Weather Prediction by Numerical Methods Module 3 (WPNM-M3)
6 – 10 February 2023, Singapore

ASEAN SPECIALISED METEOROLOGICAL CENTRE

METEOROLOGICAL SERVICE SINGAPORE
Centre for Climate Research Singapore

WEATHER PREDICTION BY NUMERICAL METHODS MODULE 3 (WPNM-M3)

WPNM-M3 REPORT

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List of Abbreviations

ASCMG	ASEAN Sub-committee on Meteorology and Geophysics
ASEAN	Association of Southeast Asian Nations
ASMC	ASEAN Specialised Meteorological Centre
BDMD	Brunei Darussalam Meteorological Department
CCRS	Centre for Climate Research Singapore
DMC	Department of Meteorology, Cambodia
DMHL	Department of Meteorology and Hydrology, Lao PDR
DMHM	Department of Meteorology and Hydrology, Myanmar
ECMWF	European Centre for Medium-range Weather Forecasts
GTS	Global Telecommunication System
MMD	Malaysian Meteorological Department
MSS	Meteorological Service Singapore
NMHS	National Meteorological and Hydrological Services
NWP	Numerical weather prediction
PAGASA	Philippine Atmospheric, Geophysical and Astronomical Services Administration
RIP	Reanalysis Intercomparison Project
SPARC	Stratosphere-troposphere Processes And their Role in Climate
TMD	Thai Meteorological Department
VMHA	Vietnam Meteorological and Hydrological Administration
WMO	World Meteorological Organization
WPNM	Weather Prediction by Numerical Methods
WRF	Weather Research and Forecasting

Introduction

Numerical weather prediction (NWP) is an important tool used by National Meteorological and Hydrological Services (NMHS) to deliver accurate and timely weather predictions. Outputs from global and regional NWP systems are often used for nowcasting, short/medium-range and seasonal forecasts. The accuracy of the forecasts relies strongly on effective design, implementation, and evaluation of the various components of NWP systems. These further require an in-depth understanding of the system's conceptualisation and limitations.

While there have been recent improvements in the NWP capability in the ASEAN region, capability building courses on NWP are still much needed. The ASEAN Specialised Meteorological Centre (ASMC) proposed at the 40th Meeting of the ASEAN Sub-Committee on Meteorology and Geophysics (ASCMG-40) held in May 2018 to conduct a training course on NWP and the proposal was well-received. The Meeting welcomed ASMC's offer to deliver such capability building courses on NWP. The Weather Prediction by Numerical Methods (WPNM) series was hence conceptualised as part of the ASMC's 5-year Regional Capability Building Programme for the ASEAN region.

An initial assessment of the training needs was undertaken in collaboration with NMHS through a questionnaire. The proposed modules of WPNM are designed to cover the basic aspects of NWP; they are: (1) Governing equations and numerical methods; (2) Physical parametrisations; (3) Data assimilation; and (4) Predictability.

The inaugural run of Weather Prediction by Numerical Methods Module 1 (WPNM-M1) was held in Singapore from 18th to 22nd November 2019. The second run (WPNM-M2) was held virtually from 3rd to 5th May 2021 in light of the travel restrictions during the COVID-19 pandemic. Feedback from participants was positive for both WPNM-M1 and WPNM-M2, with most participants indicating interest to attend future modules. This report documents the conduct of the third run (WPNM-M3), which was held in Singapore from 6th to 10th February 2023. WPNM-M3 was hosted by the ASMC and organised by the Centre for Climate Research Singapore (CCRS). Sponsorship was provided by the Meteorological Service Singapore (MSS).

In line with the proposed module theme, WPNM-M3 focused on data assimilation in NWP systems. The aims of WPNM-M3 were as follow:

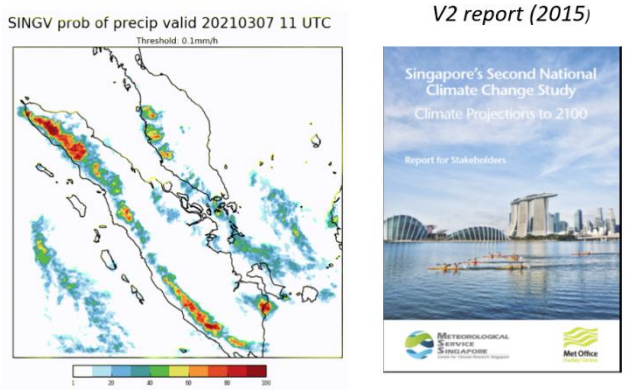
a) To equip participants with knowledge on the mathematical conceptualisation and limitations of data assimilation methods;
b) To equip participants with knowledge on data assimilation applications in weather and climate science;
c) To allow participants to experiment with a real-world community atmospheric data assimilation system to enhance their theoretical understanding.

1 Day 1: 6th February 2023, Monday

1.1 Welcome and Introduction

The module kicked off with a welcome address by Prof Dale Barker, Director of CCRS. He summarised CCRS' journey and key research achievements since its inception, including its mission *to advance scientific understanding of tropical climate variability and change and its associated weather systems affecting Singapore and the wider Southeast Asia Region, so that the knowledge and expertise can benefit decision makers and the community*. This underpins CCRS' efforts to actively engage ASEAN NMHS through the organisation of workshops and training modules such as WPNM-M3. He also thanked the participants from ASEAN NMHS for their attendance on behalf of the CCRS organising committee. Finally, he emphasised that strong partnerships and openness in data sharing through e.g. the World Meteorological Organization's Global Telecommunication System (WMO GTS) were key reasons for the success of the international data assimilation activities to date.

Mr Joshua Lee followed with a sharing on the conceptualisation of the WPNM series, its history and as well as the objectives of WPNM-M3. A round of self-introduction was also conducted with a short ice-breaker session to allow participants to familiarise with one another. To conclude the welcome and introduction session, an administrative briefing was delivered by Mr Lee to ensure that the participants had a pleasant experience in Singapore.



Snippet of the presentation on CCRS' journey by Prof Dale Barker

1.2 Fundamentals of Data Assimilation

A series of 16 lectures was planned for WPNM-M3, delivered by Prof Dale Barker, Mr Joshua Lee and Dr Krishnamoorthy Chandramouli. The morning session started with the first two lectures by Prof Barker on "Basic concepts of data assimilation" and "Overview of data assimilation methods".

In "Basic concepts of data assimilation", Prof Barker described the intended outcomes of data assimilation and the inputs to a typical data assimilation system. He highlighted the underpinning principle of Bayes theorem to find an updated best estimate of a state (called the

analysis) given new observations and a previous state forecast. A simple example using aircraft observations over Singapore was used to illustrate the principle. A few participants asked about the estimation of observation errors and treatment of 'bad' observations. Prof Barker shared that observation errors could be estimated in the lab or empirically, and 'bad' observations could be dealt with using complex quality control procedures e.g. 'buddy checks' which cross-reference with nearby observations.

Prof Dale Barker delivering the first lecture

In "Overview of data assimilation methods", Prof Barker shared about the history of data assimilation methods which evolved from subjective analysis to early objective analysis methods and then to current methods that were used in data assimilation-cycling NWP systems. He also briefly introduced ensemble and variational data assimilation methods, particularly those used in leading global NWP centres. An example with SINGV, the NWP system developed at MSS, was cited to highlight one important benefit of data assimilation – avoiding spin-up issues in convective-scale NWP. One participant sought clarification on the definition of a cycling system. Another participant asked about the typical spin-up duration, to which Prof Barker replied that it depended on location and variable. Prof Barker concluded by sharing some practical uses cases of various data assimilation methods, for example for fog forecasting in the United Kingdom and heavy rainfall nowcasting at the 2012 London Olympics.

1.3 Atmospheric Observations

The morning discussion on quality of observations was a clear segue to the next lecture: "The atmospheric observation network", delivered by Dr Krishnamoorthy Chandramouli in the afternoon.

Dr Krishnamoorthy Chandramouli delivering the third lecture

In the lecture, he outlined the purpose of the atmospheric observation network for forecasting and NWP. An illustration of the global observation system was used to demonstrate how different sources of observations helped to provide a more complete picture of the atmosphere at a given time. He showed that these observations covered various regions, atmosphere levels, and atmospheric variables. Dr Chandramouli then

focused on a few categories: radiosondes, aircraft, radar and satellite observations. He elaborated on the observation subtypes under each broad category, and how recent developments in space technology had helped establish satellite observations as the backbone of the global observation system.

1.4 Practical Session – A Bayesian Perspective

The rest of the day was spent on a hands-on practical session with a simple Gaussian mixture data assimilation setup to illustrate Bayes theorem. This was adapted from Python codes provided by Dr Javier Amezcua, a contact from the University of Reading. Shared Linux laptops were provided for the participants to complete the practical sessions. Mr Joshua Lee introduced the framework for the setup and the concept of Bayesian inference, closely related to Prof Dale Barker's lecture on "Basic concepts of data assimilation". Instructions to run the system and tweak the settings were provided. Mr Lee, Prof Barker, Dr Krishnamoorthy Chandramouli and Dr Robert Huva were present to facilitate the hands-on practical session and answer further questions regarding the key learning points. As participants had not been introduced to the details of variational data assimilation, the real-time community atmospheric data assimilation system, Weather Research and Forecasting Data Assimilation (WRFDA), was not used on Day 1.

Mr Joshua Lee discussing the results of the practical session illustrating Bayes theorem with Mr Gabriel Miro and Mr Michael Simora

To round off the evening, a welcome dinner was hosted by MSS for the participants, held at The Landmark Restaurant. This provided opportunities for further interaction between participants and lecturers.

2 Day 2: 7th February 2023, Tuesday

2.1 Variational Methods

The fourth and fifth lectures in the series were presented by Mr Joshua Lee. The topics were: "3D-Var" and "4D-Var", respectively. Mr Lee started with a recap of the key concepts outlined in Day 1. He shared about the rationale for developing the three-dimensional variational (3D-Var) data assimilation and the reasons for its popularity in many operational NWP centres, particularly in regional data assimilation systems. He then explained and derived the origin of the cost function – the cornerstone of variational methods – and its minimisation. The minimisation yields the analysis that is sought from data assimilation. Mr Lee also highlighted a key assumption in 3D-Var – that all observations were valid at the analysis time

– which was an unrealistic expectation. He also mentioned that while many operational NWP centres adopted 3D-Var, they typically implemented a variant called 3D-Var First-Guess-at-Appropriate-Time (FGAT).

Continuing from the previous lecture, Mr Lee discussed the changes to the cost function in 3D-Var FGAT in the fifth lecture, "4D-Var". He described how it was an intermediate step to four-dimensional variational (4D-Var) data assimilation. He added that in 3D-Var FGAT, the observations were compared with the model forecast at an appropriate time, so they were not assumed to all be valid at analysis time. Mr Lee then highlighted that a linearised forecast model and its adjoint was required in 4D-Var, pertaining to a question from a participant on the main difference between 4D-Var and 3D-Var FGAT. This allowed 4D-Var to account for the time evolution of forecast errors within the assimilation window of the system. However, he also caveated that this linearised forecast model and its adjoint was usually computationally expensive and was often invalid in thunderstorm regions, which limited its applicability for the ASEAN region.

2.2 WRFDA Overview

Prof Dale Barker delivered the sixth lecture "WRFDA overview", as an introduction to the WRFDA community atmospheric data assimilation system. He first introduced the design, history, and user statistics of WRFDA. He touched on WRFDA radar assimilation, radiance assimilation and chemical data assimilation to demonstrate the breadth of WRFDA capabilities. Focus was placed on the observations processing capabilities and data assimilation methods available in WRFDA, since the participants would be exploring these components in WRFDA.

Prof Dale Barker delivering the sixth lecture

2.3 Practical Session 1: 3D-Var in WRFDA

In the afternoon, Prof Dale Barker lectured on "3D-Var in WRFDA and basic namelist settings". The intention was to explain how different namelist settings would control different options in WRFDA. He introduced the observation processing namelists, formats, and example plots that were typically produced.

Thereafter, participants had a hands-on practical session using WRFDA. The practical was adapted from the standard National Center for Atmospheric Research (NCAR) WRFDA tutorial, but was set up to focus on the ASEAN domain. One exercise in the practical sheet was designed specifically to highlight how ASEAN NMHS' weather monitoring data contributed to the WMO GTS, by encouraging participants to search for contributions from their NMHS

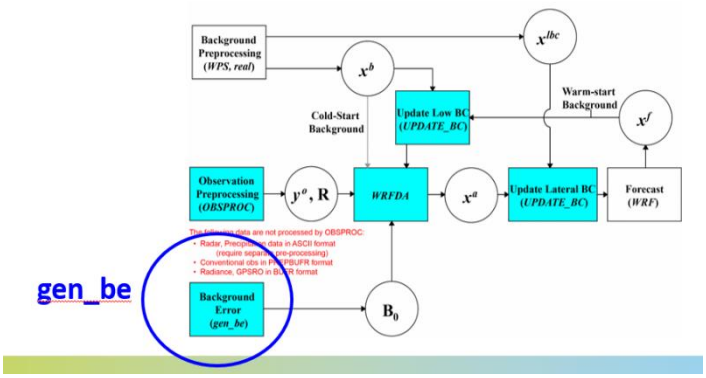
to the global observation dataset. Participants were allowed the rest of the afternoon to complete the practical sheet, which included observations processing and using the processed observations to run 3D-Var in WRFDA. They were also encouraged to ask questions during the practical session and clarify their doubts in running the WRFDA system. Prof Barker, Mr Joshua Lee, Dr Krishnamoorthy Chandramouli and Dr Robert Huva were present to facilitate the hands-on practical session.

Dr Krishnamoorthy Chandramouli guiding Ms Lai Maw Zan during the WRFDA practical session

3 Day 3: 8th February 2023, Wednesday

3.1 Background Error Modelling

Prof Dale Barker delivered the next lecture on "Background error modelling in NWP" to start off the third day. Alluding to previous WRFDA lectures, he mentioned that one of the most important components of any data assimilation system was the background error covariance matrix, which had to be modelled statistically because of practical considerations. He discussed the topic in the WRFDA context, and how the 'gen_be' code performed the background error modelling in a series of steps. These steps governed how the observation information was spread by the background error covariance matrix spatially and between variables. A few participants asked about the choice of options for background error modelling, particularly since multiple options had been developed in WRFDA. They were particularly interested in changing the options for their WRFDA systems run by their respective NMHS.



Snippet of the presentation on background error modelling in the WRFDA context

3.2 Practical Session 2: 3D-Var in WRFDA

After hearing about background error modelling in WRFDA, participants proceeded with completing the second practical sheet, which focused on background error modelling and its impact on assimilated observations. Training data from WRF over the ASEAN domain was

provided for the participants so they could run the 'gen_be' system without running the WRF forecast model. One exercise required participants to plot the analysis increments after assimilating one observation, repeating for each option in the background error modelling process. Participants were particularly intrigued that a small change in the WRFDA system had such profound impacts on the analysis. A few participants had questions about specific namelist settings and Linux terminal commands. Mr Joshua Lee, Dr Krishnamoorthy Chandramouli, Dr Robert Huva and Prof Dale Barker were present to assist with the technical setup and explain theoretical concepts illustrated through the morning practical session.

Mr Joshua Lee guiding Ms Phung Thi Vui and Ms Chu Thi Huyen Trang during the hands-on WRFDA practical session

3.3 Ensemble Methods

In the afternoon, Dr Krishnamoorthy Chandramouli delivered the ninth lecture on "Ensemble Kalman Filters". This lecture explored a new family of data assimilation methods. Dr Chandramouli shared that traditional Kalman Filter methods were computationally too expensive for NWP because large matrices were involved in such realistic systems, so an ensemble was used to provide statistical information instead. He also explained the mathematics behind the ensemble Kalman Filter and its stochastic and deterministic variants. These variants had different formulations in computing and propagating the ensemble mean and perturbations. Participants were not expected to test these methods during the WRFDA practical sessions, so less focus was placed on describing the details of localisation or inflation techniques in ensemble Kalman Filters. Drawing parallels to background error modelling concepts covered in the morning, Mr Joshua Lee commented that the ensemble Kalman Filters effectively model background error statistics using the ensemble, irrespective of Kalman Filter variants.

3.4 Hybrid Methods

In the following lecture on "Hybrid data assimilation", Mr Joshua Lee recapped key ideas from the lectures on variational methods and the benefits from ensemble-based methods. He shared the rationale for performing hybrid data assimilation, specifically ensemble-variational data assimilation, which was widely implemented by many operational global NWP centres. The original formulation of the approach was derived, along with highlighted changes in the variational cost function starting

Mr Joshua Lee and Dr Robert Huva guiding Ms Lai Maw Zan in plotting observation locations during the hands-on WRFDA practical session

from the 3D-Var cost function. Mr Joshua Lee further expounded on the ensemble-variational cost function by providing a plain English interpretation of its components. Citing recent results relevant to the tropics, he also showed how the weightings and localisation design impacted the analysis increments. He concluded with a summary on different permutations of hybrid data assimilation and encouraged participants to further explore the intricacies of these methods. One participant asked if it was possible to generate ensemble perturbations using only a deterministic NWP system. Mr Lee replied that a time-lagged approach could be used, by using older forecasts valid at the same time. Prof Barker added that a global ensemble could also be used to derive perturbations for regional hybrid data assimilation.

3.5 Practical Session 3: 3D-Var in WRFDA

Participants continued with the practical for the remainder of the day. Additional challenge exercises were included in the two practical sheets to cater to participants who had completed the preliminary exercises in the first two practical sessions. One exercise required participants to implement 3D-Var FGAT in WRFDA. Mr Joshua Lee and Dr Krishnamoorthy Chandramouli provided additional assistance to participants for this exercise, since the practical sheet deliberately excluded detailed instructions to allow participants to further explore WRFDA independently. A few participants also successfully identified specific observation quality control settings that were deliberately included in the practical setup to test the participants' understanding. Mr Peeranat Longsombun and Mr Nuthakit Singhaphet wrote shell scripts to automate the running of the experiments with various WRFDA settings. They shared that the exercises were very relevant to their work in the Thai Meteorological Department (TMD), and that they would be introducing some changes in TMD's NWP system after WPNM-M3.

4 Day 4: 9th February 2023, Thursday

4.1 Data Assimilation Applications

After covering the theory and mathematical conceptualisation of data assimilation methods, emphasis was placed on bridging theory with practice. The following lectures aimed to outline important considerations for implementing data assimilation in operational NWP systems and data assimilation applications in weather and climate science. Mr Joshua Lee started the morning session with a sharing on the operational NWP system at MSS, known as SINGV-DA. He highlighted the development pathway of SINGV-DA and mentioned key features of the data assimilation implementation that mirrored those in WRFDA. For example, Mr Lee shared how the background error modelling was designed in the Unified Model framework, which SINGV-DA adopted. He also pointed out that the analysis increments from

Mr Joshua Lee sharing about MSS' SINGV-DA system

data assimilation could introduce imbalances and 'shocks' to the NWP system and how different approaches were used to treat them in WRFDA and SINGV-DA. These provided participants with insights to the considerations required for operational implementation of data assimilation.

After the break, Prof Dale Barker continued with the twelfth lecture, "WRFDA (and other data assimilation) applications". He provided additional examples: urban data assimilation, visibility assimilation, and crowdsourcing observations. These allowed participants to be exposed to the latest data assimilation research and exploratory work, all underpinned by concepts covered in the first three days. Participants were especially intrigued by sensors mounted on seals to measure ocean temperatures. Dr Song Chen from MSS asked if there were specific rules for urban data assimilation, particularly approaching the city-scale grid resolution. Prof Barker commented that in an urban environment, observation representiveness error (e.g. large variations in observed temperatures at street-level 'sub-grid' scales) is a particular challenge, as is the choice of data assimilation technique. He concluded with a summary of ongoing WRFDA research and developments to improve the code and to introduce new features.

In the following lecture, "Reanalysis applications", Dr Krishnamoorthy Chandramouli introduced data assimilation applications in climate science. He highlighted the need for reanalyses – to provide a consistent analysis over a historical period, a reconstruction of past atmospheric states. He then described various types of reanalyses, including regional and global reanalyses, which could ingest different subsets of observations. He also briefly mentioned the Stratosphere-troposphere Processes And their Role in Climate (SPARC) Reanalysis Intercomparison Project (RIP), which compared the quality of some well-known reanalysis products. One example illustration comparing 2-metre air temperature using the SPARC RIP was highlighted to demonstrate the impacts of different data assimilation approaches on the reanalyses. Participants were asked to consider the necessity for a regional reanalysis over the ASEAN region, which was unavailable at present. Dr Chandramouli had a short discussion with a few participants on the benefits of running a regional reanalysis, including having a higher resolution model to capture convective processes and the ability to ingest local observations.

4.2 Assessing Observation Impact

Dr Krishnamoorthy Chandramouli delivered the fourteenth lecture "Assessing observation impact" in the afternoon. He underscored the importance of monitoring assimilated observations in any data assimilation system. This was necessary to ensure that high quality observations were ingested and to guide future observation systems development. He touched on the ideas behind observing system simulation experiments, forecast sensitivity to observation impact, and data denial experiments. These allowed for the forecast impact evaluation of specific observation types. Using MSS' SINGV-DA system, Dr Chandramouli presented recent results on satellite observations data denial experiments to highlight how the tropospheric moisture information from satellites influenced the short-range forecast accuracy verified against radiosondes. Mr Gabriel Miro from Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA) questioned if the forecast sensitivity to observation impact had accounted for the density and quantity of observations. Dr

Chandramouli clarified that it was implicitly accounted for, but statistics should be examined over a longer period to ensure significance.

4.3 Coupled Data Assimilation

The discussions in the first three days were mainly confined to atmospheric data assimilation. In the fifteenth lecture, Dr Krishnamoorthy Chandramouli broached the topic of "Coupled data assimilation", bringing in ocean data assimilation and coupled processes into scope. He began with an overview of coupled modelling, before highlighting the essence of strongly and weakly coupled data assimilation. Mr Joshua Lee commented that MSS was indirectly implementing weakly coupled data assimilation, since the land surface analysis and ocean analysis (soil moisture and sea surface temperature) were derived from global data assimilation systems, while the atmospheric analysis was derived by SINGV-DA. Dr Chandramouli continued by explaining the limitations of weakly coupled data assimilation, including the existence of imbalances between earth system components. He also mentioned that strongly coupled data assimilation had added complexities because cross-component background error statistics needed to be prescribed. Mr Lee then shared further insights on the timelines at a few major operational global NWP centres to develop their weakly coupled and strongly coupled data assimilation systems.

4.4 Practical Session 4: 3D-Var in WRFDA

Participants had the rest of the afternoon to complete the two practical sheets, including the additional exercises. These exercises involved plotting the analysis increments, analysis and background associated with WRFDA inputs and outputs. They were also tasked to amalgamate the observations processing and background error modelling exercises with pseudo-single observation tests to explore the variety of settings available in WRFDA. Mr Gabriel Miro and Mr Michael Simora from PAGASA were able to explore assimilating a 'bogus' single pressure observation to simulate a surface pressure observation within the eye of a tropical cyclone. Mr Awang Mohamad Noor'Arifin bin Haji Awang Yussof and Mr Mohammad Affindi bin Haji Sabli from Brunei Darussalam Meteorological Department (BDMD) ran 3D-Var FGAT and explored using modified observations in the observations processing. Ms Zureen Norhaizatul Che Hassan and Ms Wan Maisarah binti Wan Ibadullah from Malaysian Meteorological Department (MMD) shared that they were particularly interested in the background error modelling exercises, since they had previously attempted to generate the training data for it using WRF at MMD. Most participants were able to complete all exercises in both practical sheets.

5 Day 5: 10th February 2023, Friday

5.1 Machine Learning and Data Assimilation

The sixteenth and final lecture in the lecture series on "Machine learning and data assimilation" was delivered by Mr Joshua Lee. This was designed to expose participants to the conceptual and mathematical similarities between machine learning and data assimilation. Mr Lee recapped the variational data assimilation approach, including the first day's lectures on

Bayes theorem. He then introduced various families of machine learning methods – supervised, unsupervised and reinforcement learning. As with previous lectures, Mr Lee shared the motivation for exploring machine learning in the NWP forecast chain, citing the 10-year machine learning roadmap of European Centre for Medium-range Weather Forecasts (ECMWF). Apart from examples of machine learning applied in data assimilation, Mr Lee also explained the theoretical linkages between machine learning and data assimilation, illustrated using the cost function of variational data assimilation and loss function of machine learning neural networks. Most of the application examples were provided by ECMWF, since they had invested in exploring machine learning integration.

5.2 Learning Consolidation and Future Data Assimilation Efforts

In the afternoon, the key learning points throughout WPNM-M3 were consolidated and recapped in a plenary session. The session aimed to recognise the main ideas which were the most prominent for the participants, but also to test the participants on their understanding of the important concepts.

Mr Joshua Lee conducting learning consolidation activities for the participants

Mr Joshua Lee started with a short interactive "word-cloud" activity with the participants. Key themes were flashed on the screen and participants were expected to share their immediate recollection of words or phrases related to the themes. Frequently input words or phrases would appear larger in the cloud, which suggested that participants had a deeper impression of those pointers. The key themes were: Observations for data assimilation, data assimilation methods, and applications of data assimilation. The results of the activity are included in Annex A. Next, Mr Lee conducted an interactive quiz (20 questions) for the participants, introducing a competitive element where top scorers were awarded prizes. All participants passed the quiz, scoring an average of 68%. Mr Lee further explained the answers to help correct common misconceptions.

Prof Dale Barker then proceeded with a plenary session to discuss future data assimilation efforts in the region. Prior to WPNM-M3, participants were requested to gather information on their respective NMHS' plans for NWP or data assimilation. A similar activity was conducted in the first run, WPNM-M1, which allowed for a comprehensive status update on NWP plans in the region.

During the WPNM-M3 plenary session, Mr Awang Mohamad Noor'Arifin bin Haji Awang Yussof from BDMD shared that they had made notable progress in implementing WRF and were planning for WRFDA. They were also interested in the developments in the next-generation data assimilation system, Joint Effort for Data Assimilation Integration. Mr Nuthakit Singhaphet from TMD shared that they were currently using WRF and had immediate

plans to implement WRFDA. They were also planning to conduct knowledge sharing sessions with their colleagues post-WPNM-M3. Ms Lai Maw Zan from Department of Meteorology and Hydrology, Myanmar (DMHM) shared that they had implemented WRF, but DMHM had faced issues with retrieving and processing observations in WRFDA. She also expressed appreciation for the WRFDA training, with the hope that CCRS could support them if they had further queries. Ms Phetlasy Somchanmavong from the Department of Meteorology and Hydrology, Lao PDR (DMHL) and Mr Sokhom Khoeun from the Department of Meteorology, Cambodia (DMC) both expressed appreciation for the conduct of WPNM-M3. Both DMHL and DMC had no immediate plans to maintain a data assimilation system, as they had not implemented an NWP system. Mr Khoeun further suggested having a WRF and WRFDA-focused training in Cambodia. Ms Zureen Norhaizatul Che Hassan from MMD shared that they had set up WRFDA 3D-Var, running in research mode. She also highlighted that MMD had plans to assimilate radar, satellite, radio occultation, and Mode-Selective aircraft observations. Mr Gabriel Miro from PAGASA shared that they had implemented WRF and were currently experimenting with radar data assimilation and tuning of WRFDA namelist parameters. They also had an interest in convective-scale data assimilation. Ms Chu Thi Huyen Trang from Vietnam Meteorological and Hydrological Administration (VMHA) mentioned that they had implemented WRFDA with 3D-Var. Their system ingested a mix of local and global (from National Centers for Environmental Prediction) observations.

Mr Sokhom Khoeun expressing his appreciation for the conduct of WPNM-M3

Prof Barker commented that one alternative to the lack of regional observations was the blending or nudging the regional model using a global NWP analysis. He also noted several comments on radar data assimilation and encouraged participants to advocate for regional data sharing in their respective NMHS. Finally, he concluded with an announcement of the fourth and final run, WPNM-M4, which would focus on "Predictability".

Ms Phetlasy Somchanmavong sharing about DMHL's data assimilation plans

WPNM-M3 Feedback and Outcomes

Overall, the training module was well-received by participants. Based on the feedback survey responses (Annex B), participants had indicated that WPNM-M3 had achieved its three objectives. In general, many of the participants found the lectures and hands-on practical sessions interesting. Following feedback from WPNM-M1, reading materials and mathematics primers were sent to participants two weeks in advance to share fundamental mathematical concepts required for the lectures. References were also included for further reading. Additionally, compared to WPNM-M1, lecturers had reduced the number of equations and limited the mathematical rigour during the lectures. As such, most participants found the lectures and hands-on practical sessions easy to follow. Participants also strongly supported the continuation of the final module of WPNM and most indicated a strong interest to attend such modules in the future.

Following the positive feedback, CCRS will be planning the final training module, likely in 2024:

- WPNM-M4 on predictability

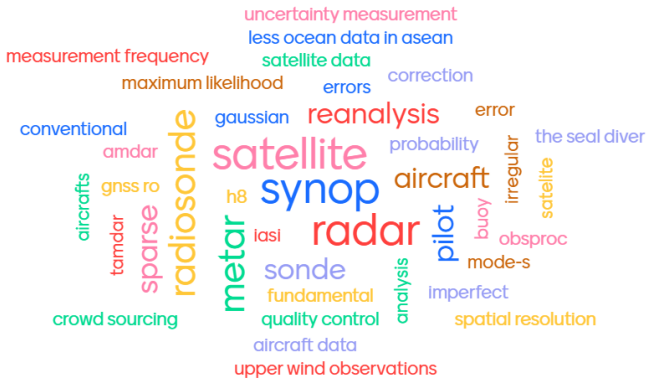
The scope for this module is to be determined but is expected to cover predictability of tropical weather systems, uncertainty estimation, ensemble prediction systems and postprocessing of NWP forecasts to extract maximum value within the weather predictability limit.

In the closing plenary session, it was highlighted that many ASEAN NMHS had plans to implement WRFDA in their existing WRF systems. It is hence highly recommended that the community continues to share results and support the technical development of data assimilation systems in the region. This could include sharing of observational data, or conducting regional intensive observation projects. Additionally, the possibility of on-site training to countries without existing NWP systems could be further explored.

The CCRS organising committee would like to extend our appreciation to the WRFDA team in NCAR’s Mesoscale and Microscale Meteorology Laboratory, who developed and maintain the system, and who provided the basic WRFDA tutorial presentations on which this Southeast Asian version has been developed.

Annex A: Plenary Session Word-Cloud Results

Observations for data assimilation

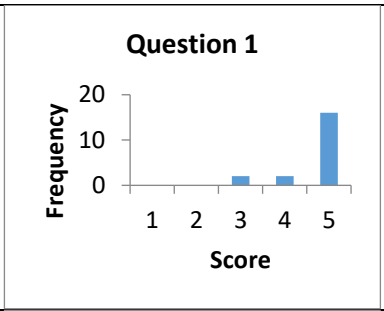
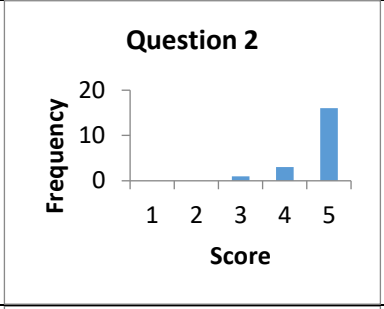
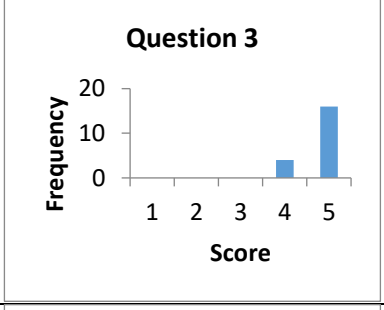
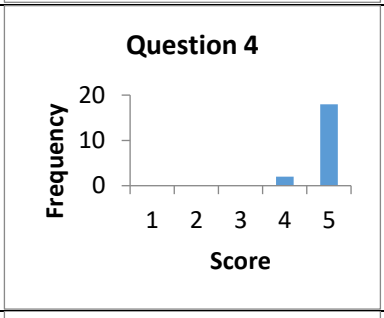
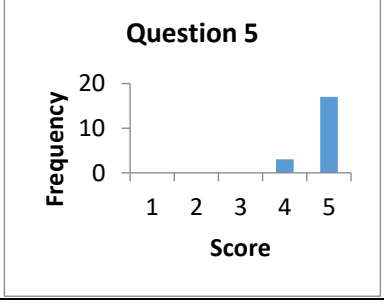


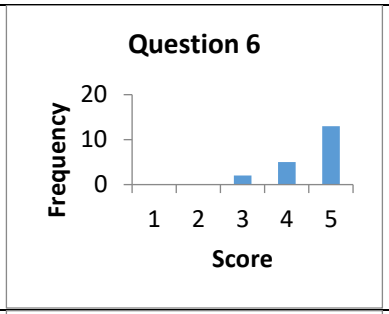
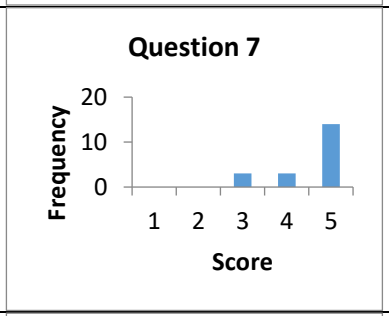
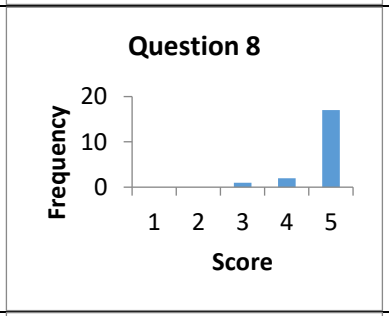
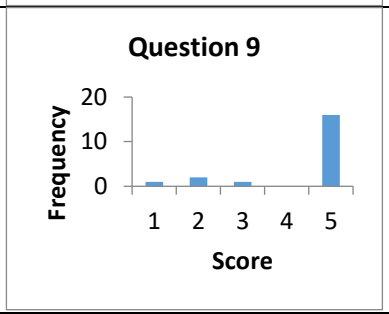
Data assimilation methods

Applications of data assimilation

Annex B: Feedback Survey Responses

The feedback survey was based on 20 responses to 9 questions, assessed with a score from 1 (strongly disagree) to 5 (strongly agree). The mean score and histogram of the responses are indicated below:

No.	Question	Mean score	Histogram of responses
1	The workshop helped me to better understand the mathematical conceptualisation of data assimilation methods.	4.70	
2	The workshop helped me to better understand the limitations of data assimilation methods.	4.75	
3	I feel better equipped with knowledge on data assimilation applications in weather and climate science.	4.80	
4	The lectures were interesting.	4.90	
5	The practical sessions were interesting.	4.85	

6	The lectures were easy to follow.	4.55	
7	The practical sessions were easy to follow.	4.55	
8	I would recommend this module to my colleagues.	4.80	
9	I would be interested to attend future modules.	4.40	

Annex C: WPNM-M3 Programme

Day 1: Monday, 6th February 2023 Chair: Joshua Lee Notetaker: Robert Huva		
Welcome and Introduction		
0800 – 0900	Registration	
0900 – 0915	Welcome address	Dale Barker
0915 – 0935	Workshop overview and objectives	Dale Barker
0935 – 1000	Administrative brief	Joshua Lee
1000 – 1030	Coffee break	
Fundamentals of Data Assimilation (DA)		
1030 – 1130	**Lecture 1:** Basic concepts of DA	Dale Barker
1130 – 1230	**Lecture 2:** Overview of DA methods	Dale Barker
1230 – 1400	Lunch	
Atmospheric Observations **Practical Session: A Bayesian Perspective**		
1400 – 1500	**Lecture 3:** The atmospheric observation network	Krishnamoorthy Chandramouli
1500 – 1530	Introduction to Python setup illustrating Bayes' theorem	Joshua Lee
1530 – 1600	Coffee break and group photo	
1600 – 1730	Hands-on practical session with Python setup and DA Q&A	CCRS facilitators
1730	End of Day 1	
1830	Welcome dinner @ The Landmark Restaurant	

Day 2: Tuesday, 7th February 2023 Chair: Joshua Lee Notetaker: Robert Huva		
Variational Methods **WRFDA Overview**		
0900 – 1000	**Lecture 4:** 3D-Var	Joshua Lee
1000 – 1030	Coffee break	
1030 – 1130	**Lecture 5:** 4D-Var	Joshua Lee
1130 – 1215	**Lecture 6:** WRFDA overview	Dale Barker
1215 – 1345	Lunch	
Practical Session: 3D-Var in WRFDA		
1345 – 1430	**Lecture 7:** 3D-Var in WRFDA and basic namelist settings	Dale Barker
1430 – 1530	Hands-on practical session using WRFDA: Practical Sheet 1	CCRS facilitators
1530 – 1600	Coffee break	
1600 – 1730	Hands-on practical session using WRFDA: Practical Sheet 1	CCRS facilitators
1730	End of Day 2	

Day 3: Wednesday, 8th February 2023 Chair: Chandramouli Krishnamoorthy Notetaker: Robert Huva		
Background Error Modelling **Practical Session: 3D-Var in WRFDA**		
0900 – 1000	**Lecture 8:** Background error modelling in NWP	Dale Barker
1000 – 1030	Coffee break	
1030 – 1230	Hands-on practical session using WRFDA: Practical Sheet 2	CCRS facilitators
1230 – 1400	Lunch	
Ensemble Methods **Hybrid Methods** **Practical Session: 3D-Var in WRFDA**		
1400 – 1445	**Lecture 9:** Ensemble Kalman Filters	Krishnamoorthy Chandramouli
1445 – 1530	**Lecture 10:** Hybrid DA	Joshua Lee
1530 – 1600	Coffee break	
1600 – 1730	Hands-on practical session using WRFDA: Practical Sheet 2	CCRS facilitators
1730	End of Day 3	

Day 4: Thursday, 9th February 2023 Chair: Chandramouli Krishnamoorthy Notetaker: Robert Huva		
DA Applications		
0900 – 1000	**Lecture 11:** MSS' SINGV-DA system	Joshua Lee
1000 – 1030	Coffee break	
1030 – 1130	**Lecture 12:** WRFDA applications	Dale Barker
1130 – 1230	**Lecture 13:** Reanalysis applications	Krishnamoorthy Chandramouli
1230 – 1400	Lunch	
Assessing Observation Impact Coupled DA		
1400 – 1445	**Lecture 14:** Assessing observation impact	Krishnamoorthy Chandramouli
1445 – 1530	**Lecture 15:** Coupled DA	Krishnamoorthy Chandramouli
1530 – 1600	Coffee break	
1600 – 1730	Hands-on practical session using WRFDA: Continuation of Practical Sheets 1 and 2	CCRS facilitators
1730	End of Day 4	

Day 5: Friday, 10th February 2023 Chair: Joshua Lee Notetaker: Robert Huva		
Machine Learning and DA Practical Session: 3D-Var in WRFDA		
0900 – 1000	**Lecture 16:** Machine learning and DA	Joshua Lee
1000 – 1030	Coffee break	
1030 – 1230	Hands-on practical session using WRFDA: Continuation of Practical Sheets 1 and 2	CCRS facilitators
1230 – 1400	Lunch	
Conclusion		
1400 – 1500	Plenary session: Recap of topics covered and learning consolidation activities	Joshua Lee
1500 – 1530	Coffee break	
1530 – 1600	Plenary session: Discussion of future DA efforts in the region	Dale Barker
1600 – 1615	Closing remarks and sharing of upcoming modules	Dale Barker
1615 – 1630	Feedback survey and certificate presentation	Joshua Lee
1630	End of Day 5	

Annex D: List of Participants and Organising Committee

Name		Organisation
Mr	Awang Mohamad Noor'Arifin bin Haji Awang Yussof	*Meteorological Officer* Brunei Darussalam Meteorological Department, Brunei
Ms	Chu Thi Huyen Trang	*Forecaster of Meteorology* Vietnam Meteorological and Hydrological Administration, Vietnam
Prof	Dale Barker	*Director* Centre for Climate Research Singapore, Singapore Organising Committee
Mr	Gabriel Miro	*Weather Specialist 1* Philippine Atmospheric, Geophysical and Astronomical Services Administration, Philippines
Ms	Joan Cher	*Assistant Manager* Meteorological Service Singapore, Singapore Organising Committee
Mr	Joshua Lee	*Research Scientist* Centre for Climate Research Singapore, Singapore Organising Committee
Dr	Krishnamoorthy Chandramouli	*Research Scientist* Centre for Climate Research Singapore, Singapore Organising Committee
Dr	Kuldeep Sharma	*Research Scientist* Meteorological Service Singapore, Singapore
Ms	Lai Maw Zan	*Staff Officer* Department of Meteorology and Hydrology, Myanmar
Mr	Michael Simora	*Weather Specialist 1* Philippine Atmospheric, Geophysical and Astronomical Services Administration, Philippines
Mr	Mohammad Affindi bin Haji Sabli	*Meteorological Officer* Brunei Darussalam Meteorological Department, Brunei

Mr	Nuthakit Singhaphet	*Meteorologist* Thai Meteorological Department, Thailand
Mr	Peeranat Longsombun	*Meteorologist* Thai Meteorological Department, Thailand
Mr	Phapasit Khamphoumy	*Meteorologist* Department of Meteorology and Hydrology, Lao PDR
Ms	Phetlasy Somchanmavong	*Technical Staff* Department of Meteorology and Hydrology, Lao PDR
Ms	Phung Thi Vui	*Forecaster of Meteorology* Vietnam Meteorological and Hydrological Administration, Vietnam
Dr	Robert Huva	*Research Scientist* Centre for Climate Research Singapore, Singapore Organising Committee
Mr	Sambath Phan	*Vice-Chief* Department of Meteorology, Cambodia
Mr	Sokhom Khoeun	*Vice-Chief* Department of Meteorology, Cambodia
Dr	Song Chen	*Research Scientist* Meteorological Service Singapore, Singapore
Ms	Wan Maisarah binti Wan Ibadullah	*Meteorological Officer* Malaysian Meteorological Department, Malaysia
Ms	Zureen Norhaizatul Che Hassan	*Meteorological Officer* Malaysian Meteorological Department, Malaysia