Using New Generation Earth Observations from Space in Asia Oceania and Southern Hemisphere

J. Le Marshall, D Howard, R Norman, S Rennie, P Lehmann, Y Xiao, C Tingwell, F Smith, D. Ren, X Wang, J Jung, T Morrow...

Bureau of Meteorology
Use of Satellite Data in the Bureau

Weather and Warning Services
- **Forecasters** repeatedly use VIS, IR, WV products for nowcasting
  - e.g. colour enhanced satellite images, volcanic ash products, fog detection products., satellite based/NWP applications…..

Numerical Weather Prediction:
- **Temperature and humidity sounding**
  - key sources - microwave and IR polar orbiting satellite radiance data
  - GPS/GNSS is an emerging data source (Radio Occultation and ground-based water vapour)
- **Wind**
  - Scatterometers, Radiometer
  - Satellite-derived Atmospheric Motion Vectors
- **Psurf.**
- **Other** (Soil Moisture, Emissivity, ….)

Earth-related applications,…:
- **Sea Surface Temperature, NDVI, Grassland Curing, Vegetation Indices, Solar Radiation** …..
<table>
<thead>
<tr>
<th>Satellites and Instrument Data used in NWP</th>
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</thead>
<tbody>
<tr>
<td>Terra - AIRS, AMV</td>
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<tr>
<td>S-NPP - ATMS, CrIS</td>
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<tr>
<td>NOAA-15 - AMSU-A</td>
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<td>NOAA-18 - AMSU-A</td>
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<tr>
<td>NOAA-19 - AMSU-A, MHS</td>
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<tr>
<td>Metop-A - IASI, AMSU-A, MHS, ASCAT, GNSS-RO</td>
</tr>
<tr>
<td>Metop-B - IASI, AMSU-A, MHS, ASCAT, GNSS-RO</td>
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<tr>
<td>Metop-C - GNSS-RO</td>
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<tr>
<td>Himawari-8 - CSR, AMV</td>
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<tr>
<td>DMSP-17 - SSMIS</td>
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<tr>
<td>GOES-15 - AMV</td>
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<tr>
<td>GOES-16 - AMV</td>
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<td>Meteosat-8 - AMV</td>
</tr>
<tr>
<td>Meteosat-11 - AMV</td>
</tr>
<tr>
<td>FY3-C - GNSS-RO</td>
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<tr>
<td>TerraSAR-X - GNSS-RO</td>
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<tr>
<td>COSMIC 6 - GNSS-RO</td>
</tr>
<tr>
<td>Coriolis – Windsat</td>
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<tr>
<td>GNSS - ZTD</td>
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</tbody>
</table>
The Importance of EOS (in the SH)

In the southern hemisphere space based observations extend the length of a high quality global numerical forecast by a factor of four when the forecast is verified using analyses incorporating satellite and conventional (all) data.
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.

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>Date: 9 November 2011</th>
<th>NOSAT</th>
<th>SAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correlation between observed and forecast rainfall (Aust. Region)</td>
<td>0.282</td>
<td>0.699</td>
</tr>
<tr>
<td>Hanssen and Kuipers (Aust. Region)</td>
<td>0.360</td>
<td>0.596</td>
</tr>
</tbody>
</table>

Daily rainfall values.
ACCESS APS2: Forecast Sensitivity to Observations

Colours:
- **Satellite**
- **Upper air network**
- **Surface network**

Global 24-hour forecast error reduction from each of the observation types assimilated:

- Three months: April, May and June 2016. Himawari-8 AMVs included in full period.
- All types of observations are beneficial, i.e. reduce the forecast error.
- **Total impact (LH panel)** is dominated by satellite instruments (e.g. the IASI, AMSU instruments carried on polar orbiters and AMVs) - due to large numbers & global coverage.
- Greater **impact per observation (RH panel)** comes from balloon upper air measurements from drifting and fixed buoys.
Two Satellite Observation Types /New/Under Transition For NWP

- AMVs for high resolution City Model, low latency requirement (also G3)
  - 10 minute Himawari Ch14 AMVs (operational)
  - 10 minute Himawari visible AMVs (under transition)
  - 10 minute water vapour AMVs (under transition)

- GNSS ZTD - water vapour
  - RT Data stream from RMIT/Geoscience Australia received at the Bureau
  - Operational
Himawari-6, 7 and 8

THE GENERATION AND ASSIMILATION OF CONTINUOUS 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 hourly 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 hourly AMVs (red) for the period 27 January to 23 February 2011.
GENERATION AND ASSIMILATION OF CONTINUOUS (10 Minute) H-8 ATMOSPHERIC MOTION VECTORS, USING GEOCAT AND 4DVAR
Himawari-8 AMV Generation

Use all Vis/IR/VW image triplets (separated by 10 min/HSF format). (2km ch 14 IR, 2km ch 2 VIS, 2km ch WV)

Employs modified GEOCAT software in initial processing.

AMV estimation is similar to GOES-R ABI ATBD / BoM system

Error characterization, selection, QC via EE, QI, ERR etc.
Fig. 3 Measured error (m/s) vs Expected Error (m/s) for low-level Himawari-8 IR winds

(1 August–31 August 2016).
Fig. 3 LBF for AMVs between 230 and 270 HPa.
<table>
<thead>
<tr>
<th>AMV Type</th>
<th>Category</th>
<th>m/s</th>
<th>NOBS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Sep km &lt;50</td>
<td>MMVD</td>
<td>2.51</td>
<td>660</td>
</tr>
<tr>
<td>Low Sep km &lt;50</td>
<td>RMSVD</td>
<td>2.96</td>
<td></td>
</tr>
<tr>
<td>Low Sep km &lt;50</td>
<td>BIAS</td>
<td>-0.10</td>
<td></td>
</tr>
<tr>
<td>High Sep km &lt;50</td>
<td>MMVD</td>
<td>3.28</td>
<td>2958</td>
</tr>
<tr>
<td>High Sep km &lt;50</td>
<td>RMSVD</td>
<td>3.96</td>
<td></td>
</tr>
<tr>
<td>High Sep km &lt;50</td>
<td>BIAS</td>
<td>-0.50</td>
<td></td>
</tr>
</tbody>
</table>

Table 3 Verification Table for Himawari-8 VIS (Channel 2) AMVs compared to radiosondes 1 March - 31 March 2017

<table>
<thead>
<tr>
<th>AMV Type</th>
<th>Category</th>
<th>m/s</th>
<th>NOBS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Sep km &lt;50</td>
<td>MMVD</td>
<td>2.48</td>
<td>473</td>
</tr>
<tr>
<td>Low Sep km &lt;50</td>
<td>RMSVD</td>
<td>2.84</td>
<td></td>
</tr>
<tr>
<td>Low Sep km &lt;50</td>
<td>BIAS</td>
<td>0.29</td>
<td></td>
</tr>
<tr>
<td>High Sep km &lt;50</td>
<td>MMVD</td>
<td>2.98</td>
<td>710</td>
</tr>
<tr>
<td>High Sep km &lt;50</td>
<td>RMSVD</td>
<td>3.67</td>
<td></td>
</tr>
<tr>
<td>High Sep km &lt;50</td>
<td>BIAS</td>
<td>-0.81</td>
<td></td>
</tr>
</tbody>
</table>
Figure 10(a) shows Channel 14 (IR) low level AMVs (yellow) with expected errors less than 2.6m/s and upper level AMVs (red) with expected errors less than 6.0m/s generated by one image triplet.

Figure 10(b) shows Channel 14 (IR) low level AMVs (yellow) with expected errors less than 2.6m/s and upper level AMVs (red) with expected errors less than 6.0m/s generated by six image triplets.
Fig. 8(a) Thinned IR Channel 14 10 minute AMVs from Himawari-8 images at 00UTC 1 May 2017

Fig. 8(b) Thinned IR plus Visible Channel 2 10 minute AMVs from Himawari-8 images at 00UTC 1 May 2017
Fig. 8(c) IR Channel 14 (yellow) and Visible Channel 2 (Beige) 10 minute AMVs from Himawari-8 images at 00UTC 18 October 2017

Fig. 8(d) IR Channel 14 (yellow) and Visible Channel 2 (Beige) 10 minute AMVs from Himawari-8 images near 00UTC 18 July 2017
Using 10 Min AMVs with Tropical Cyclone Quang

Visible image on April 29 at 06:35 UTC (2:35 a.m. EDT) from the MODIS instrument on NASA's Aqua satellite of Tropical Cyclone Quang in the Southern Indian Ocean.

Credit: NASA Goddard MODIS
TC Quang Himawari-8 AMV Generation

Used all Vis/IR image triplets (separated by 10 min/HSF format). (2km ch 14 IR, 1km ch 2 VIS)

Employs modified GEOCAT software in initial processing.

AMV estimation is similar to GOES-R ABI ATBD / BoM system

Error characterization, selection, QC via EE, QI, ERR etc.
TC Quang Himawari-8 AMV Assimilation

Used operational TCX system over Timor Sea.

Used all Vis/IR image triplets (separated by 10 min/HSF format). (2km IR, 1km VIS) plus full operational data base.

TCX is a nested TC model (nested in APS-2 ACCESS-G) of 4km resolution and has 70 levels.

Forecast start time 00UTS 29 April 2015
Fig. 15 The original forecast track error of tropical cyclone Quang from 00 UTC 29 April 2015 (yellow) and the final track error (Blue), both in six hour intervals (see text).
The Future/Operational AMV Applications

Operational C3 1.5km Resolution Capital City Nested Model and (G3) requirements are

10 minute Himawari Ch14 AMVs (operational)
10 minute Himawari visible AMVs (under transition)
10 minute water vapour AMVs (under transition)
(GEO-KOMPSAT 2A AMVs)

Operational TC3 1.5 km Tropical Cyclone nested model requirements.

10 minute Himawari Ch14, 2,10...... etc. AMVs
GROUND GPS/ZTD FOR NWP - MOISTURE ANALYSIS

The GNSS/ZTD Application project

- Partnership of Bureau of Meteorology, RMIT University and Geoscience Australia

- Aims
  - Improve moisture analysis and forecasting by developing a GPS-based ZTD/IWV estimation system across Australian Region.
  - Effective assimilation of ZTD data into the ACCESS model.

- Currently we have assimilated into next generation Capital City, Regional, and the Global ACCESS Models, and now assimilate into the operational G-3 model.

ZTD - Zenith Tropospheric Delay
Background

The measured ZTD is the delay in reception of a signal from a GPS satellite which is directly overhead as a result of the presence of the neutral atmosphere and is expressed in terms of excess path length (Bevis et al. 1992). Slant path delays are mapped to the zenith using a mapping function, for example Neill 1996. ZTD is related to the refractivity along the signal path by

$$ZTD = 10^{-6} \int_{z_a}^{\infty} N \, dz$$

where $z_a$ is antenna height (m) and $N$ is the neutral atmosphere refractivity. Expanding $N$ provides

$$ZTD = 10^{-6} \int_{z_a}^{\infty} k_1 \rho R_d \, dz + 10^{-6} \int_{z_a}^{\infty} \frac{R_d}{\epsilon} \left( k_2 - \epsilon k_1 + k_3/T \right) q \rho \, dz$$

where $R_d = 287.05 \text{ J kg}^{-1} \text{ K}^{-1}$ is the gas constant of dry air, $\rho$ is the water vapour density (kg m$^{-3}$) and $\epsilon = 0.62$ is the ratio of molar weights. The empirical constants are $k_1 = 77.6 \text{ K hPa}^{-1}$, $k_2 = 70.4 \text{ K hPa}^{-1}$ and $k_3 = 373900 \text{ K}^2 \text{ hPa}^{-1}$ (Thayer, 1974). ZTD has two components, the delay due to hydrostatic pressure and the delay due to the water vapour along the path (Bengsston et al., 2003).
Map of stations around Victoria/Australia used as sources of GNSS data and used in (near) real time processing for NWP.

ZTD - Zenith Tropospheric Delay
GROUND GPS/ZTD – Processing Approach

GROUND GNSS/ZTD Data Sources

- Sources of GNSS Observation Data:
- RMIT University - the IGS (International GNSS Service) network, which for Victoria has 8 IGS stations, the APREF (Australia Pacific Reference Network) with 34 stations of the ARGN (Australia Pacific Reference Network), and the GPSnet® network operated by the Victorian Government with 114 stations.
- Geoscience Australia - observations obtained from real-time streams sourced from the ARGN, Auscope, South Pacific and LINZ GPS networks.
- Over the whole of Australia we have over 256 GNSS stations now available for this activity and the number is increasing towards ~700. [Le Marshall et al., JSHESS,2019]
GROUND GPS/ZTD – Processing Approach

GNSS/ZTD Processing Methodology

- **RMIT** - Processing methodology - Double Difference (DD) solution. To smooth and improve the ZTD time-series, the joint estimation of ZTDs from the few last stored solutions is made. That is in the near-real-time service, the stacking of the last 7 normal equation files stored by the Bernese 5.2 software is used in the re-estimation of troposphere parameters.

- **Geoscience Aust.** - Processing methodology - Precise Point Positioning (PPP) method. Uses Bernese 5.2 software. To estimate the near-real time ZTD, it relies upon the IGS Real Time clock products and IGS ultra-rapid (UR) orbits.

- Some detail in Le Marshall et al., JSHESS, 2019. Our intent is to have a high density redundant system
Use of GROUND GPS/ZTD for NWP

GNSS/ZTD Assimilation

- ZTD Sources of GNSS Observation data: RMIT University, Geoscience Australia
- Processing methodology: DD solution (RMIT), PPP method (GA)

An example: Assimilation of GNSS-based ZTD observations in ACCESS-C3 over Victoria, 29 Nov. – 4 Dec. 2017.

- The ACCESS-C3 4DVAR system has a domain covering Victoria and Tasmania. Horizontal resolution near 1.5 km stretching to 4km at its border
- ZTD data used with the operational data base
- Nested in ACCESS-R
## Data Base

**Includes**

<table>
<thead>
<tr>
<th>Surface synoptic observations</th>
<th>10 Minute Atmospheric Motion Vectors</th>
<th>CrIS radiances</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiosonde observations</td>
<td>Scatterometer Winds</td>
<td>IASI radiances</td>
</tr>
<tr>
<td>Aircraft observations</td>
<td>ATOVS radiances</td>
<td>GPSRO bending angles</td>
</tr>
<tr>
<td>Doppler radar radial winds</td>
<td>AIRS radiances</td>
<td>ATMS and AMSU radiances</td>
</tr>
</tbody>
</table>

Some of the conventional observations and Earth Observations from Space included in the next generation observational data base for the ACCESS-C3 suite.
24 Hour Rainfall to 2/12/2017 00UTC

- Operational AWAP system
- No GNSS ZTD data
- With GNSS ZTD data
Fractions Skill Score versus Scale for 18 hour forecasts during the same period for forecasts where GPS data was and was not included in the forecast data base
Summary

Results indicate reasonableness of the forecasts and demonstrate potential for improving rainfall forecasts over Australia by inclusion of ZTD data in moisture analysis field.

The Future

Australia has already a very dense coverage of GPS receiving stations and this number will increase in coming years.

This is expected to provide improved moisture analysis and is expected to improve the quality of numerical prediction across the continent.
Summary/Future

Some developments in the application of new data have been shown.

Many new opportunities exist for further exploitation of satellite data noting the AOMSUC longitudes are probably the best meteorologically observed area over the globe.

The next decade will also provide geostationary advanced sounders in out region, which will improve high resolution NWP (~1.5km res) markedly and also forecast and warning services.