ATMOSPHERIC RADIO OCCULTATION AS A TEST FOR CLIMATE MODELS

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OUTLINE

- Radio occultation for climate studies
  - Climate benchmarking
  - Requirements for observing systems
- Satellite missions
  - The CLARREO concept
  - The FLORAD2 concept
- Applications
  - Bayesian testing of ensembles climate projections
  - Trends and variability in RO data
- Conclusions
RO FOR CLIMATE STUDIES
Climate benchmarking

- GNSS RO measurements can significantly contribute to establish a climate record (benchmark) because of their traceability and absolute calibration.
- A number of assessment studies have been carried out especially in connection with the CLARREO project
- RO is a strong benchmark (with a sensitivity < 0.1 K) in its vertical atmospheric spot around 8-20 km.
  - Apparent break in traceability in the stratosphere, possibly due to local multi-path in either CHAMP or SAC-C (Leroy et al., 2009).
- Synergy of RO data with infrared and microwave radiance satellite-based measurements: improved benchmarking.
RO FOR CLIMATE STUDIES
Testing climate models

- An independent data set free of in-orbit drift errors and satellite-to-satellite biases is desirable to intercalibrate measurements from different satellite missions (Goody et al., 2002).

- A subset of IR (infrared) and MMW (millimeter-wave) match-ups with GNSS RO observation can be used for independent and external calibration of the IR/MMW to foster a technique traceable to international standards.

SATELLITE MISSIONS

The CLARREO concept

- CLARREO (CLimate Absolute Radiance and Refractivity Observatory)
  - a thermal infrared interferometer
  - a GNSS radio occultation receiver
  - a shortwave spectrometer (for reflected solar radiation)

- These measurements will provide a benchmarking data record for
  the detection, projection, and attribution of changes in the
  climate system

- Observations are assimilated into process model with the hope
  that this will lead to better climate projections (concept
  envisioned by Goody et al. 2002, BAMS)

- Are these the best measurements to improve long term climate
  projections?
SATELLITE MISSIONS
The novelty of CLARREO

- The novelty of CLARREO data refers to the traceability to SI international standards.
  - This is an intrinsic quality of GNSS RO measurements (measurement of frequency shift against a time standard simply traceable to international standards).
- The GNSS infrastructure exists and will keep existing in the Global Positioning System (GPS) and the future Galileo constellations.
- As a consequence, the accuracy of each radio-occultation is independently testable into the indefinite future and can be easily replicated by any observing community.
NASA has delayed the CLARREO project with the first launch now planned for 2020. Some people think this may be the “kiss of death” and actually the project is cancelled.

US President’s FY 2012 budget removes $1.24B from the $2.08B FY’11 proposed Climate Initiative (years between FY 2012 and FY 2015). Directed cuts have been made to several activities, including CLARREO.

Specifically, the President's FY 2012 Budget provides for an extended pre-formulation period for the CLARREO mission definition. During this extended Pre-Phase A the mission and science team will continue to advance the science of CLARREO while working to identify implementation options for obtaining elements of the measurement suite outside of a dedicated series of CLARREO satellites.
SATELLITE MISSIONS
The FLORAD2 concept

- **FLORAD2** (Flower Constellation of millimeter–wave Radiometers and Radio occultation receivers): a feasibility study of Italian Space Agency (ASI); see Marzano and Cimini, AdGeo, 2010.

- **Flower orbits** make the constellation arranged in such a way that every time a satellite “leave a petal” another will takes its place in the observations of the same region. Such a technique will prolong the observation interval of a specified region.
SATELLITE MISSIONS
The FLORAD2 objectives

- Observing Earth troposphere
  - Temperature profile
  - Water vapor profile
  - Cloud and rain content
  - Ice and snow content
  - Profiling capability
    - Temperature in presence of clouds
    - Sounding through clouds
  ⇒ Hydro-meteorology

- Observing troposphere for a long-term
  - Legacy with existing sensors
  - Long-term sustainable space mission
  ⇒ Climatology

- Observing troposphere very frequently
  - Fast delivery of satellite data
  - Focus on a regional scale
  ⇒ Nowcasting
SATELLITE MISSIONS

The FLORAD2 payloads

- Millimeter-wave radiometer payload
  - Conical scanning imager
  - MHS-like channels + 118 GHz
    - 89 GHz V
    - 118.0±1 GHz H
    - 118.0±2 GHz H
    - 118.0±3 GHz H
    - 157 GHz V
    - 183.3±1 GHz H
    - 183.3±3 GHz H
    - 190 GHz V

- Heritage
  - NOAA-AMSU, DMSP-SSMIS
**SATELLITE MISSIONS**

The FLORAD2 payloads

- **ROSA radio-occultation payload**
  - Radio Occultation Sounder of the Atmosphere
  - Designed and developed by TAS for ASI
  - Mass ~18kg, power ~50W
  - On board of Oceansat-2
  - ROSA consists of: GPS receiver, Velocity and anti-Velocity Antenna assembly, POD antenna, RF cables

- **ROSA 2nd generation**
  - Smaller size, mass, and power consumption
  - Extended sounding (down to the surface)
  - Better ionospheric removal
  - Low latency of RO data
  - More RO events
  - Multipurpose instrument
    - Altimeter + Scatterometer
GNSS RO and MW Radiometry

- RO and MW provide similar kind of atmospheric profiles that are somewhat complementary
  
<table>
<thead>
<tr>
<th></th>
<th>GNSS RO</th>
<th>MW Radiometry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical resolution</td>
<td>high</td>
<td>low</td>
</tr>
<tr>
<td>Horizontal resolution</td>
<td>low</td>
<td>medium</td>
</tr>
<tr>
<td>Cloud/Rain</td>
<td>little effect</td>
<td>large effect</td>
</tr>
<tr>
<td>Observation/day</td>
<td>500</td>
<td>10000</td>
</tr>
<tr>
<td>Stability</td>
<td>high</td>
<td>medium</td>
</tr>
</tbody>
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- There is a significant potential for synergy
  - Meteo-climatic approaches
    - Short-term: Assimilation in NWP
    - Long-term: Benchmarking (box mean in critical climate areas)
  - Cross calibration-validation
    - Several match-ups per day (despite different observing geometry)
  - Variational approach for combined retrieval
    - Improving convergence
Another approach to improve quality of climate prediction is the method based on Bayesian inference. This is again something used in the economy and financial realm (so it may be faulty) and is based on a very simple theorem. If I know the “prior” probability of a particular event, $y$ obtained using an “ensemble” of models, $M$, $\text{Prob}(y|M)$ then we can evaluate the “posterior” probability of the same event in the presence on data. The basic formula for Bayesian inference is

$$\text{Prob}(y|\{\text{data}\},M) \propto \text{Prob}(\{\text{data}\}|y,M) \times \text{Prob}(y|M)$$

The variable $y$ can be any climatic state (temperature, etc.). The posterior probability is then modified by the presence of data. The core of the problem in this case is the so called likelihood $\text{Prob}(\{\text{data}\}|y,M)$. The posterior probability is the model prediction modified by the data acting on the initial (prior) probability $\text{Prob}(y|M)$, where $M$ could be the IPCC ensemble.
APPLICATIONS
Bayesian climate testing (2)

Summarizing the Bayes method can be written as

\[ \text{Posterior} \propto \text{Likelihood} \times \text{Prior} \]

Most of the current efforts in climatology is devoted to determine the likelihood function in presence of data. Most notably, the research in the past climate reconstruction:

- Tingley M.P., P. Huybers, 2010a, J. Climate, 23, 2759-2781
- Tingley M.P., P. Huybers, 2010b, J. Climate, 23, 2782-2800

Most of these papers has applied what is known as the Bayes Hierarchical Models.
APPLICATIONS

Bayesian climate testing (3)

Both Thernal Infrared and GPS data can be used for optimal detection (climate fingerprinting).

\[ \alpha = \text{global average surface air temperature}, \quad d = \text{GPS RO dry pressure [height]} \]

- Poleward migration of jet streams
- Increased tropical humidity
- Near perfect tracking of global average surface air temperature

Taken from S. Leroy, Y. Huang and J. Anderson at ECMWF, September 2009
APPLICATIONS
Trends and variability in RO data (1)

- The accurate, high vertical resolution of refractivity, temperature and geopotential height profiles from RO, available throughout most of the troposphere and stratosphere, can provide an unique opportunity to study trend and variability in UTLS.

- Key questions are:
  1. Is a significant trend detectable in available RO data?
  2. Is it possible to separate the trend from the natural variability?
  3. Are RO trend patterns and GCM projections consistent?

⇒ Multiple linear regression + GCM Simulations
APPLICATIONS
Trends and variability in RO data(2)

- **Data and models**
  - Seasonally mean CHAMP (2002-2008) data
  - NCAR/CAM3 run (1991-2009) with observed SST and 1%/year CO2 increase

- **Comments**
  GCM trend only partially consistent with RO data.
  Trend signal for short CHAMP period likely to be still masked by natural variability.
APPLICATIONS
Trends and variability in RO data

GCM Perturbation Runs

- Data and models
  NCAR/CAM3 perturbation runs with prescribed SST forcing using El Nino or PDO anomalies

- Comments
  Results indicate that these forcings can significantly affect the UTLS region. Longer GNSS time series will help in detecting and separating climatic signals driven by similar SST patterns.
CONCLUSIONS

- Climate benchmarking provides a method which is insensitive to data interruption.
- RO is one of the possible, fully traceable satellite-based methods.
  - RO can be easily implemented in mission concepts, like CLARREO in synergy with IR intereferometry and FLORAD2 with appropriate elliptical orbits and MMW radiometry.
- High resolution of RO profiles can be particularly useful to detect trends and variability in the upper-troposphere lower-stratopause (UTLS) region.