Using remote sensing to study the atmosphere for weather and climate

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And hundreds of resources on the WWW (eg Wikipedia)
Most graphics come from govt (US/foreign) or university servers

History of Weather Forecasting I

see eg **Air Apparent** by *Mark Monmonier*

- Early civilizations were already using astronomical observations for annual cycles
- By 1700s : barometer and thermometer were made
- By 1830s people (eg ship captains) had recognized correlations between wind, atm press, W to E storm motion
- Eventually understanding of nor'easters (winds comng from NE initially) and then after the storm passes, a reversal in the winds, as a cyclonic (CCW) wind (Coriolis effect)
- In 1850s, Smithsonian Institution funded observations sent by telegraph to Washington, DC (T, p, humidity, wind direction) → weather maps
- $\simeq$ 24 hr forecast (at least, for large synoptic storms)

History of Weather Forecasting II

Much theoretical work was being done in Europe at the same time
In Norway, **Bjerkenes** was developing equations that are the forerunners of what we use for weather

- Describe large scale atmospheric and ocean motion
- Tying **hydrodynamics** (fluid motion)
  - low pressure means air rushes in from all directions,
  - so some air must move up, cool and condense into clouds
- With **thermodynamics**
  - changes of state
  - hot air less dense and rises,
  - heat input eg energy released by latent heat processes, or transport from equator to poles, gives temperature changes
- Predictions possible from the coupled nonlinear equations $\frac{d\phi_i}{dt} = F_i(\phi_1, \phi_2, ...\phi_n)$
- So, given initial conditions T,p,ρ **V**, predict how they evolve in time/space

History of Weather Forecasting III

- Lewis Richardson took up challenge; made a Numerical Weather Prediction (NWP) using (1910) data for SW/Central Europe/UK storm
  - 5x5 grid points x 5 layers for about 50 deg longitude x 30 latitude (2500 km x 2500 km x 100 km)
  - variables were wind speed, pressure and temperature
  - Humans working out numbers with slide rules and log tables, and passing the results to each other
  - Took 1000 hours to complete 6 hr forecast, finally published in 1922 (give or take a World War, losing notebook etc)

History of Weather Forecasting IV

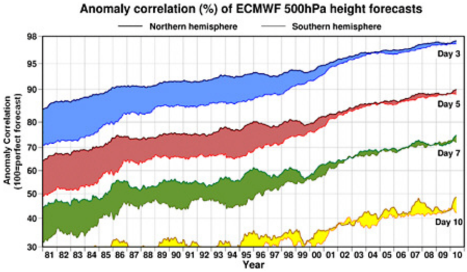
- **His results were terrible** : large wind speeds (100s of m/s) and large pressure changes (hundreds of mb)
- Reduced Fluid Equations for Weather were in their infancy, as were numerical techniques
- Had used large grid and timesteps, and incorrect reduced fluid equations
- Initial conditions poor quality (measurements from balloon ascents)

He estimated 64000 people would be needed to make a NWP for the entire planet

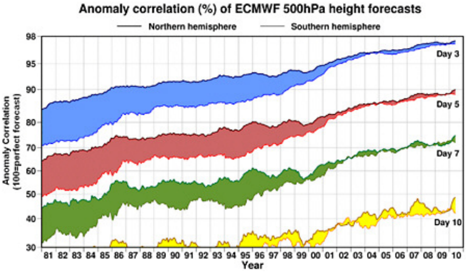
History of Weather Forecasting V

- weather forecasting in WW II (eg D-Day invasion delayed based on forecast)
- Computers invented, improved modelling of atmosphere, numerical techniques
- 1946 ENIAC (Electronic Numerical Integration and Computer) at U. Penn
- 1950 von Neumann, J. Charney, R. Fjortoft at Princeton proposed NWP using "reduced eqns"
- Operational NWP started soon after, about 1955
- Have to worry about "chaos"
- In the last 60 years, "skill" of weather forecast has improved tremendously, almost 90% accuracy for a 3 day forecast, 70% accuracy for 5 day forecast, and better
- **AIRS, IASI** were significant factors in recent improvements, as the provide data over entire Earth, twice a day

Weather Forecasting → Climate



Weather Forecasting → Climate



- Can use these models to study climate
- Don't worry, climate is long term, so inaccuracies in weather forecasting due to transients, have "washed" out
- Improvements in modeling, computer bits and faster chips mean you can run many "ensembles"
- **Need to compare results against data** takes at least 15-30 years for climate signals to manifest, at current instrument accuracies

Need for remote sensing

Weather

- Weather forecasts need temperature, humidity updates from *all* over the globe
- Cannot rely only on (mainly land based) surface observations
- Need Satellites to fill in these data gaps!!

Climate

- Need to understand the Earth System, and effects of natural and human induced changes to the System
- Other variables of relevance include cloud cover, cloud type/altitude, aerosols (pollution), changing land surface/vegetation
- Evaluation/validation of Climate Models requires statistics about atmospheric states
- Trends in retrieved parameters provide clues about climate change

Difference between weather and climate

Climate is what you expect
Weather is what you get *Mark Twain (?)*

Another way to put it :
Weather is short time scales (minutes, hours, days)
Climate is long time scales (year, decades)

$$\frac{d\phi(x,t)}{dt} \rightarrow \frac{d\phi_{climate}(x,t)}{dt})_{slow} + \frac{d\tilde{\phi}_{weather}(x,t)}{dt})_{fast}$$

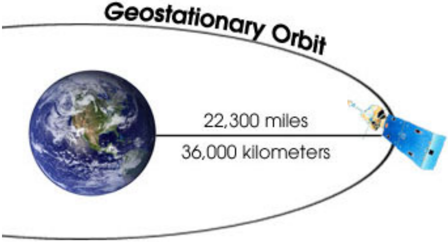
Typically climate is defined as statistics obtained from measurements over 30 years or more
This can include max, min, and moments of pdf : mean, stddev, skew, kurt

Brief History of Satellites

- Your senses (eyes/ears) are pretty good remote sensing instruments
- Optical instruments (Galileo etc) (1600s)
- Look downwards from balloon flights (1800s)
- Armed forces, telegraphs relaying measurements in late 1800s
- WW1 reconnaissance aircraft
- In 1940s suborbital rockets carried cameras
- From 1950s satellites were launched, with crude broadband instruments
- Current generation of satellites are low noise, high resolution, with very many different possible measurements for remote sensing
- Radiometers, Diffraction Grating, Interferometers, Lidars, ...

Geostationary satellites (GOES)

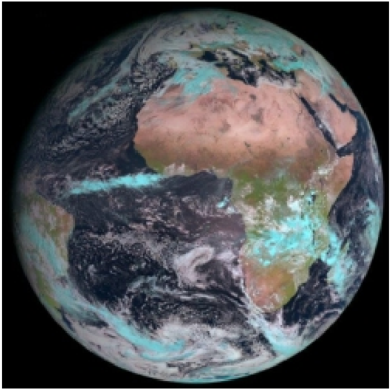
38000 km orbit → 24 hours/orbit
Look at same spot on Earth, so need a few to "cover" whole of Earth



Examples : NOAA’s Geostationary Operational Environmental Satellites (GOES) provide continuous monitoring over a region of globe, for "local" weather forecasts.

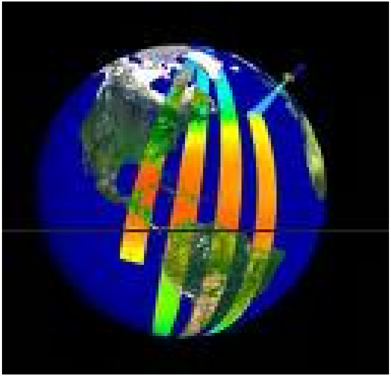
Geostationary satellites : view from Meteosat SEVIRI

http://www.eumetsat.int/Home/Main/Satellites/MeteosatSecondGener
Spinning Enhanced Visible and Infrared Imager (SEVIRI) measures reflected and emitted radiance in 11 spectral channels located between 0.6 μ m (VIS) and 14 μm (IR) with a spatial resolution of 1 or 3 km at sub-satellite point.



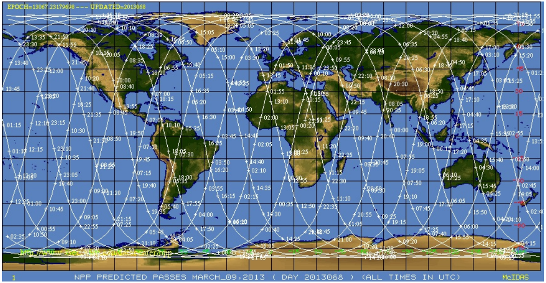
Polar Orbiting satelites (POES)

Low Earth Orbit (LEO) 700 km, means about 90 minutes/orbit.
This gives roughly twice daily coverage.
If the instrument can scan *across track* you can see almost every spot on Earth twice per day



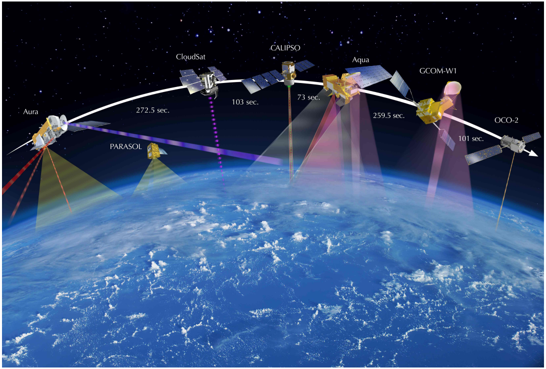
March 9, 2013 orbit tracks for the Suomi-NPP satellite

National Polar Orbiting Partnership : CRiS, ATMS, VIIRS



Remember, half the tracks are "day" and other half are "night" overpasses
So VIS/UV instruments only work "half" the time, while IR/MW and lidars work 24 hours

A-Train

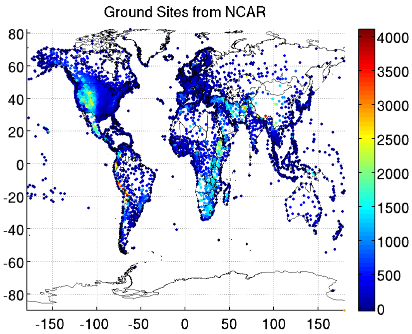


Afternoon Train (1.30 pm equator crossing time), with instruments from USA, Brazil, France
Low Earth Orbit (LEO); 700 km above Earth, 90 mins orbit

Instruments on the Satellites

Satellite	Instrument	E/M spectrum	Purpose
Aqua	AIRS	IR	Tropospheric Temperature and RH sounding Trace gas retrievals, SST (1 cm-1)
	MODIS	VIS/NIR some IR	Aerosols, clouds, chlorophyll land surface cover, snow cover
	AMSR	microwave	Precipitation rates, cloud water, winds soil moisture, snow/ice cover
	AMSU	microwave	temperature sounding in UT/LS
	HSB	microwave	humidity sounding through atmosphere
	CERES	broadband	radiation budget
Aura	HIRDLS	IR limb sounder	T(z) and O3/H20/CH4 in UT/Strat/Meso
	MLS	microwave LS	T(z) and O3/H20/CH4 in UT/LS
	TES	IR nadir	lower atmosphere sounding, high spectral resolution (0.025 cm-1)
	OMI	UV	ozone monitoring/chemistry, aerosols
PARASOL	POLDER	NIR, Vis	Clouds and aerosols (using polarization) Interaction of microphysics, radiative processes
CALIPSO	CALIOP	active LIDAR	Vertical structure of clouds and aerosols (nadir)
CloudSat	CALIOP	94 GHz RADAR	Cloud profiling (nadir only)
OCO		NIR	CO2

Contrast this to Surface Obs Stations

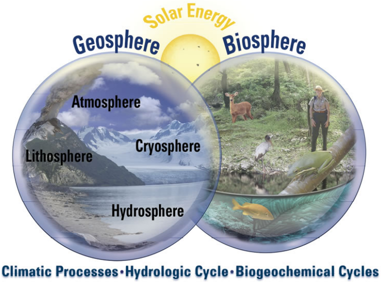


- http://www.rap.ucar.edu/weather/surface/stations.txt
- 8165 sites worldwide
- METAR (airport/aviation), WMO sites, radiosonde sites, windprofilers etc
- U of Wyoming, weather underground have surface observations

Plus you have ...

Instruments on board the Space Shuttle, International Space Station, balloons, airplanes, drones

Geospheres



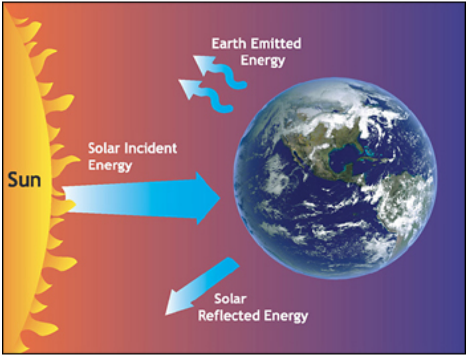
Earth System is very complicated!
We have only observations from one Earth
This is **NOT** an experiment we can control!
But we can hope to gain understandings of fundamental "climate forcings" and "steady states"
This talk focuses on atmosphere

Geospheres

Earth System Science consists of interdependant “geospheres”
no sun, no energy/warmth, no life!

- lithosphere : solid rocky crust covering earth
- hydrosphere : water on surface and in the air; mostly in oceans (salty) water is essential; release of latent heat is transported from equator to poles
- cryosphere : fresh water in ice sheets/glaciers or snow cover
- biosphere : living organisms
- atmosphere : air surrounding the surface, upto $\simeq$ 100 km

Importance of Sun

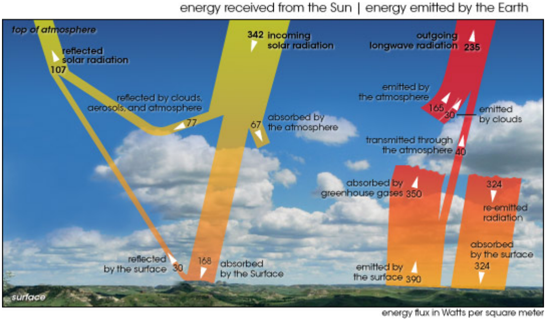


The Earth's Radiation Budget is a balance between the incoming solar radiation and outgoing terrestrial radiation

Sun/Earth interaction

Motivation
Instrument platforms
Earth and Sun
The Atmosphere
Remote Sensing
RTE
IR Instruments
Typical Spectra
Trace Gases
Other Instruments
Climate
Conclusions

1360 W/m2 is over whole Earth surface. Use flat disk area, so we have $\simeq$ 345 W incident per unit area.



The simple picture gets more complicated because we have to consider several different components of this Radiation Budget

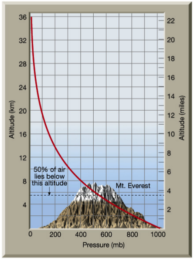
The Atmosphere : Vertical Structure

- vertical structure (pressure, density decrease with height, as does temp)
- pressure broadening (Lorentz) at surface, doppler lines beyond 20 km
- above 70 km, can't really talk about temperatures (low density, few collisions)

Uneven heating from sun compensated by heat transport

- Heat energy for atmospheric circulation from latent heat released when evaporated (tropical) ocean water condenses into clouds
- Heat energy from tropics to poles and vice versa from ocean circulation as well

Vertical Structure



	Density cm^{-3}	Mean Free Path cm	Collision Frequency per second
Surface	2×10^{19}	7×10^{-6}	7×10^{7}
TOA (600 km)	2×10^{7}	1×10^{6}	1×10^{-2}

Vertical wind speeds (quiet) $\simeq$ 1 m/s = 2 mph
Vertical wind speeds (thunderstorms) $\simeq$ tens of m/s = 50-100 mph
Surface wind speeds $\simeq$ 10 m/s; (in tornados 200-300 mph)

0D climate model

- Outer surface of Sun radiating out to space at T_{sun} = 6000K
- Energy conservation :

$$P = \sigma A_{sun} T_{sun}^4 = f 4\pi r_{sun-earth}^2$$

- solar constant $f \simeq 1360\,Wm^{-2}$
- Rate of absorption by Earth $\simeq$ Rate of emission by Earth

$$f\pi R_{earth}^2 (1 - a) = 4\pi R_{earth}^2 \sigma T_{earth}^4$$

- albedo $a \simeq 0.3$, and energy conservation gives T_{earth} = 255 K

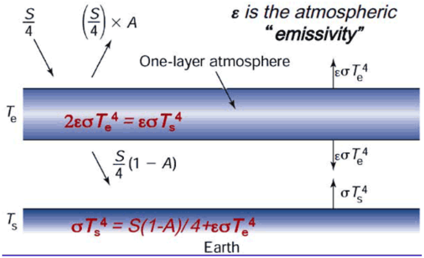
Incoming solar radiation (UV/VIS)
Outgoing terrestrial radiation (IR)

So what is going on?

We know $T_{surface} = 285$ K > T_{earth} !!!!!

- 255K would be the average temperature of a Moon-like Earth (no atmosphere, hot days, cold nights)
- **Greenhouse Effect (non transparent atmosphere in IR)**
- Weather (humidity, temp differences due to eg local sun angle)
- 255K tunrs out to be the "radiating temperature" of Planet Earth
- cold upper atmosphere also emits, so energy balance is obeyed

1D, One Layer Climate Model



One Layer Energy Balance Model.

Credit: M. Mann modification of a figure from Kump, Kasting, Crane "Earth System"

- Incoming energy = 1360/4 W/m2, albedo = 0.3
- Do energy balance at surface and TOA, yielding T_{atm} = 255K, T_{surf} = 305 K
- Lapse rate of 6K/km means Earth radiates 8 km above us
- Surface a little hot, but Not Bad!!!

More complicated Models

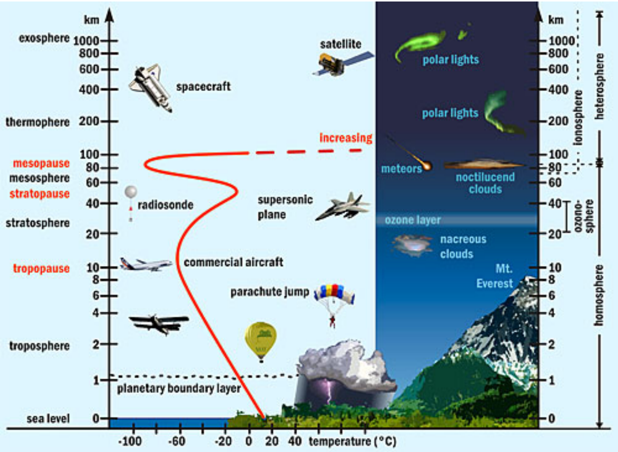
- 0D model
- 1D, One layer climate model
- 1D, Two layer climate model
- 1D, N layer climate model (very hot surface $T_{surface} \simeq (N+1)^{1/4} T_{radiate}$, very unstable atmosphere)
- 1D, N layer model with radiative-convective relaxation (to have stable dT/dz)
- 2D models
- Finally 3D climate models, with fluid dynamics, clouds, forcings etc
  - Difficult to have small/large time/space scales in the codes
  - Statistical and parameterized models in these codes
  - Compare to obs

These models can be used for stars and planetary atmospheres!

Different vertical regions

- troposphere : lowest 10 km, where "weather" happens; dT/dz $\leq$ 0, and so convection can happen, giving rise to weather, clouds etc
- stratosphere : ozone production (dT/dz $\geq$ 0, so quiet and stable)
- mesosphere : not optimal for ozone production, again we get cooling
- thermosphere : very low density, some moelcules directly absorb solar energy and so we get high temps
- exosphere : universe beyond Top of Atmosphere (sun, stars, meteors hitting us etc)

Vertical structure

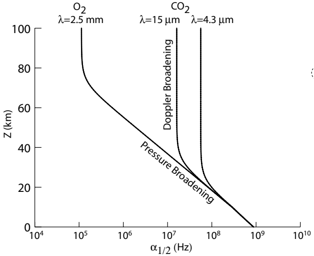


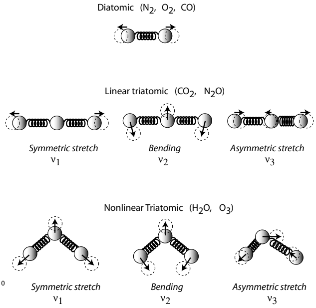
Composition

- fixed gases (N2,O2,Ar) radiatively inactive in the infrared, 99% of atmosphere
- variable gases (H2O,CO2,CO,O3,CH4) are temporally and spatially variable
- they are GREENHOUSE gases (transparent to solar radiation, strong absorbers of IR radiation)
- clouds and aerosols

Spectroscopy

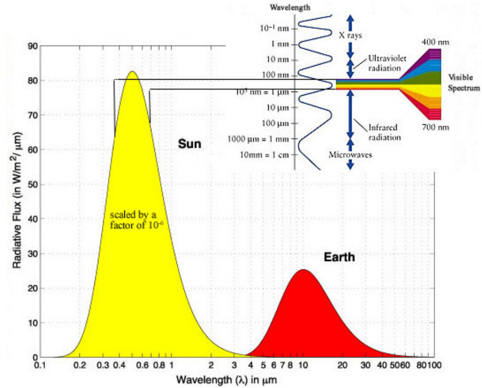
microwaves : low energy, mainly rotational transitions
infrared : medium energy, vibrational modes with rotational lines
visible/UV : higher energy, electronic transitions, can also break bonds (eg O3)



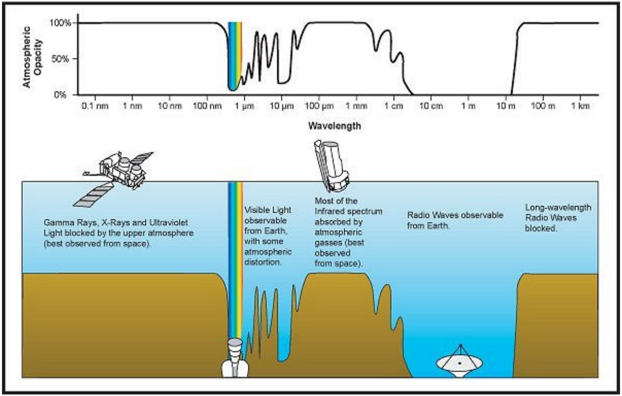


lone atoms (eg Argon) cannot have rotational/vibrational transitions
All molecules can have rotational energy, but requires $\geq$ 3 atoms for vibrational energy (so simple molecules such as N2, O2 do not interact with IR)

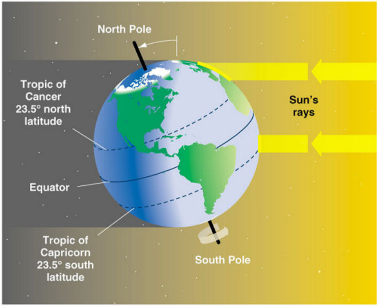
Electromagnetic Spectrum



Atmospheric Transmission

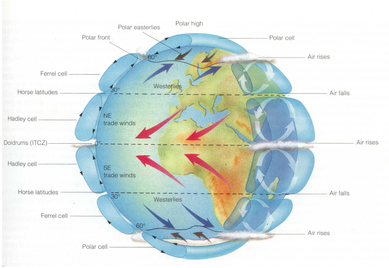


Earth Tilt and Seasons



Latitudinal differences arise from incident solar energy heating different areas ($\cos(\theta)$) in North, South Hemispheres
Four Seasons from the Earth orbiting the Sun
Summer : hemisphere tilted towards Sun (long days/short nights)

Circulation



Temperatures fall with height in lowest 10 km (troposphere)
Densities also fall with height (pressure balance against gravity)
75% of the atmosphere mass is in the troposphere
Hot surface air rises (including the evaporated waters)
Rises air expands and cools, water condenses and falls as rain
Falling air compresses (and heats) $\Longrightarrow$ desert regions
Divergence = 0, so we also have general wind directions

What is remote sensing

Gathering information about a given volume (object) without being in contact with the object

Examples include

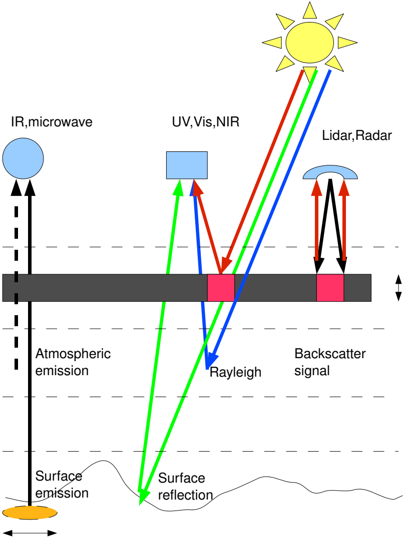
- medical (ultrasound, MRI)
- astronomical (telescopes)
- atmospheric phenomena (Earth, planets)

In this talk we limit ourselves to atmospheric remote sensing on Earth (though the same ideas could be used eg for studying Martian surface)

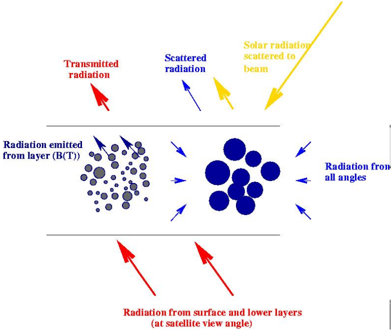
Radiance measurements need to be inverted to retrieve geophysical parameters eg T(z), RH(z), SurfaceTemp, Dust Loading, Cloud fraction

How is it done?

- Passive sensing : detect natural radiation that is emitted or reflected by object
    - Reflected sunlight (ultraviolet, visible or near infrared)
    - Emitted radiation (thermal infrared, far infrared, microwave)
- Active sensing : emit energy to probe the volume, and then detect the signal passively
    - LIDAR : use laser for light detection and ranging
    - RADAR : use eg radio-waves and use time difference between emission/reflection to quantify size of raindrops, distance away, velocity (doppler)


IR,microwave
UV,Vis,NIR
Lidar,Radar
Atmospheric emission
Rayleigh
Backscatter signal
Surface emission
Surface reflection

Source function : solar beam, scattering, transmission, reflection



Transmitted radiation

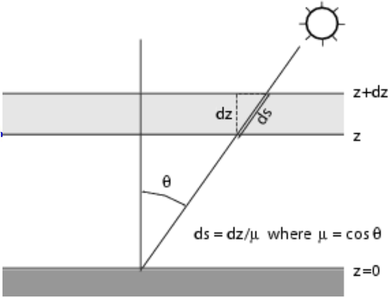
Scattered radiation

Solar radiation scattered to beam

Radiation emitted from layer (B(T))

Radiation from all angles

Radiation from surface and lower layers (at satellite view angle)



Radiative Transfer

- At steady state, the 1D Schwartzchild radiative transfer (RT) equation says

$$\mu \frac{dI(\nu,\theta)}{k_e dz} = -I(\nu,\theta) + J(\nu)$$

- $\mu = cos(\theta)$, dz is the vertical coordinate
- k_e is the total extinction (due to gases, clouds etc)
- $k_e dz = d\tau$ is the optical depth
- $I(\nu,\theta)$ is the radiance intensity
- J is the source function

Solutions of Radiative transfer Equation I

Clear sky : $J = B(\nu, T)$

- For Clear Sky, one layer only

$$I(\nu, \tau_e) = I(\nu, 0)e^{-\tau_e(\nu)/\mu} + B(\nu, T)(1 - e^{-\tau_e(\nu)/\mu})$$

- The optical depth τ_e requires accurate spectroscopy : line parameters, lineshape (doppler/lorentz/voigt or other)
- Source term J depends on atmospheric vertical temperature profile $B(\nu, T)$ and so you can retrieve $T(z)$ profiles
- k_e depends on T and Q, so if you know $T(z)$, you can retrieve $Q(z)$

Solutions of Radiative transfer Equation II

Cloudy/Aerosol laden sky : $J = B(\nu, T)$

$$\mu \frac{dI(\nu)}{dk_e} = -I(\nu) + B(\nu, T)(1 - \omega_0) + \frac{\omega_0}{2} \int_{-1}^{+1} I(\nu, k_e, \mu\prime) P(\mu, \mu\prime) d(\mu\prime) + \frac{\omega_0}{4\pi} \pi I_{sun} P(\mu, -\mu_{sun}) e^{-k_e}$$

- scatterers ($\omega_0 \geq 0$) make the eqn quite complicated
- assume your instrument operates in the visible regime
- $B(T(z)) \ll I_{sun}$; signal dominated by scattering
- No height information, but very sensitive to phase function P
- P and k_e, ω_0 depend on particle shape, size, refractive indices
- Could detect intensity only, or intensity+polarization, ...

... nice views ...

Chris Lanzycki, Antarctica

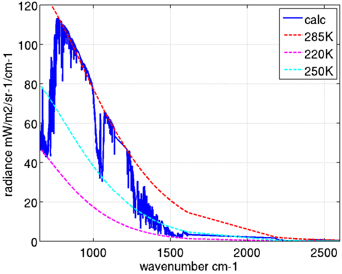
What can IR instruments provide?

- atmospheric humidity and temperature profiles
- surface temperatures
- cloud fraction and height
- trace gas transport (CO2, CH4, SO2, CO, HNO3, CFCs)
- detect and retrieve dust outbreaks

Operational day/night

Examples include NASA's *Aqua* **AIRS** (Atmospheric Infrared Sounder) 2002 (diffraction grating $dsin\theta = n\lambda$)
Europe's *MetOp-3* **IASI** (Infrared Atmospheric Sounding Interferometer) 2007, **IASI 2** launched last year
NOAA/NASA *Suomi* **CrIS** (Cross Track Infrared Sounder) 2012
Each instrument has expected 5-7 year lifetime

Typical AIRS radiance

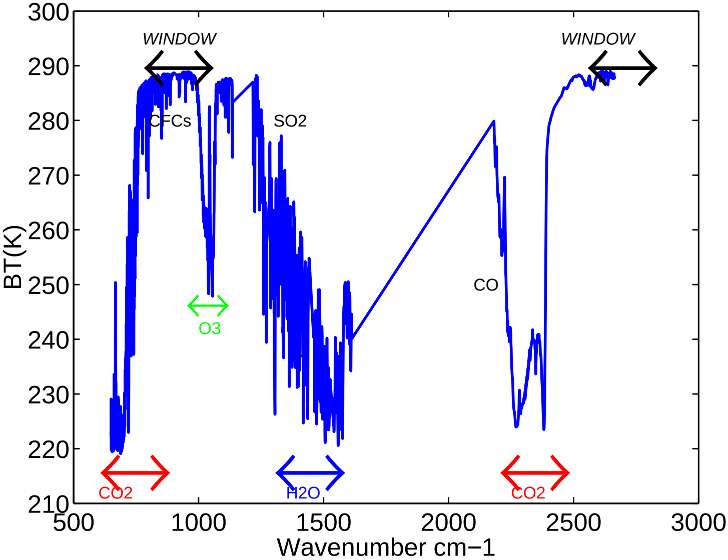


The “atmospheric window” channels (800-1200 cm-1) can see down to the surface

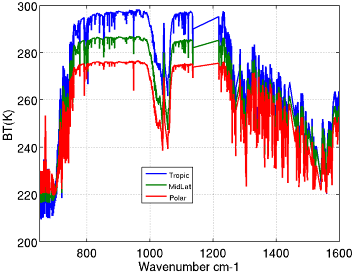
The increasing gas absorption means that you can only see emission from higher in the atmosphere, which is cooler (eg CO2 in 600-800 cm-1, O3 in 1000 cm-1, H2O in 1300-1600 cm-1)

Rule of thumb : more gas $\Longrightarrow$ more absorption $\Longrightarrow$ you see higher in atmosphere (colder temps); so if $obs - calcs \leq 0$, the *calcs* are hotter than obs $\Longrightarrow$ calcs need more gas amt (actual amt higher) and vice versa

BT vs Wavenumber : Important Gases, Window Regions



IR spectra examples

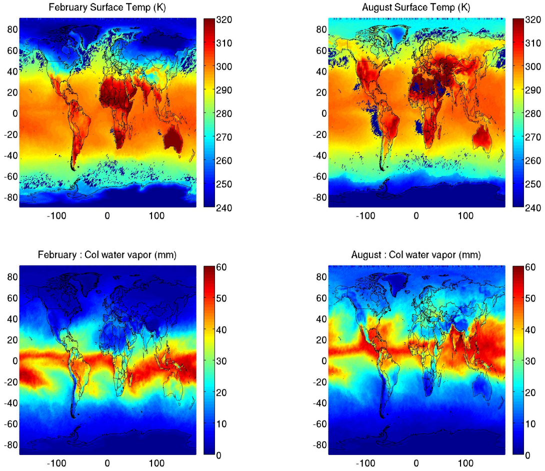


- tropics (B) averaged ±30, midlat (G) averaged between 30-60 N/S, polar (R) for 60-90 N/S
- Window region shows surface temps decrease
- Window region line depths show water amounts decrease (hot/humid VS cold/dry)
- Window region near 800 cm-1 shows increasing water vapor absorption at tropics

Column water and Surface Temps

February

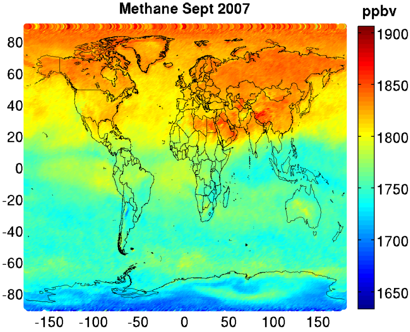
August



Feb col W

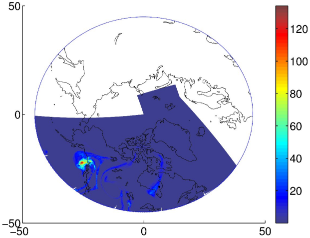
Aug col W

CH4 example



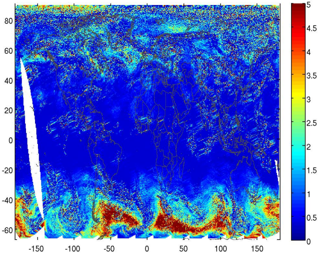
CH4 is trapped under bogs, so in winter time the bacteria are asleep and do not release this gas
Summer time, they wake up, and so bogs release this gas.
With more snow cover melting, this could provide a large, dangerous source of greenhouse gas

SO2 example from Alaskan Volcano 2008/08



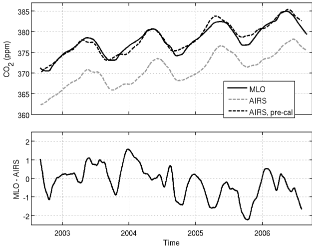
Dobson Units (nominally about 1 DU)
One of the most violent eruptions since 1991 Mt Pinatubo
The SO2 is pretty high in the atm, and in 4 days since the event, the upper atm winds has “blown” apart the SO2 cloud
Volcanic ash was also detected (separately) ... and stratospheric ash will also rapidly travel around the world (about 7 days), leading to cooling ....
Scott Hannon

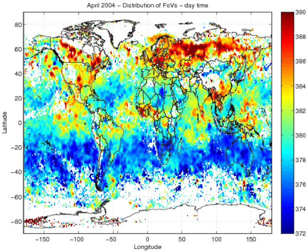
HNO3 example (typical July)



HNO3 is hydrophilic, so very little in the tropics
Freezes and crystallizes onto high polar clouds in polar winter, which provides surface for CFCs to attack and deplete O3
Scott Hannon

C02

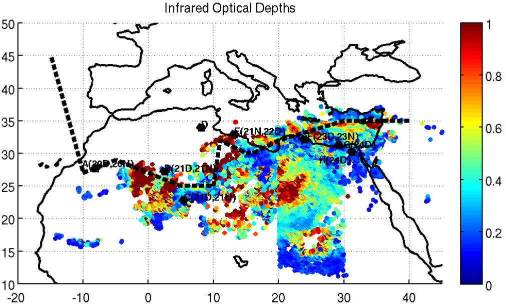




CO2 is what scares most people, even though water vapor is the most important greenhouse gas

ASL

Seeing dust storms day/night



Feb 20-24, 2007 (day/night) over land/ocean
Collage of retrieved dust ODs using IR

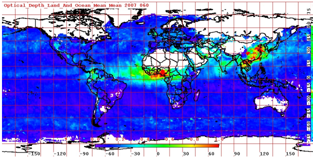
What can UV/VIS instruments provide?

- aerosol or cloud loading
- sensitivity to particle shape
- SW (solar) forcing
- visible pictures
- land surface
- ozone monitoring
- stereo imaging can yield height information

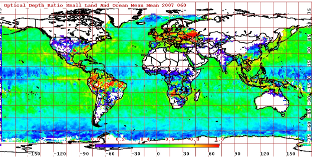
Possible only during day

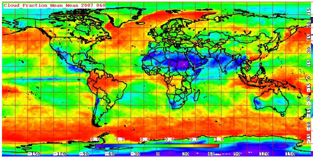
MODIS monthly products (typical Feb)

Aerosol OD

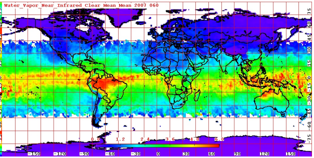


Fine Mode fraction



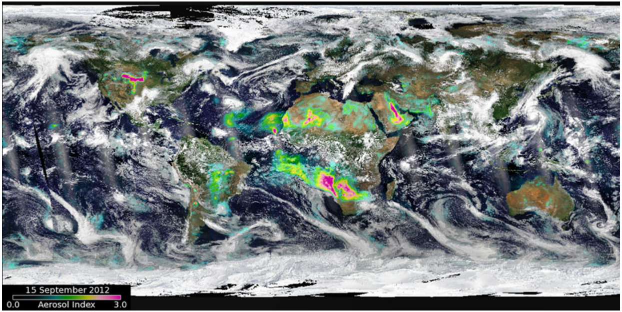


Cloud Fraction



NIR col water

VIIRS views : daytime composite on 2012/09/15



VIIRS views : nighttime composite

What can LIDAR provide?

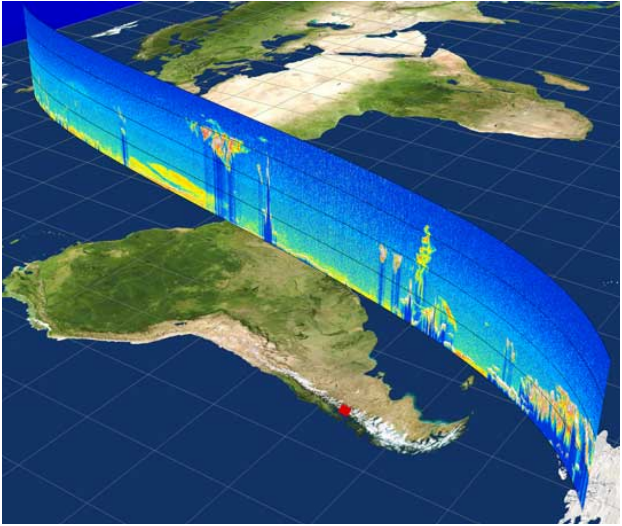
LIDAR : Light Detection and Ranging (active instrument)

- concentration of chemicals in atmosphere, temperature profiles
- accurate profiling of clouds and aerosols (can see smaller particles)
- VAAC (Volcanic ash aviation hazard)

Possible day or night

Chaitean volcano seen by MODIS, June 2011

Chaitean volcano seen by Caliop, May 2008



What can microwave instruments provide?

- Long wavelengths ⇒ unaffected by aerosols or clouds (except those associated with deep convection)
- can be operated day or night
- temperature and water vapor profiles
- much less affected by cloud than IR, but
- lower vertical and horizontal resolution than IR

Operational during day/night

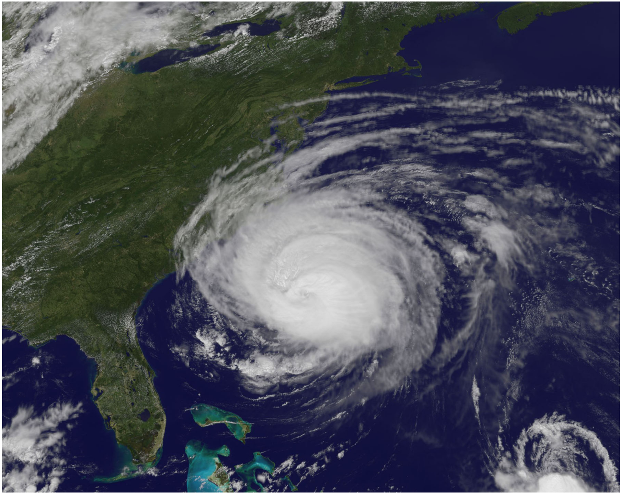
What can RADAR provide?

RADAR : Radio Detection and Ranging (active instrument)

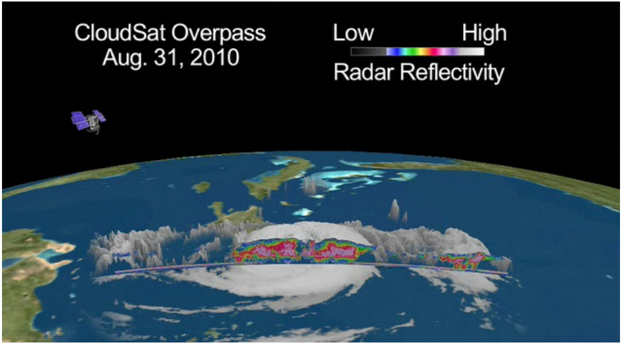
- Typical wavelengths : 1 mm $\leq \lambda \leq 1m$
- Reflectivity of Soils (dielectric constant) depends on amount of water present :
  wet soil has higher dielectric constant (reflectivity)
- Doppler Radar can detect wind speeds
- can see larger/more optically thick features in clouds

Possible day or night

Hurricane Earl seen by MODIS, Sept 2010



Hurricane Earl seen by CloudSat, Sept 2010

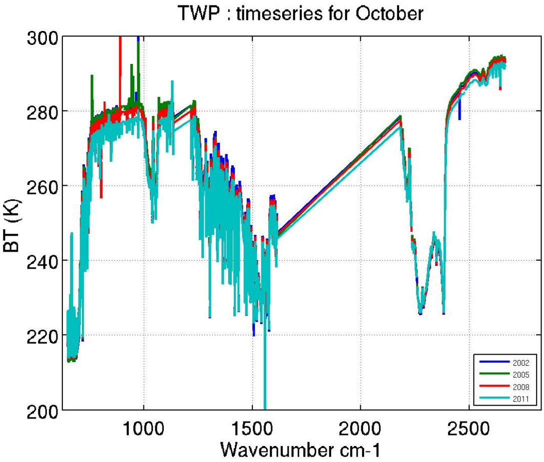


How to use the above for climate?

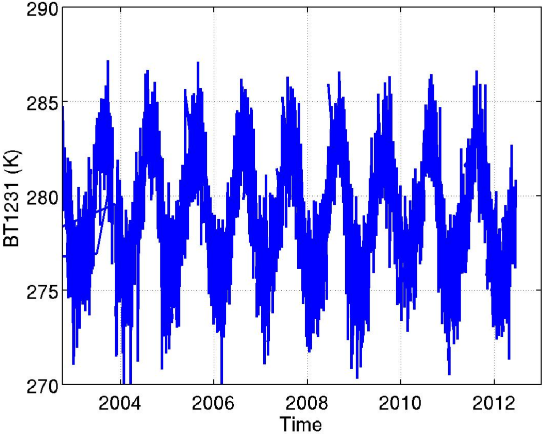
We have 10+ years of measurements and geophysical parameter retrievals (stemp, T, WV etc)

- Retrievals are **very** complicated, hard to characterize/propagate errors
- In addition, presence of clouds can drastically contaminate the retrieval, since cloud/aerosol contamination can mimic gas amount variations!
- Accuracy of WV(t,z) and T(t,z), as well as trace gas amounts $Q_i(t)$ **not good enough to detect changes** with confidence
- So we examine how **accurate, raw radiances themselves are changing**, and then determine geophysical rates
    - start with examining carefully filtered "clear only" scenes
    - now we are in process of examining "all sky" radiances

Spectral Time Series for TWP
Oct 2002 - Oct 2012



BT1231 cm^{-1} Time Series for TWP Oct 2002 - Oct 2012



The changes/signals are TINY!!
New instruments eg AIRS, IASI, CRiS are accurate, and stable

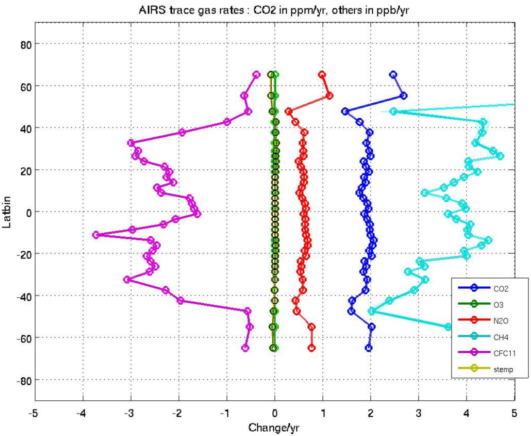
Spectral Rates of Change dBT/dt

Instruments last approximately 10-15 years, so need to "stitch" together timeseries from different generations and technology of instruments, to get long term climate time series (15+ years)
For each channel *i* fit

$$y_i(t) = A_i + B_i t + \sum_{n=1}^{4} C_n(i)cos(n\omega t) + D_n(i)sin(n\omega t)$$

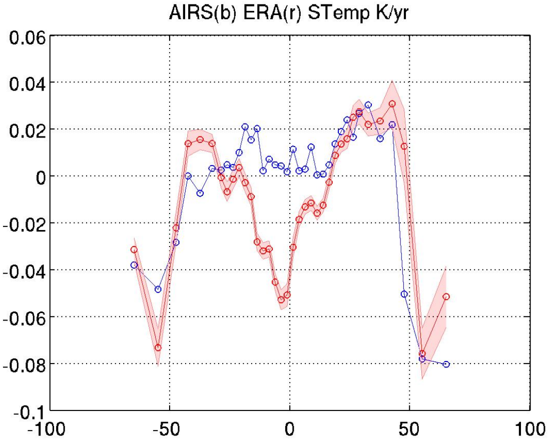
where ω is equivalent to one year
The spectral rate we are interested in is B_i
Fit this spectral rate to estimate how geophysical parameters are changing in time

10 years of AIRS data : Trace Gas Rates



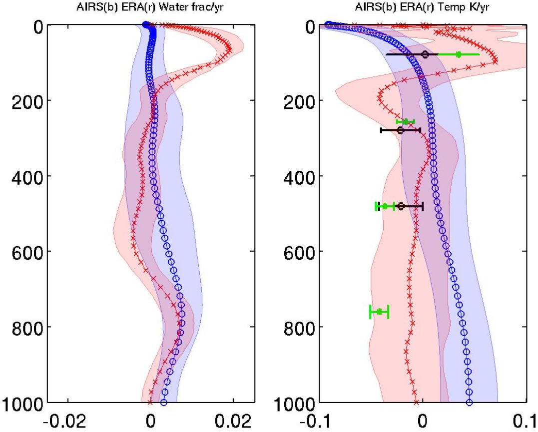
Agree well with in-situ measurements
Note CFC-11 is decreasing with time

10 years of AIRS data : Surface Temperature Rates



ERA is the "European" model which takes assimilated data from AIRS/IASI/AMSU, buoys and radiosondes

10 years of AIRS data : WV and T Rates



ERA is the "European" model which takes assimilated data from AIRS/IASI/AMSU, buoys and radiosondes

Conclusions

Weather

- Earth system is very complicated (atmosphere, land, oceans)
- Earth is rather large; hopeless to only rely on land based remote sensing, better to use space based remote sensing
- Wide range of the EM spectrum can be used for these studies (eg VIS for clouds/aerosols, UV for ozone, IR/microwave for T(z),WV(z). lidar/radar for vertical profiles)

Climate

- Careful thought allows instruments to complement each other
- Instruments do not last forever, need to be “overlapped correctly” to extend data record
- Now have 10+ years of data from extremely accurate, stable instruments; can start making meaningful comparisons to climate models
- Lots of work still needs to be done!!!