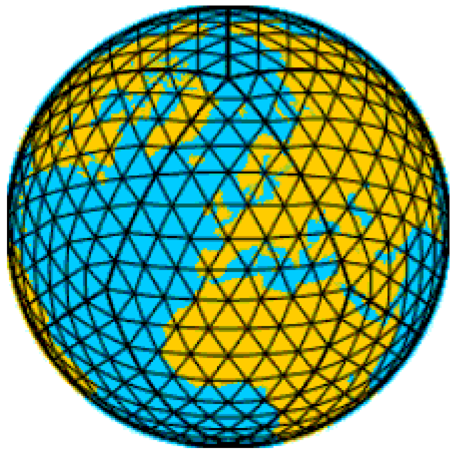
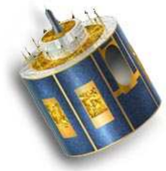
Special : Satellite Data

Part I: Introduction to satellite observations for NWP

Christina Köpken-Watts, Robin Faulwetter
Data assimilation (FE12) / Satellite data

Part II: Processing and assimilation of satellite radiances (at DWD)





Robin Faulwetter, Christina Köpken-Watts
FE12/Data assimilation

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- (I) Overview of meteorological satellites/instruments
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- (III) Passive radiance observations & instruments
  - Radiative transfer: basic processes (clear & cloudy)
  - Influence of water and land surfaces (emissivity)
  - Background: Vertical structure of the atmosphere
  - Examples of infrared & microwave radiance observations
  - Potential and limitation of radiance observations

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Introduction

Data assimilation provides the **intial conditions** for numerical prediction through

- use of all available observations
- knowledge of atmospheric dynamics

Satellite data have become

- **the major observation system component in global data assimilation** as to
  - Quantity & Data coverage
  - Parameters observed
  - Positive Forecast impact

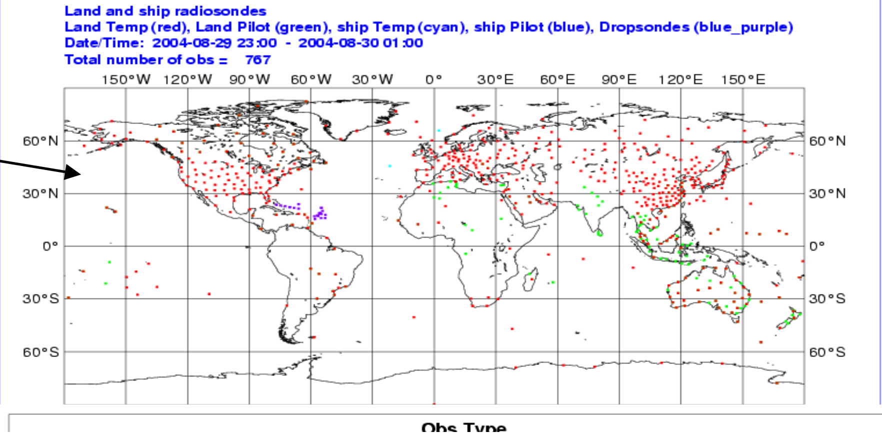
- **Important** contribution also in **regional** forecasting (esp. GEO satellites , together with ground based remote sensing)

Introduction :
Satellite data Coverage & Quantity

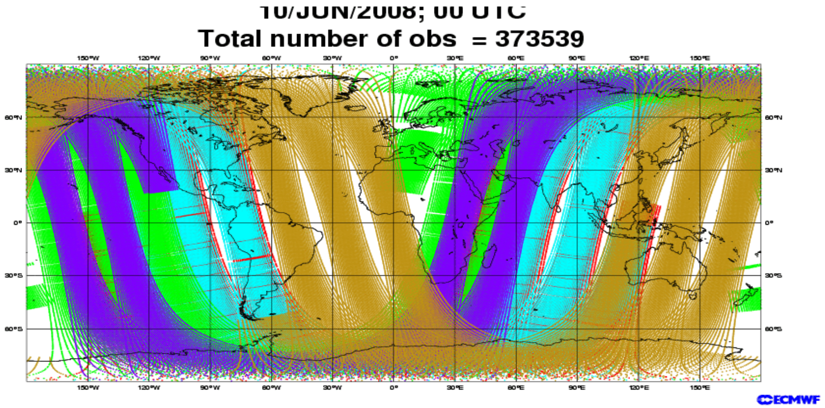
Example: Profile information from

- Conventional obs
- Satellite (ATOVS, IASI, GPS – RO)

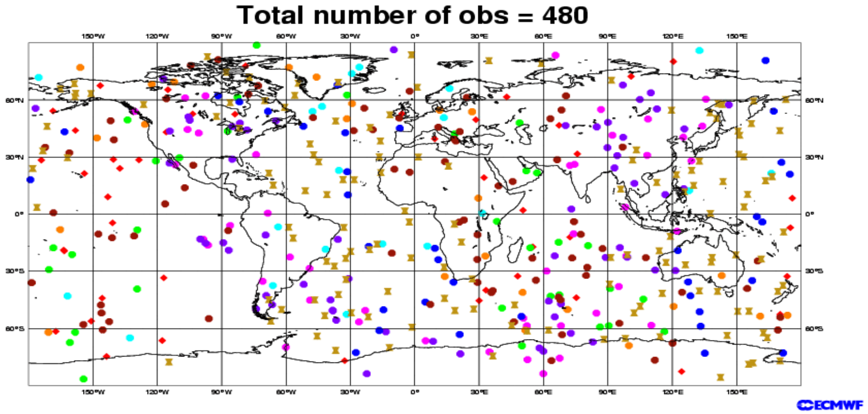
Radiosondes, PILOT, Dropsondes



ATOVS
(NOAA, EPS/METOP)



GPS
radio occultations



What do satellites measure ?

Satellite instruments measure: Radiances

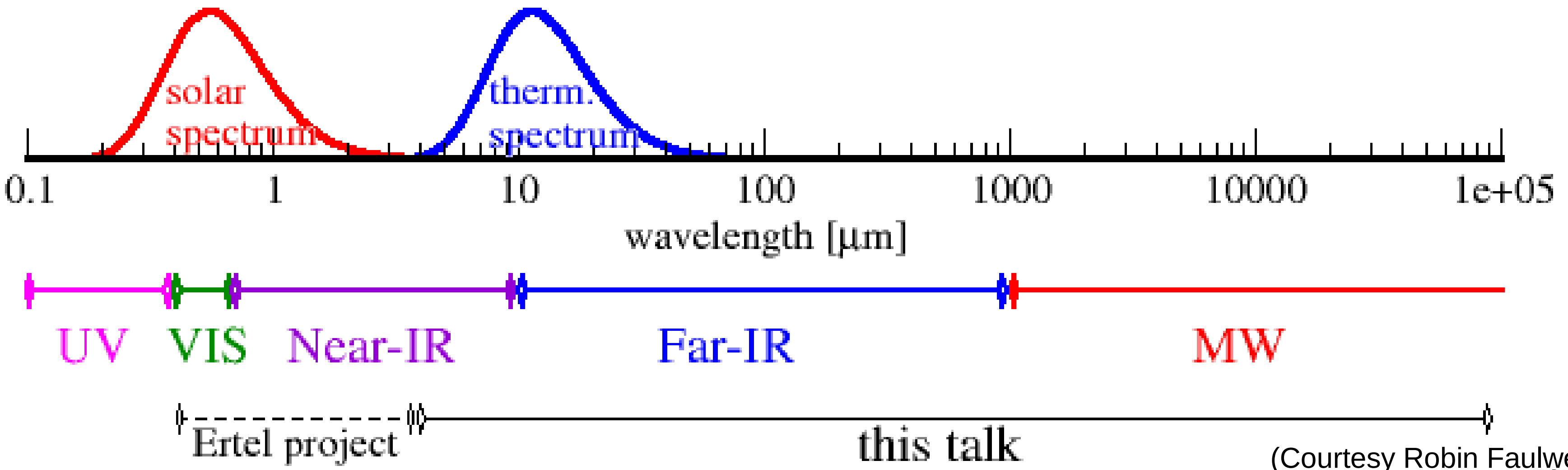
Emitted radiation	- From earth & atmosphere (thermal radiation)
Reflected radiation:	- Solar radiation - Radar / Lidar radiation

Electromagnetic spectrum

VIS = visible light

IR = infrared radiation

MW = microwave radiation

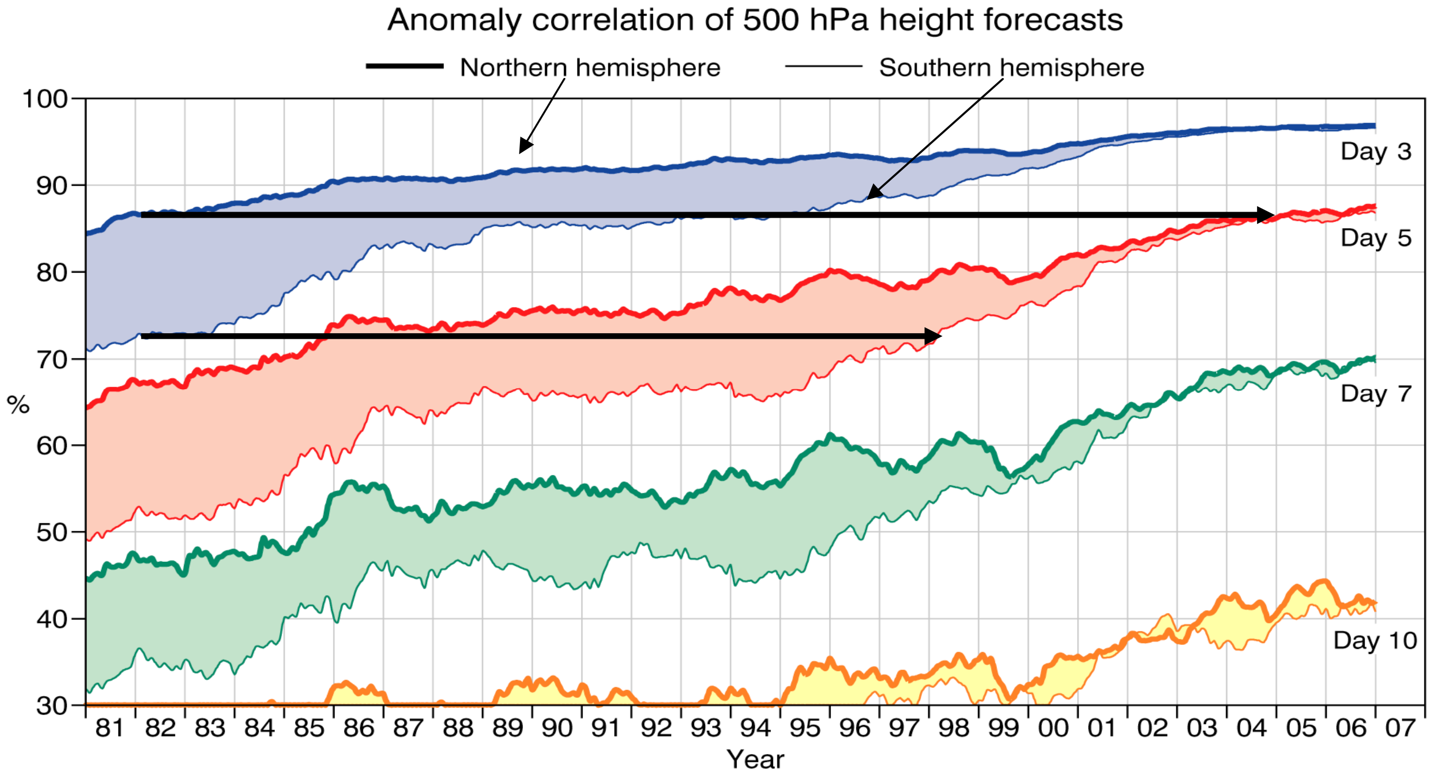


(Courtesy Robin Faulwetter)

Why are satellite data different from other observations?

- Indirect observations:
  - Physical principles of emission & radiative transfer have to be understood and modeled to extract information (→ H)
  - Observations are not localized but rather integral quantities
  - Special data assimilation methods needed (to use information well)
    → Variational assimilation methods
- One instrument provides global coverage:
  → Careful monitoring of data quality needed,
  risk of introducing erroneous data globally (→ Biases !)
- Huge data volumes:
  → Need for clever data selection, fast assimilation methods

Major global observation system component (III) : Forecast quality (evolution at ECMWF since 1981)



Courtesy, ECMWF 2008

- 5 days forecast on the NH are now better than 3 day forecasts in 1981
- Forecasts on the (data sparse) SH are now nearly as good as those on the NH !
- Improvements are due to: - model improvement
  - improvement of/new data assimilation methods
  - use of more, and better use of, observations, (satellite data !)

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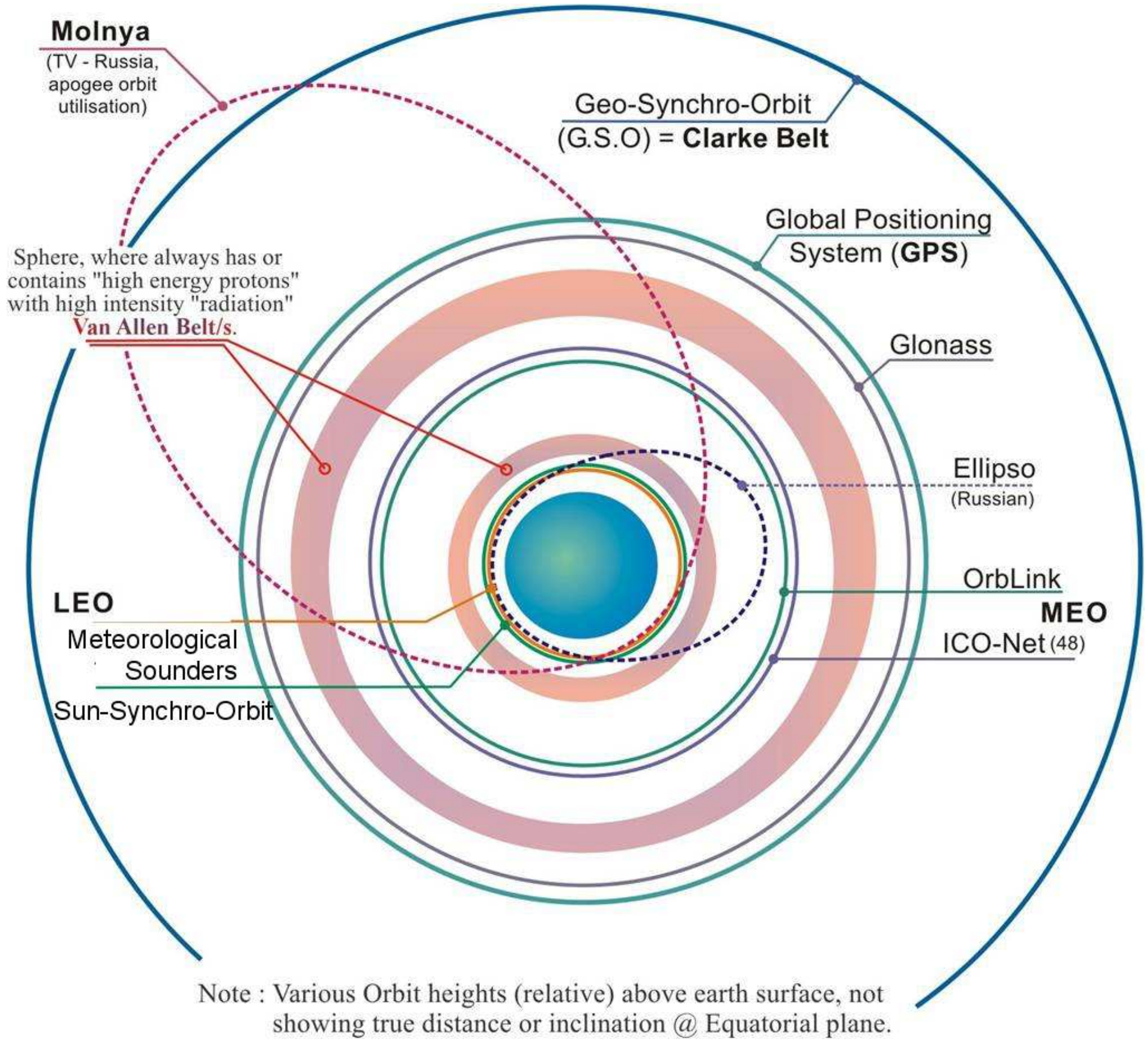
Satellite orbits: Classification



http://anityonugroho.blogspot.com/2011/04/satellite-communication-part-1.htm

Geo-**S**ynchronous **O**rbit (GSO)
Geo-stationary Orbit **(GEO)**

- Height: ~ 36000 km (35786 km)
- Period: 1 day (23h56m04s)
- Meteorological satellites: Meteosat, GOES

Medium **E**arth **O**rbit (MEO)

- Height: 1200 – 35786 km
- Period: ~ several hours
- Navigation satellites: GPS, Galileo, GLONASS

Low **E**arth **O**rbit **(LEO)**

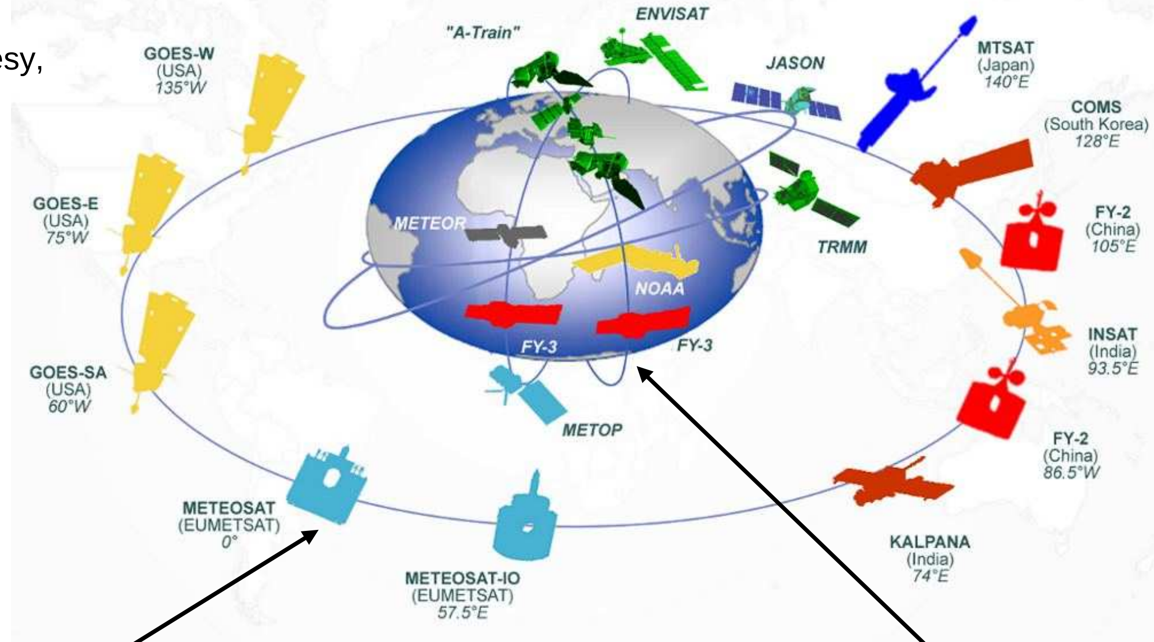
- Height: 200 – 1200 km
- Period: ~ 100 min
- Sun synchronous orbit (SSO)
- Meteorological satellites: NOAA, METOP

Highly **E**lliptical **O**rbit (HEO)

- e.g. Molnya Orbit
- Height: variable
- Future „high-latitude quasi-geostationary imager“

Global meteorological satellite configuration (I)

(Courtesy, WMO)



Special missions & Research satellites

mostly LEO/polar orbit

e.g. TRMM, „A-Train", JASON, ENVISAT.....

Geostationary satellites (GEO):

GEO orbit ~ 36000 km

USA: GOES
Europe: MSG (METEOSAT program)
Japan: MTSAT
China: FY – 2
Also: Korea, India

Polar orbiting satellites (LEO):

LEO orbit ~ 850 km

USA: NOAA, NPP
Europe: METOP-A (-B), (EPS program)

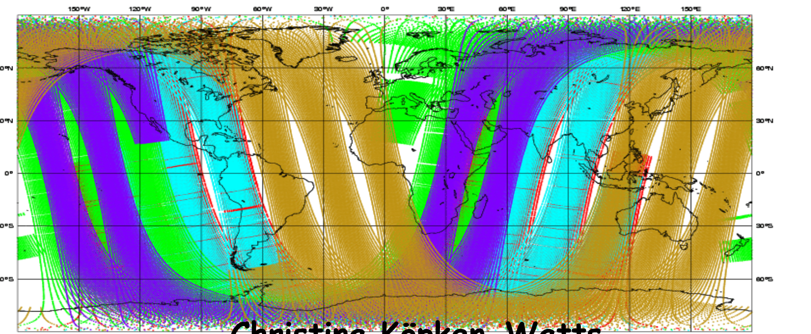
China: FY – 3
Also: Russia

Global meteorological satellite configuration (II)

LEO track
and scan (zoomed)

GEO: METEOSAT

Several polar orbiting
satellites allow
nearly complete coverage



Typical instrumentation/observed parameters:

GEO imagers:

- Cloud imagery at high time frequency (15 min. with 1-5 km)
- Few spectral channels: visible (VIS), infrared (IR), water vapour (IR-WV)

- Instruments: GOES Imager (on USA GOES satellites), 5 channels
  SEVIRI (on European Meteosat MSG), 12 channels

- Development: Temperature and humidity sounding
  Now: Coarse T-profile (atmospheric stability index)
  Ozone channel
  Future: High vertical resolution sounders (interferometer),
  (2019) similar to current LEO sounders

- Application: Forecasting, Regional numerical modelling

Typical instrumentation/observed parameters:

LEO:

- Cloud imagery with very high horizontal resolution (~ 1 km)

  -> AVHRR (VIS, IR channels)

- Profiles of temperature, humidity (horizontal resolution ~ 15 – 40 km)

  -> NOAA: HIRS, AMSU-A, AMSU-B

  -> METOP: IASI, HIRS, AMSU-A, MHS

- Many other applications:

  Sea & Land temperature, Sea ice & snow cover, Vegetation parameters
  Atmospheric trace gases,...

Research satellites & instruments, e.g.:

Precipitation
Ozone
Atmospheric composition/trace gases
Ocean surface wind
Soil moisture

Example of cloud image (AVHRR/ METOP satellite)

Karman Vortex Street
Off cap Verde Islands

(Courtesy, EUMETSAT)

AVHRR (on METOP)

Channels 1+2+4
RGB composite
(0.6, 0.8, 11.0 µm)

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Application areas in NWP:
How are satellite data being used for NWP ?

I) Derivation of physical fields for numerical forecasts

- *Assimilation*:

  Production of initial analyses for model forecasts
  - Global models
  - Regional models (+ other ground based remote-sensing data)

- Derivation of surface fields, like

  Sea ice cover, sea surface temperature,
  snow cover, vegetation information, ...

II) Verification / Model development

Detection of model deficiencies
→ improvement of numerical models

NWP application (I): Observed parameters for model initialisation & boundary fields

Boundary & Initial Field	Conventional Observations	Current Satellites or Instruments (main examples)	EPS – SG instruments
Orography Surface Type/Veg. Snow Cover Soil Moisture Albedo	 Snow obs SYNOP (T_{2m},RH_{2m}) Manual OBS	GPS AVHRR, MODIS, AIRS/IASI AVHRR, SSM/I SMOS MSG, GOES, GMS	 VII VII,LII,MWI,SCA SCAT 3MI, VII
SST/salinity Sea Ice Cover/Type Waves / Roughness	Ship, Buoy	AVHRR, AATSR, SMOS SSM/I, SSM/IS, AVHRR, AMSR-E Alt, SAR, ASAR	VII, IRS MWI, SCAT
Wind	RS, Aircraft, Pilot Profiler, SYNOP, Ship, Buoy	AMVs (GEO/MODIS), SSM/I, ASCAT, Windsat	SCAT, MWI VII
Temperature	RS, Aircraft, SYNOP	AMSU-A, HIRS, AIRS/IASI, SSM/IS GRAS, COSMIC, GRACE,…	IRS, MWS, RO
Humidity	RS, SYNOP	HIRS, AIRS/IASI, MHS, SSM/I, SSM/IS MSG, GOES, GRAS	IRS, MWS MWI
Clouds/aerosols	SYNOP	AVHRR, HIRS, GEO Sat. MODIS, AIRS/IASI, Cloudsat, CALIPSO	VII, IRS, LII MWI, 3MI UVNS
Rain	Rain gauges	TRMM/TMI, SSM/I, SSM/IS, AMSR-E	MWI, MWS
Ozone / Chemical Species	Ozone sondes	SBUV, GOME, SCIA, AIRS/IASI HIRS-9, MIPAS, GOMOS	UVNS IRS

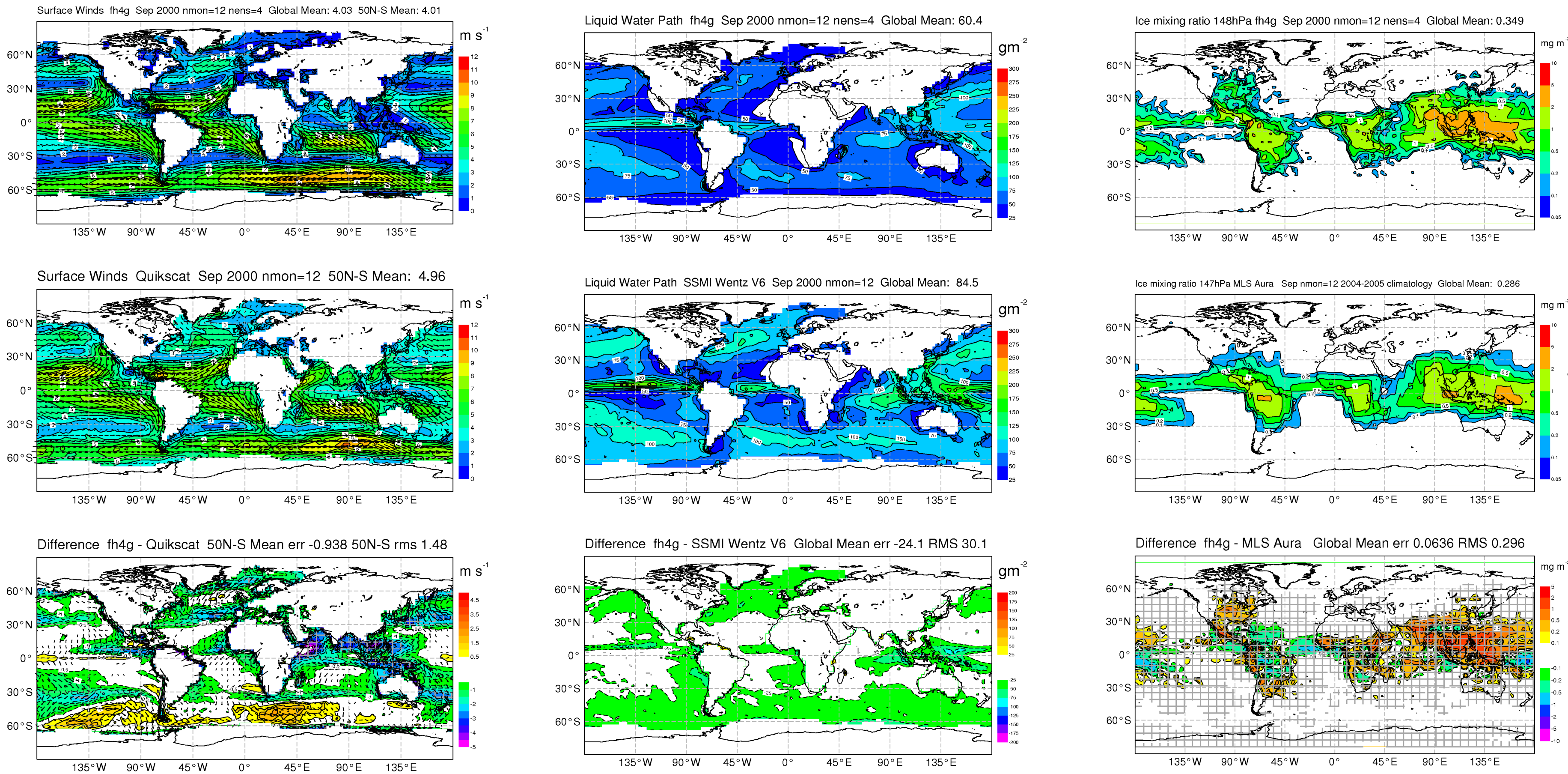
NWP application (II): Model development

Key areas of parameterization development			Typical instruments
Clouds	Occurrence	Horizontal distribution Profile Diurnal cycle	SEVIRI (GEO) AVHRR (LEO, NOAA) MODIS (LEO, research)
	Cloud phase	Ice, Snow, Water Mixed phase Particle sizes	„A-Train" and (SEVIRI, MODIS, IASI, …)
	Rain		SSMI, TRMM, ….
Radiation	Ozone		GOME, TOMS, SCIA….
	Aerosol		MODIS, ….
Surface	Soil moisture Vegetation parameters Albedo Snow, Sea ice, …..		SMOS, SSMI, ASCAT, AVHRR, MODIS, …. MODIS, SEVIRI, …. SSMI, MODIS, ….
Radiation budget			GERB, CERES, …..

Applications of satellite data in NWP / FE1:
Model development & parameterizations (FE13, FE14)

Example: Evaluation of model climate & detection of systematic biases

Monthly means of model and observed fields (ECMWF validation package, courtesy M.Köhler)



Surface wind (Scatterometer) | Cloud liquid water (SSM/I) | Cloud ice (MLS/Aura)

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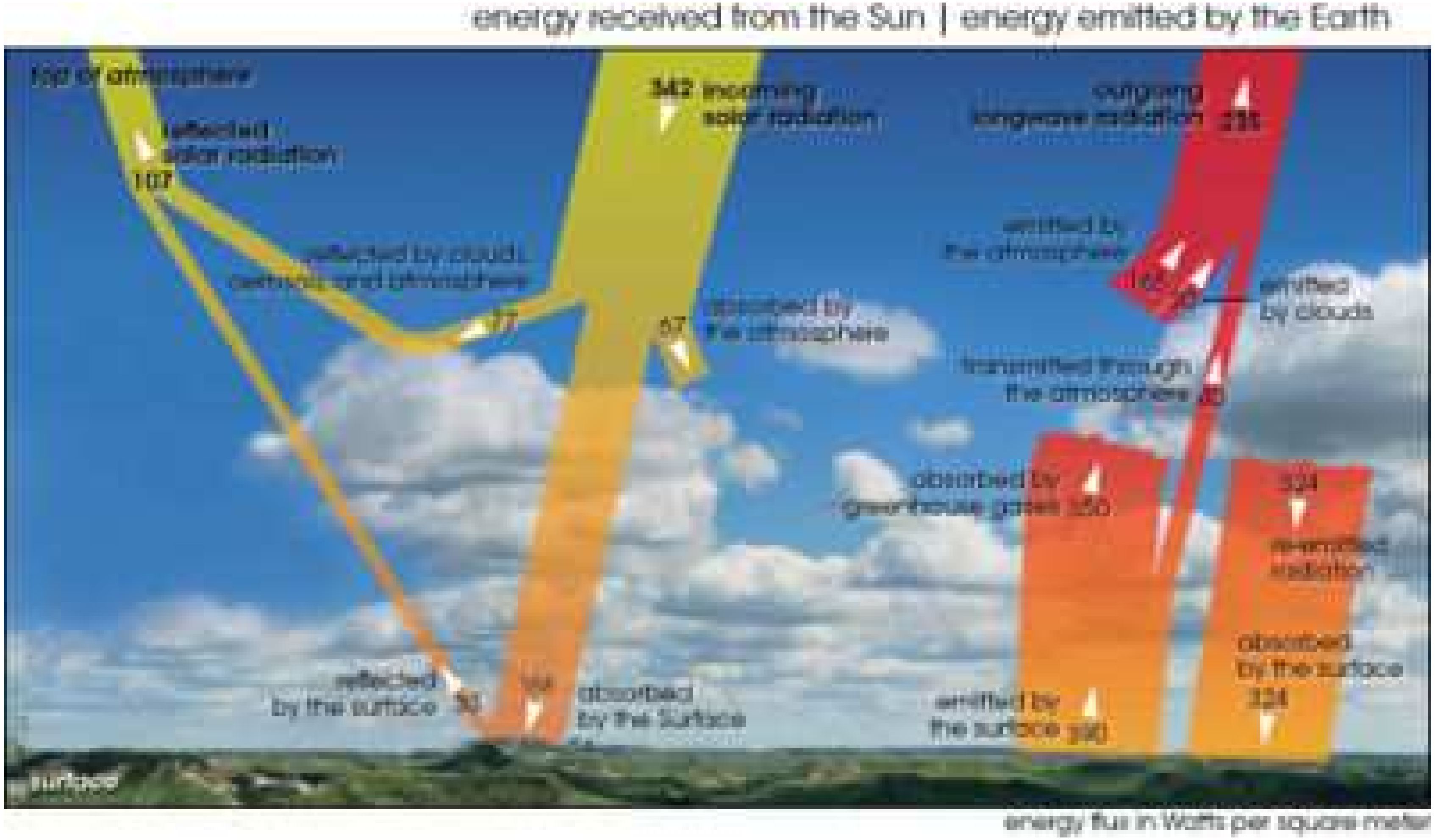
Physical measurement principles: **(I) Passive**

→ Measurement of radiation (VIS, IR, MW)
at top of the atmosphere



(http://www.noc.soton.ac.uk/jmodels/wiki/images/thumb/1/1c/EO_radiation_budget.jpg/400px-EO_radiation_budget.jpg)

Physical measurement principles: **(II) Active**

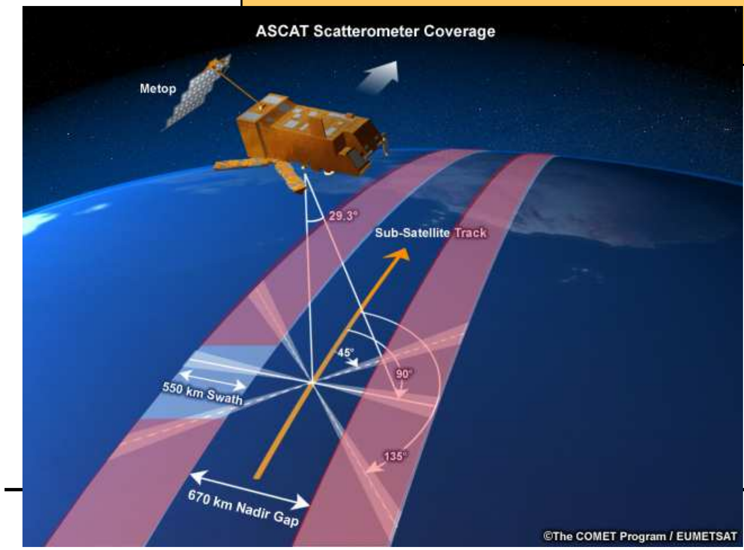
(a): Radar (MW): Wind

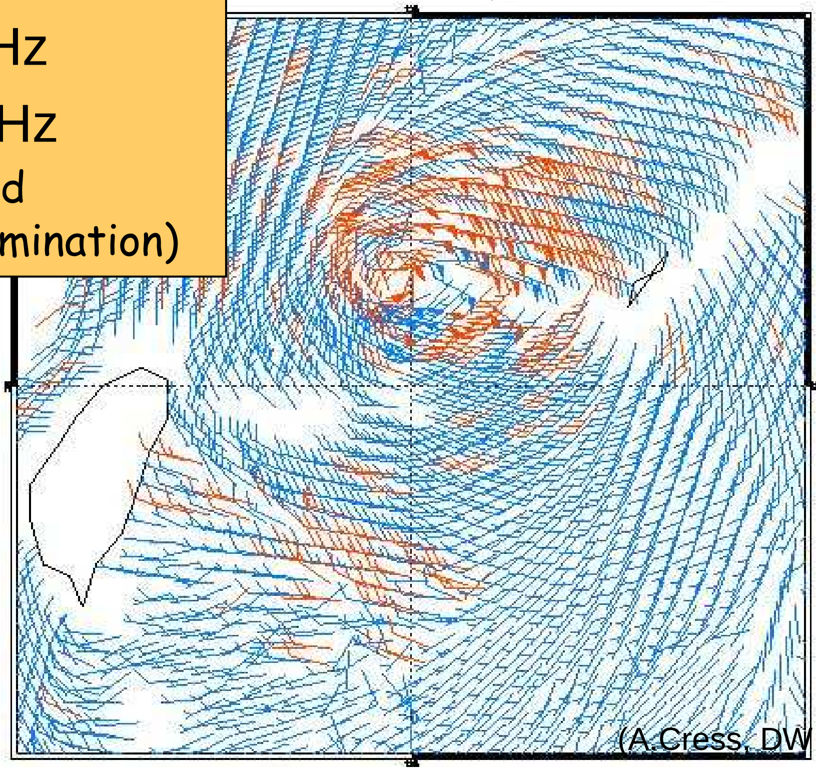
- Observed quantity: radar backscatter efficiency (cross section)
  -> related to capillary waves -> near surface wind retrieval
- Observations under most weather conditions
- Typical horizontal resolution: 25-50 km

- Satellites:

  ASCAT (METOP) : λ ~ 5.3 GHz

  Oceansat-2 (India): λ ~ 13.4 GHz
  (more affected by rain contamination)





(A.Cress, DWD)

Physical measurement principles: (II) Active

(b): Radar (Microwave): Clouds

- Backscatter of MW radiation by water droplets/rain
  -> clouds, profiles of cloud water/rain
- Nadir looking profile only (along satellite track)
- CPR on CloudSat („A-Train“, NASA) : λ ~ 94 GHz

(c): Lidar (Visible)

- Backscatter of light by aerosols & cloud

  -> clouds, aerosols (e.g. CALIOP auf satellite CALIPSO (NASA)
  -> winds (ADM-Aeolus (Europe,ESA), 2014)
- Nadir or line-of-sight only

Physical measurement principles:
(III) Limb Sounding

(a) GPS Radio occultations (passive/active)

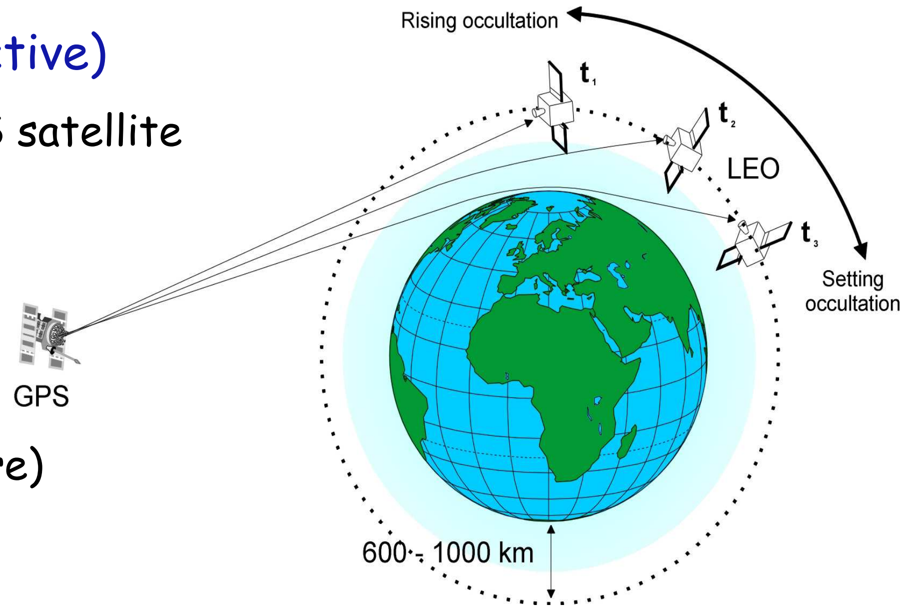
- MW ray (1.2, 1.5 GHz) from emitting GPS satellite

- Refracted in atmosphere,
  refraction depends on atmospheric
  refractive index = f (T, q, p,...)

→ **Temperature (and humidity) profiles**
  (esp. in stratosphere, upper troposphere)

→ Good vertical resolution
  Poor horizontal resolution (~ 450 km)

- Satellites: METOP, COSMIC, GRACE, TerraSAR-X, …

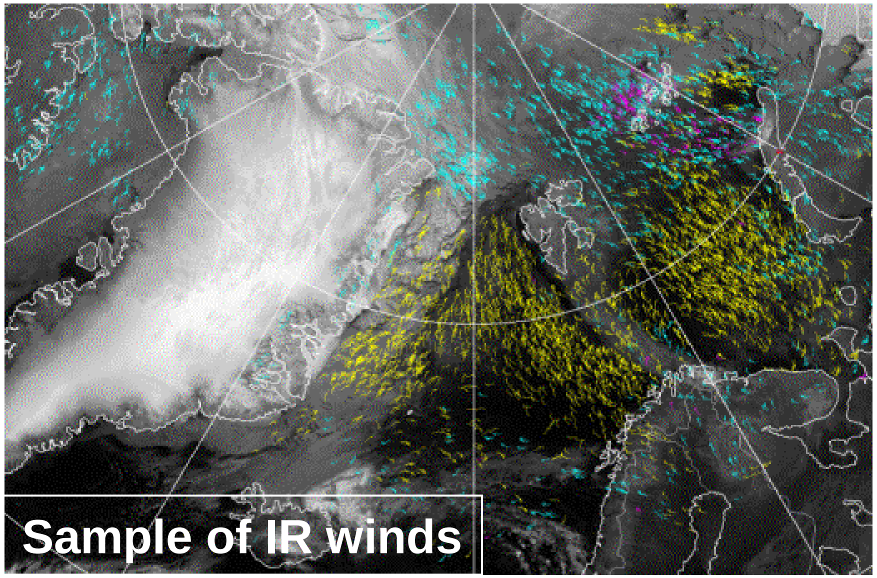


(b) IR Limb sounding (passive)

- IR emission from atmosphere (e.g. MIPAS on ENVISAT)
  → Temperature, humidity profiles
  → Trace gases

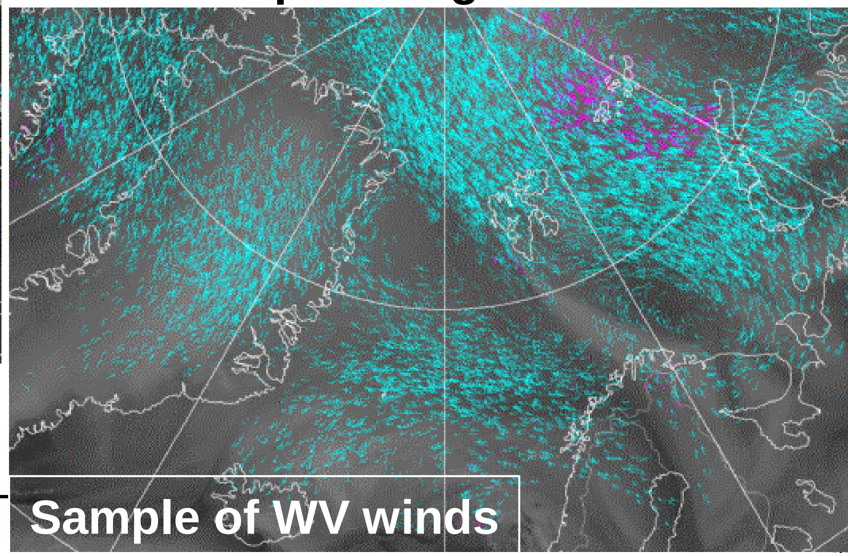
„Physical measurement principles" :
(IV) Atmospheric motion vectors (AMV)

- Tracking of cloud and other features (e.g. humidity gradients) in image sequences
- Uses visible, infrared and water vapour imagery
  - Geostationary satellites (METEOSAT, GOES, Chinese FY-2)
  - MODIS on polar orbiting Aqua & Terra satellites



Approx. 12 wind sets daily per pole
(N of 65N, S of 65S)

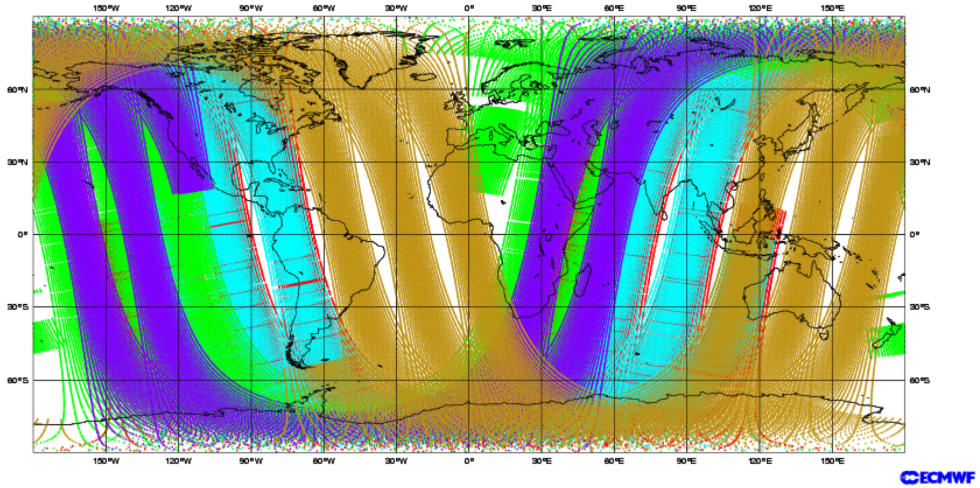
Example: MODIS winds give unprecedented coverage over the polar regions



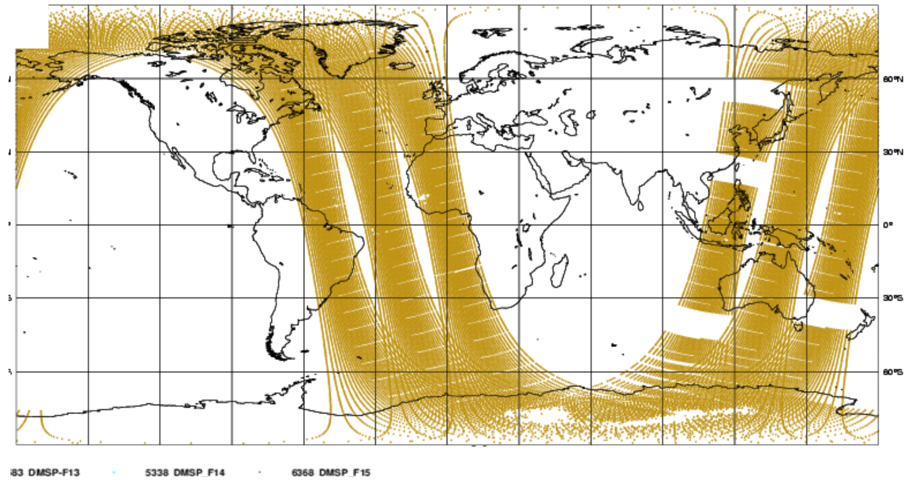
(Courtesy: N.Bormann, ECMWF)

Data coverage examples: Passive IR and MW sounders/imagers
(12 h coverage)

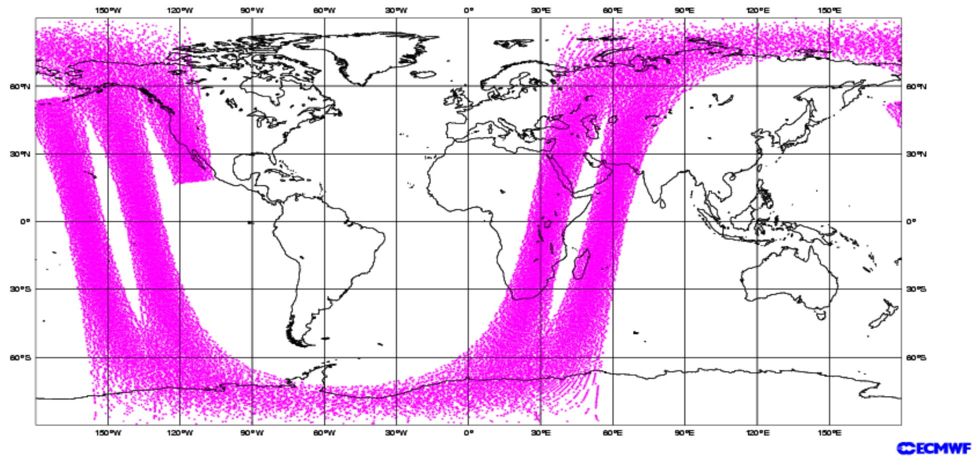
ECMWF Data Coverage (All obs DA) - ATOVS
10/JUN/2008; 00 UTC
Total number of obs = 373539



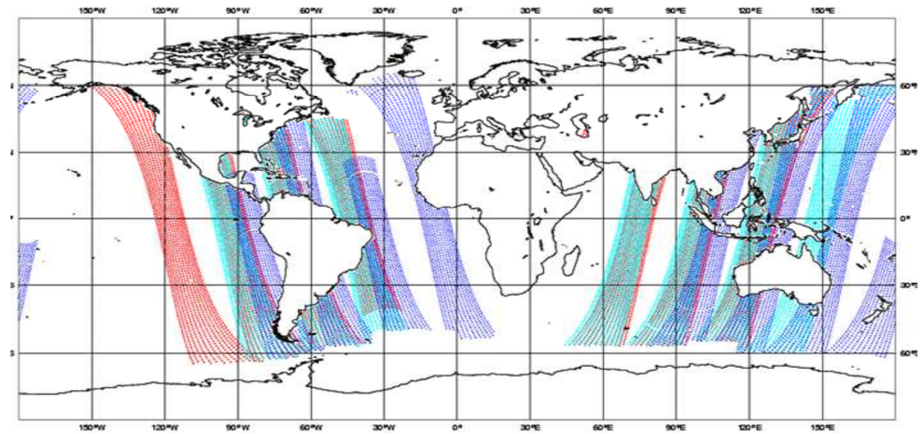
IASI radiances (METOP):
Temperature & Humidity Profiles



AIRS radiances (AQUA):
Temperature & Humidity Profiles

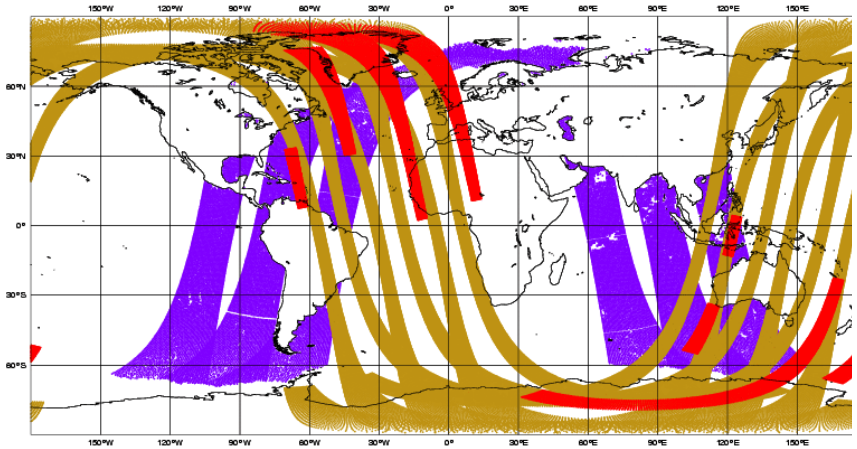


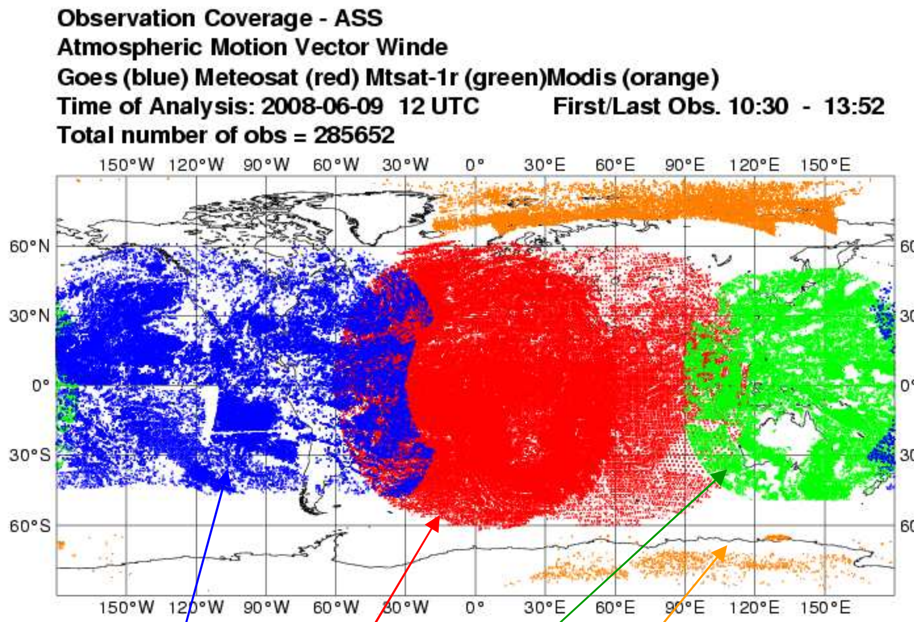
SSMI radiances: ocean wind speed, tota
water vapour content



Data coverage examples: Scatterometer, AMV and GPS radio occultation

Scatterometer (QSCAT/ERS-2/ASCAT): ocean surface wind vectors

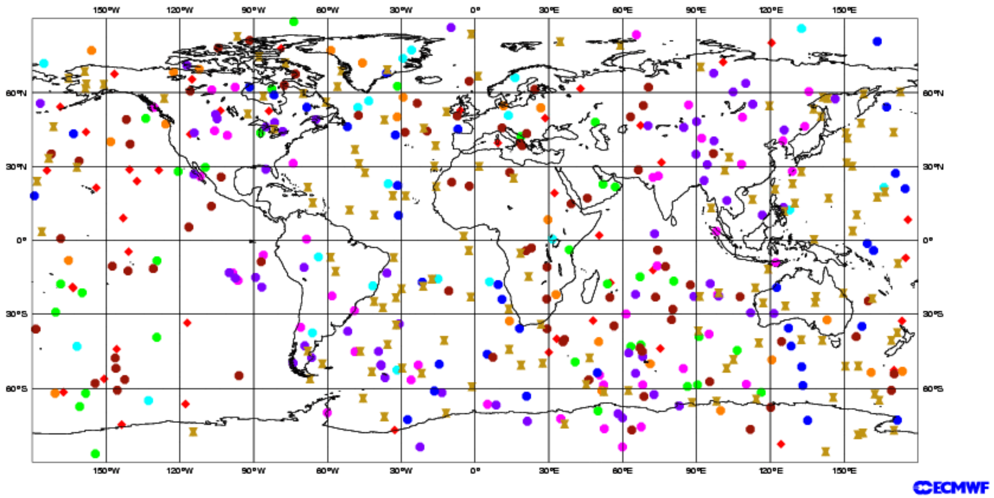




GOES/Meteosat/MTSAT: geostationary

MODIS: polar orbiting

GPS radio occultations (CHAMP/COSMIC/ GRACE/GRAS): Temperature profiles



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Radiative transfer: Basic processes / clear air

a) **Emission** from surface/atmosphere:

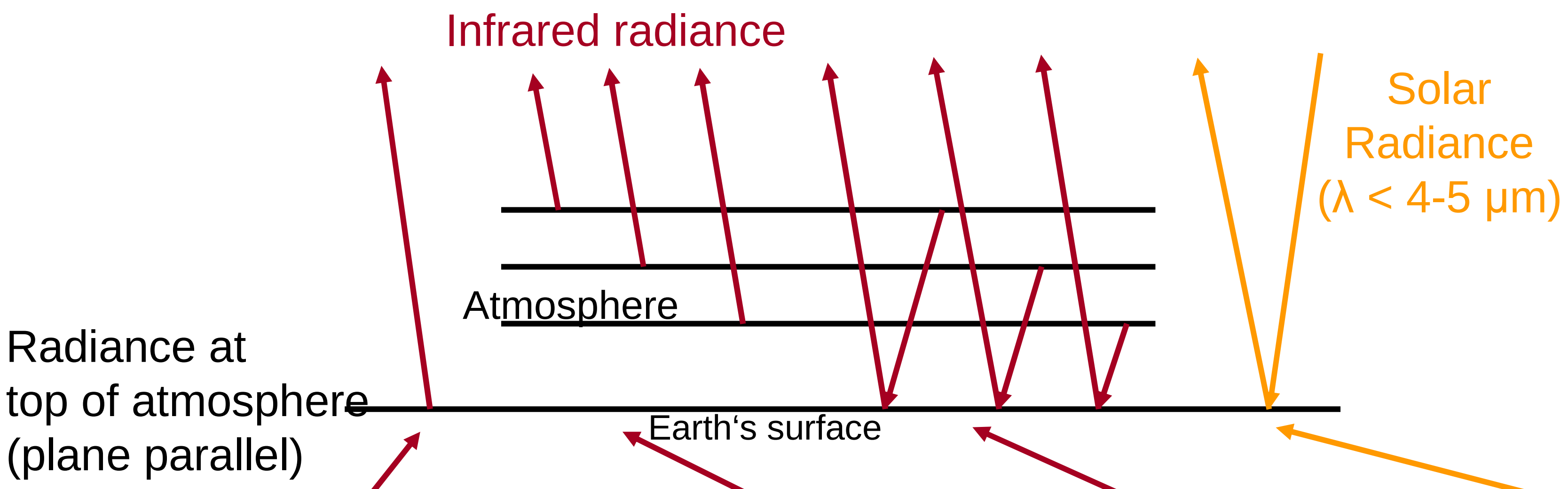
$B_\nu(T)$ Blackbody radiation (Planck function)

ε_ν Emissivity

b) **Extinction** (absorption, scattering):

$\Gamma_\nu(s_1, s_2)$ Transmittance

Γ_ν = f (distribution of absorbing gases & their extinction coefficient at ν)



$$L_\nu = B_\nu(T_s)\varepsilon_\nu\Gamma_{\nu s} + \int_0^\infty B_\nu(T(z))\frac{d\Gamma_\nu}{dz}dz + (1-\varepsilon_\nu)\Gamma_s L_\nu^\Downarrow + L_\nu^{Sun}$$

Radiative transfer: Basic processes / clear air …. with some more detail

a) Emission:

$B_\nu(T(z))$ Blackbody radiation (Planck function)

ε_ν Emissivity

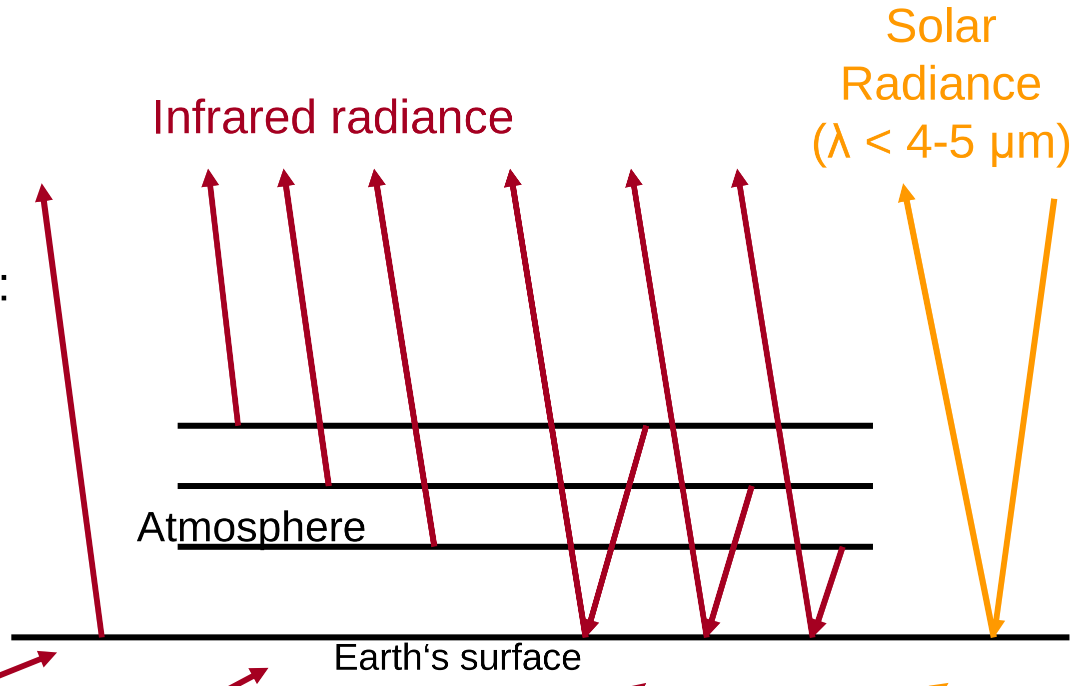
b) Extinction (absorption, scattering):

Optical depth (Ke=mass extiction cross section)

$$\tau_\nu(s_1,s_2) = \int_{s_1}^{s_2} k_e \rho \, ds'$$

Transmittance

$$\Gamma_\nu(s_1,s_2) = \exp(-\tau_\nu(s_1,s_2))$$

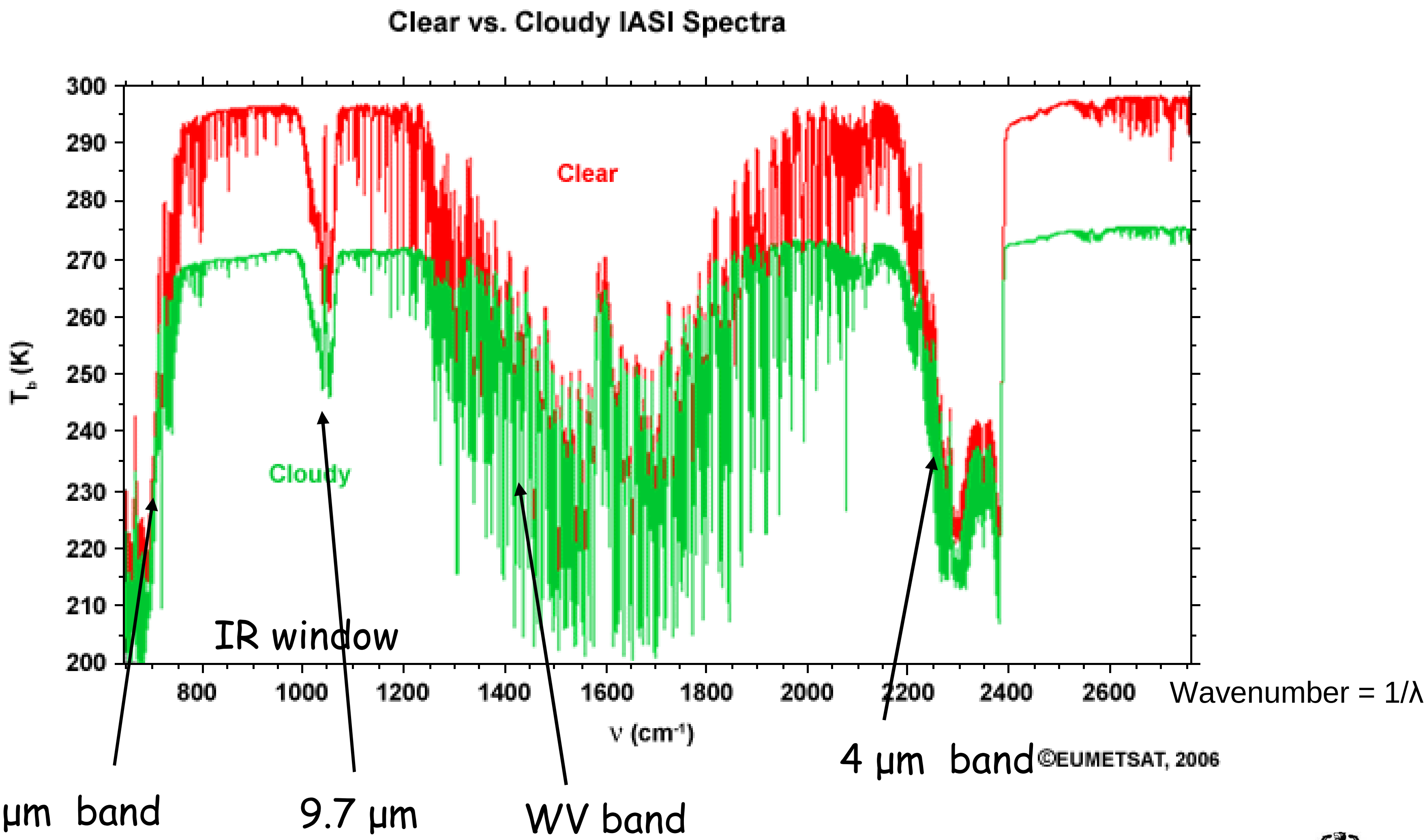


$$L_\nu = B_\nu(T_s)\varepsilon_\nu \Gamma_{\nu s} + \int_0^\infty B_\nu(T(z)) \frac{d\Gamma_\nu}{dz} dz + (1-\varepsilon_\nu)\Gamma_{\nu s}\left[\int_0^\infty \left(\frac{\Gamma_s B_\nu(T(z))}{\Gamma^2}\right)\frac{d\Gamma_\nu}{dz} dz\right] + L_\nu^{Sun}$$

Radiance at top of atmosphere (plane parallel)

Infrared (IR) Spectrum: Detailed structure

IASI can observe detailed line strucutre of emission spectrum
→ trace gas information



Weighting functions (I)

Spectral lines

(a) Interaction: Radiation ↔ Molecule:

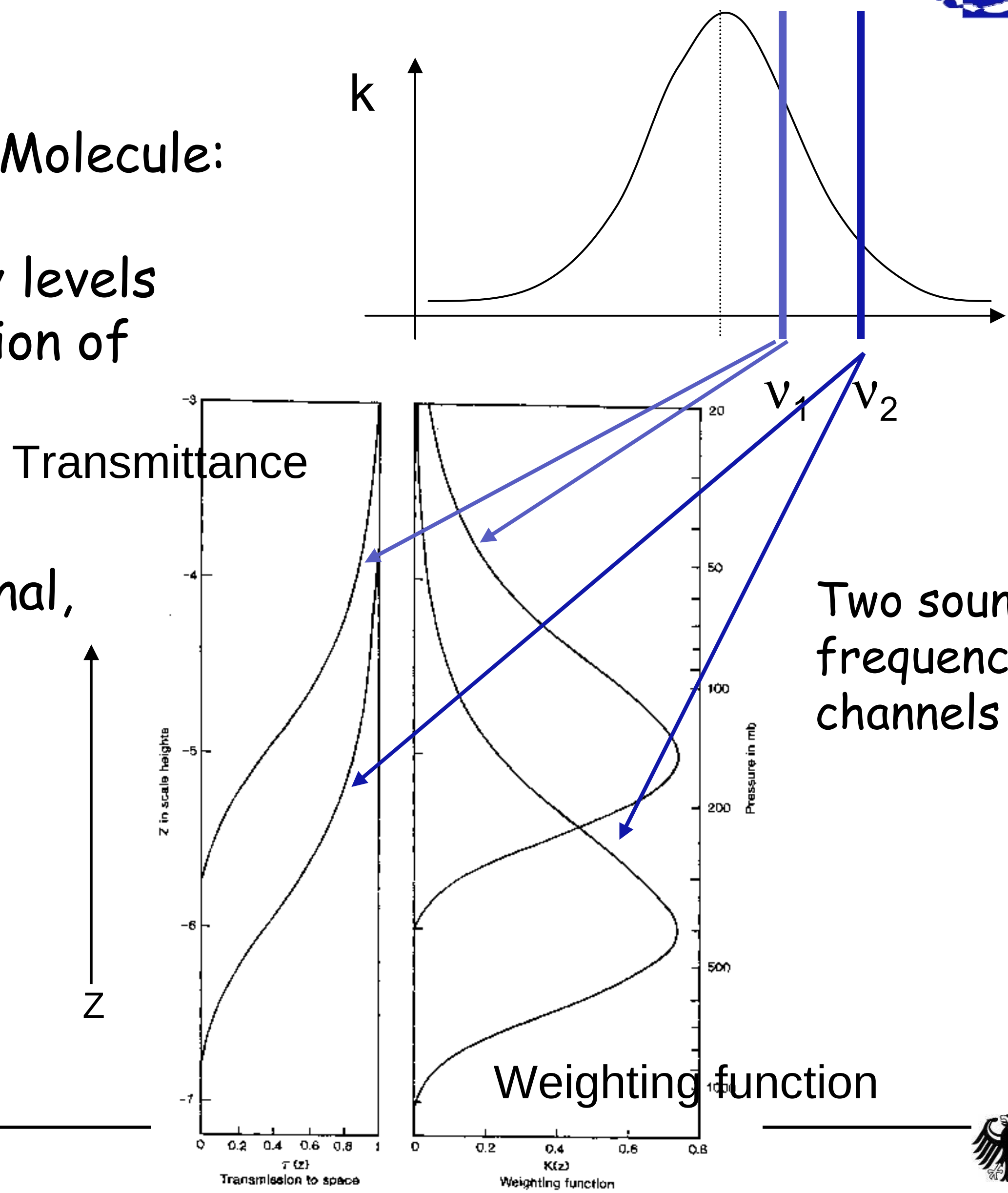
- Molecule changes energy levels through absorption/emission of electromagnetic radiation

- Discrete energy levels (electron levels, vibrational, rotational states)

(b) Lines are shaped by

- Pressure broadening (collisional broadening)

- Doppler broadening



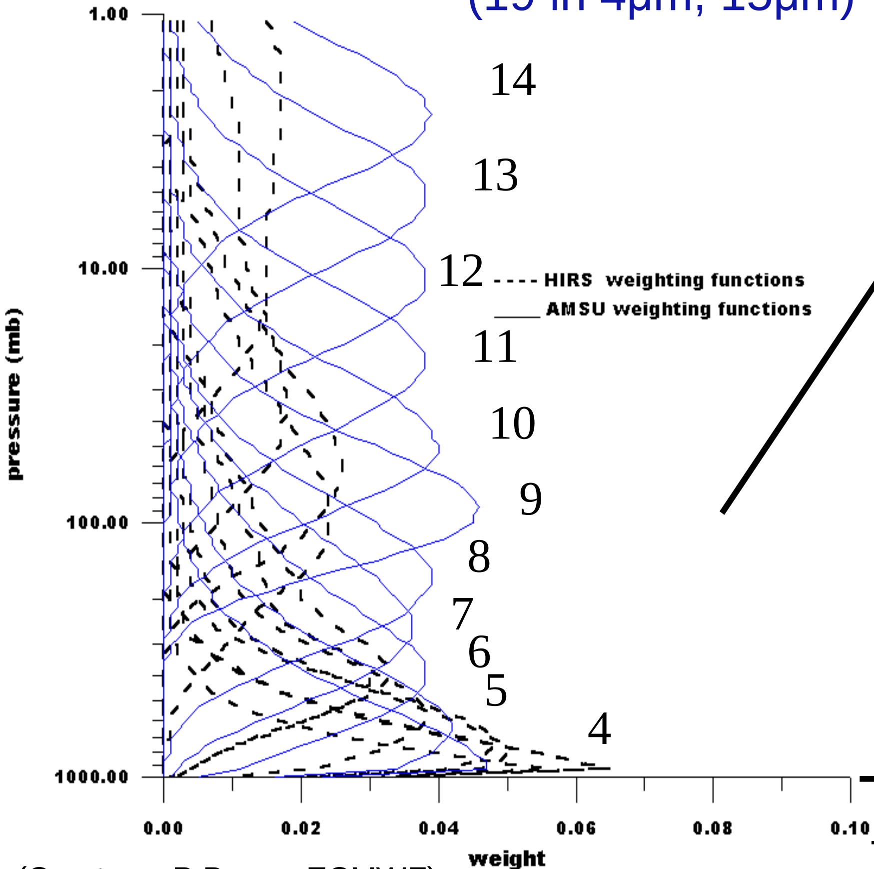
Two sounding frequencies/ channels

Weighting functions (II): Sounders (IR,MW) and High resolution sounders (IR)

AMSU-A (T)	15 channels (MW)	
	(10 in 50-57 GHz)	
HIRS (T, Hum.)	20 channels (IR)	
	(19 in 4µm, 15µm)	

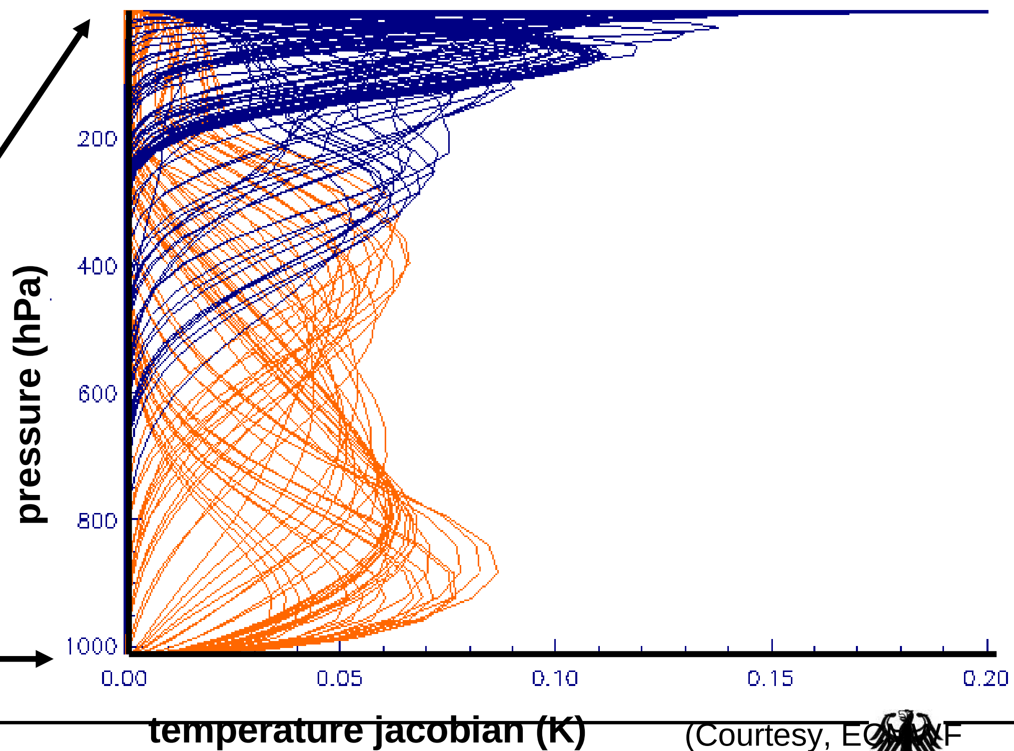
High resolution sounders:

AIRS (USA, Aqua)	2378 channels
IASI (METOP)	**8461**
CrIS (NPP)	1305



(Courtesy, P.Bauer, ECMWF)

AIRS channels



(Courtesy, ECMWF
P. Watts, 2003)

Weighting functions (III): Humidity sounding

- Peak of weighting function depends on amount of absorber

- Dry atmosphere
  → lower optical thickness
  → change of transmittance at low levels
  → low peak of weighting function
  → higher observed TB (most cases)

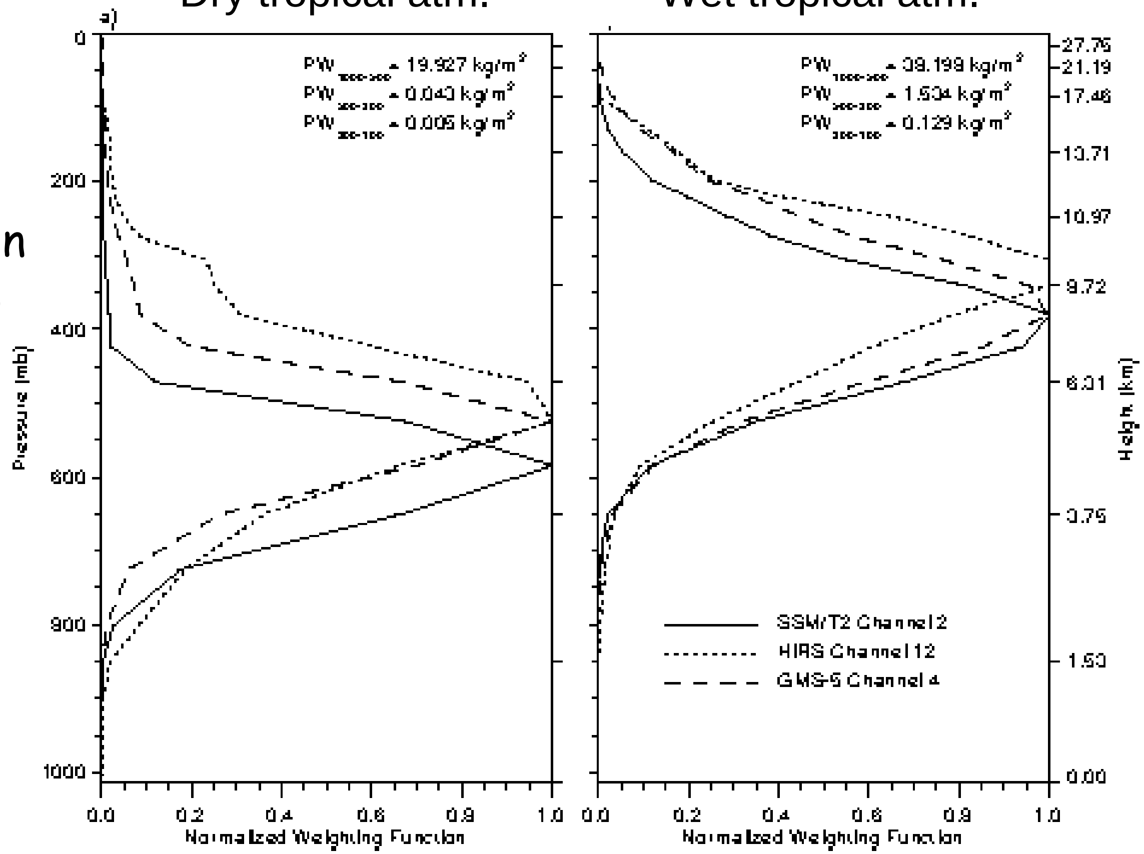
Note:

- Inversion problem from observation to humidity dependes strongly on
  - Humidity itself
  - Temperature profile

  → strongly non-linear problem !

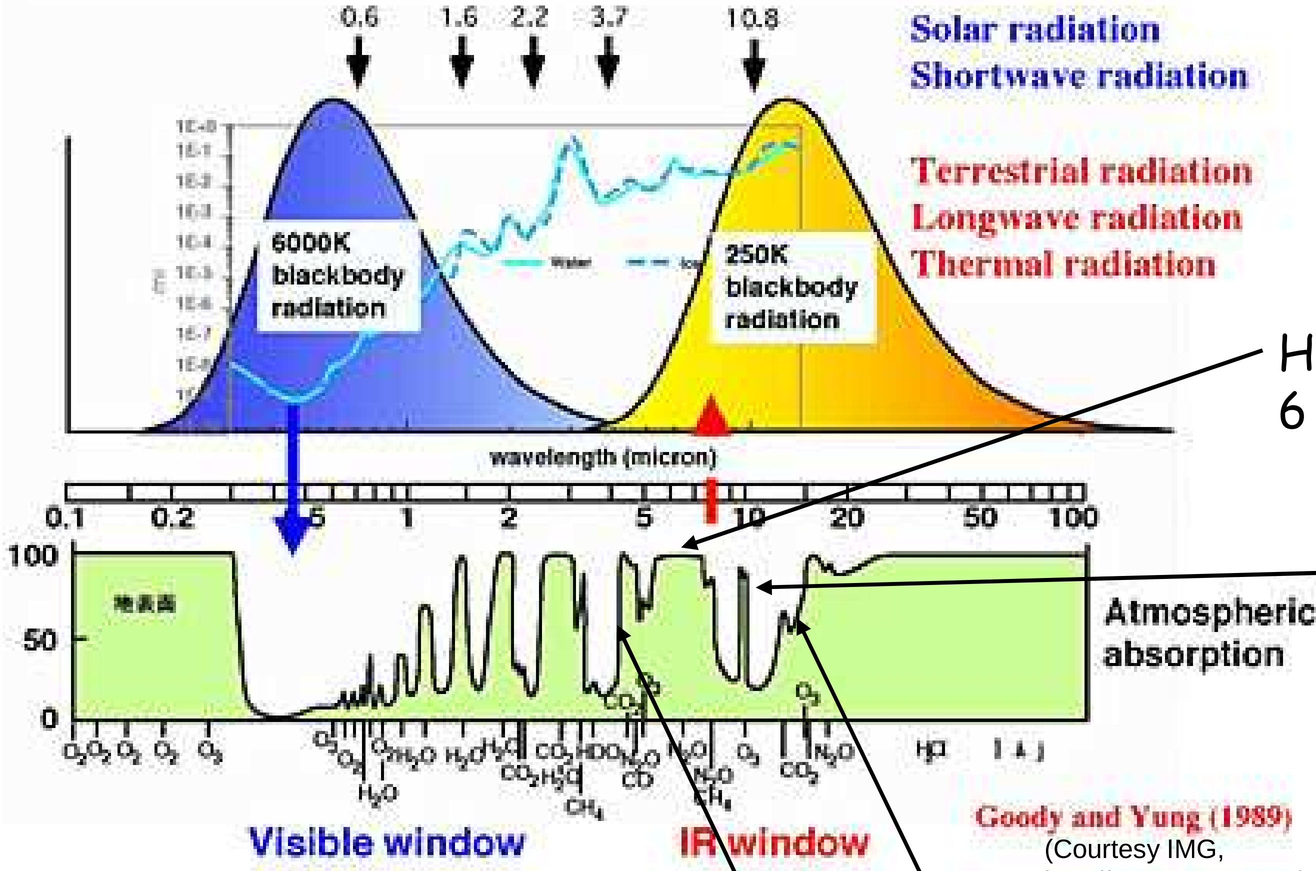
Upper tropospheric humidity sounding channel for

Dry tropical atm. Wet tropical atm.



(Fig: Courtesy, Atmos. Phys. Univ. Toronto: http://www.atmosp.physics.utoronto.ca/SPARC/WAVASFINAL_000206/WWW_wavas/Chapitre1/Fig1_10.gif

Infrared (IR) Spectrum & Important Channels



(Courtesy IMG, http://157.82.240.167/subjects/introduction/img/cli_rad_gp/fig2_e.jpg)

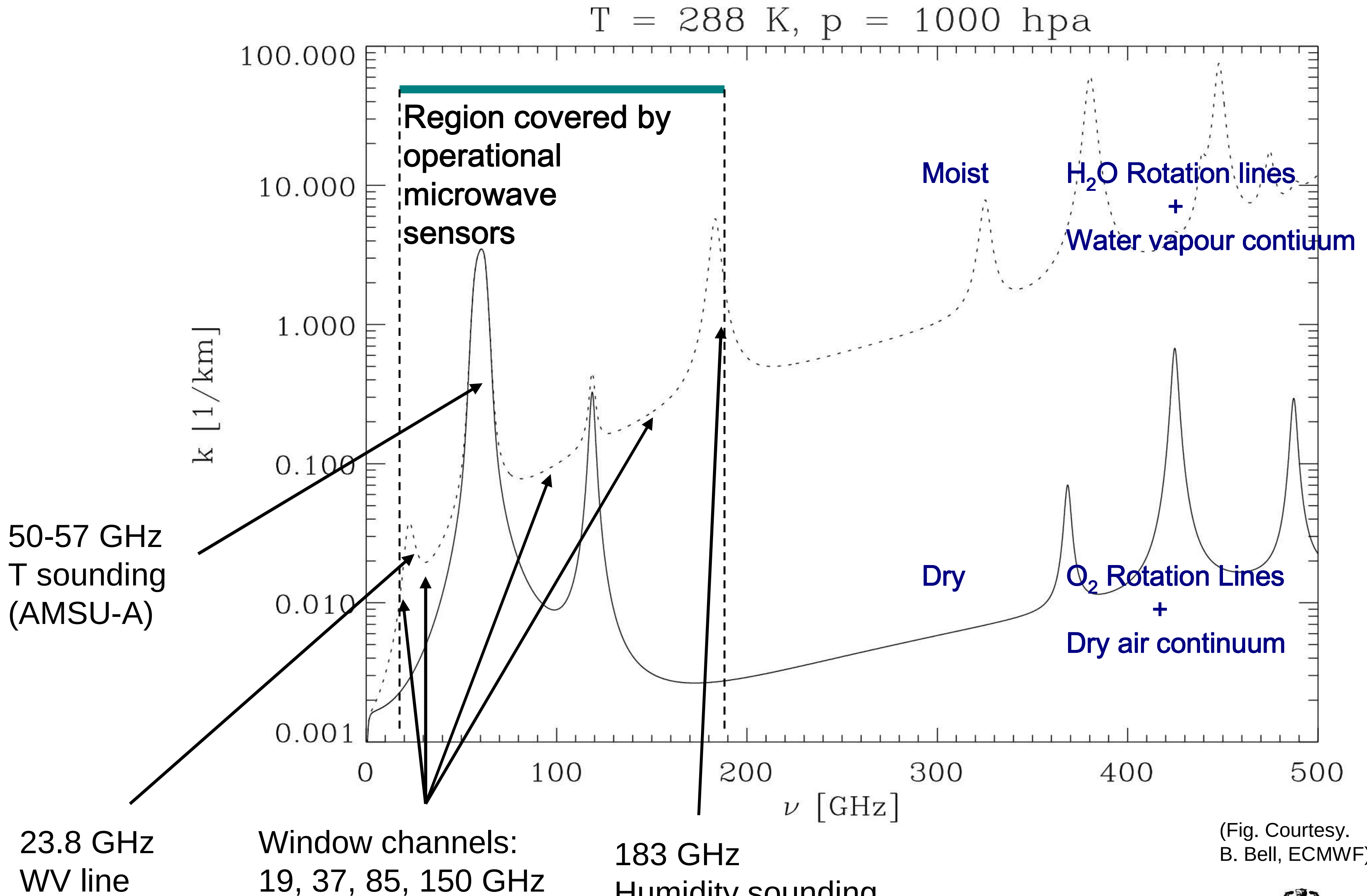
Humidity sounding (WV)
6 – 7.5 µm (6.2, 7.3 µm)

Ozone Channel:
9.7 µm

Temperature sounding: 4 µm , 15 µm bands (CO_2)

Typical imager channels:
VIS channels: 0.6, 0.8, 1.6 (NIR 3.7 µm)
IR window: 10.8, 12.0 µm

Microwave (MW) spectrum



(Fig. Courtesy. B. Bell, ECMWF)

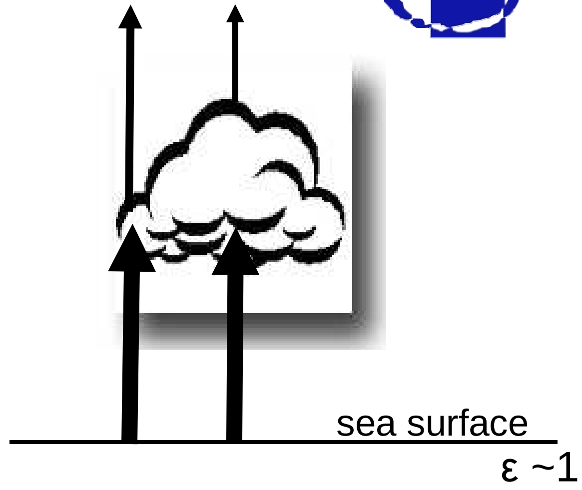
(SSMI , SSMIS, AMSR-E…)

Influence of clouds in IR and MW

IR

- Cirrus : Transmittance > 0, ε < 1

  Water clouds: Generally more opaque ε ≤ 1
- Transmittance (absorption/ emissivity, scattering) is a function of
  - wavelength
  - cloud phase (water, ice)

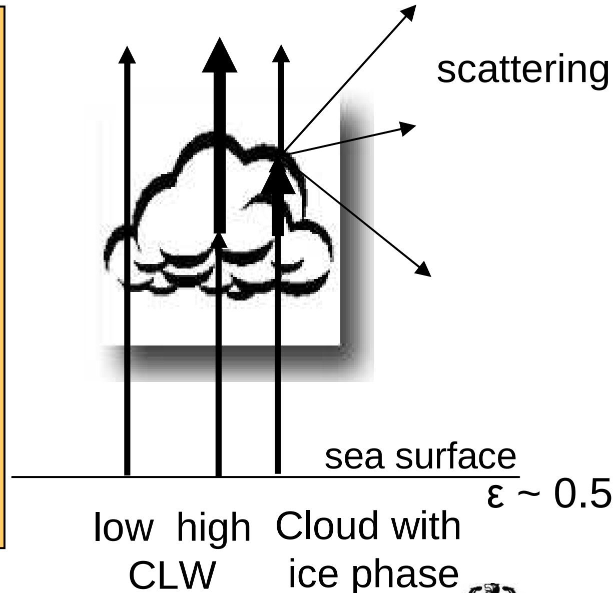


MW (λ ~2-6 mm)

- Emission: depends on cloud water contents
- Scattering: depends on size parameter: $x=2\pi r/\lambda$

  (a) Water clouds: droplets r~10µm
  -> homogeneous absorbers/emitters

  (b) Rain, ice, snow: r~1-10mm, x~1
  -> scattering important, esp. at higher frequ.



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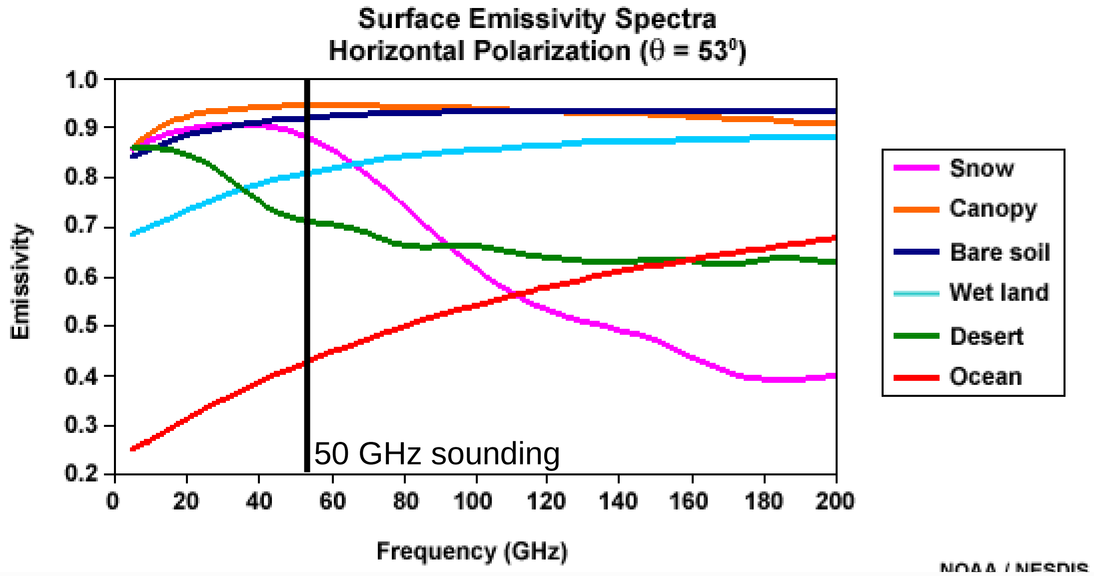
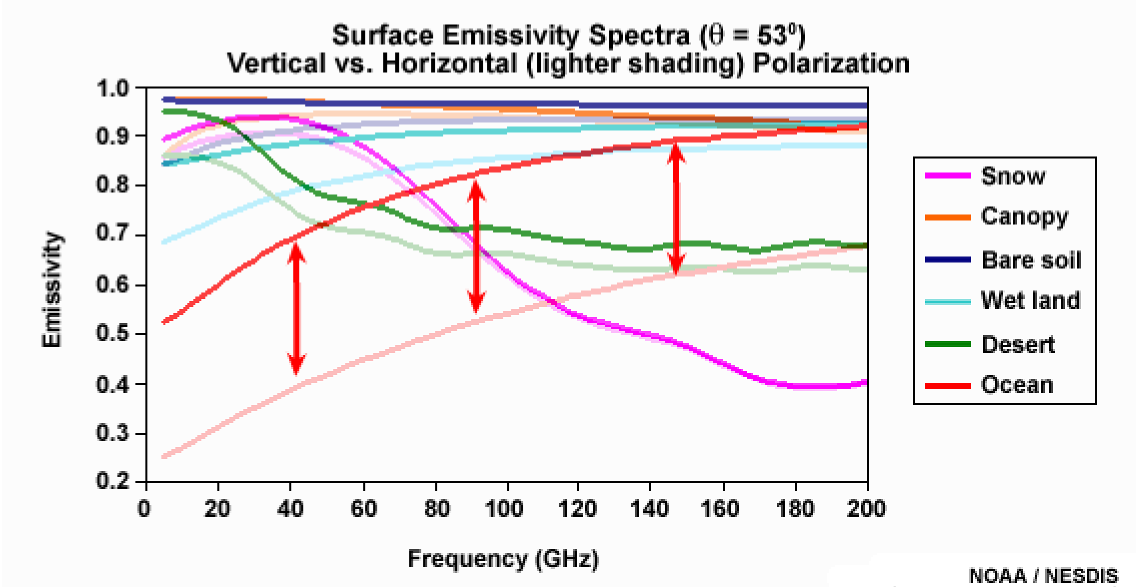
- (III) IR and MW radiance observations & instruments
    - Radiative transfer: basic processes (clear & cloudy)
    - **Influence of water and land surfaces (emissivity)**
    - Background: Vertical structure of the atmosphere
    - Examples of infrared & microwave radiance observations
    - Potential and limitation of radiance observations

Surface emissivity: MW



- Emissivity of water much lower than for most land surfaces
- Sea is "cold background" for sounding channels



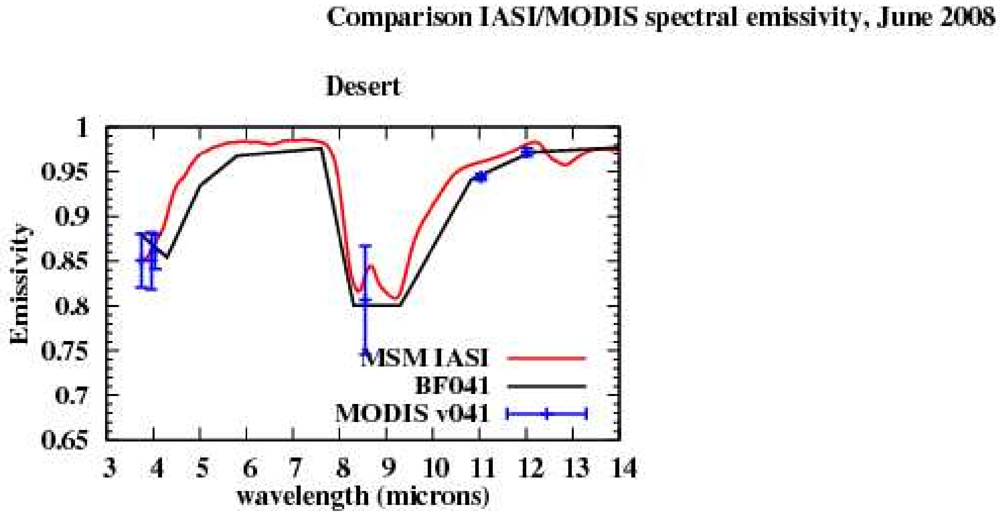
(Courtesy, COMET)

- Sea surface emission is polarised.
- Degree of polarisation reduced with rougher surface / waves.

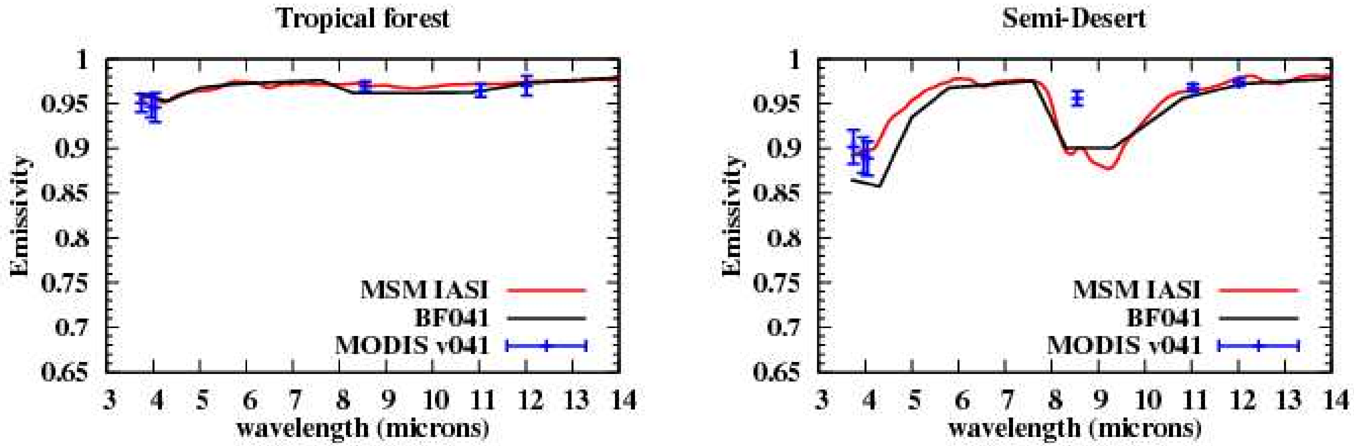
-> measured polarisation yields information on wind speed

Surface emissivity: IR

- Over land: Accurate retrievals of T – profiles and Ts need precise emissivity ε_s



- Highest ε_s variation over desert ~ 0.8 – 0.98
- Dense vegetation has relatively uniform high emissivity ε_s ~ 0.96 - 0.98



(Fig.: Courtesy, ARA/LMD/CNRS)

Note: Spectrum is combination of retrieval from IASI obs (40 selected channels) and high spectral resolution laboratory spectra (MODIS/UCSB, ASTER/JPL)

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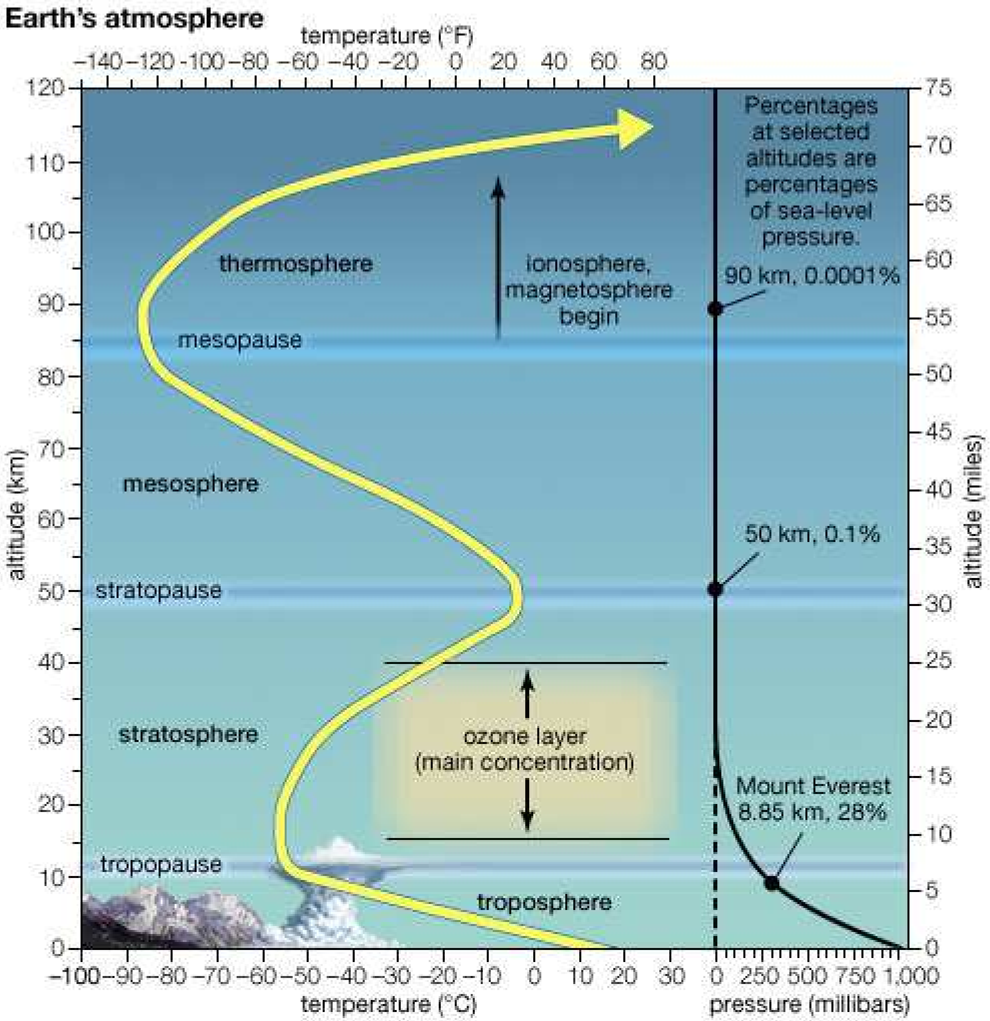
Background information:
Vertical temperature profile of the atmosphere



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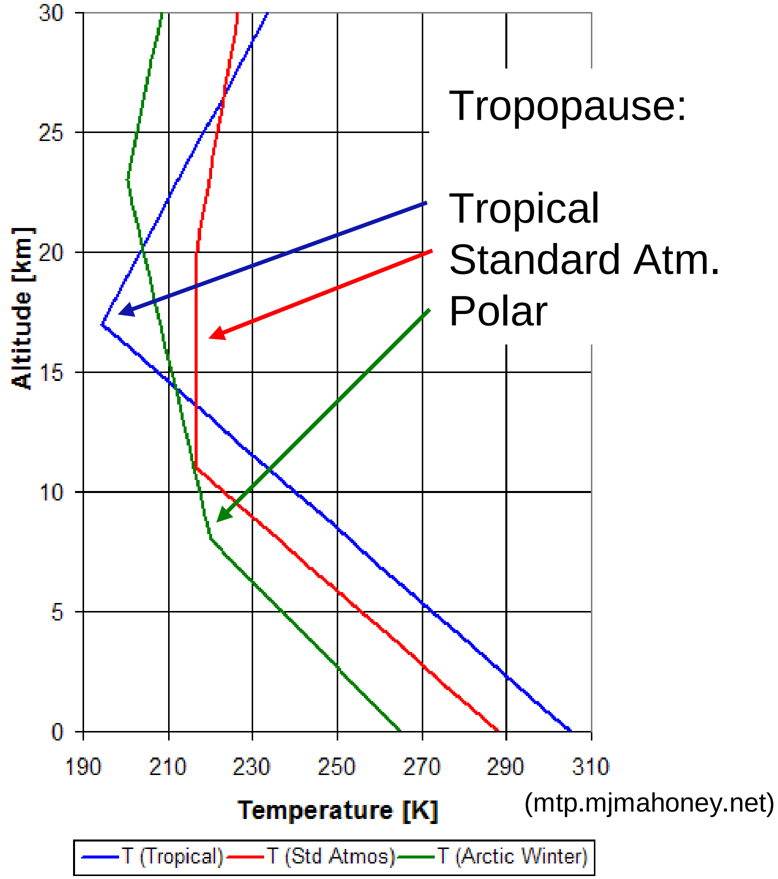
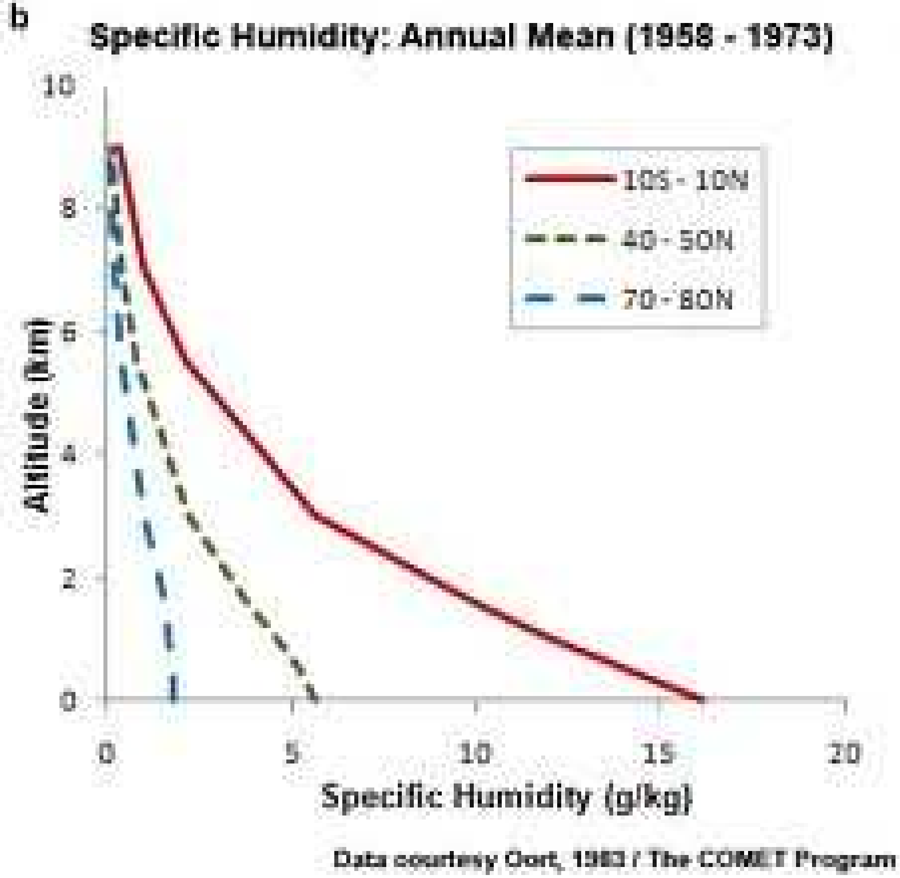
Variation of Temperature and Tropopause Height with Latitude

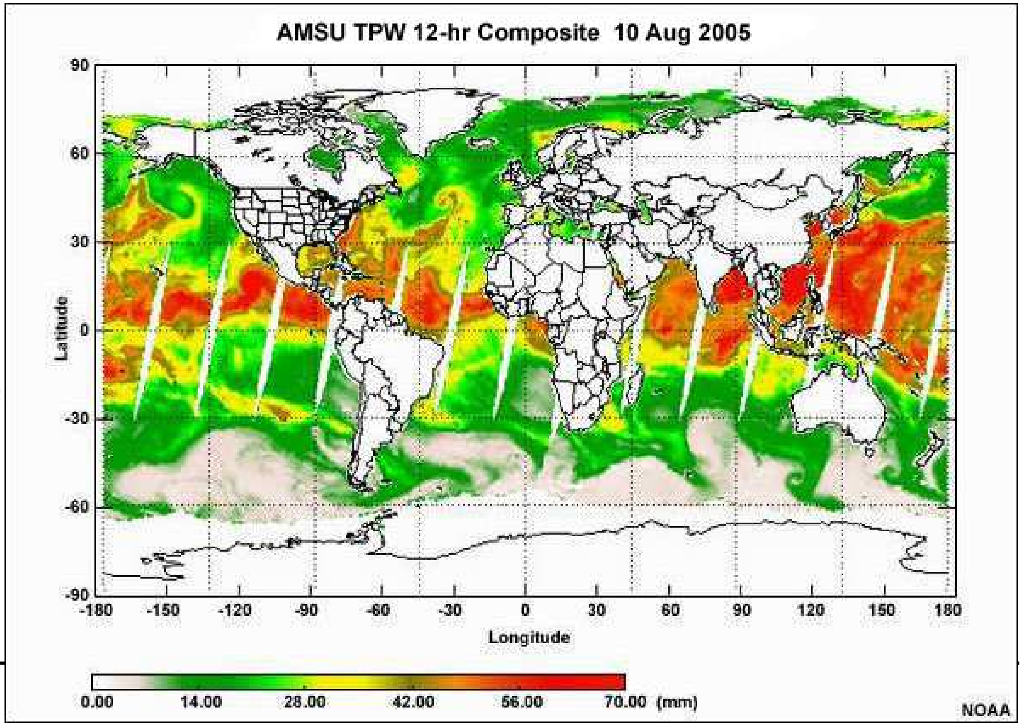


(mtp.mjmahoney.net)

Background information: Vertical humidity profile of the atmosphere

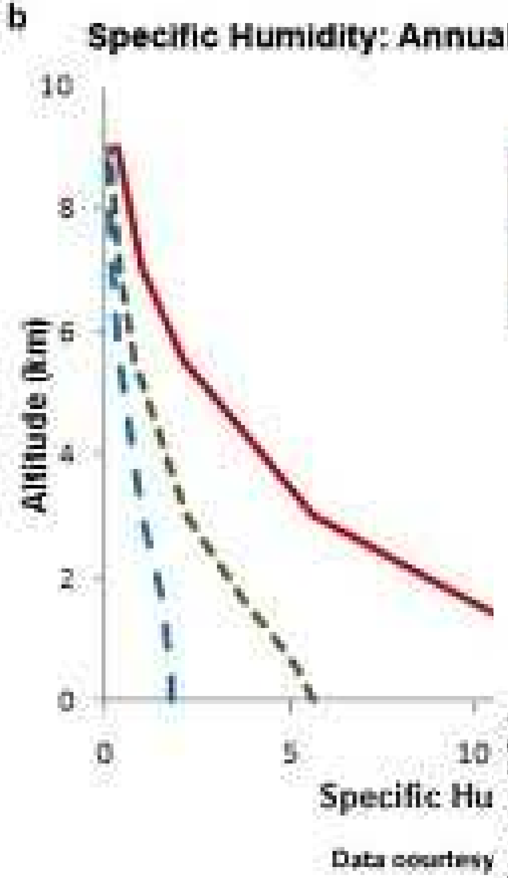


- Bulk of humidity is at low levels
- Strong variation with latitude:
  Tropics ~ 55 – 70 mm IWV
  Poles ~ 10 – 14 mm IWV



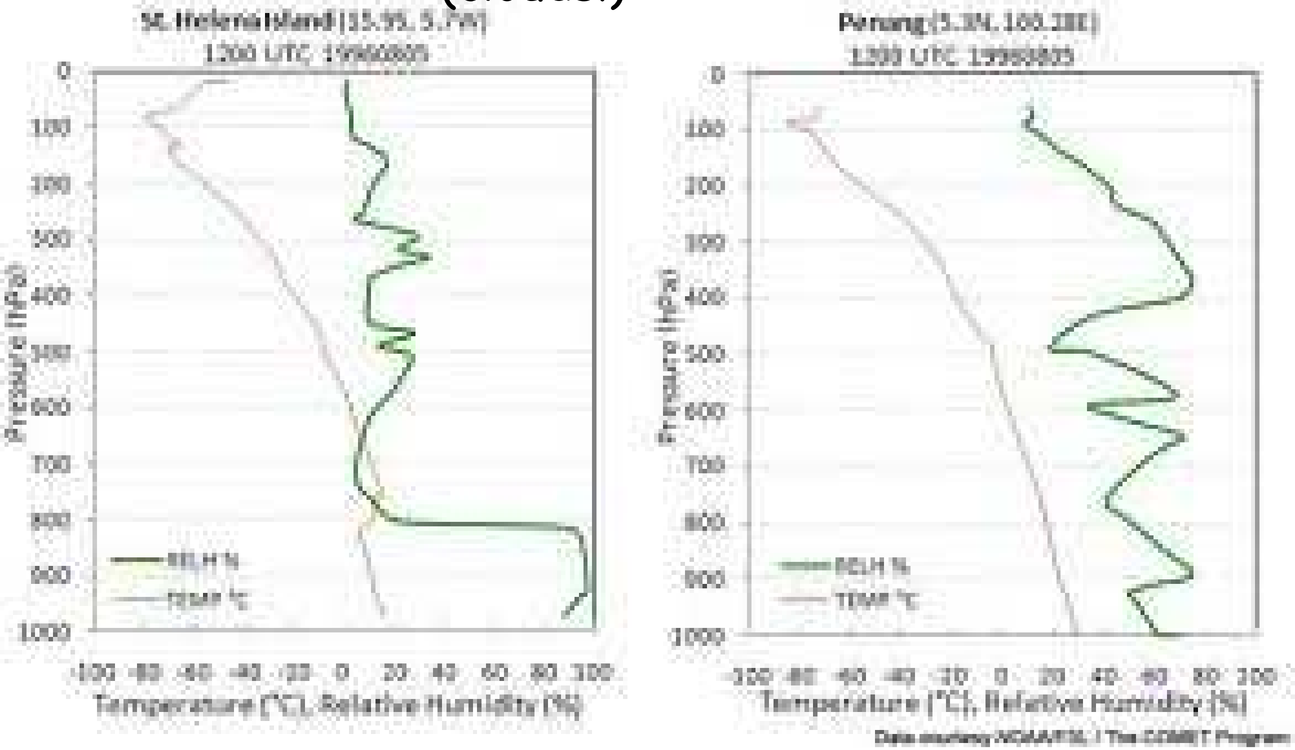
(Courtesy EUMETSAT)

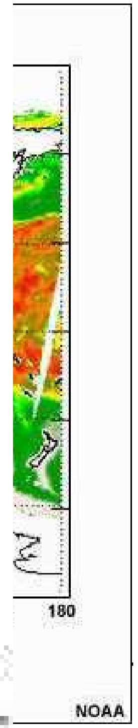
Background information: Vertical humidity profile of the atmosphere



- Bulk of humidity is at low levels
- Strong variation with latitude:
  Tropics ~ 55 – 70 mm IWV
  Poles ~ 10 – 14 mm IWV

- Profiles of Relative humidity very variable (clouds!)





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  - Potential and limitation of radiance observations

Examples of radiance measurements

Note: IR and MW

Radiances [W / m^2 sr s^{-1}] are converted to Brightness temperature TB [K]

Using Planck's law

$$B_\nu(T) = \frac{2h\nu^3}{c^2\left(e^{\left(\frac{h\nu}{kT}\right)} - 1\right)}$$

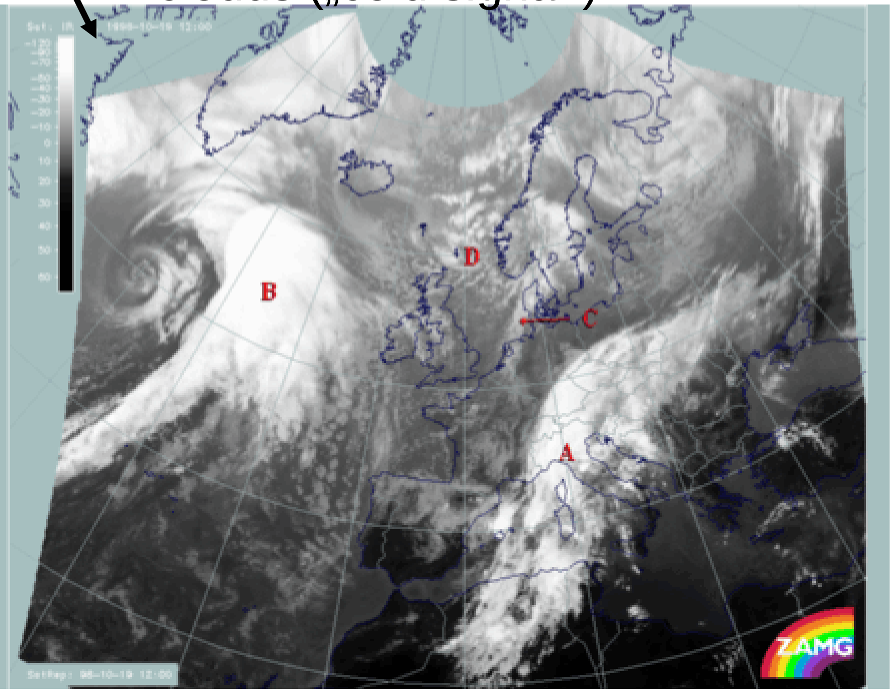
TB : Temperature of a black body emitting the same radiance at this frequency

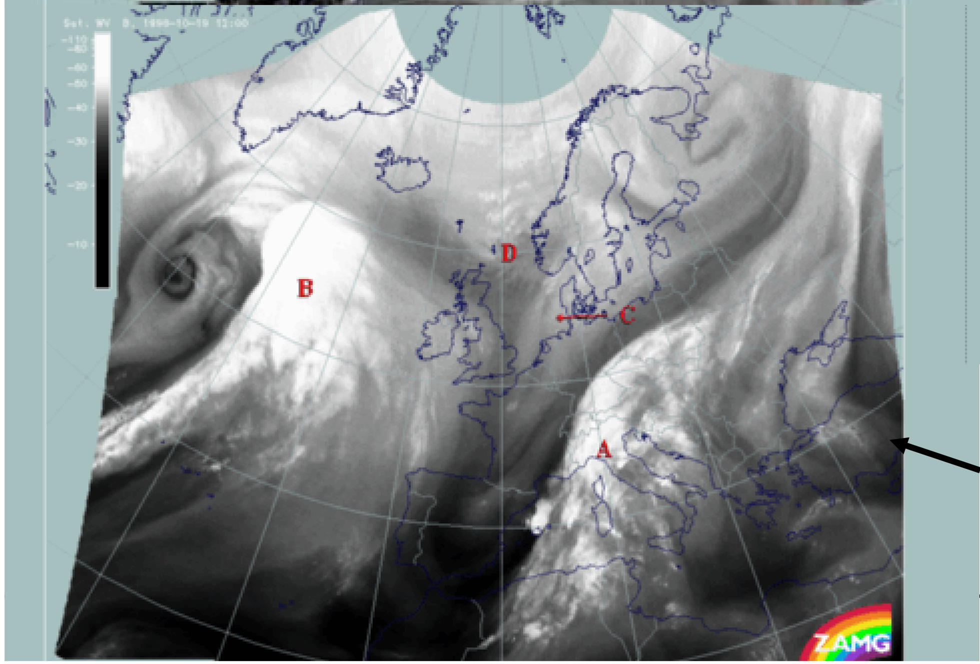
Radiance : Amount of energy crossing,
per time interval *dt*
per frequency interval υ to $\upsilon + d\upsilon$,
per area *dA* at an angle θ to the normal to *dA*,
the beam being confined to a solid angle $d\Omega$

Typical imagery. VIS, IR, WV (Meteosat)

VIS: clouds reflect solar light

IR window: thermal emission of surface („warm“) and clouds („cold signal“)



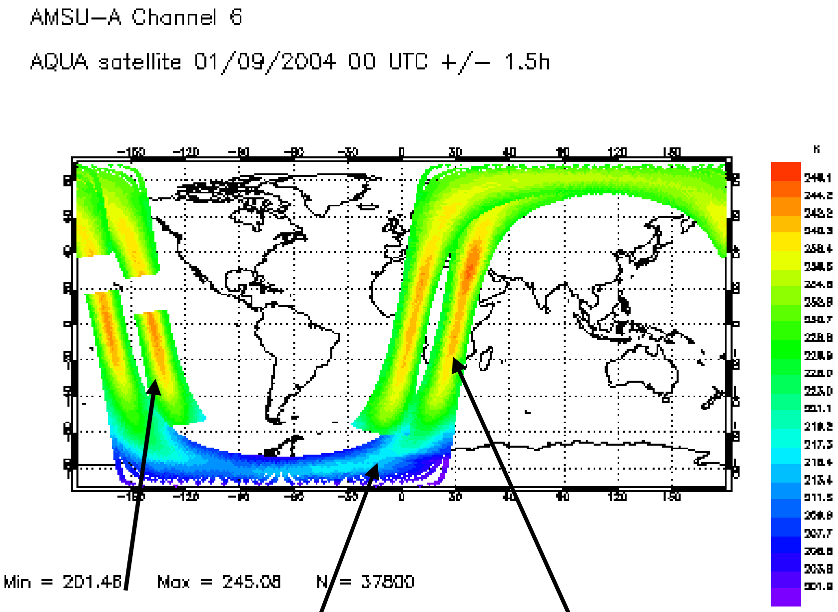


WV: upper level humidity (~ 200-400 hPa)
more WV -> less radiance („cold“)

Example of physical processes in MW

Sounding channel (Temperature)
Peaks ~ 400 hPa

Window channel
Peaks at surface/low atmosphere



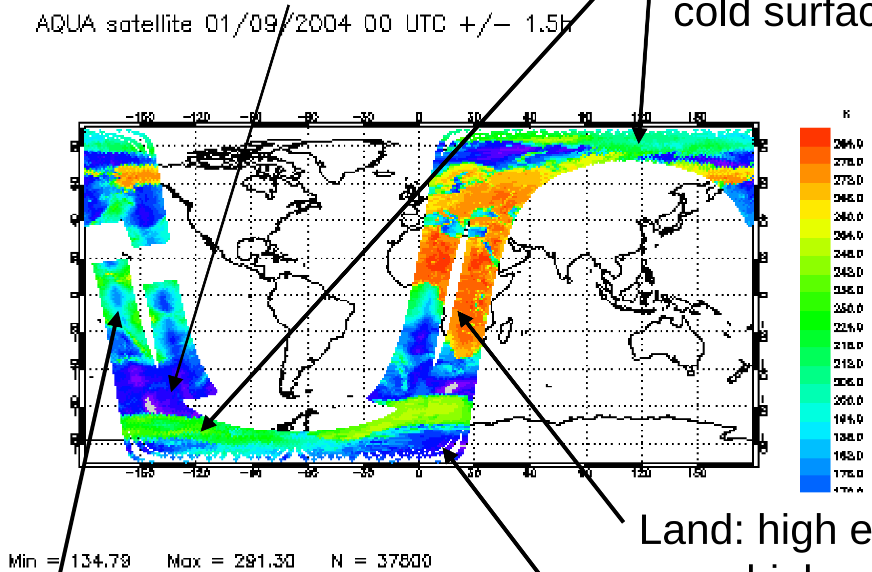
Warm tropical troposphere

Cold polar troposphere

Limb viewing effect at edge of scan
(longer path → larger optical thickness
→ higher peak of weighting function at colder T)

Sea surface:
low emissivity

Sea ice:
high emissivity,
cold surface T



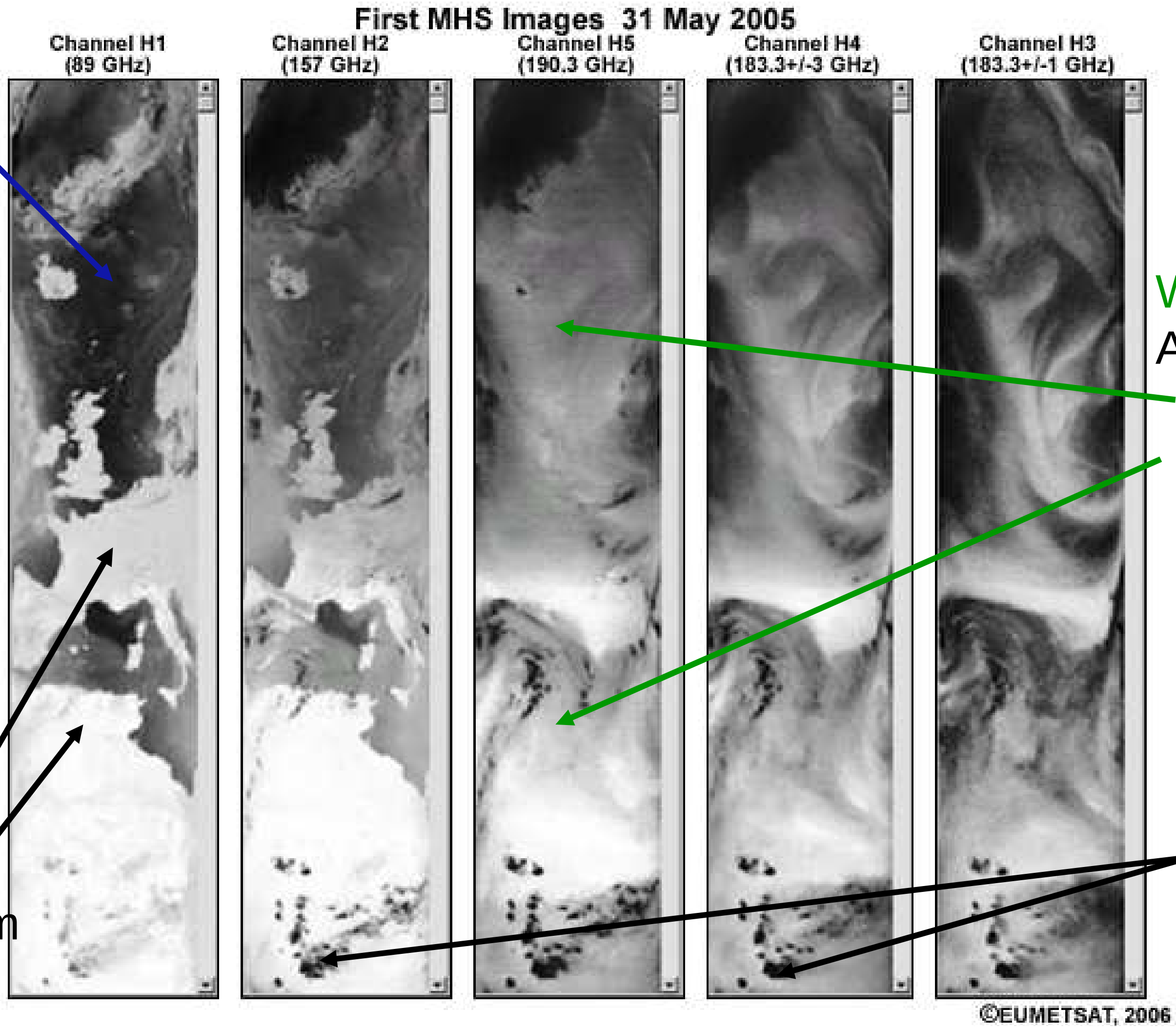
Land: high emissivity
high surface T

Tropics & warm sectors:
high water vapour contents

High elevation: very cold surface T,
or possibly cloud

Example of sounding channels: Humidity sounding MHS (~AMSU-B)

Sea surface: radiatively cold



Water vapour: Appears relatively
warm over sea
cooler over land

generally getting cooler at higher levels

Land surface: radiatively warm

Clouds over land

Window channels 89 GHz 157 GHz

Sounding channels - 183+7 GHz , 183+3 GHz , 183+1 GHz

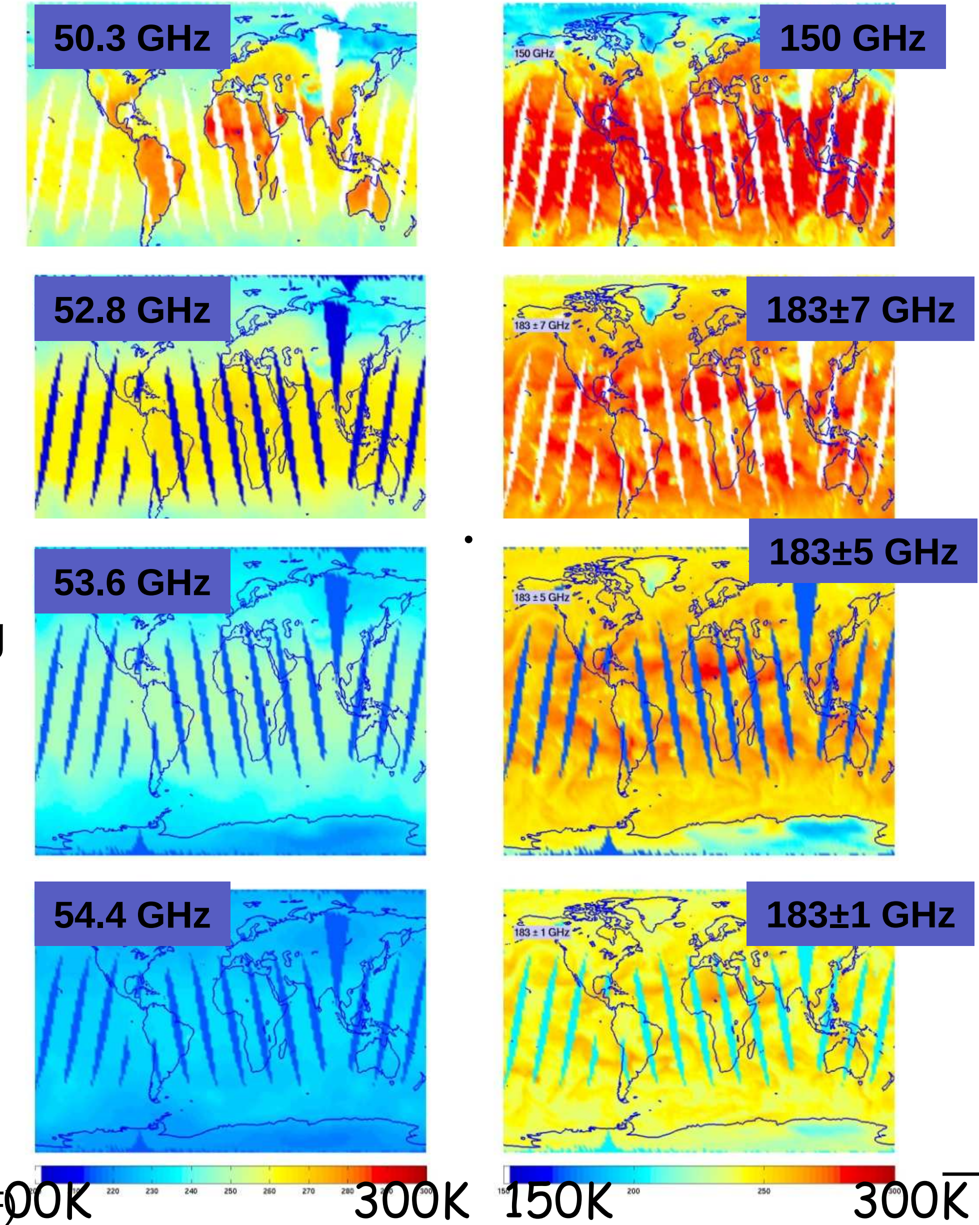
T and Hum sounding channels (SSMIS)

Brightness Temperature (TB) measurements obtained over ~12 hours by (F-16 SSMIS)

TB decreases

- For higher peaking Channels (troposphere)

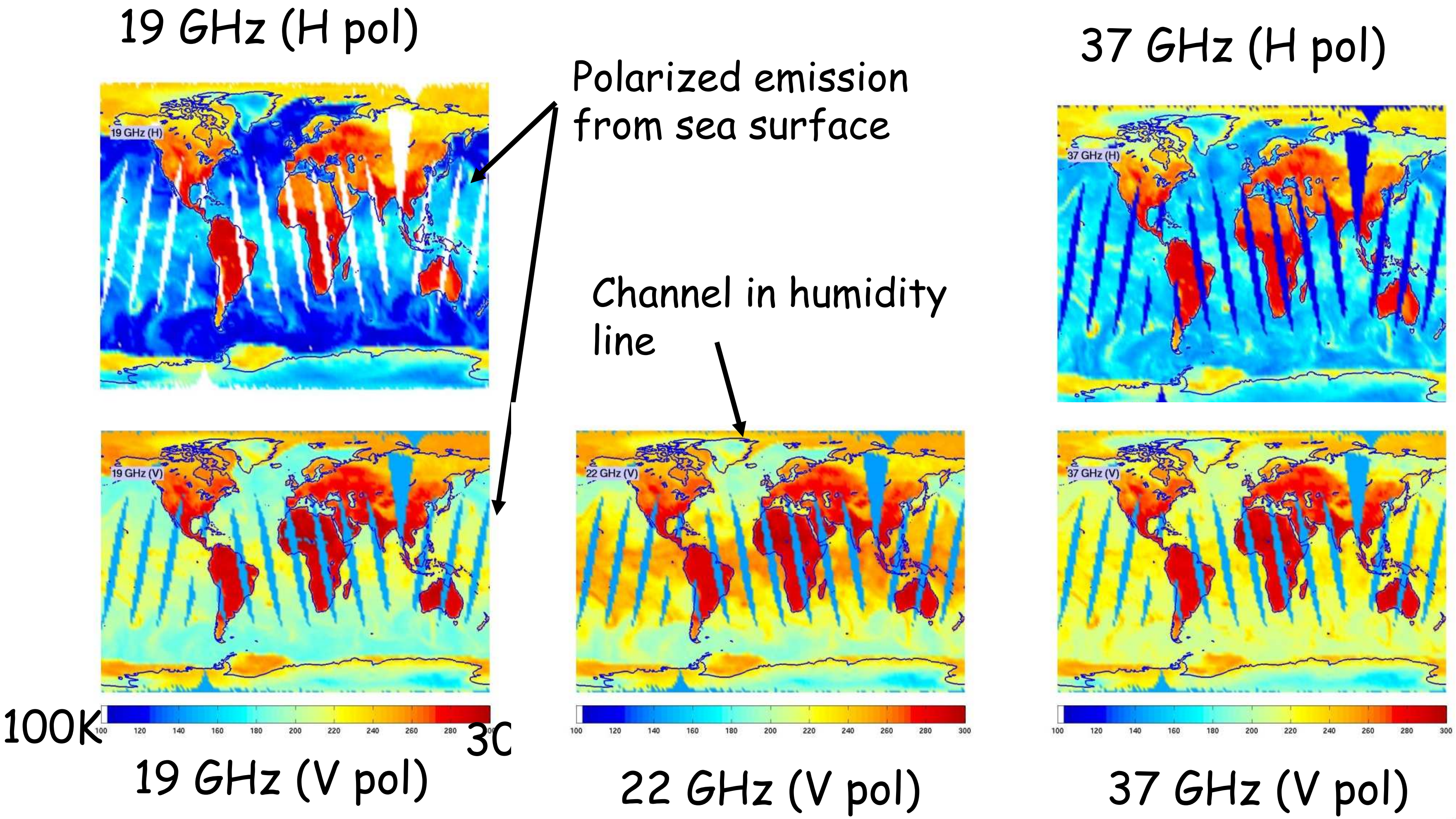
- Towards the poles



Courtesy, B. Bell, ECMWF)

Example of MW imager channels (SSMI, SSMIS)

SSMIS measurements
(12 hours)



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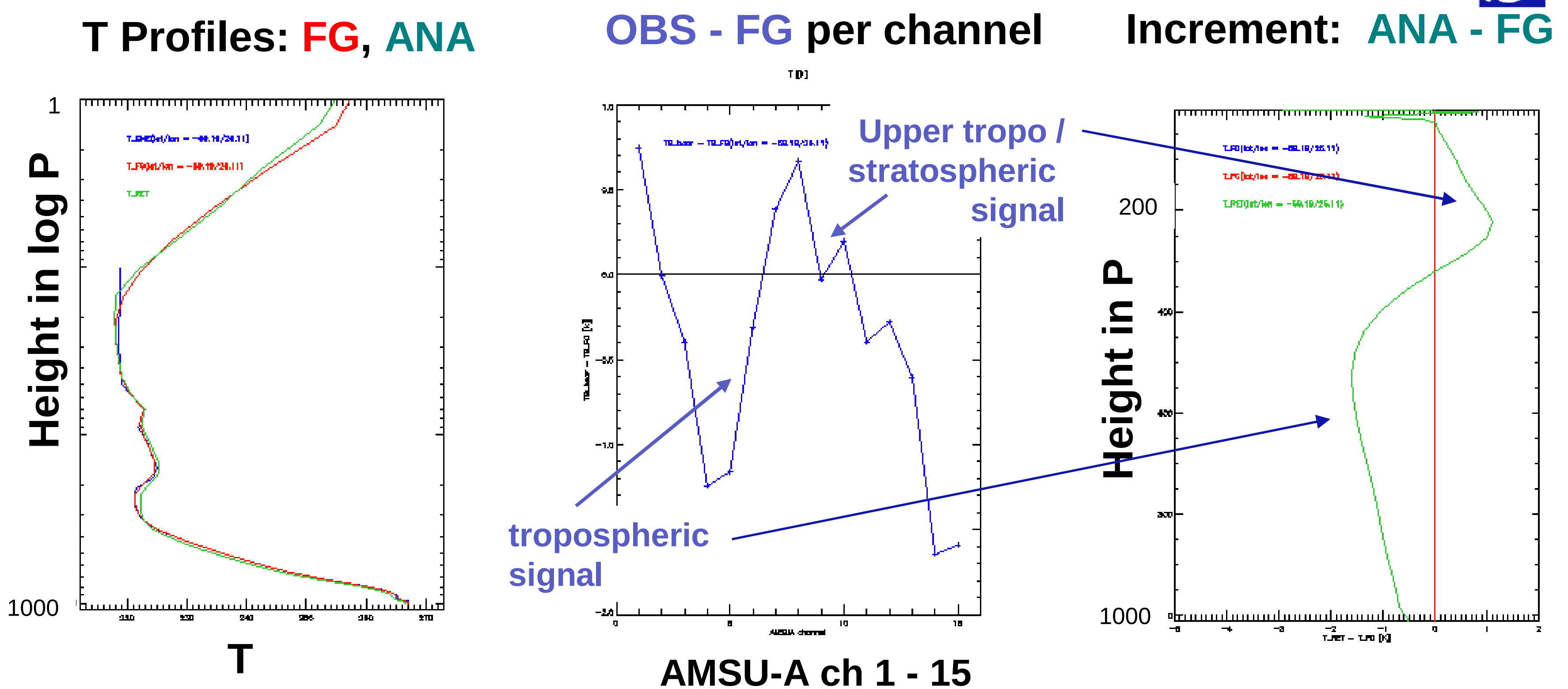
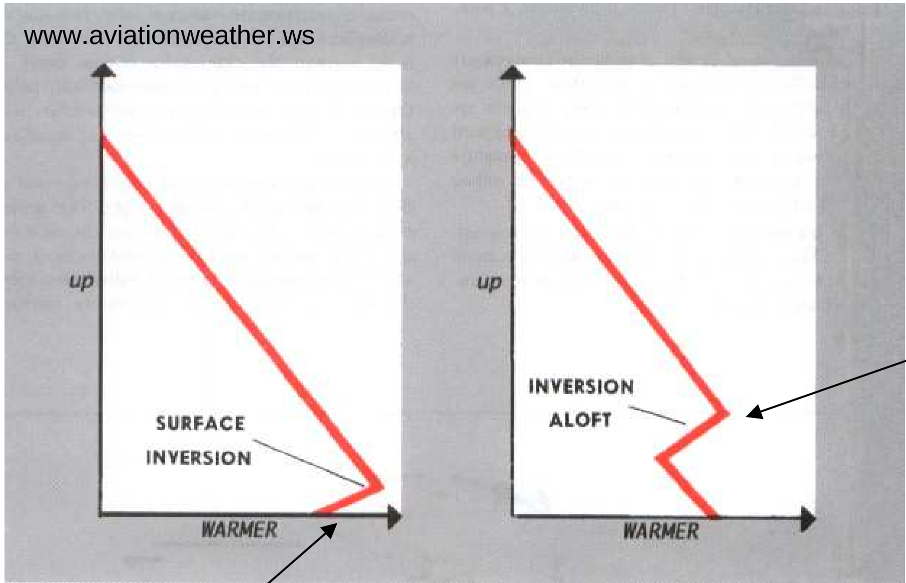
Derived temperature profile (retrieval)



- Corrections to model first guess profile (FG) are generally smooth:
  - Broad channel weighting functions
  - Shape of background error correlations

Note: Sharp vertical structures (tropopause, inversions, PBL) are not well resolved by satellites („invisible"),
More potential with high resolution sounders, e.g. IASI

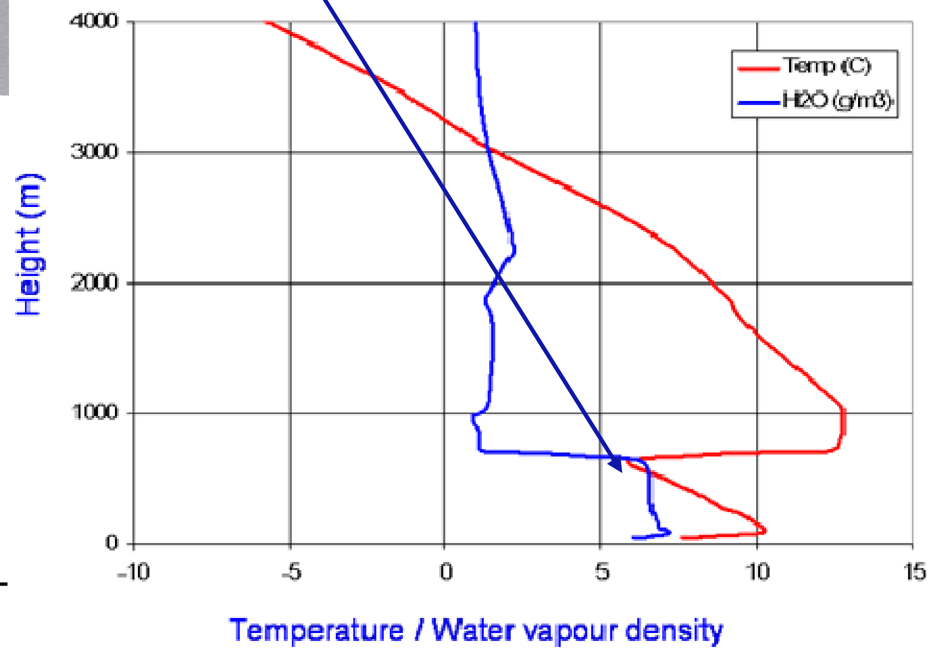
Limitations of sounding: „Invisible features“ Vertically shallow structures, e.g. inversions



Subsidence inversion in high pressure
or inversion due to warm air advection aloft
→ high humidity/clouds below

Typically: night time cooling
or subsidence inversion

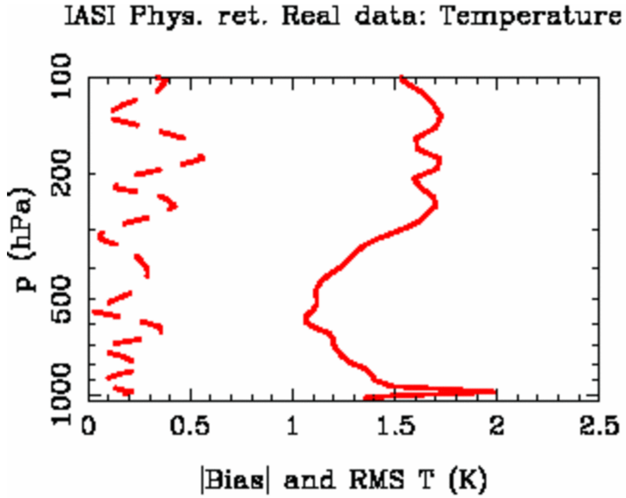
rustylopez.typepad.com

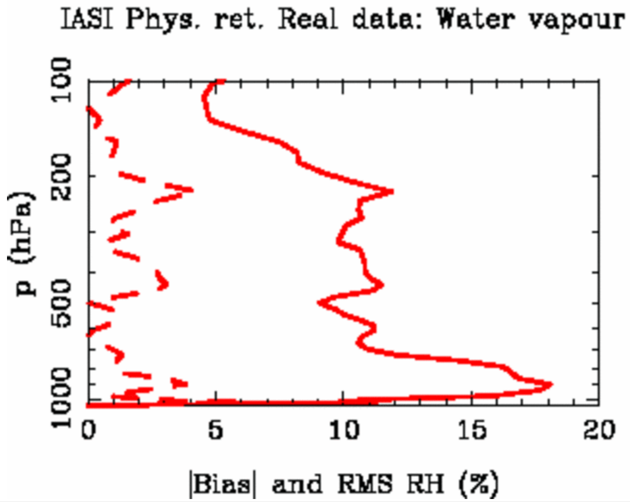


A word on retrieval accuracy:

Temperature and Humidity error

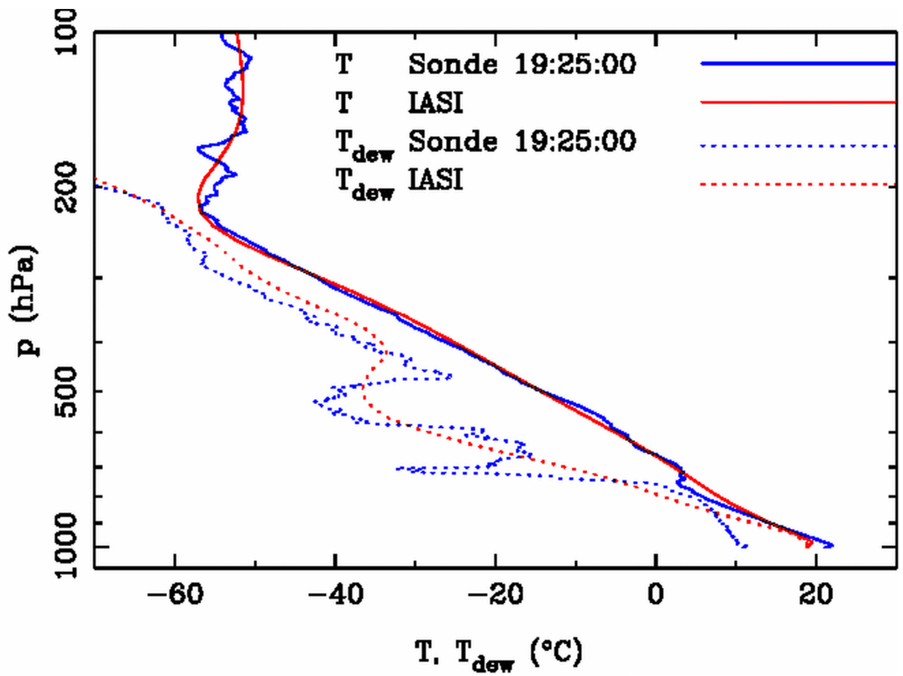
(Clear sky, Ocean; versus ECMWF analyses)





Retrieval example: Lindenberg

→ Potential to resolve some details of observed vertical profile



(Courtesy: Xavier Calbet, MetDivision, EUMETSAT)

Questions ?

Further reading:

- Goody, R.M. and Yung,Y.L., 1995: Atmospheric Radiation:Theoretical Basis . Oxford University.
- Liou, K.N., 2002:An introduction to atmospheric radiation. Academic Press.

- ECMWF trainings course material:
  „DATA ASSIMILATION AND THE USE OF SATELLITE DATA", esp.
  Infrared radiative transfer (see also Bibliography at end of talk)
  Microwaver radiative transfer (see also bibliography at end of talk)

- Overview of satellite instruments:
  file:///fe1-daten/ckoepken/public_html/infopages/info_sat/satellite_links_FE12.htm

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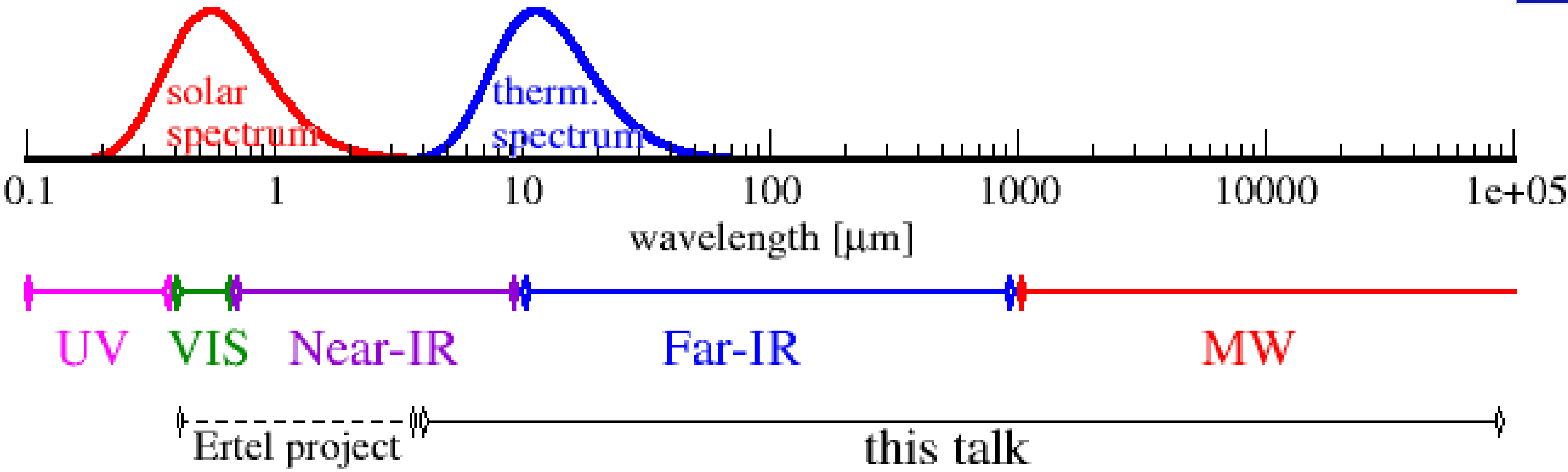
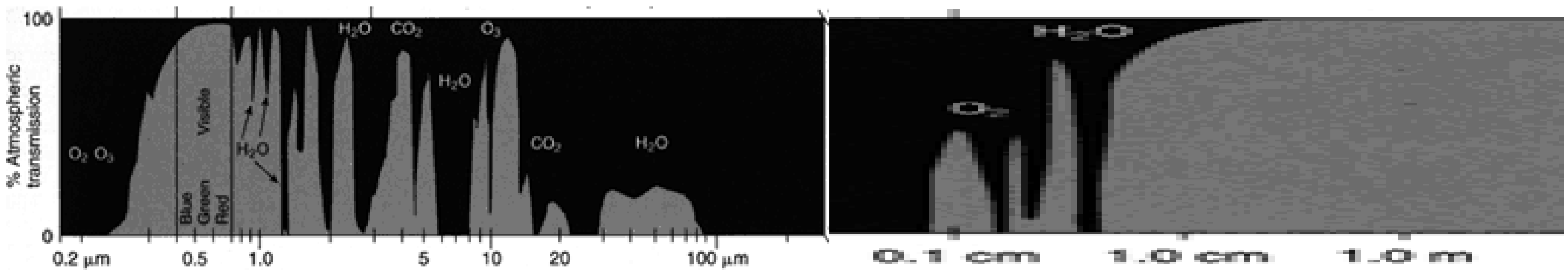
Electromagnetic spectrum



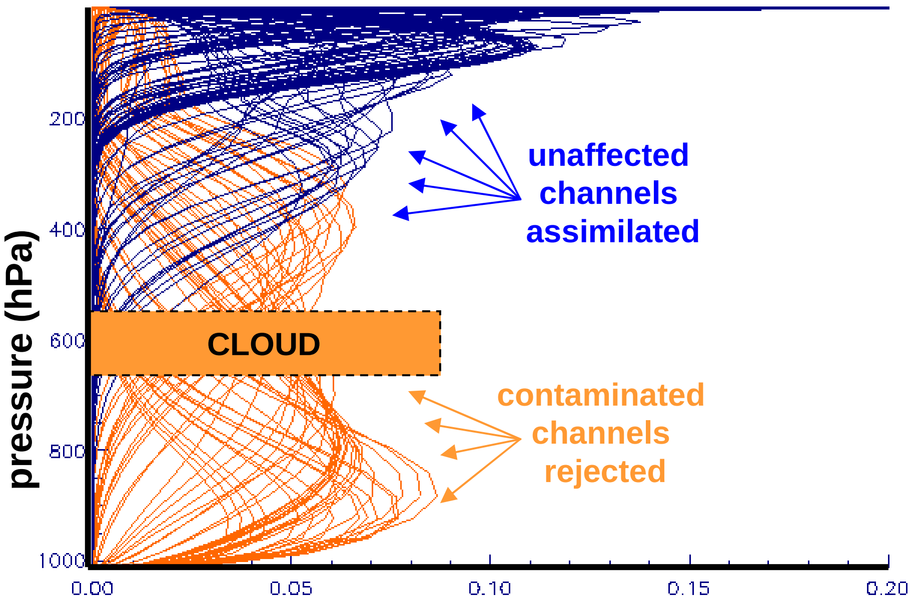


(Courtesy Robin Faulwetter)

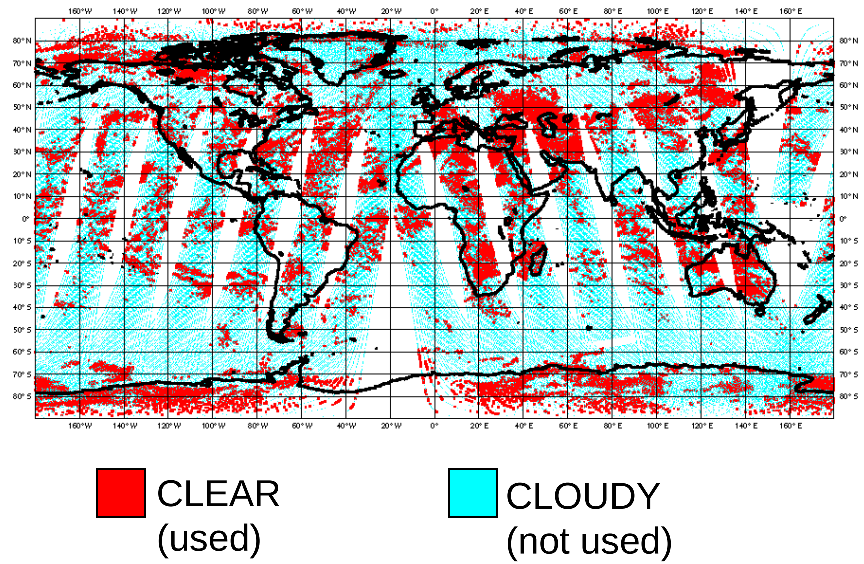
Potential for EPS – SG: Data assimilation view
Sounding missons: IRS

Challenge: Cloudy fields-of-view:
- Currently: use only high channels in cloudy areas
- But: the most interesting areas are cloudy….. !
- Research area: use of cloud affected radiances
  -> use more data, use information on clouds

Cloud influence on AIRS channels

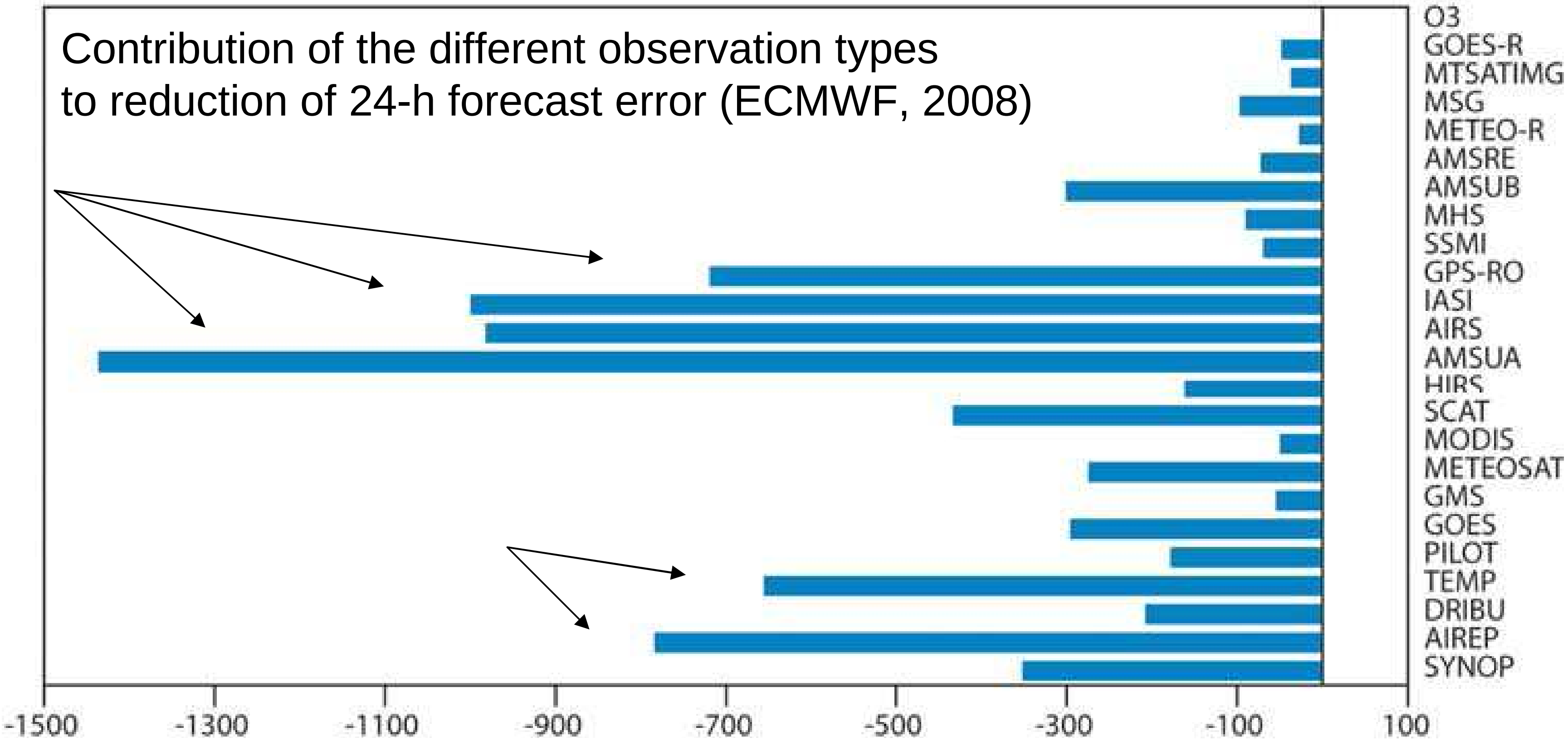


(Courtesy, ECMWF P. Watts, 2003)



AIRS channel, peaks ~ 600hPa

Major global observation system component (III) : Forecast quality (influence of observation types)



Negative values indicate decrease in the energy norm of forecast error (J) **(Carla Cardinali, ECMWF)**

- Similar results obtained for longer forecasts (2-7 days) based on observation impact experiments

- Satellite data are main contributor to accurate forecasts
- Profiling information (T, q) from IR and MW sensors is essential