Ozone Long-Term Variability Observed at Mauna Loa Observatory, Hawaii, and Table Mountain Facility, California - Transport and Steps of Recovery -

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Oak Ridge Associated Universities

Division 32 at Table Mountain Facility (TMF)

- **Providing key measurements relating to ozone and climate change:**
  - > to test and constrain models of stratospheric ozone depletion,
  - > provide observational evidence linking solar variability and atmospheric composition,
  - > for Earth Science satellites data validation data.
- **JPL DIAL Lidars:**

two of the five longest stratospheric ozone time series in the world

1993 *Mauna Loa Observatory, Hawaii (MLO, 19.5 N, 155.6 W)* - 2 sites - *Table Mountain Facility, California (34.5 N, 117.7 W)* 1988

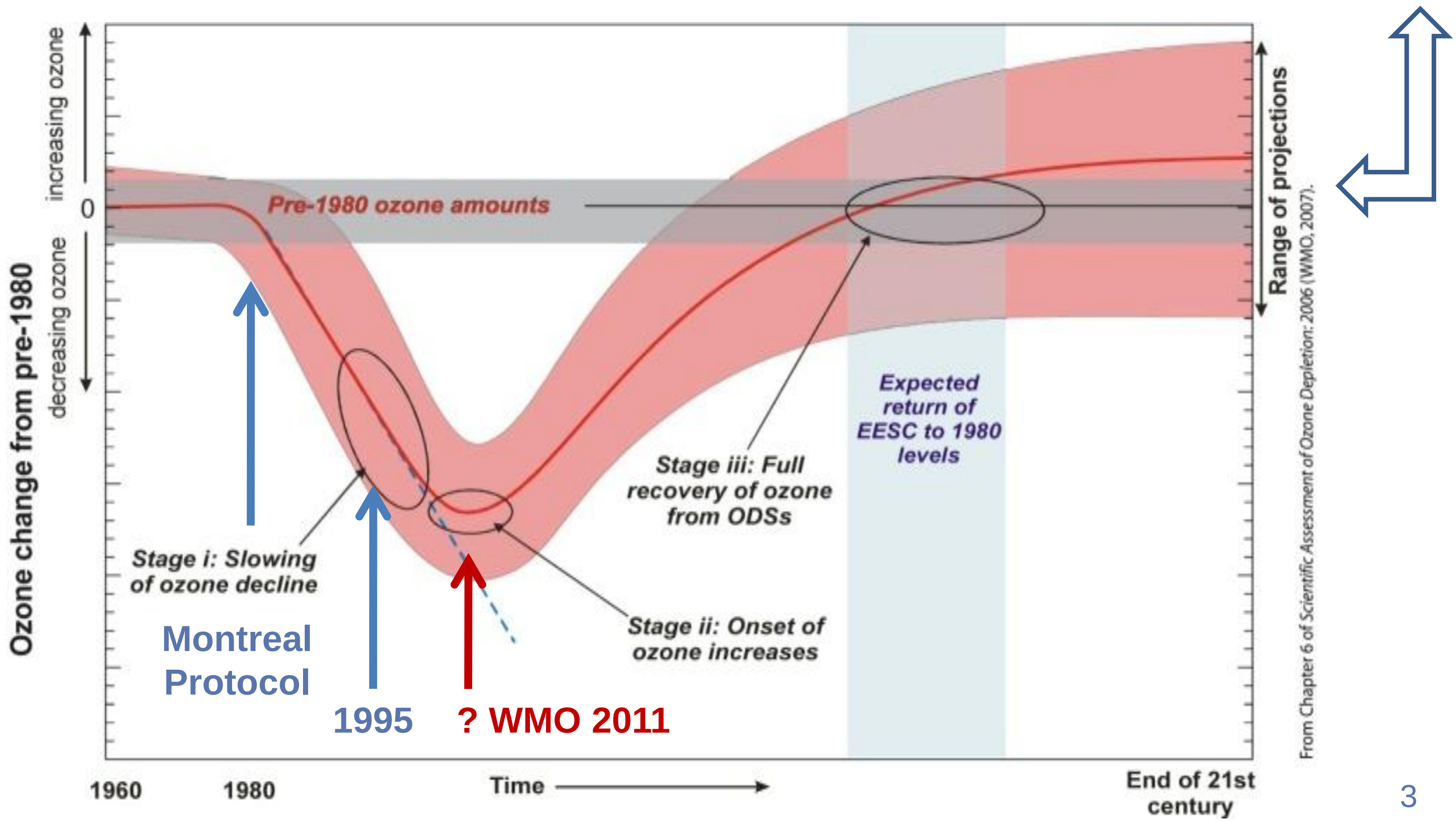
Spatially (vertically) high resolution data	Suitable for assessing long-term changes	Internally consistent
~ 300m (sampling) 600 m to 3 km (resolution) Satellite: 2.5 to 6 km	Measurement frequency: 3-5 times per week, Total number of measurements per year: 200.	Only one significantly instrumental configuration change in 2001, Produced with the same family of analysis software versions.

http://www.ndacc.org http://tmf-lidar.jpl.nasa.gov

Stratospheric ozone and …

Ozone layer evolution:
> photo-chemical processes(upper and middle stratosphere),
> dynamical processes (lower stratosphere).

Dynamical processes two way interaction with climate change.

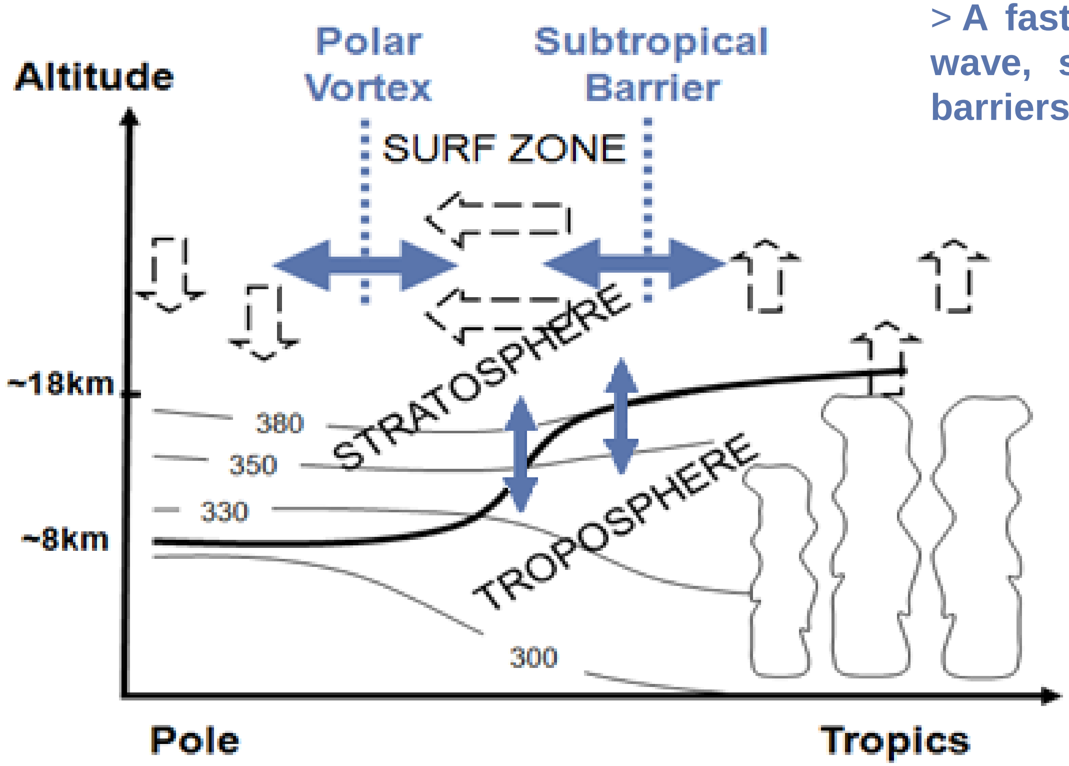


… Transport

Stratospheric circulation is divided in two parts

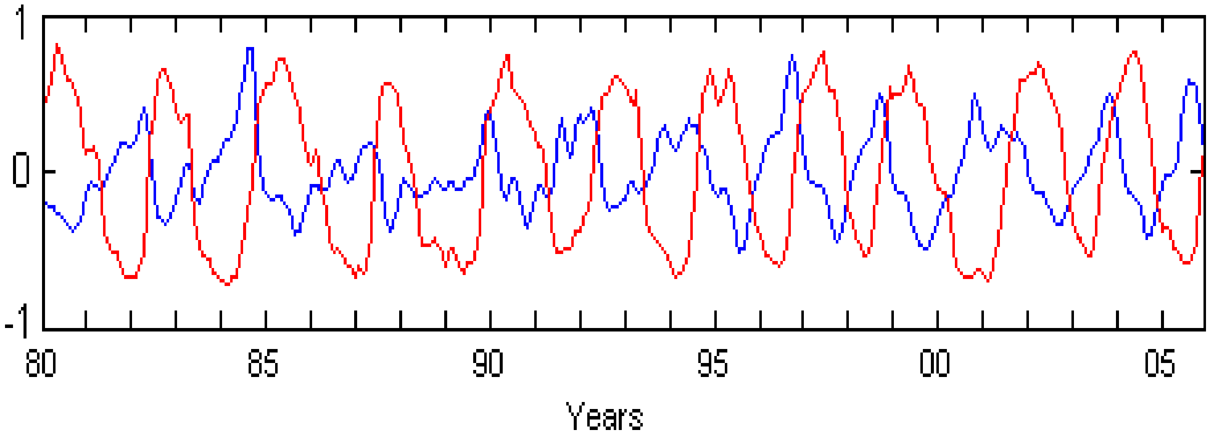
> A slow mean vertical circulation lofts air over the tropics from the troposphere into the stratosphere and sink into the pole,

> A faster horizontal circulation, due do breaking wave, stir air masses across the stratospheric barriers.



Southern Hemisphere Barriers Interannual variability

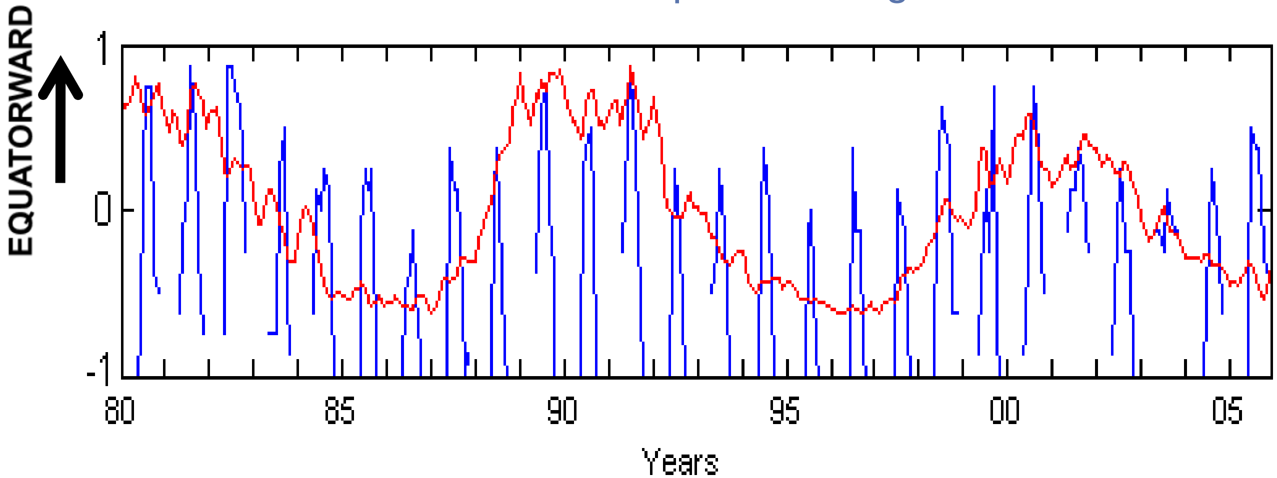
Positive anomalies reinforced by an easterly QBO phase



Subtropical barrier intensity anomalies @ 600K

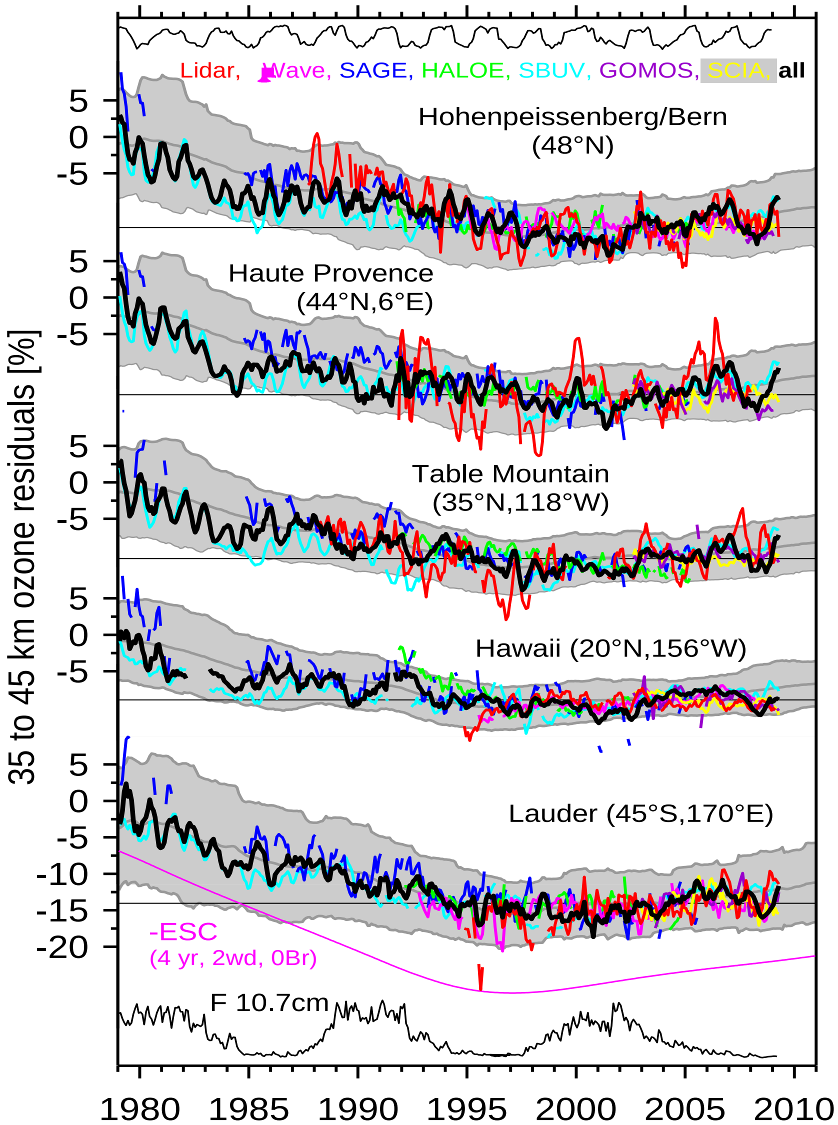
QBO @ 30 hPa

Polar vortex closer to the equator during solar maximum.



Polar Vortex position @ 600K

11 year Solar Cycle



Latest Studies (1)

- Stratospheric ozone (35-45 km changes) at five NDACC stations.
- Long-term record from lidar observations fills gaps between several satellite missions.
- Long-term measurements are critical to monitor the progress of ozone recovery .

(No apparent start of ozone recovery).

Updated from *Steinbrecht et al., 2009.*

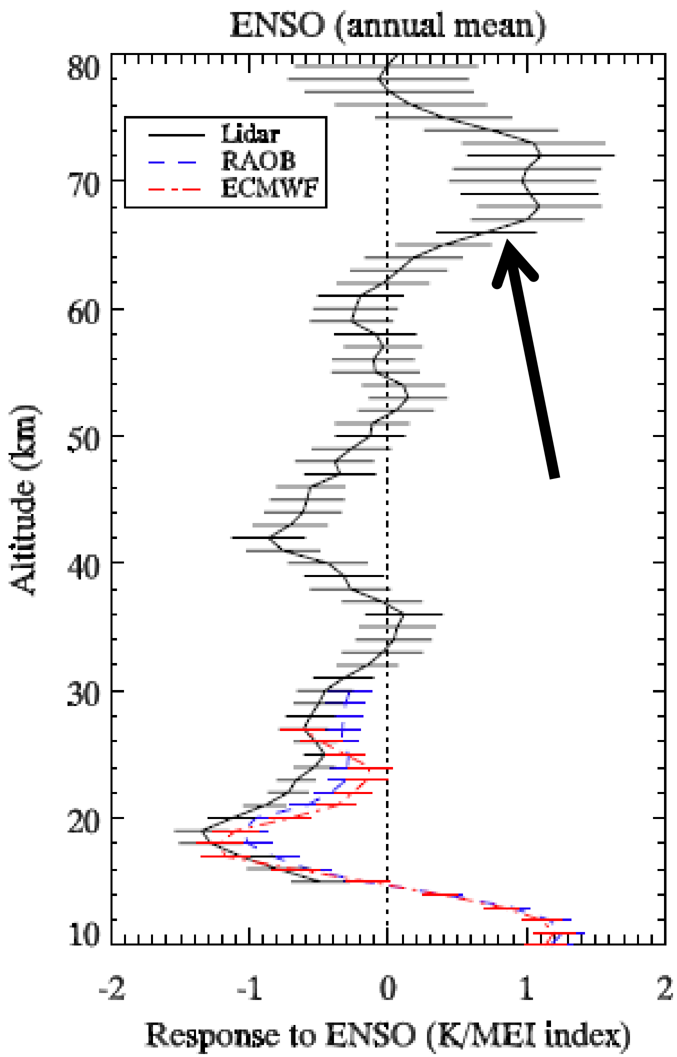
International Journal of Remote Sensing

Latest Studies (2)

- Annual mean response to ENSO derived from regression analysis applied to
  MLO lidar temperature response (black solid curve),
  Radiosonde (blue dashed),
  ECMWF (red dashed)

- Statistically significant signature of ENSO in the mesosphere, consistent with the findings of recent model simulations.

from *Li et al., 2008, JGR.*



Outline

Ozone measurement
- > Data available,
- > Climatologies over MLO and TMF,
- > Ozone time series.

Model presentation
- > Characteristics,
- > Noise sensitivity,
- > Explanatory variable description and selection.

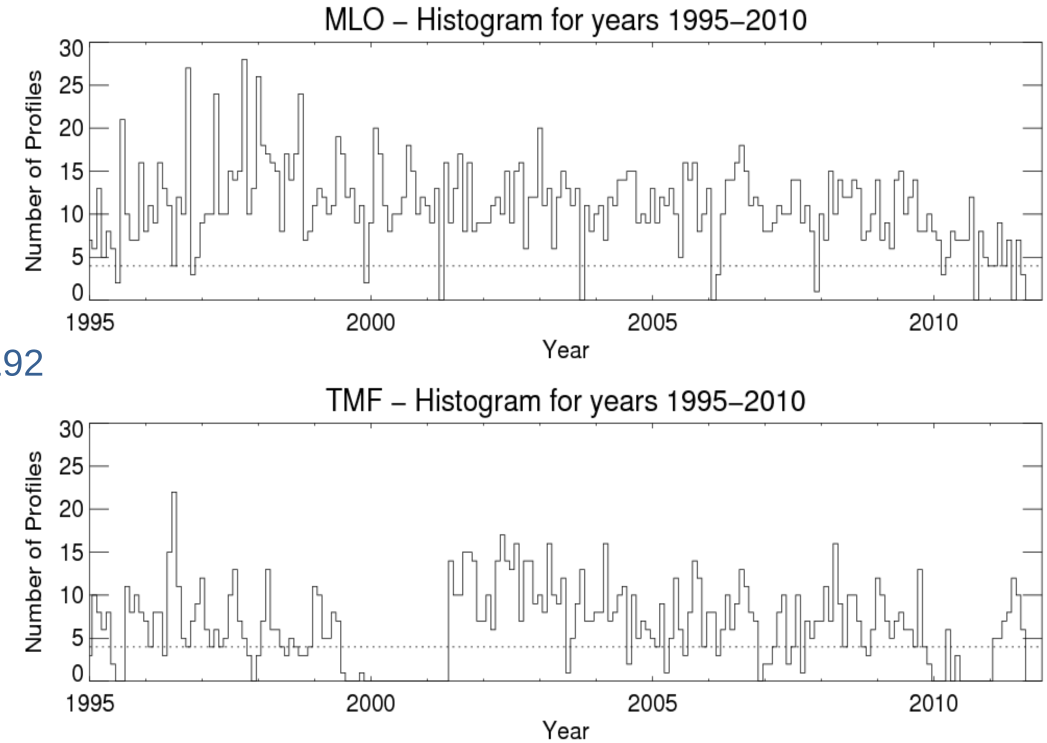
Results
- > The Quasi-Biennial Oscillation,
- > The El Nino Southern Oscillation,
- > The 11-year solar cycle,
- > Horizontal and vertical transport,
- > The mid-latitude Ozone Depleting Gas Index.

***Stratospheric Ozone Profiles** (monthly mean from 1995 to 2011)*

MLO

Profiles :
- max : 28/mth
- med : 11/mth
- less than 4 : 10/192

Points per altitude:
- 185 to 192



TMF

Profiles :
- max : 23/mth
- med : 6/mth
- less than 4 : 57/192

Points per altitude:
- 161 to 167

Month with number of profiles lower than 4 have been interpolated if at least two sides measurements could be used

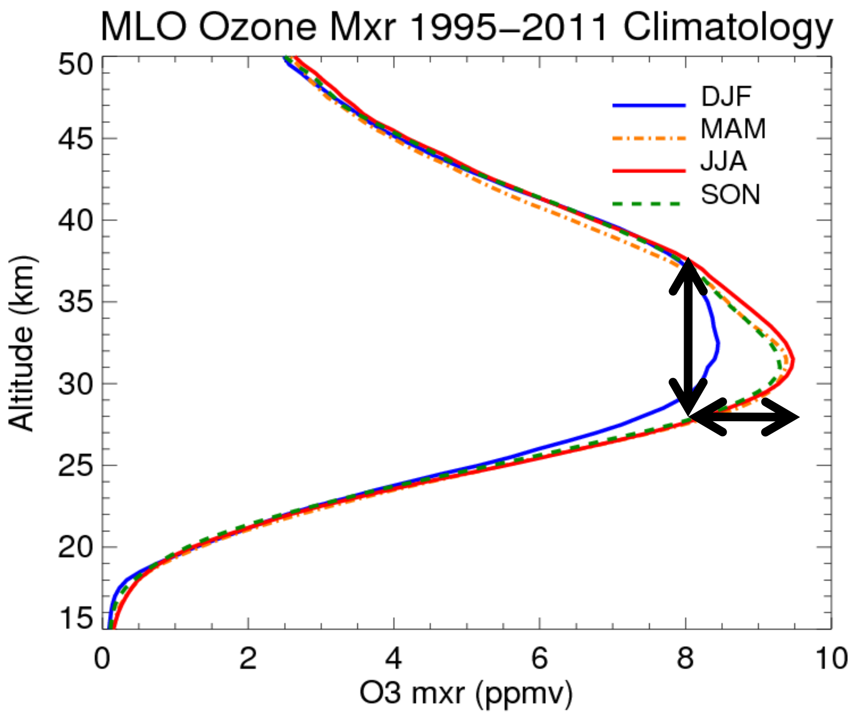
Ozone mixing ratio climatologies

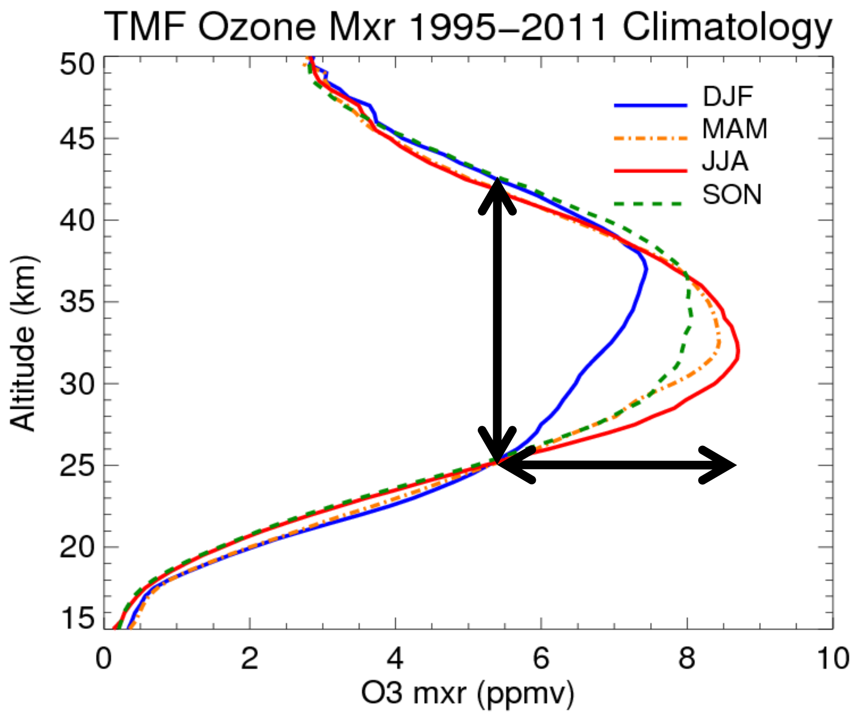
MLO
SubTropical site

- Higher ozone values on a small range,
- Small amplitude of the seasonal cycle.

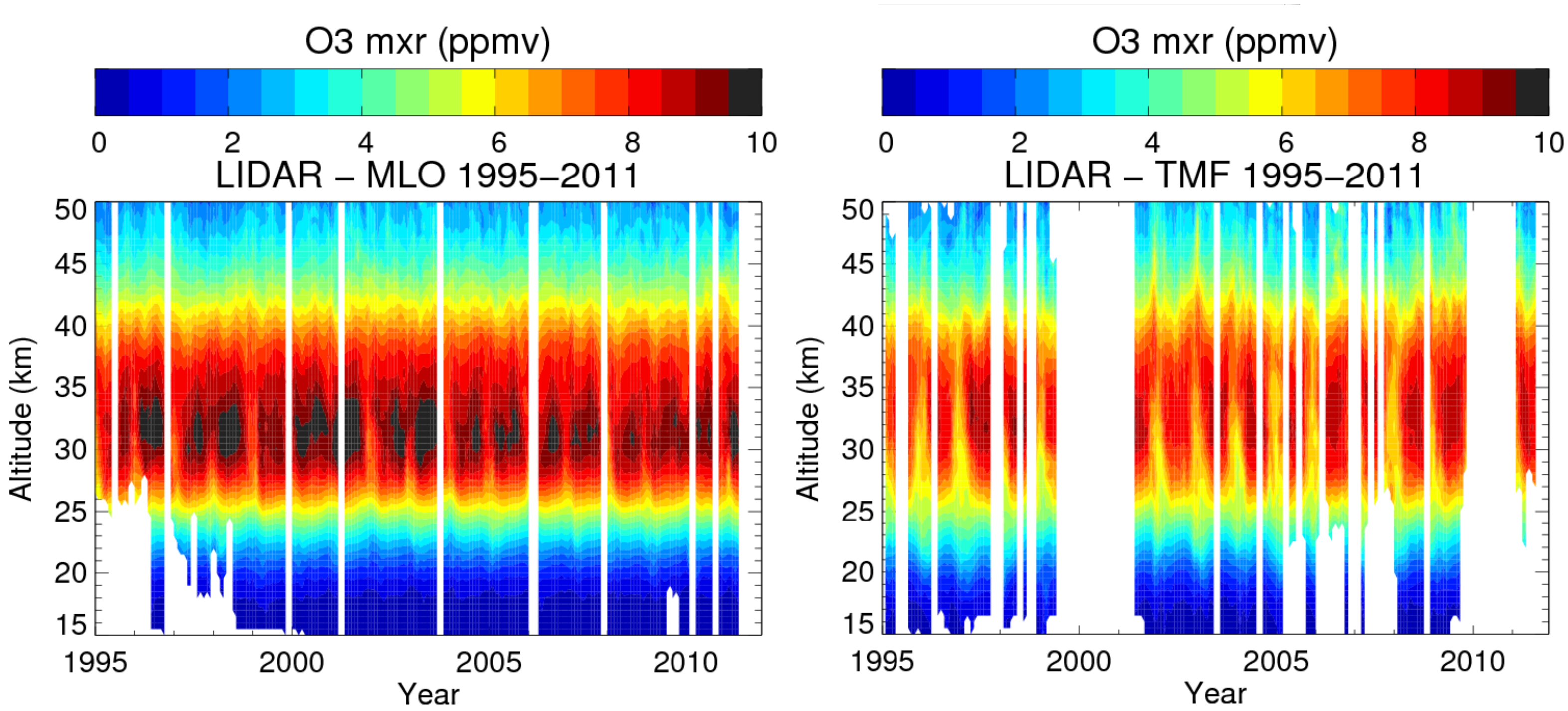
TMF
Midlatitude site

- Smaller ozone values on a higher range,
- High amplitude of the seasonal cycle.



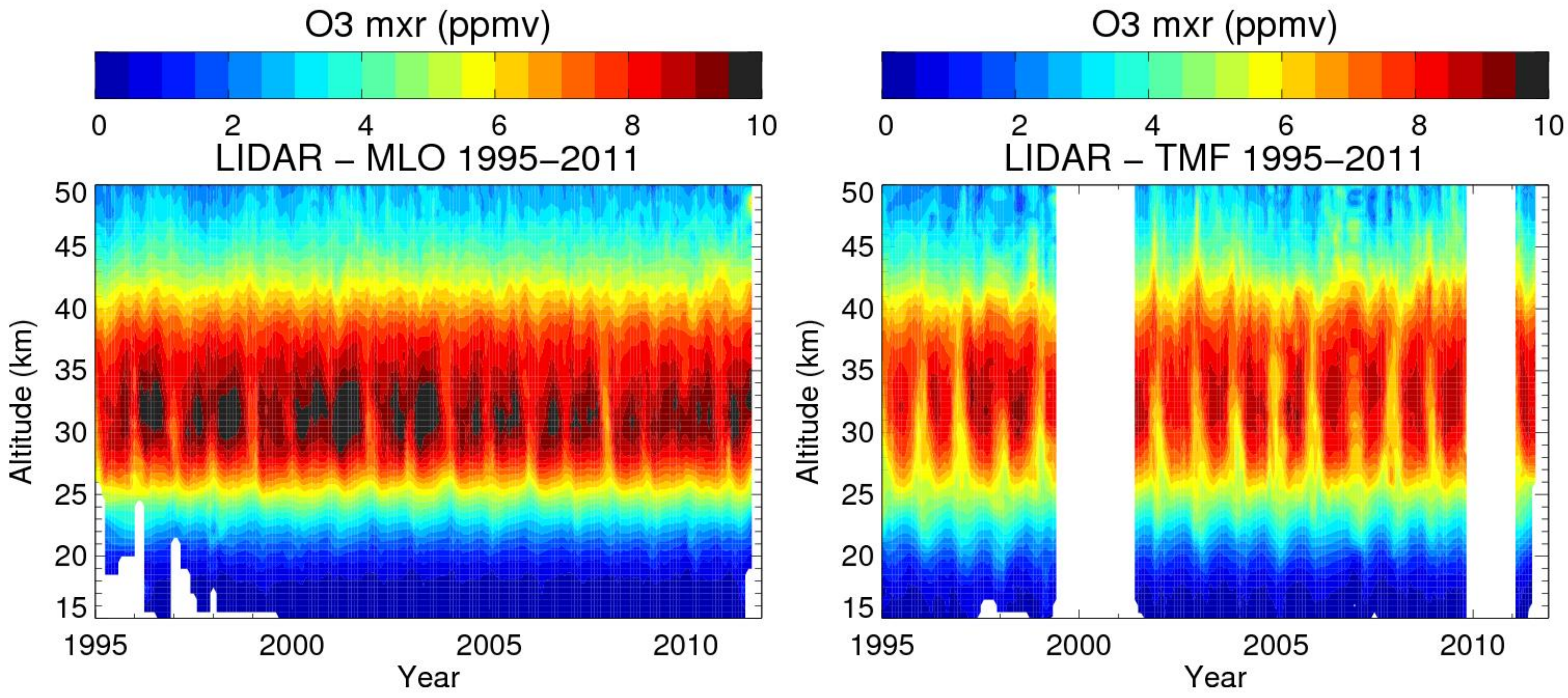


Stratospheric Ozone Profiles *(monthly mean from 1995 to 2011)*



RAW TIME SERIES

Stratospheric Ozone Profiles *(monthly mean from 1995 to 2011)*



INTERPOLATED TIME SERIES

Long-term measurements critical to monitor the progress of ozone recovery

- **Ozone mixing ratio anomalies from collocated profiles**

(5 latitude, 25 longitude, 12h)

Stratospheric Aerosol and Gas Experiment II (SAGE II),

Halogen Occultation Experiment (HALOE),

Microwave Limb Sounder (MLS) on Aura

- **Bias and drift *(Nair et al., 2011, ACP)***

Best agreement with lidar at 20-40 km

Differences are within 5% ; Drift less than 0.5%/yr^{-1}

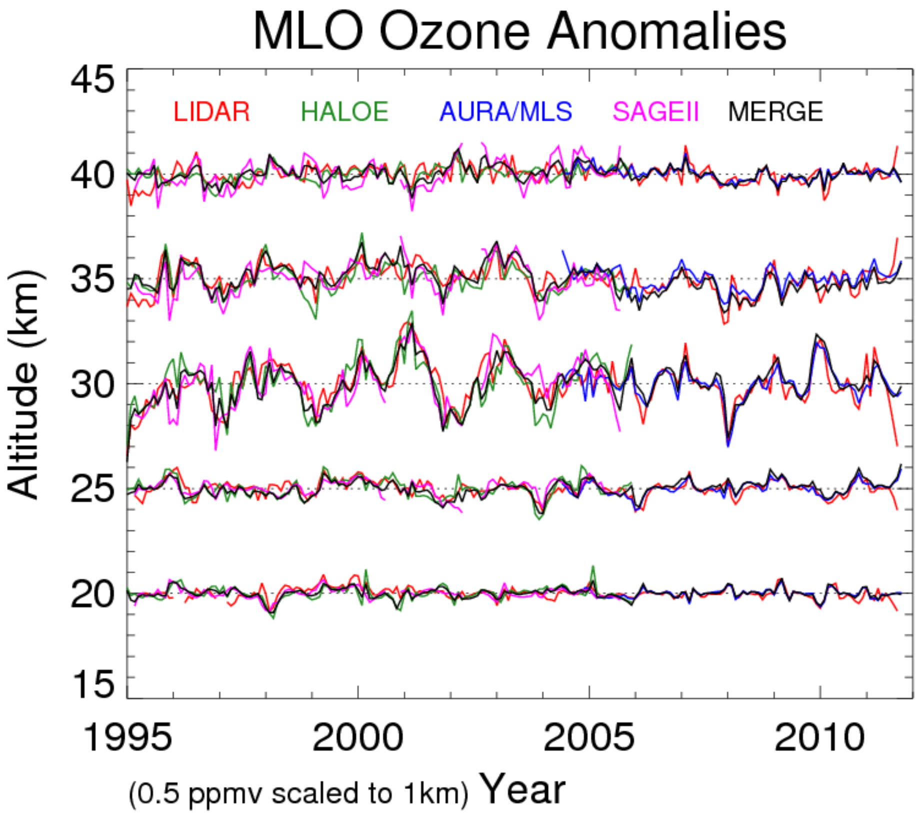
- **Merging**

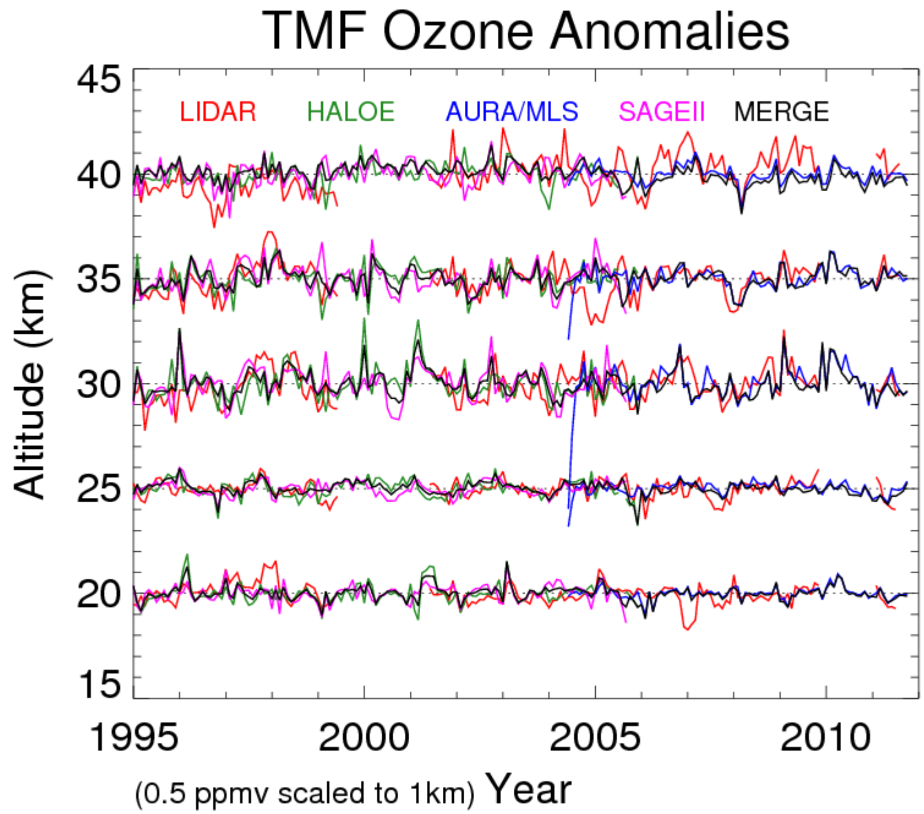
From 1995 to 2005 : Mean between HALOE and SAGE II measurements,

2005 : Difference between HALOE/SAGE II values and AURA/MLS values,

From 2006 to 2011 : Corrected AURA/MLS measurements.

Long-term measurements critical to monitor the progress of ozone recovery





Model Description

- Multi-linear regression analysis was performed on the deseasonalized monthly mean ozone time series (anomalies) by a zonally asymetric model,

$$\delta O_3(z,t) = \sum_i \alpha_i(z,t) PROXY_i(t) + residual(z,t)$$

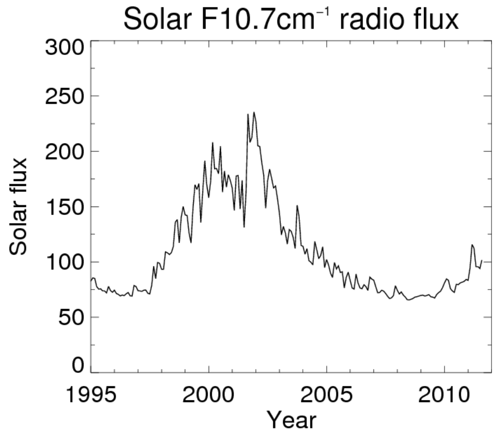
Where $\alpha_i(z,t)$ represents the 12-month seasonal fit with the form $A_0 + \sum_{i=1}^{9} (\cos i\omega t + \sin i\omega t)$

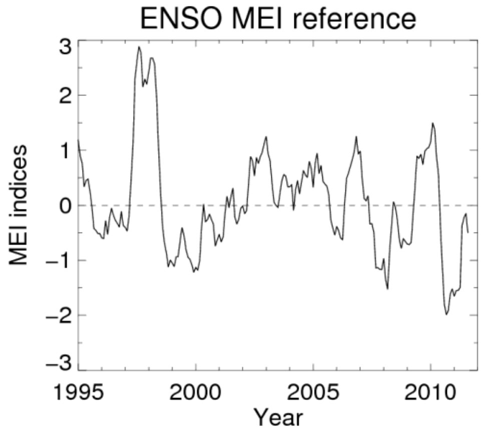
- We have selected interannual and annual components (proxies):
  - > the 11-year solar cycle (flux at 10.7 cm^{-1} wavelength measured in Penticton/Ottawa),
  - > El Nino Southern Oscillation (MEI index computed by NOAA),
  - > the Quasi-Biennal Oscillation (Singapore zonal wind),
  - > the Eliassen-Palm flux *,
  - > Horizontal and Vertical transport**,
  - > the Ozone Depleting Gas Index (computed by NOAA) compare to the classical linear trend.

→ Each proxy has been calculated using day collocated measurements,
→ * calculated from ECMWF operational analyses,
→ ** calculated from ECMWF operational analyses and CATO Vertical profiles of ozone mxr in potential temperature coordinates for 30 equivalent latitudes.

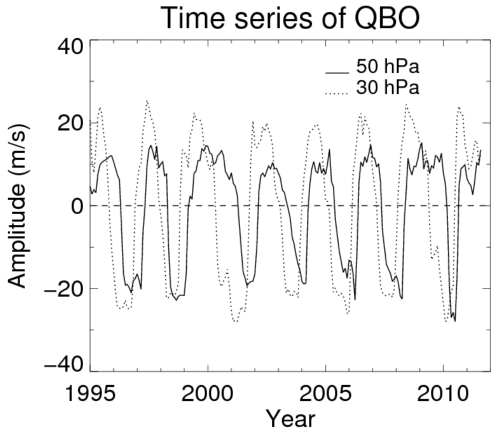
Common Proxies

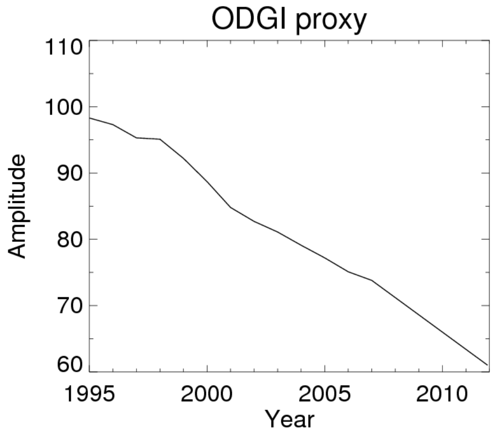
Solar flux data at 10.7 cm measured in Penticton/Ottawa, and MEI index for ENSO





QBO (Zonal wind at Singapore @ 50hPa and 30hPa) and Ozone Depleting Gas Index



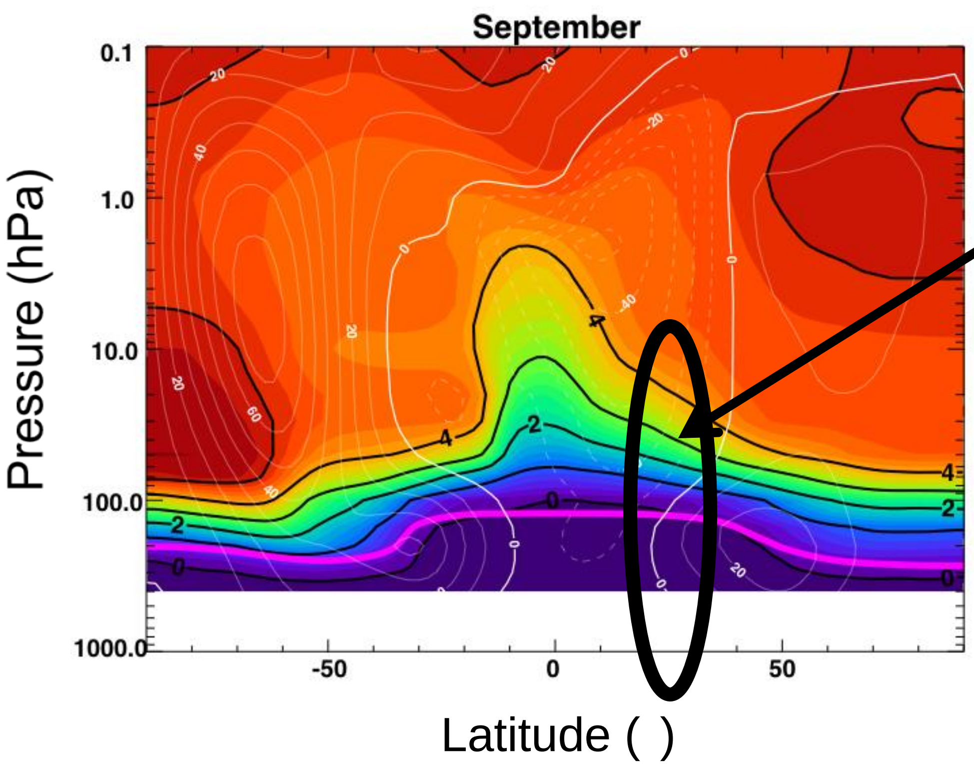


How to seek for a response to the Montreal Protocol (WMO, 2011)

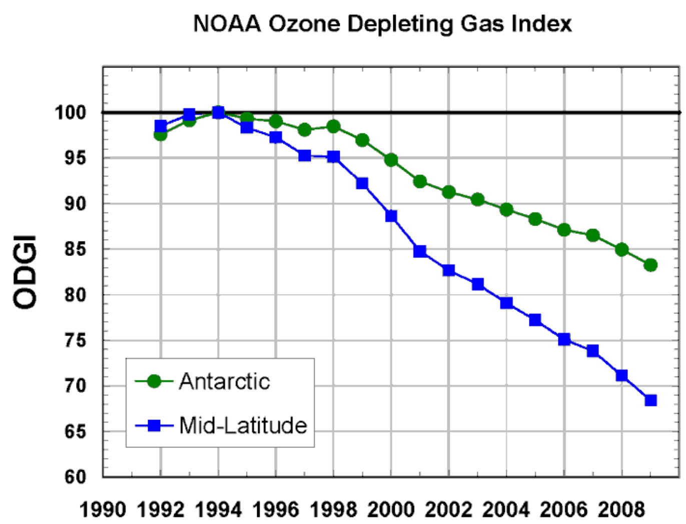
- The Ozone Depleting Gas Index (ODGI)

  > Estimated from observations of the most abundant long-lived, chlorine and bromine containing gases regulated by the Montreal Protocol (15 individual chemicals).

  > Lag the time with respect to transport into the stratosphere (Newman et al., 2006, GRL).



Age of Air in years
Calculation done with a lag time of 3 years with a width of 1.5 years



The Brewer-Dobson Circulation

Eliassen-Palm Flux (Epf)

Vertical component of the EPf vector

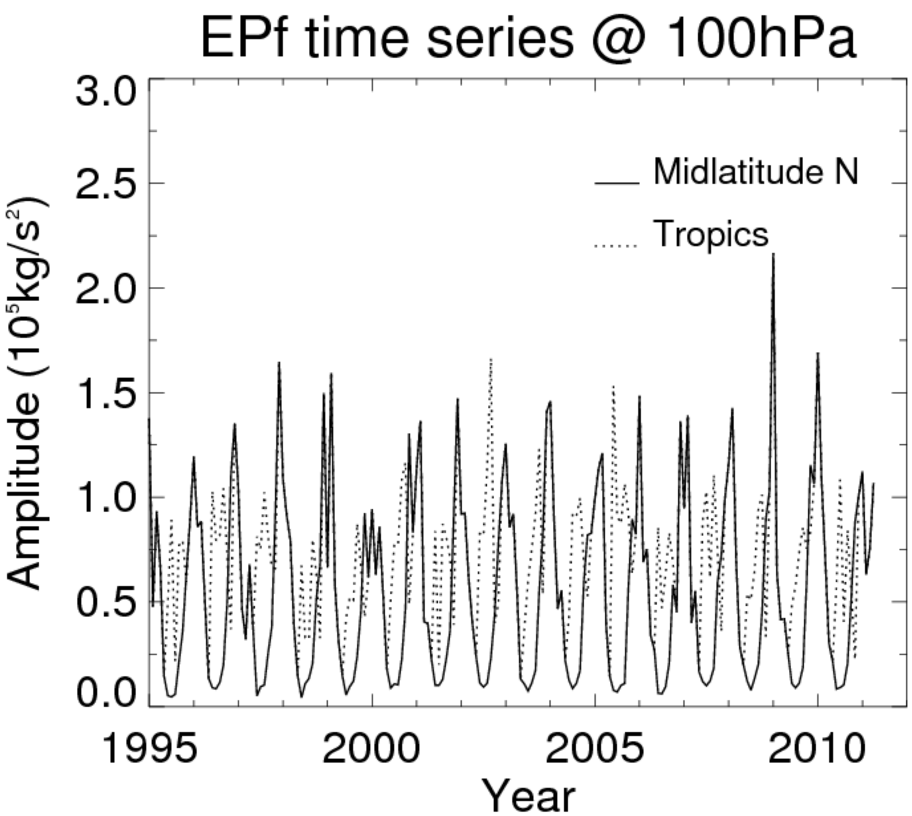
at 100 hPa

MLO = Proxy for tropics (latitudes lower than 30 degrees)

from May to October averaged spatially over 45 –75 S, otherwise averaged spatially over 45 –75 N.

TMF = Proxy for the northern hemisphere

Averaged spatially over 45 –75 N



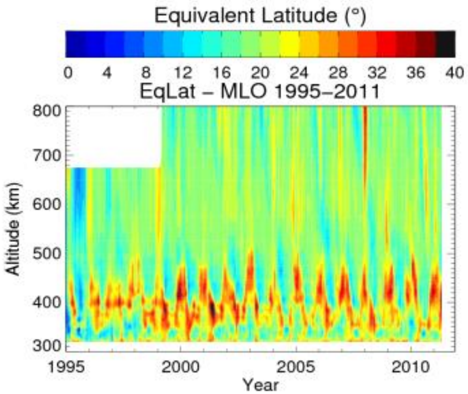
Horizontal and Vertical transport (Wohltmann et al., 2005, GRL)

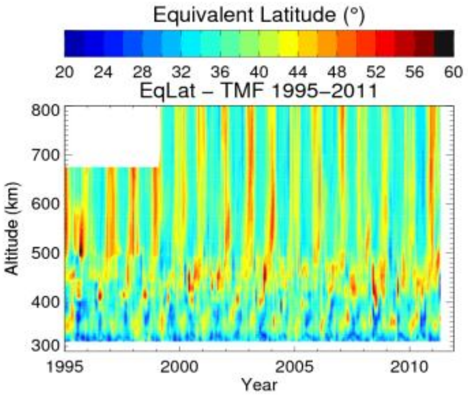
Equivalent latitude profile

Ozone mxr profile (mxr_i)

CATO climatology

Integrated using the pressure difference between two isentropic levels (Δ_i)

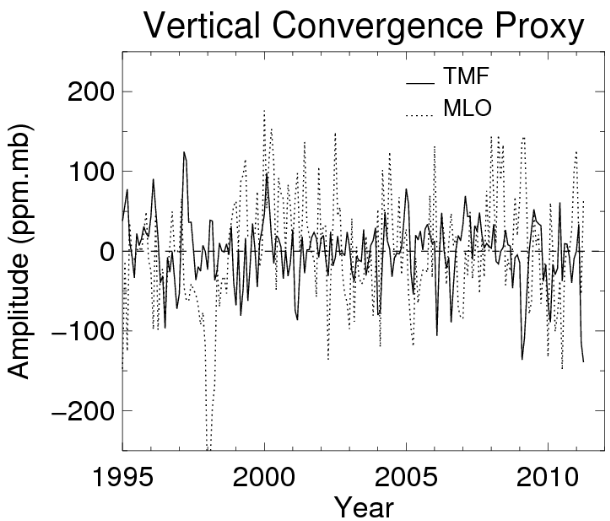


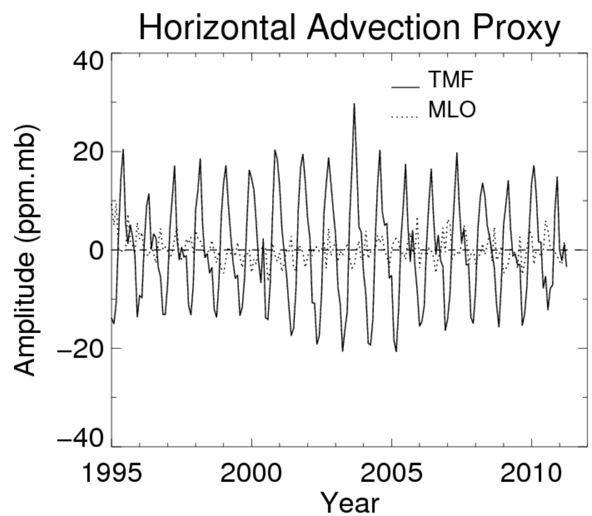


$$\sum_i mxr_i \Delta_i$$

$$= \sum_i (mxr_{0i} + \delta mxr_i)(\Delta_{0i} + \delta\Delta_i)$$

$$= \sum_i mxr_{0i}\Delta_{0i} + \sum_i mxr_{0i}\delta\Delta_i + \sum_i \delta mxr_i \Delta_{0i} + \sum_i \delta mxr_i\, \delta\Delta_i$$





Proxies selection

For each station, proxies were chosen by a backward elimination method:

1 - Determined the complete regression equation containing all the variables.

2 - Variables are checked one at a time and the least significant is dropped from the model at each stage.

Significance is tested with improvement (+5%) of adjusted coefficient of determination R^2

$$R^2 = 1 - \frac{residual\ sum\ of\ squares}{total\ sum\ of\ squares} \longrightarrow \bar{R}^2 = 1 - \frac{n-1}{n-p-1}(1-R^2)$$

3 – The procedure is terminated when all of the variables remaining in the equation provide a significant contribution to the prediction of the dependent variable.

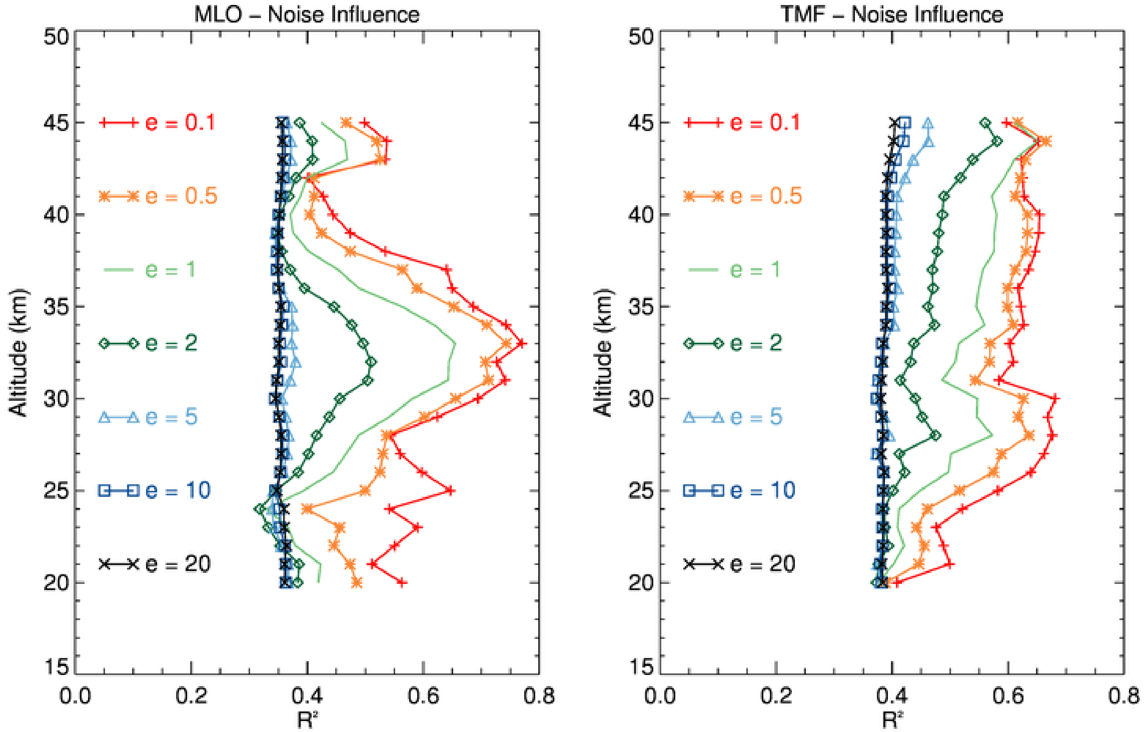
R^2_p (%)	Linear	Solar	ENSO	QBO	ODGI	Epf	INTEQL-H	INTEQL-V
MLO	1	9	9	38	10	4	6	10
TMF	3	7	8	27	18	11	12	9

Model Sensitivity

Kerzenmacher et al., 2006

- Suppress the dataset for the 1-2 years following a volcanic eruption be because of the aerosol load in the atmosphere,

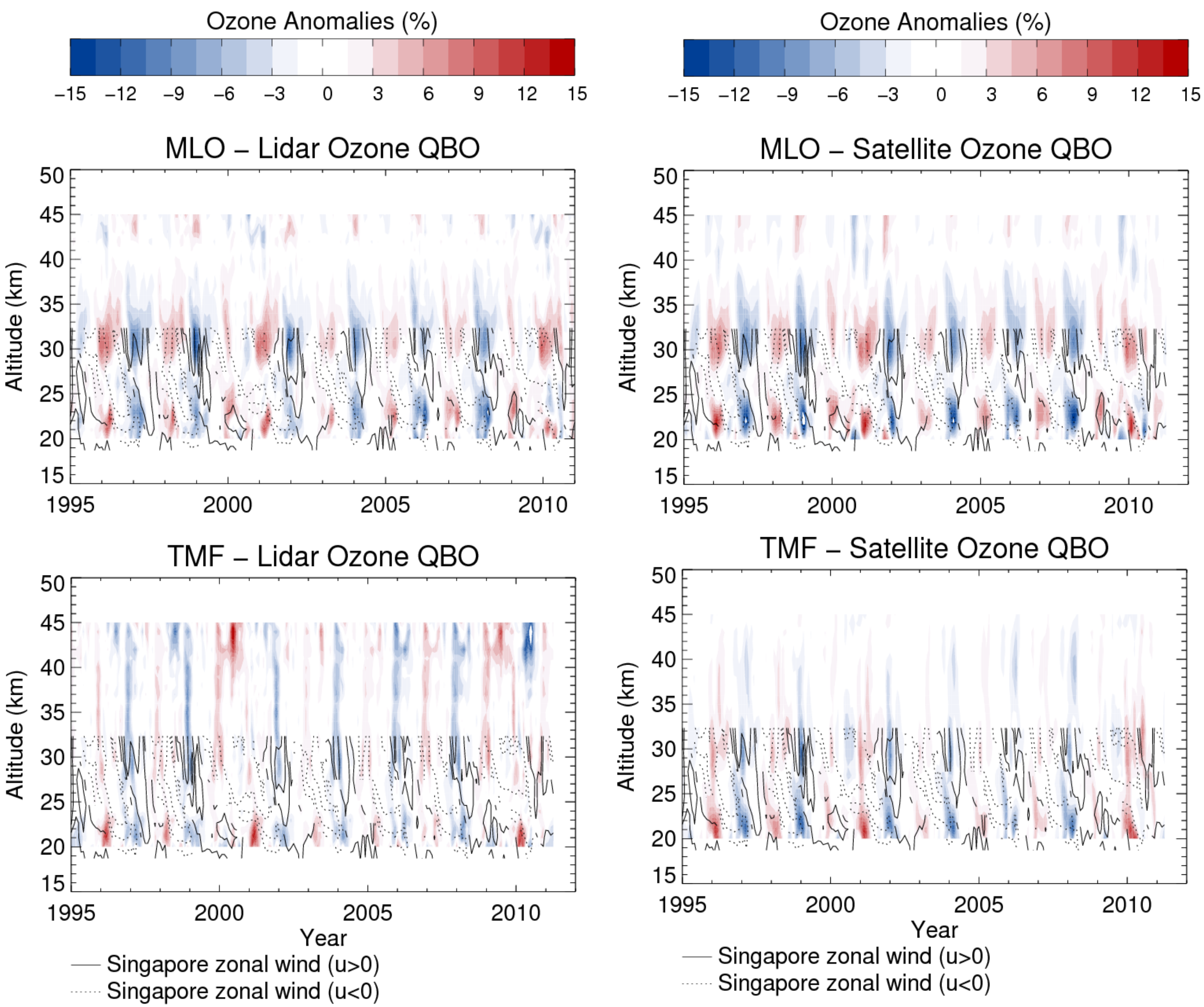
- Importance of using a regression model based on several functions, rather than a basic slope for quantification of trends for data series of limited length.



Most representative proxies (R^2_p>10%)

MLO	R^2 (%)	TMF	R^2 (%)	
Upper Stratosphere (37 to 45 km)				
SC; QBO; ENSO; INTEQL-V	49	SC; QBO; ODGI	62	Lidar
SC; QBO; ENSO; INTEQL-V; ODGI	63	QBO; ODGI; INTEQL-H	50	Satellite
O3 Maximum (29 to 36 km)				
SC; QBO; INTEQL-H	70	ENSO; QBO; EPf; INTEQL-H	60	Lidar
QBO	70	ENSO; QBO; INTEQL-V	57	Satellite
Lower Stratosphere (20 to 28 km)				
ENSO; QBO; ODGI; INTEQL-H	58	SC; QBO; ODGI; INTEQL-H	50	Lidar
ENSO; QBO	54	QBO	55	Satellite

The Quasi Biennal Oscillation – Leblanc and McDermid, 2001



MLO

Whole winter signature

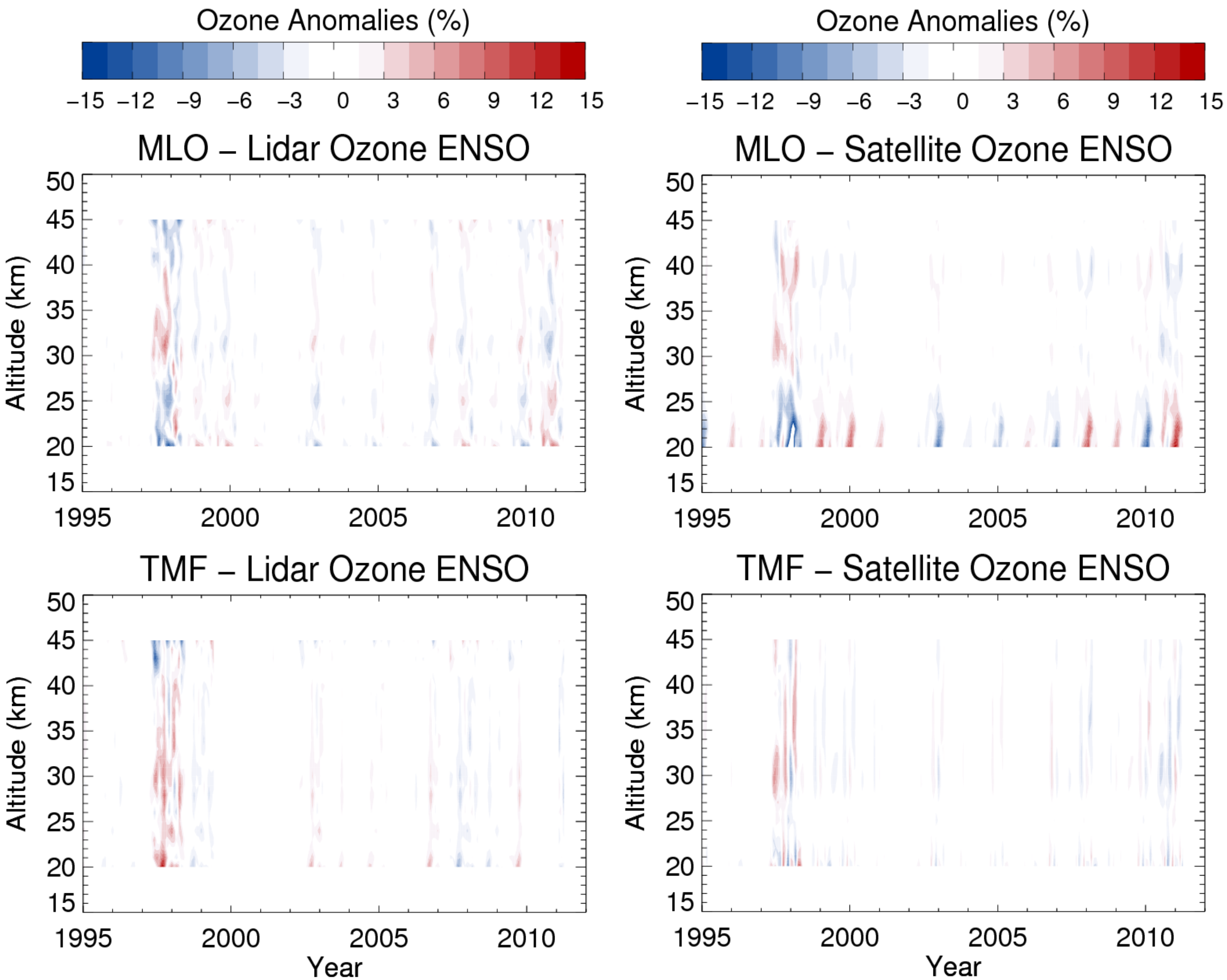
- Max signature at 23, 32 and 42 km,
- Signs of downward propagation from 38 to 28 km across the winter.

TMF

Early and late winter signature

- Max signature in the upper and lower stratosphere,
- late winter signature at 42 km

The El Nino Southern Oscillation



MLO

Early winter signature

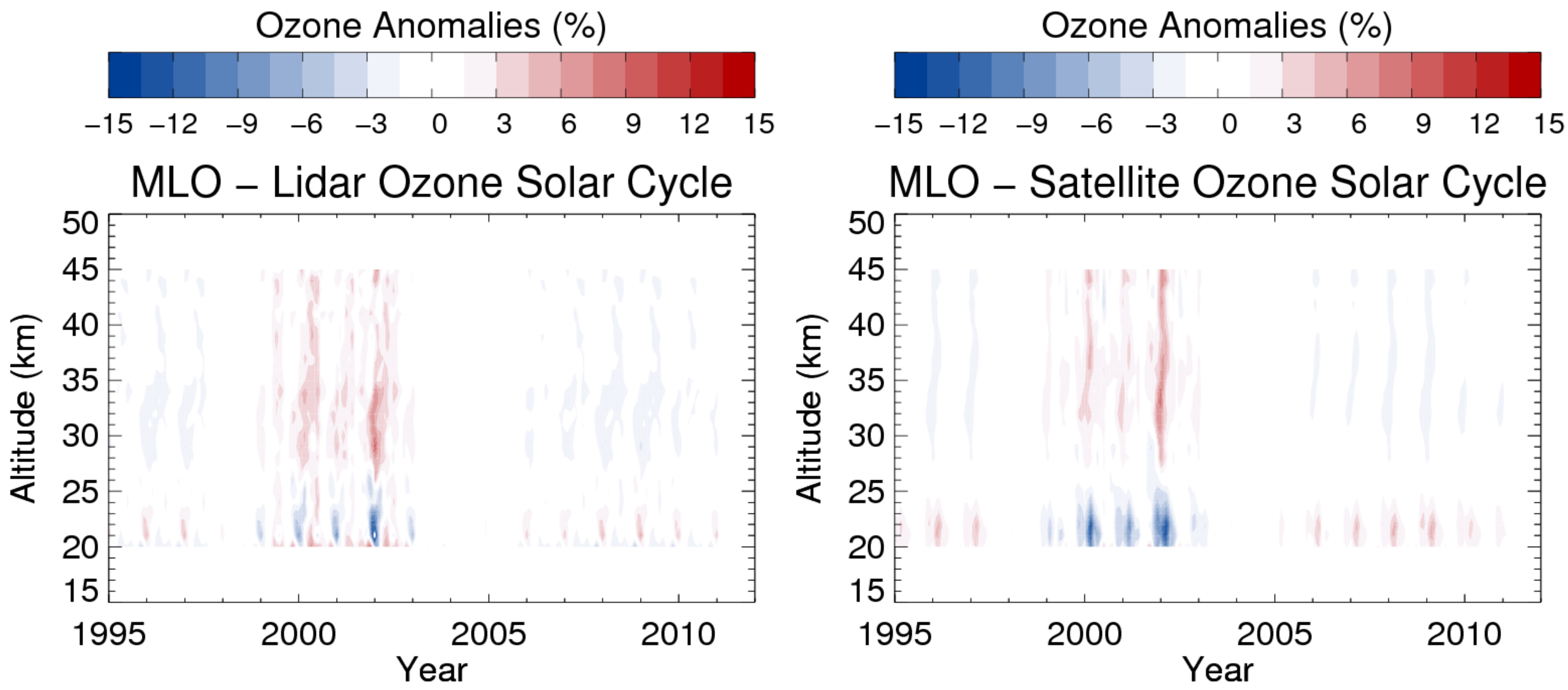
- Max signature below 28 km,
- Strong El Nino (warm event): lower ozone content,
- La Nina (cold event): increase ozone content ,

TMF

Early and late winter signature

- Strong El Nino: increase ozone content,

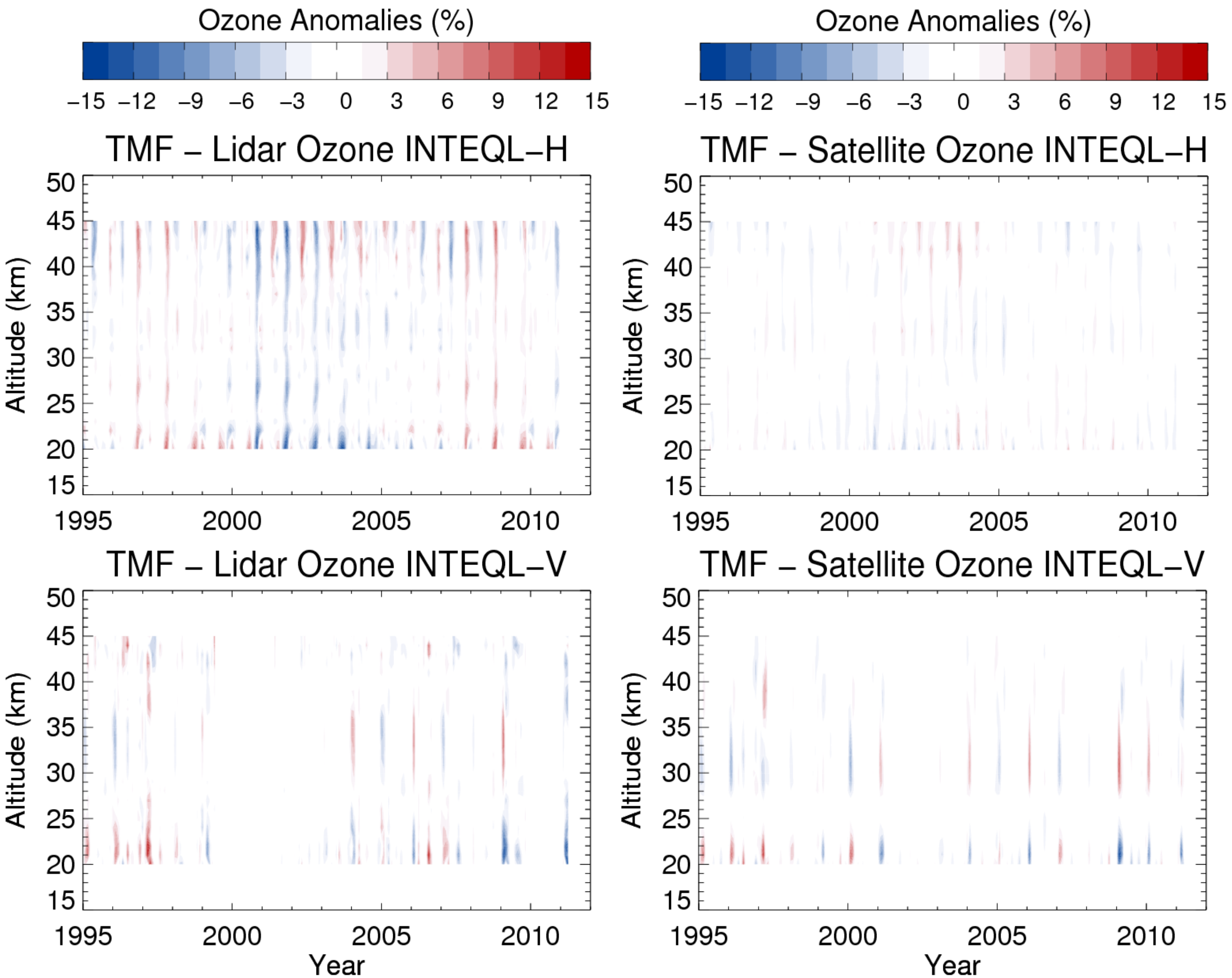
The 11-year solar cycle



Mid-winter signature

- Max signature below 25 km and 35 km,
- In phase with ozone increase during solar maxima,
- Strong out of phase mid-winter signature at 23 km

Horizontal and Vertical Transport



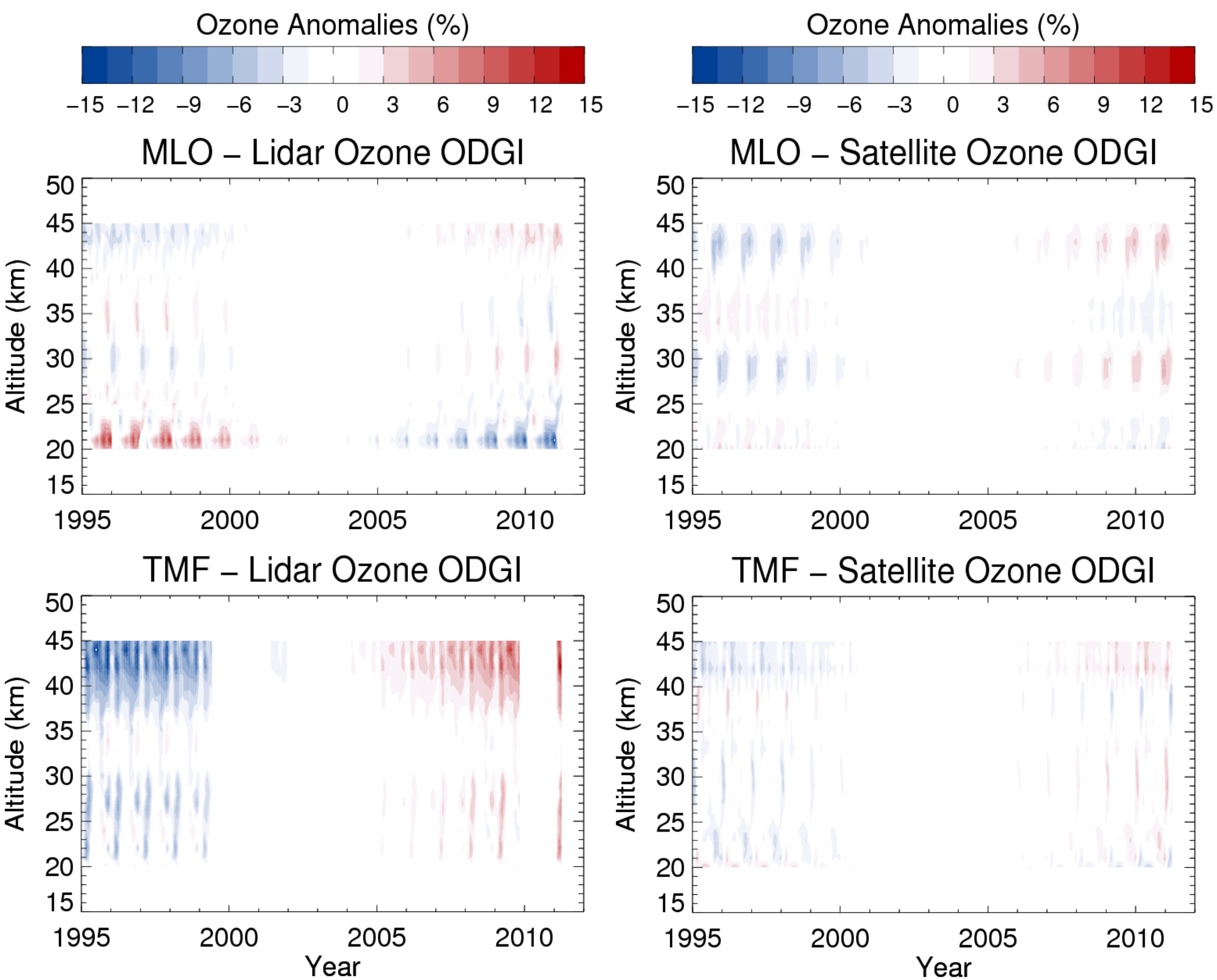
Early and late winter signature

- Maximum (in phase) early winter signature above 35 km and below 25 km.
- Maximum (out of phase) late winter signature above 40 km.

Late winter signature

- Two out of phase signature at 23 and 33 km.
- Since 2004 mostly negative (resp. positive) response at 23 km (resp. 33 km)

ODGI



MLO

Winter signature

- Negative signature after 2005 below 28 km.
- Positive signature after 2005 at 28 and 42 km.

TMF

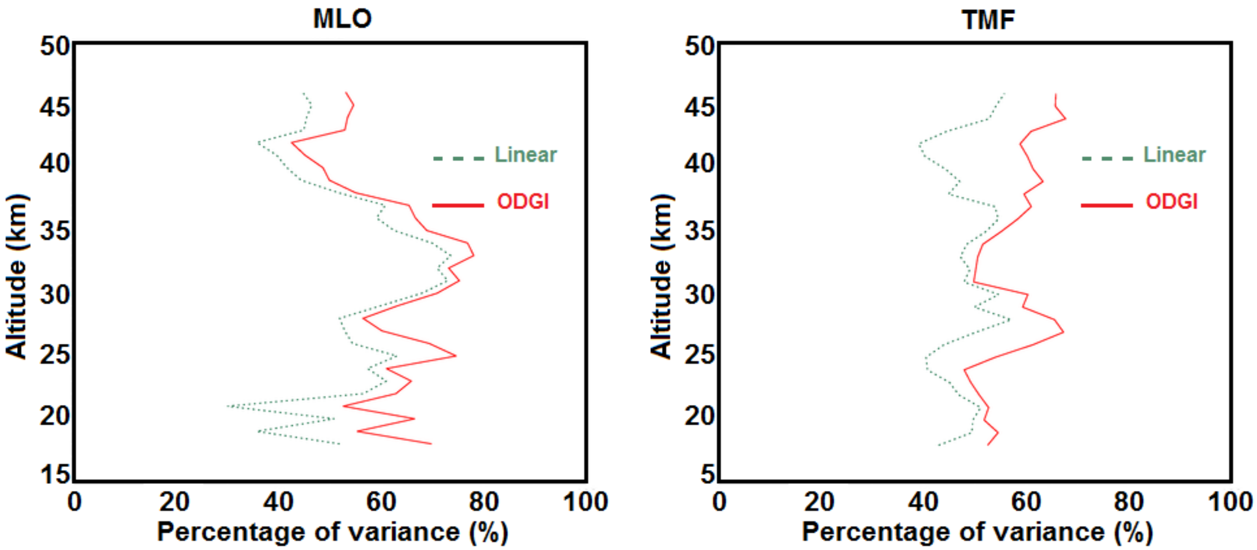
Winter signature

- Strong positive signature starting in 2004 (negative before) above 35 km,

ODGI and linear trend

- Using the ODGI increases the value of the model total explained variance:

Mean difference between R^2 profiles is ~8% for MLO and ~9% for TMF.



- ODGI response match well with models predictions:

Slow down of ozone decline until 2000,

Followed by the expected onset of the ozone recovery in 2004-2006

→ Confirm the Brewer-Dobson circulation enhancement predicted by models

(Shepherd and McLandress, 2011).

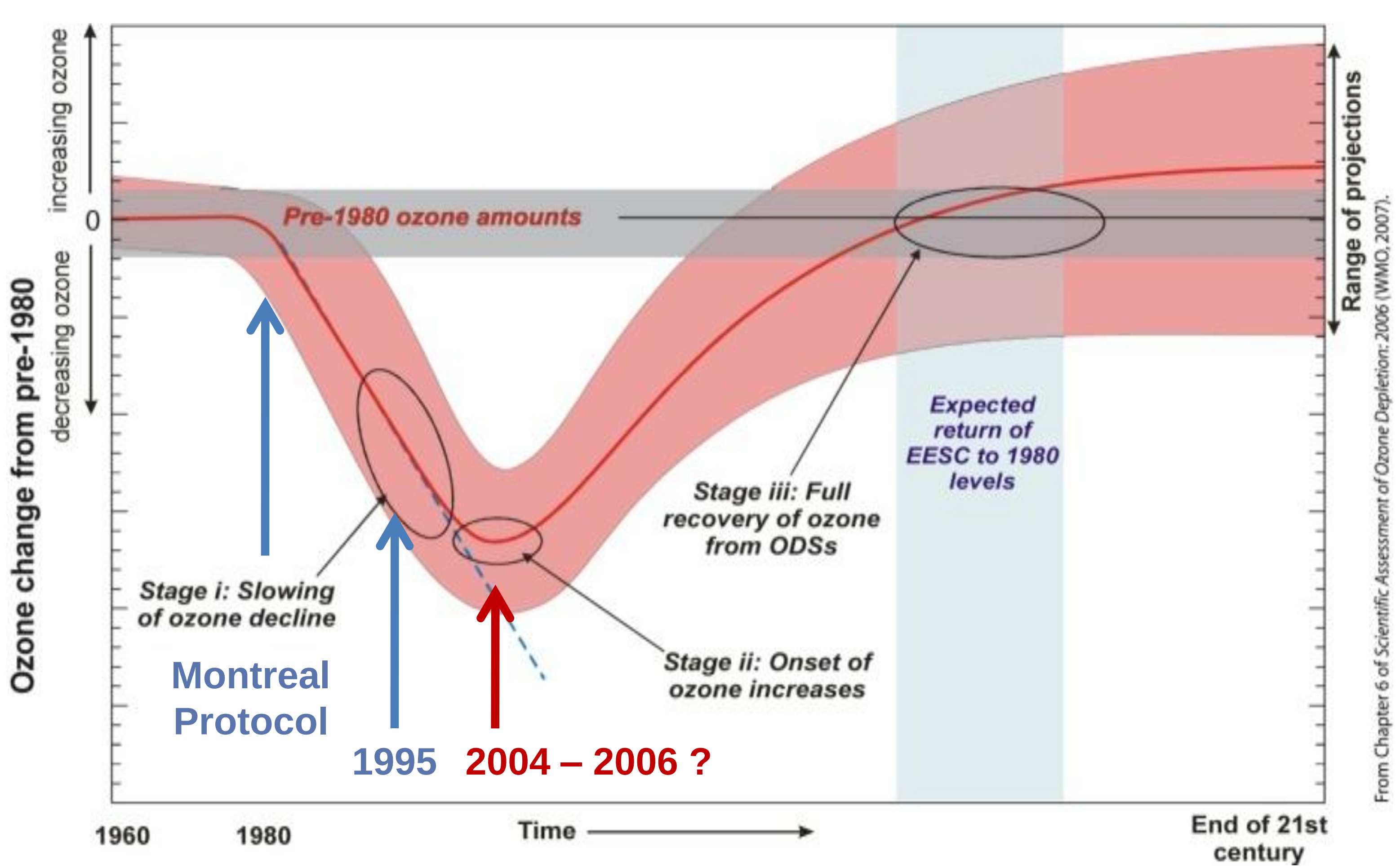
Stratospheric ozone and …

Ozone layer evolution:

> photo-chemical processes(upper and middle stratosphere),

> dynamical processes (lower stratosphere).

Dynamical processes two way interaction with clmate change.



Index correlations

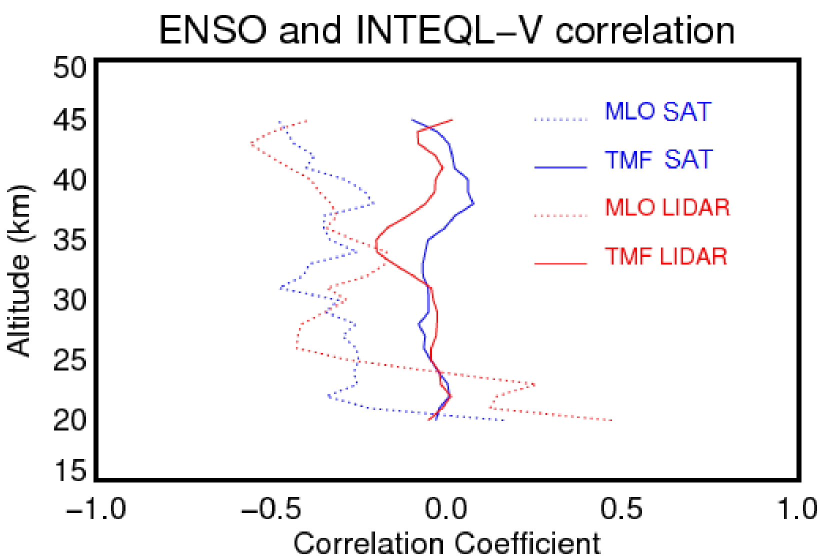
MLO

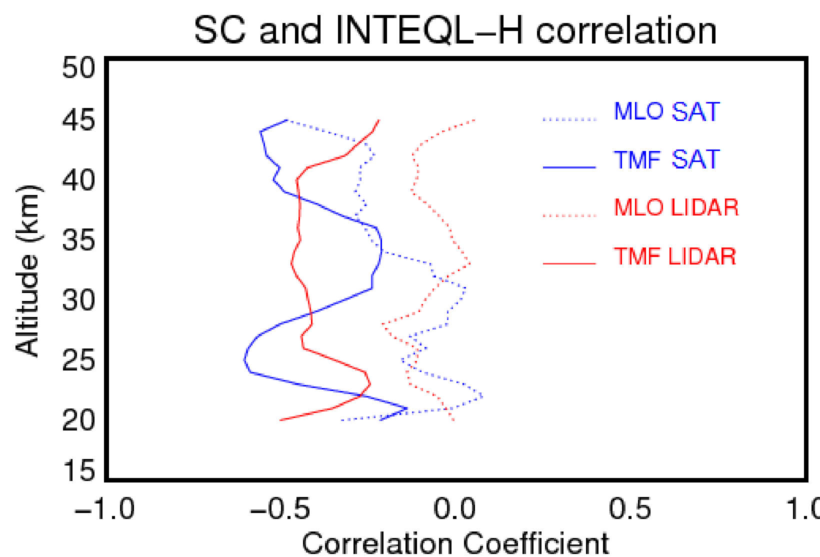
	INTEQL-H	INTEQL-V
SC	-0.2	0.2
ENSO	0.2	-0.5
QBO1	0.0	0.0
QBO2	0.1	0.1
ODGI	0.1	-0.2
Epf	0.0	-0.1
INTEQL-H	1.0	-0.5
INTEQL-V	-0.5	1.0

TMF

	INTEQL-H	INTEQL-V
SC	0.1	0.0
ENSO	0.0	0.1
QBO1	0.0	0.0
QBO2	0.0	0.0
ODGI	0.0	0.1
Epf	0.0	-0.1
INTEQL-H	1.0	0.0
INTEQL-V	0.0	1.0

Response correlations





Conclusion

- 16 years of ozone data measured by lidar and satellite distinct interannual signatures were successfully identified in the stratosphere above two NDACC stations, Mauna Loa, HI and Table Mountain, CA.

- Even if the QBO is the most pronounced signature in the stratosphere, the Solar Cycle, ENSO, vertical and horizontal transport were also found to be important contributions to ozone variability and their annual modulation were shown. Anti-correlations between interannual and annual proxies were found.

- Another step in ozone recovery was identified on both datasets with the use of the ODGI.

Prospects

- Extend this study to the other three NDACC stations, including temperature,

- Use of the potential vorticity to have a better characterization of the transport over the sites.

References

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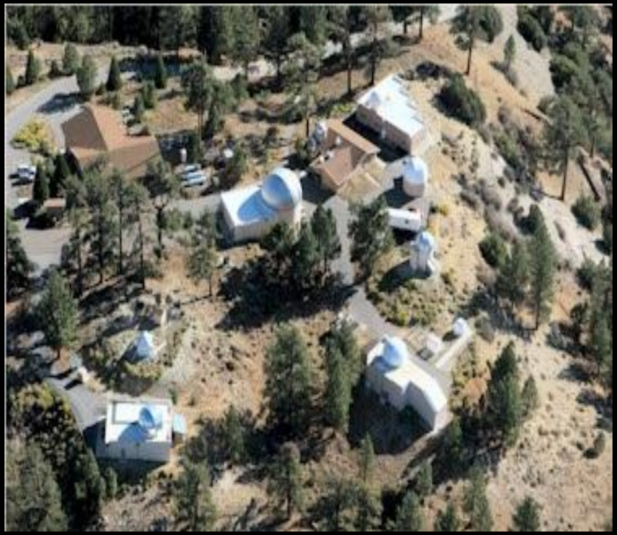

Thank you
for your attention