Practical aspect for your prediction runs / project

Realtime forecast schedule

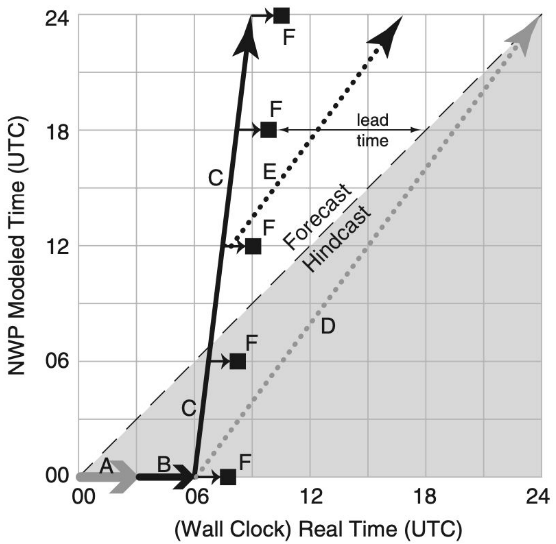

Figure 20.12
Hypothetical forecast schedule, for a 00 UTC initialization.
A: wait for weather observations to arrive.
B: data assimilation to produce the analysis (ICs).
C: coarse-mesh forecast.
D: fine-mesh forecast, initialized from 00 UTC.
E: fine-mesh forecast initialized from coarse forecast at 12 h.
F: postprocessing and creation of products (e.g., weather maps).

Fig. 20.12 shows a hypothetical forecast schedule, for a weather forecast initialized from 00 UTC synoptic observations. First, it takes a few hours (timeline A in Fig. 20.12) for all the data to be communicated from around the world to the weather forecast center (WFC). This step includes quality control, and rejection of suspected bad data.

Next, the data assimilation programs run for a few hours (B) to create a gridded analysis field. This is the optimum initial condition for the NWP model. At this point, we are ready to start making the forecast, but the initial conditions are already 6 h old compared to the present weather.

So the first part of forecast (C) is spent trying to catch up to "present". This wasted initial forecast period is not lamented, because startup problems associated with the still-slightly-imbalanced initial conditions yield preliminary results that should be discarded anyway. Forecasts that occur AFTER the weather has already happened are known as **hindcasts**, as shown by the shaded area in Fig. 20.12.

The computer continues advancing the forecast (C) by taking small time steps. As the NWP forecast reaches key times, such as 6, 12, 18, and 24 (=00) UTC, the forecast fields are saved for post-processing and display (F). **Lead time** is how much the forecast is ahead of real time. For example, for coarse-mesh model (C), weather-map products (F) that are produced for a **valid time** of 18 UTC appear with a lead time of about 8 h before 18 UTC actually happens, in this hypothetical illustration.

NWP meteorologists always have the need for speed. Faster computers allow most phases of the forecast process to run faster, allowing finer-resolution forecasts over larger domains with more accuracy and greater lead time. Speed-up can also be

A: Getting observation data

B: Data Assimilation run

C: Fast / low computational cost model run

D/E: Slow / costly model run

Mesh Design tips

Grid Spacing & smallest resolved features

INFO • Resolution vs. Grid Spacing

Theoretically, the smallest horizontal wavelength you can resolve with data at discrete grid points is $2 \cdot \Delta X$. However, the finite-difference equations that are used to describe advection and other dynamics in NWP models are unable to handle $2 \cdot \Delta X$ waves. Namely, these waves either do not advect at all (Fig. 20.11d), or they are numerically unstable.

To avoid such unphysical behavior, small wavelength waves are numerically filtered out of the model. As a result, the smallest waves that are usually retained in NWP models are about 5 to $7 \cdot \Delta X$.

Hence, the actual **resolution** (i.e., the smallest weather features that can be modeled) are about 7 times the **grid spacing**. Stated another way, if you know the size of the smallest weather system or terrain-related flow that you want to be able to forecast, then you need to design your NWP model with horizontal grid spacing ΔX smaller than 1/7 of that size.

Sample Application

What grid size, domain size, number of grid points, and time steps would you use for a numerical model of a hurricane, and how many computations would be needed to make a 3-day forecast? How fast should your computer be? [Hint: Use info from the Hurricane chapter.]

Assume tropical thunderstorms are about 14 km in diameter

Figure 16.1
Visible-spectrum satellite picture of Hurricane Katrina over the Gulf of Mexico, taken 28 Aug 2005 at 1545 UTC. (GOES image courtesy of US DOC/NOAA.)

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https://www.eoas.ubc.ca/books/Practical_Meteorology/
Chapter 20 Numerical Weather Prediction (NWP)

Mesh design

Finest resolution part

- for areas that the thunderstorm / eyewall would possibly pass
  - during the whole simulation
- Grid spacing: <feature length scale> / 7

Surrounding Environment

- Affecting TC track
  - Subtropical high ?
  - Monsoon ?
  - Another TC ?
- Appropriate domain size
- Appropriate grid spacing to resolve feature needed

> Assume the smallest feature you want to resolve is a thunderstorm in the eyewall. If tropical thunderstorms are about 14 km in diameter, then you would want **ΔX** = (14 km)/7 = **2 km** to horizontally resolve it.

> Hurricanes can be 300 km in diameter. To model the whole hurricane and a bit of its surrounding environment, you might want a horizontal **domain of 500 km by 500 km**. This works out to (500 km / 2 km) = 250 grid points in each of the x and y directions, giving $(250)^2$ = 62,500 grid points in the horizontal. If you want a model with 50 vertical levels, then you need (50) · (62,500) = **3,125,000 grid points total**.

Other settings in Mesh Specification

Estimation details

- Preview of transition
- Number of cells estimation is very preliminary
    - If you turned on “Boost orography” or “Boost coastline”, the resulting number of cells may be a lot more than estimated #cells (Note the “≥” symbol)

Max. Resolution Gradient:

- If the target of simulation is to predict / analyse rain.
- Smooth transition of resolution is recommended.
- The default 1/12 may be too steep (while economical).
- Recommend 1/36 or even smoother, increasing the cost.

Aspects in Real Simulations

Initial Value Problem

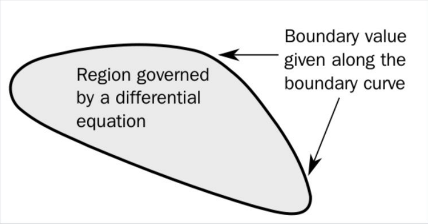
Needs Initial Condition (IC) data given only.

Evolution of states is done by the model solely.

Boundary value problem

From Wikipedia, the free encyclopedia

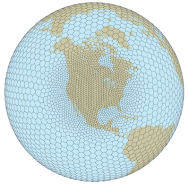
In mathematics, in the field of differential equations, a **boundary value problem** is a differential equation together with a set of additional constraints, called the **boundary conditions**.[1] A solution to a boundary value problem is a solution to the differential equation which also satisfies the boundary conditions.



Shows a region where a differential equation is valid and the associated boundary values

Boundary value problems arise in several branches of physics as any physical differential equation will have them.

Atmospheric state
Land surface state (soil moisture)



Time-integration

time

Initial Condition
(whole 3-D domain) given

Lateral boundary condition (LBC) data must be given periodically (e.g. hourly, or 3 hourly) for the lateral boundary (2-D: horizontal boundary perimeter x vertical dimension)

IC LBC LBC LBC LBC time

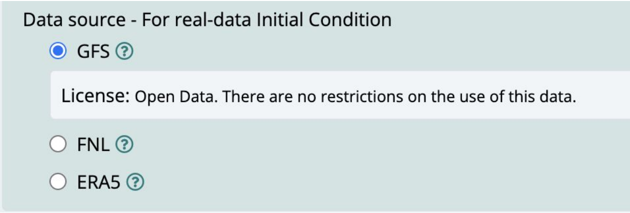
Initial Condition

Realtime forecasting for the future

US NCEP **GFS**

- The US NCEP GFS forecast data product.
- Near real-time, some hours of delay
- With GDAS (Global Data Assimilation System)

Should have Data assimilation done - got all available information of observation data



Re-simulate historic event

ERA5

- The ECMWF ERA5 reanalysis dataset.
- The data has a 5 days delay. ERA5 data since 1979 shall be available.

FNL

- The US NCEP FNL (Final) Operational Global Analysis dataset.
- The data usually has one or two days of delay. FNL data since 2015-07-08 shall be available.

State Imbalance & Spin-up

Imported Initial Condition or Data assimilation introduced imbalanced state.

Analogy:

An extra mass of water is added to a grid cell "suddenly" (due to inference from observation data)

Then this results in spurious wave until it is dissipated.

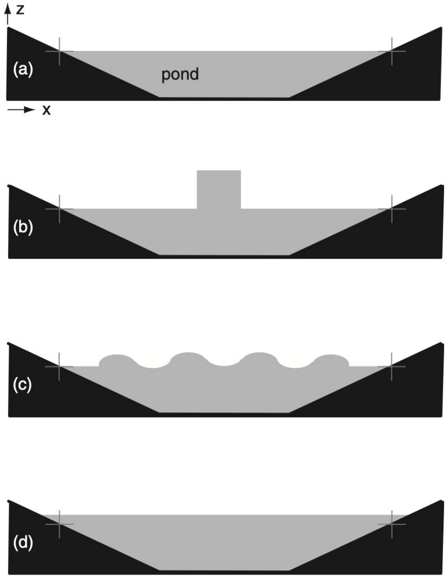


Figure 20.13
Demonstration of a dynamic system becoming balanced. (a) Balanced initial state of a pond of water (shaded grey), with no waves and no currents. (b) Extra water added in center of pond, causing the water-mass distribution to not be in equilibrium with the waves and currents. (c) Wave generation as the pond adjusts itself toward a new balanced state. (d) Final balanced state with slightly higher water everywhere, but no waves and no currents.

The transient waves and currents are an artifact of the poor initial conditions in the model, and are not representative of the true flow in the real pond. Hence, the forecast results are not to be trusted during the first few minutes of the forecast period while the model is adjusting itself to a balanced state.

Numerical forecasts of the atmosphere have the same problem, but on a longer time scale than a pond. Namely, the first 0.5 to 3 hours of a weather forecast are relatively useless while the model adjusts to imbalances in the initial conditions (see the Data Assimilation section). During this startup period, simulated atmospheric waves are bouncing around in the model, both vertically and horizontally.

After the first 3 to 12 h of forecast, the dynamics are fairly well balanced, and give essentially the same forecast as if the fields were balanced from the start. However, spurious waves in the model might also cause unjustified rejection of good data during data assimilation (see next subsection).

Throw away the data in the spin-up period

Usually, the first ~12 hours of mesoscale (around or >10km grid spacing) atmospheric simulation is regarded as the spin-up.

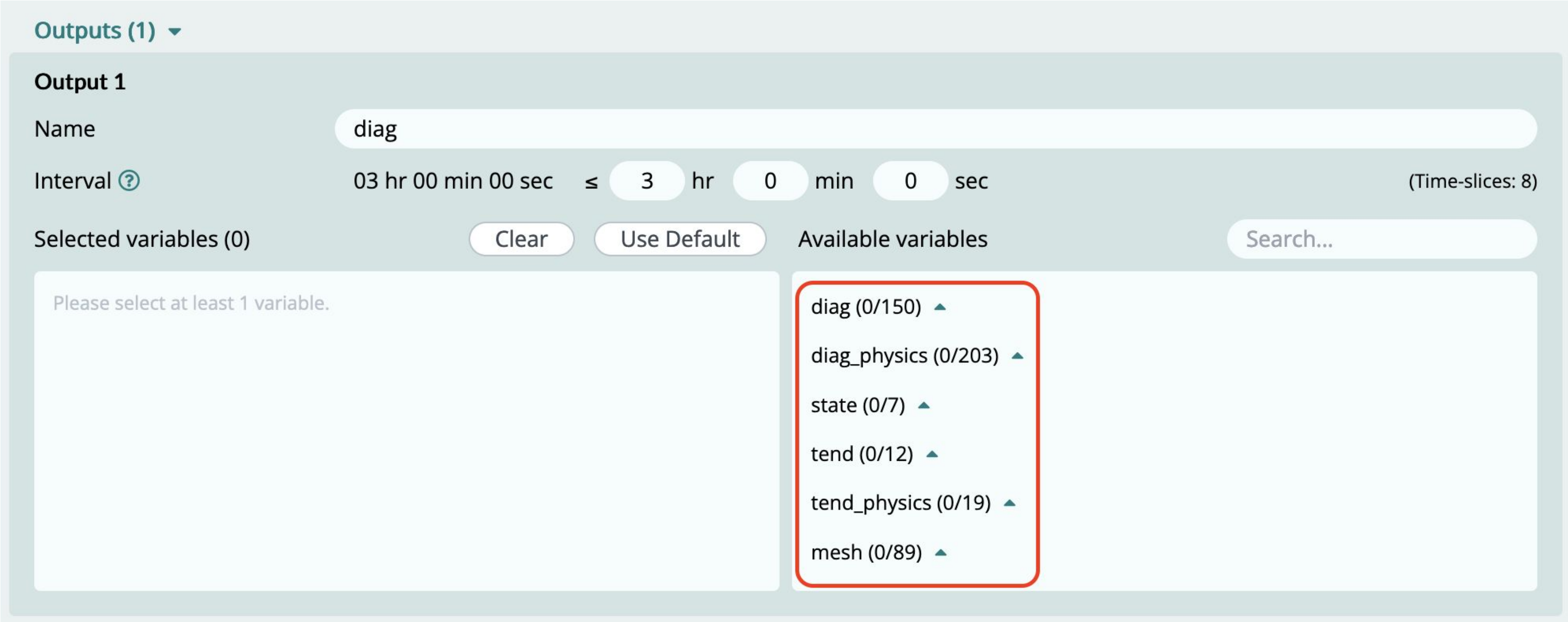
Don’t regard it as a valid forecast. Skip the spin-up period in forecast data dissemination and analysis.

Also, the erroneous waves can generate erroneous clouds that cause erroneous precipitation, etc. The net result could be an unrealistic loss of water from the model that could reduce the chance of future cloud formation and precipitation. Change of water content is just one of many **irreversible processes** that can permanently harm the forecast.

In summary, initialization problems cause a transient period of poor forecast quality, and can permanently degrade longer-term forecast skill or cause rejection of good data. Hence, data-assimilation methods to reduce startup imbalances, such as described next, are highly desirable.

Simulation Outputs

Specify what simulation outputs to write to files



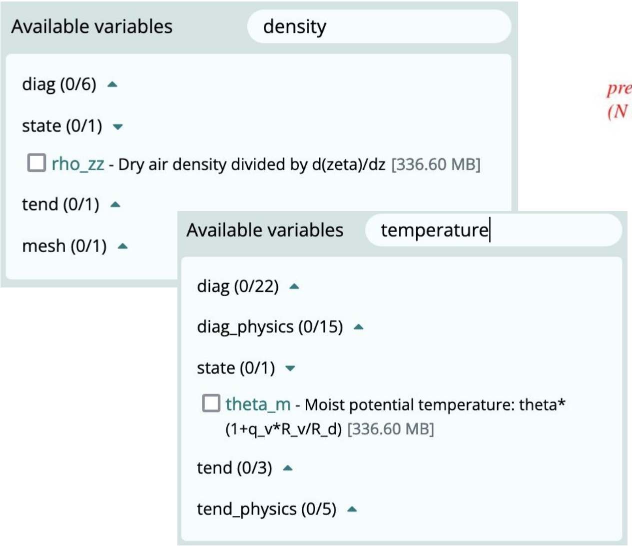
Prognostic vs Diagnostic variables

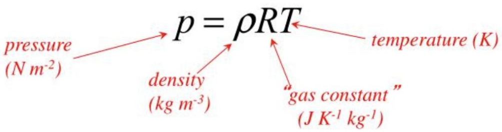
Prognostic:

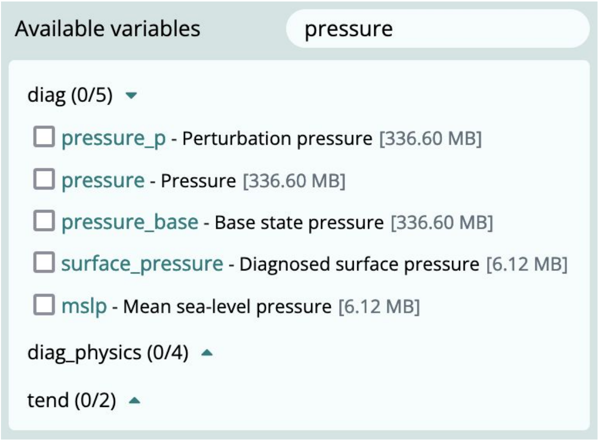
- Rate of change formulated in the model.
- Need to simulate its time evolution.

Diagnostics:

- Can be calculated by other prognostic variables.







Sub-Grid Scale Physics Parameterization

Physics Parameterization applies different length scales

... even finer

Mesoscale (coarser than ~10km)

Grey zone for Cumulus parameterization

Grey zone for Gravity Wave Drag

Convection-permitting (finer than ~4km)

Grey zone for Boundary Layer turbulence

A number of important physical processes are not resolved by the grid.

Needs various formulations to calculate parameterized source and sink terms for the PDEs.

Many physical processes are resolved by the grid.

Turn off those parameterization

Variable-resolution mesh needs
Scale-aware parameterization schemes

Challenging - frontier research underway.
Existing schemes are not perfect, a long way to improve.

Brief introduction of NWP Physics

Stull 2016 Practical Meteorology

Table 20-1. Some physics parameterizations in NWP.

Process	Approximation Methods
Cloud Coverage	• Subgrid-scale cloud coverage as a function of resolved relative humidity. Affects the radiation budget.
Precipitation & Cloud Microphysics	Considers conversions between water vapor, cloud ice, snow, cloud water, rain water, and graupel + hail. Affects large-scale condensation, latent heating, and precipitation based on resolved supersaturation. Methods: • bulk (assumes a size distribution of hydrometeors); or • bin (separate forecasts for each sub-range of hydrometeor sizes).
Deep Convection	• Approximations for cumuliform clouds (including thunderstorms) that are narrower than grid-cell width but which span many grid layers in the vertical (i.e., are unresolved in the horizontal but resolved in the vertical), as function of moisture, stability and winds. Affects vertical mixing, precipitation, latent heating, & cloud coverage.
Radiation	• Impose solar radiation based on Earth's orbit & solar emissions. Include absorption, scattering, & reflection from clouds, aerosols and the surface. • Divide IR radiation spectrum into small number of wide wavelength bands, and track up- and down-welling radiation in each band as absorbed and emitted from/to each grid layer. Affects heating of air & Earth's surface.
Turbulence	Subgrid turbulence intensity as function of resolved winds and buoyancy. Fluxes of heat, moisture, momentum as function of turbulence and resolved temperature, water, & winds. Methods: • local down-gradient eddy diffusivity; • higher-order local closure; or • nonlocal (transilient turb.) mixing.
Atmospheric Boundary Layer (ABL)	Vertical profiles of temperature, humidity, and wind as a function of resolved state and turbulence, based on forecasts of ABL depth. Methods: • bulk; • similarity theory.
Surface	• Use albedo, roughness, etc. from statistical average of varied land use. • Snow cover, vegetation greenness, etc. based on resolved heat & water budget.
Sub-surface heat & water	• Use climatological average. Or forecast heat conduction & water flow in rivers, lakes, glaciers, subsurface, etc.
Mountain-wave Drag	• Vertical momentum flux as function of resolved topography, winds and static stability.

Available choices in WRF

https://www2.mmm.ucar.edu/wrf/users/physics/phys_references.html
(Full list and reference to paper)

WRF Model Physics Options and References

For quick navigation, click buttons below:

Micro Physics | PBL Physics | Cumulus Physics | Radiation Options | Land Surface
Shallow Convect. | Surface Layer | Urban Physics | Ocean Options | Other Options
LES | WRF Specialty Systems

Micro Physics Options *(mp_physics)*

Kessler Scheme	option 1	Kessler, E., 1969: On the distribution and continuity of water substance in atmospheric circulations. *Meteor. Monogr.*, **32**, Amer. Meteor. Soc. doi:10.1007/978-1-935704-36-2_1 PDF
Purdue Lin Scheme	option 2	Chen, S.-H. and W.-Y. Sun, 2002: A one-dimensional time dependent cloud model. *J. Meteor. Soc. Japan.*, **80(1)**, 99–118. doi:10.2151/jmsj.80.99 PDF
WRF Single–moment 3–class and 5–class Schemes	options 3 & 4	Hong, Song–You, Jimy Dudhia, and Shu–Hua Chen, 2004: A revised approach to ice microphysical processes for the bulk parameterization of clouds and precipitation. *Mon. Wea. Rev.*, **132**, 103–120. doi:10.1175/1520-0493(2004)132<0103:ARATIM>2.0.CO;2 PDF
Eta (Ferrier) Scheme	option 5	NOAA, cited 2001: National Oceanic and Atmospheric Administration Changes to the NCEP Meso Eta Analysis and Forecast System: Increase in resolution, new cloud microphysics, modified precipitation assimilation, modified 3DVAR analysis. [Available online at http://www.emc.ncep.noaa.gov/mmb/mmbpll/eta12tpb/.]
WRF Single–moment 6–class Scheme	option 6	Hong, S.–Y., and J.–O. J. Lim, 2006: The WRF single–moment 6–class microphysics scheme (WSM6). *J. Korean Meteor. Soc.*, **42**, 129–151. PDF

Cumulus Parameterization Options *(cu_physics)*

Kain–Fritsch Scheme	option 1	Kain, John S., 2004: The Kain–Fritsch convective parameterization: An update. *J. Appl. Meteor.*, **43**, 170–181. doi:10.1175/1520-0450(2004)043<0170:TKCPAU>2.0.CO;2 PDF
Moisture–advection–based Trigger for Kain–Fritsch Cumulus Scheme	kfeta_trigger = 2	Ma, Lei–Ming, and Zhe–Min Tan, 2009: Improving the behavior of the cumulus parameterization for tropical cyclone prediction: Convection trigger. *Atmos. Res.*, **92**, 190–211. doi:10.1016/j.atmosres.2008.09.022 PDF
RH–dependent Additional Perturbation to option 1 for the Kain–Fritsch Scheme	kfeta_trigger = 3	
New Tiedtke Scheme	option 16	Zhang, C. and Y. Wang, 2017: Projected Future Changes of Tropical Cyclone Activity over the Western North and South Pacific in a 20-km-Mesh Regional Climate Model. *J. Climate*, **30**, 5923-5941. doi:10.1175/JCLI-D-16-0597.1 PDF

Planetary Boundary Layer (PBL) Physics Options *(bl_pbl_physics)*

Yonsei University Scheme (YSU)	option 1	Hong, Song–You, Yign Noh, Jimy Dudhia, 2006: A new vertical diffusion package with an explicit treatment of entrainment processes. *Mon. Wea. Rev.*, **134**, 2318–2341. doi:10.1175/MWR3199.1 PDF
Mellor–Yamada–Janjic Scheme (MYJ)	option 2	Janjic, Zavisa I., 1994: The Step–Mountain Eta Coordinate Model: Further developments of the convection, viscous sublayer, and turbulence closure schemes. *Mon. Wea. Rev.*, **122**, 927–945. doi:10.1175/1520-0493(1994)122%3c0927:TSMECM%3e2.0.CO;2 PDF Mesinger, F., 1993: Forecasting upper tropospheric turbulence within the framework of the Mellor-Yamada 2.5 closure. *Res. Activ. in Atmos. and Ocean. Mod., WMO, Geneva, CAS/JSC WGNE* **Rep. No. 18**, 4.28-4.29. PDF

Land Surface Options *(sf_surface_physics)*

5–layer Thermal Diffusion Scheme	option 1	Dudhia, Jimy, 1996: A multi-layer soil temperature model for MM5. the Sixth PSU/NCAR Mesoscale Model Users' Workshop. PDF
Unified Noah Land Surface Model	option 2	Tewari, M., F. Chen, W. Wang, J. Dudhia, M. A. LeMone, K. Mitchell, M. Ek, G. Gayno, J. Wegiel, and R. H. Cuenca, 2004: Implementation and verification of the unified NOAH land surface model in the WRF model. *20th conference on weather analysis and forecasting/16th conference on numerical weather prediction*, pp. 11–15. PDF

Accumulation of science community's contributions - very numerous.

Available choices in WRF

https://www2.mmm.ucar.edu/wrf/users/docs/user_guide_V3/user_guide_V3.8/users_guide_chap5.htm#Phys

(Short description of models and options)

https://www2.mmm.ucar.edu/wrf/users/docs/user_guide_V3/user_guide_V3.8/users_guide_chap5.htm#Phys

1. Microphysics (mp_physics)

a. Kessler scheme: A warm-rain (i.e. no ice) scheme used commonly in idealized cloud modeling studies (*mp_physics* = 1).

b. Lin et al. scheme: A sophisticated scheme that has ice, snow and graupel processes, suitable for real-data high-resolution simulations (2).

c. WRF Single-Moment 3-class scheme: A simple, efficient scheme with ice and snow processes suitable for mesoscale grid sizes (3).

d. WRF Single-Moment 5-class scheme: A slightly more sophisticated version of (c) that allows for mixed-phase processes and super-cooled water (4).

e. Eta microphysics: The operational microphysics in NCEP models. A simple efficient scheme with diagnostic mixed-phase processes. For fine resolutions (< 5km) use option (5) and for coarse resolutions use option (95).

f. WRF Single-Moment 6-class scheme: A scheme with ice, snow and graupel processes suitable for high-resolution simulations (6).

g. Goddard microphysics scheme. A scheme with ice, snow and graupel processes suitable for high-resolution simulations (7). New in Version 3.0.

h. New Thompson et al. scheme: A new scheme with ice, snow and graupel processes suitable for high-resolution simulations (8). This adds rain number concentration and updates the scheme from the one in Version 3.0. New in Version 3.1.

i. Milbrandt-Yau Double-Moment 7-class scheme (9). This scheme includes separate categories for hail and graupel with double-moment cloud, rain, ice, snow, graupel and hail. New in Version 3.2. (*Note*: Do not use this scheme in V3.6 and V3.6.1.)

j. Morrison double-moment scheme (10). Double-moment ice, snow, rain and graupel for cloud-resolving simulations. New in Version 3.0.

k. WRF Double-Moment 5-class scheme (14). This scheme has double-moment rain. Cloud and CCN for warm processes, but is otherwise like WSM5. New in Version 3.1.

l. WRF Double-Moment 6-class scheme (16). This scheme has double-moment rain. Cloud and CCN for warm processes, but is otherwise like WSM6. New in Version 3.1.

https://

5. Cumulus Parameterization (cu_physics)

a. Kain-Fritsch scheme: Deep and shallow co

- *kfeta_trigger* = 1 – default trigger; = 2 – when large-scale forcing is weak.
- *cu_rad_feedback* = true – allow sub-grid

b. Betts-Miller-Janjic scheme. Operational Et

c. Grell-Devenyi (GD) ensemble scheme: Mu

d. Simplified Arakawa-Schubert (4). Simple r Version 3.3.

e. Grell 3D is an improved version of the GD New in Version 3.0.

f. Tiedtke scheme (U. of Hawaii version) (6).

g. Zhang-McFarlane scheme (7). Mass-flux C

h. New Simplified Arakawa-Schubert (14). New mass-flux scheme with deep and shallow components and momentum transport. New in Version 3.3.

i. New Simplified Arakawa-Schubert (84, HWRF version). New mass-flux scheme with deep and shallow components and momentum transport. New in Version 3.4.

j. Grell-Freitas (GF) scheme (3): An improved GD scheme that tries to smooth the transition to cloud-resolving scales, as proposed by Arakawa et al. (2004). New in Version 3.5.

k. Old Kain-Fritsch scheme: Deep convection scheme using a mass flux approach with downdrafts and CAPE removal time scale (99).

l. Multi-scale Kain-Fritsch scheme (11): using scale-dependent dynamic adjustment timescale, LCC-based entrainment. Also uses new trigger function based on Bechtold.

m. New Tiedtke scheme (16): this version is similar to the Tiedtke scheme used in REGCM4 and ECMWF cy40r1. New in V3.7, updated in V3.8.

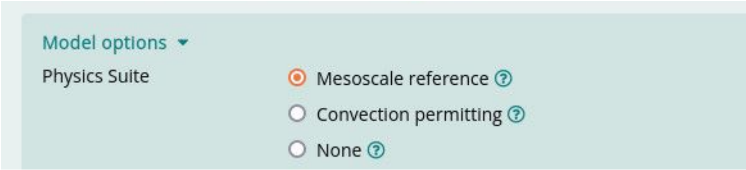
n. Kain-Fritsch-Cumulus Potential scheme (10): this option modifies the KF ad-hoc trigger function with one linked to boundary layer turbulence via probability density function (PDFs) using cumulus potential scheme. The scheme also computes the cumulus cloud fraction based on the time-scale relevant for shallow cumuli. (Berg et al. 2013.) New in V3.8.

Available choices in MPAS-A / CPAS

Table 6.3: Possible options for individual physics parameterizations. Namelist variables should be added to the &physics namelist record.

Parameterization	Namelist variable	Possible options	Details
Convection	config_convection_scheme	cu_tiedtke	Tiedtke (WRF 3.8.1)
		cu_ntiedtke	New Tiedtke (WRF 4.0.3)
		cu_grell_freitas	Modified version of scale-aware Grell-Freitas (WRF 3.6.1)
		cu_kain_fritsch	Kain-Fritsch (WRF 3.2.1)
Microphysics	config_microp_scheme	mp_wsm6	WSM 6-class (WRF 4.1)
		mp_thompson	Thompson non-aerosol aware (WRF 3.8.1)
		mp_kessler	Kessler
Land surface	config_lsm_scheme	noah	Noah (WRF 4.0.3)
Boundary layer	config_pbl_scheme	bl_ysu	YSU (WRF 4.0.3)
		bl_mynn	MYNN (WRF 3.6.1)
Surface layer	config_sfclayer_scheme	sf_monin_obukhov	Monin-Obukhov (WRF 4.0.3)
		sf_mynn	MYNN (WRF 3.6.1)
Radiation, LW	config_radt_lw_scheme	rrtmg_lw	RRTMG (WRF 3.8.1)
		cam_lw	CAM (WRF 3.3.1)
Radiation, SW	config_radt_sw_scheme	rrtmg_sw	RRTMG (WRF 3.8.1)
		cam_sw	CAM (WRF 3.3.1)
Cloud fraction for radiation	config_radt_cld_scheme	cld_fraction	Xu and Randall (1996)
		cld_incidence	0/1 cloud fraction depending on $q_c + q_i$
Gravity wave drag by orography	config_gwdo_scheme	bl_ysu_gwdo	YSU (WRF 4.0.3)

Physics Suite



Mesoscale reference

Parameterization	Scheme
Convection	New Tiedtke
Microphysics	WSM6
Land surface	Noah
Boundary layer	YSU
Surface layer	Monin-Obukhov
Radiation, LW	RRTMG
Radiation, SW	RRTMG
Cloud fraction for radiation	Xu-Randall
Gravity wave drag by orography	YSU

Convection permitting

Parameterization	Scheme
Convection	Grell-Freitas
Microphysics	Thompson (non-aerosol aware)
Land surface	Noah
Boundary layer	MYNN
Surface layer	MYNN
Radiation, LW	RRTMG
Radiation, SW	RRTMG
Cloud fraction for radiation	Xu-Randall
Gravity wave drag by orography	YSU

Do the grid cells resolve cumulus?

Small grid spacing (<3km)

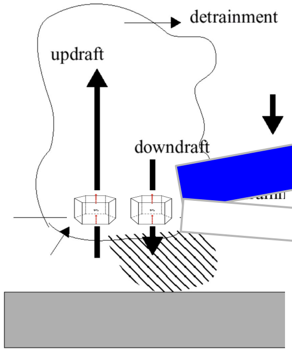
Convection resolving / permitting.
Updraft and downdraft may be simulated.

Precipitation calculated by Microphysics alone.
Turn off convection parameterization

Large grid spacing (>10km)

Grid columns completely contain convective clouds.
Convection not resolved, needs parameterization.

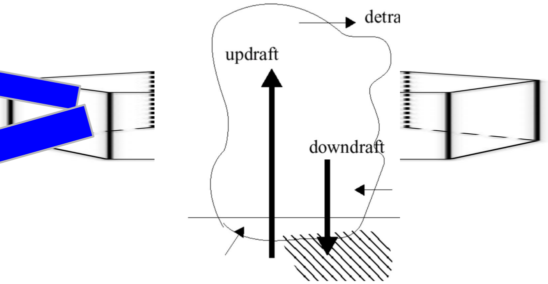
Precipitation calculated by
Microphysics + convection parameterization



Output variable

rainsum
=
rainnc
(non-convective rain by microphysics)
+
rainc
(convective rain by convection parameterization)

Wrong if convection scheme turned on

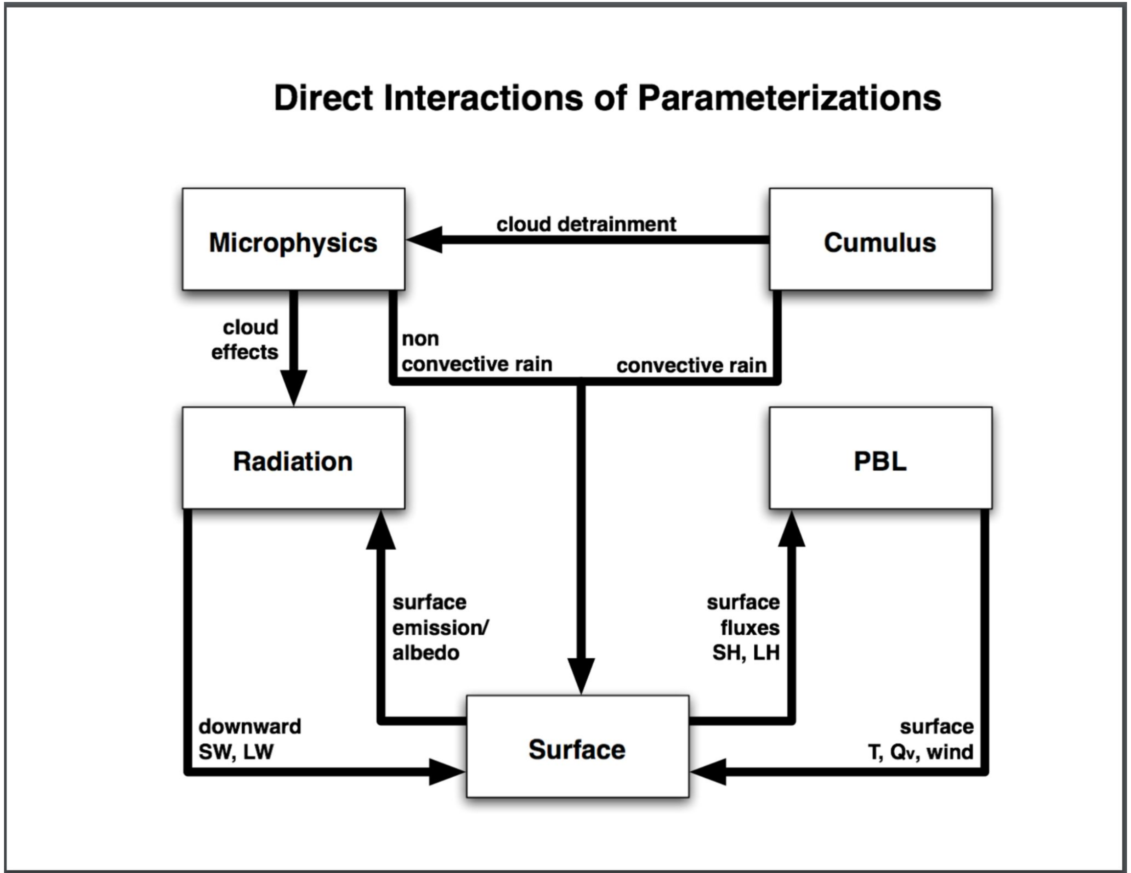


- [x] rainnc - Accumulated total grid-scale precipitation [6.12 MB]
- [x] rainc - Accumulated convective precipitation [6.12 MB]

Interactions of Parameterizations

Moisture distribution may also be affected by other modules.

Cloud affects radiation.



https://homepages.see.leeds.ac.uk/~lecag/wiser/sample_wiser_files.dir/Physics_Dudhia.ppt.pdf
Overview of WRF Physics

Microphysics

github.com/MPAS-Dev/MPAS-Model/blob/master/src/core_atmosphere/Registry.xml

```
<var_array name="scalars" type="real" dimensions="nVertLevels nCells Time">
        <var name="qv" array_group="moist" units="kg kg^{-1}"
             description="Water vapor mixing ratio"/>

        <var name="qc" array_group="moist" units="kg kg^{-1}"
             description="Cloud water mixing ratio"
             packages="bl_mynn_in;bl_ysu_in;cu_tiedtke_in;mp_kessler_in;mp_thompson_in;mp_wsm6_in"/>

        <var name="qr" array_group="moist" units="kg kg^{-1}"
             description="Rain water mixing ratio"
             packages="mp_kessler_in;mp_thompson_in;mp_wsm6_in"/>

        <var name="qi" array_group="moist" units="kg kg^{-1}"
             description="Ice mixing ratio"
             packages="bl_mynn_in;bl_ysu_in;cu_tiedtke_in;mp_thompson_in;mp_wsm6_in"/>

        <var name="qs" array_group="moist" units="kg kg^{-1}"
             description="Snow mixing ratio"
             packages="mp_thompson_in;mp_wsm6_in"/>

        <var name="qg" array_group="moist" units="kg kg^{-1}"
             description="Graupel mixing ratio"
             packages="mp_thompson_in;mp_wsm6_in"/>

        <var name="ni" array_group="number" units="nb kg^{-1}"
             description="Cloud ice number concentration"
             packages="bl_mynn_in;mp_thompson_in"/>

        <var name="nr" array_group="number" units="nb kg^{-1}"
             description="Rain number concentration"
             packages="mp_thompson_in"/>
</var_array>
```

A emulation of the processes by which moisture is removed from the air, based on other thermodynamic and kinematic fields represented within a model.

Clouds can be resolved but hydrometeors are subgrid

Parameterize micro-scale phenomena like:

- Moisture saturation
- Droplet formation & growth / evaporation
- Raindrop / snow / graupel / hail falling

Need to represent hydrometeor particle size distribution.

Simple to complex cloud models

Physics only ?
Physics + Chemistry?
Water only? Aerosol?

Simple: "Single moment":

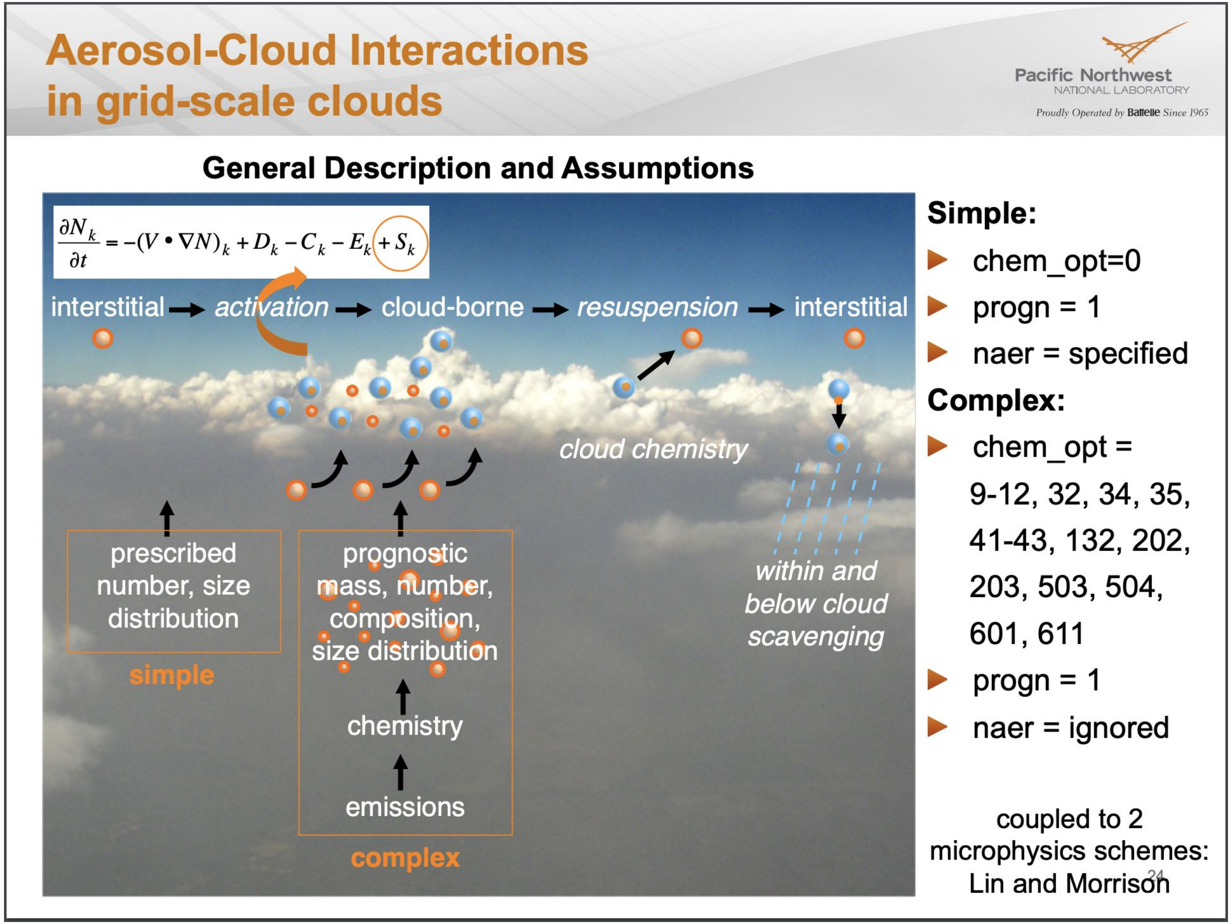
moisture distribution described by mass ratio only.

Unit: kg/kg
weight of moisture / weight of dry air

Available variables | scalars

state (0/1)

☐ scalars - Includes 6 active variables: qv, qc, qr, qi, qs, qg [2,019.62 MB]



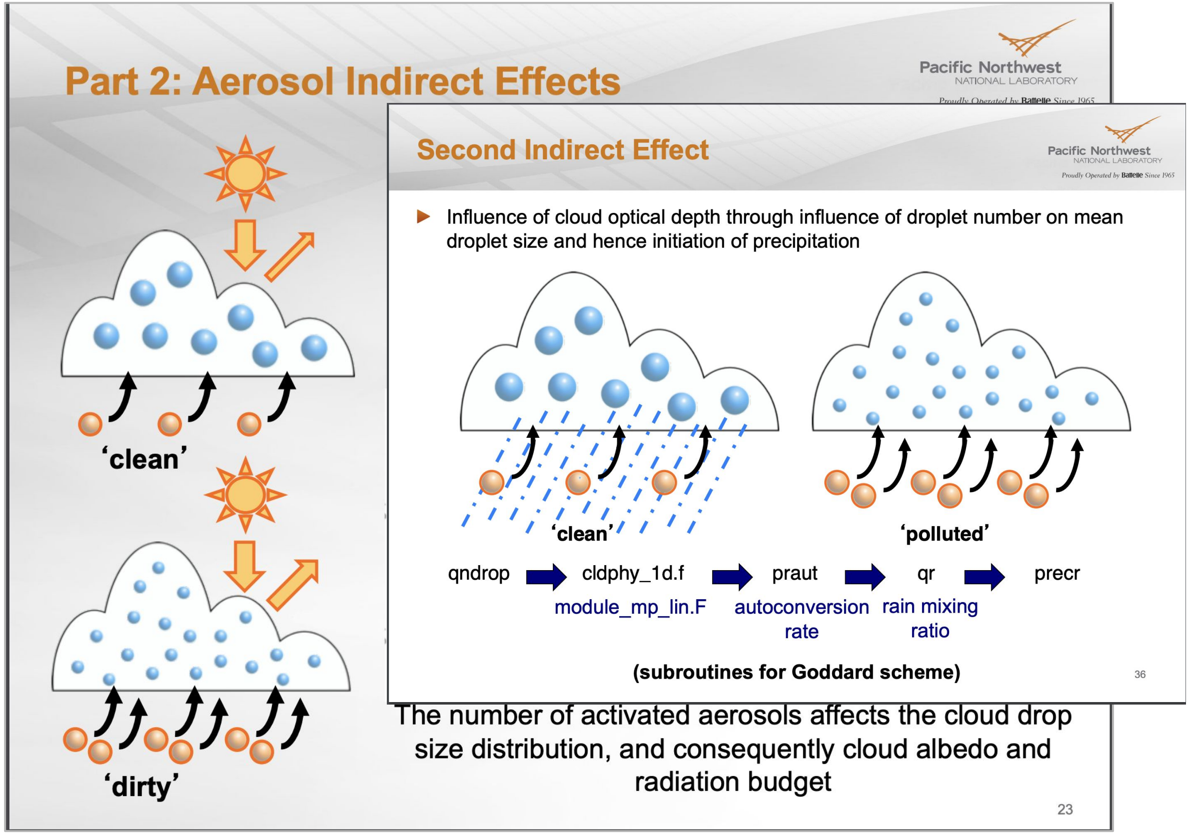
https://ruc.noaa.gov/wrf/wrf-chem/wrf_tutorial_2018/AerosolInteractions.pdf
WRF-Chem tutorial

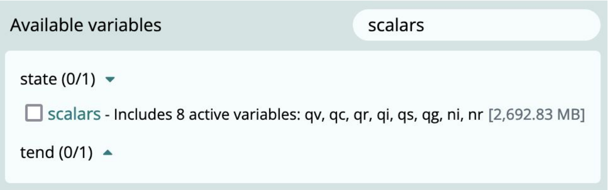
More complicated cloud model

"Double moment"

moisture distribution described by mass ratio {q•} and number concentration {n•}.

Unit: number of droplets / weight of dry air





Convection Parameterization

Cumulus Schemes

- Use for grid columns that completely contain convective clouds
- Re-distribute air in column to account for vertical convective fluxes
  - Updrafts take boundary layer air upwards
  - Downdrafts take mid-level air downwards
- Schemes have to determine
  - When to trigger a convective column
  - How fast to make the convection act

Triggers

- Clouds only activate in columns that meet certain criteria
  - Presence of some convective available potential energy (CAPE) in sounding
  - Not too much convective inhibition (CIN) in sounding (cap strength)
  - Minimum cloud depth from parcel ascent

https://homepages.see.leeds.ac.uk/~lecag/wiser/sample_wiser_files.dir/Physics_Dudhia.ppt.pdf
Overview of WRF Physics, Dudhia NCAR

Convection Parameterization Con't

Closures

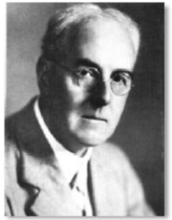
- Closure determine cloud strength (mass-flux) based on various methods
  - Clouds remove CAPE over time
    - Specified CAPE-removal time scale (KF, Tiedtke, ZM, BMJ)
    - Quasi-equilibrium (Arakawa-Schubert) with large-scale destabilization d(CAPE)/dt (SAS, NSAS)
    - Column moisture convergence
    - Low-level large-scale ascent (mass convergence)

Ensemble methods

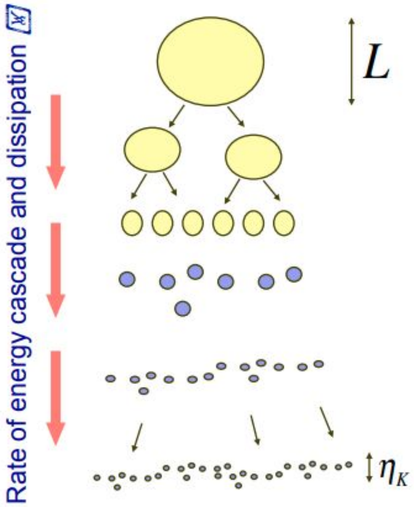
- GF, G3 and GD use ensemble of triggers and closures possibly with with varying parameters (effectively up to 144 members)
- Take mean of ensemble to feed back to model
- In principle, can be tuned to emphasize various members under different conditions

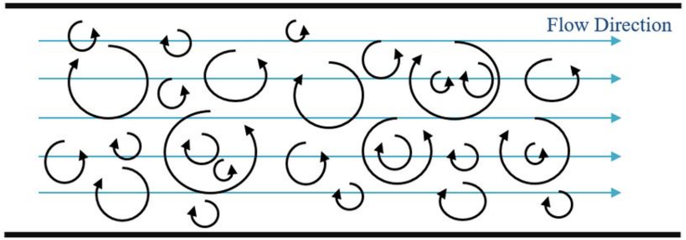
Turbulence (Richardson 1922)

Eddies of different sizes.

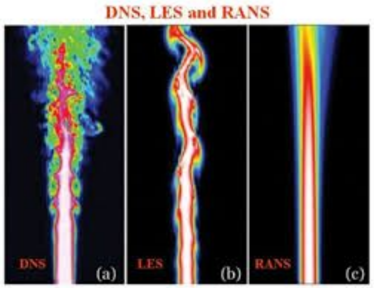


Lewis Fry Richardson





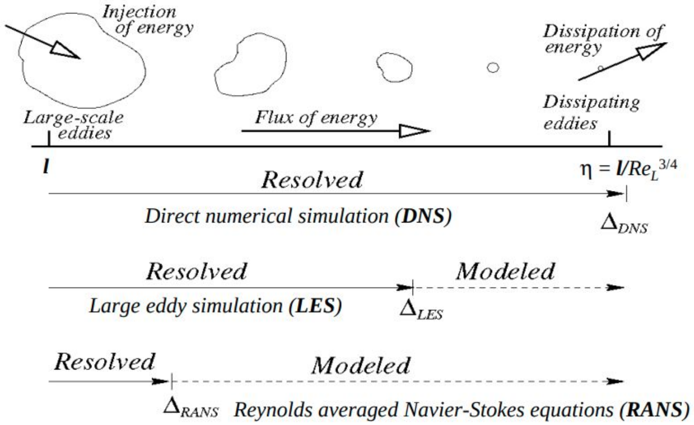
Numerical approaches

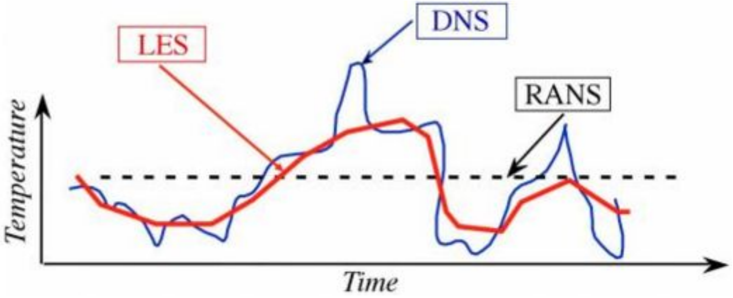


- Direct numerical simulation (DNS)
- Large eddy simulation (LES) first explored by Deardorff (1970 $\tilde{u}_i(\mathbf{x},t) = G_\Delta * u_i = \int G_\Delta(\mathbf{x}-\mathbf{x}')u_i(\mathbf{x}')d^3\mathbf{x}'$
- Reynolds-averaged Navier-Stokes equation (RANS)

$$\widehat{\overline{u}}(\omega) = \widehat{G}(\omega)\,\widehat{u}(\omega)$$

$$\overline{\overline{u}} \neq \overline{u}, \qquad \overline{u\overline{v}} \neq \overline{u}\,\overline{v}$$





Reynolds-Averaged Navier-Stokes equations (RANS)

Reynolds decomposition of the flow variables into mean and perturbation parts, Reynolds, Osborne (1895)

The flow variables can be u, v, w, T and \theta,

(averaging over a grid volume and period of time)

$$u_i(x_k, t) = U_i(x_k) + u'(x_k, t)$$

$$U_i(x_k) = \lim_{T \to \infty} \frac{1}{T} \int_0^T u(x_k, t) dt$$

RANS

$$\overline{u}_i = \frac{1}{T}\int_t^{t+T} u_i \, dt$$

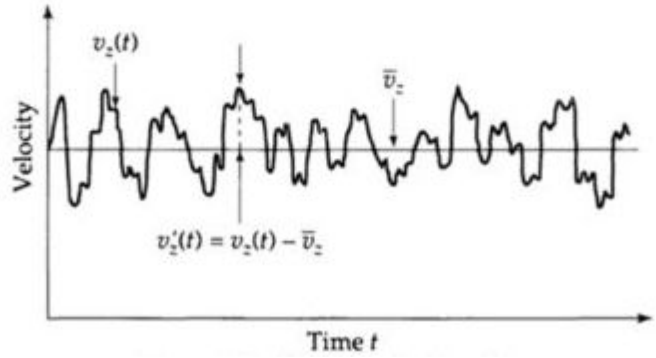
$$\frac{1}{T}\int_t^{t+T} u_i' \, dt = 0$$

averaging over a grid volume and period of time.

$$\overline{\phi'} = 0$$

$$\overline{\phi'} = \overline{\psi'} = 0, \quad \overline{\phi\psi} = \bar{\phi}\bar{\psi} + \overline{\phi'\psi'}, \quad \overline{\bar{\phi}\phi'} = \overline{\bar{\psi}\psi'} = \overline{\bar{\phi}\psi'} = \overline{\bar{\psi}\phi'} = 0 \tag{2.4}$$

$$\overline{\phi^2} = \bar{\phi}^2 + \overline{\phi'^2}, \quad \overline{\frac{\partial\phi}{\partial t}} = \frac{\partial\bar{\phi}}{\partial t}, \quad \overline{\frac{\partial\phi}{\partial x_i}} = \frac{\partial\bar{\phi}}{\partial x_i} \tag{2.5}$$



RANS

$$\frac{\partial u_i}{\partial t} + \frac{\partial}{\partial x_j}(u_i u_j) = -\frac{\partial p}{\partial x_i} + \nu \frac{\partial^2 u_i}{\partial x_j \partial x_j}$$

$$\frac{\partial \overline{u}_i}{\partial t} + \frac{\partial}{\partial x_j}(\overline{u_i u_j}) = -\frac{\partial \overline{p}}{\partial x_i} + \nu \frac{\partial^2 \overline{u}_i}{\partial x_j \partial x_j}$$

$$u = \overline{u} + u'$$
$$w = \overline{w} + w'$$
$$p = \overline{p} + p'$$

$$\overline{u_i u_j} = \overline{(\overline{u}_i + u_i')(\overline{u}_j + u_j')} = \overline{\overline{u}_i \overline{u}_j} + \overline{\overline{u}_i u_j'} + \overline{u_i' \overline{u}_j} + \overline{u_i' u_j'} = \overline{u}_i \overline{u}_j + \overline{u_i' u_j'}$$

$$\frac{\partial \overline{u}_i}{\partial t} + \frac{\partial}{\partial x_j}(\overline{u}_i \overline{u}_j) = -\frac{\partial \overline{p}}{\partial x_i} + \nu \frac{\partial^2 \overline{u}_i}{\partial x_j \partial x_j} - \frac{\partial}{\partial x_j}(\overline{u_i' u_j'})$$

u', w' are correlated

$$\overline{w'} = 0$$
$$\overline{u'} = 0$$

but...

$$\overline{w'u'} \neq 0$$

Reynolds-stress term

$$\frac{\partial(\overline{u_i'u_j'})}{\partial x_j}$$

$$\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial}{\partial x_j}(\bar{u}_i\bar{u}_j) = -\frac{\partial \bar{p}}{\partial x_i} + \nu\frac{\partial^2 \bar{u}_i}{\partial x_j \partial x_j} - \frac{\partial}{\partial x_j}(\overline{u_i'u_j'})$$

-Viscous force (molecular viscosity, diffusion by molecular motions). $\frac{\partial}{\partial z}\left[\nu\frac{\partial \bar{u}}{\partial z}\right]$

-The complete form is Reynolds-stress tensor, is symmetric, the diagonal components are normal stress and off-diagonal components are shear stress.

$$R_{ij} = -\rho\begin{pmatrix} \overline{u'u'} & \overline{u'v'} & \overline{u'w'} \\ \overline{v'u'} & \overline{v'v'} & \overline{v'w'} \\ \overline{w'u'} & \overline{w'v'} & \overline{w'w'} \end{pmatrix}$$

Theories at a glance (details skipped)

Eddy viscosity coefficient

$$\overline{(u'w')} = -K_m \frac{\partial \overline{u}}{\partial z}$$

log wind profile

$$\overline{u} = \frac{u_*}{\kappa} \ln\left(\frac{z-d}{z_0}\right)$$

Prandtl Mixing Length Theory

$$K_m = l_v^2 \left| \frac{\partial \overline{u}}{\partial z} \right|$$

Monin-Obukhov Length

$$L \equiv \frac{-u_*^3 \overline{\theta}_v}{\kappa g \overline{(w'\theta_v')}_s}$$

Friction velocity on surface layer

$$u_*^2 \equiv \left| \overline{(u'w')}_s \right|$$

Modification of log wind profile

$$\frac{d\overline{u}}{dz} = \frac{u_*}{\kappa z} \phi_m$$

$$d\overline{u} = \frac{u_*}{\kappa} \left[\frac{dz}{z} - (1-\phi_m) \frac{dz/L}{z/L} \right]$$

$$\overline{u} = \frac{u_*}{\kappa} \left[\ln \frac{z}{z_0} - \psi_m \right]$$

$$u_{10\mathrm{m}} = u_a \frac{\ln\left(\frac{10+z_0}{z_0}\right) - \psi_m\left(\frac{10+z_0}{L}\right) + \psi_m\left(\frac{z_0}{L}\right)}{\ln\left(\frac{z+z_0}{z_0}\right) - \psi_m\left(\frac{z+z_0}{L}\right) + \psi_m\left(\frac{z_0}{L}\right)}, \quad (24)$$

$$\theta_{2\mathrm{m}} = \theta_g + (\theta_a - \theta_g) \times \frac{\ln\left(\frac{2+z_0}{z_0}\right) - \psi_h\left(\frac{2+z_0}{L}\right) + \psi_h\left(\frac{z_0}{L}\right)}{\ln\left(\frac{z+z_0}{z_0}\right) - \psi_h\left(\frac{z+z_0}{L}\right) + \psi_h\left(\frac{z_0}{L}\right)}, \quad (25)$$

$$q_{2\mathrm{m}} = q_g + (q_a - q_g) \times \frac{\ln\left(\frac{\rho c_p k u_* 2}{c_s} + \frac{2}{z_l}\right) - \psi_h\left(\frac{2}{L}\right) + \psi_h\left(\frac{z_l}{L}\right)}{\ln\left(\frac{\rho c_p k u_* z}{c_s} + \frac{z}{z_l}\right) - \psi_h\left(\frac{z}{L}\right) + \psi_h\left(\frac{z_l}{L}\right)}. \quad (26)$$

Review surface layer scheme

Surface layer	config_sfclayer_scheme	sf_monin_obukhov	Monin-Obukhov (WRF 4.0.3)
		sf_mynn	MYNN (WRF 3.6.1)

Mesoscale reference physics suite – MPAS V7.0

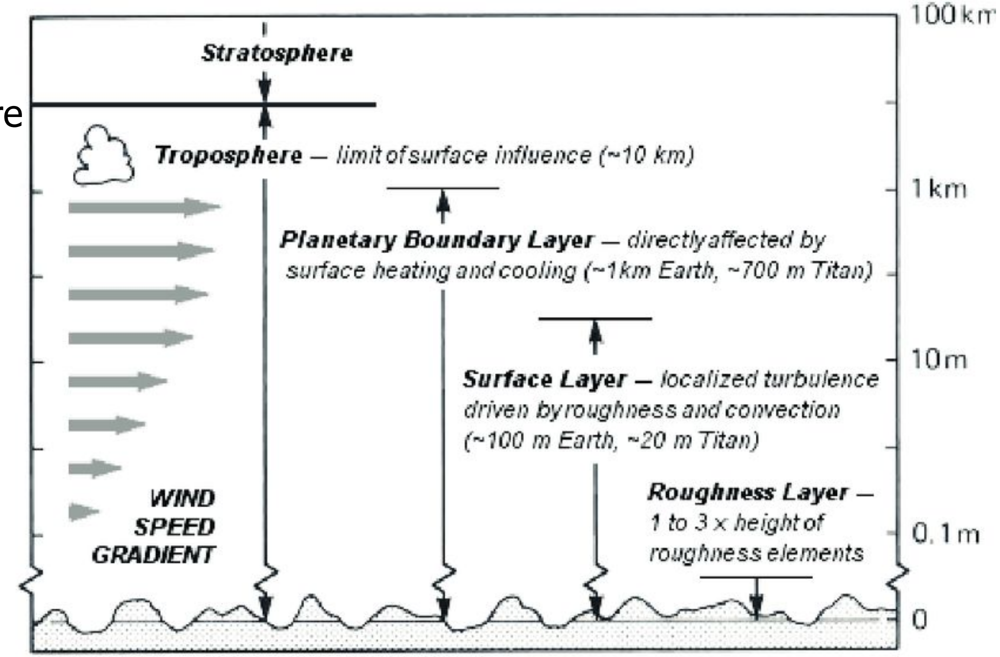
Surface Layer: (Monin Obukhov): module_sf_sfclay.F as in WRF 4.0.3
PBL: YSU as in WRF 4.0.3
Land Surface Model (NOAH 4-layers): as in WRF 4.0.3.
Gravity Wave Drag: YSU gravity wave drag scheme, as in WRF 4.0.3
Convection: new Tiedtke (nTiedtke), as in WRF 4.0.3
Microphysics: WSM6: as in WRF 4.1
Radiation: RRTMG sw as in WRF 3.8.1; RRTMG lw as in WRF 3.8.1
Cloud fraction for radiation: Xu-Randall
Ocean Mixed Layer: modified and extended from WRFV3.6

PBL schemes

Planetary Boundary Layer Scheme

$$L \equiv \frac{-u_*^3 \bar{\theta}_v}{\kappa g \left(\overline{w'\theta'_v}\right)_s}$$

- Monin-Obukhov length L Obukhov, A.M. (1946)
  - L>0, when it is stable atmosphere
  - L<0, when it is an unstable atmosphere
- PBL height
- Diurnal cycle



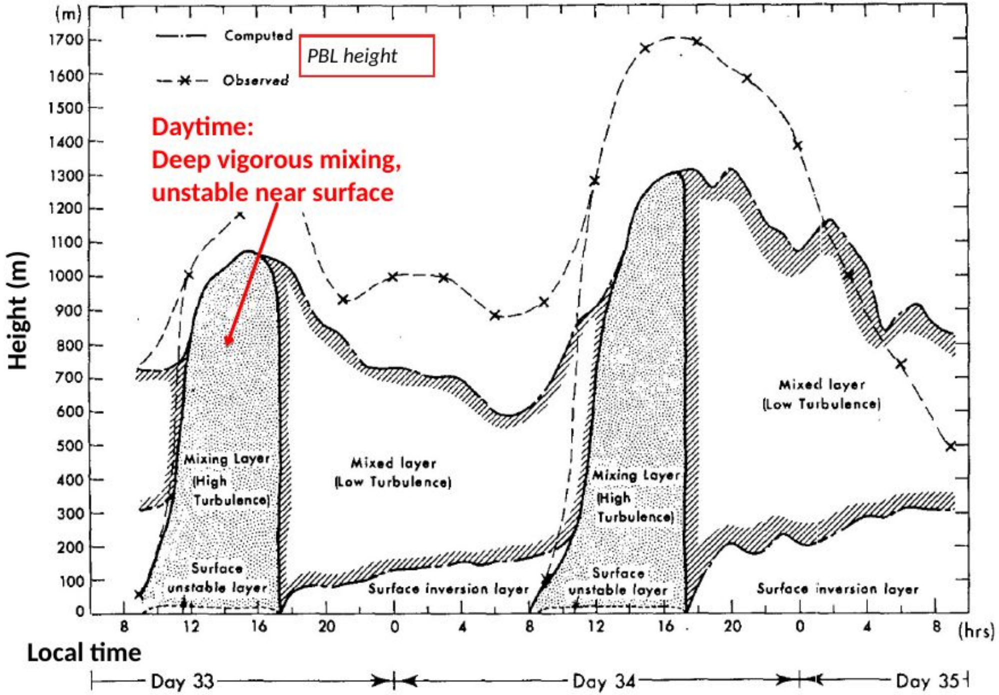
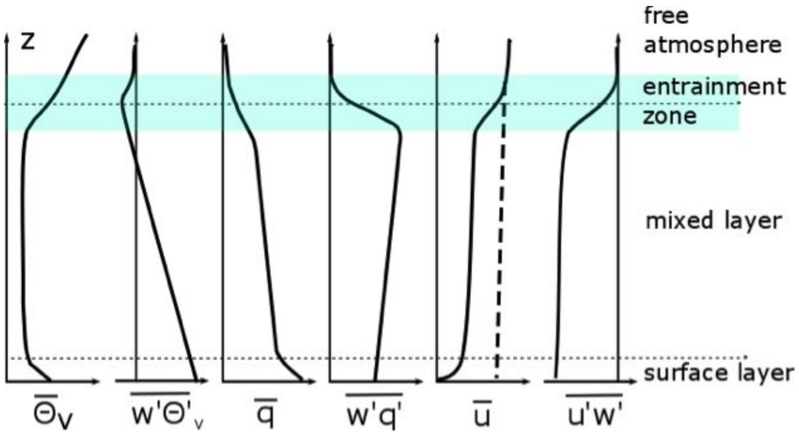


FIG. 33. Time evolution of the computed (basic case) and observed mixed layer height.

Yamada and Mellor (1975)

PBL-Daytime(Afternoon)

- Strong surface heating, the virtual potential temperature will decrease with height near the surface ground. (close to surface layer)
- Moreover, the convective turbulence or eddies mixes efficiently and it is in the mixed layer.
- Vertical profiles of virtual potential temperature, vapor mixing ratio and horizontal momentum. (time-averaged is better)



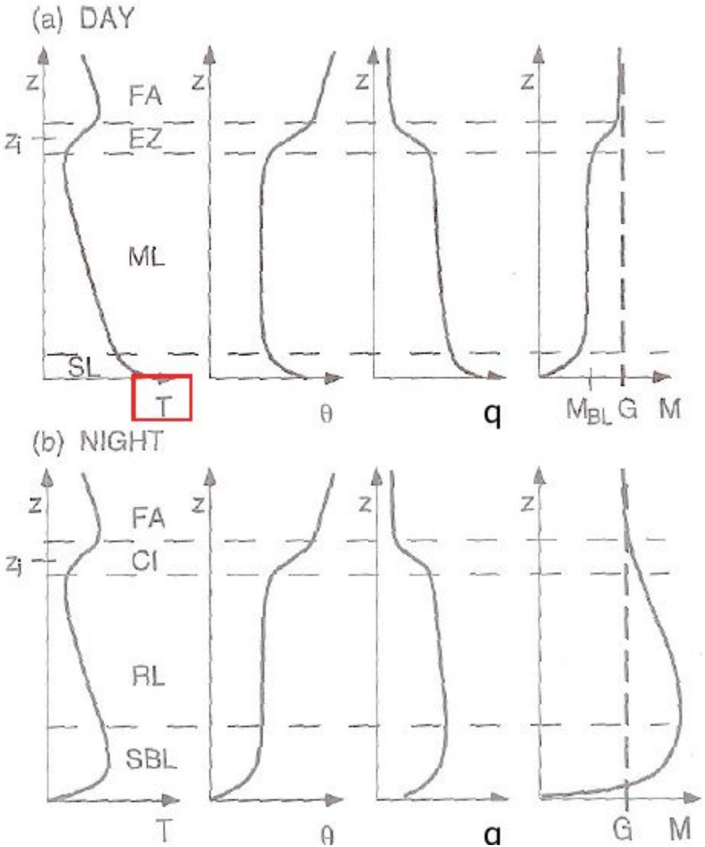
daytime conditions

Contrast day vs. night

Daytime

Nighttime

RL = residual layer
SBL = stable BL



Stull text (2000)

Modeling PBL -- YSU scheme Yonsei University Scheme

1. K-profile parameterization (KPP) over the depth of PBL
2. Another is based on turbulence kinetic energy (TKE)

$$\overline{(u'w')} = -K_m \frac{\partial \overline{u}}{\partial z}$$

The KPP was discussed as non-local K -theory [1986] and is supported by large eddy simulation.
In surface layer scheme, K_m is defined as,

$$K_m = l_v^2 \left| \frac{\partial \overline{u}}{\partial z} \right|$$

and a simple KPP formula of K_m is,

$$K_m = k w_s z \left(1 - \frac{z}{h}\right)^p,$$

\kappa is von Karman constant(=0.4),
z is height from surface,
h is PBL depth,
p=2 in usual,
w_s is velocity scale at surface (u* is friction velocity and \phi_m is stability correction in surface layer)

$$w_s = (u_*^3 + \phi_m k w_{*b}^3 z/h)^{1/3},$$

Troen, I., and L. Mahrt, 1986: A simple model of the atmospheric boundary layer sensitivity to surface evaporation. Bound. Layer Meteor., 37, 129–148.

The typical variation of eddy viscosity K

From observation,

YSU (diagnostic scheme) *imposes* this
MYJ (prognostic scheme) tries to *develop* it

$$K_m = k w_s z \left(1 - \frac{z}{h}\right)^p,$$

$$w_s = (u_*^3 + \phi_m k w_{*b}^3 z/h)^{1/3},$$

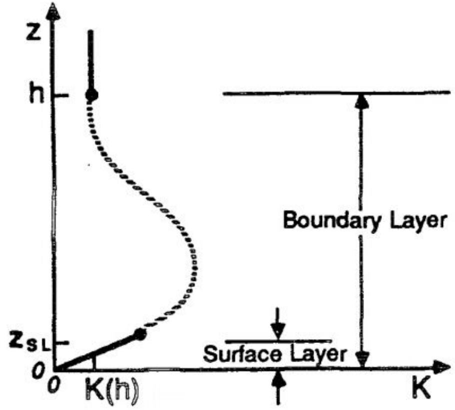
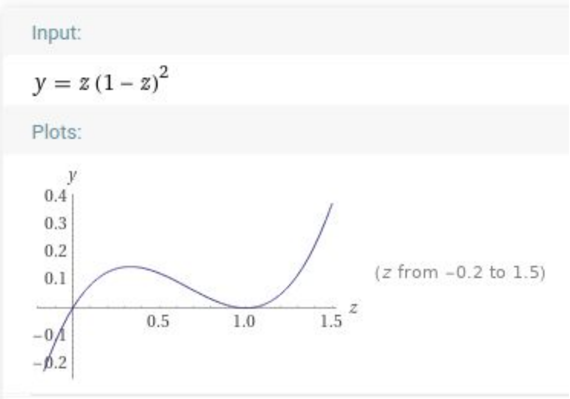


FIG. 1. Typical variation of eddy viscosity K with height in the boundary layer proposed by O'Brien (1970). Adopted from Stull (1988).



u* is the surface friction velocity
w* is the convective velocity scale on surface
b is moist air

moist air, $w_{*b} = [(g/\theta_{va})(\overline{w'\theta_v'})_0 h]^{1/3}$.

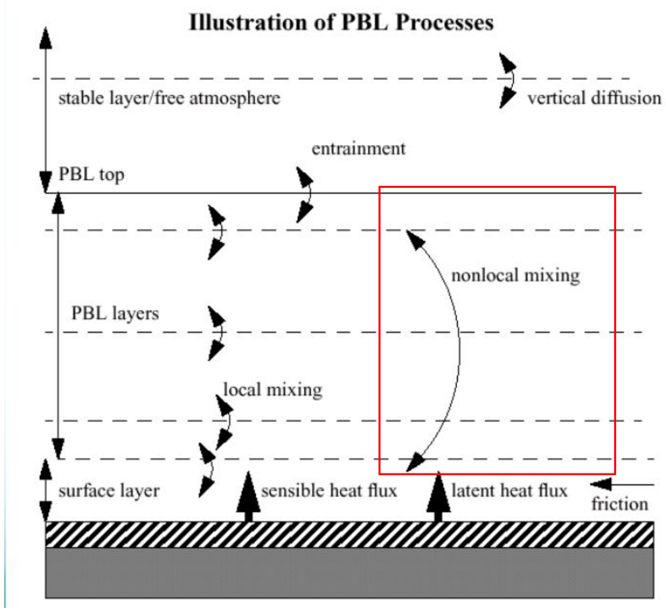
label a is at the lowest model level,
label 0 is near surface

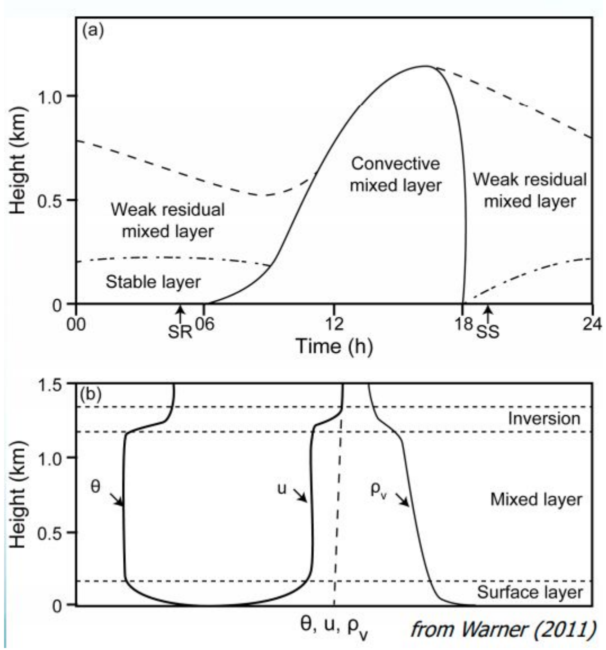
O'Brien, J. (1970), A note on the vertical structure of the eddy exchange coefficient in the PBL,J. Atmos. Sci.,27: 1213–1215.

[H06]

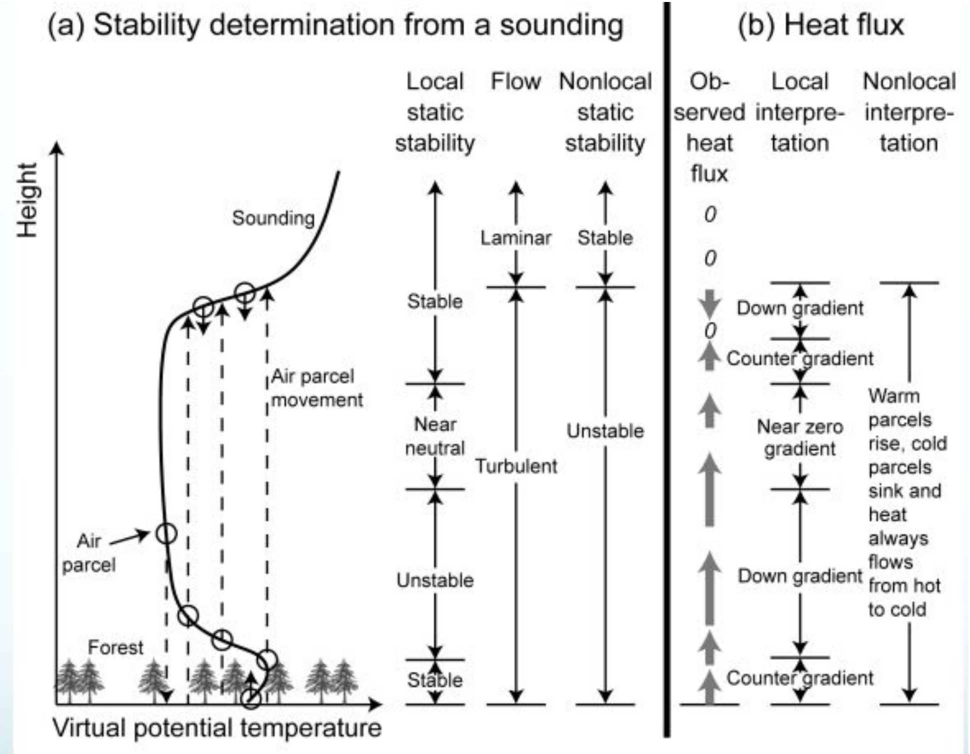
Counter-gradient term

In YSU, the counter-gradient term is applied to temperature, water vapor mixing ratio and momentum. (details on /physics_wrf/module_bl_ysu.F)





PBL Structure and Heat flux



Warner (2011)

$$\overline{w'\phi'}^{\Delta} = \overset{(1)}{-K_{\phi}\frac{\partial \overline{\phi}^{\Delta}}{\partial z}} + \overset{(2)}{F_{w\phi}^{NL}}$$

(1) Term for local (L) transport by small eddies

(2) Term for nonlocal (NL) transport by large eddies

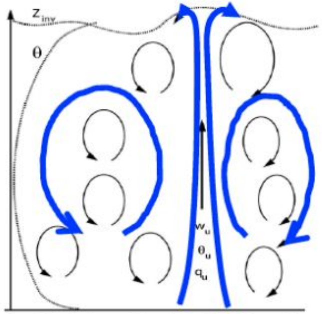


Fig. 1. Sketch of a convective updraft embedded in a turbulent eddy structure.

Explicitly included in **nonlocal PBL parameterizations**

(i.e., Mass-flux term or counter-gradient gamma)

Figure is taken from Siebesma et al. (2007, JAS)

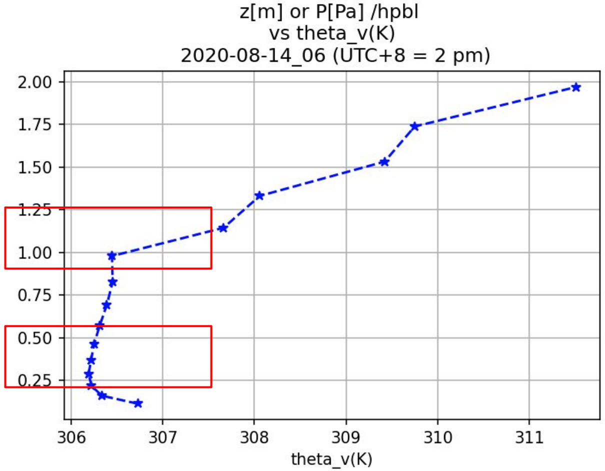
PBL-Daytime(Afternoon)--Example

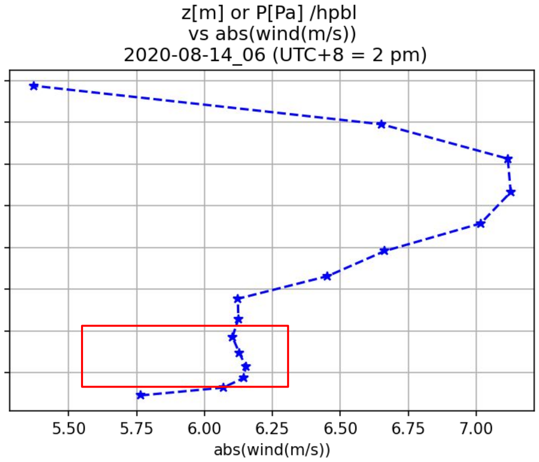
Parameterization	Scheme
Convection	New Tiedtke
Microphysics	WSM6
Land surface	Noah
Boundary layer	YSU
Surface layer	Monin-Obukhov
Radiation, LW	RRTMG
Radiation, SW	RRTMG
Cloud fraction for radiation	Xu-Randall
Gravity wave drag by orography	YSU

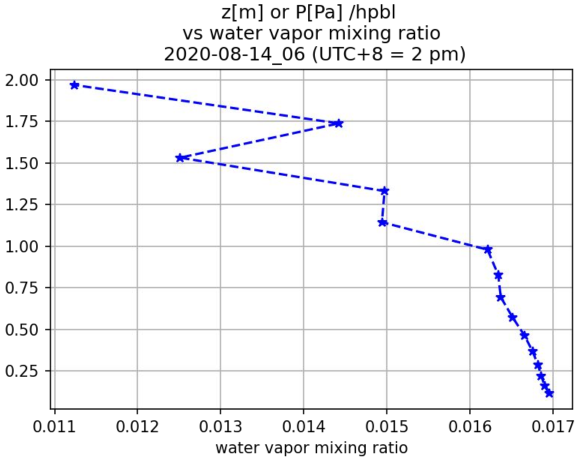
92-25km mesh, it may not be finer enough

HK 2020-8-14-06 (UTC+8 = 2 pm) by Physics Suite: mesoscale reference (YSU)

Unstable atmosphere: PBL height (hpbl = 1070.5765 m)







vertical diffusion coefficient K_h, K_m

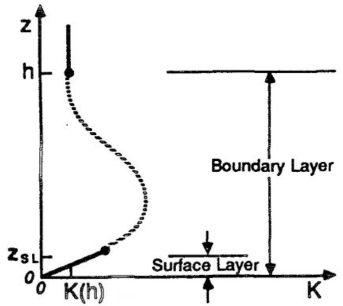
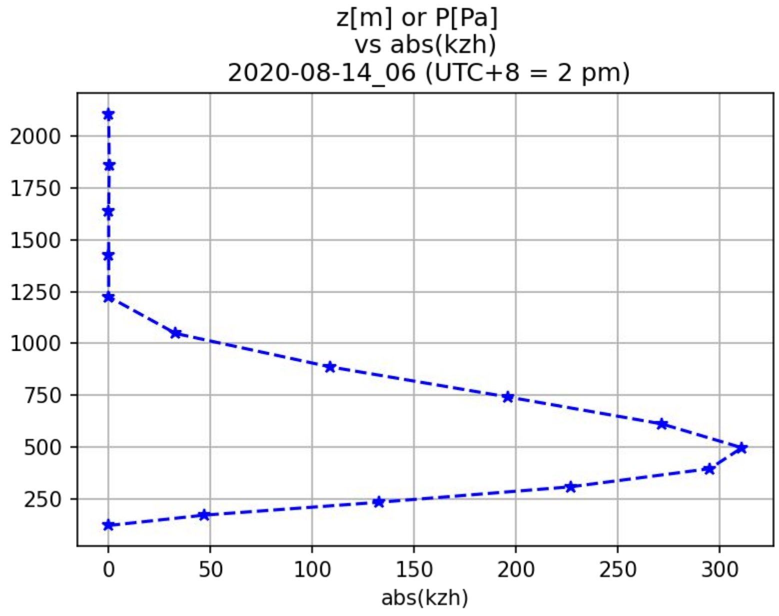
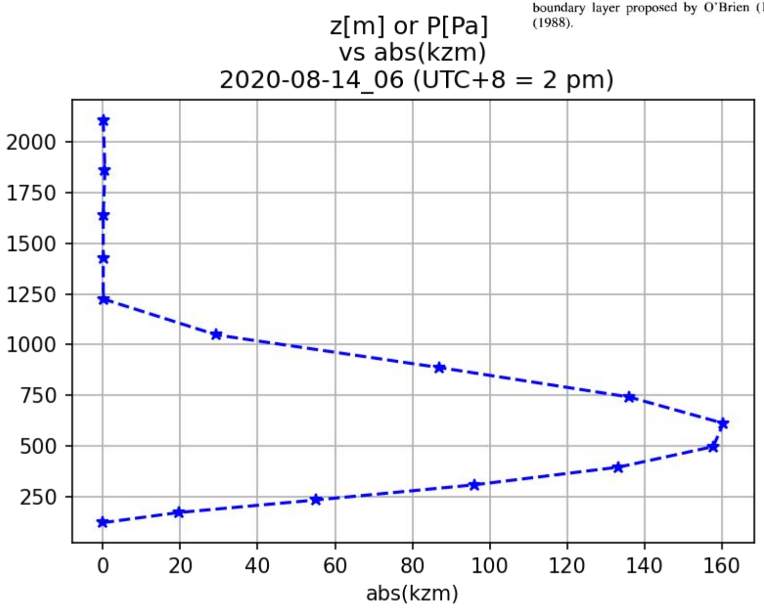


FIG. 1. Typical variation of eddy viscosity K with height in the boundary layer proposed by O'Brien (1970). Adopted from Stull (1988).



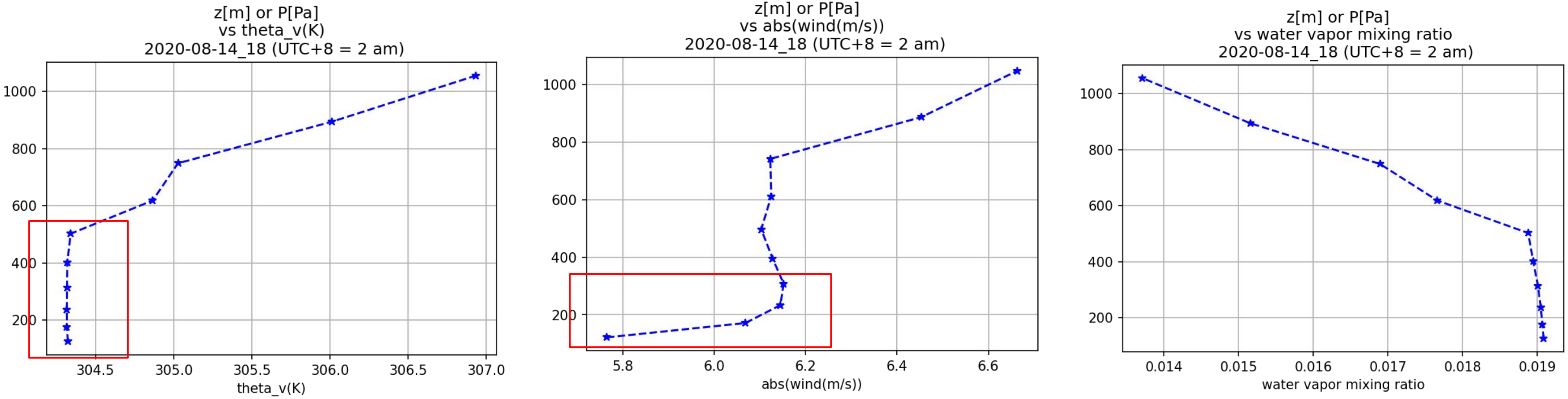


(Unstable atmosphere: PBL height(hpbl = 1070.5765 m)

PBL-Nighttime--Example: HK

HK 2020-8-14-18 (UTC+8 = 2 am) by Physics Suite: mesoscale reference(YSU)

stable atmosphere: PBL height(hpbl = 337.11786 m)



vertical diffusion coefficient K_h , K_m

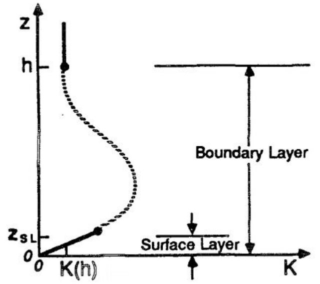
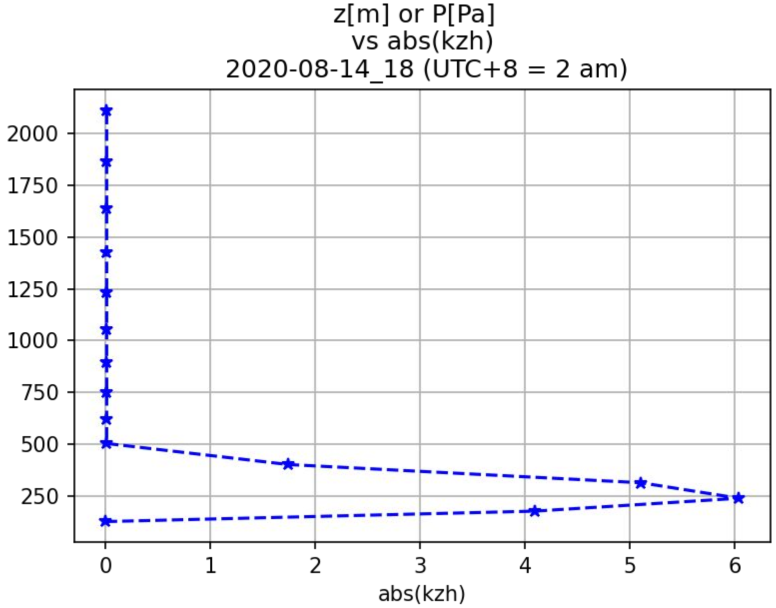
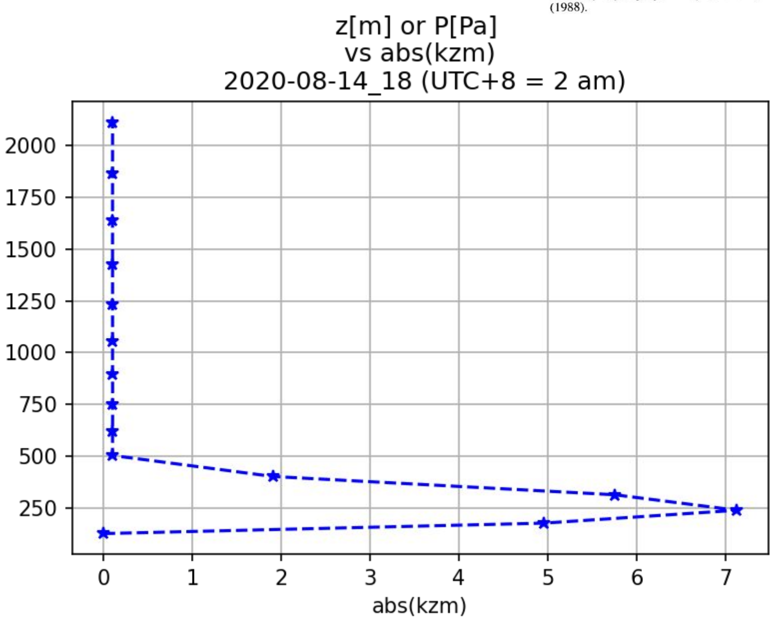


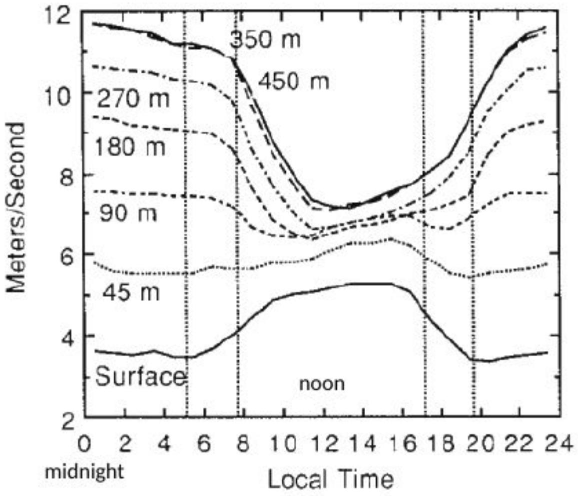
FIG. 1. Typical variation of eddy viscosity K with height in the boundary layer proposed by O'Brien (1970). Adopted from Stull (1988).

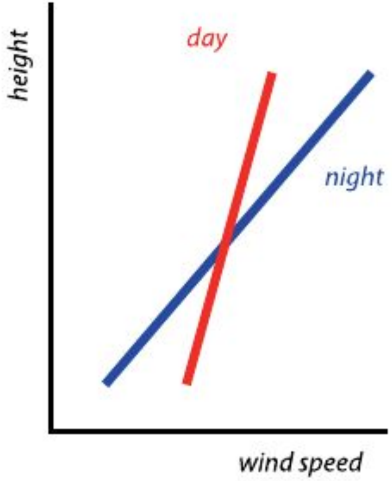




stable atmosphere: PBL height(hpbl = 337.11786 m)

Wind speed with height





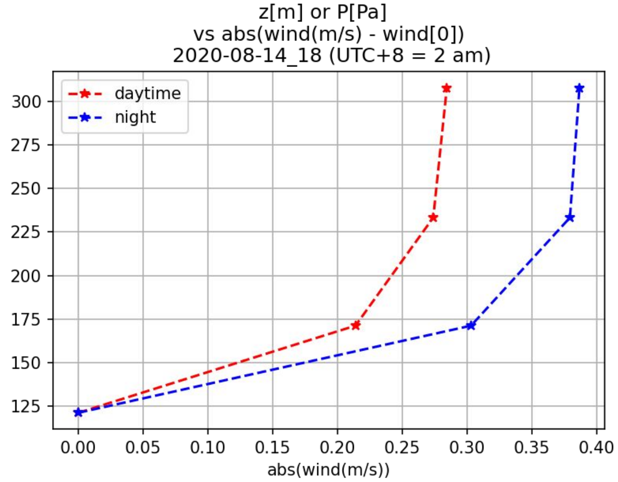


Fig. 4.9 Diurnal cycle of wind speed as a function of height measured from a tower in Oklahoma City and averaged over the period June 1966 to May 1967. [Adapted from Crawford and Hudson (1973). Reprinted with permission from the American Meteorological Society.]

How to learn more on Physics Parameterization Schemes

How to learn more about Physics Parameterizations?

The hard ways:

- Original papers:
  - E.g. How are diagnostics u10 calculated
  - "Surface layer model"
- Reference found in (some) source code
  - Some source code has a documentation header section.
  - Not all source code are well-documented

A more digestible way:

- Regular conferences
  - E.g. the P3 microphysics scheme
- Google search for slides and presentations
  - E.g. scale-aware gravity wave drag scheme

Hard: Finding originating papers - CPAS

CPAS: User Guide - Real Simulation page

https://cpas.earth/userguide/realsimulation

Click to go back, hold to see history

CPAS ClusterTech Pre-release TECHNOLOGY BUSINESS SUPPORT EVENTS & NEWS BLOG CONTACT US SIGN UP / SIGN IN 中

PHYSICS SUITES

Please refer to

- MPAS-A user guide v7.0 - pp. 22-23

Mesoscale reference	The same set of parameterization schemes as the 'mesoscale_reference' physics suite in MPAS-A.
Convection permitting	The same set of parameterization schemes as the 'convection_permitting' physics suite in MPAS-A.
None	All physics parameterizations turned 'off'; intended for idealized simulations.

CONVECTION SCHEMES

Suite	Follow the default of the suite.
Scale-aware new Tiedtke	Similar to the Tiedtke scheme used in REGCM4 and ECMWF cy40r1. See: • Zhang, C. and Y. Wang, 2017: Projected Future Changes of Tropical Cyclone Activity over the Western North and South Pacific in a 20-km-Mesh Regional Climate Model. J. Climate, 30, 5923-5941. doi:10.1175/JCLI-D-16-0597.1 • The scale-awareness formulation from this link.
Scale-aware Tiedtke	Mass-flux type scheme with CAPE-removal time scale, shallow component and momentum transport. See: • Zhang, Chunxi, Yuqing Wang, and Kevin Hamilton, 2011: Improved representation of boundary layer clouds over the southeast pacific in ARW–WRF using a modified Tiedtke cumulus parameterization scheme. Mon. Wea. Rev., 139, 3489–3513. doi:10.1175/MWR-D-10-05091.1 • The scale-awareness formulation from this link.
Kain-Fritsch	Deep and shallow convection sub-grid scheme using a mass flux approach with downdrafts and CAPE removal time scale. See: • Kain, John S., 2004: The Kain–Fritsch convective parameterization: An update. J. Appl. Meteor., 43, 170–181. doi:10.1175/1520-0450(2004)043<0170:TKCPAU>2.0.CO;2
Scale-aware Grell-Freitas	Modified version of scale-aware Grell-Freitas, which is an improved GD (Grell-Devenyi) scheme that tries to smooth the transition to cloud-resolving scales. See: • Grell, G. A. and Freitas, S. R., 2014: A scale and aerosol aware stochastic convective parameterization for weather and air quality modeling, Atmos. Chem. Phys., 14, 5233-5250, doi:10.5194/acp-14-5233-2014.

PBL (PLANETARY BOUNDARY LAYER) SCHEMES

PBL (PLANETARY BOUNDARY LAYER) SCHEMES

Suite	Follow the default of the suite.
YSU	Non-local-K scheme with explicit entrainment layer and parabolic K profile in unstable mixed layer. See: • Hong, Song–You, Yign Noh, Jimy Dudhia, 2006: A new vertical diffusion package with an explicit treatment of entrainment processes. Mon. Wea. Rev., 134, 2318–2341. doi:10.1175/MWR3199.1
MYNN	Predicts sub-grid TKE (Turbulence Kinetic Energy) terms. See: • Nakanishi, M., and H. Niino, 2009: Development of an improved turbulence closure model for the atmospheric boundary layer. J. Meteor. Soc. Japan, 87, 895–912. doi:10.2151/jmsj.87.895

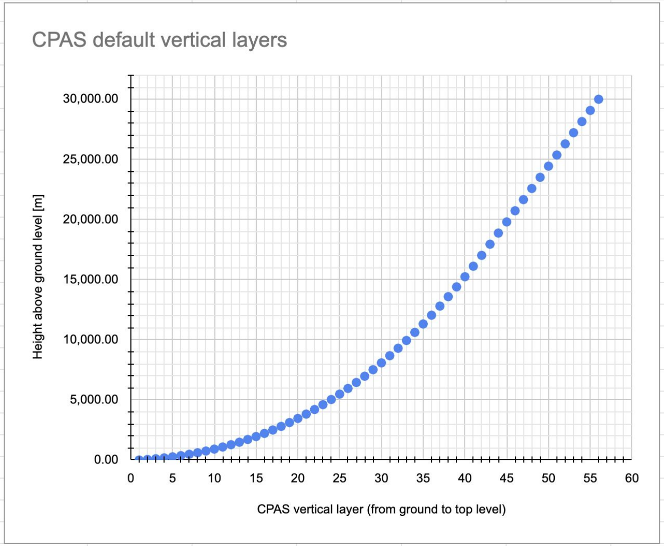
Just a summary of information from WRF for user's convenience.

Question: how are t2m, u10, v10 calculated?

Short answer:

- by the "Surface Layer" scheme
- the lowest layer is usually higher than 10m and surely higher than 2m.

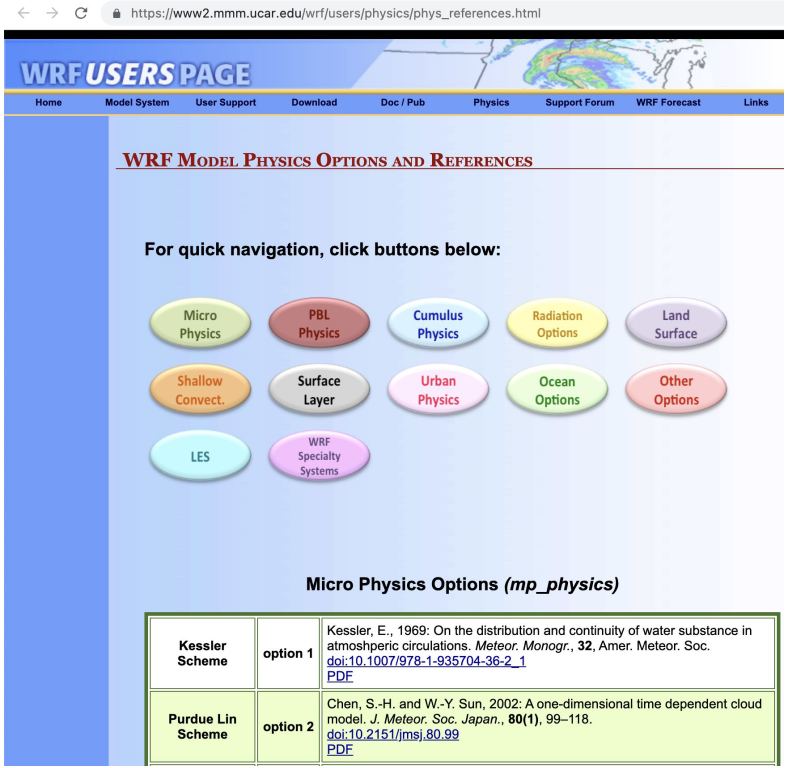
CPAS vertical layer (k)	**Height above ground [unit: m]**
1	0.00
2	46.94
3	106.24
4	178.37
5	263.80
6	362.99
7	476.40
8	604.51
9	747.76
10	906.64
11	1,081.60
12	1,273.11
13	1,481.63
14	1,707.64
15	1,951.58
16	2,213.94
17	2,495.16
18	2,795.73
19	3,116.10
20	3,456.73
21	3,818.10
22	4,200.66
23	4,604.89
24	5,031.24
25	5,480.19
26	5,952.19
27	6,447.71
28	6,967.22
29	7,511.18
30	8,080.05
31	8,674.31
32	9,294.41
33	9,940.82
34	10,614.00
35	11,314.42
36	12,042.55



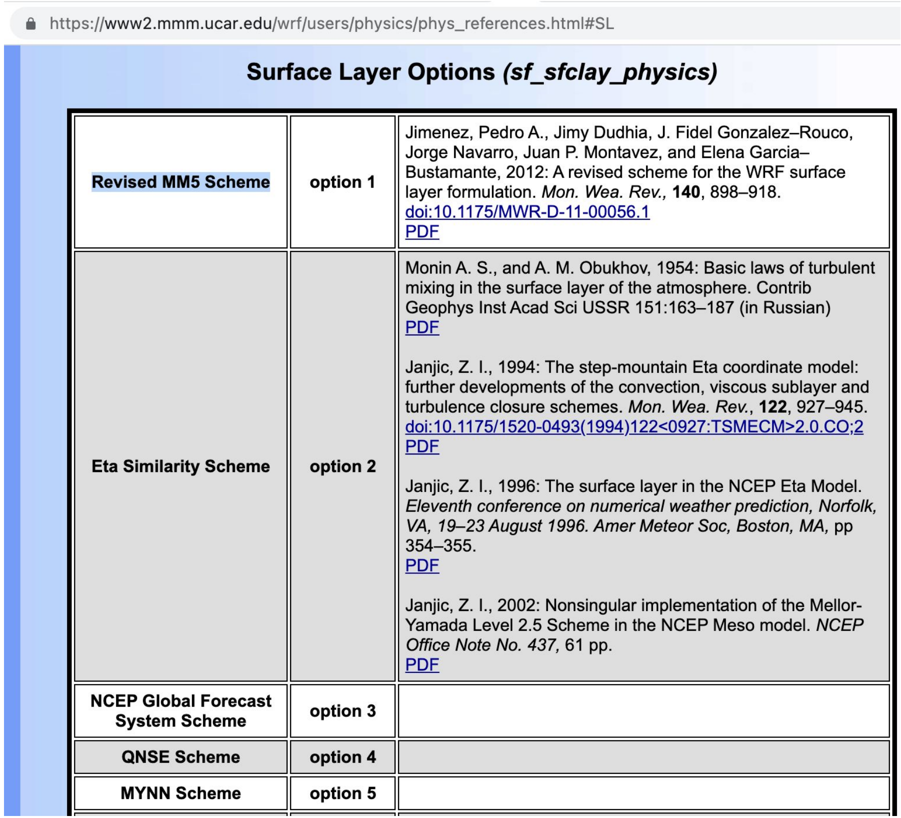
Calculation prepared in a spreadsheet:
https://docs.google.com/spreadsheets/d/1nqeD9wsI1xjlXNMmVYHJJ4lhopKEwCZsqjS2Cbi1Ys4

Hard: Finding originating papers - WRF

WRF: Physics Reference page



Kessler Scheme	option 1	Kessler, E., 1969: On the distribution and continuity of water substance in atmoshperic circulations. *Meteor. Monogr.*, **32**, Amer. Meteor. Soc. doi:10.1007/978-1-935704-36-2_1 PDF
Purdue Lin Scheme	option 2	Chen, S.-H. and W.-Y. Sun, 2002: A one-dimensional time dependent cloud model. *J. Meteor. Soc. Japan.*, **80(1)**, 99–118. doi:10.2151/jmsj.80.99 PDF

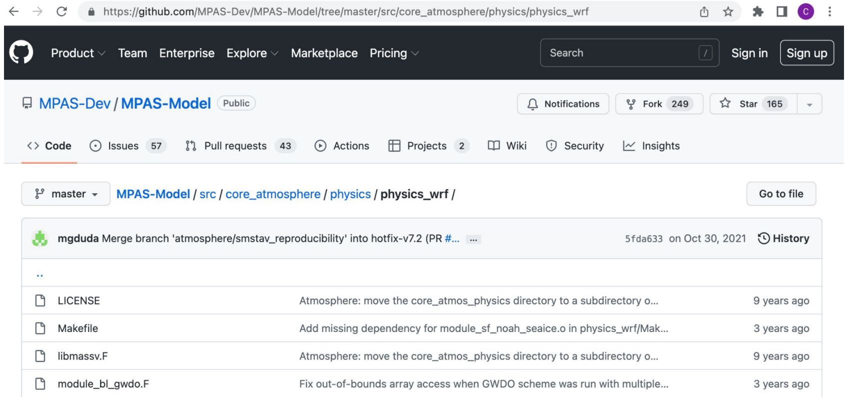


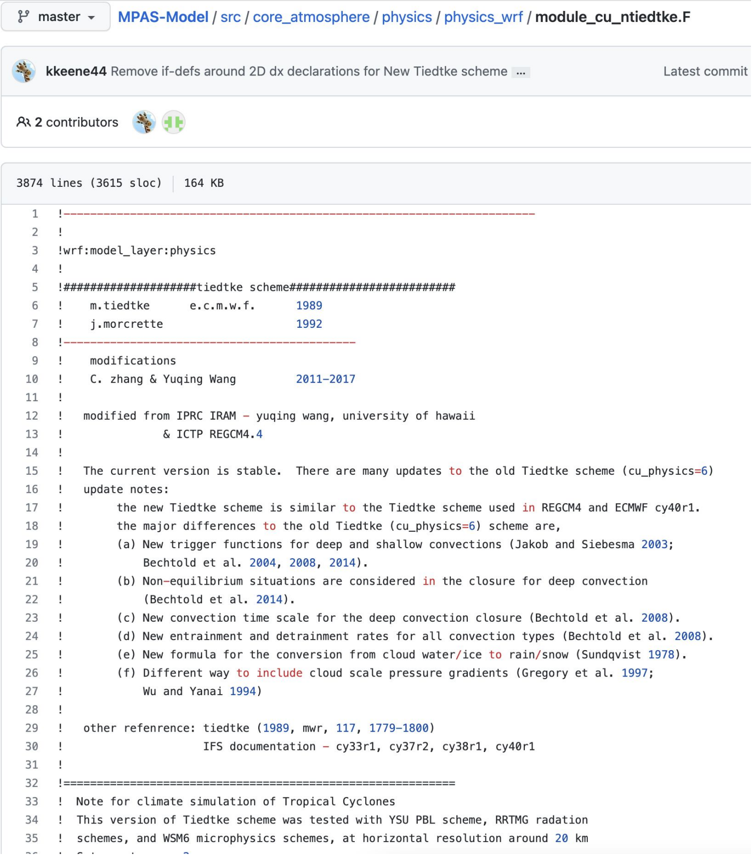
Revised MM5 Scheme	option 1	Jimenez, Pedro A., Jimy Dudhia, J. Fidel Gonzalez–Rouco, Jorge Navarro, Juan P. Montavez, and Elena Garcia–Bustamante, 2012: A revised scheme for the WRF surface layer formulation. *Mon. Wea. Rev.*, **140**, 898–918. doi:10.1175/MWR-D-11-00056.1 PDF
Eta Similarity Scheme	option 2	Monin A. S., and A. M. Obukhov, 1954: Basic laws of turbulent mixing in the surface layer of the atmosphere. Contrib Geophys Inst Acad Sci USSR 151:163–187 (in Russian) PDF Janjic, Z. I., 1994: The step-mountain Eta coordinate model: further developments of the convection, viscous sublayer and turbulence closure schemes. *Mon. Wea. Rev.*, **122**, 927–945. doi:10.1175/1520-0493(1994)122<0927:TSMECM>2.0.CO;2 PDF Janjic, Z. I., 1996: The surface layer in the NCEP Eta Model. *Eleventh conference on numerical weather prediction, Norfolk, VA, 19–23 August 1996. Amer Meteor Soc, Boston, MA*, pp 354–355. PDF Janjic, Z. I., 2002: Nonsingular implementation of the Mellor-Yamada Level 2.5 Scheme in the NCEP Meso model. *NCEP Office Note No. 437*, 61 pp. PDF
NCEP Global Forecast System Scheme	option 3	
QNSE Scheme	option 4	
MYNN Scheme	option 5	

Hard: Finding source code and references

MPAS github

https://github.com/MPAS-Dev/MPAS-Model/tree/master/src/core_atmosphere/physics/physics_wrf






```
!-----------------------------------------------------------------------------
!
!wrf:model_layer:physics
!
!###################tiedtke scheme#######################
!    m.tiedtke      e.c.m.w.f.      1989
!    j.morcrette                    1992
!--------------------------------------------
!    modifications
!    C. zhang & Yuqing Wang         2011-2017
!
!   modified from IPRC IRAM - yuqing wang, university of hawaii
!               & ICTP REGCM4.4
!
!   The current version is stable.  There are many updates to the old Tiedtke scheme (cu_physics=6)
!   update notes:
!        the new Tiedtke scheme is similar to the Tiedtke scheme used in REGCM4 and ECMWF cy40r1.
!        the major differences to the old Tiedtke (cu_physics=6) scheme are,
!        (a) New trigger functions for deep and shallow convections (Jakob and Siebesma 2003;
!            Bechtold et al. 2004, 2008, 2014).
!        (b) Non-equilibrium situations are considered in the closure for deep convection
!            (Bechtold et al. 2014).
!        (c) New convection time scale for the deep convection closure (Bechtold et al. 2008).
!        (d) New entrainment and detrainment rates for all convection types (Bechtold et al. 2008).
!        (e) New formula for the conversion from cloud water/ice to rain/snow (Sundqvist 1978).
!        (f) Different way to include cloud scale pressure gradients (Gregory et al. 1997;
!            Wu and Yanai 1994)
!
!   other refenrence: tiedtke (1989, mwr, 117, 1779-1800)
!                    IFS documentation - cy33r1, cy37r2, cy38r1, cy40r1
!
!=========================================================
!  Note for climate simulation of Tropical Cyclones
!  This version of Tiedtke scheme was tested with YSU PBL scheme, RRTMG radation
!  schemes, and WSM6 microphysics schemes, at horizontal resolution around 20 km
```

Code with documentation header

Digestible way: Google search and look for …

(Yearly) NCAR WRF & MPAS workshop

2019 Agenda 2020 Agenda 2021 Agenda 2022 Agenda

2.6	Using hierarchical time-stepping to utilize MPAS-A computational resources for customized extreme variable-resolution meshes. Ng, Ka-Ki, Kwan-Shu Tse, Yuk Sing Lui, Wai-Nang Leung, Chi Chiu Cheung, and **Sze-Chuan Suen,** *ClusterTech Limited, Hong Kong* *presentation*

Session: Physics Developments / Challenges
First Chair: Wayne Angevine, *CIRES/CU Boulder and NOAA/ESRL*
Second Chair (after break): Lulin Xue, *NCAR*

9:00-9:30	An Overview of Physical Parameterization Development for the Unified Forecast System. **Joe Olson,** *NOAA* Presentation pdf
9:30-9:50	Evaluation of Planetary Boundary Layer (PBL) Parameterizations Using Large-eddy Simulations (LES) in a Broad Range of Conditions. **George Bryan**, *NCAR/MMM* Presentation pdf
9:50–10:10	The E-epsilon PBL Scheme in the WRF Model. **Chunxi Zhang**, *NOAA/NCEP/EMC* Presentation pdf
10:10-10:30	Simulations Across Scales over Complex Terrain: Lessons Learned from a Perdigao Case Study. **Patrick Hawbecker**, Branko Kosović, Domingo Muñoz-Esparza, Jeremy Sauer, Jimy Dudhia, Edward G. Patton, *RAL/NCAR* Presentation pdf
10:30-10:50	*Break*
10:50-11:20	Microphysics: Basics of microphysics in weather and climate models. **Hugh Morrison**, *MMM/NCAR* Presentation pdf
11:20-11:40	Does WRF Have a Warm Rain Problem? **Robert Conrick**, *University of Washington* Short Abstract Presentation pdf
11:40-12:00	The Predicted Particle Properties (P3) Microphysics Scheme -- Applications for Research and Operational NWP. **Jason Milbrandt**, *Environment Canada* Presentation pdf

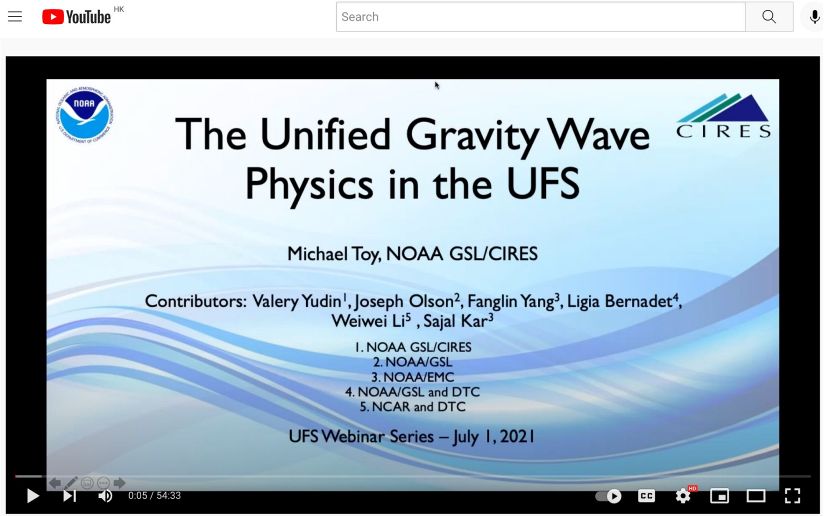
Program for the Joint WRF/MPAS Users' Workshop 2020 (Virtual)
Location: online
Date: 8 – 9 June 2020

Click on titles below for access to .pdf presentations

Monday, 8 June, 1:00 – 3:30 P.M. (All times are Mountain times) **WRF Lecture Series: Learning about Scale-Aware Physics** Chair: Jimy Dudhia	
1:00 – 1:15	An Introduction to Scale-Aware Physics. Dudhia, J., *Mesoscale and Microscale Meteorology Laboratory (MMM), National Center for Atmospheric Research (NCAR)* *Presentation Recording*
1:15 – 1:45	Deep, middle, low, and dx: almost resolving convection but not quite…. Grell, G., *Global System Laboratory, Earth System Research Laboratories (ESRL), National Oceanic and Atmospheric Administration (NOAA)* *Presentation Recording*
1:45 – 2:15	Dependence of deep convection schemes on horizontal grid-spacing in MPAS: Difference in formulation, impact on forecasts. Fowler, L., *MMM/NCAR* *Presentation Recording*
2:15 – 2:30	Break
2:30 – 3:00	A Scale-Aware Treatment of Subgrid Mixing in the WRF Model. Bao, J.-W., *Physical Science Laboratory, ESRL/NOAA* *Presentation Recording*
3:00 – 3:30	Representation of turbulent mixing in the atmospheric boundary layer at gray-zone grid spacings and its applications for idealized and real-case WRF. Shin, H.-Y., *Research Application Laboratory (RAL), NCAR* *Presentation Recording*

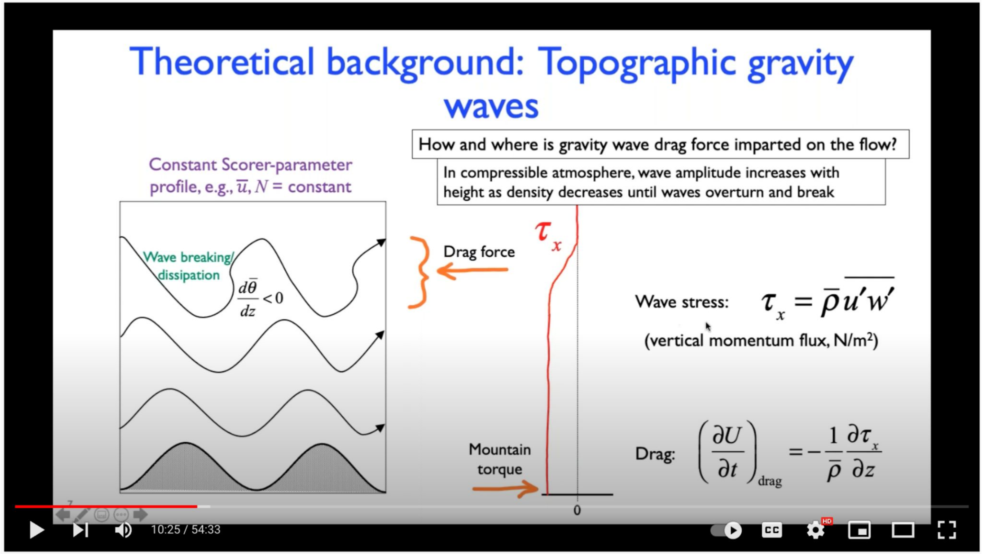
Read more and watch more!

https://www.youtube.com/watch?v=Kmax80kMddk
(54 min video)



What is "gravity wave breaking" ?

What to pay attention to when experimenting the implemented parameterization scheme?



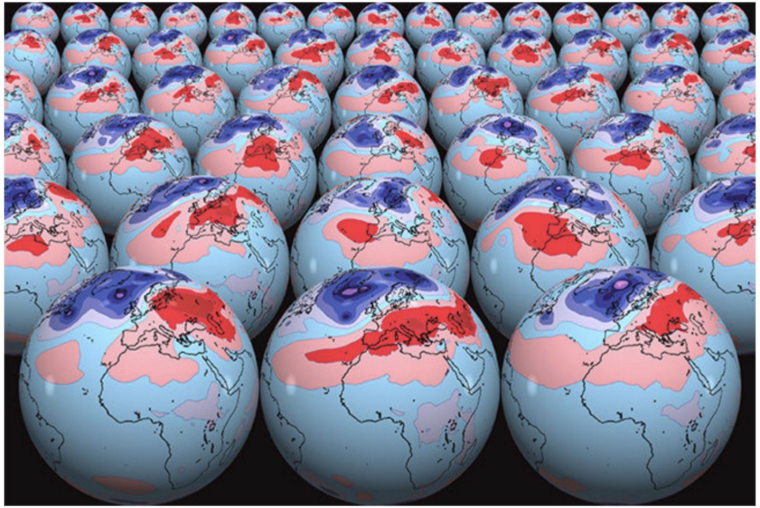
Ensemble Forecasting

ECMWF's introduction to Ensemble Forecasting

Fact sheet: Ensemble weather forecasting

23 March 2017

Share



What is ensemble weather forecasting?

An ensemble weather forecast is a set of forecasts that present the range of future weather possibilities. Multiple simulations are run, each with a slight variation of its initial conditions and with slightly perturbed weather models. These variations represent the inevitable uncertainty in the initial conditions and approximations in the models. They produce a range of possible weather conditions.

Why is it important to measure the level of uncertainty in a forecast?

The uncertainty associated with every forecast means that different scenarios are possible, and the forecast should reflect that. Single 'deterministic' forecasts can be misleading as they fail to provide this information. Take agriculture as an example: a farmer needs to know the range of possible conditions the crops may experience so that they can be protected. Ensemble forecasts show how big that range is at different forecast times.

What are the advantages of ensemble prediction?

By generating a range of possible outcomes, the method can show how likely different scenarios are in the days ahead, and how long into the future the forecasts are useful. The smaller the range of predicted outcomes, the 'sharper' the forecast is said to be. Good ensemble forecasts are not just as sharp as possible but also reliable. If a reliable forecast says that there is a 70% chance of top temperatures rising above a certain threshold, then in 70% of cases when such a forecast is made temperatures will indeed rise above that threshold.

Is uncertainty in a forecast due to a lack of knowledge?

Yes, to some extent our lack of knowledge does significantly increase uncertainty in the forecast. This is why there is much work going into improving our knowledge of initial conditions and of atmospheric processes that computer models need to mirror. In addition, the atmosphere is a chaotic system. This means that it is sensitively dependent on initial conditions. In a chaotic system, a slight change in the input conditions can lead to a significant change in the output forecast. In a non-chaotic system, small differences in initial conditions only give small differences in output. Hence, it is important in weather forecasting to investigate how sensitive the atmosphere is at any stage to initial conditions. Ensemble forecasting does this by looking at a spread of possible outcomes.

https://www.ecmwf.int/en/about/media-centre/focus/2017/fact-sheet-ensemble-weather-forecasting

Chaotic nature of the atmosphere

Well-known “Bufferfly effect”.

Prediction results will be different, given minor differences in:

- Initial Condition
- Model and model options

1. **INTRODUCTION**

Ensemble Prediction Systems (EPS) are numerical weather prediction (NWP) systems that allow us to estimate the uncertainty in a weather forecast as well as the most likely outcome. Instead of running the NWP model once (a deterministic forecast), the model is run many times from very slightly different initial conditions. Often the model physics is also slightly perturbed, and some ensembles use more than one model within the ensemble (multi-model EPS) or the same model but with different combinations of physical parameterization schemes (multi-physics EPS). Owing

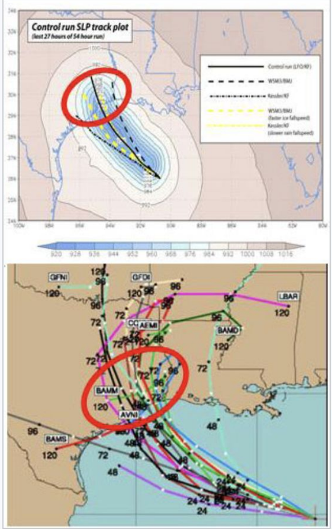
Guidelines on Ensemble Prediction Systems and Forecasting
WMO-No. 1091 © World Meteorological Organization, 2012
https://library.wmo.int/doc_num.php?explnum_id=7773

https://en.wikipedia.org/wiki/Ensemble_forecasting

Ensemble forecasting

From Wikipedia, the free encyclopedia

Ensemble forecasting is a method used in or within numerical weather prediction. Instead of making a single forecast of the most likely weather, a set (or ensemble) of forecasts is produced. This set of forecasts aims to give an indication of the range of possible future states of the atmosphere. Ensemble forecasting is a form of Monte Carlo analysis. The multiple simulations are conducted to account for the two usual sources of uncertainty in forecast models: (1) the errors introduced by the use of imperfect initial conditions, amplified by the chaotic nature of the evolution equations of the atmosphere, which is often referred to as sensitive dependence on initial conditions; and (2) errors introduced because of imperfections in the model formulation, such as the approximate mathematical methods to solve the equations. Ideally, the verified future atmospheric state should fall within the predicted ensemble spread, and the amount of spread should be related to the uncertainty (error) of the forecast. In general, this approach can be used to make probabilistic forecasts of any dynamical system, and not just for weather prediction.



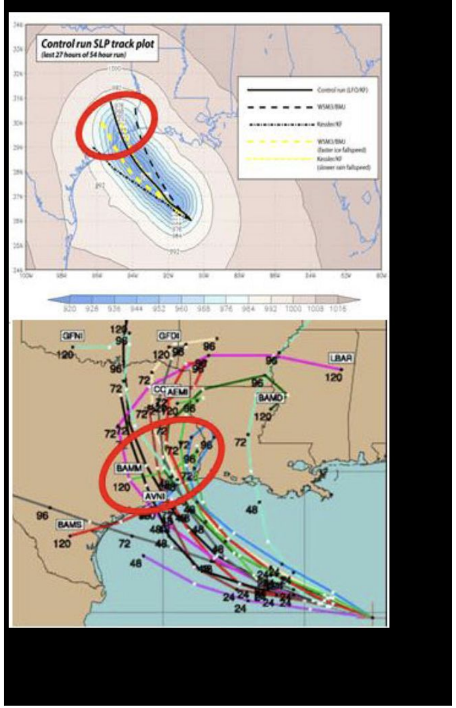
Top: *Weather Research and Forecasting model* simulation of Hurricane Rita tracks. *Bottom*: The spread of National Hurricane Center multi-model ensemble forecast.

Composing ensemble members for our CPAS project

https://en.wikipedia.org/wiki/Ensemble_forecasting#Multi_model_ensembles

Multi model ensembles [edit]

When many different forecast models are used to try to generate a forecast, the approach is termed multi-model ensemble forecasting. This method of forecasting can improve forecasts when compared to a single model-based approach.[18]



Top: *Weather Research and Forecasting model* simulation of Hurricane Rita tracks. *Bottom*: The spread of Natio multi-model ensemble forecast.

Prof. Robert Fovell (UCLA); Dr. Hui Su (JPL) - http://mls.jpl.nasa.gov/research/hurricanes.php

(Top): WRF model simulation of Hurricane Rita tracks. The model resolution is 30km. The colored field shows the lowest sea-level pressure (SLP) recorded during the last 27 hours of a 54 hour control simulation of Rita using LFO (5 class) microphysics and the Kain-Fritsch (KF) convective scheme. The superposed black line traces the model hurricane, which strikes Houston. Also shown are tracks of minimum SLP for runs using the Kessler (warm rain) scheme, the WSM3 simple ice scheme (with the Betts-Miller-Jancic convective scheme), the Kessler with reduced rain fallspeed, and WSM3 with enhanced ice fallspeed. (Bottom): The spread of NHC multi-model ensemble forecast at 06 UTC, 22 September. Note a similar ensemble spread was obtained from a single model simply by varying the model microphysics and convective schemes. Image from Jonathan Vigh, Colorado State University.

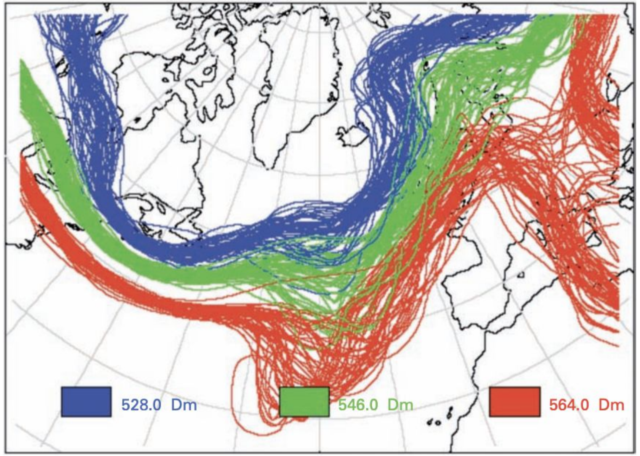
Different ICs as ensemble members:

- The latest IC at our role-paly weather conference time.
- Available ICs before that latest IC
  - Longer simulation duration needed.
  - Give up information coming from latest observation data.

People put ensemble forecasting result together to take a glance

4.1.5 ***Spaghetti maps***

Charts showing a few selected contours of variables (for example, 528, 546 and 564 Dm contours of 500 hPa geopotential height) from all ensemble members can provide a useful image of the predictability of the field. Where all ensemble member contours lie close together the predictability is higher; where they look like spaghetti on a plate, there is less predictability (see Figure 4).

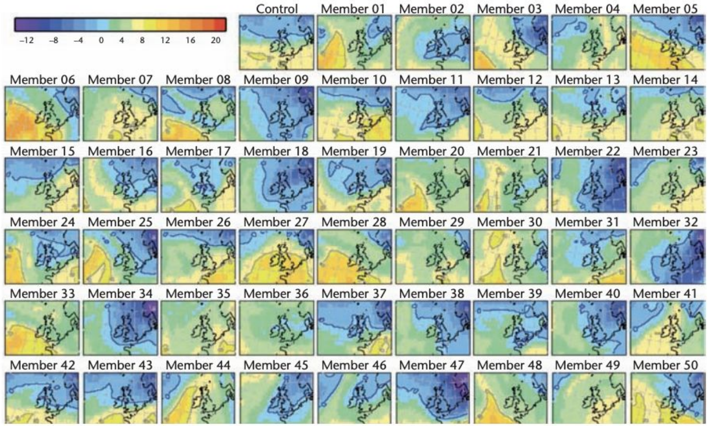


Source: UK Met Office using data from ECMWF, © British Crown Copyright

Figure 4. Ensemble 500 hPa forecast spaghetti charts for 11 February 2001 at 1200 UTC (T + 96 from 7 February 2001 at 1200 UTC)

4.1.6 ***Postage stamp maps***

A set of small maps showing contoured plots of each ensemble individual member (see Figure 5) allows the forecaster to view the scenarios in each member forecast and assess the possible risks of extreme events. However, this presents a large amount of information that can be difficult to assimilate.

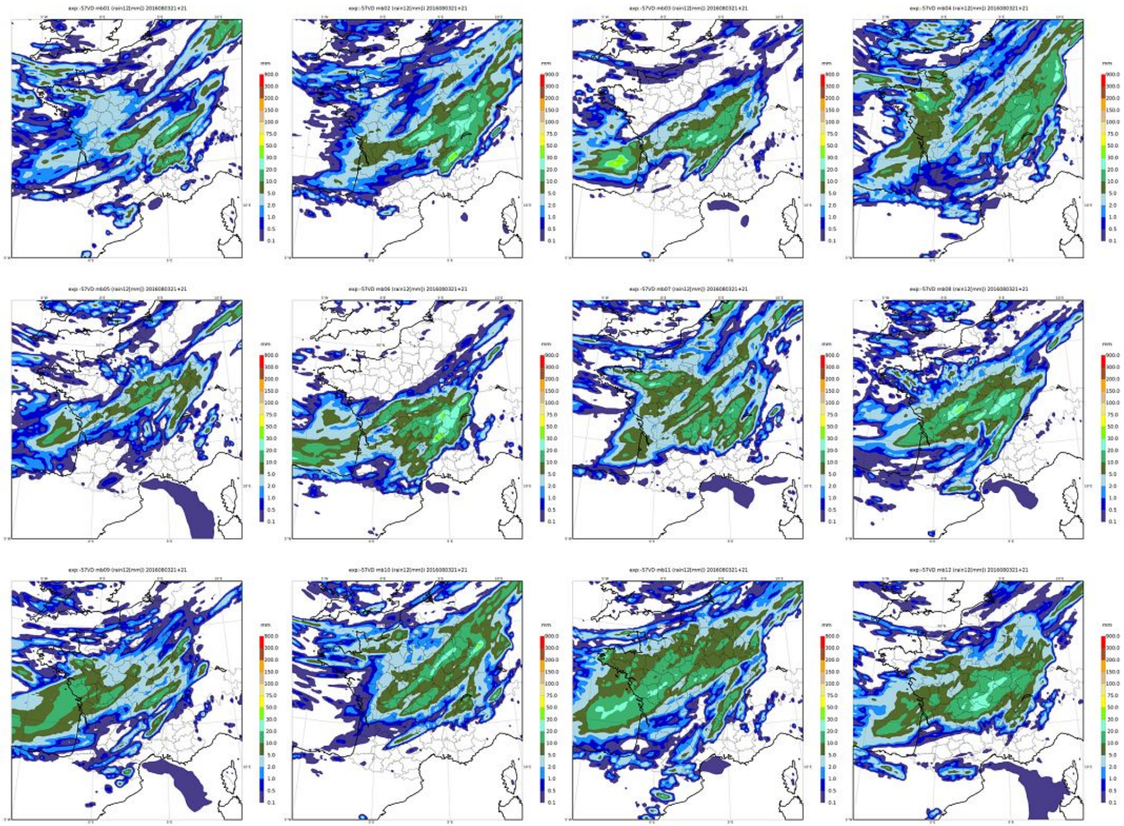


Source: UK Met Office using data from ECMWF, © British Crown Copyright

Figure 5. Postage stamp map for 7 February 2009 at 1200 UTC (850 hPa wetbulb potential temperature, in degrees Celsius; T + 300 from 26 January at 0000 UTC)

Guidelines on Ensemble Prediction Systems and Forecasting
WMO-No. 1091 © World Meteorological Organization, 2012
https://library.wmo.int/doc_num.php?explnum_id=7773

More examples



https://www.encyclopedie-environnement.org/en/air-en/overall-forecast/

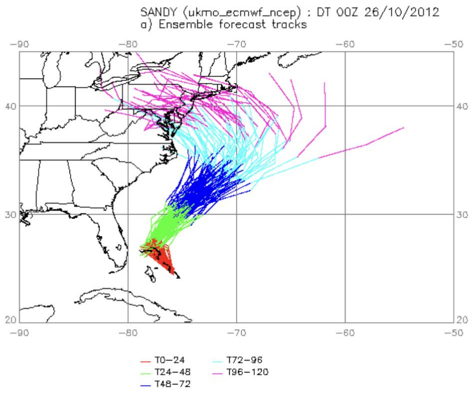


Figure 1: *Example of multi-centre ensemble track predictions for hurricane Sandy.*

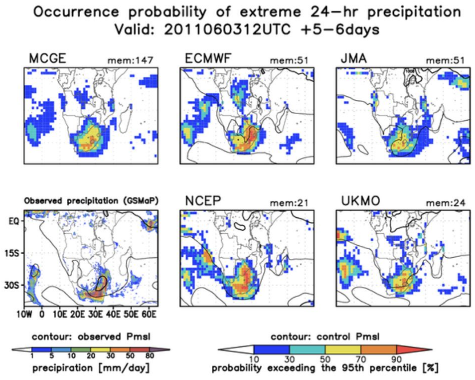


Figure 2: *The forecast probability of heavy rainfall (exceeding the 95th percentile), based on four TIGGE ensembles, and a multi-centre grand ensemble.*

http://www.geo-tasks.org/geoss_portfolio/weather_tigge.php