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Atmospheric Precipitable Water Vapor from SOFIA - Part I: Measurements of the Water Vapor Overburden with FIFI-LS

Christian Fischer

C. Iserlohe, W. Vacca, D. Fadda, S. Colditz, N. Fischer, A. Krabbe

See also: Fischer et al., DOI 10.1088/1538-3873/abf1ca

Motivation

Why do we care about water vapor?

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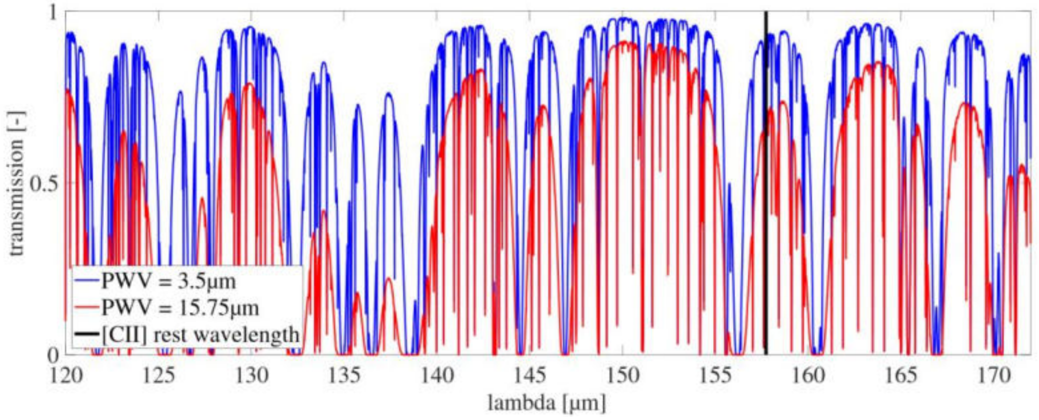
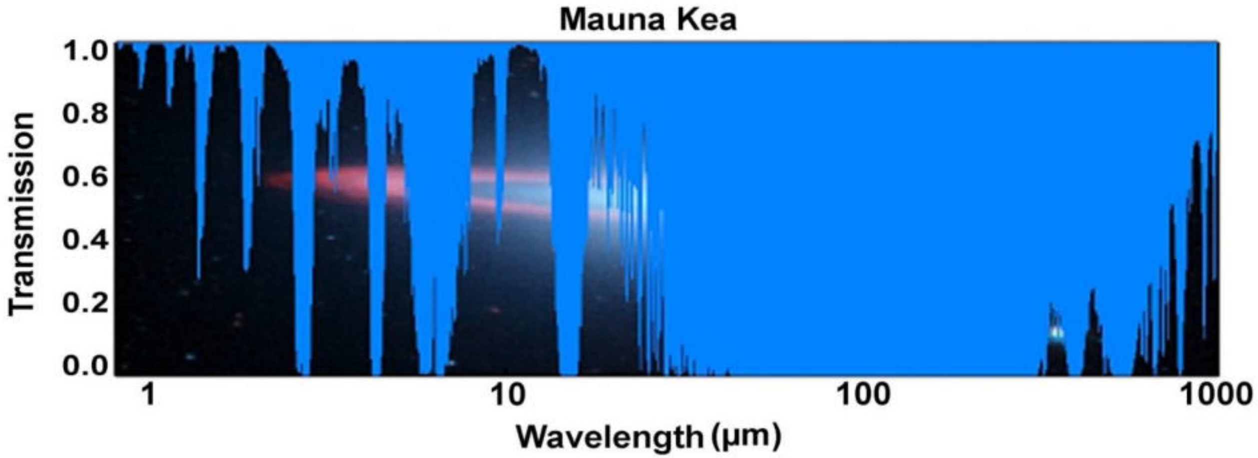
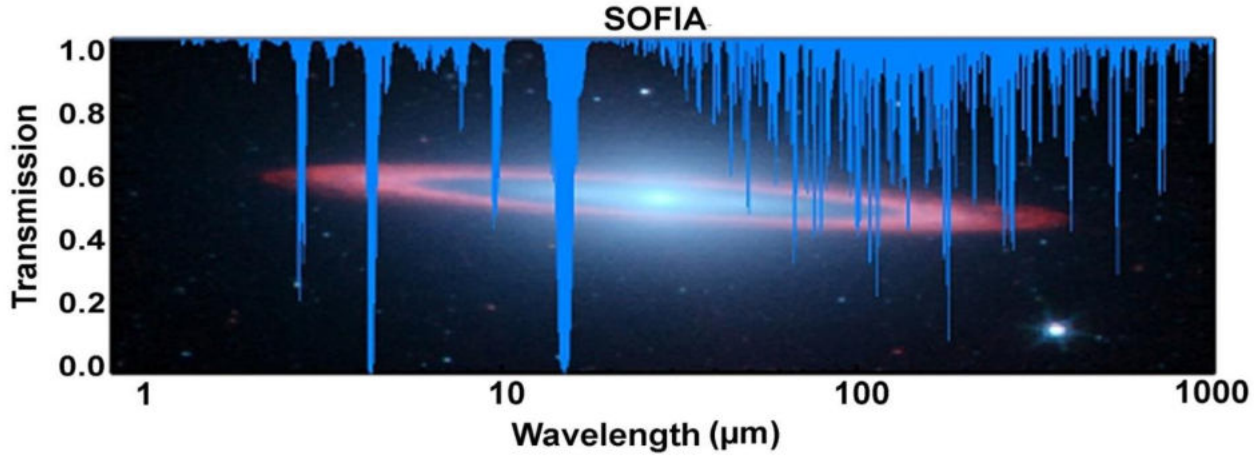
- The atmosphere that SOFIA sees through is good but not perfect
- But how constant is the transmission?



Modeled with ATRAN for 39000ft altitude, 40°elevation



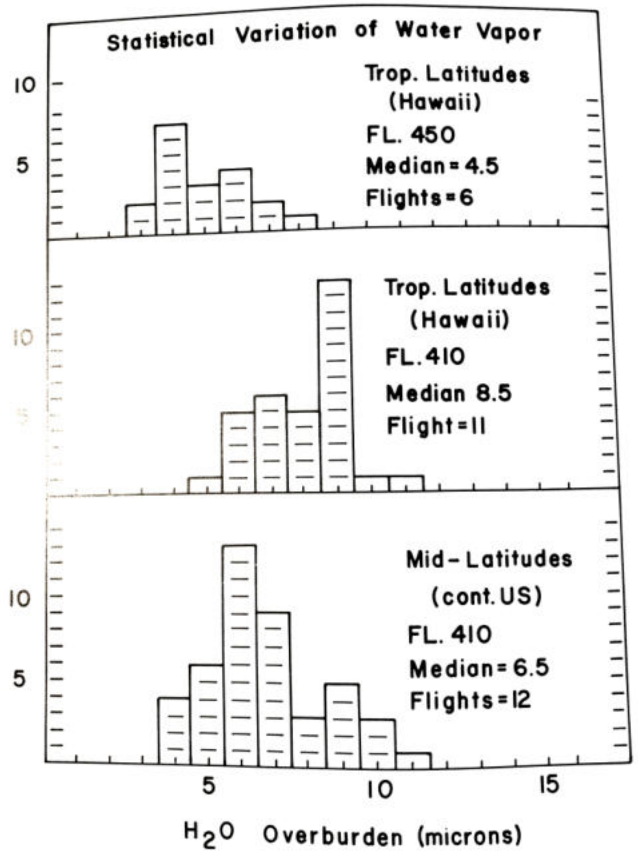


Motivation

Why do we care about water vapor?

Some suggested reading:

- Nolt&Stearns 1980, DOI: 10.1016/B978-0-12-208440-9.50025-9
- Kuhn 1982, DOI: 10.1029/GL009i006p00621
- Erickson 1998, DOI: 10.1086/316218
- Haas&Pfister 1998, DOI: 10.1086/316132
- Guan et al. 2012, DOI: 10.1051/0004-6361/201218925



Nolt & Stearns 1980

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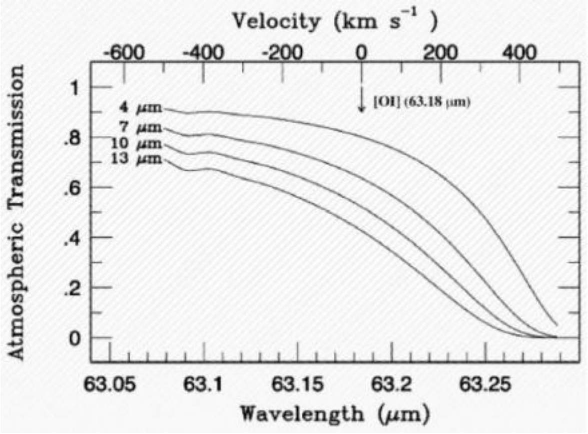
Motivation

Why do we care about water vapor?

- Water vapor can have a huge impact on transmission
- Water vapor varies with:
  - Altitude, location (not only latitude), season, day-to-day
- Limited data from KAO and some satellite data available
- Clear need for SOFIA measurements and calibration



Erickson 1998

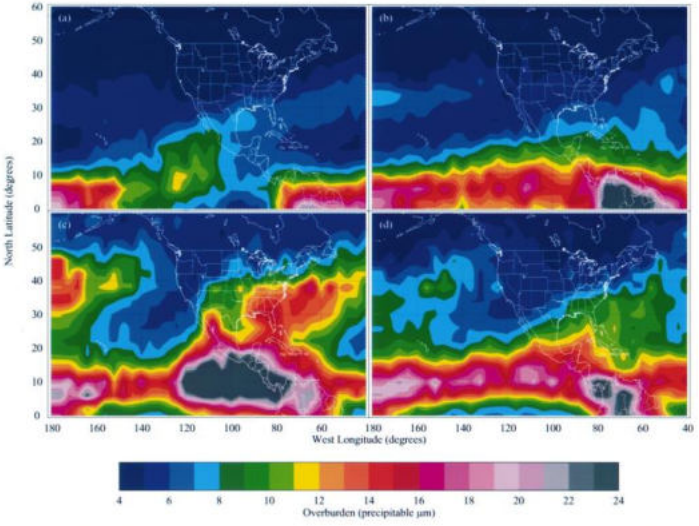
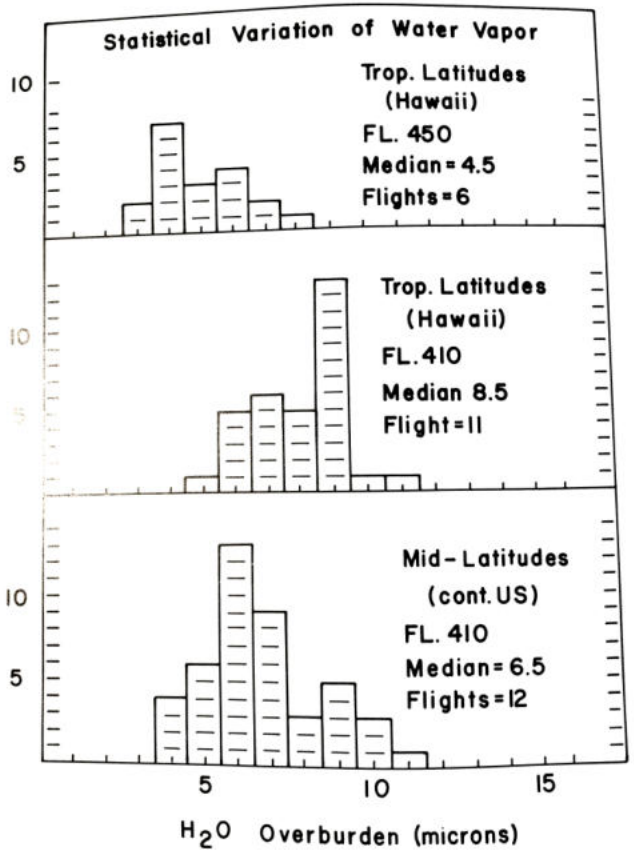


Fig. 7.—The MLS-determined zenith water vapor overburden for (a) winter (DJF), (b) spring (MAM), (c) summer (JJA), and (d) autumn (SON)

Haas & Pfister 1998



Nolt & Stearns 1980

Motivation

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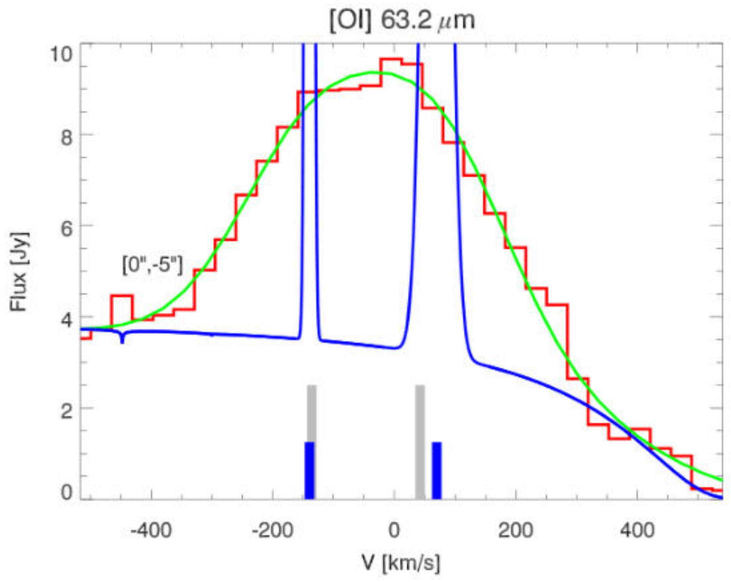
Why do we care about water vapor?

How do we correct our data for the atmosphere without measuring the water vapor overburden?

- One can always hope its doesn’t matter that much
  - “average“ values for each altitude are used
- If there is a continuum source it can be used to determine the PWV by fit
- Strong continuum source and overall good S/N needed
- Done on final data cube, so constant PWV is assumed
- Used e.g. in:
  - Iserlohe et al. 2019, DOI: 10.3847/1538-4357/ab391f
  - Sperling et al 2020, DOI: 10.1051/0004-6361/201937242



Iserlohe et al. 2019

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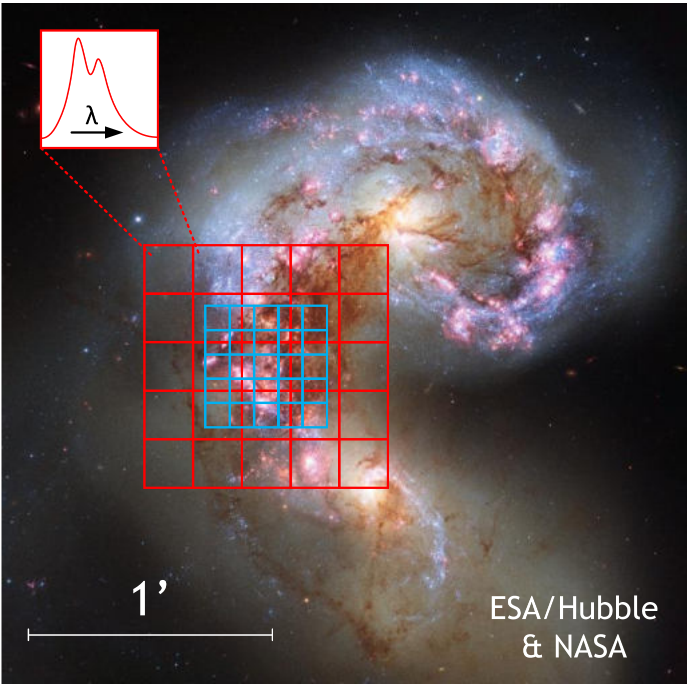
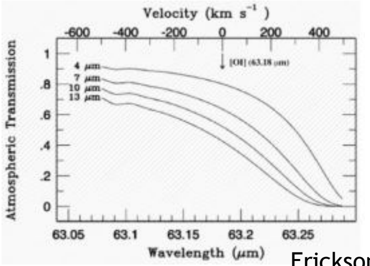
FIFI-LS overview

- Field-Imaging Far-Infrared Line Spectrometer
- Two spectral channels: 51 – 120µm and 115 – 203 µm
- Simultaneous spatial imaging in the two channels: 30"x30" and 60"x60" field of view respectively
- Each field of view resolved with 5 x 5 spatial pixels
- Medium spectral resolution: R ~ 500 – 2000 (~150 – 600 km/s)
- 16 Pixels in spectral direction in each spatial pixel
- Instantaneous spectral coverage: ~1500 km/s
  e.g. velocity distribution in galaxies including baseline on both sides
- Water lines are wide, spectral coverage is more important than spectral resolution





Erickson 1998

the measurements

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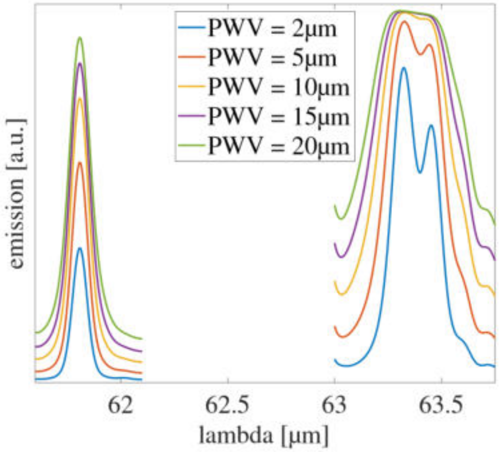
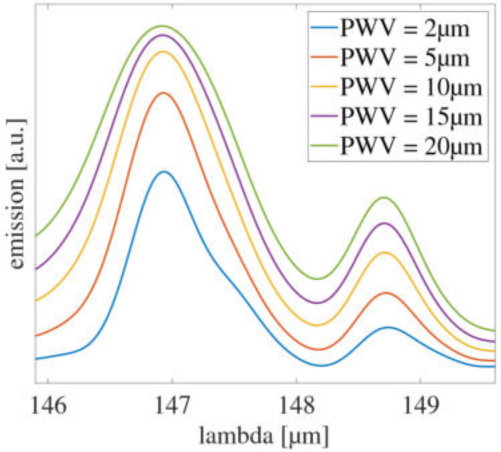
Measurement principle
Why can we do something the water vapor monitor can not?

- Two independent measurements in each channel
  - 5 integrations needed for spectral coverage
  - Takes about 1min
  - No background subtraction
- We have chosen spectral regions which are sensitive to water vapor in their relative shape
  - no need to calibrate!!!
- ATRAN is used to model the atmosphere here as well as later in the data reduction pipeline
  - We don't need to worry how accurate ATRAN processes the real water vapor value!



Blue channel



Red channel

Emission Model:

$$E(\lambda, T, PWV_{zenith}, alt, el) = \frac{1 - Tr_{ATRAN}(\lambda, PWV_{zenith}, alt, el)}{\lambda^5 e^{\frac{hc}{\lambda kT}} - 1}$$

the measurements

Measurement principle
Determination of the water vapor overburden

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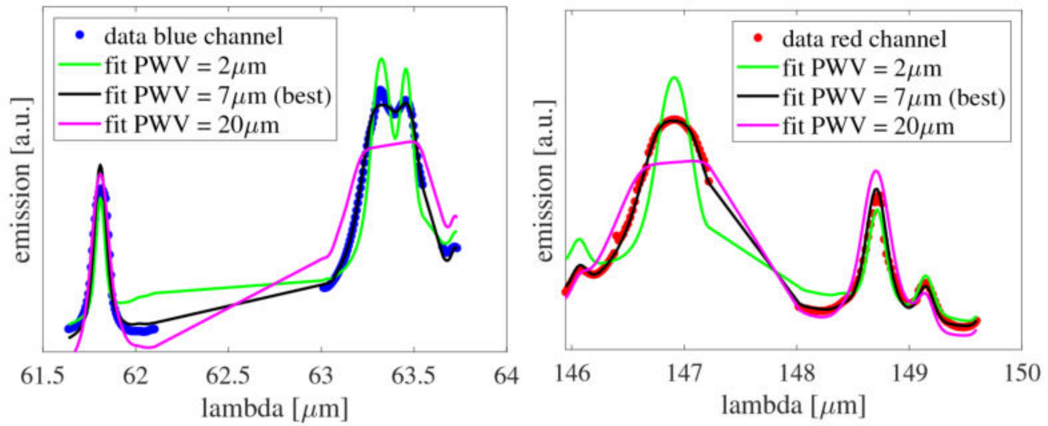
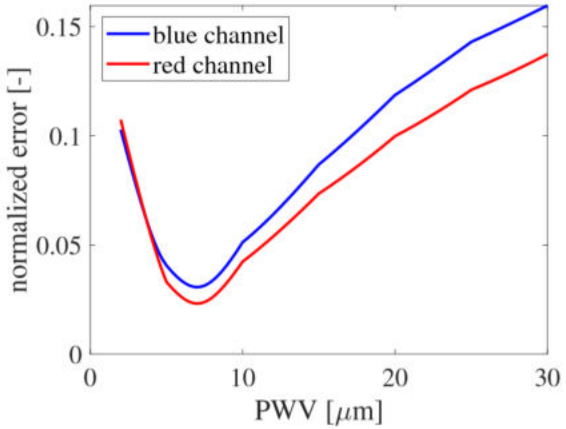
- Each channel treated separately
- The emission model is fitted for all water values ranging from 2-20µm in 0.25µm increments
- Deviation from the measured data is evaluated to find the PWV value
- PWV values are determined at telescope elevation but stated values are always at zenith
- Excellent agreement between the red and the blue channel: 3% mean systematic offset, 7% mean offset, 0.3µm mean absolute offset





Emission Model fitted:

$$EmissionModelFit(\lambda) = a + b * \lambda + c * E(\lambda, T, PWV_{zenith}, alt, el)$$

the measurements

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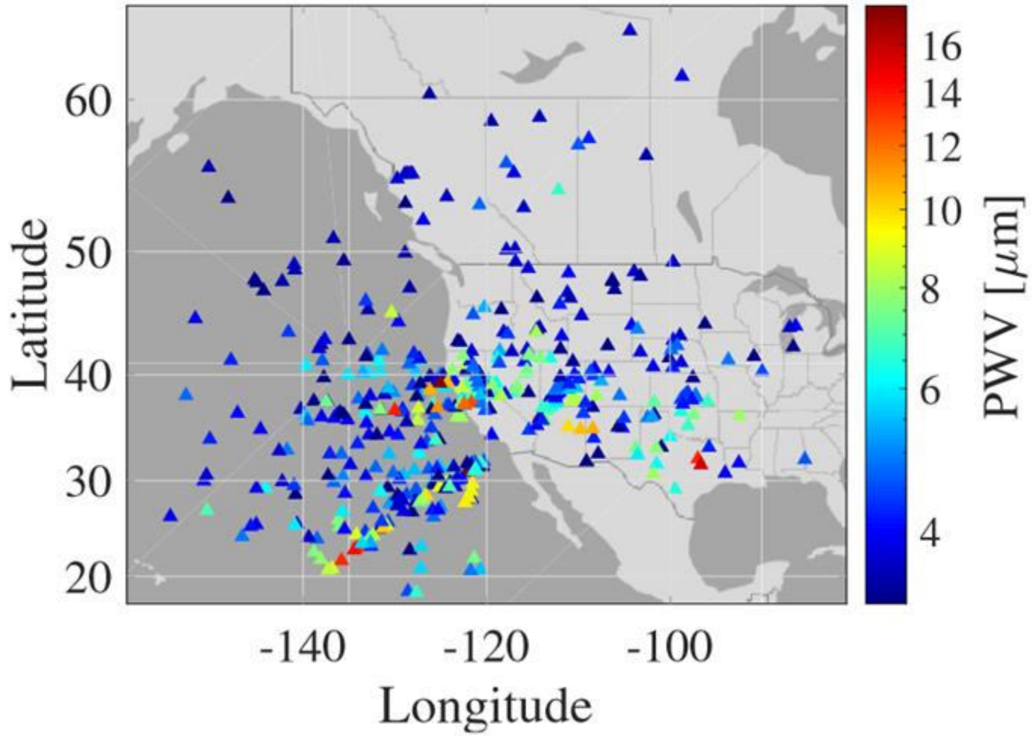

flight series	date range	number of flights
OC6M	06.11.2018 - 09.11.2018	4
OC6U	27.02.2019 - 02.03.2019	3
OC7A	01.05.2019 - 17.05.2019	11
OC7H	30.10.2019 - 14.11.2019	10
OC7L	25.02.2020 - 28.02.2020	4
OC8B	17.08.2020 - 04.09.2020	7

Flight series used for the paper

- Data from a total of 39 flights up to 09/2020
  - data collection continues
- About 10 data points per flight
- Data from all 4 season is available
- Data is collection during the setup on each leg “for free”
- Observations are paused after climbs or if science data shows signs of changing atmospheric conditions
  - Little or no loss of observing time

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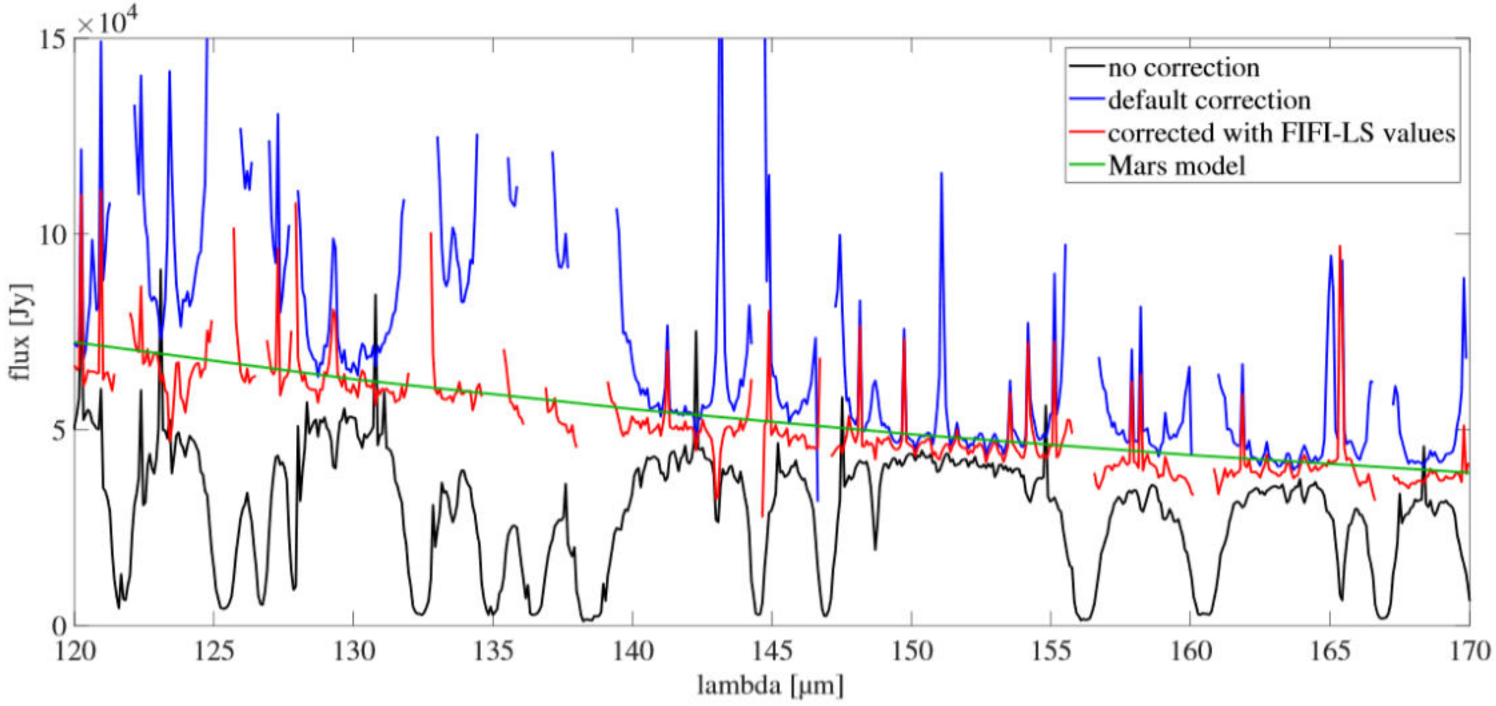
the results

Does it work?

- We want to reproduce the trusted Mars model (green) even at lower transmission
- This is a spectral mosaic
- Data was taken at 38000ft
    - Default value is 11µm (blue)
    - 6.25µm measured by FIFI-LS before and after data was taken
- Corrected spectra are cut at 20% transmission (we don't want to observe there anyhow)



Yes it does! (with some small print)

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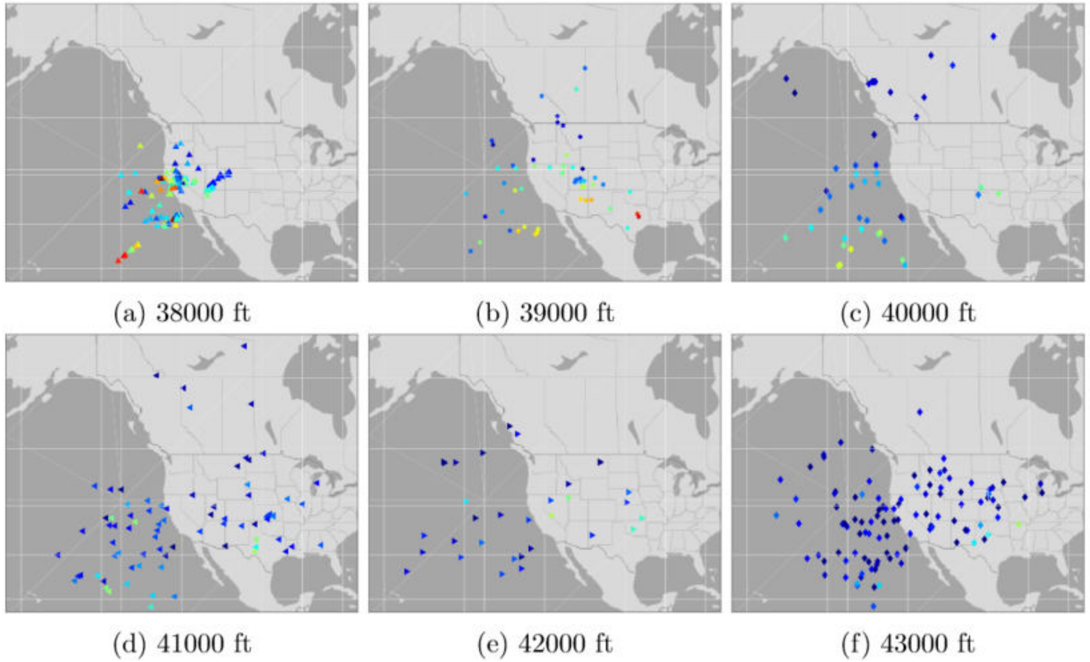
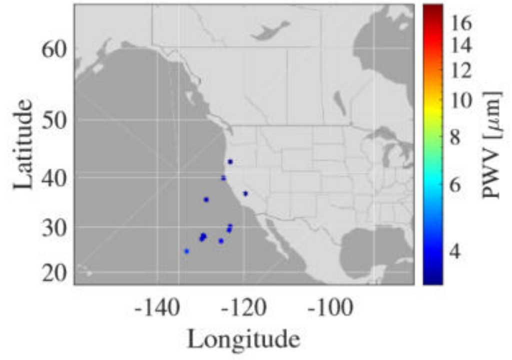
the results

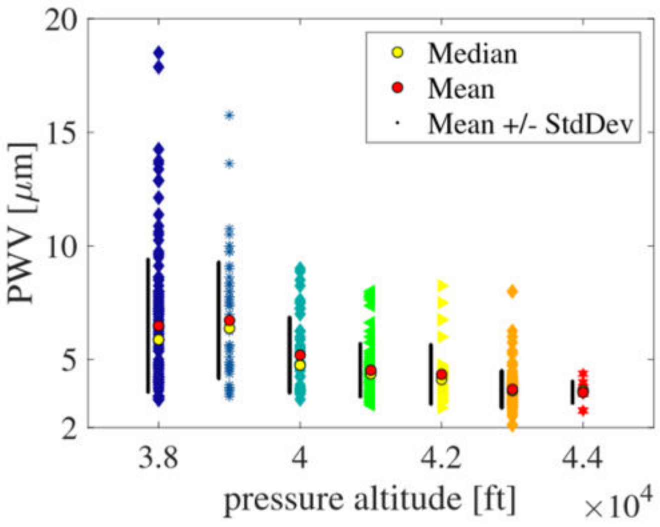


(a) 38000 ft (b) 39000 ft (c) 40000 ft
(d) 41000 ft (e) 42000 ft (f) 43000 ft



(g) ≥ 44000 ft

- Be aware of some bias in the measurement locations
  - Low altitudes close to Palmdale (beginning of the flight)
  - Most data points at 43000 ft (typically the second half of the flight)
  - South only over the Pacific (we do not fly over Mexico)
  - We are not flying close to the polar circle in summer
- Unsurprisingly there is a clear trend of lower water vapor with higher altitude
- Conditions are typically not bad at lower altitudes, but there is an increased chance of problematic values
- Life is good at 40000ft or above



the results

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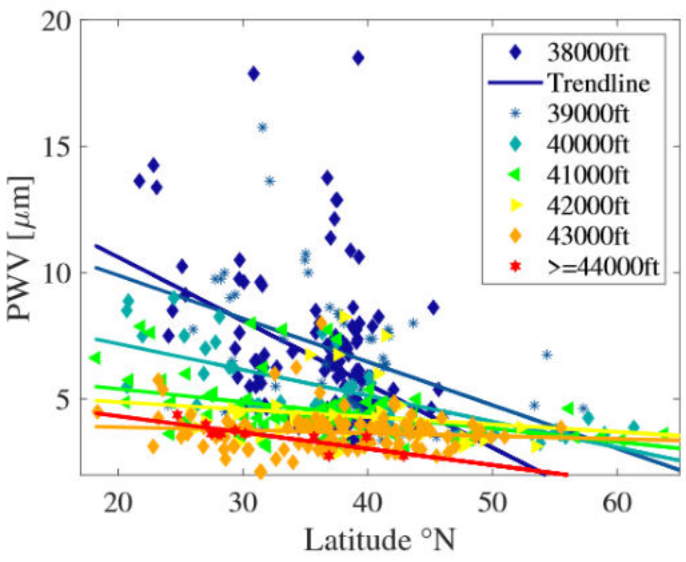

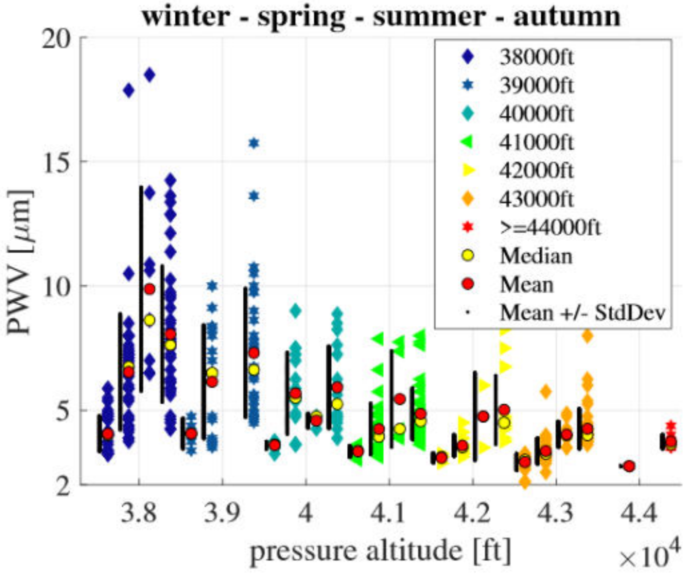

- Clear trend of decreasing water vapor further north
  - But remember the spatial distribution

- The 4 seasons are clearly distinguishable
  - Be aware of limited summer data (only from end of August)
  - No 39000ft summer data due to Covid (shorter flights)
  - There is a clear difference between spring and fall (see Hass&Pfister1998)
  - Don’t be afraid to fly 10h out of Palmdale in May… November can be worse! (even at 43000ft)

conclusion

So what is missing? (....for now)

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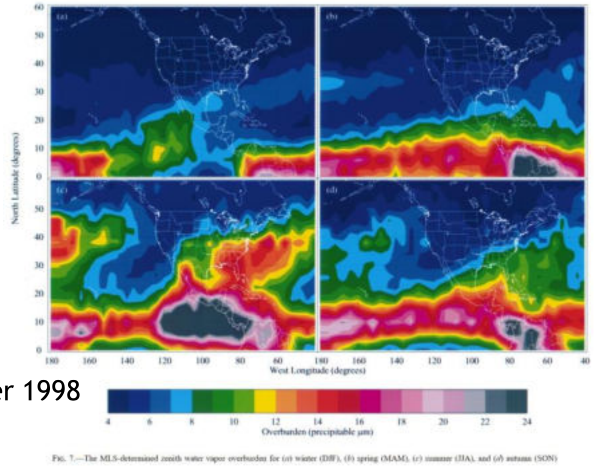
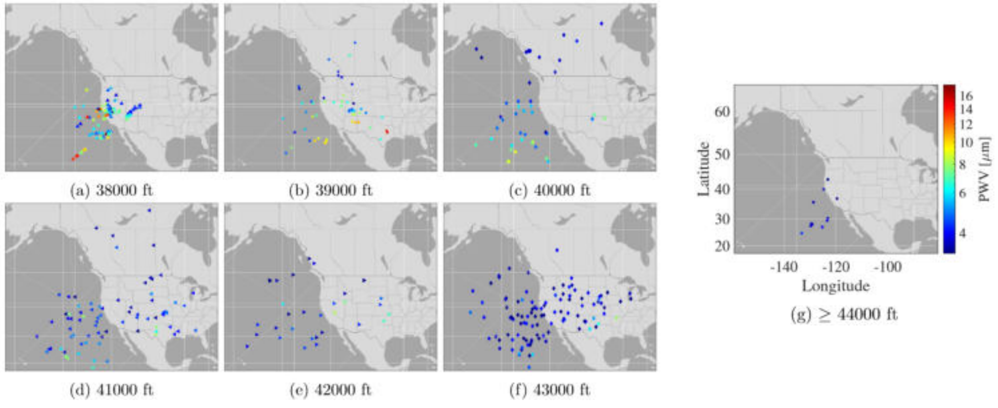
What we want



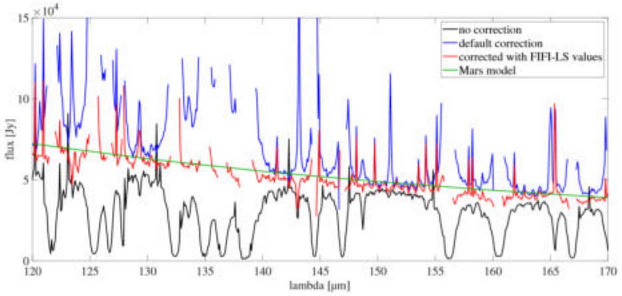
Haas & Pfister 1998

What we have



- Not enough data points to fully create maps for altitude and season
  - Is the “blue hole” real?
  - Is the SW really that bad?
- We have seen water vapor change on the timescale of minutes but only measure every 30-60min, but higher frequency will hurt observing efficiency
- We only have data for times and locations we have observed with from SOFIA
  - In general not a bad parameter space
  - Not good to evaluate deployments or peak summer flights from Palmdale
- **Can we use the FIFI-LS data to verify/calibrate satellite data?**
  - **What about other instruments or applications?**

This is about 30min of data



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Probing the atmospheric precipitable water vapor with SOFIA Part II

and

Tahiti

Christof Iserlohe

C. Fischer , W. D. Vacca , N. Fischer , S. Colditz , and A. Krabbe

See also : Iserlohe et al., DOI 10.1088/1538-3873/abef76

ECMWF

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Image: Stephen Shepherd

ECMWF : European Centre for Medium-Range Weather Forecasts

- independent intergovernmental organisation supported by 34 states.
- research institute and a 24/7 operational service, producing and disseminating numerical weather predictions to its member states.

ERA5 catalogue :

- global atmospheric model using 4D-Var data assimilation and model forecasts in CY41R2 of the ECMWF Integrated Forecast System (IFS)
- geographical resolution of 0.25 x 0.25 degree (~55 x 55 km)
- time resolution of 1 hour
- 137 pressure levels running from sea level to 80 km (we used the interpolation to 37 pressure levels and downloaded data in netCDF format)

In short: download specific humidity, q, (as a function of lon, lat, time, pressure) and integrate numerically to obtain total upward precipitable water vapor content of the atmosphere:

$$\mathrm{PWV}_{\mathrm{ECMWF}}(\mathrm{lon},\, \mathrm{lat},\, t,\, p_{\mathrm{flight}}) = -\frac{1}{g}\int_{p_{\mathrm{flight}}}^{0} q(\mathrm{lon},\, \mathrm{lat},\, t,\, p)\,dp$$

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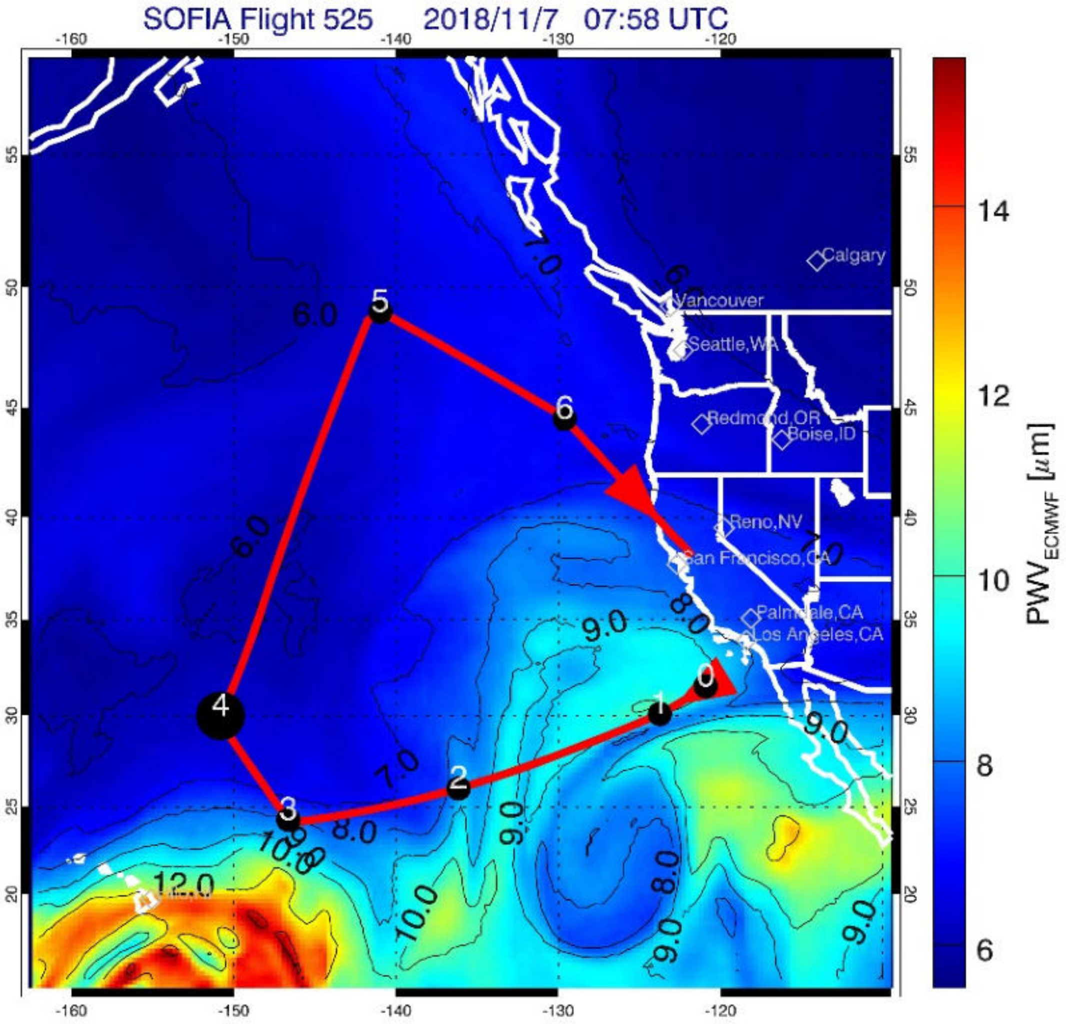
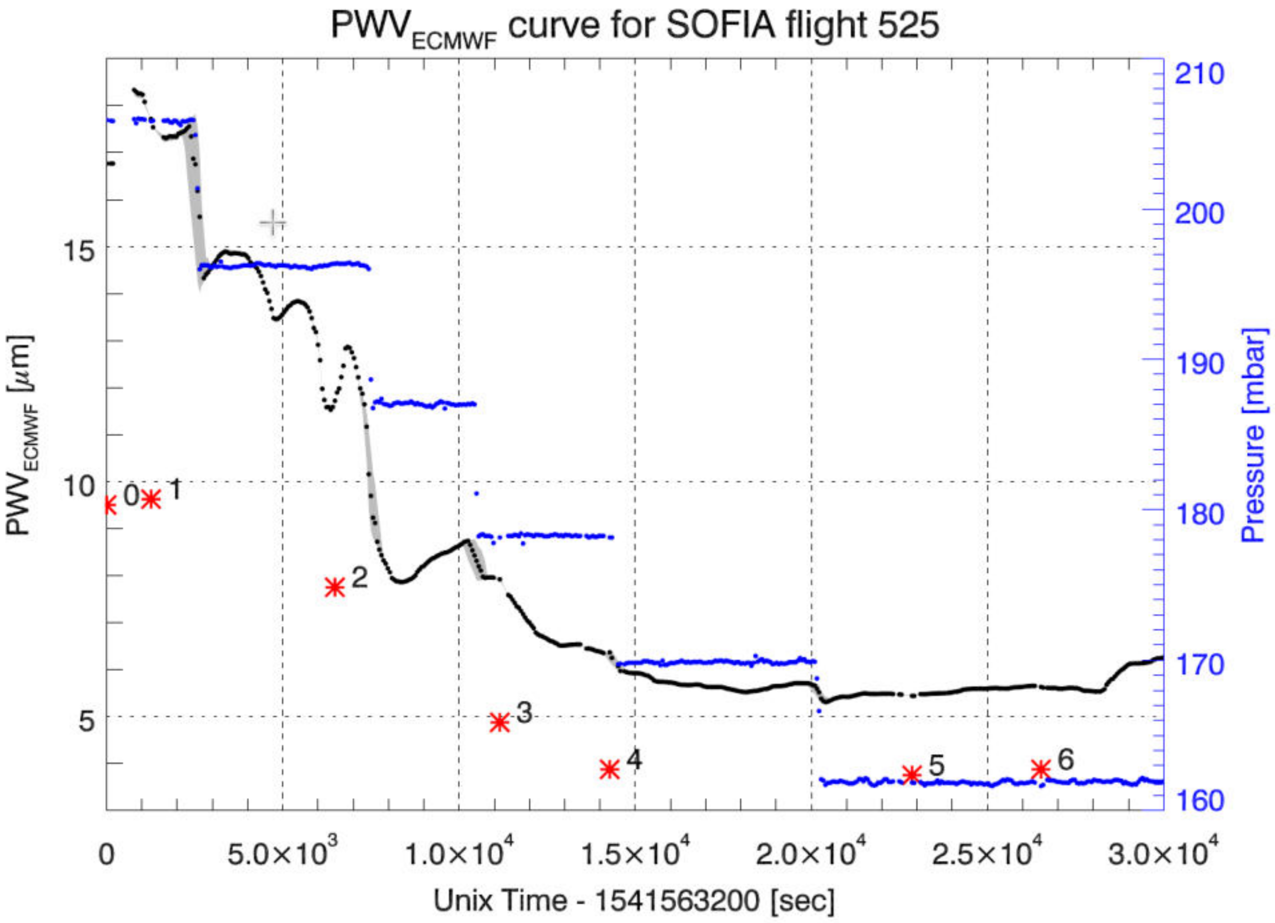
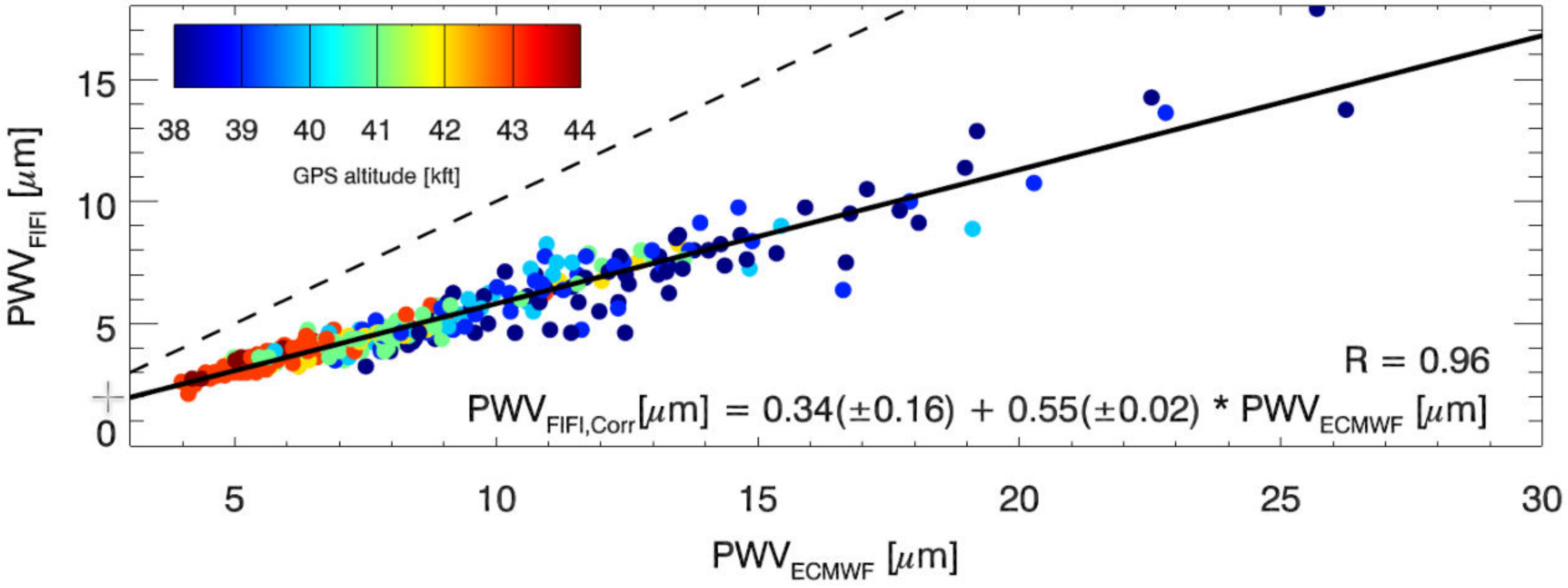
PWV predictions by ECMWF, PWV_{ECMWF}, for SOFIA flight 525

Flight positions where FIFI-LS PWV measurements were executed (red asterisks) are consecutively numbered







Correlate PWV from FIFI-LS PWV measurements (PWV_{FIFI}) with ECMWF model predictions (PWV_{ECMWF}) for given lon/lat/time/pressure altitude.

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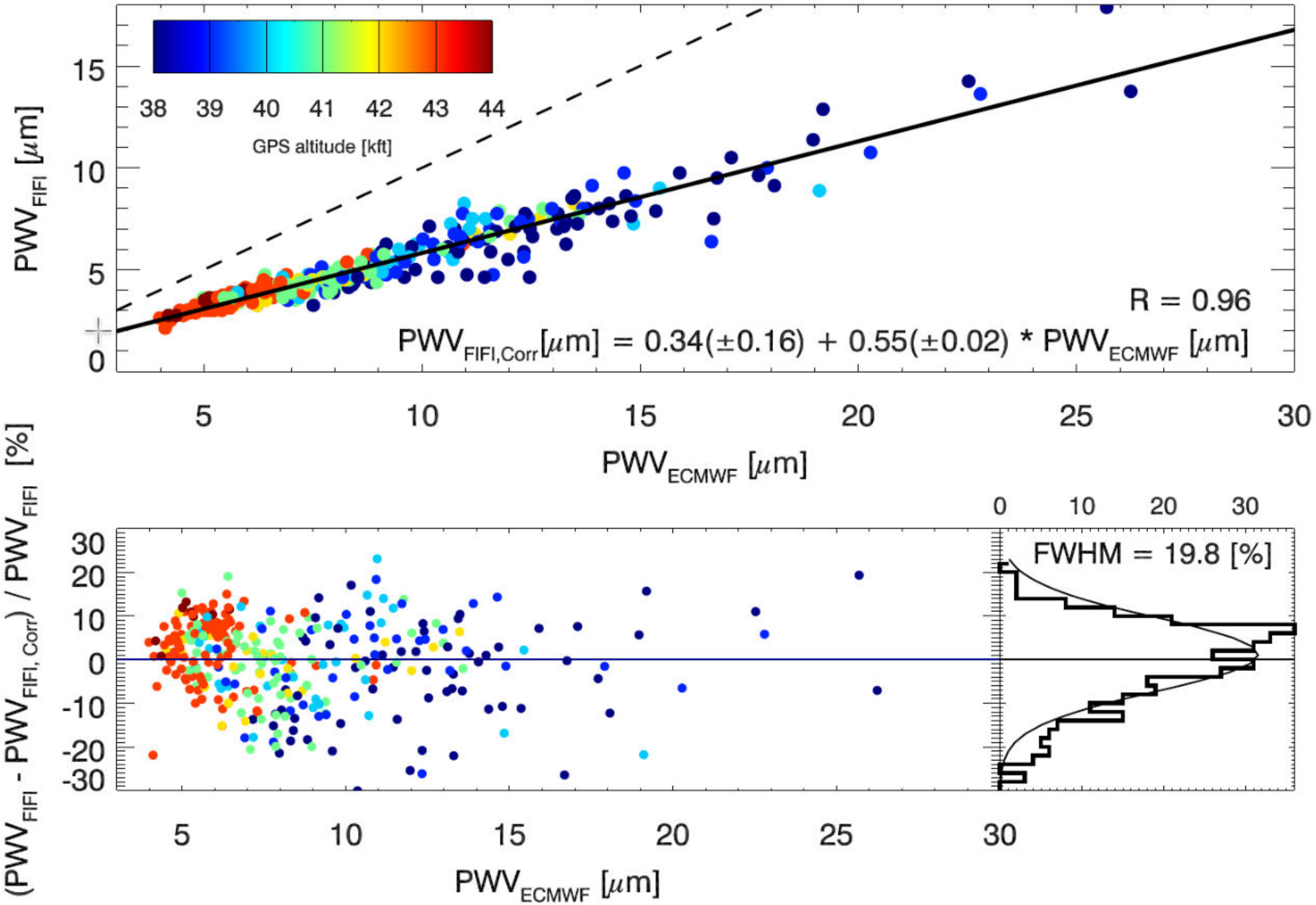

Correlate PWV from FIFI-LS PWV measurements (PWV_{FIFI}) with ECMWF model predictions (PWV_{ECMWF}) for given lon/lat/time/pressure altitude.

Average deviation from scaled ECMWF model predictions is about 10%.

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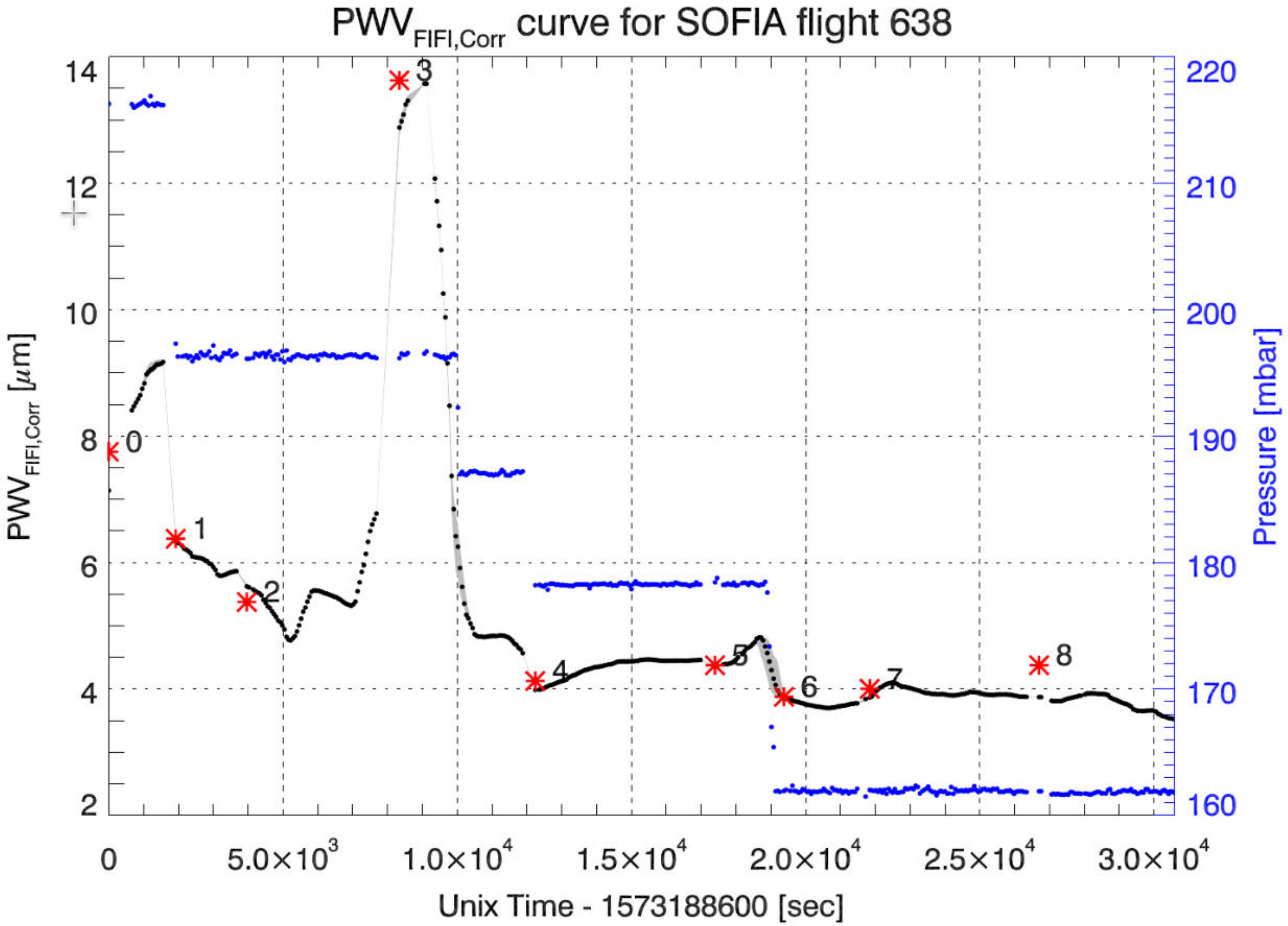

Using the correlation coefficients to scale PWV_{ECMWF} to the FIFI-LS PWV measurments, $PWV_{FIFI,\ Corr}$.

Testing the correlation with a broad band spectrum of the planet Mars

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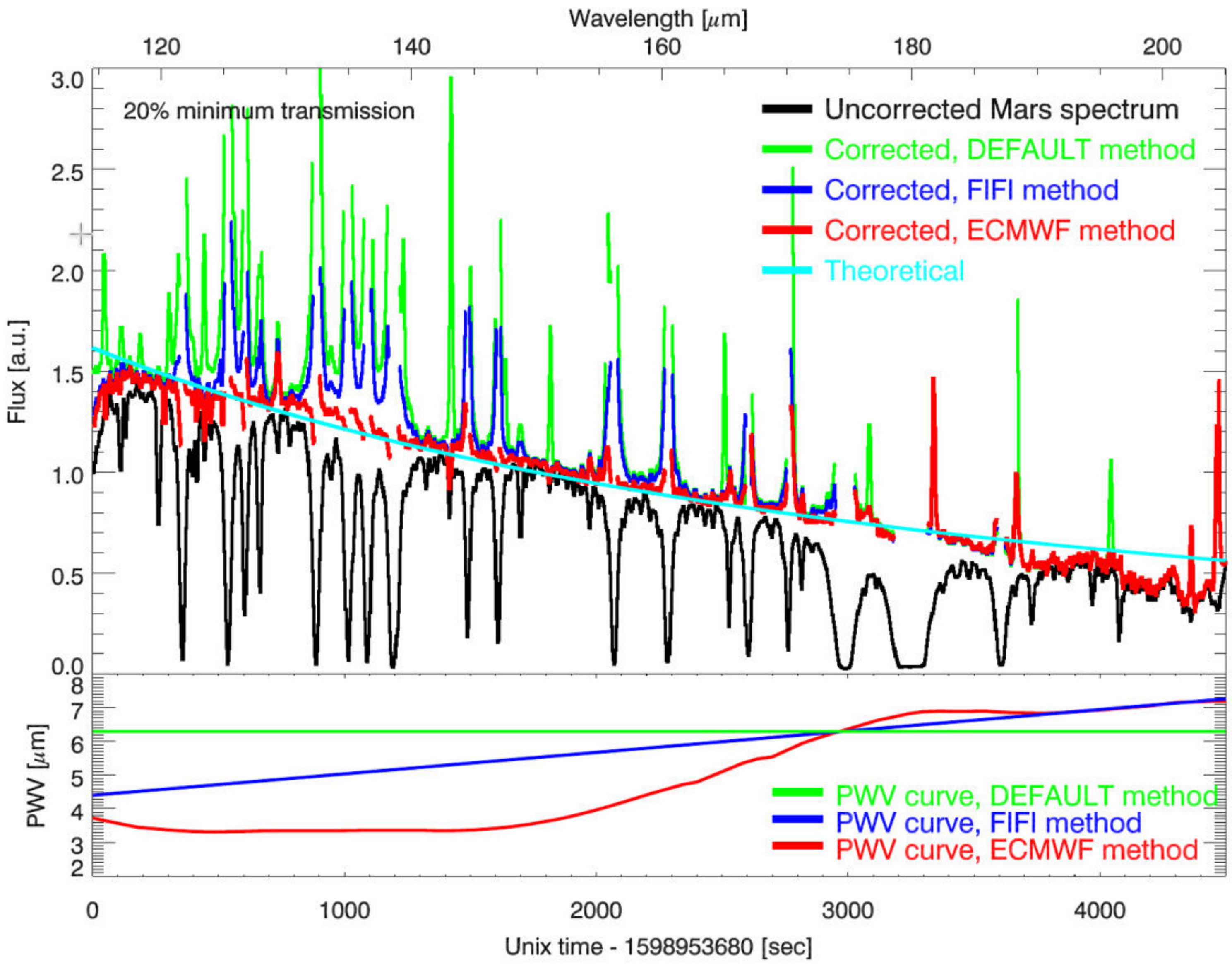


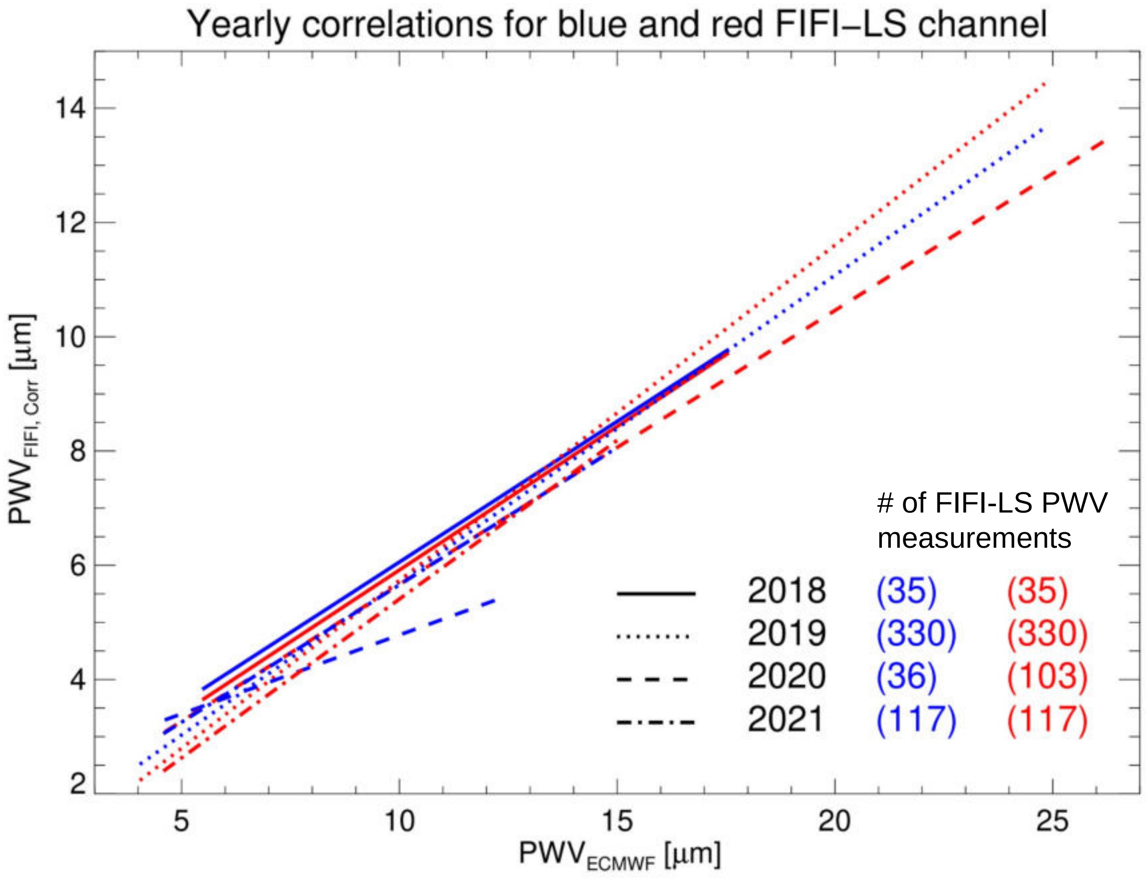
- Mars spectrum taken within about 70 minutes

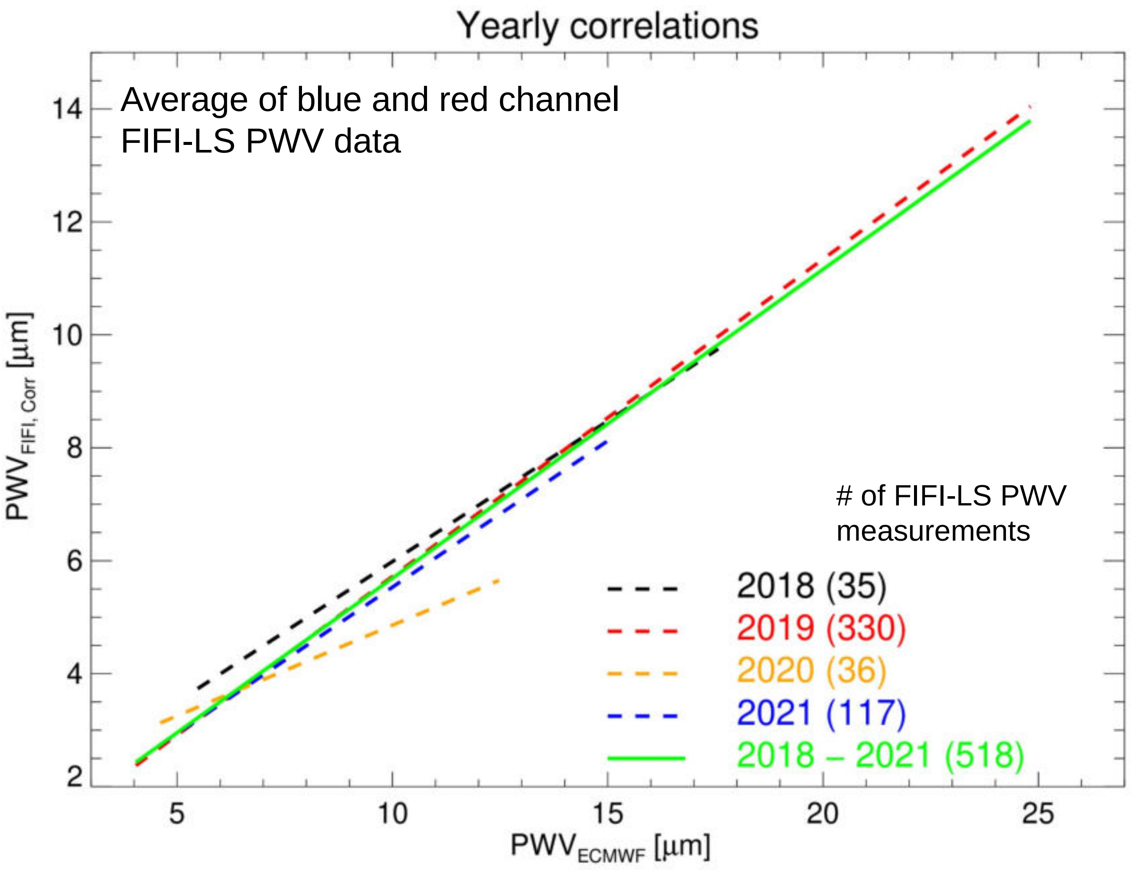
- Testing three various PWV curves:

DEFAULT	= Constant PWV (for the specific flight altitude)
FIFI	= Linear interpolation of FIFI-LS PWV measurements
ECMWF	= Using PWV predictions by ECMWF scaled with our correlation

Correction of the Mars spectrum with the PWV values from ECMWF scaled with our correlation gives the best result.

Yearly correlations





2020 : limited, biased statistics, winter only, biased towards 38 kft, rapid changes in conditions
Other years : correlations from red and blue channel data only agree quite well (within 0.5 µm PWV)

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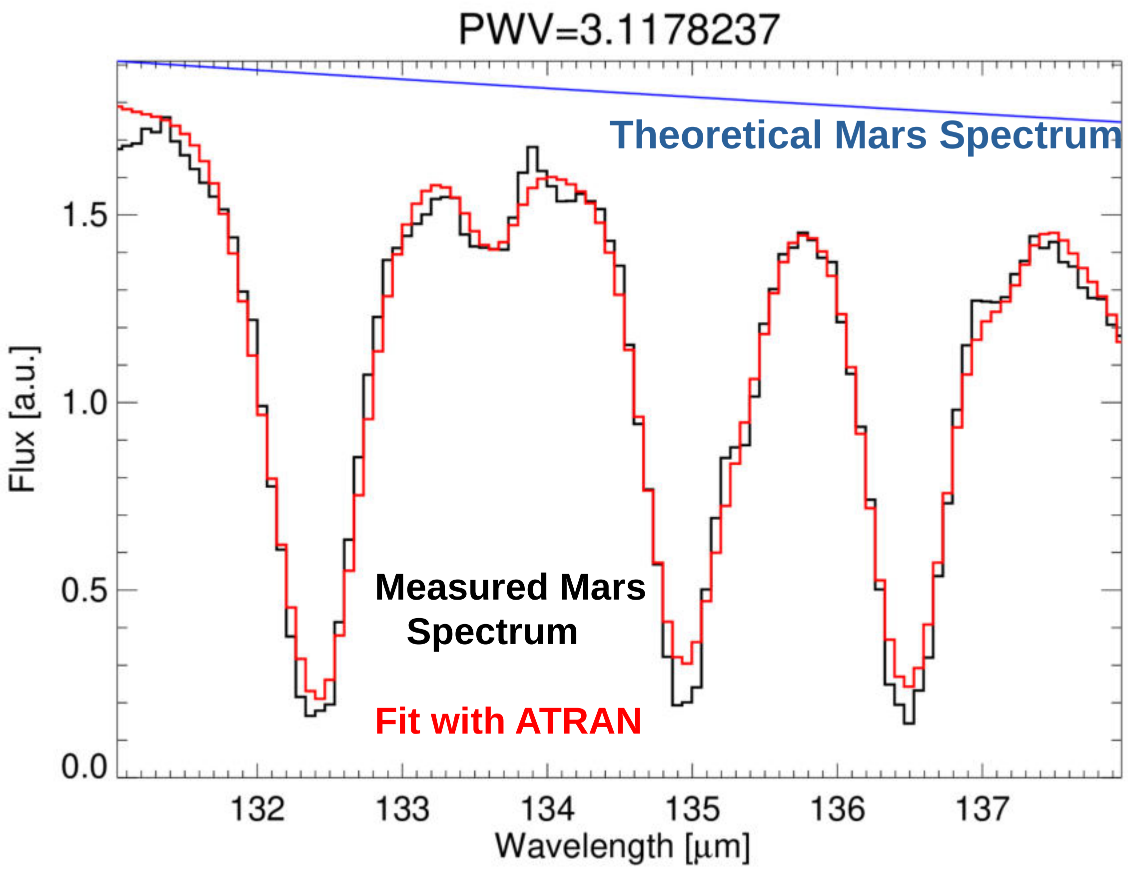
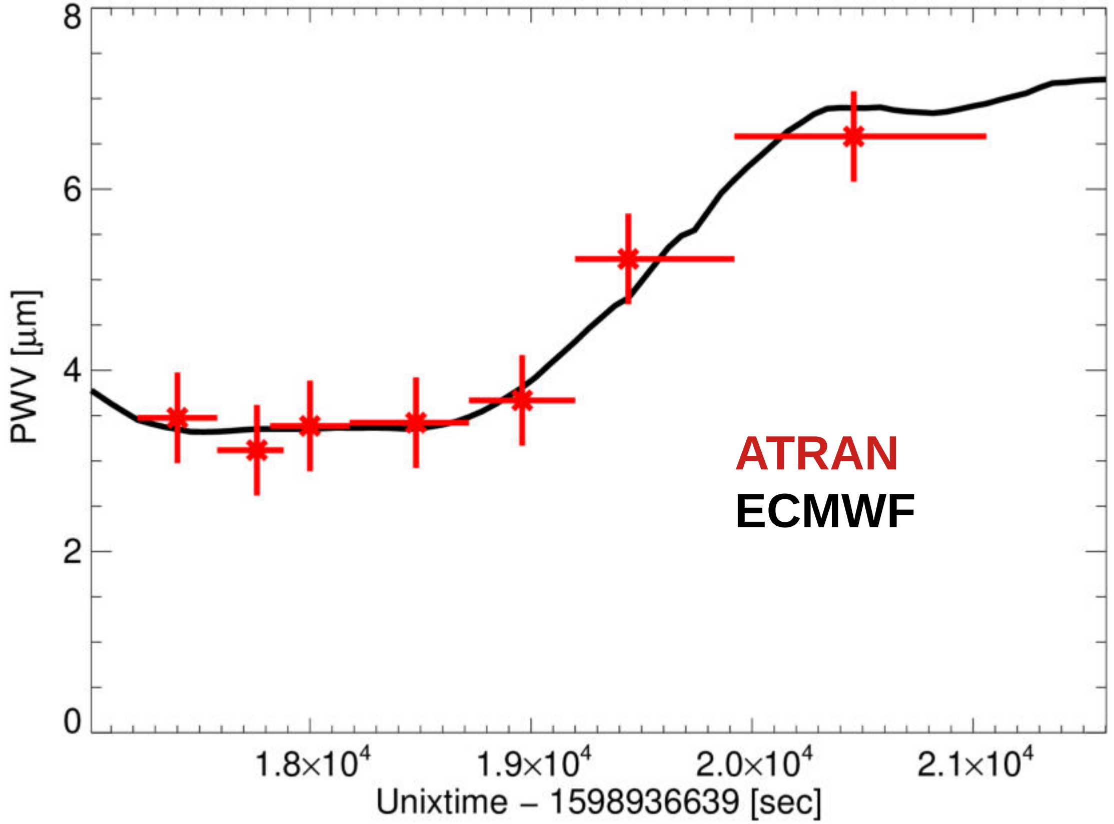
Fitting absorption features in aforementioned Mars spectrum directly with ATRAN





Summary: FIFI PWV measurements in conjunction with ECMWF PWV model predictions provide a useful atmospheric calibration for FIFI-LS data !

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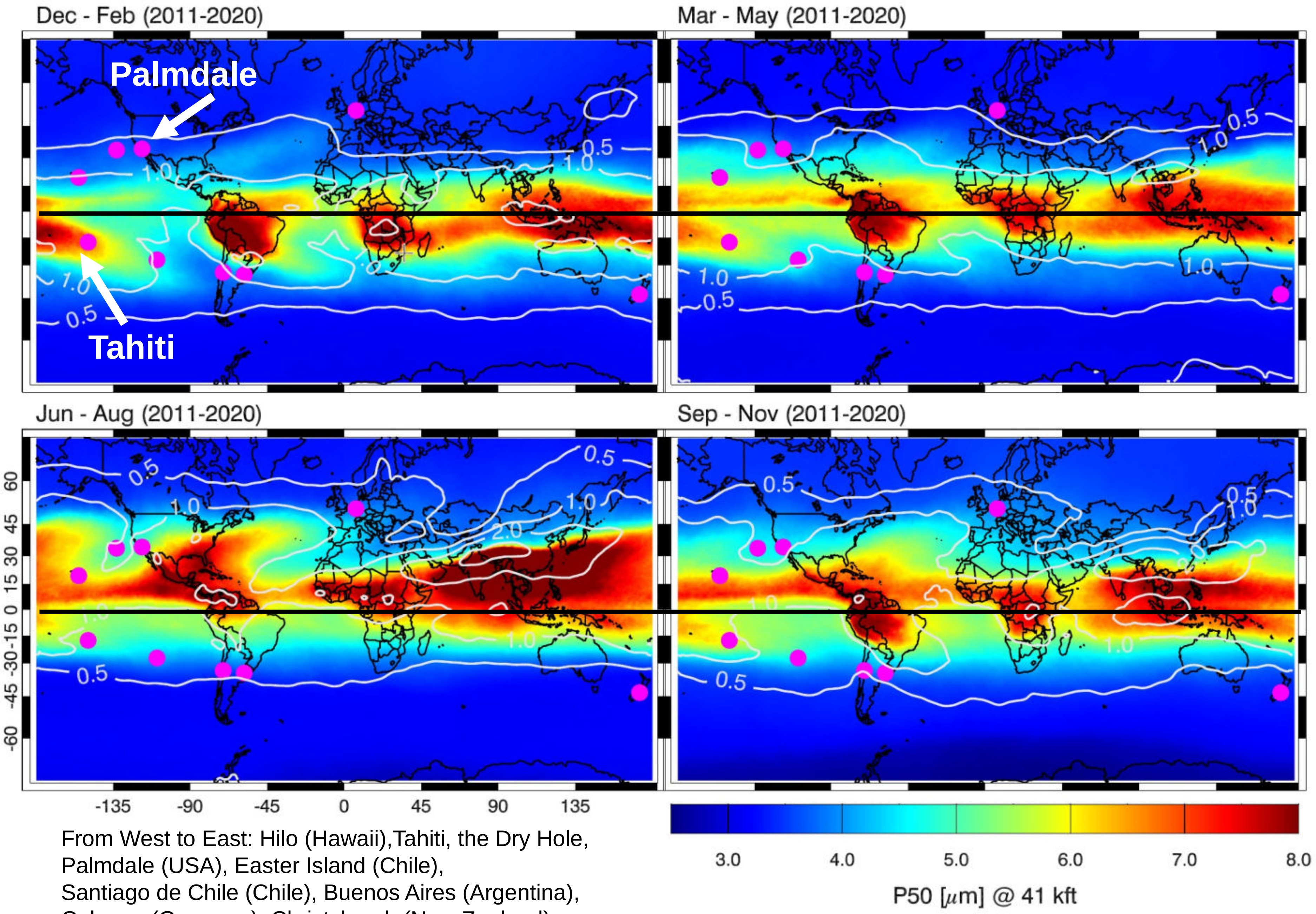
Tahiti
or better
Santiago de Chile



From West to East: Hilo (Hawaii),Tahiti, the Dry Hole, Palmdale (USA), Easter Island (Chile), Santiago de Chile (Chile), Buenos Aires (Argentina), Cologne (Germany), Christchurch (New Zealand)

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Median seasonal PWV value, P50, from ECMWF scaled with our correlation.

ECMWF data from 2011 - 2020

- Equatorial region shows the highest PWV.

- The further away from the equator the lower P50

- Seasonal dependence:
Dec – Feb: S. hemis. worse than N. hemis.
Jun – Aug: N. hemis. worse than S. hemis.

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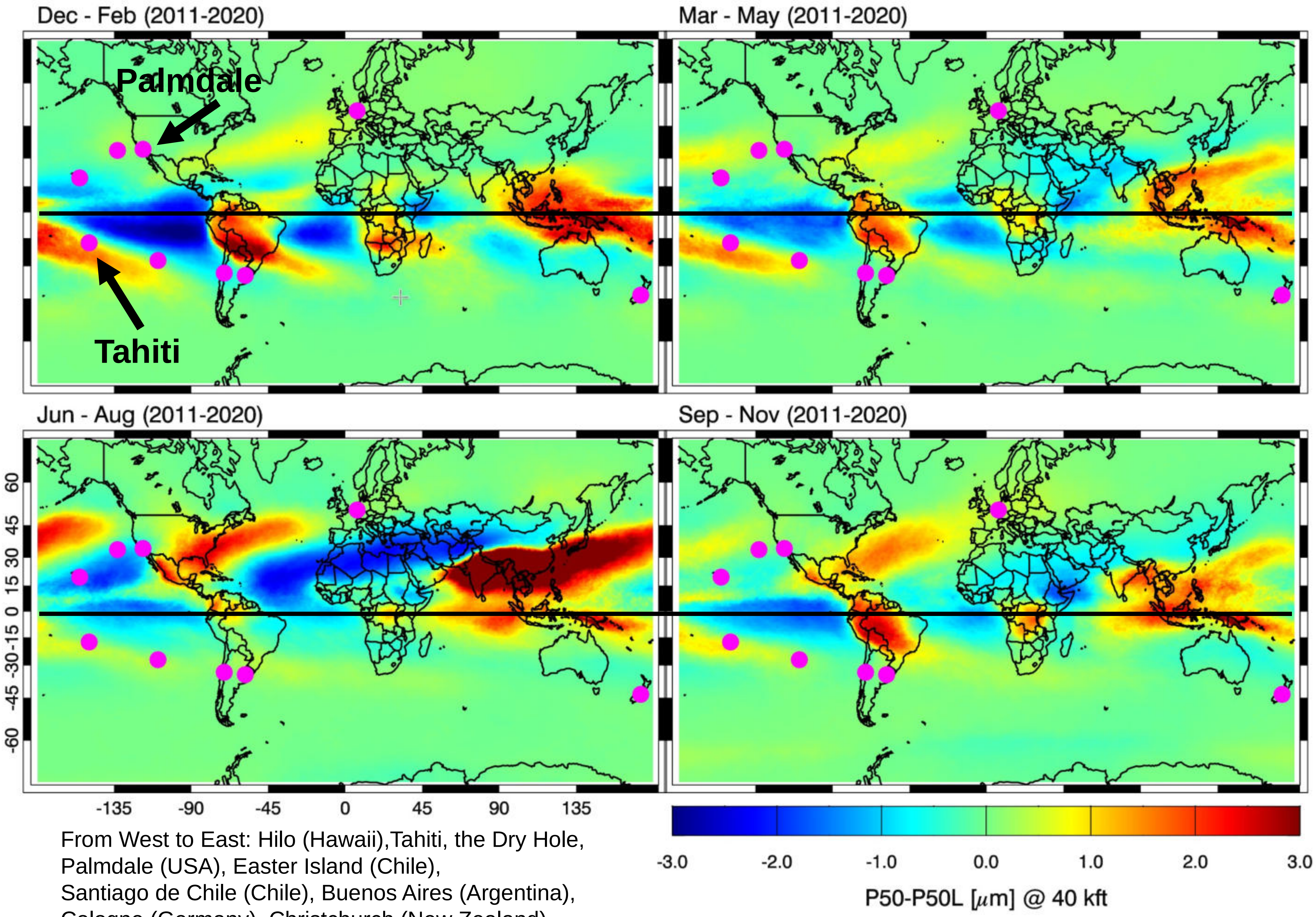


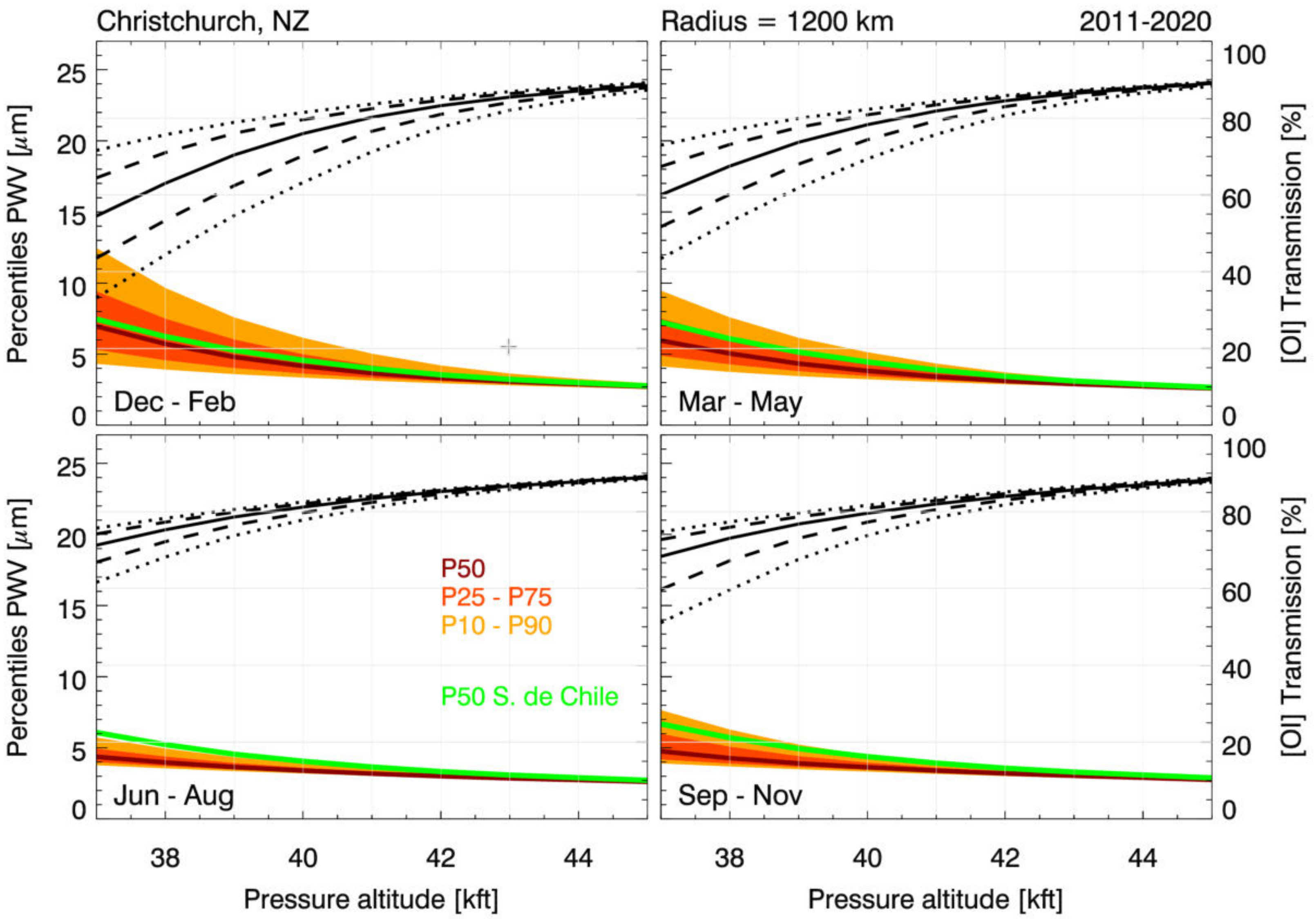
Variation of P50 with latitude, P50L

Plot left shows P50-P50L.

Tahiti shows even higher P50 than locations on the same latitude

From West to East: Hilo (Hawaii),Tahiti, the Dry Hole, Palmdale (USA), Easter Island (Chile), Santiago de Chile (Chile), Buenos Aires (Argentina), Cologne (Germany), Christchurch (New Zealand)

PWV percentiles from various locations



Median seasonal PWV, P50, and corresponding atmospheric transmission at [OI]@63 at rest (ZA=50°) calculated for a region with a radius of 1200 km around Christchurch.

[Flight paths from Palmdale are optimized for 43 kft (longest observing time intervall per flight). This height is reached at an average distance of ~1200 km towards the end of the flight.]

1. [OI]63 transmission > 60% for flight altitudes above ~37 kft

2. Santiago de Chile is similar to Christchurch

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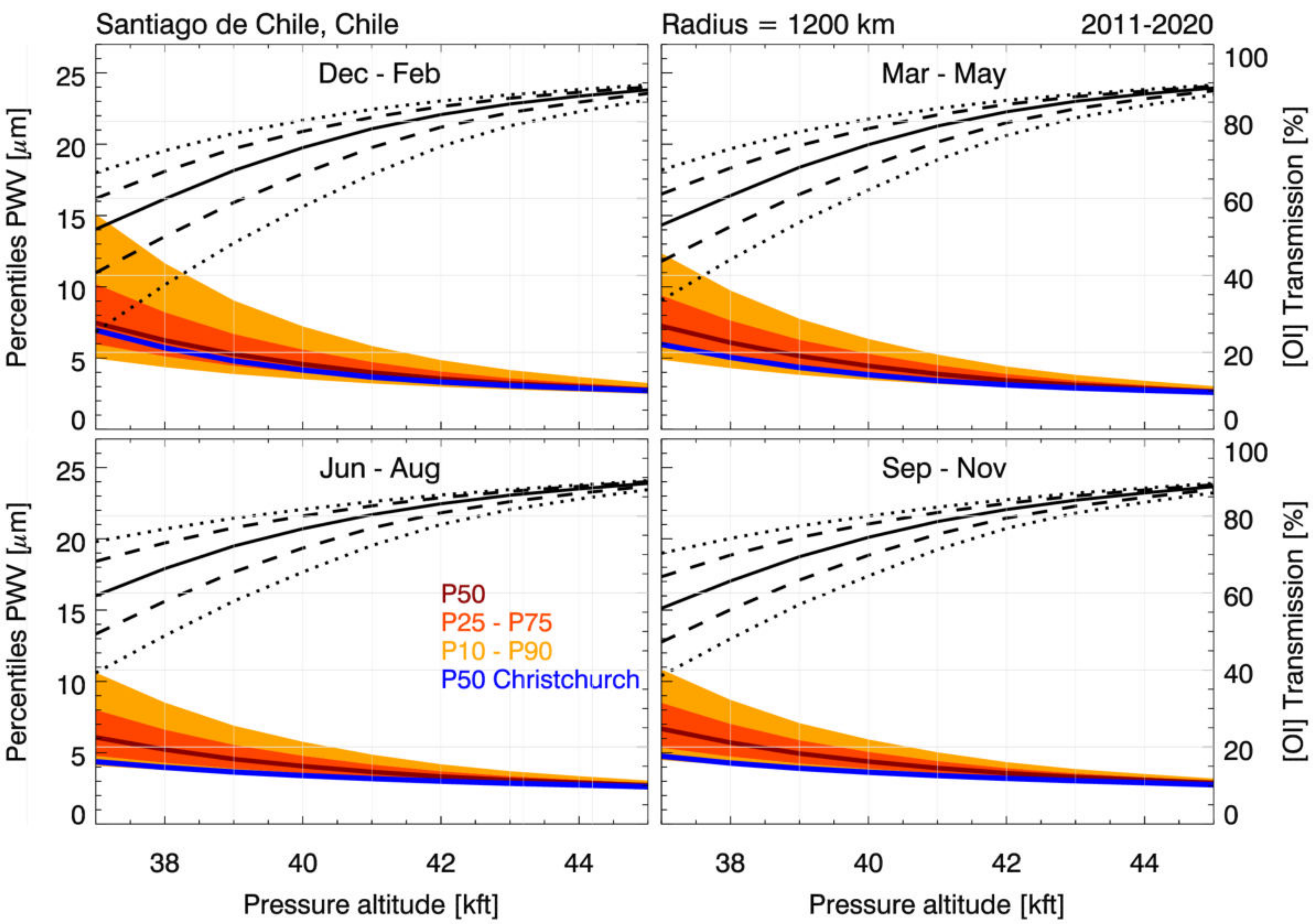
PWV percentiles from various locations



Median seasonal PWV, P50, and corresponding atmospheric transmission at [OI]@63 at rest (ZA=50°) calculated for Santiago de Chile.

Conditions comparable to Christchurch

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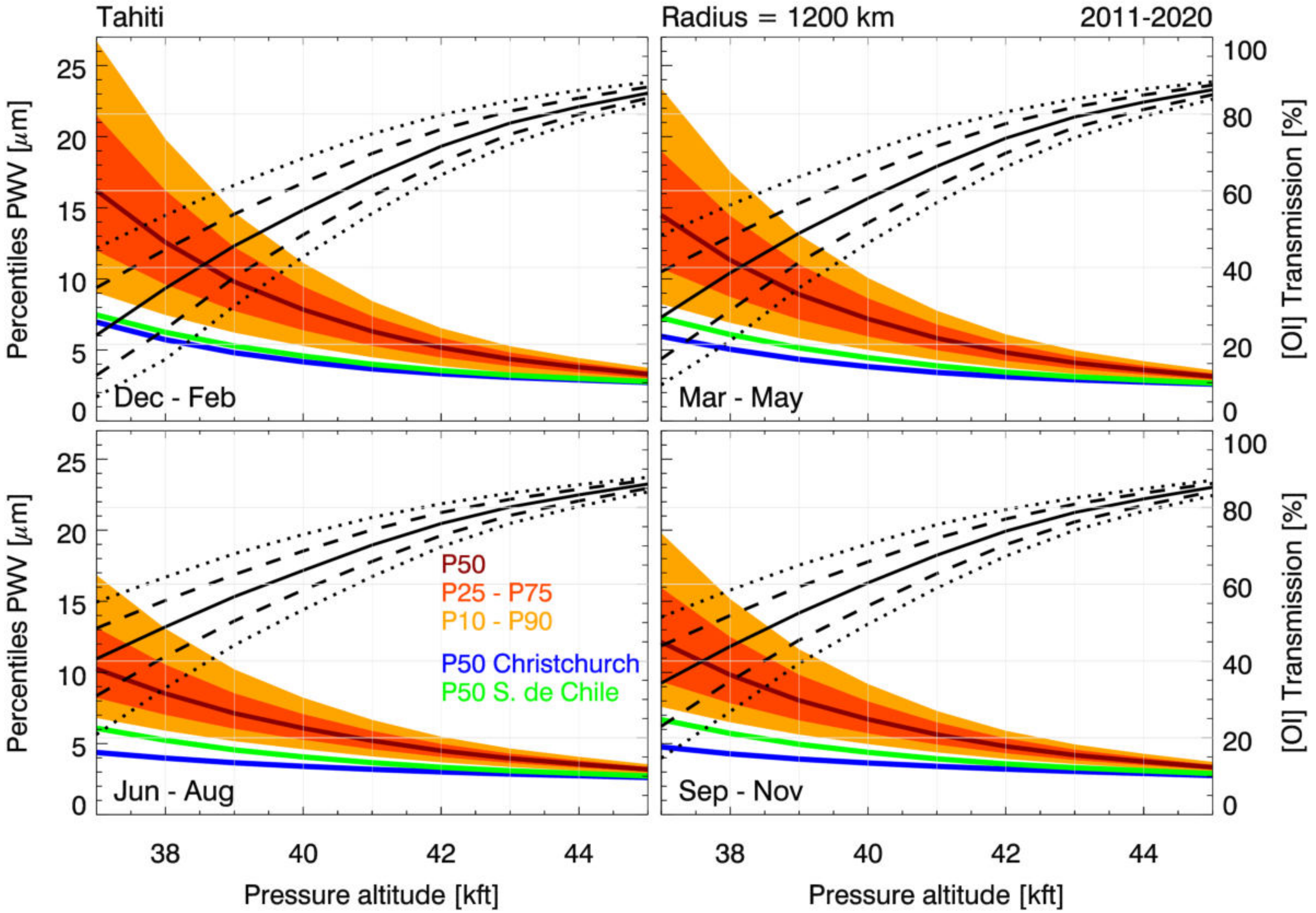
PWV percentiles from various locations



Median seasonal PWV, P50, and corresponding atmospheric transmission at [OI]@63 at rest (ZA=50°) calculated for a region with a radius of 1200 km around Tahiti.

1. Large fluctuations in seasonal PWV
2. [OI]63 transmission > 60% but only for flight altitudes above ~40 kft
3. Depending on flight profile and compared to Christchurch between 10% and 32% of the [OI]63 observing time is lost due to lower transmission at Tahiti (25% on average).

→ Conditions not ideal

Flight planning for Tahiti

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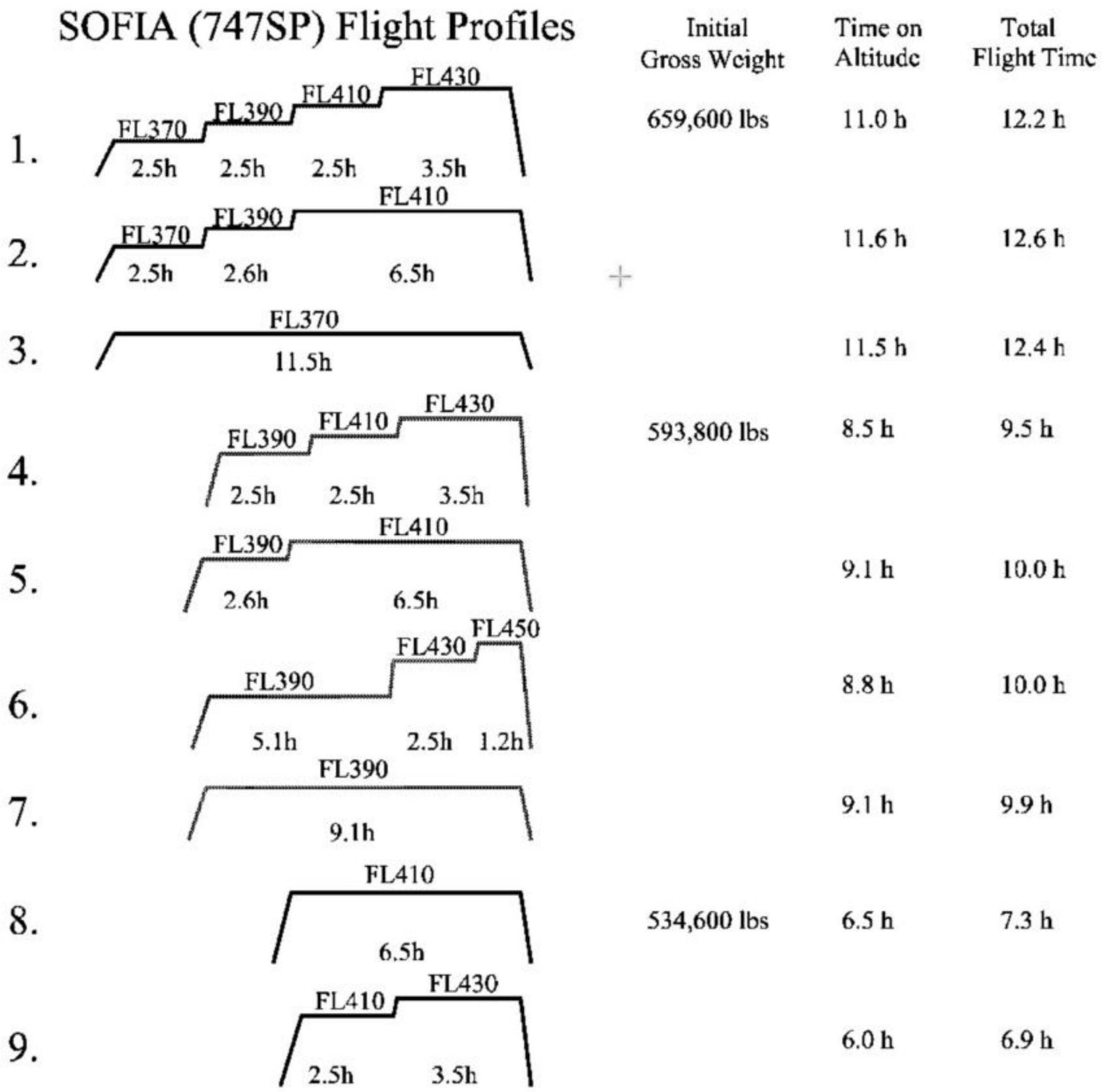

Figure from Horn & Beklin, 2001

Scenario 1 : After take-off climb as fast as possible to above 41 kft

Disadvantages :

- “Only a light bird can fly high”. The earlier you want to climb at high altitude the less kerosine must be carried at take-off.
Compare flight profile 1 and 9 → flight becomes 5 hours shorter.

- Prime targets on the southern hemisphere:
  LMC (δ=-70°) and SMC (δ=-73°).

Culmination height at Tahiti (lat=-15°) = ~30°.
Culmination height at Christchurch (lat=-44°) = ~60°.
Both locations are suitable for Sgr A* (δ = -29°).

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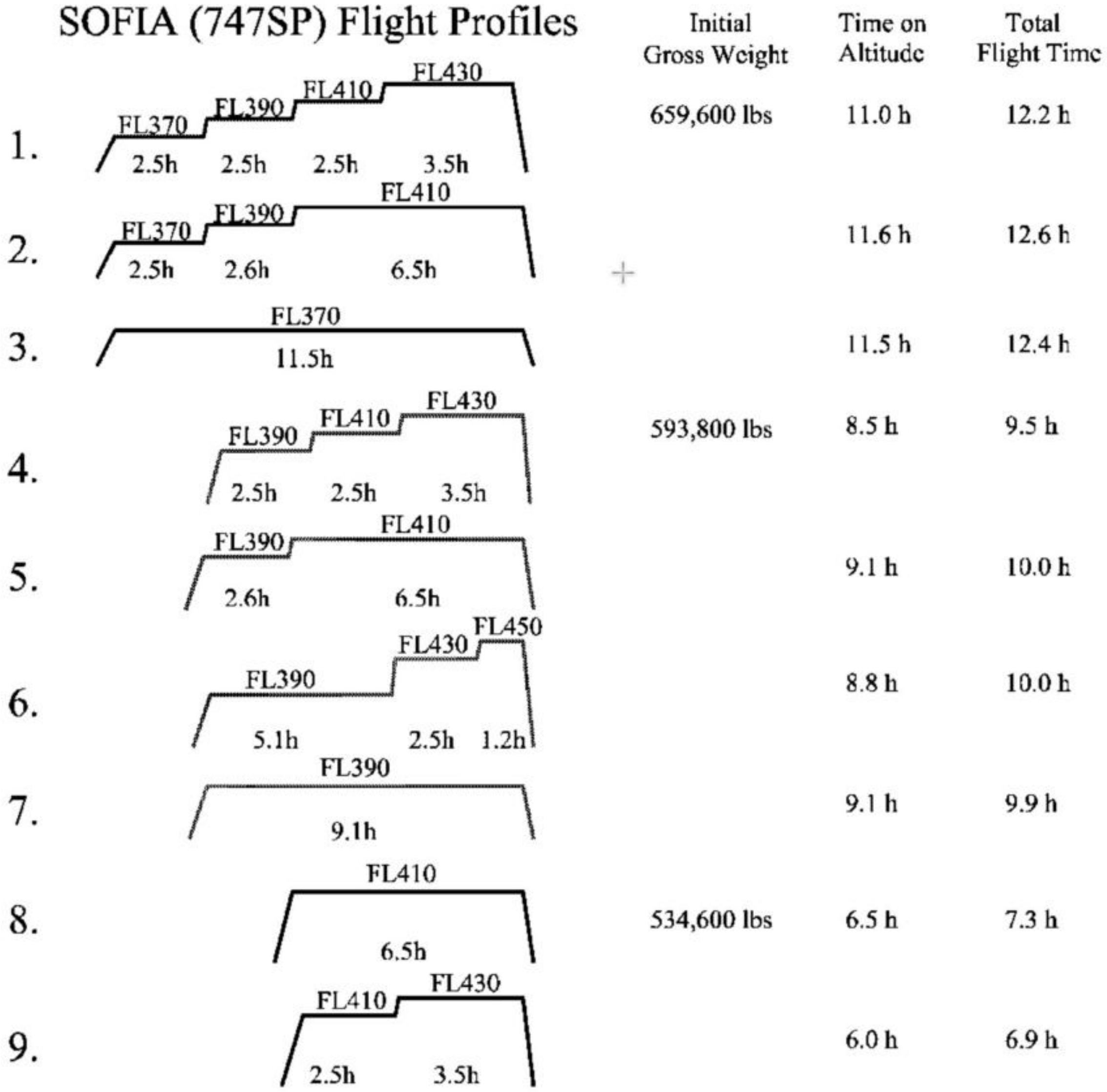

Figure from Horn & Beklin, 2001

Scenario 2 : After take-off turn straight south and observe anything but [OI]63

Disadvantages :

The first leg might be a dead leg because no object of interest may be visible

Also : Flights from Tahiti require extra kerosine for safety reasons (“island rules”).
To reach high flight altitudes towards the end of each flight the length of each flight must be shortened by about 1-2 hours compared to flights from, e. g., Palmdale.

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Summary:

1. ECMWF:
   - correlation between FIFI-LS PWV and ECMWF PWV data
   - works fine with calibrating FIFI-LS data

2. Tahiti:
   - too close to the equator
   - concerning Flight Planning turn South or climb as high as possible immediately after take-off.
   - either way, you loose several hours per single observing flight compared to flights from Christchurch/Santiago.

The end

Thanks for your attention