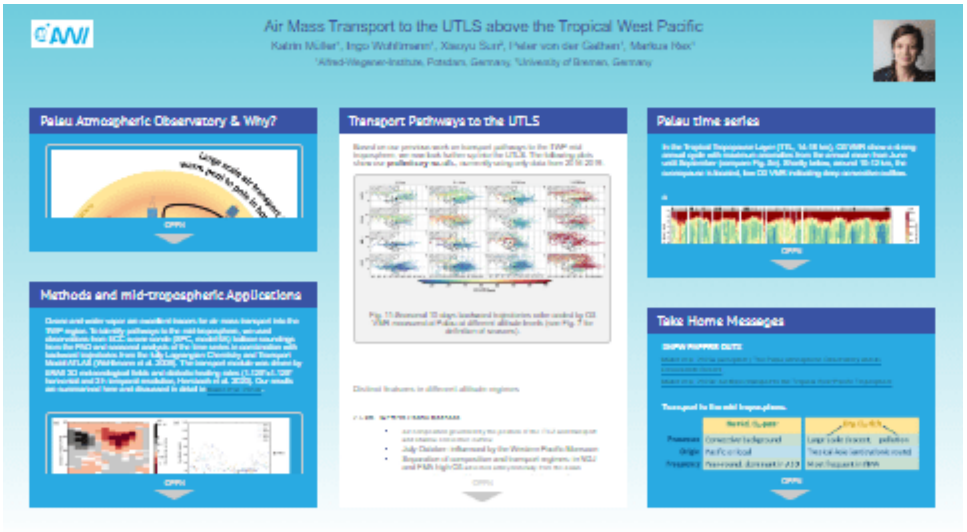
Air Mass Transport to the UTLS above the Tropical West Pacific



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PALAU ATMOSPHERIC OBSERVATORY & WHY?

The Tropical West Pacific (TWP) warm pool has been identified as the major source region for stratospheric air, coinciding with a tropospheric ozone minimum (Rex et al. 2014). The close coupling of ozone concentration and oxidizing capacity of the clean tropical troposphere thus influences the overall transport of chemical species to the stratosphere.

To close the observational gap (Fig. 2) in this key region the Palau Atmospheric Observatory (PAO) was established on Palau (7° N, 135° E) in fall 2015 with a comprehensive setup of instruments (Fig. 4).

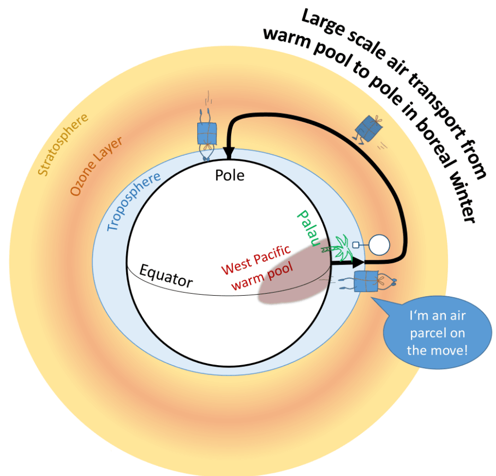


Fig. 1: Schematic of air mass transport from the Tropical West Pacific to the global stratosphere.

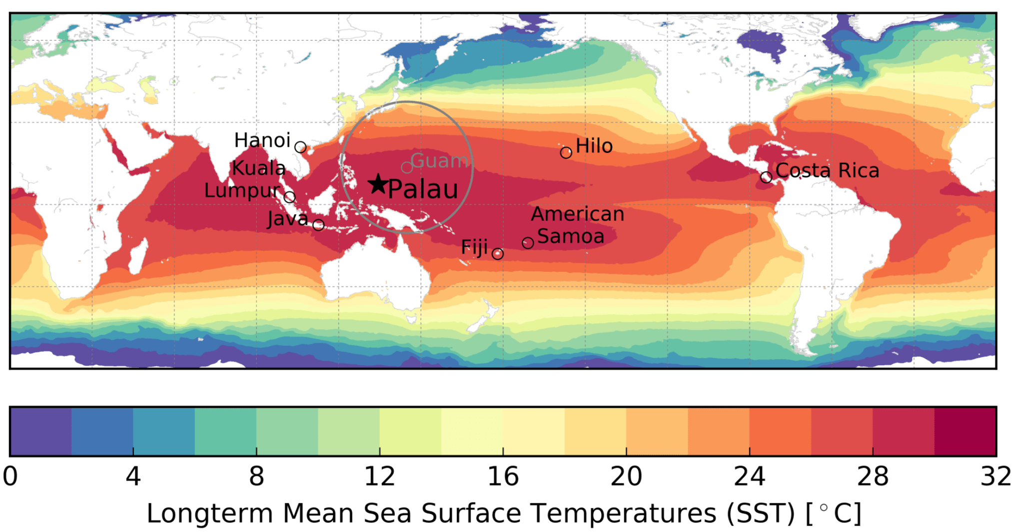


Fig. 2: Location of Palau (black star), selected SHADOZ sites (black circles) and CONTRAST campaign domain around the airbase in Guam (grey circle). Longterm Mean Sea Surface Temperatures (SST) in °C derived from monthly ERA5 data from 1959-2021 show the location of the global warm pool area (Müller et al. 2023a (https://egusphere.copernicus.org/preprints/2023/egusphere-2023-1023/))

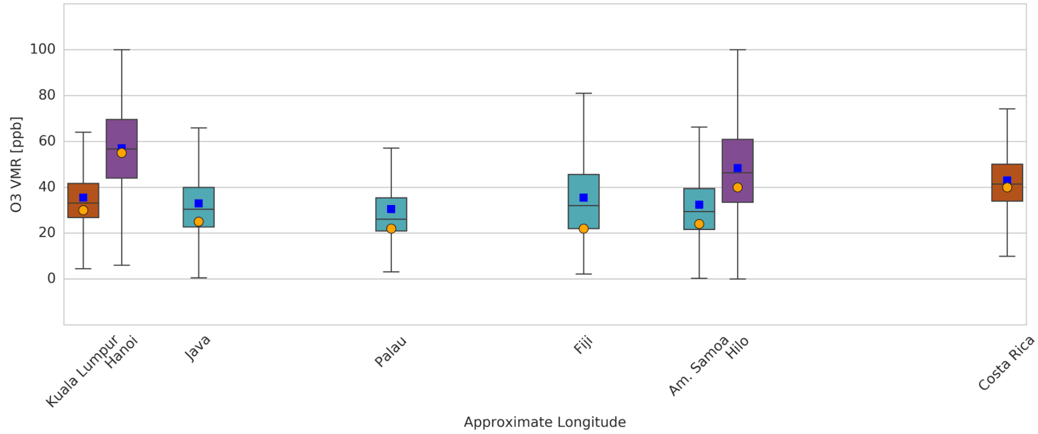


Fig. 3: Free-tropospheric (3-14 km) O3 VMR statistics for VMR ≤ 100 ppb for Palau and selected SHADOZ stations, colored according to specific O3/RH distribution characteristics (see Müller et al. 2023a (https://egusphere.copernicus.org/preprints/2023/egusphere-2023-1023/)for more info); outliers are not shown and whiskers are a function of the interquartile range (IQR=Q3-Q1, i.e. Q3 or Q1 + or - 1.5x IQR respectively); blue squares are mean values; orange circles refer to the most frequent O3 VMR; arrangement of boxplots on the horizontal axis is an approximation to longitudinal positions.

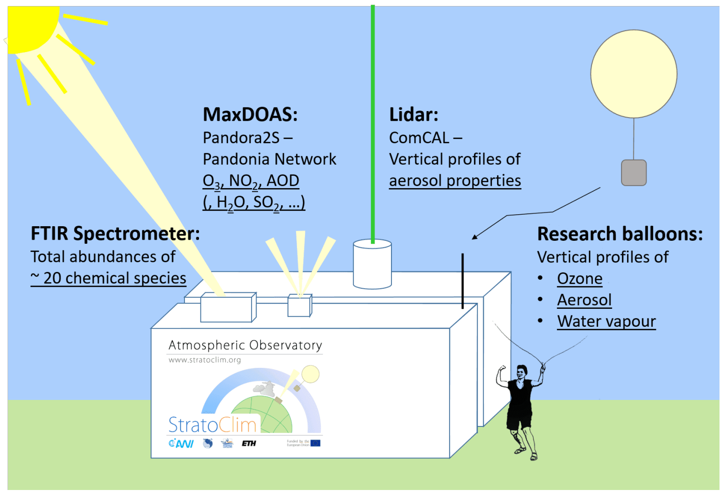


Fig. 4: Instrumental Setup at the Palau Atmospheric Observatory (Müller et al. 2023a (https://egusphere.copernicus.org/preprints/2023/egusphere-2023-1023/)).

Further Reading:

AGU Meeting 2020 iPoster (https://essopenarchive.org/doi/full/10.1002/essoar.10505805.1)

Müller et al. 2023a (accepted!): The Palau Atmospheric Observatory and its Ozonesonde Record (https://egusphere.copernicus.org/preprints/2023/egusphere-2023-1023/)

Müller et al. 2023b (minor revisions): Air Mass transport to the Tropical West Pacific Troposphere

(https://egusphere.copernicus.org/preprints/2023/egusphere-2023-1518/)

Sun et al. 2023: Determination of a Chemical Equator from GEOS-CHem (https://doi.org/10.5194/acp-23-7075-2023)

METHODS AND MID-TROPOSPHERIC APPLICATIONS

Ozone and water vapor are excellent tracers for air mass transport into the TWP region. To identify pathways to the mid-troposphere, we used observations from ECC ozone sonde (SPC, model 6A) balloon soundings from the PAO and seasonal analysis of the time series in combination with backward trajectories from the fully Lagrangian Chemistry and Transport Model ATLAS (Wohltmann et al. 2009). The transport module was driven by ERA5 3D meteorological fields and diabatic heating rates (1.125°x1.125° horizontal and 3 h temporal resolution, Hersbach et al. 2020). Our results are summarized here and discussed in detail in Müller et al. 2023b (https://egusphere.copernicus.org/preprints/2023/egusphere-2023-1518/).

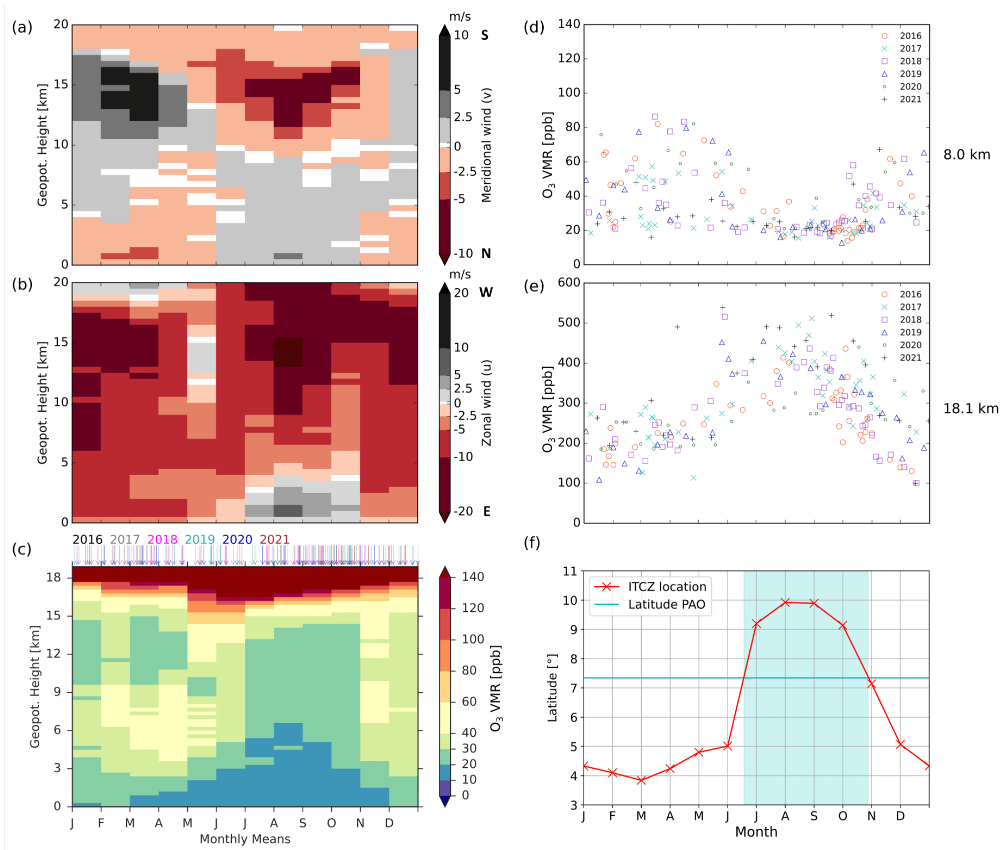


Fig. 5: Monthly mean zonal (a) and meridional (b) wind from daily radio soundings from the operational NOAA-associated observing site at the Palau airport (WMO station ID PTRO 91408) averaged from 2016-2019 as well as O3 VMR (c) averaged from 08/2016-2021 (i.e. excluding El Nino 2016) as time-height cross-sections, alongside mean O3 VMR of individual soundings of all years (different markers and colors) in 300 m altitude layers centered around 8 km (d) and 18 km (e). Panel (f) shows the monthly mean latitudinal movement of the ITCZ from TRMM averaged from 1998-2009 for 125-175° E, 0-20° N after (Shonk et al. 2018), whereby the ITCZ location is defined in terms of the zonal mean rainfall rate across this region using a threshold of 50 % of the peak zonal-mean rainfall intensity. Palau's latitude is marked by the horizontal turquoise line. (Müller et al. 2023a (https://egusphere.copernicus.org/preprints/2023/egusphere-2023-1023/))

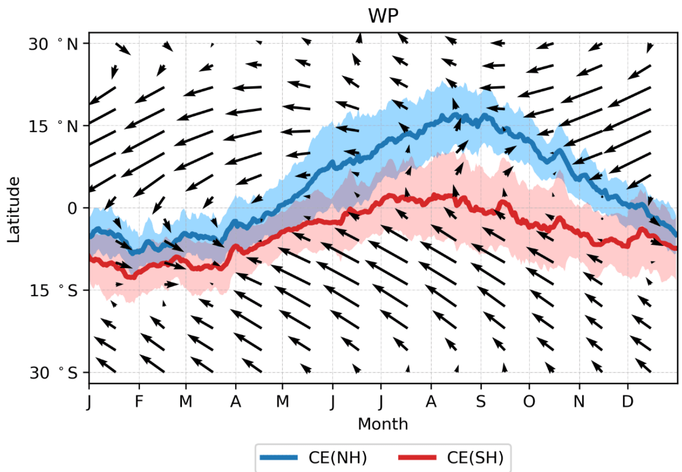


Fig. 6: Annual movement of the Chemical Equator derived from GEOS-Chem simulations for the Tropical West Pacific (WP) (Sun et al. 2023 (https://doi.org/10.5194/acp-23-7075-2023)).

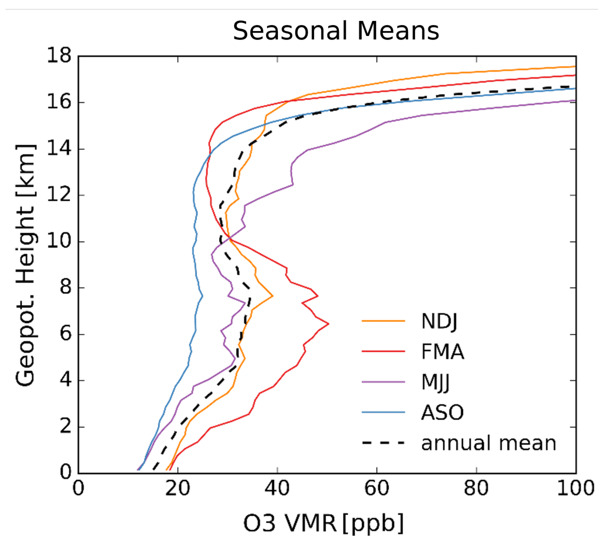


Fig. 7: Palau seasonal mean O3 VMR profiles for November-December-January (NDJ), February-March-April (FMA), May-June-July (MJJ), August-September-October (ASO); the seasons where chosen with respect to profile shapes (Müller et al. 2023b (https://egusphere.copernicus.org/preprints/2023/egusphere-2023-1518/)).

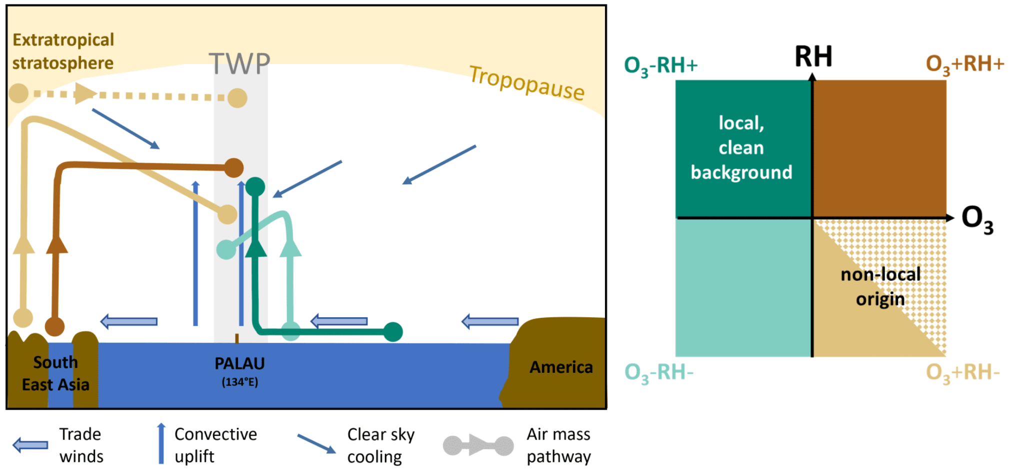


Fig. 8: Schematic for transport pathways to the TWP troposphere on the zonal plane, major dynamical drivers are marked with arrows (blue colors), transport pathways are color-coded according to the air masses' O3/RH characteristics shown in the qualitative grid (turquoise colors for O3-, brown colors for O3+, hue for RH+/-); O3+RH- air masses (light brown) above Palau may have followed two of the five shown pathways (Müller et al. 2023b (https://egusphere.copernicus.org/preprints/2023/egusphere-2023-1518/))

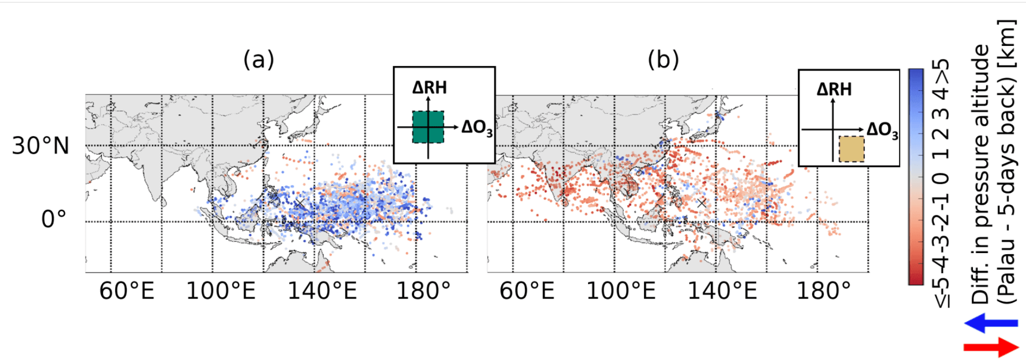


Fig. 9: Origin of air masses by air mass anomalies: 5-days backward trajectory earliest points arriving in Palau in the 5-10 km altitude range for background air (green) and anomalous O3+RH- air masses (light brown) as indicated by the pictograms, color-coded by difference in pressure altitude, sonde - endpoint. Note, that the air mass categories here refer to anomalies from a statistically defined monthly background, for details see Müller et al. 2023b (https://egusphere.copernicus.org/preprints /2023/egusphere-2023-1518/).

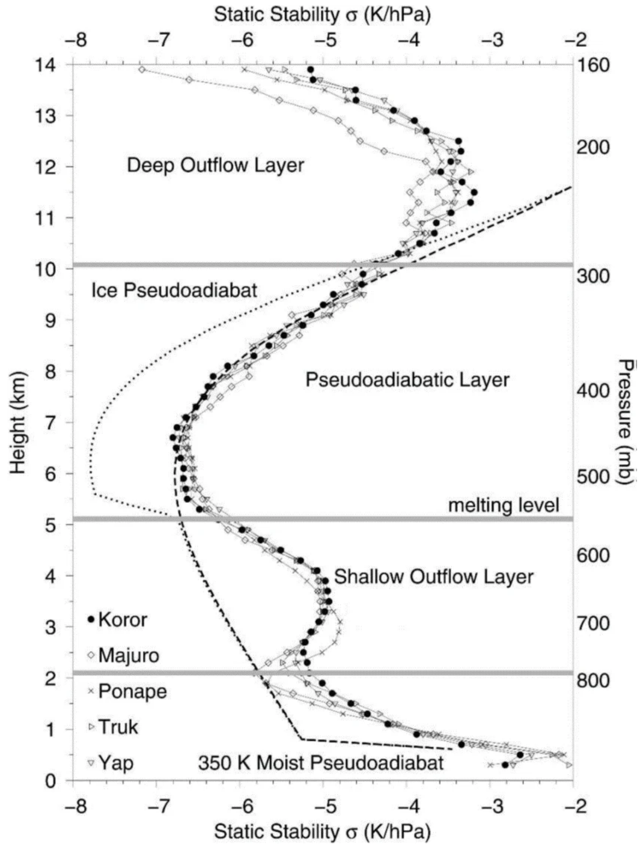


Fig. 10: Different atmospheric layers related to convective activity in the TWP and annual mean profiles of static stability [K/hPa] from average radiosounding data (1999-2001) at Palau (Koror, filled circle) and close by stations in the Federate States of Micronesia (other markers), thick lines indicate static stability for a moist pseudoadiabat, with water vapor either condesing to water (dashed) or ice (dotted)
(adapted from Folkins and Martin, 2005).

TRANSPORT PATHWAYS TO THE UTLS

Based on our previous work on transport pathways to the TWP mid-troposphere, we now look further up into the UTLS. The following plots show our **preliminary results**, currrently using only data from 2016-2019.

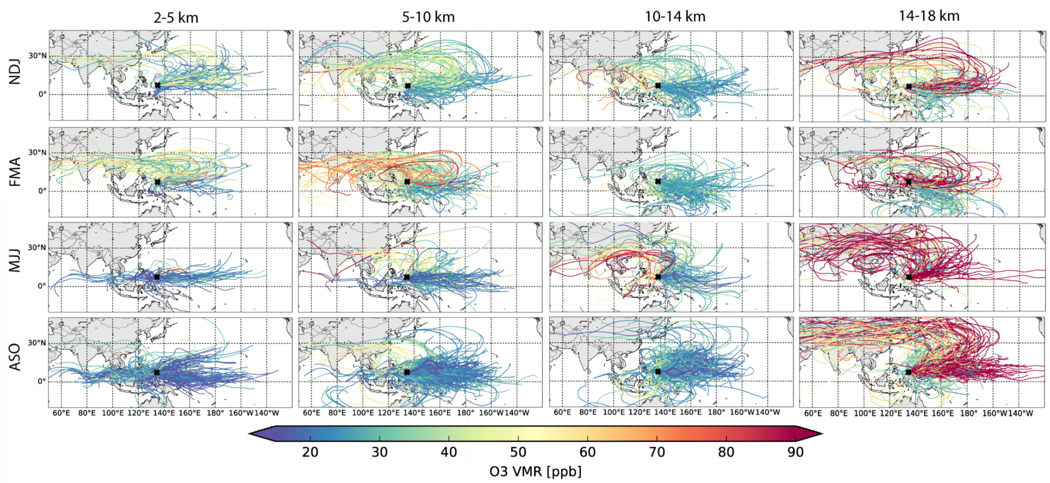


Fig. 11:Seasonal 10-days backward trajectories color-coded by O3 VMR measured at Palau at different altitude levels (see Fig. 7 for definition of seasons).

Distinct features in different altitude regimes

2-5 km - Western Pacific Monsoon

- Air composition governed by the position of the ITCZ and transport and shallow convective outflow
- July-October: influenced by the Western Pacific Monsoon
- Separation of composition and transport regimes: in NDJ and FMA high O3 advected anticyclonically from the Asian continent, MJJ and ASO predominantly low O3 form the East via a Pacific route

5-10 km - Eastern Pacific (local) and Asian Pathways

- Air composition governed by the position of the ITCZ and transport, weak cloud-mass divergence (see Fig. 10)
- High O3, mostly during FMA, advected anticyclonically from the Asian continent, low O3 of local or Pacific origin, mostly during ASO, transported with the trade winds
- see **Müller et al. 2023a,b**

10-14 km - Region of the Ozonopause

- Air composition governed by deep convective outflow and the Hadley circulation
- Low O3 present in all seasons but MJJ (Fig. 7): here, troposphere altitude at its lowest, potential stratosphere-troposphere exchange (PV >1.5 during 5 days back for more than 1 day: around 10% of trajectories, not shown here)
- Dominant uplift of local/Pacific, clean air masses
- In NDJ: a particular low PV event, i.e. air masses potentially advected from the Southern hemispheric stratosphere, to be investigated further in the future

14-18 km - Tropical Tropopause Layer:

- Transition from tropospheric to stratospheric composition (Fig. 14), active exchange between regimes, region where Hadley and Brewer-Dobson circulation are equally strong, beginning of large scale ascent, also indicated by sub-visible cirrus above the cold point tropopause measured by the lidar (Fig. 18)
- Anticyclonic routine is present throughout the year, transport from longer distances compared to lower altitudes, most pronounced during ASO (compare strong winds in Fig. 5 a,b), least during FMA, when mostly equatorial air masses reach Palau from the East

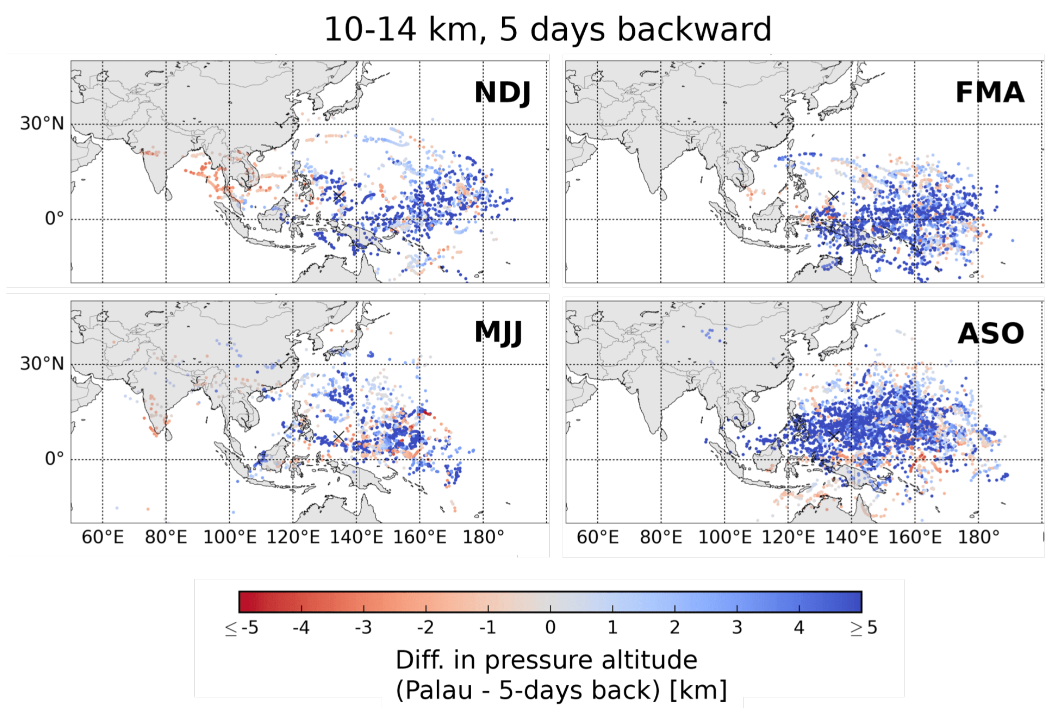


Fig. 12: 5-days backward trajectory ending points color-coded by difference in pressure altitude, Palau minus 5-days back, arriving in Palau at 10-14 km altitude.

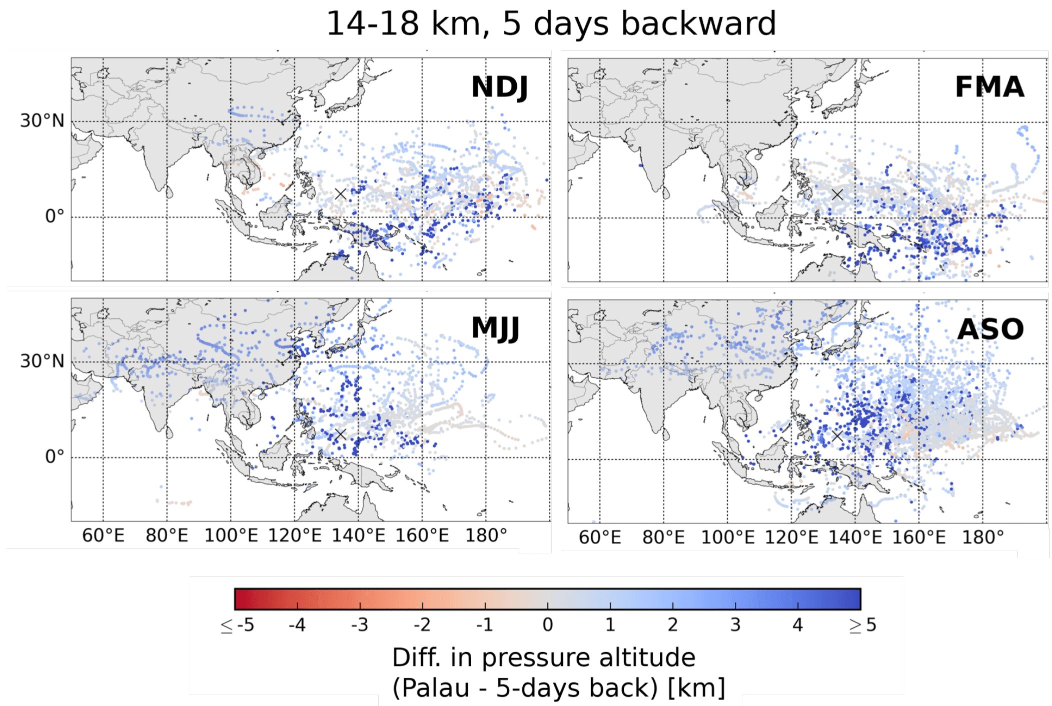


Fig. 13: 5-days backward trajectory ending points color-coded by difference in pressure altitude, Palau minus 5-days back, arriving in Palau at 14-18 km altitude.

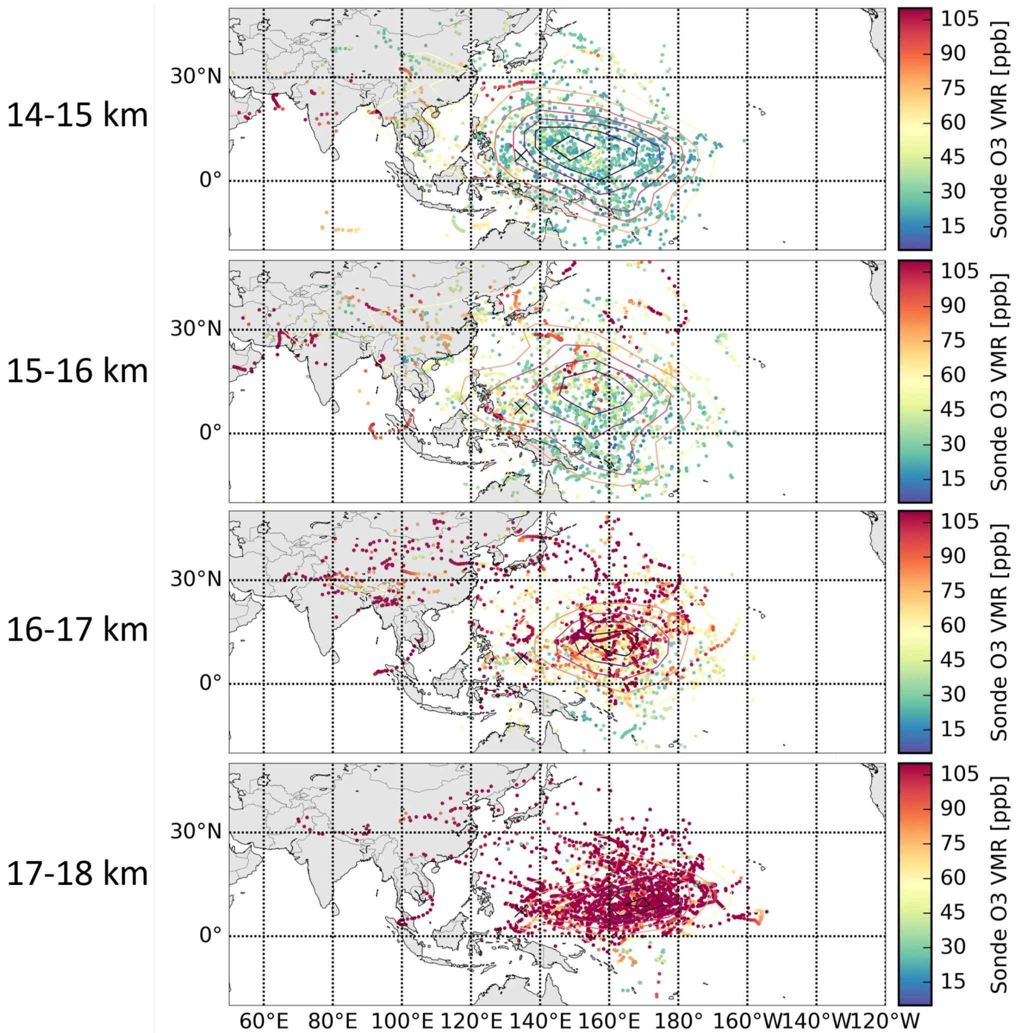
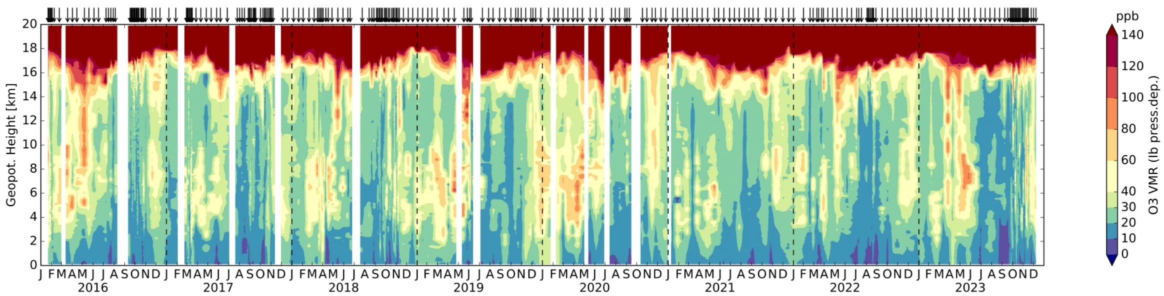


Fig. 14: 5-days backward trajectory ending points color-coded by O3 VMR measured at Palau, arriving in Palau at different altitude ranges within 14-18 km

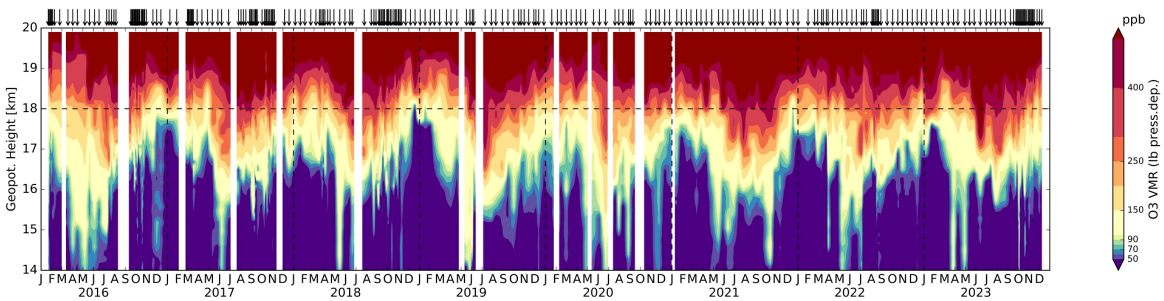
PALAU TIME SERIES

In the Tropical Tropopause Layer (TTL, 14-18 km), O3 VMR show a strong annual cycle with maximum anomalies from the annual mean from June until September (compare Fig. 5e). Shortly below, around 10-12 km, the ozonopause is located, low O3 VMR indicating deep convective outflow.

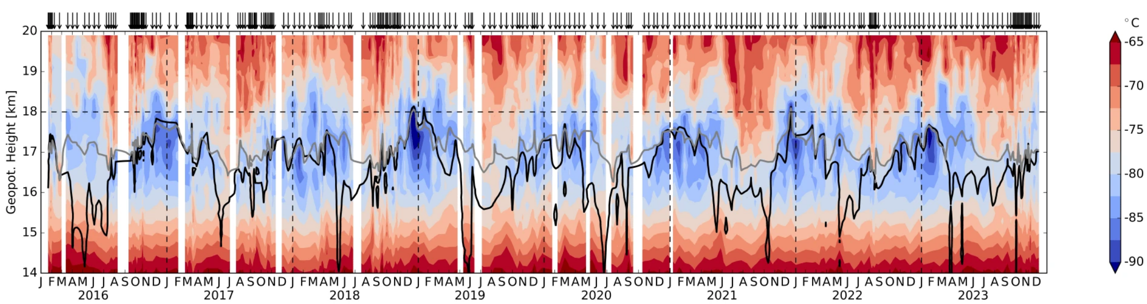
a



b



c



d

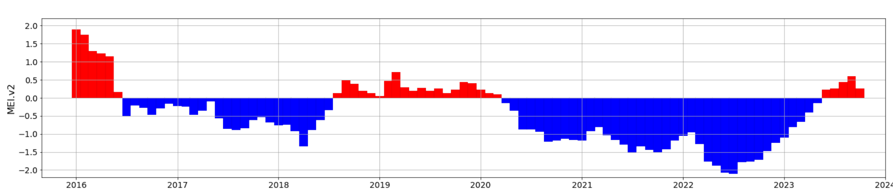


Fig. 15: Time-height-cross-sections for tropospheric (0-20 km, a) and UTLS (14-20 km, b) ozone derived from PAO sounding data, as well as for temperature (14-20 km, c) with 90 ppb O3 VMR highlighted as a black line and 380 K

potential temperature as a grey line. Multivariate ENSO index (MEI) (d), data provided by NOAA (https://psl.noaa.gov/enso/mei/), (Wolter et al. 2011). Arrows on top of a,b,c indicate individual soundings; data is linearly interpolated between soundings; measurement gaps longer than 20 days are in white, beginning 7 days after/before the last/next sounding; note the non-linear scaling; O3 VMR are calculated using a pressure dependent background current correction, see Müller et al. 2023a (https://egusphere.copernicus.org/preprints/2023/egusphere-2023-1023/) for more details.

HIGHLIGHTS

ACCLIP

During the aircraft campaign we performed 8 ECC ozone soundings, 2 combined ECC-CFH-COBALD soundings and nightly Lidar measurements, data all available at http://doi.org/10.26023/SBQR-HPJV-3V08 (http://doi.org/10.26023/SBQR-HPJV-3V08) and http://doi.org/10.26023/SD3W-WKBH-5X13 (http://doi.org/10.26023/SD3W-WKBH-5X13).

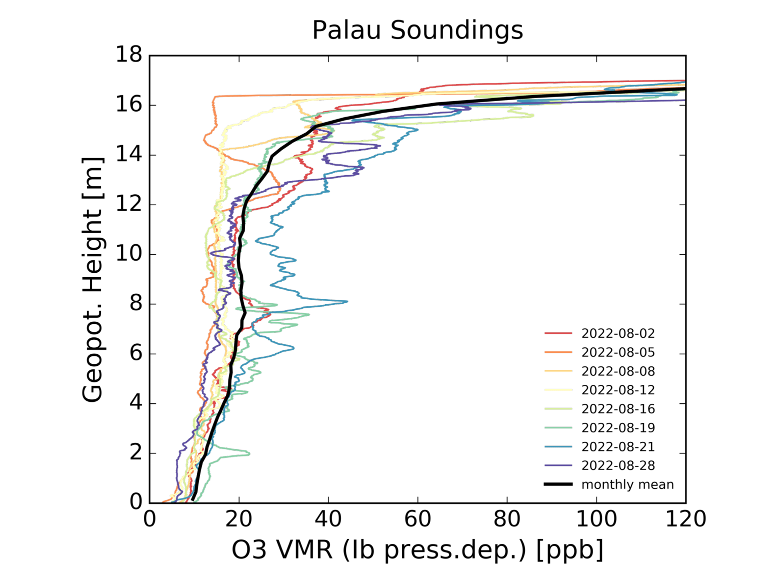
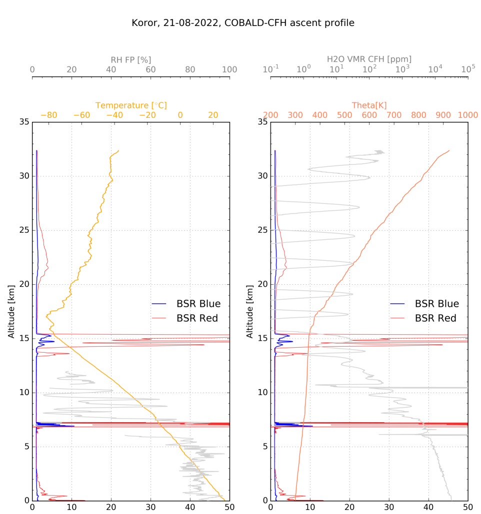


Fig. 16: ACCLIP ozone soundings and multi-year monthly mean for August.



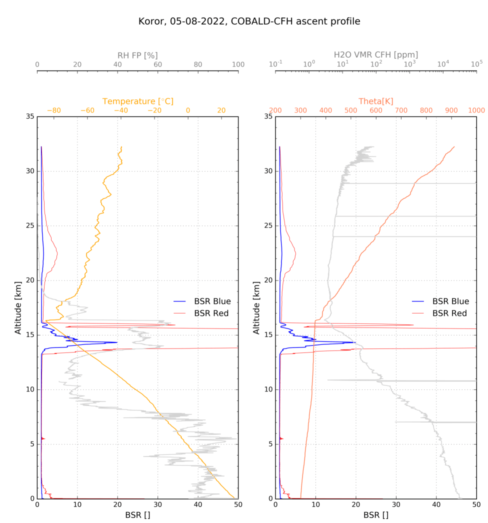


Fig. 17: ECC-CFH-COBALD Soundings during ACCLIP.

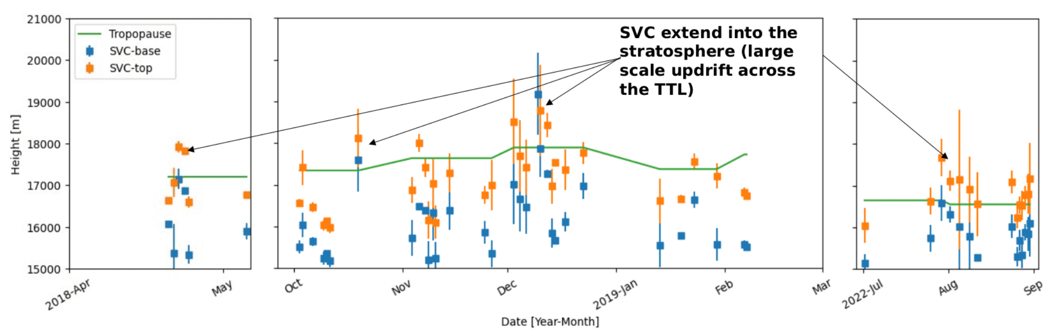


Fig. 18: Cloud top (orange) and base (blue) height derived from ComCAL lidar data at PAO for sub-visible cirrus from 2018-2022 (Sun et al. in prep.).

Ongoing El Nino

The annual low O3 season in Palau (ASO) was not affected by the El Nino. Anomalies were rather observed from February until July, in neutral ENSO conditions. In comparison to 2016 (see Fig. 14), we expect anomalous signals in the UTLS and mid-troposphere during FMA, if the El Nino remains strong, i.e. a weaker O3 gradient in the TTL over the course of the season and temperature anomalies.

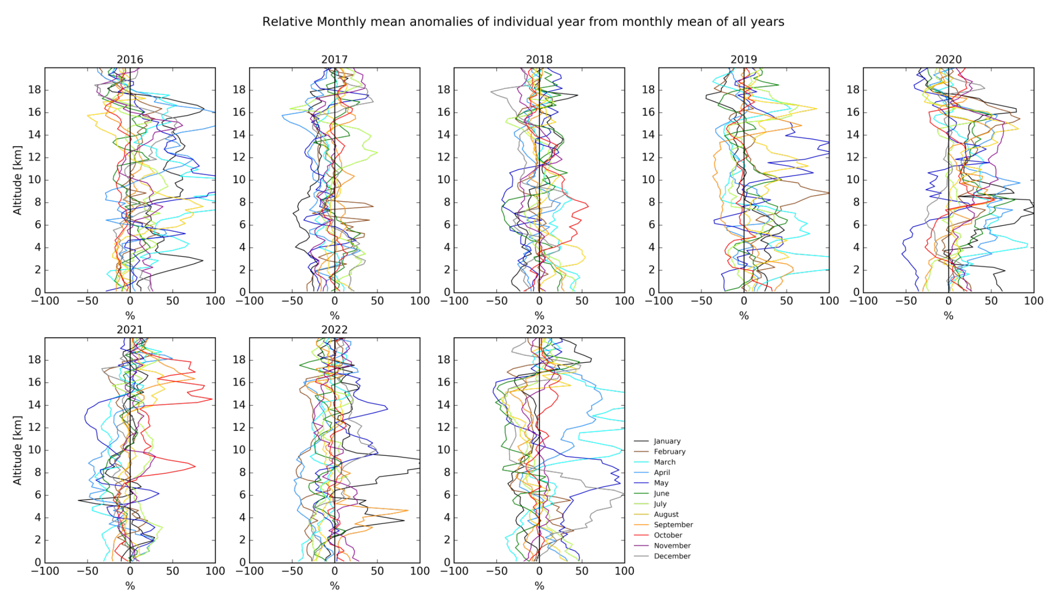


Fig. 19: Relative anomalies of annual monthly means compared to multi-year monthly means from 2016 to 2023.

TAKE HOME MESSAGES

!!NEW PAPERS OUT!!

Müller et al. 2023a (accepted!): The Palau Atmospheric Observatory and its Ozonesonde Record (https://egusphere.copernicus.org/preprints/2023/egusphere-2023-1023/)

Müller et al. 2023b: Air Mass transport to the Tropical West Pacific Troposphere (https://egusphere.copernicus.org/preprints/2023/egusphere-2023-1518/)

Transport to the mid-troposphere:

	Humid, O_3-poor	Dry, O_3-rich
Processes	Convective background	Large scale descent, pollution
Origin	Pacific or local	Tropical Asia (anticyclonic route)
Frequency	Year-round, dominant in ASO	Most frequent in FMA

Transport to the UTLS:

- We started expanding our analyses of the Palau Atmospheric Observatory time series to the UTLS/TTL region and compared O3 composition and transport for different altitude regimes.
- The region of deep convective outflow (10-14 km) is characterized by the ozonopause, i.e. low O3 uplifted from local/Pacific region, in all seasons but from May to July, when transport from the stratosphere to the troposphere occurs.
- In the TTL (14-18m) anticyclonic long distance transport is present throughout the year, most pronounced during ASO, least during FMA

Open Questions/Upcoming:

- Extention of the time series and analyses
- Investigation of ACCLIP campaign time period and comparison with other measurements
- ITCZ with altitude: Looking deeper into the interhemispheric transport boundary in the UTLS
- ENSO: multi-regression time series analysis (new PhD project)
- impact of QBO on transport (new PhD project)
- also: analysis of an exciting multi-instrumental measurement of the Hunga Tonga eruption stratospheric H2O layer from March 2022 (Master project)

Please approach us for questions, data access and collaborations!

TRANSCRIPT

ABSTRACT

The Tropical West Pacific (TWP) is the key entry point of air into the stratosphere during Northern Hemispheric winter. Our previous work showed how transport to the TWP troposphere is modulated by the movement of the Intertropical Convergence Zone, allowing transport of polluted air masses from tropical Asia during spring (Müller et al., 2023a, Müller et al. 2023b). Here, we present insights on air mass transport to the upper troposphere/lower stratosphere (UTLS) in this region using the ozone and relative humidity time series (2016-2023) from the Palau Atmospheric Observatory (PAO), located in the center of the tropical warm pool (7°N, 134°E). We further give an overview of all observations performed at the PAO during the ACCLIP summer campaign 2022, including ozone, CFH and COBALD sonde and lidar measurements.
In analogy to Müller et al. 2023b, Lagrangian backward trajectories calculated with a stochastic convection scheme (Wohltmann et al. 2019) are used to identify transport from remote locations. The time series already allows some interpretation regarding interannual variability mainly to the ENSO cycle. Here, we show anomalies during the 2016 strong El Nino and potentially the El Nino in the upcoming winter 2023. The PAO proves to be an excellent site to study UTLS composition and dynamics in the TWP region.