Satellite Radiance Assimilation

John C. Derber
Environmental Modeling Center
NCEP/NWS/NOAA
With input from:
Many others
Typical Coverage IR
Typical Coverage – Microwave AMSU-A
Typical Coverage – Microwave
AMSU-B/MHS
Atmospheric analysis problem (theoretical)

\[ J = J_b + J_o + J_c \]

\[ J = (x-x_b)^T B_x^{-1} (x-x_b) + (K(x)-O)^T (E+F)^{-1} (K(x)-O) + J_C \]

\[ J = \text{Fit to background} + \text{Fit to observations} + \text{constraints} \]

\[ x = \text{Analysis} \]
\[ x_b = \text{Background} \]
\[ B_x = \text{Background error covariance} \]
\[ K = \text{Forward model (nonlinear)} \]
\[ O = \text{Observations} \]
\[ E+F = R = \text{Instrument error} + \text{Representativeness error} \]
\[ J_C = \text{Constraint term} \]
Note!

- I will be talking about satellite radiances today. But everything I say today applies with other data sources. The problems may be different, but the problems of similar complexity exist with almost every data set.
Operational radiance data requirements

• Requirements for operational use of observations
  – Available in real time in acceptable format
  – Assurance of stable data source
  – Quality control procedures defined (conservative)
  – Observational errors defined (and bias removed if necessary)
  – Accurate forward model (and adjoint) available
  – Integration into data monitoring
  – Evaluation and testing to ensure neutral/positive impact
Data available in real time in acceptable format

• Data formats
  – WMO acceptable formats – BUFR – CREX (not really relevant) – used by most NWP centers
  – Almost every satellite program uses a different format
  – Significant time and resources used understanding/converting/developing formats

• If data is not available in time for use in data assimilation system – not useful
NCEP Production Suite
Weather, Ocean, Land & Climate Forecast Systems

2007

Percent Used

6 Hour Cycle: Four Times/Day
GFS analysis/forecast cycle

- Data Cut-off: 2:45
- Data Processing: 2:46-2:52
- Analysis: 2:54-3:20
- Forecast: 3:20-4:06

- Any data not available by Cut-off will not be used
- Later catch up cycle at +6:00
POES Data Delivery

00Z Average 1B Data Counts

- Global Data Cutoff
- Regional Data Cutoff
- Final Data Cutoff

Locations Received (M)

Dump Time - Cycle Time (Hours)

- HIRS-2 (1bhrs2)
- HIRS-3 (1bhrs3)
- AMSU-A (1bamua)
- AMSU-B (1bamub)
- MSU (1bsmu)
Satellite data delivery

• Satellite data must wait until ground station within sight to download
• Conflicts between satellites
• Blind orbits
• Future – More ground stations – Less latency
NPOESS SafetyNet™ Architecture
POES Data Delivery

00Z Average 1B Data Counts

Global Data Cutoff

Next-generation Satellite Data Delivery

Regional Data Cutoff

Graph showing the average 1B data counts over time, with marked cutoffs for global and regional data.
Assurance of stable data source

• Changes in data processing can result in changes in observation error characteristics
• Notification, testing and provision of test data sets essential prior to changes
• For operational satellites – situation OK
• For research satellites – means loss of control by instrument/program scientists
Accurate forward model

• One of the biggest data assimilation developments in the last 15 years was allowing the observations to be different from the analysis variables
  – In variational and ensemble schemes this is done through the $K$ operator
  – In OI, the same thing could be done – but was only rarely done.
  – The development allows us to use the observations as they were observed AND allows the use of analysis variables with nice properties.
Radiance data differ from many conventional data in that the observations are often indirect observations of meteorological parameters.

- If $x$ is the vector of meteorological parameters we are interested in and
- $y$ is the observation,
- then $y = K(x,z)$,

...where $z$ represents other parameters on which the observations is dependent

...$K$ is the physical relationship between $x$, $z$ and $y$
Satellite data

• Example –
  – $y$ are radiance observations,
  – $x$ are profiles of temperature, moisture and ozone.
  – $K$ is the radiative transfer equation and
  – $z$ are unknown parameters such as the surface emissivity (dependent on soil type, soil moisture, etc.), CO2 profile, methane profile, etc.

• In general, $K$ is not invertible – thus retrievals.
  – Physical retrievals – usually very similar to 1D variational problems (with different background fields)
  – Statistical retrievals – given $y$ predict $x$ using regression
Satellite data

- 3-4 D variational analysis can be thought of as a generalization of “physical retrieval” to include all types of data and spatial and temporal variability.

- To use data in 2 steps – retrieval and then analysis-- can be done consistently if K is linear and if one is very careful – but is generally suboptimal.
Satellite data

• Key to using data is to have good characterization of $K$ – forward model.

• If unknowns in $K(x,z)$ – either in formulation of $K$ or in unknown variables ($z$) are too large data cannot be reliably used and must be removed in quality control.
  – example, currently we do not use radiances containing cloud signal

• Note that errors in formulation or unknown variables generally produce correlated errors. This is a significant source of difficulty.
Satellite data

• Additional advantages of using observations directly in analysis system
  – easier definition of observation errors
  – improved quality control
  – less introduction of auxiliary information
  – improved data monitoring
Forward Model

Radiances

- Convert analysis variables to T, q, Ps, u, v, ozone
- Interpolate T profiles, q profiles, ozone profiles, \( u_1, v_1, P_s \) and other surface quantities to observation location
- Reduce \( u_1 \) and \( v_1 \) to 10m values
- Calculate estimate of radiance using radiative transfer model (and surface emissivity model)
  - Tangent linear of calculation – inner iteration
  - Currently simulation does not include clouds
- Apply bias correction
- Compare observation to estimate
Satellite Radiance Observations

• Measure upwelling radiation at top of atmosphere
• Measure deep layers
  – IR not quite as deep as microwave
  – New IR instruments (AIRS, IASI, GIFTS) narrower, but still quite deep layers
  – Deep layers generally implies large horizontal scale
Forward model for RT

- RTTOV – CRTM two examples of fast forward models
- From CRTM get both simulated radiance and

\[
\frac{\partial R}{\partial T} \quad \frac{\partial R}{\partial q} \quad \frac{\partial R}{\partial q} \quad \frac{\partial R}{\partial O_3} \quad \ldots
\]
Surface Emissivity
Infrared
Surface Emissivity
Microwave
Accounting for size and shape of Field of View

- Size and shape of FOV can have a large impact – especially when the FOV covers different surface types.
  - Emissivity of land and sea quite different so a mixture will give very different results
  - Power from any point of FOV also important
- Microwave FOVs tend to be much larger than IR FOVs
- Major problem knowing what you are looking at
  - Freezing and thawing of lakes
  - Flooding
  - Snowfall
  - Vegetation (leaf water content)
  - Dew
  - High enough resolution (in space and time) land use maps
- Ability to properly model % surface characteristics in radiative transfer important
AMSU-A FOV

SNOW

SEA ICE

AMSU-A FOV

WATER

SNOW-FREE LAND

MODEL MASK ~ 12KM
IMPACT: ACCOUNTING FOR FOV

EX: NOAA-15 AMSU-A, CHANNEL 2

CONTROL:
OBS. MINUS GUESS $T_b$

IMPACT: CHANGE IN
OBS. MINUS GUESS $T_b$

NORTHERN CANADA

NEGATIVE IS IMPROVEMENT
Quality control procedures

• The quality control step may be the most important aspect of satellite data assimilation
• Data must be removed which has gross errors or which cannot be properly simulated by forward model
• Most problems with satellite data come from 3 sources
  – Instrument problems
  – Clouds and precipitation simulation errors
  – Surface emissivity simulation errors
Quality control procedures

• IR cannot see through clouds
  – Since deep layers not many channels above clouds – cloud height difficult to determine
• Microwave impacted by clouds and precipitation but signal from thinner clouds can be modeled and mostly accounted for in bias correction
• Surface emissivity and temperature characteristics not well known for land/snow/ice
  – Also makes detection of clouds/precip. more difficult over these surfaces
Quality control procedures (thinning)

- Some data is thinned prior to using
- Three reasons
  - Redundancy in data
    - Radiances
    - AMWs
  - Reduce correlated error
    - AMWs
  - Computational expense
    - Radiances
Five Order of Magnitude Increases in Satellite Data Over Fifteen Years (2000-2015)

### Daily Satellite & Radar Observation Count

- **Level 2 Radar**
  - 1990: 210 M obs
  - 2000: 125 M obs
  - 2015: 100 M obs

### Daily Percentage of Data Ingested into Models

- **Received Data**: 239.5M
- **Selected Data**: 17.3M
- **Assimilated Data**: 5.2M

*2005 Data

Received = All observations received operationally from providers
Selected = Observations selected as suitable for use
Assimilated = Observations actually used by models
Observational errors

- Observation errors specified based on instrument errors and o-b statistics. Note difference between instrument errors and o-b statistics tend to be quite small. (see later slides)
- Generally for satellite data errors are specified a bit large since the correlated errors are not well known.
- Bias must be accounted for since it is often larger than signal
Satellite observations

• Different observation and error characteristics
  – Type of data (cloud track winds, radiances, etc.)
  – Version of instrument type (e.g., IR sounders - AIRS, HIRS, IASI, GOES, GIFTS, etc.)
  – Different models of same instrument (e.g., NOAA-15 AMSU-A, NOAA-16 AMSU-A)
Bias Correction

• The differences between simulated and observed observations can show significant biases
• The source of the bias can come from
  – Biased observations
  – Inadequacies in the characterization of the instruments
  – Deficiencies in the forward models
  – Biases in the background
• Except when the bias is due to the background we would like to remove these biases
Bias Correction

- Currently we are only bias correcting, the radiances and the radiosonde data (radiation correction)
- For radiances, biases can be much larger than signal. Essential to bias correct the data
- NCEP currently uses a 2 step process for radiances (others are similar)
  - Angle correction (very slowly evolving – different correction for each scan position)
  - Air Mass correction (slowly evolving based on predictors)
platform:  amsua
region:  global
variable:  observed–simulated (without bias correction) (K)
valid:  00Z 20FEB2001 00Z 22MAR2001
Satellite radiance observations

Bias correction

• Air Mass prediction equation for bias
  – Coefficients in equation analysis variable w/ background (previous analysis) values
  – Predictors
    • mean
    • path length (local zenith angle determined)
    • integrated lapse rate
    • integrated lapse rate ** 2
    • cloud liquid water
NOAA 18 AMSU-A
No Bias Correction

channel 7
\( \chi = 0.3765 \)
\( f = 54.94 \text{ GHz} \)
\( \lambda = 5456.69 \mu\text{m} \)
avg: 1.837
sdv: 0.389

channel 8
\( \chi = 0.3955 \)
\( f = 55.50 \text{ GHz} \)
\( \lambda = 5401.64 \mu\text{m} \)
avg: 1.263
sdv: 0.505
NOAA 18 AMSU-A
Bias Corrected

channel 7
κ 0.3765
f 54.94 GHz
λ 5456.69 μm
avg: −0.022
sdv: 0.200

channel 8
κ 0.3955
f 55.50 GHz
λ 5401.64 μm
avg: −0.026
sdv: 0.222
Observation - Background histogram

DMSP15  July2004 : 1month

- Before bias correction
- After bias correction

gl use 2004070200-073118(63cases)
Data Monitoring

- It is essential to have good data monitoring.
- Usually the NWP centres see problems with instruments prior to notification by provider (UKMO especially)
- The data monitoring can also show problems with the assimilation systems
- Needs to be ongoing/real time
Quality Monitoring of Satellite Data

AIRS Channel 453 26 March 2007

Increase in SD
Fits to Guess
Data impact

• Satellite data extremely important part of observation system.
• Much of the improvement in forecast skill can be attributed to the improved data and the improved use of the data
• Must be measured relative to rest of observing system – not as stand alone data sets
• Extremely important for planning ($$$")
Observing System Experiments (ECMWF - G. Kelly et al.)

**NoSAT** = no satellite radiances or winds

**Control** = like operations

**NoUpper** = no radiosondes, no pilot winds, no wind profilers
JCSDA AIRS Testing

- NCEP operational system
  - Includes first AIRS data use
- Enhanced AIRS data use
  - Data ingest includes all AIRS footprints
  - 1 month at 55 km resolution
  - Standard data selection procedure

N. Hemisphere 500 mb AC Z
20N - 80N  Waves 1-20
1 Jan - 27 Jan '04

Graph showing anomaly correlation over forecast days for operators and operators + AIRS.
Summary

• Operational data assimilation of radiance data requires:
  – Data available in real time in acceptable format
  – A stable data source
  – Quality control procedures to be defined
  – Bias correction and observational errors defined
  – An accurate forward model
  – Data monitoring
  – Evaluation and testing to ensure neutral/positive impact
  – All of the above are more important than assimilation technique.

• Lots more work to be done!
Keeping up with the observing system

• New data sets
  – GOES-13 and 14
  – SEVERI
  – SSM/IS
  – NPP and JPSS
  – GOES-R
  – International satellites (Metop-SG, FY, etc.
  – Research satellites
Improved use of radiance data

- Improved CRTM (v2.0.2)
- Inclusion of cloudy radiance
  - Forward model includes model physics and cloudy CRTM
- Improved surface temperatures and emissivities
- Improved geometry
- Trace gases and aerosols
Cloud/precipitation assimilation

- Developing tangent linear and adjoint of cloud/precipitation physics
  - Eliminating discontinuities – produces similar results to original physics
- Inclusion of Clouds and Precipitation in radiative transfer
  - Probably not accurate in all location (heavy precipitation – thick clouds)
  - Will need to pick and choose
- Inclusion of diabatic balance in analysis
  - Inclusion of cloud/precipitation/surface physics in strong constraint
  - 4dvar
  - Hybrid assimilation (background errors include more cross correlations)
- Choice of analysis variable
  - Consistency between water vapor, cloud water and precipitation
  - Met Office has chosen single analysis variable for moisture (total moisture
- Very difficult problem which will require years of development.
Useful References