Use of satellite data in Polar regions

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or

(from Mark Drinkwater’s talk)

European Centre for Medium-range “Geophysical Noise” Forecasts
Overview

…what atmospheric information (for NWP, reanalysis, climate) can we estimate from satellite observations in polar regions? …

• types of satellite observation available
• the data assimilation system
• radiative transfer (forward) modelling
• quality control and data selection
• surface ambiguity
• handling of systematic errors
• some successes
• summary
Satellite observations available / used

NOAA satellites (N15/N16/N17/N18)
(AMSUA, AMSUB, HIRS, SBUV)

NASA AQUA/TERRA
(AIRS, AMSUA, MODIS-AMV)

NASA QuikSCAT
(SeaWinds)

DMSP satellites (F13,F14,F15,F16)
(SSM/I, SSM/IS)

GPS satellites
(CHAMP, COSMIC)

ESA ENVISAT
(MIPAS,GOMOS,SCIAMACHY)

red = radiance observations
green = retrieved products

Note that we make no great distinction between “operational” and “research” missions
What do these instruments measure?

They **DO NOT** measure TEMPERATURE
They **DO NOT** measure HUMIDITY or OZONE
They **DO NOT** measure WIND
They **DO NOT** measure SNOW/ICE properties

Satellite instruments (active and passive) can only measure the **radiance** $L$ that reaches the top of the atmosphere at given frequency $v$

The measured radiance is **related to geophysical atmospheric variables** by the **radiative transfer equation**

$$L(v) = \int_0^\infty B(v, T(z)) \left[ \frac{d\tau(v)}{dz} \right] dz + \text{Surface emission} + \text{Surface reflection/scattering} + \text{Cloud/rain contribution} + \ldots$$
Radiance Observations
Sensitivity and Weighting Functions

The sensitivity of a particular radiance observation to temperature (or indeed other geophysical parameters) at different altitudes is described by its **weighting function** (closely related to the jacobian of the radiative transfer model).

In general these have a **broad vertical extent** and e.g. data sensitive to the lower troposphere are also **sensitive to the surface**.
Radiance observations made in channels (=frequencies) where the atmospheric absorption is relatively weak are sensitive to the lower troposphere and surface.
Tropospheric / surface sensing channels

Microwave AMSU-A

Infrared HIRS / AIRS

summer

winter
Radiance observations made in channels (=frequencies) where the atmospheric absorption is strong are sensitive to the upper troposphere and stratosphere.
Stratospheric sensing channels

Microwave AMSU-A (~5hPa)

Infrared AIRS (~1hPa)

summer

winter
Retrieved Products
Observed radiance observations are **pre-converted** to geophysical products (externally) before being provided to the NWP data assimilation system.

In most cases these have been phased out and replaced with the **preferred direct assimilation** of the original radiance observations.

However some have been retained and are still assimilated.
Satellite retrieved products

- NASA QuickScat
- TERRA / AQUA MODIS
- NOAA SBUV

Plus composite products of SSM/I, AVHRR feeding into sea ice / SST fields

Sea surface wind vectors

TERRA / AQUA MODIS

atmospheric wind vectors

NOAA SBUV

ozone concentrations
Satellite radiance assimilation
The data assimilation system

Radiances are assimilated directly in to the 4D-Var analysis system, which finds the trajectory of atmospheric states that best minimizes a cost or penalty function

$$J(x) = (x - x_b)^T B^{-1} (x - x_b)$$

$$+ \sum_i (y_i - H[x_i])^T R^{-1} (y_i - H[x_i])$$

$$+ Jc$$

Subject to the additional implicit hard constraint that the atmospheric states follow the model equations

$$\forall i, x_i = M_0 \rightarrow i(x)$$
The key elements of satellite radiance assimilation

- Radiative Transfer (or forward) Model
- Quality Control (data screening)
- Handling of surface ambiguity
- Observation errors (inc errors in RTM)
- Handling of systematic errors (biases)
- Background errors
Radiative Transfer
Radiative Transfer (1)

Atmospheric Radiation Spectrum

Scat, Altimeter
AMSU, SSM/I

HIRS GOES
METEOSAT
AIRS

SBUV
Radiative Transfer (2)

The RTM is used to simulate radiance from the NWP model fields for comparison to the satellite observed radiances. The main issues in polar areas are:

- We must ensure that if fast RTM is based on regression against LBL, that the atmospheric profiles used in training are representative of possibly extreme polar situations.
- Assumptions about trace gas concentrations may not be appropriate to extreme polar atmospheres (e.g. polar night)
- Great care must be taken with the modelling of surface emissivity
Modelling the surface emission contribution is particularly problematic for microwave channels (especially cross-track scanning as opposed to conical scanning instruments, single v many angles mixed polarized)
Microwave surface emissivity over sea ice and snow is highly variable and poorly known.

Large meltponds can further complicate the sub satellite surface emissivity.

NB. Incorrectly specifying the emissivity introduces errors of 10s of kelvin!
Zeeman splitting of microwave absorption lines combined with strong mesospheric lapse rates can result in significant errors if the effect is not parameterized.
Quality Control
Quality Control (1)

With modern day instruments QC is more concerned with identifying situations where our assumptions (both discrete and statistical) are invalid, rather than identifying bad observations....e.g. ...

- Cloud contamination (IR and MW)
- Rain (precipitation) contamination (MW)
- Poor surface characterization (or heterogeneous scenes)
Cloud detection in polar areas:

Clouds over very cold surfaces can often appear \textbf{warmer} in infrared data compared to the underlying surface.

This is the \textbf{opposite} signal many cloud detection schemes are looking for.
Cloud detection algorithms generally rely on an accurate **a priori knowledge** of the underlying surface emission.

Errors in the modelling the underlying surface emission ($T^*$ or $E$) can compromise our ability to **safely detect clouds**.

Single channel cloud detection (i.e. window channel checks) can be **dangerous** (cloud compensates in window channel, but not channels above).

If these problems are severe, we may have to **blacklist** (i.e. a priori reject) the radiance observations.
Quality Control (4)

Single window channel cloud detection checks must be tuned to allow for warm departures over cold surfaces, but even then can be problematic if the cloud is at the same temperature as the surface.

(* without more information we cannot eliminate the possibility that a cloud at the same temperature as the ice actually stops at exactly the ice edge … although unlikely *)
Cloud detection schemes **must be also extended into the polar stratosphere** as undetected PSCs can alias into erroneous temperature and ozone increments.
Quality Control (6)

Due to the large variation in microwave surface radiative properties even a **slightly heterogeneous surface** (compared to the satellite field of view) can **alias large errors into the analysis** if undetected.

E.g. a small amount of ice contamination produces large wind departures in scatterometer sea surface wind retrievals.
The variability of the polar surface (particularly in terms of microwave surface emissivity) is significant. Channels designed to provide temperature information in the mid-troposphere still have ~ 10% sensitivity to the surface.

In channels such as AMSU-5 and MSU-2 (very important for NWP and reanalysis) the surface variability (e.g. going from sea to ice) is ~ 2K whereas the atmospheric variability (i.e. due to temperature variations) is typically less than 0.5K.

Thus errors in modelling the surface emission in these channels can completely dominate the useful atmospheric signal!
Handling Surface Ambiguity (2)

Options for handling the surface contribution:

1. Model the surface emissivity explicitly from our knowledge of the surface conditions (e.g. ice type, snow cover ...) and then use a fixed value in the RTM

2. Use indicators from the radiance observations to estimate or classify the surface and then fix in the RTM

3. Add emissivity to the analysis variables and estimate it simultaneously with other geophysical variables within the assimilation

4. Use radiances from sensors better suited to handling surface effects (e.g. conical scanning SSM/IS rather than cross-track scanning AMSUA)
Systematic Errors (biases)
Systematic Errors (1)

- Biases in satellite observations and/or RTM are a serious problem as they can quickly propagate into large scale biases in the analysis.

- Traditionally satellite bias corrections are estimated from monitoring data against the NWP system (in the absence of any other globally available ground truth)
Systematic Errors (2)

• Satellite instrument
  (calibration / characterization / environmental effects)

• Radiative transfer (RT) model
  (physics / spectroscopy / emissivity)

• Pre-processing of observations
  (cloud-precipitation detection / level-2 processing)

• NWP model *
  (systematic errors in the background state)

  most acute over the poles
Systematic Errors (3)

**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
Systematic Errors (4)

- Over the **polar regions** (particularly in the stratosphere) we can have **large systematic errors in the NWP model** (suggesting *apparent* air-mass and scan dependent biases in the satellite observations).

- It is important that we do not derive observation bias corrections that **actually compensate for systematic errors in the NWP model** as this will perpetuate or even reinforce the system bias.
A number of independent sensors confirm the existence of a significant cold temperature bias in the NWP model for the polar night stratosphere.
In addition, systematic errors in the NWP model lapse rate for the polar night stratosphere will also compute the wrong limb effect. This will give an apparent satellite scan bias between the NWP model and observations.

Asymmetric scan dependent bias associated with large systematic lapse rate error in the polar night.
Systematic Errors (7)

So what can we do if the NWP model has a significant bias?

- **Force** the (uncorrected) satellite observations into the data assimilation system to correct the NWP model bias (can be problematic).

  or

- **Pragmatically** apply a bias correction to the observations to **compensate** for the model error (produces a biased analysis).
Forcing these data uncorrected into the assimilation improves the NWP model top, but causes significant spurious oscillations in the temperature profile below.

The temperature changes at the model top (> 30K) verify well with other independent data, but the spurious oscillations are in the null-space of the radiances and are essentially an artefact of the assimilation system.
Miscellaneous issues in polar areas

• Observation weights (errors and spatial correlations) and thinning to account for high density of radiance observations over the poles

• Constituent estimation (humidity, CO2 and ozone) from passive sensors is very difficult in some isothermal polar atmospheres.

• Assimilation of rain / snow affected microwave radiances very difficult over bright frozen surfaces

• A general lack of verification / validation information
... but on the brighter side ...
Examples of the successful exploitation of satellite data in polar regions
Polar successes with satellite data

- Validation of ERA-40 and operational analyses suggest that satellite radiance observations are used well in polar areas and are a vital component of the observing system.
- Surface mapping products now taken for granted and are a mainstay of polar studies.
- Monitoring / forecasting sudden warming of the polar stratosphere.
- Polar ozone analysis.
- MODIS winds products have a good impact on forecasts.
- Constraining the polar wind field with temperature sounder data.
- Synergy between nadir and limb sounding data.
- Tuning physical parameterizations with satellite observations.
Synergy between nadir and limb (GPS) sounding

= the path of the ray perigee through the atmosphere
Nadir radiance data (AIRS,AMSUA) can be forced into the assimilation system with little or no bias correction if GPS data (with very high vertical resolution) are used to control oscillations in the stratosphere.

Radiosonde observations confirm that the GPS data are very effective at controlling the spurious oscillations.
Temperature sounding radiances controlling the polar wind field

The assimilation of temperature sensitive radiance data (particularly AIRS) constrains the wind field and results in a better fit to radiosonde wind observations in Polar regions.

- **Analysis and background fit to radiosonde wind data** (u-comp) averaged over the **N Pole**
- **Analysis and background fit to radiosonde wind data** (u-comp) averaged over the **S Pole**

(2 week average in June 06)
The Assimilation of MIPAS Ozone Retrievals

High vertical resolution MIPAS ozone retrievals are very effective in constraining the vertical distribution of ozone in the assimilation system (nadir data cannot).

Ozone profiles at Neumayer (71°S, 8°W)

- 26 Aug. 2003
- 11 Sept. 2003
- 22 Sept. 2003
Tuning NWP model parameters to observations

Some of the temperature biases in the stratosphere have been reduced by tuning parameters such as Rayleigh friction.

- Mean AMSUA ch-14 radiance departures with OLD Rayleigh friction
- Mean AMSUA ch-14 radiance departures with NEW Rayleigh friction
Occurrence of sudden warmings

NOAA-15 AMSU-A
(Autumn 98 – Spring 2002)

Mean observed brightness temperature (70-90N)

NOAA-15 radiance observations (70-90N)

- Ch 14 (2hPa)
- Ch 13 (5hPa)
- Ch 12 (10hPa)
- Ch 11 (20hPa)
Vertical structure of sudden warmings (from AMSUA and AIRS)

NOAA-15 radiance observations (70-90N)

Mean observed brightness temperature (70-90N)

Winter 1998 / 1999
Forecasts of Southern Polar Vortex Split

Verifying analyses

Day-5 forecasts
Summary

• There is a vast amount of satellite data available at the poles, however the polar regions present some particular assimilation challenges:

  • The variability of the polar surface (and our poor knowledge of it) makes mid-lower tropospheric radiance data difficult to use safely (both from a RT perspective and the detection of clouds when the surface variability far exceeds the atmospheric signal).

  • However, microwave and infrared radiance data sensitive to the upper troposphere and stratosphere are used extensively and have a significant measurable impact on Polar NWP / reanalysis.

  • Systematic errors in the NWP model can be large in the polar stratosphere and care must be taken how the radiance data are bias corrected and introduced into the assimilation system.
Systematic Errors (9)

**Vertical correlation of background temperature errors**
These are generally very **sharp** (describing random background errors) and as such do not prevent oscillating increments in between broad overlapping channels.

Globally averaged correlation of temperature errors in 4DVAR
Multispectral Cloud detection scheme for AIRS

A non-linear pattern recognition algorithm is applied to departures of the observed radiance spectra from a computed clear-sky background spectra.

This identifies the characteristic signal of cloud in the data and allows contaminated channels to be rejected.
Systematic Errors (8)

Analysis fit to MIPAS temperature data (with and without AIRS radiances)


20K warming!