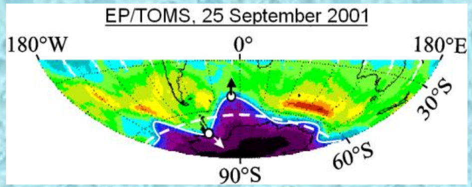
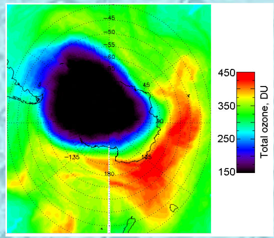
Latest tendency in the Antarctic ozone longitudinal distribution

Gennadi Milinevsky[1], Asen Grytsai[1], Andrew Klekociuk[2], Oleksandr Evtushevsky[1]
[1]Taras Shevchenko National University of Kyiv (genmilinevsky@gmail.com), [2]Australian Antarctic Division



Planetary waves in ozone distribution



Ozone depletion was first observed in Antarctica during spring in the 1980s. The Antarctic ozone hole is formed inside polar stratospheric vortex, which is under influence of large-scale planetary waves.

The quasi-stationary wave (QSW) in the spring Southern Hemisphere (SH) stratosphere is mainly contributed by zonal wave number 1. QSW determines the strong **zonal asymmetry in ozone distribution**. The geographical location of the total ozone extremes in spring is: QSW minimum in the South Atlantic, maximum – in the Australian sector.

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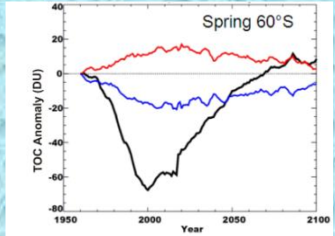
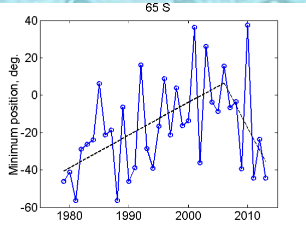
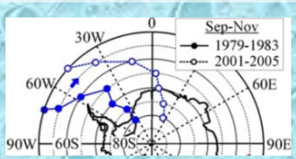


Model study





Ozone zonal asymmetry

Ozone minimum eastward shift

Eastward shift hiatus

SCAR Action Group PACT and Polar FORCeS project 4012 of Australian Antarctic Science Program

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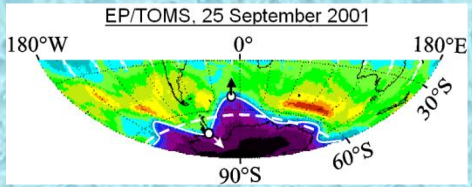
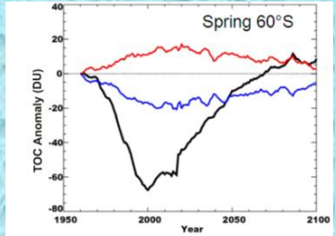


Planetary waves in ozone distribution

Our previous study demonstrated a systematic **eastward shift** of the QSW minimum region (Grytsai et al., 2007).

In this PICO, we extended the analysis to 2013 and obtained new results that exhibited a probable **cessation in** that **eastward shift**. The polynomial fit for all the chosen latitudes is even evidence of a change in the tendency to opposite. Our analysis indicates the change in QSW minimum shift tendency in the early 2000s.



Model study

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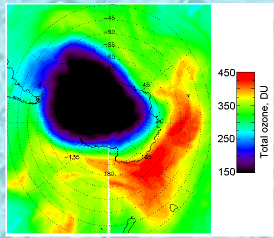

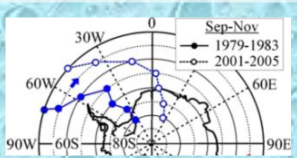

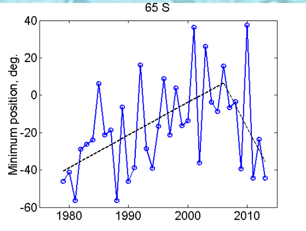

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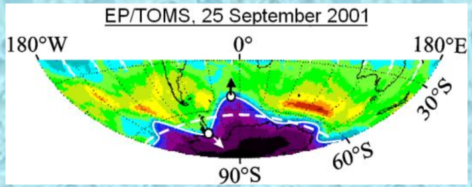
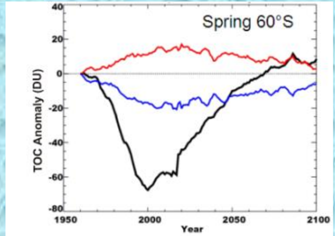


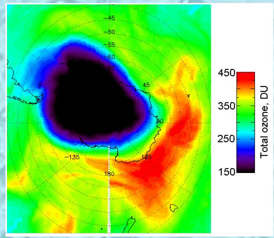
Planetary waves in ozone distribution

The calculated linear trend in the QSW minimum longitude decreased from 14–21 degrees per decade in 1979–2007 (in dependence on latitude) to 6–13 degrees per decade.

The minimum in 2013 is significantly **shifted westward.** The shift at latitudes 50–60S reaches start position of the minimum as in 1979. Longitude of the QSW maximum does not demonstrate any clear tendency.



Model study



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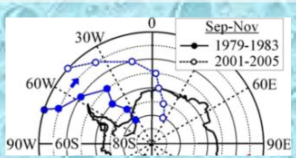

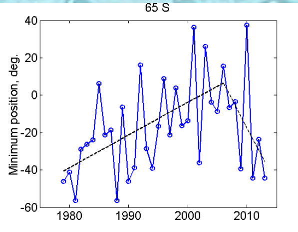

Ozone zonal asymmetry → Ozone minimum eastward shift → Eastward shift hiatus

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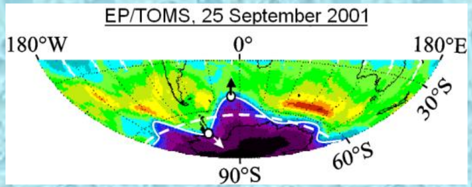
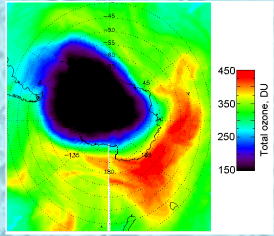


Planetary waves in ozone distribution



Therefore, satellite data for the last years imply that **QSW minimum in the Antarctic ozone distribution has not shifted farther eastward**.

Model studies indicate that ozone recovery over Antarctica may delay or reverse from 20 century tendencies and our results are possible evidence of such changes in the QSW. Our results suggest that the rate of **eastward migration** of the **zonal ozone minimum** over Antarctica has **slowed and/or reversed in direction** during the last decade. This is potentially related to the expected recovery in Antarctic ozone layer.

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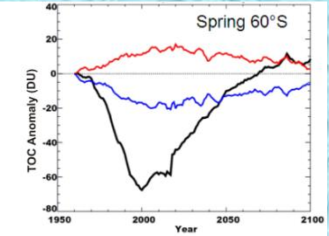
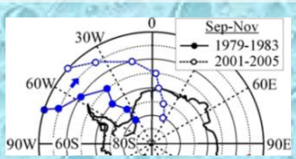
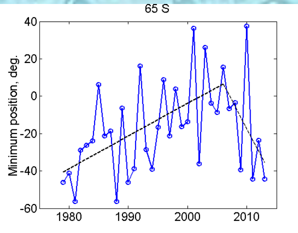


Model study





Ozone zonal asymmetry → Ozone minimum eastward shift → Eastward shift hiatus

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Latest tendency in the Antarctic ozone longitudinal distribution

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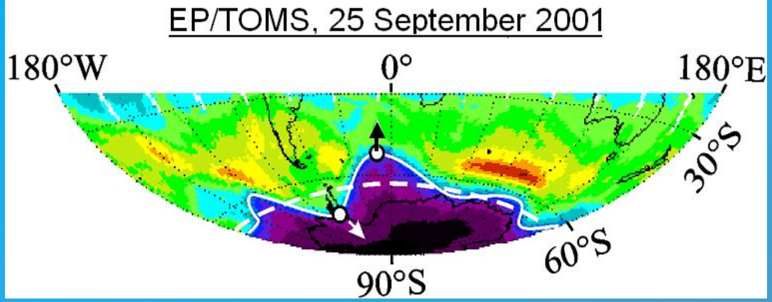
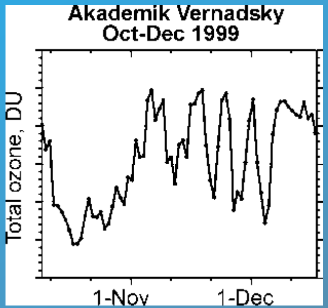
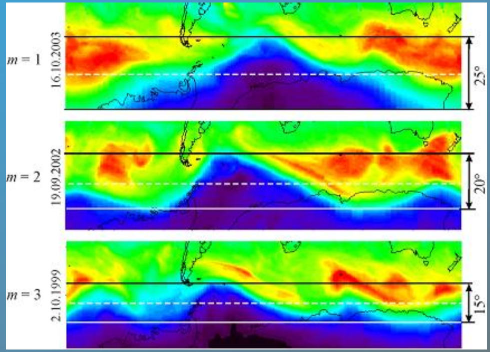
Planetary waves in ozone distribution



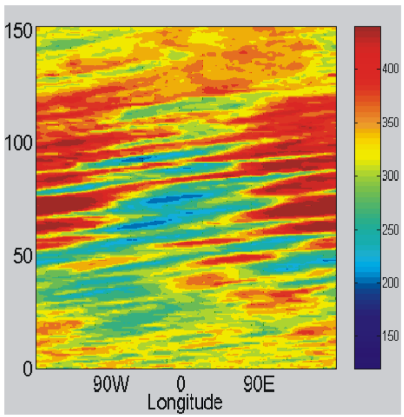
TOC distribution in the Southern Hemisphere, 25.09.2001

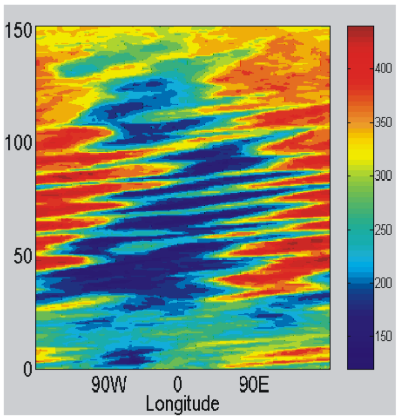


Traveling wave from surface



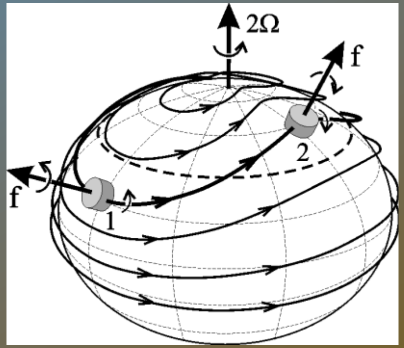
Planetary waves with zonal wave 1, 2, 3





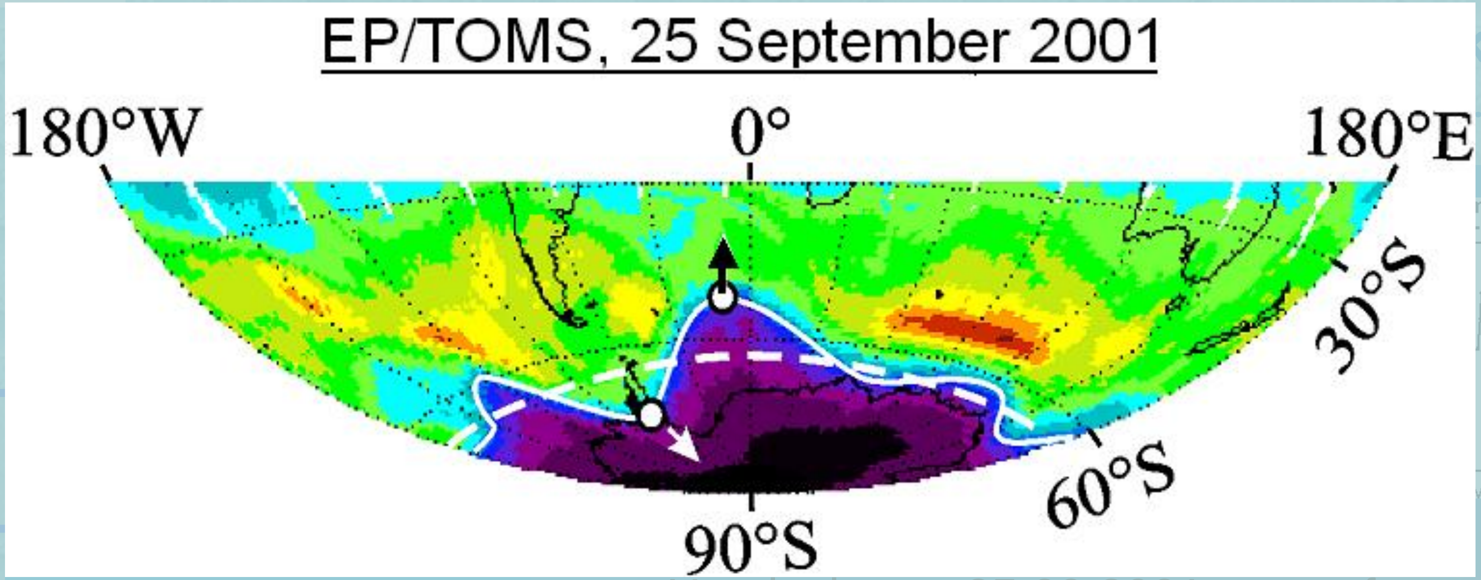
Traveling and QSW planetary waves in ozone layer

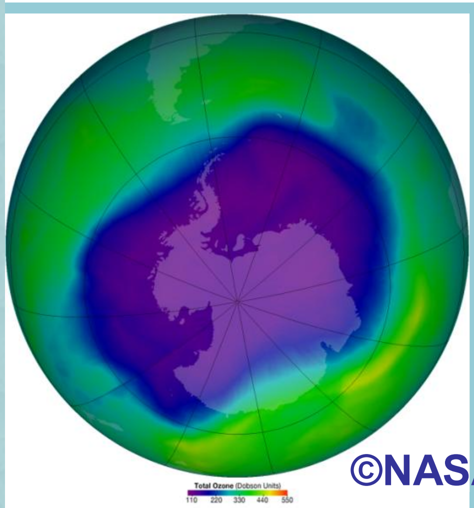
The Antarctic ozone hole is formed inside polar stratospheric vortex, which is under influence of large-scale planetary waves.



Planetary wave generation

Planetary wave generation in the atmosphere





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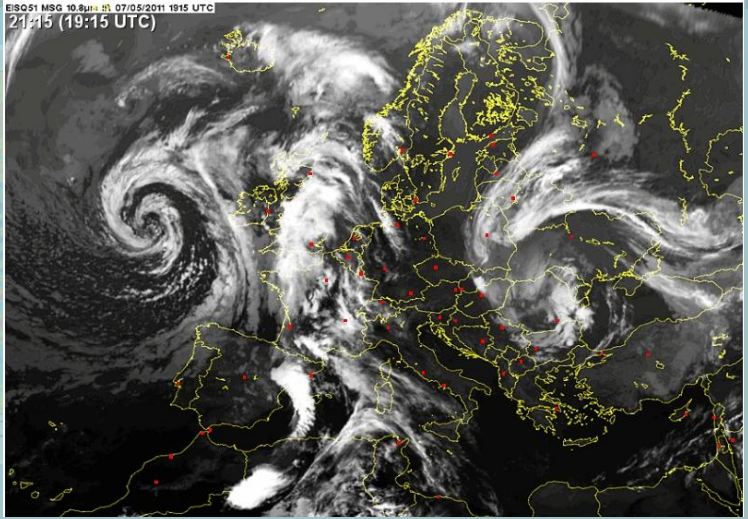
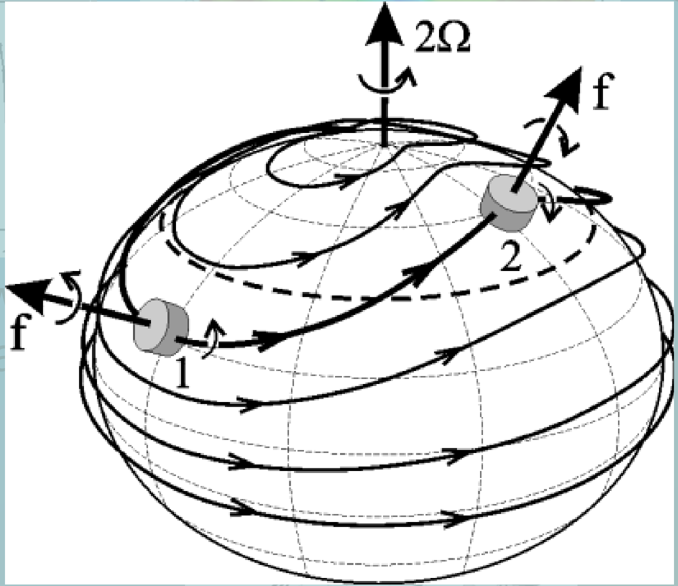
Biggest ozone hole in 2006



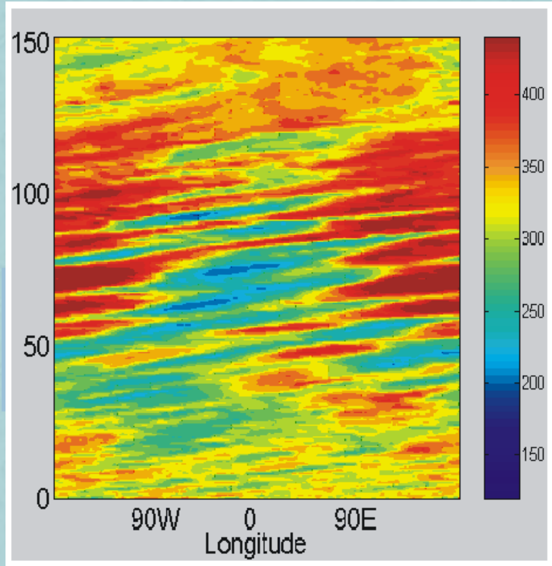


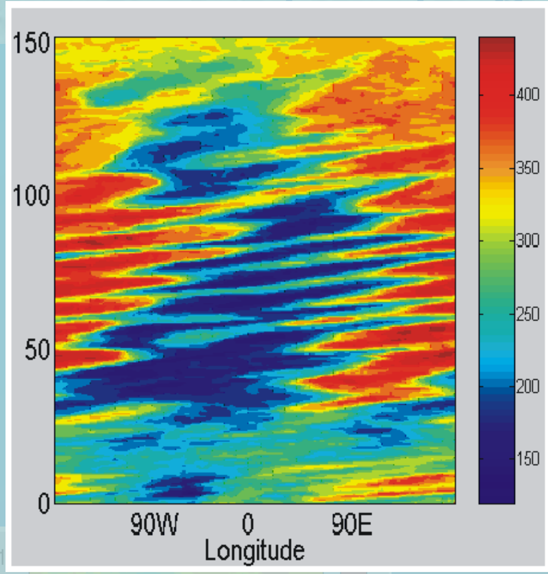
From Salby, 1996

$f = 2\Omega \sin\varphi$

Coriolis parameter

Traveling and quasi-stationary (QSW) planetary waves in ozone layer, Hovmöller diagrams: Longitude/Days/DU





1983 **1996**

0-150: days since August, 1

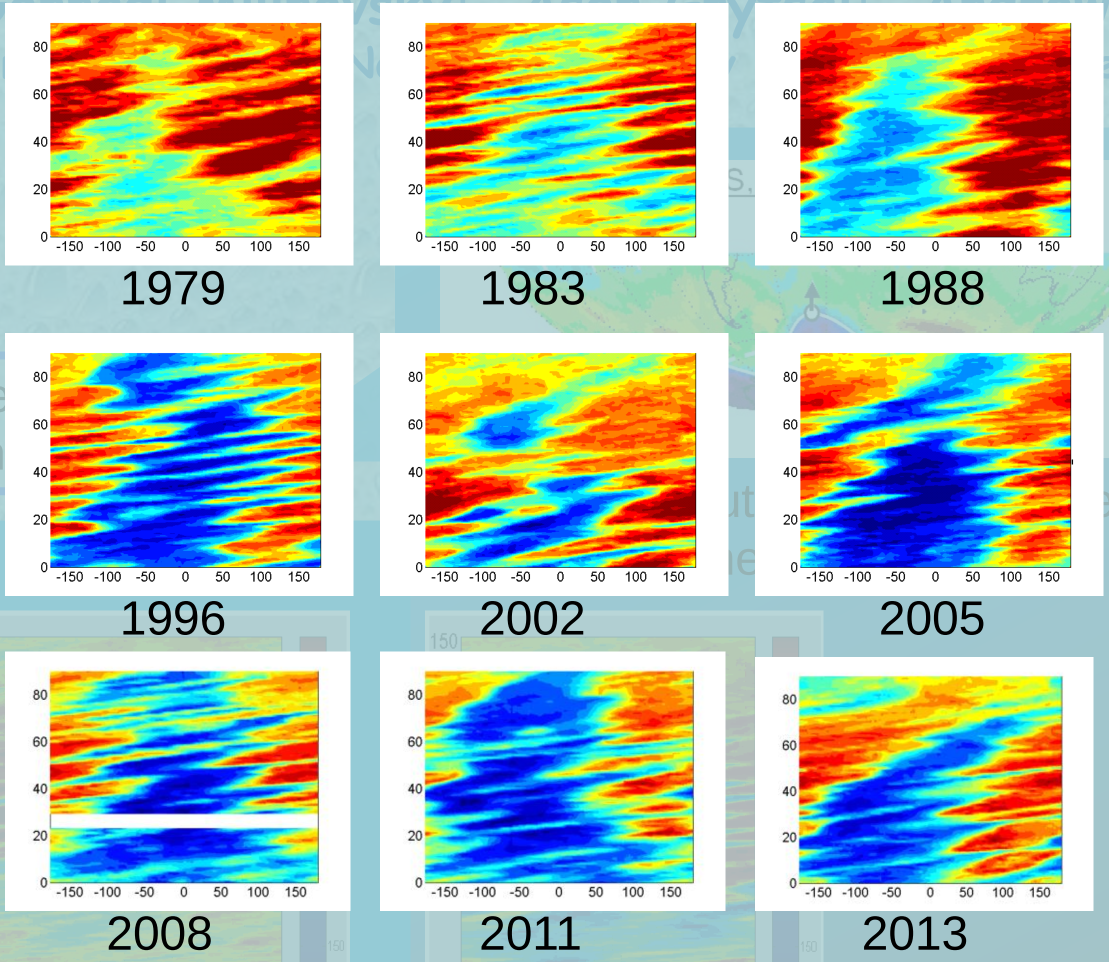
65°S Latitude

Large scale atmospheric disturbances in a form of the planetary waves are widely investigated during the last decades. The quasi-stationary component of the wave disturbances causes relatively steady spatial distribution of the atmosphere parameters with a wave-like structure in horizontal or vertical directions.

The waves with the low zonal wave numbers of $m = 1$ and $m = 2$ dominate usually in the spring Antarctic stratosphere.

This leads (1) to the zonal asymmetry in the stratosphere with one maximum and one minimum located in the approximately opposite longitudinal sectors and (2) to the related regional distinctions in atmospheric conditions.

Total ozone in September–November at 65 S

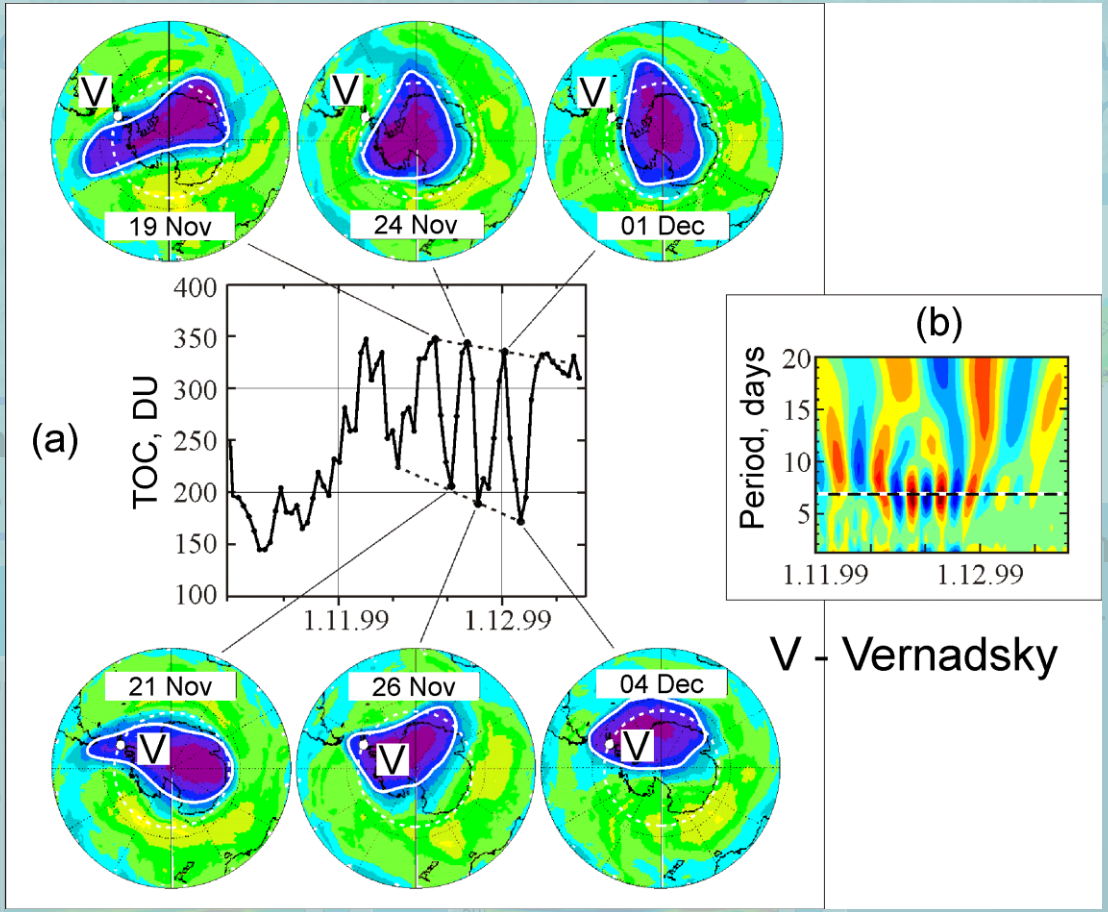


Westward shift in the ozone zonal pattern is typical for several last years.

Quasi-stationary pattern exists till the stratospheric polar vortex weakening and break up in November or December.

Hovmöller diagrams of ozone longitude distribution

The planetary waves effects observed in the stratospheric vortex structure



(a) Formation of the large-amplitude TOC oscillations over Vernadsky station due to the traveling planetary wave motion in spring 1999.
(b) Oscillation periodicity from the wavelet transform.

In general, the effects of the planetary waves observed in the stratospheric vortex structure are displayed in the ozone hole structure. Antarctic Peninsula can appear under both the low-ozone inner area of the ozone hole and the mid-latitudinal stratospheric air masses with the high ozone amount.

Among the events showing the measure of the planetary wave influence on the TOC dynamics in the Antarctic Peninsula region, a development of periodic large-amplitude oscillations in November 1999 (see figure on left).

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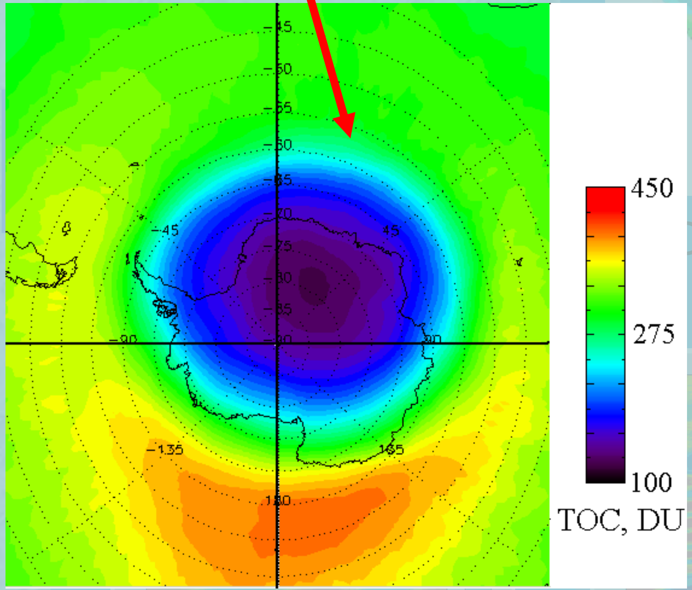
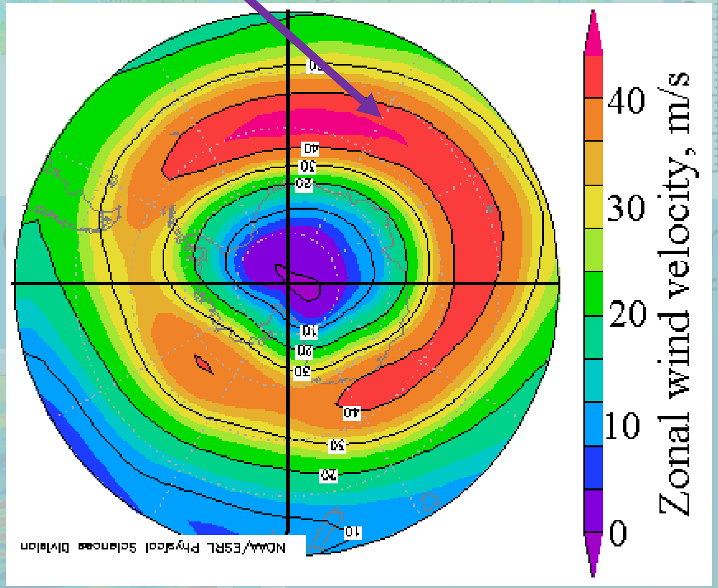
Planetary waves in the stratosphere

The ozone hole shift and deformation are caused by influence of the large-scale atmospheric planetary waves.

Ozone hole

Polar vortex





Monthly mean distribution of the TOC and zonal wind at the 100 hPa pressure level, October 2009

Under the influence of the QSW, the stratospheric polar vortex over Antarctica is displaced relative to the South Pole.

The polar vortex center in spring moves off the Pole more than 10° in latitude and typically shifts to the Atlantic longitudinal sector (Waugh and Randel, 1999).

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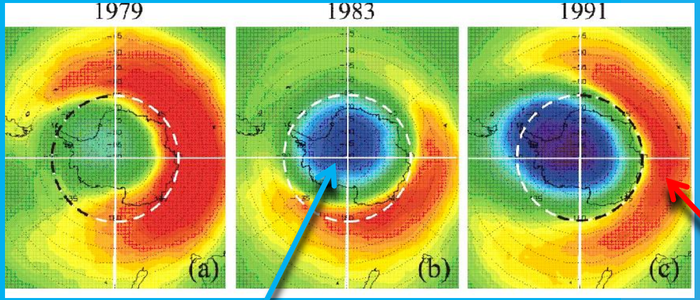
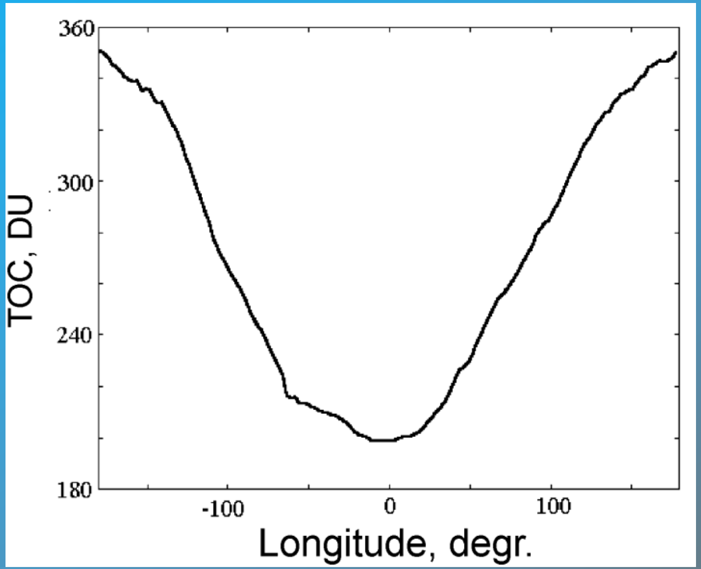
Asymmetry in ozone hole (Grytsai et al. 2007)



Ozone hole (blue) and ozone rich collar (red)

Ozone zonal asymmetry

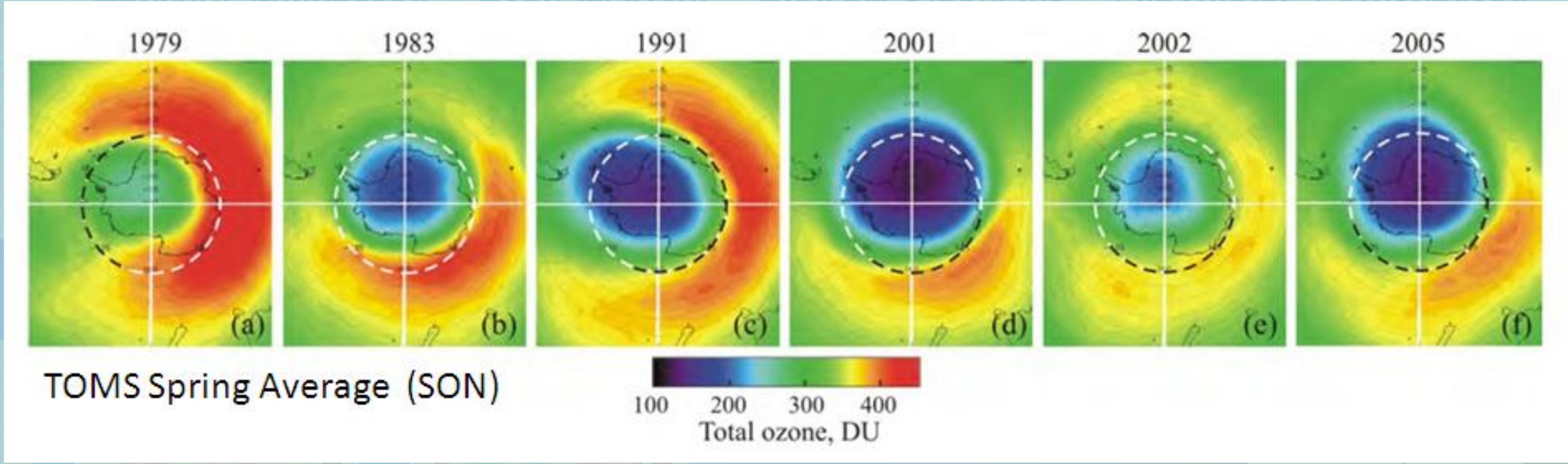


The longitudinal TOC distribution in Antarctic region along the latitude circle 65°S averaged for September–November 1996, TOMS data.

Variability of the zonal TOC distribution in the latitude range 50–80°S is caused by the steady displacement of the ozone hole relative to the pole (m = 1) that results in asymmetry: the quasi-stationary TOC minimum in Atlantic sector near the zero meridian.

X

Asymmetry in ozone distribution in Antarctic spring



The wave with the low zonal wave number of *m* = 1 dominates usually in the spring Antarctic stratosphere that leads to the zonal asymmetry in the stratosphere with one maximum and one minimum located in the approximately opposite longitudinal sectors and to the related regional distinctions in atmospheric conditions.

Latest tendency in the Antarctic ozone longitudinal distribution

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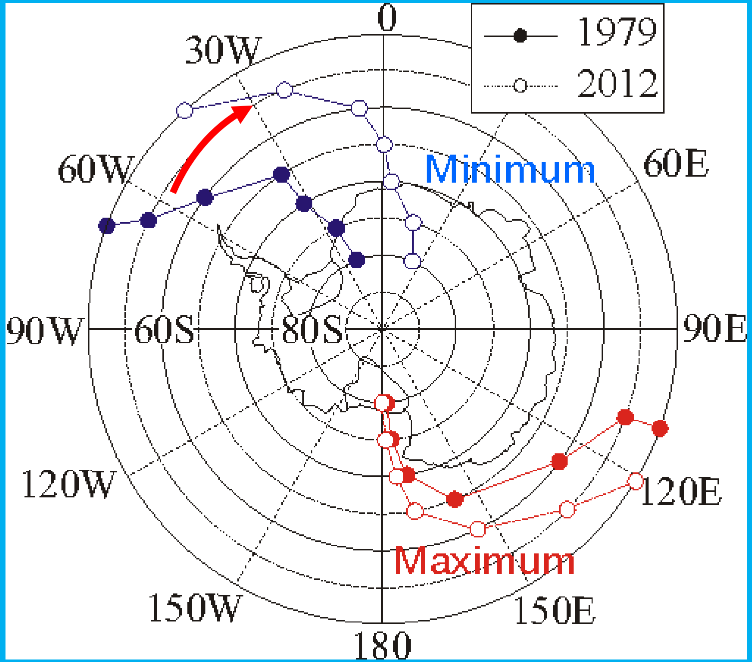
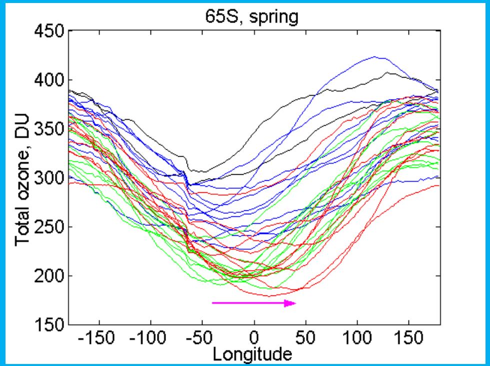
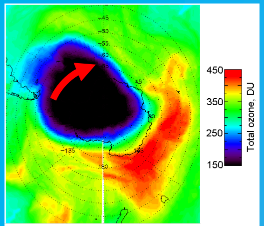


Decadal longitudinal displacements of the quasi-stationary wave (QSW) maximum and minimum in the mean September–November TOC



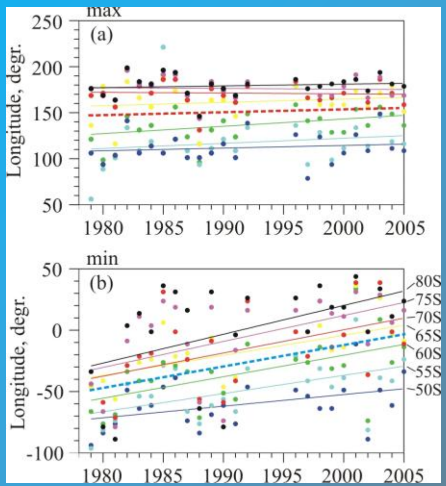
TOMS spring average (65S, 1979-2010, SON)



October 15, 2000 (TOMS)

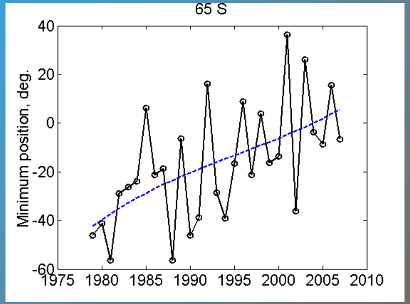
Ozone minimum eastward shift

X



Zonal ozone max stable

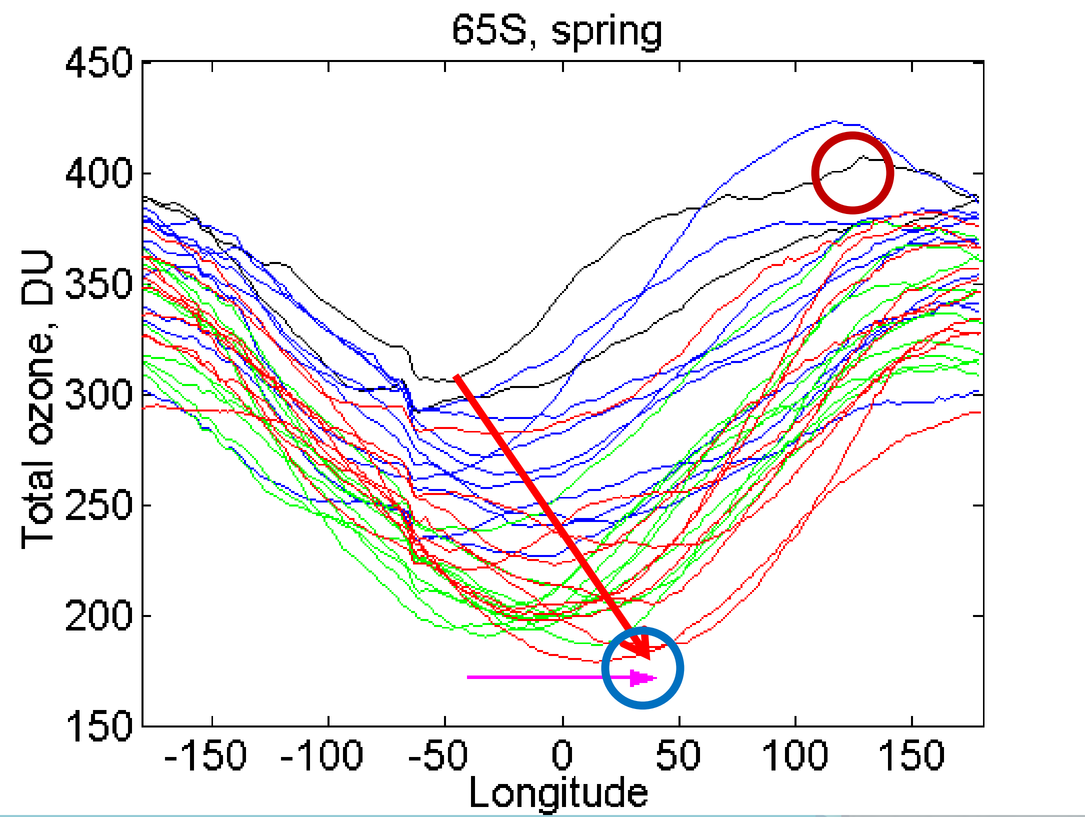
Zonal ozone min shifted eastward



QSW min eastward shift by the 1979–2007 data

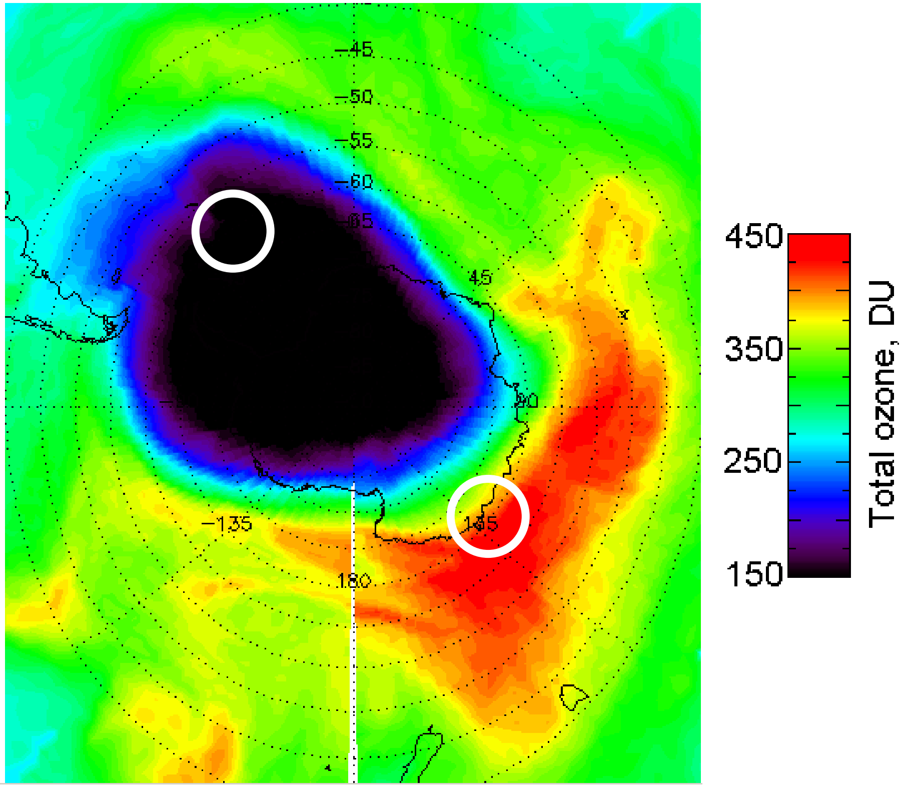
Zonal ozone distribution – QSW 1

X



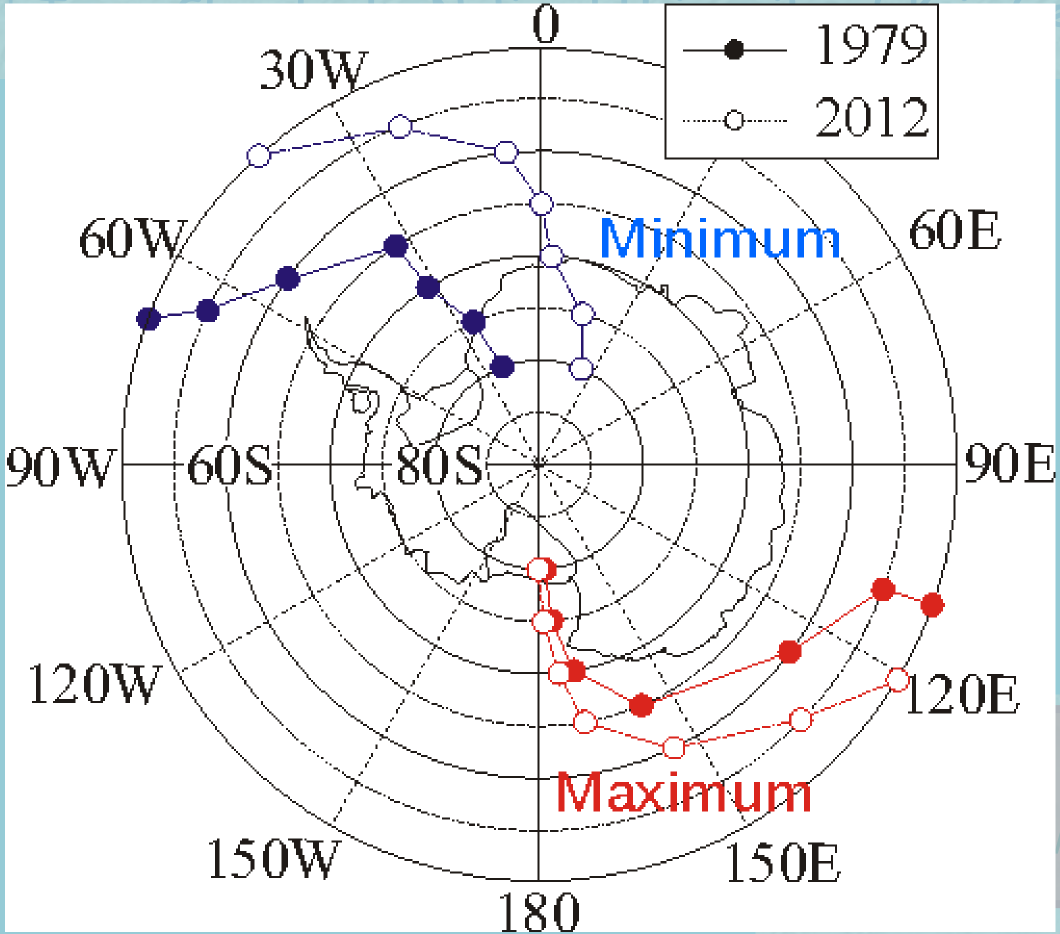
TOMS Spring Average
(65S, 1979-2010, SON)

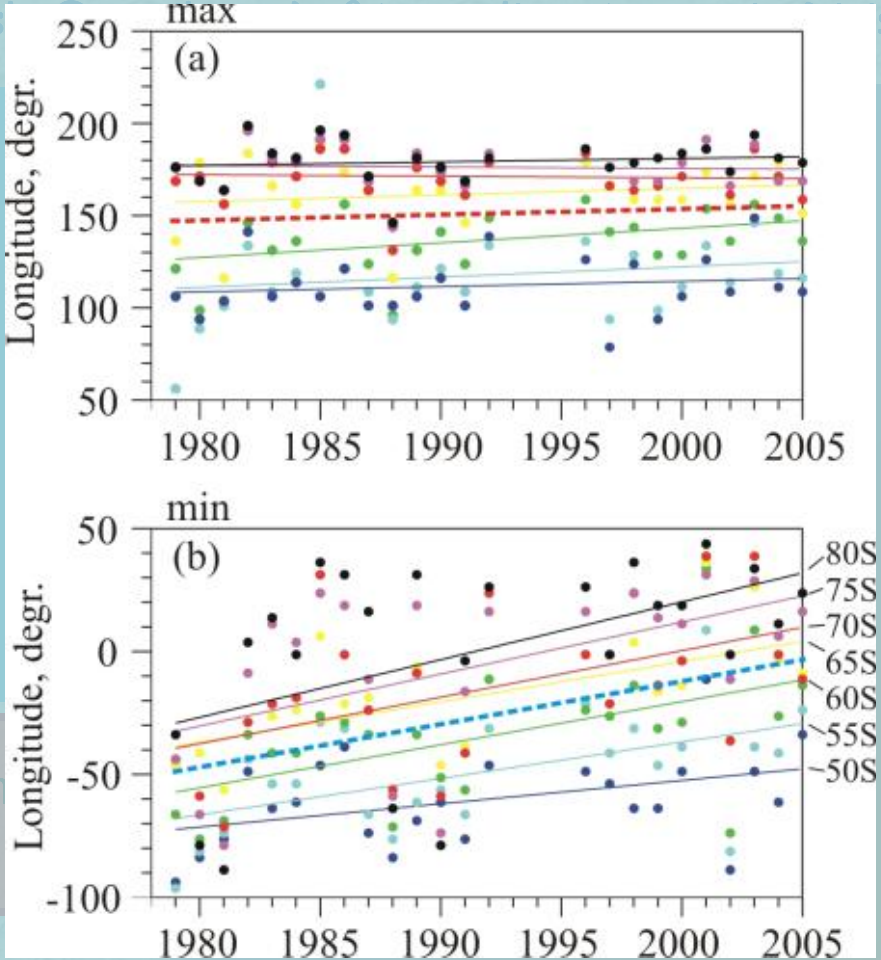
Red arrow shows QSW min eastward shift



Ozone distribution over Antarctica
October 15, 2000 (TOMS)

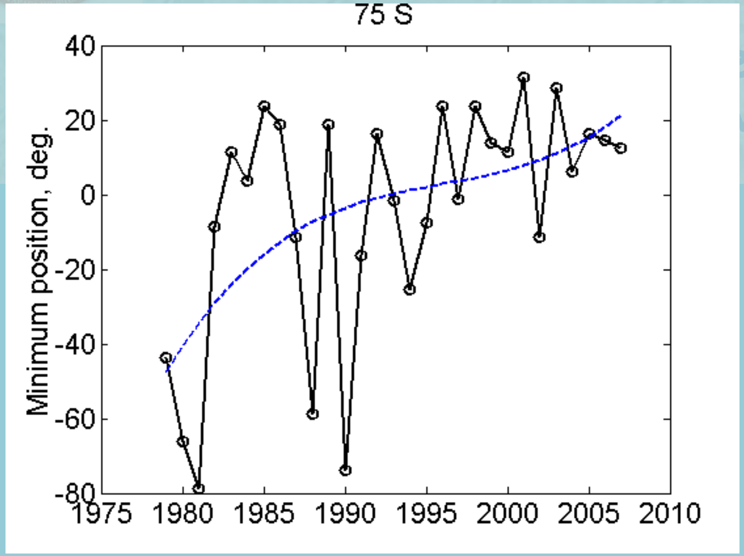
The SON ozone minimum shifted about 45˚ eastward during 1979-2012, observations

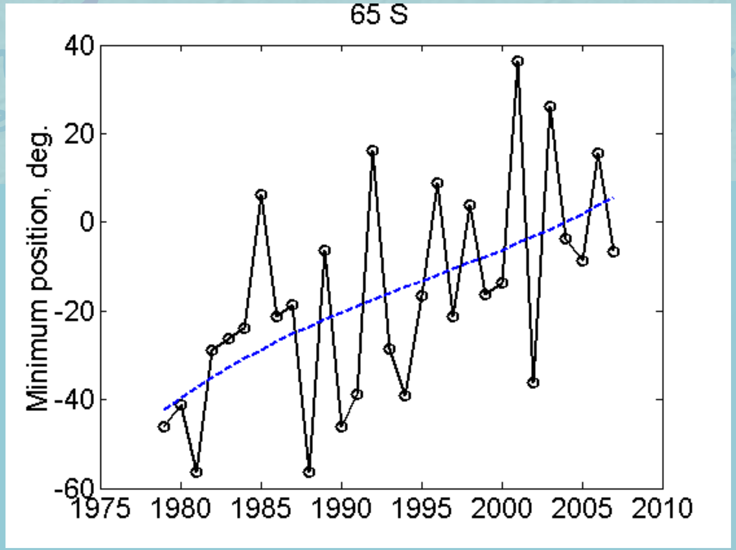


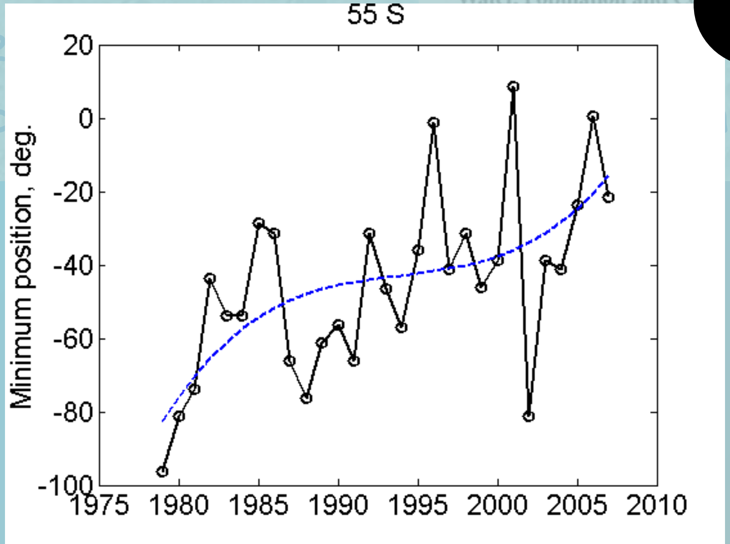


Zonal ozone max quasi-stable, zonal ozone min shifted eastward at all latitudes.

The earlier described tendency 1979–2007







Data of 1979–2007 have exhibited a clear **eastward shift** without signs of its cessation. The presented cubic fitting is close to linear at 65 S.

All longitudes of the TOS minimum for the 2000s (except 2002 with major stratospheric warming) are far to the east from its extreme western locations in 1979–early 1980s. Therefore, linear trend was suitable for the data description.

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Australian Government
Department of Sustainability, Environment, Water, Population and Communities
Australian Antarctic Division

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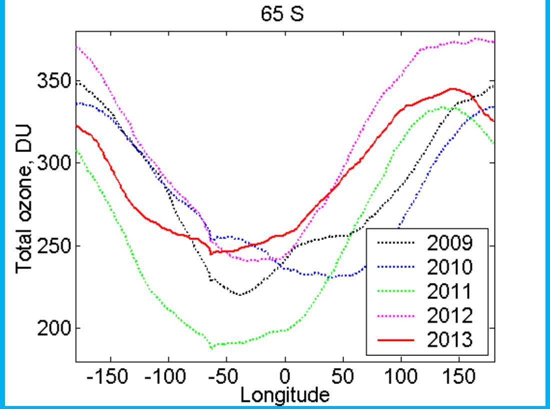
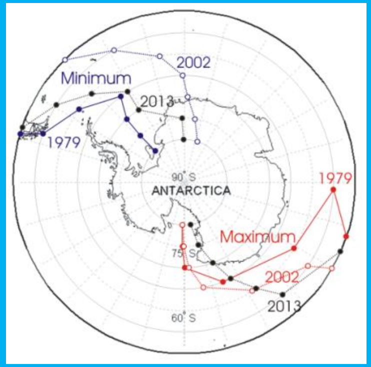
Eastward shift hiatus

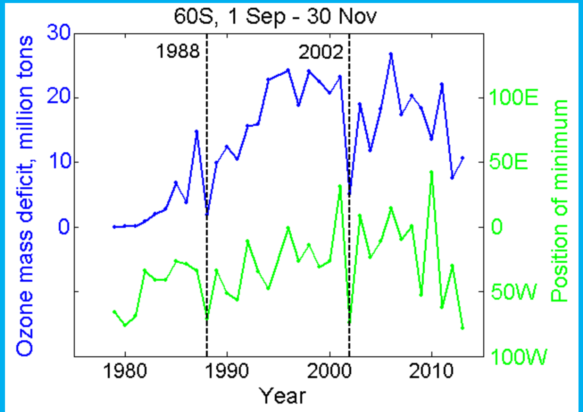


Ozone min/max geographical position

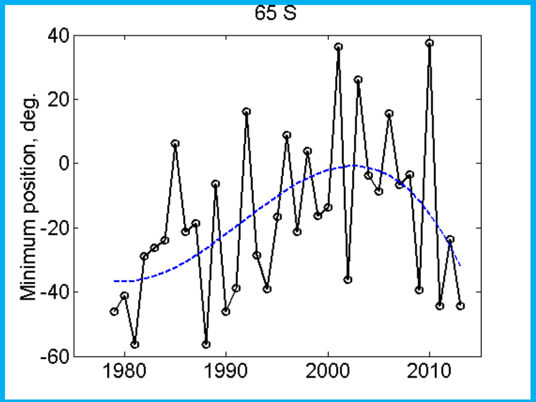


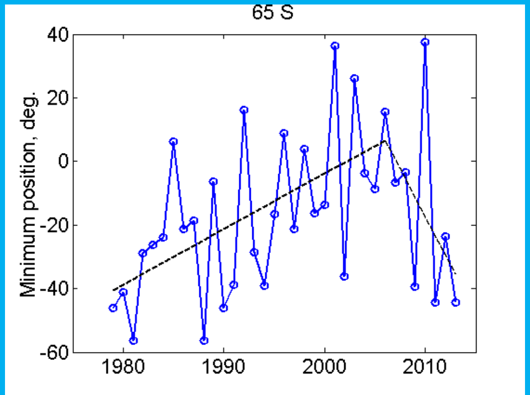
The effect of the hiatus is clearly visible at all latitudes in the 50–80 S range.

QSW minimum position and ozone mass deficit



Hiatus in the ozone minimum behaviour

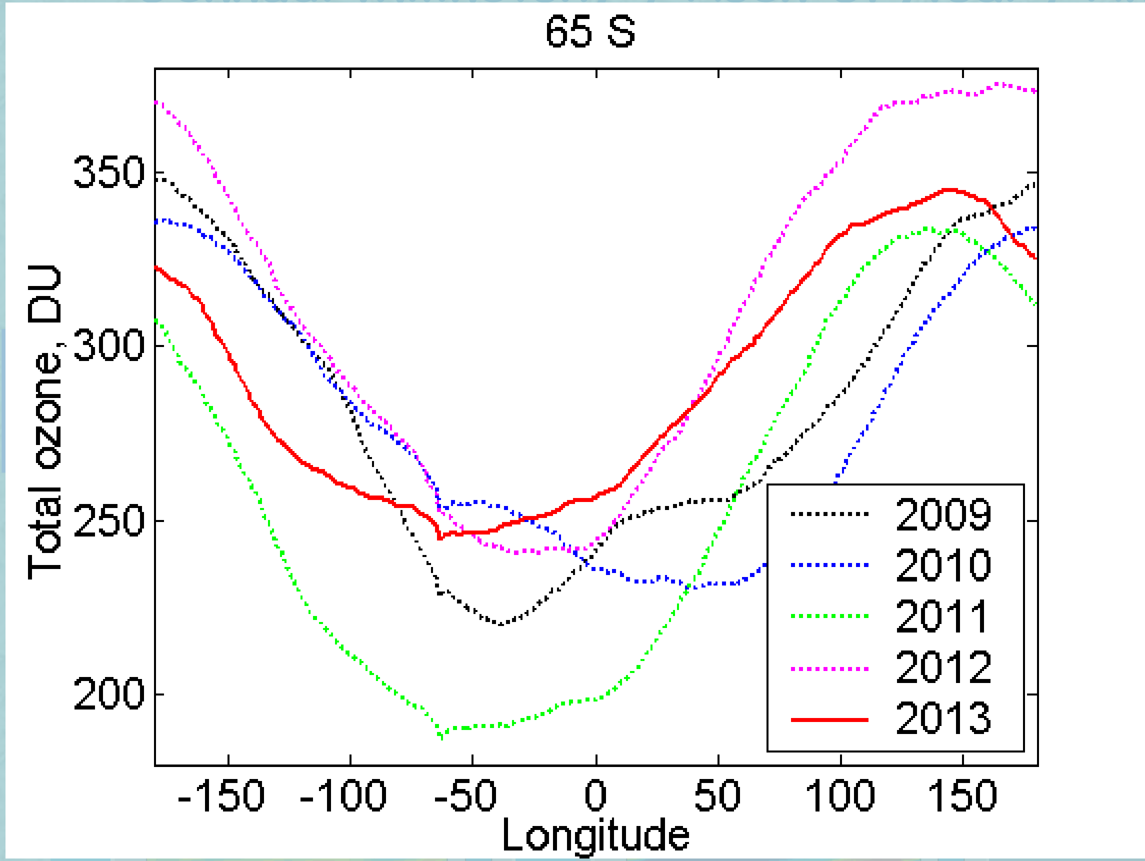




Time of the change in the tendency can be approximately determined as the early 2000s.

Eastward shift hiatus

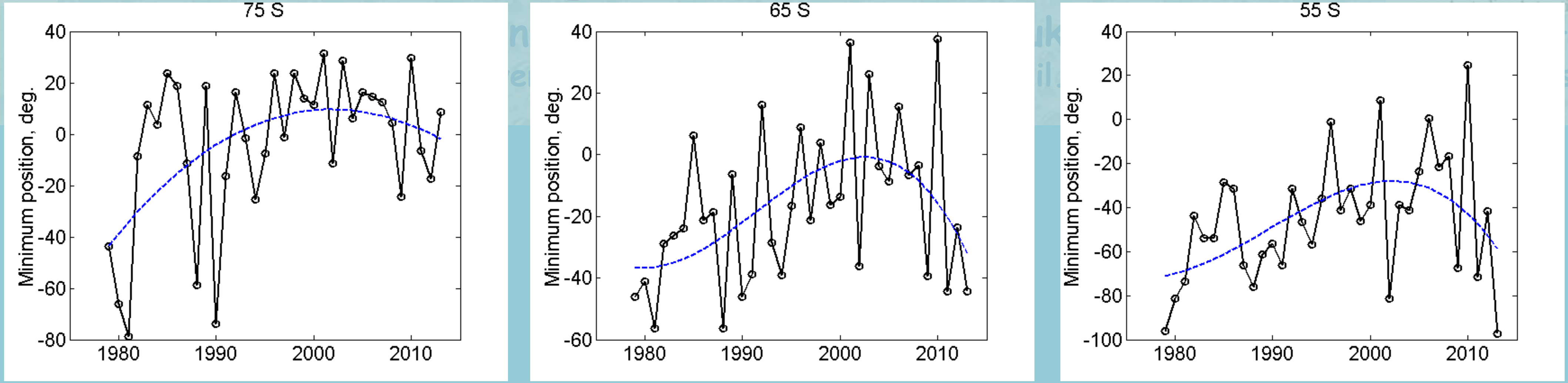
Zonal asymmetry and quasi-stationary ozone distribution, eastward ozone min shift



September–November averaged TOC distribution at 65S

The range of the interannual zonal ozone variations is shown. In the last five years, only 2010 is characterized by a noticeable eastward shift of the ozone minimum's region. It is interesting that even low ozone levels in 2011 was associated with westward displacement of the ozone minimum. At 65 S, time-averaged TOC minimal values are predominantly higher than ozone hole threshold (220 DU).

Hiatus in the ozone minimum behaviour



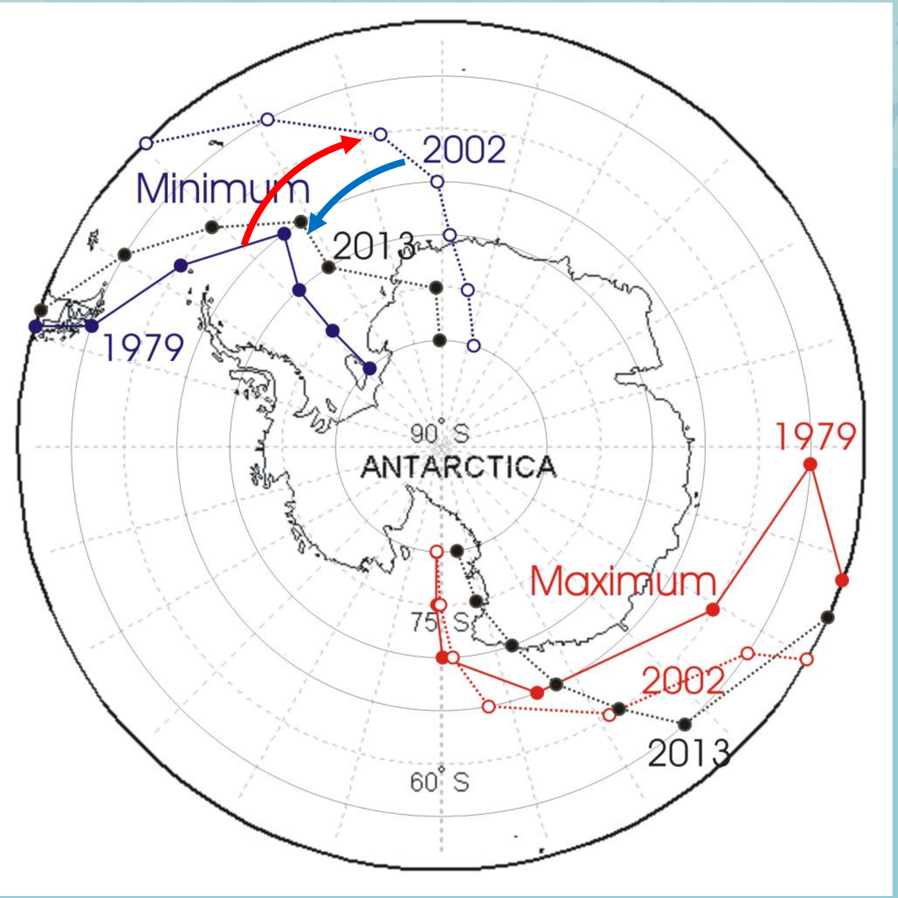
The ozone QSW minimum’s position polynomial fit order of 3. The effect of the hiatus is clearly visible at all latitudes in the 50–80 S range.

The QSW minimum behaviour is approximated by linear trend incorrectly.

Time of the change in the tendency can be approximately determined as the early 2000s. Observations are necessary during a longer period in order to specify whether a stabilization or an opposite westward shift would proceed.

QSW Fourier harmonics with zonal number 1 shows similar behavior.

Geographical location of the ozone minimum and maximum

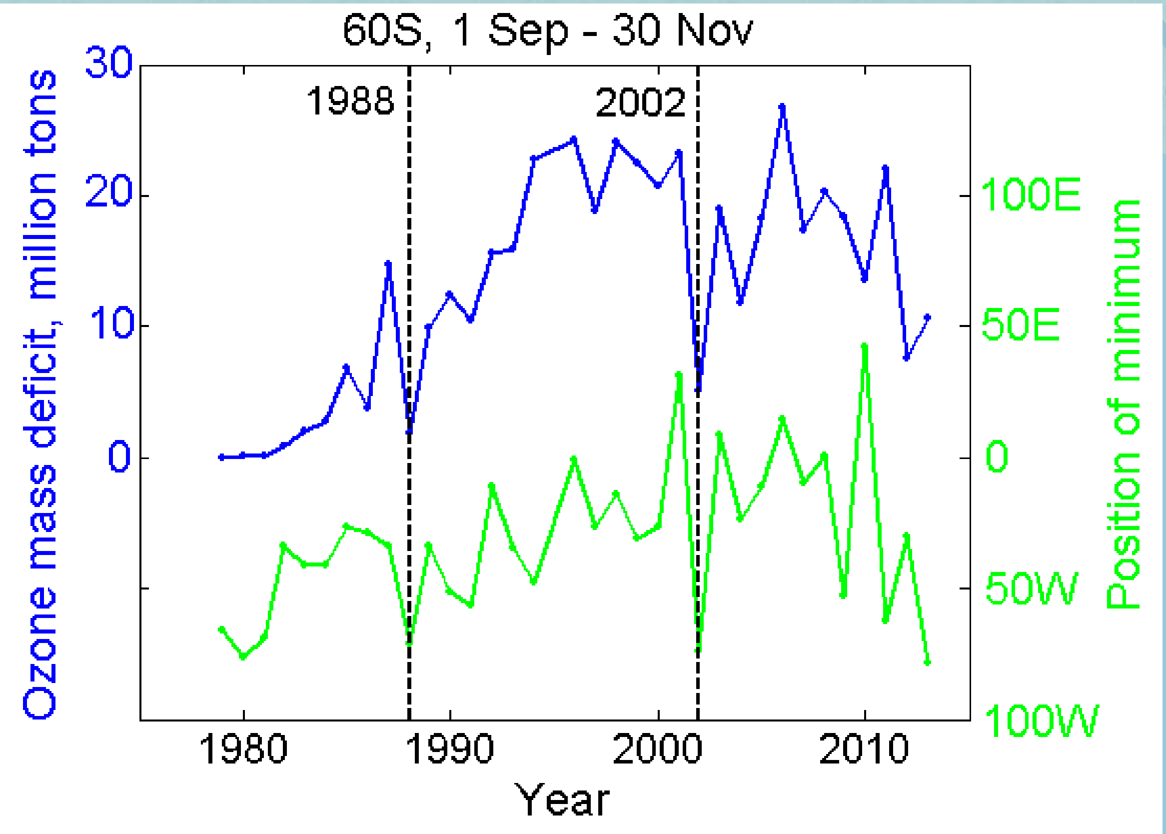


Quasi-stationary ozone minimum and maximum positions from the satellite data for the 1979–2013 September–November range.

Eastward shift of the ozone minimum was observed during the 1980s and 1990s. Cubic polynomial fit shows for 2013 the longitude values, which are intermediate between ones for 1979 and 2002.

Changes in the maximum’s position are not systematical

QSW minimum position and ozone mass deficit



Position of the quasi-stationary minimum in the ozone distribution at 60°S and ozone mass deficit. Correlation coefficient *r* = 0.57. Data from http://ozonewatch.gsfc.nasa.gov/meteorology/.

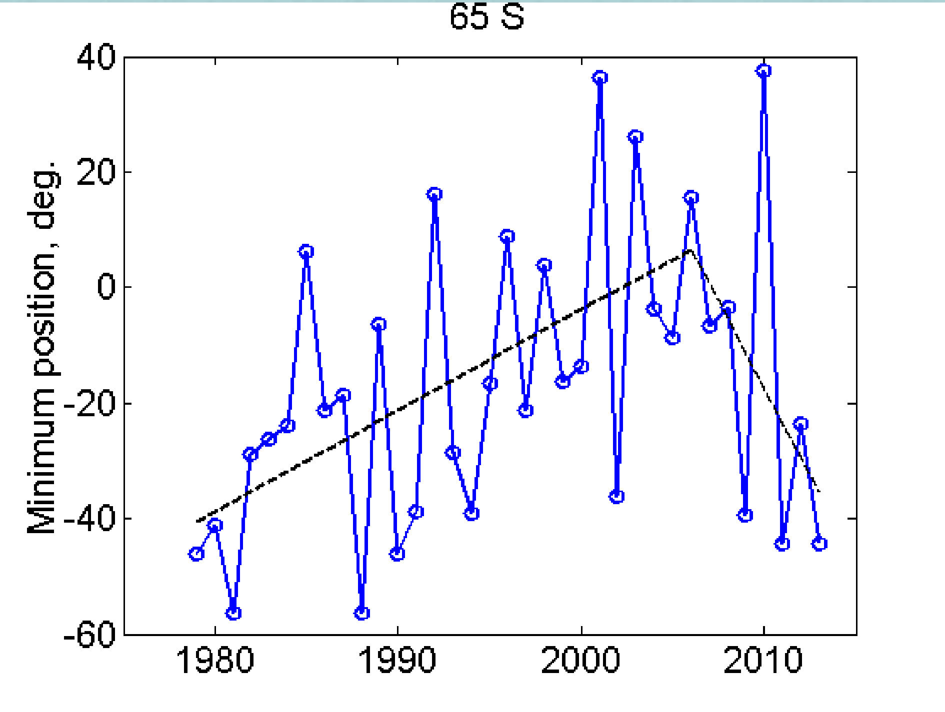
X

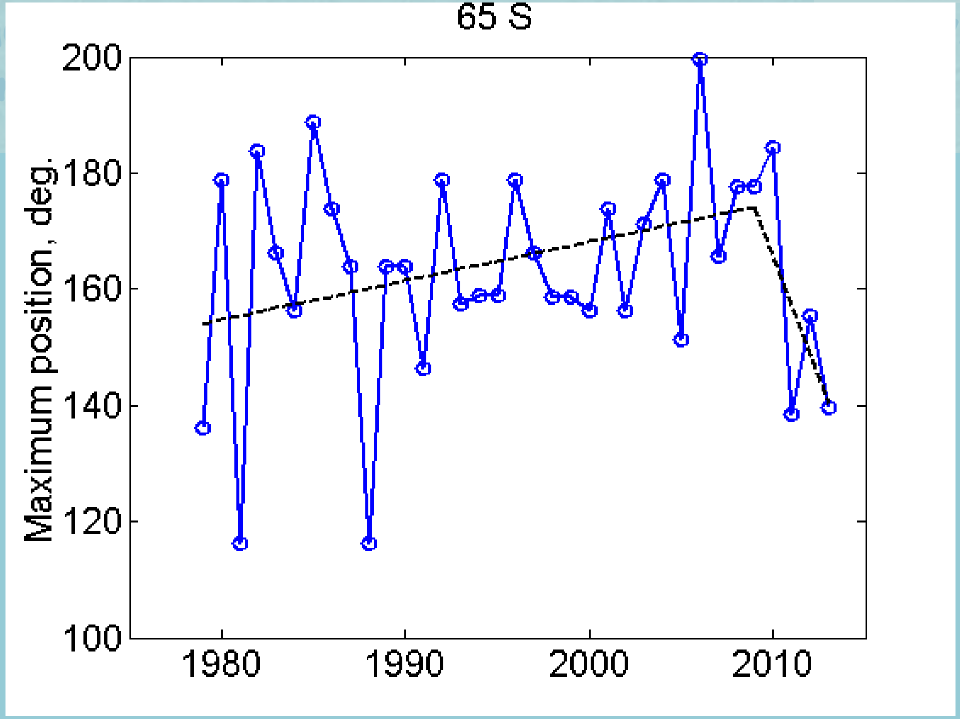
The **ozone mass deficit** is determined as the total amount of mass that is deficit relative to the amount present for a value of 220 DU. There is reasonable **correlation** between ozone mass deficit and QSW minimum's position (except last years).

1988 – large stratosphere warming

2002 – major stratosphere warming

Double-line fit



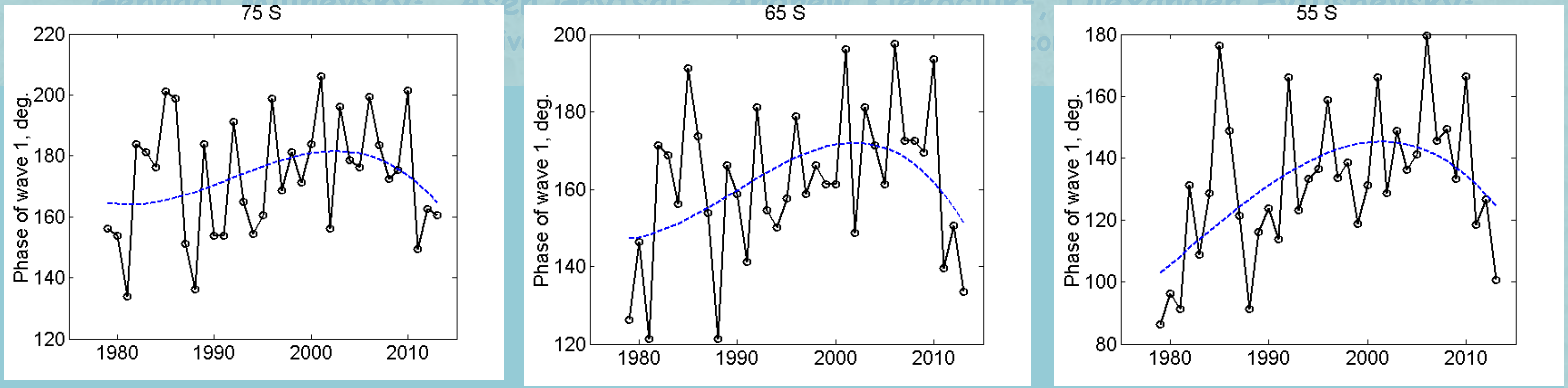


The hiatus in the ozone **minimum** eastward shift can be also supposed from double-line fitting.

Linear trend for ozone **maximum** is less evident.

X

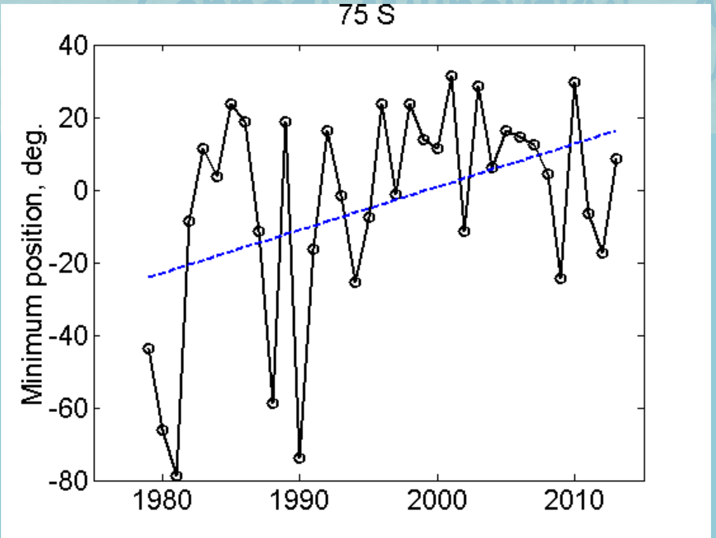
QSW Fourier harmonics with zonal number 1



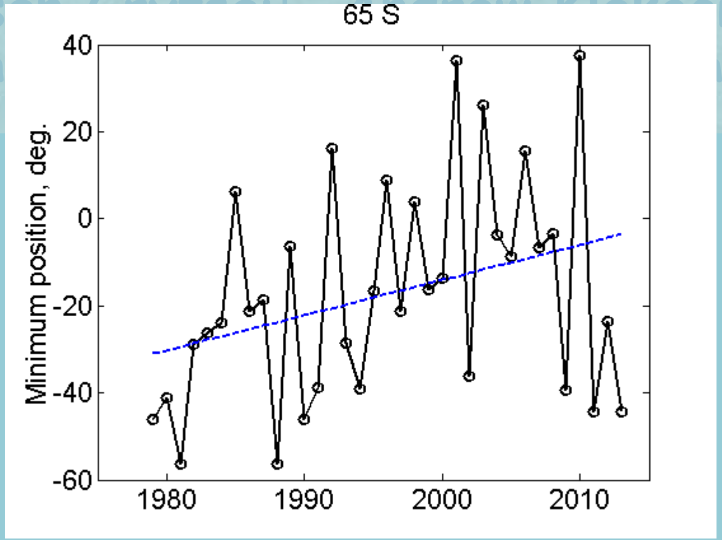
Quasi-stationary wave structure is mainly determined by a harmonics with zonal number 1. Variations of its phase are similar to ones for the quasi-stationary minimum obtained from total spectral pattern.

Phase on the plot is a position of the TOC maximum and the TOC minimum on the sinusoidal harmonics is at the 180 longitude distance.

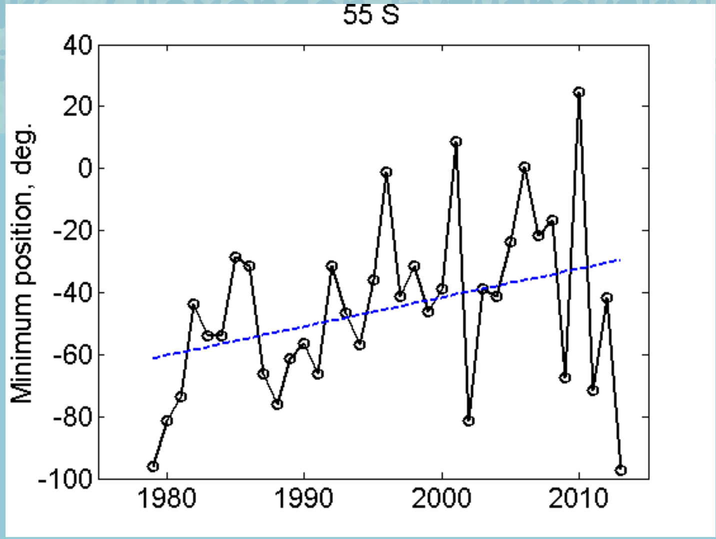
Linear fit of QSW ozone minimum



k = 12±9 °/decade



k = 8±8 °/decade

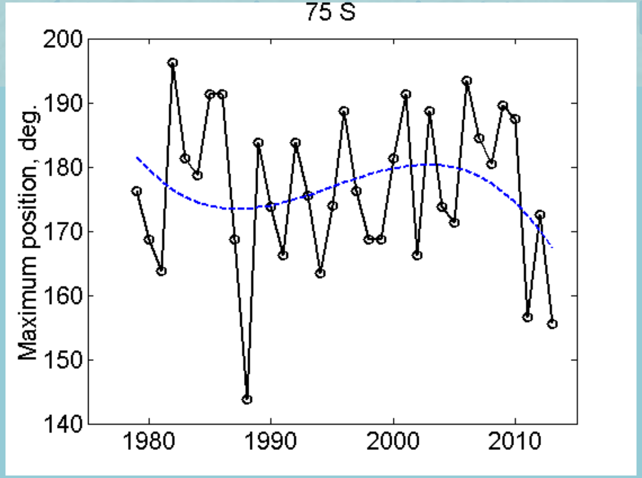


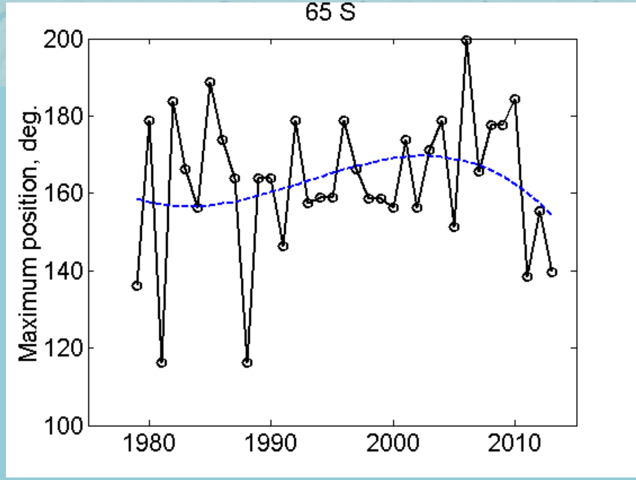
k = 9±9 °/decade

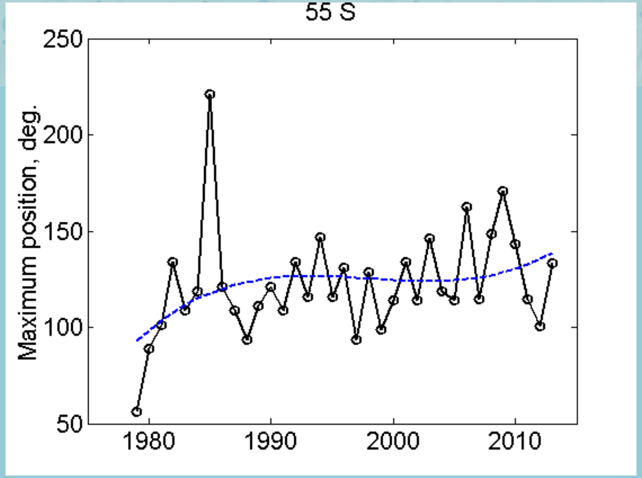
The QSW minimum behaviour is poorly approximated by linear trend, in particular, during recent years. The level 2σ is indicated after the ‘ ’ sign.

In the edge and outer zone of the ozone hole, the TOC minimum locations in 2009, 2011, 2013 are close to those in the pre-ozone hole years 1979–1981.

The ozone maximum position variation







A clear shift of the QSW maximum position was absent in contrast to the QSW minimum shift.

Changes in the longitudinal position of the QSW maximum in the considered range of latitudes are less regular than for the QSW minimum.

Latest tendency in the Antarctic ozone longitudinal distribution

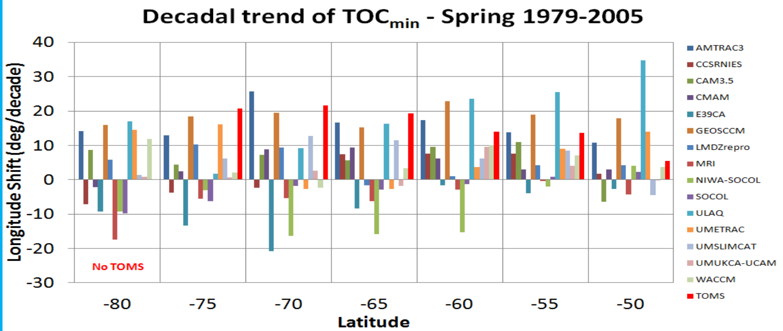
Gennadi Milinevsky[1], Asen Grytsai[1], Andrew Klekociuk[2], Oleksandr Evtushevsky[1]
[1]Taras Shevchenko National University of Kyiv (genmilinevsky@gmail.com), [2]Australian Antarctic Division

Australian Government
Department of Sustainability, Environment, Water, Population and Communities
Australian Antarctic Division

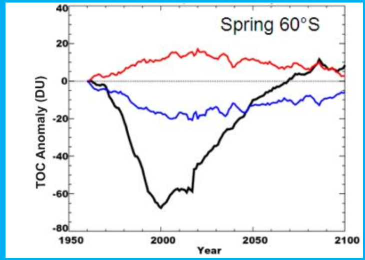
X

Evaluation of CCMVal-2 models: prescribed GHG, ODS, aerosols, ozone chemistry

Past, REF-B1 trend ensemble for 1979–2005

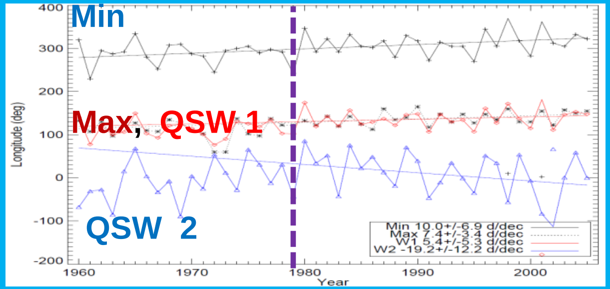


Recovery

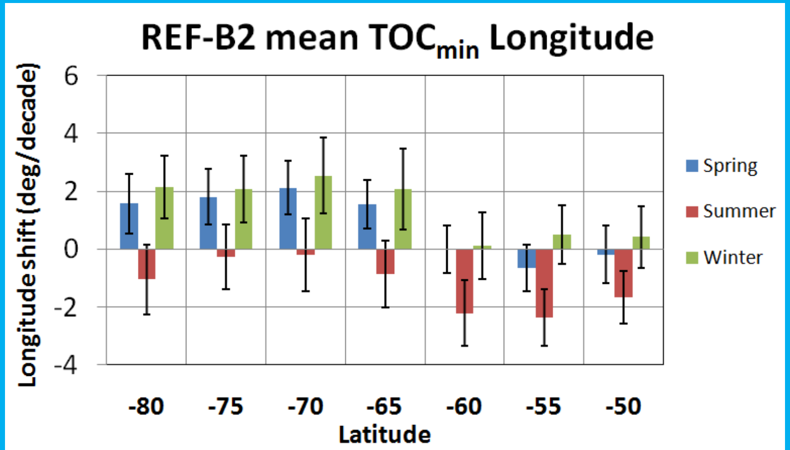


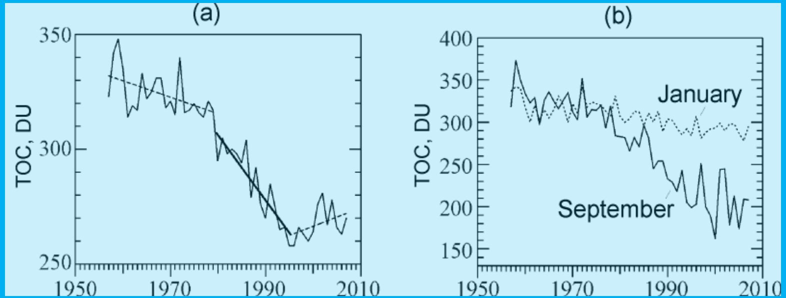
Model study

Future, REF-B2 trend ensemble for 2005–2100



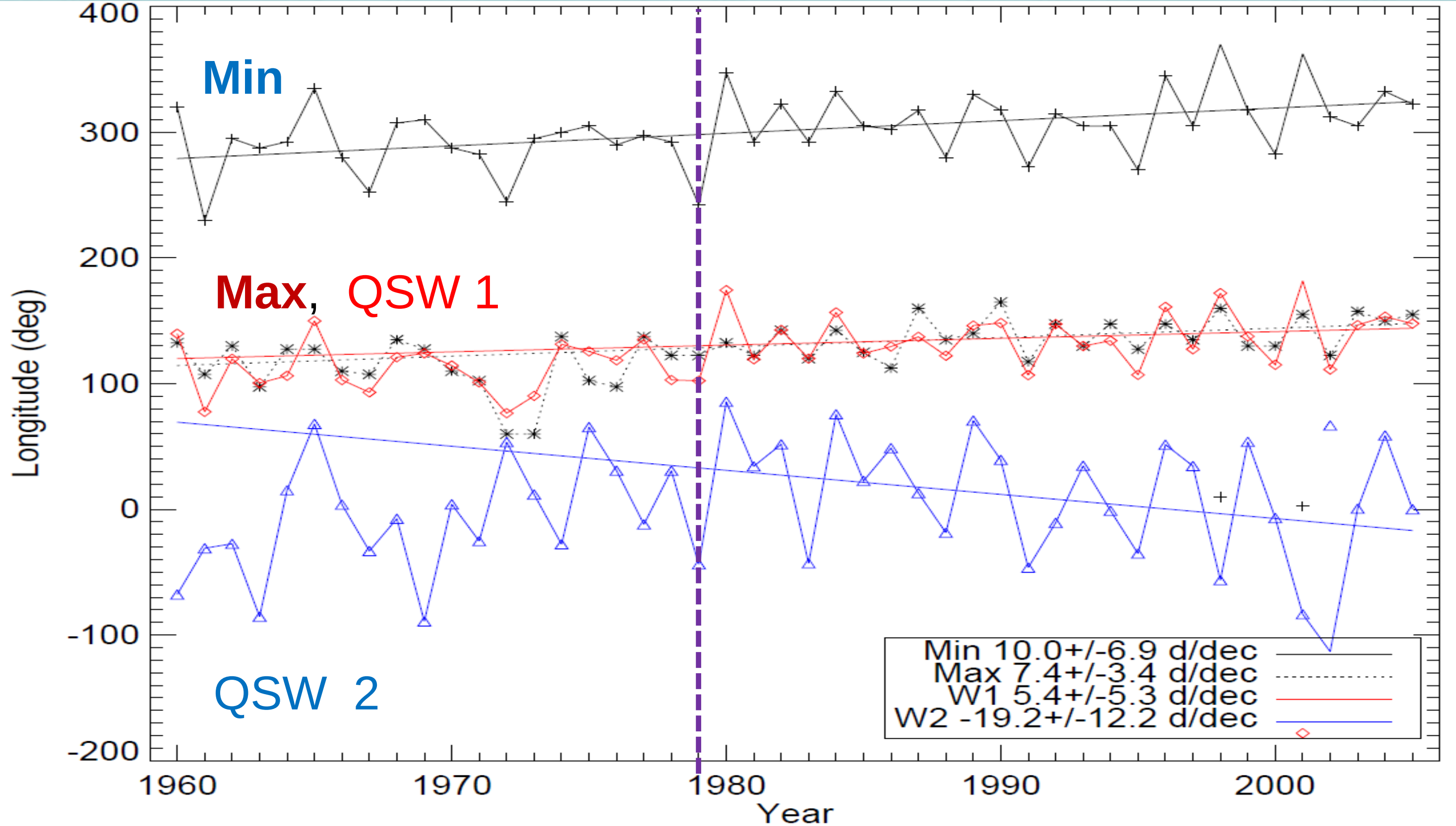
Example for WACCM REF-B1 60°S Spring (SON), linear fit 1979–2005





Ozone recovery: the TOC changes over Faraday/Vernadsky in 1957–2007, (a) annual means and (b) monthly means.

Evaluation of CCMVal-2 Models: prescribed GHG, ODS, aerosols, ozone chemistry



Amplitudes:
Wave 1 ~100 DU
Wave 2 ~10 DU

15 models REF-B1 (1960-2005) and 12 models REF-B2 (1960-2100)

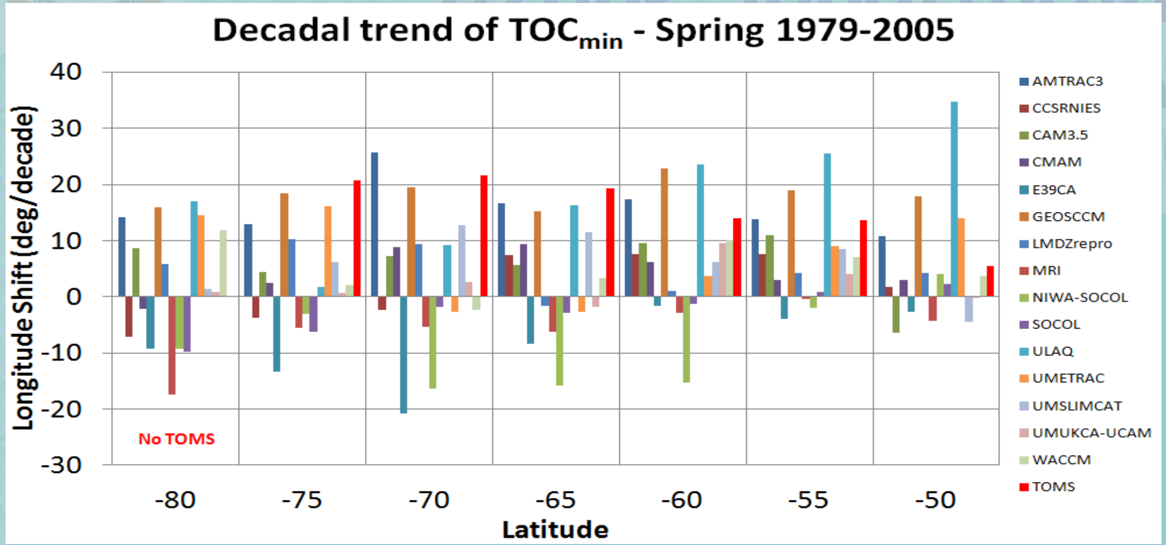
V. Eyring et al., Multi-model assessment of stratospheric ozone return dates and ozone recovery in CCMVal-2 models, Atmos. Chem. Phys., 10, 9451-9472, 2010

Example for Whole Atmosphere Community Climate Model (WACCM) REF-B1 60°S Spring (SON), linear fit 1979-2005

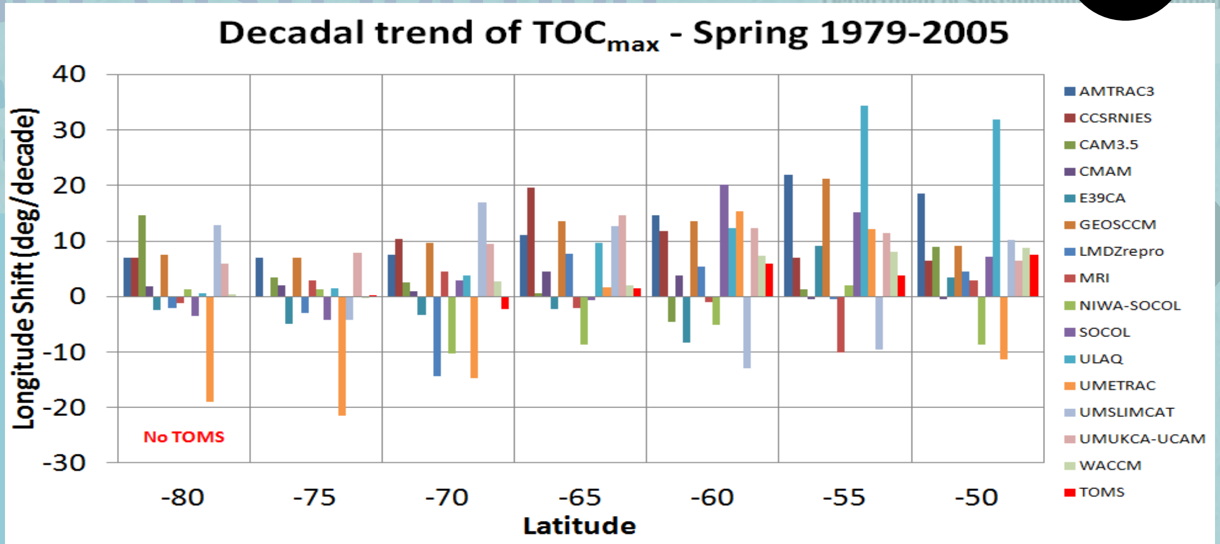
Thanks to CCMVal investigators and teams: http://www.pa.op.dlr.de/CCMVal

Variability in the REF-B1 trend ensemble 1979 - 2005

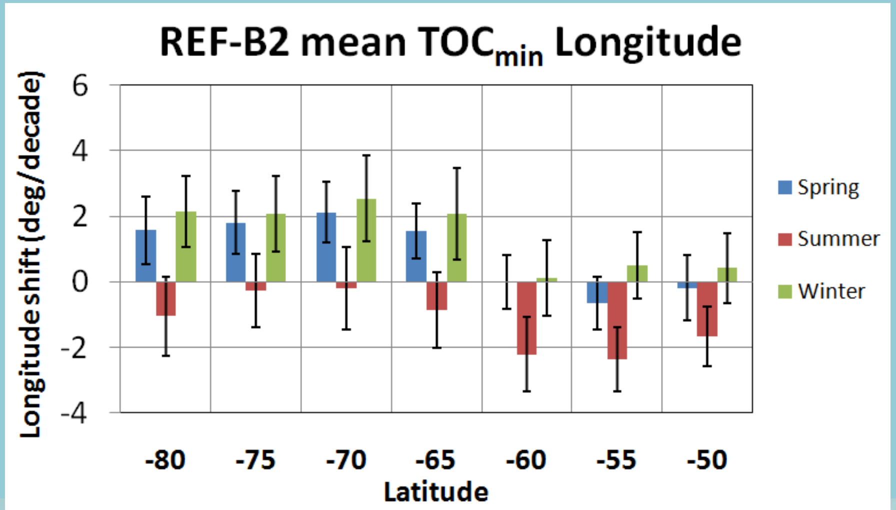
min

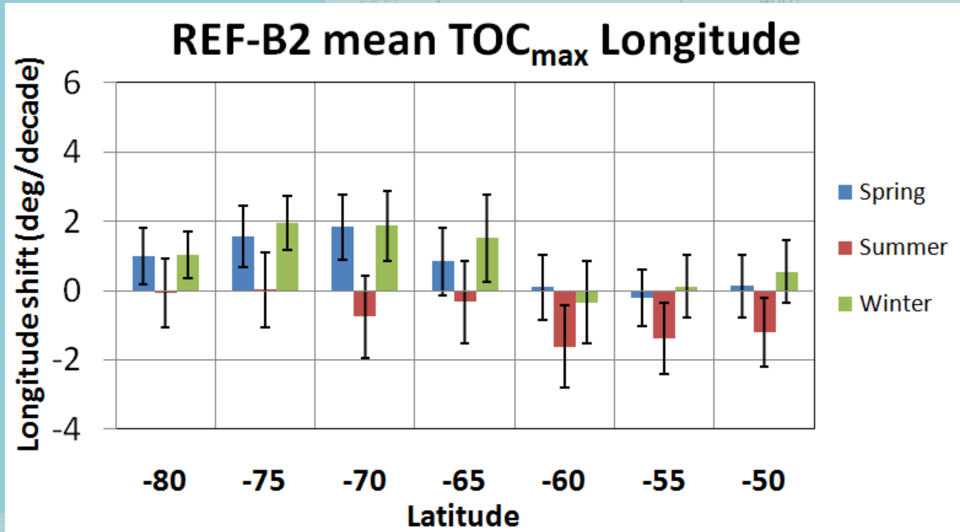


max

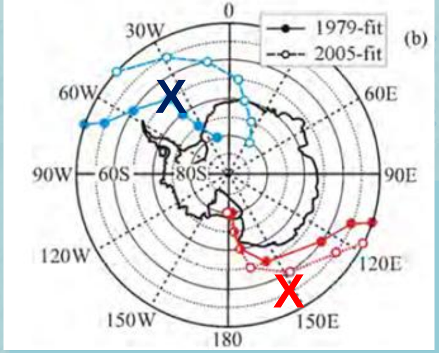


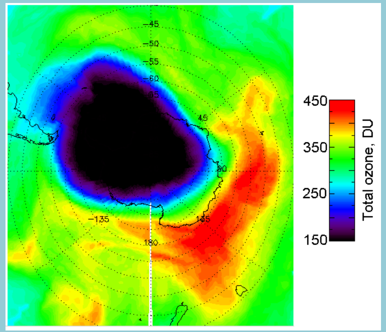
REF-B2 ensemble trends for 2005-2100 suggest an overall reduction or reversal in QSW shift



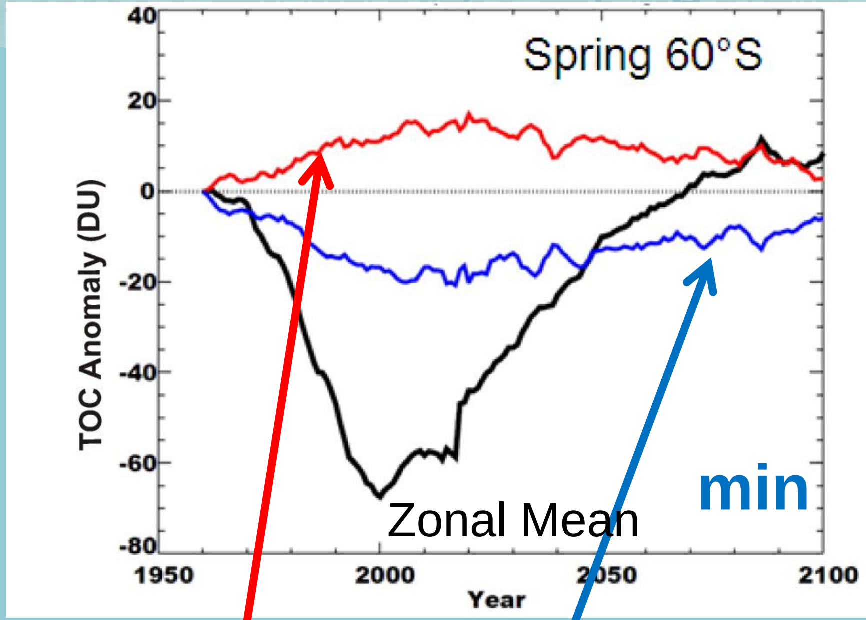


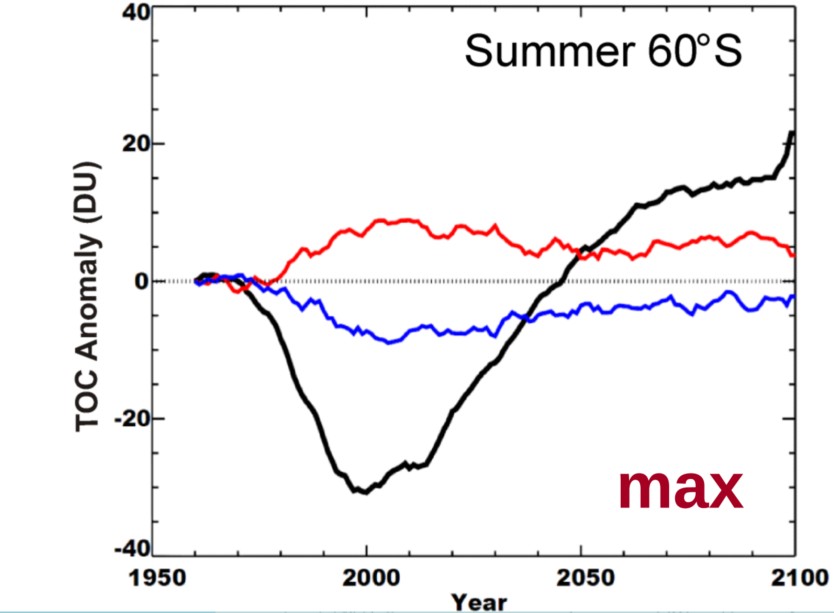
Delay in Weddell Sea ozone recovery relative to the zonal mean, CCMVal-2





REF-B2 ensemble means





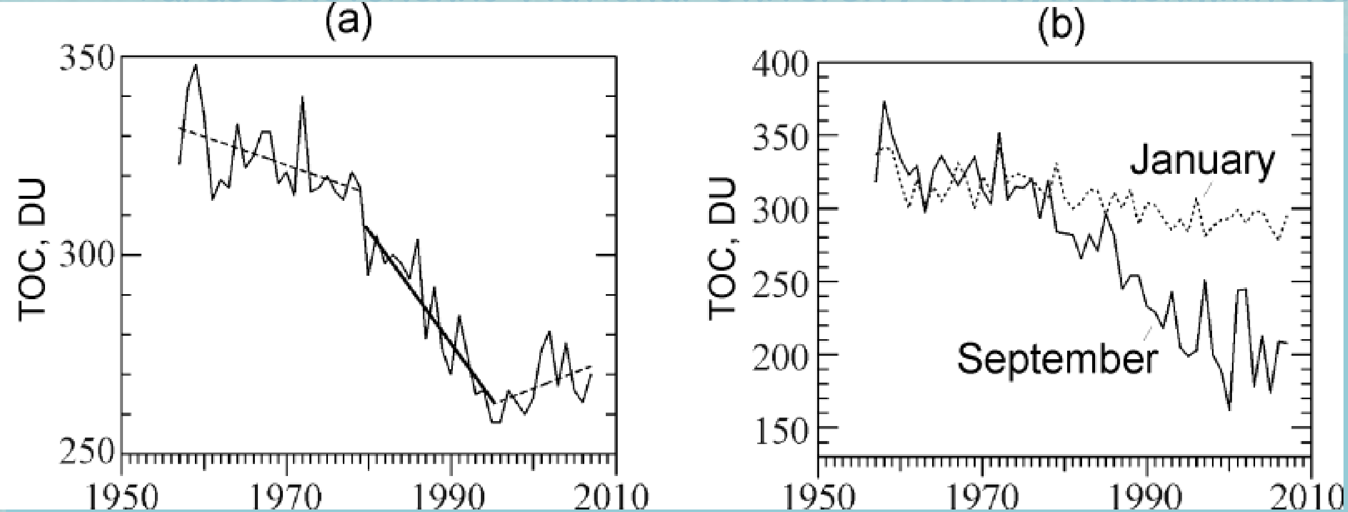
Pacific 150°E

South Atlantic 30°W

Possible causes of shift and hiatus

- **Ozone recovery will show regional asymmetry**
- **Delay with recovery due to asymmetry**
- **Connection of the QSW eastward shift trend to feedbacks from ozone and GHG forcing**
- **We expect (and observe!) a reduction in the eastward TOC shift during ozone recovery (model study)**

Sign of ozone recovery: the TOC changes over Faraday/Vernadsky



Ozone recovery: the TOC changes over Faraday/Vernadsky in the period 1957–2007:

(a) annual means and (b) monthly means for Jan (dotted curve) and Sep (solid curve).

The time series of the long-term changes of the annual mean TOC values at Faraday/Vernadsky Antarctic Station.

The linear trends for the three observational periods, when the noticeable changes of the Antarctic ozone layer are seen:

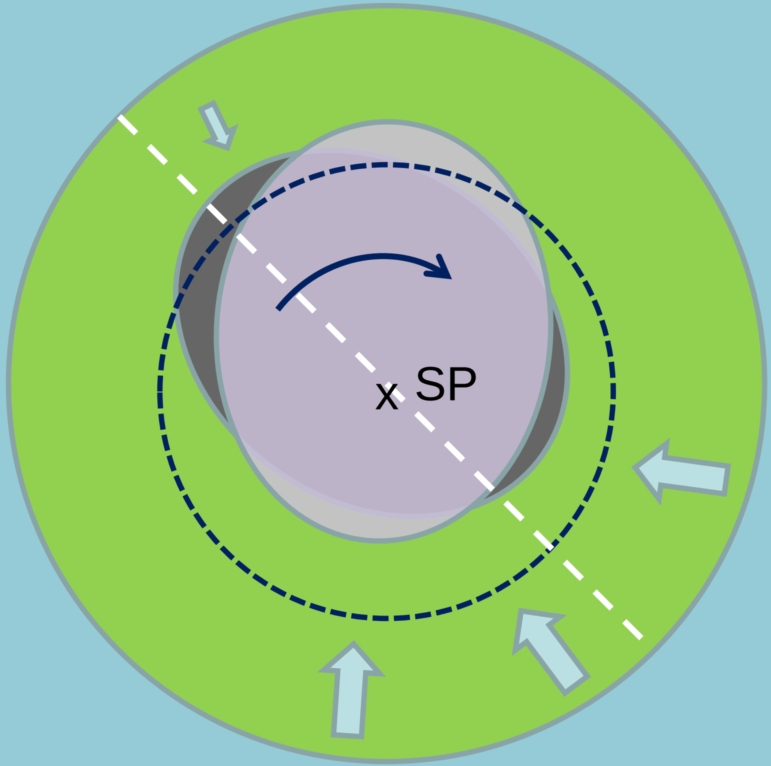
(1) “normal-level” period of Antarctic ozone lasted since observation start in 1957 to the early 1980s;

(2) to the mid-1990s, intense spring ozone depletion in the South Polar Region took place that resulted in the global decrease of the annual mean TOC levels;

(3) the Antarctic ozone leveling-off and the first signs of ozone recovering in the mid-1990s were noted.

Possible causes of shift and hiatus

Changes in the Polar Vortex and feedbacks to/from the tropopause region



Wave 1 pattern: Planetary wave and vortex asymmetry effects

Asymmetry effects:

- Change in temperature gradients,
- Tropopause height,
- Vortex size,
- Brewer–Dobson circulation

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Waugh, D.W. and Randel, W.J., 1999, Climatology of Arctic and Antarctic vortices using elliptical diagnostics. Journal ... e Atmospheric Sciences, 56, pp. 1594–1613.

Latest tendency in the Antarctic ozone longitudinal distribution

Ann. Geophys., 25, 361–374, 2007
www.ann-geophys.net/25/361/2007/

Annales Geophysicae

Structure and long-term change in the zonal asymmetry in Antarctic total ozone during spring

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Received: 13 October 2006 – Revised: 10 January 2007 – Accepted: 15 January 2007 – Published: 8 March 2007

Abstract. The quasi-stationary asymmetry of total ozone over Antarctica during spring is studied by TOMS data during the period 1979–2005. Statistics on the amplitude and longitudinal position of zonal anomalies are obtained from the distribution of total ozone along seven individual latitudes at 5-degree intervals between 50° S and 80° S. As shown by the September-November means, the mid-latitude collar of ozone-rich stratospheric air has a sub-Antarctic maximum with a mean location in the quadrant 90° E–180° E and a total ozone level of about 380 DU between 50° S and 60° S. The steady displacement and elongation of the ozone hole under the influence of planetary waves causes a zonal anomaly of low ozone in the sector 0°–60° W with total ozone levels of about 200 DU between 70° S and 80° S. Cli-

Mechanisms involved in the formation and decadal change in the total ozone asymmetry, as well as possible influences of the asymmetry on the stratospheric thermal regimes and regional UV irradiance redistribution are discussed.

Keywords. Atmospheric composition and structure (Pressure, density, and temperature) – Meteorology and atmospheric dynamics (Middle atmosphere dynamics; Waves and tides)

1 Introduction

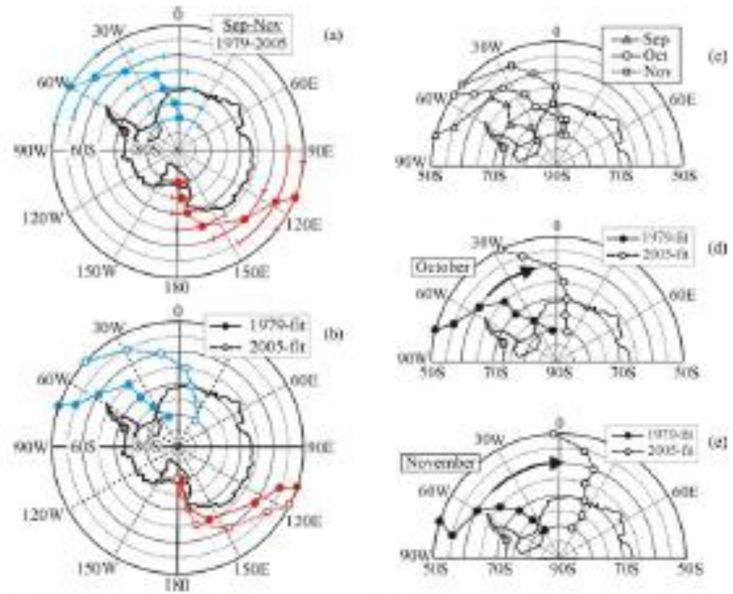

Fig. 6. **(a)** The 1979–2005 mean longitudinal position of the zonal wave extremes with the standard deviation bars; **(b)** initial (1979, closed circles) and final (2005, open circles) extreme positions obtained from the linear fits shown in Fig. 5; **(c)** monthly mean positions of zonal minimum for September (triangles), October (circles) and November (squares) and **(d, e)** eastward shift of zonal minimum during 1979–2005 in October and November, respectively, estimated by linear fit.

Ozone recovery: the TOC changes over Faraday/Vernadsky in the period 1957–2007: (a) annual means and (b) monthly means for Jan (dotted curve) and Sep (solid curve)

Backward movement of ozone minimum longitudinal position as a possible consequence of ozone recovery over Antarctica

Gennady Milinevsky[1], Asen Grytsai[1], Andrew Klekociuk[2], Oleksandr Evtushevsky[1]

[1]Kyiv National Taras Shevchenko University, Physical Department, Space Physics Laboratory, Kyiv, Ukraine

[2]Australian Antarctic Division, Kingston, TAS, Australia.

genmilinevsky@gmail.com

Abstract. Ozone hole over Antarctica is formed inside polar stratospheric vortex, which is under influence of large-scale planetary waves. Quasi-stationary wave (QSW) component in the spring Southern Hemisphere (SH) stratosphere is mainly contributed by zonal wave number 1 which in turn determines location of the total ozone extremes in spring: QSW minimum (maximum) is located in the South Atlantic (Australian) sector. Our previous studies have revealed decadal eastern drift in the longitudinal location of the total ozone minimum. Predicted ozone recovery over Antarctica could possibly lead to change in the longitudinal drift tendency. Using TOMS/OMI data 1979–2012 we have analyzed the monthly mean locations of the total ozone minimum in September–November over the latitudes 50–80S. By polynomial fit (order 3), the ozone minimum was the farthest east (near 0E) in early 2000s and it exhibits beckward (westward) motion later. Persistent Antarctic ozone losses during 1980s–1990s are known to be associated not only with strengthening of the zonal circulation in the SH stratosphere and longitudinal trends in total ozone zonal extremes, but also with delay in the breakdown of the SH polar vortex, summer surface warming in the Antarctic Peninsula region, and many other combined/competing effects. Model studies indicate that ozone recovery over Antarctica may reverse/delay/cancel these tendencies and our results is possible evidence of such changes in the QSW.

Due to the QSW influence, stratospheric polar vortex over Antarctica is displaced relative to the South Pole. The polar vortex center in spring moves off the Pole more than 10° by latitude and is typically shifts to the Atlantic longitudinal sector (Waugh and Randel, 1999).

On the decadal time scale, a tendency exists which is evidence of eastward rotation of the displaced vortex and related minimum in the zonal TOC/stratospheric temperature distributions (Grytsai et al, 2007; Lin et al., 2009).

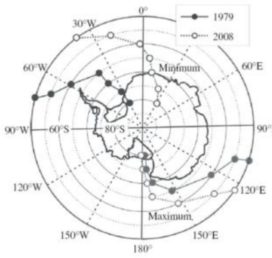

Figure 1. Decadal longitudinal displacements of the quasi-stationary wave maximum and minimum in the mean September–November TOC in the latitude range 50–80°S (Grytsai, 2010). Closed (open) circles mark initial and final locations of the QSW extremes during 1979–2008 from the linear trend of the time series at the individual latitudes with a 5°-step.

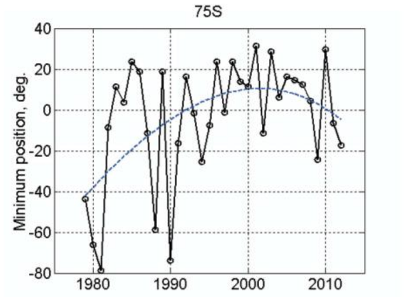

Figure 2. Interannual variability of the quasi-stationary TOC minimum longitude at 75°S (open circles and solid line) during 1979-2012 averaged through September-November. Dashed curve shows polynomial fit of degree 3.

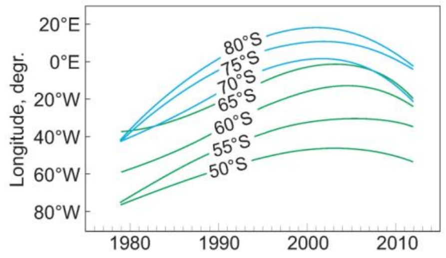

Figure 3. Decadal changes of the longitudinal position of QSW minimum in TOC distribution at 50-80°S from the polynomial fits applied to the time series 1979-2012. Blue (green) curves mark polar (subantarctic) latitudes.

It is seen that reverse motion of the zonal ozone minimum at polar latitudes 70-80°S started near 2000. This corresponds to decadal tendencies in the gradual rebound apparent in the springtime antarctic ozone changes and in evolution of calculated Equivalent Effective Antarctic Stratospheric Chlorine, EEASC (Salby et al., 2012).

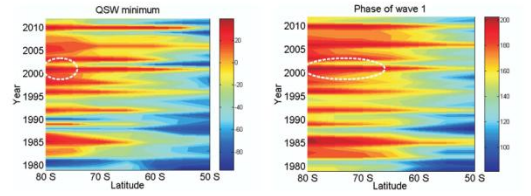

Figure 4. September–November mean longitudes of (a) the QSW minimum and (b) wave numbe 1 phase in the total ozone data in the latitude range 50–80°S.

White ovals show that, in the polar region (70-80°S), eastward shift in 1980s-1990s reached limited longitude of about 30°E in 2001 and moves westward later.

Conclusions: Eastward shift of zonal ozone minimum was accompanied by changes of stratospheric air masses over the stations located close to the vortex edge that contributes to detected ozone loss (Hassler et al., 2011). The results show that observed reverse of the zonal QSW shift and first indications of Antarctic ozone recovery may be coupled in future regional climate change of the Southern Hemisphere. These tendencies should be taken into account in observations and modeling.

Acknowledgements. This work was partly supported by Taras Shevchenko National University of Kyiv, project 11BF051-12, and by the Polar FORCeS project no. 4012 of the Australian Antarctic Science Program.

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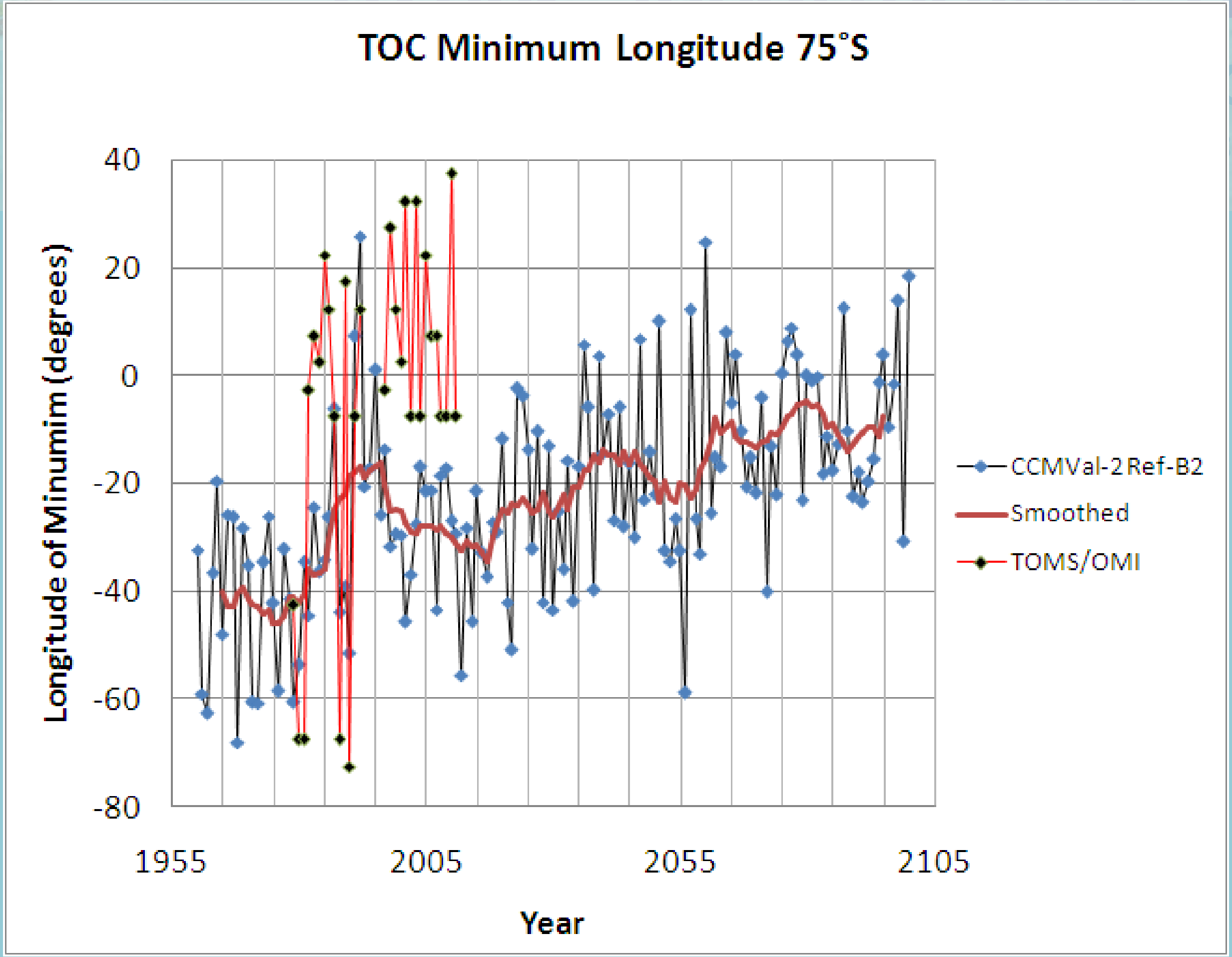
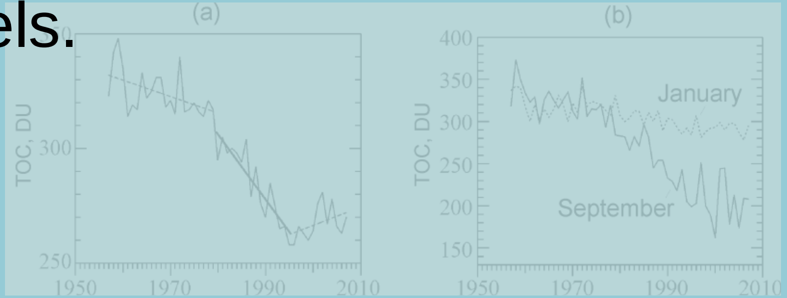
SCAR Action Group PACT and Polar FORCeS project 4012 of Australian Antarctic Science Program

Latest tendency in the Antarctic ozone longitudinal distribution



Comparison of multi-model mean of September–November TOC minimum longitude near 75°S from 8 CCMVal-2 Ref-B2 models.



Ozone recovery: the TOC changes over Faraday/Vernadsky in the period 1957–2007: (a) annual means and (b) monthly means for Jan (dotted curve) and Sep (solid curve).

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