Radio Occultation for Numerical Weather Prediction Climate Monitoring and Space Science in the Southern Hemisphere

John Le Marshall 1,2, Yi Xiao1, K. Zhang 2, R. Norman2, S. Soldatenko, C Tingwell, 1, P. Steinle, Jin Lee1, D Howard, ….
Overview

• Background/Introduction
• The Importance of Satellite Data (in the SH)
• The Challenge – Key Data
• Advances/RO in Analysis and Prediction
• Monitoring the Climate
• Some additional GNSS/RO activities
• Plans/Future Prospects
• Summary
Subtitle: The benefit of RO in the SH
The Importance of Satellite Data (in the SH)

Observing System Experiments (OSEs)

With and Without Satellite Data

- **Systems Examined**
  - ACCESS (APS1) – Operational data base (Australian Op. Sys)
    - 28 October to 30 November 2011
    - 15 August to 30 September 2010
GPS RO
SATELLITE WINDS
SYNOPS AND SHIPS
BUOYS
RADIOSONDES
PILOTS AND PROFILERS
AIRCRAFT
IR AND MW SOUNDERS
SATELLITE WINDS
WATER-VAPOUR RADIANCES
SSMIS
SCATTEROMETER
GPS RO
AIRS/IASI/CrIS
ETC.
A high quality (AC=0.9) 24 hour (1 day) forecast without using satellite data is of the same quality as a 96 hour (4 days) forecast using satellite data.

From Le Marshall et al. 2013 AMOJ.
Earth observations From Space

**Fig. 8(c).** SH 500hPa height anomaly correlation for the control (SAT) and no satellite (NOSAT), 28 October to 30 November 2011 using ACCESS and verifying against the control analysis

**Fig. 8(f).** NH 500hPa height anomaly correlation for the control (SAT) and no satellite (NOSAT), 28 October to 30 November 2011 using ACCESS and verifying against the control analysis
Earth observations From Space

Fig. 8(g). SH 500hPa height anomaly correlation for the control (SAT) and no satellite (NOSAT), 15 August to 30 September 2010 using GFS and verifying against the control analysis.

Fig. 8(hNH 500hPa height anomaly correlation for the control (SAT) and no satellite (NOSAT), 15 August to 30 September 2010 using the GFS and verifying against the control analysis.
Earth observations From Space

SH 500hPa height anomaly correlation for the control (SAT) and no satellite (NOSAT), 28 October to 30 November 2011 using ACCESS-G and verifying against the control analysis.

SH 500hPa height anomaly correlation for the control (SAT) and no satellite (NOSAT), 15 August to 30 September 2010 using GFS and verifying against the control analysis.
ACCESS-G 48 to 72 hour rainfall forecast for 9 November 2011 using satellite data.

ACCESS-G 48 to 72 hour rainfall forecast for 9 November 2011 using no satellite data.

Daily rain gauge analysis for 9 November 2011.

Daily rainfall values.
ACCESS-G 48 to 72 hour rainfall forecast for 9 November 2011 using satellite data.

ACCESS-G 48 to 72 hour rainfall forecast for 9 November 2011 using no satellite data.

Daily rain gauge analysis for 9 November 2011.

<table>
<thead>
<tr>
<th></th>
<th>NOSAT</th>
<th>SAT</th>
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<tbody>
<tr>
<td>9 November 2011</td>
<td></td>
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<tr>
<td>Correlation between observed and forecast rainfall (Aust. Region)</td>
<td>0.282</td>
<td>0.699</td>
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<tr>
<td>Hanssen and Kuipers (Aust. Region)</td>
<td>0.360</td>
<td>0.596</td>
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Daily rainfall values.
<table>
<thead>
<tr>
<th>1 – 30 November 2011 (72-96 hrs)</th>
<th>NOSAT</th>
<th>SAT</th>
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<tr>
<td>Correlation between observed and forecast rainfall (Full Aust. Region)</td>
<td>0.25</td>
<td>0.41</td>
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<tr>
<td>Hanssen and Kuipers (Full Aust. Region)</td>
<td>0.36</td>
<td>0.51</td>
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</table>
Atlantic basin mean hurricane track errors for the control (all data) and no satellite data case, 15 August to 30 September 2010 using GFS and verifying against the control (all data) analysis.
Atlantic basin tracks for hurricane Earl commencing 00UTC 27 August 2010. The control (all data) forecast is red and the no satellite data forecast case is green. The blue line is the best track. Circles represent 00 UTC on 27 August, squares 00 UTC on 28 August and diamonds 00 UTC on 29 August 2010.
Observing the Atmosphere
Satellite systems

THE CHALLENGE
Operational ECMWF system September to December 2008. Averaged over all model layers and entire global atmosphere. % contribution of different observations to reduction in forecast error.

Advanced Sounders have largest single instrument impact in reducing forecast errors.

Courtesy: Carla Cardinali and Sean Healy, ECMWF 22 Oct. 2009
Ultraspectral Advanced Sounders

AIRS
IASI
CrIS
AIRS Data Assimilation


1 January 2004 – 31 January 2004

Used operational GFS system as Control

Used Operational GFS system Plus AIRS as Experimental System
Figure 1(a). 1000hPa Anomaly Correlations for the GFS with (Ops.+AIRS) and without (Ops.) AIRS data, Southern hemisphere, January 2004
Advanced Sounders and Radio Occultation

Advanced Sounders and RO Constellation - Complementary

Resolution and Accuracy

Bias correction and error characterisation (Tuning)

[CIMSS-1992]

(Collard+Healy, QJRMS, 2003)
THE GENERATION AND ASSIMILATION OF CONTINUOUS (HOURLY) ATMOSPHERIC MOTION VECTORS WITH 4DVAR
Fig. 6(a). The RMS difference between forecast and verifying analysis geopotential height (m) at 24 hours for ACCESS-R (green) and ACCESS-R with AMVs (red) for the period 27 January to 23 February 2011.

Fig. 6(b). The RMS difference between forecast and verifying analysis geopotential height (m) at 48 hours for ACCESS-R (green) and ACCESS-R with AMVs (red) for the period 27 January to 23 February 2011.
Fig. 10. Average track error (NM) by forecast hour for the control simulation and experiments where AMSU, HIRS, GEO winds and QuikSCAT were denied. The Atlantic Basin results are shown in (a), and the Eastern Pacific Basin results are shown in (b). A small sample size in the number of hurricanes precludes presenting the 96 hour results in the Eastern Pacific Ocean.
Radio Occultation for Numerical Weather Prediction in the Southern Hemisphere/Australia
Australian BoM ACCESS-G
Accepted observations coverage
GPSRO
20160301 0000 UTC
Total number of obs = 444

Issue time 05UTC 01 Mar 2016
26 February – 26 March 2009

Used

- Refractivity Data from
  - the COSMIC Constellation
  - GRACE and METOP

- Operational Global Forecast Model (ACCESS-G N144 L50) and Operational Data Base
The Characteristics of the ACCESS-G Forecast System

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<tbody>
<tr>
<td><strong>DOMAIN</strong></td>
<td>GLOBAL</td>
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<tr>
<td>UM Horizontal Resolution (lat x lon)</td>
<td>217x288 (~125km x 83 km)</td>
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<td>Analysis Horizontal resolution (lat x lon)</td>
<td>163x216 (~166km x 111km)</td>
</tr>
<tr>
<td>Vertical Resolution</td>
<td>L50</td>
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<tr>
<td>Observational Data Used (6h window)</td>
<td>AIRS, ATOVS, Scat, AMV, SYNOP, SHIP, BUOY,AMDARS, AIREPS, TEMP, PILOT, GPS-RO…</td>
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<tr>
<td>Sea Surface Temperature Analysis</td>
<td>Weekly, global 1° sst analysis</td>
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<td>Model Time Step</td>
<td>15 minutes (96 time steps per day)</td>
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<tr>
<td>Analysis Time Step</td>
<td>40 minutes</td>
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<tr>
<td>Suite Definition</td>
<td>SCS vn18.2</td>
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Table 1: N144L50 System Specification   APS-0
GPS/COSMIC

GPS radio occultation sounding positions for 15 March 2009. (Image courtesy of UCAR.)
A plot of the mean temperature difference (red) between COSMIC and radiosonde observations for the period, 5 March to 20 March 2009. The number of samples (blue) is also shown. (Data courtesy of UCAR.)
Figure 8(a). RMS Errors and anomaly correlations for ACCESS-G MSLP forecasts to five days, for the Australian region. Control (black), and with GPS RO data (red) for the period 26 February to 26 March, 2009.

Figure 8(b). RMS errors and anomaly correlations for ACCESS-G 500hPa forecasts to five days, for the Australian region. Control (black) and with GPS RO data (red) for the period 26 February to 26 March, 2009.

Figure 8(c). RMS errors and anomaly correlations for ACCESS-G 200hPa forecasts to five days, for the Australian region. Control (black) and with GPS RO data (red) for the period 26 February to 26 March, 2009.
RMS errors and anomaly correlations for ACCESS-G MSLP forecasts to five days, for the Australian region (left) and the southern hemisphere annulus: 60°S-20°S, 0°E-360°E (right). Shown are results for Control (black), and with GPS RO data (red).
RMS errors and anomaly correlations for ACCESS-G 500hPa geopotential height forecasts to five days, for the Australian region (left) and a similar plot for 200hPa geopotential height forecasts (right). Shown are results for Control (black), and with GPS RO data (red).
Used

- Refractivity Data from
  - the COSMIC Constellation
  - GRACE and METOP

- Operational Global Forecast Model (ACCESS-G N144 L50) and Operational Data Base
## The Characteristics of the ACCESS-G Forecast System

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**Table 1: N144L50 System Specification**  APS-0
GPS/COSMIC

GPS radio occultation sounding positions for 13 October 2010. (Image courtesy of UCAR.)
Figure 5(a). RMS Errors and anomaly correlations for ACCESS-G MSLP forecasts to five days, for the Australian region. Control (black), and with GPS RO data (red) for the period 13 October to 12 November 2010.

Figure 5(b). RMS errors and anomaly correlations for ACCESS-G 500hPa forecasts to five days, for the Australian region. Control (black) and with GPS RO data (red) for the period 13 October to 12 November 2010.

Figure 5(c). RMS errors and anomaly correlations for ACCESS-G 200hPa forecasts to five days, for the Australian region. Control (black) and with GPS RO data (red) for the period 13 October to 12 November 2010.
RMS errors and anomaly correlations for ACCESS-G 200hPa geopotential height (left) and 100hPa temperature forecasts to five days, for the Australian Region. Shown are results for Control (black), and with GPS RO data (red).
**OPERATIONAL TRIAL**

**NEW OPERATIONAL SYSTEM ACCESS-G**

1 November – 30 November 2010

**Used**

- Bending Angle data from
- the COSMIC Constellation
- GRACE and METOP

- New Operational Global Forecast Model (ACCESS-G N288 L70) and Operational Data Base
The Characteristics of the ACCESS-G Forecast System

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<td><strong>DOMAIN</strong></td>
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<td>UM Horizontal Resolution (lat x lon)</td>
<td>640 X 481(0.5625Deg X 0.375Deg) ~47km.</td>
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<tr>
<td>Analysis Horizontal resolution (lat x lon)</td>
<td>288 X 217 (1.250Deg X 0.833Deg) ~106km.</td>
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Table 1: N288L70 System Specification  APS- 1
Figure 10(a). RMS Errors and anomaly correlations for ACCESS-G MSLP forecasts to five days, for the Australian region. Shown are results for Control (black), and with GPS RO data (red) for the period 1 November to 30 November 2010.

Figure 10(b). RMS errors and anomaly correlations for ACCESS-G 500hPa forecasts to five days, for the Australian region. Shown are results for Control (black) and with GPS RO data (red) for the period 1 November to 30 November 2010.

Figure 10(c). RMS errors and anomaly correlations for ACCESS-G 200hPa forecasts to five days, for the Australian region. Shown are results for Control (black) and with GPS RO data (red) for the period 1 November to 30 November 2010.
Figure 11(a). RMS Errors and anomaly correlations for ACCESS-G MSLP forecasts to five days, for Southern Hemisphere. Control (black), and with GPS RO data (red) for the period 1 November to 30 November 2010.

Figure 11(b). RMS errors and anomaly correlations for ACCESS-G 500hPa forecasts to five days, for Southern Hemisphere. Control (black) and with GPS RO data (red) for the period 1 November to 30 November 2010.

Figure 11(c). RMS errors and anomaly correlations for ACCESS-G 200hPa temperature forecasts to five days, for the Australian region. Control (black) and with GPS RO data (red) for the period 1 November to 30 November 2010.
Enhanced Model (N512, L70)
Enhanced Operational Data Base*
Significant Improvement in Operational Trials

■ Bending Angle data from the COSMIC Constellation
GRACE, METOP, …
■ New Operational Global Forecast System will use updated Operational Data Base (CrIS, ATMS, 10 Min DMVs….)

THE IMMEDIATE FUTURE
MOVING TO NEW OPERATIONAL SYSTEM ACCESS-
THE IMMEDIATE FUTURE
NEW OPERATIONAL SYSTEM ACCESS - G

Trial Impact New Model/All Data

New elements still to be added to data base (10 minute AMVs etc.)

Impact of RO in new system being documented
Further Characterize the Impact of GPS in ACCESS (with new elements in data base (10 min. DMVs etc.))

Use RO data in calibration/tuning

Enhance Moisture fields using satellite to ground GNSS data, Advanced Sounder, RO etc.
Improve Tropospheric Moisture through

Assimilating Hyperspectral Infrared Water Vapor Channels

Assimilating satellite to ground GNSS data

Improved surface characterization

RO
Analysing Tropospheric Moisture by Assimilating Hyperspectral Infrared Water Vapor Channels

Figure 3: Specific humidity fits to rawinsondes humidity data during the time period March to May 2010 for the analysis, 6(Ges)-, 12-, 24-, 36- and 48-hour forecasts. Note the considerable improvement in the 6-hour and 12-hour forecasts.
GNSS ZTD

- Existing meteorological technologies - limited number of reliable meteorological WV sensors

14 Radiosondes

- A large number of reliable, high frequency and high density WV GNSS NPI observations \(\rightarrow\) ZTD or IWV
Australian Positioning Infrastructure (NPI)

Darwin

Perth/WA

South Australia

Brisbane/QLD

Tasmania

Victoria

3/14/2016
Multi-GNSS – Australia is in the “hot spot”

By 2020, Australia is projected to be in the GNSS “hot-spot” with access to 35 GNSS satellites and 7+ constellations at any time.

Source: Australian Space Policy Unit
Current RMIT NRT system (1)

RNS Platform – RMIT NRT System

Total: 156 stations
Mean dist.: ~70 km

Real-time/near realtime data stream, up to 1Hz observations
The NDRG project

• NDRG – Natural Disaster Resilience Grant
  – Funded by the Commonwealth Attorney-General’s Department under the Australian National Partnership Agreement on Natural Disaster Resilience signed by Prime Minister and state Premier of Victoria.

• Partnership
  – RMIT University, Bureau of Meteorology, Department of Environment and Primary Industries (DEPI), Univ of Melbourne, CRC-SI, UKMO

• Aims/objectives
  – Develop a smart GPS-based WV estimation system for disaster management users to reduce the risks/impact of natural weather disaster events
    – Assimilation in the Australian Community Climate and Earth-System Simulator (ACCESS) model.
    – Assimilation tests underway

• Complementary to the EU COST Action project
  – Advanced GNSS tropospheric products for monitoring severe weather events and climate (GNSS4SWEC)
Monitoring the Climate

2006 - 2012

Used

● Sounding Data from UCAR

● the COSMIC Constellation

● Examined

Aust. Region

SH/Globe

Antarctica
Climate Monitoring

Figure 2(a). Mean Annual Atmospheric Temperatures (°C) 2007 to 2010 in the Australian region measured by radiosonde (2006 is an incomplete year - see text)

Figure 2(b). Mean Annual Atmospheric Temperatures (°C) 2007 to 2010 in the Australian region measured by radio occultation at radiosonde sites (2006 is an incomplete year - see text)

Figure 2(c). Mean Annual Atmospheric Temperatures (°C) 2007 to 2010 in the Australian region measured by area weighting all radio occultation observations in the Australian region (2006 is an incomplete year - see text)
Figure 3(a). Mean Annual Atmospheric Temperatures (°C) 2007 to 2010 over the Southern Hemisphere measured by radiosonde (2006 is an incomplete year—see text)

Figure 3(b). Mean Annual Atmospheric Temperatures (°C) 2007 to 2010 over the Southern Hemisphere measured by radio occultation at a radiosonde sites (2006 is an incomplete year—see text)

Figure 3(c). Mean Annual Atmospheric Temperatures (°C) 2007 to 2010 over the Southern Hemisphere measured by area weighting all radio occultation observations over the Southern Hemisphere (2006 is an incomplete year—see text)
Figure 4(a). Annual average mean and R.M.S. temperature differences in the Australian region between co-located and contemporaneous radiosonde and radio occultation observations. (2006 is an incomplete year-see text)

Figure 4(b) Annual average mean and R.M.S. temperature differences over the Southern Hemisphere between co-located and contemporaneous radiosonde and radio occultation observations. (2006 is an incomplete year-see text)
Some additional GNSS/RO activities

Geometrical Optics (ray tracing)

- We have developed a 3-D numerical ray tracing technique that can simulate GNSS RO signal paths. The technique traces ray tubes using models of the ionosphere (IRI model) and atmosphere.
- We have also developed a new 3-D analytic ray tracing technique (3-D SMART).
- We have developed a new Homing in algorithm so that we can accurately determine the direction of the signal that will hit a target location (i.e., GPS receiver on board COSMIC satellite).
- The ray tracing methods can be used to examine GNSS RO signal paths traversing a host of different ionospheric and atmospheric features. We recently completed a study on a severe weather event over Melbourne, Australia where we examined the effects of transverse horizontal gradients on RO signal paths.
The Future

COSMIC II Groundstation
Northern Australia
**COSMIC II THE FUTURE**

Increased coverage with COSMIC II

Local processing of space weather data

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**Fig. 12** Distribution of simulated daily COSMIC II RO events in the Australasian region with GPS, Galileo, Glonass and QZS-1

**Fig. 13.** Ionospheric profile obtained from Fedsat radio wave occultation measurements on day 170, 2003 at 15.3N 170E.
Conclusions

• The great benefit of current RO data in the Australian Region and Southern Hemisphere have been recorded using data impact studies

• COSMIC, GRACE, METOP, …data have been successfully assimilated into the current ACCESS system and the data are being used in the BoMs new operational forecast system

• The data are important for climate quality analyses helping particularly with calibration and sounding.

• The data are important for climate monitoring

• COSMIC – 2 will be an important data source for Australia
Looking Down

Is

Looking Up

TC LAURENCE - Dec. 2009
低头是仰视