Importance of satellites for stratospheric data assimilation

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1 Introduction

It is easy to understand why satellites are important for stratospheric data assimilation, since few other types of observations of the stratosphere exist. However, since the subject of this year's Annual Seminar is the use of satellite observations for numerical weather prediction (NWP), some obvious questions are: Why is stratospheric data assimilation important for NWP in the first place, and what are the some of the special challenges associated with it?

The main motivation for including a stratosphere in an NWP system is to improve the use of satellite observations of the troposphere. This is because direct assimilation of radiance data involves calculating the radiative transfer along the path observed by the satellite, using estimates of the atmospheric state generated by the assimilating model. Since many tropospheric sounding channels important for NWP have some sensitivity to the stratosphere, the model must provide accurate information on the entire atmospheric column to allow data from these channels to be used well.

There are various studies indicating the important role that stratospheric variability plays in driving tropospheric weather on monthly and seasonal timescales. An improved representation of the stratosphere may therefore ultimately help to extend the useful forecast range in NWP models.

Most NWP models nowadays extend far into the stratosphere, and often include part of the mesosphere. Since February 2006 the top level of the ECMWF forecast model has been at 0.01hPa, with approximately half of the 91 vertical levels outside the troposphere. The uppermost 4 of these serve as a sponge layer, whose purpose is to absorb upward propagating waves and prevent spurious reflection at the upper boundary. Consequently the highest model level that can be considered as physically meaningful is located at 0.1hPa, which corresponds to an altitude of around 65 km well into the mesosphere.

Challenges in stratospheric data assimilation arise from the presence of large model errors combined with incomplete observational coverage. Satellite observations of the stratosphere mainly contain information about temperature and ozone. Radiance assimilation produces changes to the model wind field via balance constraints imposed by the analysis, but whether these constraints as currently formulated are actually suitable for the stratosphere is an open question. Furthermore, the dynamical constraint imposed by 4D-Var can affect the wind field as well. This is a potential benefit of 4D-Var, but we have found that the assimilation of ozone profile data in the lower stratosphere can generate large and unrealistic changes to upper stratospheric flow. This is mainly due to the large biases in the ozone data relative to the model, together with the lack of observational constraints available for the upper stratosphere.

Acknowledgements

This presentation has relied on input and results provided by Rossana Dragani, Sean Healy, Elias Hólm, Marco Matricardi, Tony McNally, Beatriz Monge-Sanz, and Sakari Uppala. Shinya Kobayashi has gracefully allowed

the presentation of his work in progress on the homogenisation of SSU radiances and the correction of RTTOV for AMSU-A. The importance of his work for the reconstruction of a coherent stratospheric climate record cannot be underestimated.

Presentation Slides

Importance of satellites for stratospheric data assimilation

Dick Dee

With major help from:

Shinya Kobayashi

and

Rossana Dragani, Sean Healy, Elias Hólm, Thomas Jung, Beatriz Monge-Sanz, Marco Matricardi, Tony McNally, Sakari Uppala

Seminar on Recent developments in the use of satellite observations in Numerical Weather Prediction

ECMWF, 3-7 September 2007

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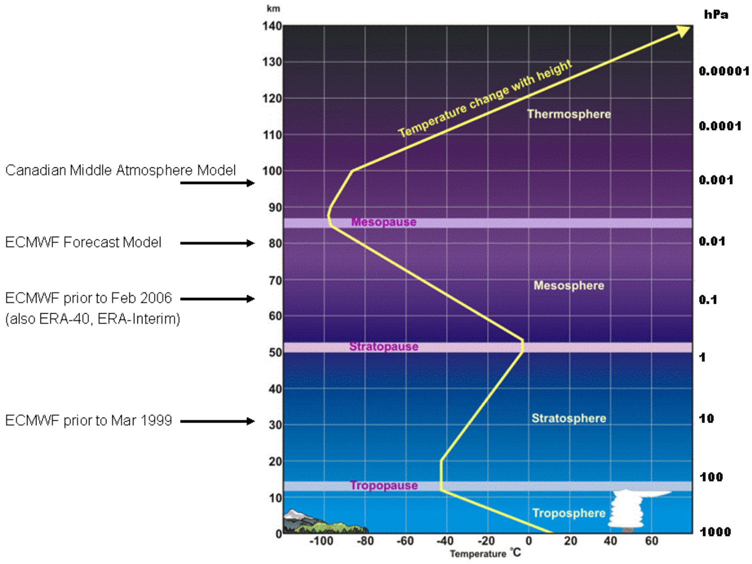
Outline

- Introduction
  - Why include a stratosphere in NWP models?
  - Satellite observations of the stratosphere
  - Special challenges in stratospheric data assimilation
- Dealing with systematic errors
  - SSU and cell-pressure leaks
  - AMSU-A and the Zeeman effect
  - Impact of GPS radio occultation data
- The lack of wind observations
  - Quality of the wind analysis
  - Use of ozone data in 4D-Var
- Summary

Including the stratosphere in NWP models



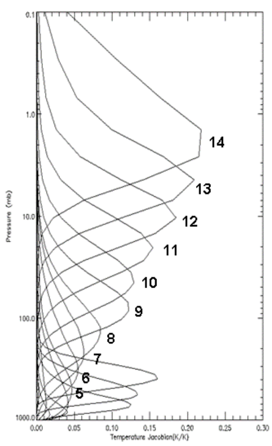
Why include the stratosphere?
Better use of radiance data for NWP

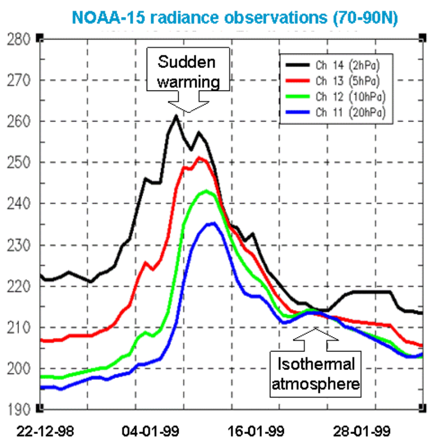
- Assimilate raw radiance measurements rather than pre-processed products that combine data from different sensors
- Advantages:
  - Eliminates errors introduced in the pre-processing
  - Radiance quality control can be tailored to the NWP system and use up-to-date state information
  - Faster access to raw radiance data for real-time applications
- Requires an observation operator for each sensor, to simulate radiance measurements from the forecast model state:
  - Fast radiative transfer
  - Limb and emissivity adjustments, etc.
- Many tropospheric nadir sounding channels are also sensitive to stratospheric temperatures, so these must be accurately represented in the NWP system

(Title of this talk: *"The importance of satellites for stratospheric data assimilation"*
should be
"The importance of the stratosphere for satellite data assimilation")

Illustration: AMSU-A and the stratosphere

AMSU-A sensitivity to temperature





(Tony McNally)

Satellite observations of the stratosphere used in ECMWF operations

Nadir sounding data:

Radiances: HIRS, AMSU-A, (AIRS), IASI, (SSMIS)
Ozone: SBUV, Sciamachy, (OMI), (GOME2), (MIPAS), (MLS)

Limb sounding data:

Radiances: (MLS)
RO bending angles: COSMIC, (CHAMP), (GRACE-A), (GRAS)

Issues for data assimilation:

- Information mainly about temperature and total ozone
- No information about humidity (until MLS)
- No direct information about winds (until ADM)

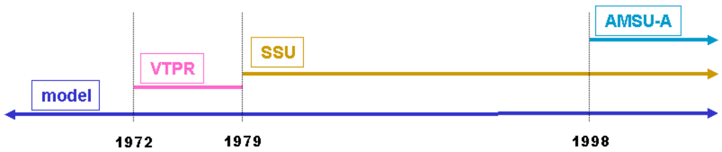
Satellite observations of the stratosphere used in ERA-40, ERA-Interim

Nadir sounding data:

Radiances: VTPR, HIRS, MSU, SSU, AMSU-A
Ozone: TOMS, SBUV, GOME

Additional issues for data assimilation:

- Especially concerned with time consistency of reanalysis
- Changing data coverage
- Inter-satellite biases



Special challenges in stratospheric data assimilation

- Dealing with systematic errors (biases):
  - In the radiance data
  - In the observation operators
  - In the forecast model
- The scarcity of wind information:
  - Winds inferred from temperature information – determined by balance constraints embedded in the analysis
  - Winds inferred from trace gas observations – determined by dynamic constraints embedded in the forecast model

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Systematic errors and data assimilation

Systematic errors in the observations:

Instrument calibration, environmental effects, …

Systematic errors in the radiative transfer models:

Spectroscopy, unmodelled physics, discretisation, …

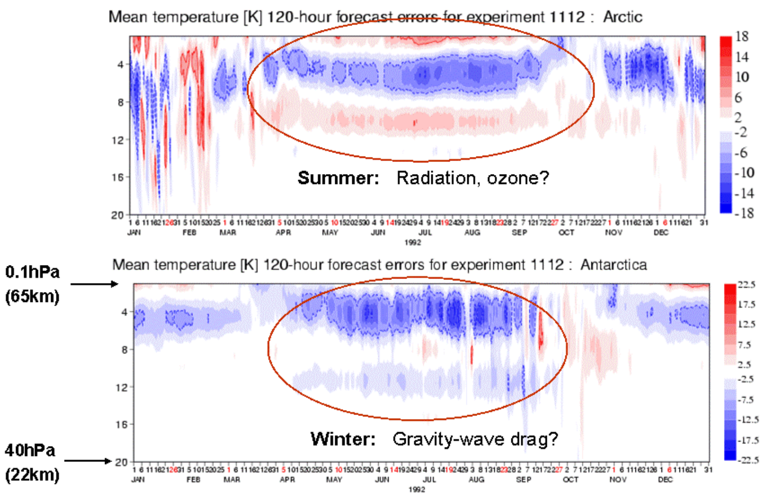
Uncorrected, these errors cause biases in the analysis that depend on data coverage (space-time sampling) as well as on details of the assimilation system (covariance modelling):

$$\mathbf{J}(\mathbf{x}) = (\mathbf{x}_b - \mathbf{x})^T \mathbf{B}^{-1}(\mathbf{x}_b - \mathbf{x}) + [\mathbf{y} - \mathbf{h}(\mathbf{x})]^T \mathbf{R}^{-1}[\mathbf{y} - \mathbf{h}(\mathbf{x})]$$

Usually (in NWP) biases in the data / RT model are diagnosed and corrected against the analysis (or first guess) in the context of all other observations

… but this does not work well in the upper stratosphere

Systematic model errors in the upper stratosphere
T255L60 model currently used for ERA-Interim

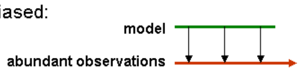


Variational bias correction of radiance data
Interaction with model bias

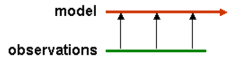
The analysis may include extra degrees of freedom for radiance bias correction:

$$J(\mathbf{x},\boldsymbol{\beta}) = (\mathbf{x}_b - \mathbf{x})^T \mathbf{B}_x^{-1}(\mathbf{x}_b - \mathbf{x}) + (\boldsymbol{\beta}_b - \boldsymbol{\beta})^T \mathbf{B}_\beta^{-1}(\boldsymbol{\beta}_b - \boldsymbol{\beta}) + [\mathbf{y} - \mathbf{b}(\mathbf{x},\boldsymbol{\beta}) - \mathbf{h}(\mathbf{x})]^T \mathbf{R}^{-1}[\mathbf{y} - \mathbf{b}(\mathbf{x},\boldsymbol{\beta}) - \mathbf{h}(\mathbf{x})]$$

When constrained by enough (?) unbiased observations this method will produce unbiased analyses, even if the model is biased:

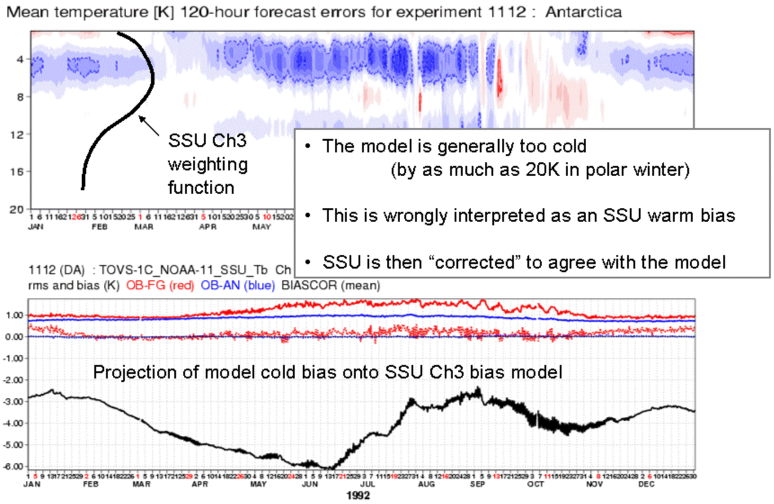


But if all available observations are allowed to be bias-corrected the analysis will simply be made to agree with the model background:

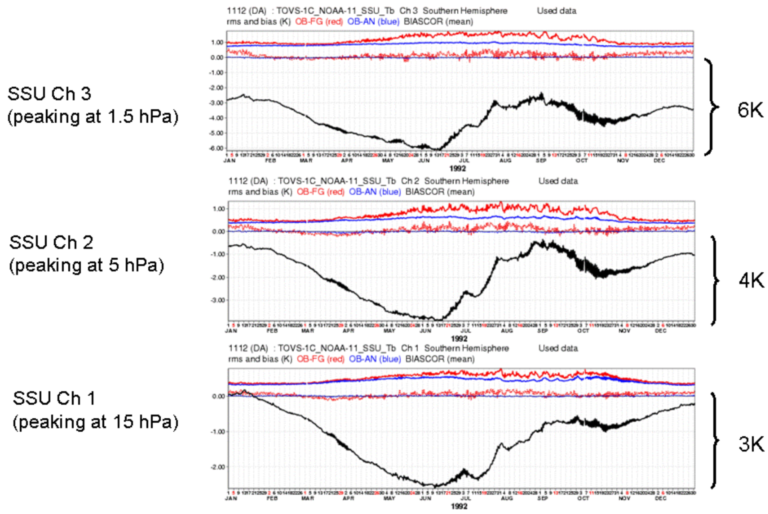


Works well in well-observed regions, or where model errors are small

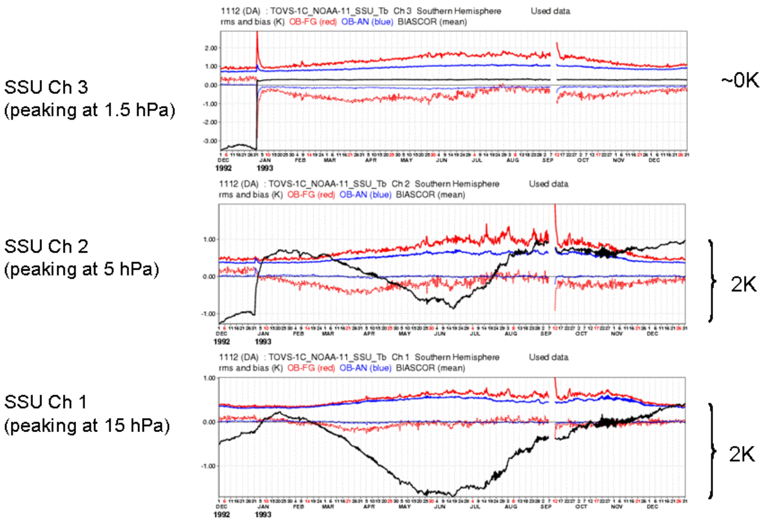
Limitations of variational bias correction:
Upper stratospheric model bias



Adaptive radiance bias correction in the upper stratosphere:
Removal of the large-scale mean signal in SSU



Situation improves when SSU Ch3 is not bias-corrected:



Systematic errors and data assimilation

Systematic errors in the observations:

Instrument calibration, environmental effects, …

Systematic errors in the radiative transfer models:

Spectroscopy, unmodelled physics, discretisation, …

Systematic errors in the forecast model:

Radiation, ozone climatology, gravity wave parameterisation, …

The available observations are the starting point …

- Models can only be improved based on data
- Are the observations being interpreted correctly?
- Can we resolve inter-satellite biases?

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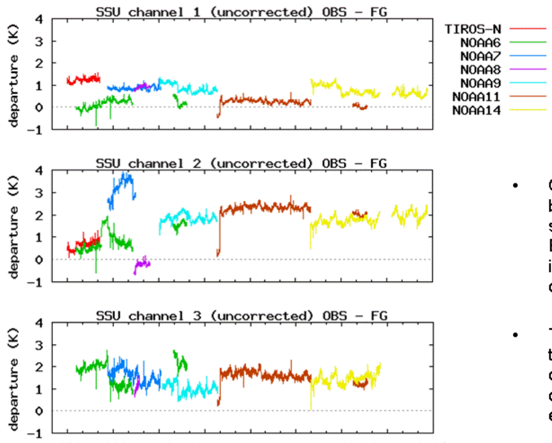
Bias in the radiance data
The use of SSU for reanalysis

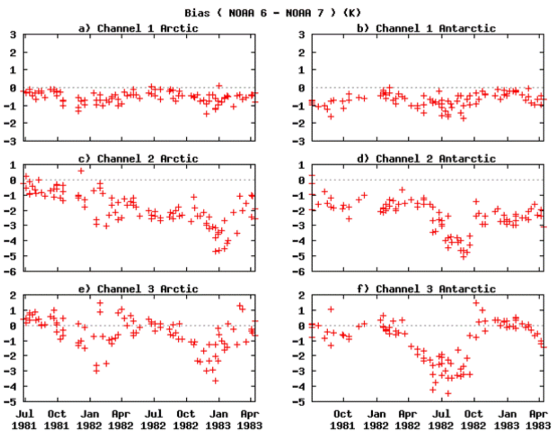
- The Stratospheric Sounding Unit (SSU) was flown on NOAA satellites from 1979 – 2006
- These data represent the most important source of climate information for the upper stratosphere
- SSU is a 3-channel radiometer using a pressure modulation technique to measure radiation emitted from the absorption band of CO_2 in the stratosphere
- Bias changes in each sensor and inter-satellite biases are mainly due to gas leaks from the pressure cell (S. Kobayashi)

Inter-satellite biases
SSU uncorrected radiance departures (ERA-40)



- Global mean differences between observed and simulated SSU radiances in ERA-40 show large inconsistencies between different satellites
- These inter-satellite biases are thought to be mainly due to changes in cell pressure that occurred during the lifetime of each satellite

Inter-satellite biases
SSU inconsistencies between NOAA-6 and NOAA-7



Simultaneous Nadir Overpass (SNO)

The SNO technique compares observations from different satellites which happen to be viewing the same place at the same time

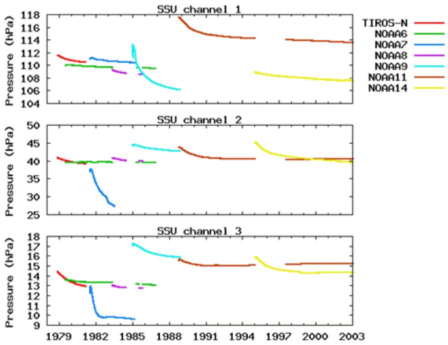
Use of the SNO technique shows that weighting functions for SSU channels on different satellites are not identical

However RTTOV is based on a single transmittance dataset for each channel and applies the transmittance to all the instruments

SSU estimated changes in cell pressure

- SSU makes use of a pressure modulation technique to measure the radiation emitted from the absorption band of CO_2
- Instrument response is rather sensitive to changes in cell pressure
- Due to a sealing problem, cell pressure changes significantly during the lifetime of each instrument

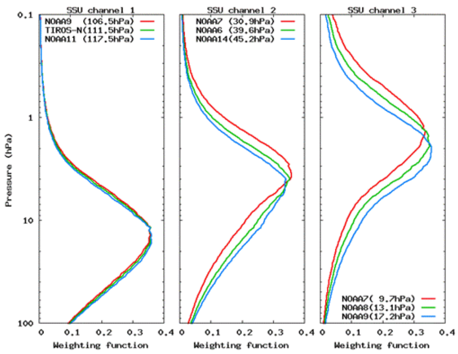
Cell pressure evolution by satellite
(estimated from modulation frequency records)



Impact of cell pressure changes on instrument response

- The outgassing from the cell effectively raises the weighting function
- This is thought to be the main cause of the biases in the SSU radiances
- SSU transmittances will be recalculated for each satellite, taking into account the estimated cell pressure changes
- An effort to collect all relevant information on the SSU instrument is currently being made in collaboration with the Met Office

Dependence of weighting functions on cell pressure



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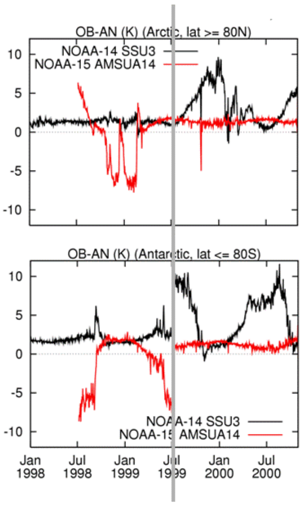
Transition from SSU to AMSU-A in ERA-40:
Both could not be used simultaneously



There was a major discrepancy between SSU Ch3 on NOAA-14 and AMSU-A Ch14 on NOAA-15, especially in polar winter

Many AMSU-A data were initially rejected by the first-guess check in ERA-40

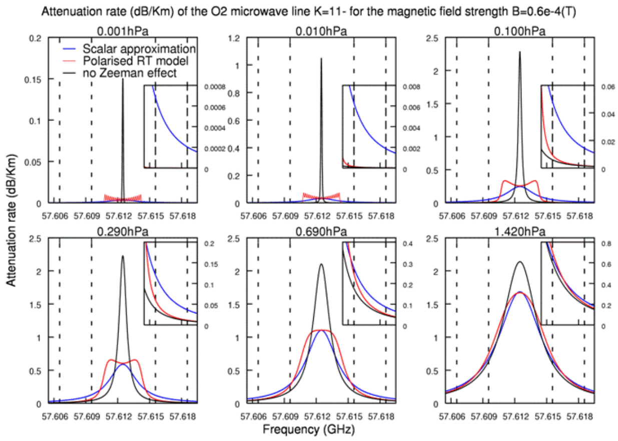
SSU Ch3 was blacklisted after 3 July 1999

The weighting functions for these channels are reasonably similar, and cell pressure for SSU on NOAA-14 was fairly stable

Could there be a problem with the radiative transfer model used for AMSU-A ?

Representation of the Zeeman effect for AMSU-A in RTTOV

The line-by-line model used to train RTTOV includes a scalar approximation for the Zeeman effect
This approximation is accurate at the centre of the absorption line,
but it is not appropriate for AMSU-A simulation !

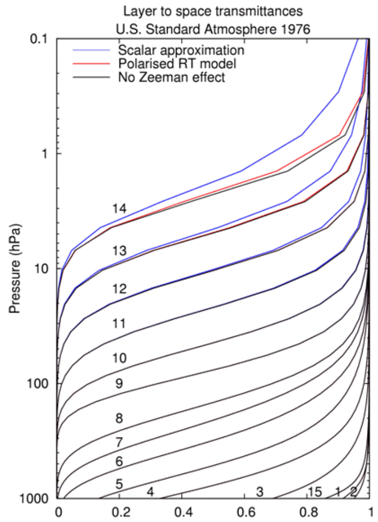


Representation of the Zeeman effect in RTTOV
Impact on AMSU-A transmittances

Transmittances for stratospheric channels are much too low when the scalar approximation is used in line-by-line simulations

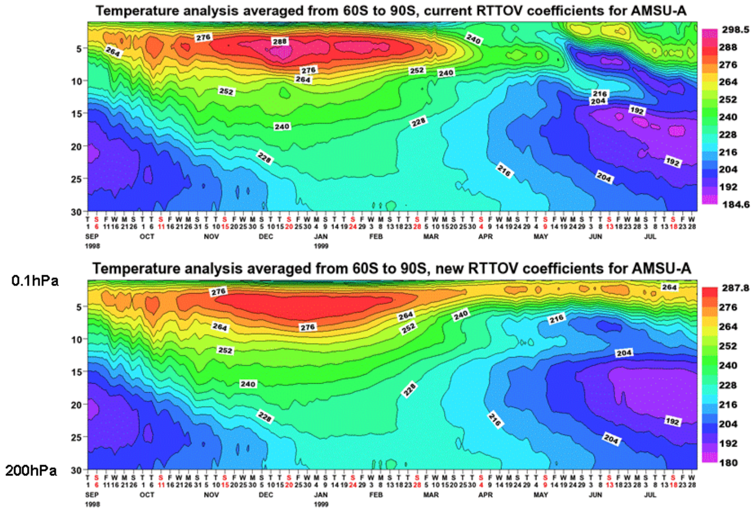
It is preferable not to include the Zeeman effect at all in RTTOV

Proper representation of the Zeeman effect requires information about the electromagnetic field strength



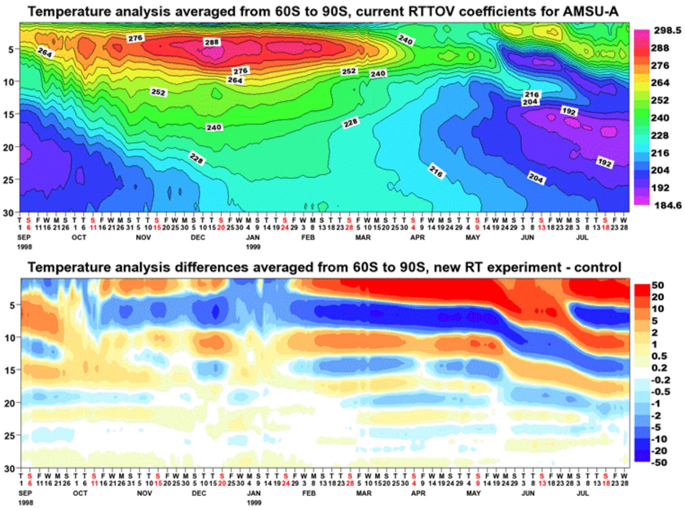
Representation of the Zeeman effect in RTTOV

Impact on stratospheric temperature analysis



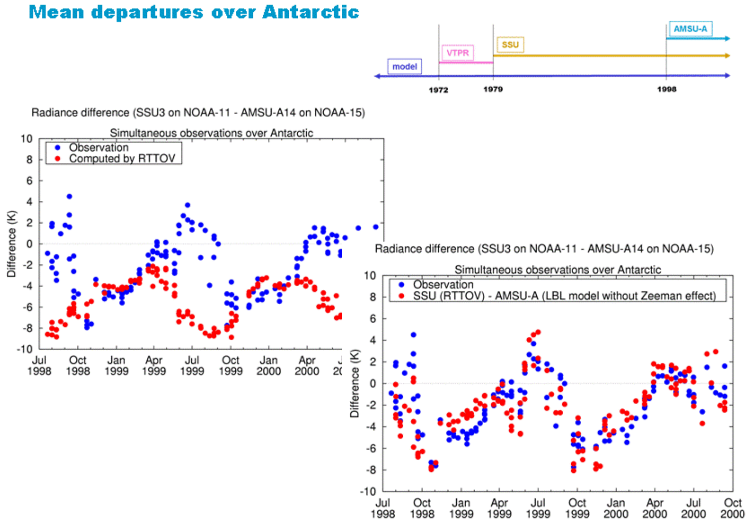
Representation of the Zeeman effect in RTTOV

Impact on stratospheric temperature assimilation



Consistency between AMSU-A and SSU

Mean departures over Antarctic



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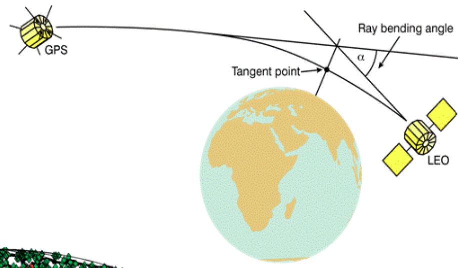
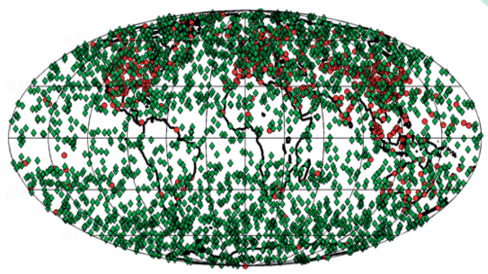
Toward a consistent stratosphere: The introduction of GPS

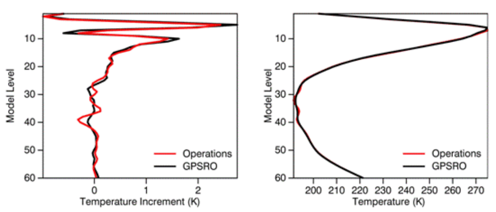




24h global coverage for COSMIC in its final configuration

Implementation of GPS in ECMWF operations: Impact in terms of temperature

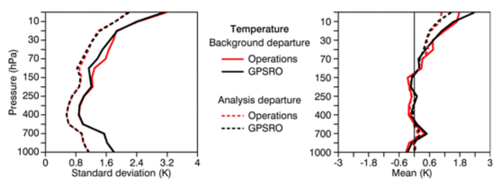
Global mean temperature increments and analysis



- Bending angles are assimilated without bias correction
- Main GPS impact is between 10-25 km

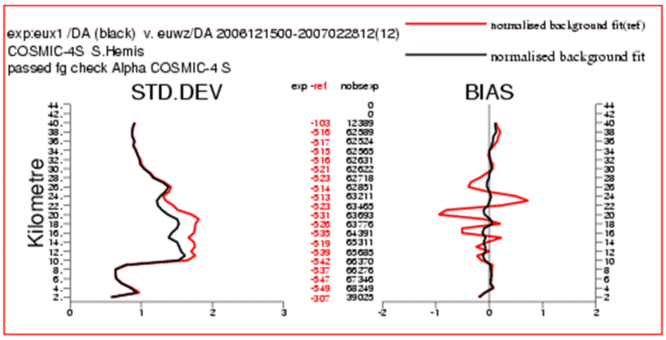
- GPS removes some of the spurious oscillations in the stratosphere
- This is a long-standing problem related to bias, vertical resolution of nadir sounders, and analysis method

Fit to radiosondes at 12 Antarctic stations



Implementation of GPS in ECMWF operations: Impact in terms of bending angles

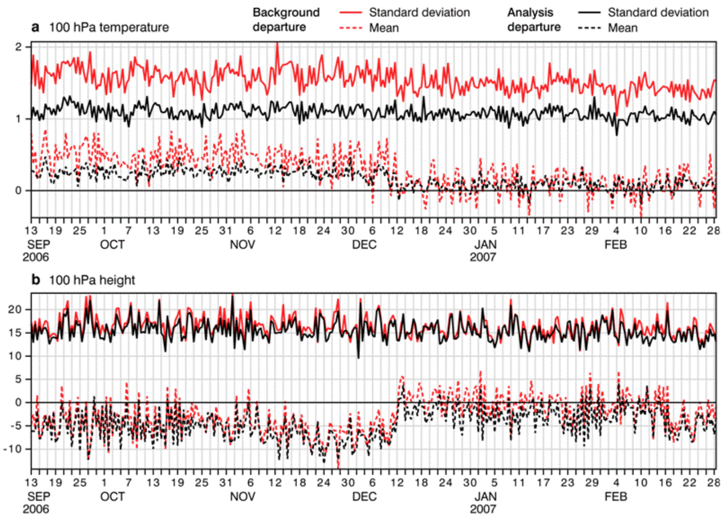
Background departures for bending angle observations



Red: GPS bending angle observations *passively monitored*

Black: GPS bending angle observations *actively assimilated*

Implementation of GPS in ECMWF operations: Improved fit to radiosonde observations



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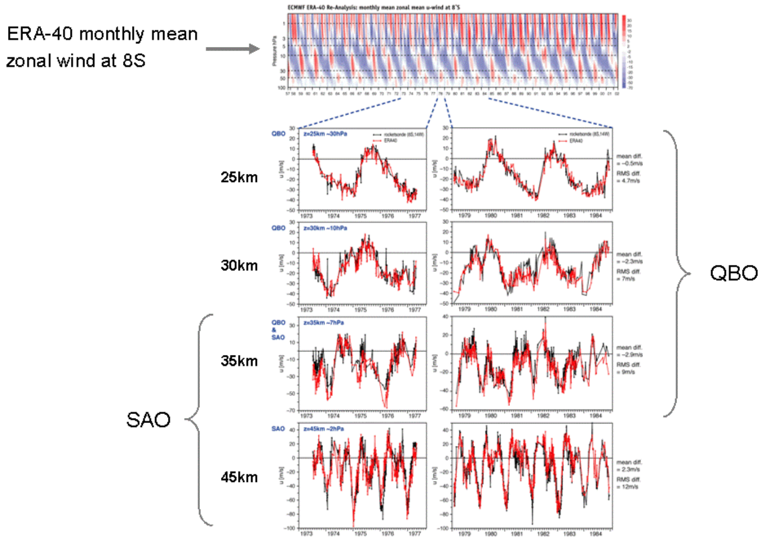
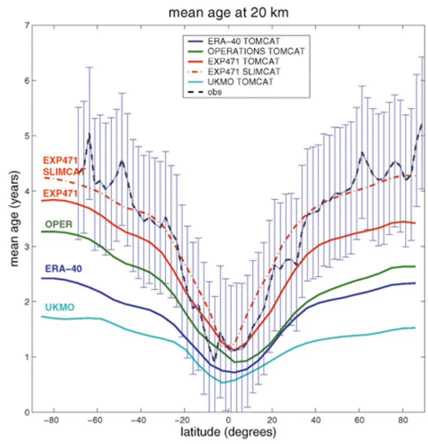
Quality of stratospheric wind analyses
ERA-40 validated against independent rocketsonde data



Quality of stratospheric wind analyses
Age-of-air diagnostic

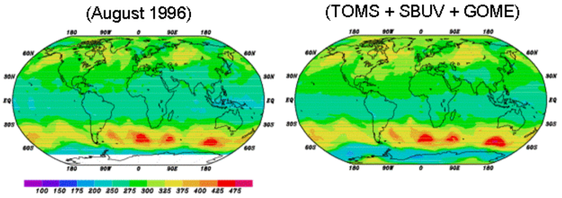
- Winds in the lower stratosphere are reasonably good (against radiosondes)
- Low-frequency variability is captured remarkably well
- ERA-40 problems concerning Brewer-Dobson circulation are being resolved
- We think this is mainly due to 4D-Var (improved dynamic consistency) and the use of VarBC (conflict resolution)



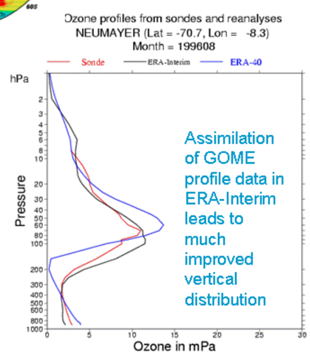
(Beatriz Monge-Sanz)

Ozone assimilation
Can ozone data be used to infer stratospheric winds?

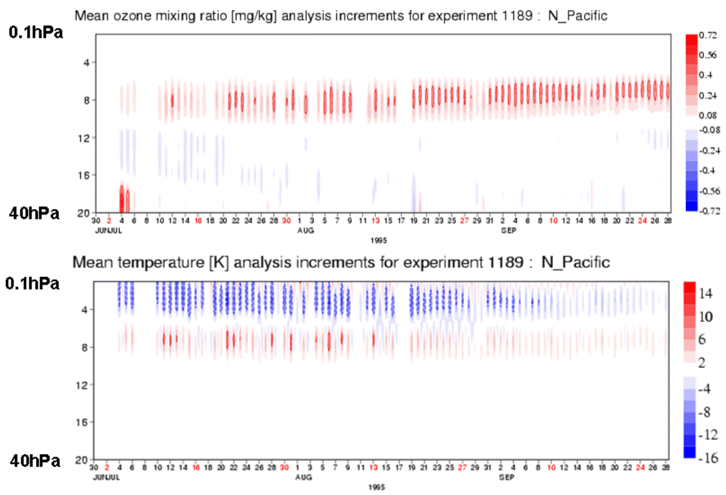
Total ozone from TOMS (August 1996) | ERA-Interim (TOMS + SBUV + GOME)



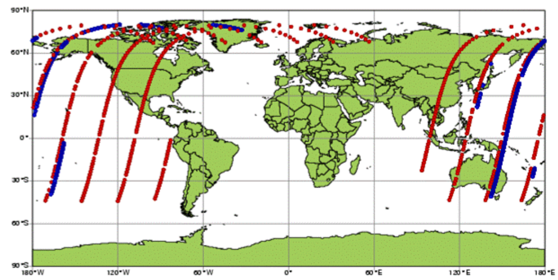
- Ozone observations contain information about the flow
- 4D-Var should be able to extract this information, since it uses the forecast model as a dynamical constraint
- **How does this work in practise ?**



Introduction of GOME ozone profile data in ERA-Interim
Ozone and temperature increments in the upper stratosphere

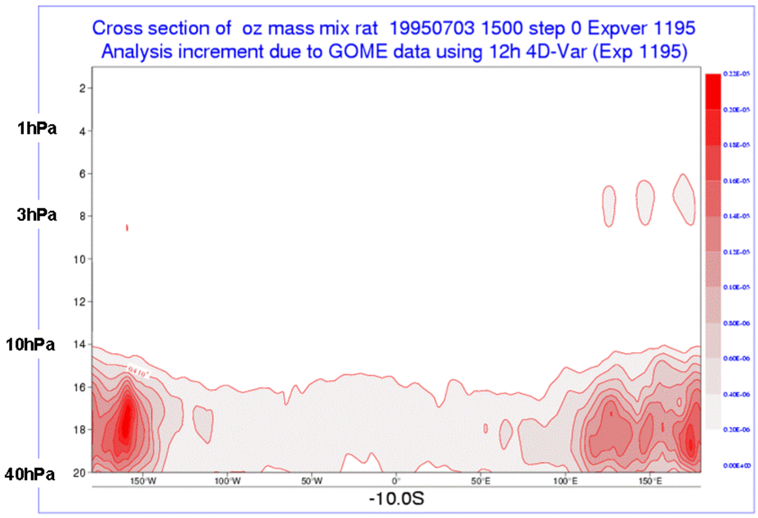


4D-Var ozone-only analysis experiment
Ozone observation locations on 4 July 1995, 0 UTC

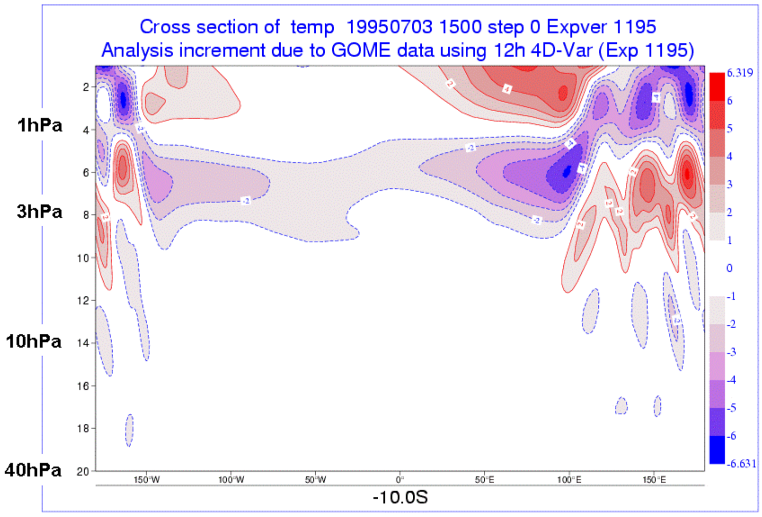


Blue: GOME 15-layer profiles (~15,000 per day)
Red: SBUV 6-layer profiles (~1,000 per day)

4D-Var ozone-only analysis experiment
The impact of the ozone data on the ozone analysis at 10S



4D-Var ozone assimilation
The impact of the ozone data on the temperature analysis at 10S



Ozone assimilation
Can 4D-Var infer stratospheric winds from ozone data?

- The answer is: **Not yet.**
- Assimilation of ozone profile data causes large and unrealistic T/U/V increments near the stratopause to accommodate the observed discrepancies between background and data
- A large part of these discrepancies are due to biases (in both data and model)
- It is natural for 4D-Var to make adjustments to the flow where constraints are few:
  - Lack of wind observations
  - Large background uncertainties
- A short-term fix is to disable this feature for the assimilation of ozone and other trace gases (use the background flow for ozone transport during minimisation)
- Comprehensive ozone bias correction (as for radiances) will help.

Summary

Stratosphere in NWP:

- Better stratosphere ⟶ better use of radiance data
- Extend the range of predictability in the troposphere?

Dealing with systematic errors

- No true reference: Large model biases
- Are the data interpreted correctly?
- GPS and other new data (SSMIS, MLS) will help

Scarcity of wind observations

- Constraints embedded in the analysis determine wind increments
- Use of ozone data in 4D-Var: Requires bias correction