GEOGRAPHICAL REPORTS
OF TOKYO METROPOLITAN UNIVERSITY 54 (2019) 1–10

# GEOSTATIONARY SATELLITE DATA ASSIMILATION IN MESOSCALE FORECAST SYSTEMS: A REVIEW

**Michiko OTSUKA, Jun MATSUMOTO and Hiromu SEKO***

*Abstract* This article reviews the current status and ongoing developments in assimilating so-called next generation geostationary satellite data into mesoscale numerical weather forecast systems. While increased quality and quantity of data have brought unprecedented opportunities for data assimilation (DA) to improve initial conditions of mesoscale forecasts, taking full advantage of these high-resolution data, including cloud and precipitation affected weather observations is a challenge for current DA systems. We overview some key issues in the development of the effective utilization of geostationary satellite data in mesoscale forecasts.

**Keywords**: geostationary satellite, numerical weather prediction, data assimilation

## 1. Introduction

Mesoscale in the meteorological sense refers to atmospheric phenomena of a few to several hundred kilometers on a horizontal scale (e.g. Orlanski 1975; AMS 2018). Because this article concerns issues within the field of numerical weather prediction (NWP), we focus on such weather systems that can be captured and represented by operational regional or local forecast models of major NWP centres with a horizontal scale of more than one to several kilometers over short time periods (typically 1–2 days). Mesoscale events include a variety range of weather events from thunderstorms, precipitation bands, and fronts which are smaller than synoptic scale weather systems, to topographically generated phenomena such as sea and land breezes. These phenomena can have a great impact on our daily social and economic activities and sometimes cause serious disasters due to their severity and low predictability.

Currently, weather forecasts issued by national meteorological services around the world are based on NWP, whose history and development for more than half a century have been reviewed by several papers (e.g. Kalnay 2002; Harper *et al.* 2007; Yoden 2007). NWP requires both that the computer model is a realistic representation of the atmosphere, and that the initial conditions are accurately known (Kalnay 2002). Data assimilation (DA) is a key component of NWP because it produces initial conditions as accurately as possible by constraining model variables with observations through statistically optimal estimation. There are also many papers and books that can be used as a reference to theories and methods of DA (e.g. Talagrand 1997; Tsuyuki and Miyoshi 2007; Reich and Cotter 2015).

While global NWP systems are necessary for extended forecast ranges (5–10 days), regional

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* Forecast Department, the Meteorological Research Institute.

mesoscale systems are capable of efficiently producing short-range forecasts of mesoscale patterns over limited areas, especially for predictions of cloud and precipitation. The challenges posed for mesoscale NWP systems include quickly evolving processes that require rapid update of the assimilation cycles, complex, non-linear, and flow-dependent relationships between model variables and observations that come from dealing with convective disturbances (Fabry and Sun 2008) and the influence of lateral boundary conditions usually obtained by global systems with larger domains (Vukicevic and Paegle 1989). Keeping in mind these general issues, one solution to realize practical capability improvements for more accurate mesoscale forecasts in the current DA systems is to better exploit the information obtained from observations and to better estimate the initial conditions. The increased availability of new data obtained by a variety of remote sensing instruments including those onboard satellites enables to explore potential impacts of such data on mesoscale forecasts. The nature and characteristics of the new data which need to be accounted for in mesoscale DA systems are not fully understood.

Satellite observations in the visible, infrared, and microwave spectrum have been assimilated in NWP systems for decades and improved forecast skills by increasing the amount of data, particularly in areas such as over the oceans and in the Southern Hemisphere where in-situ observations are scarce. These observations have been found to be useful in detecting synoptic-scale disturbances. The improvements in DA techniques including the direct assimilation of radiances has increased the amount and varieties of satellite data used for NWP in the last few decades. Satellite data now provide a significant part of impacts of all the observations routinely assimilated for global NWP (Geer *et al*. 2017; Langland and Barker 2004). However, assimilating them into mesoscale systems have yet to be fully explored, partly due to the lower spatial resolution and less frequent observations compared to surface-based radar and other observations. Moreover, it may be preferable to initialize mesoscale systems using local observations so that they can be run closer to real time rather than waiting for observations to be collected from around the globe.

Operational geostationary earth orbit satellites (hereafter GEOs) are usually equipped with visible and infrared imagers, and provide valuable data for assimilation in near-real time as one of major components of the World Weather Watch's Global Observation System (CGMS 2018) together with near-polar orbiting satellites and other research and development satellites. GEOs can continuously observe a region of interest, apart from the Polar Regions, and therefore may be more suitable for use in mesoscale DA than polar orbiting satellites or lower orbit satellites whose orbits are closer to the atmosphere and are sometimes equipped with advanced sounders, but provide less frequent observations. Obviously, a primary disadvantage of GEOs was the lower spatial resolution regardless of the higher temporal resolution. The so-called new generation GEOs launched by JMA (the Japan Meteorological Agency), NOAA (the National Oceanic and Atmospheric Administration, U. S. Department of Commerce), CMA (the China Meteorological Administration), KMA (the Korean Meteorological Administration) and EUMETSAT (the European Organization for the Exploitation of Meteorological Satellites) before 2020 are equipped with advanced imagers; those with hyper-spectral sounders and/or lightning sensors will provide unprecedented amount of data with increased spatial and temporal resolution for the key applications of severe weather monitoring, nowcasting, short range forecasting and other application areas (CGMS 2018). It would be beneficial for mesoscale forecast systems to be able to assimilate these frequent GEO observations with increased spatial resolutions and to extract useful information on initialization of cloud and hydrometeor fields.

This article reviews the current status and ongoing developments towards assimilating next generation GEO data in mesoscale NWP systems. Section 2 describes the current status in major operational NWP centres around the world with regards to the assimilation of GEO data into mesoscale systems. Section 3 describes new generation GEO data and their possibilities for assimilation use in mesoscale NWP, and Section 4 addresses key issues for the future developments. Finally, section 5 provides conclusions.

## 2. Current Status of Assimilation of GEOs

### Mesoscale DA systems of the JMA and other national NWP centres

National NWP centres including the JMA usually run mesoscale systems beside global systems for limited local domains aiming at short-range prediction of up to 1 to 2 days with horizontal resolutions around 1 km (so-called ‘convective-scale’) to several kilometers. Gustafsson *et al.* (2018) review mesoscale and convective-scale DA systems operated by major NWP centres in detail, while Geer *et al.* (2018) review them with regards to the state of cloud and precipitation affected satellite radiance assimilation. Mainly based on their surveys, Table 1 summarizes the models and methods of mesoscale DA systems currently operated in centres of Japan (JMA), the U. S. (National Centers for Environmental Prediction, NCEP), the U. K. (Met Office), France (Météo France), and Germany (Deutscher Wetterdienst, DWD). The names of GEOs and their products in use for assimilation are also listed. In contrast to global systems where most centres have begun to adapt a so-called *hybrid* of 4D-var (four dimensional variational method) and ensemble methods, 4D-EnVar (Bannister 2017), a variety of methods are applied to mesoscale systems including variational methods (3D-Var and 4D-Var), ensemble methods (Local Ensemble Transform Kalman Filter, LETKF), and hybrid systems (3D-EnVar). 3D-EnVar (4D-EnVar) is considered to have some advantages over 3D-Var (4D-Var) because it can also consider flow-dependence of forecast errors obtained by ensemble methods. The basic theories of these different methods can be found in Gustafsson *et al*. (2018) and other literature mentioned in the previous section. The choice of DA methods depends on computational cost for running in real-time with frequent updates in high resolution, the scale of targeted phenomena, and the availability of observations according to different local needs and interests. All centres listed in Table 1 except DWD operationally assimilate GEO data such as the Atmospheric Motion Vector (AMV), Clear Sky Radiance (CSR), and other cloud products.

The JMA has employed a 4D-var system to provide initial conditions for the Meso-scale Model (MSM) since 2002 and became the first NWP centre to adapt 4D-Var to an operational limited-area system (JMA 2013). The MSM was upgraded to the JMA’s Non-Hydrostatic Model, JMA-NHM (Saito *et al.* 2006) in 2004, and the current JMA Nonhydrostatic model-based Variational Analysis Data Assimilation (JNoVA; Honda *et al.* 2005) was introduced in 2009. It is a 4D-Var system adopting the incremental approach (Courtier *et al.* 1994) with a spatial resolution of 5 km and 15 km for the outer and inner model of 50 vertical layers and is updated every three hours. A wide variety of observations including surface, upper air, radar, satellite, and ground-based Global Navigation Satellite System data are assimilated hourly within a 3-hour time window. In 2012, the local DA system started its operation for the Local Forecast Model (LFM), the high-resolution forecast model targeting small-scale severe weather events (JMA 2013).

### Geostationary satellite data used for assimilation

This subsection summarizes the status of GEO data used for mesoscale DA systems as described in Table 1. AMVs and CSRs, or cloud-free pixel radiances for Météo France, are two major components of GEO data currently assimilated in operational NWP. When utilized for mesoscale systems these two products are usually higher resolution than those used in global systems in order to take advantage of the finer resolutions of models.

**Table 1** Summary of operational mesoscale NWP systems and GEOs assimilated

| Centre | Model | | DA Method | GEO | |
|---|---|---|---|---|---|
| | Name | Resolution | | Sensor | Data Product |
| JMA | MSM/<br>LFM | 5.0 km/<br>2.0 km | Increm. 4D-Var/<br>3D-Var | Himawari -AHI | AMV, CSR |
| NCEP | HRRR (High-Resolution Rapid Refresh system) | 3.0 km | Increm. Hybrid 3D-EnVar | GOES- ABI (Advanced Baseline Imager) | AMV, cloud top pressure |
| Met Office | Unified Model | 1.5 km | Increm. 4D-Var | MSG-SEVIRI | AMV, CSR, cloud top pressure |
| Météo France | AROME (Applications de la Recherche l´Opérationnel à Méso-Echelle) | 1.3 km | 3D-Var | MSG-SEVIRI | AMV, cloud-free radiance |
| DWD | COSMO (COnsortium for Small scale Modeling) | 2.8 km | LETKF | Not assimilated | Not assimilated |

*AMV*

AMVs are wind observations derived as motion vectors by tracking clouds and water vapor in consecutive satellite images. These have been used in operational NWP systems since the 1970s (Menzel 2001) and proven useful for identifying synoptic air flows due to their good coverage including oceanic areas. Now that AMV datasets are available with much finer resolutions, they can represent local-scale flow in mesoscale systems as well as synoptic winds in global systems (Bedka and Mecikalski 2005). High-resolution AMV products such as the High Resolution Winds obtained from MSG (Meteosat Second Generation) SEVIRI (Spinning Enhanced Visible and Infrared Imager) images at 15-min intervals and the NOAA’s High Density Winds using GOES (Geostationary Operational Environmental Satellite) AMVs incorporated with polar-orbiting AMVs are used for mesoscale NWP in some countries.

The JMA’s mesoscale and local scale DA systems have assimilated AMVs derived from Himawari-8 since March in 2016 (Yamashita 2016). Himawari-8 has enabled the production of AMVs with much higher resolutions and in many more channels than multi-functional transport satellites (MTSATs), the former geostationary satellite series before Himawari-8 and -9. The Meteorological Satellite Center (MSC) of the JMA currently provides mesoscale NWP with high-resolution AMVs on a 20 km grid (at nadir) over the Japanese region in addition to ordinary AMVs with a 34 km resolution for global systems using 10-min full-disk scans in six different channels (Shimoji and Nonaka 2016).

*CSR*

CSRs obtained by GEOs are brightness temperatures and radiances averaged over some grids of cloud-free pixels derived from infrared imagery in water vapor channels (Uesawa 2009). They provide information on water vapor and clouds in the high troposphere. In the process of assimilating them into NWP, simulated brightness temperatures are obtained using vertical profiles of temperature and water vapor and surface information of models as input for radiative transfer models (RTMs). There are two fast RTMs commonly used in operational NWP, the Community Radiative Transfer Model (CRTM, Liu and Boukabara 2014) and the Radiative Transfer model for TIROS (Television and Infrared Observation Satellite) Operational Vertical Sounder (RTTOV, Saunders *et al*. 2013). No centres yet assimilate cloud-affected infrared radiance operationally, although several of them are aiming to achieve it in near future (Geer *et al*. 2018).

The JMA's mesoscale system started to assimilate MTSAT CSRs in 2010 along with radiance temperatures in the microwave spectrum from polar-orbiting satellites (Kazumori 2014). The local scale system has assimilated Himawari-8 CSRs and other radiance data since January in 2017. The horizontal resolution of CSRs was increased to 32 km from 64 km when Himawari-8 data became available, thanks to the improved spatial resolution of observations (Kazumori 2018). Though only one channel (Band 8) of Himawari-8 is currently used, assimilation of the other two water vapor channels (Bands 9 and 10) is being developed with the expectation of extracting more information about water vapor fields from multi-spectral water vapor channels.

*Cloud properties*

While direct assimilation of cloud-affected infrared radiance and visible reflectance in NWP is still difficult, cloud properties such as top pressure, fraction, and optical depth can give useful information on water vapor fields where clouds exist. These are usually inferred by using infrared and visible radiances from satellites together with temperature profiles of models and are also utilized for other purposes such as weather and climate monitoring over years (Rossow and Schiffer 1991) as well as in assimilation for NWP. The Met Office assimilates cloud fraction known as GeoCloud using cloud top pressures derived from 15-min multispectral MSG SEVIRI imagery (Renshaw and Francis 2011). The NCEP utilizes cloud top pressures derived from GOES to improve the hydrometer analysis (Hu *et al.* 2017) in their mesoscale DA system.

## 3. Future Development of Assimilation Use of GEOs

### Himawari-8 and assimilation experiments using its new data

Himawari-8, one of the two current JMA's GEOs, was launched in 2014 and began observation in 2015, becoming the first new generation GEO followed by NOAA/NASA's GOES-16 and -17 in 2016 and in 2018, Himawari-9 in 2016, CMA's FY (Feng-Yon)-4A in 2016 and others to follow in the coming years. The Advanced Himawari Imagers (AHIs) on board Himawari-8/9 have 16 observation channels, greatly increased from 5 channels of the previous MTSAT series, and their enhanced spatial resolution is 0.5 to 1 km for visible and near-infrared channels and 2 km for infrared channels. Furthermore, the temporal resolution became even higher than MTSATs, reducing the time interval of observations from 30 min to 10 min for Full Disk, from 5 min to 2.5 min for sector rapid scans, in addition to 30 s super rapid scans. Bessho *et* *al.* (2016) overviewed the specifications of AHI and products produced for the use in NWP and other applications. With these advantages combined, Himawari-8 data have already benefited the JMA's operational NWP by increasing the quality and quantity of data such as AMVs and CSRs available for assimilation (Yamashita 2016; Kazumori 2018).

Although only hourly AMV and CSR data are assimilated operationally, recent studies have assimilated 10 min Himawari-8 data or rapid scan observations of even shorter time periods in order to improve forecasts of mesoscale severe weather. Honda *et al*. (2018) assimilated all-sky (clear, cloudy and precipitation) infrared radiances from Himawari-8 every 10 min with a regional model in a tropical cyclone (TC) case study and showed the improvement in analysis and forecasts of the intensity and structure of the TC. Rapid scan AMVs (RS-AMVs) obtained from Himawari-8 rapid sector scan imagery around Japan or in the vicinity of typhoons are computed every 10 min from image triplets with time intervals of 2.5 min for visible and 5 min for near-infrared and infrared channels. Reducing the time interval of the consecutive imagery helps to better capture small-scale wind fields. Some DA experiments with Himawari-8 RS-AMVs showed a positive impact on the forecasts of a heavy rainfall and a cold vortex event (Kunii *et al.* 2016; Otsuka *et al.* 2018). In fact, assimilation of RS-AMVs had been gaining attention before Himawari-8 because several case studies showed their positive impacts on forecasts of TCs and heavy rainfall events (e.g. Langland *et al.* 2009). Now that new generation satellites are operated in rapid scan mode as fast as 30 seconds to a few minutes, even higher resolution AMVs are available for mesoscale assimilations.

### New censors and future data of GEOs

The other next generation GEOs are boarded with imagers with the similar specifications to AHI onboard Himawari-8/9. With regards to new sensors other than imagers, the GLM (Geostationary Lightning Mapper) and the LMI (Lightning Mapping Imager) are onboard GOES-16 and FY-4A, respectively. Because lightning information by ground-based systems is already assimilated operationally in the U.S. (Gustafsson *et al.* 2018), assimilating lightning data by space observations may be highly possible for predicting severe storm updrafts and the growth and decay of these systems. There are some studies investigating impacts of GLM data on NWP using OSSEs (Observing System Simulation Experiment) (e.g. Allen *et al*. 2016).

A hyper-spectral infrared sounder (HSIS) is another new potential target for use in assimilation because it can retrieve temperature and water vapor profiles via RTMs. FY-A4 became the first GEO boarded with a HSIS, the GIRS (Geostationary Interferometric Infrared Sounder), as well as being a wind profiler by tracking water vapor features. MTG (Meteosat Third Generation) to be launched in 2021 will also be equipped with HSIS as a component of the FCI (Flexible Combined Imager). Some OSSE studies showed positive impact of HSIS data on mesoscale NWP (e.g. Li *et al.* 2018). JMA is also trying to see the benefits of introducing a HSIS to the next Himawari series after Himawari-8/9 by conducting OSSEs. A microwave sounder (MS) may detect water vapor fields better than HSIS. Although a MS on board GEO is not likely to be realized in near future, Duruisseau *et al.* (2017) conducted OSSE studies to see its impact on mesoscale NWP.

## 4. Discussion

Most observations affected by cloud and precipitation are discarded in current DA systems because assimilation of such data is not straightforward, given the limited predictability of cloud formation and precipitation and the non-linear, discontinuous nature of moist atmospheric processes (Geer *et al.* 2017). Computational costs and other associated variables of RTMs which are necessary for directly assimilating infrared all-sky radiances are much more expensive and numerous than for clear sky radiances or for all-sky radiances in microwave spectrums (e.g. McNally 2009). While development towards operational assimilation of all-sky infrared radiances is being pursued (Okamoto *et al.* 2014, Okamoto 2017), next generation GEOs have already begun to provide huge amount of data with higher frequency. In order to utilize them in current mesoscale forecast systems, the assimilation of cloud properties may be an option to realize assimilation of all-sky radiances, as demonstrated operationally in the U. K. and the U. S.

Retrievals from radiances such as AMVs and cloud properties have the advantage of requiring less resources during the assimilation process and are often the same meteorological variables as used in model. The disadvantage is in uncertainties added during the process of retrievals and from unknown error characteristics. Considering recent advancement both in sensor and in retrieval algorithm, the quality of retrievals may be improving as shown in the case of Himawari-8 AMVs (Otsuka *et al.* 2018). Jones *et al.* (2013) assimilated cloud water paths derived from GOES-13 observations and successfully reproduced the convective storm. Hayashi (2016) developed Himawari-8 Optimal Cloud Analysis, which employs the radiances of all sixteen channels of AHI to estimate cloud top pressure, optical depth, and other cloud properties thorough 1D-Var. Assimilation of such cloud retrievals can make use of the information from visible and near-infrared channels, while direct assimilation of such channels is far more difficult than that from infrared radiances. DWD undertook initial case studies to directly assimilate visible radiances of SEVIRI (Scheck *et al.* 2016).

Another important issue is how to deal with observation error correlations and extract meaningful information out of high spatial and temporal GEO data. Under the common assumption of DA systems that observation errors at each grid should be uncorrelated in order to avoid degradation of analysis (e.g. Liu and Rabier 2003), a large amount of data is currently discarded by spatially thinning original data to distances of several dozens to a few hundred kilometers. Inter-channel observation error correlations should also be considered in handling such multispectral GEO data. Data transmission and storage for real time use may also be a problem when ingesting such a large amount of data in DA update cycles.

Finally, new sensors onboard future GEOs need to be designed well ahead of launch. OSSE studies can help investigate potential impacts of such new candidate sensors by assimilating simulated observations. While the implementation in the real world is not as simple as the settings of OSSEs, it may be worthwhile to explore possible impacts of new sensors for the further developments of future GEOs and mesoscale forecasts.

## 5. Conclusion

Emerging new generation GEOs have brought opportunities to improve mesoscale forecasts with better data of increased quality and quantity. However, we need further technical developments both in operational and research fields in order to exploit them in existing DA systems. The difficulties of dealing with a huge amount of high-resolution data in multi- channels including cloud and precipitation affected observations are primary issues and seem to hinder the benefits of GEO data. How to make the best use of those novel observations still requires further research efforts. Further understanding of the data characteristics and representativeness can help to optimally design the DA systems, thus improve initial conditions of mesoscale forecasts.

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