WEATHER PREDICTION BY NUMERICAL METHODS MODULE 1 (WPNM-M1)

WPNM-M1 REPORT

Table of Contents

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
BMKG	Badan Meteorologi, Klimatologi, dan Geofisika
CCRS	Centre for Climate Research Singapore
DA	Data assimilation
DCMIP	Dynamical Core Model Intercomparison Project
DMH	Department of Meteorology and Hydrology (Lao PDR/Myanmar)
DOM	Department of Meteorology (Cambodia)
ECMWF	European Centre for Medium-Range Weather Forecasts
GFS	Global Forecast System
MSS	Meteorological Service Singapore
NMHS	National Meteorological and Hydrological Services
NWP	Numerical weather prediction
PAGASA	Philippine Atmospheric, Geophysical and Astronomical Services Administration
SINGV	Singapore variable resolution model
SUSS	Singapore University of Social Sciences
TMD	Thai Meteorological Department
UM	Unified Model
VMHA	Viet Nam Meteorological and Hydrological Administration
WPNM	Weather Prediction by Numerical Methods
WRF	Weather Research and Forecasting

Introduction

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

During the 40th Meeting of the ASEAN Sub-Committee on Meteorology and Geophysics (ASCMG-40) held in May 2018, it was highlighted that capability building courses on NWP were much needed in the ASEAN region. The Meeting welcomed the offer from ASEAN Specialised Meteorological Centre (ASMC) to deliver such capability building courses on NWP. Weather Prediction by Numerical Methods (WPNM) was hence conceptualised as part of ASMC 5-year Regional Capability Building Programme for the ASEAN region.

Following an initial assessment of training needs in collaboration with respective ASEAN NMHS, a series of modules were designed to cover the basic aspects of NWP. The modules of WPNM 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. WPNM-M1 was hosted by the ASMC and organised by the Centre for Climate Research Singapore (CCRS). Sponsorship was provided by the Meteorological Service Singapore (MSS).

Focus was placed on the dynamical core component of NWP models; the aims of WPNM-M1 were as follows:

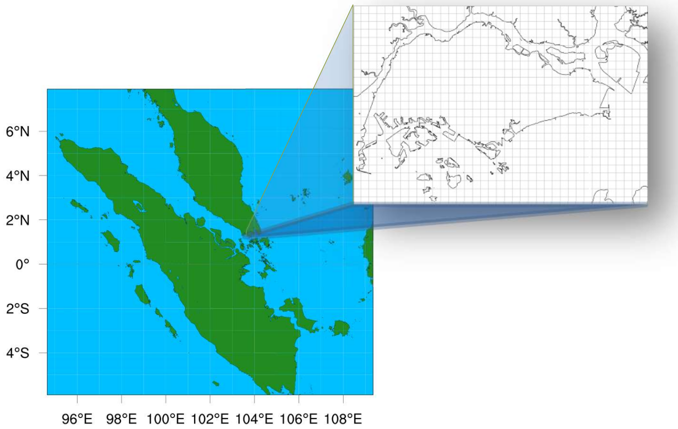
a) To equip participants with knowledge on the governing equations in NWP models;
b) To equip participants with knowledge on associated numerical methods and their limitations.
c) To allow participants to experiment with computer codes to obtain an in depth understanding of the concepts covered in the lectures.

1 Day 1: 18th November 2019, Monday

1.1 Welcome and Overview

The programme began with a welcome address delivered by Prof Erland Källén, thanking the participants from ASEAN NMHS for their attendance. He also shared about the conceptualisation of WPNM-M1, and introduced the overview and objectives of the training module. Mr Joshua Lee then performed an administrative briefing to ensure that the experience for the participants in Singapore was smooth and pleasant. To round up the welcome and overview, participants gave a short introduction about their role and the NWP setup used in their respective NMHS. Some participants were working directly on tuning the parameters for their NWP model; others were focused on analysing model outputs.

Dr Jeff Chun-Fung Lo presented an overview on NWP efforts in Singapore and the Unified Model (UM) partnership. He highlighted the latest developments in Singapore; in particular, the NWP model (SINGV) used at MSS. Participants were exposed to the intricacies of operational NWP, changes which led to improvements in SINGV forecast skill, and MSS' contribution to NWP efforts in the tropics. He further emphasised the importance of collaboration within the UM partnership, and further possibilities within the ASEAN region.



SINGV domain and setup; convective-scale NWP

1.2 Fundamentals of NWP

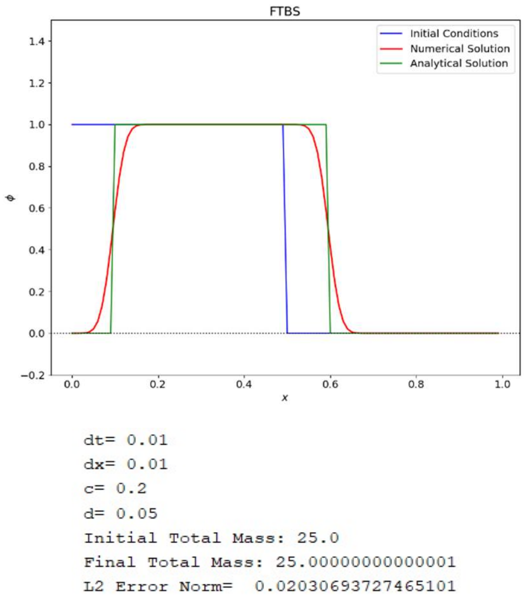
The afternoon kicked off the series of nine lectures. The first lecture was given by Prof Erland Källén, related to the fundamentals of NWP, entitled: "Navier-Stokes equations with the hydrostatic, anelastic and Boussinesq approximations". Participants were introduced to the mathematical equations which underpin NWP models. Prof Källén then discussed the concepts of conservation of mass, momentum and energy in NWP models and the observed atmosphere. He related various atmospheric phenomena with the components and associated balances in the equations. Questions were directed to the participants, to promote critical thinking and deepen their


Prof Erland Källén delivering the first lecture

understanding of these equations. He concluded by highlighting the relevance of the simplified models used during the hands-on practical sessions for illustrating important concepts in NWP.

1.3 Linear Advection Equation

Dr Peter Heng continued the lecture series with: "Linear advection equation, its discretisation in space and time". He presented on advection, an important component of the governing equations, and the mathematical analysis required for solving advection numerically. Participants were exposed to various numerical methods and schemes, applied to the linear advection equation. Both explicit and implicit were mentioned, each with their advantages and associated limitations. Starting from their discretisation in space and time, he demonstrated the stability conditions, or lack thereof, for various numerical schemes. He highlighted that these ideas were also applicable to NWP models.



Output from the 1-D linear advection model

The rest of the day was spent on a hands-on practical session with the 1-D linear advection model which was coded in-house by CCRS staff. Mr Joshua Lee introduced the framework for the model and the instructions to run it. The model outputs were explained together with the relevance of the simplified model to NWP. Participants were required to tweak the settings in the model and observe its effect on the output, following the instructions in a practical sheet designed to demonstrate key learning points. This allowed participants opportunities to bridge theory with praxis. Mr Joshua Lee, Dr Peter Heng and Dr Teo Chee Kiat were present to facilitate the hands-on practical session and answer further questions regarding the key learning points.

To round off the evening, a welcome dinner was hosted by MSS for the participants, held at the Malayan Council (Winsted Branch). This provided opportunities for further interaction between participants and lecturers.

Prof Erland Källén delivering the opening address during the welcome dinner

2 Day 2: 19th November 2019, Tuesday

2.1 Primitive Equations

The third and fourth lecture in the series were presented by Prof Koh Tieh Yong. The topics were: “Non-linear advection equation and conservation properties” and “Primitive equations” respectively. These were related to previous topics, with further complexities introduced systematically. In the third lecture, he presented on the 1-D non-linear advection equation, followed by the 1-D shallow water equations, and finally the concept of 2-D non-divergent flow. Participants were provided with mathematical derivations and proofs of the conservation properties inherent to the equations. For the fourth lecture, Prof Koh further developed the concepts of conservation to outline the 2-D shallow water equations and highlighted their similarities to the primitive equations – the set of equations solved numerically in NWP models.

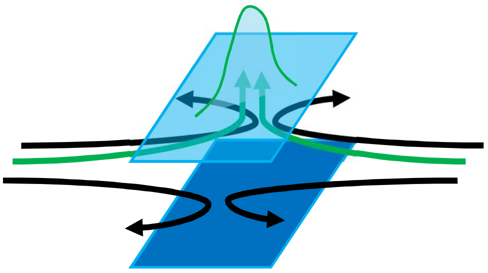
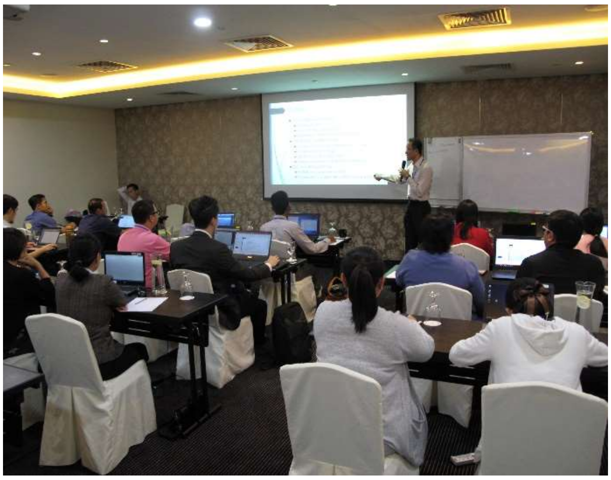


Illustration of the solution for the 2-D shallow water equations



Prof Koh Tieh Yong delivering the third lecture

2.2 Selecting Grids

Dr Teo Chee Kiat lectured on “Selecting horizontal and vertical grids, staggered grids and vertical discretisation”. He focused mainly on the derivation of the linearised 1-D shallow water equations and the advantages of solving them on a staggered grid compared to an unstaggered grid. As an extension, the linearised 2-D shallow water equations was also used to illustrate the various grid staggering options in two dimensions. Dr Teo then briefly introduced some options for vertical grid staggering. To conclude, a few examples of grid staggering in NWP models were cited to relate theory with operational implementation. The horizontal and vertical grid staggering implementation in the UM was chosen as an illustration. Mr Joshua Lee also highlighted the grid staggering option that was used by the Weather Research

Dr Teo Chee Kiat delivering the fifth lecture and Forecasting (WRF) model, which is the choice of limited area NWP model set up by most of the participating countries.

2.3 Semi-Lagrangian Methods

In the afternoon, Mr Joshua Lee delivered the sixth lecture of the series: “Semi-Lagrangian methods”. The lecture was aimed at providing participants with an understanding of the classical semi-Lagrangian method used in NWP models, appreciate its complexities, and explore its advantages and disadvantages compared to other numerical methods. Mr Lee provided illustrations of the differences between Eulerian and Lagrangian frames of reference for describing fluid flow and the formulation of the classical semi-Lagrangian method. Other practical considerations such as the lack of conservation of mass and non-monotonicity of higher order interpolation methods were also mentioned. In particular, he described the methods which operational centres such as the European Centre for Medium-range Weather Forecasts (ECMWF) use in their formulation of the semi-Lagrangian method to address these limitations.

Mr Joshua Lee delivering the sixth lecture

The participants were allowed the rest of the afternoon to complete the practical sheets, which covered the relevant concepts related to semi-Lagrangian methods. Participants who had completed the basic questions in the practical sheets were challenged with more difficult tasks, such as the mathematical derivation of other numerical schemes which were not covered in the lectures. Mr Joshua Lee, Dr Peter Heng and Dr Teo Chee Kiat were present to facilitate the hands-on practical session.

Dr Peter Heng guiding Mr Wuttisak Ratinonsakul and Mr Theerachai Auttachaipanit during the hands-on practical session

3 Day 3: 20th November 2019, Wednesday

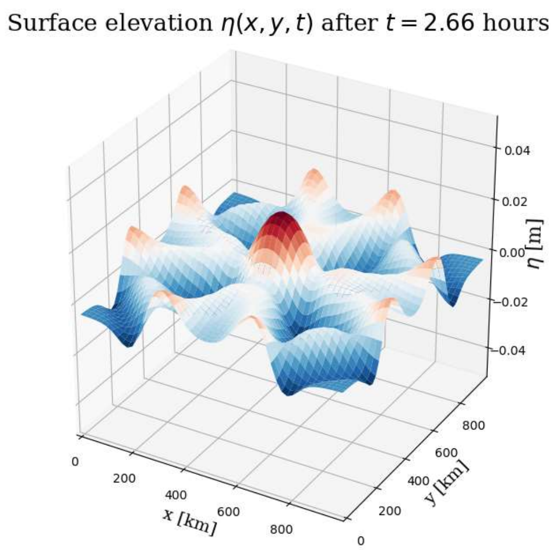
3.1 Semi-Implicit Methods

Dr Anurag Dipankar delivered the seventh lecture on "Semi-implicit time-stepping and elliptic solvers". Alluding to previous lectures on stability conditions of numerical schemes, he described the need for special treatment of certain components in the primitive equations to improve numerical stability in NWP models. This naturally led to the introduction of semi-implicit methods. Starting with the framework for the 1-D linear advection model, he demonstrated the limitations of the semi-implicit methods compared to explicit methods. He then described their advantages using the framework for a 1-D shallow water model, showing the differences between numerical solutions using explicit, implicit and semi-implicit methods. To provide participants with a grasp of the mathematics underpinning semi-implicit methods, Dr Dipankar included details on the classical elliptic solvers used and their derivation. He also related these to some NWP models which use semi-implicit methods.

Dr Anurag Dipankar delivering the seventh lecture

3.2 Practical Session Focus 1

To further illustrate the concepts highlighted during the lectures, the 2-D linear shallow water model was introduced to the participants. This was also coded in-house by CCRS staff, tailored specifically to highlight other key learning points not covered using the 1-D linear advection model. Mr Joshua Lee gave a short recap of the concepts covered during the first, fourth and fifth lecture which formed the mathematical basis for the 2-D linear shallow water model, along with its relevance to NWP models. Mr Lee then described the various switches and parameters used to run the model, along with its outputs. One of the key outputs of the model was a 3-D animation of the



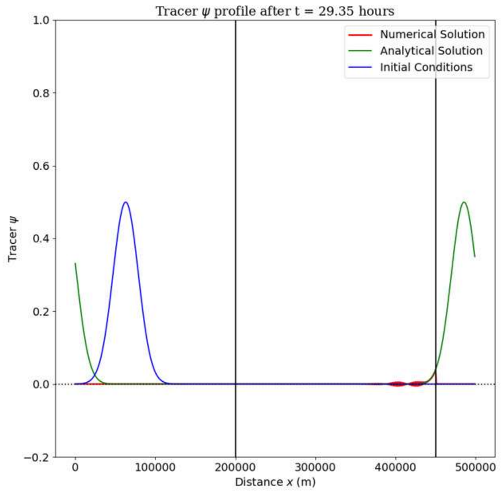
Snapshot of the 3-D animation output from the 2-D linear shallow water model simulation, which was essential for the participants to visualise the effect of changing the parameters and switches. Guiding instructions were also provided in a second practical sheet to setup the experiments required for effective learning. Half a day was allocated for the hands-on practical session focus to allow participants to sufficiently explore both the 1-D linear advection and 2-D linear shallow water models. Mr Joshua Lee, Dr Peter Heng and Dr Teo Chee Kiat were present to facilitate the hands-on practical session.

Dr Teo Chee Kiat guiding Ms Somsanouk Vanhlakhalack and Ms Khaemeuy Chao during the hands-on practical session

4 Day 4: 21st November 2019, Thursday

4.1 Boundary Conditions in Limited Area Models

Dr Hans Huang continued the lecture series with the eighth lecture: “Treatment of boundary conditions in limited area models”. A nested version of the 1-D linear advection model was coded to illustrate the concepts in this lecture. Various methods to prescribe the lateral boundary conditions were presented, along with their mathematical formulation. Using animations output from the 1-D linear advection model, Dr Huang demonstrated the ill-posed problem of over-specification of the lateral boundary conditions, regardless of the method to prescribe them. He further described different methods to address this issue. In particular, he showed the derivation of the most popular method currently used in all limited area NWP models, and demonstrated the benefit when applying it to previous experiments using the nested 1-D linear advection model. Many of the participants were able to appreciate the relevance of this lecture to their respective operational NWP model setup using WRF. Dr Huang also showed some results from SINGV to emphasise the importance of the lateral boundary conditions on limited area models and its effect on the forecast performance. Participants commented that they were considering exploring various global NWP model options to drive their limited area NWP model, in hope of improving its forecasts.



Snapshot of the animation output from the nested 1-D linear advection model

4.2 Dynamical Core Model Intercomparison Project

The relevance of some of the methods described in previous lectures to operational NWP models were explained by Dr Anurag Dipankar. He referenced Ullrich et al. (2017) on

Short name	Long name	Modeling center or group
ACME-A	Atmosphere model of the Accelerated Climate Model for Energy	Sandia National Laboratories and University of Colorado, Boulder, USA
CSU	Colorado State University Model	Colorado State University, USA
DYNAMICO	DYNAMical core on the ICOsahedron	Institut Pierre Simon Laplace (IPSL), France
FV^3	GFDL Finite-Volume Cubed-Sphere Dynamical Core	Geophysical Fluid Dynamics Laboratory, USA
FVM	Finite Volume Module of the Integrated Forecasting System	European Centre for Medium-Range Weather Forecasts
GEM	Global Environmental Multiscale model	Environment and Climate Change Canada, Canada
ICON	ICOsahedral Non-hydrostatic model	Max-Planck-Institut für Meteorologie, Germany
MPAS	Model for Prediction Across Scales	National Center for Atmospheric Research, USA
NICAM	Non-hydrostatic Icosahedral Atmospheric Model	AORI/JAMSTEC/AICS, Japan
OLAM	Ocean Land Atmosphere Model	Duke University/University of Miami, USA
Tempest	Tempest Non-hydrostatic Atmospheric Model	University of California, Davis, USA

Summary table of models involved in DCMIP, taken from Ullrich et al. (2017) and presented by Dr Anurag Dipankar the Dynamical Core Model Intercomparison Project (DCMIP), a review of the non-hydrostatic dynamical core design in 11 different global NWP models. Using the summary tables from Ullrich et al. (2017), Dr Dipankar compared the different grid choices, staggering and temporal discretisation implemented in different global NWP models. Some of the methods had been highlighted in the lectures. Dr Dipankar then discussed the general direction of the community in the design and development of future NWP models. These were aimed at providing participants with exposure to global efforts in the development of NWP models and the applicability of numerical methods taught to operational NWP models.

4.3 Practical Session Focus 2

The remaining half a day was allocated for a second hands-on practical session focus to allow participants to sufficiently explore both the 1-D linear advection and 2-D linear shallow water models. Instructions for further experiments to illustrate key learning points from the eighth lecture were the focus of the afternoon. Many participants took the opportunity to clarify their experimental results from the previous hands-on practical sessions. Participants who had completed most of the experiments were further challenged with difficult tasks related to the 2-D linear shallow water model, such as coding new initial conditions to initialise the model and investigating the ability of the model to simulate atmospheric phenomena. To consolidate the intended key learning pointers from the previous hands-on practical sessions, Mr Joshua Lee showed a demonstration of some of the experiments in the first practical sheet and discussed the results. Dr Peter Heng and Dr Teo Chee Kiat were also present to facilitate the hands-on practical session.

5 Day 5: 22nd November 2019, Friday

5.1 Spectral Methods

Prof Erland Källén delivering the ninth lecture

The ninth and final lecture in the lecture series on "Spectral Methods" was delivered by Prof Erland Källén. This was designed to expose participants to other methods more commonly used in global NWP models instead of limited area NWP models. Prof Källén presented a brief derivation of the transforms on a sphere required to apply spectral methods. He emphasised the benefits of the spectral methods associated with computing derivatives of variables but also commented on the limitations of the spectral methods related to the necessary truncation of the spectrum. Examples of global NWP models that use spectral methods were cited, together with the qualitative procedure for performing the spectral method with the semi-Lagrangian and semi-implicit methods described in previous lectures. Many of the participants use the ECMWF or Global Forecast System (GFS) NWP models to prescribe the boundary conditions for their limited area NWP model at their respective NMHS. Both of these global NWP models use spectral methods, so this lecture was directly relevant to them.

5.2 Peer-learning and Summary Session

Dr Tin Mar Htay sharing her experimental results and key takeaways

In the afternoon, the key learning points were consolidated and summarised through a peer-learning session and a plenary summary session to identify the main ideas which were most prominent for the participants throughout WPNM-M1. For the peer-learning session, some of the participants presented on their experimental results during the practical. Dr Tin Mar Htay from the Department of Meteorology and Hydrology (Myanmar) presented some of her results and key takeaways from the hands-on practical sessions. Mr Gabriel Miro from the Philippine Atmospheric, Geophysical and Astronomical Services Administration presented some of his results using the 2-D linear shallow water model with new initial conditions that he coded in the model. He also commented on the similarity of the numerical solutions with certain atmospheric phenomena.

Mr Joshua Lee concluded the lectures and practical sessions with a plenary summary session of WPNM-M1. He started with a recap of the key learning points from the nine lectures and their relevance to NWP models. He then conducted a collaborative "word-cloud" activity, where participants were expected to recall concepts related to a given key word based on the objectives of WPNM-M1. The key words were: Governing equations and approximations; numerical methods; and key considerations and desirable properties. The results of the activity are shown in Annex A.

5.3 Current and Future NWP Efforts in ASEAN

Information on the current NWP setup at each ASEAN NMHS was collated during WPNM-M1. This is summarised in the table below:

Country	Limited Area Model	Global Driving Model	Domain	Horizontal resolution	Forecast length	Manpower
Indonesia	WRF	GFS	1. Indonesia 2. Java 3. Jakarta	- 9km - 3km - 1km	- 3 days	5-6
Myanmar	WRF	GFS	1. Myanmar	- 30km - 9km	- 10 days - 3 days	5
Philippines	WRF	GFS	1. Philippines and South China Sea 2. Philippines Archipelago	- 12km - 3km	- 6 days - 2 days	6
Singapore	UM (SINGV)	ECMWF	1. Sumatra, Peninsula Malaysia and Singapore	- 1.5km	- 2 days	6
Thailand	WRF	GFS	1. Asia 2. South-east Asia 3. Thailand	- 18km - 6km - 2km	- 10 days - 3 days - 3 days	6
Viet Nam	WRF	ECMWF	1. Viet Nam	- 3km	- 3 days	20
Brunei			No NWP setup, but in planning			
Cambodia Lao PDR			No NWP setup			

Summary table of current NWP efforts in ASEAN NMHS

It was necessary to assess the current NWP efforts and status in ASEAN before proceeding to discuss future efforts. Prof Erland Källén closed the training module with a plenary session on future NWP efforts in ASEAN. Some of the countries had plans for future NWP development. Participants from Brunei indicated that they had plans for setting up an NWP system. Participants from Indonesia mentioned that they had started incorporating data assimilation (DA) into their NWP system, while participants from Myanmar indicated that they were planning to set up WRF-DA. Participants from Thailand were particularly keen on testing various changes to their namelist parameters in their NWP setup by following some of the other NWP setups in ASEAN NMHS. Prof Källén highlighted the importance of collaboration, especially through sharing of observation data for the success of data assimilation. He also shared the background and history of ECMWF as an example and that effective collaboration was a key pillar of its success. He surmised if ASEAN could follow suit. A proposal was made to consolidate the current NWP efforts in ASEAN in a peer-reviewed paper, so that opportunities for future collaboration and NWP efforts can be identified.

WPNM-M1 Feedback and Outcomes

Overall, the training module was well-received by participants. From the feedback survey responses (Annex B), participants had indicated that the training module had achieved its objectives; it has helped them to understand the conceptualisation, formulation and limitations of NWP models. They also indicated that they felt better equipped with the knowledge on the governing equations in NWP models, and the knowledge on associated numerical methods and their limitations.

Most participants found the lectures and hands-on practical sessions interesting. Some suggested providing reading and refresher materials prior to the training module, references for further reading, and an extension of the duration of the training module to make it less compact. Participants strongly supported the continuation of the remaining three training modules of WPNM and a possible repeat run of WPNM-M1.

Following the positive feedback, CCRS will be planning the following training modules in the near future:

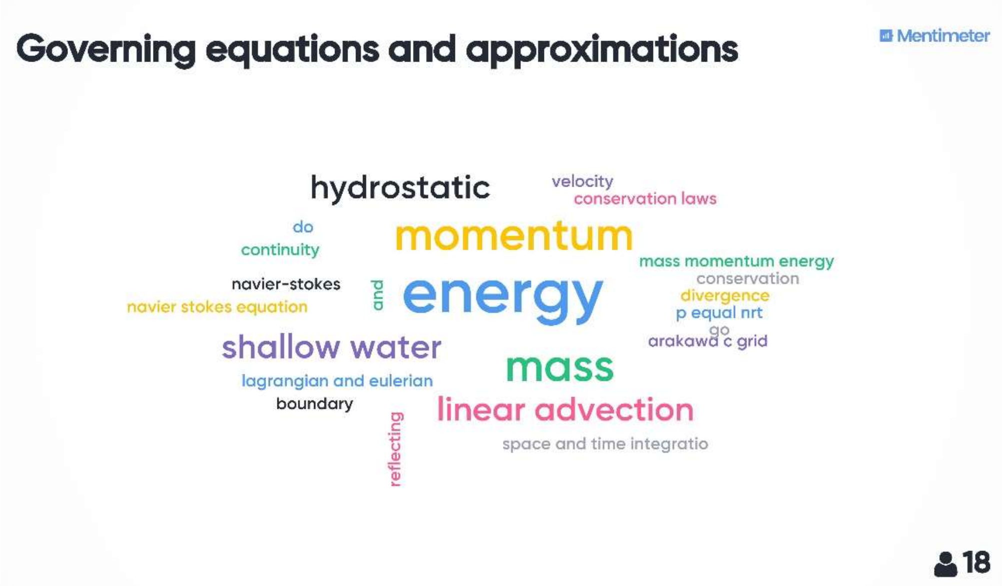
- WPNM-M2 on physical parametrisations
- WPNM-M3 on data assimilation

In the closing plenary session, it was highlighted that current literature on NWP efforts in ASEAN is sparse and limited. WPNM-M1 provided a platform for the sharing of current NWP efforts in the region. It is hence highly recommended that a peer-reviewed paper consolidating the current NWP efforts in ASEAN be published. This will both raise the international profile of the region, and highlight potential opportunities for future collaboration and NWP efforts. The paper will be led by researchers from CCRS, with contributions by all ASEAN NMHS in attendance.

References

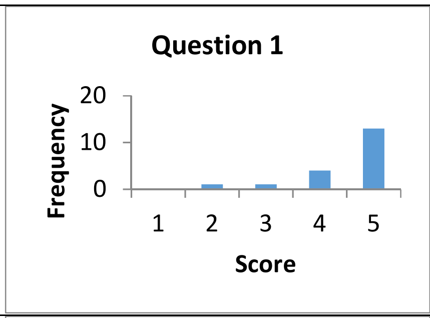
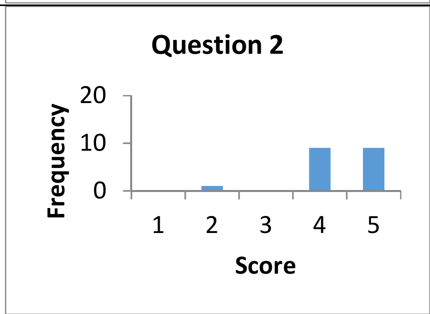
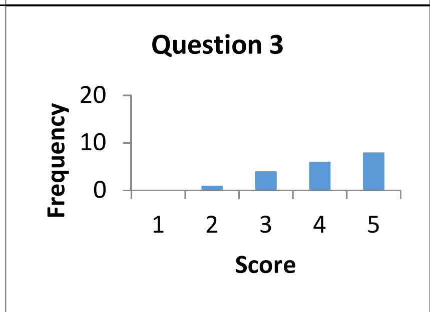
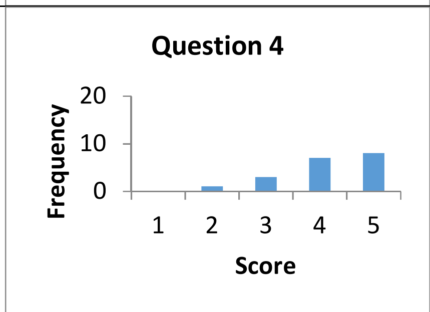
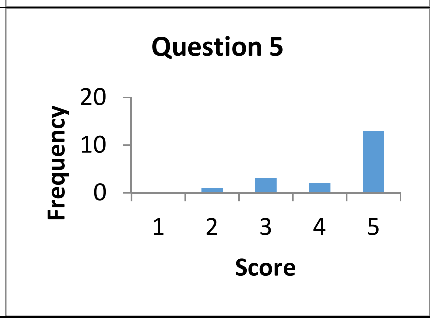
Ullrich, P.A., Jablonowski, C., Kent, J., Lauritzen, P.H., Nair, R., Reed, K.A., Zarzycki, C.M., Hall, D.M., Dazlich, D., Heikes, R. and Konor, C., 2017. DCMIP2016: a review of non-hydrostatic dynamical core design and intercomparison of participating models. *Geoscientific Model Development*, *10*, pp.4477-4509, doi:10.5194/gmd-10-4477-2017.

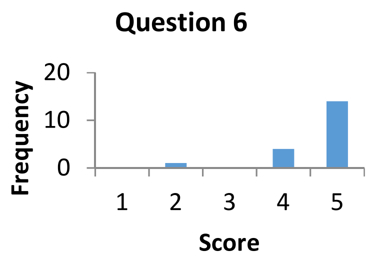
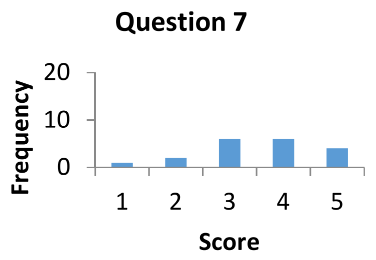
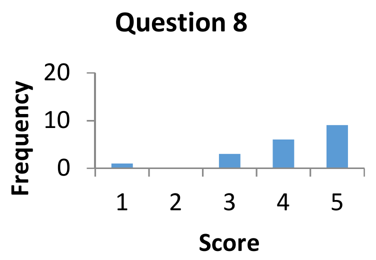
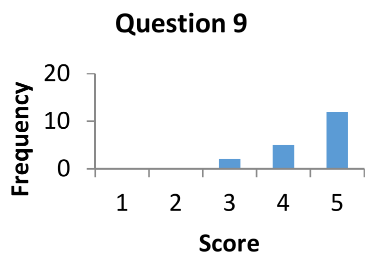
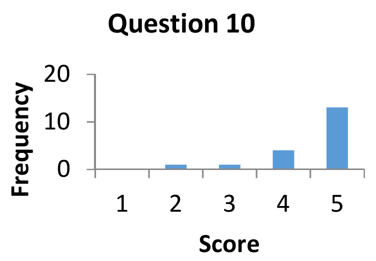
Annex A: Summary Session Word-Cloud Results



Annex B: Feedback Survey Responses

The feedback survey was based on 19 responses to 10 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 module helped me to better understand the conceptualisation of numerical weather prediction models.	4.53	
2	The module helped me to better understand the limitations of numerical weather prediction models.	4.37	
3	I feel better equipped with knowledge on the governing equations in weather prediction models.	4.11	
4	I feel better equipped with the knowledge on numerical methods and their limitations for applications to numerical weather prediction.	4.16	
5	The lectures were interesting.	4.42	

6	The practical sessions were interesting.	4.63	
7	The lectures were easy to follow.	3.53	
8	The practical sessions were easy to follow.	4.16	
9	I would recommend this module to my colleagues.	4.53	
10	I would be interested to attend future modules.	4.47	

Annex C: WPNM-M1 Programme

Day 1: Monday, 18th November 2019		**Chair: Mr Joshua Lee**
Welcome and Introduction		
0800 – 0900	Registration	
0900 – 0915	Welcome address	Prof Erland Kallen
0915 – 0935	Workshop overview and objectives	Prof Erland Kallen
0935 – 0950	Administrative brief	Mr Joshua Lee
0950 – 1000	Group photo	Mr Joshua Lee
1000 – 1030	Coffee break	
1030 – 1115	NWP efforts in Singapore and the UM partnership	Dr Jeff Chun-Fung Lo
Fundamentals of NWP		
1115 – 1215	**Lecture 1:** Navier-Stokes equations with the hydrostatic, anelastic and Boussinesq approximations	Prof Erland Kallen
1215 – 1330	Lunch (distribution of per diem)	
Linear Advection Equation		
1330 – 1530	**Lecture 2:** Linear advection equation, its discretisation in space and time	Dr Peter Heng
1530 – 1600	Coffee break	
1600 – 1615	Introduction to the 1-D linear advection model	Mr Joshua Lee
1615 – 1730	Hands-on practical session with 1-D linear advection model	CCRS facilitators
1730	End of Day 1	
1830	Welcome dinner @ The Malayan Council	

Day 2: Tuesday, 19th November 2019		**Chair: Dr Teo Chee Kiat**
Non-linear Advection Equation Primitive Equations Selecting Horizontal and Vertical Grids		
0900 – 1000	**Lecture 3:** Non-linear advection equation and conservation properties	Prof Koh Tieh Yong
1000 – 1030	Coffee break	
1030 – 1130	**Lecture 4:** Primitive equations	Prof Koh Tieh Yong
1130 – 1230	**Lecture 5:** Selecting horizontal and vertical grids, staggered grids and vertical discretisation	Dr Teo Chee Kiat
1230 – 1330	Lunch	
Semi-Lagrangian Methods		
1330 – 1430	**Lecture 6:** Semi-Lagrangian methods	Mr Joshua Lee
1430 – 1530	Hands-on practical session with 1-D linear advection model	CCRS facilitators
1530 – 1600	Coffee break	
1600 – 1730	Hands-on practical session with 1-D linear advection model	CCRS facilitators
1730	End of Day 2	

Day 3: Wednesday, 20th November 2019		**Chair: Dr Peter Heng**
Semi-implicit Time-stepping		
0900 – 1000	**Lecture 7:** Semi-implicit time-stepping and elliptic solvers	Dr Anurag Dipankar
1000 – 1030	Coffee break	
1030 – 1130	**Lecture 7 (cont):** Semi-implicit time-stepping and elliptic solvers	Dr Anurag Dipankar
1130 – 1230	Hands-on practical session with 1-D linear advection model	CCRS facilitators
1230 – 1330	Lunch	
Practical Session Focus		
1330 – 1400	Introduction to the 2-D shallow water model	Mr Joshua Lee
1400 – 1530	Hands-on practical session with 2-D shallow water model	CCRS facilitators
1530 – 1600	Coffee break	
1600 – 1730	Hands-on practical session with 2-D shallow water model	CCRS facilitators
1730	End of Day 3	

Day 4: Thursday, 21st November 2019 Chair: Dr Peter Heng		
Treatment of Boundary Conditions in Limited Area Models		
0900 – 1000	**Lecture 8:** Treatment of boundary conditions in limited area models	Dr Hans Huang
1000 – 1030	Coffee break	
1030 – 1130	**Lecture 8 (cont):** Treatment of boundary conditions in limited area models	Dr Hans Huang
1130 – 1230	Hands-on practical session with 1-D linear advection and 2-D shallow water models	CCRS facilitators
1230 – 1330	Lunch	
Practical Session Focus		
1330 – 1530	Hands-on practical session with 1-D linear advection and 2-D shallow water models	CCRS facilitators
1530 – 1600	Coffee break	
1600 – 1730	Hands-on practical session with 1-D linear advection and 2-D shallow water models	CCRS facilitators
1730	End of Day 4	

Day 5: Friday, 22nd November 2019 Chair: Mr Joshua Lee		
Spectral Methods		
0900 – 1000	**Lecture 9:** Spectral methods	Prof Erland Kallen
1000 – 1030	Coffee break	
1030 – 1130	**Lecture 9 (cont):** Spectral methods	Prof Erland Kallen
1130 – 1230	Hands-on practical session with 1-D linear advection and 2-D shallow water models	CCRS facilitators
1230 – 1330	Lunch	
Conclusion		
1330 – 1430	Breakout session: Peer-learning through discussion of answers to practical sheet questions	CCRS facilitators
1430 – 1500	Plenary session: Recap of topics covered and relevance to NWP models	Mr Joshua Lee
1500 – 1530	Coffee break	
1530 – 1600	Plenary session: Discussion of future NWP efforts in the region	Prof Erland Kallen
1600 – 1615	Closing remarks and sharing of upcoming modules	Prof Erland Kallen
1615 – 1630	Feedback survey and certificate presentation	Mr Joshua Lee
1630	End of Day 5	

Annex D: List of Participants

Name		Organisation	Contact Details
Mr	Alfan Sukmana Praja	*Junior Researcher* Badan Meteorologi, Klimatologi, dan Geofisika (BMKG), Indonesia	alfan.sukmana@gmail.com
Dr	Anurag Dipankar	*Senior Research Scientist* Centre for Climate Research Singapore (CCRS), Singapore	anurag_dipankar@nea.gov.sg
Ms	Chaw Su Hlaing	*Staff Officer* Department of Meteorology and Hydrology (DMH), Myanmar	chawsuhlaing.dmh@gmail.com
Prof	Erland Källén	*Director* Centre for Climate Research Singapore (CCRS), Singapore	erland_kallen@nea.gov.sg
Mr	Gabriel Miro	*Weather Specialist 1* Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA), Philippines	gabriel.miro@pagasa.dost.gov.ph
Mr	Gerald Lim	*Research Officer* Centre for Climate Research Singapore (CCRS), Singapore	gerald_lim@nea.gov.sg
Dr	Hans Huang	*Senior Principal Research Scientist* Centre for Climate Research Singapore (CCRS), Singapore	hans_huang@nea.gov.sg
Ms	Hazlita Sulaiman	*Senior Officer* Centre for Climate Research Singapore (CCRS), Singapore	hazlita_sulaiman@nea.gov.sg

Ms	Heinritz Majella Miguel	*Weather Specialist 1* Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA), Philippines	heinritzms.miguel@gmail.com
Dr	Jeff Chun-Fung Lo	*Senior Research Scientist* Centre for Climate Research Singapore (CCRS), Singapore	jeff_lo@nea.gov.sg
Mr	Jing Ngei Yip	*Meteorologist* Meteorological Service Singapore (MSS), Singapore	yip_jing_ngei@nea.gov.sg
Mr	Joshua Lee	*Research Officer* Centre for Climate Research Singapore (CCRS), Singapore	joshua_lee@nea.gov.sg
Ms	Khaemeuy Chao	*Technical Staff on Meteorologist* Department of Meteorology and Hydrology (DMH), Lao PDR	khaemeuy@gmail.com
Prof	Koh Tieh Yong	*Associate Professor* Singapore University of Social Sciences (SUSS), Singapore	tykoh@suss.edu.sg
Mr	Mohammad Affindi bin Haji Sabli	*Meteorological Officer* Brunei Darussalam Meteorological Department (BDMD), Brunei	affindi.sabli@met.gov.bn
Mr	Monichoth Soim	*Deputy Director* Department of Meteorology (DOM), Cambodia	monichoth@gmail.com

Mrs	Nga Thi Nguyen	*Forecaster* Viet Nam Meteorological and Hydrological Administration (VMHA), Viet Nam	nganguyenhp87@gmail.com
Mr	Nrak Lonh	*Government Official* Department of Meteorology (DOM), Cambodia	lonhnrak.cs@gmail.com
Mr	Nurdeka Hidayanto	*Junior Climate Forecaster* Badan Meteorologi, Klimatologi, dan Geofisika (BMKG), Indonesia	nurdeka.hidayanto@bmkg.go.id
Dr	Peter Heng	*Senior Research Scientist* Centre for Climate Research Singapore (CCRS), Singapore	peter_heng@nea.gov.sg
Mr	Satry Nugraha bin Abd Razak	*Officer-in-charge of Health, Safety, Security and Environment* Brunei Darussalam Meteorological Department (BDMD), Brunei	nugraha.razak@met.gov.bn
Ms	Somsanouk Vanhlakhalack	*Technical Staff on Meteorologist* Department of Meteorology and Hydrology (DMH), Lao PDR	sn_nouk@yahoo.com
Mrs	Tam Thi Nhuy Nguyen	*Forecaster* Viet Nam Meteorological and Hydrological Administration (VMHA), Viet Nam	nhuytamkttv@gmail.com
Dr	Teo Chee Kiat	*Senior Research Scientist* Centre for Climate Research Singapore (CCRS), Singapore	teo_chee_kiat@nea.gov.sg

Mr	Theerachai Auttachaipanit	*Meteorologist* Thai Meteorological Department (TMD), Thailand	theerachai3@hotmail.com
Dr	Tin Mar Htay	*Assistant Director* Department of Meteorology and Hydrology (DMH), Myanmar	tmarhtay@gmail.com
Mr	Wuttisak Ratinonsakul	*Meteorologist* Thai Meteorological Department (TMD), Thailand	wuttisak.ra@gmail.com