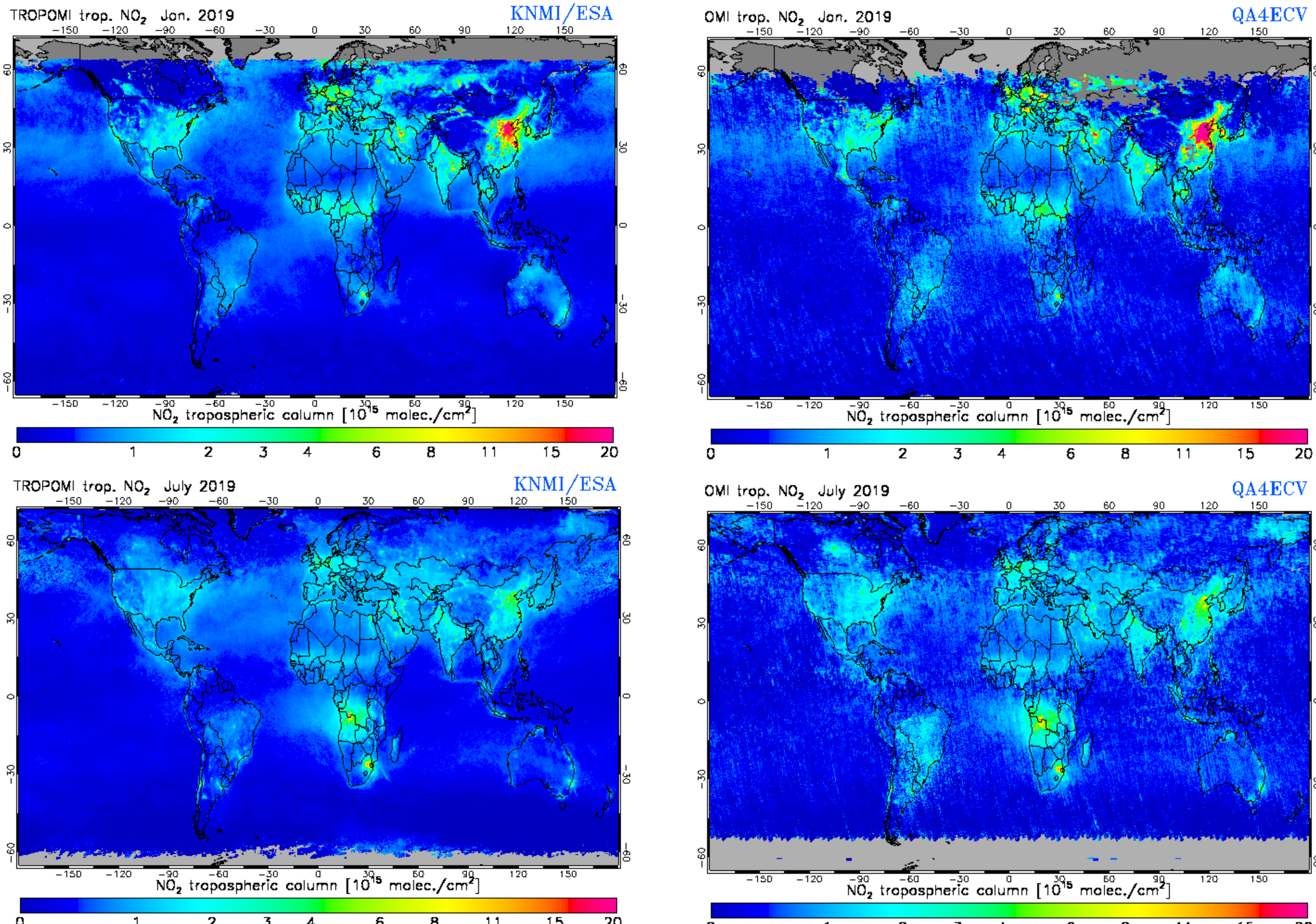


From total SCD to tropospheric VCD:

$$\Omega_t = \frac{S_t}{M_t} = \frac{S - S_s}{M_t}$$



Tropospheric NO_2 Column: OMI versus TROPOMI

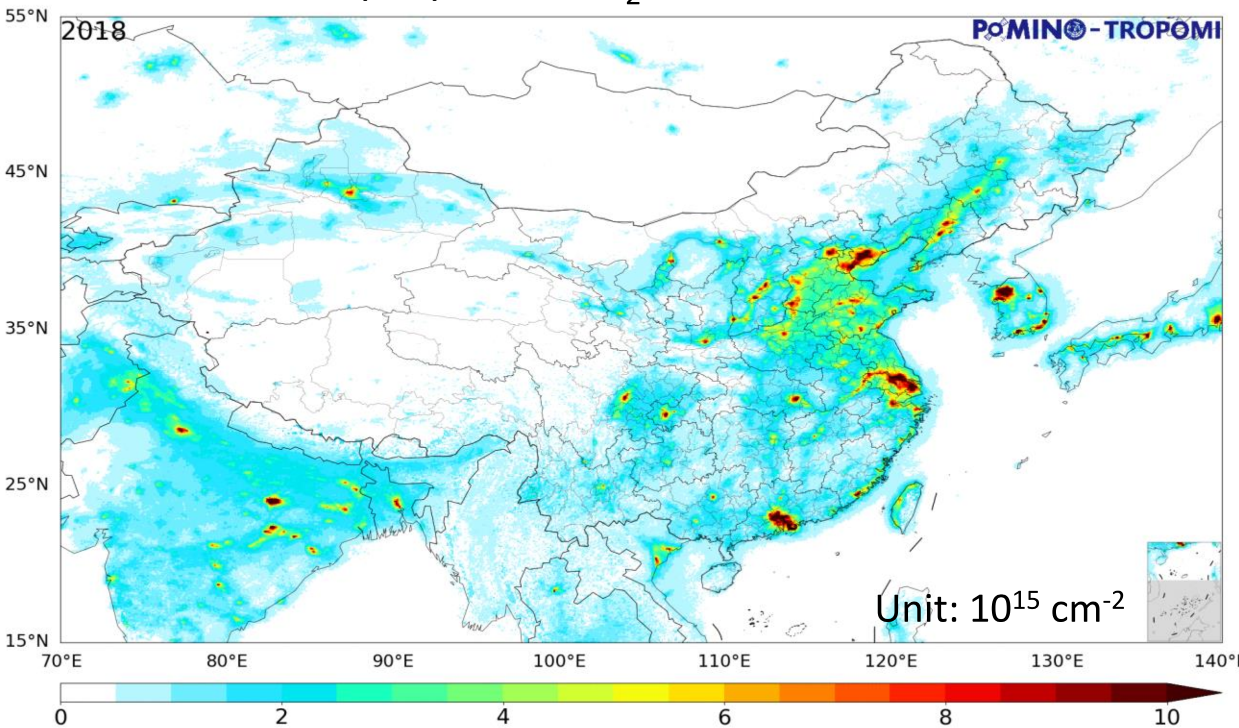


POMINO NO_2 VCD Products for OMI, TROPOMI & GEMS

http://www.pku-atmos-acm.org/acmProduct.php

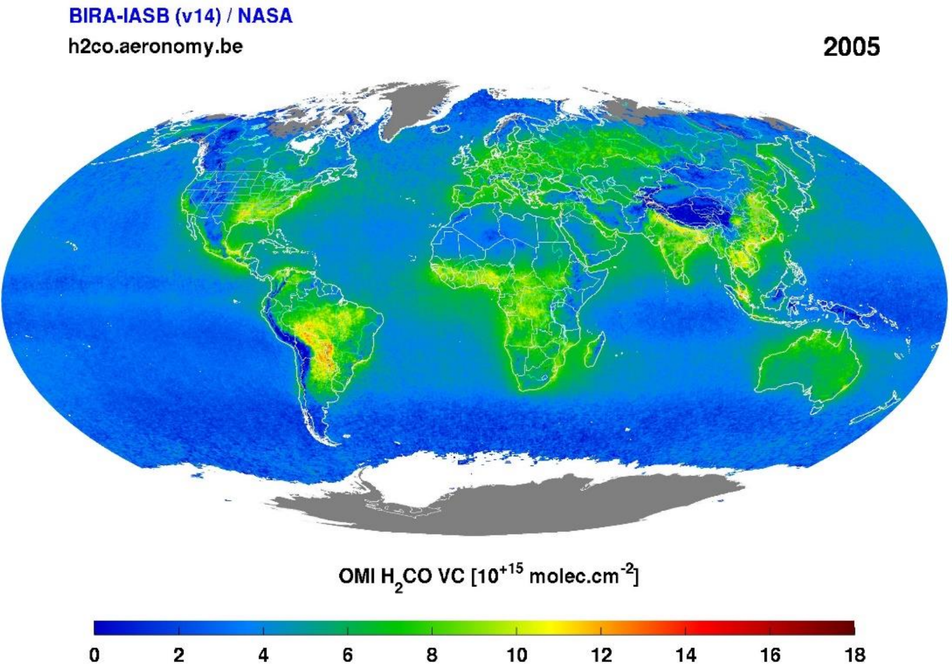
All Level-2 and Level-3 data are freely available (2004-present)

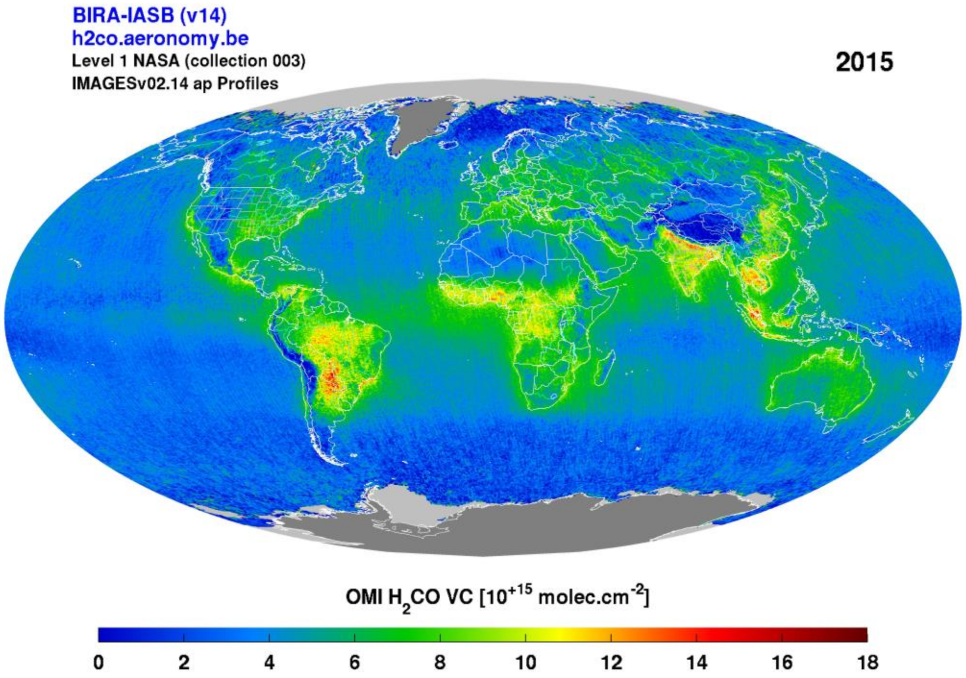
5 km-res Tropospheric NO_2 VCDs in JJA 2018–2022



Lin et al., ACP, 2014;
Lin et al., ACP, 2015;
Liu et al., AMT, 2019;
Liu et al., AMT, 2020;
Zhang et al., NRSB, 2022
Zhang et al., AMT, 2023

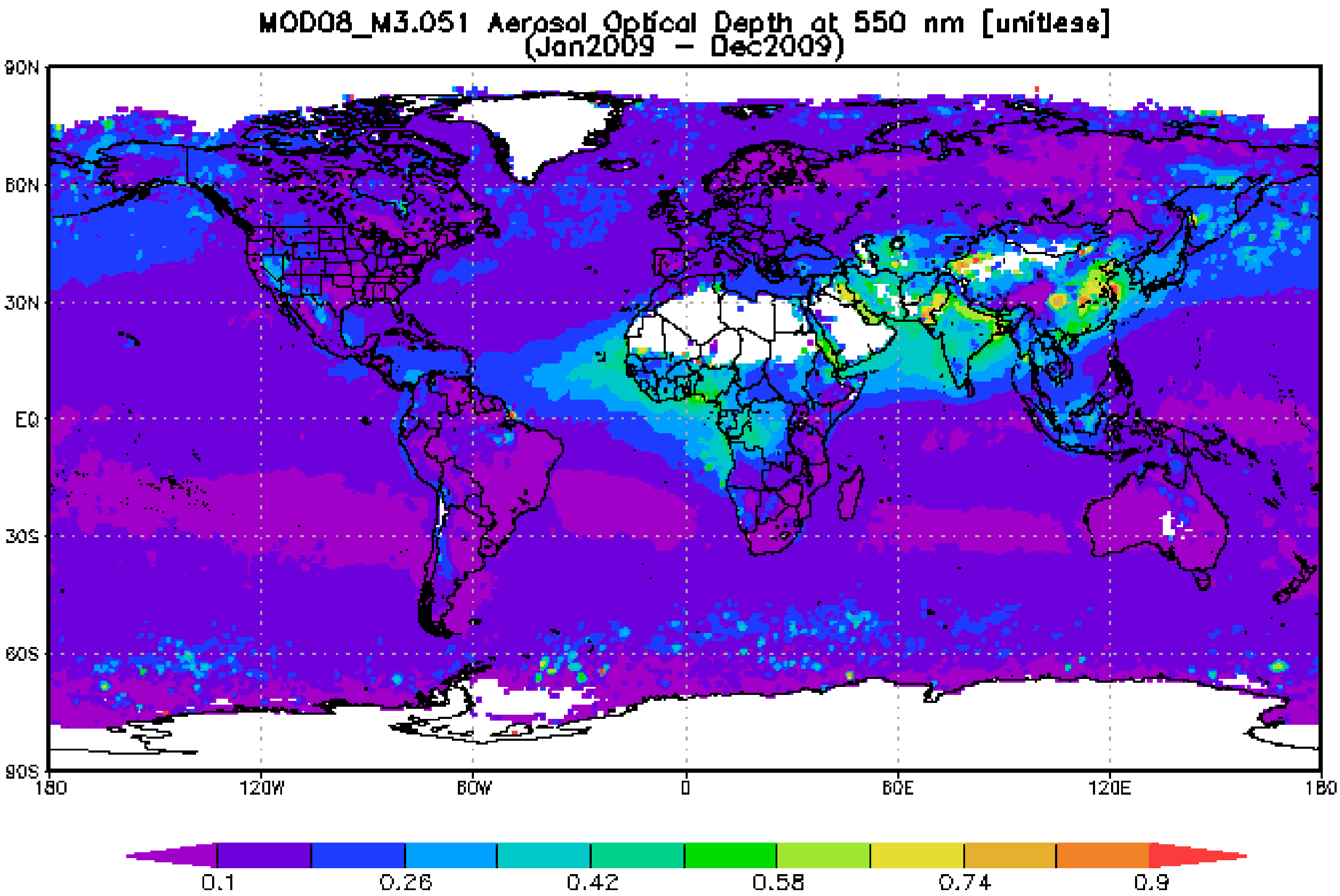
OMI-Retrieved Tropospheric HCHO Column: 2005-2015



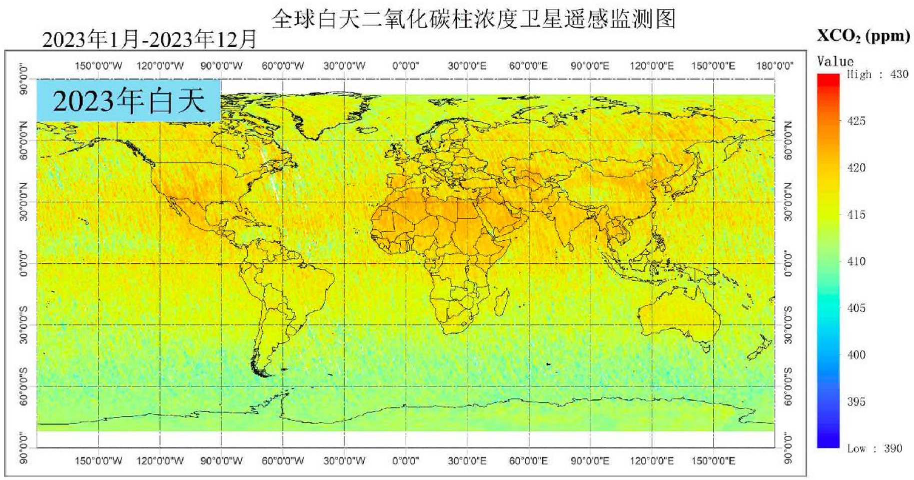


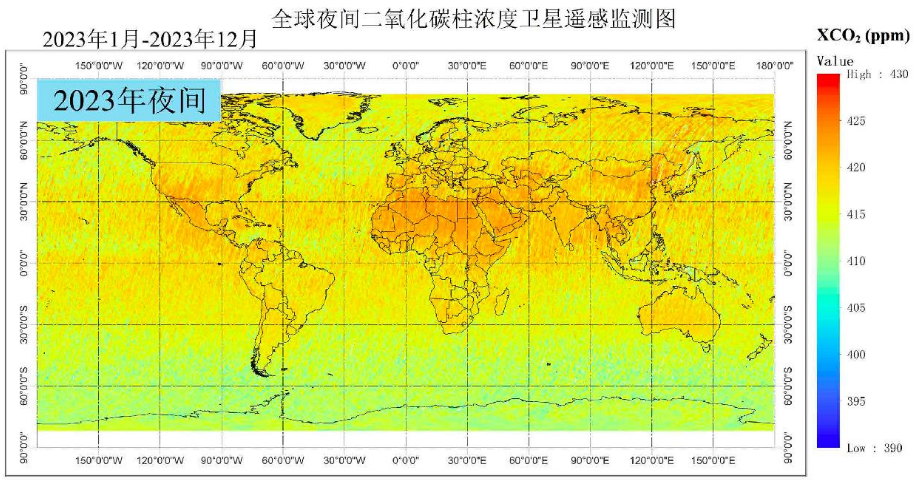
www.temis.nl

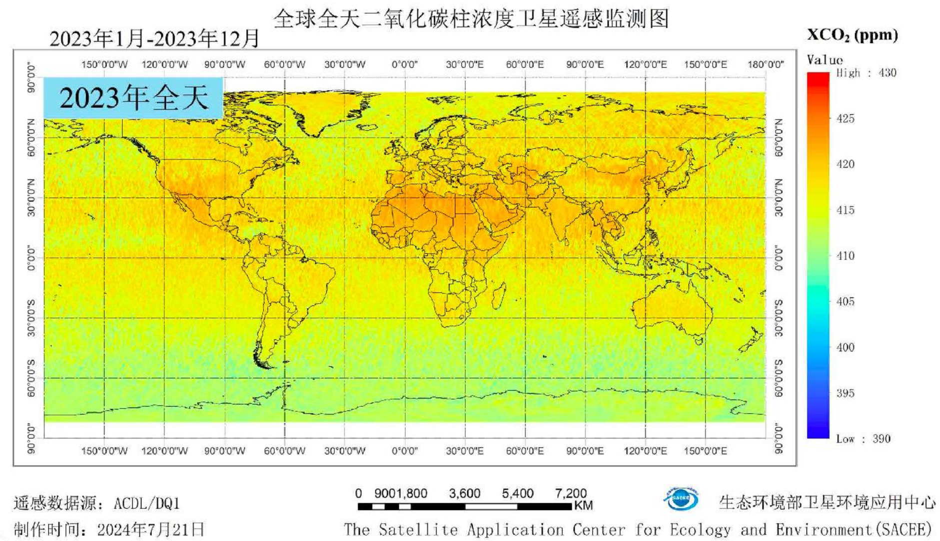
Annual Average AOD from MODIS: 2009



Global XCO_2 in 2023 from DQ-1 Satellite



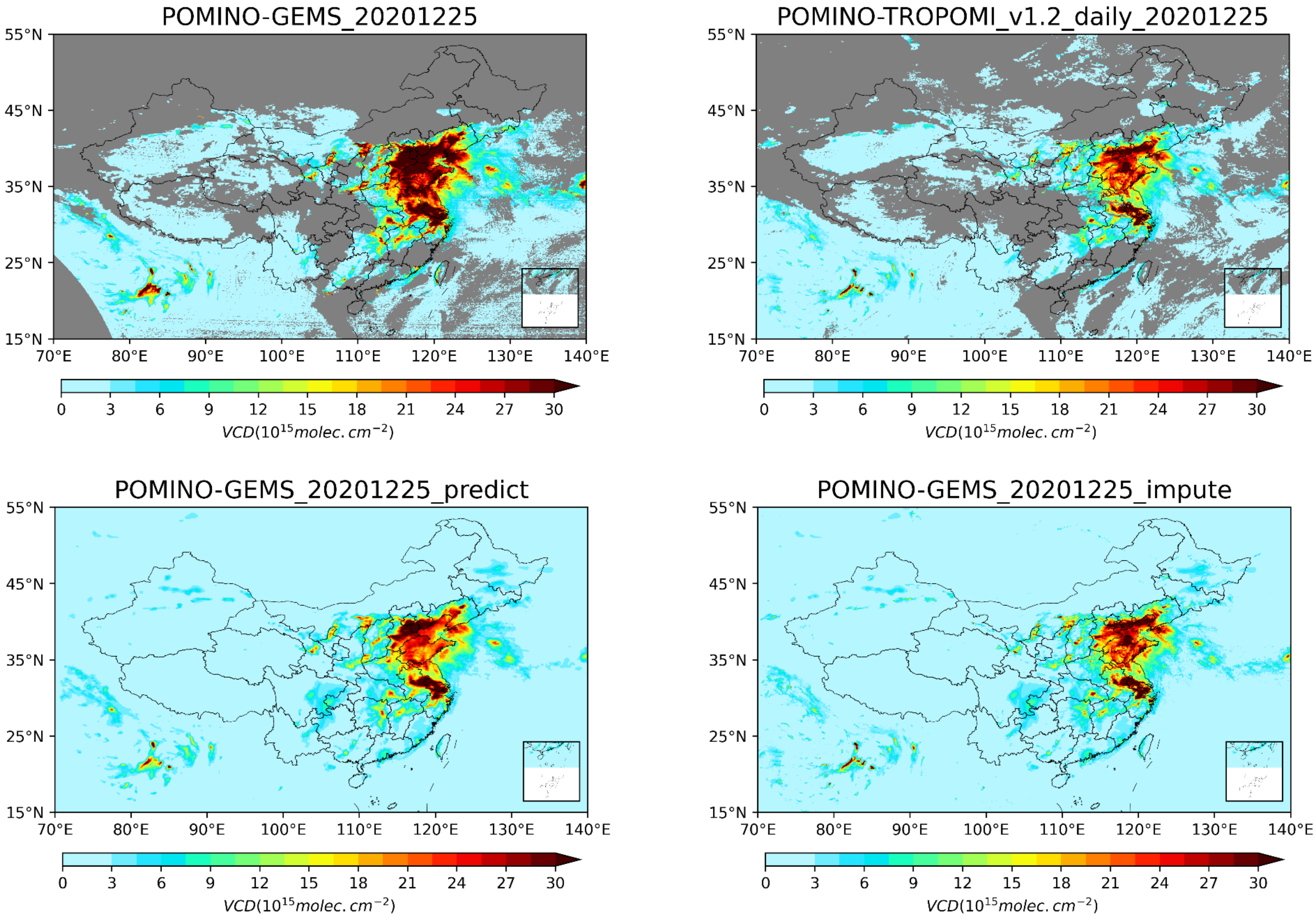




https://content-static.cctvnews.cctv.com/snow-book/index.html?item_id=17437730038915246254&toc_style_id=feeds_default&track_id=BEE03866-04A6-4927-B3DE-150E88A7205F_743580087526&share_to=wechat

Gap Filling for Satellite Data: NO_2

GEMS + GEOS-CF + Unet → TROPOMI



Campaign

- **Measurement campaigns: intensive measurements of targets (e.g., pollutants) in a short period (weeks to months), employing a variety of instruments.**
- **TRACE-P**
- **ICARTT**
- **INTEX-B**
- **ARCTAS**
- **PRIDE-PRD**
- **CAREBEIJING**
- **……**

✓ **Aircraft measurements are used in these campaigns**

National Basic Research Program of China (973)

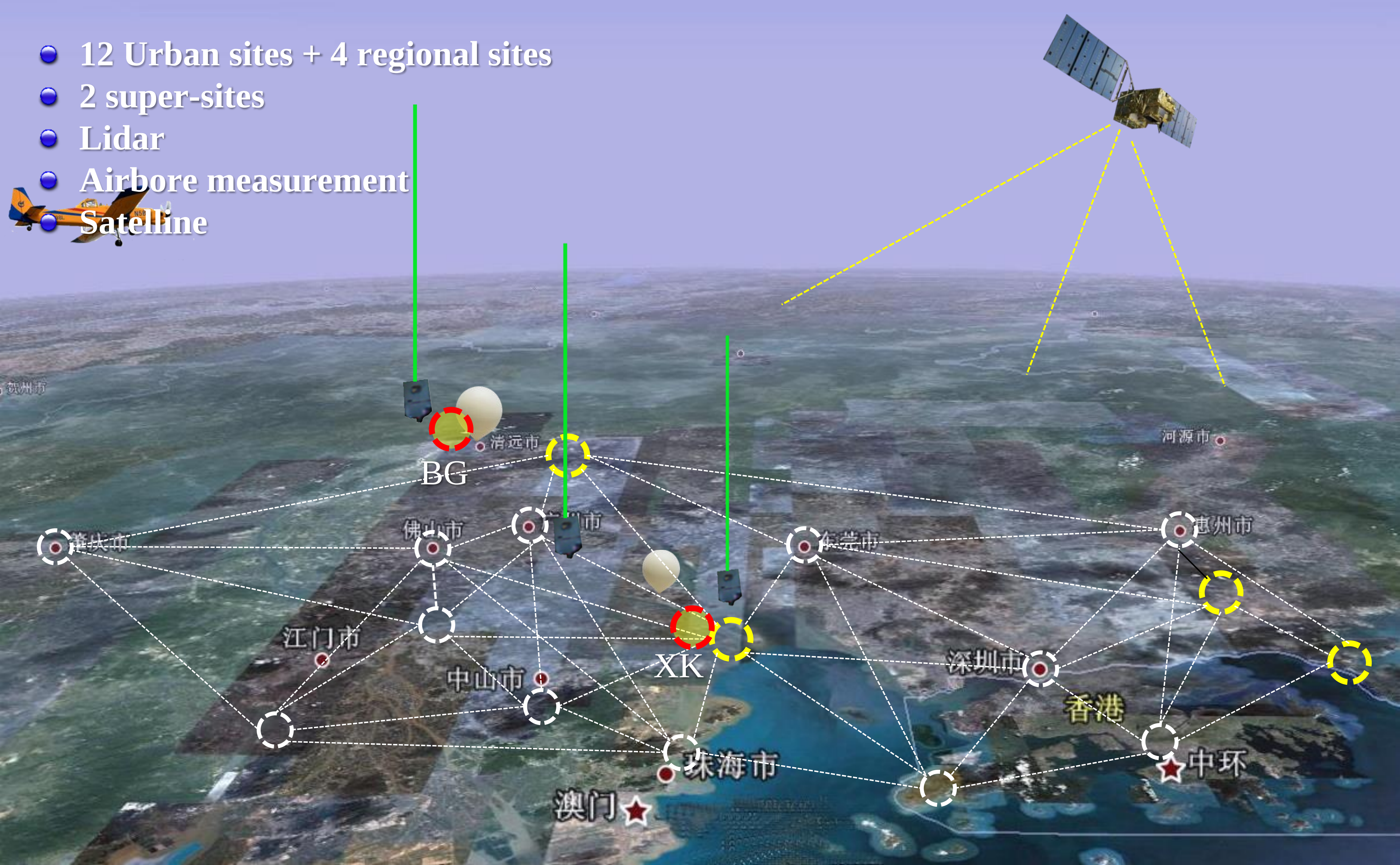
PRIDE-PRD(Program of Regional Integrated Experiments of Air Quality over Pearl River Delta)

- PRIDE-PRD2004
- PRIDE-PRD2006
- PRIDE-PRD2008

  (3C-STAR2008)

PRIDE-PRD 2004, 2006, 2008

- 12 Urban sites + 4 regional sites
- 2 super-sites
- Lidar
- Airbore measurement
- Satelline

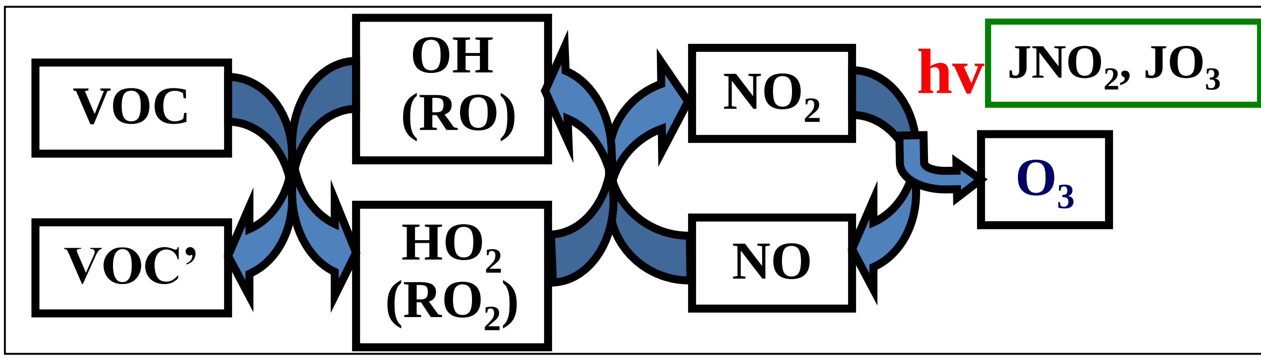


Field Measurement Parameters

Gases:

- O_3, NOx, NOy, CO, SO_2
- H_2O_2, ROx VOCs,
- HNO_2, HNO_3, HCl, NH_3
- OVOCs, OH, H_2SO_4

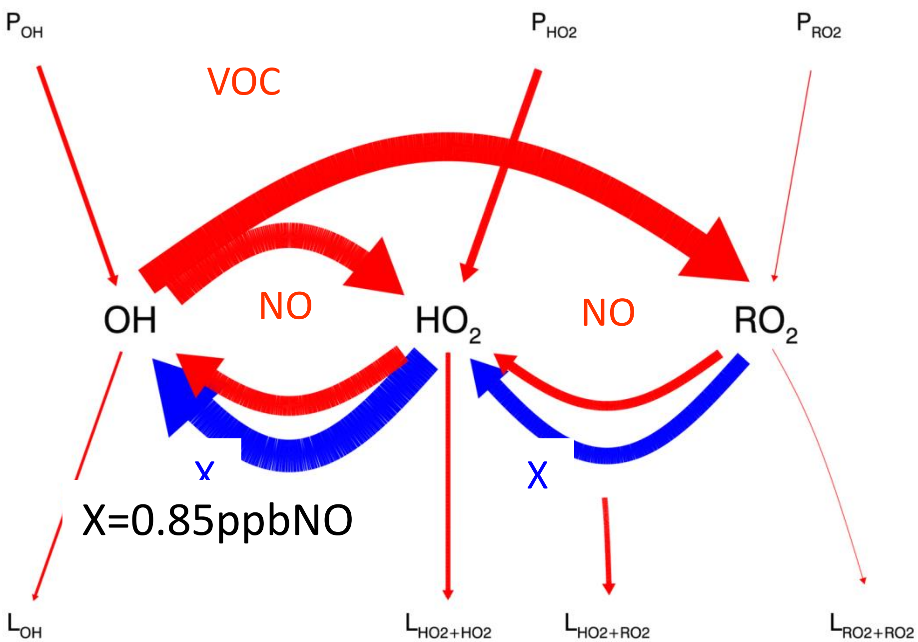
Process: radicals photolysis rates



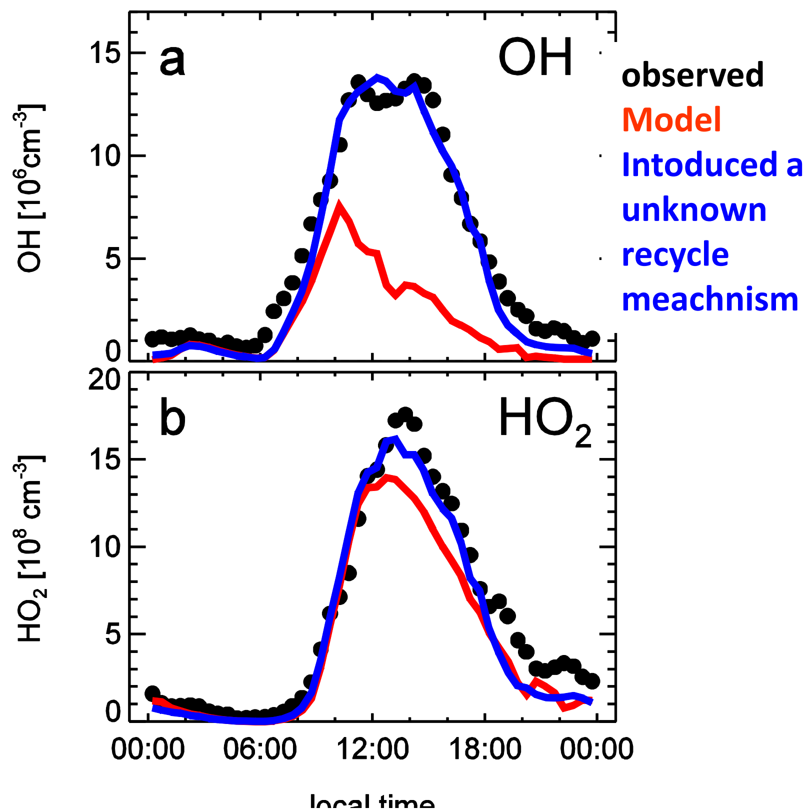
Particles: Size distribution Optical property Chemical comp.

- Trace elements, ions, OC/EC, POM, WSOC
- SO_4^{2-}, NO_3^-, NH_4^+, Cl-
- Na^+, K^+, Ca^{2+}, Mg^{2+}
- PM, Number distribution (0.01-10 um)
- Light scattering Light absorption

With an Assumed OH Recycle Mechanism, Model Calculated OH Concentrations Fit the Observed



Observed vs model



Hofzumahaus, A., F. Rohrer*, K. D. Lu, B. Bohn, T. Brauers, C. C. Chang, H. Fuchs, F. Holland, K. Kita, Y. Kondo, X. Li, S. R. Lou, M. Shao, L. M. Zeng, A. Wahner and *Y. H. Zhang** (2009). "Amplified Trace Gas Removal in the Troposphere." *Science* 324(5935): 1702-1704.

Numerical Models in Atmospheric Research

- Type
  - Statistical model, AI model, physical model
  - Parameterization
- Purpose
  - Meteorological, climate, ocean, sea ice, chemical transport, …, Earth system
- Dimension
  - Box model, 1-D, 2-D, 3-D
- Scale (domain)
  - Global, regional, nested
- Proceeding
  - Forward, backward (back-trajectory), adjoint

Primitive Equations (for Large-scale Motions)

Meteorological and climate models are based on these equations

Hypsometric equation (hydrostatic)
$$\frac{\partial \Phi}{\partial p} = -\frac{RT}{p} \qquad d\Phi = g dz$$

Horizontal equation of motion
$$\frac{d\boldsymbol{V}(u,v)}{dt} = -\nabla\Phi - f\boldsymbol{k}\times\boldsymbol{V} + \boldsymbol{F}$$

Continuity equation
$$\frac{\partial \omega}{\partial p} = -\nabla\cdot\boldsymbol{V} \qquad \omega = \frac{dp}{dt}$$

Thermodynamic energy equation
$$\frac{dT}{dt} = \frac{\kappa T}{p}\omega + \frac{J}{c_p} \qquad \kappa = R/c_p$$

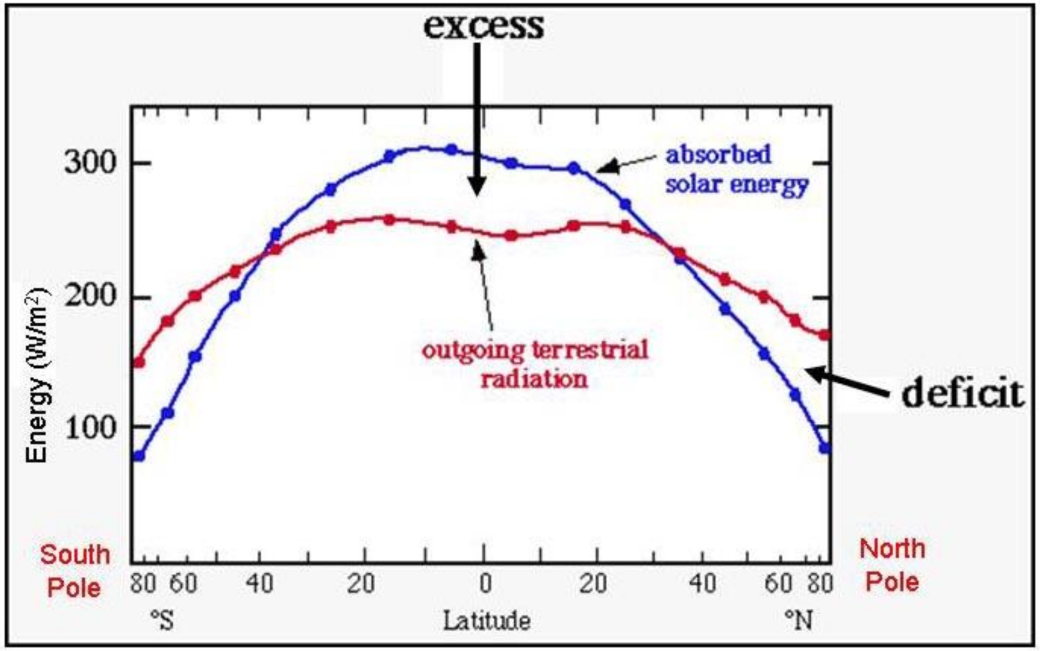
Bottom boundary condition
$$\frac{\partial p_s}{\partial t} = -(\boldsymbol{V}\cdot\nabla p\,)_s - \left(w\frac{\partial p}{\partial z}\right)_s - \int_0^{p_s}(\nabla\cdot\boldsymbol{V})dp$$

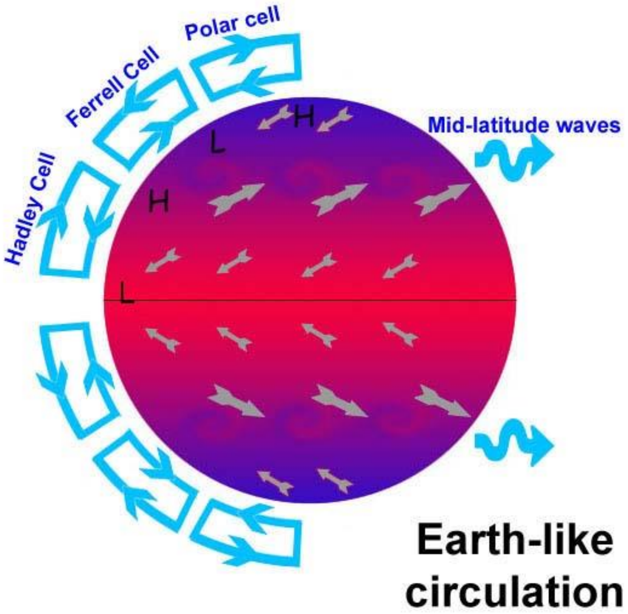
Five unknowns
$$\mathbf{V}(u,v), \omega, \Phi, T$$

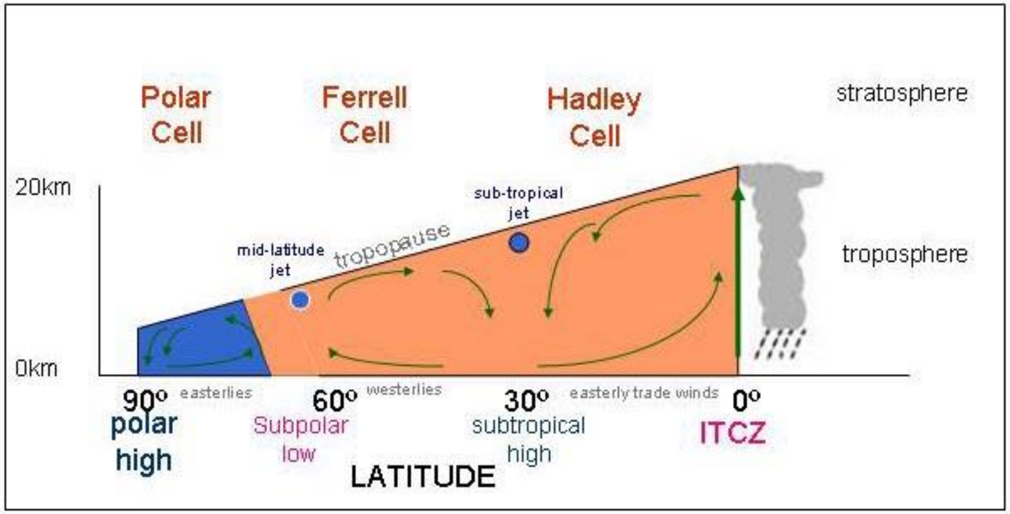
Wallace and Hobbs, 2006

J and $\boldsymbol{F}$ need to be parameterized

Meridional Circulation





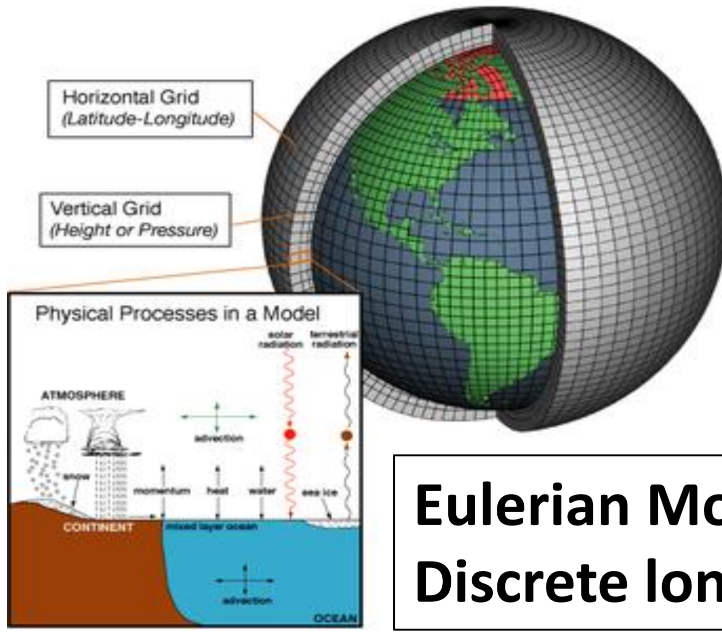


Atmospheric Chemical Transport Modeling

Emis　Dep　Transport & Mixing　Chemistry

$$\frac{\partial C}{\partial t} = E - D - \nabla \cdot C\boldsymbol{V} - \nabla \cdot \overline{C'\boldsymbol{V}'} + (P - L)$$

Grid-resolved　Unresolved

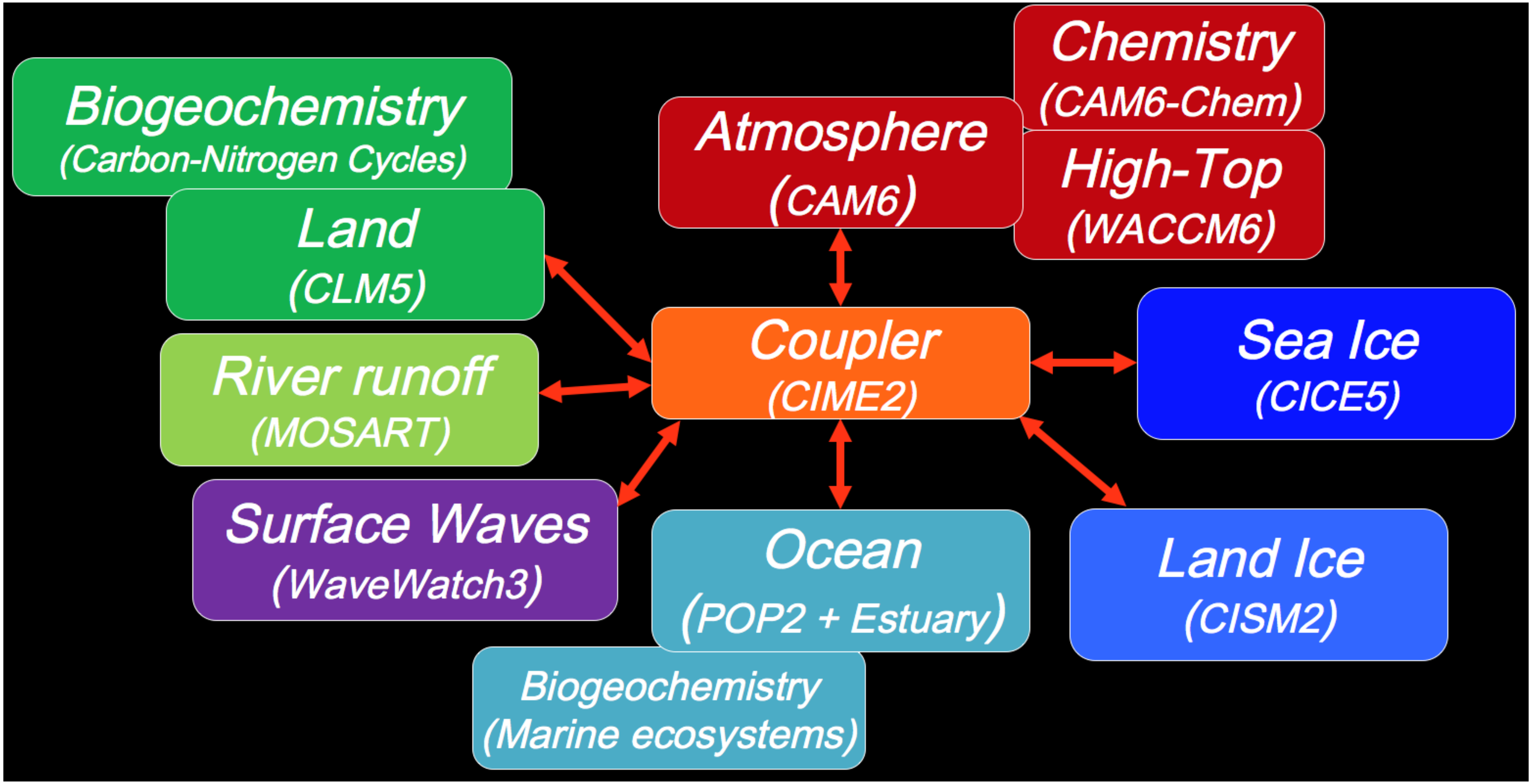


Eulerian Model:
Discrete lon-lat grid

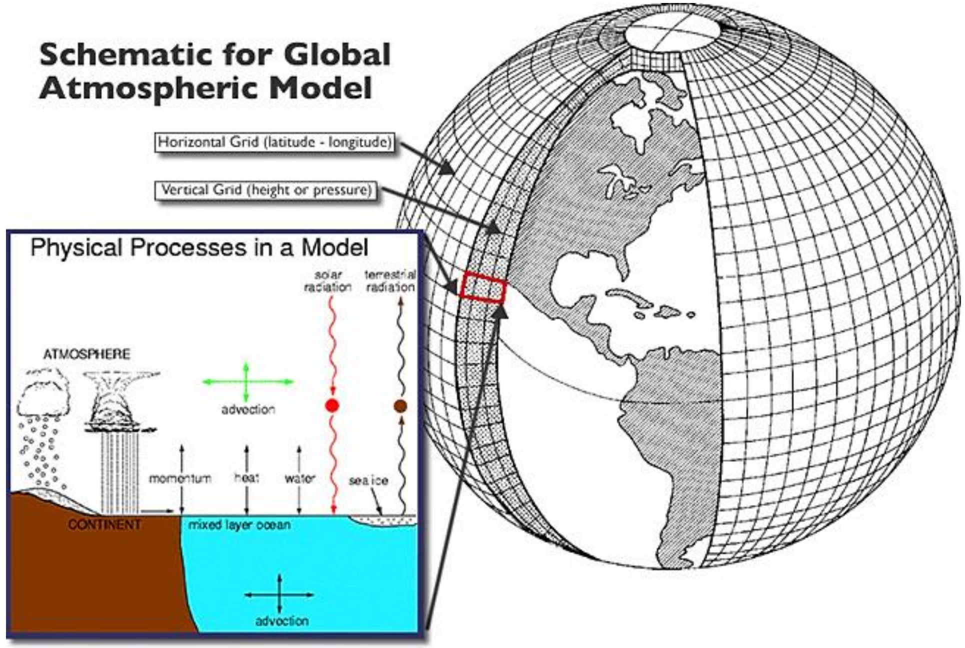
Atmospheric chemical transport models:

– Simulating spatiotemporal variations of trace species after they or their precursors are emitted into the atmosphere

Earth System Models

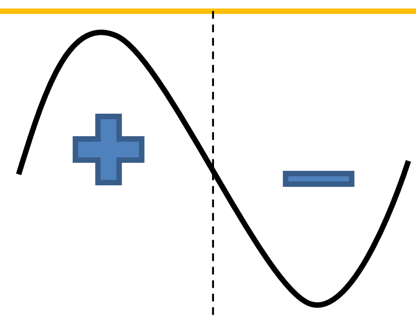


Numerical Modeling of Atmosphere



Initial conditions → Governing equations
Parameterizations
Numerical dissipation
Boundary conditions ? → Evolution of atmosphere

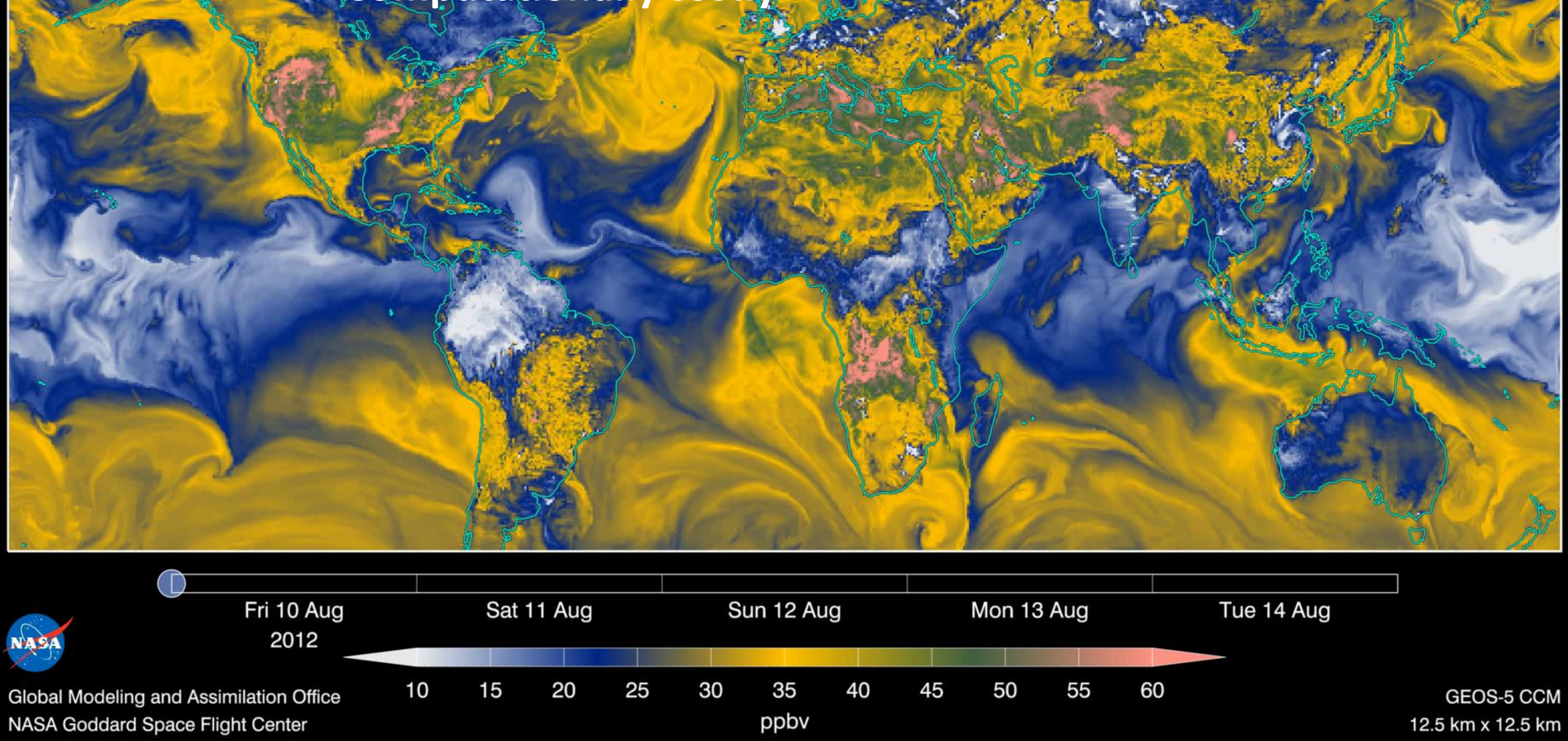
Resolution
&
Parameterization



Global High-Resolution Simulation of Surface Ozone

Surface ozone simulation at 12.5 km x 12.5 km

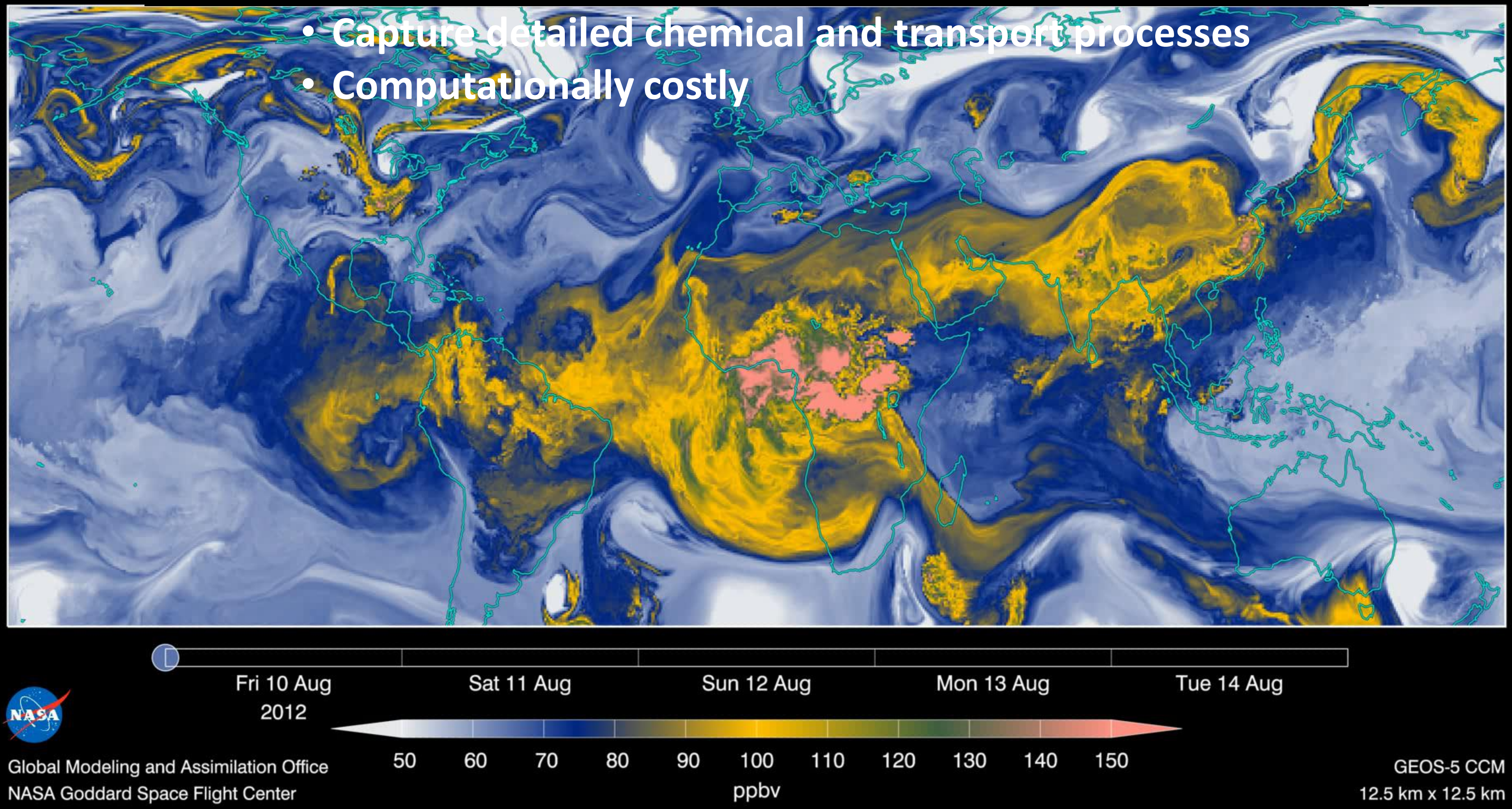
- Capture detailed chemical and transport processes
- Computationally costly



Global High-Resolution Simulation of Tropospheric CO

Upper Tropospheric (250 hPa) CO simulation at 12.5 km x 12.5 km

- Capture detailed chemical and transport processes
- Computationally costly



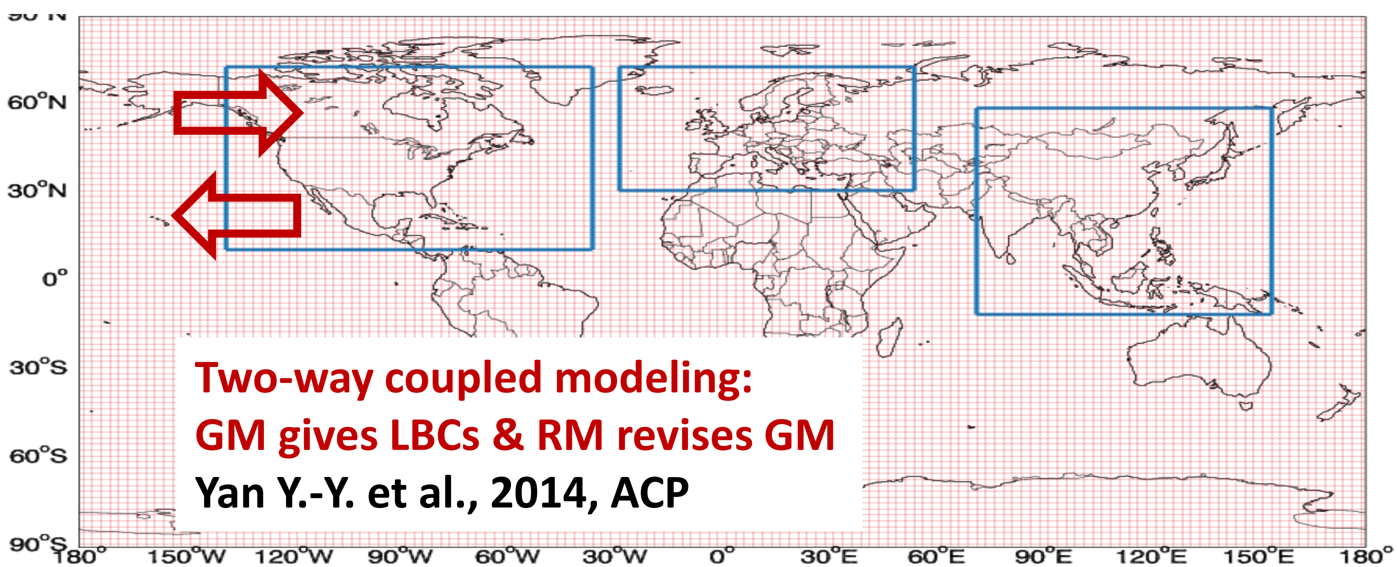
Global versus Regional Models

Global Models

- Covers the globe
  - Good for global studies
  - No LBCs are necessary
- Low-resolution (≥ 100 km)
  - Sim. or no small-scale processes
- Example: GEOS-Chem, AM3

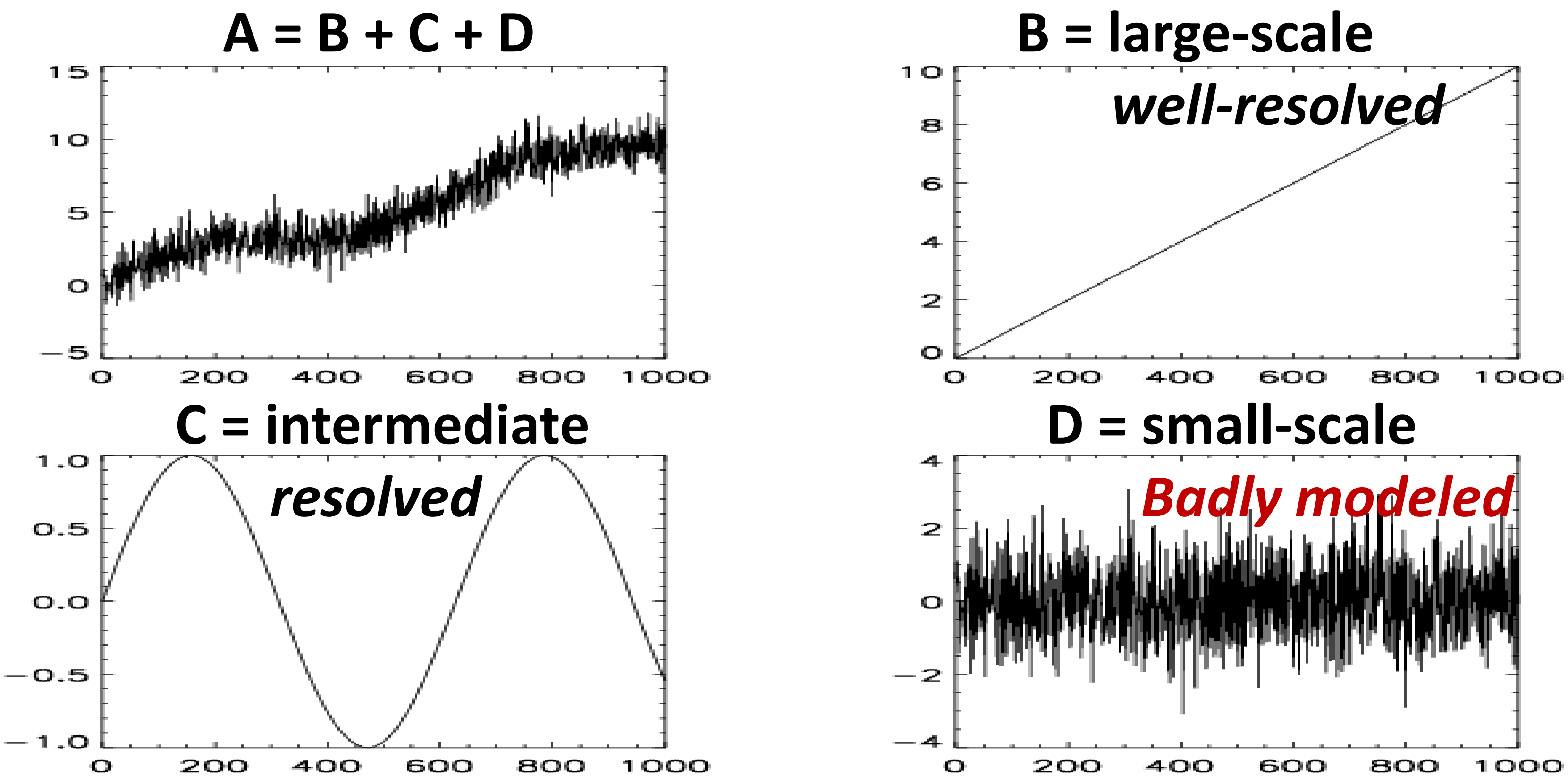
Regional Models

- Covers a region
  - Need LBCs from global models via nesting
- High-resolution (~ 10 km)
  - Resolve small-scale processes
- Example: CMAQ, WRF-Chem



Models Often Miss or Misrepresent Small-scale Processes

- **Atmospheric chemical & physical processes have multiple scales**
- **Models often misrepresent scales smaller than 2 x grid size**
  - **Critical, because small-scale processes affect large-scale ones**
  - **Affect both distribution and total mass of trace species**



A Simple Case

How Small Scales Affect Large Scales

$X_0 = 1$

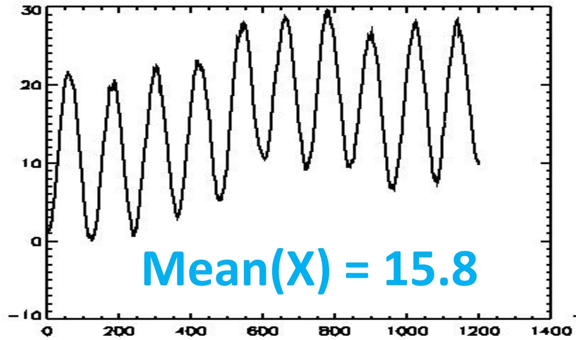
$X_{t+1} = X_t + 0.5*\sin(t/P) + Xr$

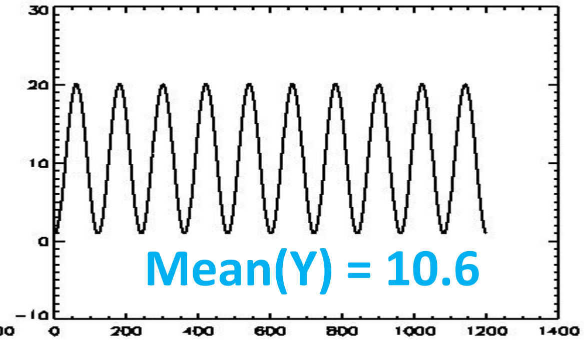
$Xr = N(0,0.2)$; $P = 120$

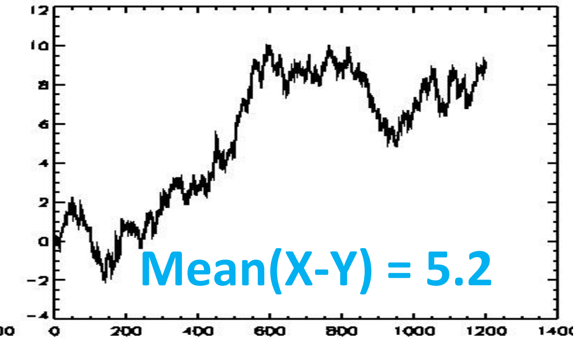
$Y_0 = 1$

$Y_{t+1} = Y_t + 0.5*\sin(t/P)$

$X_t - Y_t$

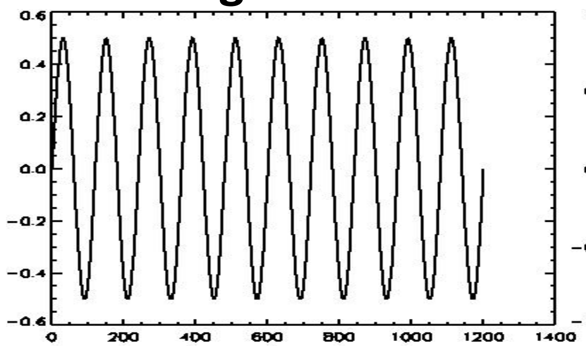






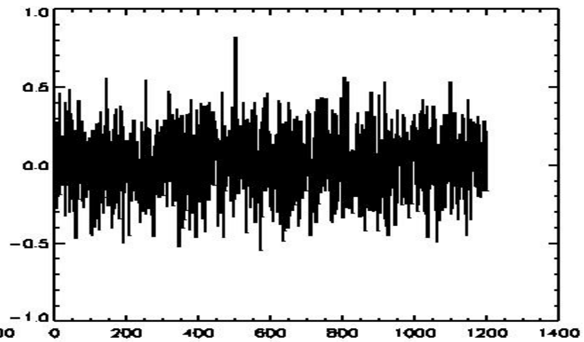
0.5*sin(t/P)

larger scale



Xr = N(0,0.2)

smaller scale



Limited by Resolution
Models Often Miss or Misrepresent Small-scale Processes

- **Un-even terrain**
- **Small-scale meteorology**
- **Variability in land use, vegetation, etc.**
- **Small-scale horizontal & vertical transport**
- **Small-scale variability in chemistry & emissions**

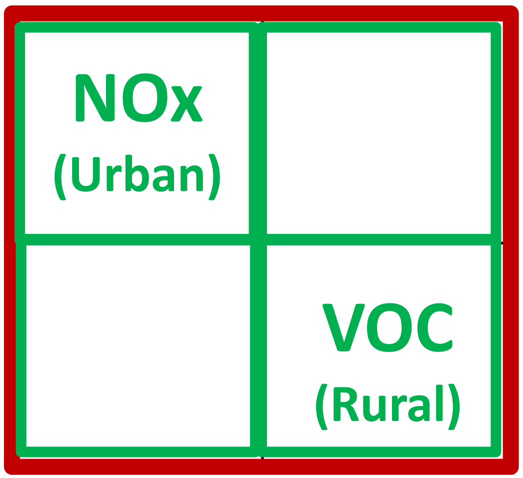
model **reality**

$$\bar{A} \cdot \bar{B} - \overline{A \cdot B} = -\overline{A' \cdot B'} = -r_{AB} \cdot \sigma_A \cdot \sigma_B$$

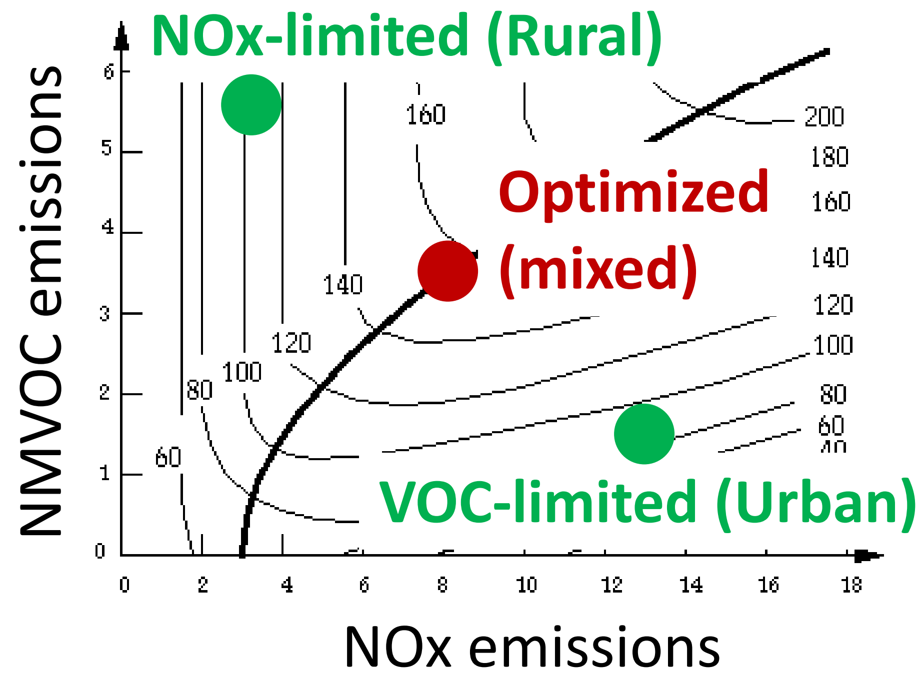
- $r_{AB} < 0$: **Model has an overestimation**
- $r_{AB} > 0$: **Model has an underestimation**

Coarse Models Tend to Overestimate Ozone Production

1 coarse gridcell = 4 fine gridcells



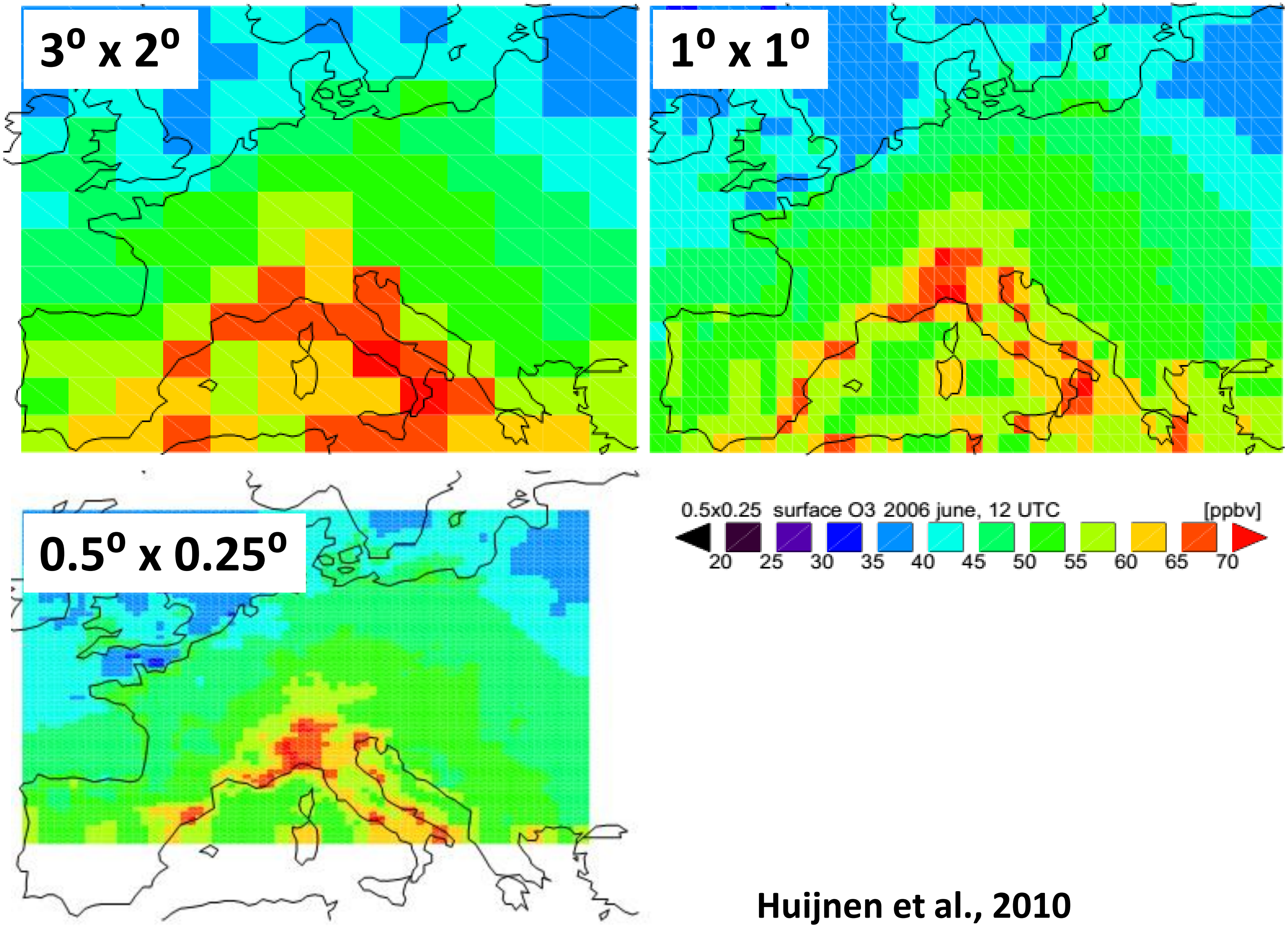
O_3 Production Rate



Sillman et al., 1990

Finer Resolution Leads to Less Ozone

Surface Ozone over Europe in June 2006 at 12:00 UTC

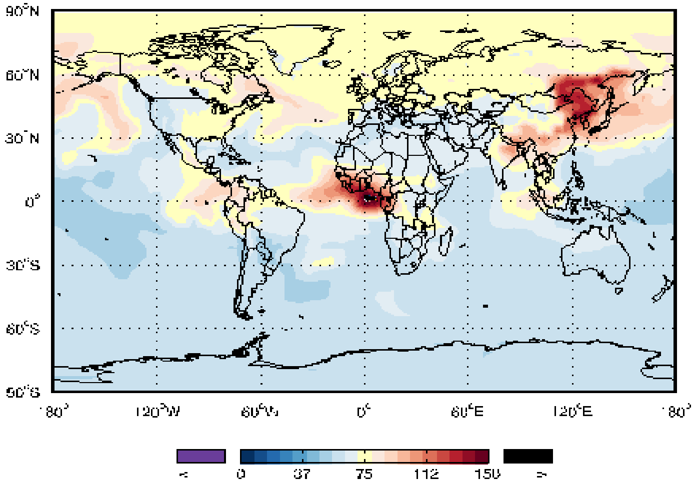


Huijnen et al., 2010

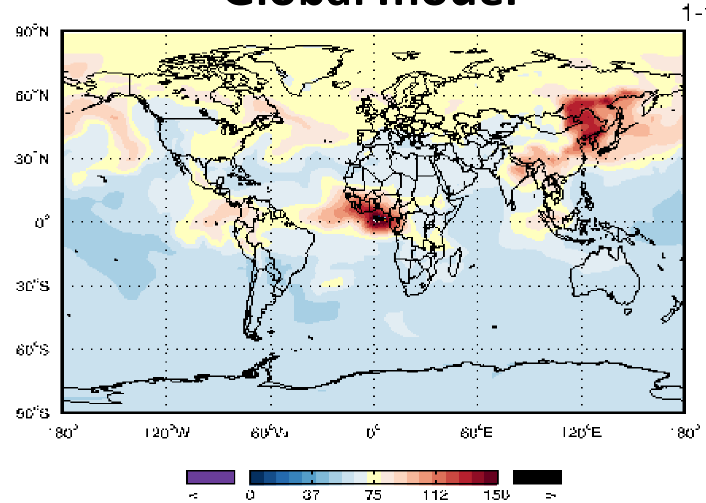
2-way Coupling Better Simulates Tropospheric CO

CO at 6.5 km altitude.   2008/07/01 – 2008/08/15

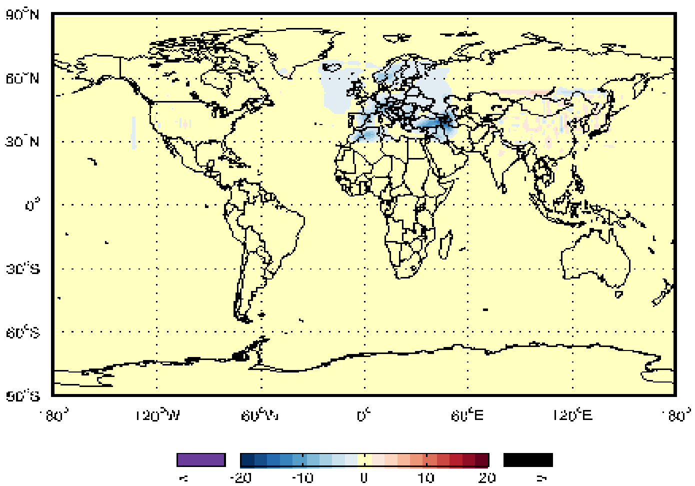
Two-way model



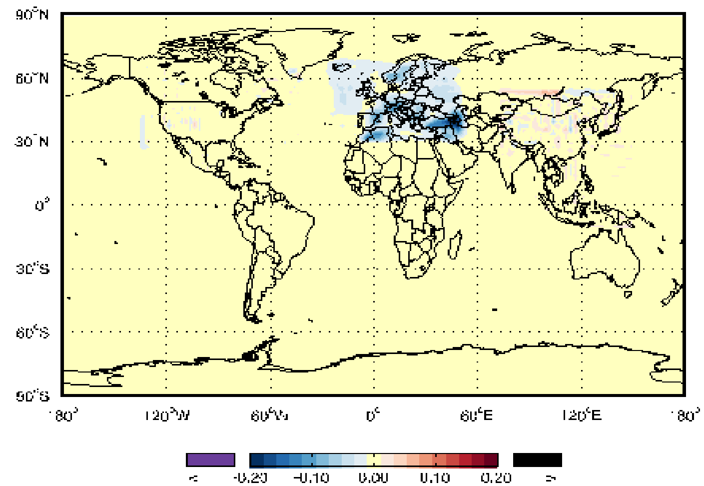
Global model



Two-way minus Global

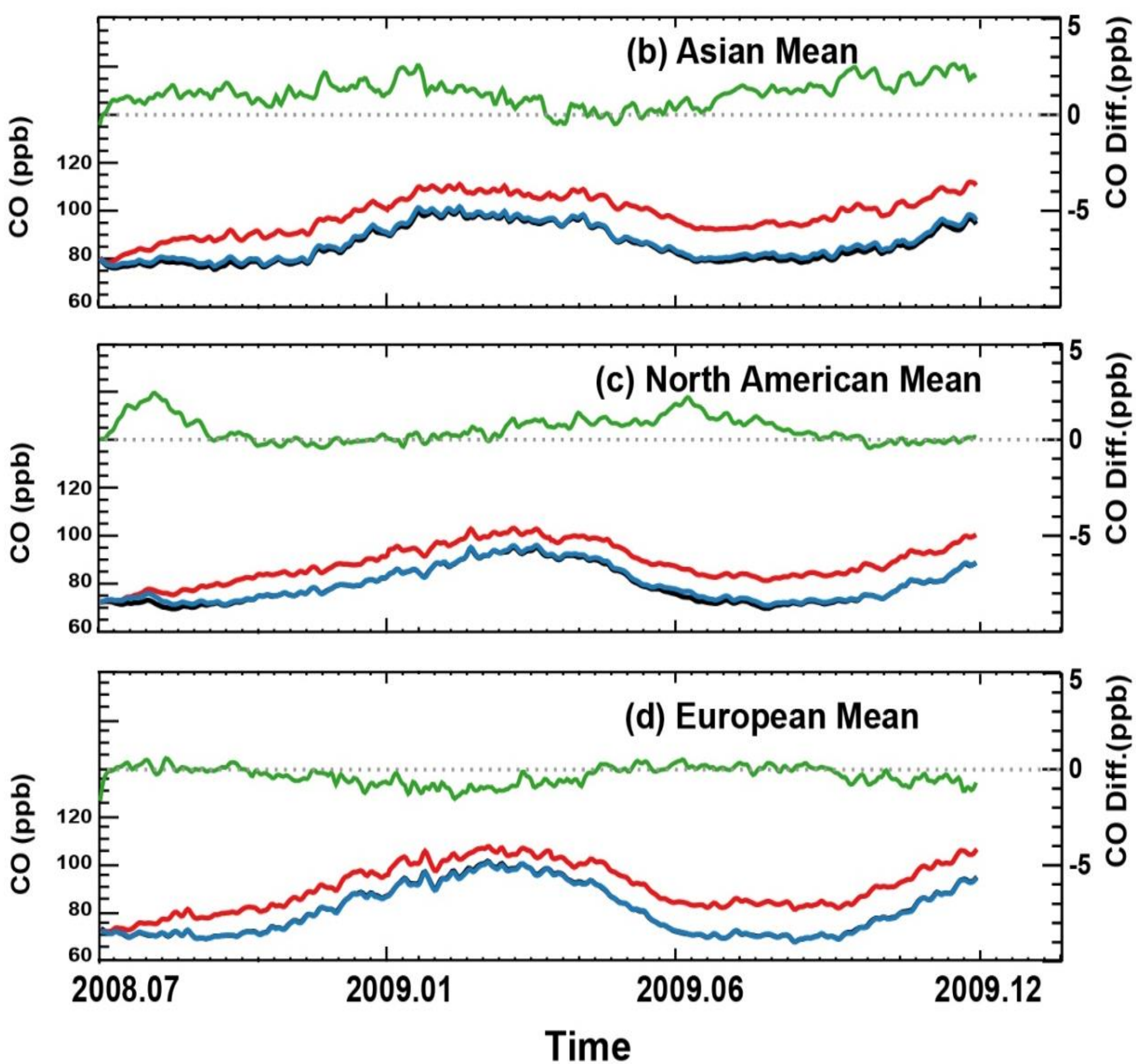


Relative difference



Yan Y.-Y. et al., ACP, 2014, 2016

2-way Coupling Better Simulates Tropospheric CO



Global model

Two-way coupled model

One-way nested model

One-way nested model minus Global model

2-way Coupling Improves Tropospheric Simulation by Reducing Modeled Oxidative Capability

	Global Model	Two-way Model	'Observation'
OH (10^5 cm^{-3})	11.8	11.2 (– 5% *)	10.4 – 10.9
O_3 (DU)	34.5	31.5 (– 8.7%)	31.1 ± 3 (OMI/MLS)
O_3 (Tg)	384	348 (– 9.5% #)	
NOx (TgN)	0.169	0.176 (+ 4.1%)	
CO (Tg)	359	398 (+ 10.8% &)	
MCF lifetime (yr)	5.58	5.87 (+ 5.2%)	6.0 – 6.3
CH_4 lifetime (yr)	9.63	10.12 (+ 5.1%)	10.2 – 11.2
NMVOC (TgC)	10.1	10.2	

* Greater than its interannual variability (2.3%)

\# Greater than the change from 2000 to 2100 under RCP6.0

& Equivalent to a 25% increase in global CO emissions

Yan Y.-Y. et al., ACP, 2014, 2016

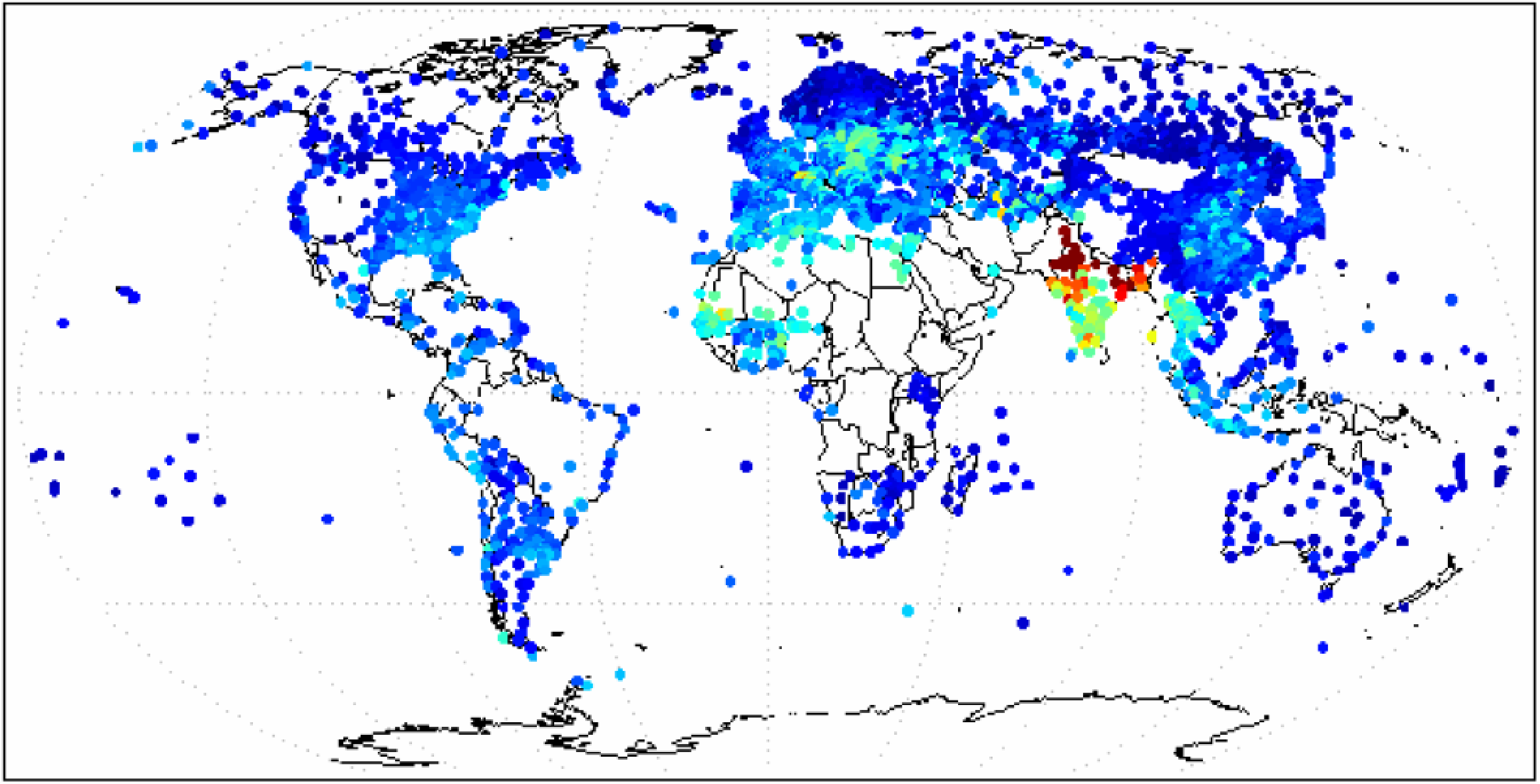
Assimilation

- Data assimilation combines the strengths of observations and numerical models to reproduce the evolution of the atmosphere, where observations provide critical information to adjust calculations of models.
  - ERA-40, EAC4 (欧洲中心)
  - NCEP/NCAR, NCEP/DOE R-2
  - GEOS, MERRA, MERRA-2
  - JAXA (日本)
  - CRA-Land (中国气象局)
  - OVALS, PODEn4DVar (中科院大气所)
  - AI-based or AI-aided?
- Extremely useful in meteorology, climate, and chemistry, etc.

Quiz

1. How to design surface measurement network considering the costs and benefits?
2. Is it necessary to conduct targeted measurements for specific (types of) events, and what would be the scientific challenges?
3. Should we retrieve many species from satellite remote sensing using a single algorithm?
4. For a horizontal resolution of 200km, what is the smallest scale a model can resolve?
5. How to balance the benefits and trade-offs in accounting for the interactions between different model components (e.g., atmosphere, ocean, chemistry, etc.)?
6. How can AI methods be used in combination with physical models? What would be challenges and benefits? Is *AI for Science* the future direction?

Surface Meteorological Measurement Stations



DOAS（差分吸收）：多种气体测量

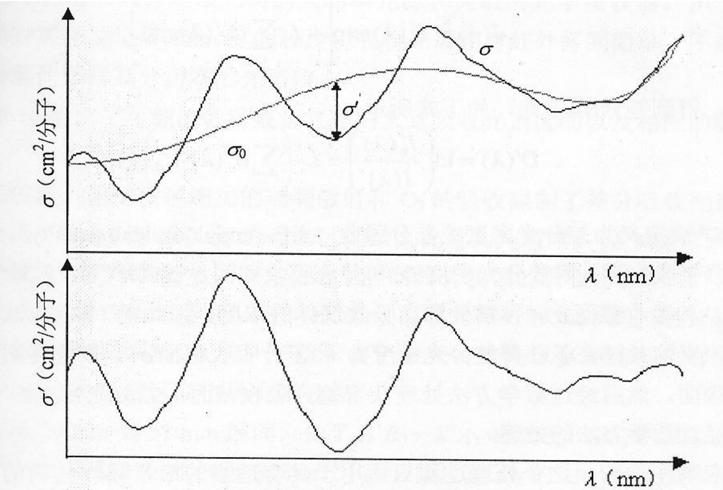


图 2－4 吸收截面与差分吸收截面

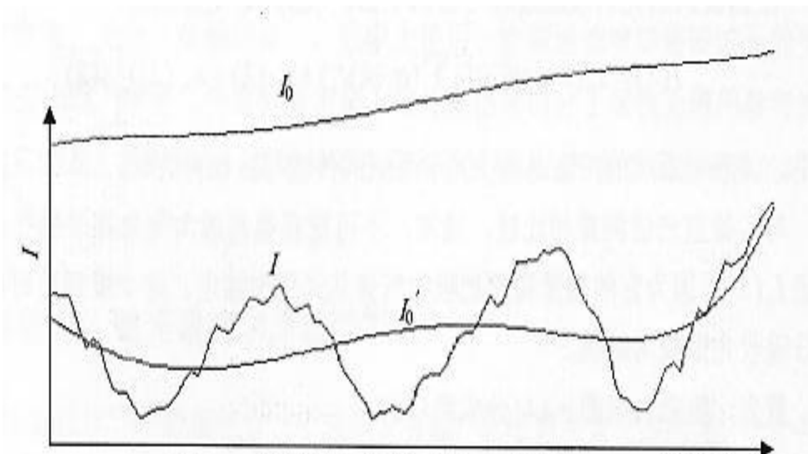


图 2－5 差分吸收光谱技术原理示意图

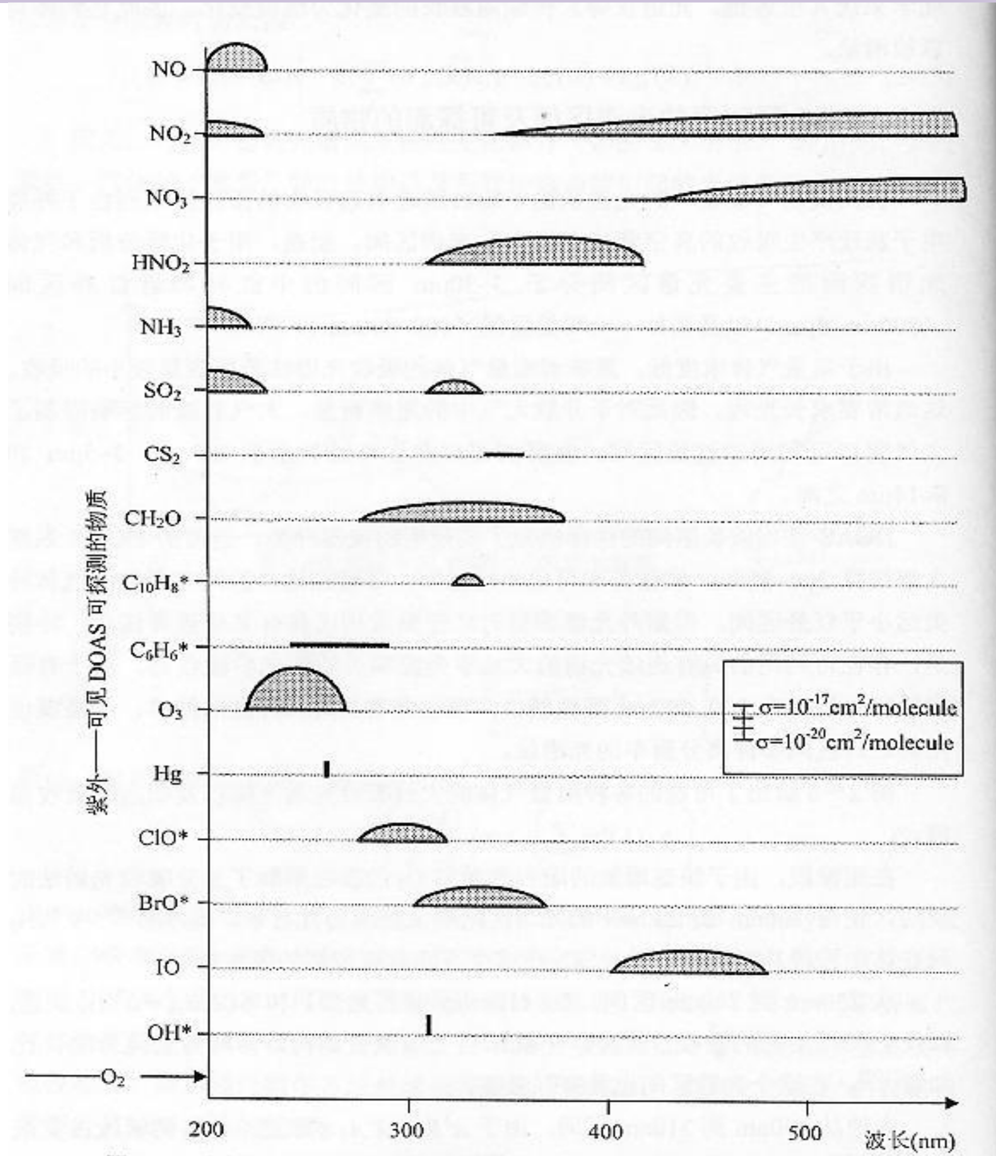


图 2－6 大气痕量气体探测可使用的紫外——可见波长区间一览表。纵坐标：分子吸收截面（10^{-20}～10^{-17} $cm^2/molecule$，见插图）。分子在大气压力下表现出强转动结构用星号（*）表示。