Developing the Rapid Refresh (RAP) and High-Resolution Rapid Refresh (HRRR) Physics to Better Perform Across the Grey Zone

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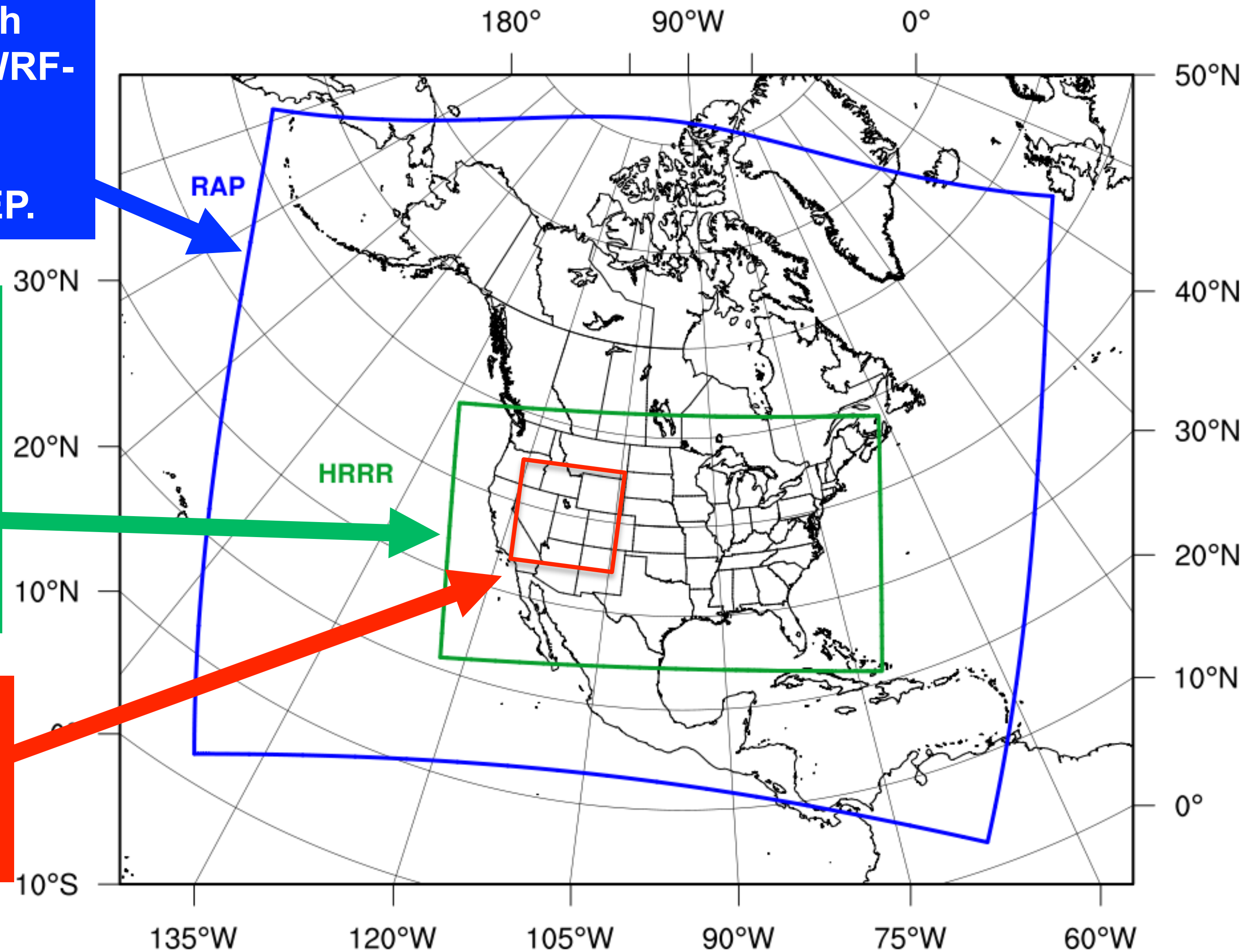
13 km Rapid Refresh (RAP) (mesoscale) – WRF-based with hourly updating. Runs operationally at NCEP.

3km High-Resolution Rapid Refresh (HRRR) (storm-scale) – WRF-based with hourly updating. Scheduled to run operationally at NCEP in fall 2014.

Experimental 1-km nest (WRF-based) for modeling complex flows (exact position will vary)



Motivation/Outline

1. **RAP/HRRR physics need to adapt to changing model resolutions.**
   – Overview of RAP/HRRR physics, including new developments not yet in operational NCEP runs.
2. **Test Case: Grey Zone Project**
   – Organized by the U.K. Met Office with many participants from around the world.
   – Cold-air outbreak case over N. Atlantic.
   – Primarily shallow-cumulus regime with very little or no deep convection.
3. **Sensitivity tests to improve cloud structures**

Model Configuration

	RAP (13 km)	HRRR (3 km)
Model version	WRFv3.5.1	WRFv3.5.1
LSM	RUC 9-level	RUC 9-level
Surface layer	MYNN (M-O-based)	MYNN (M-O-based)
PBL	MYNN level 2.5	MYNN level 2.5
SW Radiation	RRTMG	RRTMG
LW Radiation	RRTMG	RRTMG
Microphysics	Thompson	Thompson
Deep Convection	Grell 3D (G3)	---
Shallow Convection	Grell	---
Time step	60 s	20 s
Radiation time step	10 min	5 min
Vertical levels	51 levels (50 layers)	51 levels (50 layers)
6th-order diffusion	On	Off

Modified to include explicit mixing of qc and qi; Reduced Ri_c to ~20

New: Grell-Freitas scale-aware convective schemes

Double levels below 2 km (63 levels)

Grell-Freitas Convective Schemes

Deep-Cu Scheme (Grell and Freitas 2014, ACP; already in v3.6)

- **Aerosol-aware**
- **Stochastic approach adapted from the Grell-Devenyi scheme**
- **Scale-aware: transitions to shallow-cumulus scheme as grid spacing decreases:**
  - ✧ Arakawa et al.'s (2011, ACP) fractional areal coverage approach.
  - ✧ Parameterized convection becomes much shallower – cloud tops near 800 mb (down from 200-300 mb).
  - ✧ Tendencies become very small, practically shutting off below 5 km grid spacing.

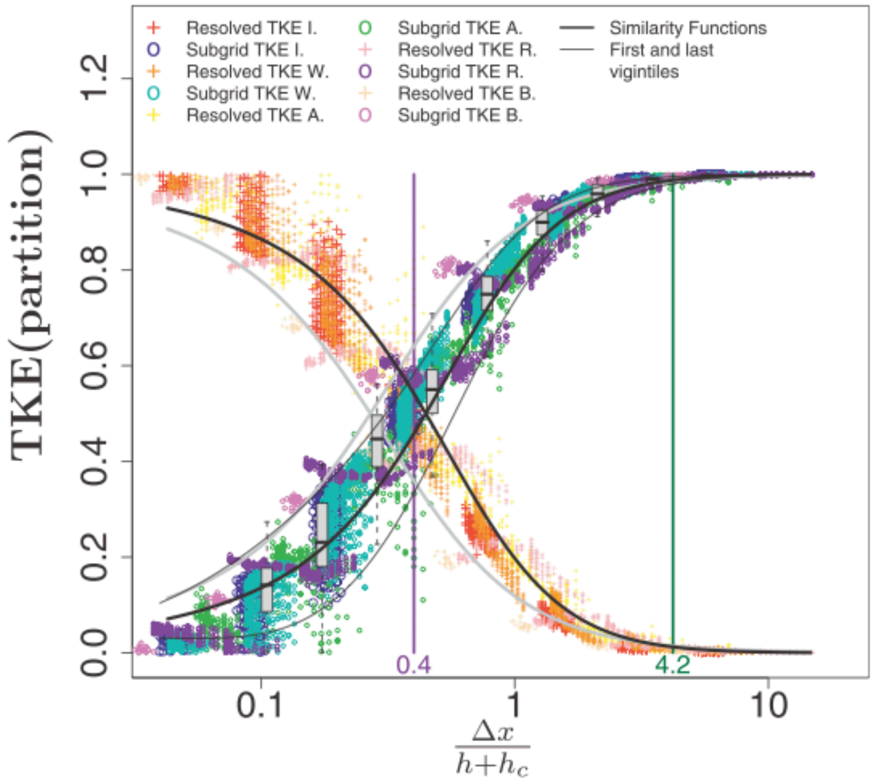
Shallow-Cu Scheme (manuscript upcoming; likely in v3.6.1)

- **Scale-aware mass-flux control from Honnert et al. 2011 (JAS)**
  - ✧ Similarity based on TKE in entrainment/cloud layer
- **Non-precipitating; currently mixing only q_v and θ**
- **Produces sub-grid q_c and q_i for coupling to LW and SW schemes.**
- **Weighted average of 3 different closures:**
  - ✧ BL quasi-equilibrium, CAPE, and moist static energy.

Tapering of Shallow-Cu Scheme

- **Based off of Honnert et al. (2011, JAS):**
  - ✧TKE partition in the entrainment layer

Figure 5 (a) $0.85 \leq \frac{z}{h} \leq 1.1$

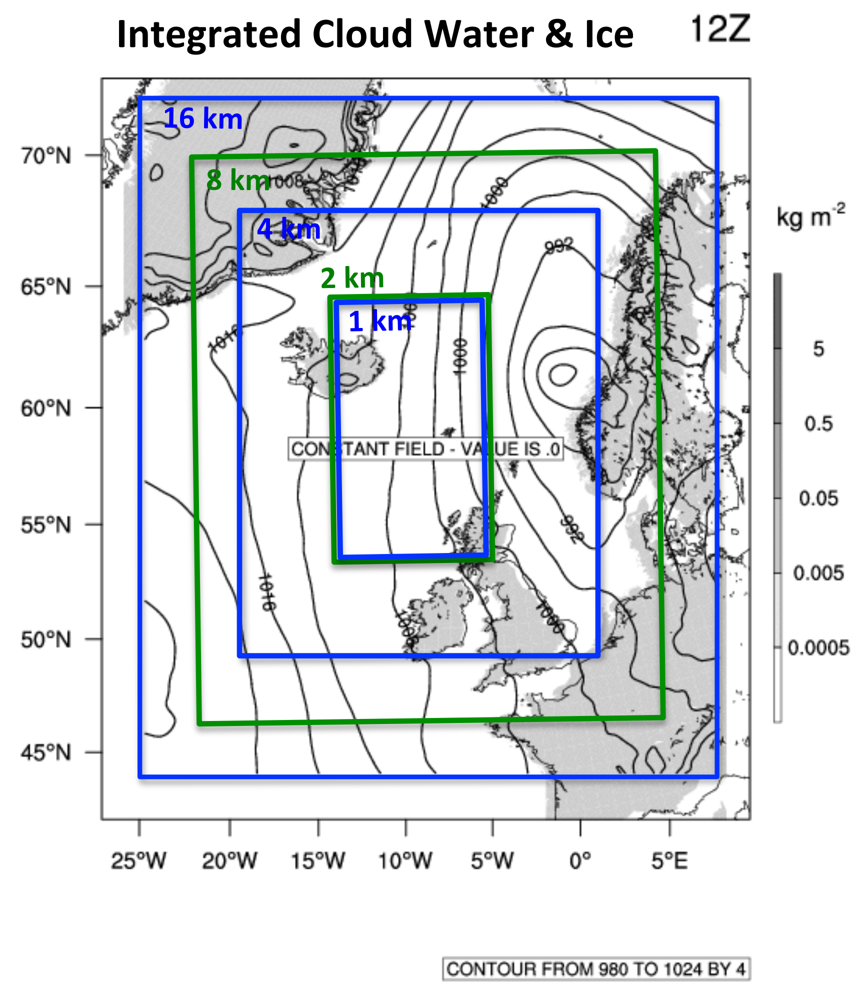


- **Other method will be tested (i.e., Shin and Hong 2013, JAS).**

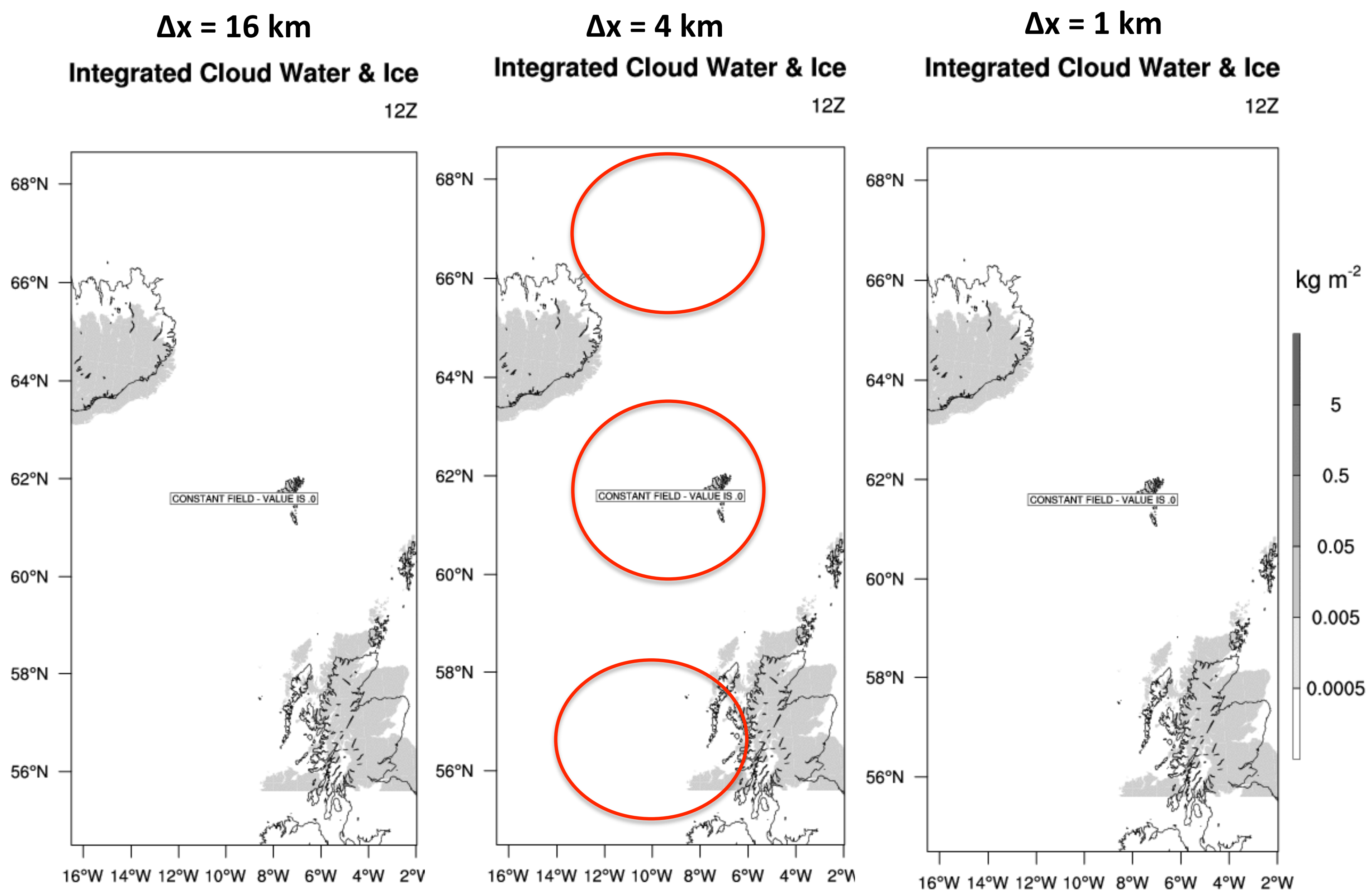
Grey Zone Project

The Grey Zone Project (headed by UK Met Office) aims to systematically explore convective transport and cloud processes in NWP models at resolutions ranging from 1 to 16 km.

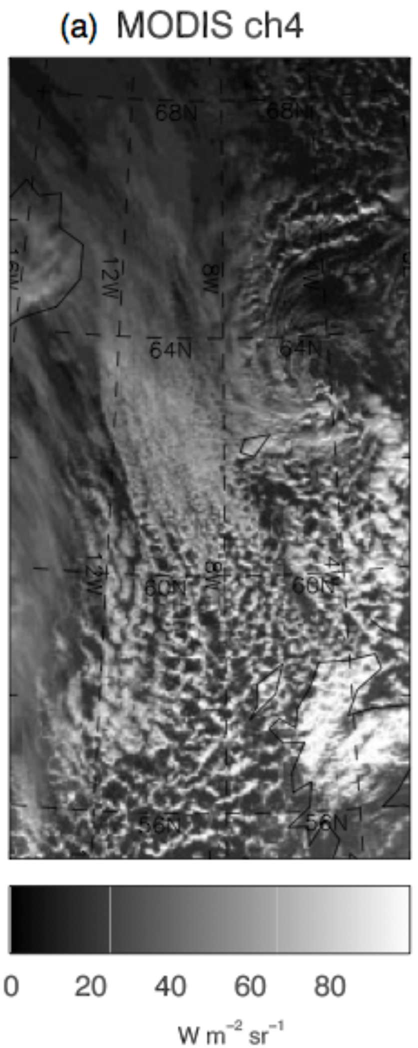
- For each set of the LAM simulations (at grid spacings of 1, 2, 4, 8, 16 km), two permutations were run:
  1. GF deep-cu scheme **OFF**
     GF shallow-cu scheme **OFF**.
  2. GF deep-cu scheme **ON**
     GF shallow-cu scheme **ON**.
- 36 hour simulations are done using ECMWF analyses beginning at 12 UTC 30 Jan 2010, and used every 6h to generate LBCs for the coarsest domains.
- Two set of nested domains are used:
  - 16-4-1 km grids
  - 8-2 km grids



Evolution of BL clouds (NoCu)



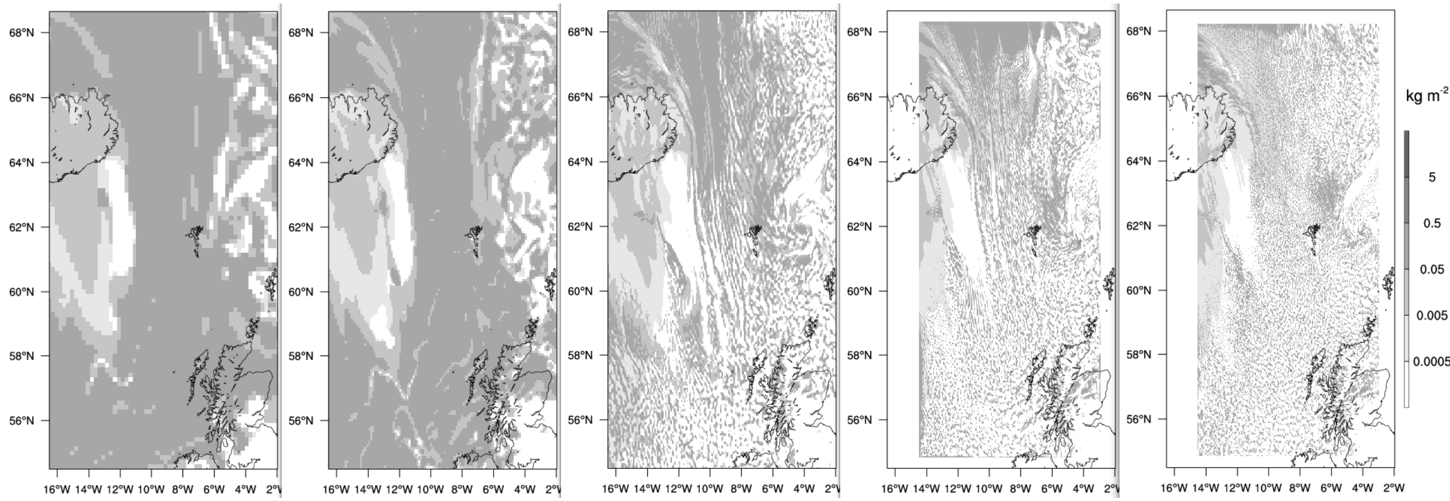
Comparison of integrated qc & qi



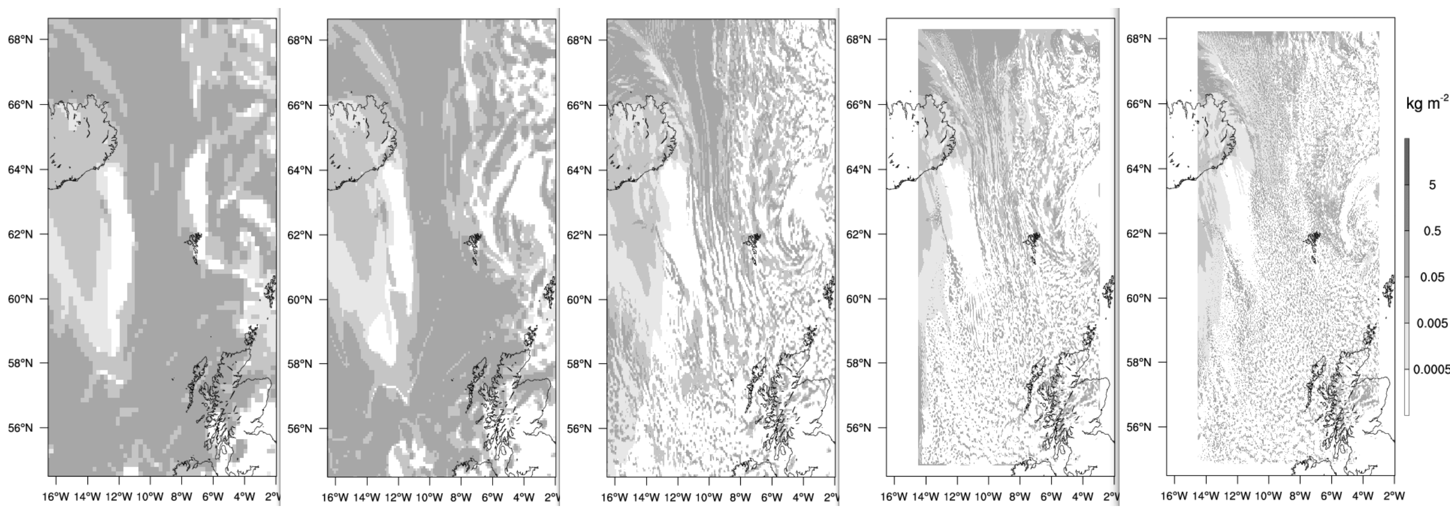
Above figure taken from Field et al (2013).

Δx = 16 km | Δx = 8 km | Δx = 4 km | Δx = 2 km | Δx = 1 km

DpCu off, ShCu off (current HRRR configuration)



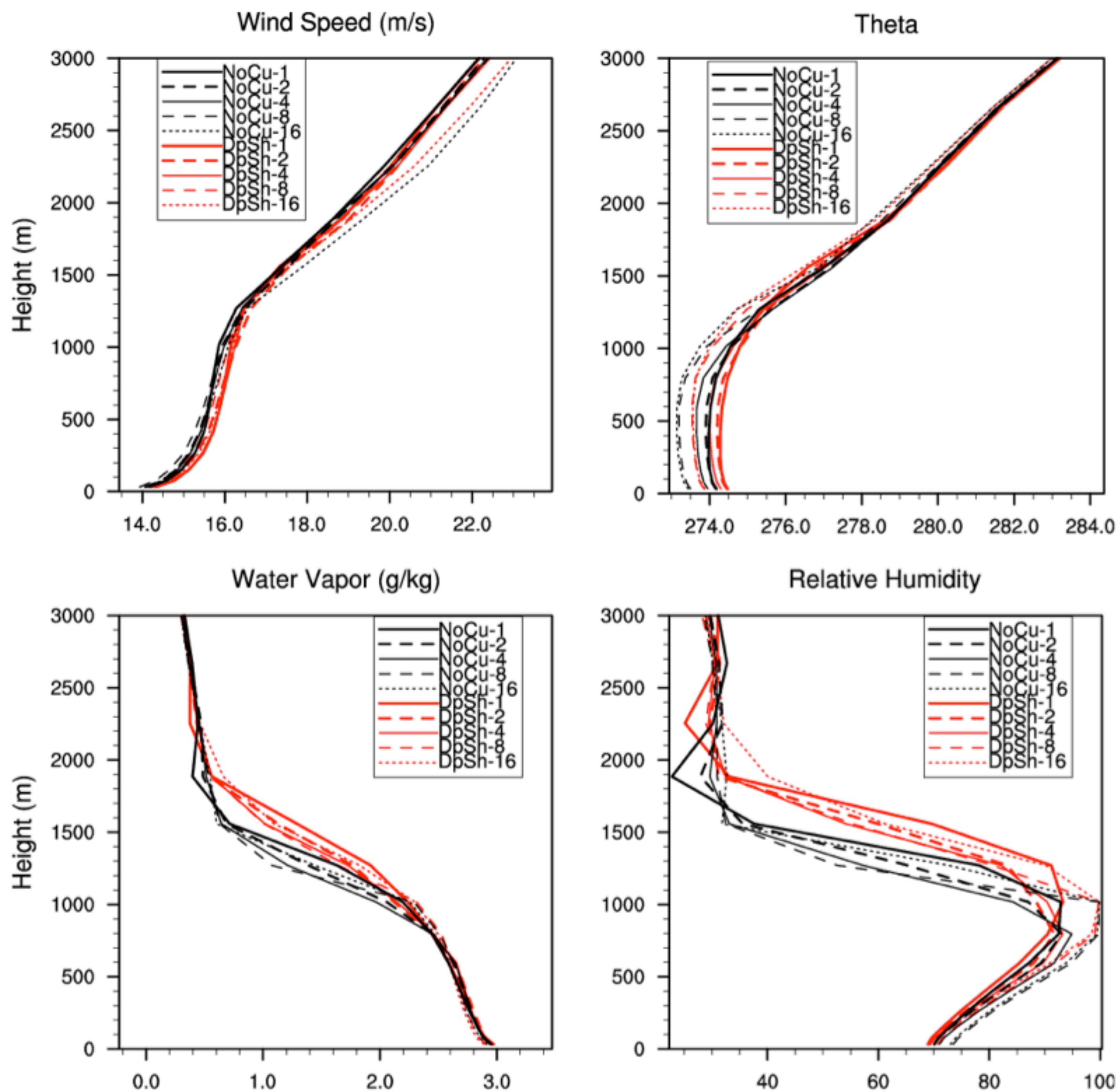
DpCu on, ShCu on (current RAP configuration)



Mean Profile Comparisons

Mean Profiles over the transition region for hrs 23-27

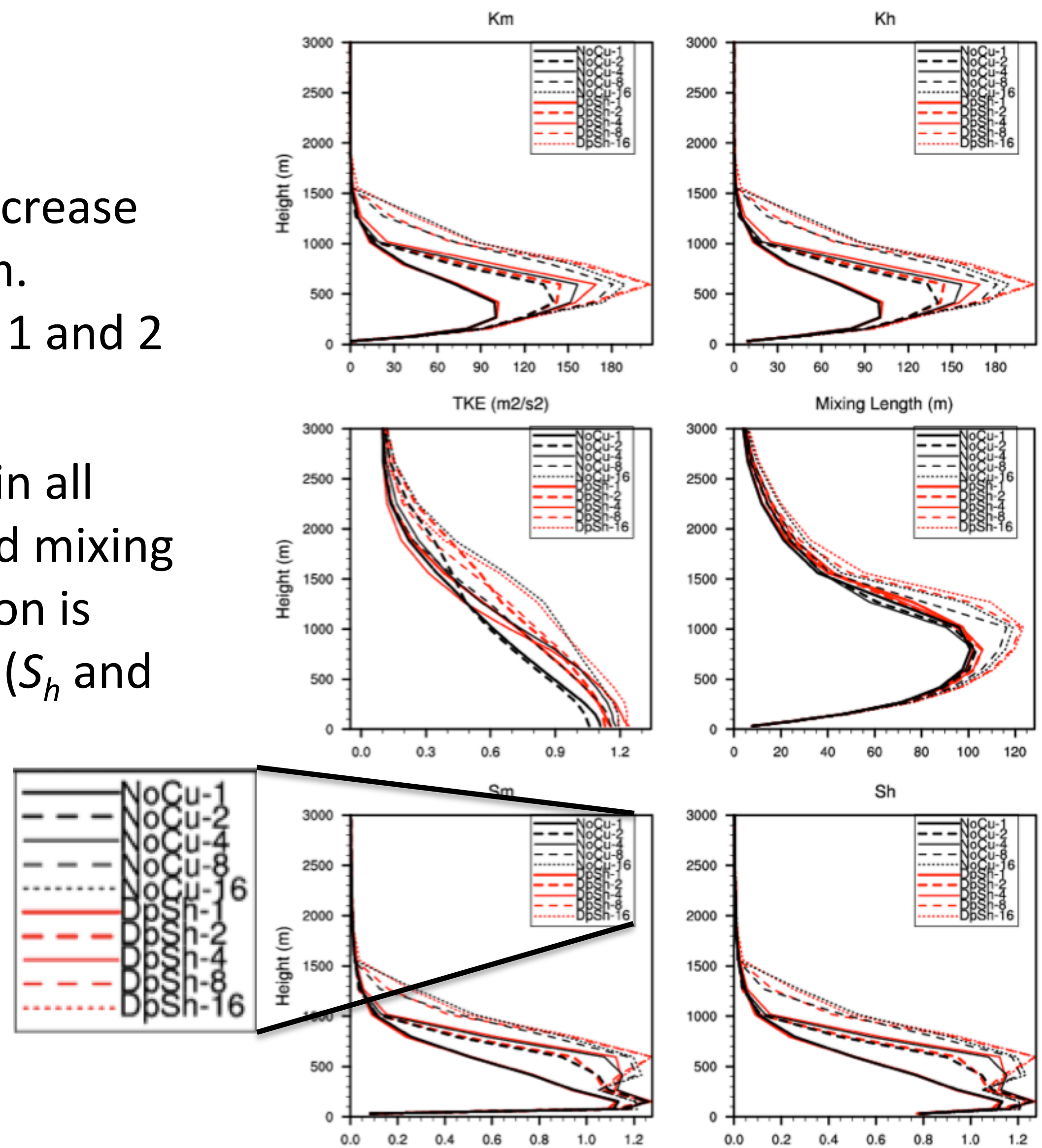
- Overall differences between convective (DpSh) and non-convective (NoCu) simulations show that the extra mixing from the shallow-cu scheme erodes the cloud/transition layer, which:
  - Increases the coupling between BL and free troposphere.
  - Warms the BL.
  - Increases the wind speeds in the BL.
  - Moistens the top of the cloud layer.



Eddy Diffusivity

$$K_\phi = S_\phi\,(2*TKE)^{1/2}\, l_m$$

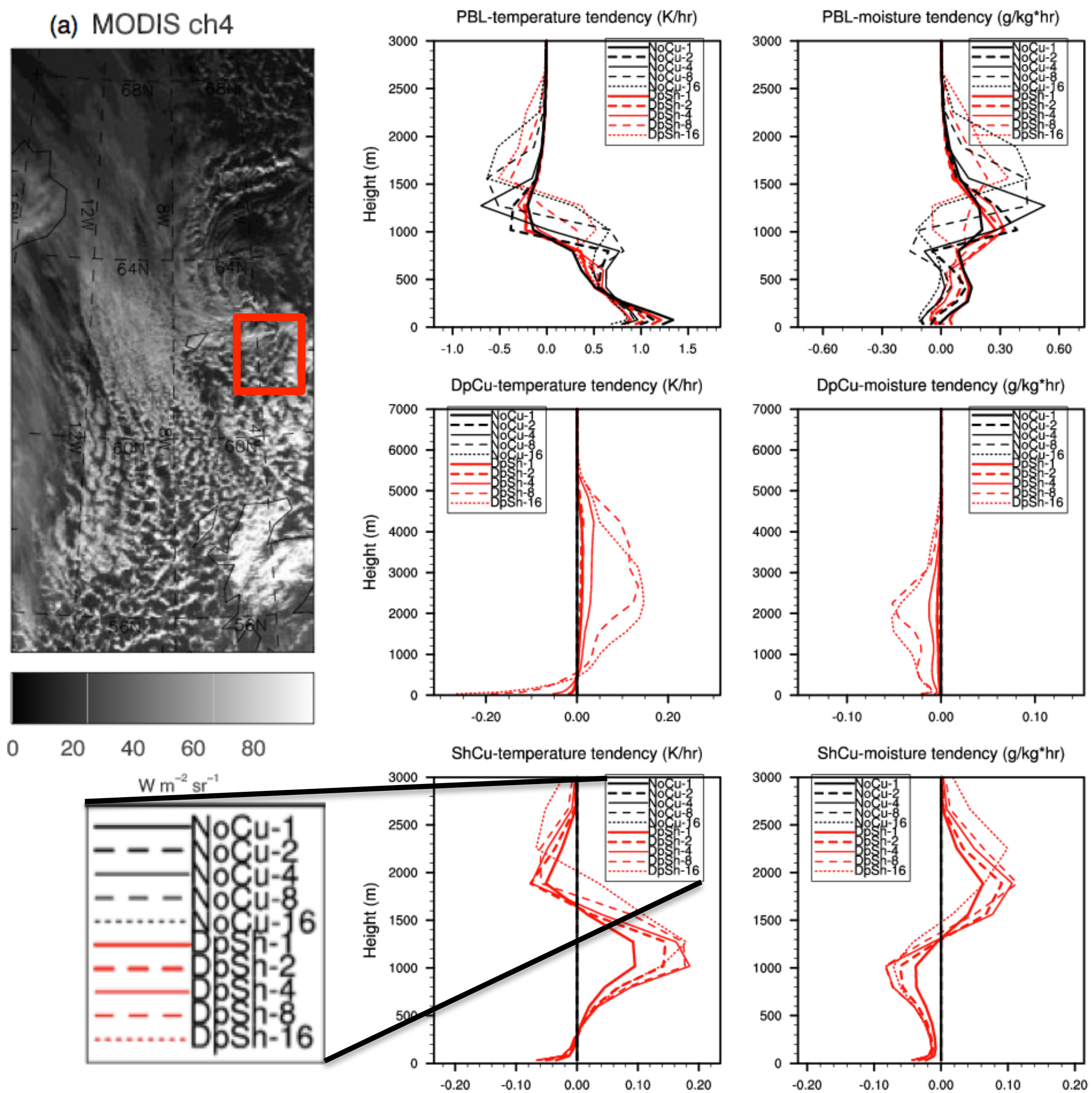
- Eddy diffusivities/viscosities decrease by a factor of 2 from 16 to 1 km.
  - ✧ Largest decrease between 1 and 2 km.
- Some of this reduction is seen in all three components (S_ϕ, *TKE*, and mixing length), but the largest reduction is found in the stability functions (S_h and S_m).



Behavior of Sh/Dp Cu schemes

Mean Profiles over the convective region for hrs 23-27

- The deep-cu scheme was only active off the coast of Norway, but tendencies were very small for dx < 8 km. More gradual transition found in Grell and Freitas (2014).
- The shallow-cu scheme produces smallest tendencies at higher resolutions, with heating maxima (at dx = 1km) ~50% less than that at dx = 16, 8 and 4 km.
- Scale aware shallow-cumulus will be implemented in WRF-ARWv3.6.1



Summary Part I (Cu on/off)

- Developmental RAP/HRRR physics quantitatively reproduces the transition of stratus to open-cellular convection at 4 km grid spacing (HRRR scales), however:
  - Clouds were trapped in layers at low resolutions (16 & 8 km).
  - Stratus clouds too broken up at high resolutions (2 & 1 km) and open-cellular structures were too small.
- The GF deep-cu scheme (correctly) shuts off below 8 km, but there was not much convection to test this scheme.
- The GF shallow-cu scheme begins to taper off at dx = 2-3 km with a mass flux tapered off 50% near dx = 1 km.
- The MYNN PBL scheme appears to taper itself off with increasing resolution, presumably due to reduced dynamic instability by resolved-scale mixing.
  - Eddy diffusivity at 1km was about 1/2 that at 16 km.
  - Tapering was largest between 2 and 1 km.
  - TKE was smaller and maxima were lowered (more surface-based) at high resolutions.

Sensitivity Tests

Modifications to improve cloud structures across scales:

- Double vertical resolution below 2 km (51 -> 63 levels) to better resolve cloud layers.
- Hybrid PBL Height variability – allow TKE-based PBLH more weight to allow more mixing in the cloud layer.
- Combined

MYNN Hybrid-PBLH mod

Hybrid PBL height (z_i) definition in MYNN PBL scheme:

1. θ_v Definition: $z_{i\_\theta v}$ is the height at which $\theta_v = \theta_{vsfc} + 0.5$.
2. TKE Definition: z_{i_TKE} is the height at which the TKE falls below $TKE_{max}/20$.

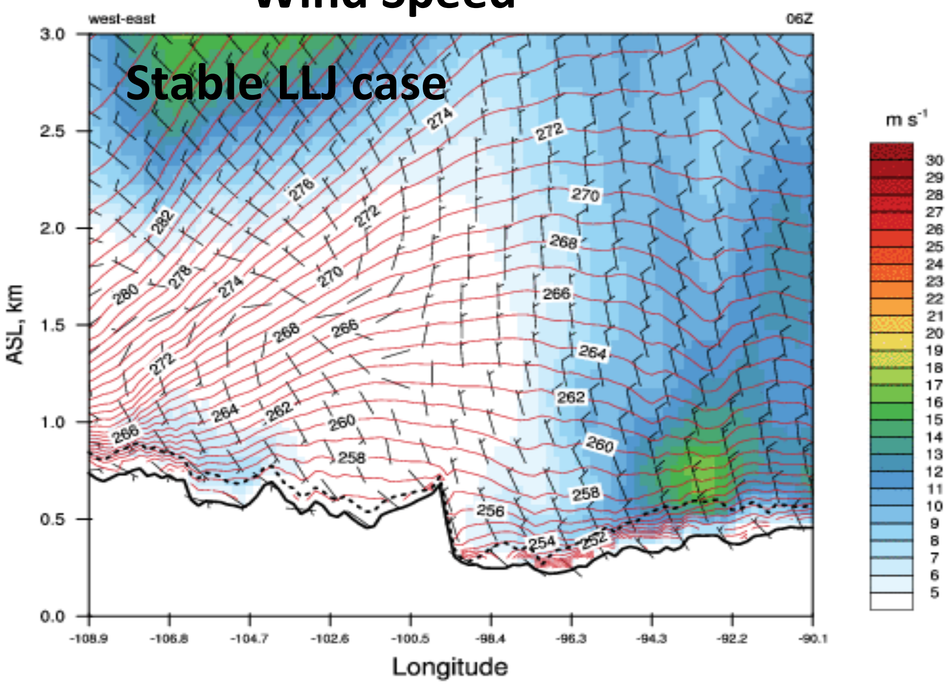
The two definitions are then blended according to stability ($z_{i\_\theta v}$):

$$zi = z_{i\_TKE} * (1.-wt) + z_{i\_\theta v} * wt$$

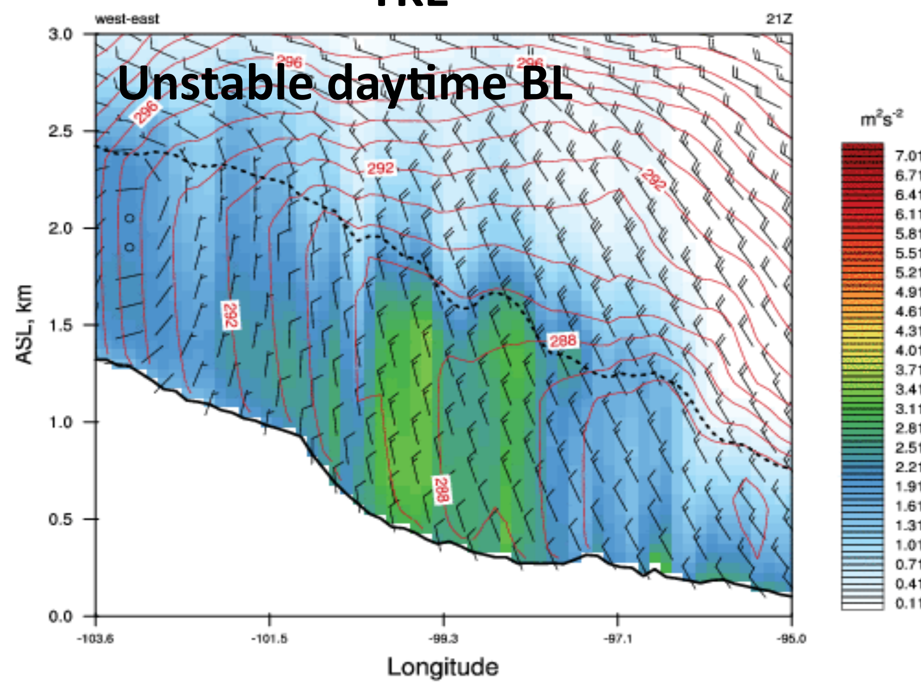
$$wt = .5 * TANH((z_{i\_\theta v} - Z_{SBL})/(2Z_{SBL})) + .5$$

Z_{SBL} is changed from 200 m to 500 m – to get more variability

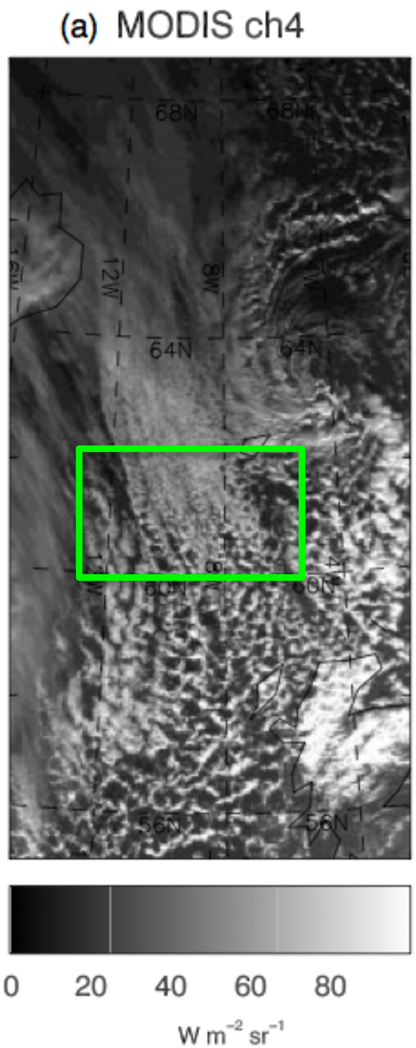
Wind Speed



TKE



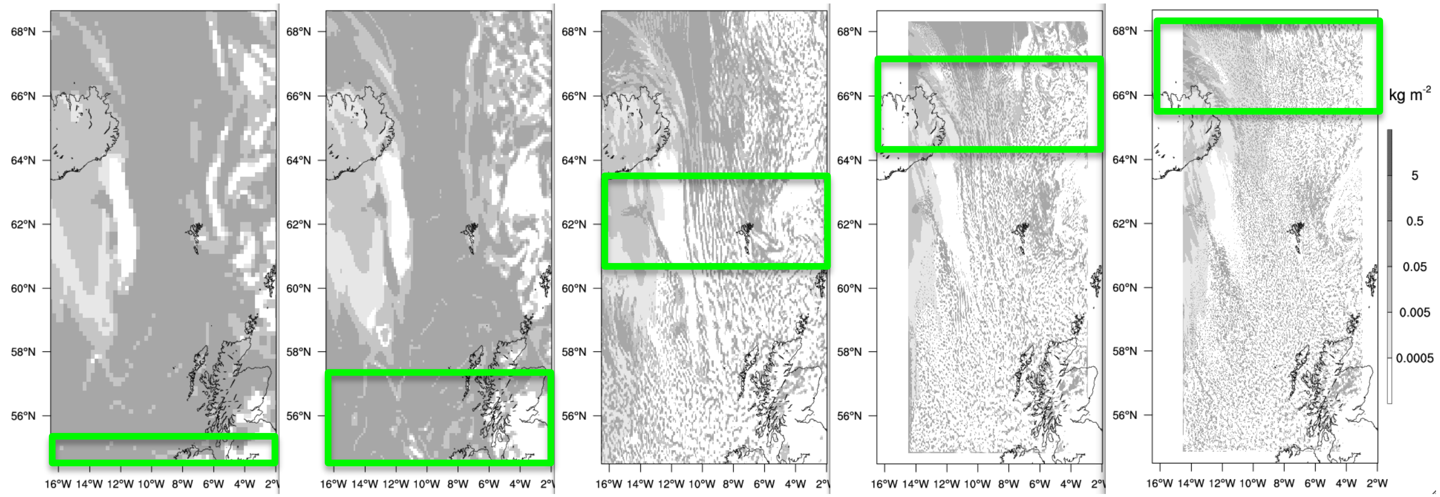
Improvements with PBL mods



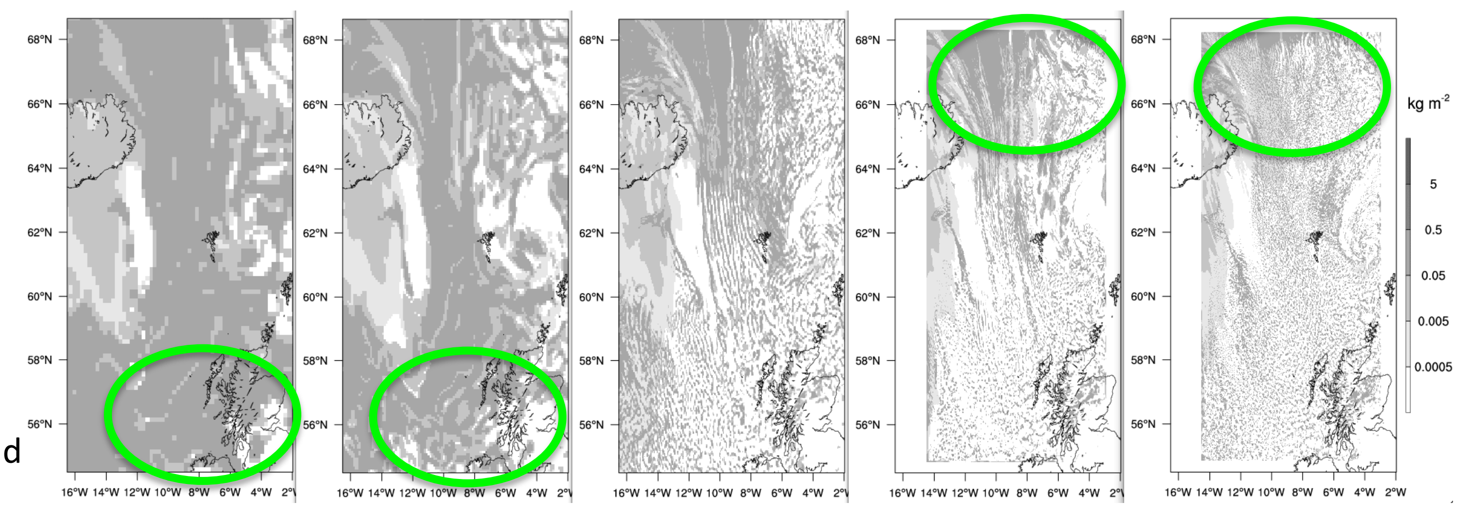
Above figure taken from Field et al (2013).

Δx = 16 km | **Δx = 8 km** | **Δx = 4 km** | **Δx = 2 km** | **Δx = 1 km**

Cu off, ShCu off, Control

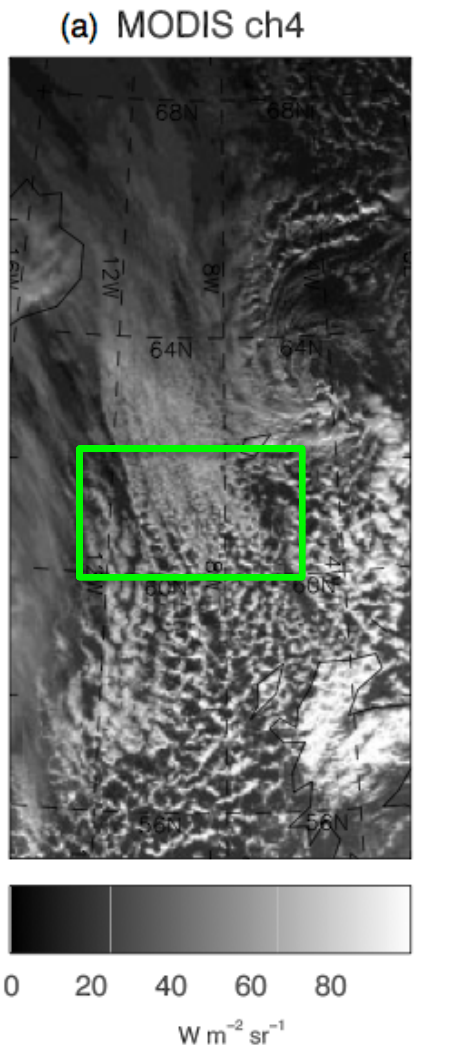


Cu off, ShCu off, PBL mods

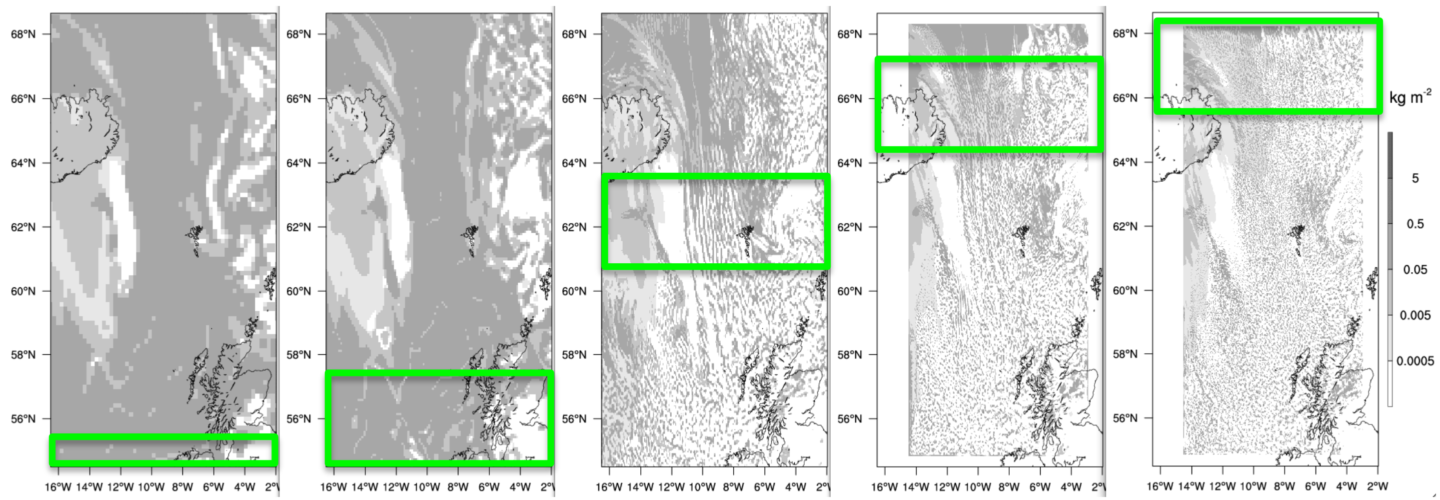


Combined Improvements

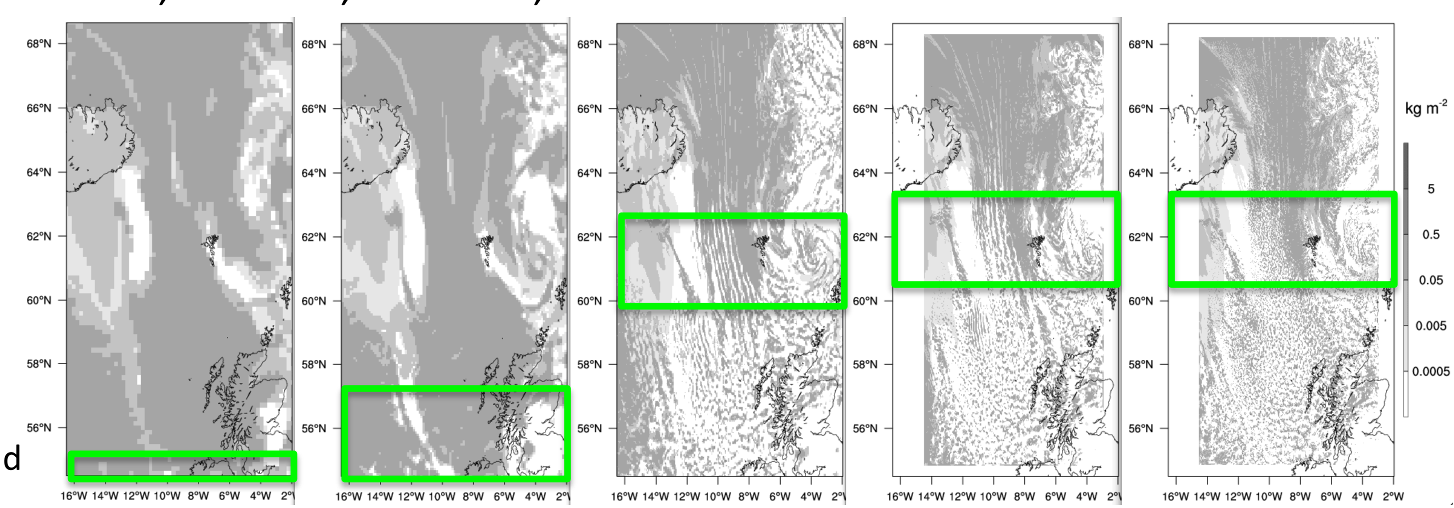
Δx = 16 km   Δx = 8 km   Δx = 4 km   Δx = 2 km   Δx = 1 km



Cu off, ShCu off, 51 levels (Control)



Cu on, ShCu on, 63 levels, with PBL mods



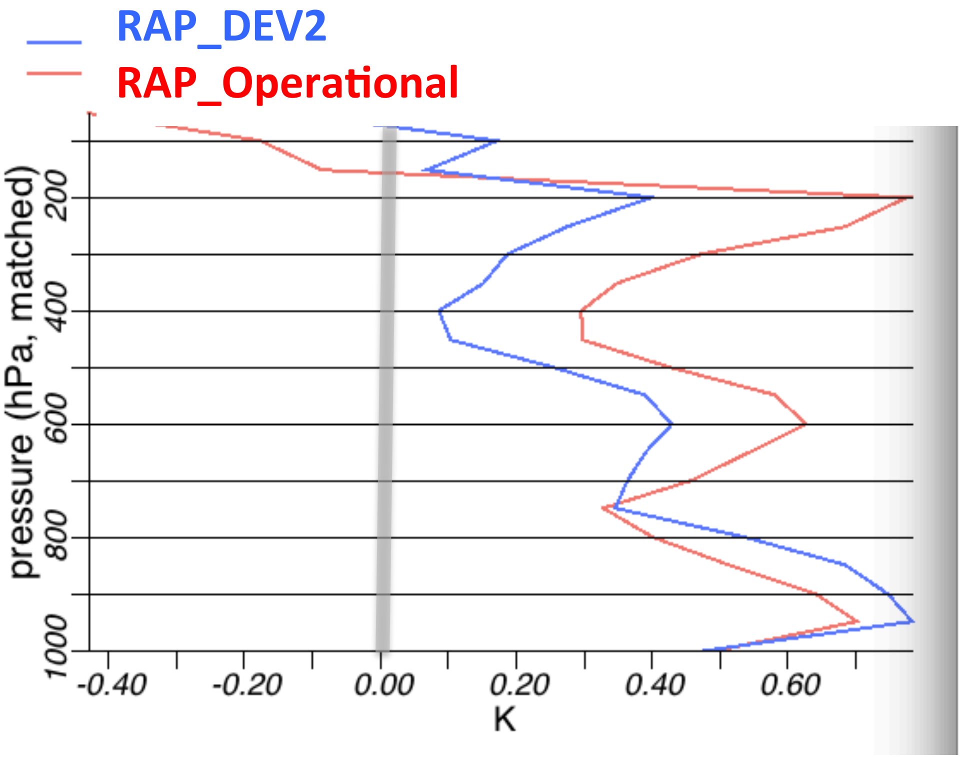
Above figure taken from Field et al (2013).

Improvements over Land

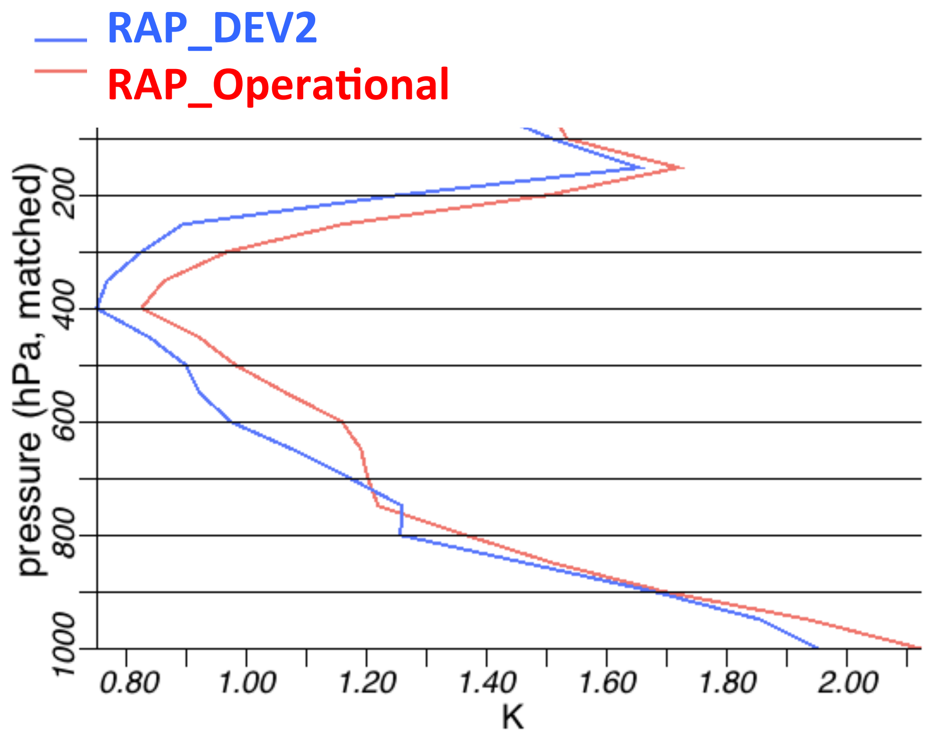
RAP (13 km) Rawindsone Verification over CONUS

6-HR forecasts valid at 00 UTC between 16-25 June 2014

BIAS



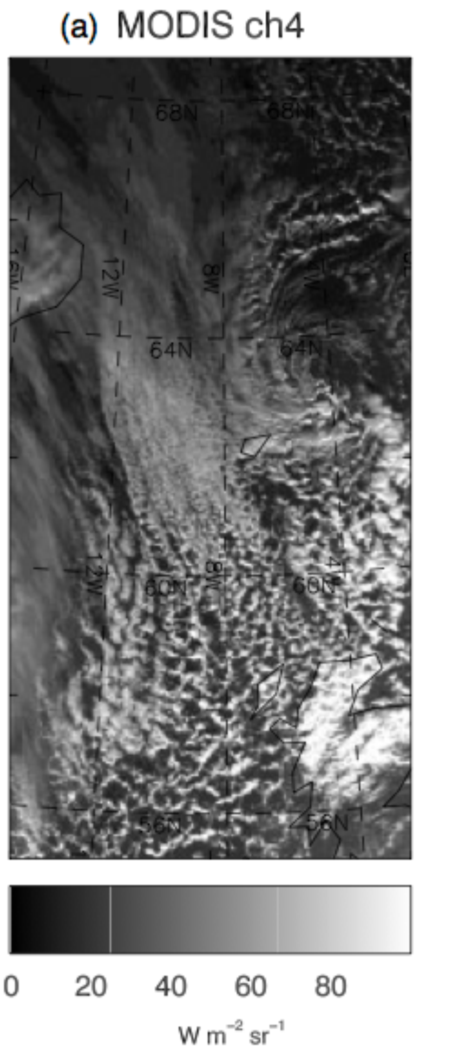
RMSE



Summary Part II

- The combined impacts (PBLH mod + vertical resolution) improve the consistency of the cloud structures at high-resolutions but not at lower resolutions.
- New scale-aware GF deep- and shallow-cumulus schemes improve RAP temperature profiles over land.
- Future work:
  - Non-local (mass-flux, entrainment, cloud-top cooling) additions may be necessary for improved cloud structures. These features will probably require scale-dependent control.
  - Other regimes (deep convection and LLJ) need to be tested to see if these results are general.

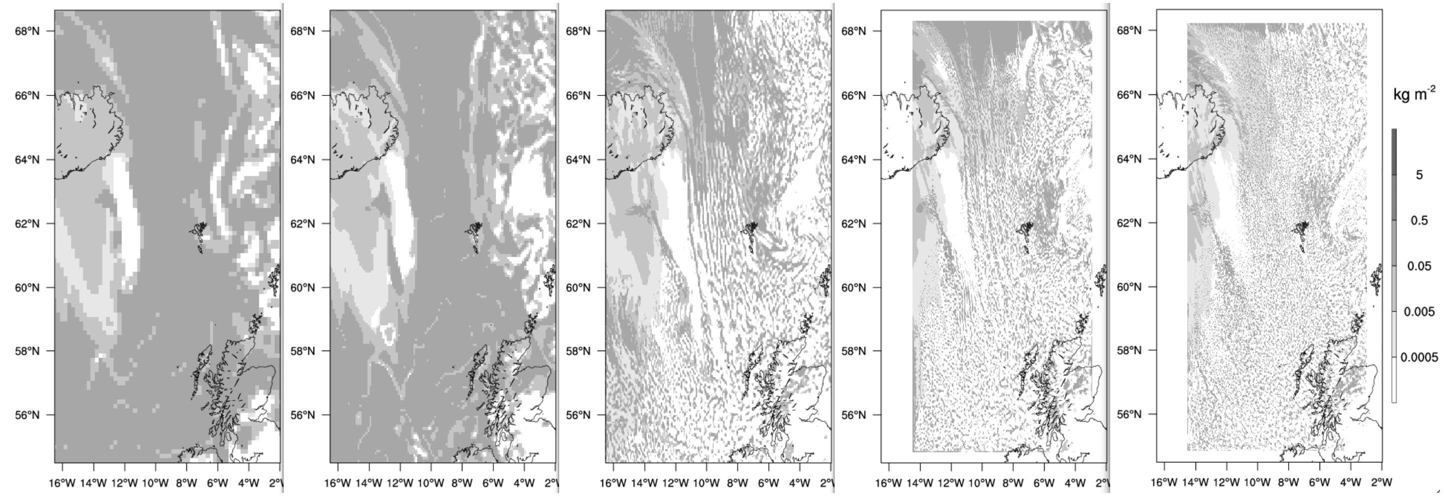
Effects of Higher Vertical Resolution



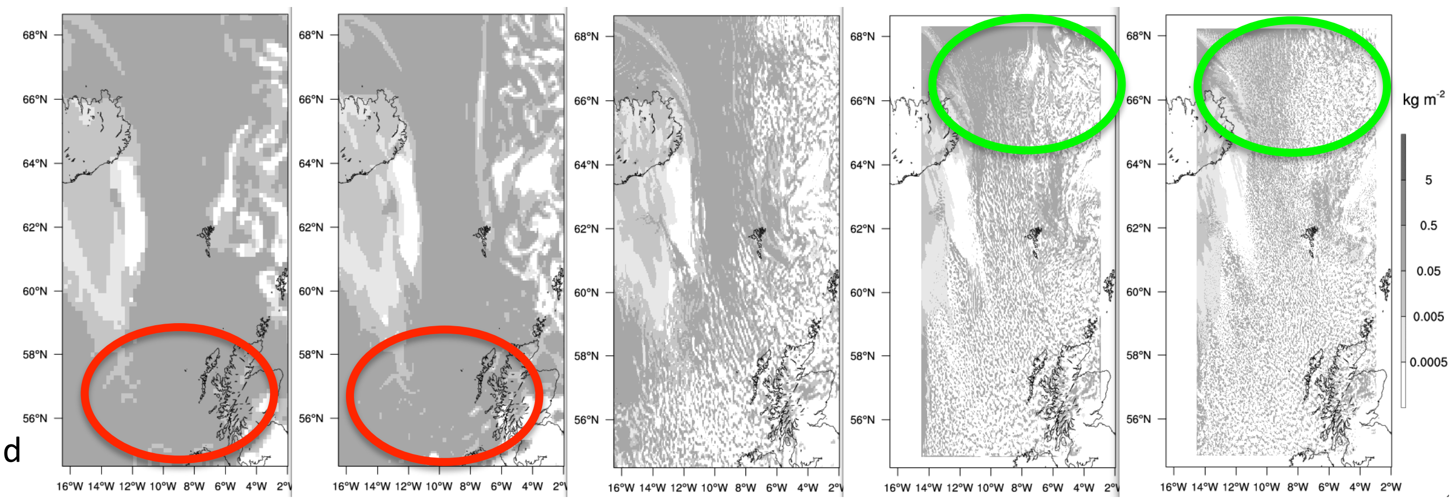
Above figure taken from Field et al (2013).

Δx = 16 km Δx = 8 km Δx = 4 km Δx = 2 km Δx = 1 km

Cu off, ShCu off, 51 levels (8 layers below 900 mb, 12 below 800 mb)

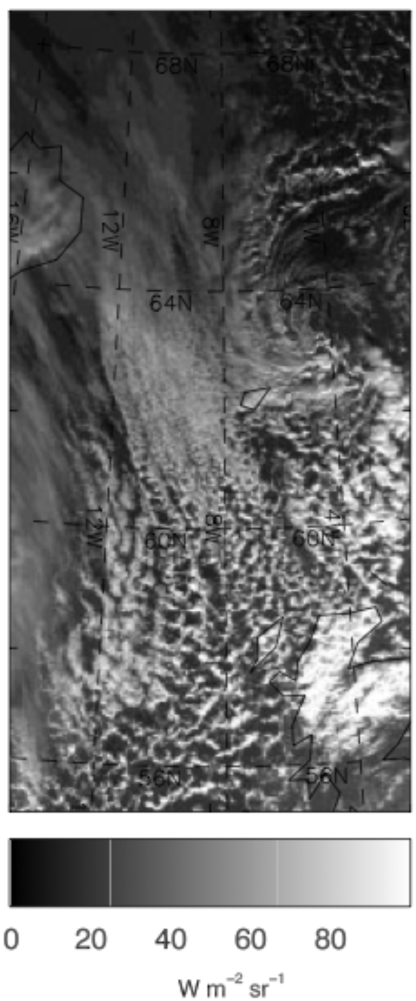


Cu off, ShCu off, 63 levels (14 layers below 900 mb, 21 below 800 mb)



Effects of 6th-Order Diffusion

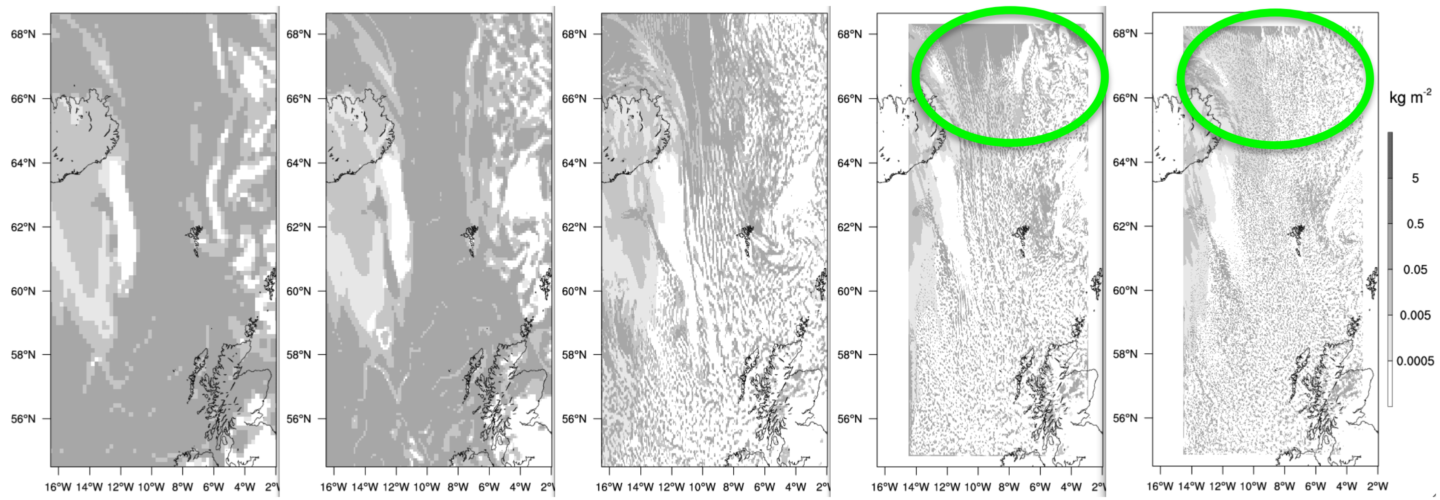
(a) MODIS ch4



Above figure taken from Field et al (2013).

Δx = 16 km | **Δx = 8 km** | **Δx = 4 km** | **Δx = 2 km** | **Δx = 1 km**

Cu off, ShCu off, 6th order diffusion on (RAP)



Cu off, ShCu off, 6th order diffusion off (HRRR)