Historical satellites and climate reanalysis

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Outline

1. Historical meteorological satellites

2. Weather and climate reanalyses

3. Use of satellite data in reanalyses
   - Problems and lessons learnt
   - Progress towards improved use of satellite data

The space race… Rocket history

• “Fathers of modern rocketry”
  – Robert H. Goddard in the USA (1882-1945). Inventor of the bazooka. Experimented with rockets from Roswell, New Mexico. First flight of a liquid-fueled rocket in 1926. First rocket with scientific payload in 1929 (camera + barometer). Testing of gyroscope in the 1930s. Struggled all his life for public funding support (which his widow received in compensation for patent infringement after his death). Convinced that the atmosphere must be explored for rockets to work properly.

Sources: nasa.gov, wikipedia.org, nndb.com
First picture from space

• Taken by a V-2 rocket on 24 October 1946
  — Launched from White Sands Proving Ground (now White Sands Missile Range), in New Mexico, USA, by US (and German) scientists. More about the V-2: http://www.wsmr.army.mil/PAO/WSHist/V2/Pages/default.aspx
  — Reached an altitude of 105 km altitude (Reichhardt, 2006)
  — In 1940, Nazi Germany launched rocket program. The first successful V-2 launched in 1942, from Peenemünde. Nordhausen construction underground facility included 18 miles of tunnels. Up to 30 rockets manufactured per day
  — In 1945: about 100 scientists enrolled in US “Operation Paperclip” and 300 freight cars of seized rocket parts send to New Mexico (including nozzles, gyroscopes…)
  — No V-2 was transferred from Germany ready-to-fly. Instead, General Electric built the U.S. V-2 with help of US and German scientists

Sources: army.mil, aip.org, v2rocket.com
More ‘first from space’ …and the beginning of the cold war space race

1954, from a Viking rocket (NRL scientists)

Sputnik-1, launched by USSR on 4 October 1957 for the International Geophysical Year

Explorer I, launched by USA on 31 January 1958 for the International Geophysical Year (launched by a Jupiter-C, developed under the lead of Dr. Wernher Von Braun). Scientific experimentation lead by Dr. James Van Allen

Sources: nasa.gov, navy.mil
First picture from a satellite in orbit

• Taken by the first satellite designed specifically for meteorological applications: Television Infrared Observation Satellite-1 (TIROS-1)

• Actual image date corrected after comparing imagery with reanalysis map of cloud cover: see Kållberg et al., 2010
Improvements over 50 years

- Controlling trajectory and attitude
- Transmitting data back to Earth
- Geolocating observations
- Increasing accuracy, new sensing techniques (now remote sensing not only EM radiation but also gravitational field)
- Monitoring ageing (moving parts, detectors)
- Calibrating observations
- Transmitting within a few minutes large volumes
- Keeping archive of whole mission, including metadata
- Reprocessing consistently entire missions when finished
- Rescuing data from ancient/early missions
Historical imagery capabilities

• From the 1960s onwards: many imagery missions (often serving also other purposes...)
• Represent today mines of images to determine with precision the historical evolution of sea-ice extent and to locate precisely timing and location of storms for validation

TIROS-N AVHRR VIS

ERI-Interim total cloud cover

19 May 1979, 15 UTC
Review of the meteorological satellite record

Microwave radiances
- temperature sounding
- water vapor sounding

Infrared radiances
- temperature and water vapor sounding
- stratospheric temperature sounding

Imagery
- visible, near infrared, water vapor

Hyper-spectral infrared
- mostly ultra-violet,
  but also some limb-viewing infrared

Ozone
- Geostationary (GEO)
- Low-Earth orbit (LEO)

Atmospheric motion vectors

Bending angles from GPS radio occultation
- near-surface wind above ocean
This (seemingly simple) picture hides instrument evolutions. Example: HIRS

HIRS

TIROS-N
NOAA-6
NOAA-7
NOAA-8
NOAA-9
NOAA-10
NOAA-11
NOAA-12
NOAA-14
NOAA-15
NOAA-16
NOAA-17
NOAA-18
METOP-A

Blue: typical brightness temperature for a mid-latitude, clear atmosphere
Orange: regions of sensitivity to constituents
Grey: pressure range where transmission reaches maxima

\( \frac{d\tau}{d(\ln(P))} \)

Missing here: the very first HIRS on Nimbus-6 (1975-1976) and the very last HIRS on NOAA-19 (2009-) and Metop-B
Placing satellite data in the global meteorological record

- **Opportunity sensors:** cell phones, UAVs, vehicles, rooftops, …
- **First operational satellite soundings (NOAA-2)**
- **Improved sounding from polar orbiters; Winds from geostationary orbit; More data from commercial aircraft; First drifting buoys**
- **First radiosonde networks, systematic soundings**
- **IGY restored West/East scientific interchange. Global data exchange set-up**
- **Manual observations from stations and ships, limited data exchange**

**Timeline:**
- 1938: First radiosonde networks, systematic soundings
- 1957: IGY restored West/East scientific interchange. Global data exchange set-up
- 1973: First operational satellite soundings (NOAA-2)
- 1979: Improved sounding from polar orbiters; Winds from geostationary orbit; More data from commercial aircraft; First drifting buoys
- 2020: Opportunity sensors: cell phones, UAVs, vehicles, rooftops, …
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Reanalysis objective: Reconstruct past history

“Observations-only” climatology

Gross exaggeration towards discontinuity

“outliers”

“Model only” integration

Gross exaggeration towards continuity
ECMWF global weather and climate reanalyses

- **Production sequence number**
  - #
  - Heritage / deprecated
  - Current / state-of-the-art
  - Latest (produced 2013-2014)
  - Upcoming / next-generation

- **Observation Input Diversity**
  - +Satellites
  - +Upper-air
  - +Surface
  - Gridded: Forcings only

- **FGGE**
- **ERA-15**
- **ERA-Interim**
  - 18,995 users as of 26 March 2015
- **ERA-PRESAT**
- **ERA-40**
- **ERA-20C**: 1 deterministic product + a 10-member ensemble
- **ERA-20CM**: a 10-member model-only integration

- **ERA5**
Other reanalyses of the environment

- Land-surface (e.g. ERA-Interim Land, ERA-20C Land)
- Ocean (e.g. ORA-S4)
- Atmospheric composition (e.g. MACC reanalysis)
- Carbon cycle (e.g. CARBONES)

- European move towards greater integration
  - EU-funded project ERA-CLIM2
Model forcing data: essentially “gridded observation” input

- In the satellite community, these are “level 3/ level 4” data
  - Sea-surface temperature (Hadley Centre) [remember that top 2 meters of ocean contain as much heat as entire atmosphere above, so these “long memory” data are crucial to constrain the global atmospheric trends]
  - Sea-ice cover (Hadley Centre) [for albedo and global radiation budget]
  - Solar irradiance (CMIP5) [for solar cycle]
  - Greenhouse gases (CMIP5) [for global radiation budget]
  - Ozone for radiation (CMIP5) [for radiation and stratospheric circulation]
  - Tropospheric and stratospheric aerosols (CMIP5) [e.g. for volcanic eruptions]
Realism of a model integration constrained by forcings (ERA-20CM), compared to a full reanalysis (ERA-Interim)

- Temperature anomaly (K) at 50hPa
- Temperature anomaly (K) at 500hPa
- Temperature anomaly (K) at 2m

Hersbach et al., 2013
This produces the “most probable”
atmospheric state *

* In a maximum-likelihood sense, which is equivalent to the minimum variance, provided
that background and observation errors are Gaussian, unbiased,
uncorrelated with each other; all error covariances are correctly specified; model
errors are negligible within the analysis window
Reanalysis using only surface observations of pressure and marine surface wind (ERA-20C)

Monthly temperature anomalies (computed with respect to 110-year climatology)
Improved accuracy with upper-air observations

Hand-drawn analysis for 6 June 1944, 13 UTC, by Stagg and his team

- Surface observations
- Upper air (mostly pilot balloons)
Impact of satellite data on reanalysis accuracy

All other surface, upper-air & satellites
+ NOAA-14 MSU radiances
+ Surface marine winds
+ Surface pressures
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Records used in ERA-Interim (blue)

Valuable records that could be used, if available, and pending assimilation tests (grey)

Records to be improved during ERA-CLIM2 as Fundamental Climate Data Records, FCDRs (red)
Variational bias correction

- First implemented by NCEP (Derber and Wu, 1998). Implemented at ECMWF in 2006
- Designed to correct observations towards the background and all other uncorrected observations. Not designed to correct for a bias in the NWP model.
- Iterative scheme that (slowly) evolves the bias estimates ($\beta$), given prior bias estimate
- There is a model for the observation bias, called bias model ($b$), which takes the bias parameters and multiplies them by predictors. Depending on the types of satellite radiances, these predictors include a selection of the following

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<th>$\Delta z$ 5 mb</th>
<th>Total col wv</th>
<th>Skin Temp.</th>
<th>Sfc wind speed</th>
<th>Nadir view angle NVA</th>
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<th>NVA</th>
<th>NVA</th>
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</table>
Sources and sinks of information

- **Sources**: differences (or departures) between observation and prior background (or first-guess), in observation space
- **Sinks**: analysis increments and updates to the bias corrections

**Control knobs**
- **Data selection**: filters the data — only reduces observation amounts
  - Importance of gross error detection (quality controls)
- **How much trust** is given to prior background (fields and bias corrections)
  - Importance of background errors
  - Importance of observation errors
- **Which observations are considered ‘stable’ over time**
  - Varying amounts in these introduce spurious trends, if they disagree with the underlying model
Time-series of departures for lower stratospheric microwave channel w.r.t. ERA, MSU 3 (a.k.a TTS)

Mean of \( y^0 - h(M(x)) \) = Mean (O-B) before bias correction

Standard deviation of \( y^0 - h(M(x)) \) = Stdev. (O-B) before bias correction

Mean of \( b(M(x), \beta) \) = Mean bias correction

Standard deviation of \( b(M(x), \beta) \) = Stdev. bias correction

Mean of \( y^0 - h(M(x)) - b(M(x), \beta) \) = Mean (O-B) after bias correction

Stdev. of \( y^0 - h(M(x)) - b(M(x), \beta) \) = Stdev. (O-B) after bias corr.
Microwave instrument passband
central frequency
mis-characterization

Blue dots show stdv(O-B) w.r.t. to ERA-Interim, when shifts are used in radiative transfer

Shifting on the order of 10-100 MHz

Lu and Bell (2014), after initial investigations by C. Peubey for EUMETSAT post-MetOp mission specifications
Impact of satellite data on mean temperature analysis increments (and hence mean temperature analyses)

Why? From 1998 onwards, AMSU-A (ch.14) is used as unbiased reference instead of SSU (ch.3). Since they observe different sub-spaces and have different biases, these are mapped differently onto the analysis increments.

What was learnt? Modelling of SSU and AMSU-A instruments now known to be suboptimal. See later slides.
Improved modelling of SSU instrument

**OLD**

- TIROS-N Ch. 1
  - 232847 obs.
  - Similar to ERA-Interim

- TIROS-N Ch. 2
  - 234925 obs.
  - Similar to ERA-Interim

**NEW**

- TIROS-N Ch. 1
  - 234620 obs.

DIFFERENCES OLD vs NEW:
2. CO$_2$ profile now used as predictor
3. SSU cell pressure better characterized

Full assimilation run, 1 Feb 1981 — 17 Mar 1981, ECMWF IFS CY36R4, NWP-SAF RTTOV-10, following work initially conducted by S. Kobayashi (JMA)
Time-series of departures across microwave instruments (MSU and then AMSU-A)

Stdev(O-B), before bias correction (in K)

Thick line: S.Hem.
Thin line: N.Hem.

MSU Ch. 4 or
AMSU-A Ch. 9
a.k.a TLS
or 90 hPa

MSU Ch. 3 or
AMSU-A Ch. 7
a.k.a TTS
or 300 hPa

MSU Ch. 2 or
AMSU-A Ch. 5
a.k.a TMT
or 600 hPa

March 2015
ECMWF/EUMETSAT Training Course on Assimilation of Satellite Data
39-year time-series (1973-2012) Std. dev. differences infrared channel $\sim 746 \text{ cm}^{-1}$ w.r.t. ERA

Stdev(O-B), without bias correction (K)

VTPR1, ch.7, 747.65 cm$^{-1}$
VTPR2, ch.7, 747.55 cm$^{-1}$
HIRS, ch.6, 748.27 cm$^{-1}$
AIRS, ch.333 746.01 cm$^{-1}$

VTPR ERA-40
HIRS ERA-40
HIRS ERA-Interim
AIRS ERA-Interim

Thick line: S.Hem.
Thin line: N.Hem.
Dangers of a tight variational bias correction

- Problem was only detected after the fact. Solution could have been to force a VARBC restart.
- Future solution: detect prior breaks in o-b time-series, and relax background errors in bias correction to allow for faster correction around break times.

Distribution of NOAA-9 HIRS channel 7 observation minus background in ERA-Interim [all data]
Satellite data volume increase over time

Number of satellite data used in ERA-Interim, 1 degree x 1 degree, 12-hour time period

1 Dec 1978, 00UTC

1 Dec 2011, 00UTC

Number of satellite sensors and retrieval types

Number of data every 12 hours

1979

March 2015

ECMWF/EUMETSAT Training Course on Assimilation of Satellite Data

2012

3.5M
Scan-dependent biases

Note asymmetric shapes and changes over time (1 curve per month)
Why would biases change over time?
Signals picked up by bias correction, but which could be actual instrument changes

MSU NOAA-14 channel 2

Variational bias estimates for NOAA-14

Actual warm-target temperatures on board NOAA-14 (Grody et al. 2004)

Dee and Uppala, 2009
Environmental signals picked up by bias correction

Mean obs-background departures (K) in the Tropics for MSU channel 4

Mean departures (K) in the Tropics for radiosondes, 60—40 hPa

Before bias correction

After bias correction

Background

Analysis
Environmental variability picked up by bias correction: sudden stratospheric warmings

Mean bias correction (K) in the Arctic for AMSU-A channel 10

Mean observed Bright. T. (K) in the Arctic for AMSU-A channel 10

Mean observed temperature (K) in the Arctic radiosondes 40——25 hPa
Sensitivity to introduction of satellite data which aren’t bias corrected

(a) Temper. diff. NH land RS minus ERA-Interim (in K), Pressure layer 60-40hPa

(b) Temper. diff. NH land RS minus ERA-Interim (in K), Pressure layer 85-60hPa

(c) Temper. diff. NH land RS minus ERA-Interim (in K), Pressure layer 125-85hPa

Observing System Experiment, in which GPSRO data are *not* assimilated

Introduction of GPSRO COSMIC
Agreement between bias corrections from runs initialized at two different dates

Run started in Oct. 1978

Run started in Oct. 1978

Run started in Oct. 1988

Run started in Oct. 1988

MSU channel 4 (lower stratosphere)
Another example of discontinuity introduced by satellite data in ERA-Interim: SSM/I

With the 2012 version of ECMWF system, the systematic difference between SSM/I assimilation and no assimilation is much reduced as compared to ERA-Interim (which used a 2006 version of the ECMWF system)

With 2012 version of ECMWF system: ~0.07 mm/day

In ERA-Interim: this was around ~0.2-0.3 mm/day, causing breaks or false trends in precipitation, radiation and water budget time-series.
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Case study: Infrared Interferometer Spectrometer (IRIS) Nimbus-4

References: Nimbus IV User’s Guide and Hanel et al. (1970)
**Why is this instrument interesting?**

- Essentially the first Michelson in space to have worked *very well*
  - Half a million spectra gathered between Jan 1970 and Apr 1971
  - Spectral resolution $2.8 \text{ cm}^{-1}$
  - Wavenumbers $400-1600 \text{ cm}^{-1}$, wavelengths $25-6.25 \text{ microns}$

- Predates by +30 years current hyper-spectral infrared sounders
  - Unique early measurements of fine spectral bands, interest to detect changes

- Same design as the IRIS instruments onboard the Voyager-1 and -2 spacecrafts, launched in 1977, the first of which left the solar system

- This brings us back to the space pioneers — who had dreamt of space exploration — though maybe not interstellar travel...
First-look at the Nimbus-4 IRIS dataset

- Read documentation: Nimbus IV User’s Guide & Hanel et al. (1970)
- Decide which attributes to retain
- Import these attributes for the whole dataset
- Carry out simple range checks

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Unit or format</th>
<th>Range of values found in the data</th>
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</thead>
<tbody>
<tr>
<td>Latitude</td>
<td>degrees North</td>
<td>-80.17 to 80.17</td>
</tr>
<tr>
<td>Longitude</td>
<td>degrees East</td>
<td>-180.0 to 179.99</td>
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<td>Date</td>
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<td>Time</td>
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<tr>
<td>Channel number</td>
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<td>1 to 862</td>
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<tr>
<td>Wavenumber</td>
<td>cm(^{-1})</td>
<td>400.5 to 1600.7</td>
</tr>
<tr>
<td>Radiance</td>
<td>W/m(^2)/ster/cm(^{-1})</td>
<td>-79.36 to 423,178.62</td>
</tr>
<tr>
<td>Brightness temperature</td>
<td>K</td>
<td>54.17 to 21,222.54</td>
</tr>
</tbody>
</table>
Spatio-temporal distribution

Important to look at for any dataset: dealing here with environmental data.
Need to know where and when…

April 1970    January 1971
Simple data overview

- Plot complete dataset as a density plot

535,742 spectra, each containing 862 channels
After flagging suspicious (possibly calibration) spectra

525,887 spectra
Next? Compare with another dataset

• What else than a spatially complete 4D reanalysis...
• Which can be mapped into the observation space using RTTOV
• Derivation of RTTOV coefficients carried out by EUMETSAT NWP-SAF

![Graph showing IRIS IASI CRIS 1C ISRF response function](image)
Nimbus-4 IRIS RTTOV simulation for a mid-latitude, clear atmosphere

Green: typical brightness temperature for a mid-latitude, clear atmosphere
Orange: regions of sensitivity to constituents

Red: pressure range where transmission reaches maxima

\( \frac{d\tau}{d(\ln(P))} \)
Result of comparison to ERA-40

Channels below wavenumber $511 \text{ cm}^{-1}$ cannot be simulated yet.
After simple cloud screening (departures in two window channels)

Departures under 1.5 K standard deviation for some lower-peaking CO$_2$ channels. Quite amazing for 1970-1971!

Stratosphere: more realistic variability in ERA-20C,
Troposphere more realistic in ERA-40
Systematic biases around -2K: mis-specification of the central wavenumbers observed?
Density plot of all spectra found in the dataset (after removal of suspicious, possibly calibration, spectra), for each day of the mission
What can we figure out from the metadata?

- Extract all the instrument health status metadata found

Excerpt: instrument internal temperature monitoring sensors

Noise equivalent radiance: quite variable. Data are not of constant quality
Final thoughts

• Today we quickly browsed through decades of improvements in meteorological satellite data — starting from imagery.

• Modern satellite data are still as demanding to exploit as permitted by current technology (large volumes, multi-dimensional), but they surely present lower noise and much better calibration.

• They still push further our limits of fundamental knowledge (e.g. spectroscopy, wave optics, gravitational fields).

• Yet the ancient data are invaluable, because they may tell us about the detailed status of the Earth’s atmosphere 50 years ago, and also because we now understand so much more that we can probably use them ‘more easily’.

• There is now shared awareness of the value of all satellite data to contribute to the global pool of knowledge as Climate Data Records.

• Continued improvement in data usage (through better understanding of “observation errors” and instrument models) will feed further progress in reanalysis quality, including time continuity.
References


• Poli, P, and Co-authors, 2013: The data assimilation system and initial performance evaluation of the ECMWF pilot reanalysis of the 20th-century assimilating surface observations only (ERA-20C). ERA Report Series 14, [http://www.ecmwf.int/publications/library/do/references/show?id=90833](http://www.ecmwf.int/publications/library/do/references/show?id=90833)