Stratospheric ozone: satellite observations, data assimilation and forecasts

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1) Ozone and Numerical Weather Prediction

Assimilation of ozone at NWP centres

The major weather centres have programmes on ozone data assimilation
(extension of the models into the stratosphere/mesosphere)

- ECMWF
  - ERA-40 (TOMS, SBUV)
  - Operational (GOME, SBUV)
- NOAA/NCEP
- DAO (TOMS, SBUV)
- Meteo France (TOVS)
- UKMO, Univ.Reading (GOME, MLS)
- ...

Ozone assimilation in numerical weather prediction

Benefits for atmospheric chemistry science community:

Multi-year data base of 4D ozone fields,

- consistent with the available (satellite) observations,
- consistent with the dynamical state of the atmosphere

Science questions:

- Recovery ozone layer
- Chemistry - climate interaction

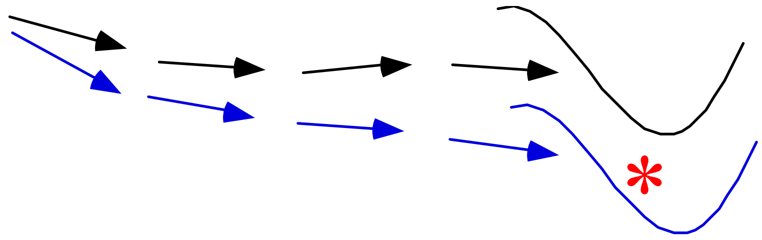
ECMWF ERA-40:

satellite observations 1978-present, TOMS, SBUV

Impact of ozone on NWP

Benefits of accurate ozone observations to numerical weather prediction

- Radiation: ozone has strong influence on temperature (and wind)
- Satellite retrieval: TOVS
- Assimilated ozone observations lead to wind increments
- UV forecast

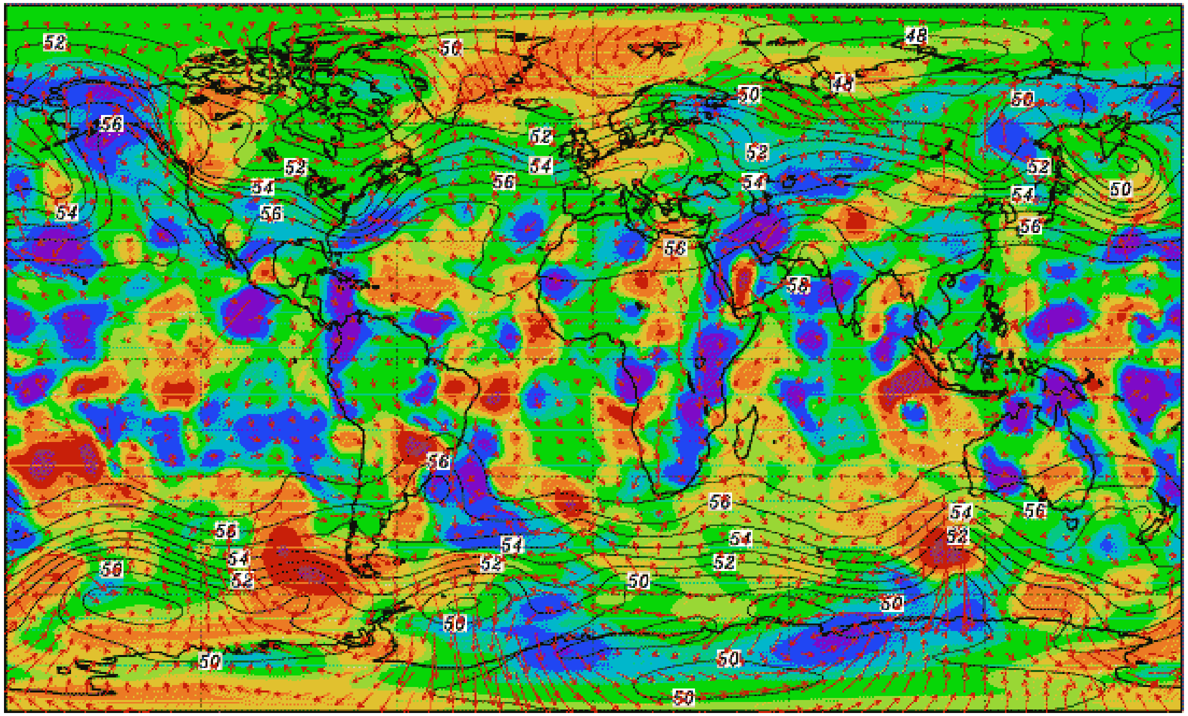


Impact of ozone on NWP

Wind increments
due to
TOVS ozone
observations

ECMWF model

(EU SODA project)

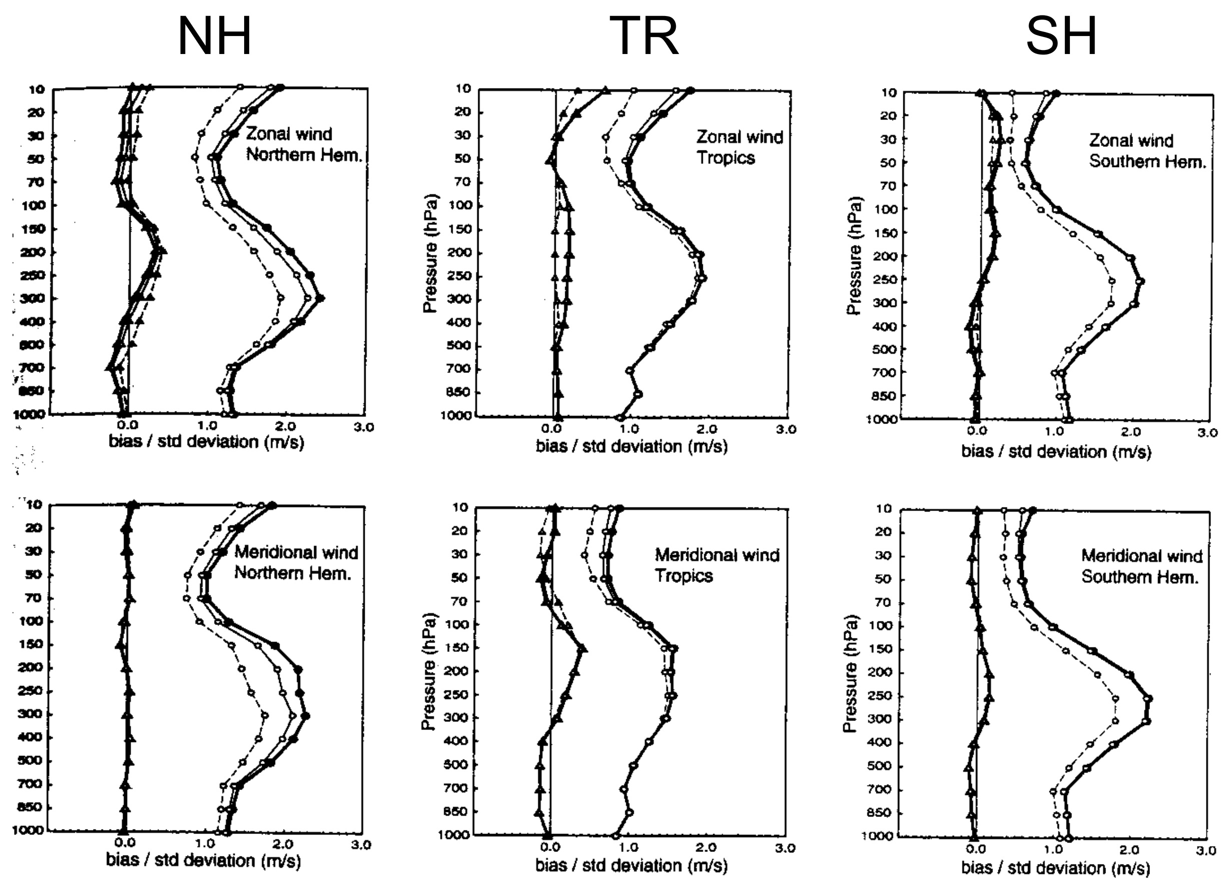


Wind increments ~ 0.5 m/s

OSSE: Impact of TOVS column retrievals on winds

Zonal wind

Merid. wind



A. Peuch et al, QJRMS 126, 1641, 2000

top story Goddard Space Flight Center

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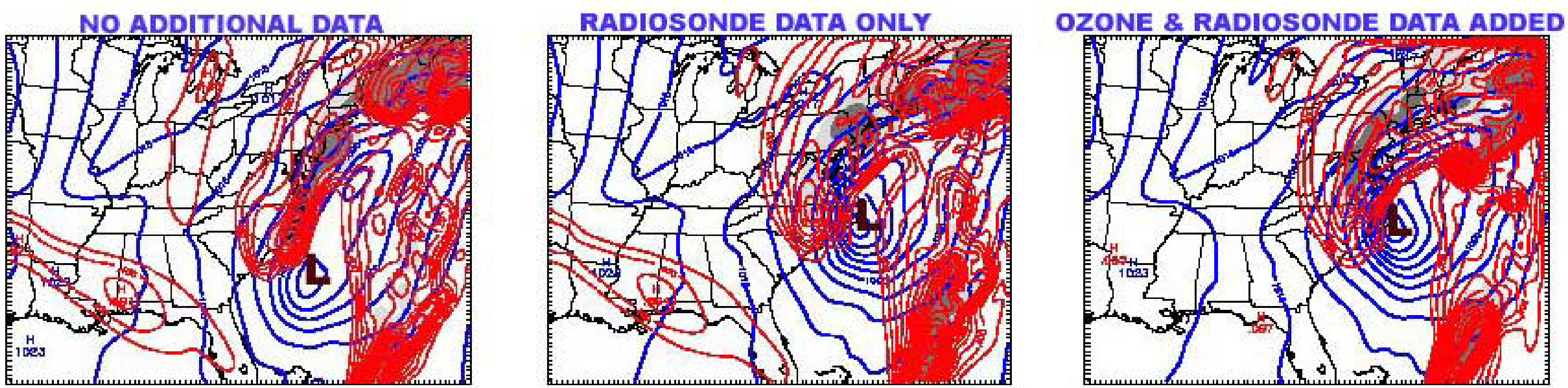
August 07, 2003- (date of web publication)

NASA OZONE SATELLITE IMPROVES SNOWSTORM FORECASTS

With TOMS data



Jang et al, J.Appl.Meteorol. 42, 2003

2) Satellite observations of ozone

Satellite instruments

UV-Vis nadir

- TOMS (1978-present), SBUV, SBUV-2, GOME, SCIAMACHY

Occultation

- HALOE, SAGE, POAM, GOMOS

Limb (IR, MW, UV-Vis)

- MLS on UARS, MIPAS, OSIRIS, SMR

Nadir (IR)

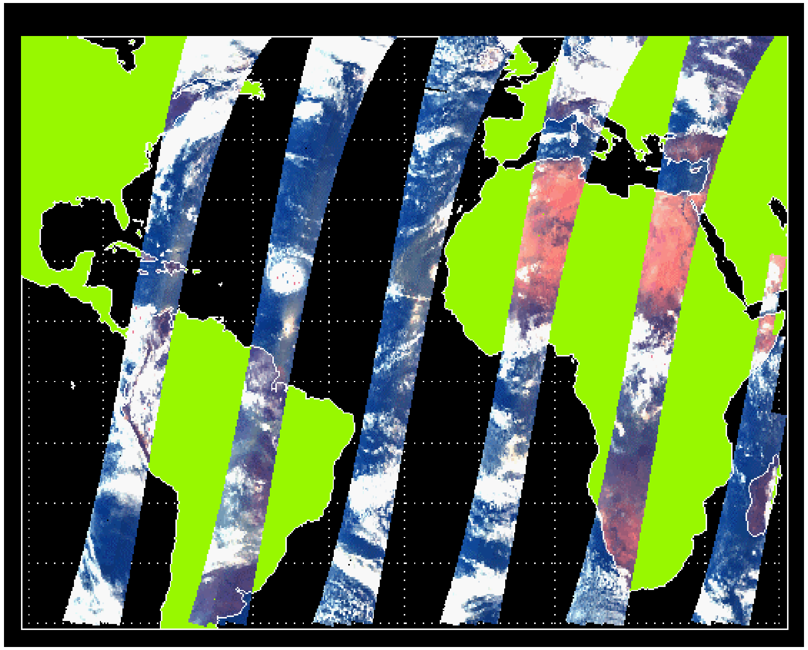
- TOVS, AIRS

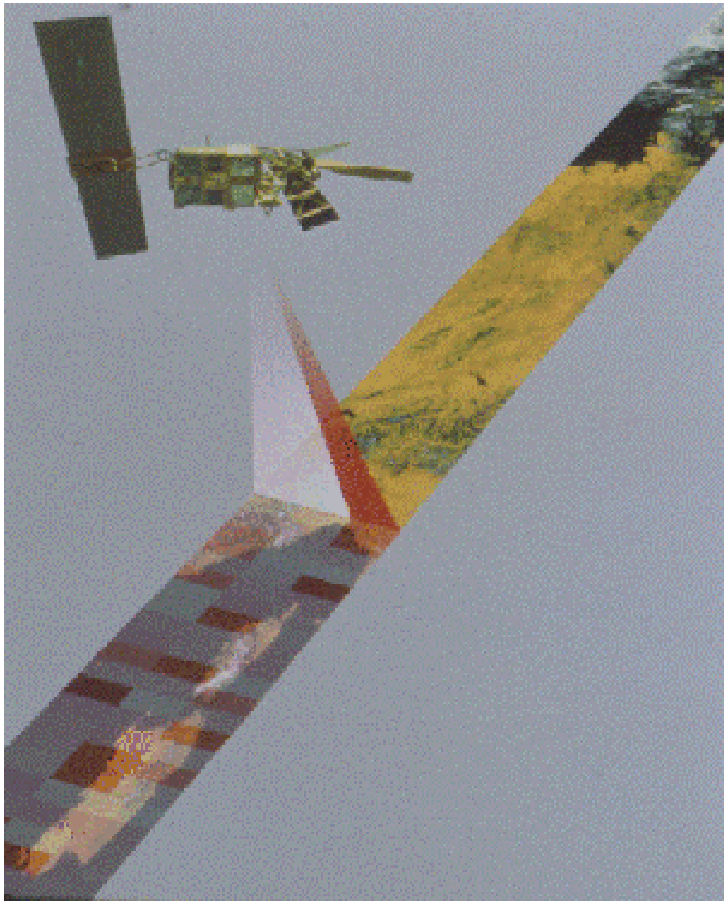
Information on the troposphere:

TOMS, GOME, SCIAMACHY

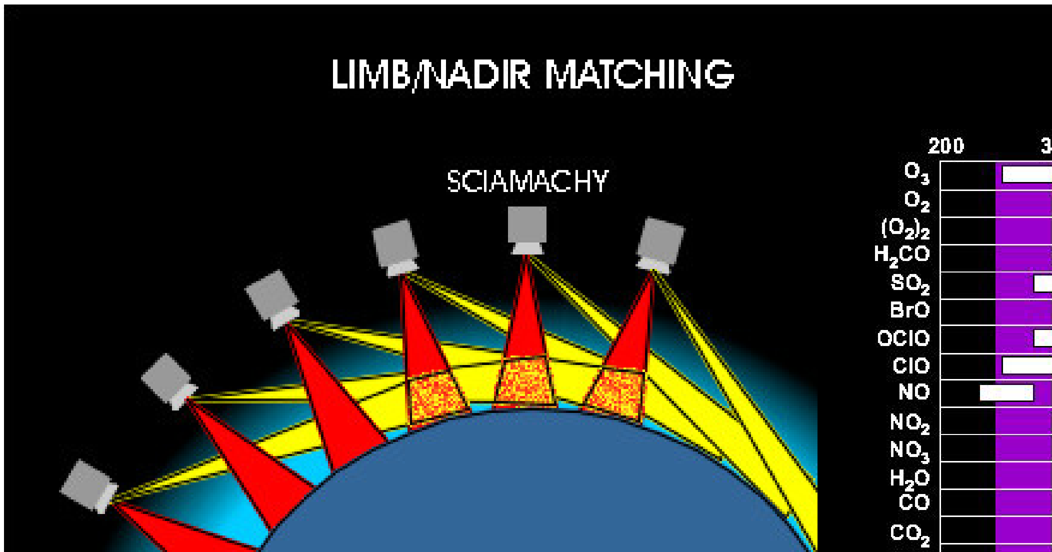
Ground-based observations

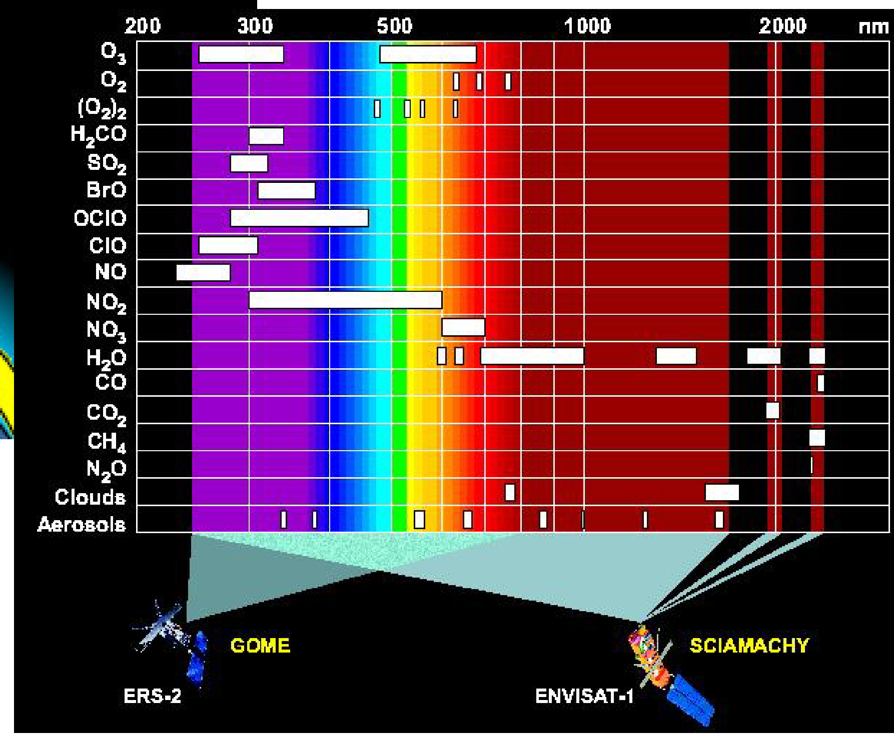
GOME on ERS-2, 1995 -





SCIAMACHY on ENVISAT, 2002 -

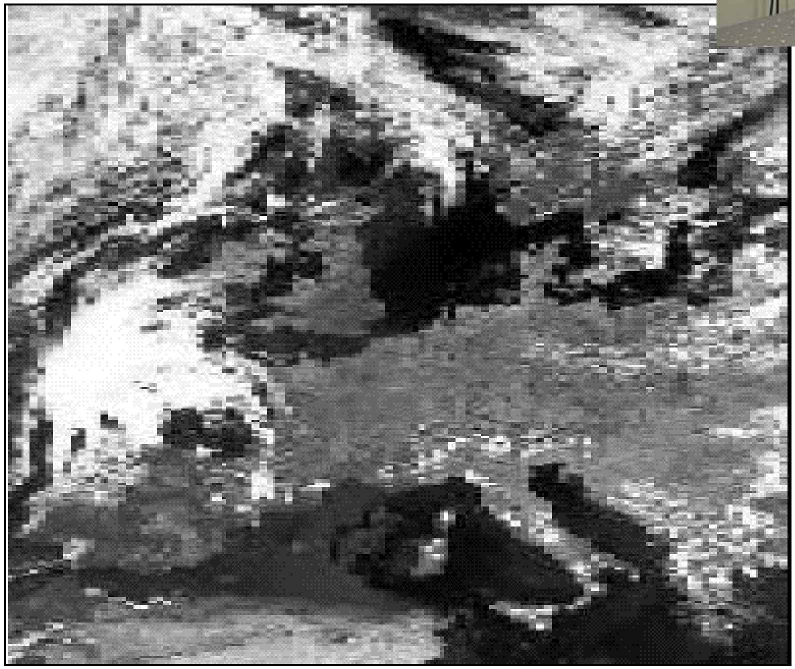


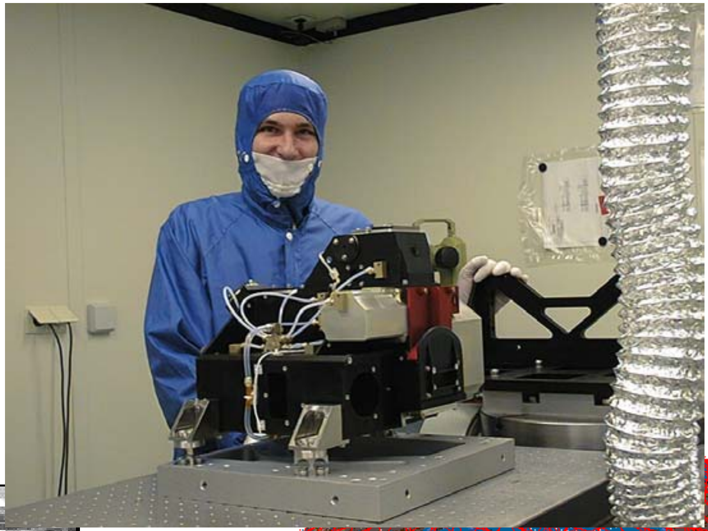


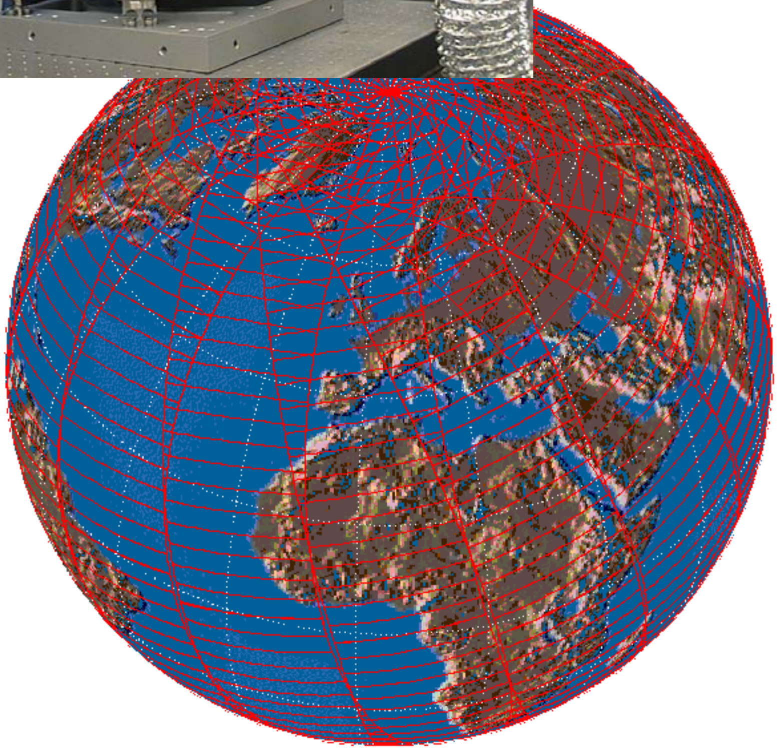
Troposfeer & stratosfeer

- O_3, NO_2, H_2CO, SO_2
- CH_4, CO, CO_2

OMI on EOS-AURA, 2004 -

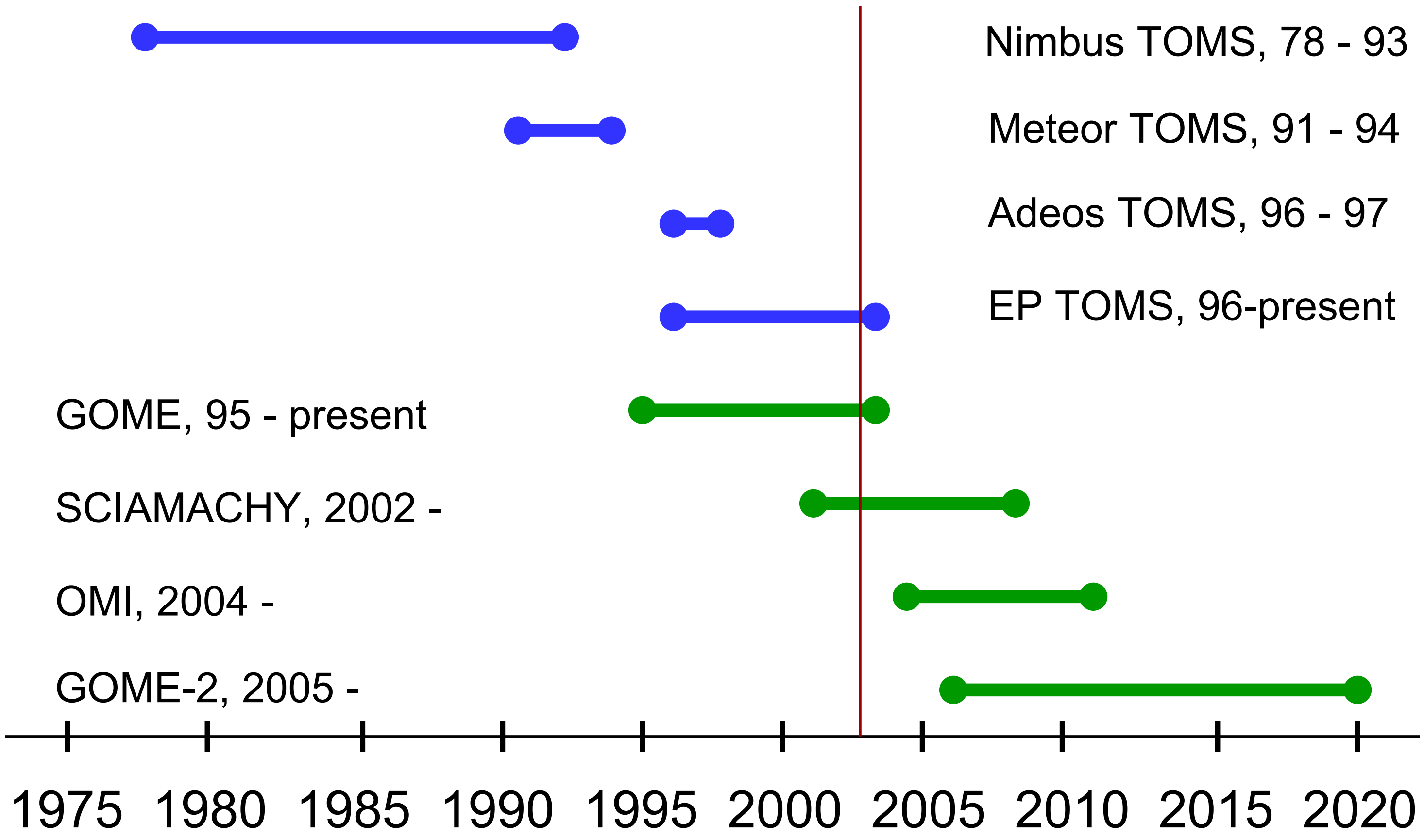






GOME-2 on METOP, 2005-2020

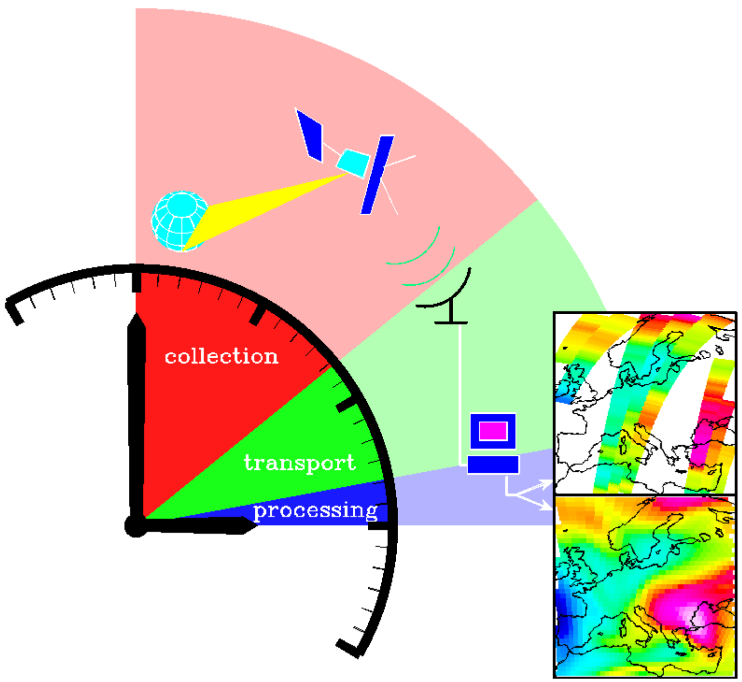
Ozone column measurements, 1978 - 2020



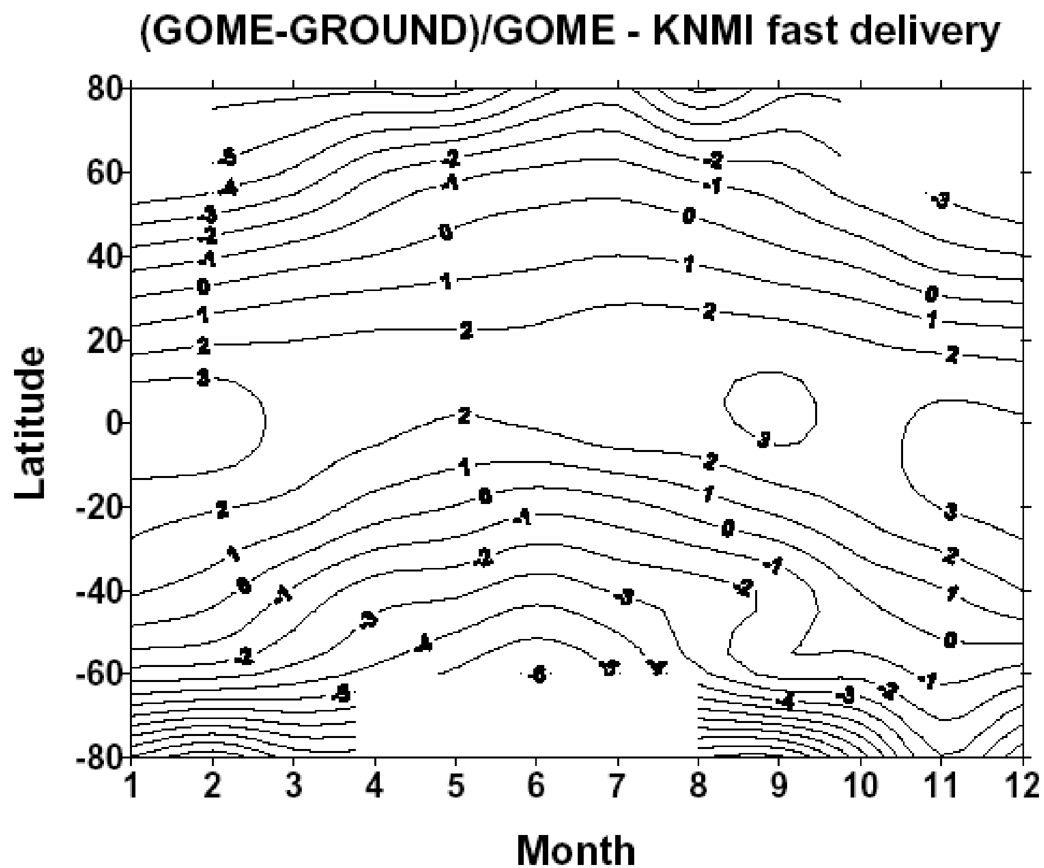
3) Retrieval

KNMI/ESA GOME Fast Delivery total ozone product

- Availability of ozone observations in less than 3 hours after the measurement (ESA Data User Programme)
- Used in ECMWF operational analyses



KNMI/ESA GOME Fast Delivery total ozone product



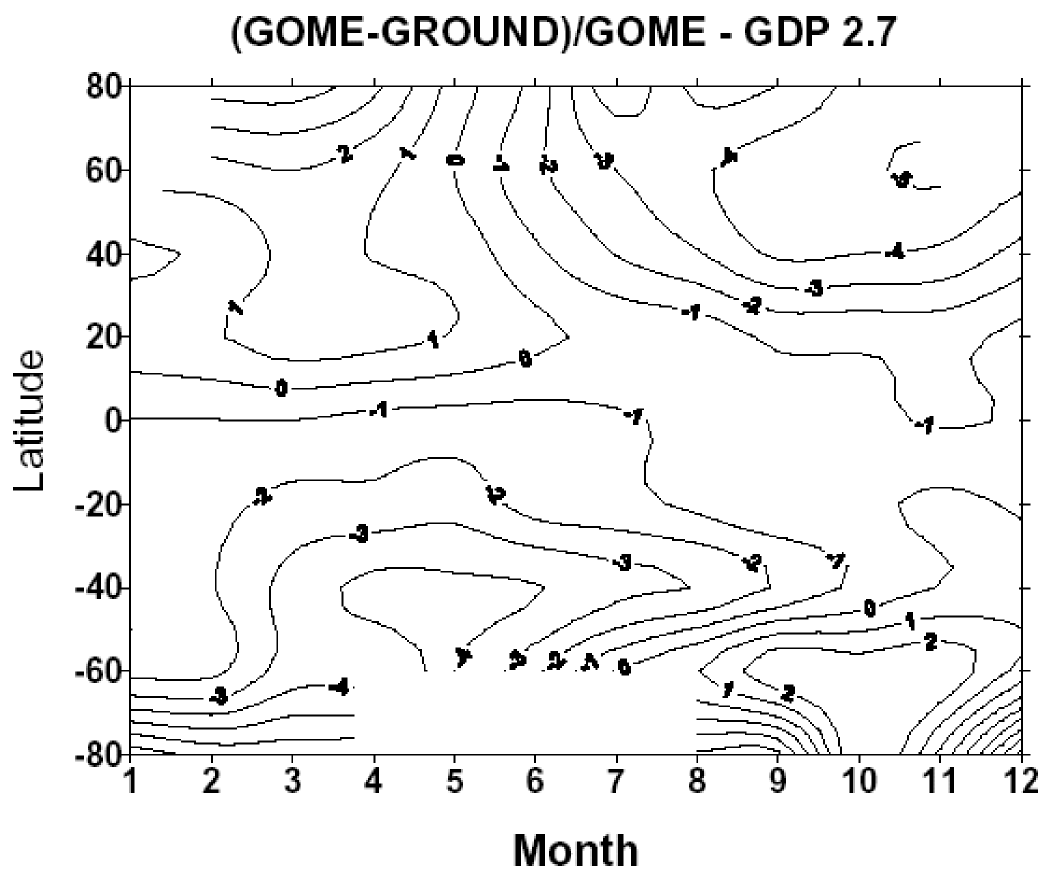
Validation:

Dimitris Balis, LAP

Fast Delivery vs.3

KNMI

ESA/DLR GOME Data Processor

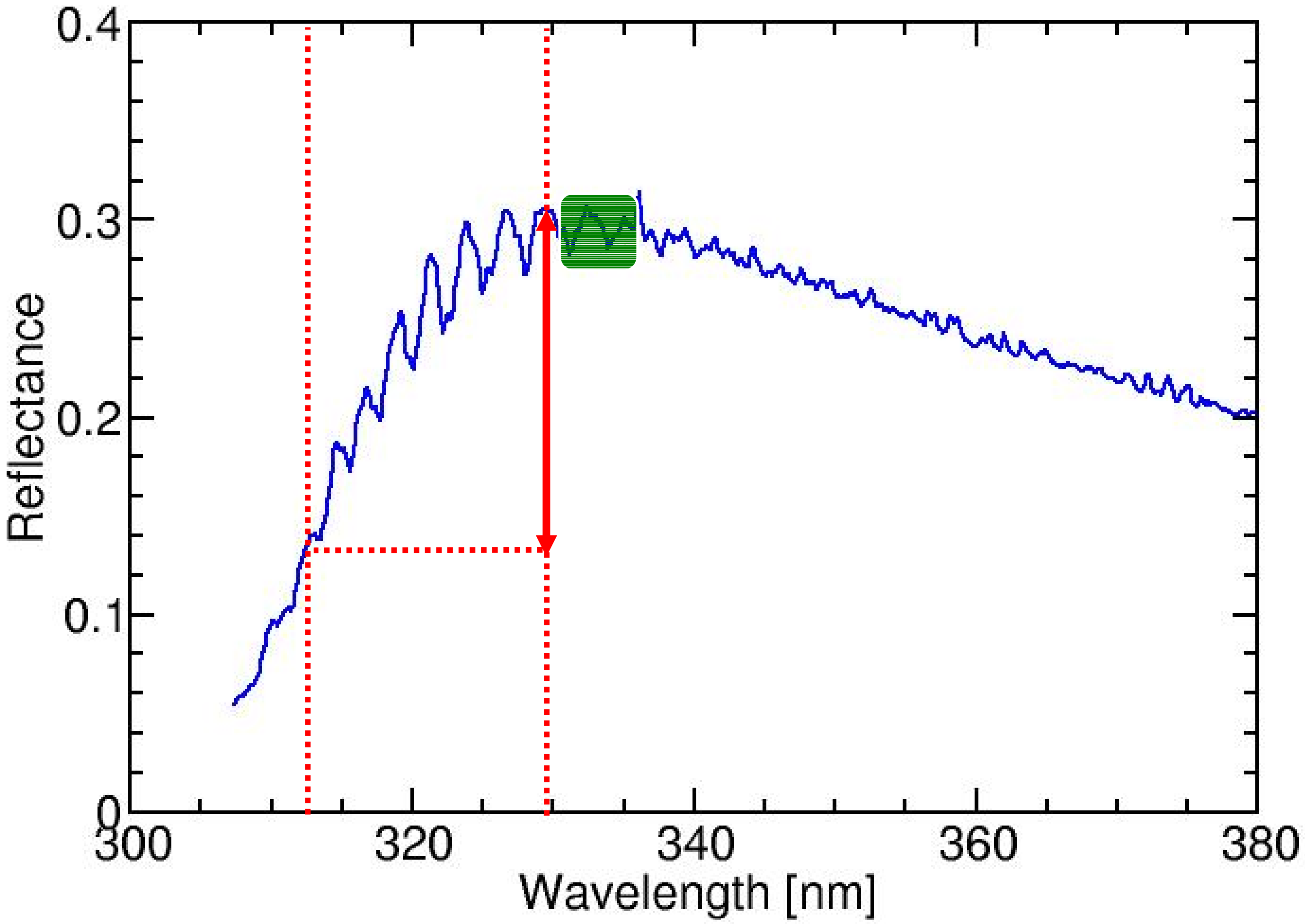


Validation:

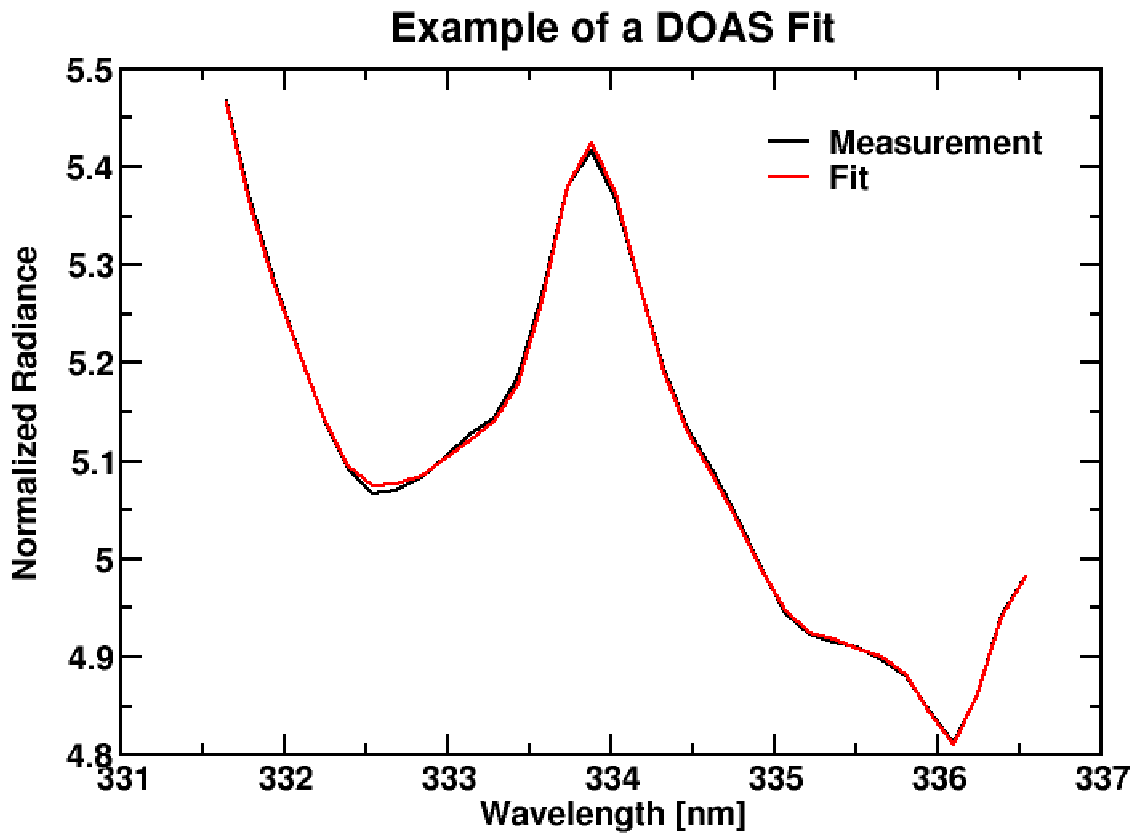
Dimitris Balis, LAP

DLR GDP v2.7

Ozone retrieval: TOMS retrieval vs. DOAS



Ozone retrieval: DOAS



First OMI ozone measurements

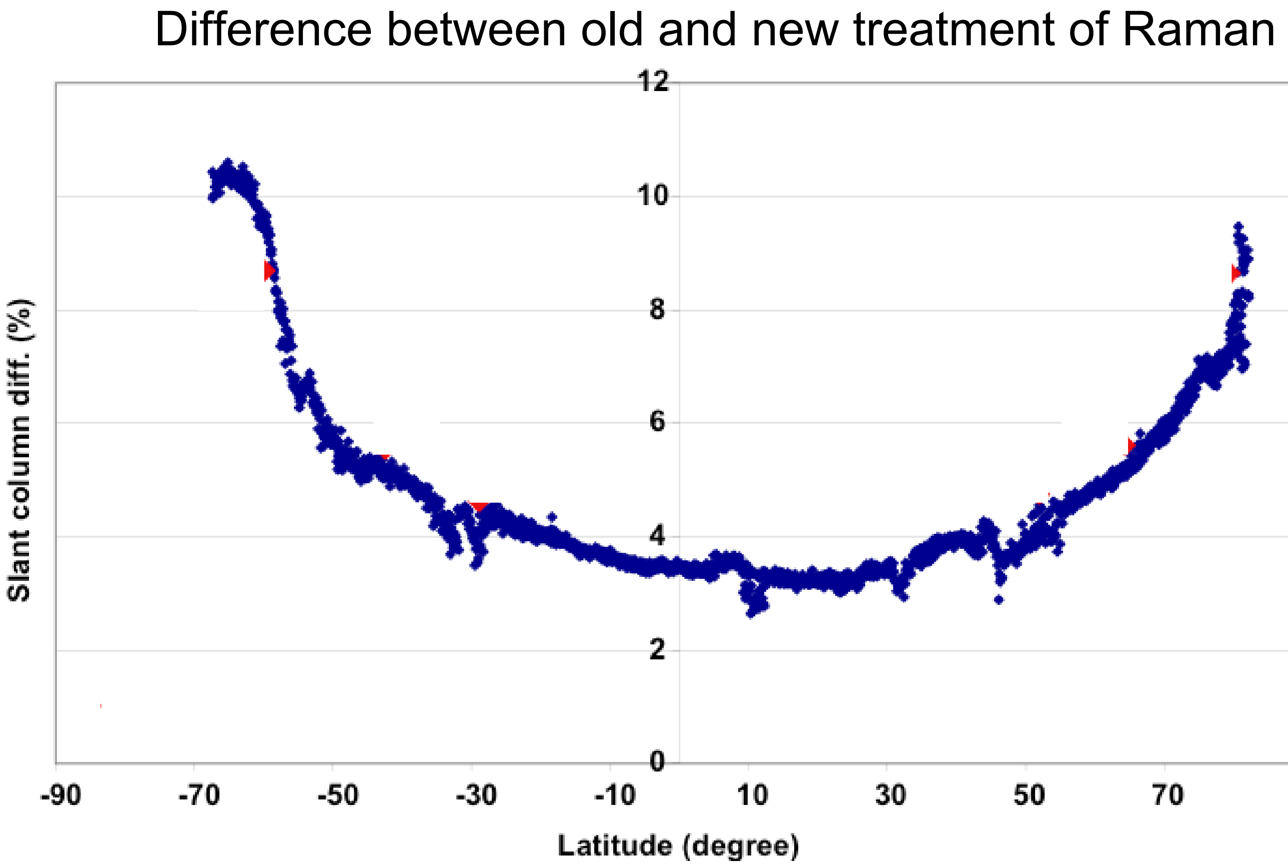
Ozone retrieval: new DOAS algorithm

Based on the OMI-DOAS operational algorithm (P. Veefkind)
Implementations for GOME (P. Valks) and Sciamachy

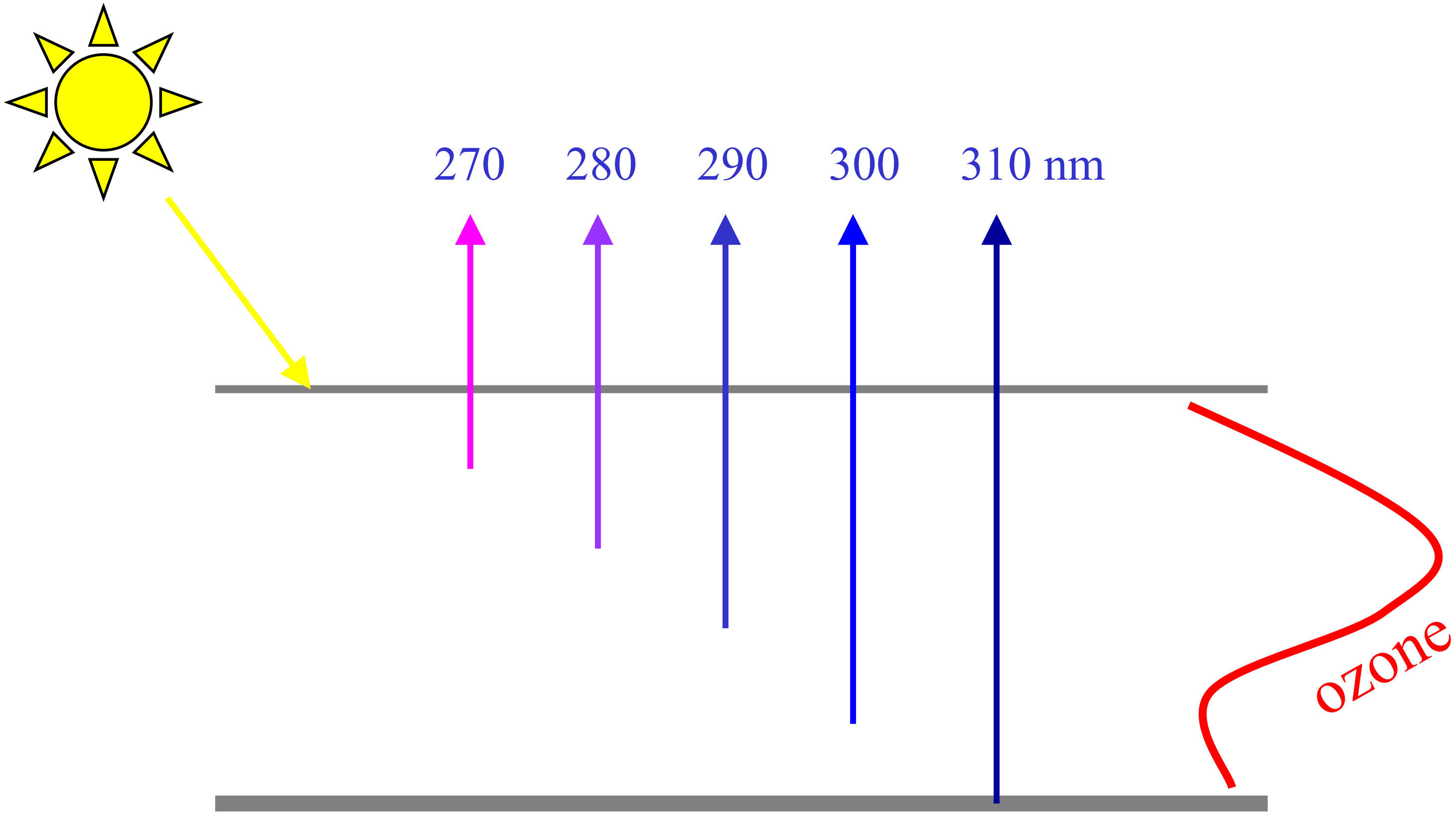
Innovations compared to Fast Delivery, vs 3

- New treatment of Raman scattering (J. de Haan)
- Empirical air-mass factor approach
- Wavelength window - reduced T dependence
- TOMS v8 ozone profile data base
- Radiative transfer improvement

New approach to Raman scattering



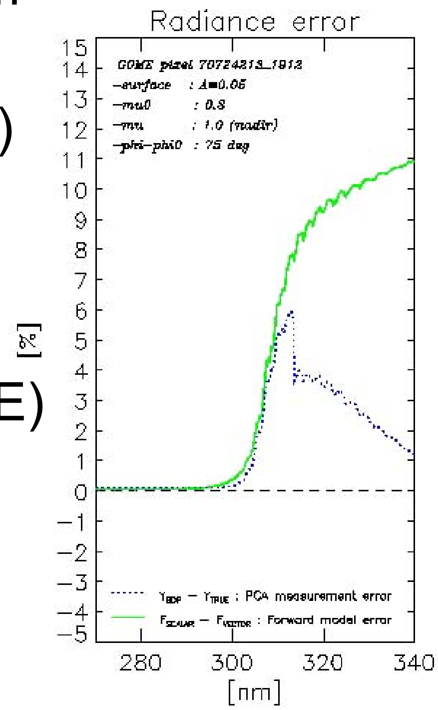
Ozone nadir profile retrieval

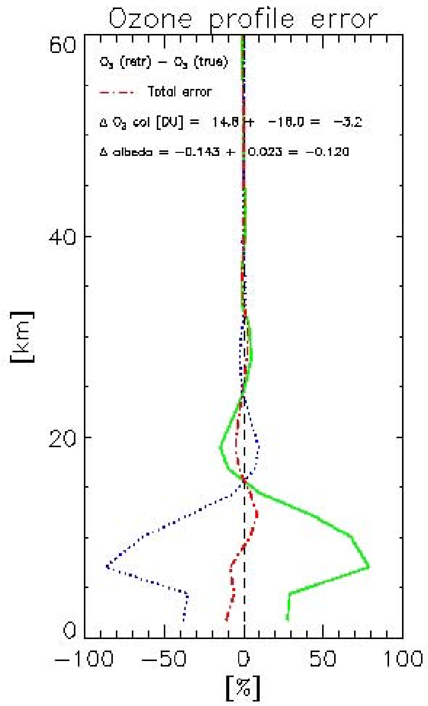


Ozone profile retrieval: challenges

Understanding/ Explaining spectrum

- Radiation modelling:
  - ✓Raman scattering (*Ring effect*)
  - ✓Spherical atmosphere
  - ✓Polarisation





- Instrumental characteristics (GOME)
  - ✓Degradation
  - ✓Radiometric calibration
  - ✓Wavelength calibration
  - ✓Polarisation correction

4) Ozone assimilation

GOME ozone assimilation: motivation

- Extend the use of GOME data (level-4 products)
  - 4D ozone data base
  - global synoptic maps every 6 hours
- Feedback on error statistics
  - Quality of observations
  - Quality of model
- Participation in satellite validation
- Ozone forecasts
- Case studies, e.g. mini-holes, 2002 ozone hole break-up

GOME ozone assimilation

Chemistry-transport assimilation model TM3DAM:

- GOME data: KNMI NRT ozone columns
- 2.5 degree resolution, 44 layers
- ECMWF meteo (60 layer)
- Prather second moment advection
- Parameterised stratospheric chemistry
  - Gas-phase
  - Heterogeneous
- Detailed forecast error modelling

Stratospheric chemistry parametrization

Gas-phase chemistry

Cariolle, Déqué, JGR 91, 10825, 1986

$$\frac{d\chi}{dt} = \langle S \rangle + \left\langle \frac{\partial S}{\partial \chi} \right\rangle (\chi - \langle \chi \rangle) + \left\langle \frac{\partial S}{\partial T} \right\rangle (T - \langle T \rangle) + \left\langle \frac{\partial S}{\partial \Phi} \right\rangle (\Phi - \langle \Phi \rangle)$$

- χ ozone concentration
- S sources - sinks
- Φ ozone column above point

Stratospheric chemistry parametrization

Heterogeneous chemistry

(Peter Braesicke, CAS, Cambridge Univ.)

$$\frac{d\chi}{dt} = -\frac{1}{\tau} A\chi$$

$$\frac{dA}{dt} = \frac{1}{\tau_p}(1-A) - \frac{1}{\tau_l} A$$

χ	ozone concentration
A	activation tracer field (cold tracer)
τ	ozone depletion time scale
τ_p	activation time scale
τ_l	cold tracer life time

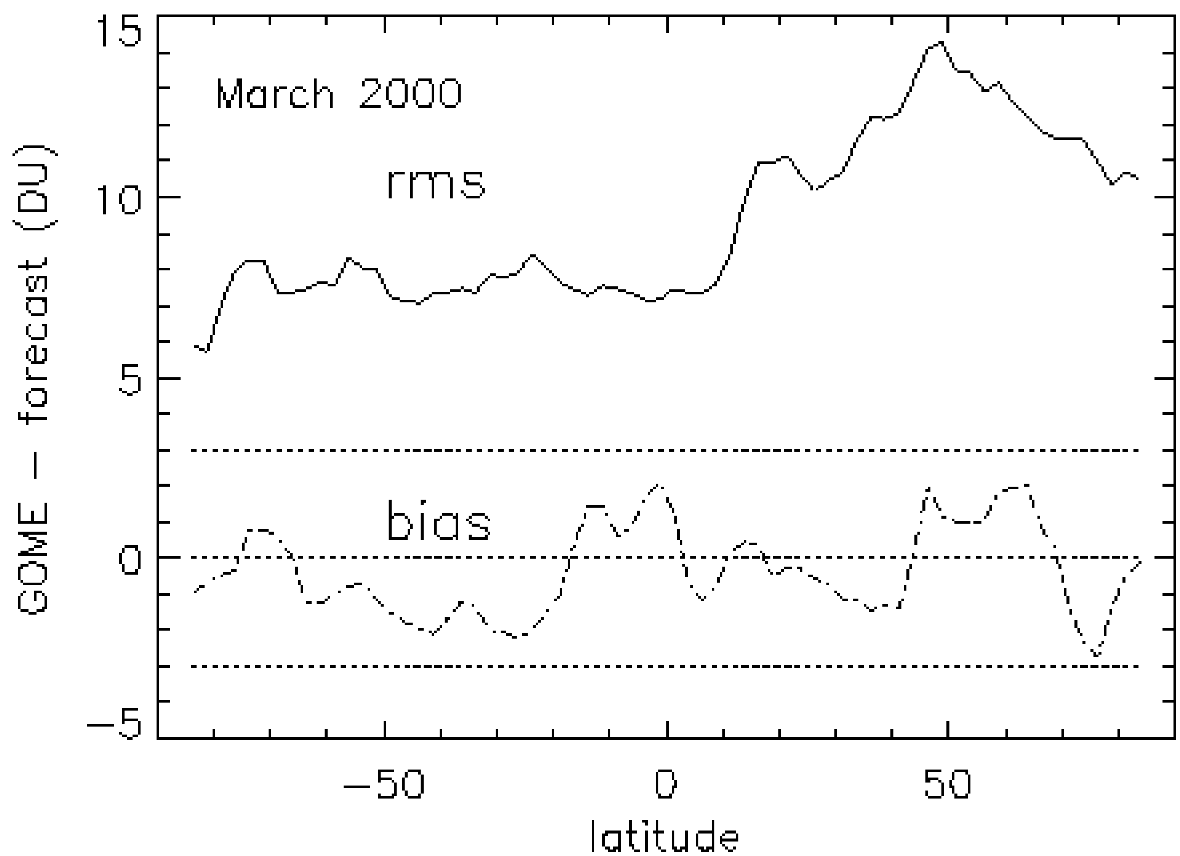
Stratospheric chemistry

A serious chemistry scheme for the stratosphere involves order 40 transported species - very expensive for NWP

Alternative:
Import ozone production and loss rates from a lower resolution CTM

$$\frac{\partial \chi}{\partial t} = P - \frac{1}{\tau_{loss}} \chi$$

Observation minus forecast statistics

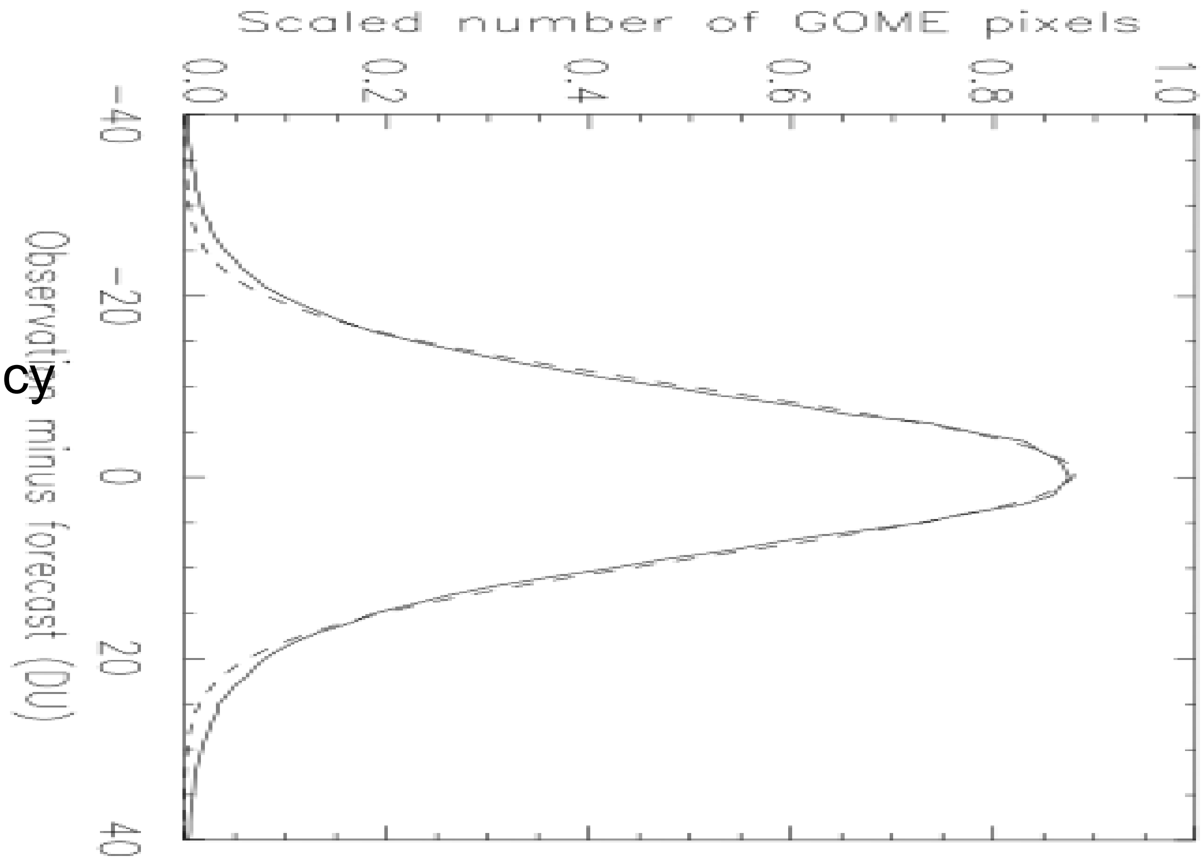


Gaussian statistics

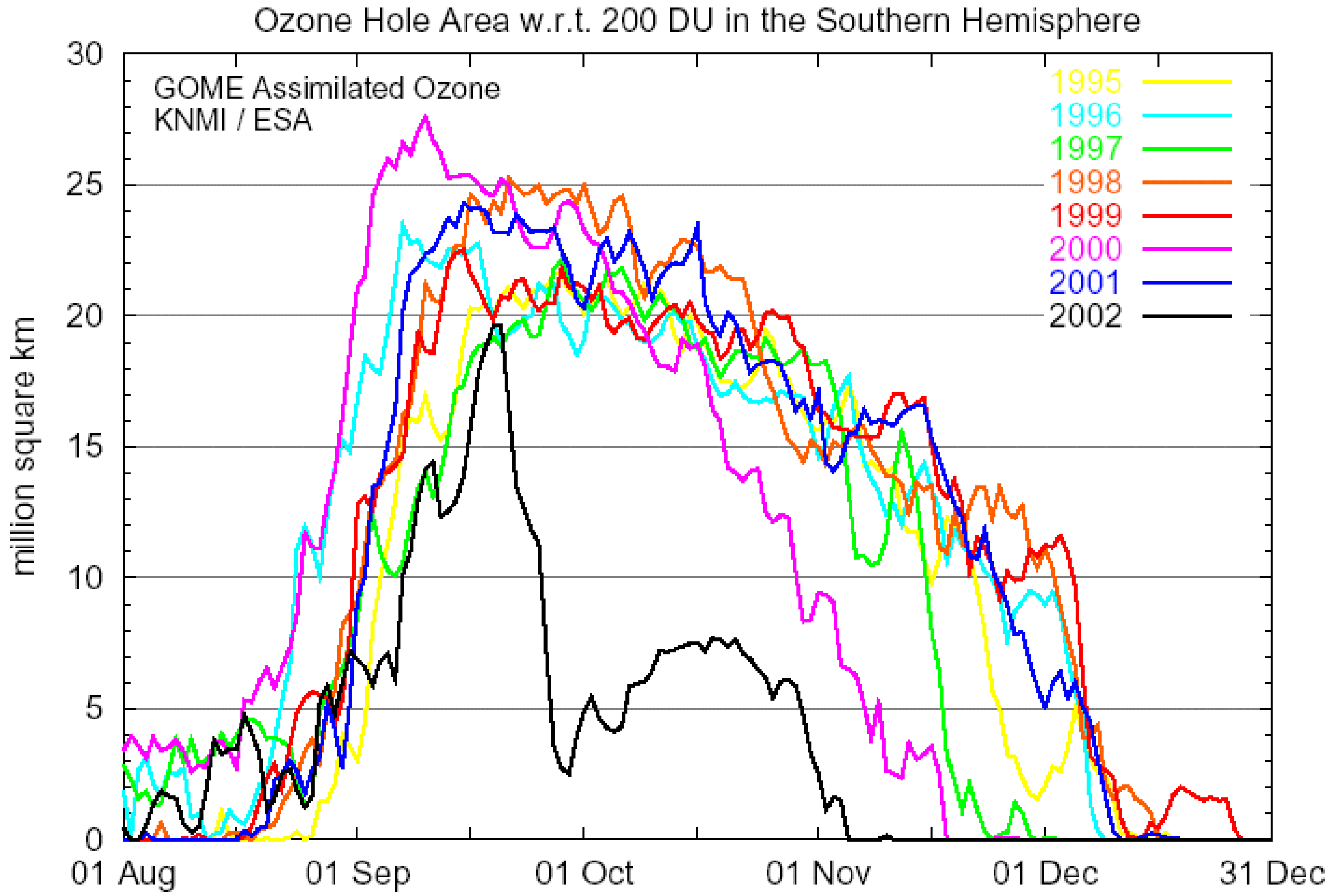
Internal consistency GOME data

Low noise (< 2%)

No quality control needed



7 year GOME data set http://www.knmi.nl/goa

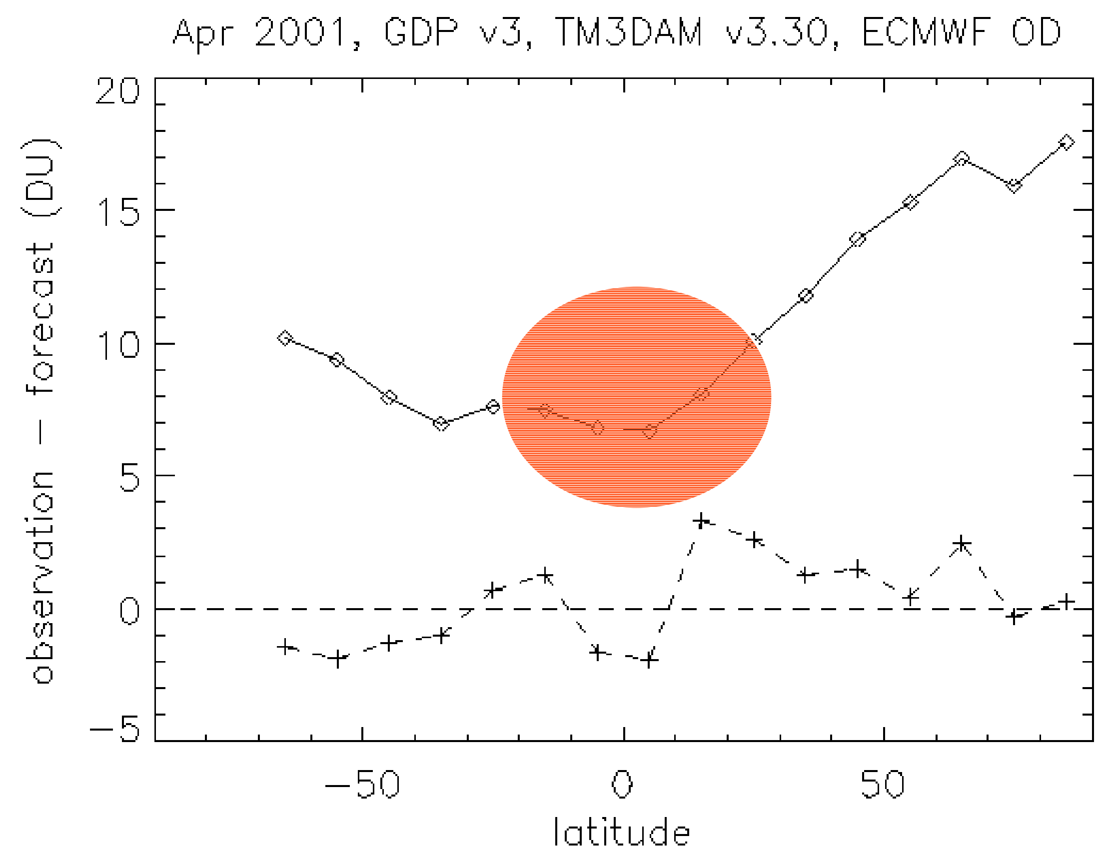


5) Residual circulation and trace gas distributions: Brewer-Dobson, STE

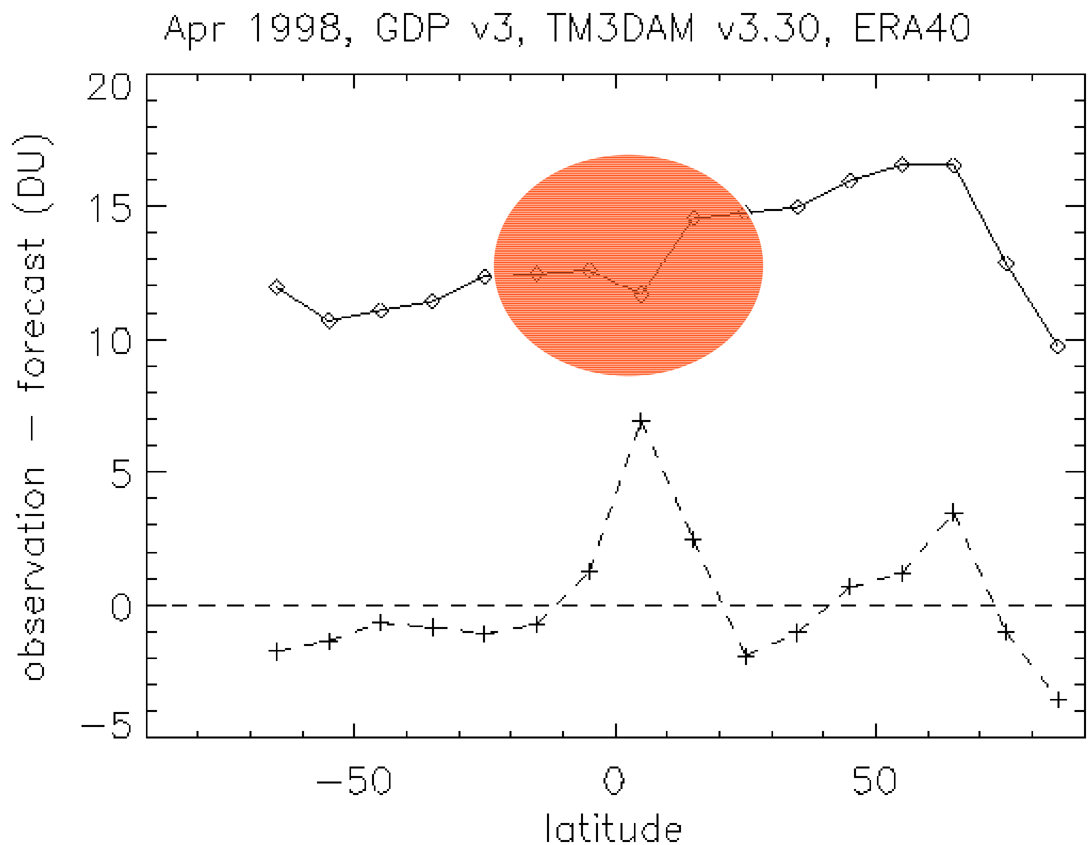
Ozone assimilation: dependence on ECMWF meteorology

- ERA-40 (1995-1999)
- OD (1999-2002)

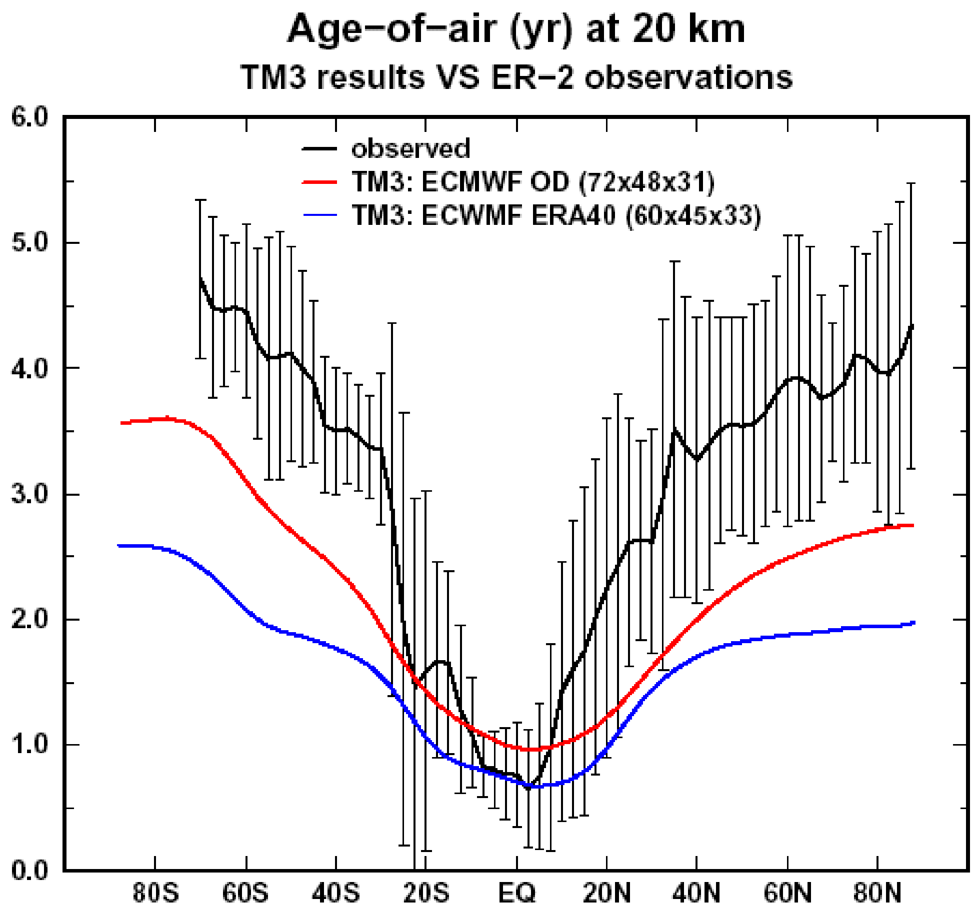
Observation minus forecast statistics: ECMWF OD



OmF vs latitude, GDP3, ECMWF ERA-40



Age of air

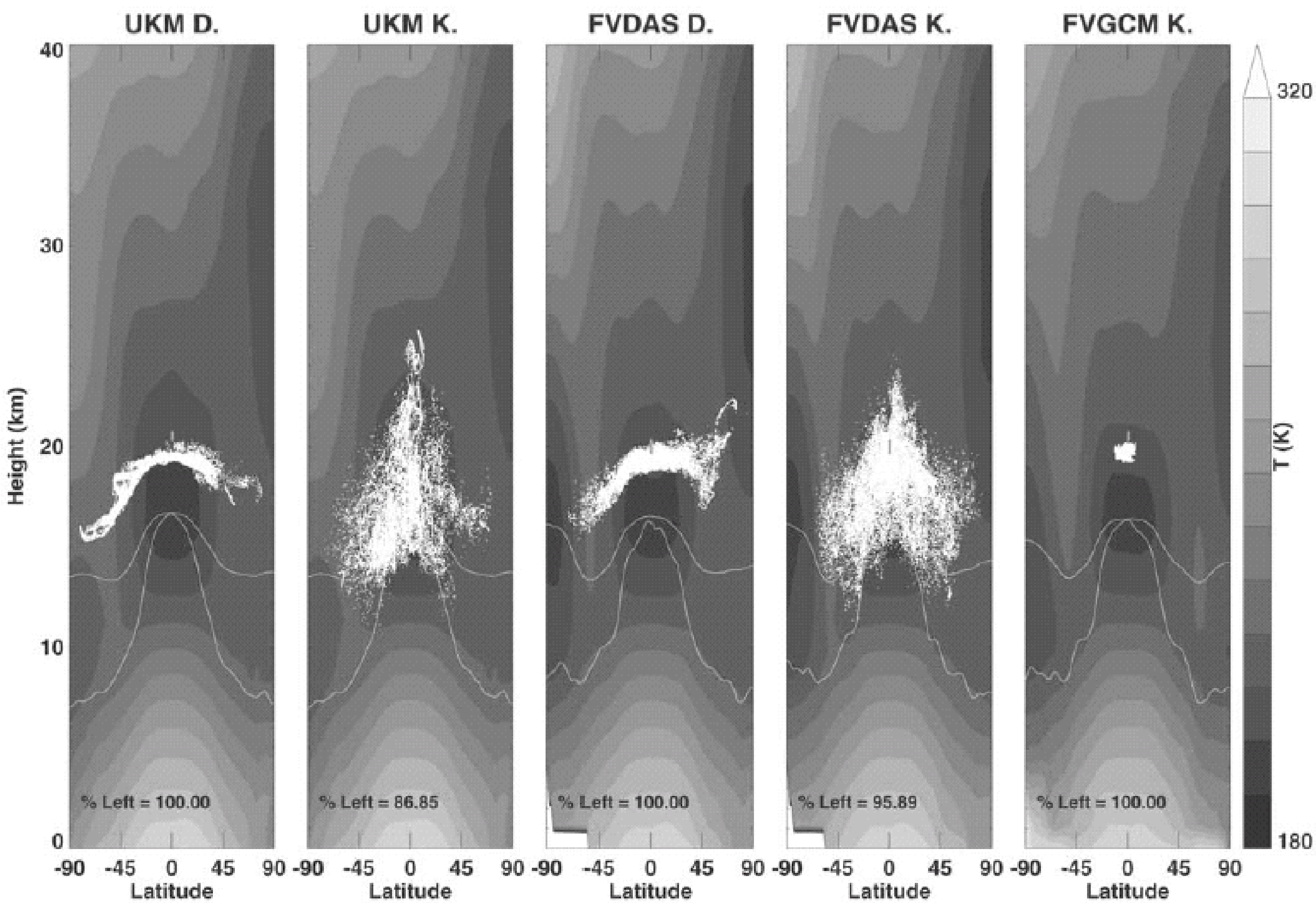


Bram Bregman, proc. ozone symp, Goteborg, 2002

Ozone flux from the stratosphere (TM3 CTM)

Simulation	Stratospheric influx (Tg/year)
OD 2001	568
OD 2000	611
OD 1996	575
ERA40 1996	1329
ERA40 1993	1155
ERA15 1993	530
ERA40 1991	1168
ERA40 1974	1055

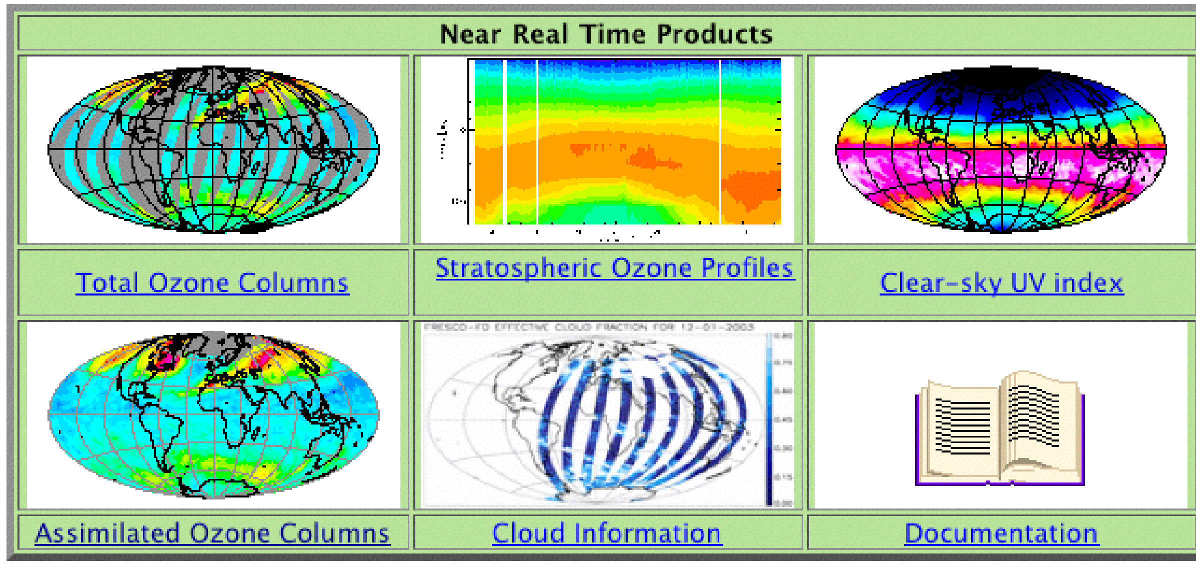
Trajectory study: Schoeberl et al, jgr 108, 2003



6) Ozone forecasts, based on GOME total ozone

http://www.knmi.nl/gome_fd

GOFAP project (ESA-DUP)



Products:
¥ **NRT GOME level-2 ozone columns**
¥ **NRT ozone profiles**
¥ **Cloud properties (Fresco)**
¥ **Clear-sky UV index**
¥ **Assimilated ozone fields (level-4)**
¥ **Daily ozone and UV forecasts**
¥ **Data base of assimilated fields, 1999-2002**
¥ **Ozone hole statistics**

http://www.knmi.nl/gome_fd
(service discontinued 22 June 2003)

KNMI Ozone analyses and forecasts

- Transport-chemistry model for ozone
  driven by ECMWF meteorlogical analyses and forecasts
- GOME ozone data
  near-real time
- Data assimilation scheme
  sub-optimal Kalman filter

--> Daily ozone analyses and 5-day forecasts (9-day from 2002)

Anomaly correlation, RMS error

Anomaly correlation

$C = \langle (f-c)(a-c) \rangle \; / \; \sqrt{\langle (f-c)^2 \rangle} \sqrt{\langle (a-c)^2 \rangle}$

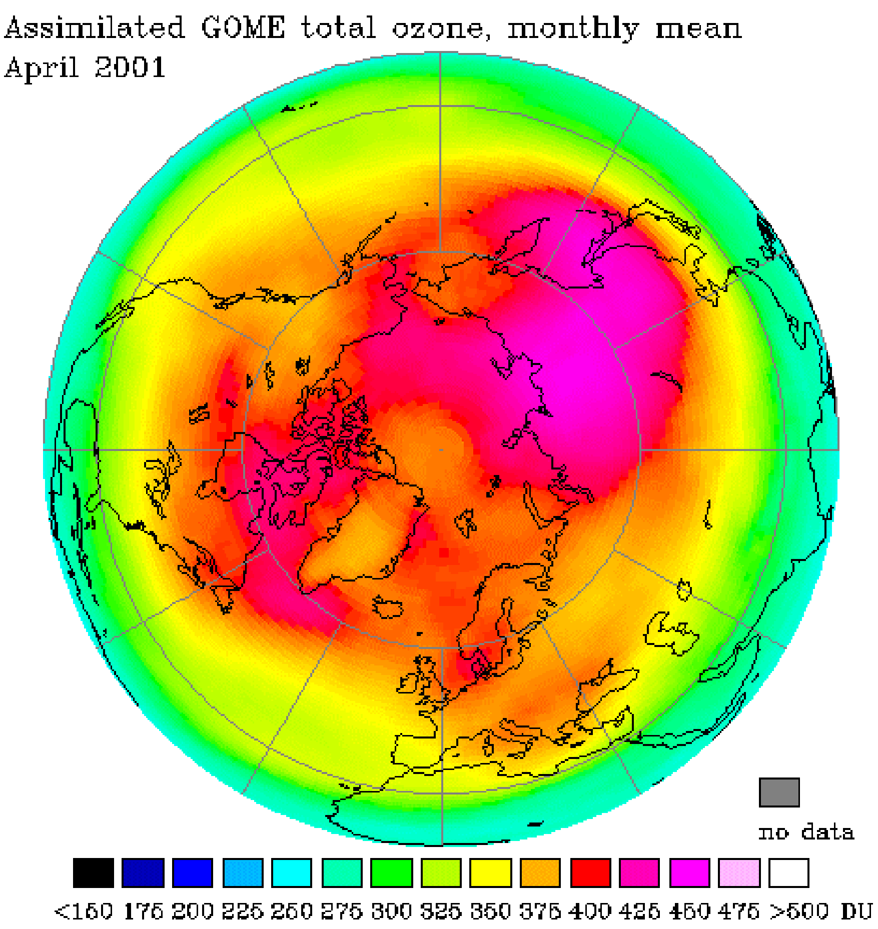
Root mean square error

$E = \sqrt{\langle (f-a)^2 \rangle}$

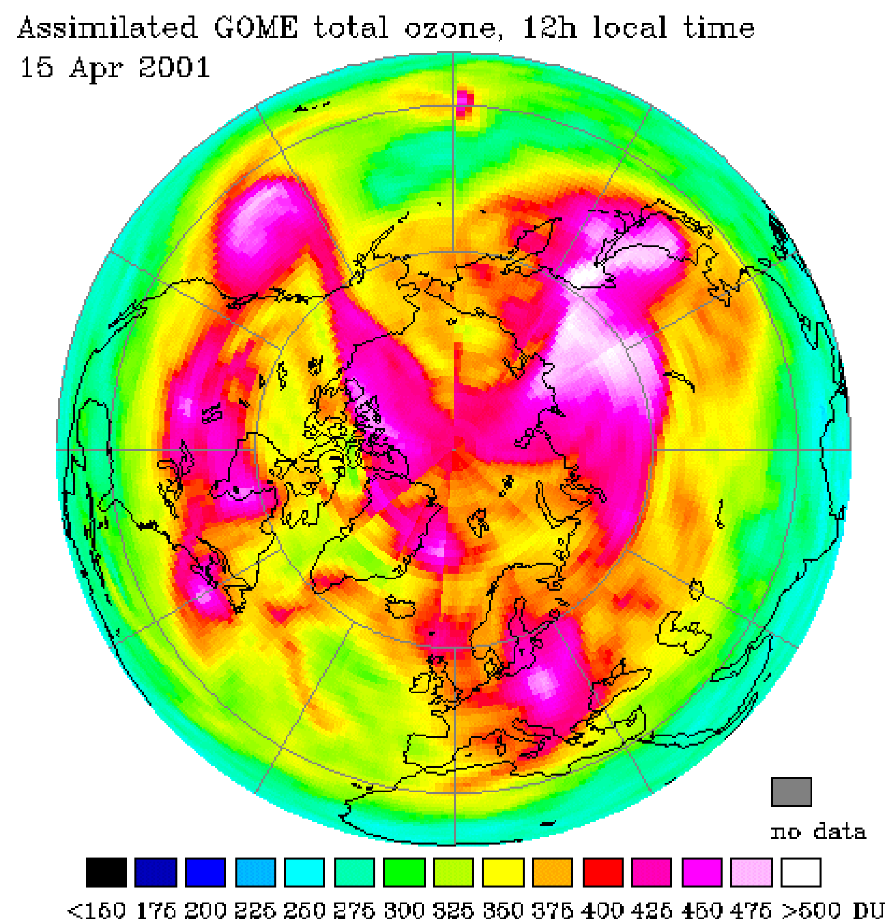
(f = forecast, a = analysis, c = climatology)

- Anomaly defined w.r.t. climatology "c" :
  Not useful for ozone - artificially high scores
- Alternative: "c" = running monthly mean

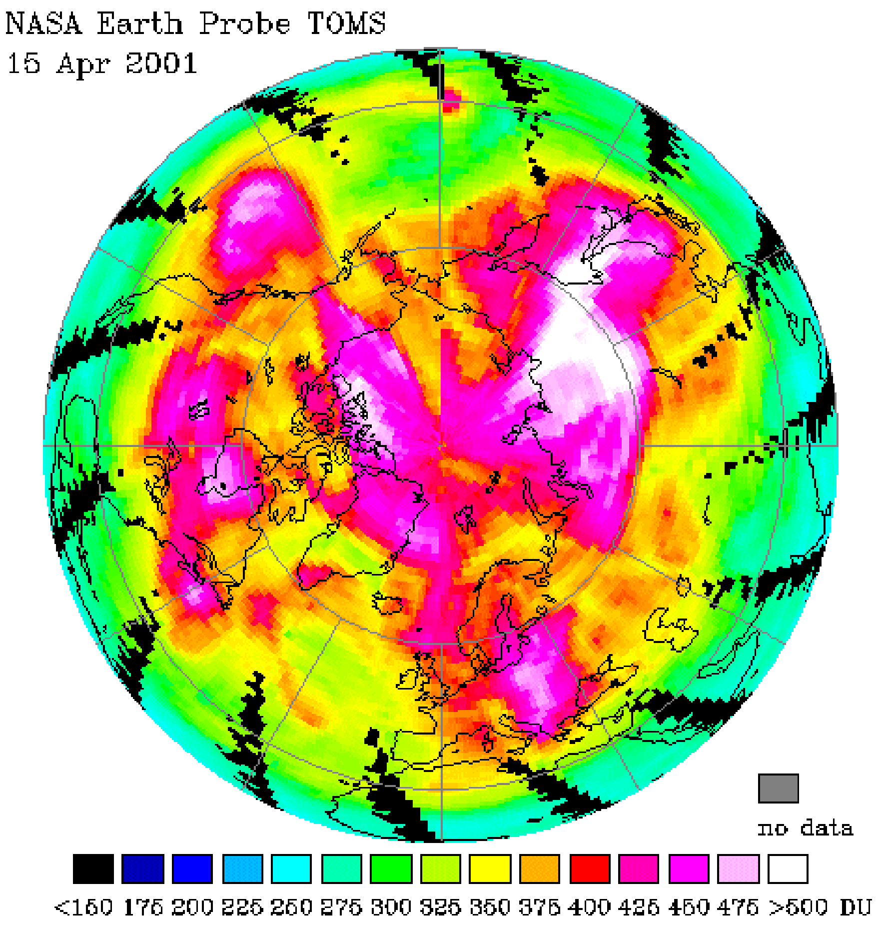
April 2001
Monthly mean



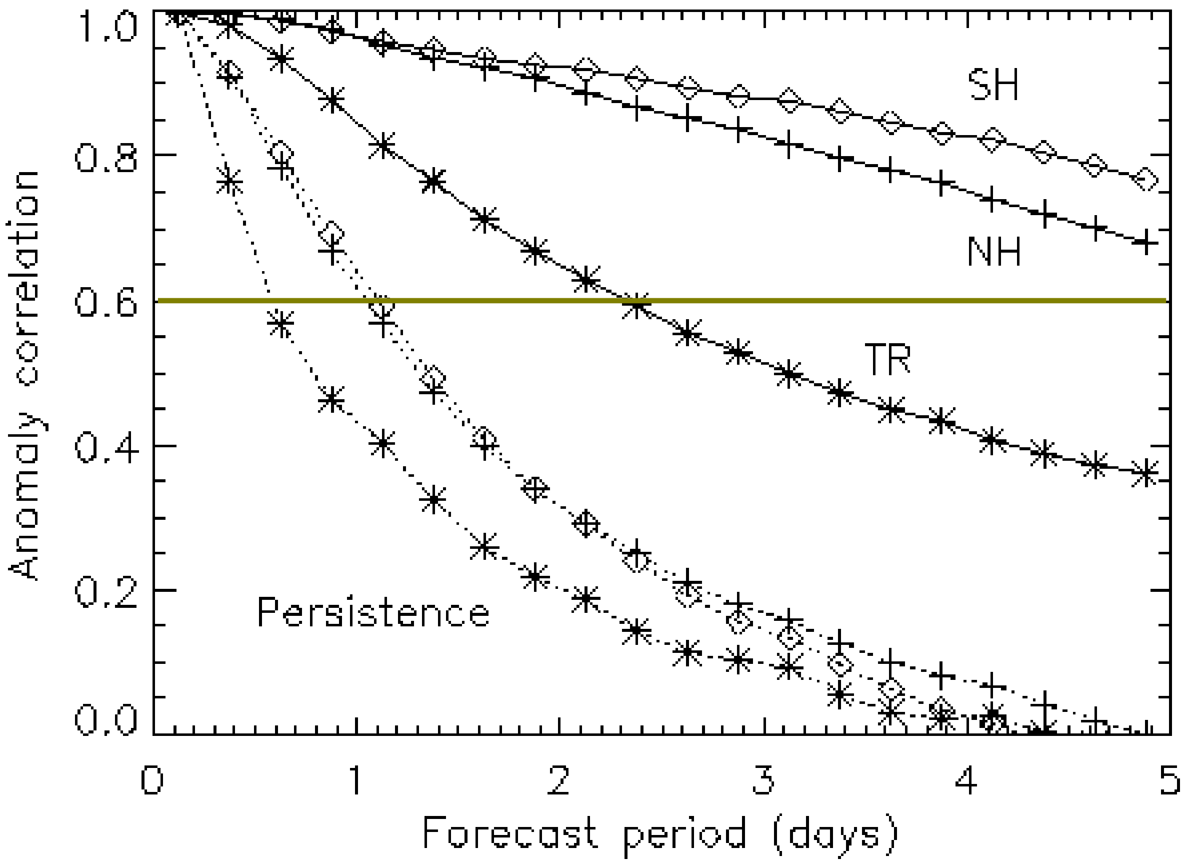
Analysis
15 April 2001



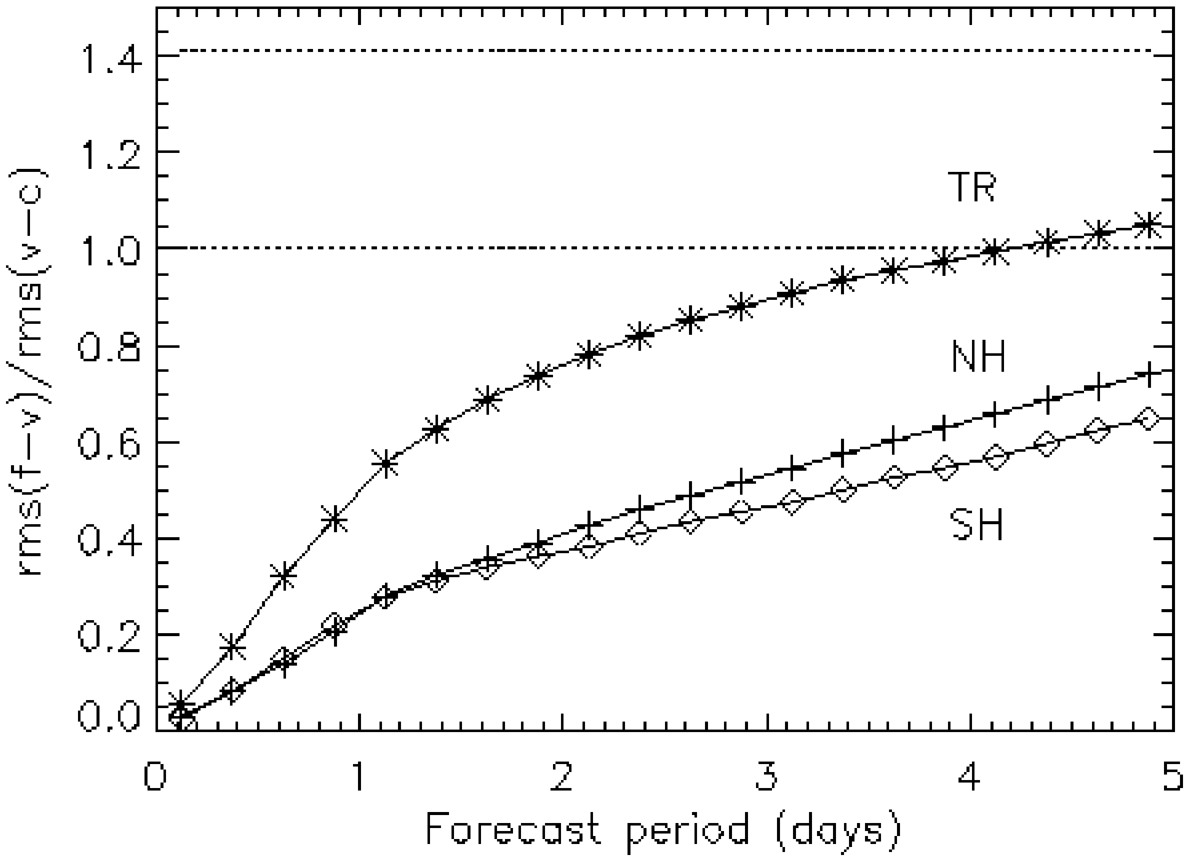
TOMS
15 April 2001



Anomaly correlation



RMS error



rms(f−v)/rms(v−c)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
TR
NH
SH
0
1
2
3
4
5
Forecast period (days)

Tropics

In tropics anomaly forecast score lower than in extratropics

-> Anomaly small (2-3% compared to 5-10%)

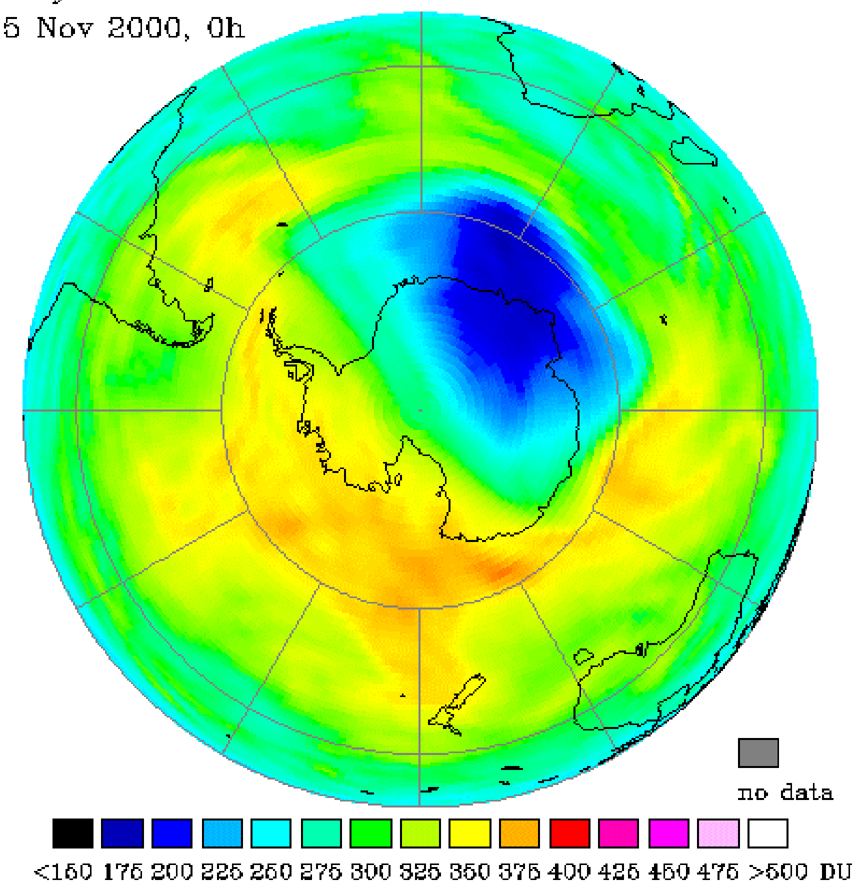
-> More sensitive to observation noise, retrieval errors

-> Anomaly mainly tropospheric

No tropospheric ozone chemistry in model

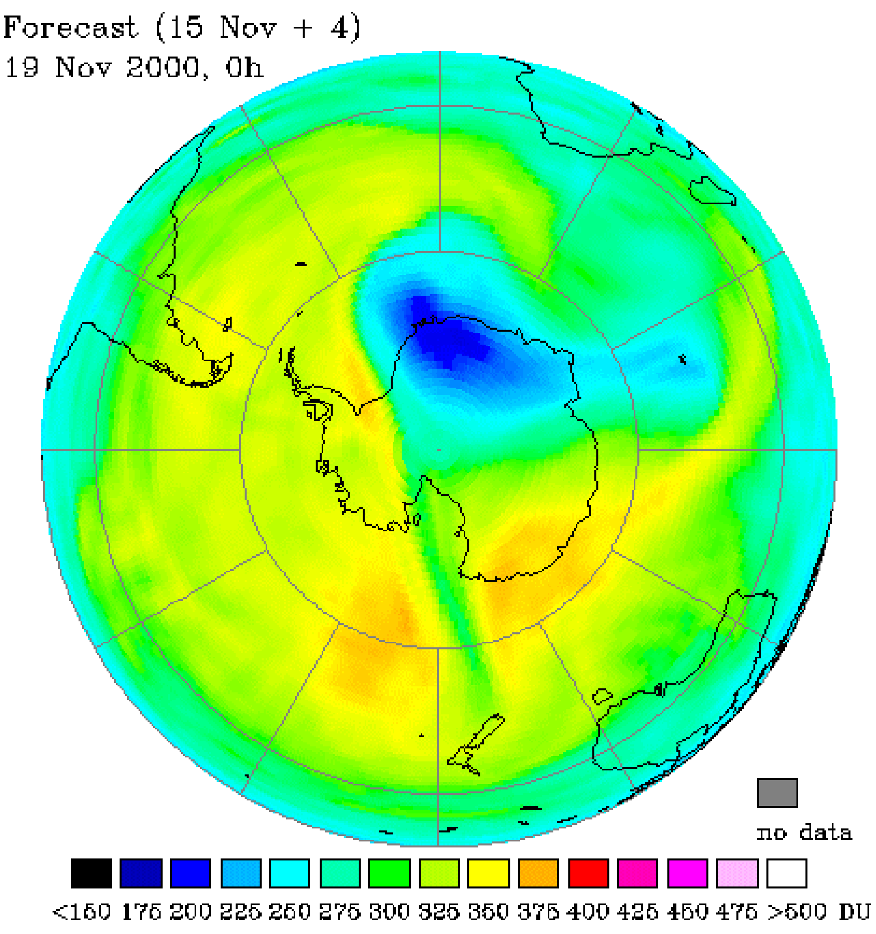
Breakup 2000 ozone hole

15 November 2000 analysis
based on GOME ozone observations



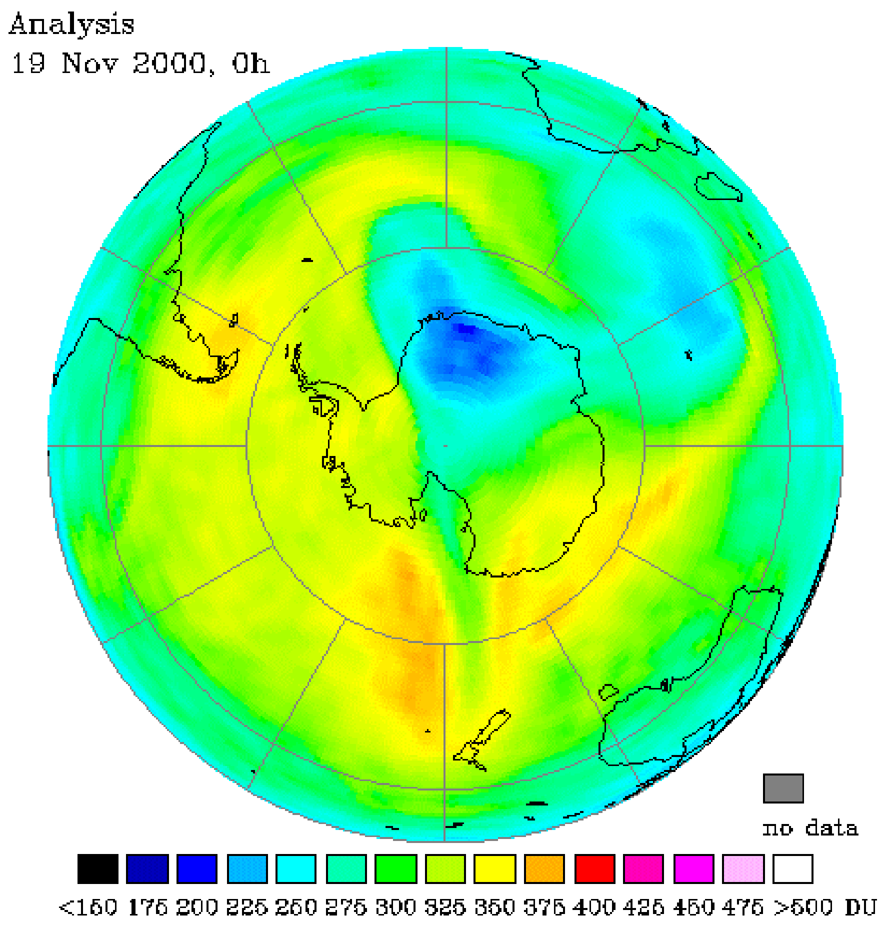
Breakup 2000 ozone hole

19 November 2000
4-day forecast



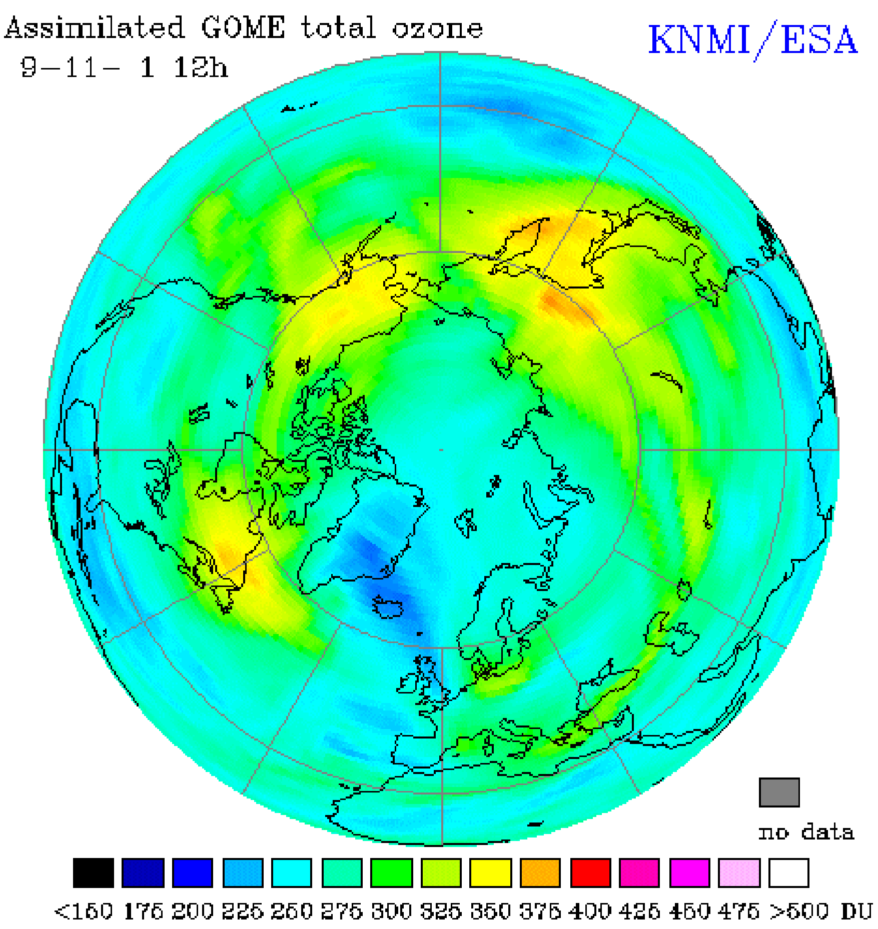
Breakup 2000 ozone hole

19 November 2000 analysis



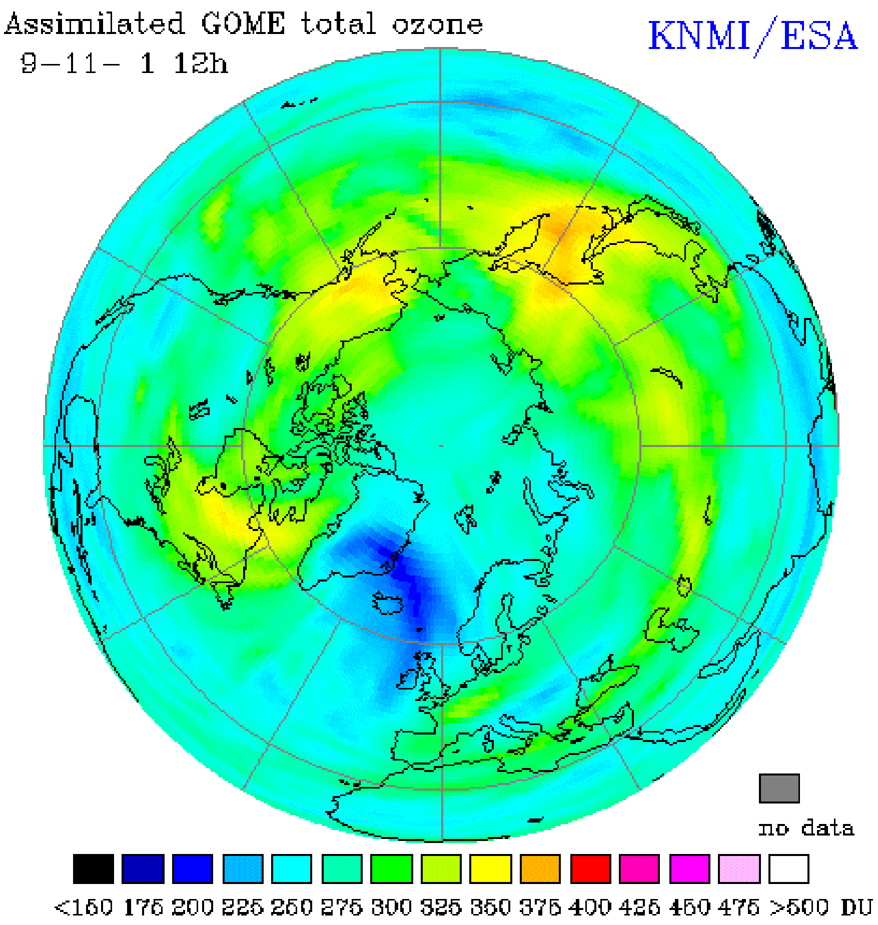
Low ozone episode

5-day forecast
9 November 2001



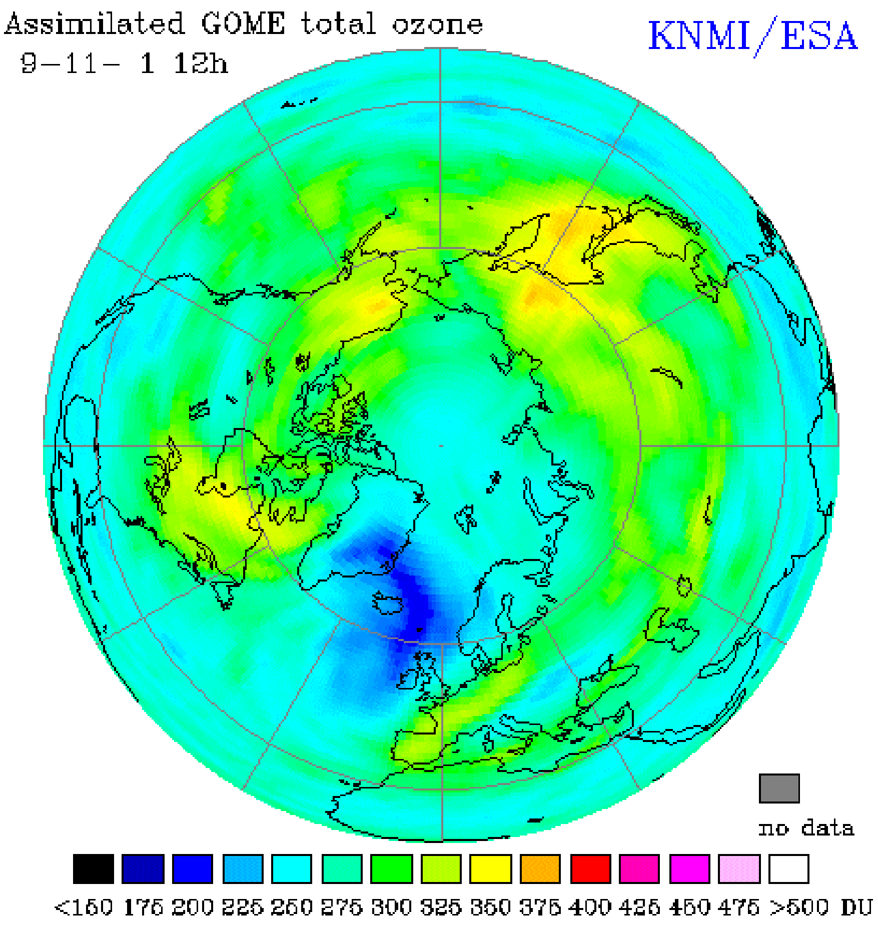
Low ozone episode

3-day forecast
9 November 2001



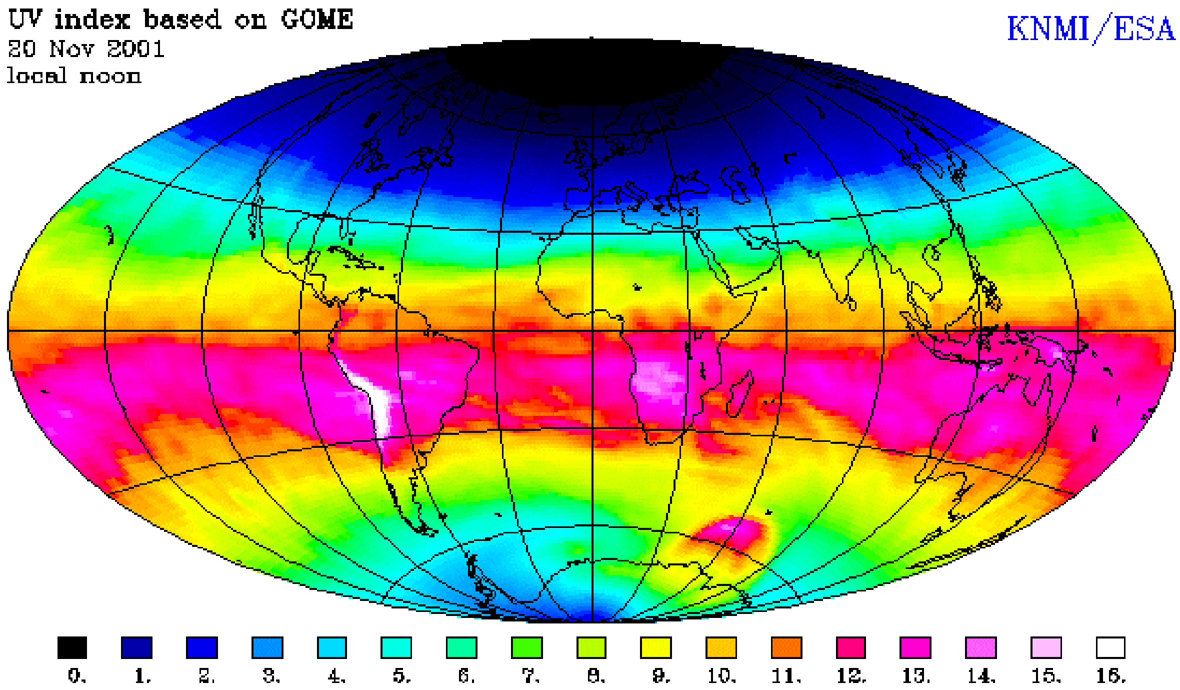
Low ozone episode

analysis
9 November 2001

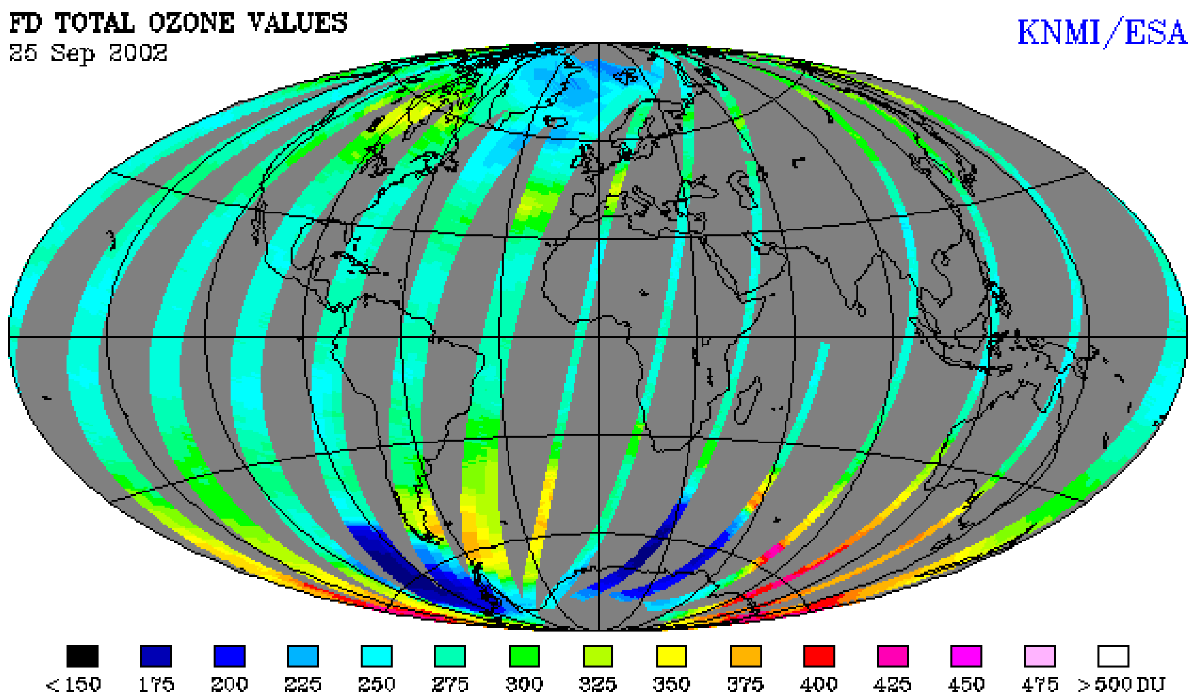


UV forecast

20 November 2001
(5-day forecast)

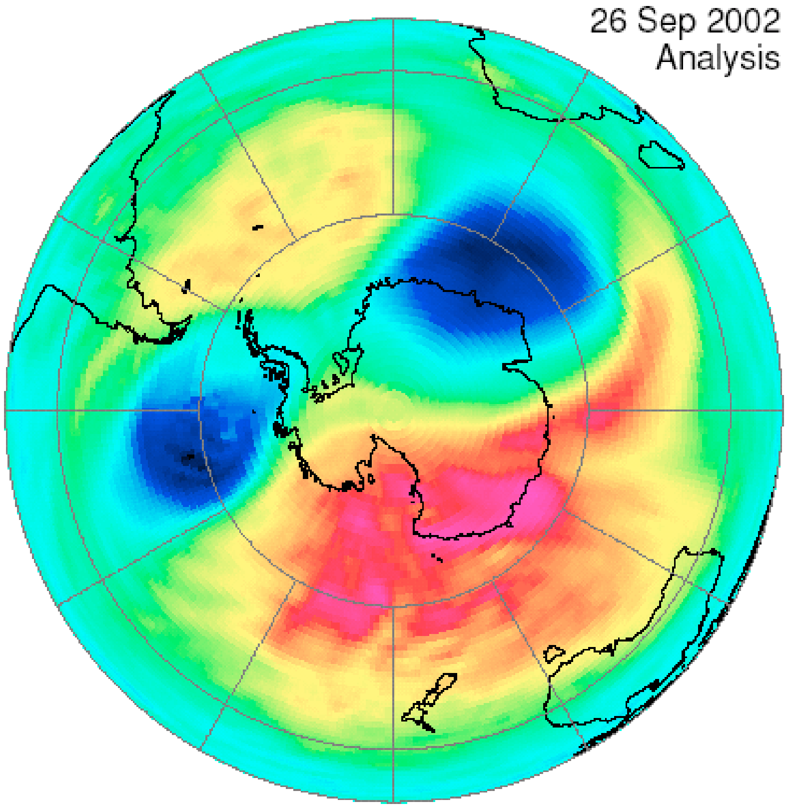


GOME measurements at 25 September 2002



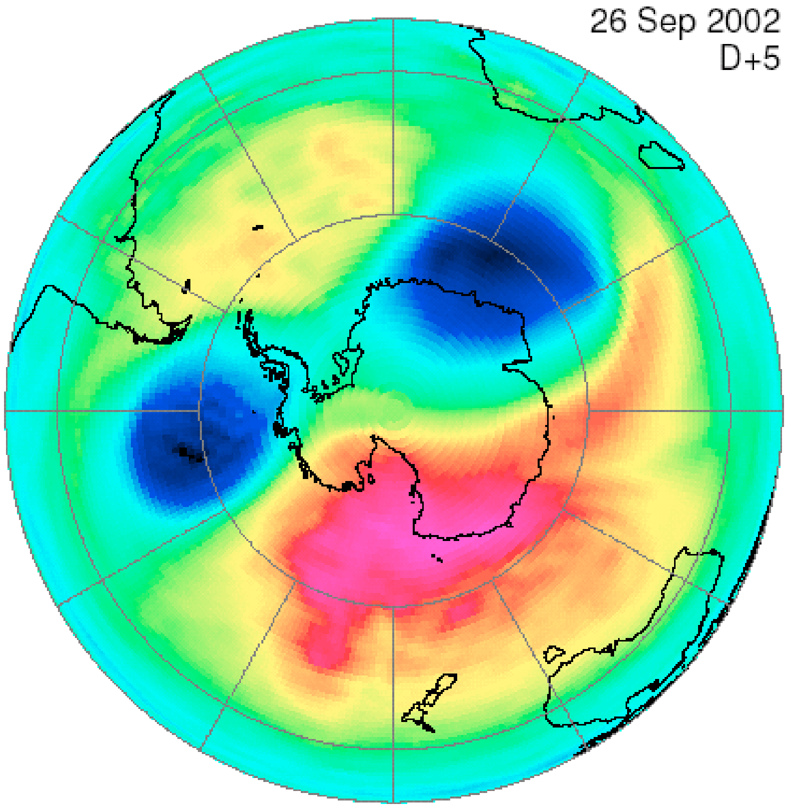
Ozone hole breakup, 2002

26 September 2002
Analysis based on GOME



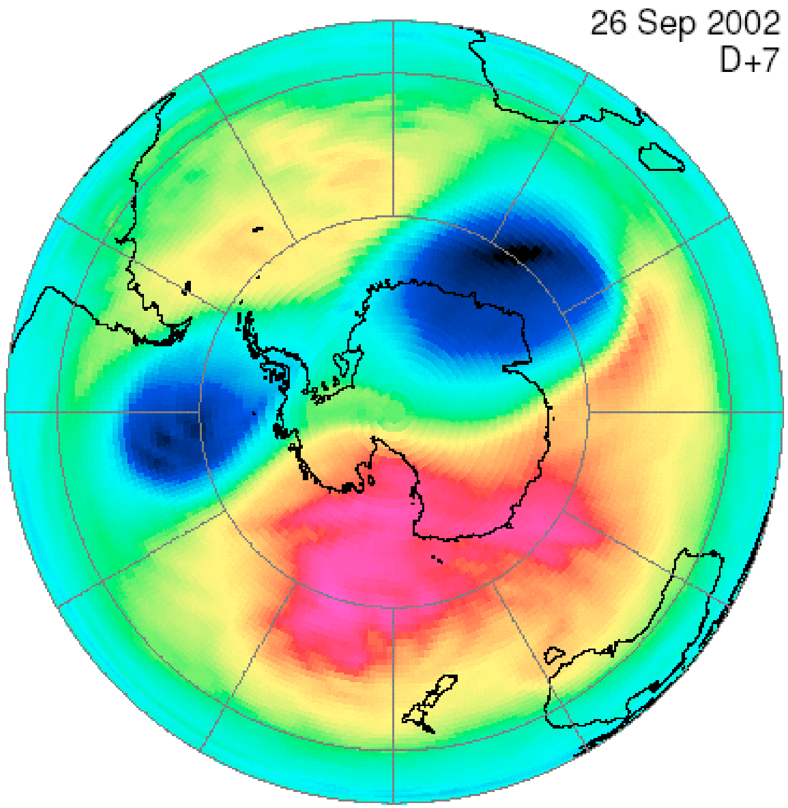
Ozone hole breakup, 2002

26 September 2002
5-day forecast



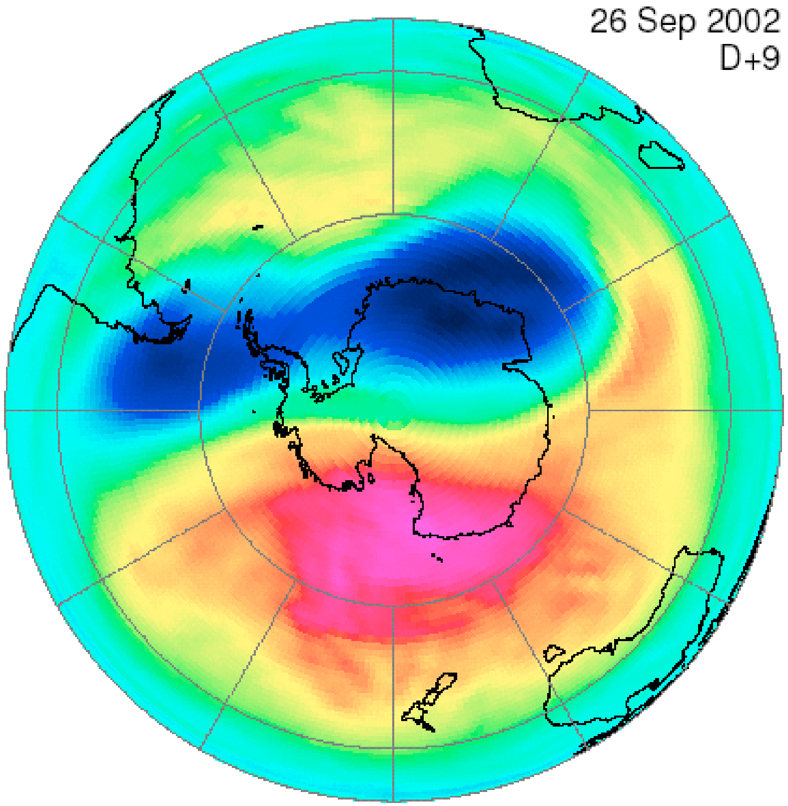
Ozone hole breakup, 2002

26 September 2002
7-day forecast



Ozone hole breakup, 2002

26 September 2002
9-day forecast



Summary (1)

Satellite instruments measuring ozone

- GOME, Sciamachy, OMI, GOME-2 will play important role to continue the TOMS ozone record

Total ozone retrieval

- Total ozone products of GOME can be improved
- New KNMI total ozone algorithm: applied to GOME, Sciamachy, OMI

Summary (2)

Ozone assimilation

- CTM driven by ECMWF winds describes features of stratospheric ozone in fair detail
- (O-F) total ozone typically 3-4 %
- Noise level GOME total ozone small: < 2 %

Age of air, strat-trop exchange

- Assimilation models: too strong mixing tropics-extratropics (M. Schoeberl)
- ERA-40 compared to OD:
  small age of air, large STE

Summary (3)

Ozone forecasting

- Meaningful forecast up to one week in extratropics
- Tropics: forecast up to 2 days
  (small anomaly, measurement noise, no tropospheric chemistry)
- Examples
  * Breakup 2002 ozone hole
  * Ozone "mini-holes" over Europe