Cargese International Summer School

3 – 17 October 2005 – Cargese, Corsica

The role of Upper Troposphere and Lower Stratosphere in the climate system

A place called *Corsica*…

Corsica!!

(Bari!!)

It looked like this the day I arrived…

…and like this few hours later!

Main Topics and Courses

- ## Observations
  - Satellite instruments, in-situ and remote measurements of water vapour and chemical compounds, clouds in the UT/LS, data evaluation.
- ## Data assimilation
  - Theory, assimilation of satellite data, numerical weather prediction, assimilation in global models of atmospheric chemistry
- ## Modelling and understanding
  - Dynamics and global circulation, transport and mixing, ozone chemistry, cirrus clouds, water budget in the UT/LS, tropical dehydration

Part One:

<u>Tuesday 4 October 2005</u>

KEY 1: Radiative transfer (Bruno Carli)
OBS 1: Microwave limb sounders (Stefan Buehler)
KEY 2: The Data Assimilation problem (Olivier Talagrand)
OBS 2 – OBS 3: Radiative transfer for thermal radiation (Bruno Carli)
KEY 3: The tropopause (Bernard Legras)

<u>Wednesday 5 October 2005</u>

DA 1: Data assimilation methods (Olivier Talagrand)
KEY 4: Gravity waves (Geraint Vaughan)
OBS 4: Infrared satellite sensors / Envisat MIPAS (Bruno Carli)
Extra # 1: Satellite data analysis (Andrew Gettelman)
OBS 5: Ground-based radar and lidar observations (Geraint Vaughan)
DA 2: Data assimilation methods (Olivier Talagrand)
OBS 6: Ground-based radar and lidar observations (Geraint Vaughan)

<u>Thursday 6 October 2005</u>

MOD 1 – MOD 2: The stratospheric circulation (Alan O'Neill)
KEY 5: Ozone and ozone trends in the UTLS (Dominique Fonteyn – given by William Lahoz based on DF material)
Extra # 2: Preparing data graphics (Mark Baldwin)
MOD 3: The role of the stratosphere on low-frequency atmospheric variability (Mark Baldwin)
DA 3: Chemistry and the UTLS (Dominique Fonteyn – given by William Lahoz based on DF material)
KEY 6: Stratosphere-troposphere connections (Mark Baldwin)

<u>Friday 7 October 2005</u>

DA 4 - DA 5: Chemistry and the UTLS (Dominique Fonteyn – given by William Lahoz based on DF material)
KEY 7: Exchange between PBL and UTLS (Heini Wernli)
DA 6: Dynamics and data assimilation (Richard Swinbank)
MOD 4 – MOD 5: STE in mid-latitudes (Heini Wernli)

<u>Saturday 8 October 2005</u>

DA 7: Numerical models and data assimilation (Richard Swinbank)
KEY 8: NWP and the UTLS (Francois Bouttier)
KEY 9: Ensemble forecasting: THORPEX and the future for NWP (Richard Swinbank)

Week Two

<u>Monday 10 October 2005</u>

DA 8: Radiance assimilation (Francois Bouttier)
OBS 7: UV-Vis satellite sensors / Envisat SCIAMACHY, GOME (Hennie Kelder)

Part two

<u>Monday 10 October 2005</u>

DA 8: Radiance assimilation (Francois Bouttier)
OBS 7: UV-Vis satellite sensors / Envisat SCIAMACHY, GOME (Hennie Kelder)
DA 9: Mesoscale assimilation (Francois Bouttier)
Extra # 3: Practical aspects of data assimilation (Olivier Talagrand)
OBS 8: UV-Vis satellite sensors / Envisat SCIAMACHY, GOME (Hennie Kelder)
OBS 9: UV-Vis satellite sensors / OMI (Pieternel Levelt)
MOD 6: Transport and mixing theory (Bernard Legras)

<u>Tuesday 11 October 2005</u>

MOD 7: Transport and mixing theory (Bernard Legras)
OBS 10: Eos AURA mission (Pieternel Levelt
KEY 10: Water and the UTLS (Andrew Gettelman)
Extra # 4: Writing skills (Liz Moyer)
OBS 11: Humidity observations in the UTLS region (Liz Moyer)
MOD 8: TTL and water vapour (Andrew Gettelman)
OBS 12: Humidity observations in the UTLS region (Liz Moyer)

<u>Wednesday 8 October 2005</u>

MOD 9: TTL and water vapour (Andrew Gettelman)
MOD 10: Cirrus clouds (Klaus Gierens)
MOD 11: Introduction to climate-chemistry modelling (Andrew Gettelman)
MOD 12: Aerosols in the UTLS (Klaus Gierens)
OBS 13: Microwave nadir sounders (Stefan Buehler)
KEY 11: Microphysical processes in the UTLS (Klaus Gierens)

<u>Thursday 13 October 2005</u>

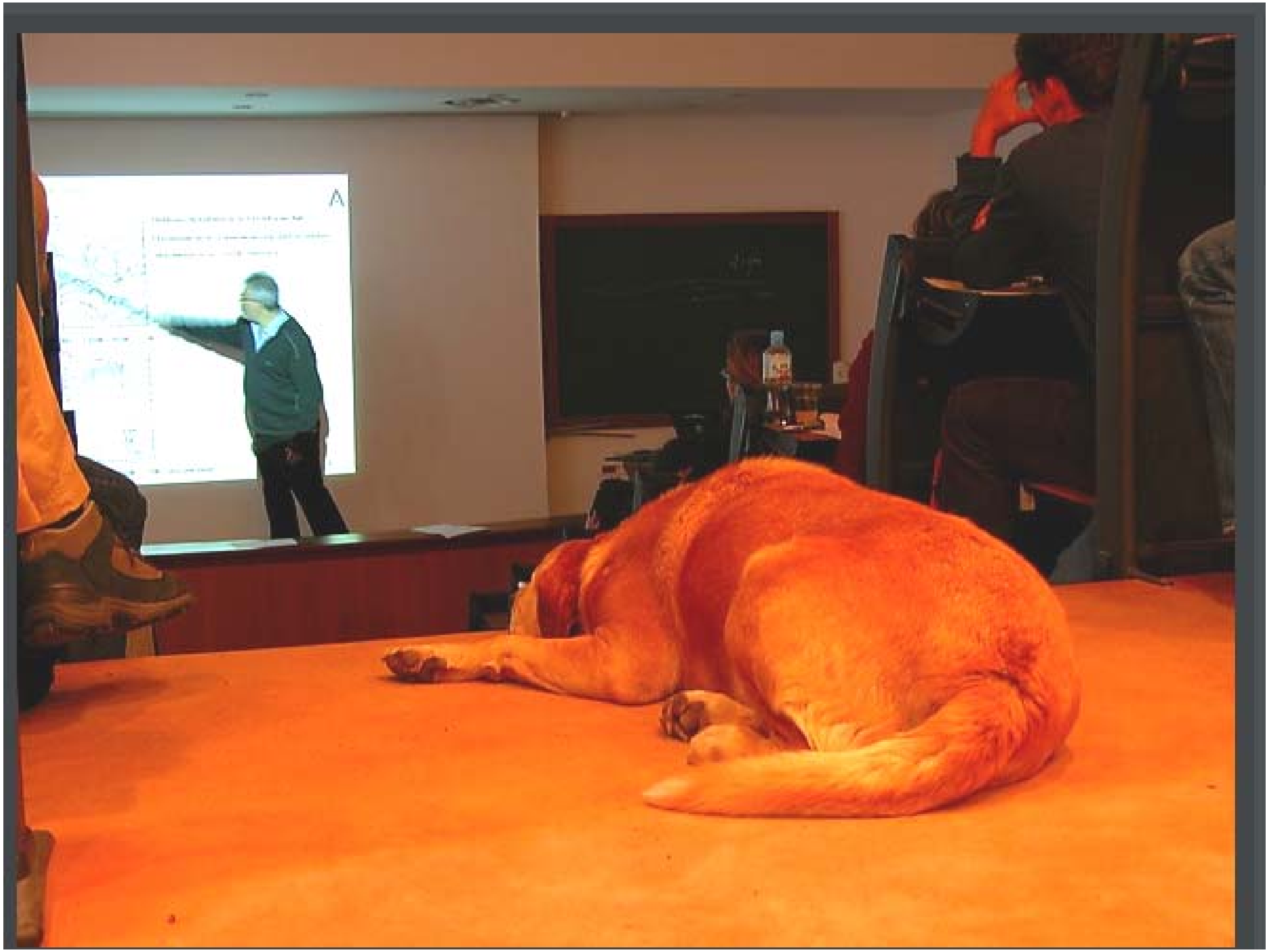
Extra 5: To be filled in or left free
DA 10: Evaluation/validation (Olivier Talagrand)
MOD 13 – MOD 14: Modelling of cirrus clouds (Klaus Gierens)
KEY 12: The extra-tropical tropopause mixing layer (Jean-Pierre Cammas)
OBS 14: Aircraft observations of the UTLS region (Jean-Pierre Cammas)

<u>Friday 14 October 2005</u>

OBS 15: New sensors to study cirrus clouds using sub-mm range (Stefan Buehler)
DA 11: Research satellites and data assimilation (William Lahoz)
OBS 16: New sensors for humidity observations in the UTLS region from Radio Occultation (Stefan Buehler)
DA 12: Evaluation of future missions (William Lahoz)
KEY 13: The future observing system in the UTLS (William Lahoz)
+ EXTRA DAYS Lectures

And ready to start!

Soon everybody felt involved…



Radiative transfer (Bruno Carli, CNR, Italy)

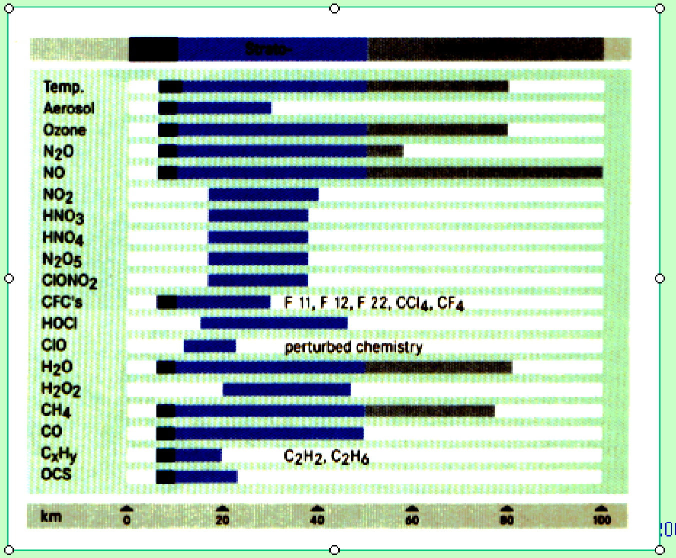
http://www.ifac.cnr.it/retrieval/products.html

MIPAS: Michelson Interferometer for Passive Atmospheric Sounding

MIPAS is a Fourier Transform (FT) Spectrometer that measures the middle infrared (MIR) emission of the atmosphere at the limb.

- Spectral range: 685 - 2410 cm^{-1}, (14.6 – 4.15 μm)
- Spectral resolution: 0,025 cm^{-1} unapodized
- Spectral resolution: FWHM $\leq$ 0.035 cm^{-1}
- Vibrational spectra of molecules

MIPAS possible products



MIPAS can simultaneously observe most molecular constituents of the Earth's atmosphere

MIPAS is the first instruments that provided vertically resolved global maps of atmospheric composition !!

Recent difficulties & Conclusions

- MIPAS instrument was stopped on 26th March 2004 for too frequent anomalies in the drive of the interferometric mirrors.
- A reduction of spectral resolution was considered in order to extend instrument life-time.
- At reduced spectral resolution the quality of Level 2 products is not compromised (new microwindows and longer computing time, improved resolution).
- Operation at reduced spectral is presently performed with a duty cicle of 30 - 35%.
- Distribution, validation and exploitation of data progress slowly becouse of insufficient fundings

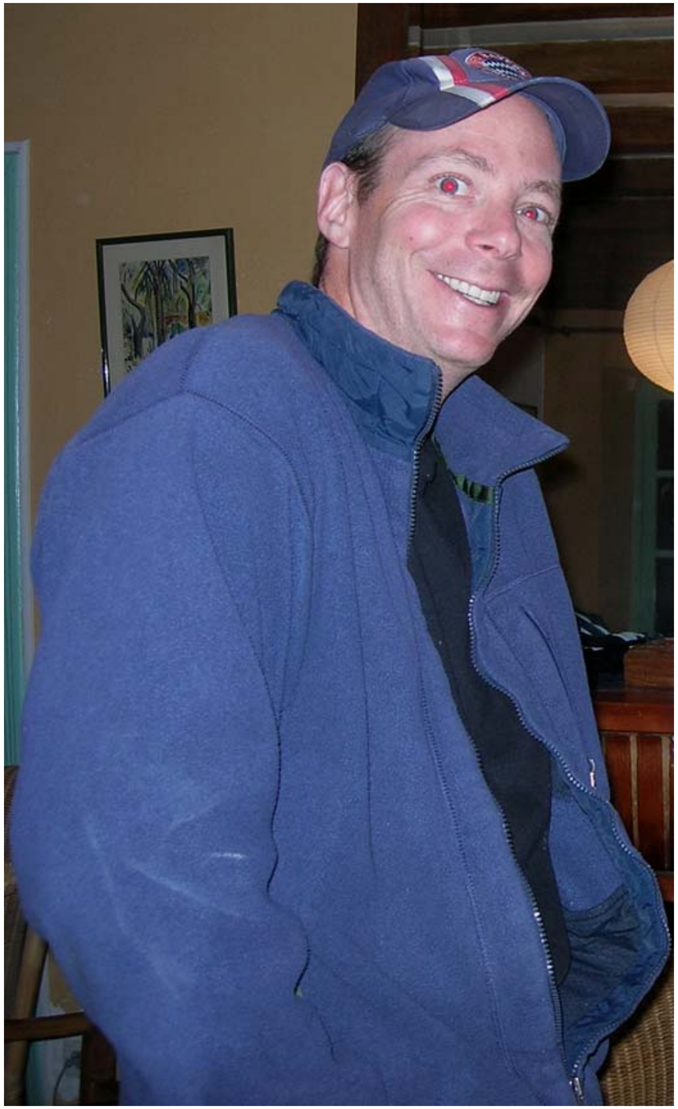
COST 723 Training School - Cargese 4 - 14 October 2005

Observations of water in the UTLS (Liz Moyer, Harvard Univ.)

- **How heterogeneous is water in the UTLS?**
- **How important is convective detrainment?**
- **Will mean RH stay constant in the future?**
- **Positive/negative effects?**
- **How much of mid-lat water vapour derives directly from the tropics? And vice-versa?**
- **Will that change in the future?**
- **Where does air ascend in the stratosphere?**
- **How important is tropical and midlat deep convection?**
- **Is water vapour really limited by saturation mixing ratio?**

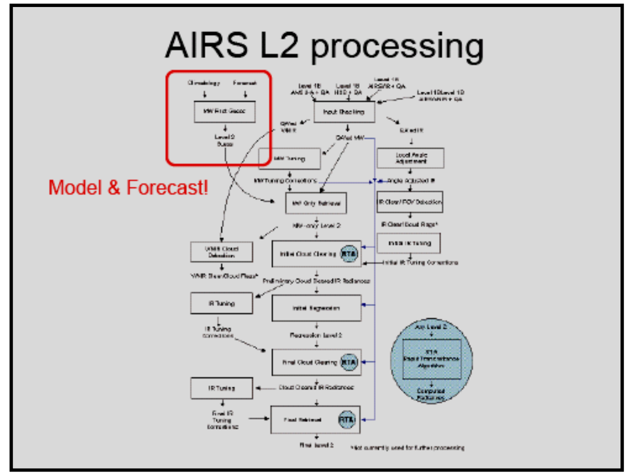
Water Vapor and the UTLS

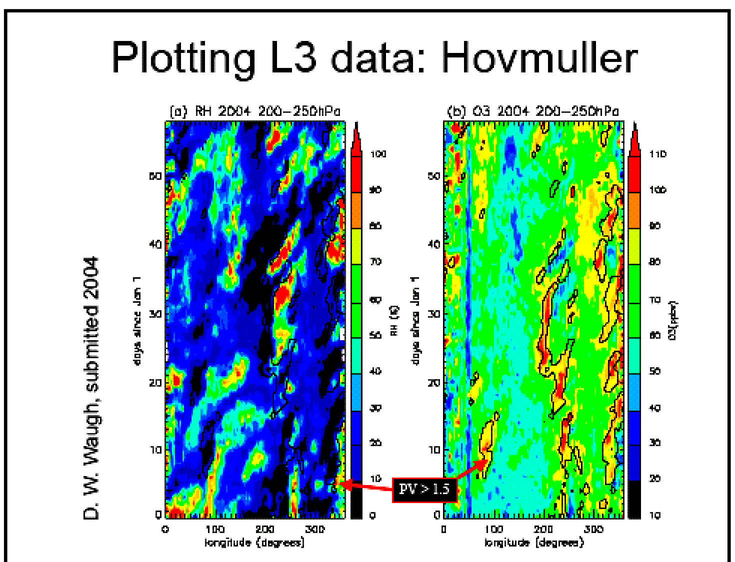
(Andrew Gettelman, NCAR)



- Satellite data analysis
- Water and the UTLS
- TTL and water vapour
- Introduction to climate chemistry modelling

1) "Satellite data analysis A (ab)user perspective"





'Quality Flags'

Example:

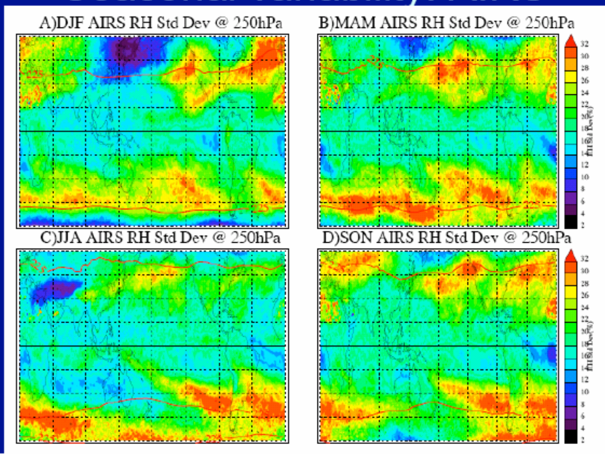
AIRS v4 data

Qual_MW_Only_Temp_Strat	Overall quality flag for MW-Only temperature fields for altitudes above 201 mbar
Qual_MW_Only_Temp_Tropo	Overall quality flag for MW-Only temperature fields for altitudes at and below 201 mbar, including surface temperature.
Qual_MW_Only_H2O	Overall quality flag for MW-Only water (both vapor and liquid) fields. The possible values this flag are 0 (H2O retrieval fully valid), 1 (only total precipitable water vapor is valid), 2 (H2O invalid); we are working on it; users are advised to proceed with caution
Qual_Cloud_OLR	Overall quality flag for cloud parameters and clear and cloudy OLR
Qual_H2O	Overall quality flag for water vapor fields
Qual_CO	Quality flag for CO
Qual_O3	Quality flag for ozone
Qual_Temp_Profile_Top	Quality flag for temperature profile at and above Press_mid_top_bndry mbar (currently 200 mb)
Qual_Temp_Profile_Mid	Quality flag for temperature profile below Press_mid_top_bndry mbar and above Press_bot_mid_bndry mbar (currently 3 km above surface)
Qual_Temp_Profile_Bot	Quality flag for temperature profile at and below Press_bot_mid_bndry mbar, including surface air temperature
Qual_Surf	Overall quality flag for surface fields including surface temperature, emissivity, and reflectivity
Qual_CC_Rad	Overall quality flag for cloud cleared radiances
Qual_Guess_PSurf	Quality flag for surface surface pressure guess input. The possible values are 0 (good surface pressure guess from valid forecast), 1 (surface pressure guess estimated from topography), and 2 (do not use)

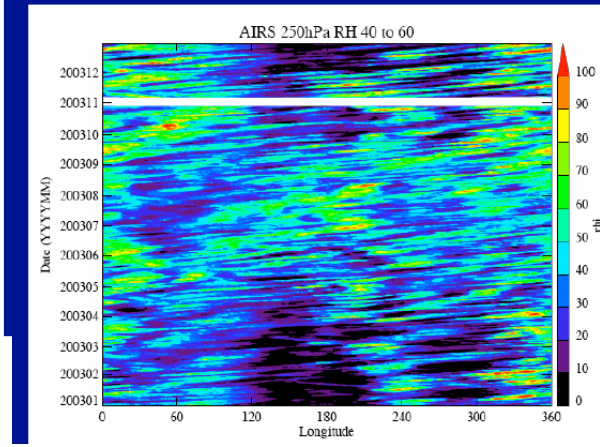
Table 2. New Quality Control Flags for Retrieved Geophysical Quantities

Humidity trends (AIRS data)

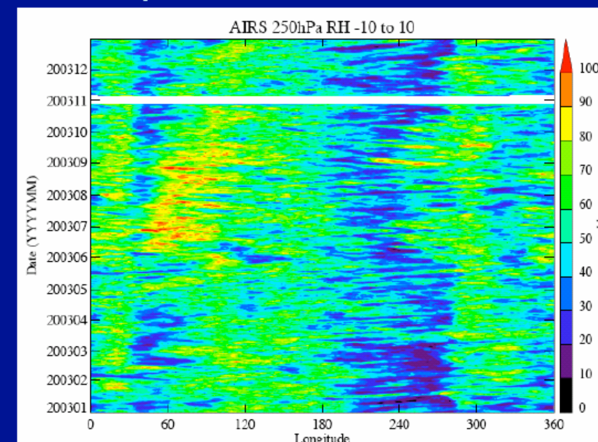
Seasonal variability: AIRS



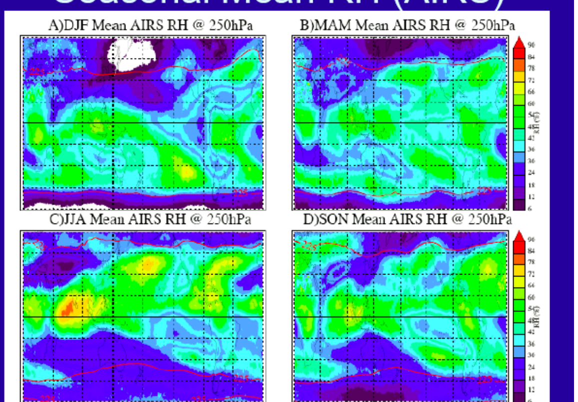
Mid-lat UT/LS Variations



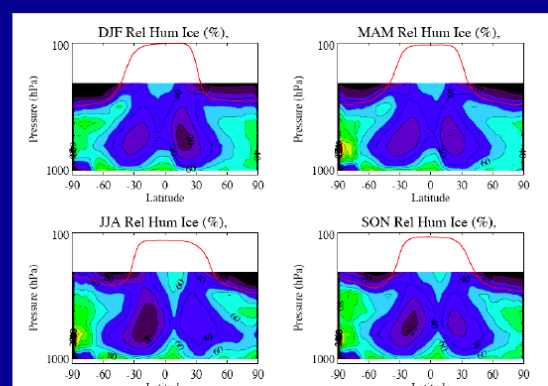
Tropical UT/LS variations



Seasonal Mean RH (AIRS)



Seasonal Zonal Mean (AIRS)



3) TTL and water vapor

Outline

PART I:

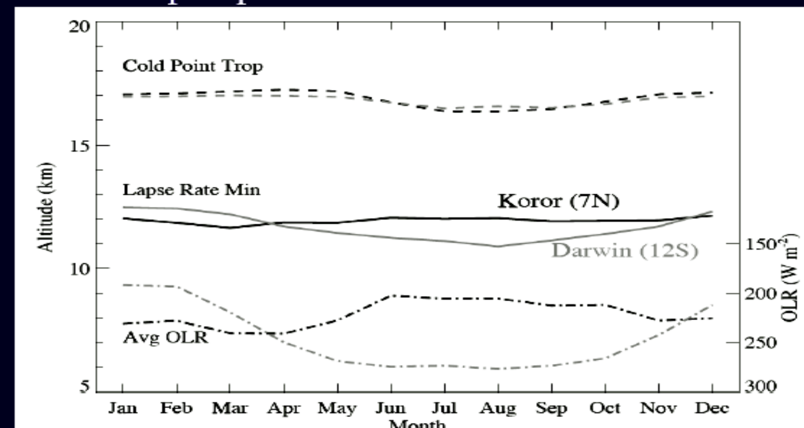
- Definition of the TTL
- Key Processes, Interactions & Variability

PART II:

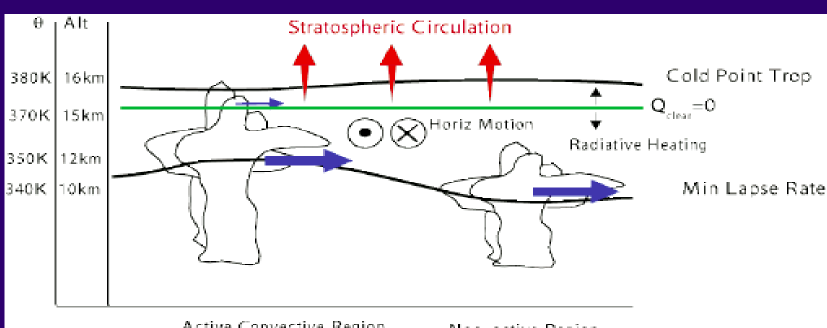
- Use existing variability to understand how air and water vapor enters the stratosphere
- TTL Trends

Lapse Rate and Convection

Potential Temp Lapse Rate Minimum related to convection

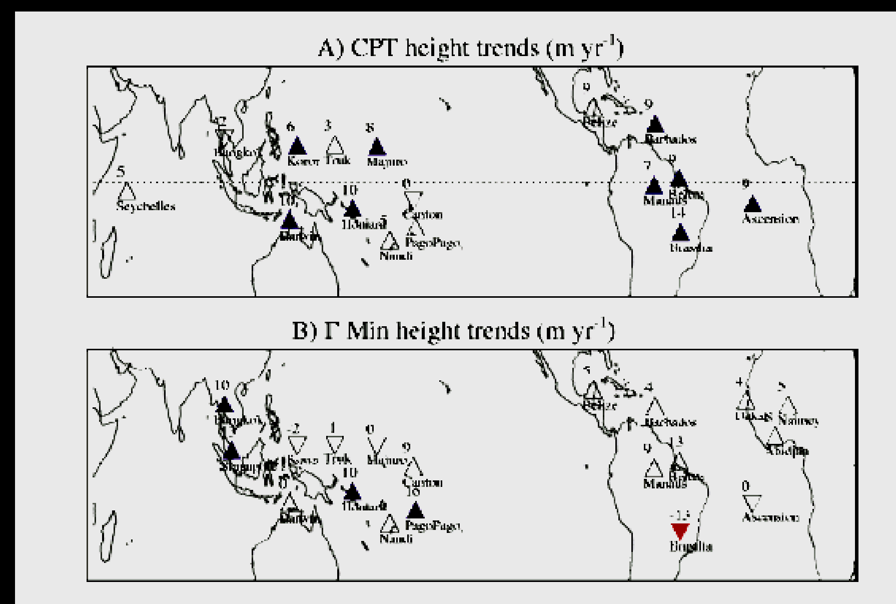


Definition of the TTL

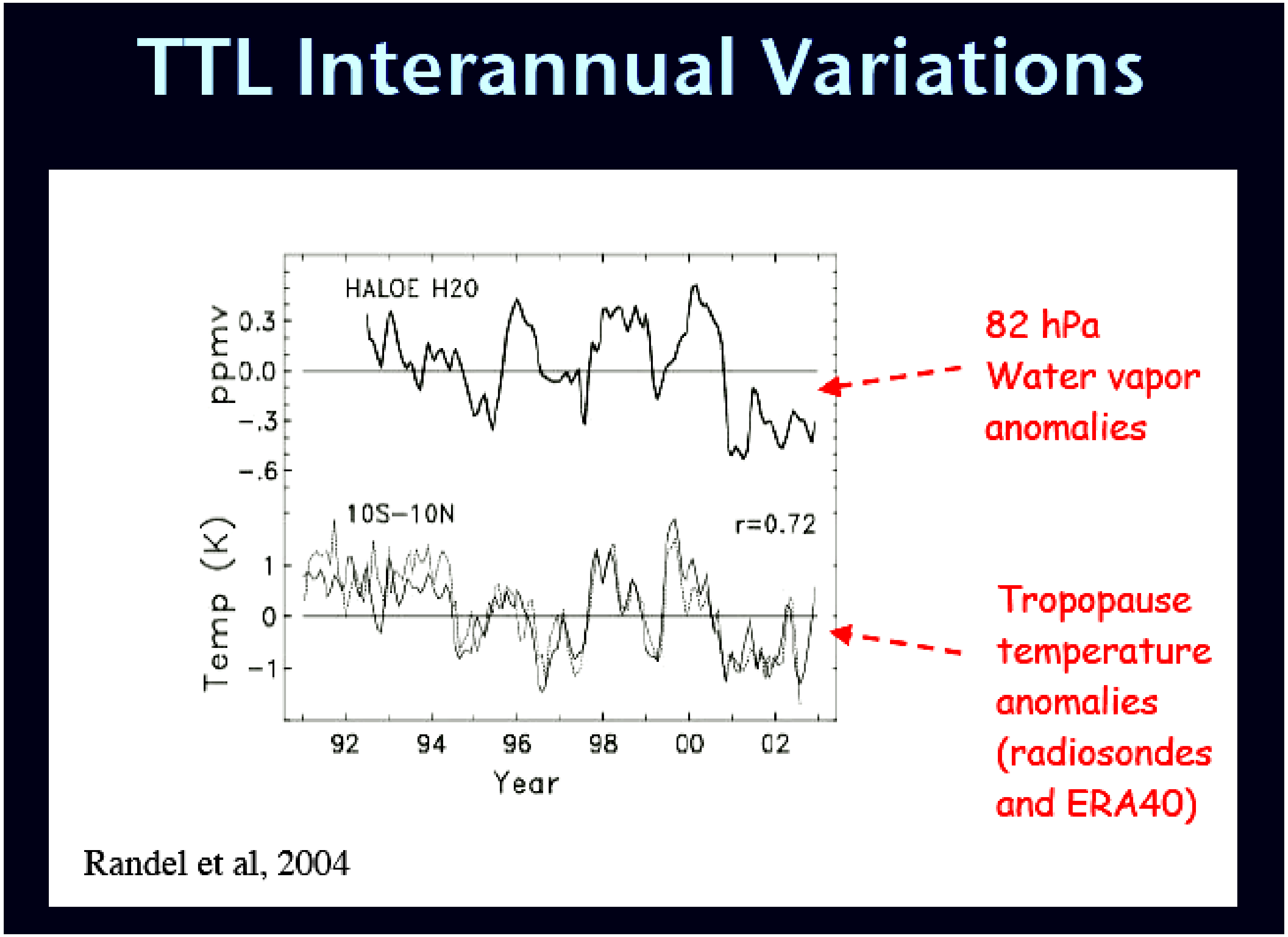


Gettelman & Forster, JMSJ 2002

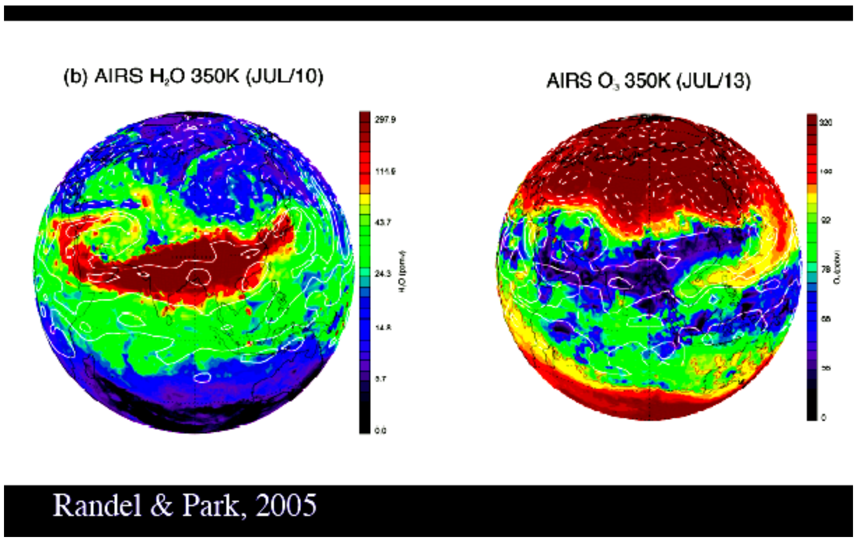
Trends in TTL Boundaries

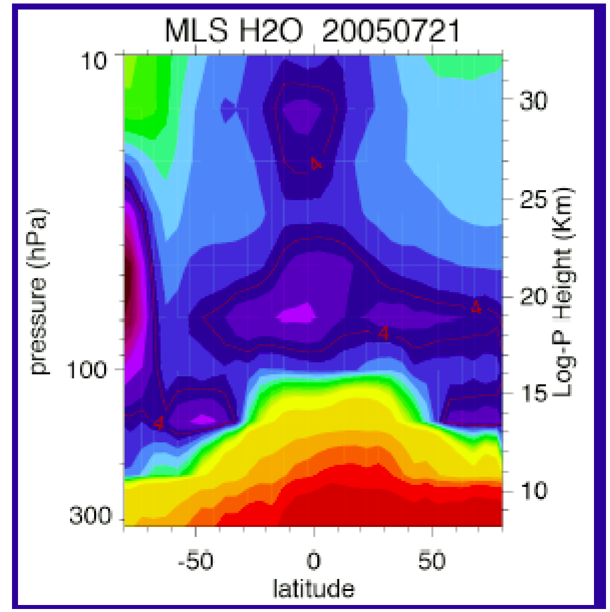


Anomalies in the TTL



Impact of Northern Summer Monsoon on the UTLS exchange

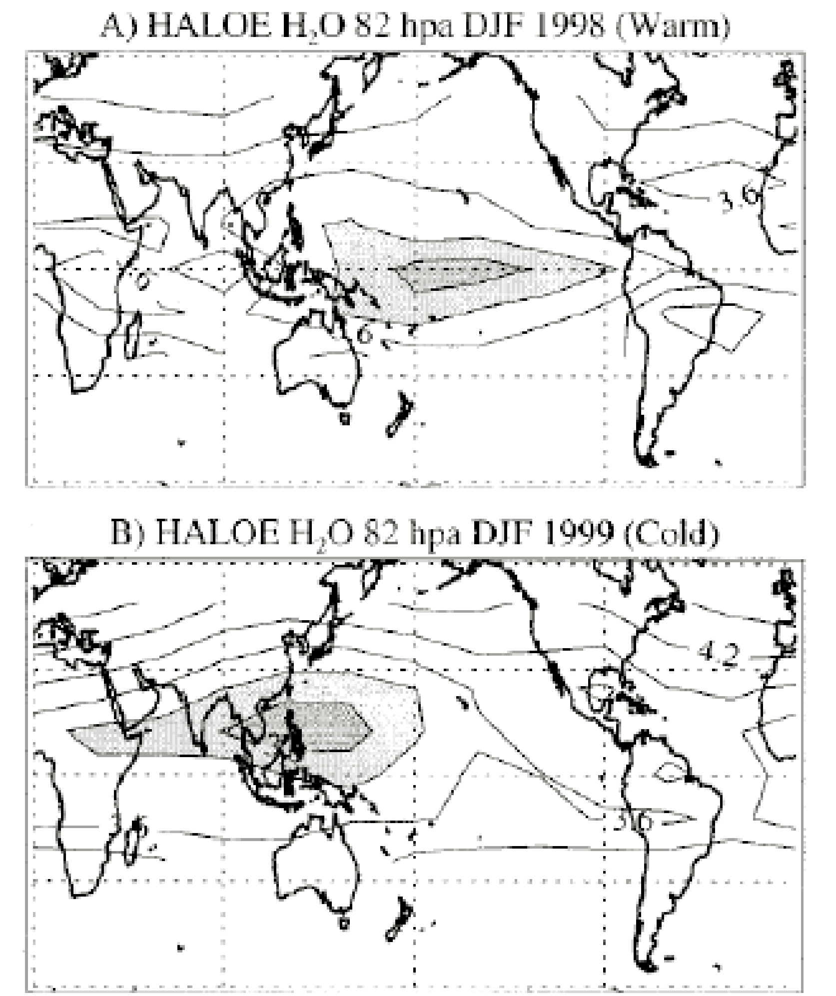




A detailed analysis of model fluxes of water vapor and ozone indicates that the Asian monsoon circulation may contribute 75% of the total net upward flux in the tropics at tropopause levels from July to September. Some of this air may enter the tropical stratosphere and bypass the tropical tropopause altogether.

Effects of ENSO

ENSO 'Reorganizes' the Hadley-Walker Circulation and affects H_2O up to the top of the TTL

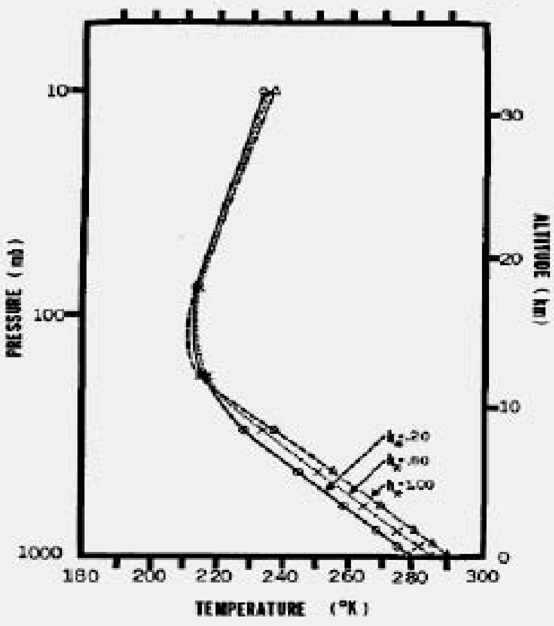


Gettelman et al, 2001, J. Clim

4)From the lecture "*Introduction to climate-chemistry modeling*"

Key Uncertainties for Climate (3):

3. Water Vapor: largest greenhouse gas
   Increasing Temp=Increasing water Vapor (more greenhouse)
   Effect is expected to 'amplify' warming through a 'feedback'



1D Radiative-Convective Model:
Higher humidity=>warmer surface

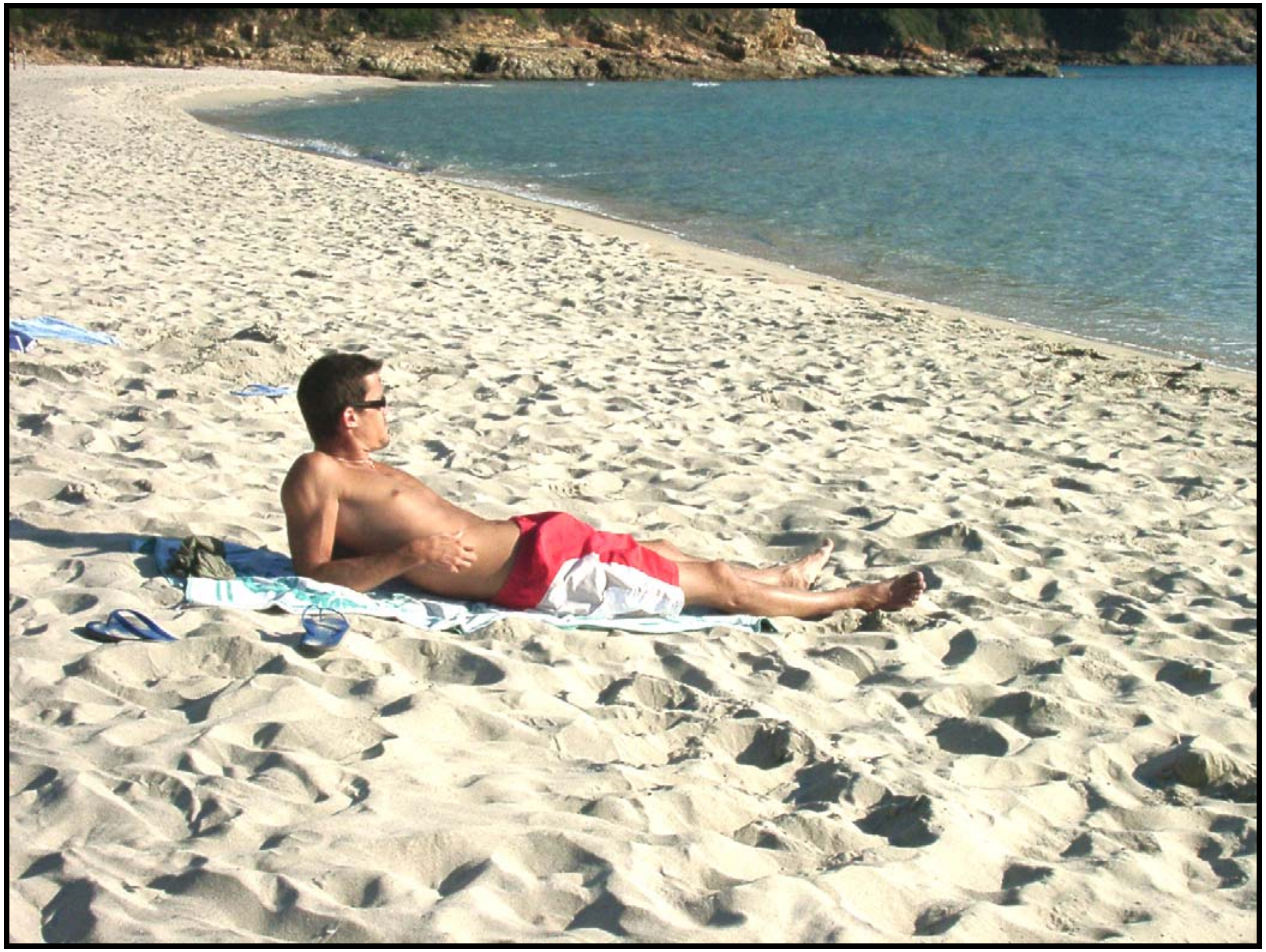
NCAR

Gettelman: October 2005

…Someone started to feel suspicious…

So, someone decided to explore more…

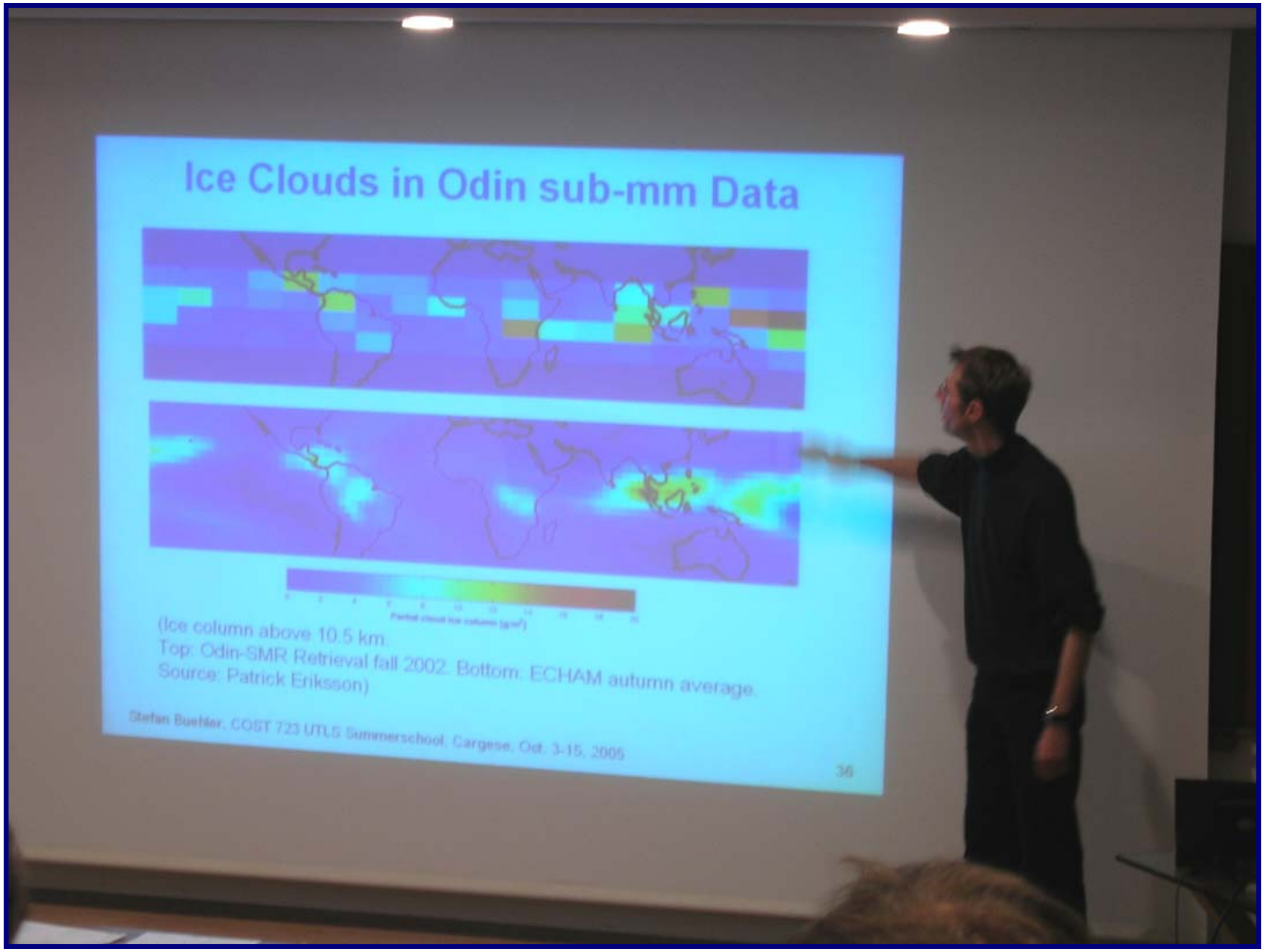
…and after some hard thinking…



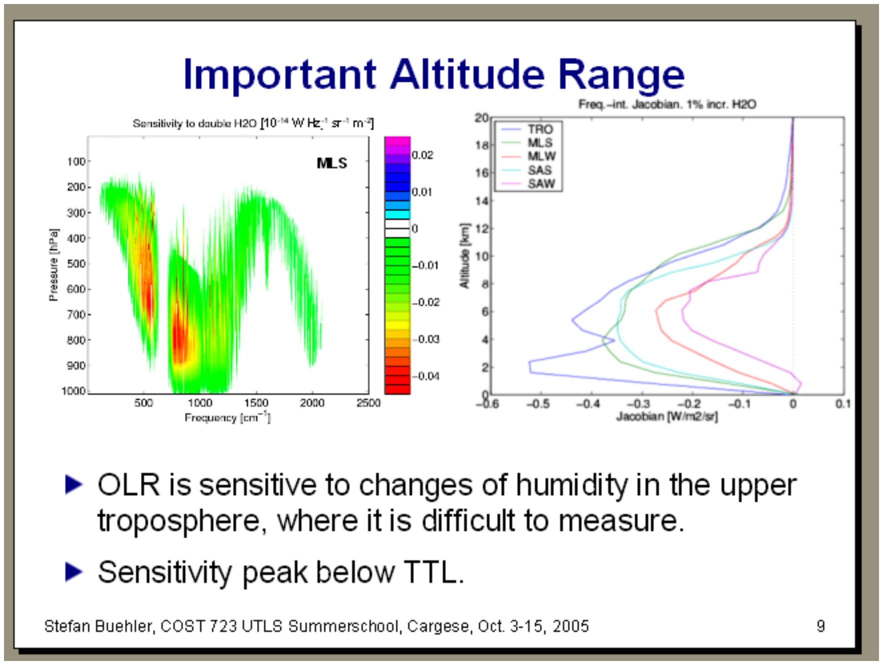
…decided that water can be fun!!!!

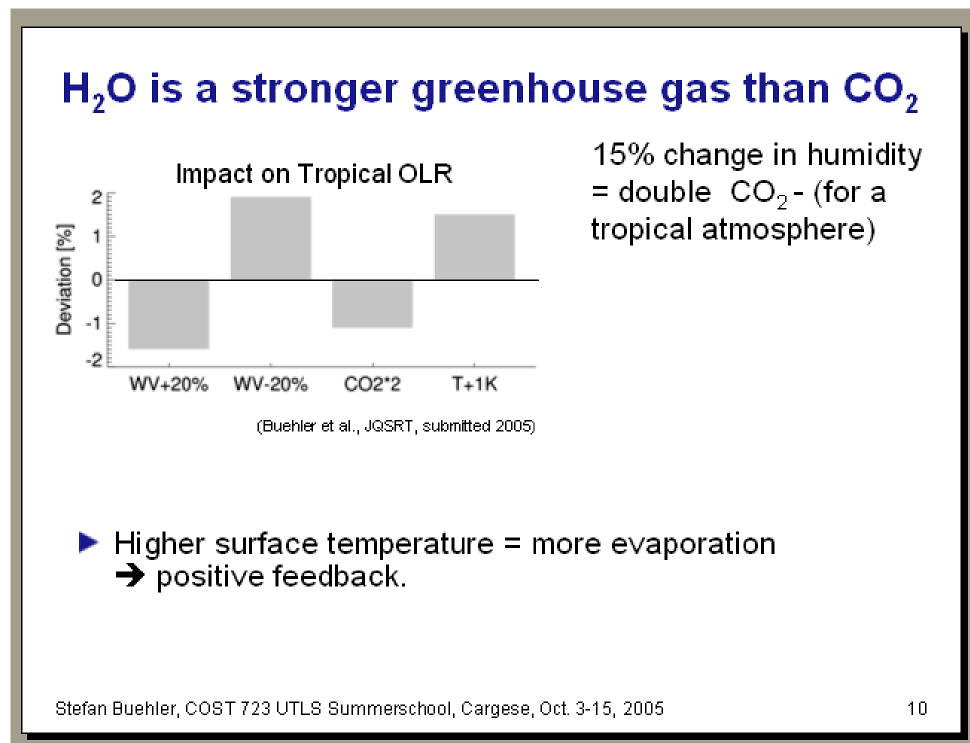
Some people started to believe it…

…Some other did not!!



Measuring Upper Tropospheric humidity with Operational Microwave Satellite Sensors (AMSU-B)
(Stefan A. Buehler, University of Bremen, Germany)

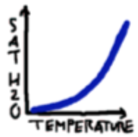




The Water Vapor Feedback

How will UTH (and cloudiness) react to a warming of the lower troposphere?

Assumption of constant humidity
⟹ positive feedback.



Too simple minded: H_2O in UTH governed by interplay of dynamical and thermodynamical processes:

- Convection and cyclones transport moisture into the UT (see lectures of Heini Wernli and Andrew Gettelman)
- Ascending air is dried by condensation processes
- High spatial and temporal variability
- Residence time of water substance ~10 days

Is it **positive** . . .

Inamdar, 1998:
Constant relative humidity
⟹ moistening.

Udelhofen et al., 1995:
Increased convection
⟹ incr. hum. near convection
+ increased fraction of UT where this is felt
⟹ moistening.

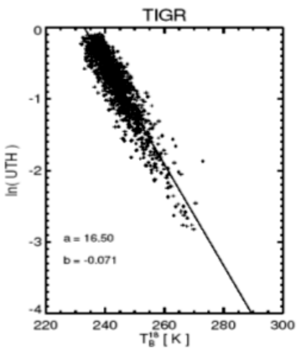
or **negative**?

Ellsaesser, 1984:
Increased convection
⟹ increased Hadley Cell circ.
⟹ increased clear air return
⟹ drying.

Lindzen, 1990:
Increased convection
⟹ increased subsidence some distance away from convective cells
⟹ drying.

AMSU-B measurements of upper tropospheric water vapor

Regression UTH Retrieval

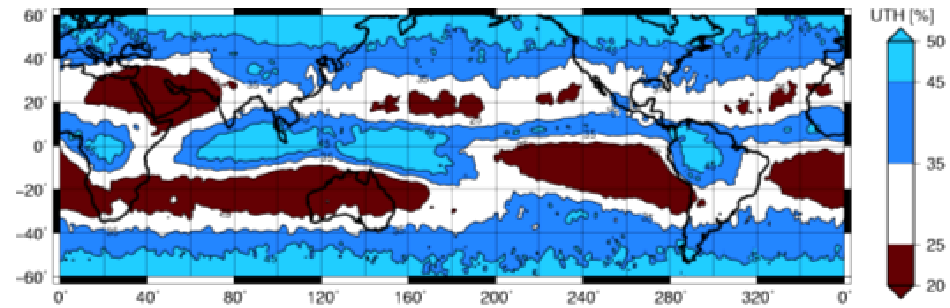


- UTH = Jacobian-weighted relative humidity ≈ mean relative humidity between 500 and 200 hPa
- Simple relation:

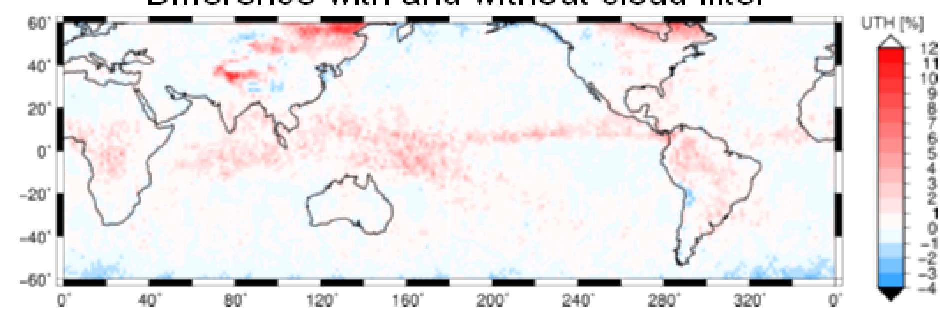
  $\ln(UTH) = a + b\,T_b$

- Determine *a* and *b* by linear regression with training data set
- Details: Buehler and John, JGR, 2004
- Method originally invented by Brian Soden for IR data.

UTH, AMSU-B, Channel 18, NOAA 16, 2002

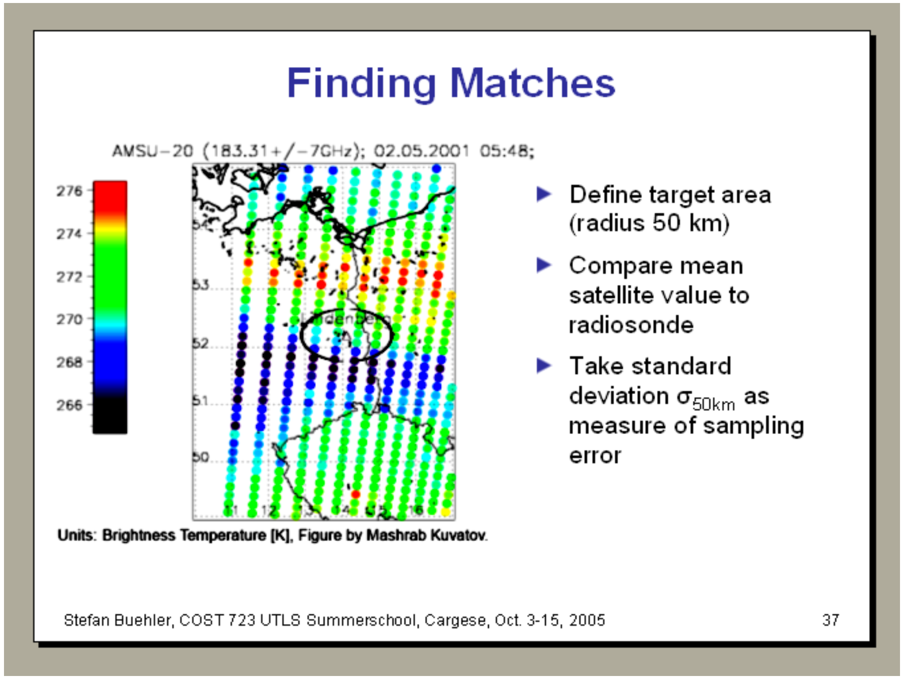


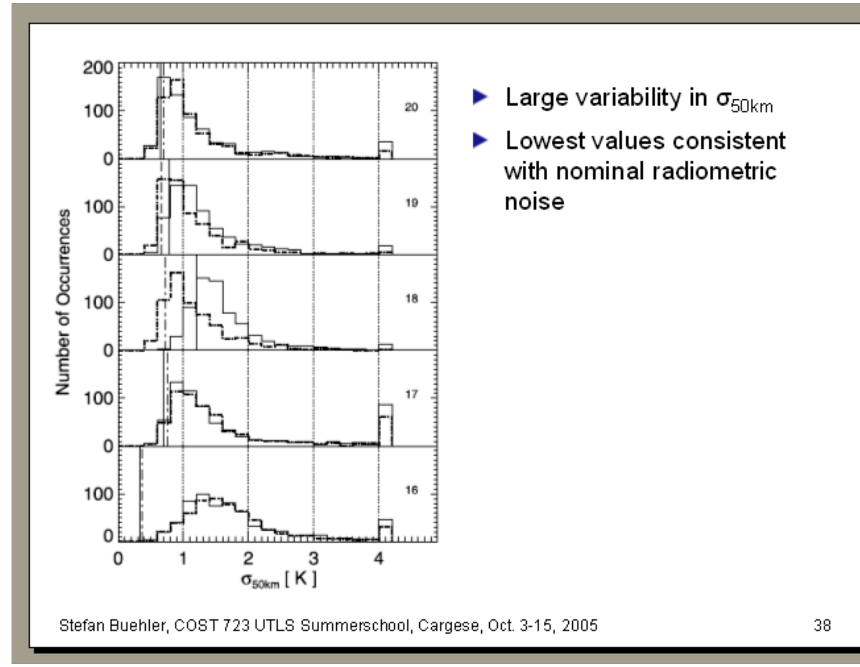
Difference with and without cloud filter

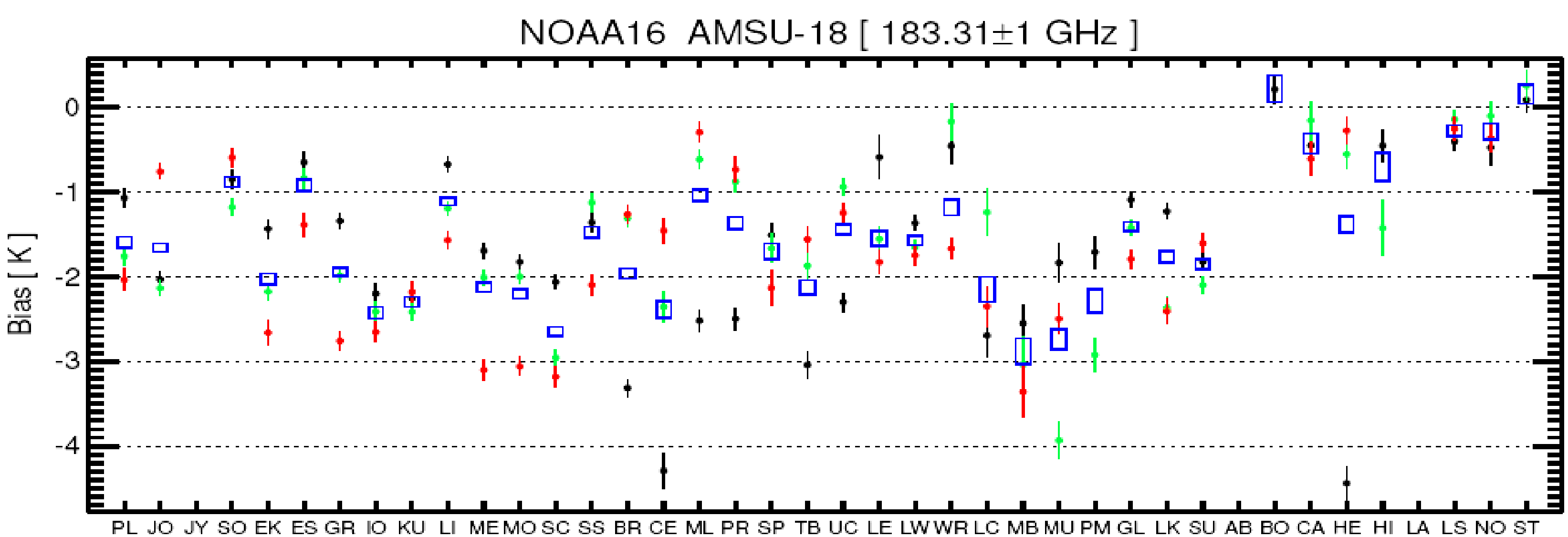


(Figures by Mashrab Kuvatov)

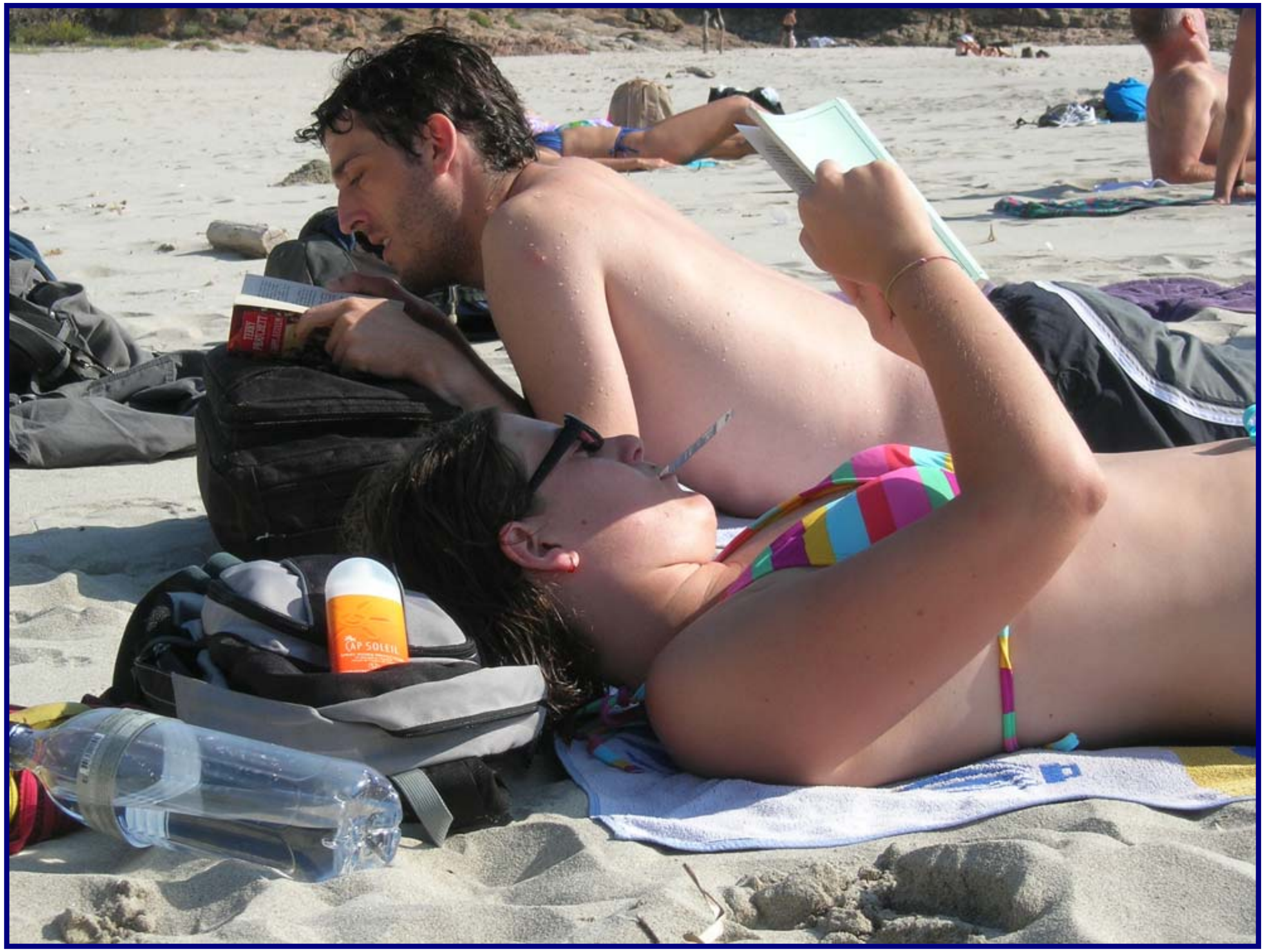
Validation of AMSU-B UTH retrievals







People started to take it seriously…
while exploring new study techniques



The Belgians followed them…

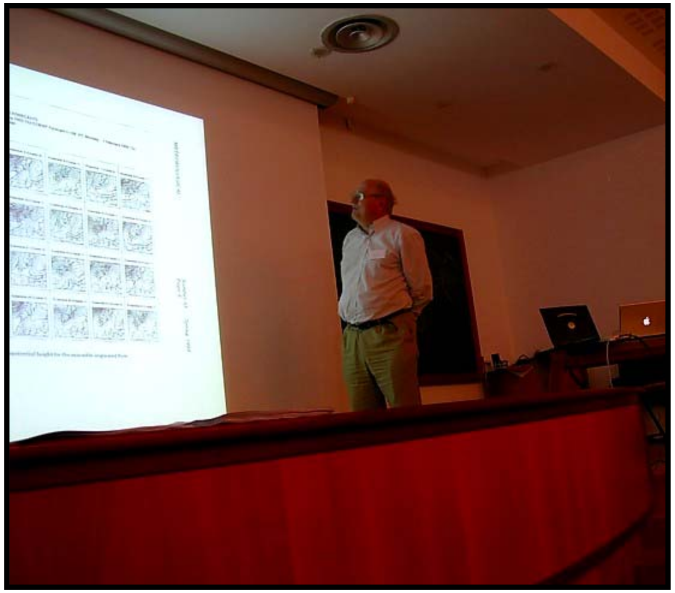
…and the Russians…

…and the Canadians…

…and the Ukrainians…

…and the Russians…

…Someone did not follow them!!



“The most general form of statistical linear estimation: the Best Linear Unbiased Estimator (BLUE)”
(Olivier Talagrand, Laboratoire Meteorologie Dynamique, Paris)

Lectures on *Assimilation of Observations*
(Olivier Talagrand, lecturer)

Basic Formulæ for Assimilation

For a random quantity x (either scalar or vector), $E(x)$ denotes statistical expectation, and $x' = x - E(x)$ the corresponding centred quantity. The upper index ^{T} denotes transposition.

1. *Optimal Interpolation.* One wants to estimate a random vector $\boldsymbol{x}$ from the known value of a random vector $\mathbf{y}$. The linear function x^a of y that minimizes the expectation of $E[(x^a - x)^T (x^a - x)]$ of the corresponding quadratic estimation error is equal to

$$x^a = E(x) + E(x'y'^T)\,[E(y'y'^T)]^{-1}\,[y - E(y)] \tag{1a}$$

The covariance matrix of the corresponding estimation error is equal to :

$$P^a = E[(x^a - x)(x^a - x)^T] = E(x'x'^T) - E(x'y'^T)\,[E(y'y'^T)]^{-1}\,E(y'x'^T) \tag{1b}$$

2. *The most general form of Statistical Linear Estimation. The Best Linear Unbiased Estimator (BLUE).*

One wants to estimate an unknown vector $\boldsymbol{x}$, belonging to *state space*, with dimension n, from a known *data vector* z, with dimension m ($m \geq n$, $m = n + p$). The data vector is of the form :

$$z = \Gamma x + \zeta \tag{2}$$

where Γ is a known operator from state space into data space, with rank n, and ζ is a random 'error', assumed to be centred [$E(\zeta) = 0$], with known covariance matrix $S = E(\zeta\zeta^T)$.

One looks for an estimate x^a, depending linearly on z, satisfying the following two conditions :

a) x^a est invariant in a change of origin in state space.

b) x^a minimizes the expectation $E[(x^a - x)^T (x^a - x)]$ of the corresponding quadratic estimation error.

That estimate is equal to:

$$x^a = (\Gamma^T S^{-1} \Gamma)^{-1}\, \Gamma^T S^{-1} z \tag{3a}$$

with corresponding estimation error covariance matrix :

TAKE THE NOTES!

$$P^a = E[(x^a - x)(x^a - x)^T] = (\Gamma^T S^{-1} \Gamma)^{-1} \quad (3b)$$

Variational form. The estimate x^a can also be obtained by minimization of the following scalar *objective function*, défined on state space:

$$\xi \rightarrow \mathcal{J}(\xi) = (1/2)\,(\Gamma\xi - z)^T S^{-1} (\Gamma\xi - z) \quad (4)$$

The estimate x^a is the *Best Linear Unbiased Estimator* (*BLUE*) of x from z. In the particular case when the error ζ is gaussian, $\zeta = \mathcal{N}[0, S]$, equations (3) achieve bayesian estimation in the sense that the conditional probability distribution for x, knowing z, is the gaussian distribution $\mathcal{N}[x^a, P^a]$.

The right-hand-sides of eqs (3) are unambiguously defined iff $rank\Gamma = n$, That *determinacy condition* ensures that the data z contain information, either directly or indirectly, on every component of x, Under the determinacy condition, the data vector can be decomposed as

$$x^b = x + \zeta^b \quad (5a)$$
$$y = Hx + \varepsilon \quad (5b)$$

with $E(\zeta^b \varepsilon^T) = 0$. (6)

In those expressions, the vector x^b, with dimension n, is the *background* estimate of the unknown state vector. The vector y, with dimension p, contains additional information.

Setting

$$E(\zeta^b \zeta^{bT}) = P^b \quad ; \quad E(\varepsilon\varepsilon^T) = R \quad (7)$$

equations (3) take two equivalent forms:

$$x^a = x^b + P^a H^T R^{-1} (y - Hx^b) \quad (8a)$$
$$(P^a)^{-1} = (P^b)^{-1} + H^T R^{-1} H \quad (8b)$$

and

$$x^a = x^b + P^b H^T (H P^b H^T + R)^{-1} (y - Hx^b) \quad (9a)$$
$$P^a = P^b - P^b H^T (H P^b H^T + R)^{-1} H P^b \quad (9b)$$

In equations (8a) et (9a), the estimate x^a is the sum of the background x^b and of a correction that is proportional to the *innovation vector* $y - Hx^b$. The corresponding multiplicating matrix $K = P^a H^T R^{-1} = P^b H^T (H P^b H^T + R)^{-1}$ is called the *gain matrix*.

In decomposition (5), the objective function (4) becomes :

$$\mathcal{J}(\xi) = (1/2)\,(\xi - x^b)^T (P^b)^{-1} (\xi - x^b) + (1/2)\,(H\xi - y)^T R^{-1} (H\xi - y) \quad (10)$$

It is an objective function of that time that is minimized in '*3D-Var*', with the background x^b and the observation vector y being valid at the same time.

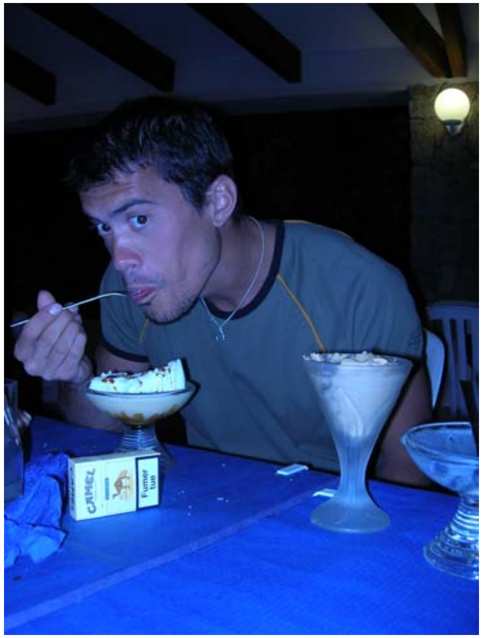
Even the dog fell asleep…!

But someone had different plans…

Someone discovered the pleasure of local drinking…




…and local eating

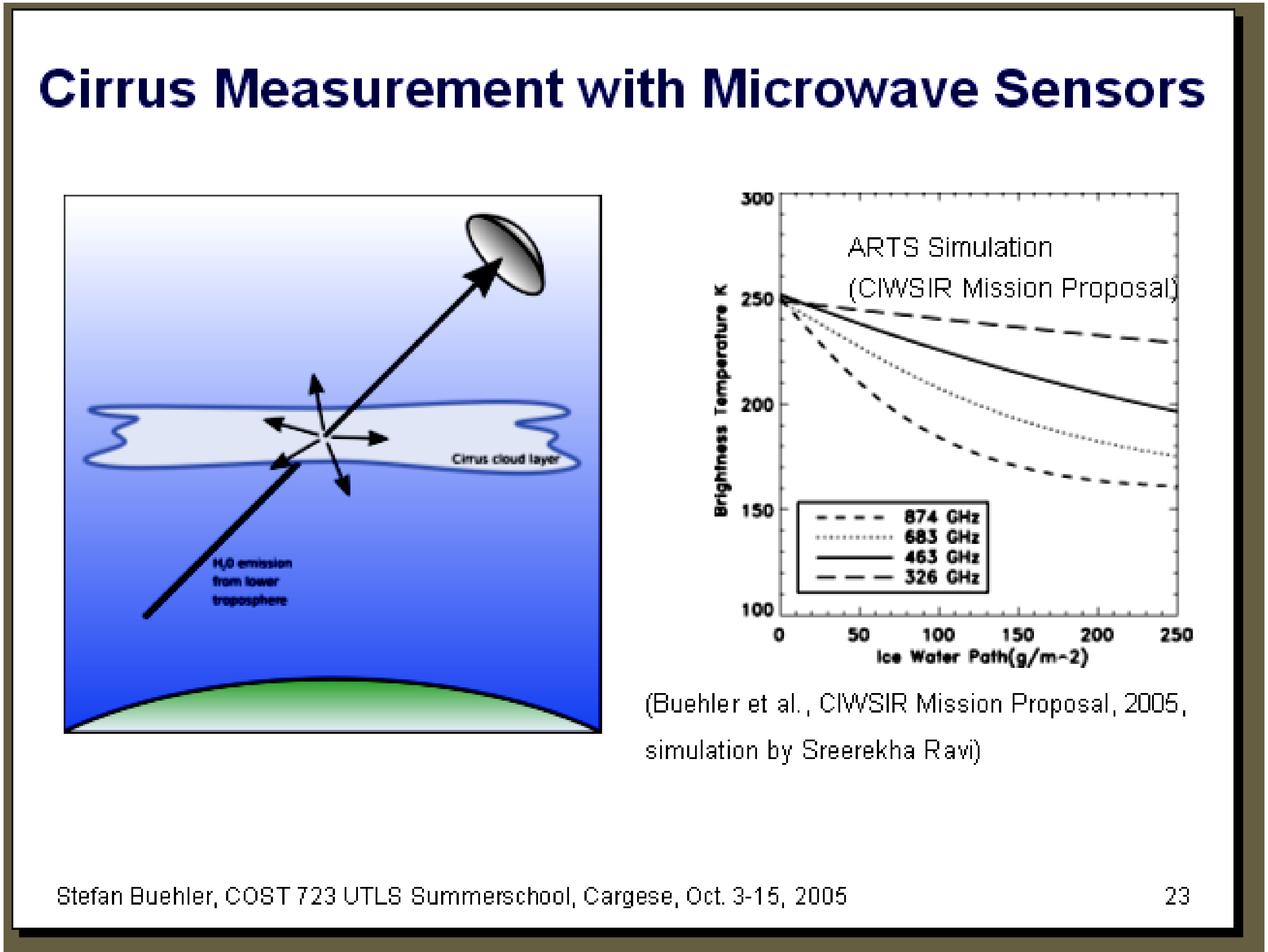


(Someone –by the way- had very beautiful shoes…)

…Someone decided to escape…

…The clouds were so beautiful that day…

Cirrus Clouds & New Satellite Sensors to study Cirrus Clouds in the sub-mm Spectral Range
(Klaus Gierens, DLR Germany & Stefan Buehler)



- Cirrus clouds reflect sunlight and thus increase the planetary albedo (Low thick clouds)

▶Cirrus clouds are radiatively cold and thus reduce the OLR (High thin clouds)

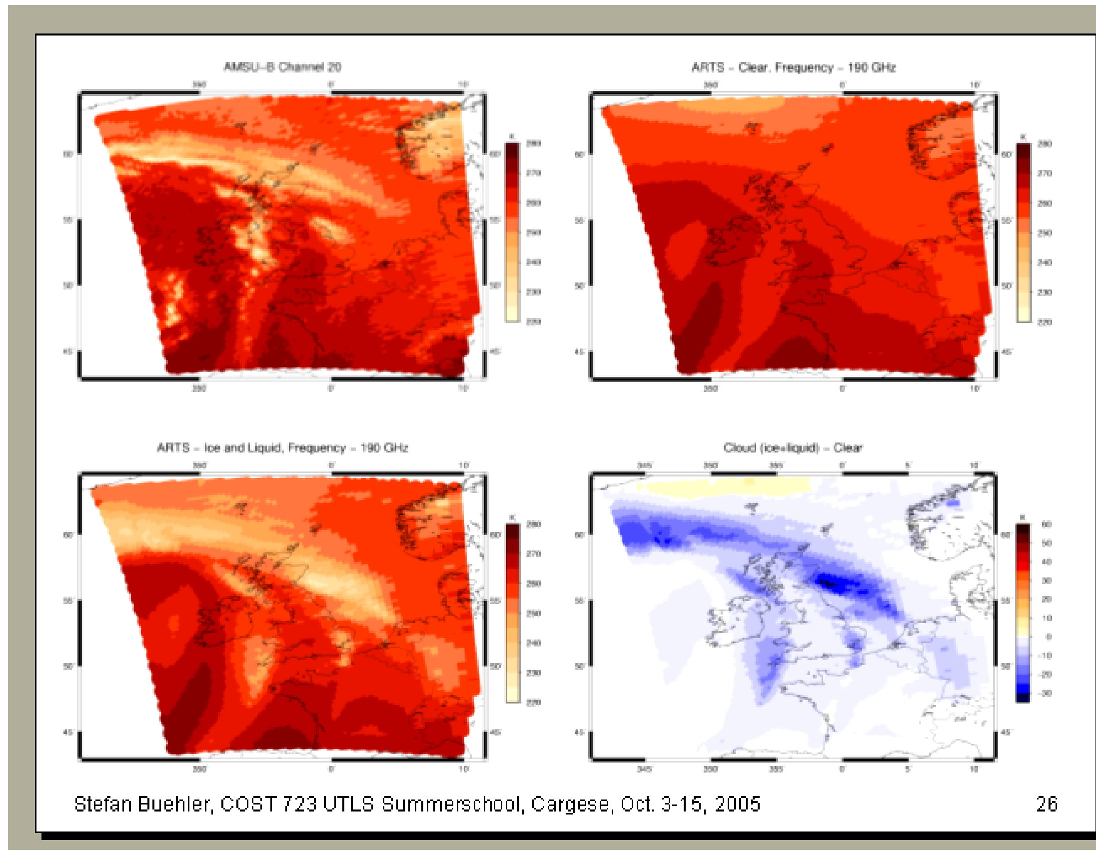
▶How will the net effect change for a changing surface temperature?

Influence of Cirrus Clouds on AMSU-B

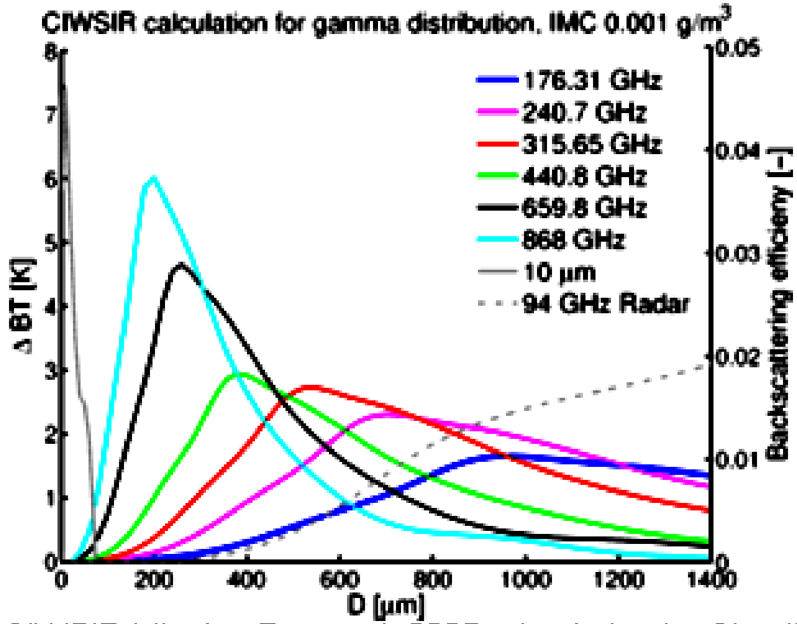
- **Strong Cirrus clouds have an important influence on AMSU-B measurements near 183 GHz, but**
- **to determine the ice water content of weaker clouds (and ice particle size/shape) we need more channels at higher frequencies.**

→ **NASA proposal SIRICE (PI Steve Ackerman).**

→ **ESA Opportunity Mission Proposal CIWSIR (Cloud Ice Water Sub-millimeter Imaging Radiometer).**



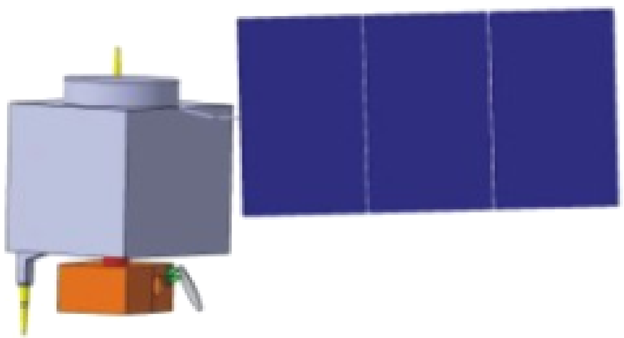
Different Particle Sizes

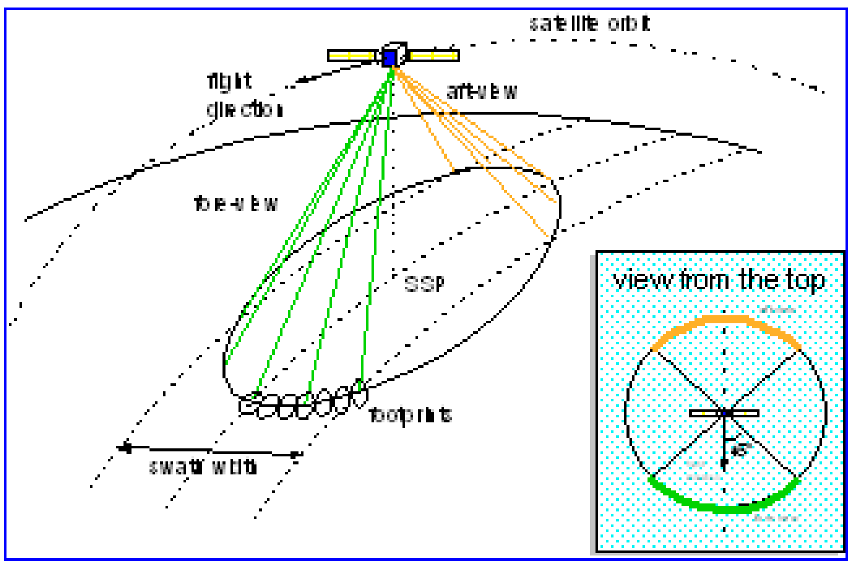


(Buehler et al., CIWSIR Mission Proposal, 2005, simulation by Claudia Emde)

- Different frequencies sample different parts of the size distribution
- IR sees only smallest particles, radar only largest particles (compare lecture by Geraint Vaughan)

The CIWSIR Instrument





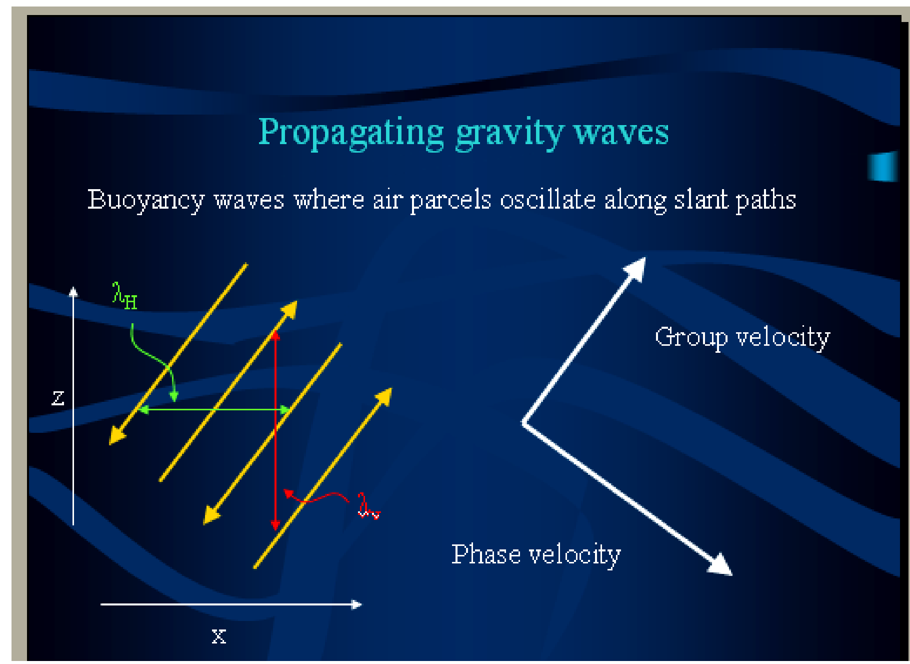
- Mission proposal to ESA for current explorer call.
- Conical scanner.
- Goal: Ice water path and effective ice particle size with 15 km horizontal resolution and 25% accuracy.
- Preparation: Aircraft campaigns with sub-mm receivers and simultaneous in-situ measurements.

Coffee break…

And maybe more than *one* coffee…

Talking about gravity waves… Geraint Vaughan, Univ. of Manchester, UK

- They can propagate vertically and horizontally, transporting momentum from their source to their sink
- They are difficult features to represent correctly in global models – this is an area of active current research.
- Waves propagate vertically into the stratosphere and mesosphere
- Wave amplitudes vary as $\rho^{-½}$: density decreases so waves grow in amplitude with height



Why do we care about gravity waves?

- **They transport momentum vertically. This momentum transfer is crucial to the large-scale momentum balance of the stratosphere**
- **They break, causing mixing of air from different origins. This can be important around the tropopause**
- **Mountain waves in particular can cause significant aviation hazards e.g through rotors or turbulence**

Mathematical theory of gravity waves

The basic equations of atmospheric dynamics are the three momentum equations, the continuity equation, the thermodynamic energy equation and the equation of state for air. They are non-linear.

Gravity wave theories start by postulating some background state of the atmosphere, and introducing small departures from the background state. This is a standard technique in mathematical physics for linearising the equations.

The linear equations have harmonic solutions: $u \propto \exp(kx - \omega t)$

Actual gravity waves can be represented as superpositions of these harmonic solutions

Properties of harmonic solutions

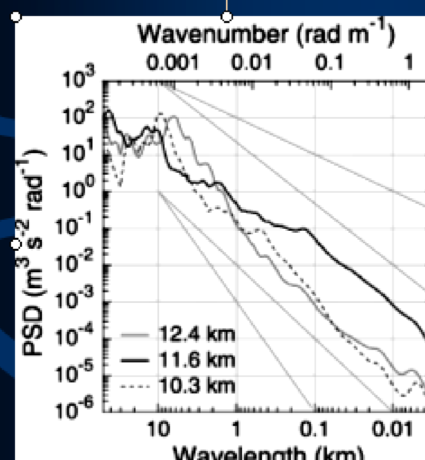
In an atmosphere with a background wind U, the wave frequency ω is replaced by the intrinsic frequency Ω in the dispersion equation:

$$\Omega = \omega - kU$$

As the wave propagates up in the atmosphere ω remains constant (by definition) so if U changes the intrinsic frequency Ω must change. Thus the horizontal and vertical wavelengths, which are related to Ω, also change.

In the extreme case, Ω can become zero. No gravity wave solutions can exist in this case. A level where $\Omega=0$ is called a critical level – in practice waves tend to break just below it.

Observed spectra from aircraft measurements shown earlier



Log-averaged vertical wind kinetic energy spectral densities for each level measured in a frame of reference relative to air. Slanted grey lines show −1, −5/3, −2 and −3 power law dependencies.

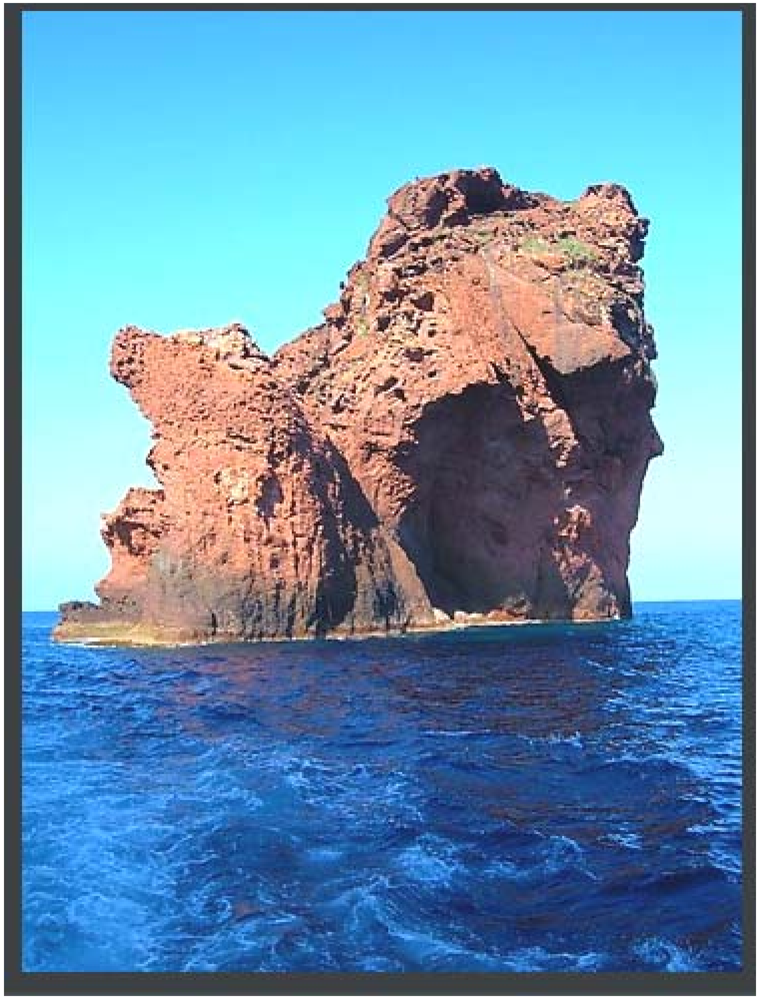
T. Duck and J. A. Whiteway, The spectrum of waves and turbulence at the tropopause, Geophysical Research Letters, 32, L07801, 2005

Some final notes…

Exploring the interland

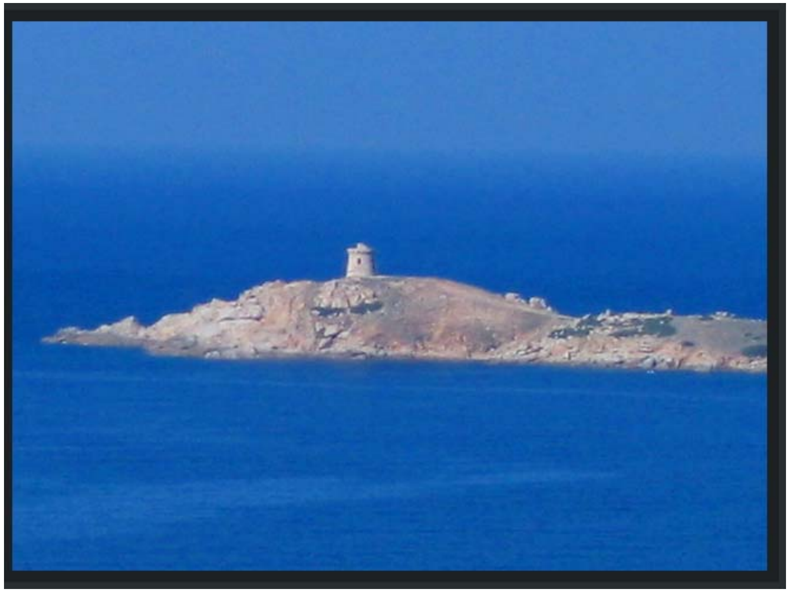
(Filitosa)

Exploring along the coast…



(Girolata)

(Cargese)

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BONIFACIO
21


4978 HE 2B


5873 GM 2A
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