WEATHER PREDICTION BY NUMERICAL METHODS MODULE 2 (WPNM-M2)

Meeting Report

3 — 5 May 2021, Virtual

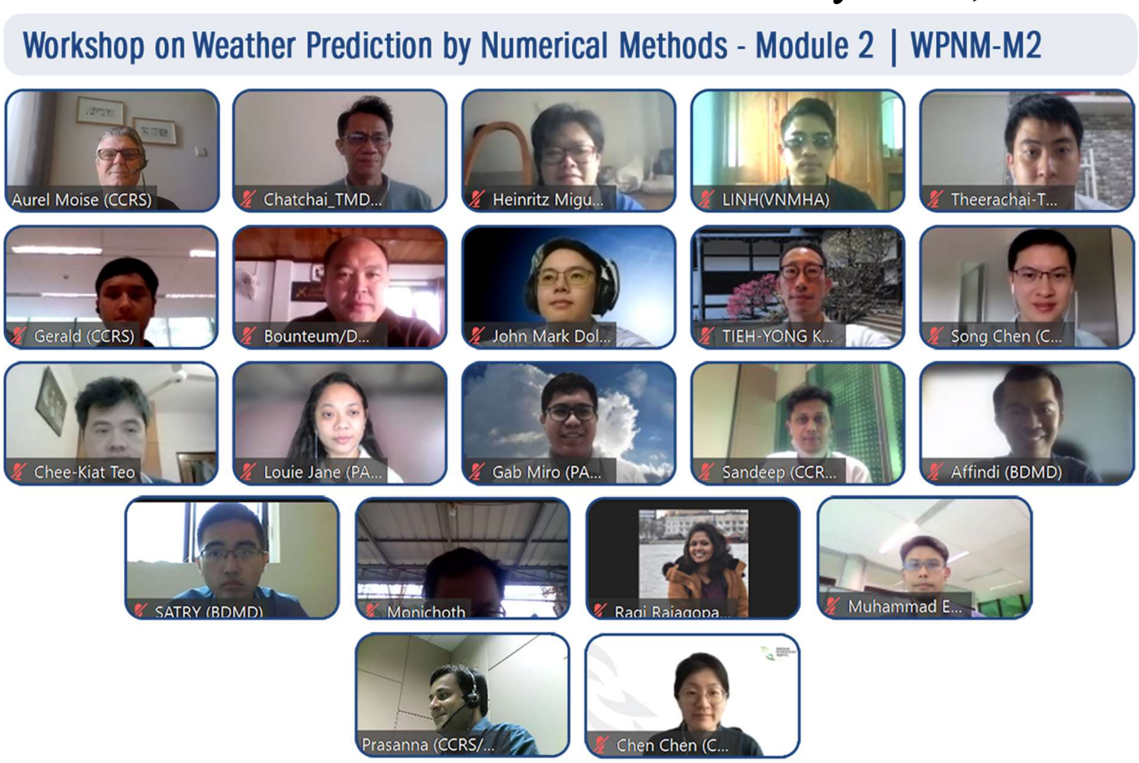


Table of Contents

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
CCRS	Centre for Climate Research Singapore
DMH	Department of Meteorology and Hydrology, Myanmar
DOM	Department of Meteorology, Cambodia
MetMalaysia	Malaysia Meteorological Department
MSS	Meteorological Service Singapore
NMHS	National Meteorological and Hydrological Services
NWP	Numerical weather prediction
PAGASA	Philippine Atmospheric, Geophysical, and Astronomical Services Administration
SUSS	Singapore University of Social Sciences
TMD	Thai Meteorological Department
UKM	National University of Malaysia
UKMO	Meteorological Office (United Kingdom)
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) model is widely used by National Meteorological and Hydrological Services (NMHSs) to deliver accurate and timely weather predictions. Outputs from global and regional NWP models are often used for nowcasting, short-range, medium-range and sub-seasonal through 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' construction, design and limitations.

While there have been recent developments in NWP capability in the ASEAN region, capability building courses on NWP are still much needed. ASEAN Specialised Meteorological Centre (ASMC) had proposed at the 40^{th} 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. Weather Prediction by Numerical Methods (WPNM) was conceptualised as part of ASMC 5-year Regional Capability Building Programme for the ASEAN region.

An initial assessment of the training needs was performed in collaboration with NMHSs through a questionnaire. The following proposed modules of WPNM are designed to cover the basic aspects of NWP:

(a) Governing equations and numerical methods;
(b) Physical parameterizations;
(c) Data assimilation; and
(d) Predictability

Feedback gathered from the participants during the inaugural run of the first module was very Positive, hence it was decided to roll out the remaining modules on an annual basis. In this workshop, the module-2 of the WPNM the second topic "Physical parameterizations" are covered.

1 Day 1: 3 May 2021

Welcome and Introduction

1.1 **Prof Dale Barker, Director of CCRS, Singapore,** delivered the welcome address, thanking all ASEAN NMHS Participants for their attendance and the all lecturers for their continued support of the WPNM series and wished a successful workshop.

1.2 **Dr Aurel Moise, CCRS, Singapore,** highlighted the objectives of the workshop as part of ASMC 5-year regional capability building program for the ASEAN region, and gave an overview for all the lectures. He mentioned that the first module of WPNM (WPNM-M1) covered basic aspects of NWP like governing equations and numerical methods. The present module (WPNM-M2) is aimed to train the participants to understand the physical parameterizations of NWP and climate models.

1.3 **Dr Venkatraman Prasanna, CCRS, Singapore,** as a workshop organiser, introduced the hosts and highlighted invited lecturers for Day 1. He also gave general guidelines for the participants and started the workshop with a group Photo.

Lectures on Day 1

1.4 Lecture 1: Radiative transfer Theory and its implementation in the model, shortwave radiative

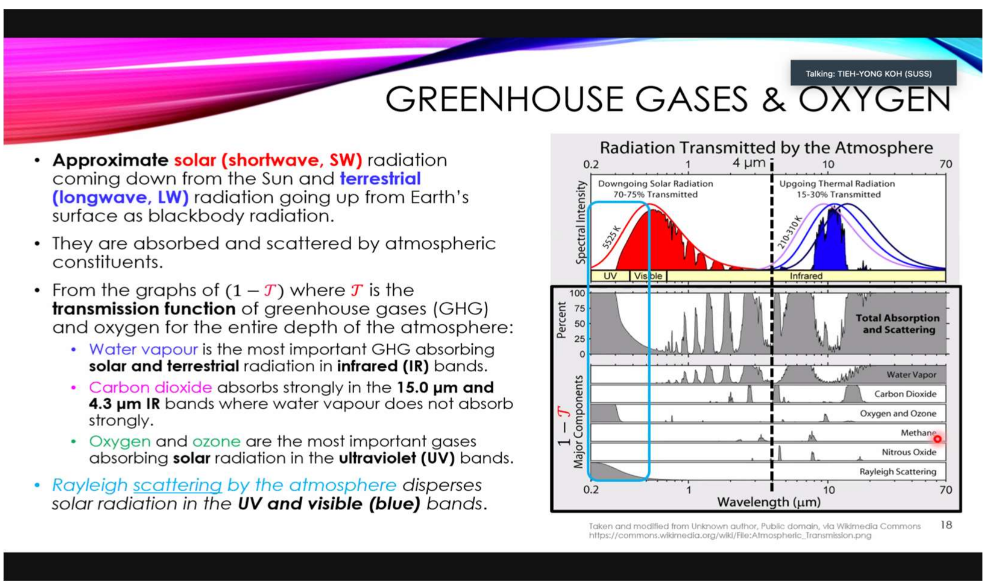
Prof Koh Tieh Yong started with the outline of his lecture, and with basic concepts like the atmospheric structure. He spent time to explain details for four sections including blackbody radiation, atmospheric absorption, radiative transfer theory, and atmospheric scattering. He ended the lecture by giving several examples of radiation calculation used in numerical models.

In the first section, Prof Koh introduced a series of basic concepts:

1. The atmospheric layers, cooling and heating of the atmosphere, longwave radiation, shortwave radiation.
2. Three types of molecular processes including spontaneous emission, absorption, scattering. The concept of extinction at the cross-section due to absorption and scattering.
3. Transmission function, the optical path, radiance and flux density.

In the blackbody radiation section, Prof Koh mentioned:

1. Planck’s law
2. Stefan-Boltzmann Law.



1.5 Lecture 2: Radiative transfer Theory and its implementation in the model, shortwave radiative

In the atmospheric absorption section, Prof Koh introduced:

1. Incoming solar radiation is absorbed and scattered by atmospheric constituents, including water vapour, carbon dioxide, oxygen, ozone, etc.
2. Transitions of molecular energy states form absorption lines and bands.

In the radiative transfer theory section, Prof Koh mentioned:

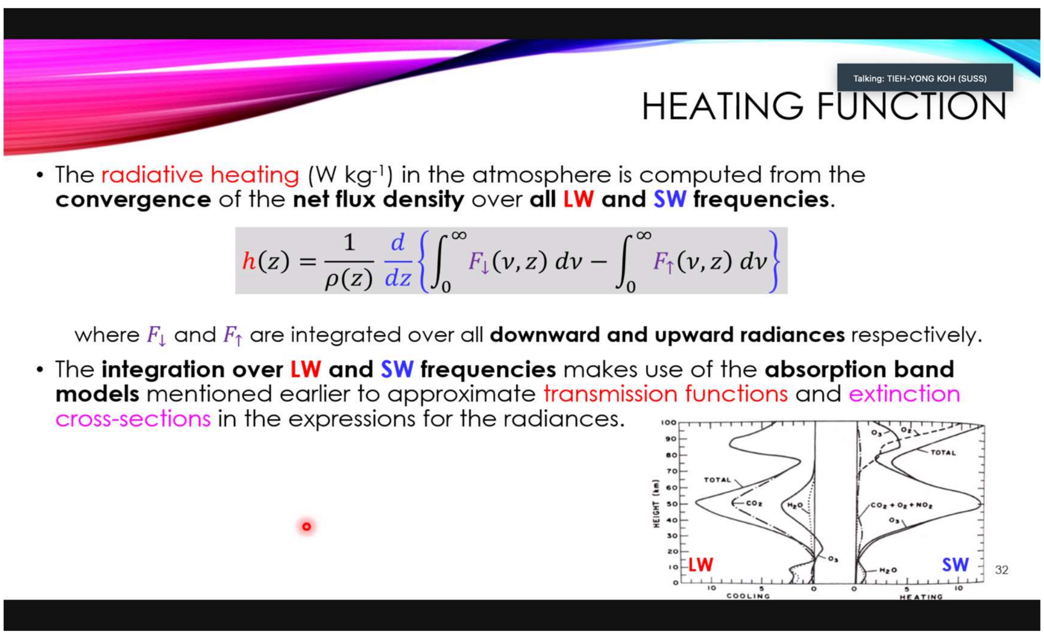
1. In the theory, earth's sphericity is neglected, and the radiation field varies only vertically. He then gave details for the longwave and shortwave radiative transfer.
2. It is computationally expensive for the line-by-line models of the atmospheric absorption at every frequency to get the spectral positions of absorption lines and their line shapes for all major atmospheric constituents.
3. So in the numerical models, band models are widely used. They assume non-overlapping absorption bands. These models may differ in details as to the treatment of temperature and pressure variations.

In the Atmospheric scattering section, Prof Koh introduced:

1. Rayleigh scattering
2. Mie scattering

In the ending section, Prof Koh mentioned that:

1. In numerical models, Monte-Carlo Independent Column Approximation (MCICA) is used.
2. One example is the rapid radiative transfer model for global simulations (RRTMG)



Q&A

1. Xin Rong Chua (CCRS) asked: TP separation treatment in the band model generally works. Whether in some cases, this kind of treatment fails and creates major problems?

Prof answered: he personally does not do research in this field, so he could not provide specific examples. But he stated that there are many different assumptions used in the model, and the possible errors due to TP separation should be relatively small (<10%) compared to other modelled processes.

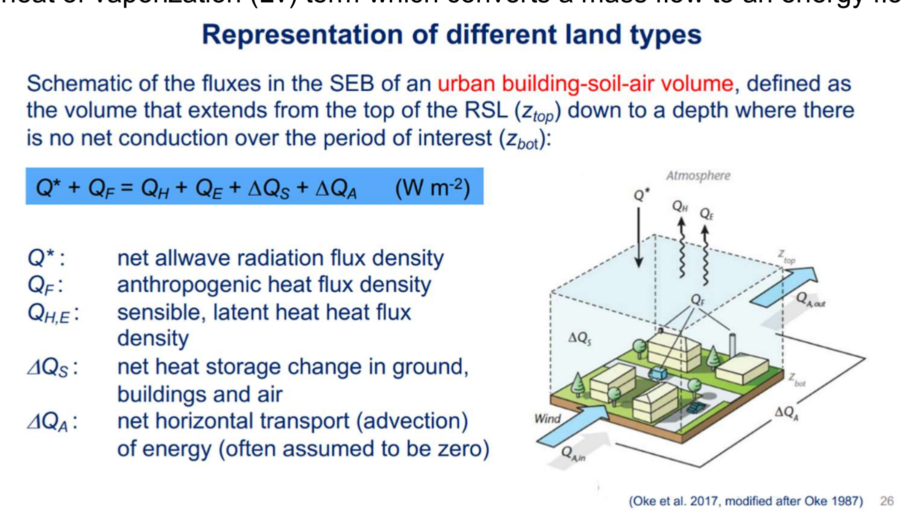
2. Xin Rong Chua (CCRS) asked: For different CO2 vibration models, whether we may say that: small molecules absorb more in the long wave radiation?
Prof answered: Energy absorption may be not simply related to the size of the molecular but could also depend on the jump in energy levels. So the line-by-line calculation is highly non-trivial and not that straightforward.

3. Xin Rong Chua (CCRS) asked TP treatment do not appear explicitly in the calculation of radiative transfer, how do we interpret this?
Prof answered that everything related to optical path is kind of linked to the TP treatment in the detailed calculation.

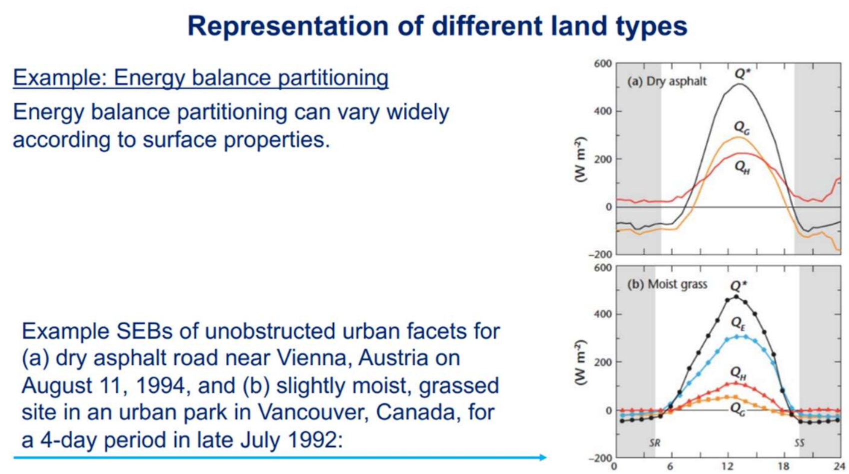
4. Xin Rong Chua (CCRS) asked: besides RRTMG, whether other schemes use similar radiative calculations, or they could use a totally new way of calculation?
Prof answered that all schemes may depend on similar overall physical assumptions, but they may differ in specific details, e.g., they may have angle-dependent scattering methods.

1.6 Lecture 3: Surface fluxes and energy balance: Representation of different land types

Professor Matthias Roth commenced the afternoon session of Day 1 with the third lecture of the workshop: Surface fluxes and energy balance, Representation of different land types. Professor Roth began by introducing participants to the concepts behind the energy balance framework, drawing parallels between energy flow/conservation in an Earth-atmosphere system and water flow in a soil-atmosphere system. He then provided an overview on the two fundamental equations that underpin the energy balance framework, 1) Surface energy balance (SEB) and 2) Mass balance, and explained how they were linked through the latent heat of vaporization (Lv) term which converts a mass flow to an energy flow.



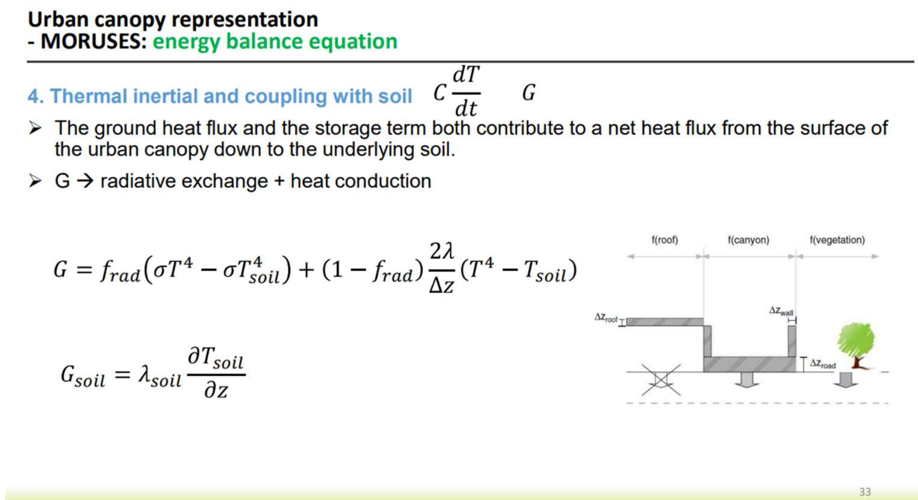
Professor Roth proceeded to discuss and provided real-world estimates for the individual flux terms that make up the SEB equation: Surface radiation balance (Q*), Conduction (QG), Turbulent transfer (QH, QE). Moving on to the next section of his lecture, Professor Roth introduced how the earlier concepts are applied when considering the representation of different land types. In particular, the case of the urban building-soil-air volume involves additional terms that represent anthropogenic heat flux (QF), net heat storage in ground, buildings and air (ΔQS) and net advection of energy (ΔQA). Case studies on how the energy balance partitioning can vary widely depending on the surface properties as well as clear sky/overcast conditions were also presented to participants. The lecture concluded with a sharing of various instruments and measuring techniques such as the flux-gradient, eddy-covariance approaches and scintillometery.



During the Q&A session, Dr Chua Xin Rong queried on the typical costs of such flux sensors, to which Professor Roth shared that eddy covariance sensors can cost up to $20K and even data logging devices up to $5K. He noted that measurements tend to be very time consuming as well, and require the right knowledge on the correct calibration and correction methods. In response to Dr Anurag Dipankar's question on how canopy layers were measured in Singapore, Professor Roth shared that typically buildings require sensors to be placed at double their height for effective measurement. Dr Chen Chen wondered if a sensor network akin to those based on traffic lights/ lamp posts would be an effective set up. Professor Roth felt that these are more appropriate for capturing mean atmospheric parameters (wind speed, humidity).

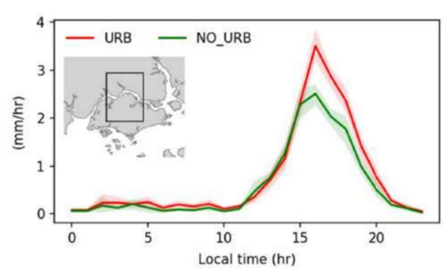
1.7 **Lecture 4: Urban Canopy Models**

Dr Song Chen delivered the last lecture of the day on Urban Canopy Models, beginning with how rapid urbanisation has motivated a growing need for understanding the urban impacts on weather forecasting and regional climate modelling. Dr Song then introduced participants to the various concepts behind the urban atmosphere, such as how its components differed under day and night conditions and the varying scales of processes involved e.g. corner vortices which are microscale and urban plumes that are considered mesoscale (up to multiple-city size), along with the modelling challenges that they present.



Participants also learnt how urban areas can interact with the atmosphere and impact weather/climate through storm bifurcation and the urban heat island (UHI) effect. Following this, Dr Song introduced various modelling methodologies, starting with the CFD/Micro-scale and Urban Canopy Models (UCM) approaches for representing the urban canopy. He then discussed the three different types of UCMs, 1) slab models, 2) the most widely used single-layer models (roof-canyon approach) and 3) multi-layer models. An example of a roof-canyon approach single-layer model, the MORUSES urban scheme used in the UKMO's Unified Model, was discussed in deeper detail to expose participants to how the SEB equations from the earlier lecture tie in with the construction of urban schemes and the necessary parameterisations involved (e.g. the heat transfer coefficient CH). To round off the lecture, Dr Song shared results from several studies that used MORUSES centred around investigating urban-induced changes to the diurnal cycle of rainfall over parts of Singapore and Johor.

➢ **Doan et al., 2021, Urban-induced modifications to the diurnal cycle of rainfall over a tropical city. *Quarterly Journal of Royal Meteorological Society.***



Diurnal cycle of simulated rain rate with URBAN and without URBAN

QNA

Prof Koh wasn't sure if the results shared by Dr Song could truly attribute the modelled changes in rainfall diurnal cycle to urban effects due to similarities in the pattern changes seen under strong sea breeze conditions. Dr Song felt that while Prof Koh made a valid observation, the studies had been run over multiple simulations and over different specific times/seasons (e.g. Monsoon seasons).

2 Day 2: 4 May 2021

Lectures on Day 2

2.1 Lecture 5 PBL Scheme, Surface Parameterization, Turbulence Closure

The theme on Tuesday morning was the parameterisation scheme of the boundary layer in NWP. The morning session was separated into two lectures. The first lecture was conducted by Chee Kiat Teo.

In the first lecture, the dynamics in the boundary layer was reviewed and the necessity to parameterise the unresolved turbulent fluxes was explained. In the second lecture, the emphasis was placed on boundary layer schemes and the applicability of different schemes at different model grid resolutions. The second lecture ended with a discussion of large eddies simulation of boundary layer.

The Planetary Boundary Layer (PBL)

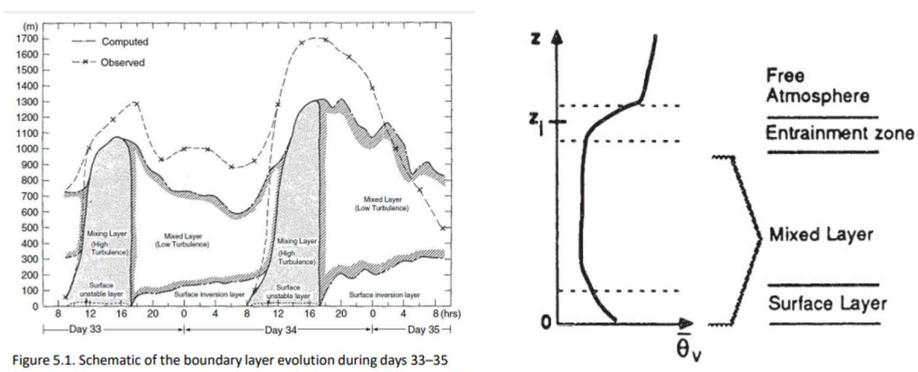
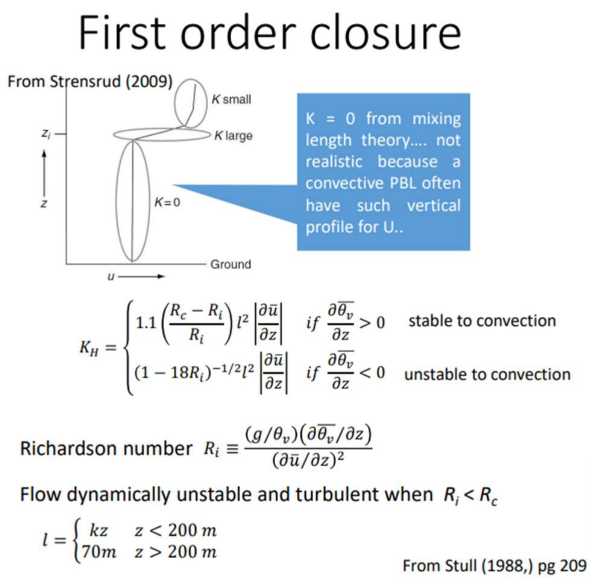


Figure 5.1. Schematic of the boundary layer evolution during days 33–35 from the Wangara experiment. During the daytime the mixing layer grows to depths above 1km and is characterized by high levels of turbulence and a shallow and unstable surface layer. As the sun sets, the level of turbulence drops precipitously, leaving a residual layer behind. The surface inversion layer grows throughout the nighttime hours, influenced by episodic turbulence and radiational cooling. From Yamada and Mellor (1975).

PBL is the lowest layer of air where the **land surface directly influences the atmosphere via turbulent mixing**.

The first lecture began with the application of the dynamical equations to the boundary layer. In reality, it is impossible for a numerical model to resolve the dynamics to an infinitesimally small length scale. Hence, it is necessary for the equations that will be solved by the numerical model to reflect this. To account for the stochastic nature of turbulence in the PBL, each of the dynamical variables is separated into a "mean state" and the corresponding "residual eddy". With the simplification from "Reynolds averaging", the prognostic equations of the mean state can almost be separated from the eddy terms, except for an outstanding turbulent flux term. The challenge to eliminate the higher order turbulent flux terms is called the "closure problem" in fluid dynamics. This is because the attempts to derive a prognostic equation for a moment of the turbulent flux term at a given order always end up with a set of equations that involves even higher order moment flux terms. Therefore, the equation cannot be properly "closed".



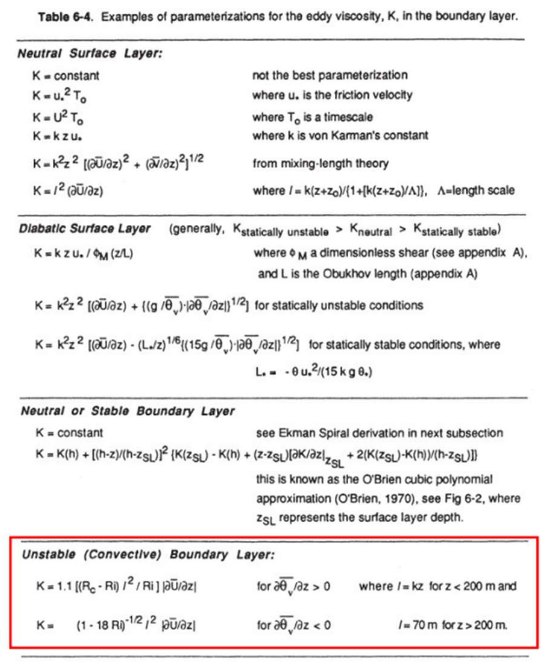


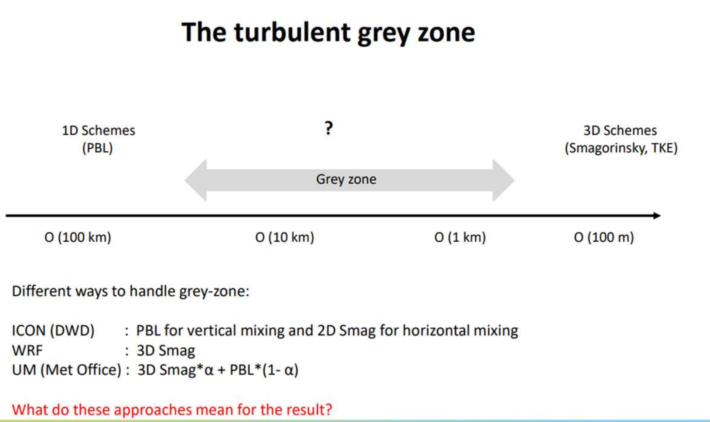
Table 6-4. Examples of parameterizations for the eddy viscosity, K, in the boundary layer.

Neutral Surface Layer:	
K = constant	not the best parameterization
$K = u_*^2 T_o$	where u_* is the friction velocity
$K = U^2 T_o$	where T_o is a timescale
$K = k z u_*$	where k is von Karman's constant
$K = k^2 z^2 [(\partial \bar{U}/\partial z)^2 + (\partial \bar{V}/\partial z)^2]^{1/2}$	from mixing-length theory
$K = l^2 (\partial \bar{U}/\partial z)$	where $l = k(z+z_o)/\{1+[k(z+z_o)/\Lambda]\}$, Λ=length scale
Diabatic Surface Layer (generally, $K_{\text{statically unstable}} > K_{\text{neutral}} > K_{\text{statically stable}}$)	
$K = k z u_* / \phi_M (z/L)$	where ϕ_M a dimensionless shear (see appendix A), and L is the Obukhov length (appendix A)
$K = k^2 z^2 [(\partial \bar{U}/\partial z) + \{(g/\overline{\theta_v}) \cdot \lvert \partial \overline{\theta_v}/\partial z \rvert\}^{1/2}]$	for statically unstable conditions
$K = k^2 z^2 [(\partial \bar{U}/\partial z) - (L_*/z)^{1/6}\{(15g/\overline{\theta_v}) \cdot \lvert \partial \overline{\theta_v}/\partial z \rvert\}^{1/2}]$	for statically stable conditions, where $L_* = -\theta u_*^2/(15 k g \theta_*)$
Neutral or Stable Boundary Layer	
K = constant	see Ekman Spiral derivation in next subsection
$K = K(h) + [(h-z)/(h-z_{SL})]^2 \{K(z_{SL}) - K(h) + (z-z_{SL})[\partial K/\partial z \rvert_{z_{SL}} + 2(K(z_{SL})-K(h))/(h-z_{SL})]\}$	this is known as the O'Brien cubic polynomial approximation (O'Brien, 1970), see Fig 6-2, where z_{SL} represents the surface layer depth.
Unstable (Convective) Boundary Layer:	
$K = 1.1 [(R_c - Ri)\, l^2 / Ri]\, \lvert \partial \bar{U}/\partial z \rvert$	for $\partial \overline{\theta_v}/\partial z > 0$ where $l = kz$ for $z < 200$ m and
$K = (1 - 18\, Ri)^{-1/2}\, l^2\, \lvert \partial \bar{U}/\partial z \rvert$	for $\partial \overline{\theta_v}/\partial z < 0$ $l = 70$ m for $z > 200$ m.

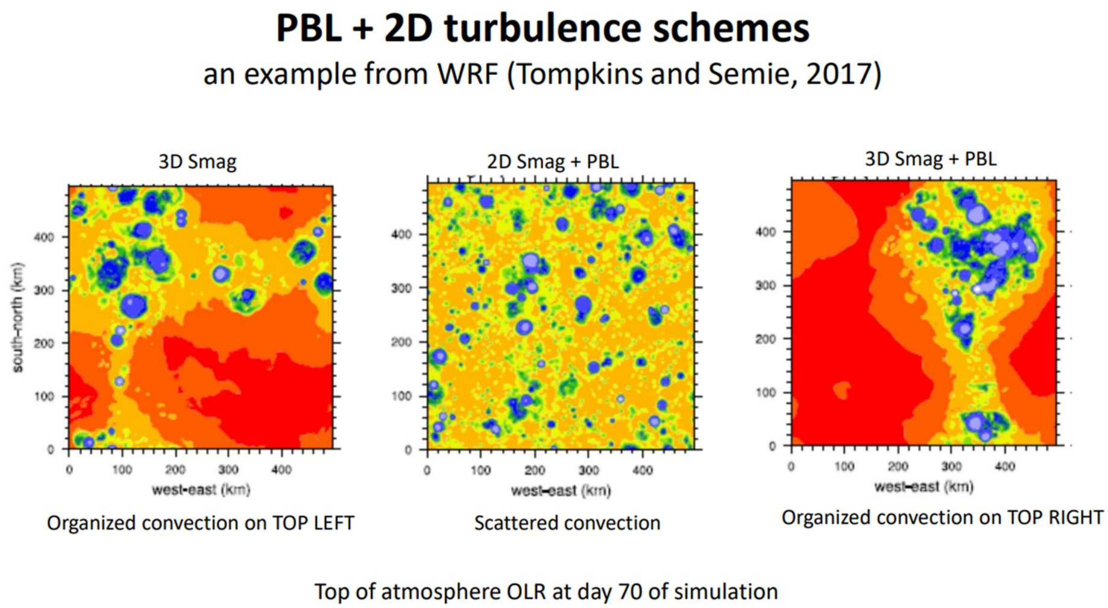
To address the "closure problem" in boundary layer dynamics, many educated guesses have been proposed to parameterize the unknown flux moment terms. The schemes that estimate the turbulent flux term at a spatial point using only the mean state values from that point are called "local closure". For example, the 1st order local closure schemes estimate the turbulent flux terms from the mean state. On the other hand, the schemes that use also the values from neighbouring spatial points are called "nonlocal closure".

2.2 Lecture 6 Surface-boundary layer coupling and large eddy simulation (LES)

The theme on Tuesday morning was the parameterisation scheme of the boundary layer in NWP. The morning session was separated into two lectures. The second lecture was conducted by Anurag Dipankar.



In the second lecture, different boundary layer schemes were introduced, starting from the simpler 1-D planetary boundary layer scheme and then moving to the higher dimensional schemes. The 1-D scheme considers only the vertical mixing and it is applicable to models with large grid sizes of ~100 km or larger. For models with small grid sizes of ~100 m or smaller, horizontal mixing needs to be considered and hence a 3-D scheme (e.g. smagorinsky scheme and turbulent kinetic energy scheme) should be applied. However, it is unclear what scheme should be used for the grid sizes between ~100 m to ~100 km. This range is called the “turbulent grey zone”. Different weather centres have different flavours of combining different schemes when simulating in the grey zone.



Large eddy simulation (LES) of the boundary layer is an approach to probe into the dynamic at the length scale that otherwise would have been represented by only the dissipative parameterization schemes. LES reformulates the “Reynolds averaging” approach so that part of the turbulent eddies could be resolved in the LES model. One theoretical goal is to capture the dynamics of the inertial subrange of K^ (5/3) of the energy spectrum as predicted by Komolgorov. For practical purposes, a comparison of LES and NWP run at similar grid sizes helps to understand the capability of NWP in capturing smaller scale dynamics.

2.3 Hands-on session

Dr Prasanna gave a brief introduction on the 1D radiative-convective model. He talked about the Earth’s radiation budget, radiative equilibrium in the no-atmosphere, black atmosphere and grey atmosphere, radiative vs radiative-convective equilibrium (RCE) and explained the MIT single column radiative convective model effects and how to run the model.

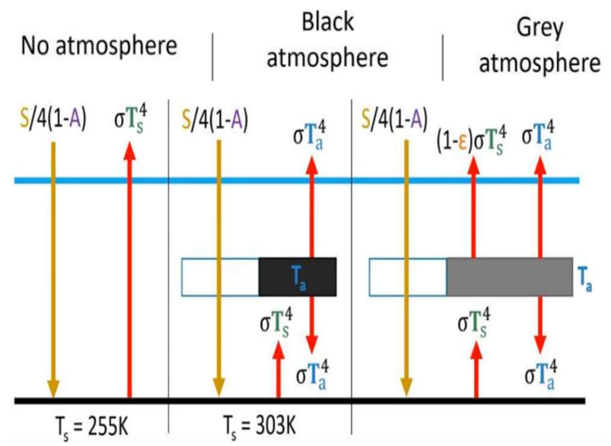
the atmosphere as a (grey) body…

The zero dimensional energy balance model is simple and useful tool to estimating the balance of energy.

But, don't get us the right answer, unless we "tune" them to account for greenhouse effect …

This simple model do not incorporate feedbacks, other factors..

Then we move to the next level of complexity.. the Radiative Convective Equilibrium (RCE..)



Ts = 255K (33 deg. C colder than Obs.) ~ No atm.
Ts = 303K (15 deg. C Warmer than Obs.) ~ Blk. atm.
Ts ~ 288K = 15 deg. C ~ Grey atm.

He concluded the lecture with explaining the differences of single column model and real world models.

Radiative convective equilibrium

- Dry Adiabatic Lapse Rate = - 9.8 K/km. (Not temp. dependent)

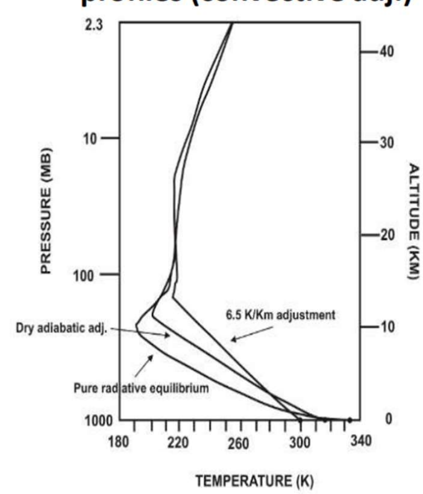
$$\Gamma_d = \frac{-g}{c_p}.$$

- Moist Adiabatic Lapse Rate ~ 4 - 6.5 K/km (varies..)

$$\Gamma_S = \frac{g + \frac{q^* L g}{RT}}{c_p + \frac{q^* L^2}{R_v T^2}}$$

g = 9.8 m/s2 (acceleration due to gravity)
cp = 1005.7 J/kg/K (heat capacity of dry air)
R = 287 J/kg/K (gas constant for dry air)
Rv= 461 J/kg/K (gas constant for water vapor)
L = 2.5E6 J/kg (Latent Heat of Condensation)
q*= Saturation specific humidity

Dry & Moist convective profiles (convective adj.)



(further discussion on theory of RCE and exercises by Xin Rong..)

There were no questions at this point of the lecture.

Hands-on session Continued

Dr Xin Rong continued the session Hands-on session using the MIT one column radiative-convective model http://12.340x.scripts.mit.edu/. Before the hands-on experiments she gave brief introduction on the radiative equilibrium in zero and one dimension with the radiative equilibrium solution, how the radiative substances maintain the temperature at radiative equilibrium, accuracy of the radiative equilibrium, dry and moist air concepts with the adiabatic, hydrostatic processes and moist convective adjustment. She also discussed the key concepts in RCE: water vapour concentrations and balances in the atmosphere is considered and physics parameterizations in the MIT 1D model.

Hands-on experiments:

Q1: Understanding the approach of the system towards equilibrium

1. Set “length of simulation” to 100 days and press “run model” to run the model and record the value of net radiative flux at the top of atmosphere (FTOA) from the table, which are averages over the last 25 days. Repeat this for “length of simulation” = 300 and 500 days. Find the values of FTOA for each simulation and post it in the chat.
2. Does the magnitude of FTOA increase or decrease as simulation length increases? Post your answer in the chat.
3. What is the significance of FTOA being close to zero?
4. What features of the climate system might affect the length of simulation required for FTOA to be close to zero?

Participants answered the questions in chat and Gab Miro talked about how he calculated it and after that Dr Xin Rong explained the answers and gave more details.

Answers:

1. FTOA = 3.3, 0.9 and 0.4 for 100, 300 and 500 days.
2. The magnitude of FTOA decreases as simulation length increases.
3. FTOA ≈ 0 indicates that the system has reached equilibrium, and that 500 days is a suitable simulation length for this exercise.
4. Increasing the heat capacity of the system would increase the time required to reach equilibrium (e.g. increasing the mixed layer depth from the default of 1 meter)

Q2: Exploring the top-of-atmosphere (TOA) radiative balance

1. What do you notice about the difference between the SW and LW terms?
2. Is there larger variability in the SW or LW term? Why?

Dr Xin Rong explained how to find the answers using the TOA radiative fluxes from the time series plot.

Answers:

1. The differences between SW and LW fluxes becomes small as equilibrium is reached.
2. Variability is larger in the LW term than the SW term.

Dr Xin Rong Chua (CCRS) then gave a summary for the TOA radiative balance.

Q3: Exploring the hydrological cycle in RCE

1. Estimate the mean precipitation and evaporation over the last 25 days. Post the values in the chat.
2. What conservation principle does this illustrate?

Dr Xin Rong explained how to find the answers using the precipitation option from the time series plot.

Answers:

1. 3.3 mm/day.

2. Conservation of moisture: precipitation ≈ evaporation

Q4: Exploring the atmospheric energy balance

1. In the lecture, we saw that LWsfc - LWTOA + SWsfc- SWTOA+ LHsfc+ SHsfc ≈ 0. Compute the sum of the radiative terms based on the values in the table. How is it balanced by sensible and latent heat fluxes?
2. The ratio of sensible to latent heat fluxes, known as the Bowen ratio, reflects the roles of temperature and moisture in balancing the radiative cooling. The simulations here are run with an ocean surface. How might the Bowen ratio differ if half the surface was land and half was ocean?

Answer:

1. Radiative cooling: -110 Wm-2, Latent heating: 96 Wm-2, Sensible heating: 15 Wm-2
2. In the lecture, we discussed that the latent heat fluxes increases with the fraction of the surface that is water. We expect that replacing water with land would decrease the latent heat fluxes and increase the Bowen ratio.

Participants asked some questions in the chat and Dr Xin Rong explained all the answers and concluded the session.

2.4 Lecture 7: Cloud cover parameterization, Sub-grid scale variability of humidity, Connecting cloud cover to clouds

This lecture covered the representation of cloud cover in NWP and climate models.
Dr Muhammad Eeqmal Hassim started the lecture with why clouds are essential variable in the numerical models as it interact with atmospheric radiation (both LW & SW) and can influence atmospheric circulation through diabatic heating and cooling and quantities needed to describe effect of clouds on the atmosphere. He also briefly discussed the types of clouds and concept of cloud layers in the models.

Example of PDF scheme with *fixed* moments (Smith, 1990)

$$C = \begin{cases} 0, & \overline{q}_t/\overline{q}_s \le \mathrm{RH}_{\mathrm{crit}}, \\ \dfrac{1}{2}\left[1 + \dfrac{(\overline{q}_t/\overline{q}_s - 1)}{(1 - \mathrm{RH}_{\mathrm{crit}})}\right]^2, & \mathrm{RH}_{\mathrm{crit}} < \overline{q}_t/\overline{q}_s \le 1, \\ 1 - \dfrac{1}{2}\left[1 - \dfrac{(\overline{q}_t/\overline{q}_s - 1)}{(1 - \mathrm{RH}_{\mathrm{crit}})}\right]^2, & 1 < \overline{q}_t/\overline{q}_s < 2 - \mathrm{RH}_{\mathrm{crit}}, \\ 1, & 2 - \mathrm{RH}_{\mathrm{crit}} \le \overline{q}_t/\overline{q}_s. \end{cases}$$

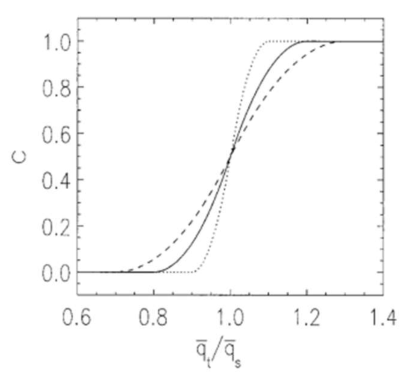
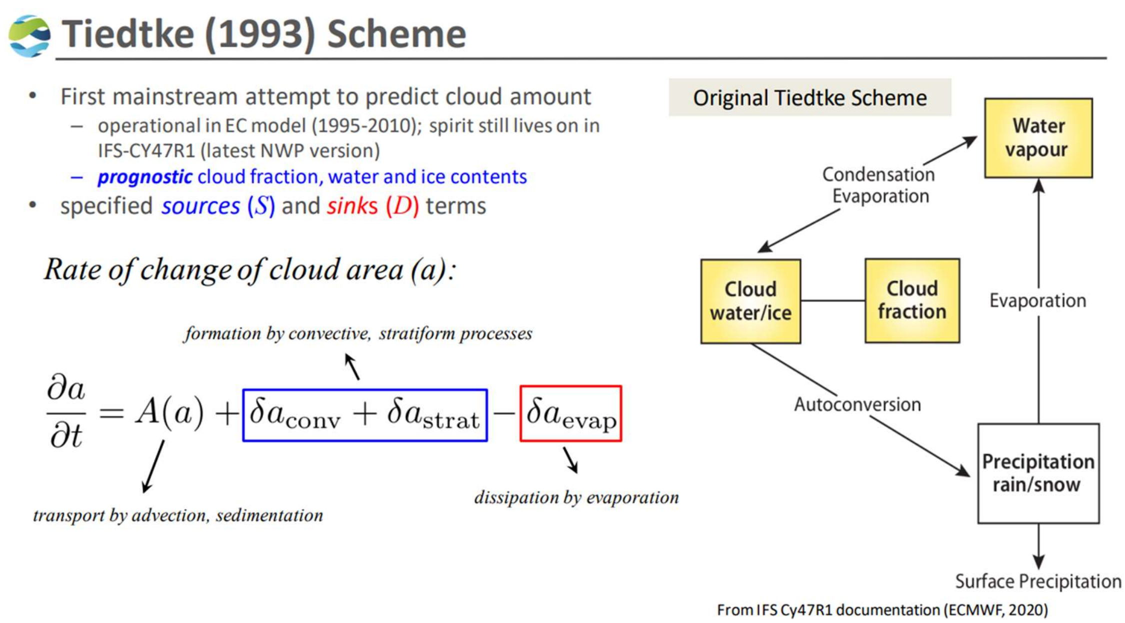
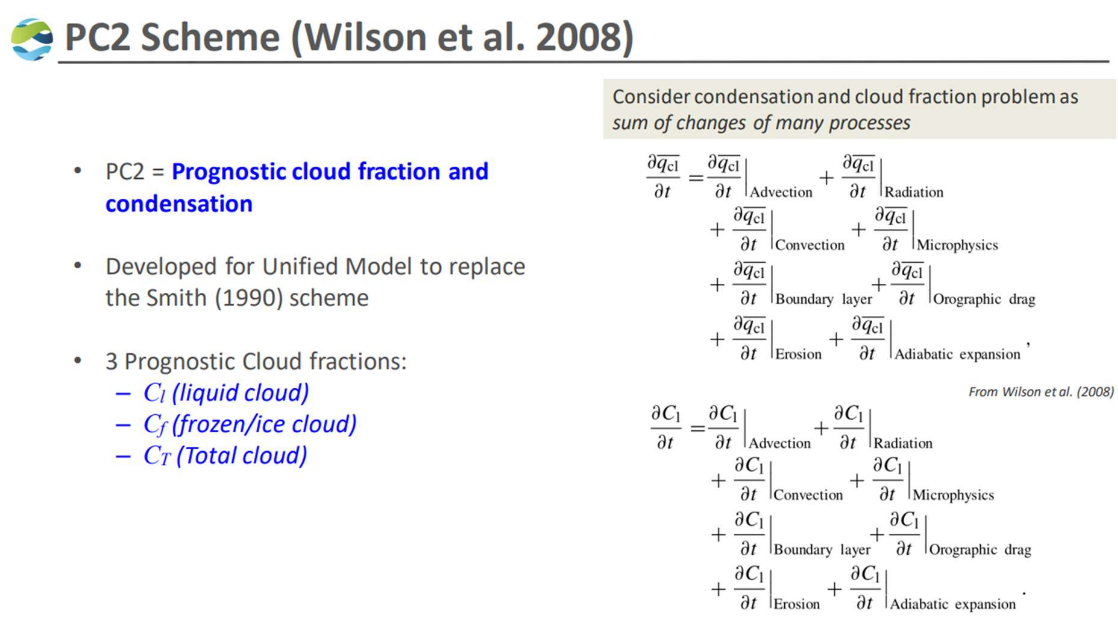


FIG. 7. Form of the diagnostic cloud fraction prediction scheme from Smith (1990). Cloud fraction is plotted against the run-mean total water content $\overline{q}_t$ normalized with the run-mean saturation specific humidity $\overline{q}_{s(0,T)}$. Curves for three values of RH_{crit} are shown: dashed, $\mathrm{RH}_{crit} = 0.7$; solid, $\mathrm{RH}_{crit} = 0.8$; and dotted, $\mathrm{RH}_{crit} = 0.9$.

From Wood and Field (2000)

Dr Hassim then explained some of the cloud parameterization schemes: Simple Diagnostic Scheme – relative humidity based method, “critical” RH, a few RH based schemes and their advantages and drawbacks, Statistical Schemes (including assumed and predicted moments)– specification of PDFs to represent sub-grid heterogeneity, a few PDF based schemes, processes affecting PDF moments, and ended the talk by discussing two Prognostic Schemes - Tiedtke (1993) Scheme and PC2 Scheme (Wilson et al. 2008).





3 Day 3: 17 March 2021

Lectures on Day 3

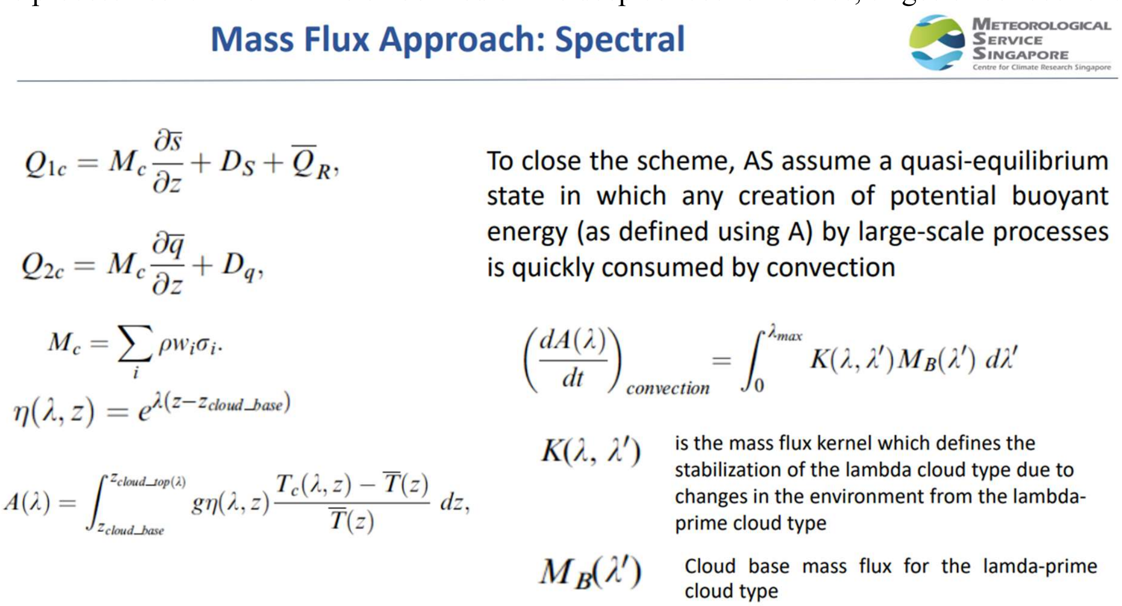
3.1 Lecture 8. Discussion of convective and stratiform rainfall, moisture species typically used in paramterization schemes

This lecture was cancelled as Dr Hassim got sick and continued with Hands-on session by Dr Xin Rong Chua after Lecture 9.

3.2 Lecture 9: Mass flux scheme, convective adjustment, convective closure, interaction with large scale circulation

This lecture is about the convection and cloud parametrizations in the models.

Dr Sandeep Sahany started the lecture by discussing the importance of convective parameterizations in the numerical models. He then explained the governing laws and equations in the numerical models and how and why parametrization comes in to play. Parameterization can be thought of as modeling the effects of a process rather than modeling the process itself. After that he elaborated on the deep convection basics, stages of convection.



He continued the talk with Mass flux approaches: (i) Spectral approach and (ii) Bulk approach. He asked the participants about sensitive parameters and explained that some parameters used for parameterization are well constrained and some are highly sensitive, If we change the parameter value the whole simulation results will change these are called sensitive parameters. He proceeded in detail about the fundamentals and equations for both approaches and closure problems: "dynamical" and "adjustment" types.

Convective Adjustment Approach: Manabe

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	$h<1$		$h \geq 1$
$-\frac{\partial T}{\partial P} \leq \gamma_d$	No condensation, no convection $\delta r=0$ $\delta T=0$ (No adjustment)	$-\frac{\partial T}{\partial P} \leq \gamma_m$	Large-scale condensation only $\delta r,\ \delta T \text{ from } \begin{cases} r+\delta r=r_s(T+\delta T,\ P) & (3.3) \\ c_p\delta T+L\delta r=0 & (3.4) \end{cases}$
$-\frac{\partial T}{\partial P} > \gamma_d$	Dry convection only $\delta r=0$ $\delta T \text{ from } \begin{cases} \frac{\partial}{\partial P}\theta(T+\delta T,\ P)=0 & (3.1) \\ \frac{c_p}{g}\int_{P_B}^{P_T}\delta T dP=0 & (3.2) \end{cases}$	$-\frac{\partial T}{\partial P} > \gamma_m$	Moist convection and large-scale condensation $\delta r, \delta T \text{ from } \begin{cases} \frac{\partial}{\partial P}\theta_e(T+\delta T,\ r+\delta r,\ P)=0 & (3.5) \\ r+\delta r=r_s(T+\delta T,\ P) & (3.6) \\ \frac{1}{g}\int_{P_B}^{P_T}(c_p\delta T+L\delta r)dP=0 & (3.7) \end{cases}$

$$p_{LC} = -\frac{1}{g}\int_{c}^{P_*} \delta r \, dP$$

Manabe (1965)

He concluded the lecture by discussing about his work on the triggers and closure assumptions used in CMIP5 models.

3.3 **Hands-on session (Continued...)**

Q5: Exploring the temperature profile in RCE

1. Estimate the lapse rate and post it in the chat. Hint: 600 hPa is about 3.7km; 800 hPa is about 1.7 km.
2. How does it compare to the dry and moist adiabatic lapse rates discussed in the lecture?

Dr Xin Rong gave instruction to compute the answers: “Profile” plot and plot “Temperature” with the replot button.

1. The lapse rate is about (0.3- -14.3)/ (1.7-3.7), i.e. temperature decreases with height at a rate of 7.2 K/km.
2. This is between the dry and moist lapse rates calculated in lecture. This indicates that moisture plays a role in setting the lapse rate of the atmosphere. The real world contains both the dry poles and the moist tropics and as such is in between a dry and moist adiabat.

Dr Xin Rong discussed in detail about CO2 doubling and started the hands-on for this experiment.

Q1: Connecting the single-column model to the zero-dimensional radiative equilibrium model

1. Describe the changes in LW TOA fluxes with time, with respect to changes in the SW fluxes.
2. Does surface temperature (SST in the table) increase or decrease?
3. We discussed a zero-dimensional model in lecture. Which terms in the model change under increased CO2?

Dr Xin Rong gave details on how to compute it: “Timeseries” plots and plot “TOA radiative fluxes” with the replot button.
Answer:
1. LW TOA fluxes are initially lower than SW fluxes, but subsequently increase to balance SW fluxes in equilibrium. It is thus important to consider the timescale when discussing the radiative response to CO_2.
2. Surface temperature increases by 2.2C from 17.3C in BASE. This surface temperature response to a doubling of CO¬2 is also known as equilibrium climate sensitivity, which has historically been estimated to be around 1.5-4.5K and ranges from 1.8-5.6K in 27 state-of-the-art global climate models (Zelinka et al., 2020).
3. Increase in CO_2 acts to decrease emissivity of the Earth system, reducing LW TOA. Subsequently, the effective temperature of the system (e.g. if we were to imagine the Earth as a point) increases to bring LW TOA back in equilibrium with SW TOA.
Q2: Changes in the vertical profile of temperature
1. Is the temperature increase in the upper troposphere larger, or smaller, than changes in the lower troposphere?
2. In the lecture, we discussed the basic physics that sets the lapse rate for the atmosphere. How do the dry and moist adiabatic lapse rates change with temperature?
3. Can you explain the result in (1)?
Answers:
1. The temperature increase in the upper troposphere is larger than the temperature increase the lower troposphere.
2. The dry adiabatic lapse rate does not change with temperature; the (magnitude) of the moist adiabatic lapse rate decreases with temperature.
3. Since the moist adiabatic lapse rate decreases with temperature, temperatures decrease more slowly with height. The schematic illustrates how the differences in temperature are magnified with height. Remark: This upper-tropospheric amplification acts as a negative feedback on the warming caused by CO_2.

Q3: Changes in specific humidity
1. Estimate the increase in lowest level specific humidity in g/kg and in percentage change.
2. Estimate the increase in lowest level relative humidity in terms of the absolute numbers and in percentage terms.
3. In the lecture, we discussed how changes in saturation specific humidity can be estimated with the Clausius-Clapeyron equation. Use the equation to estimate the changes in saturation specific humidity (q^*). Take the lowest level temperature in the base case to be 287 K.

Answers:
1. 1.4 g/kg, about a 20% increase from the 7.1 g/kg in the base case.
2. RH is the same to two decimal places (0.7), less than a 1% increase.
3. $dq^*/q^* = 2.5*10^6*2.4/(461*287*287) = 16\%$. Most of the changes in specific humidity are driven by changes in saturation specific humidity predicted from thermodynamics (the Clausius-Clapeyron relationship). $16/2.4 \approx 7\%/K$. Changes in specific humidity under warming has implications for rainfall extremes.

Participants answered all the questions in chat and after that Dr Xin Rong described the answers.

3.4 Hands-on session (Continued...)

Q4: changes to the atmospheric energy balance after doubling CO2.
Model shows increases in latent heat, decreases in sensible heat, and decreases in the Bowen ratio. Lu and Cai (2009) mentioned that global climate models show similar features for the change.

Q5: Changes to the hydrological cycle.
Models shows

1. Precipitation and evaporation are about 3.5 mm/day, an increase of 0.2 mm/day from the base case.
2. The increase is about 2.6%/K. Global models robustly predict an increase in precipitation of 1-3%/K.
3. This is smaller than the 7%/K we estimated from the Clausius Clapeyron equation, reflecting that mean and extreme precipitation are each subject to different constraints.

Dr Xin Rong Chua (CCRS) then gave a summary for the doubling CO2 case:

- CO2 doubling warms the surface
- The atmosphere warms as well, with greater warming in the upper troposphere than lower troposphere.
- The atmosphere also moistens.
- The increase in atmospheric radiative cooling is mainly balanced by an increase in latent heat fluxes, implying an increase in global mean precipitation.

Dr Xin Rong Chua (CCRS) then gave an overview for all the hands-on questions and answers. She provided additional comments and background information.

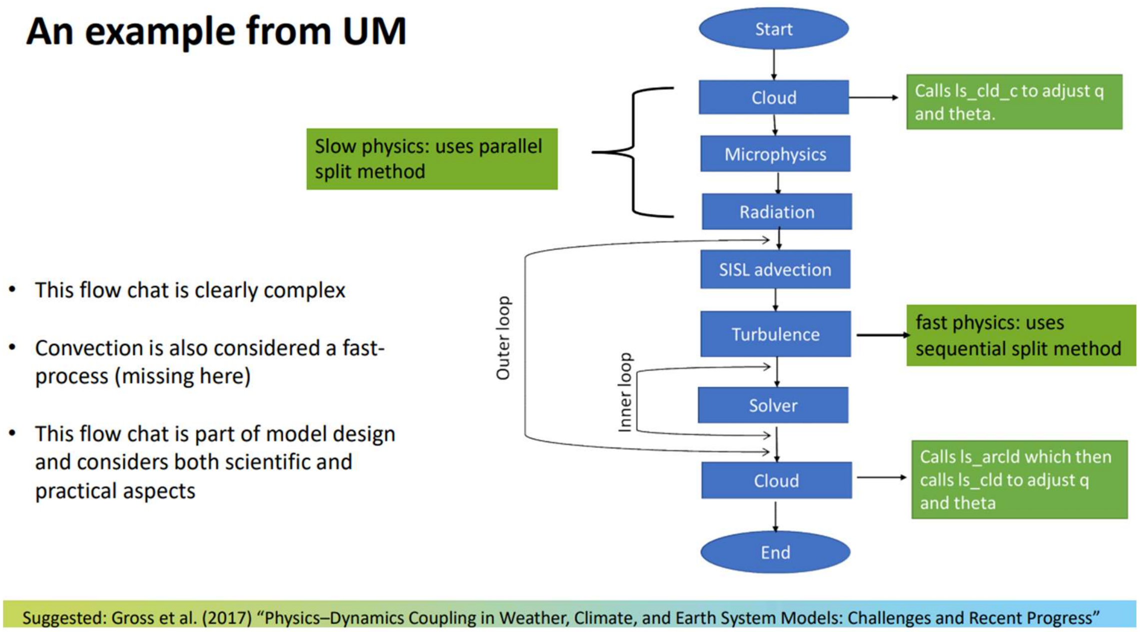
Participants provided feedback.
Gab Miro (PAGASA) mentioned that he thinks the basic concepts and theories learned from lectures are very useful to understand the complex codes when configuring the numerical models.

The day with a recap of the past three days, thanking everybody for their presentations and contributions, as well as sharing the inputs that were submitted for the roundtable discussions so far.

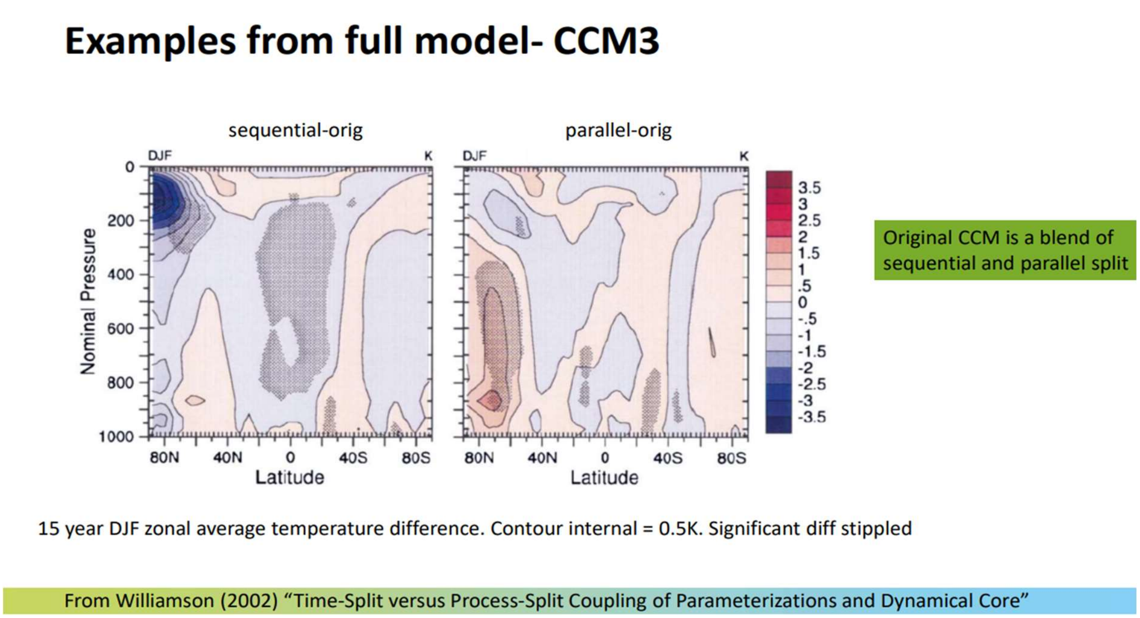
3.5 14:45-16:40 Lecture 10: coupling of dynamics and physics

This lecture covers how dynamics and physics are coupled.

Dr Dipankar started the lecture by using the UM model as one example to showcase the complex coupling between dynamics and physics. Model first calculates the clouds to adjust q and theta, and also calculate other slow physics using parallel split method, then the fast physics (convection, turbulence, etc) using the sequential split method, then gets back to the cloud module to adjust q and theta.



Dr Dipankar then used a simple equation to help explain the procedure of the coupling. He introduced three ways to solve the equation: Concurrent method (solved at once), Parallel split method (each source in isolation), and Sequential split method (in order).



He mentioned that in numerical models, concurrent methods are not practical. Typical ways are parallel and sequential methods. In practical use of parallel methods, an alpha term is often implied with the time step to make sure the stability. For the sequential-split method, the order for modules may differ. e.g., some models call cloud schemes first, other models may call radiation scheme first. The order of physical processes is very important. Also in the sequential calculation, now there are two terms, alpha and delta. Different combinations give explicit/ fully implicit/semi-implicit schemes. The advantage of sequential-split is to reduce the storage of memory. He mentioned that WRF treats most cases in parallel. He then gave examples from a full model of CCM3 to show that using sequential or parallel could lead to different outputs, e.g., warmer or cooler for 15year DJF zonal averaged temperature.

Q&A:

Sandeep Sahany (CCRS) asked, what the second accuracy is? Dr Dipankar answered that secondary accuracy is mainly referred to the truncation errors. Normally after running the full model simulation with different resolution, one can compare the truncation error and see if secondary accuracy is improved with high resolution.

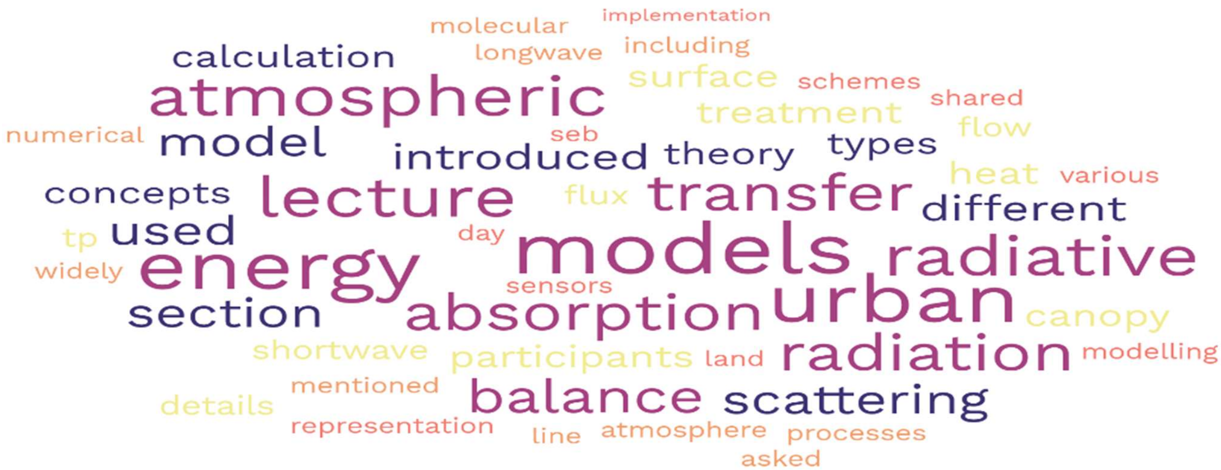
Xin Rong Chua (CCRS) asked why do UM models call the cloud scheme twice in the beginning and in the end? Dr. Dipankar said that may be due to diagnostics reasons, and the new version of UM models may have removed this back calling of cloud scheme.

3.6 **Dr Aurel Moise, CCRS, Singapore,** wrapped up the WPNM M-2 workshop, thanking everyone for their participation and enthusiasm over the past three days. He shared a consolidation of key messages from the workshop, illustrated through the word clouds made from participants' feedback.

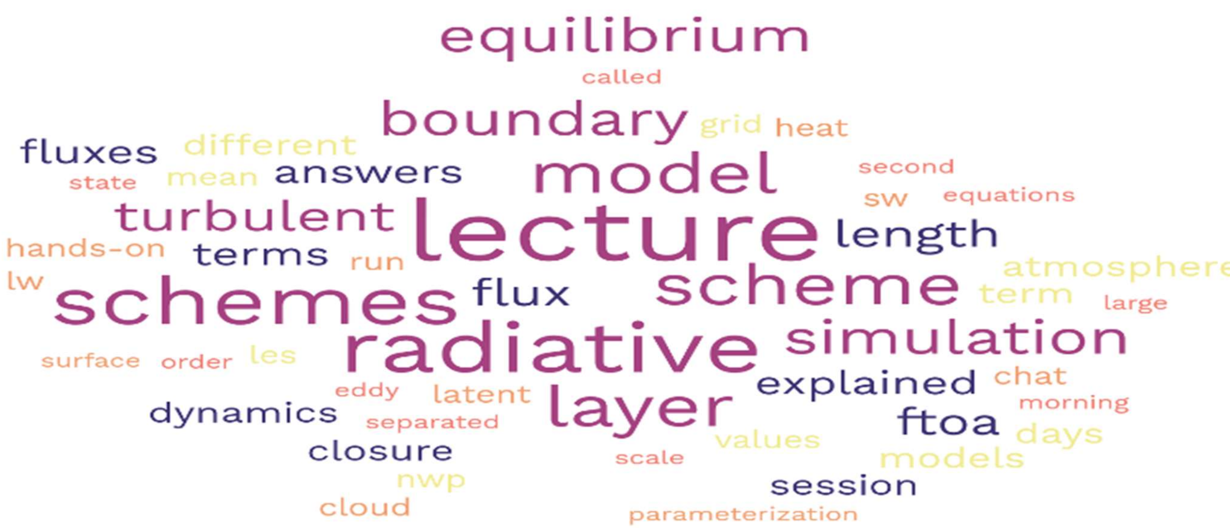
Workshop came to a formal close.

Each Day the participants learnt, in the form of a word cloud.

Day-1



Day-2



Day-3

Annex A: List of Participants

Title	Name	Organisation	Contact
Mr	Mohan Kumar Sammathuria	Malaysia Meteorological Department (MetMalaysia)	mohan@met.gov.my
Mr	Mahludin Sahrin	Malaysia Meteorological Department (MetMalaysia)	udin@met.gov.my
Ms	Nur Syafeenatul Alfda Rosli	Malaysia Meteorological Department (MetMalaysia)	syafeenatul@met.gov.my
Ms	Nurul Athirah Mohd Ezani	Malaysia Meteorological Department (MetMalaysia)	athirah@met.gov.my
Mr	Mohammad Affindi bin Haji Sabli	Brunei Darussalam Meteorological Department	affindi.sabli@met.gov.bn
Mr	Satry Nugraha bin Abd Razak	Brunei Darussalam Meteorological Department	nugraha.razak@met.gov.bn
Mr	So Im Monichouth	Department of Meteorology Cambodia	monichoth@gmail.com
Mr	Bounteum SISOUPHANT HAVONG	Lao PDR	s.bounteum@hotmail.com
Ms	Chaw Su Hlaing	Department of Meteorology and Hydrology Myanmar	chawsuhlaing.dmh@gmail.com
Dr	Tin Mar Htay	Department of Meteorology and Hydrology Myanmar	tmarhtay@gmail.com
Ms	Louie Jane Rico	Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA)	louiejanerico@gmail.com
Mr	Gabriel Miro	Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA)	gabmiro17@gmail.com
Ms	Heinritz Majella Miguel	Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA)	heinritzms.miguel@gmail.com

Mr	John Mark Dolendo	Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA)	jmdolendo@pagasa.dost.gov.ph
Ms	Chatchai CHAIYASAEN	Thai Meteorological Department (TMD)	chatchai.c@tmd.mail.go.th
Mr	Theerachai Auttachaipanit	Thai Meteorological Department (TMD)	theerachai3@hotmail.com
Mr	Nguyen Manh Linh	Viet Nam Meteorological and Hydrological Administration (VNMHA)	linhnguyennchmf@gmail.com
Ms	LUU Khanh Huyen	Viet Nam Meteorological and Hydrological Administration (VNMHA)	luukhanhhuyen258@gmail.com
Prof	Koh Tieh Yong	Singapore University of Social Sciences (SUSS)	geomr@nus.edu.sg
Prof	Matthias Roth	National University of Singapore (NUS)	tykoh@suss.edu.sg
Ms	Micheline Fong	Meteorological Service Singapore (MSS)	fong_tet_min@nea.gov.sg
Prof	Dale Barker	Centre for Climate Research Singapore (CCRS)	dale_barker@nea.gov.sg
Dr	Aurel Moise	Centre for Climate Research Singapore (CCRS)	aurel_moise@nea.gov.sg
Dr	Venkatraman PRASANNA	Centre for Climate Research Singapore (CCRS)	Venkatraman_PRASANNA@nea.gov.sg
Dr	Chen Chen	Centre for Climate Research Singapore (CCRS)	chen_chen@nea.gov.sg
Dr	Chua Xin Rong	Centre for Climate Research Singapore (CCRS)	chua_xin_rong@nea.gov.sg
Dr	Chee Kiat Teo	Centre for Climate Research Singapore (CCRS)	TEO_Chee_Kiat@nea.gov.sg
Mr	Gerald Lim	Centre for Climate Research Singapore (CCRS)	gerald_lim@nea.gov.sg
Dr	Anurag Dipankar	Centre for Climate Research Singapore (CCRS)	Anurag_DIPANKAR@nea.gov.sg

Dr	Song Chen	Centre for Climate Research Singapore (CCRS)	CHEN_Song@nea.gov.sg
Dr	Muhammad Eeqmal Hassim	Centre for Climate Research Singapore (CCRS)	muhammad_eeqmal_hassim@nea.gov.sg
Dr	Ragi Rajagopalan	Centre for Climate Research Singapore (CCRS)	Ragi_RAJAGOPALAN@nea.gov.sg
Dr	Sandeep Sahany	Centre for Climate Research Singapore (CCRS)	Sandeep_SAHANY@nea.gov.sg
Dr	Zhong Yi CHIA	Centre for Climate Research Singapore (CCRS)	CHIA_Zhong_Yi@nea.gov.sg

Annex B: Workshop Programme

WEATHER PREDICTION BY NUMERICAL METHODS MODULE 2 (WPNM-M2) (Virtual on Zoom) 03 - 05 May 2021

Day 1: Monday, 03rd May 2021			
Welcome and Introduction			
9:15 - 9:30		Zoom Attendance	
09:30 - 09:40	1.1	Welcome Address	Prof Dale Barker, Director, CCRS, Singapore
09:40 - 09:45	1.2	Course introduction, module overview and objectives	Dr Aurel Moise (CCRS)
09:45 - 09:50	1.3	Administrative Brief	Dr Venkatraman Prasanna (CCRS)
09:50 - 10:00		Workshop Group photo	
Radiation Parameterization			**Note taker: Dr Chen Chen**
10:00 - 11:30	1.4	*Lecture 1* *Radiative transfer Theory and its implementation in the model, shortwave radiative transfer, long wave radiative transfer, Role of clouds in radiative transfer*	Prof Koh Tieh Yong *(Singapore University of Social Science)*
11:30 - 11:40	Break		
11:40 - 13:10	1.5	*Lecture 2* *Continuation of Radiation parameterization lecture*	Prof Koh Tieh Yong *(Singapore University of Social Science)*
13:10 - 14:00		Lunch	
Land Surface Parameterization			**Notetaker: Mr Gerald Lim**
14:00 - 15:30	1.6	*Lecture 3* *Surface fluxes and energy balance, Representation of different land types*	Prof Matthias Roth *(National University of Singapore)*
15:30 - 15:40	Break		
15:40 - 17:10	1.7	*Lecture 4* *Urban Canopy model.*	Dr Song Chen *(CCRS)*
17:10	End of Day 1		

Day 2: Tuesday, 04th May 2021			
Boundary Layer Parameterization			**Note taker: Mr Zhong Yi Chia**
10:00 - 11:30	2.1	*Lecture 5* *PBL Scheme, Surface Parameterization, Turbulence Closure*	Dr Chee Kiat TEO *(CCRS)*
11:30 - 11:40	Break		
11:40 - 13:10	2.2	*Lecture 6* *Surface-boundary layer coupling and large eddy simulation (LES)*	Dr Anurag Dipankar *(CCRS)*
13:10 - 14:00		Lunch	
Convection & Cloud Parameterization			**Note taker: Dr Ragi Rajaoplan**
14:00 - 15:30	2.3	*Hands on* *MIT Kerry Emanuel Model (Single column model) & worksheet exercises*	Dr Venkatraman Prasanna & Dr Xin Rong Chua *(CCRS)*
15:30 - 15:40	Break		
15:40 - 17:10	2.4	*Lecture 7* *Cloud cover parameterization, Sub-grid scale variability of humidity, Connecting cloud cover to clouds*	Dr Muhammad Eeqmal Hassim *(CCRS)*
17:10	End of Day 2		

Day 3: Wednesday, 05th May 2021			
Convection & Cloud Parameterization			**Note taker: Dr Ragi Rajaoplan**
10:00 - 11:30	3.1	*Lecture 8 (Hands On Continued….)* *Discussion of convective and strati form rainfall, Moisture species typically used in parameterization schemes (e.g. Rain, Snow, Ice, Graupel), Microphysical processes (e.g. deposition, coalescence, riming, aggregation), Types of microphysics schemes (Single moment, Double moment, Spectral Bin)*	Dr Muhammad Eeqmal Hassim *(CCRS)* *(Lecture Cancelled and instead Hands On Continued….)*
11:30 - 11:40	Break		
11:40 - 13:10	3.2	*Lecture 9* *Mass flux scheme, Convective adjustment, Convective closure, Interaction with large scale circulation.*	Dr Sandeep Sahany *(CCRS)*
13:10 - 14:00		Lunch	
Hands on lecture			**Note taker: Dr Chen Chen**
14:00 - 15:30	3.3	*Hands on Lecture* *MIT Kerry Emanuel Model (Single column model) & worksheet exercises*	Dr Xin Rong Chua *(CCRS)*
15:30 - 15:40	Break		
15:40 - 17:10	3.4	*Lecture 10* *coupling of dynamics and physics*	*Dr Anurag Dipankar* *(CCRS)*
17:10	End of Day 3		

Annex C: Workshop Feedback

Linear scale-based questions

Question	Average score (out of 5, unless stated otherwise)
Did the workshop achieve the programme objectives?	5.0 (Everyone Answered: Yes)
How was the duration of the workshop?	Too-Short:80%; Just Right-20%
How would you rate the overall organisation of the workshop?	4.4
The knowledge and information gained from this workshop met my expectations	4.2
The knowledge and information gained from this workshop will be relevant to my work	4.8
How likely are you to recommend your colleagues to attend similar workshops in the future?	4.8

Selected responses to short answer questions:

1. What were the key points that you took away from this workshop?
    - *Parameterization is a specialized field in NWP, but having a basic grasp of all these different schemes will help in the overall understanding of NWP.*
    - *Land surface Boundary Layer, Radiation, Convection Cloud Parameterization and Radiative - Convective Model*
    - *PBL, Land Surface, Radiation, convective and cloud parameterizations, Radiative-convective Model*
    - *Urban Canopy Model, convective parameterizations*
    - *I really appreciated how the lectures were the right amount of technical and emphasized more on the important concepts about parameterization and the different parameterization schemes. As someone who has a very limited background about these concepts in NWP, the workshop was very educational and I learned a lot.*

2. How do you think the workshop could have been more effective?
    - *An opening lecture giving a short review of Module 1 and focusing on why we need parameterization would have been nice - this is to set the tone for the whole workshop. Also, maybe more discussion/wrap-up on the interaction between these parameterization schemes.*
    - *We need more hands on Lecture*
    - *Better if theory and hands on lectures balance.*

- *I have no comment.*
- *I think the workshop was very effective, even with the current constraints and limited interaction.*

3. Are there any topics that should have been covered in MORE detail?
    - *Interaction between physics.*
    - *My knowledge is limited so every topics related with the parameterization is useful for me.*
    - *I was really looking forward to the microphysics lecture. Maybe the lecture slides can still be provided if possible.*

4. Any final comments or suggestions?
    - *Thank you very much to ASMC and CCRS/MSS for sponsoring and organizing this series, and also for pushing through with Module 2 despite the pandemic. Please also extend our gratitude and appreciation to all resource persons who have shared their valuable knowledge and expertise on this course. Virtual workshop will do given our situation now, but I hope we get to have a physical workshop again on future modules.*
    - *Also, maybe the hands-on worksheet could have been assigned as homework prior to the activity, so that everyone could give input to the discussion and making the whole thing more interactive.*
    - *Thank you all lecturers.*
    - *Please give more the hands on in case study*
    - *Thank you for the workshop. Thank you for still continuing the WPNM workshop series even if we have the COVID situation. Also, for allowing more participants this time. Looking forward to M3.*