GEMS
Global Earth-system Monitoring using Space and in-situ data

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with help from

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ECMWF

Scope of the talk

Demands for estimates of sources /sinks / transport of atmospheric constituents

- Policy Needs: Assessment, Validation of treaties
  - Convention on Long-Range Transport of Air Pollutants
  - Montreal Protocol
  - UNFCCC- Kyoto Protocol / carbon trading ….
- Operational Needs
  - Air quality forecasts
  - Chemical Weather Forecasts
- Scientific Needs
  - IPCC
  - WMO / Global Atmospheric Watch
  - World Climate research programme
  - IGBP

1979 Convention on Long-range Transboundary Air Pollution: Regional Pollution is a Global Issue

- One cannot study N.American, European, Asian Pollution in isolation. Long range transport is a global phenomenon.

- Global information is required to determine the global sources, sinks and transports of key pollutants

- Key pollutants measurable on global scale from space include
    - Sulphur dioxide
    - Aerosol / Particulate Matter
    - Nitrogen dioxide
    - Carbon monoxide
    - Ozone

- Issue: How to provide accurate global information on source / sink / transport variations in space and time?

1985 Vienna Convention on Protection of Ozone Layer
1987 Montreal Protocol

- Nations agreed to take appropriate measures...to protect human health and the environment against adverse effects of human activities affecting the Ozone Layer.

- In late 1985, Dr. Joe Farman's team offered the first proof of severe ozone depletion,

- In 1987 agreement was reached on specific mitigation measures, with the signing of the Montreal Protocol on Substances that Deplete the Ozone Layer. The work continues in 'quadrennial assessments'

- Ozone has a complex and rapidly varying distribution in space and time. The main source is 40km above the equator. The main sink is at the surface in mid-latitudes

- Issue: How to provide accurate global information on source / sink / transport variations in space and time?

1992 United Nations
Framework Convention on Climate Change

ARTICLE 2: OBJECTIVE

- Achieve stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.

- Such a level should be achieved within a time-frame sufficient
  - to allow ecosystems to adapt naturally to climate change
  - to ensure that food production is not threatened
  - to enable economic development to proceed in a sustainable manner.

1997 KYOTO PROTOCOL TO THE UNFCCC

- Commitments to reduce emissions by the Commitment period 2008-2012

- At least three GHGs (Carbon dioxide, Methane, Nitrous oxide) are measurable from space, while all species are measurable on the ground

- Carbon-credits & Emissions-trading are beset with difficult issues of verification

- Issue: How to provide accurate global information on source / sink / transport variations in space and time?

Environmental Concerns have triggered $25B for New satellite missions in 2001-2007

N.America	Europe / Collabs.	Asia /Collabs.
	JASON-1	
TERRA	ENVISAT	ADEOS-II
AQUA	MSG	GPM
SSMI/S	GOCE	COSMIC
AURA	CRYOSAT	
CALIPSO	METOP	
CLOUDSAT	ADM	
OCO		
HYDROS	SMOS	
GIFTS		

How to provide accurate global information on source / sink / transport variations in space / time?

- Transparent, accurate and verifiable information is a key requirement for States which are parties to the Kyoto protocol.
- 'National Technical Means' to check such information is of interest to States which are not parties the Kyoto protocol, but nevertheless make major contributions to space hardware.
- Policymakers' key information requirements can be met by:
  1. Extending meteorological/ oceanographic modelling & data-assimilation techniques to atmospheric trace constituents (GHGs, reactive gases, aerosol) measured from space.
  2. Extending current inversion techniques to make an optimal blend of in-situ and space-based data and so provide the most accurate possible estimates of sources/ sinks/ transports.
- Substantial work is already in progress at ECMWF on Ozone and Carbon dioxide.

Synergy of NWP & Environmental Monitoring

- New remotely-sensed data offers unprecedented levels of measurement accuracy.
-
- In the domain of atmospheric sounding, for example, we are moving from levels of accuracy of ~ 1K over thick layers in the last decade, to levels of ~0.1 - 0.5 K over much thinner layers in this decade.
- Full exploitation of instrumental accuracy requires accounting for a wide range of physical and surface biophysical processes that have hitherto been inaccessible to measurement, and thus neglected (aerosol, trace-gases, land…)
- It is increasingly necessary for NWP to model and assimilate satellite data on many of these aspects of the Earth-system.
- Such developments offer products of great scientific and societal interest for climate and other issues.

Cost-effective information provision through partnerships of Weather & Environment experts

- Policymakers' global environmental information needs cannot be met without an Earth-system modelling and data assimilation capability.

- Numerical Weather Prediction (NWP) Centres will exploit most of the new instruments anyway. To achieve good estimates of T, q, O_3, ocean stress…., NWP centres must do a superb job on key tasks such as Calibration, Channel selection, Cloud detection, Assimilation…

- The NWP tasks are essential pre-requisites to meeting environmental information needs

- A partnership of environmental and NWP experts offers two big PAYOFFS
    1. a thorough exploitation and validation of satellite data and in-situ data for both weather and environmental purposes.
    2. Improved models for Weather & short-range climate & environmental forecasts, because of the experience from long data assimilations.

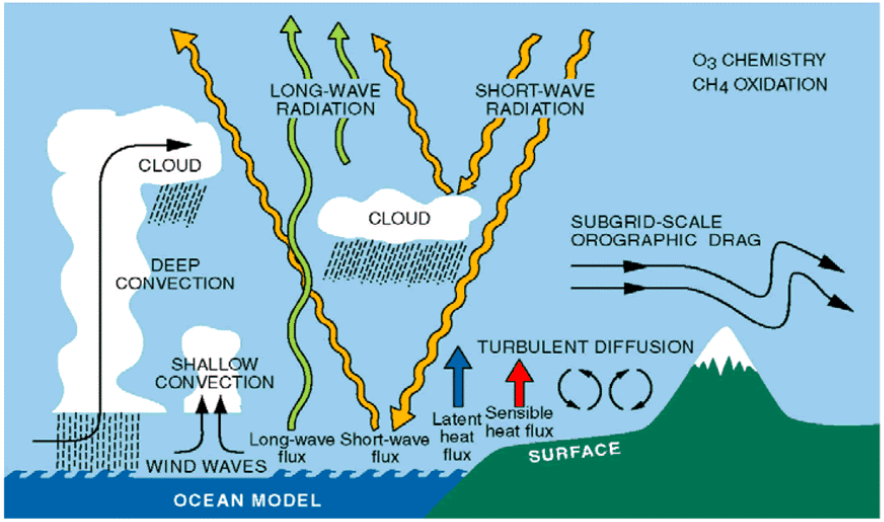
The ECMWF Earth-system model used for Numerical Weather Prediction

High-resolution model

- T_L511 spectral resolution
- N256 reduced Gaussian grid (40 km in the mid-latitudes)
- 60 hybrid vertical levels from the surface to about 65km
- Parametrized physical processes
- GEMS will develop and validate extensive new modelling capabilities

ECMWF MODEL / ASSIMILATION SYSTEM

ATMOSPHERE	STRATOSPHERE	DYNAMICS–RADIATION–SIMPLIFIED CHEMISTRY		
	TROPOSPHERE	DYNAMICS–RADIATION–CLOUDS–ENERGY & WATER CYCLE		
OCEAN / LAND		OCEAN	LAND HYDROSPHERE	LAND BIOSPHERE
		OCEAN SURFACE WAVES OCEAN CIRCULATION SIMPLIFIED SEA ICE	SNOW ON LAND SOIL MOISTURE FREEZING	LAND SURFACE PROCESSES SOIL MOISTURE PROCESSES SIMPLIFIED VEGETATION



GEMS (i) Global Earth-system Monitoring using Space and in-situ data

GEMS: Extend the Data Assimilation system at ECMWF to describe atmospheric dynamics, thermodynamics and composition:

- GREEHOUSE GASES
- REACTIVE-GASES
- AEROSOL

- Collaborate closely with 3 related EU Framework 6 funded projects
  - GEOLAND: Model and assimilate data on the Land Biosphere and global carbon cycle, using best available met input.
  - MERSEA: Model and assimilate upper-ocean, incl. Ocean-colour to estimate ocean carbon uptake, using best available met input.
  - HALO: Harmonisation of Atmosphere, Ocean, Land Projects
- By 2008
  - Operational GEMS system; 10-year reanalysis of EOS / ENVISAT era
  - Best possible estimates of trace constituent sources /sinks / transport

GEMS (ii) Global Earth-system Monitoring using Space and in-situ data

- **GEMS data assimilation projects**
  - **Monitor-GREEHOUSE GASES: Monitor seasonal variations of non-reactive Greenhouse Gases such as CO_2, CH_4, N_2O (+CO)**
  - **Monitor-REACTIVE-GASES: Monitor ozone and its precursors, and sulphate aerosol and its precursors.**
  - **Monitor-AEROSOL: Model and assimilate global aerosol information**

- **Cross-Cutting projects**
  - **SYSTEM-INTEGRATION Integrate the data-assimilation sub-projects in a unified pre-operational system**
  - **RETROSPECTIVE REANALYSIS Validate the pre-operational system through observational verification of retrospective analyses for the "EOS - ENVISAT" epoch 2000-2007, and perhaps for the epoch 1947-2007.**

Global Earth-system Monitoring using Space and in-situ data

Related Land & Ocean Projects

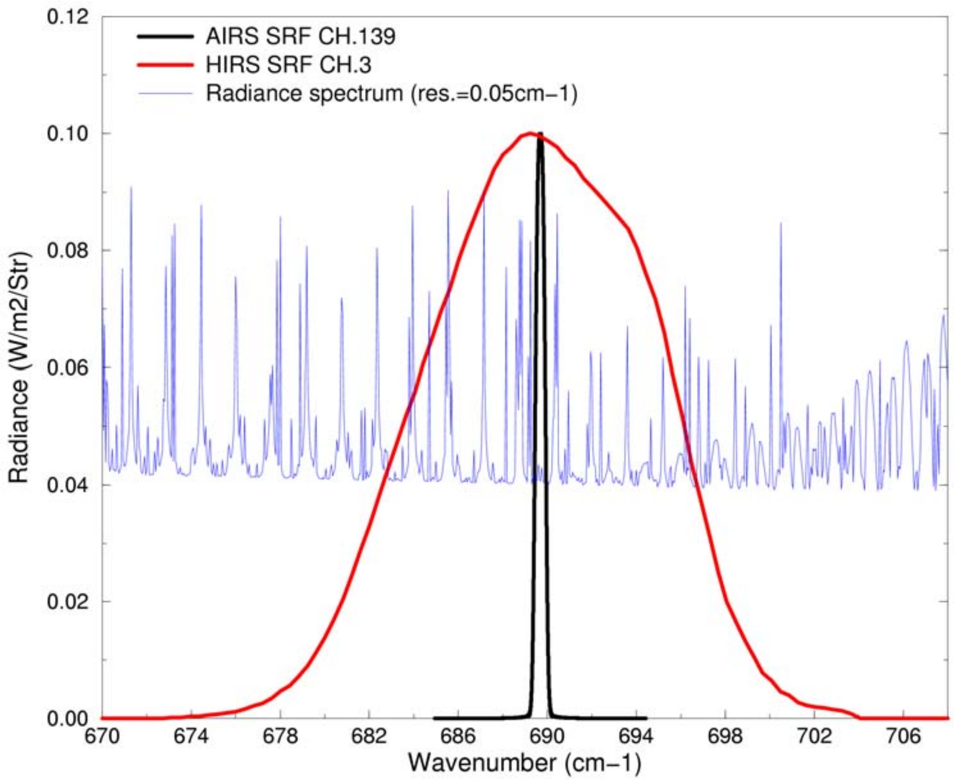
- **GEOLAND**: Model and assimilate information on the Land Biosphere and carbon cycle.

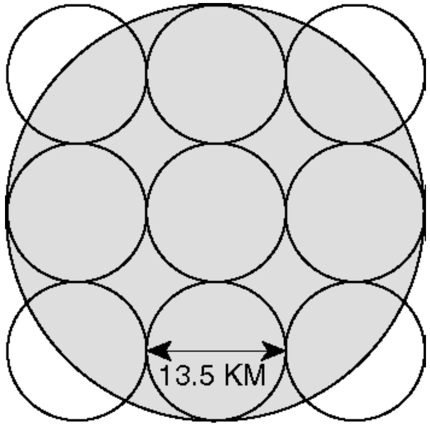
- **MERSEA** Model and assimilate upper-ocean, to estimate ocean carbon uptake.

GEMS-GREEHOUSE GASES:

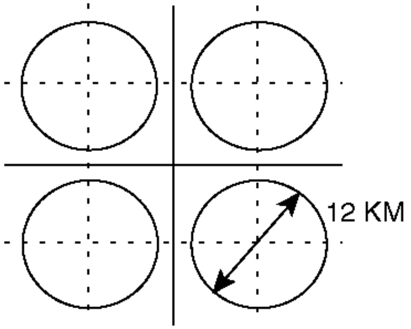
- Monitor seasonal variations of non-reactive Greenhouse Gases such as CO_2, CH_4, N_2O, CO
- Heritage: COCO (FP5)
- Instruments: AIRS, SCIAMACHY, IASI, OCO
- Data Mgt
- R/T develop from COCO
- Modelling develop from COCO
- Sources / Sinks Current Methods
  + 3D-InVar; variational method
  using CTM very close to ECMWF model
- Data Assim. ECMWF & ….
- Validation build on COCO validation team

High spectral resolution of AIRS (2002) & IASI (2005) => high vertical resolution in temperature & humidity



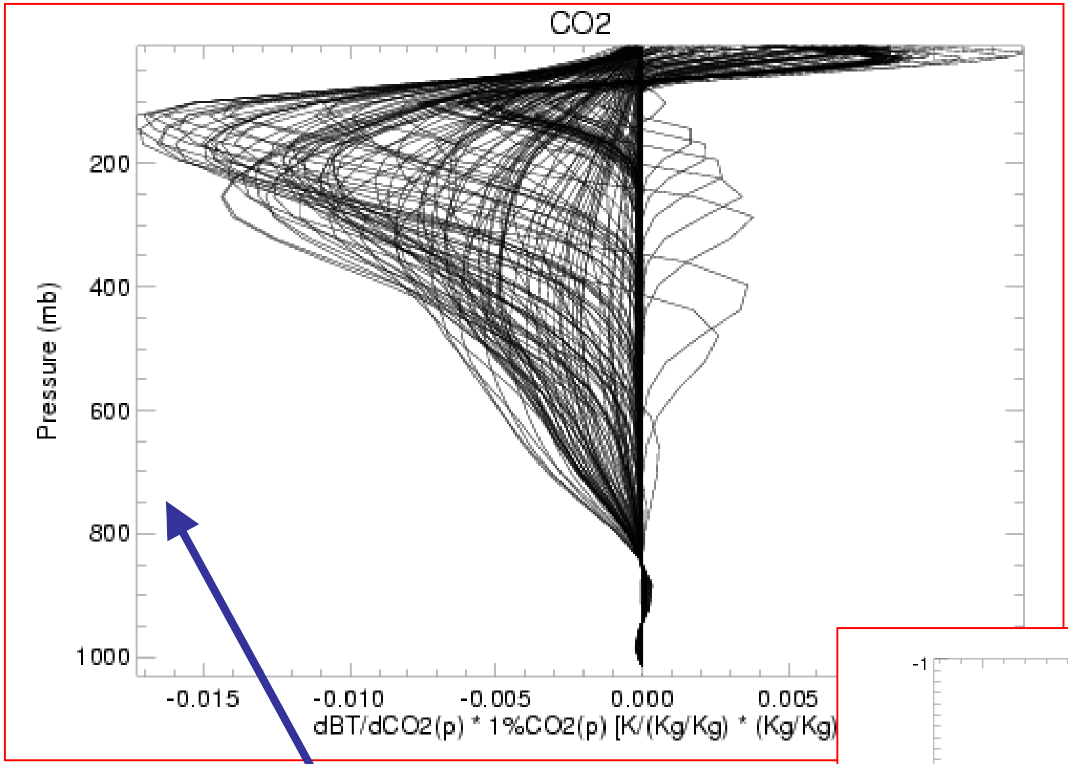


AIRS fields of view at nadir superimposed on AMSU-A field of view



IASI fields of view at nadir

AIRS CO_2 Jacobians

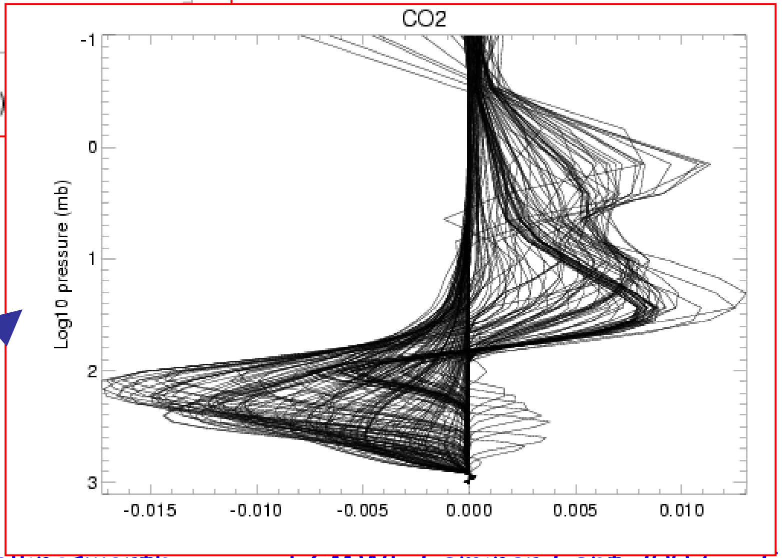


Good coverage in upper troposphere

Many channels with sensitivity to UT & LS

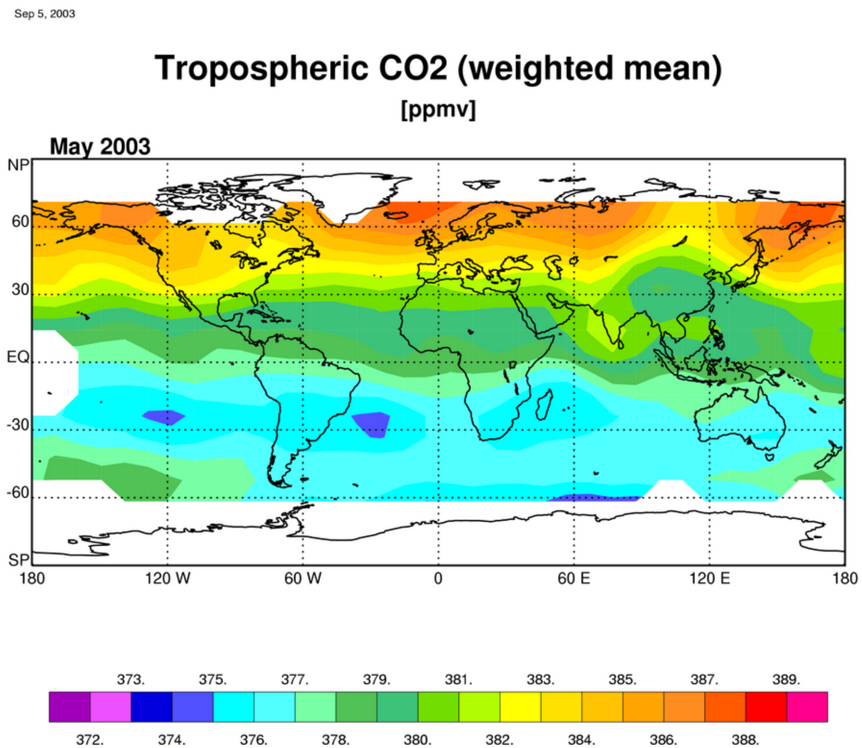
Zero sensivity near surface

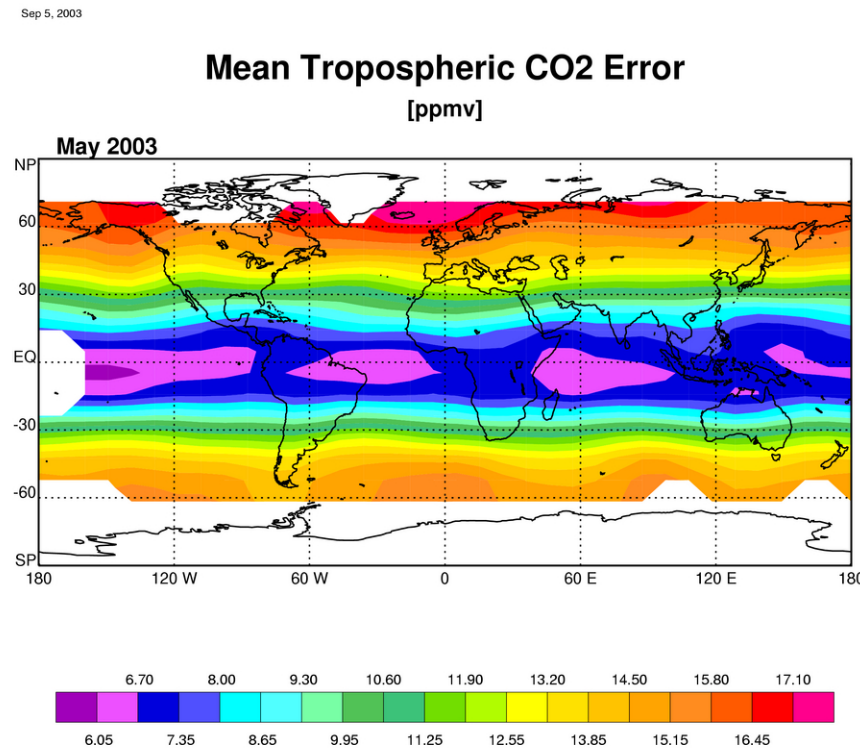
100 – 1000 hPa



0.1 – 1000 hPa

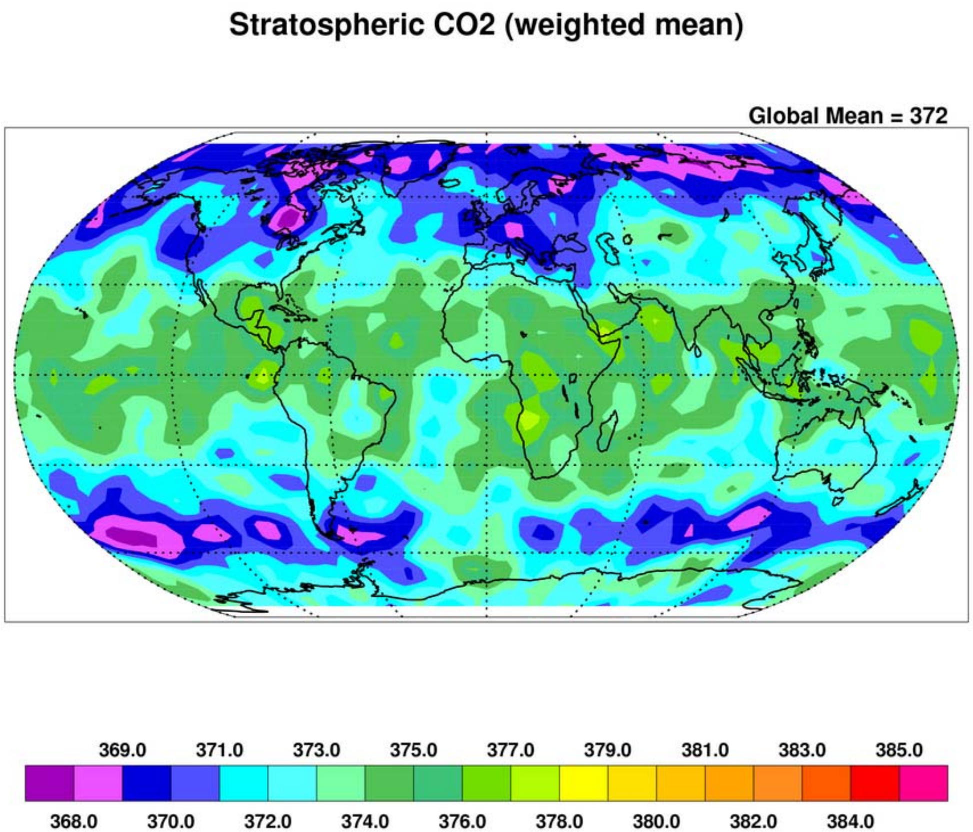
CO_2 assimilation -Troposphere





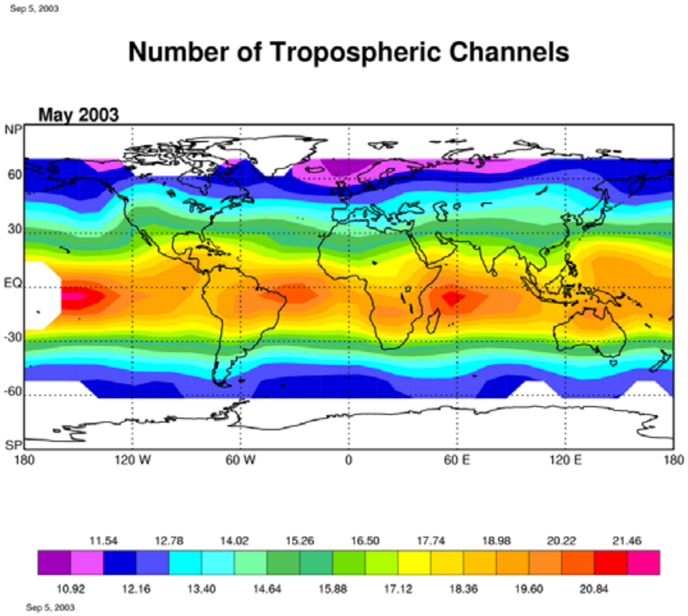
CO_2 tropospheric columns are being assimilated from AIRS infrared observations. Monthly mean distribution for May 2003 is shown on the left, and the upper boundary for the error estimate is shown on the right.

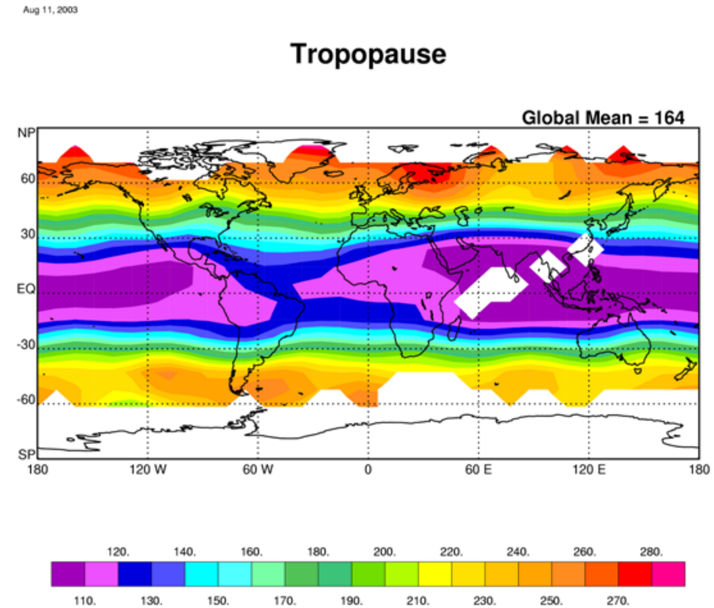
CO_2 assimilation - Stratosphere

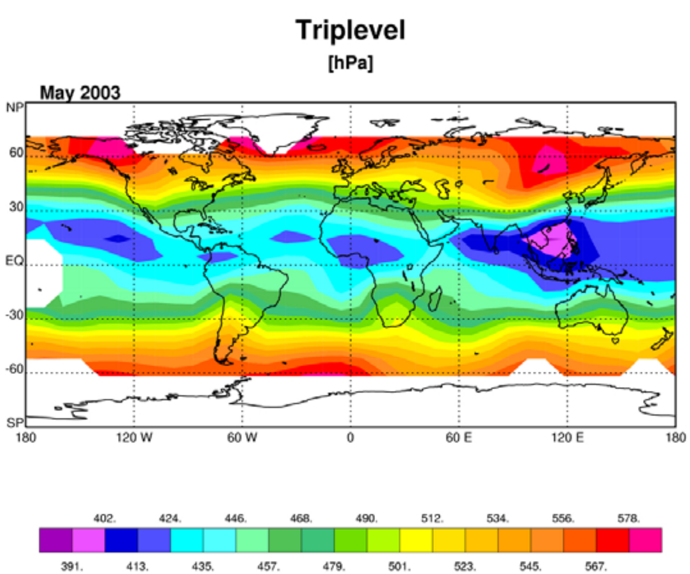


First analysis of stratospheric CO_2 shows Brewer-Dobson type of circulation. Variability is also much smaller than in troposphere.

Number of channels used in assimilation



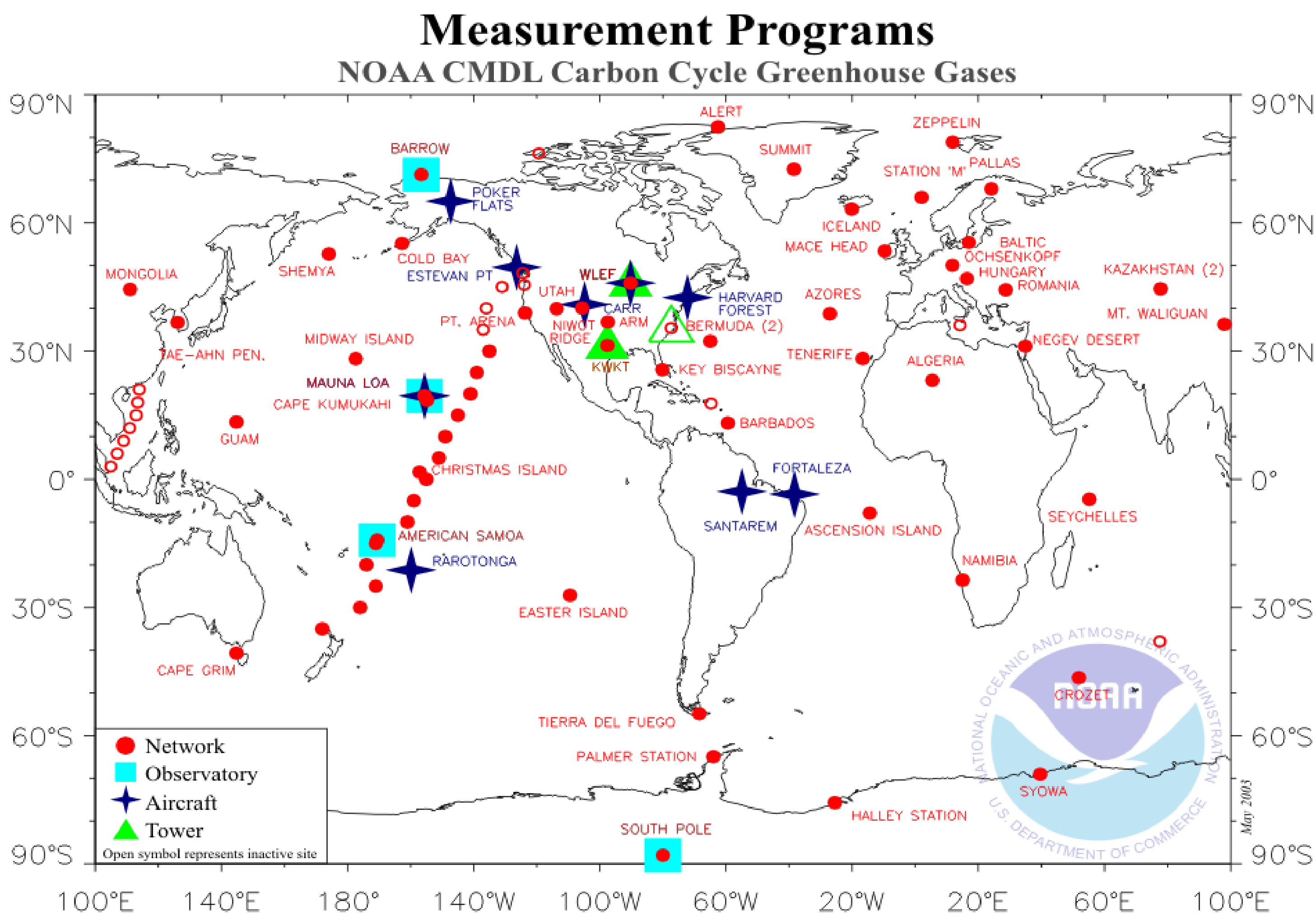




The total number of channels used in the tropospheric assimilation is a function of the tropopause height and the top level of clouds. At higher latitudes this significantly decreases the number of useful channels.

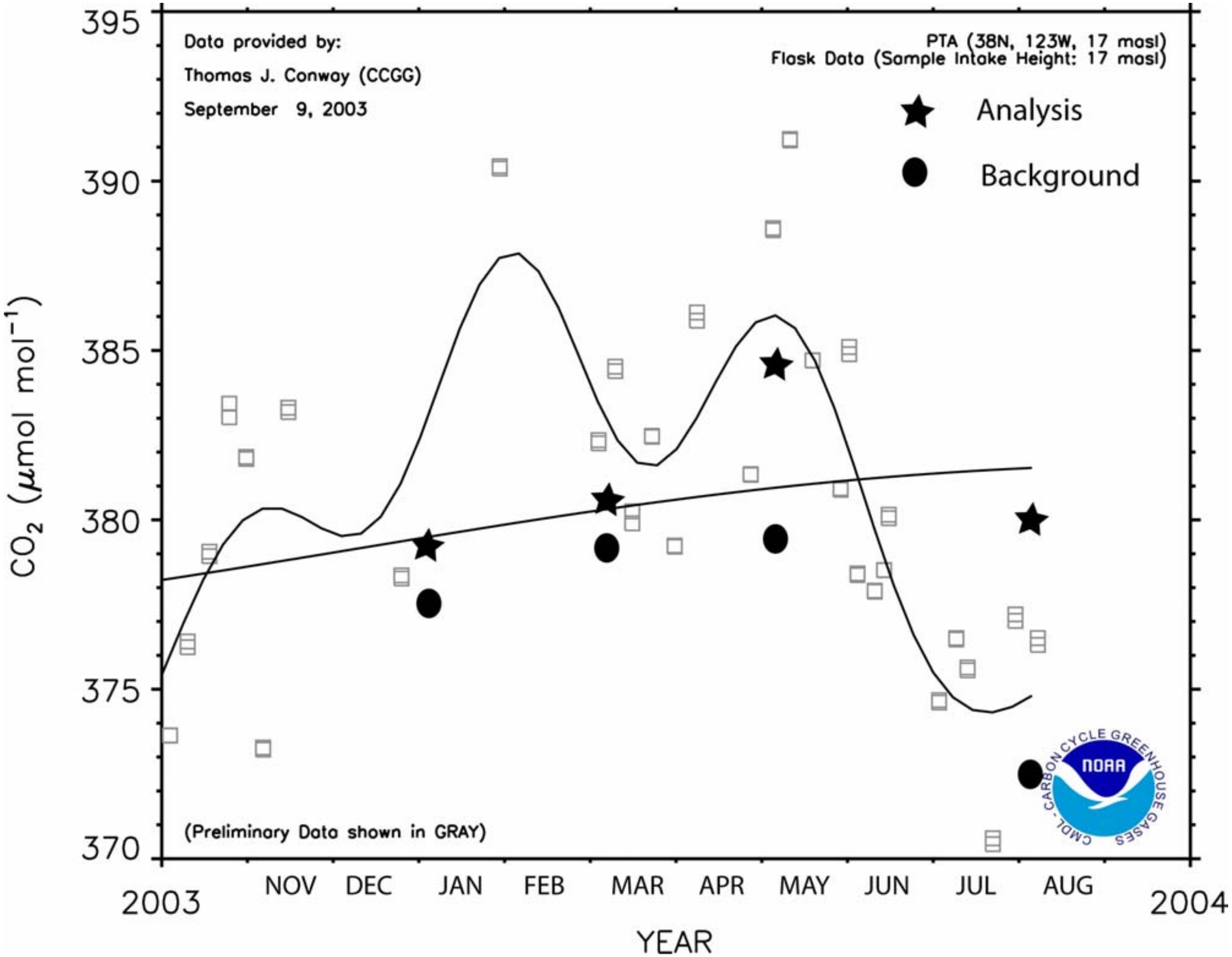
The trip level (left) shows how deep on average we look into the troposphere.

CO_2 flask observation network



The NOAA CMDL Carbon Cycle Greenhouse Gases group operates 4 measurement programs. In situ measurements are made at the CMDL baseline observatories: Barrow, Alaska; Mauna Loa, Hawaii; Tutuila, American Samoa; and South Pole, Antarctica. The cooperative air sampling network includes samples from fixed sites and commercial ships. Measurements from tall towers and aircraft began in 1992. Presently, atmospheric carbon dioxide, methane, carbon monoxide, hydrogen, nitrous oxide, sulfur hexafluoride, and the stable isotopes of carbon dioxide and methane are measured. Group Chief: Dr. Pieter Tans, Carbon Cycle Greenhouse Gases, Boulder, Colorado, (303) 497-6678 (pieter.tans@noaa.gov, http://www.cmdl.noaa.gov/ccgg).

Seasonal cycle

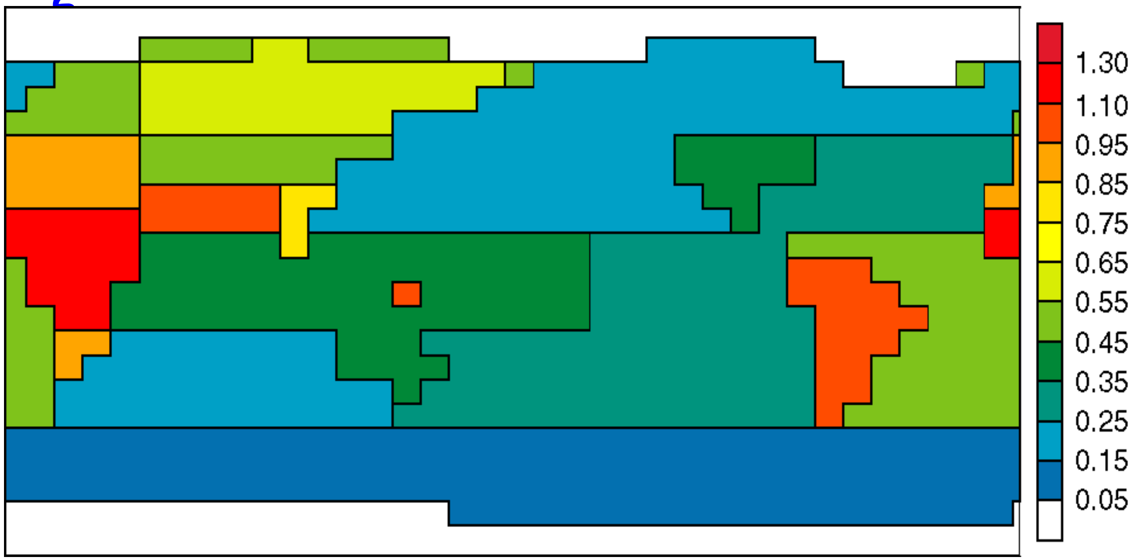


First comparisons with preliminary flask data show mixed results. For a mid-latitude coastal flask station, the analysis seems to improve on the background.

But interpretation is difficult because of the mismatch between flask observations (surface, selective sampling) and analysis values (deep layer).

CMDL flask data in grey are preliminary, not fully calibrated results.

AIRS / IASI Total-Column CO_2 Data will Reduce the Uncertainty of CO_2 Source / Sink Attribution

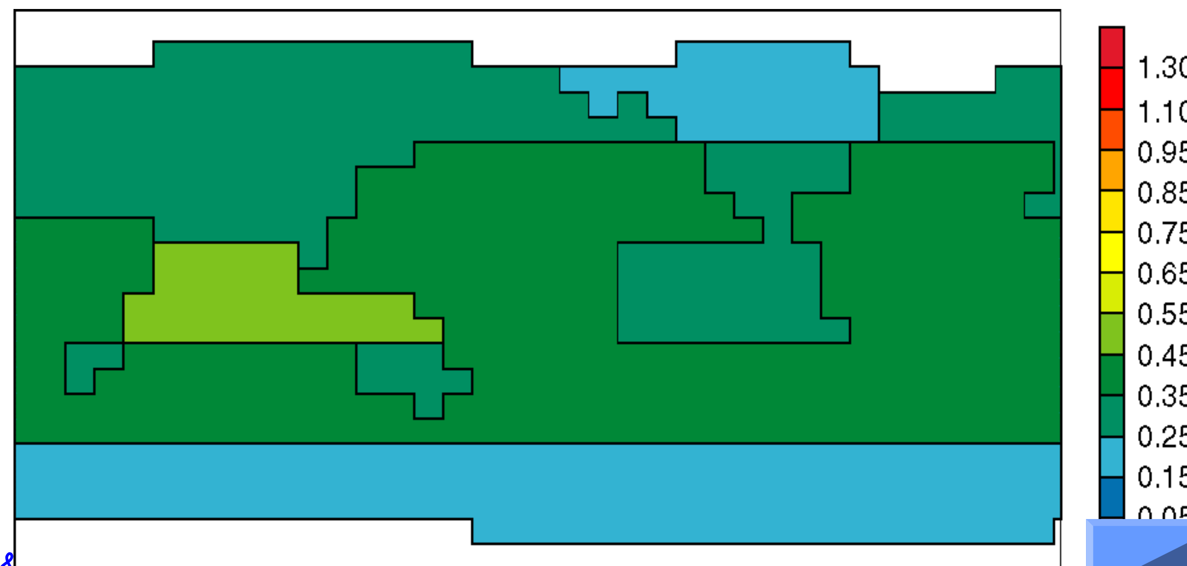


Rayner and O'Brien
Geophys. Res. Let., Jan 1, 2001

Unit: GT C / yr / region

Current Uncertainty with Surface data

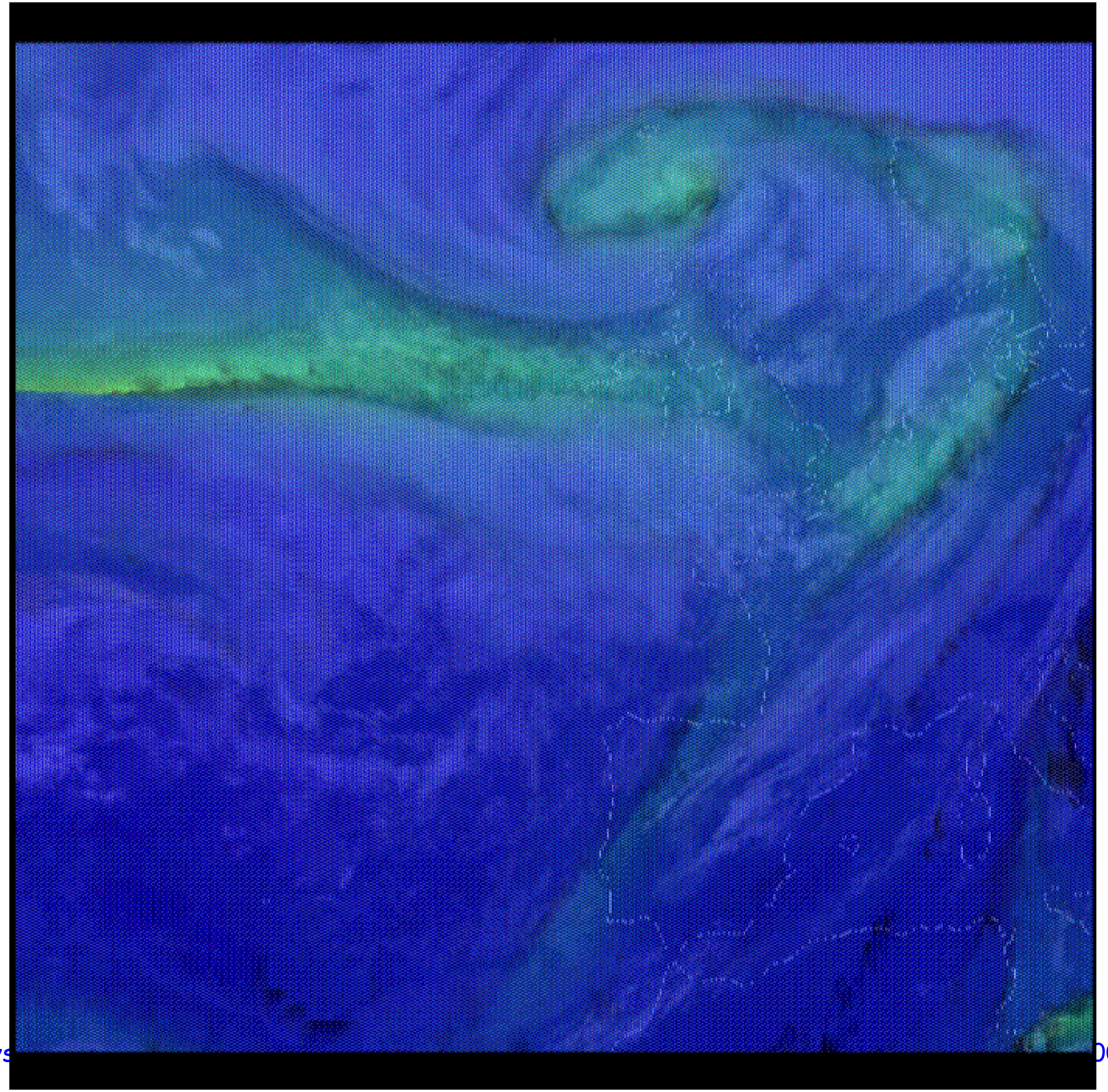
Expected uncertainty with surface data +satellite data, assuming 2.5ppmv accuracy



GEMS REACTIVE-GASES [and Forecast Chemical Weather]

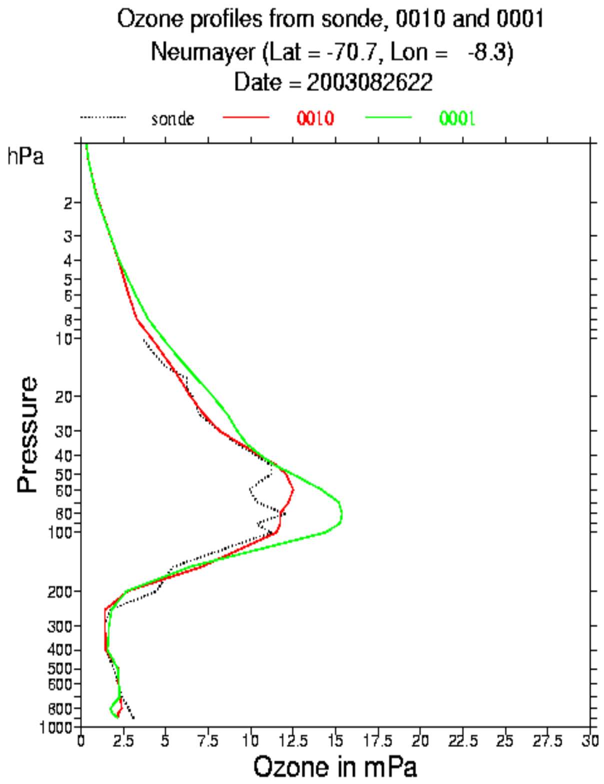
- Deliverables
  - Determine the magnitude and location of stratospheric / tropospheric ozone exchanges
  - Determine the modes and magnitudes of intercontinental transport of ozone and other constituents.
  - Provide global Chemical Weather Forecasts including UV-B forecasts, plus initial and boundary conditions for regional Chemical Weather Forecasts.
- Data Assimilation Approach
  - Stream 1: 4d Var with simplified chemistry to retrieve Ozone (12hr window).
  - Stream 2: Chemical Transport Model uses Atmospheric transport from stream 1 to assimilate / transport up to 50 species. A priori surface flux fields specified from RIVM-EDGAR database
- Instruments: UARS, AIRS, MIPAS, SCIAMACHY, GOMOS, SEVIRI, OMI, TES
- R/T & Retrievals
- Modelling
- Sources / Sinks
- Data Assim.
- Validation

- Halloween **Storm viewed from above**
- **Ozone isopleth - f(p) - is colour-coded by temp.**
- **Yellow is warm**
- **Meteosat imagery shown below the ozone**



- **24-hour loop in steps of 3 hours**
- **12z on 29/10 /00 to 12Z on 30/10/00**

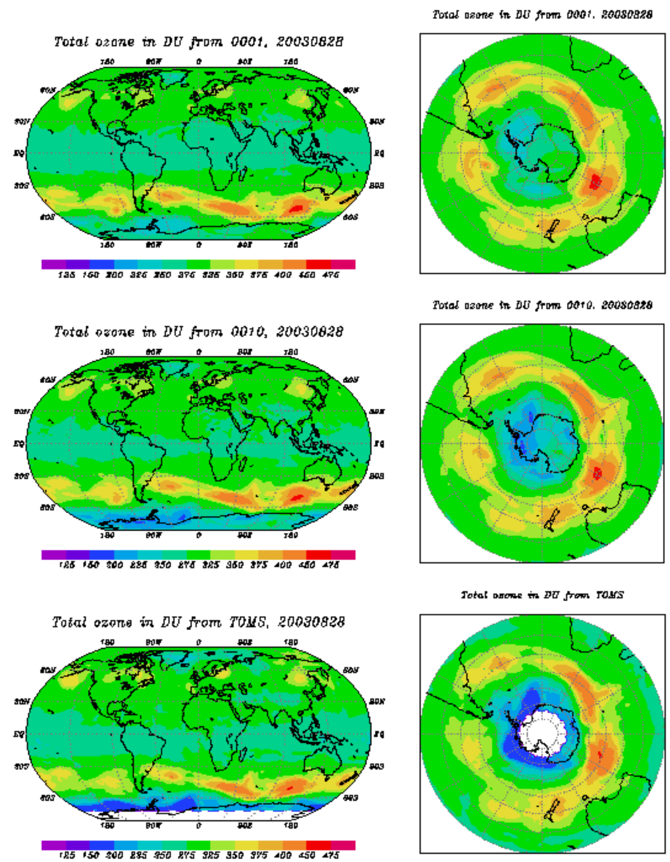
Assimilation of ozone data from MIPAS



No MIPAS

MIPAS

TOMS verif



Inclusion of ozone profiles from MIPAS (ENVISAT) improves substantially the representation of the ozone field in the ECMWF model

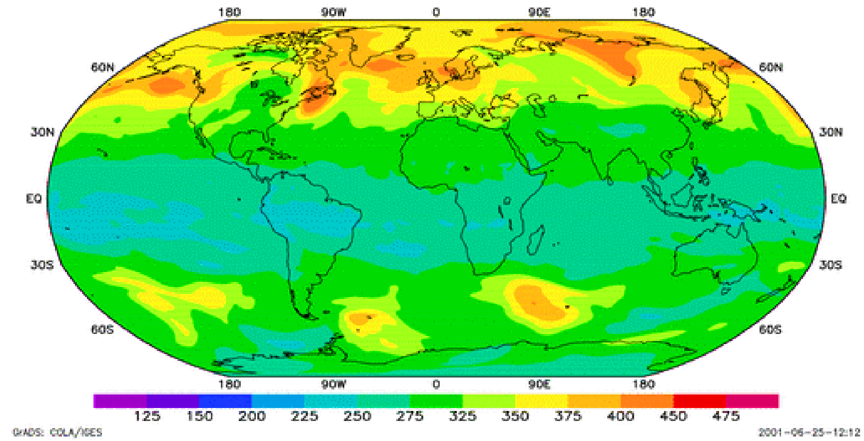
Global Monitoring / Forecasting of Reactive Gases:
The Chemical Weather Forecast

Current operational ozone monitoring capability is a good basis for developing a global capability to monitor reactive gases and associated aerosols

3.1 Integrate chemical modules with weather models, to provide global assimilation & forecasts of the distributions of
- ozone and its precursors
- sulphate aerosol
- other aerosol

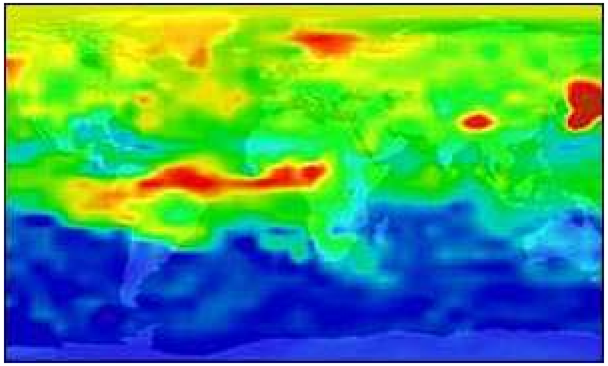
The global models can drive regional chemistry / air quality models.

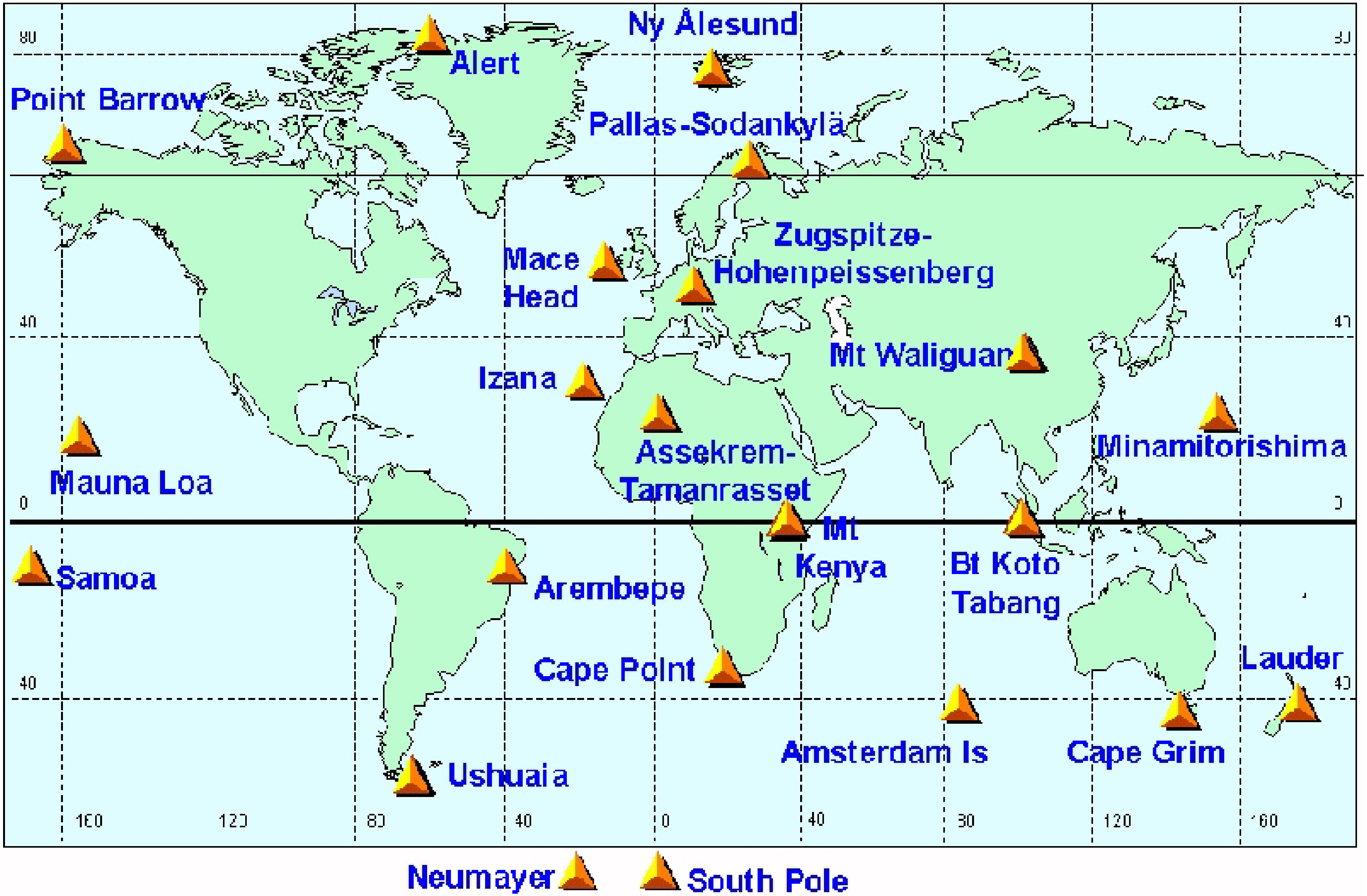
The cost could be modest at 1 degree resolution



Ozone

CO

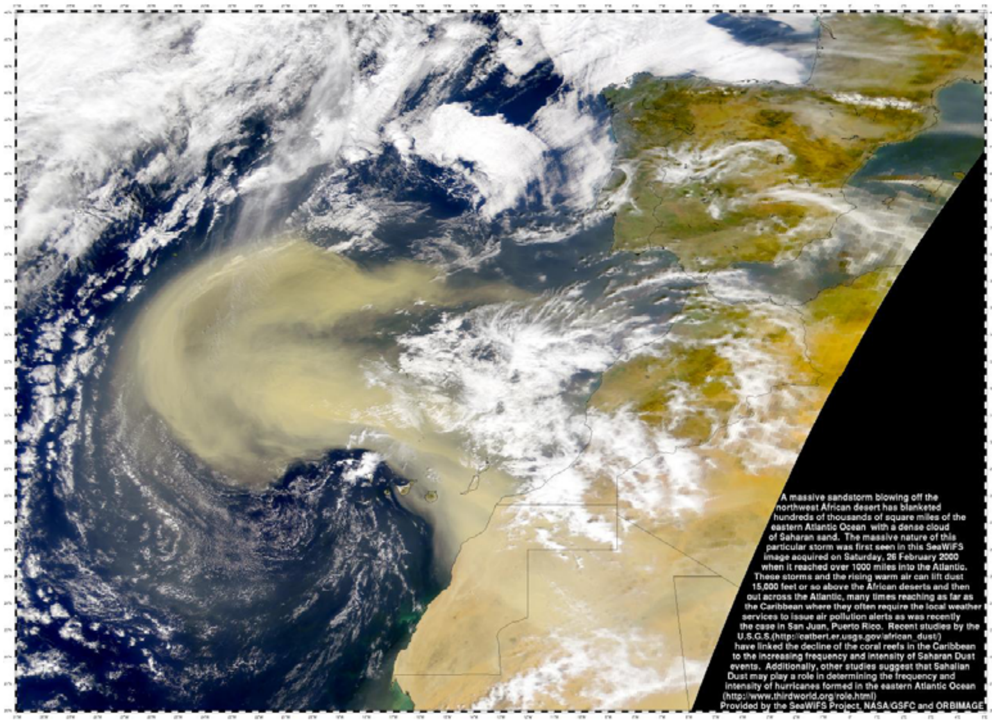




GAW Network of world Stations

Monitor-AEROSOL:

- Model and assimilate global aerosol information
- Heritage: -
- Instruments: MERIS, MODIS x 2, MISR, SEAWIFS, POLDER
- Data Mgt tbd
- R/T
- Modelling "
- Sources/ Sinks "
- Data Assim. "
- Validation "

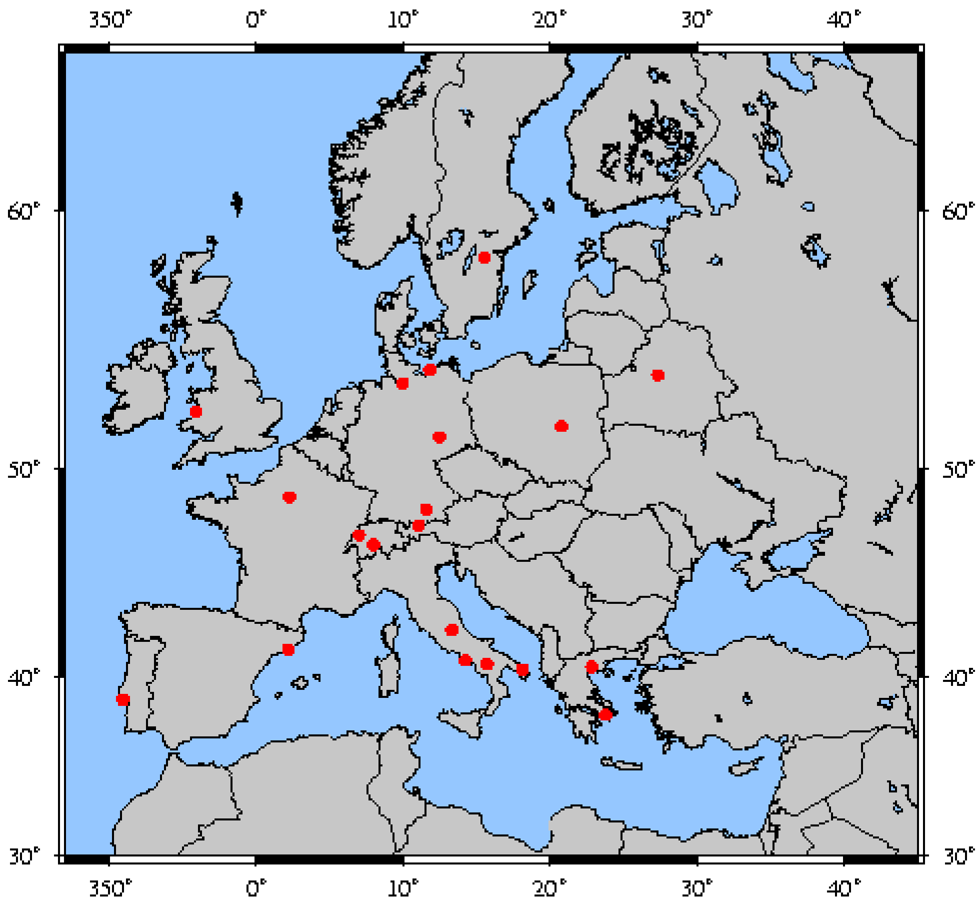


Aerosol modelling and assimilation is an emerging issue for NWP

- 'HIRS channels sensitive to the surface temperature, lower tropospheric temperature, and moisture are subject to a 0.5 K or more reduction in the brightness temperature during heavy dust loading conditions. (Weaver, Joiner, Ginoux JGR April 2003)

- Aerosol is the biggest source of error in ECMWF clear-sky radiation computations (JJ Morcrette, pers.comm.)

EARLINET



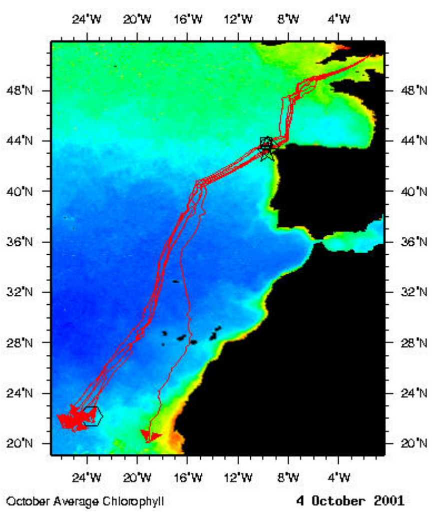
Closing the loop on Global Monitoring of Greenhouse Gases

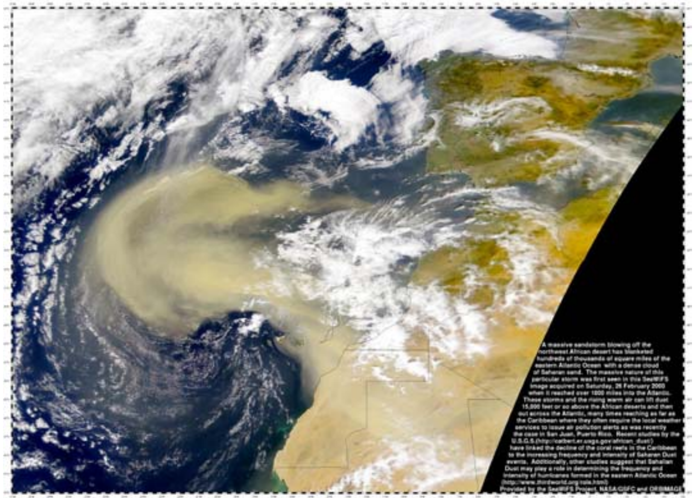
2.1 Map the seasonal variations of total column amounts of Greenhouse Gases

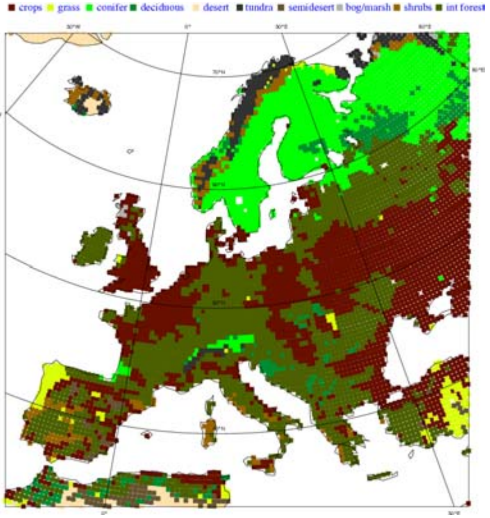
2.2 Model and assimilate ocean colour data, to estimate ocean carbon uptake.

2.3 Model and assimilate global aerosol information (to improve weather forecasts & the use of ocean colour data)

2.4 Model and assimilate information on the Land Biosphere and carbon cycle.

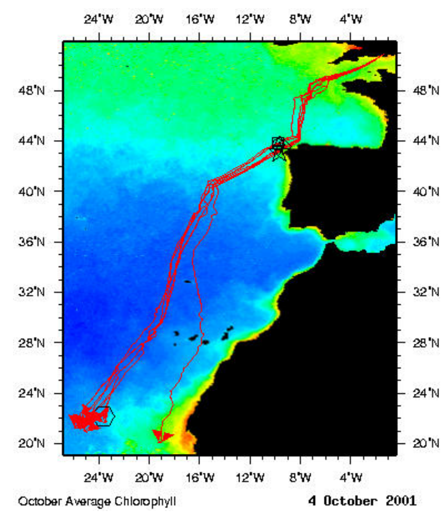






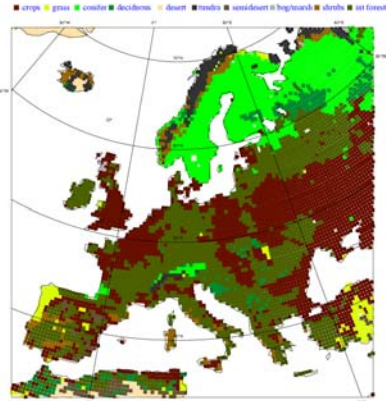
MERSEA collaboration

- Deliverables
  - Monthly estimates of ocean carbon uptake through assimilation of data on the dynamics and biology of the upper-ocean.
- Instruments:
  - QSCAT, ASCAT, RA2, JASON, MERIS, MODIS, MISR, SeaWifs,
- R/T & Retrievals
  - Satellite agencies' baseline meteo retrievals;
- Modelling
- Sources/ Sinks
- Data Assim.
- Validation



GEOLAND collaboration

- Deliverables
  - 2006 Stage I: Prototype offline assimilation system of remote sensing products and land surface model(s) to provide boundary conditions for the GHG and AEROSOL sub-projects. Data assimilation products: Soil moisture, LAI, biomass, snow, fluxes of carbon, water and energy.
  - 2008 Stage II: As above but with refined assimilation scheme and land surface model(s) and below- and above-ground carbon storage as deliverables.
- Data Assimilation Approach
  - Build on existing FP5 projects (ELDAS, CAMELS, Land-SAF); model and product benchmarking; off-line assimilation with several models (ISBA-A-gs, MOSES, C-TESSEL). Transition from assimilation of derived geophysical products (Stage I) to top of the atmosphere radiances (Stage II).
- Instruments:
  - AVHRR, ATSR, GRACE, POLDER, VEGETATION, SEVIRI, MERIS, MISR, MODIS, SMOS
- R/T & Retrievals
  -
- Modelling
- Data Assim.
- Validation



Land Missions, Modelling, Assimilation

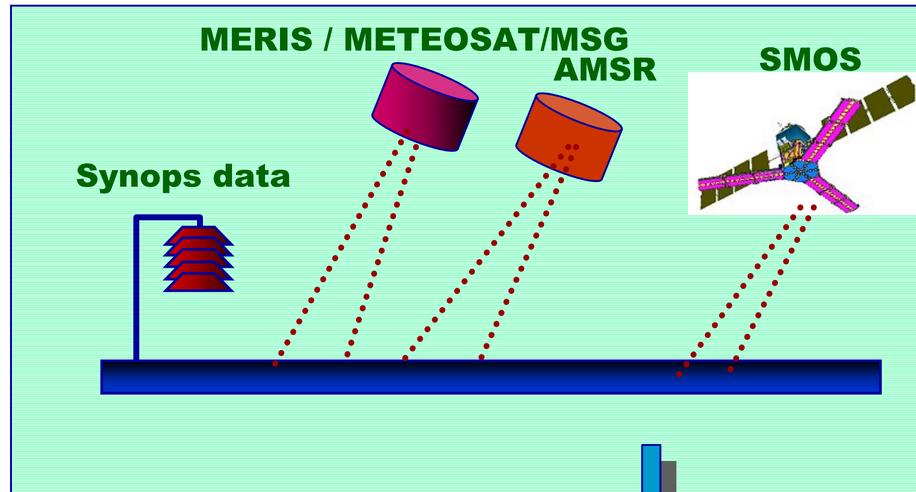
Several missions will enable an improvement of the ECMWF soil moisture and vegetation

Observations driving The land model

precipitation

radiation

Observations driving soil moisture correction

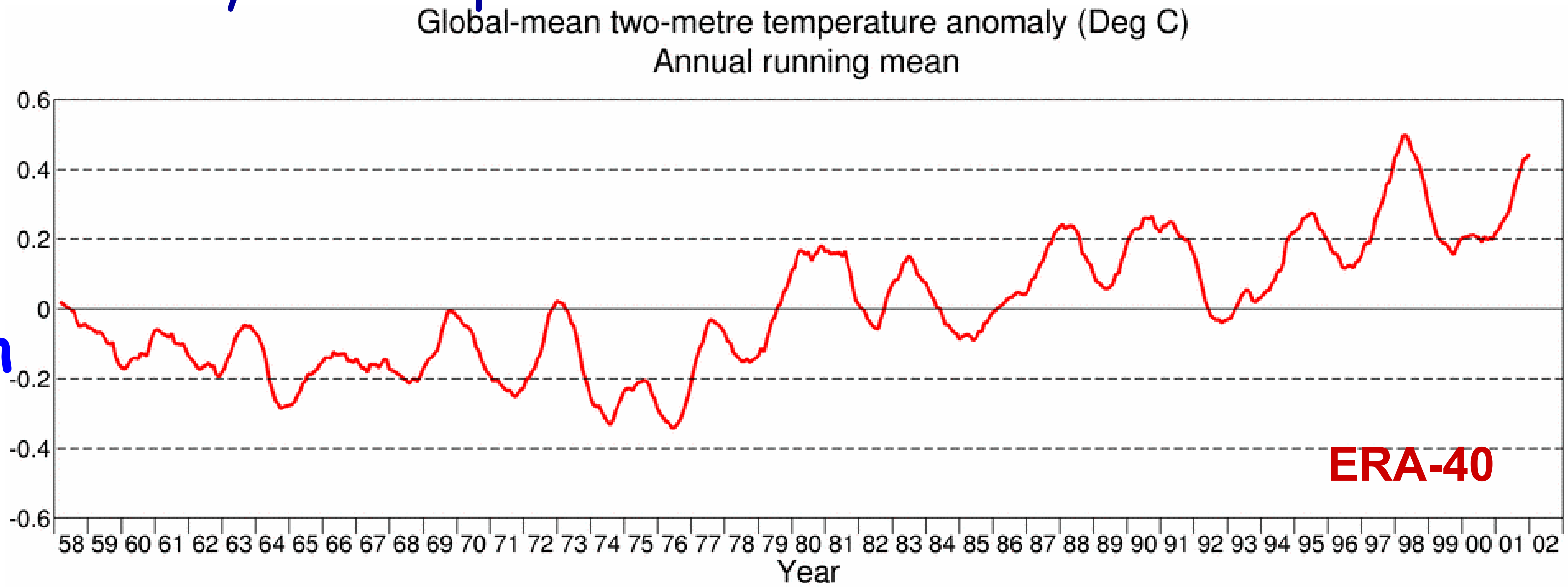


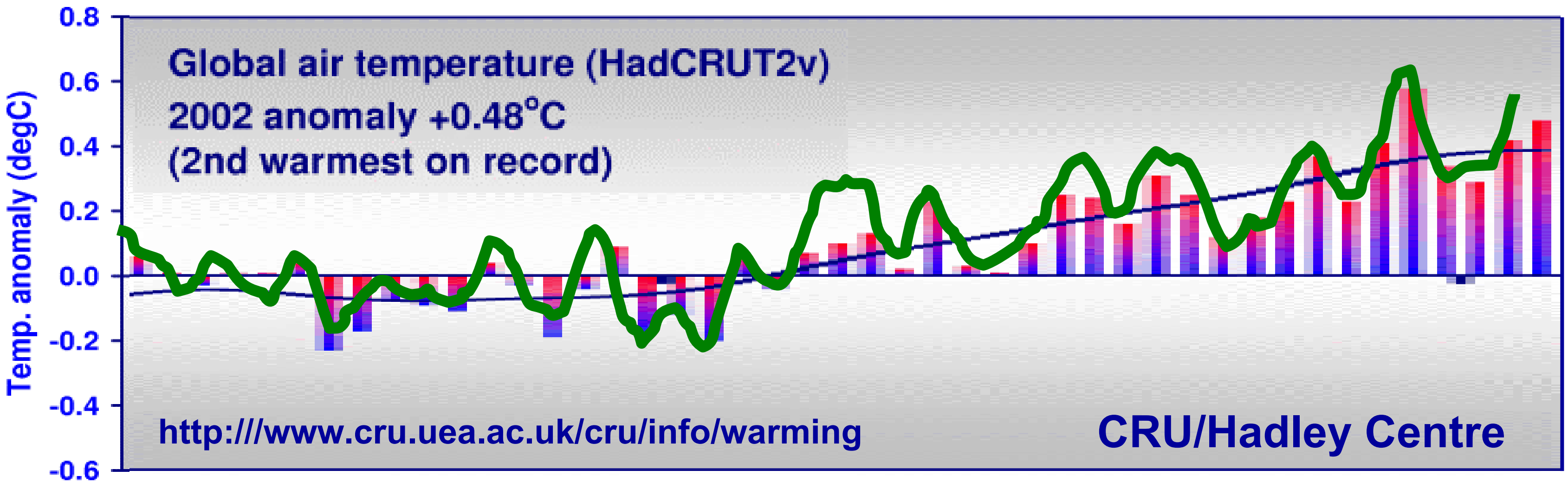
Atmosphere/Land / biosphere model + 1DVAR assimilation

soil moisture/ vagetation

GEMS Reanalysis Component

Trends in ERA-40





Computing Power to use the Satellites

- Full exploitation of the huge investments in space hardware requires appropriate investment in
  - computing power
  - advanced data-assimilation systems.

- High spatial resolution (I.e. heavy computing power) is vital for the accuracy of both assimilation and forecasts
  - Japan has invested $400M in the Earth Simulator computer (40Tflop peak, 12Tflop sustained, installed 2002)
  - ECMWF invests ~£12M annually in HPC and ancillary equipment (2004 will see Blue Storm - 25Tflop peak, 2.5Tflop sustained)
  - European, US and Japanese Numerical-Weather-Prediction & Climate-modelling centres each have annualised investments of £3 – 10M

The GEMS Partnerships

- GEMS partnerships include
    - European space agencies
    - Leading in-situ observational teams
    - Leading modelling and assimilation teams
    - Leading inverse-modelling teams

- GEMS will have strong support from GAW, GCOS, WCRP…

- GEMS will build on examples of successful EU-funded partnerships such as for ERA-40, PRISM, ELDAS, ACCENT..

- GEMS will have important spin-offs for Numerical Weather Prediction

END

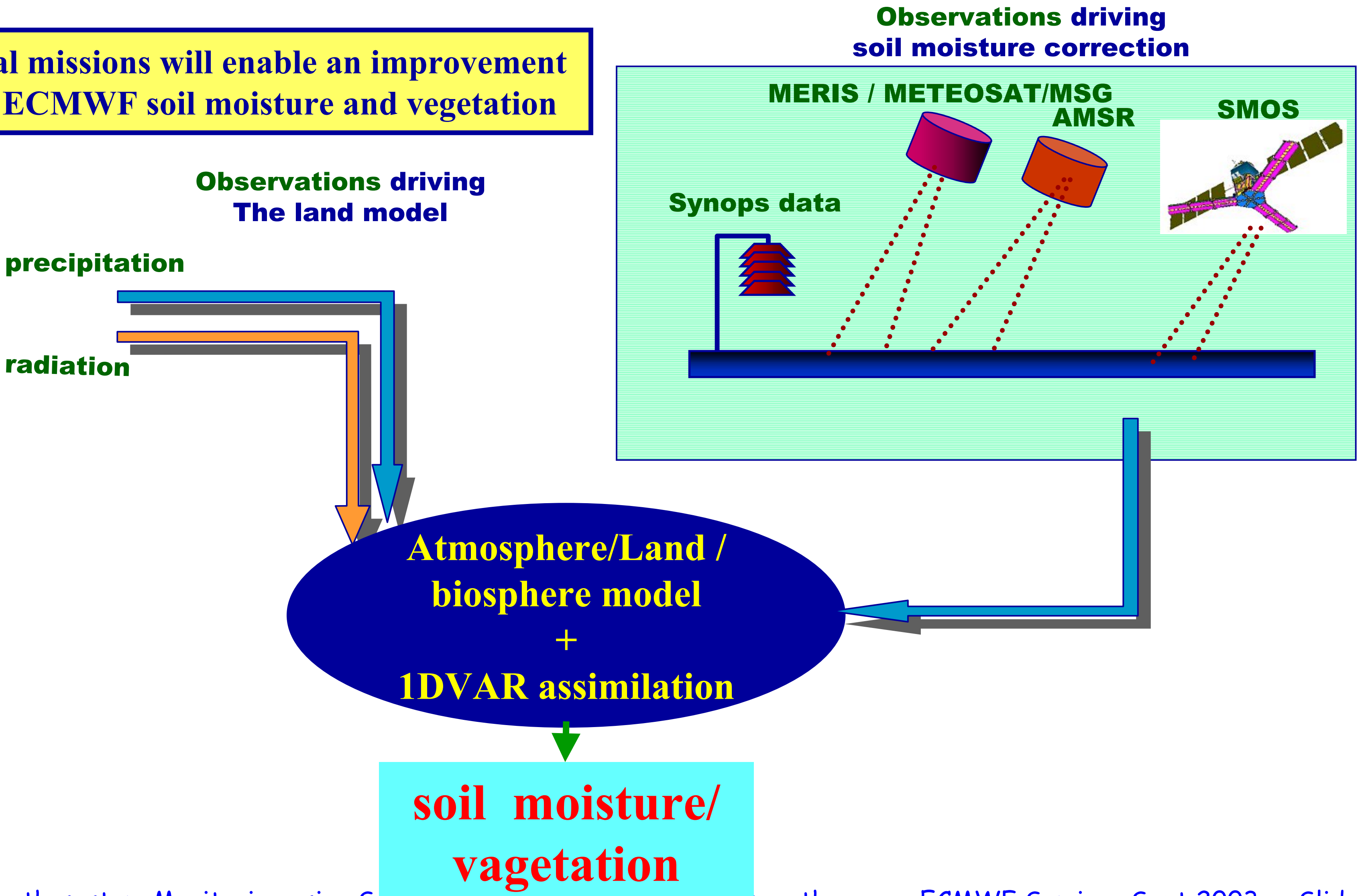
thank you for your attention!

Cost-effective information provision in a Numerical Weather Prediction (NWP) setting

- Policymakers' key global environmental information needs cannot be met without an Earth-system modelling and data assimilation capability.
- Numerical Weather Prediction Centres will exploit most of the new instruments anyway, for their own purposes of forecasting weather & short-term climate variations.
- To achieve good estimates of T, q, O_3, ocean stress…., NWP centres must do a superb job on key tasks
  - Calibration
  - Channel selection
  - Cloud detection…
- These tasks are essential pre-requisites to meeting policymakers' needs
- With modest additional effort, NWP centres can do a thorough exploitation and validation of the satellite data for weather and for environmental purposes.
- REMARK: important pay-offs for NWP will include better models, better assimilations… The approach outlined above is one of the best ways to sharpen the performance of the NWP & Climate forecast systems

Land Missions, Modelling, Assimilation

Several missions will enable an improvement of the ECMWF soil moisture and vegetation



Monitor-AEROSOL:

- Model and assimilate global aerosol information
- Heritage: -
- Instruments: MERIS, MODIS x 2, MISR, SEAWIFS, POLDER
- Data Mgt tbd
- R/T "
- Modelling "
- Sources/ Sinks "
- Data Assim. "
- Validation "

Monitor-GREEHOUSE GASES:

- Monitor seasonal variations of non-reactive Greenhouse Gases such as CO_2, CH_4, N_2O, CO
- Heritage: COCO (FP5)
- Instruments: AIRS, SCIAMACHY, IASI, OCO
- Data Mgt ECMWF
- R/T LMD & ECMWF
- Modelling ECMWF & UKMO
- Sources / Sinks
- Data Assim. ECMWF & UKMO
- Validation MPI-BG, LSCE, F.U.Amst. U.Tuscia, NUI_G

GEMS Global Earth-system Monitoring using Space and in-situ data

GEMS: Build a Data Assimilation system at ECMWF (at lower than operational resolution) which extends the medium range system to assimilate

- GREEHOUSE GASES
- REACTIVE-GASES
- AEROSOL

- **Operational by 2008**
- **Deliver a 10-year reanalysis of the EOS / ENVISAT era**
- **Collaborate with 3 EU Framework 6 funded projects**
  - GEOLAND: Model and assimilate data on the Land Biosphere and global carbon cycle.
  - MERSEA: Model and assimilate upper-ocean, incl. Ocean-colour to estimate ocean carbon uptake.
  - HALO: Harmonisation of Atmosphere, Ocean, Land Projects

to deliver the best possible description of atmosphere dynamics, thermodynamics and composition.

Global Earth-system Monitoring using Space and in-situ data: GEMS

GEMS Monitoring sub-projects

- GREEHOUSE GASES: Monitor seasonal variations of non-reactive Greenhouse Gases such as CO_2, CH_4, N_2O, CO
- REACTIVE-GASES: Monitor ozone and its precursors, and sulphate aerosol and its precursors.
- AEROSOL: Model and assimilate global aerosol information
- SYSTEM-INTEGRATION & RETROSPECTIVE REANALYSIS:- Integrate the above projects in a pre-operational system, and validate through retrospective analyses

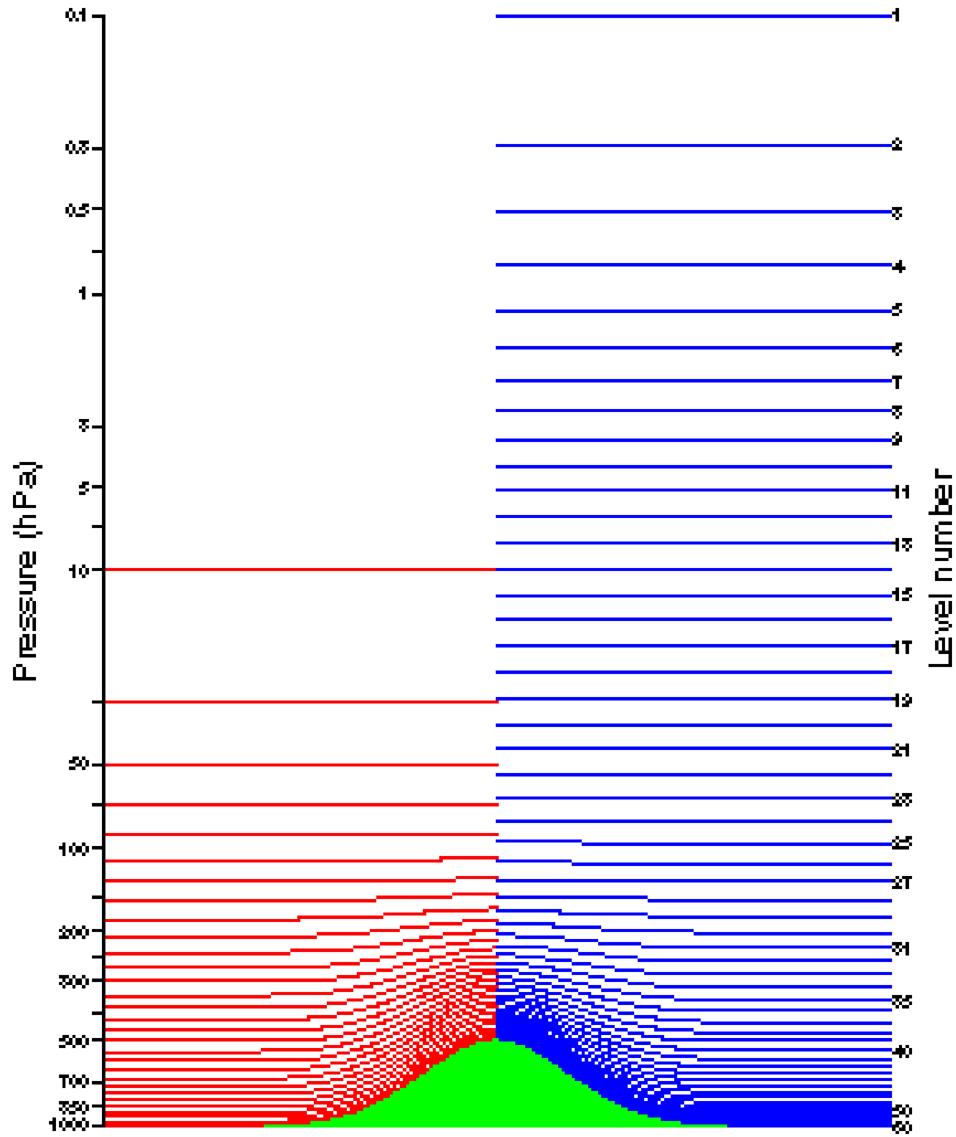
- LAND: Model and assimilate data on the Land Biosphere and carbon cycle.
- UPPER-OCEAN incl. OCEAN-COLOUR: Model and assimilate upper-ocean, to estimate ocean carbon uptake.

Much important work already in progress!

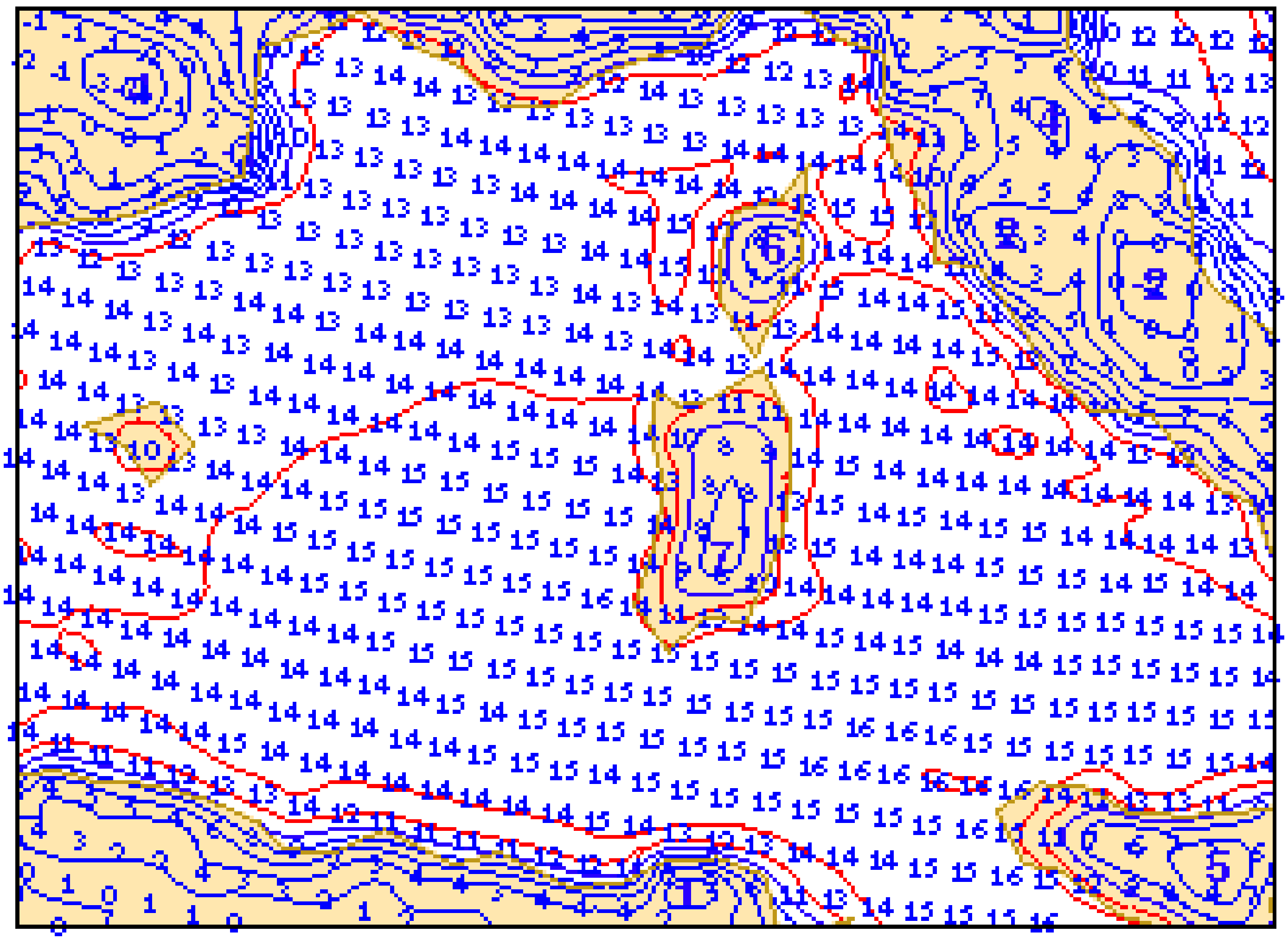
The Vertical Grid

60 levels between surface and 65km.

The levels are closely spaced near the surface .



Two meter temperature forecast T511 Thursday 1 February 2001 12 UTC+60h



The Horizontal Grid

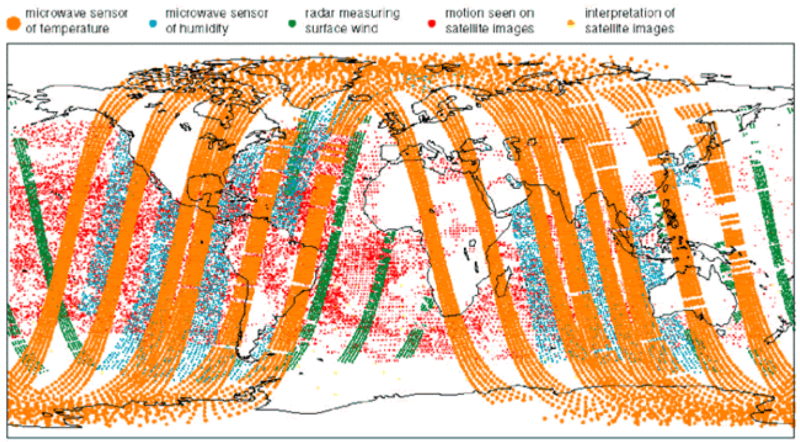
The high-resolution model has a 40 km horizontal grid

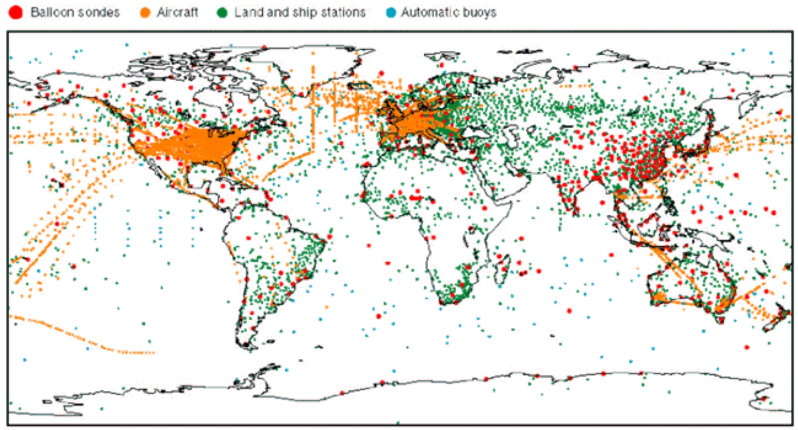
Initial conditions

For accurate forecasts, we need to know the current weather

- Observations are available for the whole globe
- About 3,000,000 observations are processed every 12 hours

To define the initial state of the system, very complex procedures have to be used



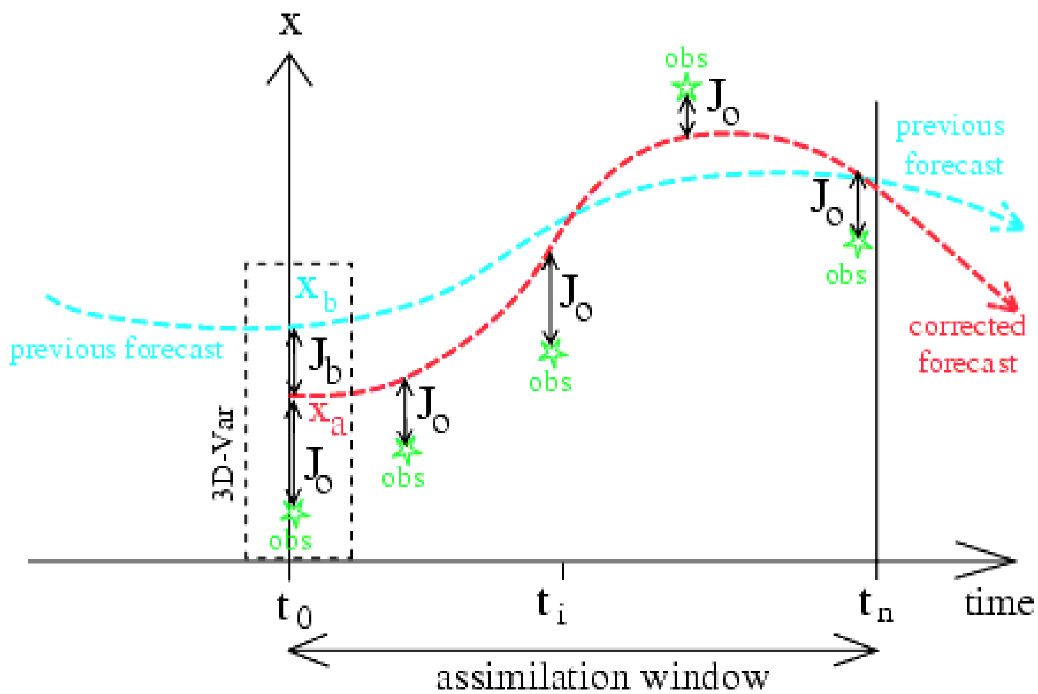


Four-Dimensional Variational Data Assimilation (4D-Var): Adjusting the model trajectory to fit diverse observations irregularly distributed in space and time

•The data within a 12 hour period are used simultaneously, in one global estimation problem
•4D-Var finds the 12-hour forecast evolution that best fits the available observations

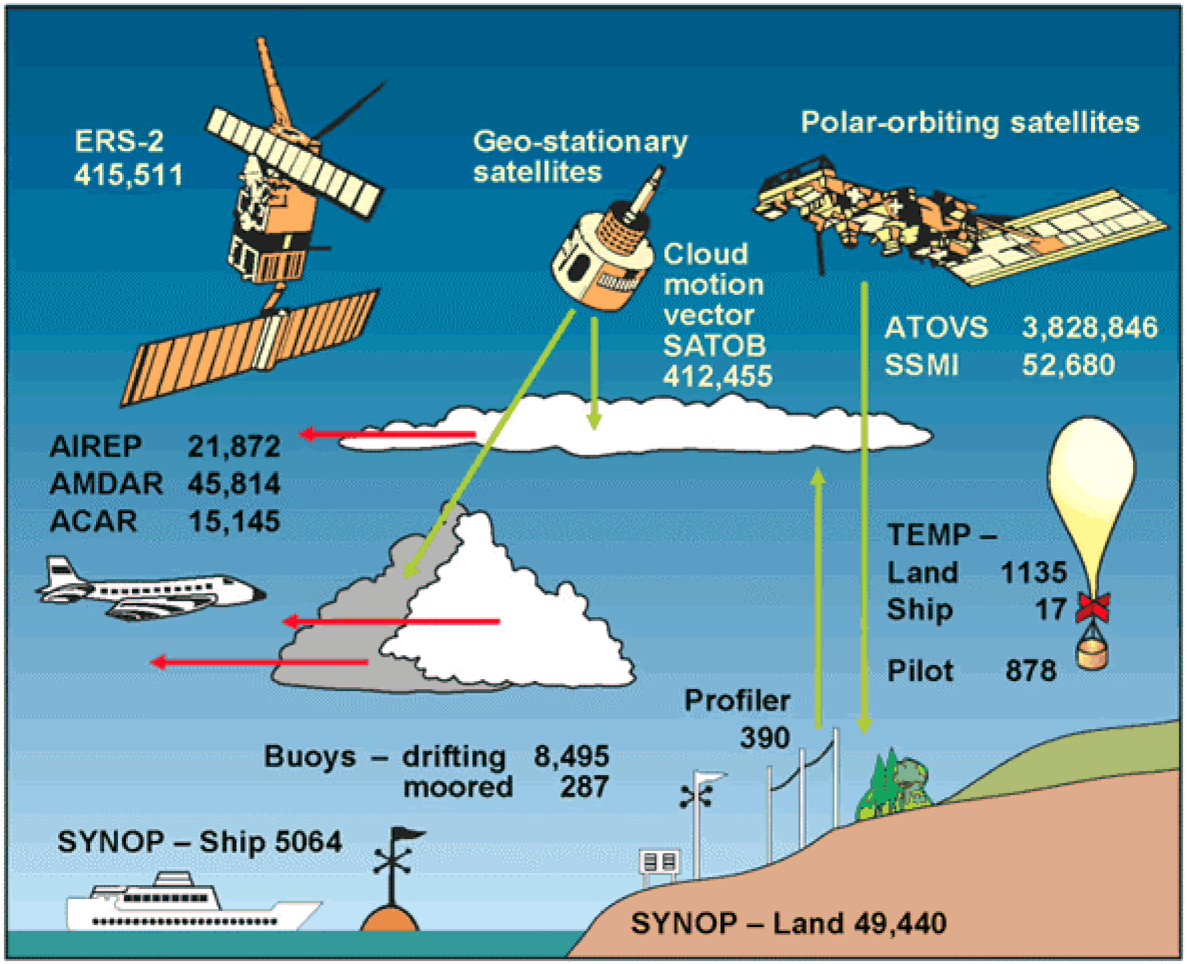
•4D-Var adjusts surface pressure an upper air fields of
- •Temperature
- •Wind
- •Specific humidity, cloud, rain
- •Ozone….

• In the minimization of the cost function, small corrections to the trajectory are propagated forwards and backwards in time, in a huge variational optimization (O(10**7))

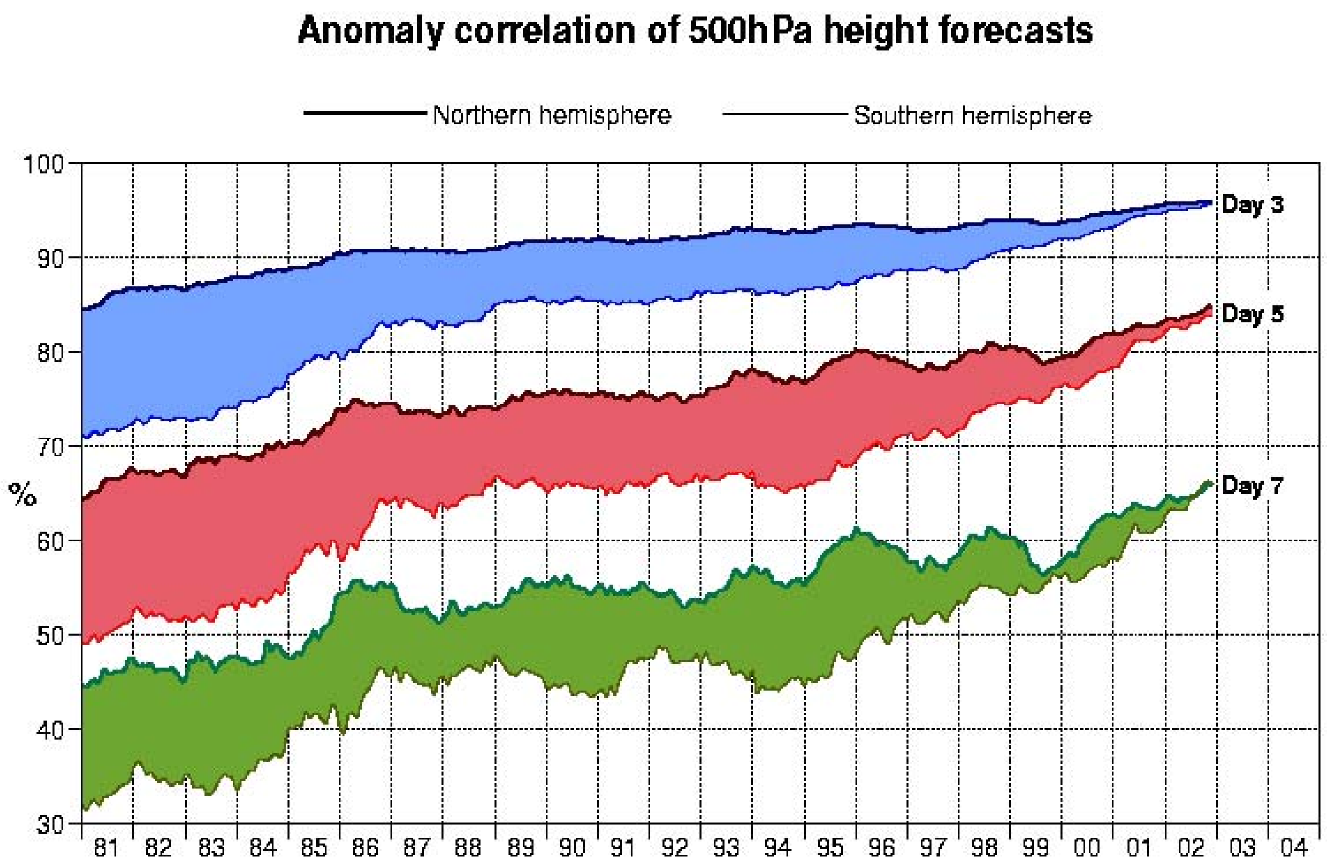


Data sources

(number of data items refer to 24 hour period in a specific date)



Evolution of forecast skill for northern and southern hemispheres 1981-2002



Evolution of forecast skill in Typhoon Track Forecasts 1991-2000

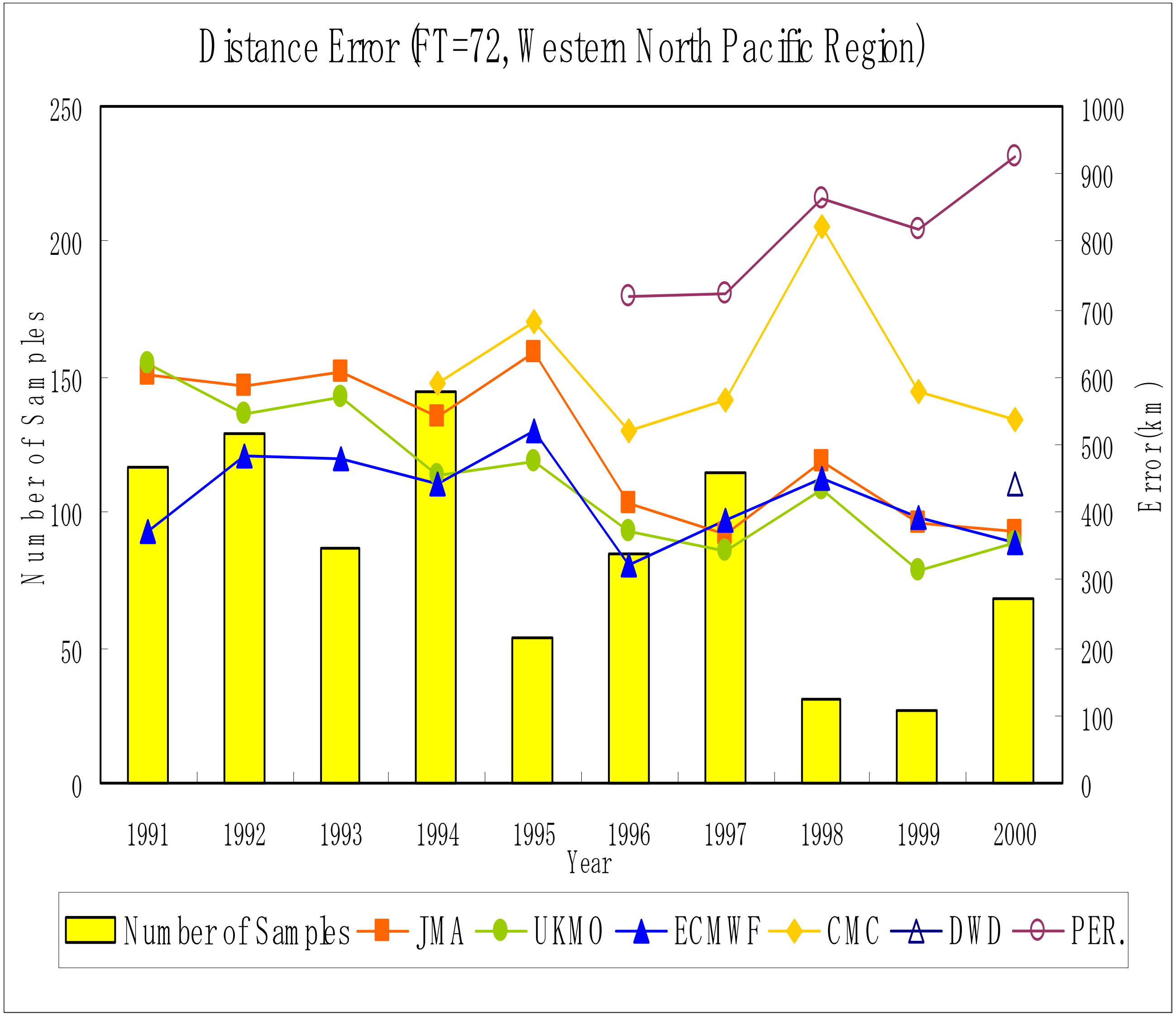
Tsuyuki, et al

WMO Bulletin, July 2002

Western North Pacific

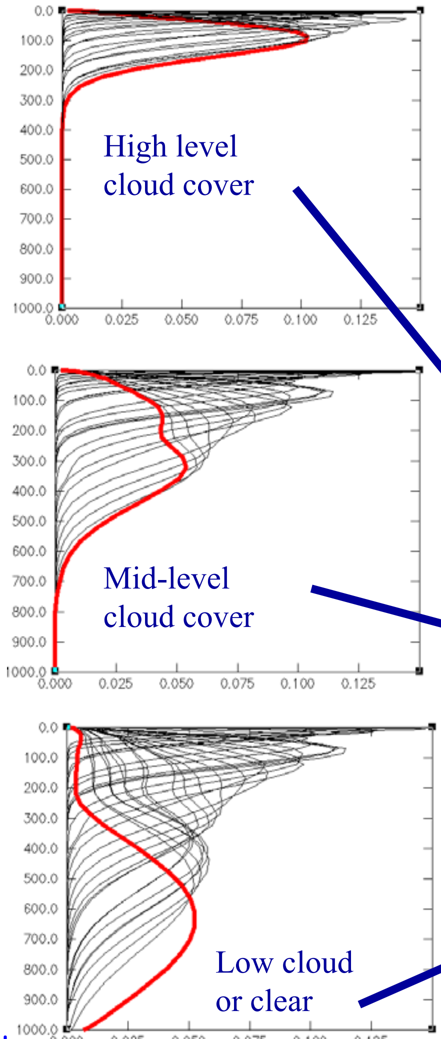
D+3

In 1986-1990, JTWC error was ~650km

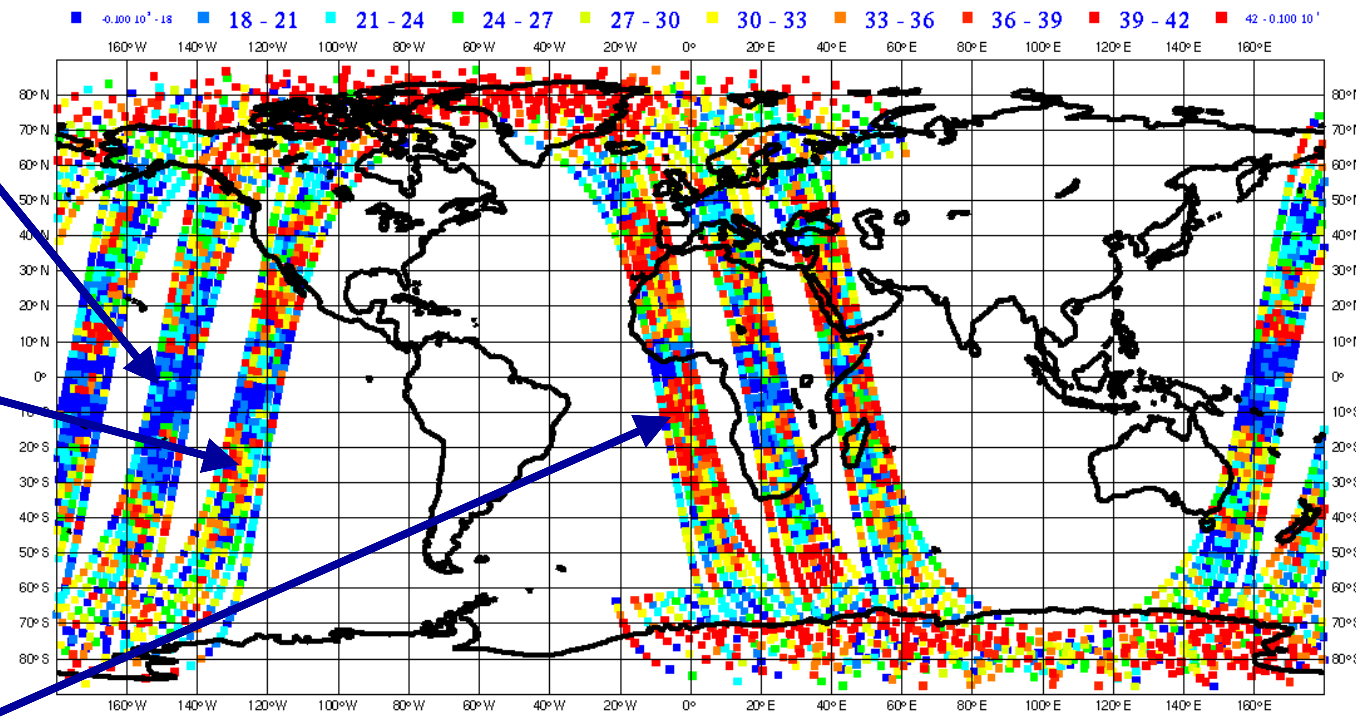


Cloud detection and channel use above clouds

Temperature weighting functions



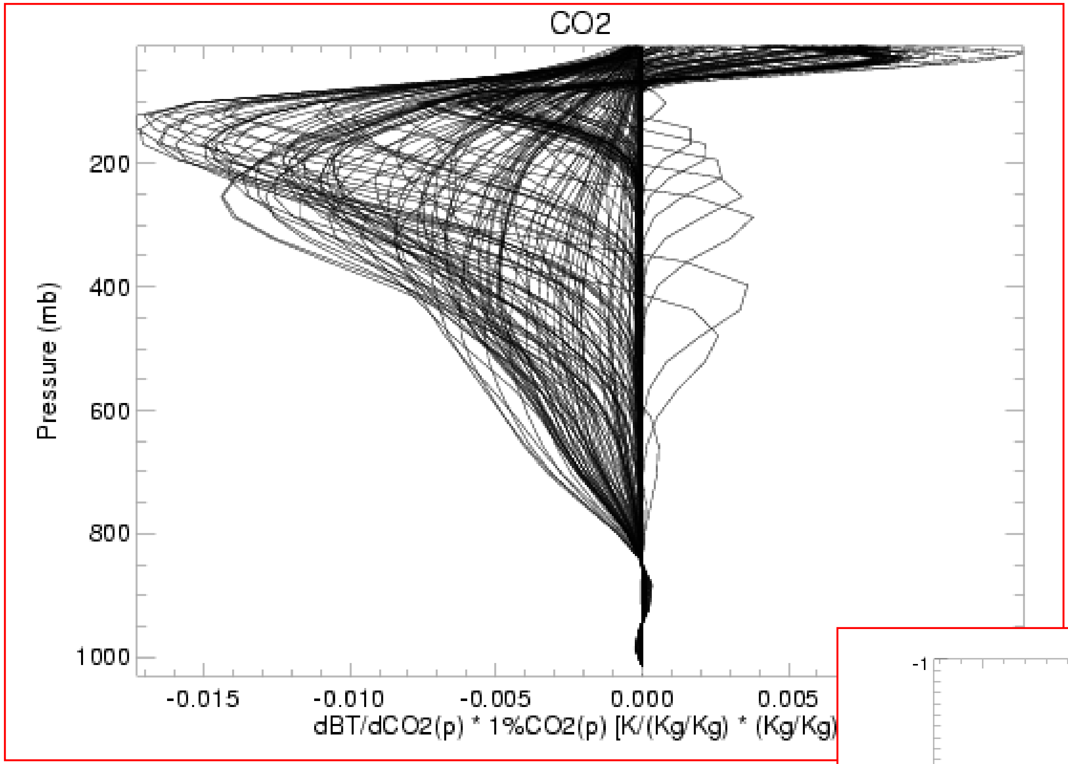
Index of lowest AIRS long-wave channel determined cloud-free
(clouds and AIRS radiances simulated from ECMWF model)

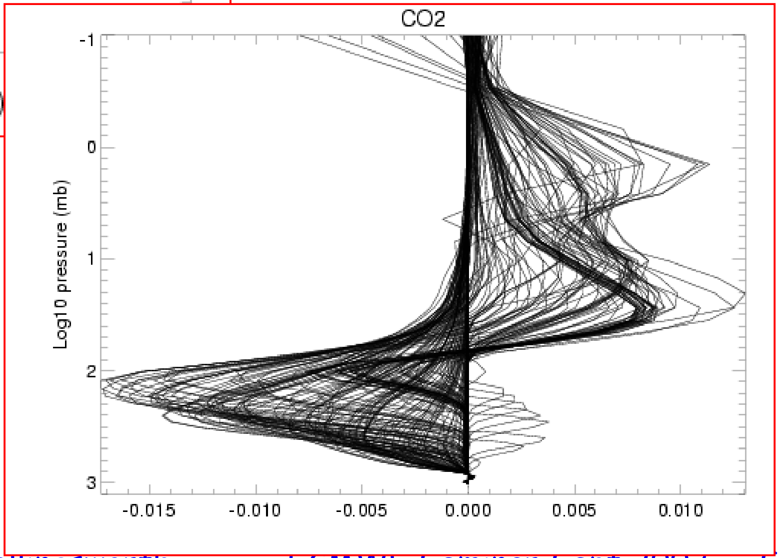


AIRS
CO_2 Jacobians

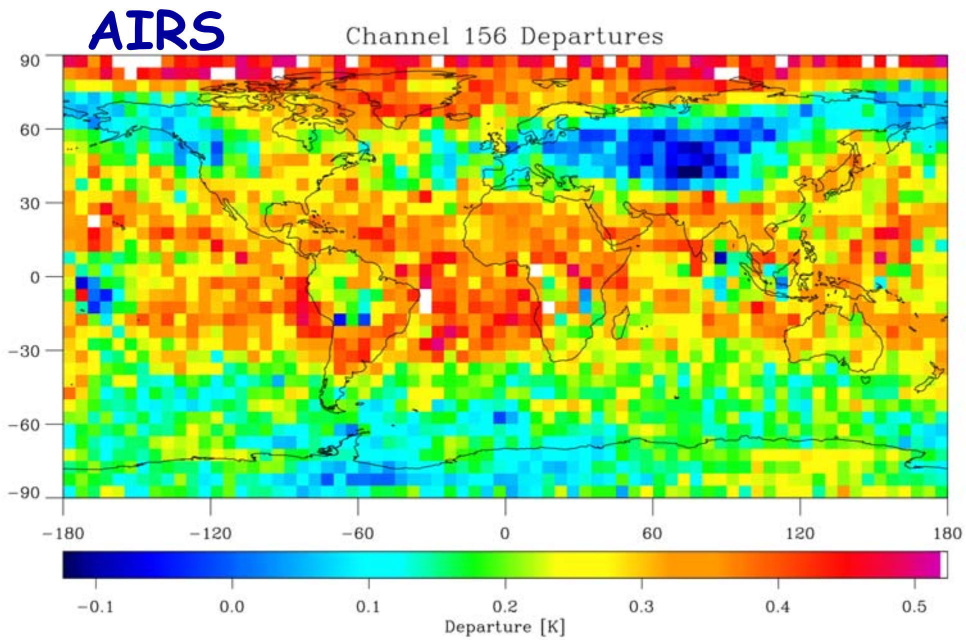
Good coverage in upper troposphere

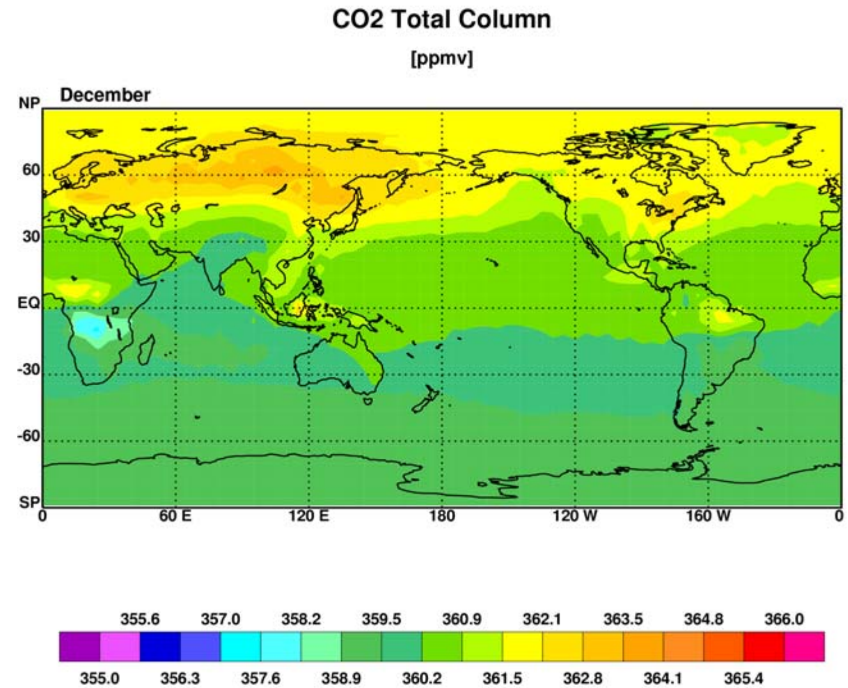
Many channels with sensitivity to UT & LS
Zero sensivity near surface

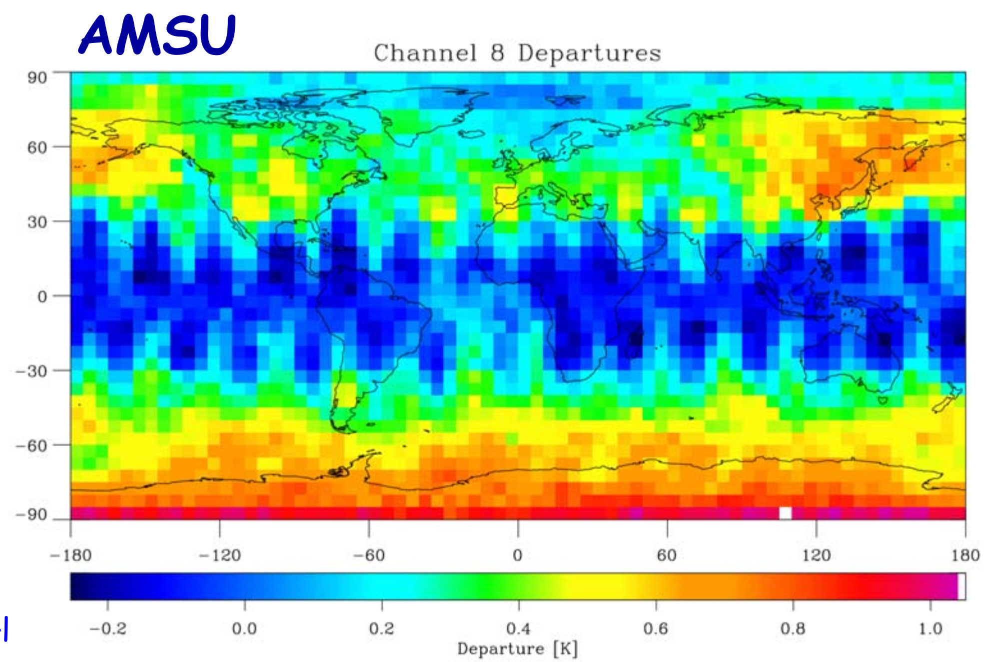




SCIAMACHY (& OCO in 2006) have capability to measure **CO_2** **in the lower atmosphere**







FIRST CO2 SIGNALS FROM NASA's AIRS on AQUA

Model-AIRS departures for a CO_2 sensitive channel show clearly different spatial patterns than the corresponding AMSU departures. Over Siberia it corresponds with anomalous high CO_2 values from climatological model output.

The 1979 Convention on Long-range Transboundary Air Pollution: History

- 1960s: Scientists show how sulphur emissions in continental Europe led to acidification of Scandinavian lakes.
- 1972-77: After 1972 UN Stockholm Conference on Human Environment, studies confirm that air pollutants could travel thousands of kilometres before deposition and damage occurred
- 1979: Convention on Long-range Transboundary Air Pollution signed by 34 Governments and the European Community – the first international legally binding instrument to deal with problems of air pollution on a broad regional basis.
- The Convention set up an institutional framework bringing together research and policy. Continuing work has led to the development of 8 further protocols on different pollutants.

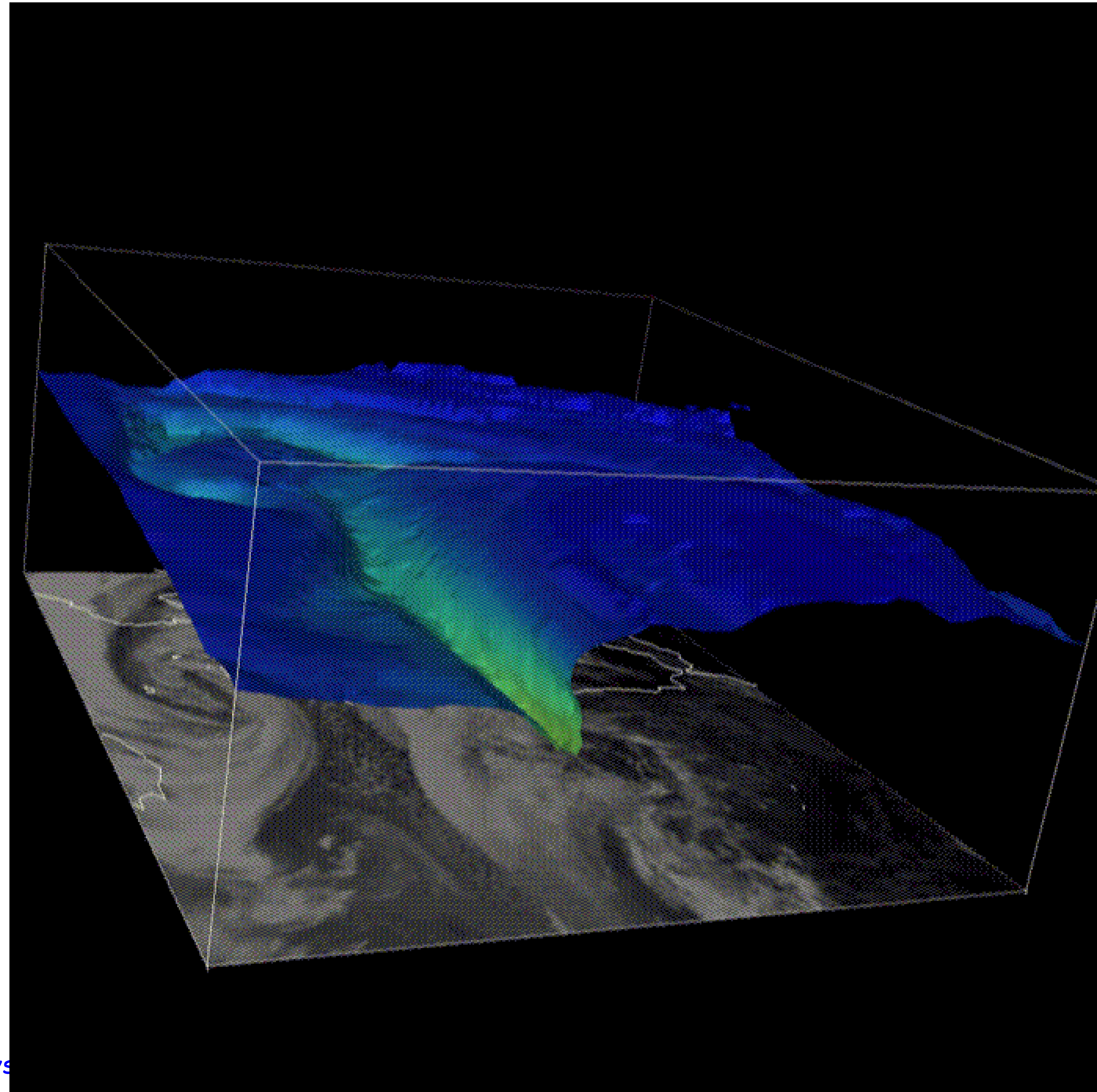
CARBO_EUROPE Network

•Halloween **Storm viewed from above Greenland**

•Ozone isopleth - f(p) - is colour-coded by temp.

•Yellow is warm

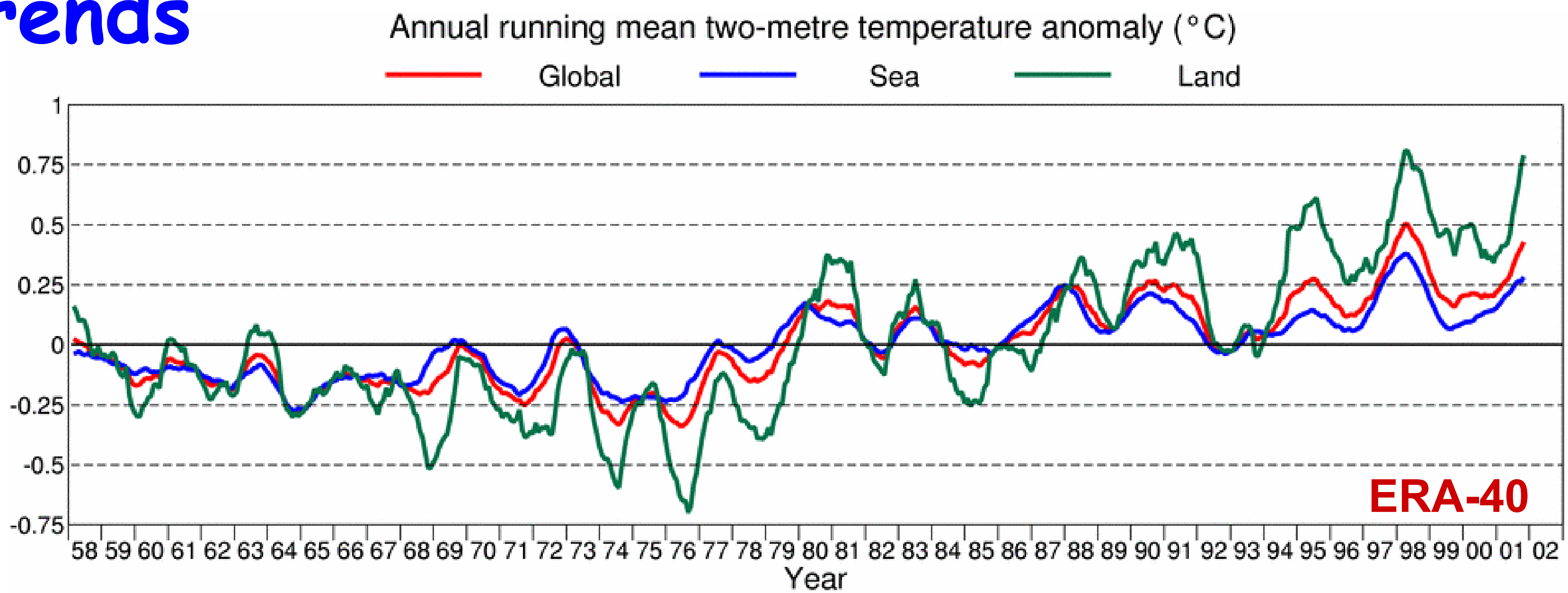
•Meteosat imagery shown below the ozone



•24-hour loop in steps of 3 hours

•12z on 29/10 /00 to 12Z on 30/10/00

Trends



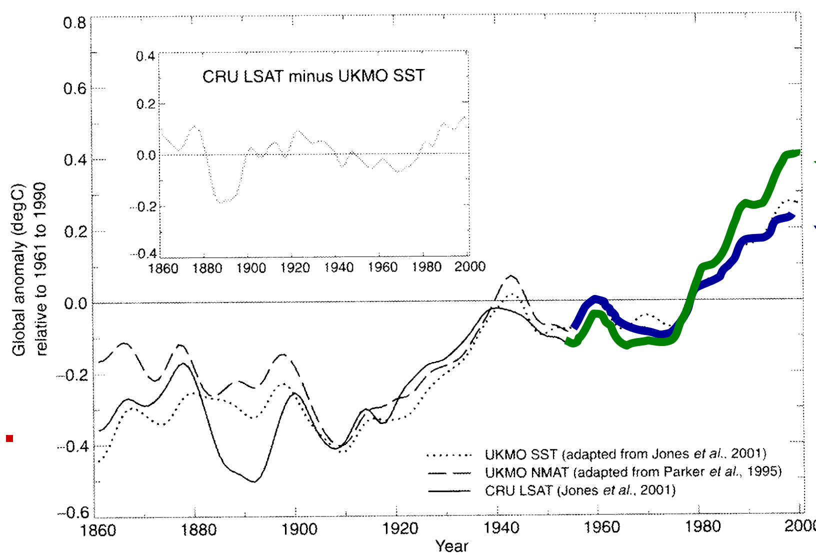


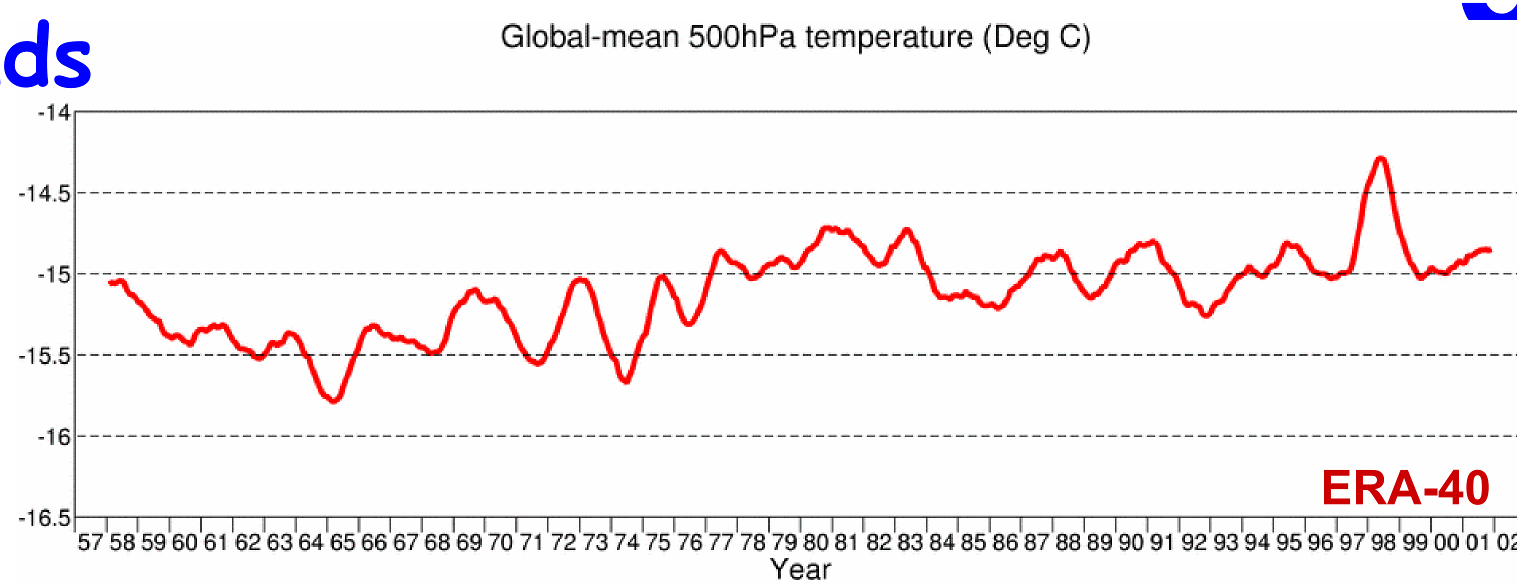
Fig. 1 Smoothed annual anomalies of global average sea surface temperature (SST) (degC), 1861–2000 relative to 1961–90 (dotted), night marine air temperature (NMAT) (dashed), and land-surface air temperature (LSAT) (solid). The smoothed curves were created by using a 21-point binomial filter giving near-decadal averages. Also shown (inset) are smoothed differences between LSAT and SST anomalies.

Folland et al. (2002)

Land — **Jones et al.**

Sea — **Parker et al.**

Trends



Time series of MSU-2 brightness-temperature anomaly (K), from Wentz and colleagues