Development of a Taiwan full-physics vector vorticity equation model (VVM)

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Goal

- Develop a full physics cloud resolving model that can be used to study land-atmosphere-topography interactions in Taiwan.

Cloud Forest in Taiwan Chi-Lan Mountain

The model

- A three dimensional anelastic cloud-resolving model that predicts vector vorticity equation and diagnoses velocity (VVM) (Jung and Arakawa 2008).

- This model has been used to study diurnal cycle of deep convection (Wu et al 2015), stratocumulus break up (Tsai and Wu 2016) and meso-scale organization (Tsai and Wu 2016).

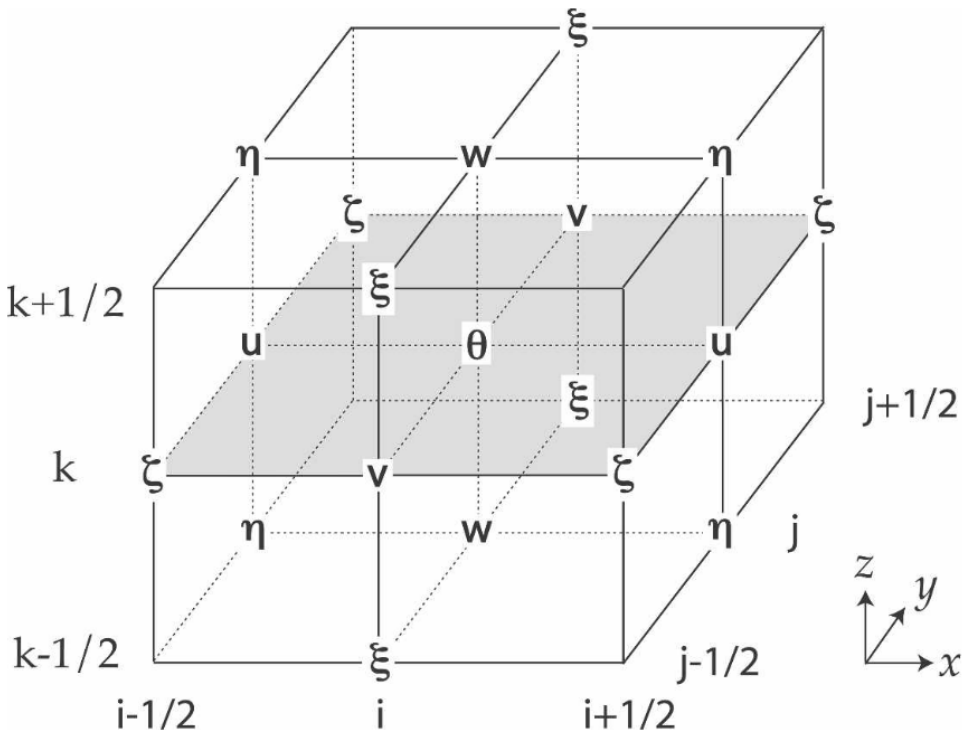
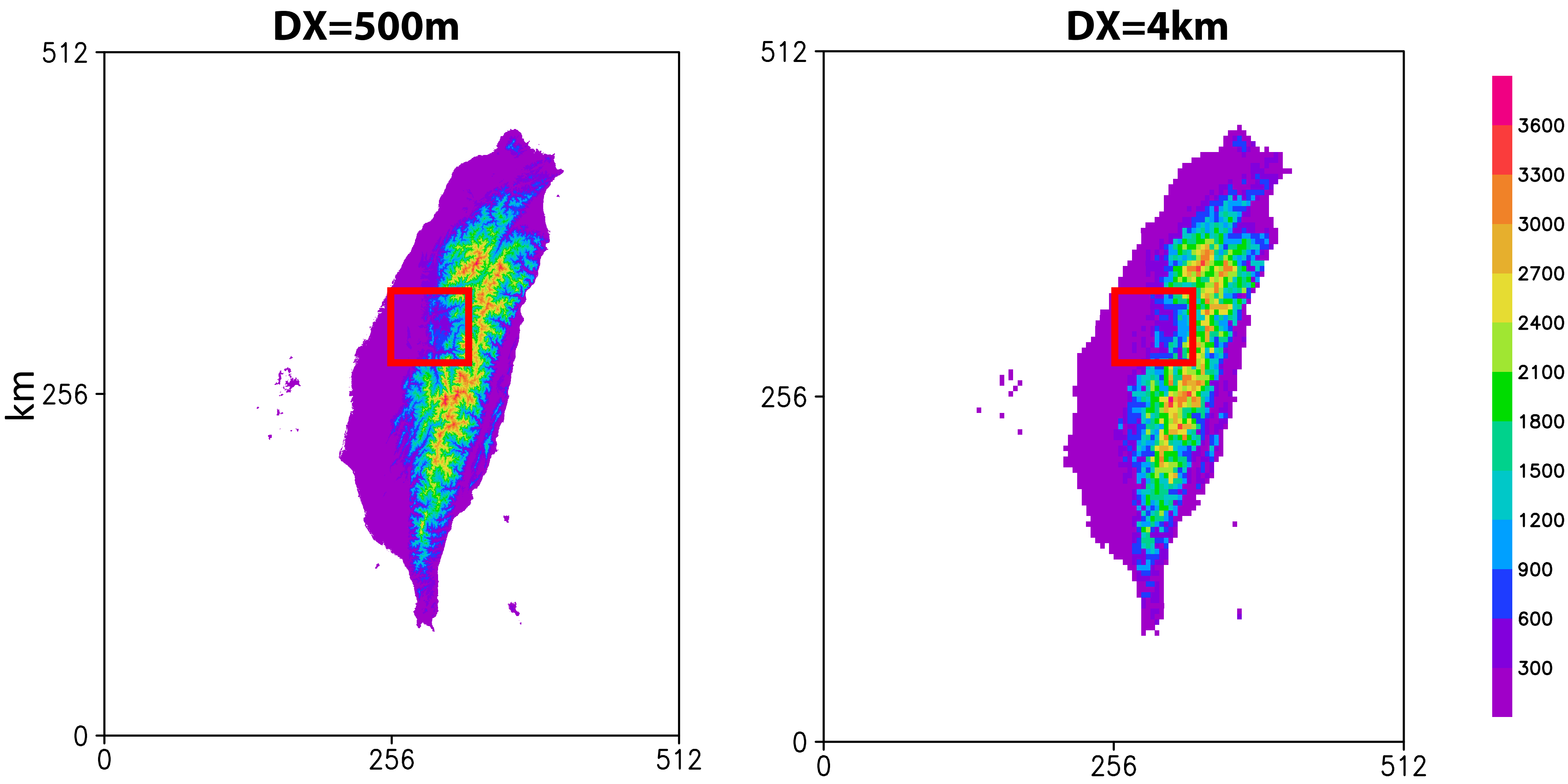


FIG. 2. A three-dimensional view of the model grids.

On the complex topography

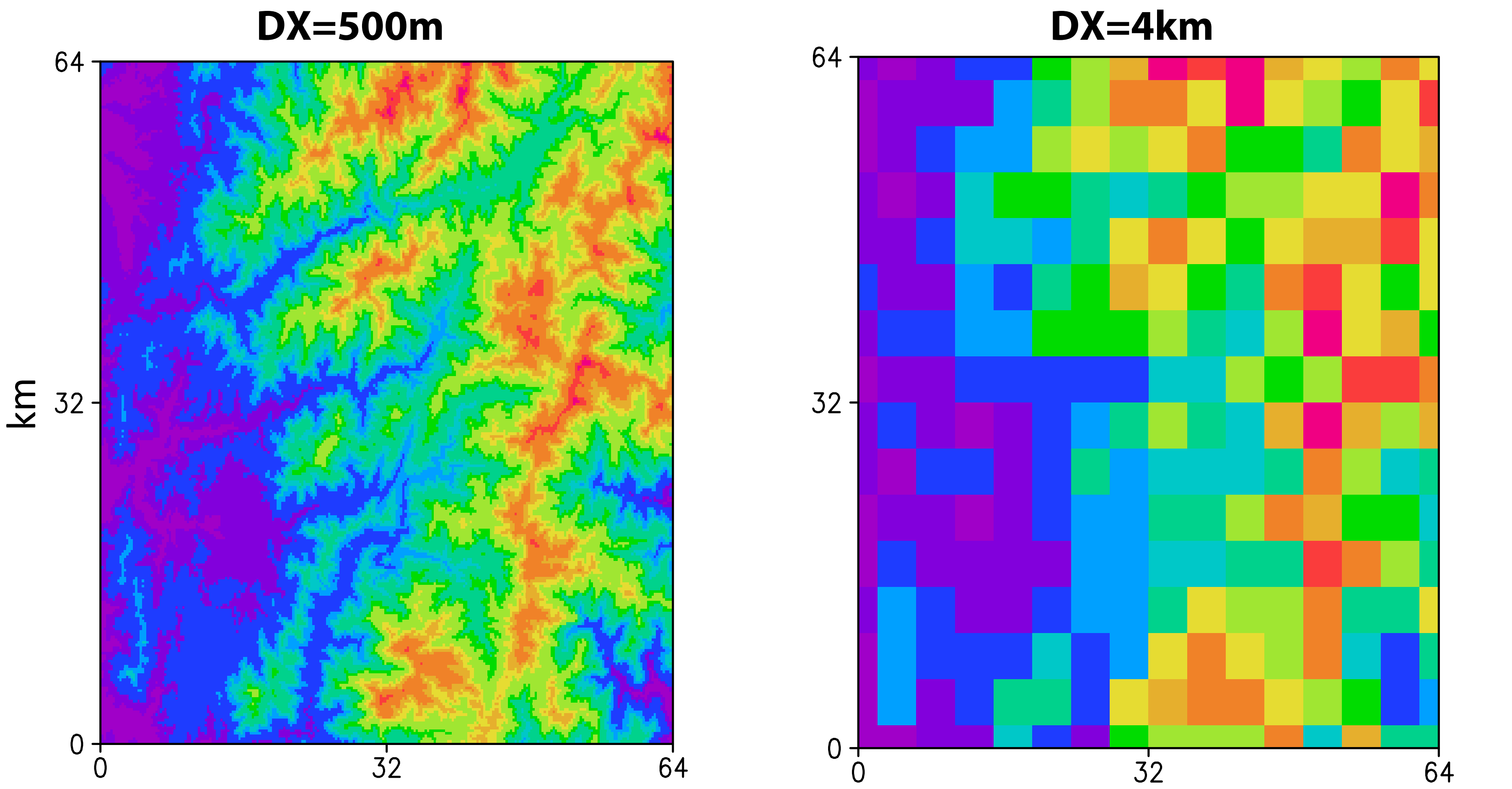
- It is typical to use 3-5km resolution to simulate synoptic or mesoscale system over Taiwan.
- The use of high resolution in Taiwan might not be an issue in simulation of typhoon tracks.



Taiwan topography

On the complex topography

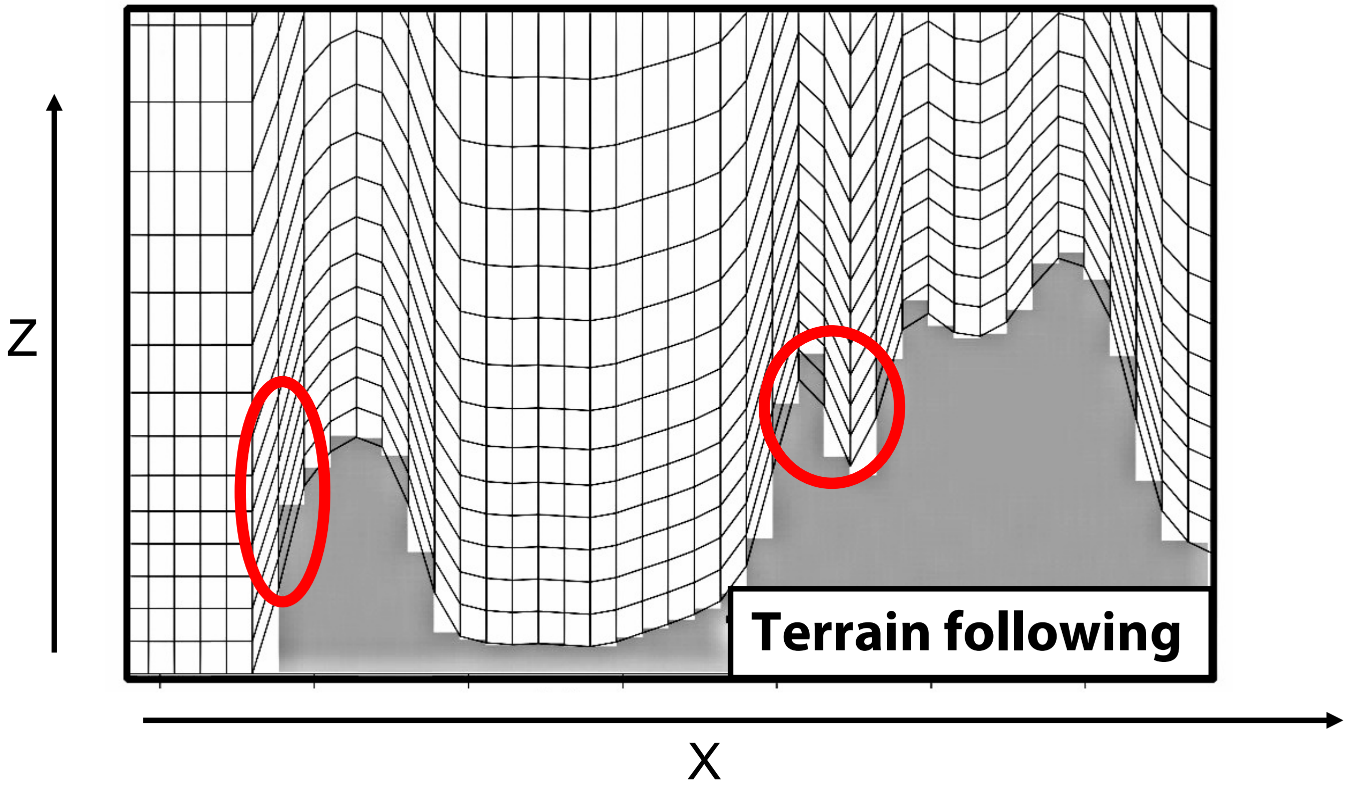
- For local scale impacts, it is crucial to use high resolution that is capable of capturing flow around local ridges and valleys.
- Nested-domain generally causes problems over complex topography.
- A high resolution CRM covering who Taiwan is necessary for local studies.



Central Taiwan topography

As we increase the horizontal resolution, the terrain following coordinates has difficulties viewing the distribution of model variables through irregular surface topography. (Janjić 1989; Zängl et al. 2004)

Therefore, we use height coordinate if the computational problems can be properly handled.

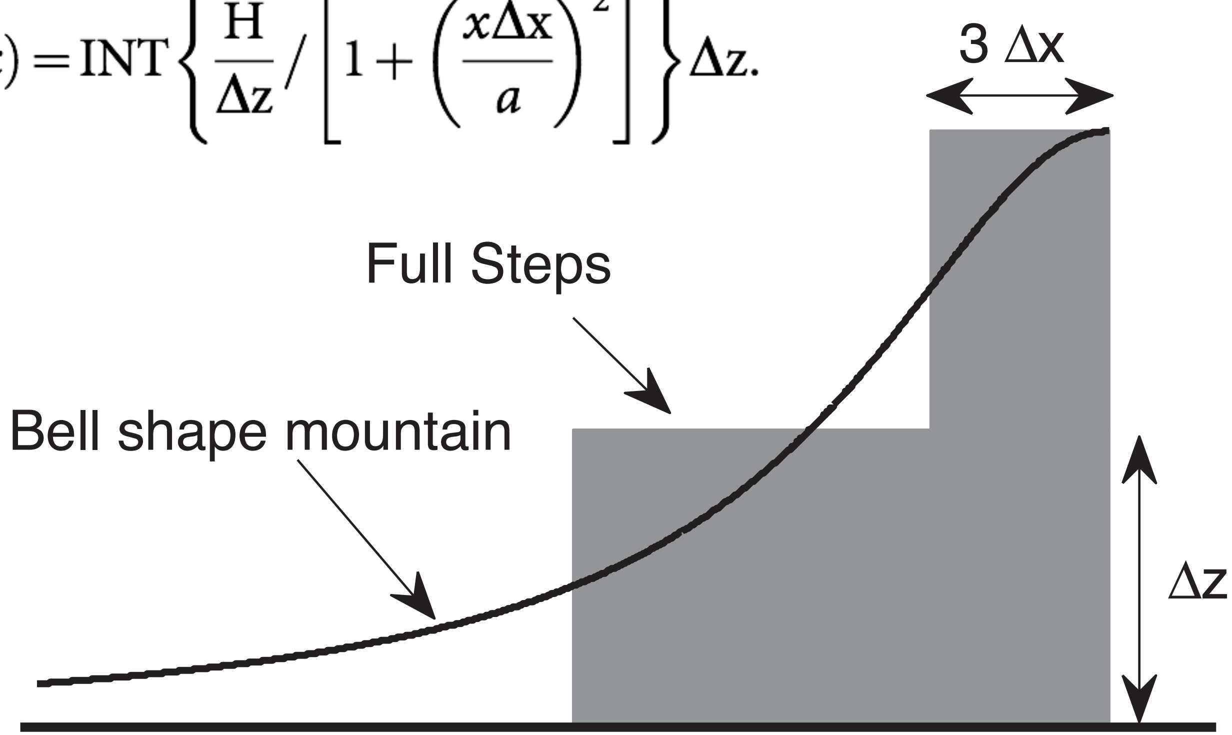


Problem of the full step approach

- Representation of bell shape mountain in the full step approach is restricted to vertical grid size.

Bell shape mountain in full step approach

$$h(x) = \mathrm{INT}\left\{ \frac{\mathrm{H}}{\Delta \mathrm{z}} \Big/ \left[1 + \left(\frac{x \Delta \mathrm{x}}{a} \right)^2 \right] \right\} \Delta \mathrm{z}.$$



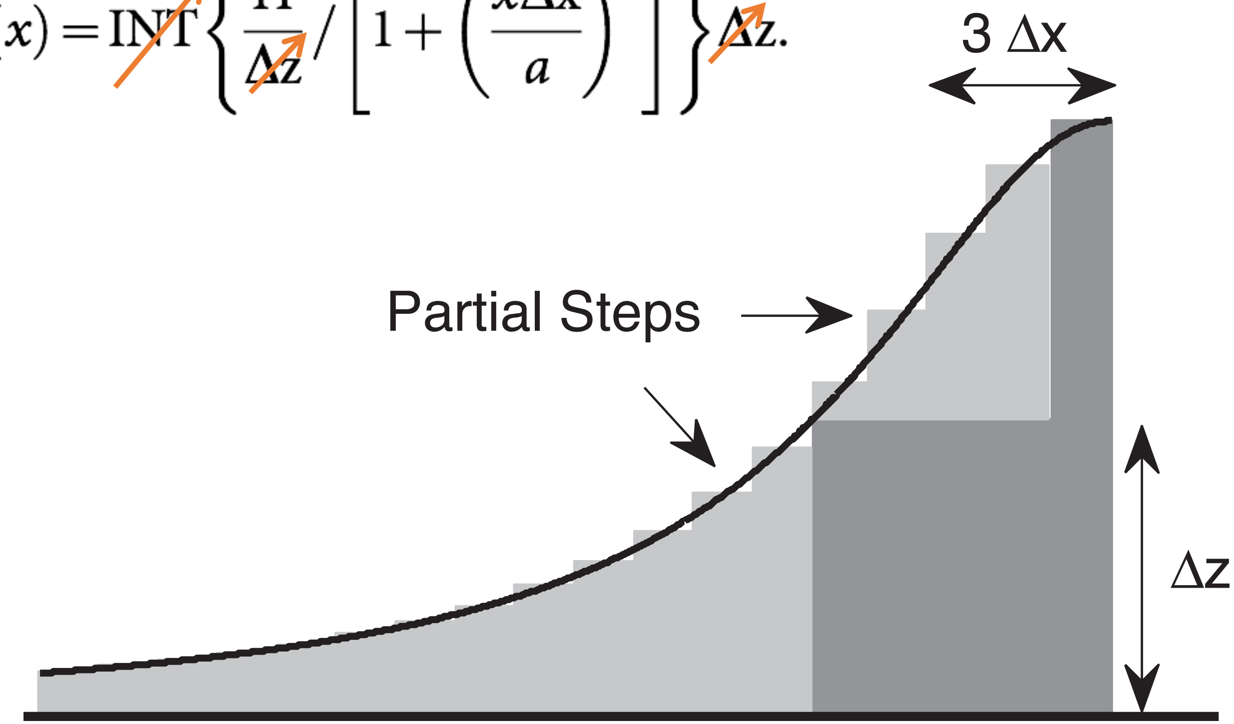
Wu and Arakawa (2011)

Improvement in partial step approach

- Partial steps mountain better capture topography effects with gentle slopes and micro mountains.

Bell shape mountain in ***partial*** step approach

$$h(x) = \cancel{\mathrm{INT}}\left\{\frac{\mathrm{H}}{\cancel{\Delta z}} \Big/ \left[1+\left(\frac{x\Delta \mathrm{x}}{a}\right)^{2}\right]\right\}\cancel{\Delta}z.$$

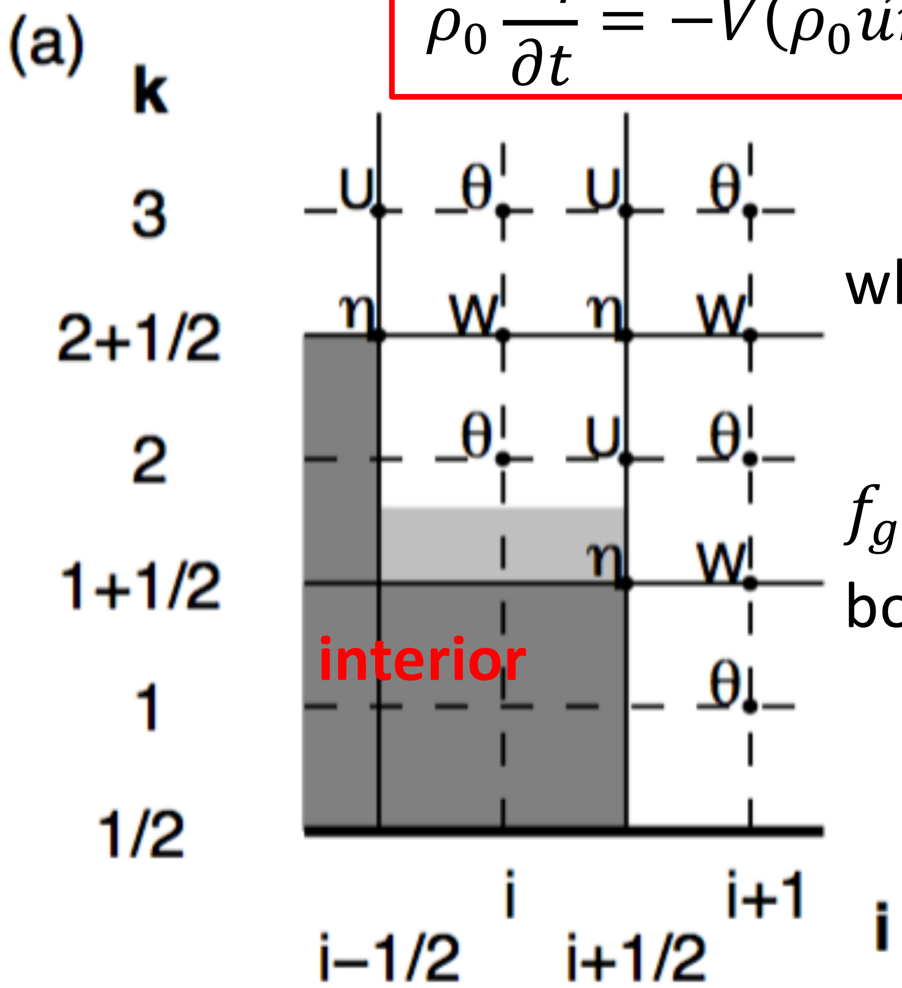


Chien and Wu (2016)

Topography in partial step approach

- Partial steps describes boundary implicitly, by adding a forcing term to the governing equation.

$$\boxed{\rho_0 \frac{\partial \eta}{\partial t} = -\nabla(\rho_0 \vec{u} \eta) + \rho_0 \vec{\xi} \cdot \nabla u - \frac{\partial B}{\partial x} + F_g}$$



where, $F_g = \begin{cases} f_g, & \textit{for the interior points} \\ 0, & \textit{elsewhere} \end{cases}$

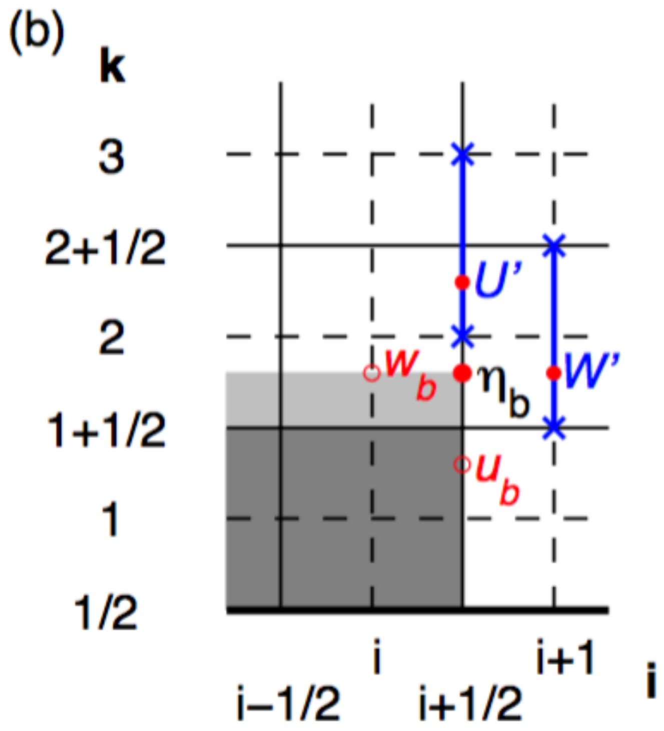
$f_g = -RHS + \frac{\eta_e}{\delta t}$, where η_e is desired boundary condition.

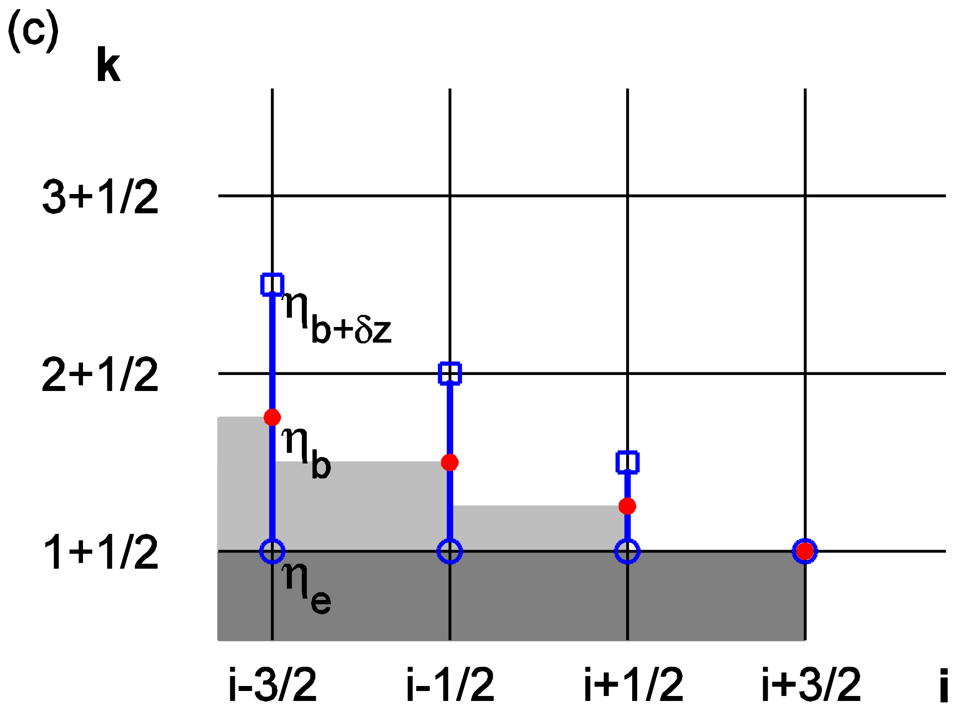
Topography in partial step approach

•η_b and $\eta_{b+\delta z}$ is determined by the definition of vorticity, and the associated velocities are determined by kinetic boundary condition and linear interpolation.

•The topography forcing, η_e, is then computed by image method

$$\boxed{\eta_e = 2\eta_b + \eta_{b+\delta z}}$$





Procedures in partial step approach

- Vertical velocity is obtained by solving the w-equation with added topography forcing at the boundary

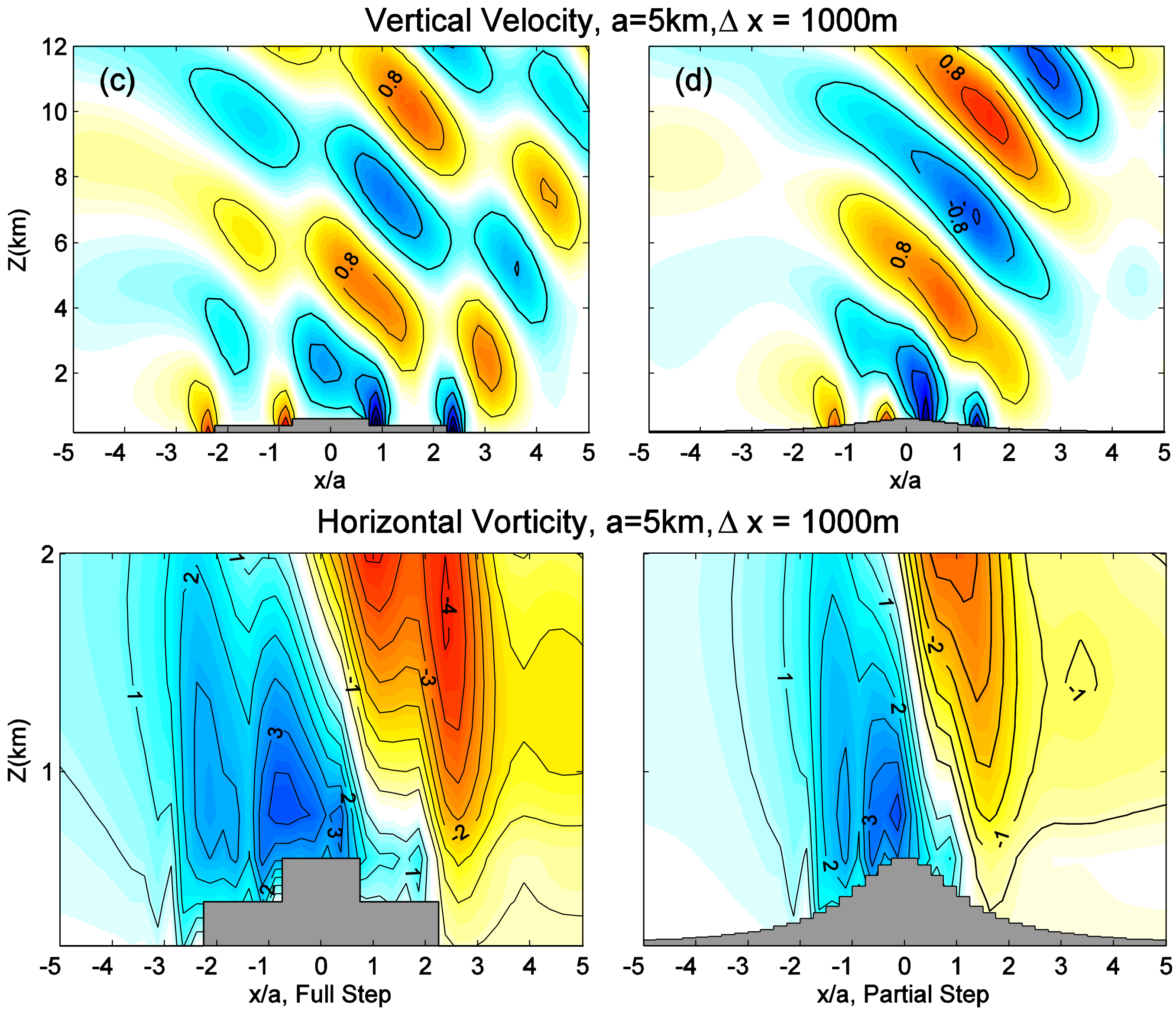
$$\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}\right)w+\frac{\partial}{\partial z}\left[\frac{1}{\rho_0}\left(\frac{\partial}{\partial z}\rho_0 w\right)\right]=\boxed{-\frac{\partial\eta}{\partial x}+\frac{\partial\xi}{\partial y}}$$

- The w-equation is then solved through Portable Extensible Toolkit for Scientific Computing (PETSc) for better efficiency in parallel codes.

Results

Hydrostatic waves over bell-shaped mountain

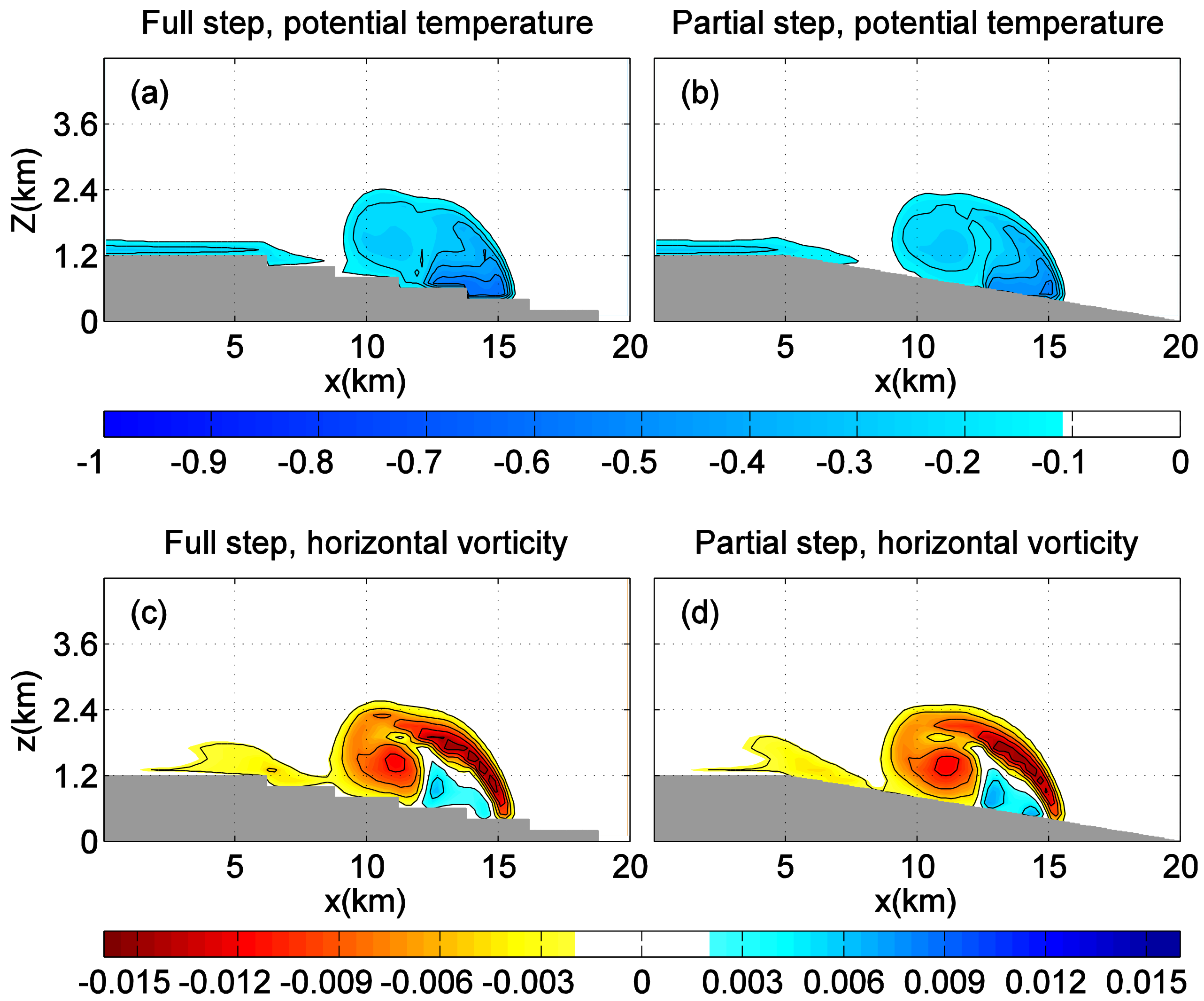
- The partial step approach produces continuous shape due to additional topographic forcing.



Results

Cold bubble over a gentle slope

- The partial step approach produces smoother results compared to the stair-like ones in the full step approach.



Original method in VVM

† In VVM based on the flux-profile relationship in Deardorff (1972), the default kinematic sensible and moisture fluxes are derived from

$$\left(\overline{w'\theta'}\right)_s = \frac{(\theta_s - \theta_m)\boxed{\left(\overline{w'\theta_v'}\right)_a}}{\boxed{\theta_{vs} - \theta_{vm}}}$$

$$\left(\overline{w'q'}\right)_s = \frac{(q_s - q_m)\boxed{\left(\overline{w'\theta_v'}\right)_a}}{\boxed{\theta_{vs} - \theta_{vm}}}$$

Ventilation factor

∗ a: anemometer level
∗ s: surface value
∗ m: mean value within PBL

Revised method using NOAH LSM

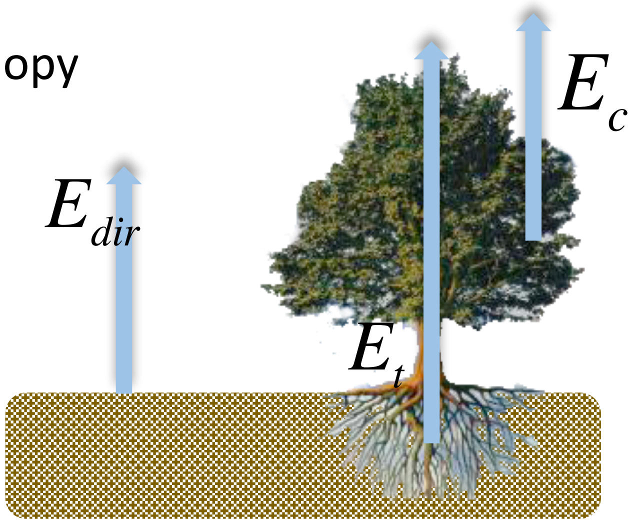
- Surface latent heat flux, or total evapotranspiration (E) is defined as

$$\overline{w'q'_s} = \boxed{E_{dir}} + \boxed{E_c} + \boxed{E_t} + E_{snow}$$

the direct evaporation from the top shallow soil layer

evaporation of precipitation intercepted by the canopy

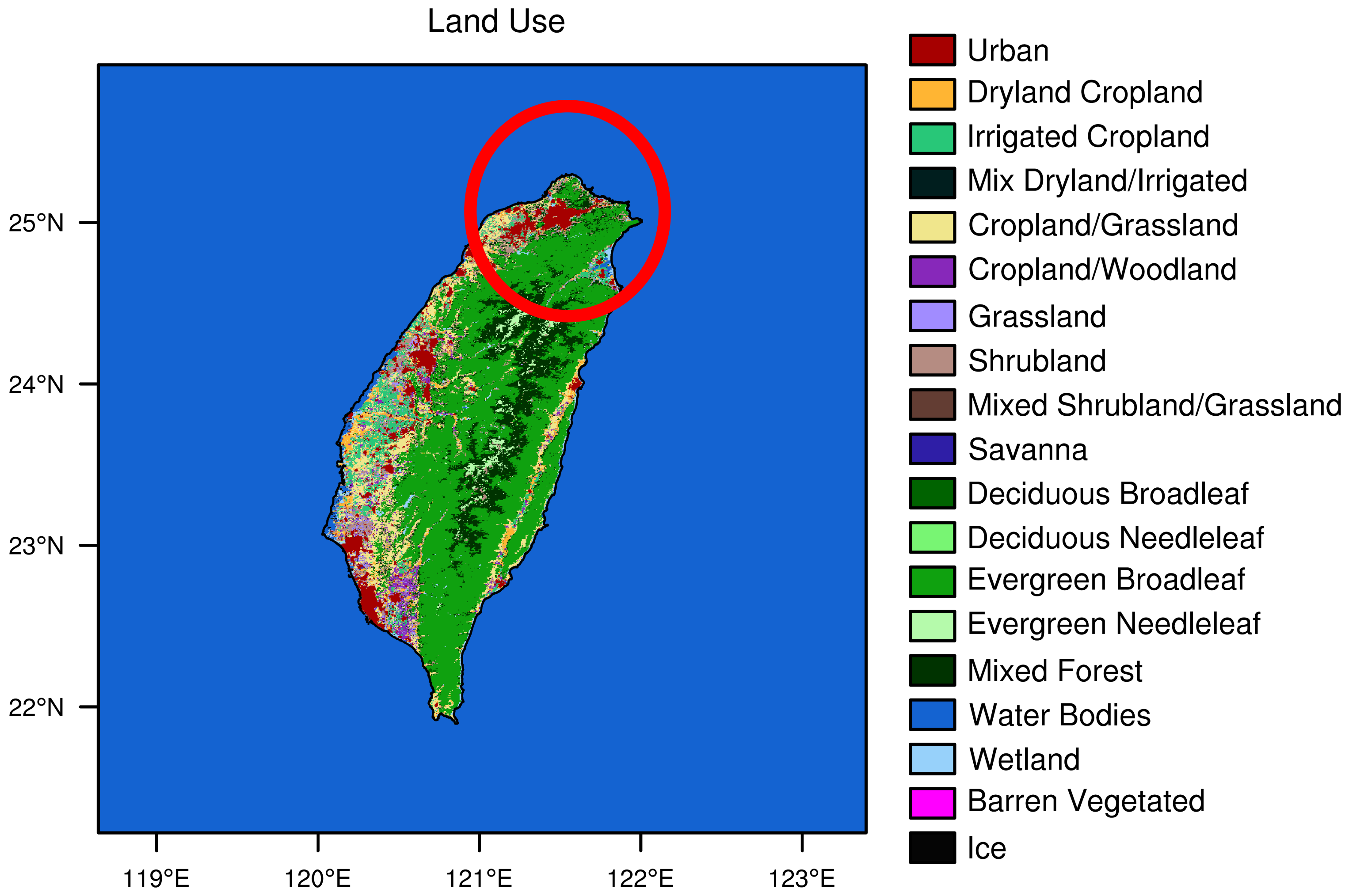
transpiration via canopy and roots



(Chen and Dudhia 2001)

On the land surface processes

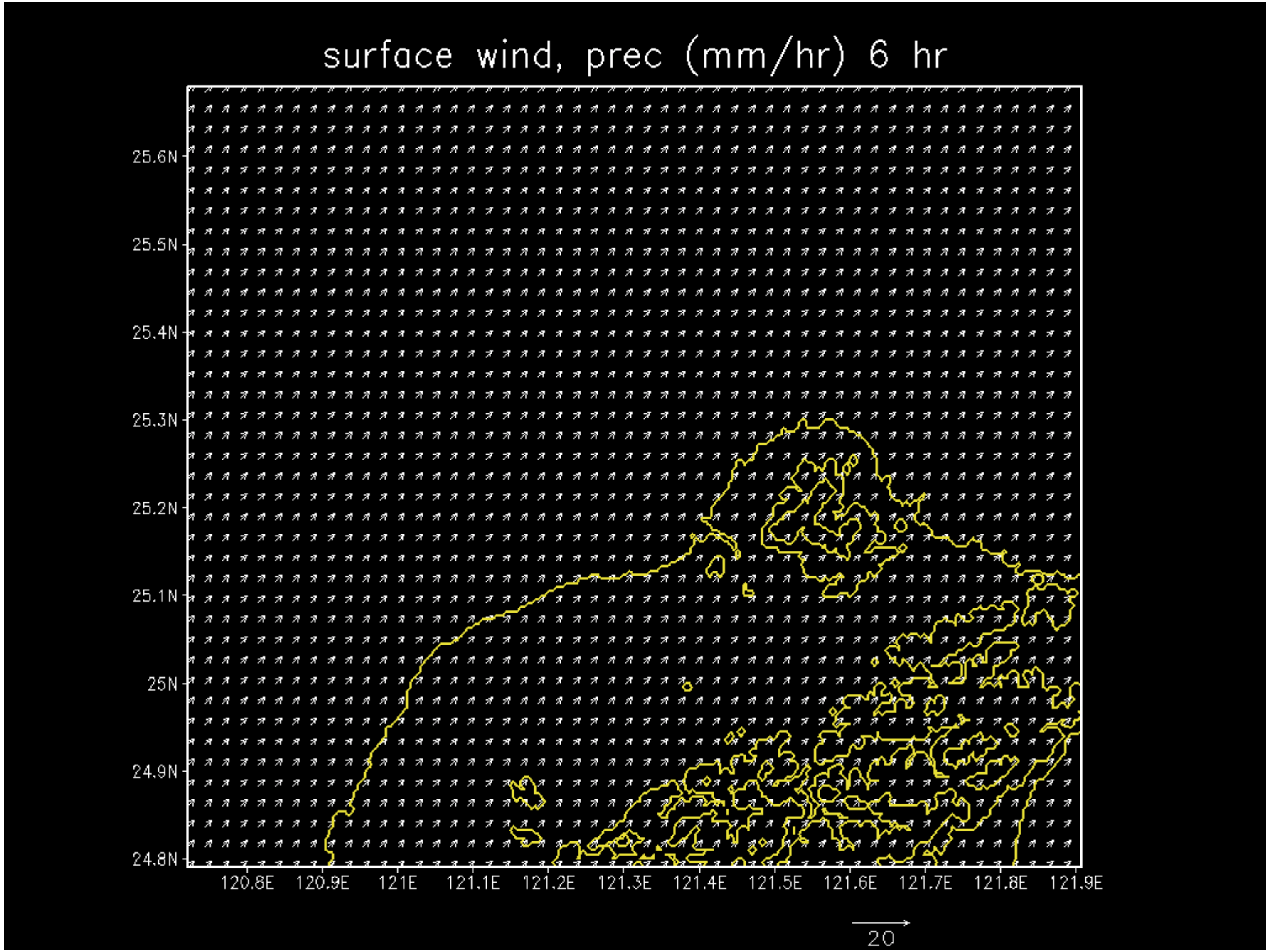
- Land type is updated to represent current Taiwan's surface distribution.
- Surface data is carefully implemented to match land type and topography (**500m** resolution).



(Leung and Chen 1997; Zobler 1986; Cheng et al. 2013; Lin and Cheng 2015)

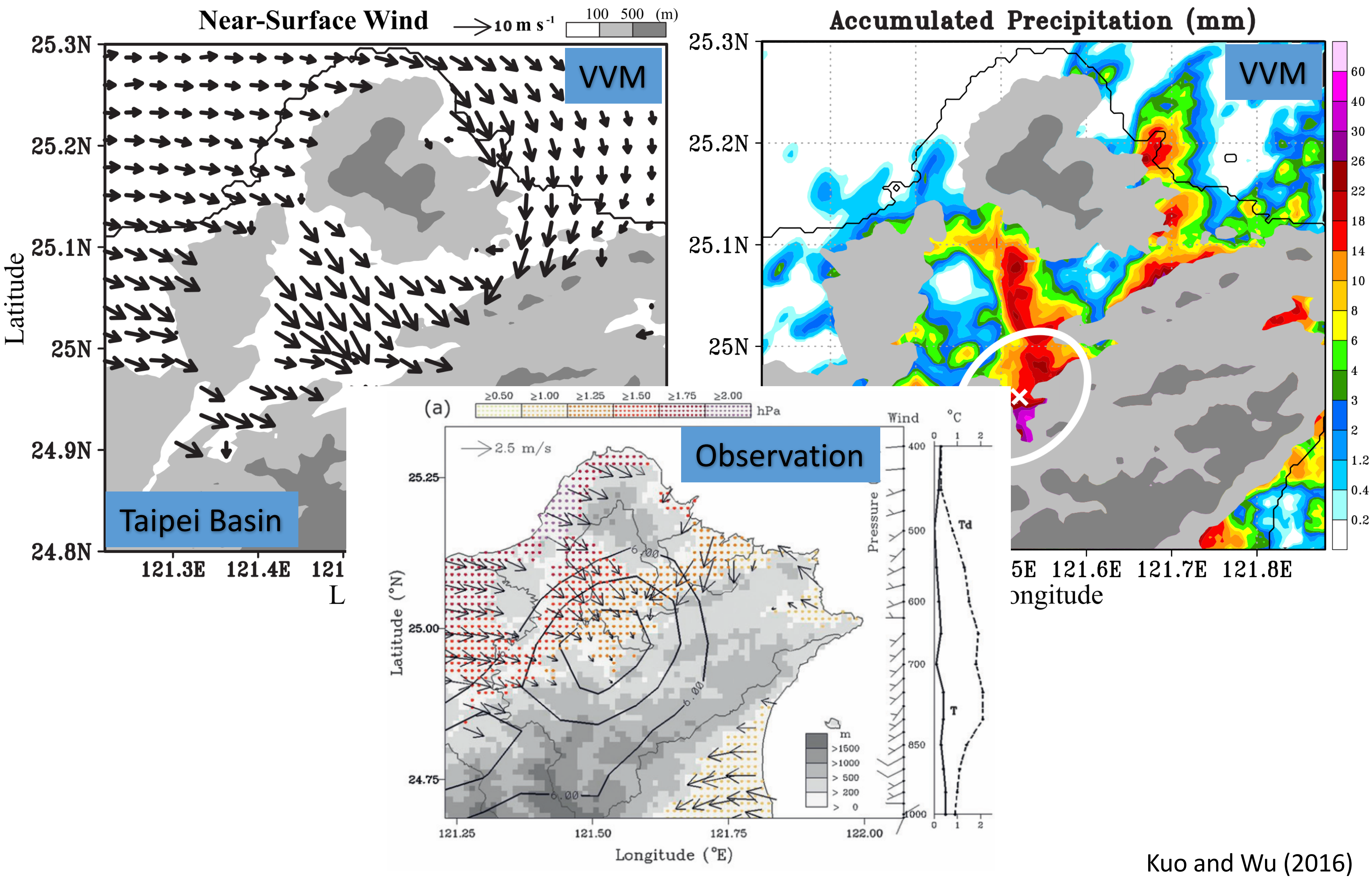
Results

- A 12 hr simulation (from 6am to 6 pm) covering whole Taiwan focusing on afternoon thunderstorm over Taipei basin demonstrating the interactions among sea breezes-convection-complex topography.



Results

- The model produces reasonable sea breeze convergence and precipitation hotspots compared with observations.



Kuo and Wu (2016)

Future work

- Implementation of topographic shadow effects in the radiation parameterization (through modifying surface albedo).
- Turbulence parameterization over complex topography.