Course outline, objectives, workload, projects, expectations

Introductions

Remote Sensing Overview

Elements of a remote sensing observing system

1. platform (satellite, surface, etc)
2. experimental design - forward problem
3. retrieval components - inversion/estimation

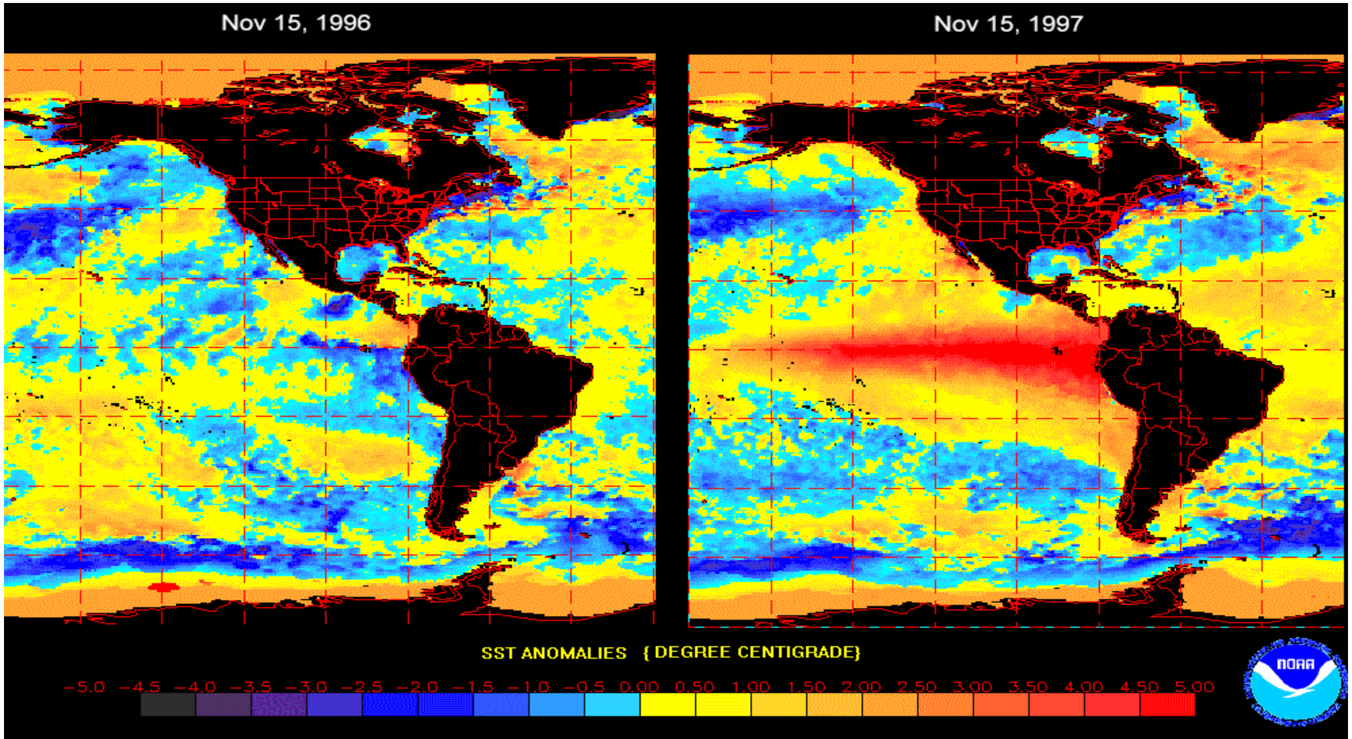
http://reef.atmos.colostate.edu/~odell/at652/

Why remote sensing?

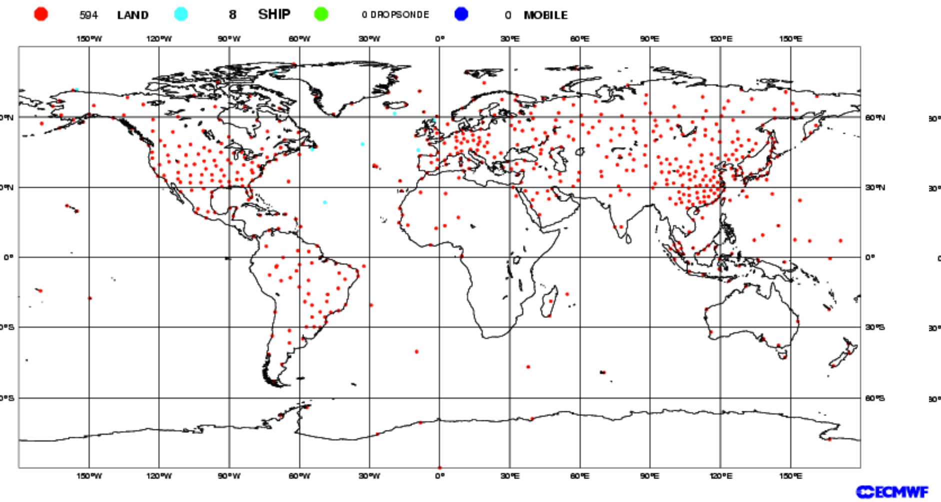
Much of the atmosphere is inaccessible to routine in situ measurements

→ Only way to provide large enough sample to provide a large-scale view of the Earth system is from space

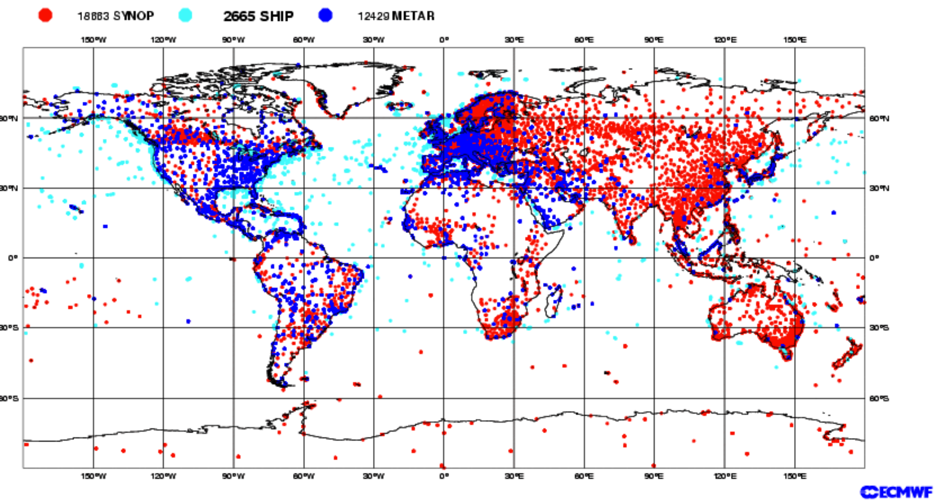
AVHRR
SST anomalies
Nov 96,97



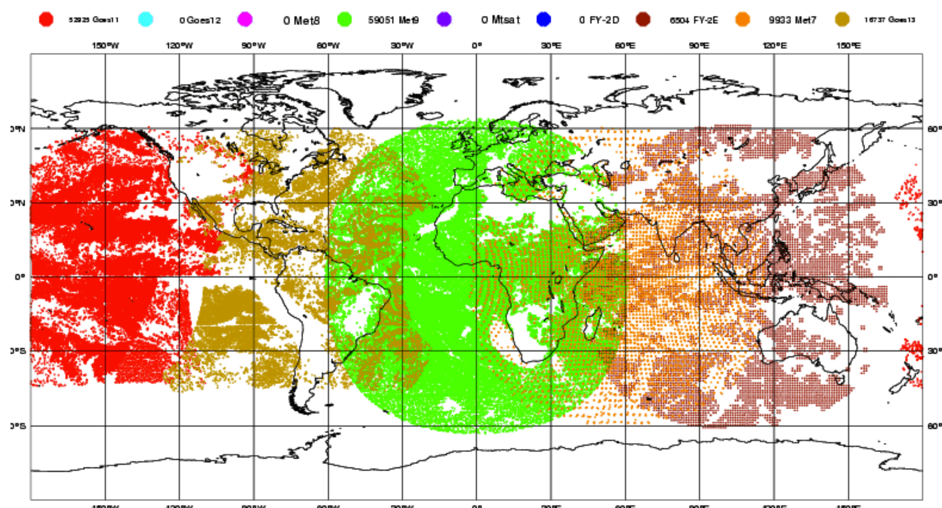
ECMWF Data Coverage (All obs DA) - TEMP
11/SEP/2010; 12 UTC
Total number of obs = 602



ECMWF Data Coverage (All obs DA) - SYNOP/SHIP
11/SEP/2010; 12 UTC
Total number of obs = 33757



ECMWF Data Coverage (All obs DA) - AMV IR
11/SEP/2010; 12 UTC
Total number of obs = 145150



Related Classes

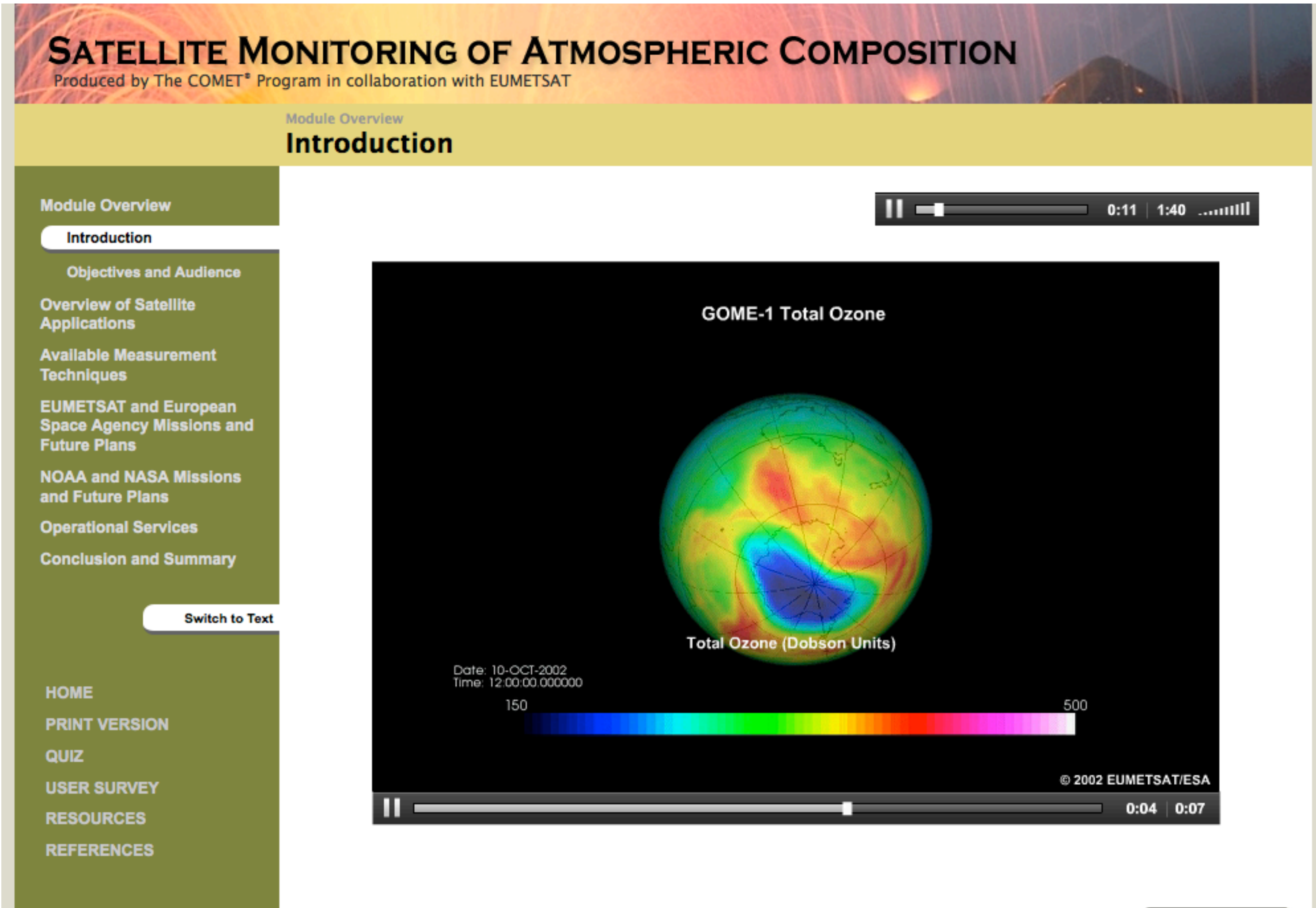
- **AT721 – Advanced Techniques in Radiative Transfer**
  Spring 2014, O'Dell
  Will focus on RT techniques in various parts of the spectrum, with application primarily to remote sensing but also energy budget. Bulk of the class is a single large application-based project of the student's choice.

- **AT752 – Inverse methods in the atmoospheric sciences (Fall 2014, O'Dell)**
  Fall 2014, O'Dell
  Provides an introduction to inverse modeling, with application to modern retrieval theory, flux inversions, and data assimilation.

- **AT737 – Satellite Observations**
  Spring 2015?, VonderHaar
  Satellite measurements; basic orbits and observing systems; applications of remote sensing and imaging to investigations of atmospheric processes.

UCAR Comet Lectures

We will occasionally draw on lecture material from the UCAR Comet "MetEd" series, either in place of class or out of class.



What is remote sensing?

"The observation of radiation* that interacted with a remote object or collection of objects"

- Does not mean satellites specifically! (surface, ballon-borne, etc can also count)
- Usually it is the *amount* of radiation that matters, but sometimes *timing* is also used (e.g. radar & lidar)

* Some don't use radiation (e.g. GRACE uses gravity field)

Properties of the earth system that are subject to remote sensing

- ***Temperature***: land surface, ocean surface, atmospheric profile (troposphere & stratosphere)
- ***Gases***: water vapor, ozone, CO_2, methane, oxygen, NO_2, CO, BrO, D_2O, ... (integrated & profile info)
- ***Clouds***: Optical depth, cloud profile, particle sizes, ice vs. liquid (phase) , cloud fraction
- ***Aerosols***: Types (sulfates, sea salt, dust, smoke, organics, black carbon) , optical depth, height
- ***Surface features*:** surface height, ocean winds, vegetation properties, ocean color, sea ice, snow cover.

Applications?

Applications?

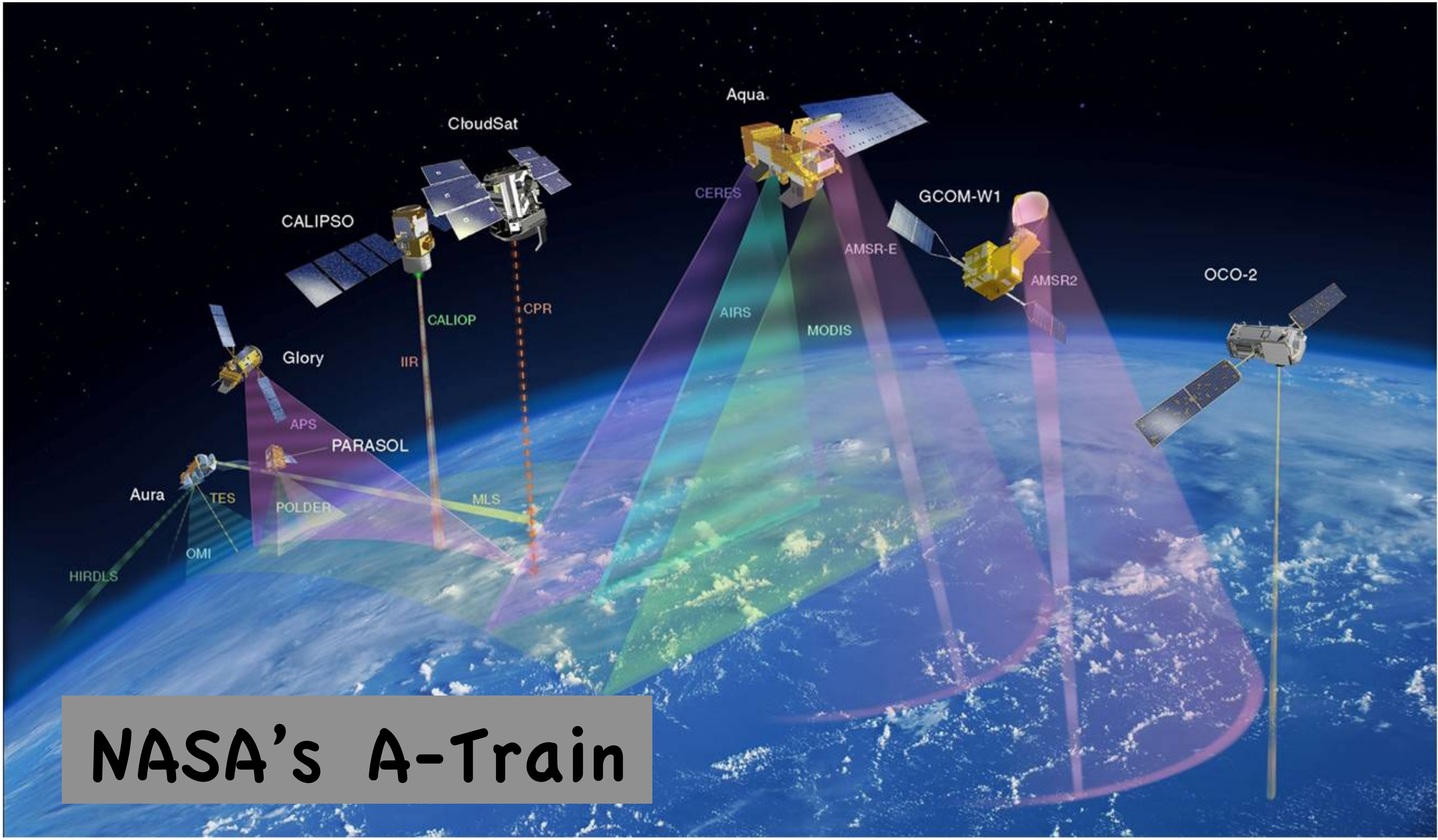
- ***Weather prediction (data assimilation)***
- ***Climate state observations (e.g. clouds, sea ice loss)***
- ***Climate Model validation/comparisons***
- ***Air quality state / forecasts***
- ***Solar power forecasts***
- ***Carbon cycle***
- ***Hydrology/water cycle***
- ***Biogeochemical modeling***

Example: Data assimilation for NWP

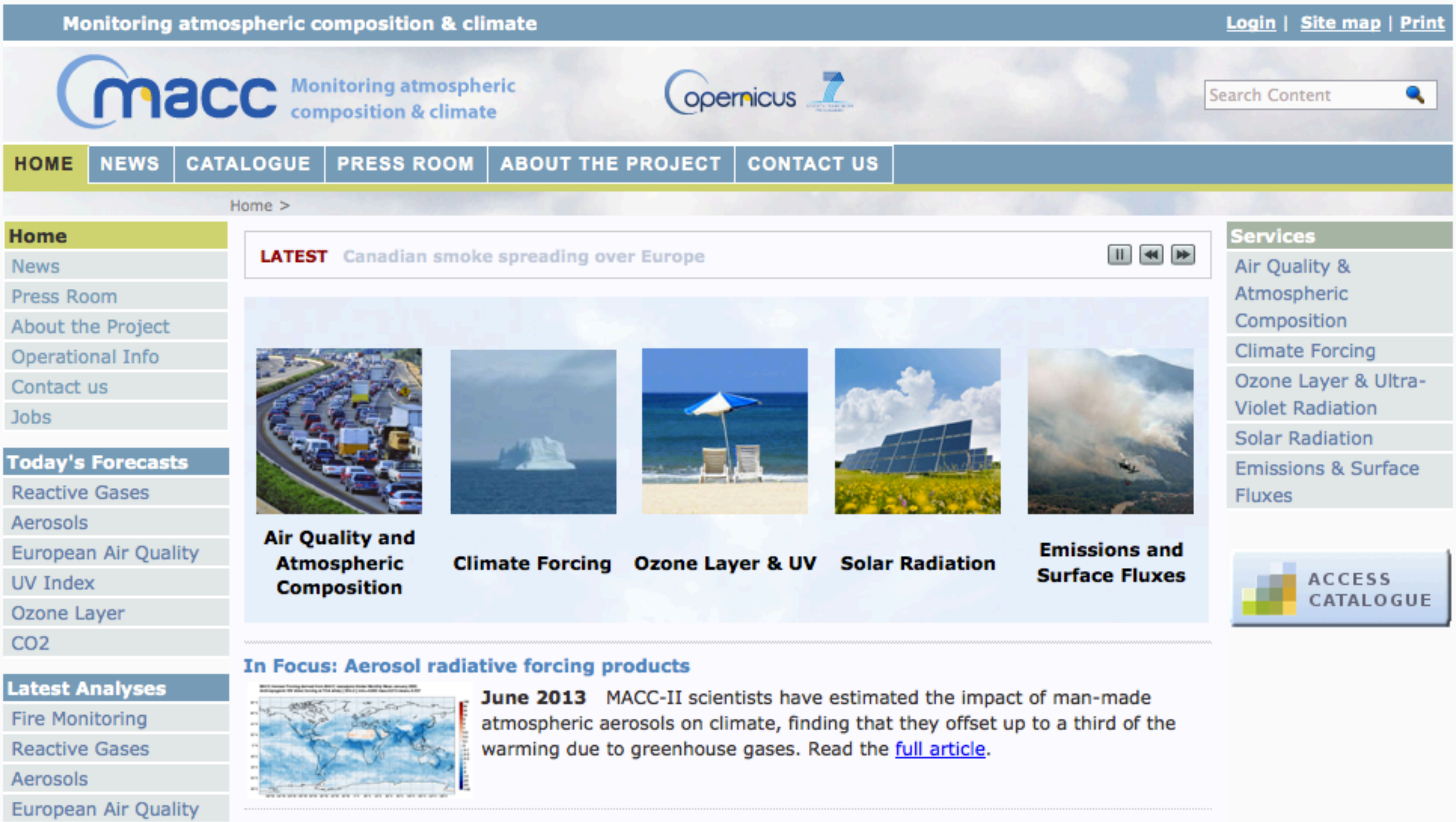
ECMWF assimilated data breakdown

Terrestrial based	
Surface synoptic and ships	31,497
Data buoys, drifting and moored	8,694
Aircraft	52,557
Radio sonde	645
Balloon winds	1,452
Total terrestrial	94,845
Space based	
Cloud motion winds	262,132
Surface winds - Scatterometer	505,140
Microwave - temperature and water vapour	799,644
Infra-red clear sky temperature and water vapour	611,839
Total space based	1,730,253
Total all data Note	1,825,098

“Golden Age of Remote Sensing”



Example: Monitoring of Atmospheric Composition & Climate (MACC) at ECMWF

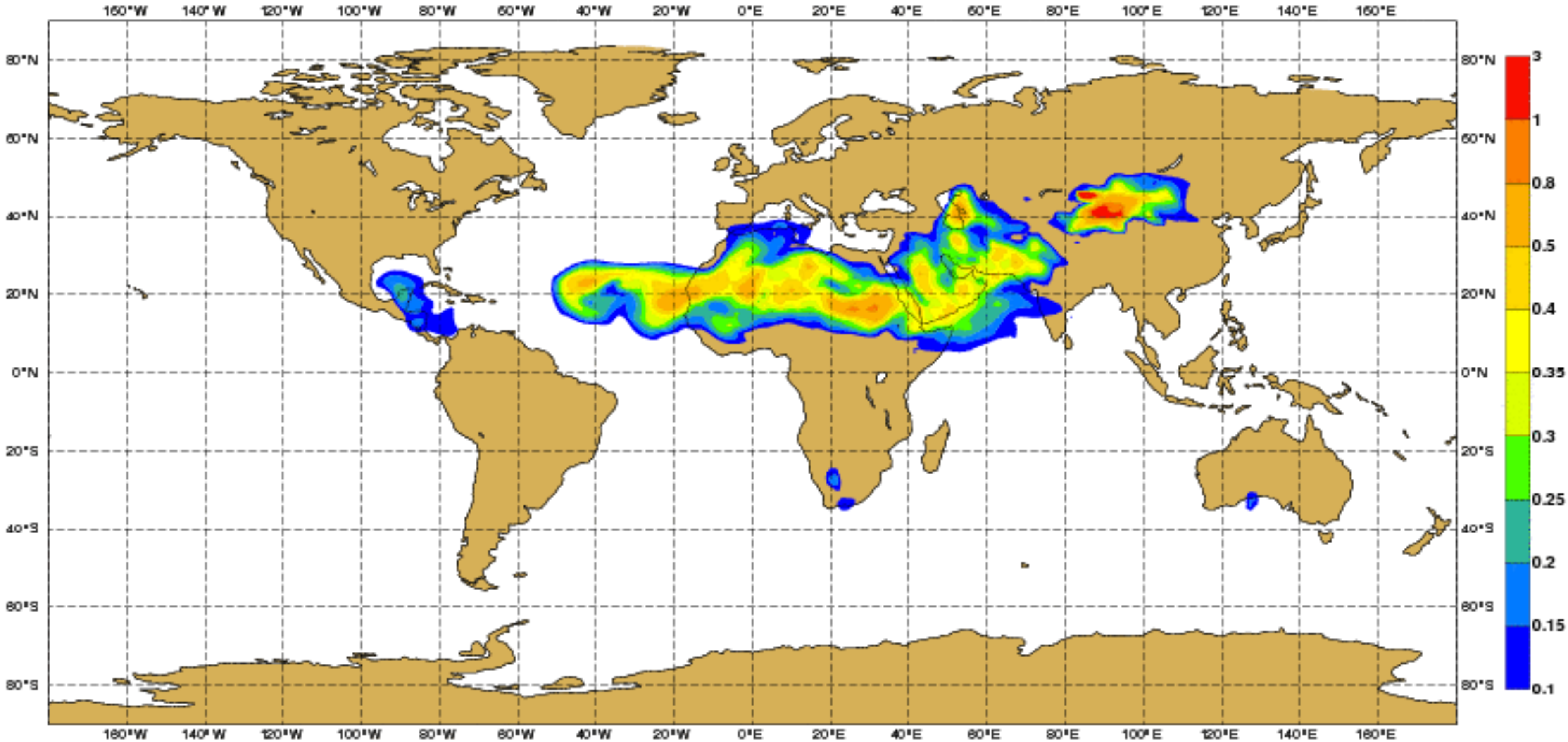


Forecast of Aerosols Optical Depth

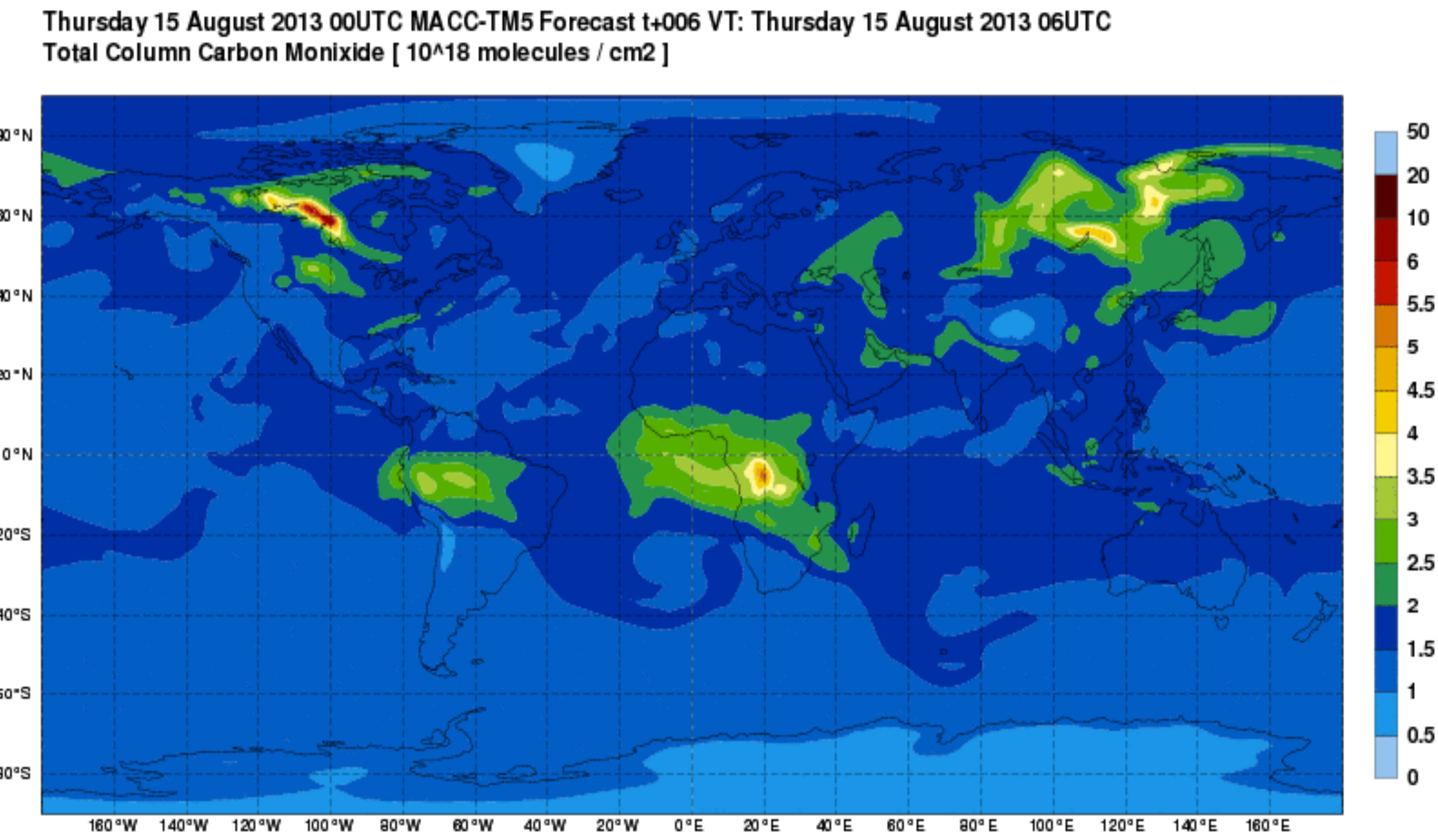
Step (-> valid time) | Forecast base time

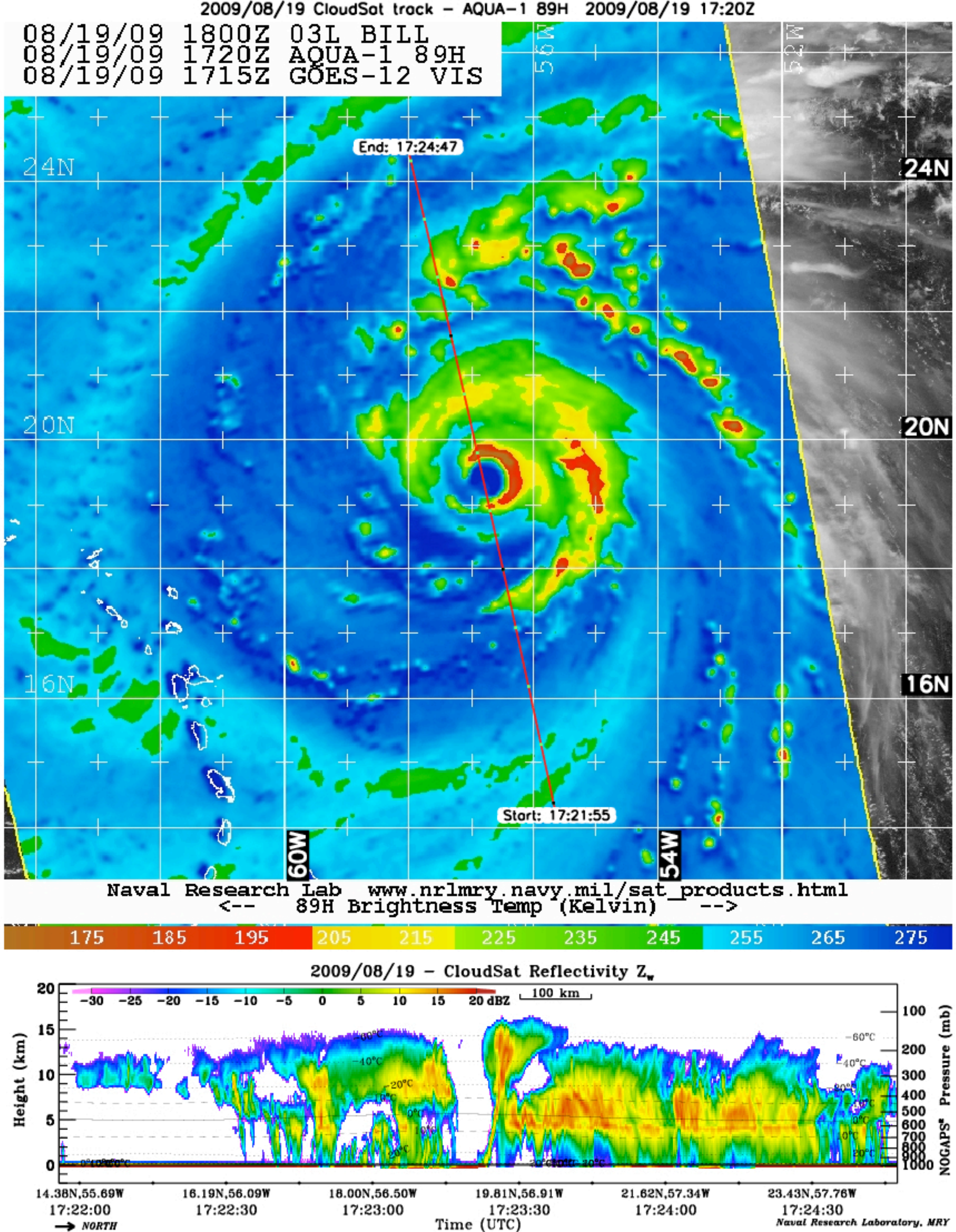
03 (Mon 26 Aug 2013 03UTC) | Mon 26 Aug 2013 00UTC

Monday 26 August 2013 00UTC MACC Forecast t+003 VT: Monday 26 August 2013 03UTC
Dust Aerosols Optical Depth at 550 nm



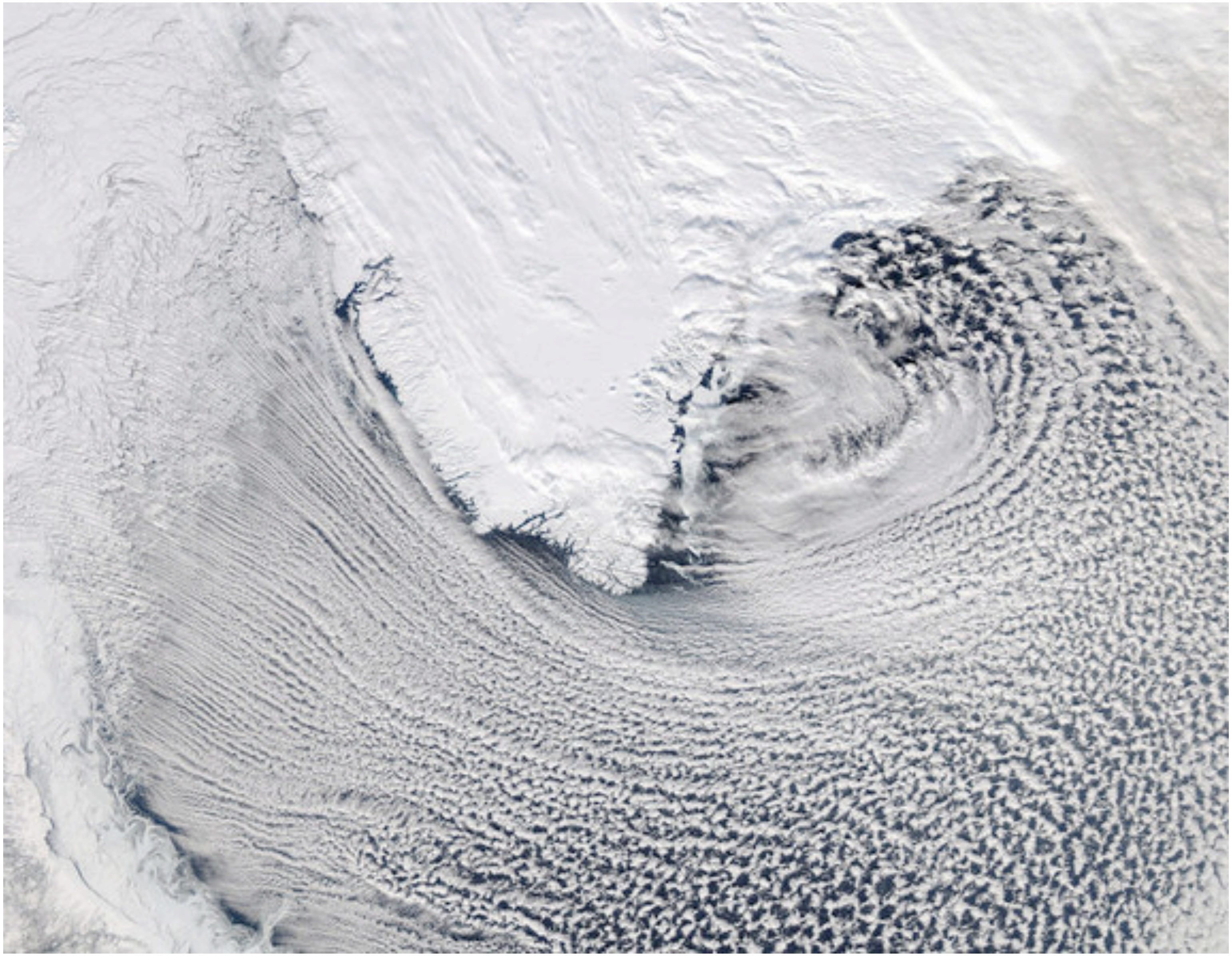
Carbon Monoxide Forecast





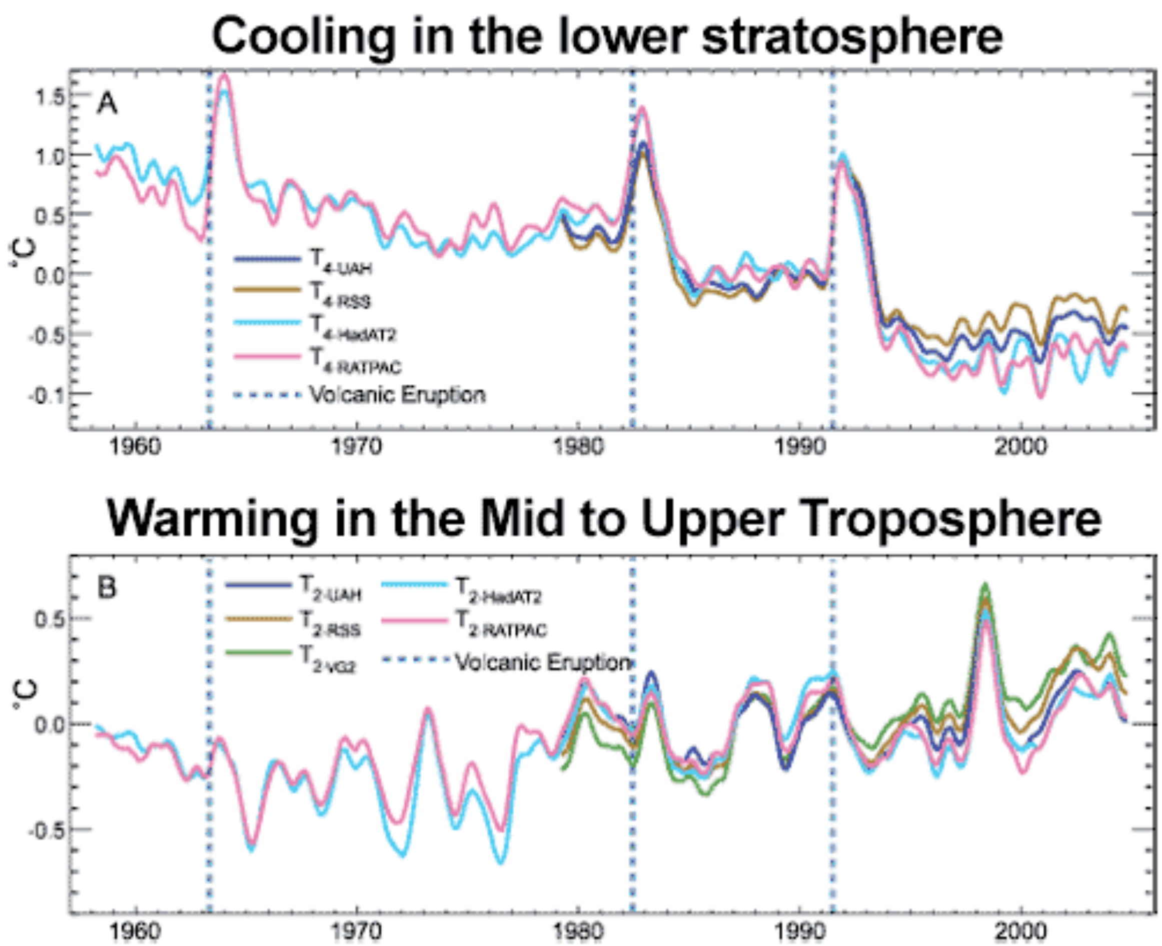
2009/08/19 CloudSat track - AQUA-1 89H 2009/08/19 17:20Z
08/19/09 1800Z 03L BILL
08/19/09 1720Z AQUA-1 89H
08/19/09 1715Z GOES-12 VIS
End: 17:24:47
Start: 17:21:55
24N
20N
16N
60W
54W
56W
52W
Naval Research Lab www.nrlmry.navy.mil/sat_products.html
<-- 89H Brightness Temp (Kelvin) -->
175 185 195 205 215 225 235 245 255 265 275
2009/08/19 - CloudSat Reflectivity Z_w
-30 -25 -20 -15 -10 -5 0 5 10 15 20 dBZ
100 km
Height (km)
NOGAPS Pressure (mb)
14.38N,55.69W 17:22:00
16.19N,56.09W 17:22:30
18.00N,56.50W 17:23:00
19.81N,56.91W 17:23:30
21.62N,57.34W 17:24:00
23.43N,57.76W 17:24:30
Time (UTC)
→ NORTH
Naval Research Laboratory, MRY

“Cloud Streets” over near Greenland from MODIS

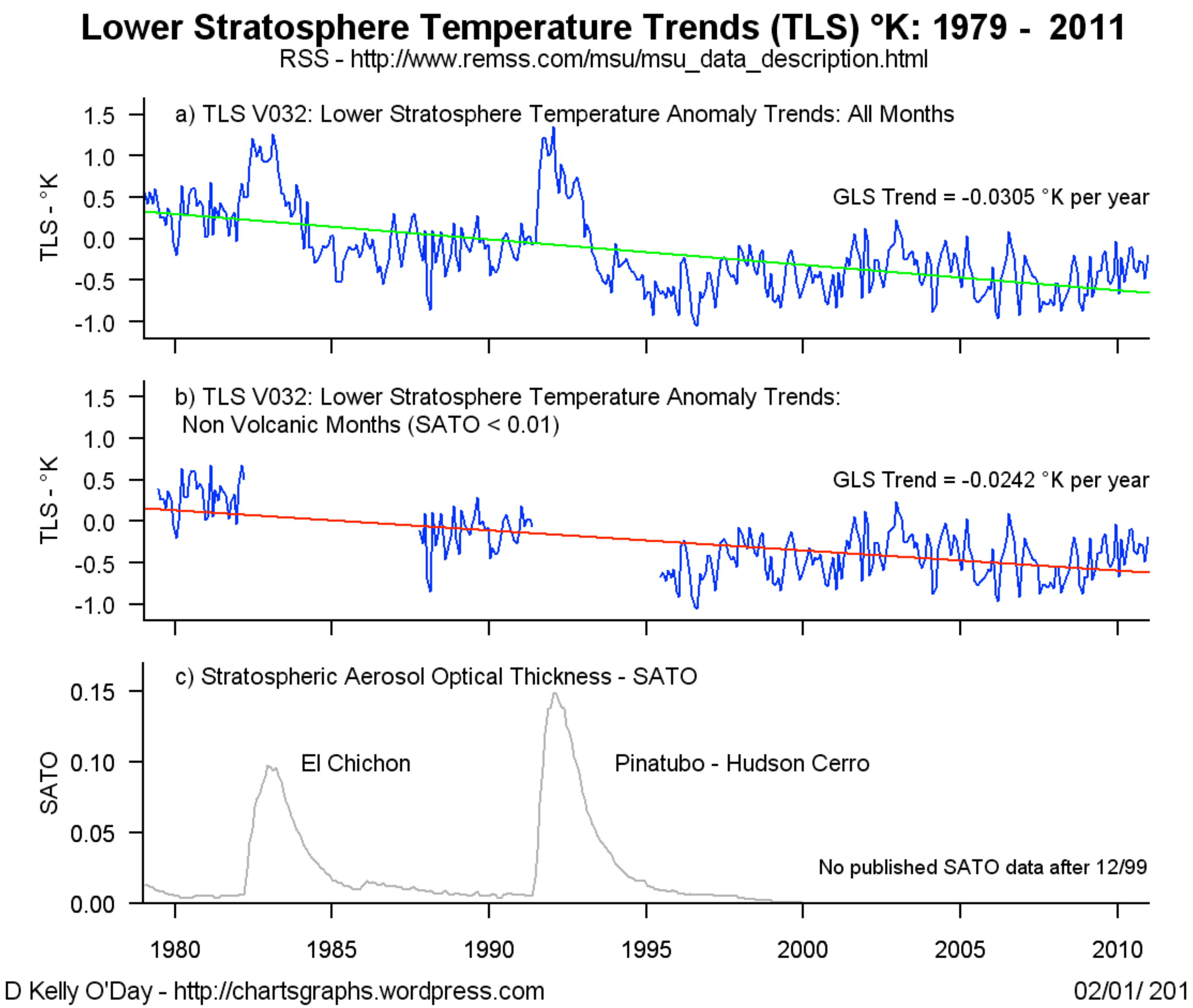


Monitoring Climate Change:

Stratospheric cooling & tropospheric warming with microwave O_2



A puzzle?


Lower Stratosphere Temperature Trends (TLS) °K: 1979 - 2011
RSS - http://www.remss.com/msu/msu_data_description.html
a) TLS V032: Lower Stratosphere Temperature Anomaly Trends: All Months
GLS Trend = -0.0305 °K per year
TLS - °K
1.5
1.0
0.5
0.0
-0.5
-1.0
b) TLS V032: Lower Stratosphere Temperature Anomaly Trends:
Non Volcanic Months (SATO < 0.01)
GLS Trend = -0.0242 °K per year
c) Stratospheric Aerosol Optical Thickness - SATO
SATO
0.15
0.10
0.05
0.00
El Chichon
Pinatubo - Hudson Cerro
No published SATO data after 12/99
1980
1985
1990
1995
2000
2005
2010
D Kelly O'Day - http://chartsgraphs.wordpress.com
02/01/ 2011

There are multiple aspects to remote sensing:

- ***Platform*** (aircraft, satellite, balloon, ground-based) – this dictates the time/space sampling characteristics & errors

- ***Source of EM Radiation***

- ***Radiation interaction mechanism***

- ***Forward and inverse models*** - this defines the physical and system errors (user in principle has more control over this facet of the system)

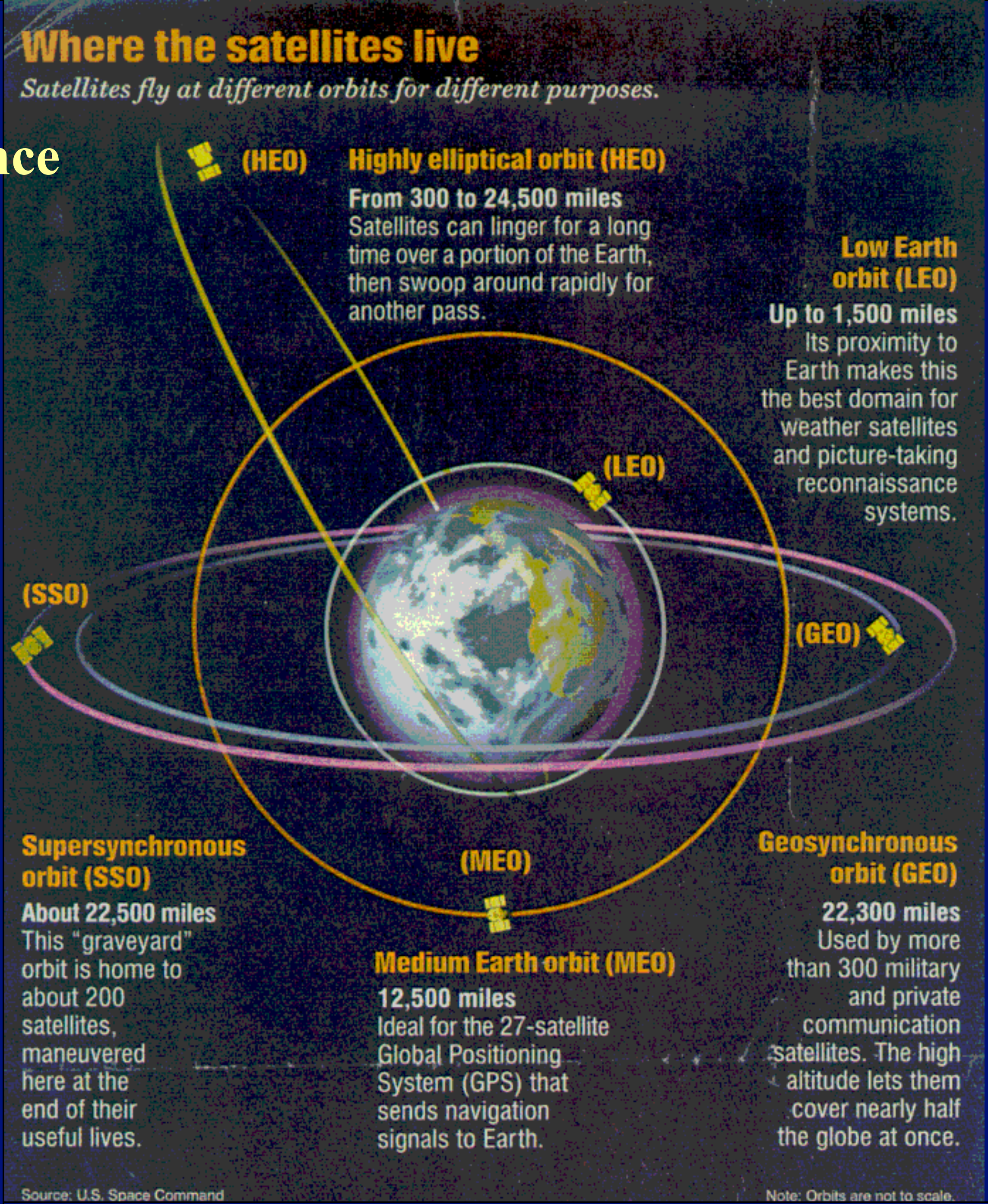
Observing Platforms

- Ground-based: Radiometers, sunphotometers, lidar, radar, doppler wind arrays. Local but good time coverage.

- Aircraft: local-to-regional spatial, limited time coverage (measurement campaigns)

- Satellite (orbit determines spatial & temporal coverage)

Substantial influence on sampling - e.g. synoptic like versus asynoptic



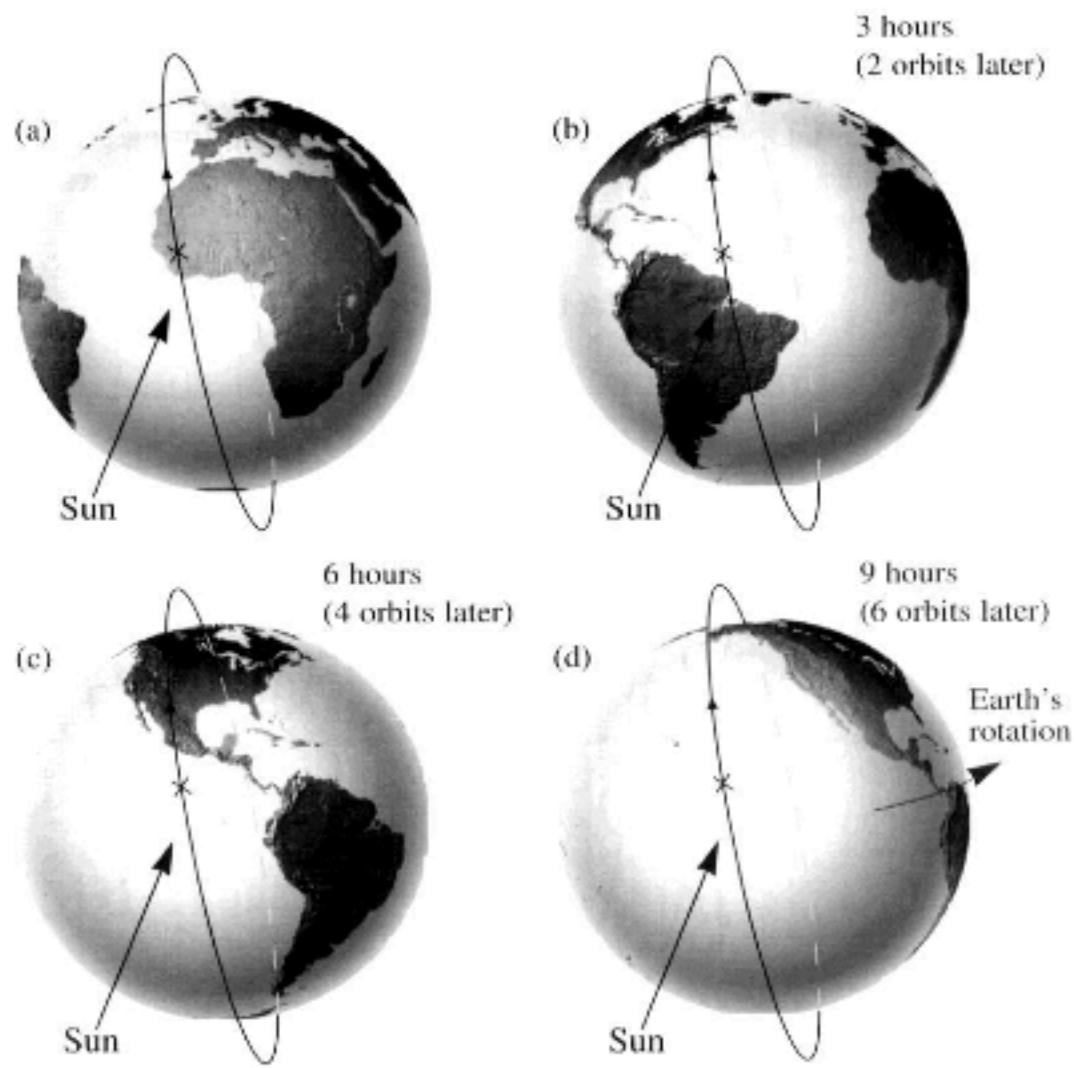


Figure 1.7 Oblique orbiting (near-polar orbiting) satellites: Sun-synchronous orbits (each 3 hours)

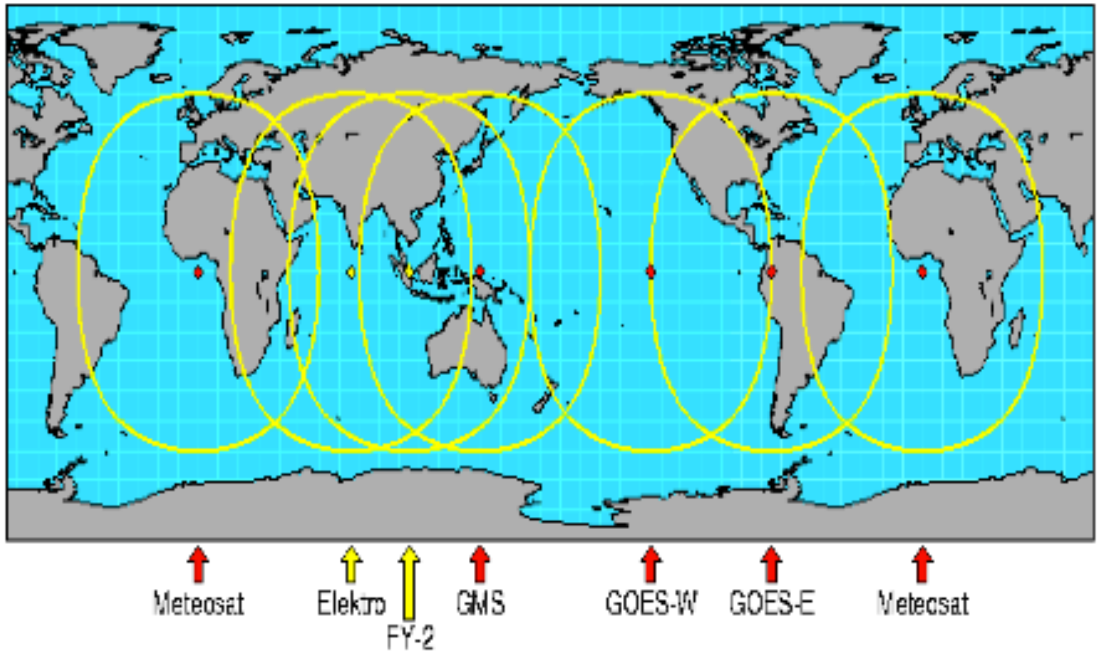


Figure 1.8 Example of geostationary satellite coverage.

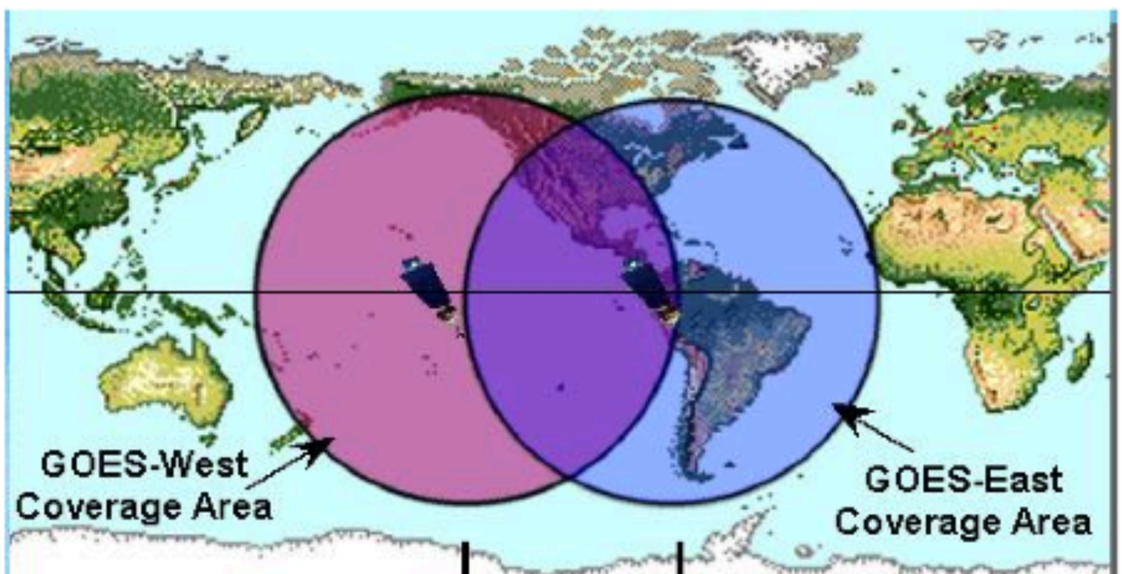
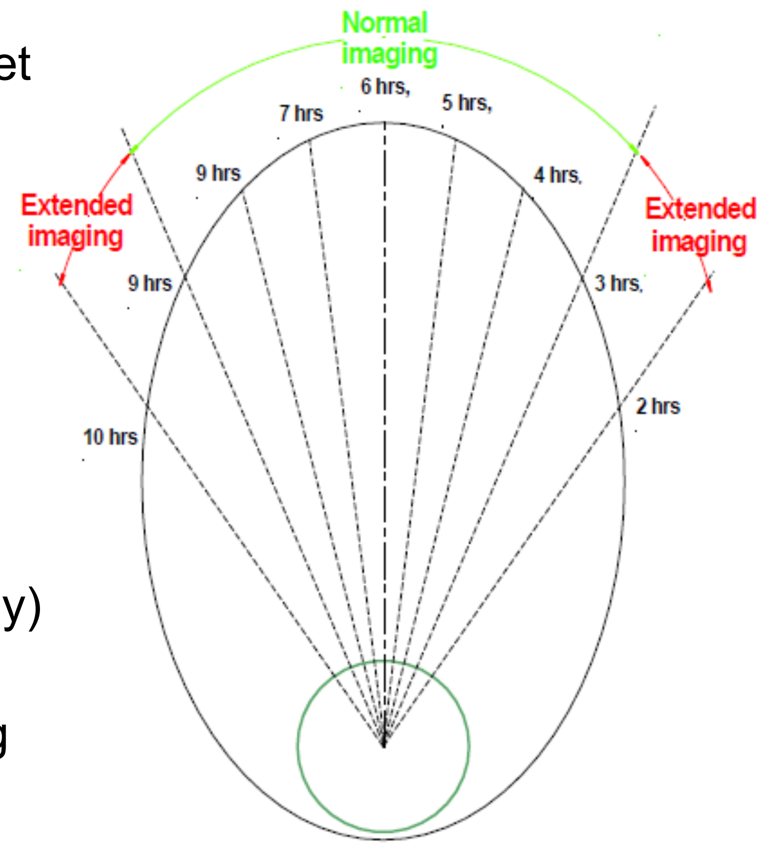


Figure 1.9 U.S. geostationary satellites: GOES

HEO Example: PCW-PHEMOS from Environment Canada

- Polar Communications and Weather (**PCW**) mission (2017): 2 operational met satellites in Highly Elliptical Orbit (HEO) for quasi-geostationary observations along with a communications package
- Polar Highly Elliptical Molniya Orbit Science (**PHEMOS**) suite of imaging spectrometers
- Weather Climate and Air quality (**WCA**) option is now entering phase-A study (see talk by *J.C. McConnell* on Thursday)
- Quasi-continuous coverage of GHGs over the high latitudes (~40-90°N) using TIR+NIR would help constrain GHG sources/sinks at fine temporal scales



Trischenko & Garand (2011)

Source of Radiation

PASSIVE

- Sunlight (UV, Vis, Near IR): May be scattered (by atmospheric constituents or surface) or absorbed.

- Thermal Emission (Thermal IR, microwave, radio)

ACTIVE

- Radar (radio & microwave), GPS (radio)
- Lidar (visible and near-infrared)

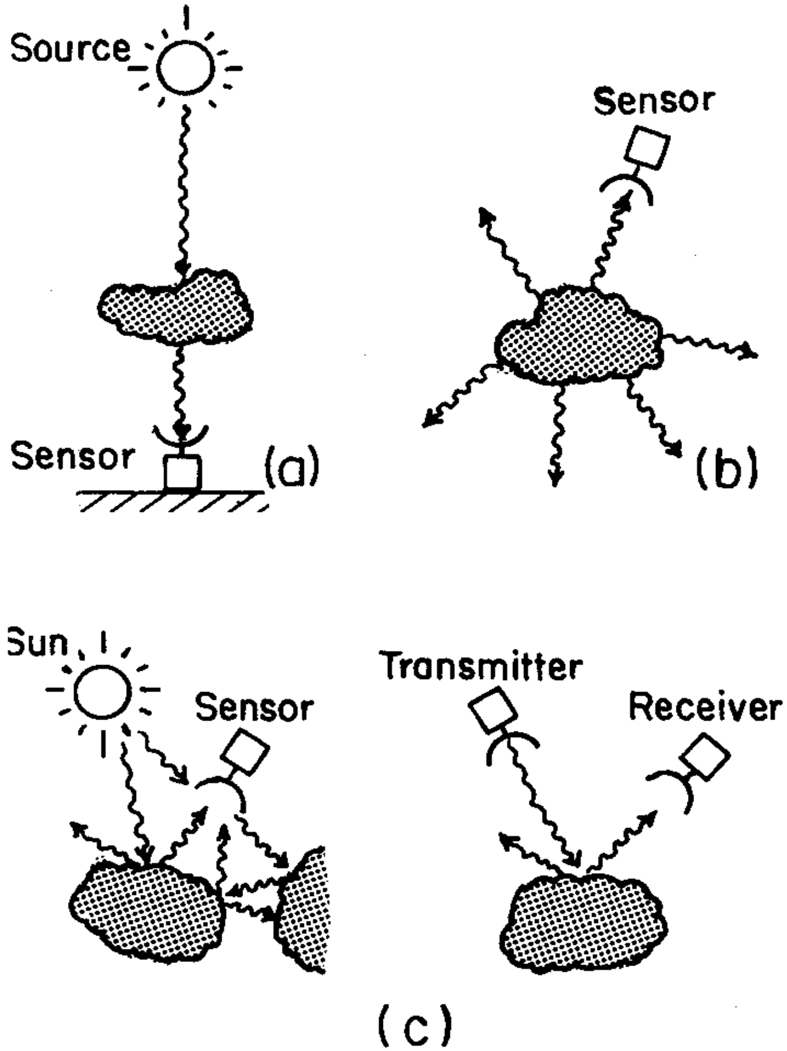
Radiation Interactions

- **Extinction**
  - Radiation removed from some background source (typically the sun or a laser)
  - Can be removed because of scattering, absorption, or both

- **Emission**
  - Adds radiation to a beam because of THERMAL EMISSION (thermal IR & microwave only)

- **Scattering**
  - Adds radiation to a beam
  - From clouds, aerosols, or surface.
  - Affects solar & thermal
  - Passive or active

Experimental Design



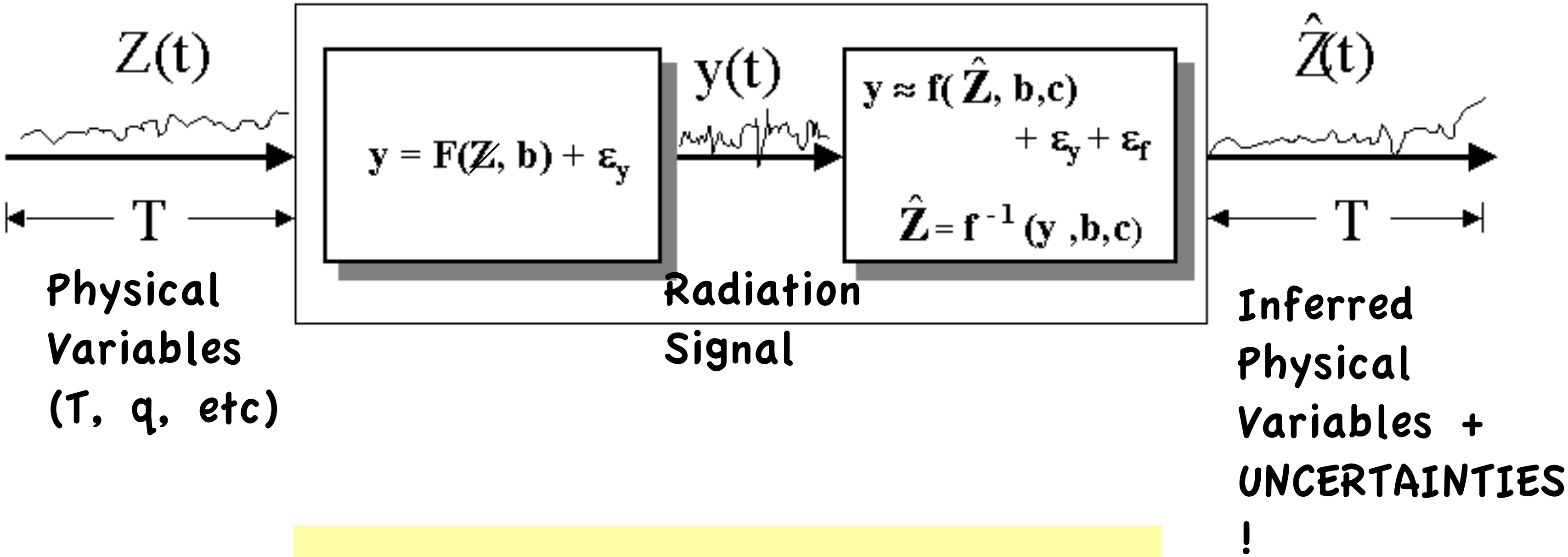
Based on some sort of relation defined by a physical process:

(a) extinction – aerosol OD, TCCON CO2, occultation

(b) emission - atmospheric sounding, precipitation,..

(c) scattering - passive, cloud aerosol, ozone,..
- active, radar & lidar

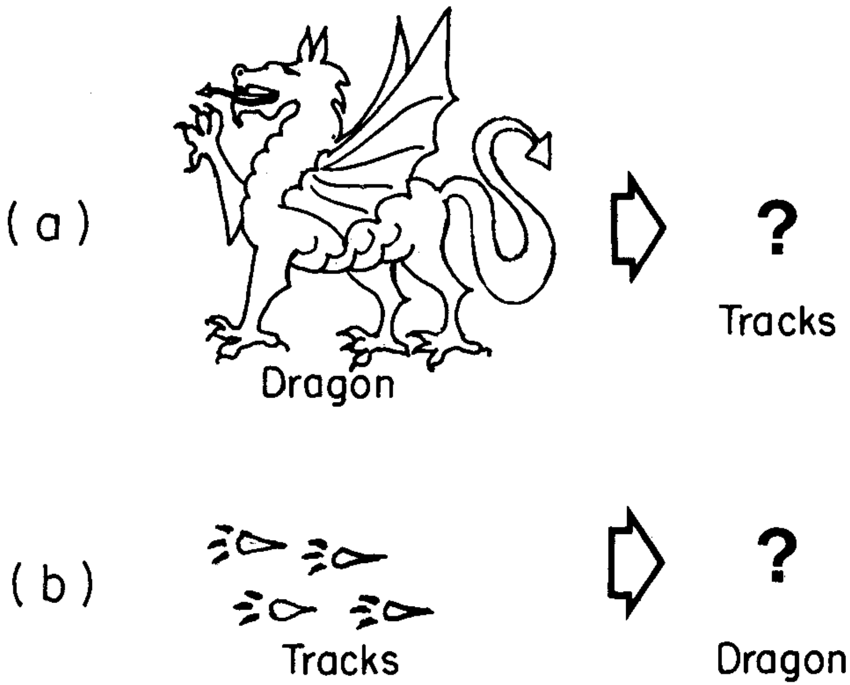
The Observing System Transfer Function



Key parameters & steps :

- Measurement, y(t) and error ε_y
- Model f & its error ε_f
- Model parameters b and errors
- Constraint parameters c

The Retrieval Problem



Inverse Problem

$\hat{x} = I(y,b)$

Forward Problem (real)

$y=F(x) + \varepsilon_y$

y = measurement

F = Nature's forward model

x = parameter desired

ε_y = error in measurement (noise, calibration error,…)

Often the relation between the measurement y and the parameter of interest x is not entirely understood

$$y=f(\hat{x},b) + \varepsilon_y + \varepsilon_f$$

b = 'model' parameters that facilitate evaluation of f

ε_f = error of model

PROBLEM:

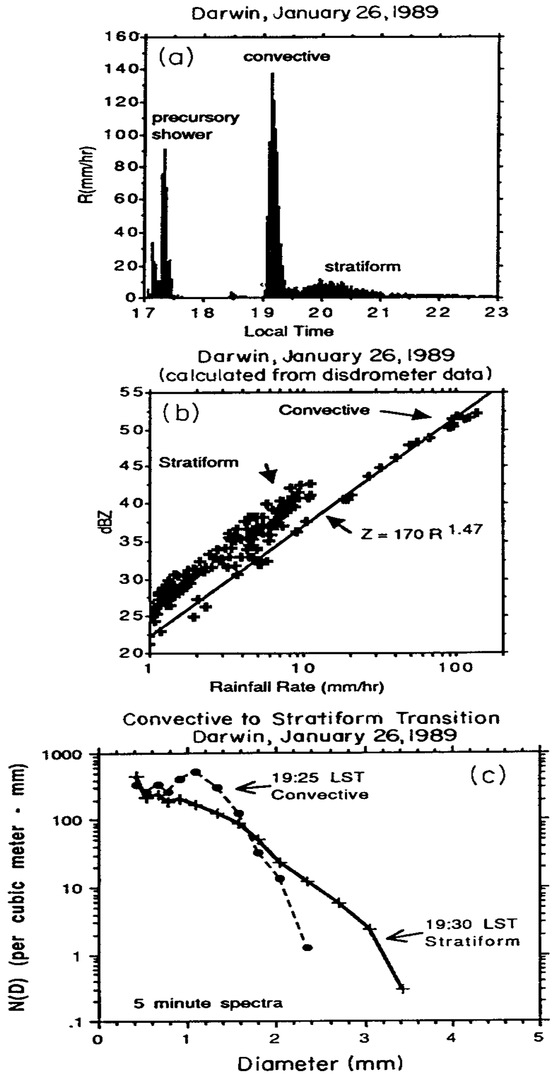
The performance of the 'system' is affected by the performance of the individual parts. Examples of issues:

(i) Properly formed forward models – [e.g. Z-R relationships, poorly formed forward model without an understanding of what establishes the links between the observable y(Z) and the retrieved parameter X(R)]

(ii) Need for prior constraints – temperature inversion problem

(iii) Poorly formed inverse model: simple regressions or neural network systems might not produce useful errors

Inversion versus estimation - radar/rainfall example



Radar -rainfall relationship

$Z= AR^b$

'Inversion'

$R= (Z/A)^{1/b}$

but……

A and b are not-unique and vary from rain-type to rain-type implicitly involving some sort of 'cloud' model

Stephens, 1994

Non-uniqueness and Instability $\longrightarrow$ Estimation

Cost Function: $\Phi = M\,[y-f(x)]$

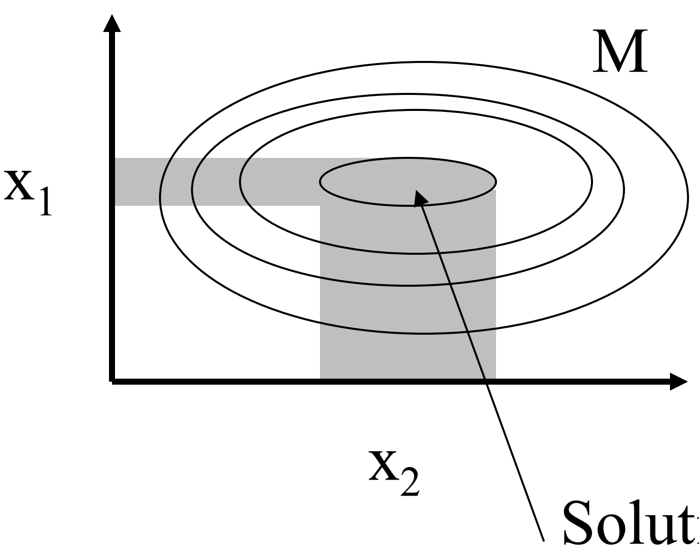
'metric' of length (e.g. least squares)

measurement

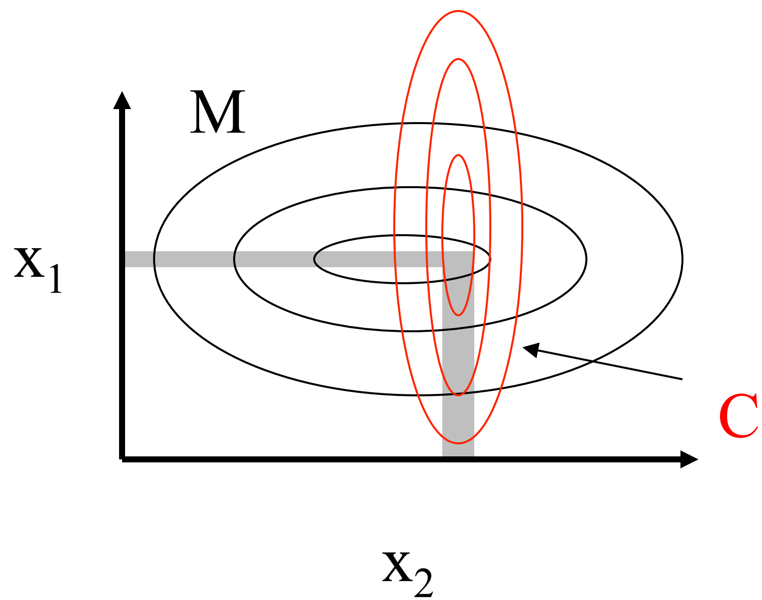
Prediction of measurement

<u>Unconstrained</u>

<u>Constrained</u> $\Phi = M\,[y-f(x)] + C(x)$



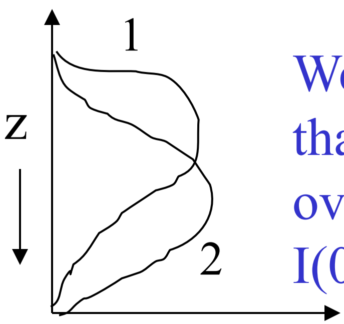
Solution space
non-unique



$C(x)$= initial or *a priori* constraint

Non-uniqueness and instability: example from emission

Physically:



Weighting functions that substantially overlap

$I(0) = \int B(z')W(0,z')dz'$

- Will generally not yield unique solution in the presence of instrument noise & finite # of channels

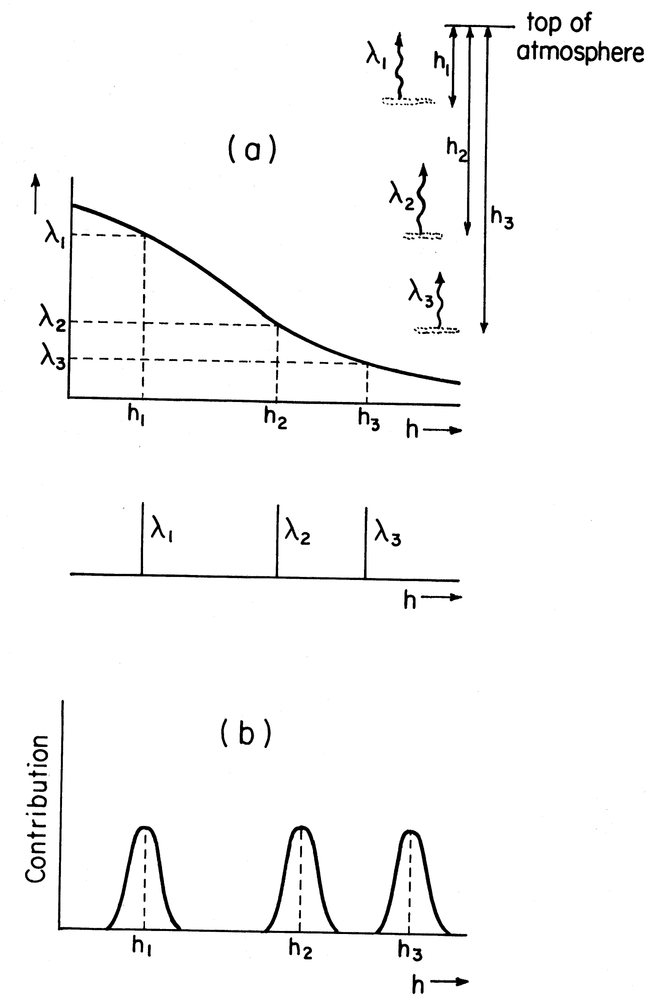
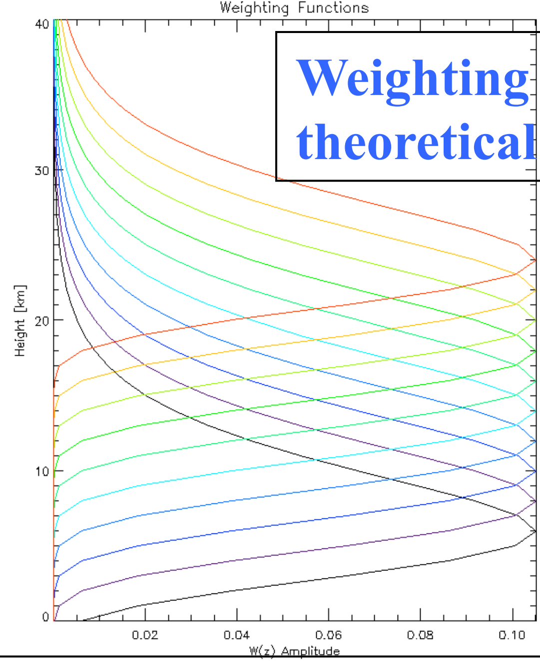


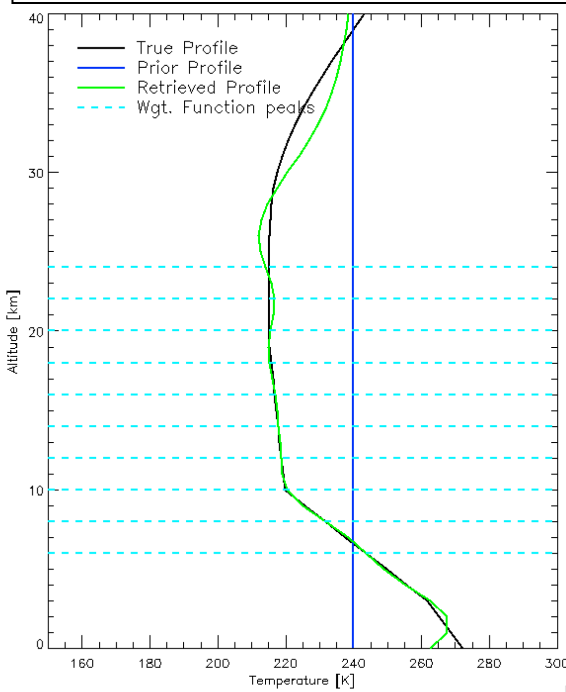
Figure 1.3 (a) Schematic diagram for a satellite-based atmospheric temperature profile measurement. The contribution to the radiation measured at the selected wavelength arises from a discrete level. (b) A version of the contribution function of Fig. 1.3a corresponding to a more practical case where the measured radiation originates from a range of different levels in unequal proportions (from Twomey, 1977).



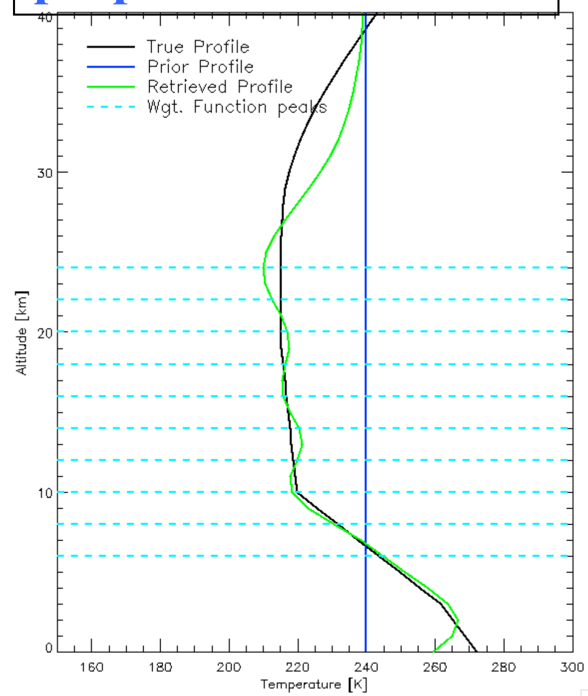
Weighting Functions from a theoretical instrument

Results from temperature retrieval project

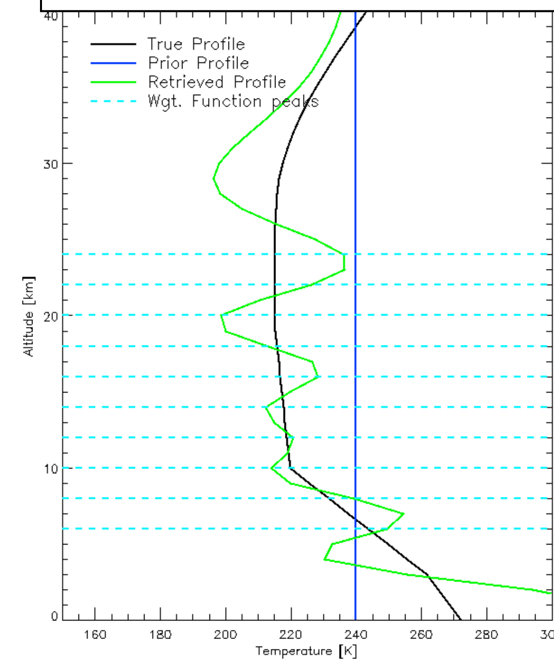
Noiseless Retrieval



Realistic noise, proper noise model

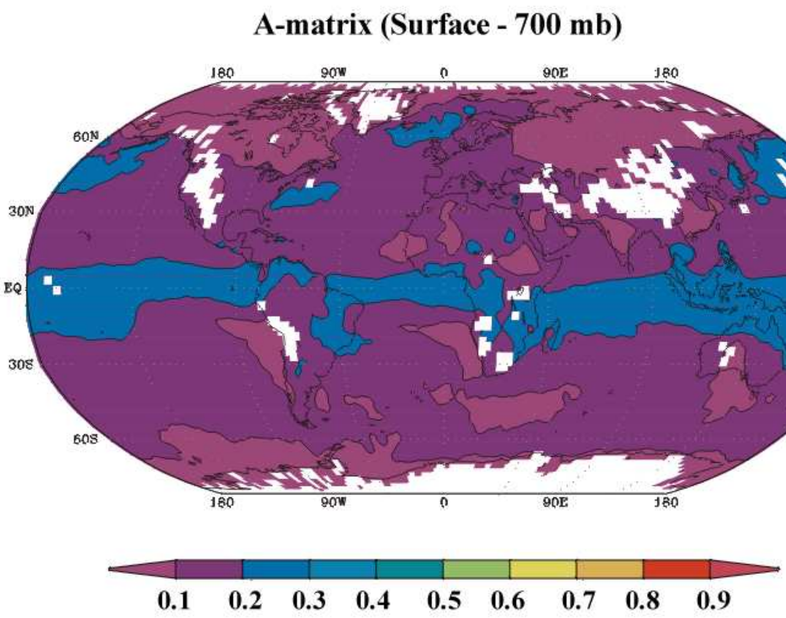


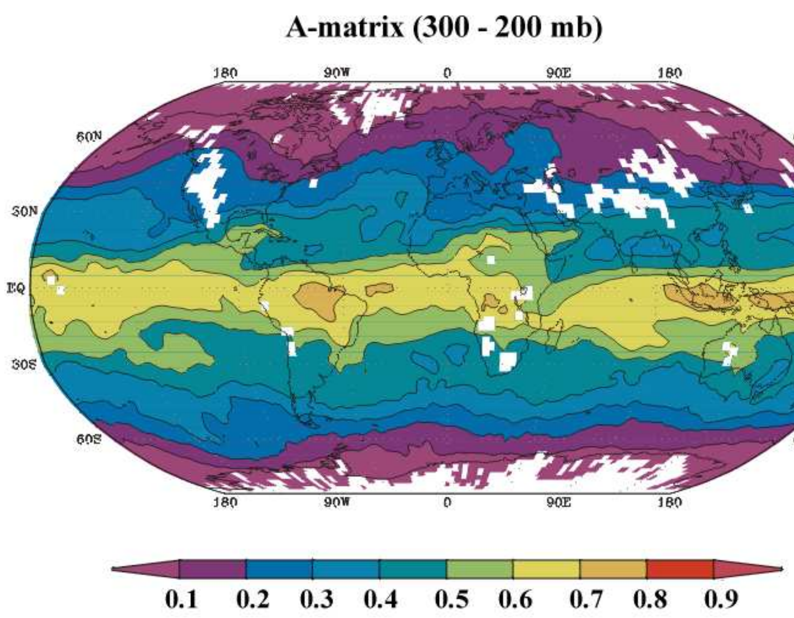
Realistic noise, assumed noiseless



Information Content: The example of IR-based retrieval of water vapor

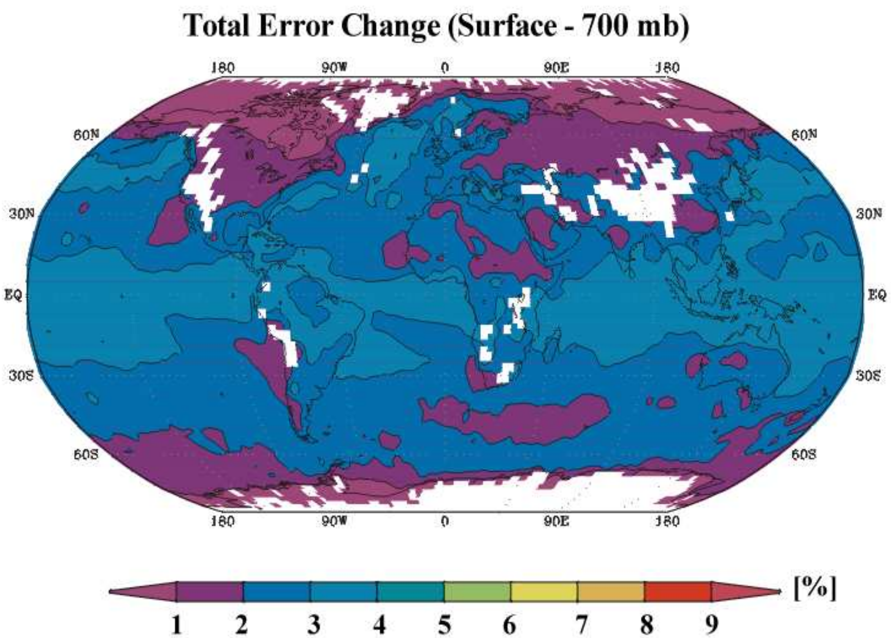
Metric of how much a priori constraint contribute to the retrieval
A→0, all a priori, no measurement
A→1, no a priori, all measurement

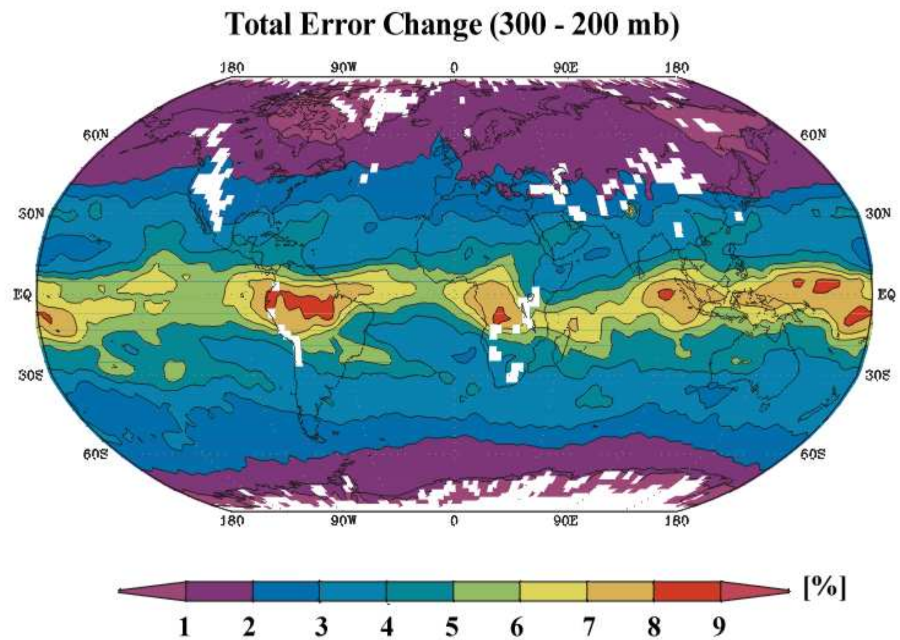




Change Calibration (i.e. measurement error by 100%) error

Largest impact where measurements contribute most





Forward Problem (applied)

$$y = f(\hat{x}, \hat{b}) + \varepsilon_y + \varepsilon_f$$

f = our depiction of the forward model

$\hat{x}, \hat{b}$ = estimates of x,y

ε_f = F(x,b) - f $(\hat{x}, \hat{b}) + \partial f / \partial b(\hat{b} - b)$,

= error in forward model

Radiative transfer model (most common)

Radiation + physical model

Radiation model + NWP (radiance assimilation)

For the most challenging problems we encounter, it is generally true that the largest uncertainty arise from forward model errors. If you see error estimates on products that exclude these errors – then you ought to be suspicious – really suspicious

Geostationary allows us to see cloud mov