ECMWF Training Course on Data Assimilation

The Analysis of Satellite Radiance Observations

Tony McNally
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Why do we need satellites?
Why do we need satellites?

To forecast many days in the future we need a global picture of the current atmospheric state...

Dust as a tracer of atmospheric motion.
500hPa Vorticity and wind forecast

Cape Verde Islands

Simulated Satellite imagery
Operational data use

All satellites denied

Thursday 31 August 2017 00 UTC ecmf 500 hPa Vorticity (relative)

Thursday 31 August 2017 00 UTC ecmf 500 hPa U component of wind/V component of wind

gt0v

Initial conditions 31/8 00z

700hPa humidity and wind with satellites

Red shading humidity > 95%

700hPa humidity and wind without satellites
Can we quantify how important satellites radiance are?

1 day of skill lost!
Can we quantify how important satellites radiance are?

3 days of skill lost!
What do satellite instruments measure?
They **DO NOT** measure TEMPERATURE

They **DO NOT** measure HUMIDITY or OZONE

They **DO NOT** measure WIND
SATELLITES CAN ONLY MEASURE OUTGOING THERMAL RADIATION FROM THE ATMOSPHERE
SATELLITES CAN ONLY MEASURE OUTGOING THERMAL RADIATION FROM THE ATMOSPHERE
Every atmosphere has its own complex spectral fingerprint ...
What do satellite instruments measure?

Satellite instruments measure the radiance $L$ that reaches the top of the atmosphere at given frequency $v$.

The measured radiance is related to geophysical atmospheric variables ($T,Q,O_3,$ clouds etc…) by the

**Radiative Transfer Equation**

$$L(v) = \int_0^\infty B(v, T(z)) \left[ \frac{d \tau(v)}{dz} \right] dz$$

- **Planck source term** depending on temperature of the atmosphere
- Absorption in the atmosphere
- Surface emission
- Surface reflection/scattering
- Cloud/rain contribution
- Other contributions to the measured radiances
The Radiative Transfer (RT) equation

\[ L(\nu) = \int_{0}^{\infty} B(\nu, T(z)) \left[ \frac{d\tau(\nu)}{dz} \right] dz + \text{Surface emission} + \text{Surface reflection/scattering} + \text{Cloud/rain contribution} + \ldots \]
The Radiative Transfer (RT) equation

\[ L(\nu) = \int_{0}^{\infty} B(\nu, T(z)) \left( \frac{d\tau(\nu)}{dz} \right) dz + \text{Surface emission} + \text{Surface reflection/scattering} + \text{Cloud/rain contribution} + \ldots \]

...given the state of the atmosphere, what is the radiance...?
Radiation simulated from forecast state

Radiation simulated from analysis state
The Radiative Transfer (RT) equation

...given the radiance, what is the state of the atmosphere...?

\[ L(\nu) = \int_0^\infty B(\nu, T(z)) \left[ \frac{d\tau(\nu)}{dz} \right] dz + \text{Surface emission} + \text{Surface reflection/scattering} + \text{Cloud/rain contribution} + \ldots \]
The Radiative Transfer (RT) equation

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measured by the satellite

depends on the state of the atmosphere

"Forward problem"

"Inverse problem"

OBSERVATION OPERATOR

MINIMISATION
How can we simplify the forward and inverse problems?
Channel selection
Measuring radiances in different frequencies (channels)

By deliberately selecting radiation at different frequencies or CHANNELS, satellite instruments can provide information on specific geophysical variables for different regions of the atmosphere.

In general, the frequencies / channels used within NWP may be categorized as one of 3 different types …

1. **atmospheric sounding** channels (passive instruments)
2. **surface sensing** channels (passive instruments)
3. **surface sensing** channels (active instruments)

**Note:**
In practice (and often despite their name!) real satellite instruments have channels which are a combination of atmospheric sounding and surface sensing channels.
Example:
absorption / emission of infrared radiation in the atmosphere
Atmospheric sounding channels
Atmospheric sounding channels

Graph showing transmittance (percent) vs. wavelength (microns) with peaks indicating absorption by molecules such as CO$_2$, H$_2$O, etc.
Atmospheric sounding channels
Atmospheric sounding channels

Transmittance (percent)

Wavelength (microns)

Absorbing Molecule

O$_2$, H$_2$O, CO$_2$, O$_3$, H$_2$O, CO$_2$, O$_3$, H$_2$O, CO$_2$, CO$_2$
Atmospheric sounding channels

...selecting channels where there is no contribution from the surface....

\[ L(\nu) = \int_{0}^{\infty} B(\nu, T(z)) \left[ \frac{d\tau(\nu)}{dz} \right] dz + \text{Surface emission} + \text{Surface reflection/scattering} + \text{Cloud/rain contribution} + \ldots \]
Atmospheric sounding channels

...selecting channels where there is no contribution from the surface....

\[ L(\nu) = \int_{0}^{\infty} B(\nu, T(z)) \left[ \frac{d\tau(\nu)}{dz} \right] dz \]

Surface emission + Surface reflection/scattering + Cloud/rain contribution + ...
Atmospheric sounding channels

...selecting channels where there is no contribution from the surface....

\[ L(\nu) = \int_{0}^{\infty} B(\nu, T(z)) \left[ \frac{d\tau(\nu)}{dz} \right] dz \]

Screen data to remove clouds / rain
ATMOSPHERIC SOUNDING CHANNELS

These channels are located in parts of the infra-red and microwave spectrum for which the main contribution to the measured radiance is from the atmosphere and can be written:

\[ L(\nu) \approx \int_0^\infty B(\nu, T(z)) \left[ \frac{d\tau(\nu)}{dz} \right] dz \]

Where \( B \) = Planck function
\( t \) = transmittance
\( T(z) \) = the temperature
\( z \) = a height coordinate

That is they try to avoid frequencies for which surface radiation and cloud contributions are important. They are primarily used to obtain information about atmospheric temperature and humidity (or other constituents that influence the transmittance e.g. \( CO_2 \)).

AMSUA-channel 5 (53GHz)  
HIRS-channel 12 (6.7micron)
Surface sensing
Channels (passive)
Surface sensing
Channels (passive)
Surface sensing
Channels (passive)
Surface sensing
Channels (passive)

...selecting channels where there is no contribution from the atmosphere....

\[ L(\nu) = \int_{0}^{\infty} B(\nu, T(z)) \left[ \frac{d\tau(\nu)}{dz} \right] dz \]

+ Surface emission
+ Surface reflection/scattering
+ Cloud/rain contribution + ...
Surface sensing Channels (passive)

...selecting channels where there is no contribution from the atmosphere....

$L(\nu) = \int_{0}^{\infty} B(\nu, T(z)) \left[ \frac{d \tau(\nu)}{dz} \right] dz + \text{Surface emission} + \text{Surface reflection/scattering} + \text{Cloud/rain contribution} + ...$
Surface sensing Channels (passive)

...selecting channels where there is no contribution from the atmosphere....

\[ L(\nu) = \int_0^\infty B(\nu, T(z)) \left[ \frac{d\tau(\nu)}{dz} \right] dz \]

Surface emission + Surface reflection/scattering + Cloud/rain contribution + ...

IR \sim zero
Surface sensing
Channels (passive)

...selecting channels where there is no contribution from the atmosphere....

\[ L(\nu) = \int_{0}^{\infty} B(\nu, T(z)) \left[ \frac{d\tau(\nu)}{dz} \right] dz \]

Screen data to remove clouds / rain

Surface reflection/scattering

Cloud/rain contribution + ...

Surface emission +
SURFACE SENSING CHANNELS (PASSIVE)

These are located in window regions of the infra-red and microwave spectrum at frequencies where there is very little interaction with the atmosphere and the primary contribution to the measured radiance is:

$$L(\nu) \approx B[\nu,T_{\text{surf}}] \varepsilon(u,v)$$ \text{(i.e. surface emission)}

Where $T_{\text{surf}}$ is the surface skin temperature and $\varepsilon$ the surface emissivity

These are primarily used to obtain information on the surface temperature and quantities that influence the surface emissivity such as wind (ocean) and vegetation (land). They can also be used to obtain information on clouds/rain and cloud movements (to provide wind information)

SSM/I channel 7 (89GHz)  
HIRS channel 8 (11microns)
Surface sensing
Channels (active)
Surface sensing Channels (active)

- Gamma rays, X-rays, and ultraviolet light blocked by the upper atmosphere (best observed from space).
- Visible light observable from Earth, with some atmospheric distortion.
- Most of the infrared spectrum absorbed by atmospheric gasses (best observed from space).
- Radio waves observable from Earth.
- Long-wavelength radio waves blocked.

Wavelength Range:
- Gamma rays: <0.1 nm
- X-rays: 0.1-1 nm
- Ultraviolet: 1-4 nm
- Visible: 4-0.7 μm
- Infrared: 0.7 μm-300 μm
- Radio waves: >300 μm

Atmospheric opacity:
- 100% obstruction at short wavelengths.
- Transparency increases at longer wavelengths.
SURFACE SENSING CHANNELS (ACTIVE)

...selecting channels where there is no contribution from the atmosphere or emission from the surface....

\[
L(\nu) = \int_{0}^{\infty} B(\nu, T(z)) \left[ \frac{d\tau(\nu)}{dz} \right] dz + \text{Surface emission} + \text{Surface reflection/scattering} + \text{Cloud/rain contribution} + \ldots
\]
SURFACE SENSING CHANNELS (ACTIVE)

...selecting channels where there is no contribution from the atmosphere or emission from the surface....

$$L(v) = \int_0^\infty B(v, T(z)) \left[ \frac{d\tau(v)}{dz} \right] dz + \text{Surface emission} + \text{Surface reflection/scattering} + \text{Cloud/rain contribution} + ...$$
These (e.g. scatterometers) **actively illuminate the surface** in window parts of the spectrum such that

\[ L(\nu) = \text{surface scattering} \ [ \varepsilon(u,\nu) ] \]

These primarily provide information on **ocean winds** (via the relationship with sea-surface emissivity) **without** the strong surface temperature ambiguity.
What type of channels are most important for NWP?
Atmospheric temperature sounding
ATMOSPHERIC TEMPERATURE SOUNGING

If radiation is selected in an atmospheric sounding channel for which

\[ L(\nu) = \int_0^\infty B(\nu, T(z)) \left[ \frac{d\tau(\nu)}{dz} \right] dz \]

and we define a function \( H(z) = \left[ \frac{d\tau}{dz} \right] \)

When the primary absorber is a well mixed gas (e.g. oxygen or CO\textsubscript{2}) with known concentration it can be seen that the measured radiance is essentially a weighted average of the atmospheric temperature profile, or

\[ L(\nu) = \int_0^\infty B(\nu, T(z)) \cdot H(z) dz \]

The function \( H(z) \) that defines this vertical average is known as a WEIGHTING FUNCTION.
IDEAL WEIGHTING FUNCTIONS

If the weighting function was a delta-function - this would mean that the measured radiance in a given channel is sensitive to the temperature at a single level in the atmosphere.

If the weighting function was a box-car function, this would mean that the measured radiance in a given channel was only sensitive to the temperature between two discrete atmospheric levels.
A lot of radiation is emitted from the dense lower atmosphere, but very little survives to the top of the atmosphere due to absorption.

At some level there is an optimal balance between the amount of radiation emitted and the amount reaching the top of the atmosphere.

High in the atmosphere very little radiation is emitted, but most will reach the top of the atmosphere.
Satellite sounding radiances are broad vertical averages of the atmospheric temperature structure.
The altitude at which the peak of the weighting function occurs depends on the strength of absorption for a given channel.

Channels in parts of the spectrum where the absorption is strong (e.g. near the centre of CO2 or O2 lines) peak high in the atmosphere.

Channels in parts of the spectrum where the absorption is weak (e.g. in the wings of CO$_2$ O$_2$ lines) peak low in the atmosphere.

By selecting a number of channels with varying absorption strengths we sample the atmospheric temperature at different altitudes.
MORE REAL WEIGHTING FUNCTIONS ...

AMSUA
15 channels

HIRS
19 channels

AIRS
2378

IASI
8461
How do we extract atmospheric information (e.g. temperature) from satellite radiances?

...i.e. how do we solve the inverse problem....
The Radiative Transfer (RT) equation

\[ L(\nu) = \int_0^\infty B(\nu, T(z)) \left[ \frac{d\tau(\nu)}{dz} \right] dz + \text{Surface emission} + \text{Surface reflection/scattering} + \text{Cloud/rain contribution} + \ldots \]

depends on the state of the atmosphere

measured by the satellite

“Inverse problem”

“Forward problem”

OBSERVATION OPERATOR

MINIMISATION
The Inverse problem

As the weighting functions are broad, if we have a finite number of channels, the inverse problem is formally ill-posed because an infinite number of different temperature profiles could give the same measured radiances !!!

...so to solve the inverse problem we need to bring in additional information ....

...satellite data relies strongly on background information and Data Assimilation skill...
“Direct Radiance Assimilation”
The cost function $J(X)$

$$J(x) = (x - x_b)^T B^{-1} (x - x_b) + (y - H[x])^T R^{-1} (y - H[x])$$

- model state
- background error covariance
- observations
- observation error covariance
- observation operator (maps the model state to the observation space)
The cost function components \((J_b)\)

\[
J(x) = (x - x_b)^T B^{-1} (x - x_b) + (y - H[x])^T R^{-1} (y - H[x])
\]

Fit of the solution to the background estimate of the atmospheric state weighted inversely by the background error covariance \(B\)
The cost function components \((J_0)\)

\[
J(x) = (x - x_b)^T B^{-1} (x - x_b) + (y - H[x])^T R^{-1} (y - H[x])
\]

Fit of the solution to the observations weighted inversely by the measurement error covariance \(R\) (observation error + error in observation operator \(H\))
Various implementations of the assimilation algorithm

- 1D-Var
- 3D-Var
- 4D-Var
One dimensional variational analysis (1D-Var)

\[ J(x) = (x - x_b)^T B^{-1} (x - x_b) + (y - H[x])^T R^{-1} (y - H[x]) \]

observation Operator = radiative transfer model

\[ L(\nu) = \int_0^\infty B(\nu, T(z)) \left[ \frac{d\tau(\nu)}{dz} \right] dz \]
Three dimensional variational analysis (3D-Var)

\[ J(x) = (x - x_b)^T B^{-1} (x - x_b) + (y - H[x])^T R^{-1} (y - H[x]) \]

3D model state

Global vector of measured radiances

Observation operator = spatial interpolation + radiative transfer model

\[ L(\nu) = \int_0^\infty B(\nu, T(z)) \left[ \frac{d\tau(\nu)}{dz} \right] dz \]
Four dimensional variational analysis (4D-Var)

$$J(x) = (x - x_b)^T B^{-1} (x - x_b) + (y - H[x])^T R^{-1} (y - H[x])$$

where $J(x)$ is the cost function, $x$ is the model state, $x_b$ is the background state, $B$ is the background error covariance matrix, $R$ is the observation error covariance matrix, and $H$ is the observation operator.

The observation operator $H$ is defined as:

$$L(v) = \int_0^\infty B(v, T(z)) \left[ \frac{d\tau(v)}{dz} \right] dz$$

This equation represents the radiative transfer model within the observation operator.

The 4D model state is represented graphically, with global time windows of measured radiances and the observation operator shown as a combination of spatial interpolation and forecast model radiative transfer model.
The 4D-Var Algorithm $J_b$

$$J(x) = (x - x_b)^T B^{-1} (x - x_b) + (y - H[x])^T R^{-1} (y - H[x])$$
The 4D-Var Algorithm $J_0$

\[
J(x) = (x - x_b)^T B^{-1} (x - x_b) + (y - H[x])^T R^{-1} (y - H[x])
\]
The key elements of a satellite data assimilation system
Key elements of a data assimilation system

- observation operator
- background errors
- observation errors
- bias correction
- data selection and quality control
Key elements of a data assimilation system

- observation operator
- background errors
- observation errors
- bias correction
- data selection and quality control
Observation operator

• The observation operator must map the model state at beginning of the assimilation window (t=0) to the observation time and location.

• In the **direct assimilation of radiance observations**, the observation operator must incorporate an additional step to compute radiances from the model state variables (radiative transfer model RTTOV).

• This means that radiance observations are significantly more computationally expensive than conventional observations (e.g. radiosonde temperature data)
Observation operator

1) Time evolution of forecast model field to OBS time

\[ X_{t=0} \rightarrow X_{t=t(\text{obs})} \]
Observation operator

2) Spatial interpolation of model grid to OBS location
Observation operator

3) Radiative transfer calculation from model state at that location to radiances at that location

RTTOV
Observation operator (RT component)

- The RT model should produce an accurate simulation of the satellite radiance from the model state, based upon the best knowledge of the instrument characteristics and up to date spectroscopic information.

- However, the model must be fast enough to process huge quantities of data in near real time (thus line-by-line models are not suitable)

- In addition, the adjoint and tangent linear versions of the RT model are required by the algorithm that minimises the cost function

- Ideally the same RT model should be used for all satellite sensors being assimilated
Key elements of a data assimilation system

- observation operator
- background errors
- observation errors
- bias correction
- data selection and quality control
Background errors (and vertical resolution)

- The matrix $B$ must accurately describe errors in the background estimate of the atmospheric state. It determines the weight given to the background information.

- A very important aspect for the assimilation of near-nadir viewing satellite radiances are the vertical correlations that describe how background errors are distributed in the vertical (sometimes called structure functions).

- These are important because satellite radiances have very limited vertical resolution (previous lecture).
Background errors (and vertical resolution)

"Difficult" to correct

"Easy" to correct
Background errors (and vertical resolution)

We can quantify the **improvement** of the analysis of the satellite radiances compared to the background (for a given sensor) for these two different regimes of background error:

\[
S_a = B - [HB]^T[HBH^T + R]^{-1} HB
\]

**improvement term**

The **improvement** has been simulated for the assimilation of all 8461 channels of IASI.
Background errors (and vertical resolution)

**Sharp / anti-correlated background errors**

*Only a small improvement over the background*

---

**Broad / deep correlated background error**

*a larger improvement over the background*
Background errors (and vertical resolution)

Sharp / anti-correlated background errors

Broad / deep correlated background error

So the same satellite can have a big impact or small impact depending on how the background errors are distributed

Error standard deviation (K) $S_a$
Background errors (and vertical resolution)

**700hPa T error**

- Sharper error correlations in the Tropics
- Broader vertical correlations in the mid-latitudes
Key elements of a data assimilation system

- observation operator
- background errors
- observation errors
- bias correction
- data selection and quality control
Observation errors:

• These determine the weight we give to the radiance observations. The observation error must account for random uncertainties in the observation operator (e.g. RT model), errors in data screening (e.g. residual clouds) and errors of representativeness (e.g. scale mismatch).

• It is important to model both the magnitude of errors (diagonals of R) and any inter-channel correlations.

• Wrongly specified observation errors can lead to an analysis with larger errors than the background!
Observation errors:

- Specifying the correct observation error produces an optimal analysis with minimum error.
Observation errors:

- Over-estimating the OBS error degrades the analysis, but the result will not be worse than the background.
Observation errors:

- Under-estimating the OBS error degrades the analysis, and the result can be worse than the background!
Key elements of a data assimilation system

- observation operator
- background errors
- observation errors
- bias correction
- data selection and quality control
Bias correction:

Systematic errors must be removed otherwise biases will propagate in to the analysis (causing global damage in the case of satellites!). A bias in the radiances is defined as:

\[
\text{bias} = \text{mean} \left[ Y_{\text{obs}} - H(X_{\text{true}}) \right]
\]

Sources of systematic error in radiance assimilation include:

- instrument error (scanning or calibration)
- radiative transfer error (spectroscopy or RT model)
- cloud / rain / aerosol screening errors
Bias correction:

- **HIRS channel 5**
  - simple flat offset biases that are constant in time

- **AMSU-A channel 14**
  - biases that vary depending on location or air-mass

- **AMSU-A channel 7**
  - biases that vary depending on the Scan position of the satellite instrument
Bias correction:

But sometimes **NWP systematic errors** can make it difficult to diagnose and correct observation biases

What we would like to quantify is:

$$\text{Bias} = \text{mean} \left[ Y_{obs} - H(X_{true}) \right]$$

But in practice all we can monitor is:

$$\text{Bias} = \text{mean} \left[ Y_{obs} - H(X_{b/a}) \right]$$
Key elements of a data assimilation system

- observation operator
- background errors
- observation errors
- bias correction
- data selection and quality control
Data selection and quality control (QC):

The primary purpose of this is to ensure that the observations entering the analysis are consistent with the assumptions in the observations error covariance (R) and the observation operator (H).

Primary examples include the following:

- Rejecting bad data with gross error (not described by R)
- Rejecting data affected by clouds if H is a clear sky RT
- Thinning data if no correlation is assumed (in R)
- Always blacklisting data where we do not trust our QC!
Data selection and quality control (QC):

Often checks are performed using the forecast background as a reference. That is an observations is rejected if the departure from the background exceeds a threshold $T_{QC}$:

$$Y_{obs} - H(X_{true}) > T_{QC}$$

But sometimes large errors in the background can lead to:

- False rejection of a good observation
- Missed rejection of a bad observation
Data selection and quality control:

- Missed rejection of a **bad** observation

The radiance are contaminated by cloud (**cold 5K**) compared to the clear sky value.

But our computation of the clear sky value from the background is also **cold by 5K** due to an error in the surface skin temperature.

Thus our checking (against the background) sees no reason to reject the observation and is it **passed**!
A QUICK REVIEW OF KEY CONCEPTS

• Satellite instruments measure **radiance** (not T,Q or wind)

• Sounding radiances are **broad vertical averages** of the temperature profile (defined by the weighting functions)

• The estimation of atmospheric temperature from the radiances is **ill-posed** and all retrieval algorithms use some sort of **prior information**

• The correct specification of observation errors, background errors (vertical correlations) , bias corrections and QC are all **crucial**!
End
Day 5 forecasts of Hurricane Sandy with (red) and without (blue) satellites!