Global and long-term remote sensing of tropospheric {H_2O,δD*} pairs: status and perspectives after the project MUSICA

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Introduction: Tropospheric {H_2O,δD} pairs and MUSICA

Status: {H_2O,δD} pairs remote sensing products with demonstrated high quality.

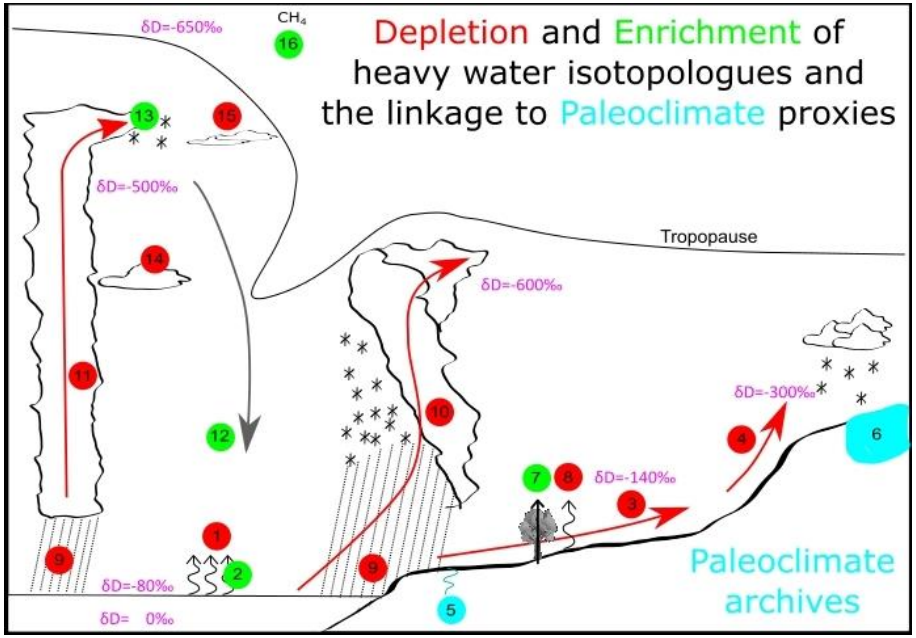
Perspectives: {H_2O,δD} pairs for diagnosing moisture transport in models

Acknowledgement: This work has been made within the project MUSICA. MUSICA is funded by the European Research Council under the European Community's Seventh Framework Programme (FP7/2007-2013) / ERC Grant agreement n° 256961.

*$\delta D = (HDO/H_2O)/R_S - 1$; $R_S = 3.1152 \times 10^{-4}$

The tropospheric water cycle: {H_2O,δD} pairs

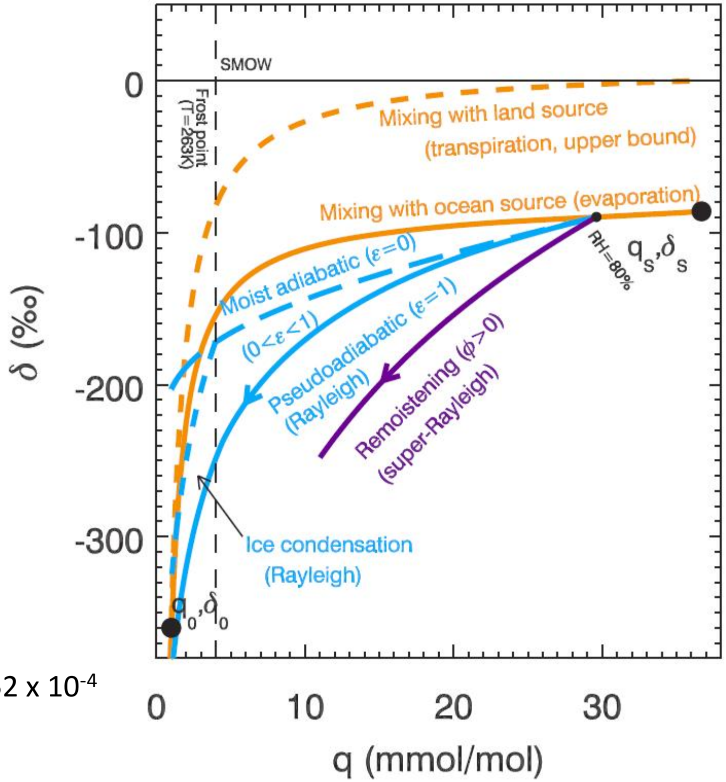
Tropospheric {H_2O,δD} pairs can tag moisture sources and pathways in present day and past tropospheres:



[Christner, PhD-thesis 2015]

δD= (HDO/H_2O)/R_S-1, where R_S=3.1152 x 10^{-4}

The {H_2O,δD} pairs can identify different tropospheric moisture sources and pathways.



[Figures 2 from D. Noone, Journal of Climate, 2011]

<u>Remote sensing</u> of {H_2O,δD} pairs

MUSICA:

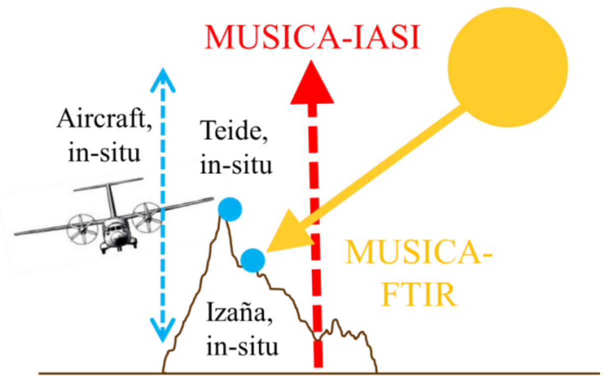
MUlti-platform remote **S**ensing of **I**sotopologues for investigating the **C**ycle of **A**tmospheric water

<u>Focus of MUSICA:</u> Develop and validate **OE retrieval of {H_2O,δD} pairs**.

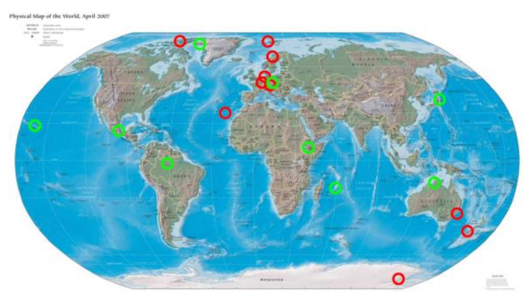
- No individual OE of H_2O and HDO!
- No individual OE of H_2O and δD!

<u>Quality assurance strategy:</u> Combine different measurement techniques and platforms:

Reference data by calibrated in-situ observations

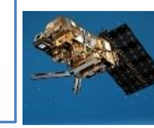


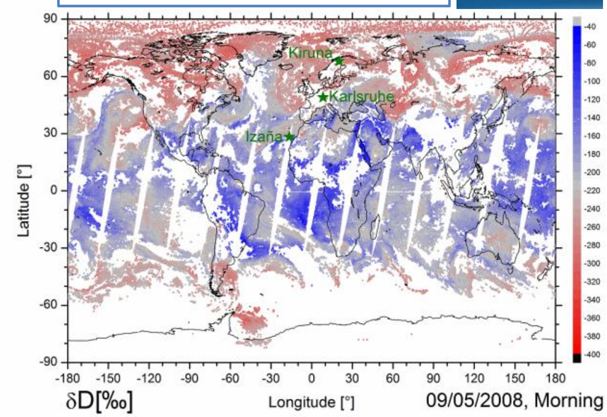
Long-term data from a ground-based remote sensing network:



NDACC/FTIR

Global coverage with space-based remote sensing:



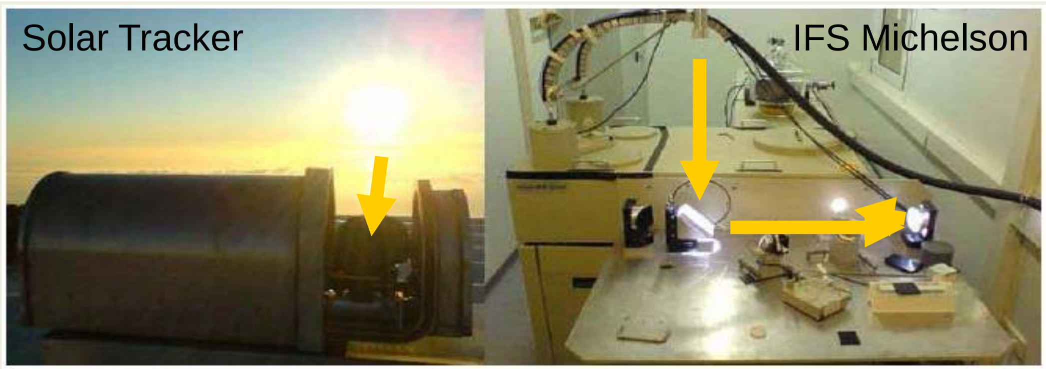


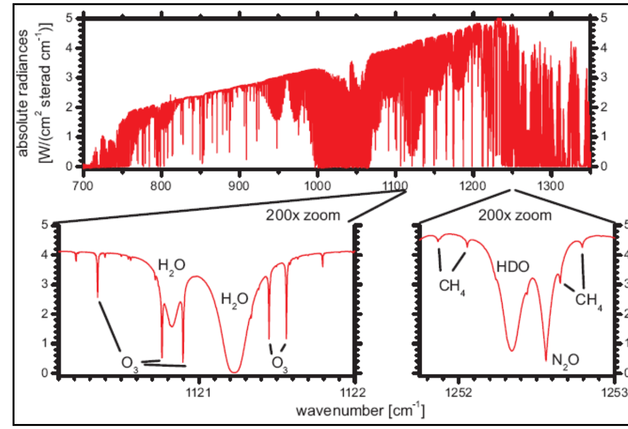
METOP/IASI

Schneider and Hase (2011); Schneider et al. (2012); Wiegele et al. (2014); Barthlott et al. (2015); Dyroff et al. (2015); Schneider et al. (2015); Gonzalez et al. (2015)

Remote sensing of {H_2O,δD} pairs: instrumentation

(1) Ground-based FTIR (international networks, e.g. NDACC):





Sabine Barthlott[1], Matthias Schneider[1], Frank Hase[1], Thomas Blumenstock[1], Matthäus Kiel[1], Darko Dubravica[1], Omaira E. García[2], Eliezer Sepúlveda[2], Gizaw Mengistu Tsidu[3,4], Samuel Takele Kenea[3,*], Michel Grutter[5], Eddy F. Plaza[5], Wolfgang Stremme[5], Kim Strong[6], Dan Weaver[6], Mathias Palm[7], Thorsten Warneke[7], Justus Notholt[7], Emmanuel Mahieu[8], Christian Servais[8], Nicholas Jones[9], David W. T. Griffith[9], Dan Smale[10], and John Robinson[10]

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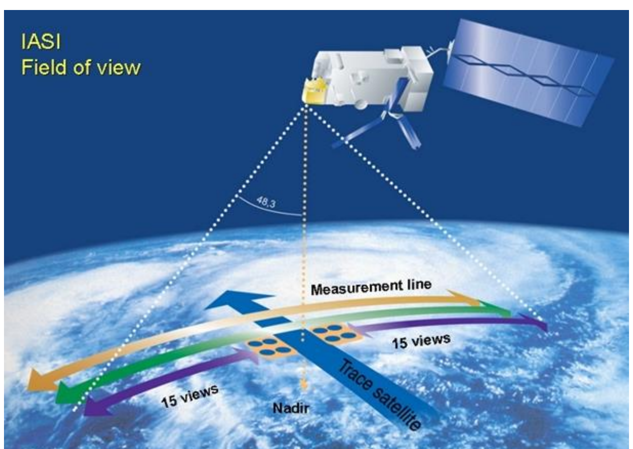
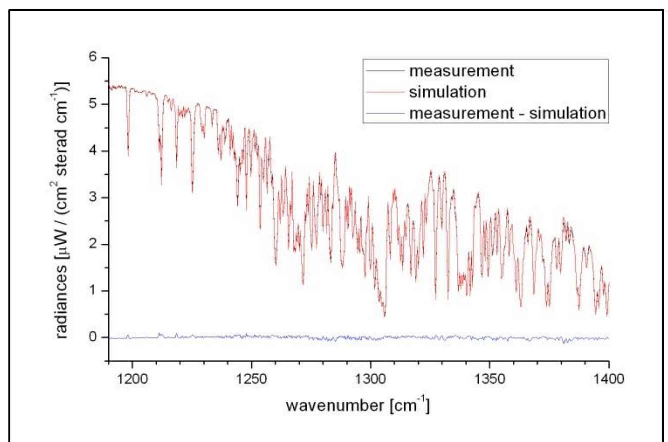
[6]Department of Physics, University of Toronto, Toronto, Ontario, Canada
[7]Institute of Environmental Physics, University of Bremen, Bremen, Germany
[8]Institute of Astrophysics and Geophysics, University of Liège, Liège, Belgium
[9]Centre for Atmospheric Chemistry, University of Wollongong, Wollongong, New South Wales, Australia
[10]National Institute of Water and Atmospheric Research, Lauder, New Zealand
[*]now at: Department of Physics, Samara University, P.O. BOX 132, Samara, Ethiopia

many people, many institutes, many years

(2) Satellite instrument MetOp/IASI (operations controlled by EUMETSAT):



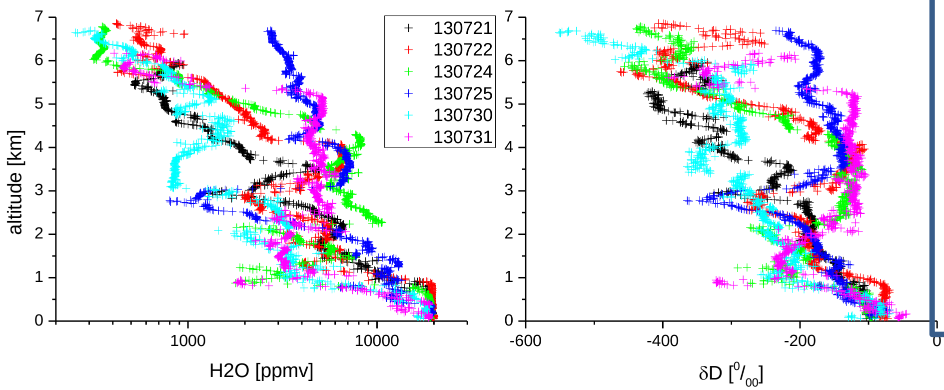


[Schneider and Hase 2011]

References for calibrating water isotopologue products

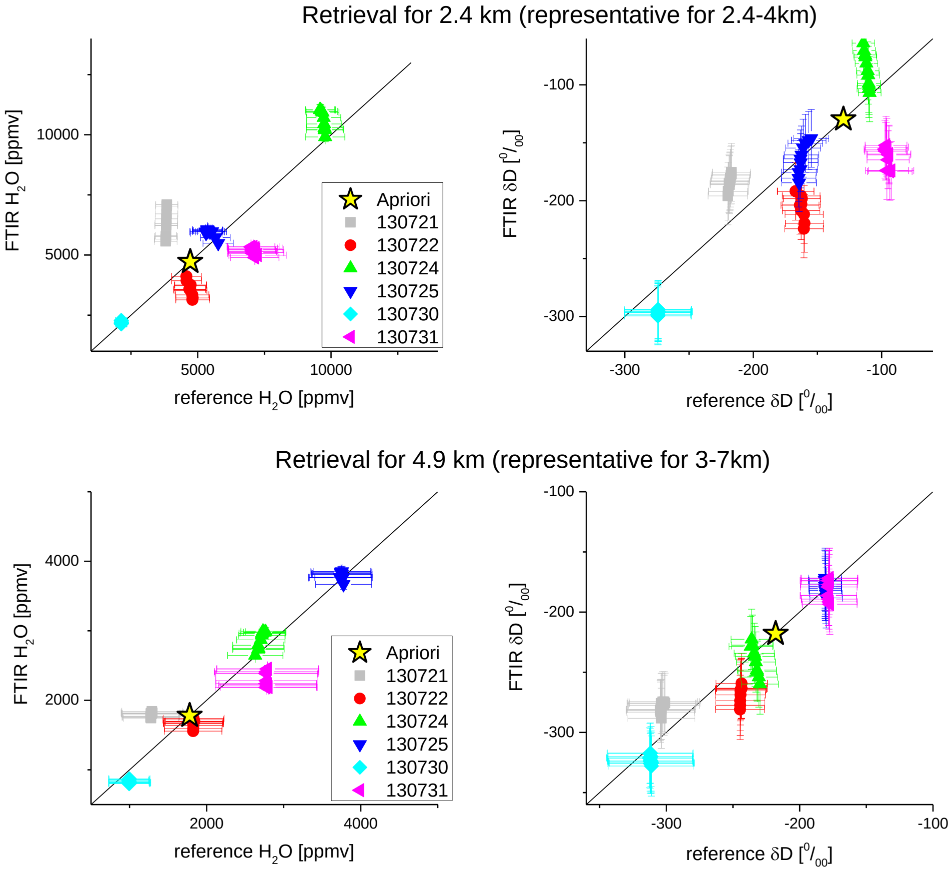
The aircraft component (joint IMK-ASF / AEMET / INTA effort in the context of MUSICA):

Aircraft profile in-situ references:



Dyroff et al., AMT 2015; Schneider et al., AMT 2015

Result: calibrated remote sensing profiles



<u>Status:</u> remote sensing {H_2O,δD} pairs can identify moisture pathways

Surface in-situ reference sites (joint effort of IMK-ASF and AEMET)

Teide: 3550 m a.s.l.

Izaña: 2370 m a.s.l.

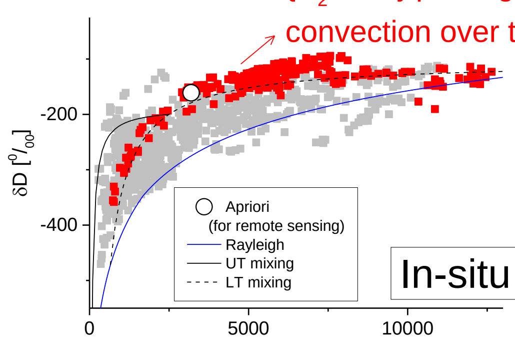
Photos: courtesy of AEMET

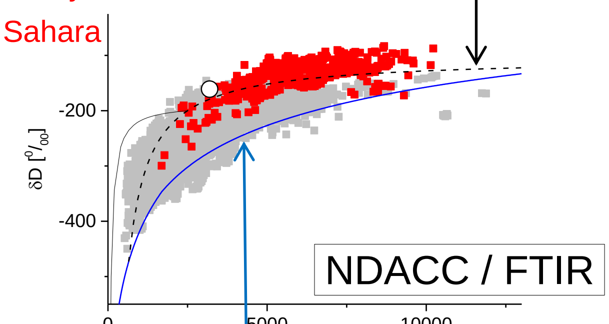
<u>Example:</u>

We use the dry convection mixing events over the Sahara for validating the added value of the isotopologues:

Mixing lines: drying by mixing between humid and dry airmass (no condensation, δD is mainly determined by the humid airmass).

{H_2O,δD} pair signal of dry convection over the Sahara



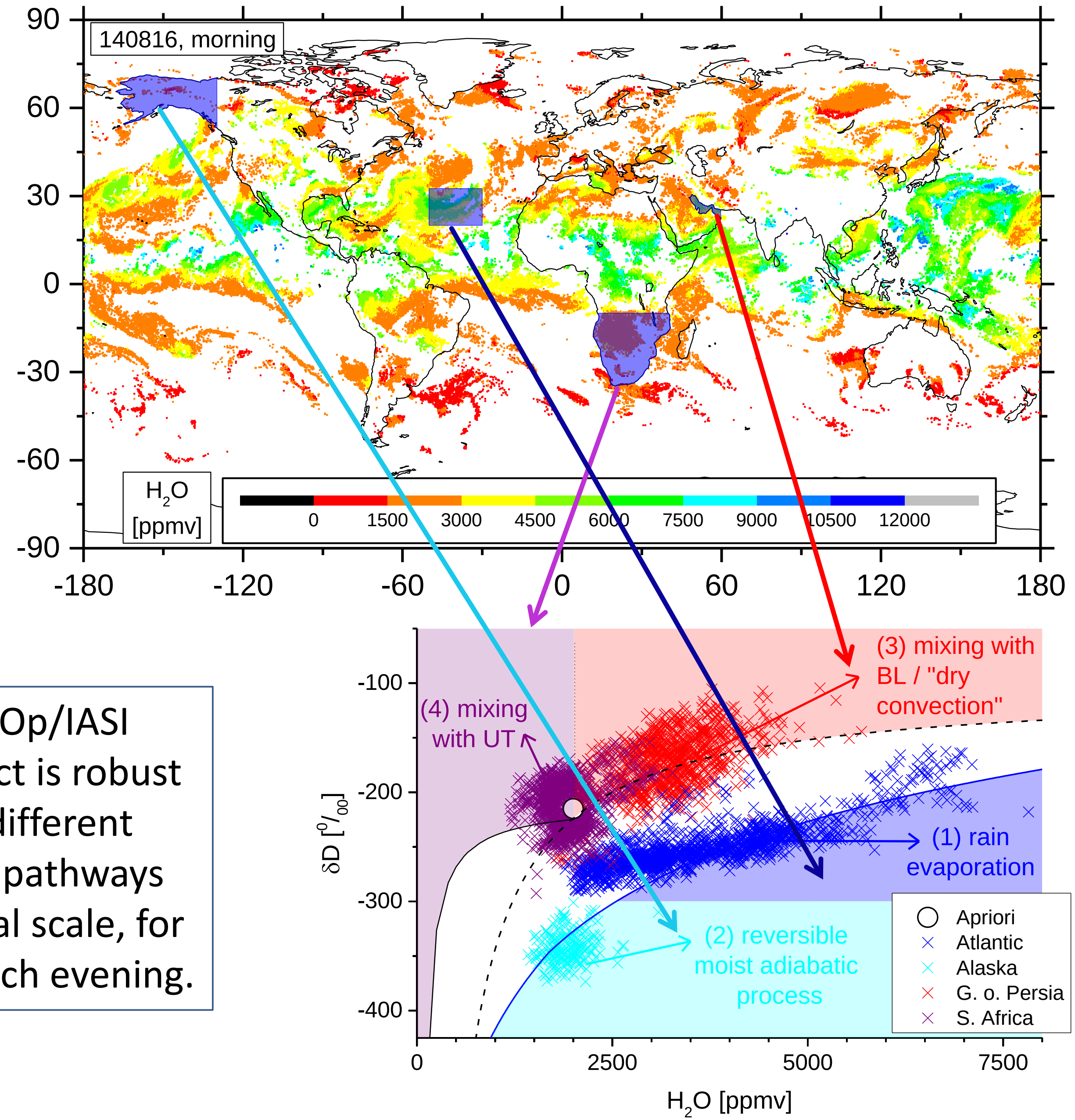


Rayleigh line: drying by condensation (vapour becomes increasingly depleted in HDO)

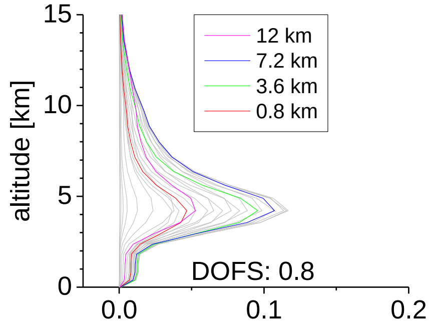
Schneider et al., AMT 2015

IASI: global {H_2O,δD} pairs at high resolution (space and time)

Example of a daily map generated from IASI-A and B morning observations



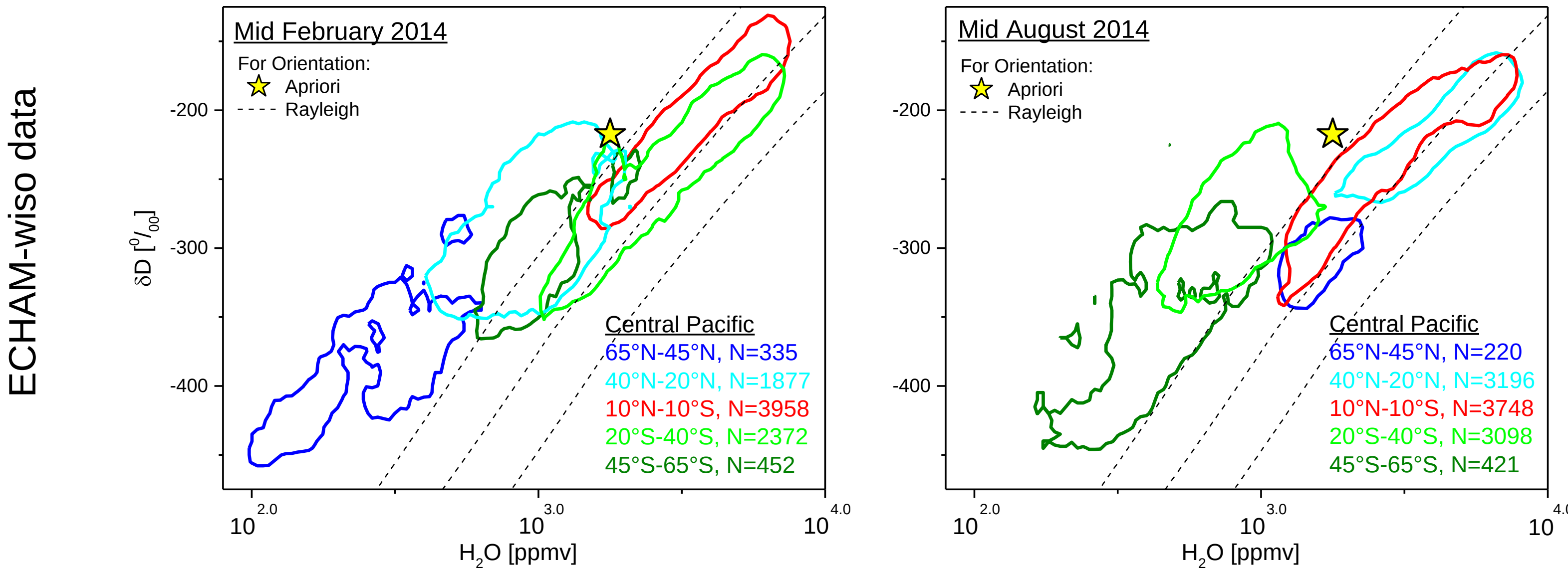
Data are filtered for "good" kernels for H_2O-δD pairs:



The MUSICA MetOp/IASI {H_2O,δD} pair product is robust and can identify different moisture transport pathways consistently on global scale, for each morning and each evening.

Perspective for evaluating moisture transport in models: example, latitudinal cut over the Pacific

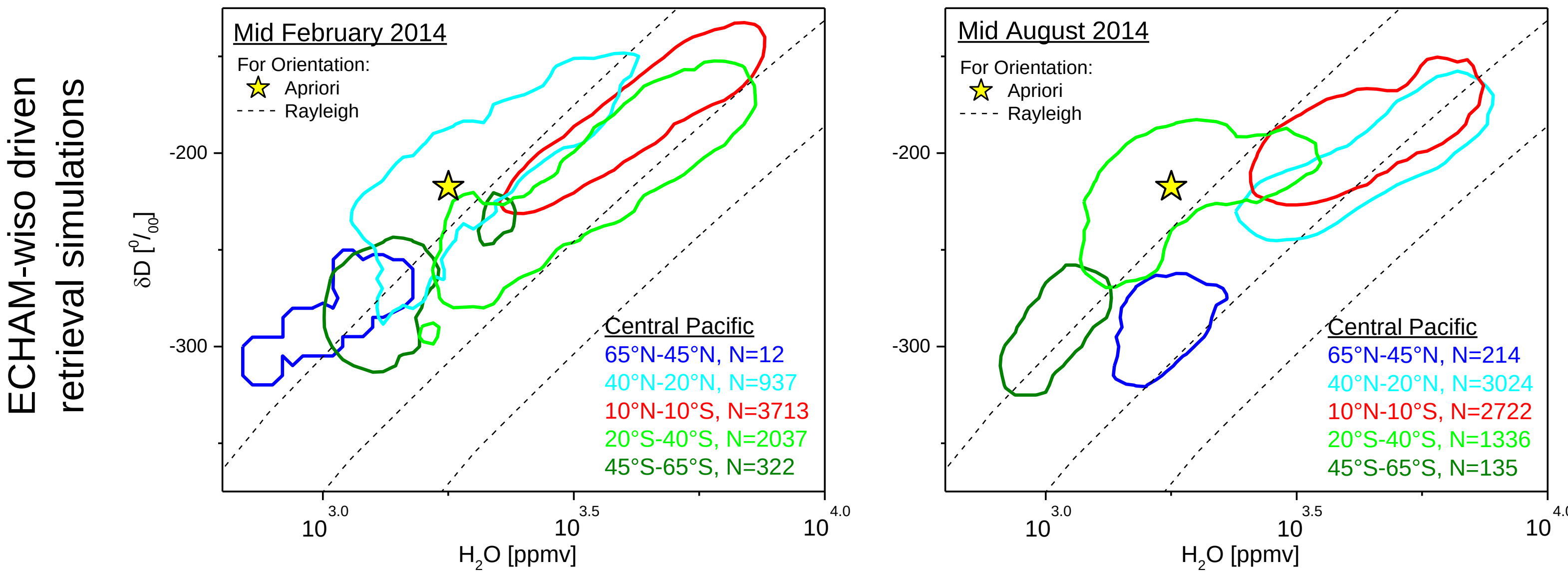
Model data: ECHAM5-wiso (Martin Werner, AWI)



Shown are cloud free situations (RH<90% between surface and 12 km a.s.l.)

Evaluating models: example, latitudinal cut over the Pacific

ECHAM5-wiso model data that have the MUSICA MetOp/IASI {H_2O,δD} remote sensing data characteristics assimilated (retrieval simulator M. Schneider et al., AMTD 2016*)



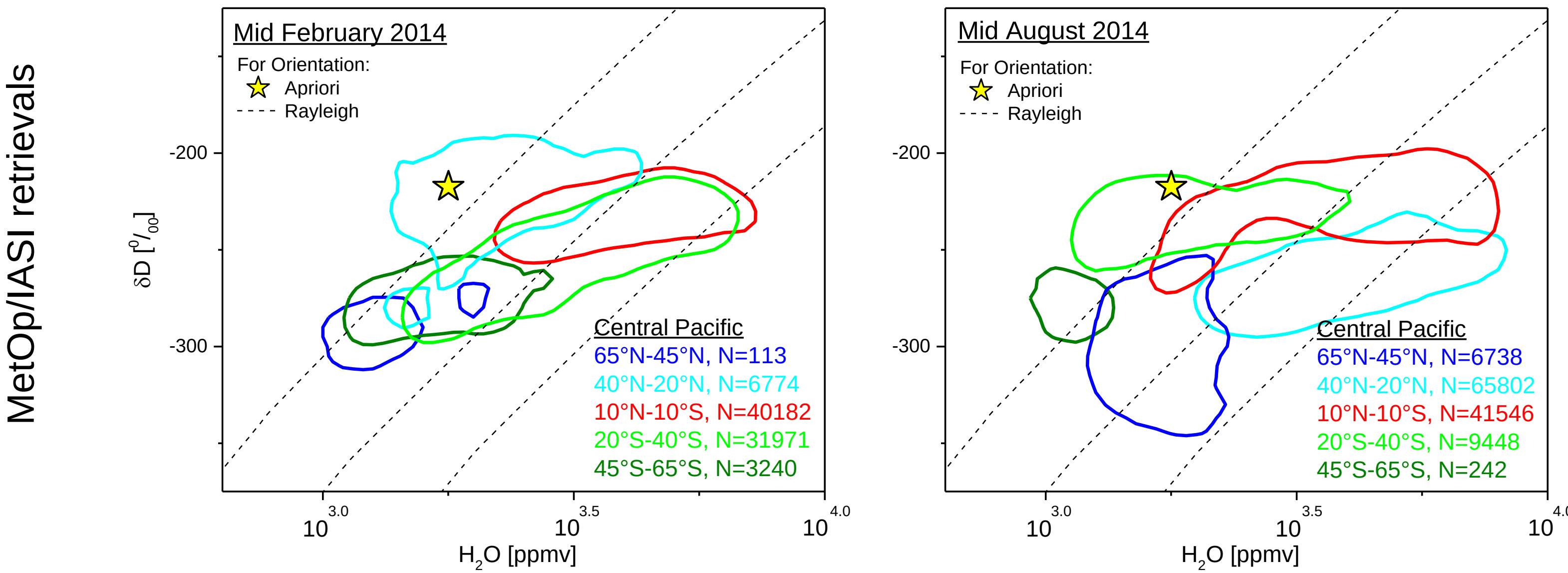
Shown are:

- cloud free situations (RH<90% between surface and 12 km a.s.l.).
- only data with significant sensitivity wrt free tropospheric {H_2O,δD} pairs.

*The retrieval simulator is available as simple MATLAB or Python routine and can be easily connected to any model.

Evaluating models: example, latitudinal cut over the Pacific

MUSICA MetOp/IASI remote sensing data



Shown are:

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- data with significant sensitivity wrt free tropospheric {H_2O,δD} pairs.

<u>The MUSICA MetOp/IASI retrieval simulator for model studies:</u>

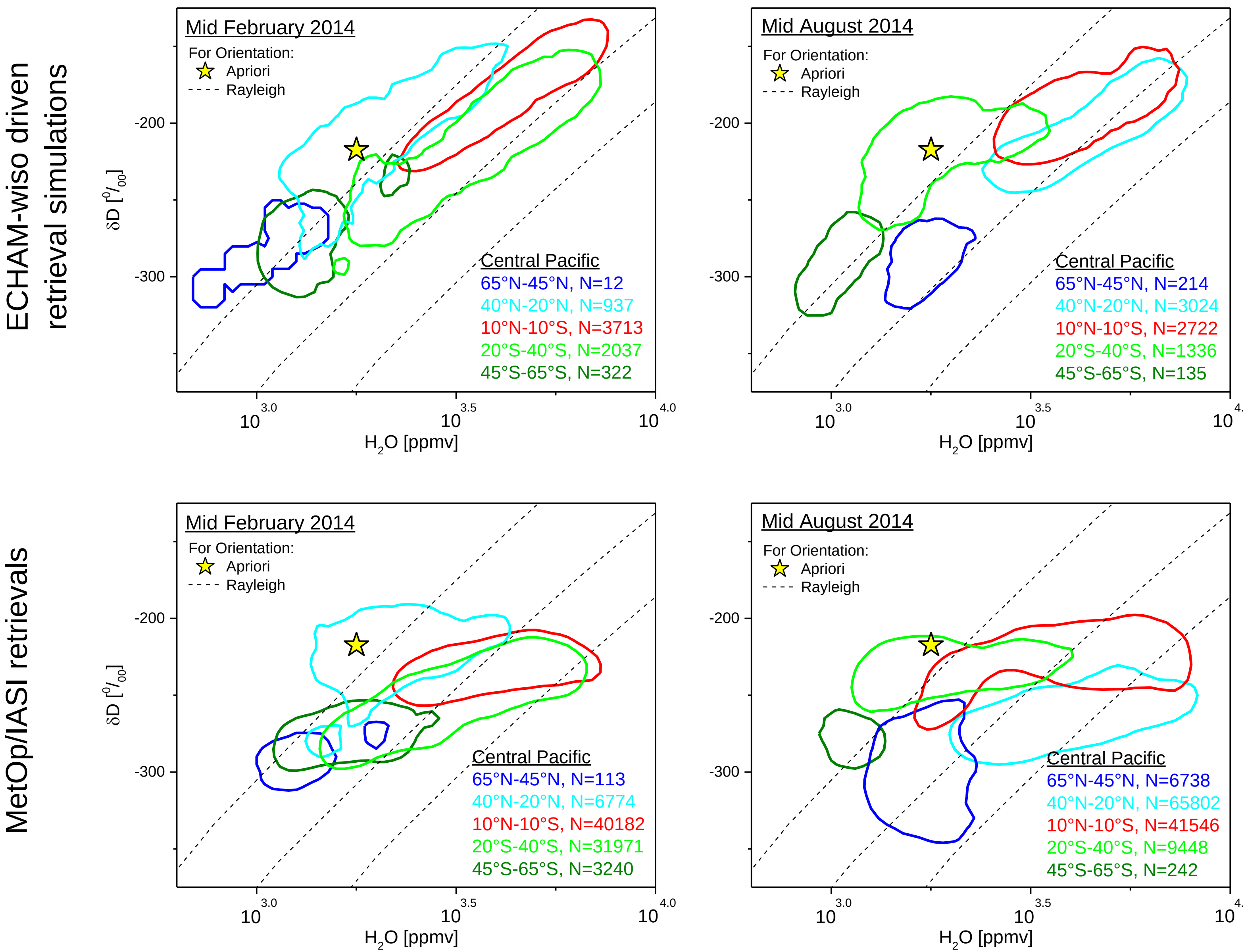
1: Model runs for different scenarios and use {H_2O,δD} pairs as diagnosis tool.

2: Assimilate MUSICA MetOp/IASI data characteristics by means of the retrieval simulator.

3: Perform MetOp/IASI retrievals for confirming/disproving the modelled scenarios.

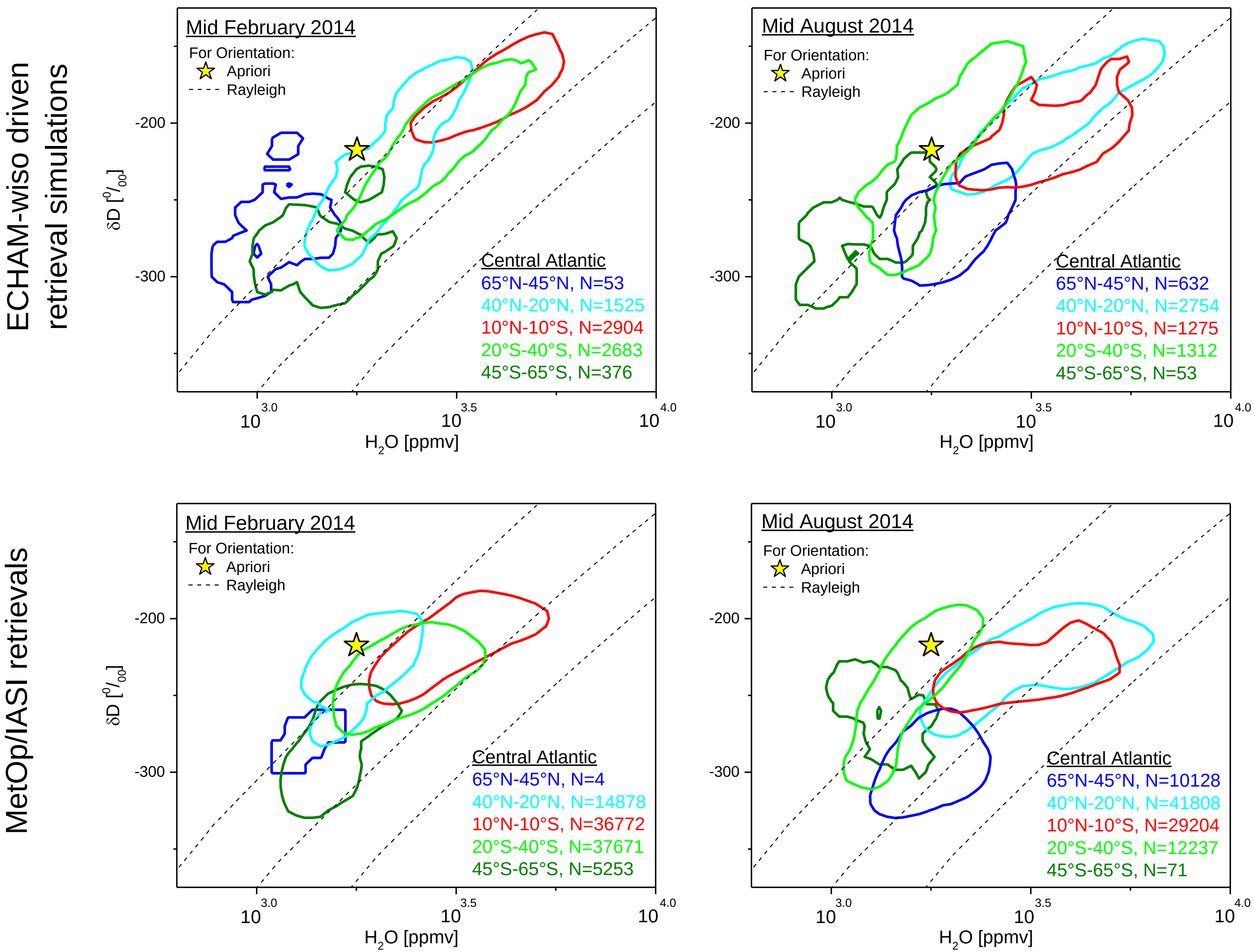
Example global signatures: differences between ocean basins

Pacific ocean



Example global signatures: differences between ocean basins

Atlantic ocean

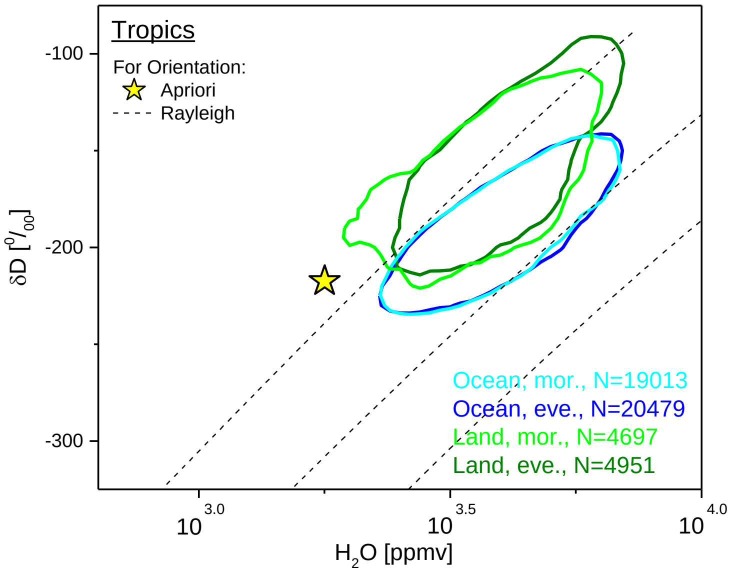


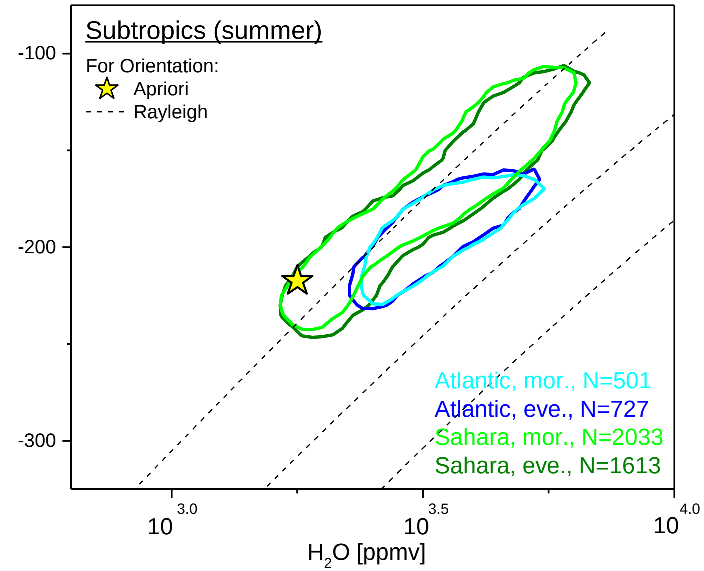
Example diurnal signals in tropics and subtropics

Tropics (ocean/land)

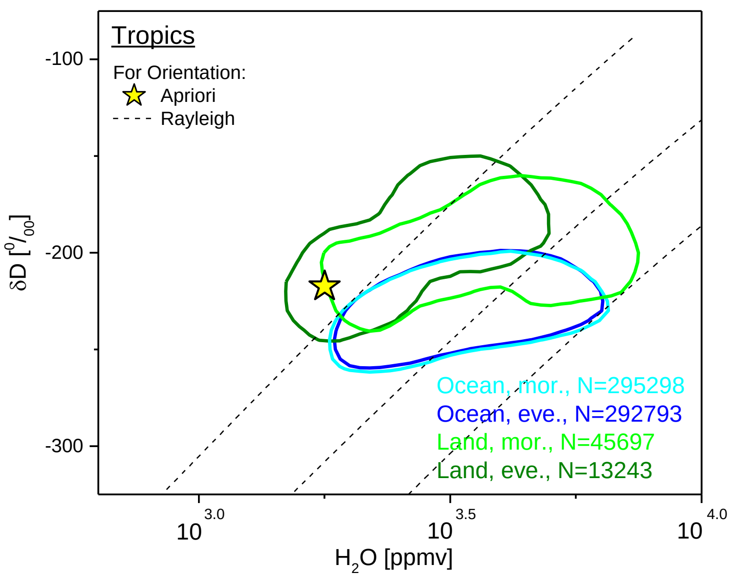
Subtropics (Atlantic/Sahara)

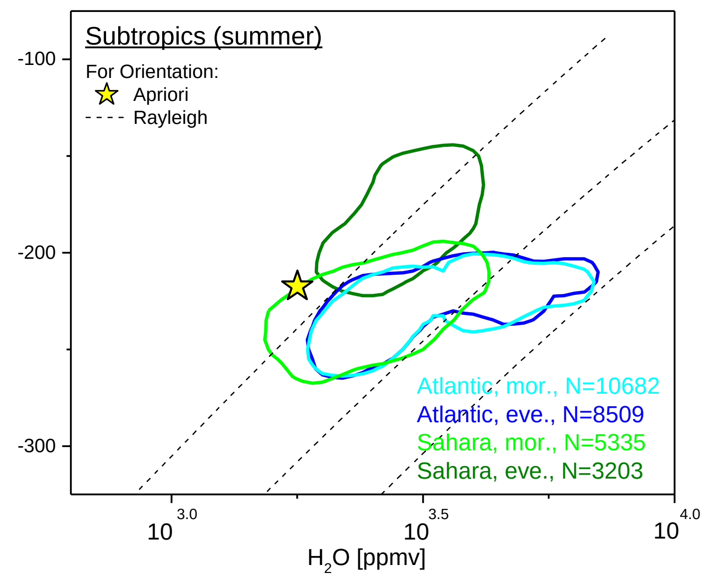
ECHAM-wiso driven retrieval simulations





MetOp/IASI retrievals





Summary

- {H_2O,δD} pairs are a good proxy for tropospheric moisture pathways
- Remote sensing of free tropospheric {H_2O,δD} pairs is possible from ground and space.
- The remote sensing data have a well understood quality.
- The characteristics can be well simulated (retrieval simulator).
- The high quality {H_2O,δD} remote sensing data are a good tool for validating/diagnosing moisture transport pathways in the models.

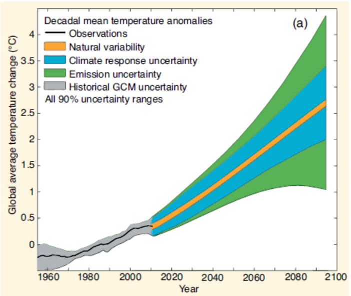
T H A N K S

EXTRA SLIDES

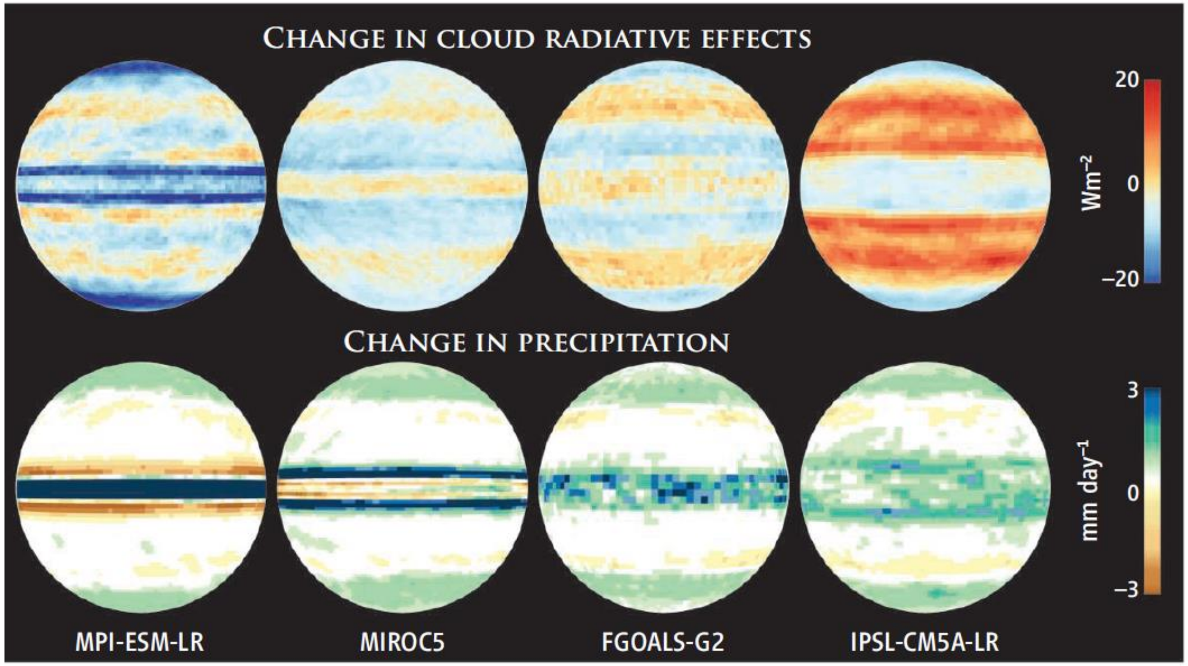
Climate feedback uncertainty and the tropospheric water cycle

"An adequate description of basic processes like cloud formation, moist convection, and mixing is what climate models miss most."

Water cycle feedback assessments by water planet simulations; responses to a uniform T_{sfc} increase of 4 K:



[Chapter 1 of IPCC AR5, 2013]



[Stevens and Bony, Science 2013]

- For comparison: present time anthropogenic CO_2 RF is about 2 Wm^{-2}.
- Inhomogeneous response: strong impact on circulation.

Impact on land-atmosphere carbon fluxes, i.e. on carbon cycle feedbacks.

http://www.wcrp-climate.org/grand-challenges: clouds, circulation and climate sensitivity

Ground-based FTIR remote sensing in networks

Sabine Barthlott[1], Matthias Schneider[1], Frank Hase[1], Thomas Blumenstock[1], Matthäus Kiel[1], Darko Dubravica[1], Omaira E. García[2], Eliezer Sepúlveda[2], Gizaw Mengistu Tsidu[3,4], Samuel Takele Kenea[3,*], Michel Grutter[5], Eddy F. Plaza[5], Wolfgang Stremme[5], Kim Strong[6], Dan Weaver[6], Mathias Palm[7], Thorsten Warneke[7], Justus Notholt[7], Emmanuel Mahieu[8], Christian Servais[8], Nicholas Jones[9], David W. T. Griffith[9], Dan Smale[10], and John Robinson[10]

Principle NDACC/FTIR collaborators for MUSICA

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[2]Izaña Atmospheric Research Center, Agencia Estatal de Meteorología (AEMET), Santa Cruz de Tenerife, Spain
[3]Department of Physics, Addis Ababa University, P.O. Box 1176, Addis Ababa, Ethiopia
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[5]Centro de Ciencias de la Atmósfera, Universidad Nacional Autónoma de México, 04510 Ciudad de México, México
[6]Department of Physics, University of Toronto, Toronto, Ontario, Canada
[7]Institute of Environmental Physics, University of Bremen, Bremen, Germany
[8]Institute of Astrophysics and Geophysics, University of Liège, Liège, Belgium
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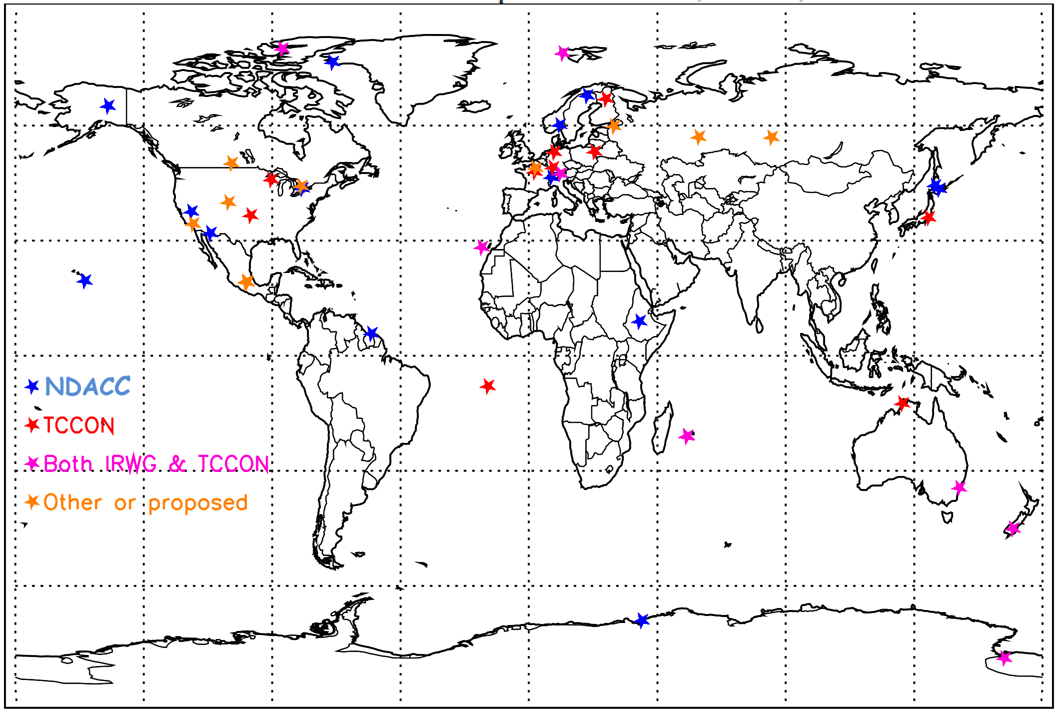
[10]National Institute of Water and Atmospheric Research, Lauder, New Zealand



A continuous coordinated effort by many colleagues around the world!

Remote sensing of {H_2O,δD} pairs: theory

Optimal estimation retrieval: combine apriori knowledge with the measured spectra and estimate the most likely atmospheric state!

Minimise cost function (Rodgers 2000):

$$\underbrace{[\vec{y} - \vec{f}(\vec{x}, \vec{b}, \vec{p})]^T \mathbf{S}_\epsilon{}^{-1} [\vec{y} - \vec{f}(\vec{x}, \vec{b}, \vec{p})]}_{\text{measurement information}} + \underbrace{[\vec{x} - \vec{x_a}]^T \mathbf{S_a}{}^{-1} [\vec{x} - \vec{x_a}]}_{\text{a priori information}}$$

measurement information + a priori information

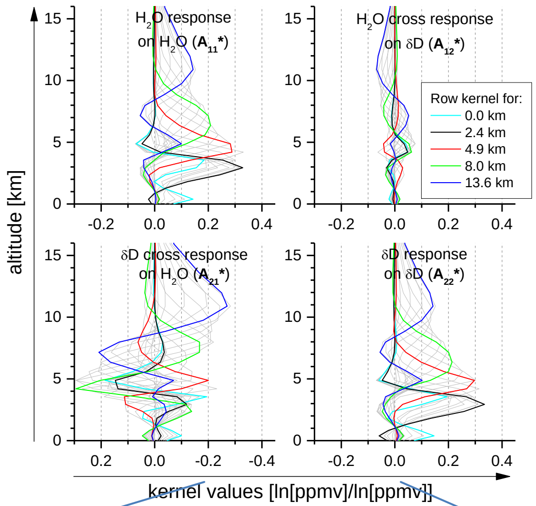
Retrieval „trick" for achieving an optimal estimation of {H_2O,δD} pairs:

(1) Transfer the problem on a logarithmic scale.

(2) Transformation from the {**ln[H2O]}** and **{ln[HDO]}** states to the {**(ln[H2O] + ln[HDO])/2}** and **{(ln[HDO] - ln[H2O])}** states, which are good proxies for the H_2O and δD states.

(3) Postprocessing in order to assure that the H_2O and δD products have the same sensitivity.

Remote sensing: {H_2O,δD} averaging kernels, example IASI



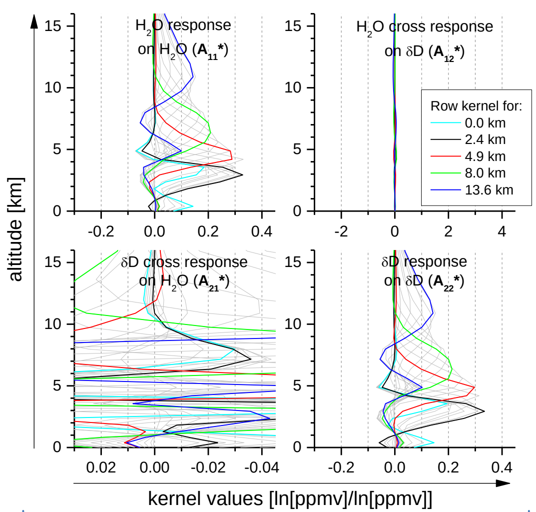
It can be well characterised:

$$\mathbf{A}' = \mathbf{P}\mathbf{A}\mathbf{P}^{-1}$$

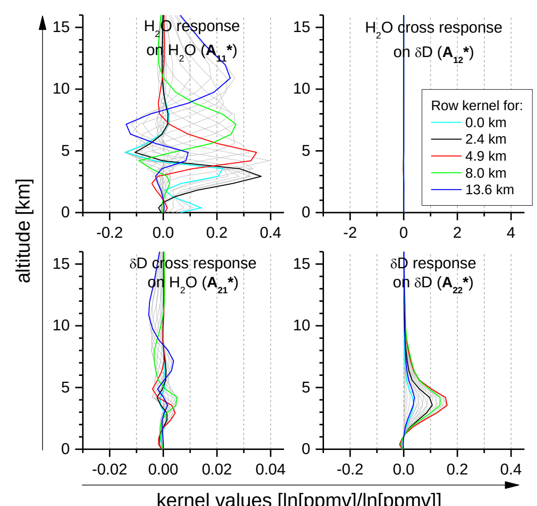
$$\mathbf{A}'' = \mathbf{C}\mathbf{A}'$$

$$\mathbf{S}''_{\mathrm{e}} = \mathbf{C}\mathbf{P}\mathbf{G}\mathbf{K}_p\mathbf{S}_p\mathbf{K}_p^T\mathbf{G}^T\mathbf{P}^T\mathbf{C}^T$$

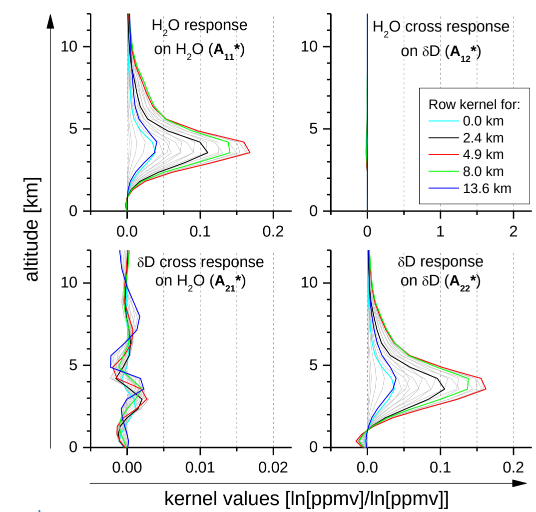
This is the kind of remote sensing product we need!



retrieval of H_2O and HDO



retrieval of H_2O and δD

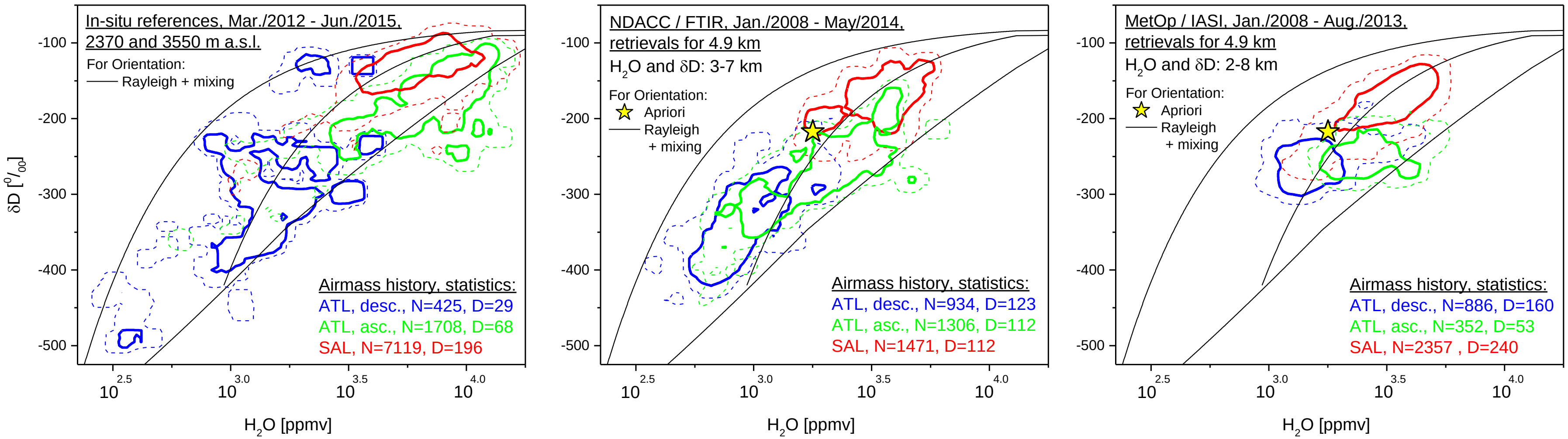


retrieval of {H_2O,δD} pairs

Status: consistent moisture pathway signals in the {H2O,δD} data sets

Example: moisture pathways to the in the north Atlantic subtropical free troposphere

In-situ measurements | Ground-based remote sensing | Space-based remote sensing



Schneider et al., AMT 2016

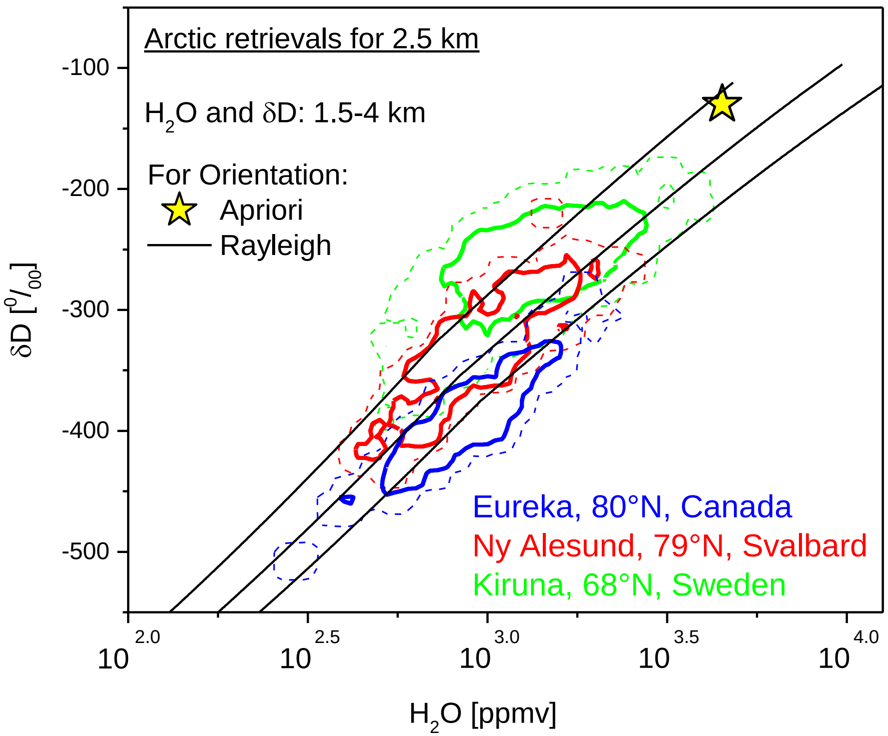
The in-situ, MUSICA NDACC/FTIR, and MUSICA MetOp/IASI {H_2O,δD} pair distributions consistently reflect the different moisture transport pathways!

→ General conclusion on feasibility: {H_2O,δD} remote sensing data can identify moisture pathways.

→ Concrete scientific conclusion for the subtropics: long-term observations of {H_2O,δD} pairs can identify subtropical climate feedbacks.

NDACC/FTIR: long-term {H_2O,δD} pairs time series

Example Arctic winter/spring: observation in the free troposphere (February, March, April, May, 2005-2014)



- Same humidity levels at Eureka and Ny Alesund.
- Difference in δD of about 80‰.

Number of days with observations:

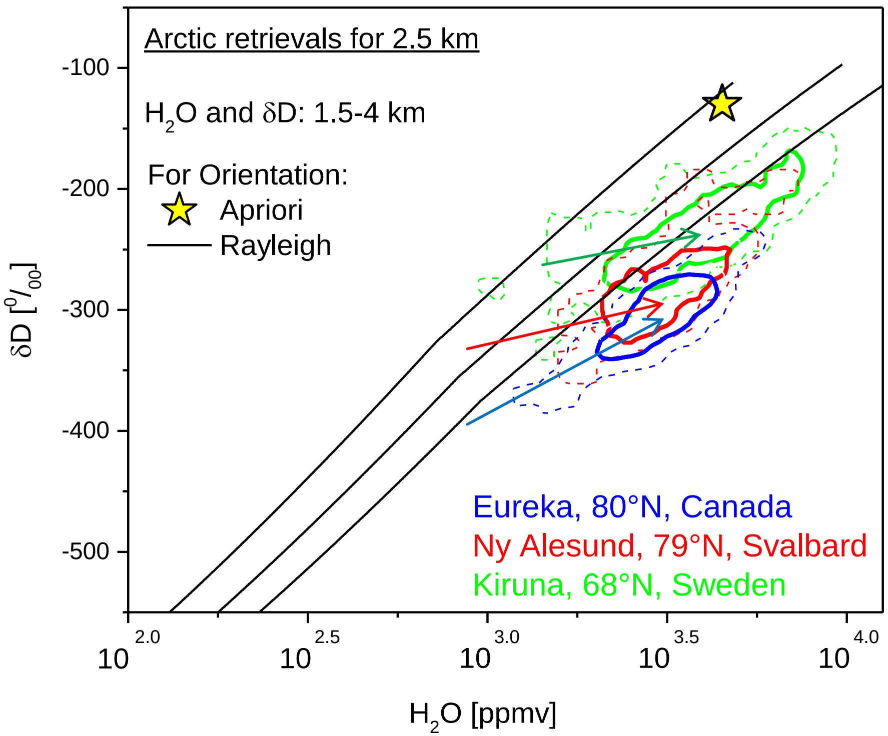
Eureka: 150

Ny Alesund: 130

Kiruna: 407

NDACC/FTIR: long-term $\{H_2O,\delta D\}$ pairs time series

<u>Example Arctic summer/autumn:</u> observation in the free troposphere (July, August, September, October, 2005-2014)



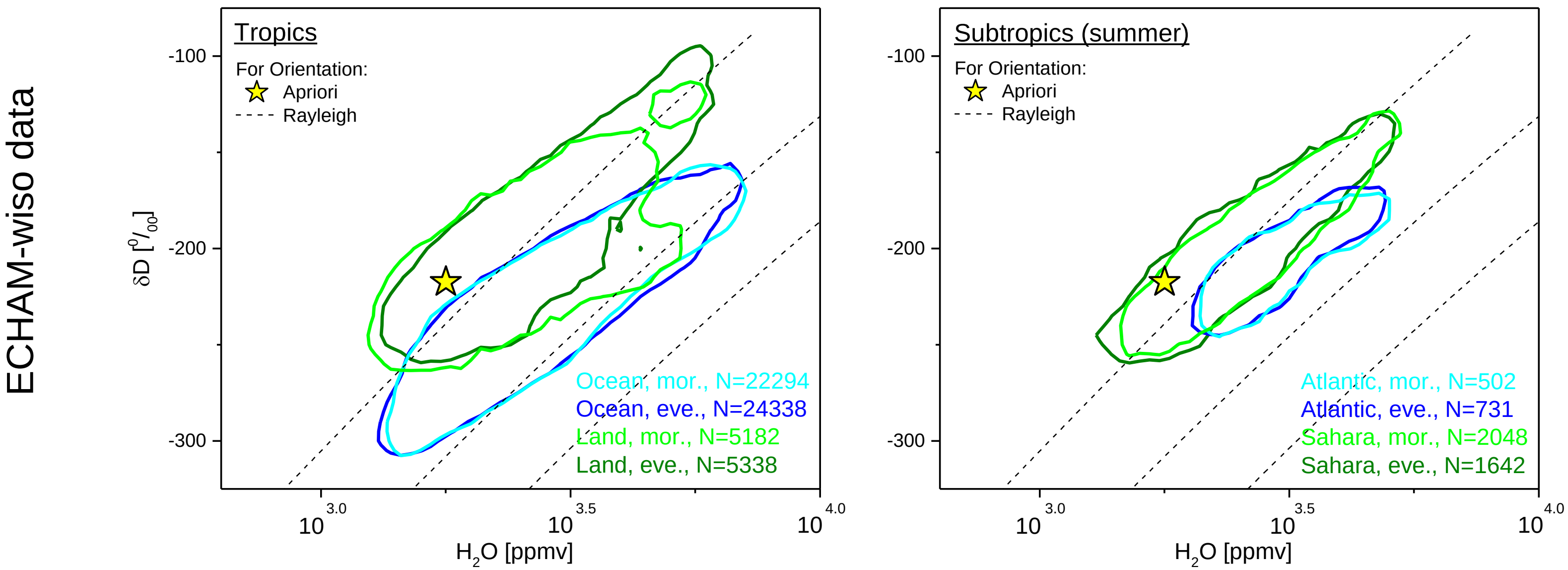
- Higher Humidity but similar δD: importance of $\{H_2O,\delta D\}$ pair observations!
- Same humidity levels at Eureka and Ny Alesund.
- $\{H_2O,\delta D\}$ pair change not along Rayleigh lines: indication of different moisture sources?
- Difference in δD strongly reduced (only about 20‰).

Number of days with observations:
Eureka: 168
Ny Alesund: 86
Kiruna: 274

The MUSICA NDACC/FTIR $\{H_2O,\delta D\}$ pair product is has a robust long-term characteristics and can document climatological patterns and/or anomalies.

Evaluating models: example, diurnal signals in tropics and subtropics

Model data: ECHAM5-wiso (Martin Werner, AWI)

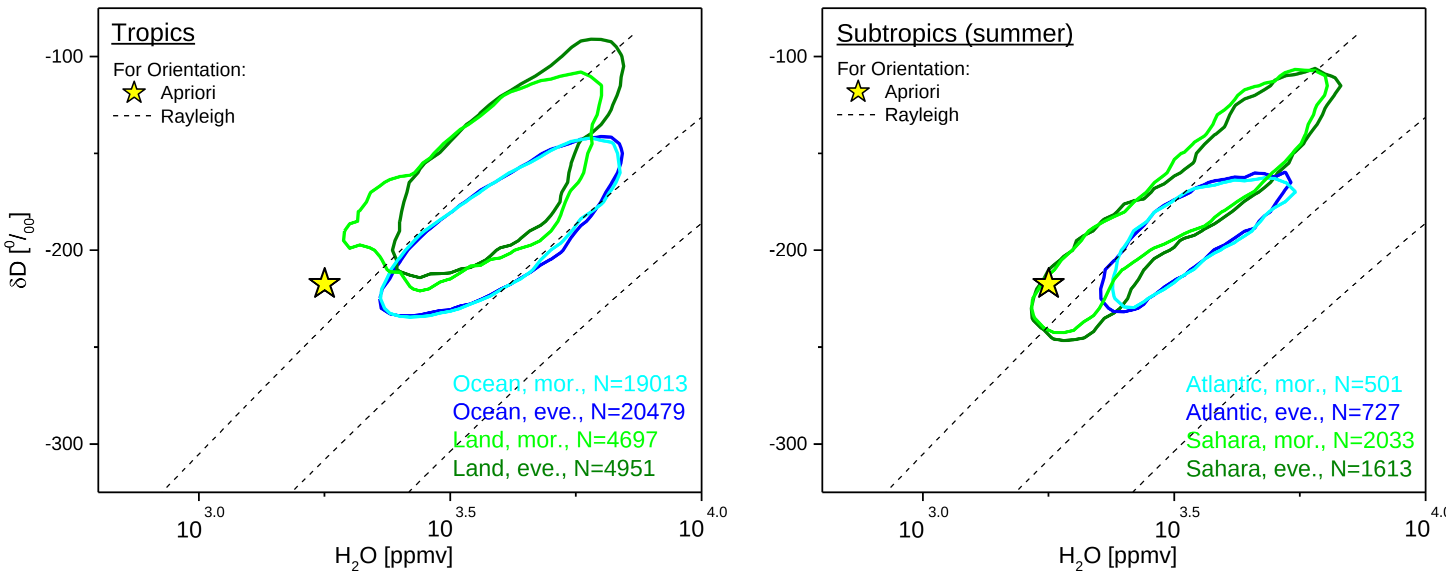


Shown are cloud free situations (RH<90% between surface and 12 km a.s.l.)

Evaluating models: example, diurnal signals in tropics and subtropics

ECHAM5-wiso model data that have the MUSICA MetOp/IASI {H_2O,δD} remote sensing data characteristics assimilated (retrieval simulator M. Schneider et al., AMTD 2016*)

ECHAM-wiso driven retrieval simulations



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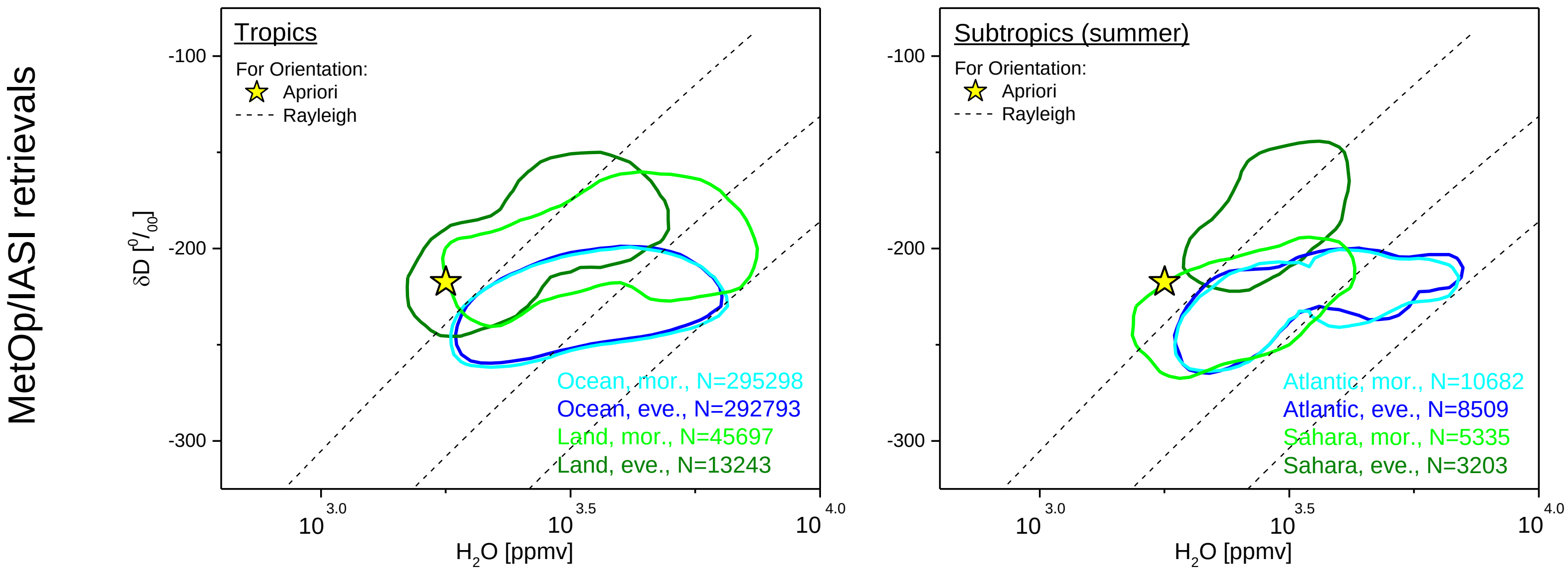
Evaluating models: example, diurnal signals in tropics and subtropics

MUSICA MetOp/IASI remote sensing data



Shown are:

- cloud free situations (RH<90% between surface and 12 km a.s.l.).
- data with significant sensitivity wrt free tropospheric {H_2O,δD} pairs.