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Recent Modifications to the PBL Scheme

R. McTaggart-Cowan, A. Zadra and plenty of others

RPN-A

29 March 2012

Outline

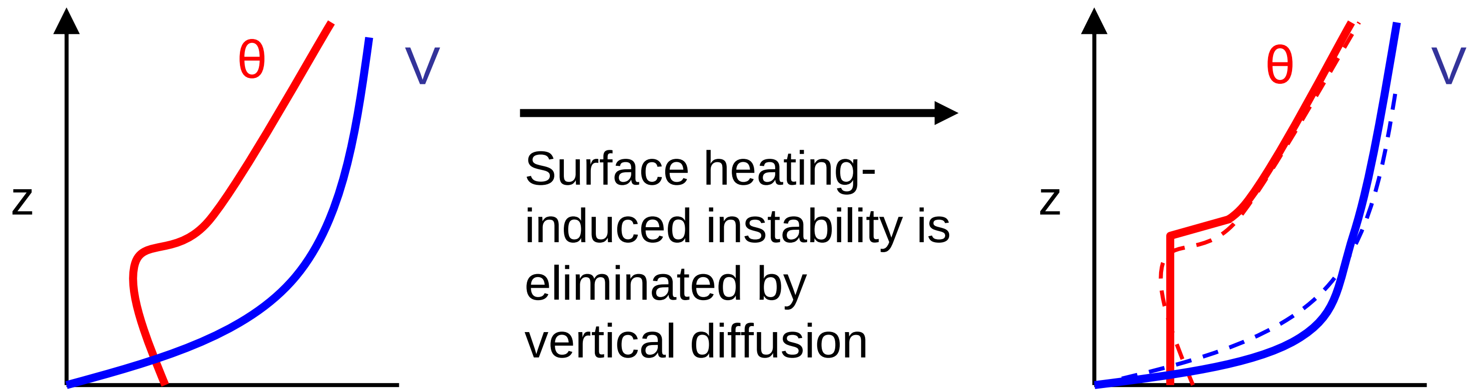
- Description of the PBL scheme (GEM4)
- Issues with the current implementation:
  - Boundary layer depth increases
  - Convergence of the solution
- Coupled PBL approach
- “Episode chaud” errors:
  - Description of a known error mode
  - Introduction of turbulent hysteresis
- GDPS implementation of the PBL

What is the PBL Scheme?

- The PBL scheme represents the **mixing** action of **sub-gridscale turbulence**
- It is implemented as a **vertical diffusion**, and is often called the "vertical diffusion scheme"
- The PBL scheme is active in layers where **static stability** is weak and/or vertical **wind shear** is strong (i.e. near the surface and at jet-level)

What is the PBL Scheme?

- The PBL scheme eliminates static instabilities (θ decreases with height)
- Layers in which the PBL scheme is active are characterized by uniform profiles of θ and winds



Diffused variables

Diffusion equation

$$\frac{\partial \psi}{\partial t} = -\frac{1}{\rho}\frac{\partial}{\partial z}(\rho \overline{w'\psi'})$$

$$= \frac{1}{\rho}\frac{\partial}{\partial z}\left(\rho K_\psi \frac{\partial \psi}{\partial z}\right)$$

Two PBL schemes available:

CLEF
(used in GDPS)

$q_c = 0$

MOISTKE
(used in RDPS)

$q_c \neq 0$

Variables

$$K_M \begin{cases} u \\ v \end{cases}$$

$$K_T \begin{cases} \theta_l = \theta - \dfrac{L}{\Pi c_p} q_c \\ q_w = q_v + q_c \end{cases}$$

where $\Pi = \left(\dfrac{p}{p_r}\right)^{-R/c_p}$

Diffusion coefficients

$$K_\psi = c\lambda_{mix}\sqrt{E}$$

TKE
turbulent kinetic energy

mixing length

where

$$c = 0.516$$

$$\lambda_{mix} = \frac{\lambda_0(z)}{\phi_\psi}$$

neutral mixing length
e.g. Blackadar formulation :
$\lambda_0(z) = \min[\kappa(z + z_0), 200m]$

$$\phi_\psi = \phi_\psi(Ri_g)$$

stability functions

Gradient Richardson number

$$Ri_g = \frac{\frac{g}{\theta_v}[C_\theta \cdot \frac{\partial \theta_l}{\partial z} + C_q \cdot \frac{\partial q_w}{\partial z}]}{\left|\frac{\partial \mathbf{V}}{\partial z}\right|^2}$$

← *static stability*

← *shear*

where

$$C_\theta = 1 + \delta \cdot q_w - \beta \cdot b \cdot f_N N$$

$$C_q = \alpha + \beta \cdot a \cdot f_N N$$

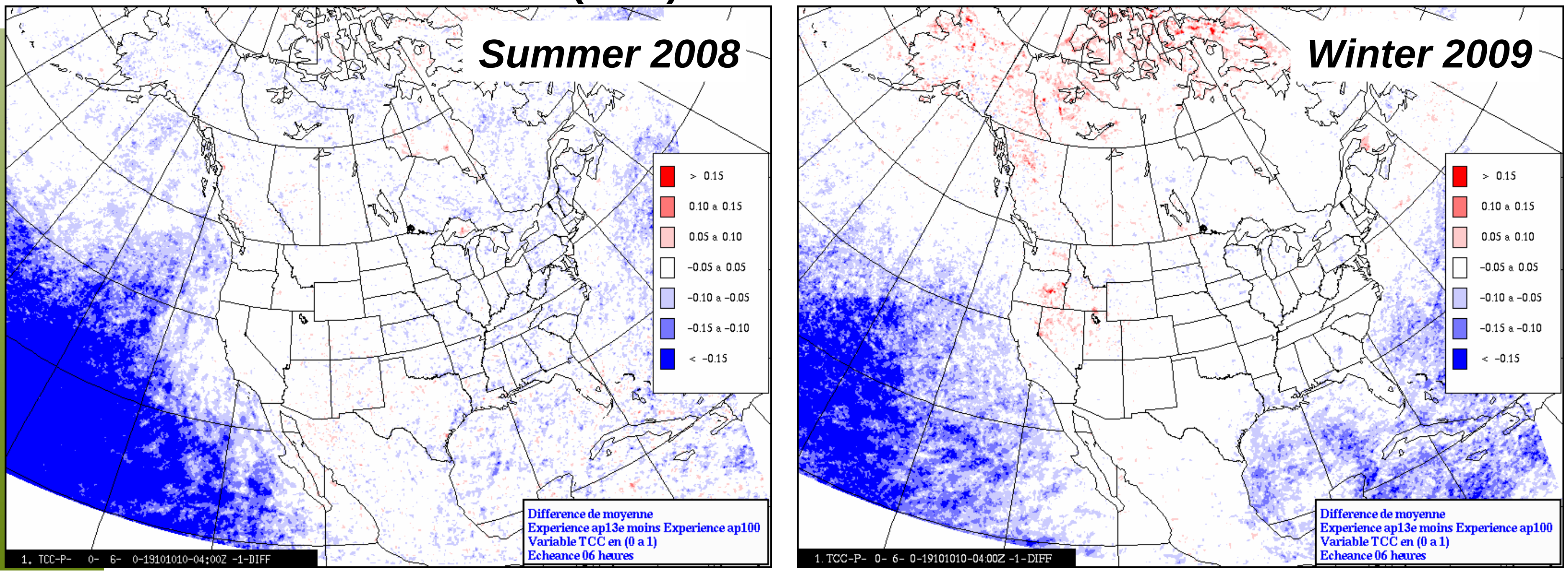
$$\theta_v = \theta_l + \alpha \cdot q_w + \beta \cdot q_c$$

flux enhancement factor
associated with clouds
(CLEF and MOISTKE use different formulations)

So what's the problem?

- During preliminary tests using **GEM4 in the RDPS**, it was noted a significant reduction of total cloud cover over the oceans, within 6h of integration.

Total Cloud Cover (TCC): difference between GEM4 and GEM3



So what's the problem?

- Changes in **latent heat fluxes** (LHF) and **total cloud cover over the oceans in GEM4** – most noticeable in the RDPS, but also seen in the GDPS
- **Systematic increase in PBL depth in GEM4** that differed from the relatively stable PBL depths predicted by GEM3
- As the PBL deepens, it entrains (potentially) warm and dry air from the PBL-capping inversion, leading to a **warmer, dryer PBL in GEM4**

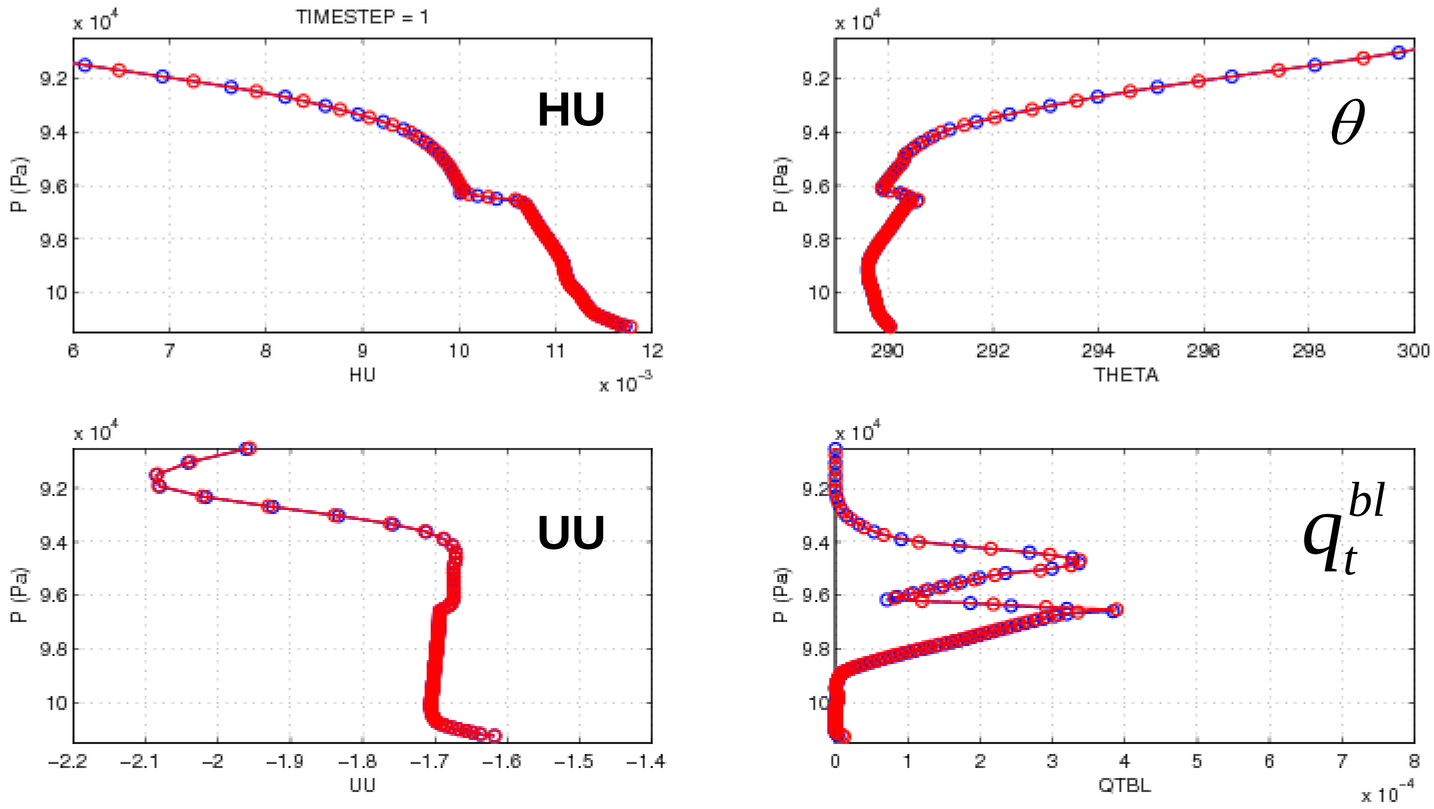
Comparison of PBL Structures

Single Column Model (SCM) simulations

- Time step: **45s**
- Duration: **3h**
- Vertical resolution: ~ **5m**
- Initial conditions: **grid point over north-east Pacific**,
- No forcings; only active scheme is **moistke**
- **Surface fluxes: constant** sensible and latent heat fluxes

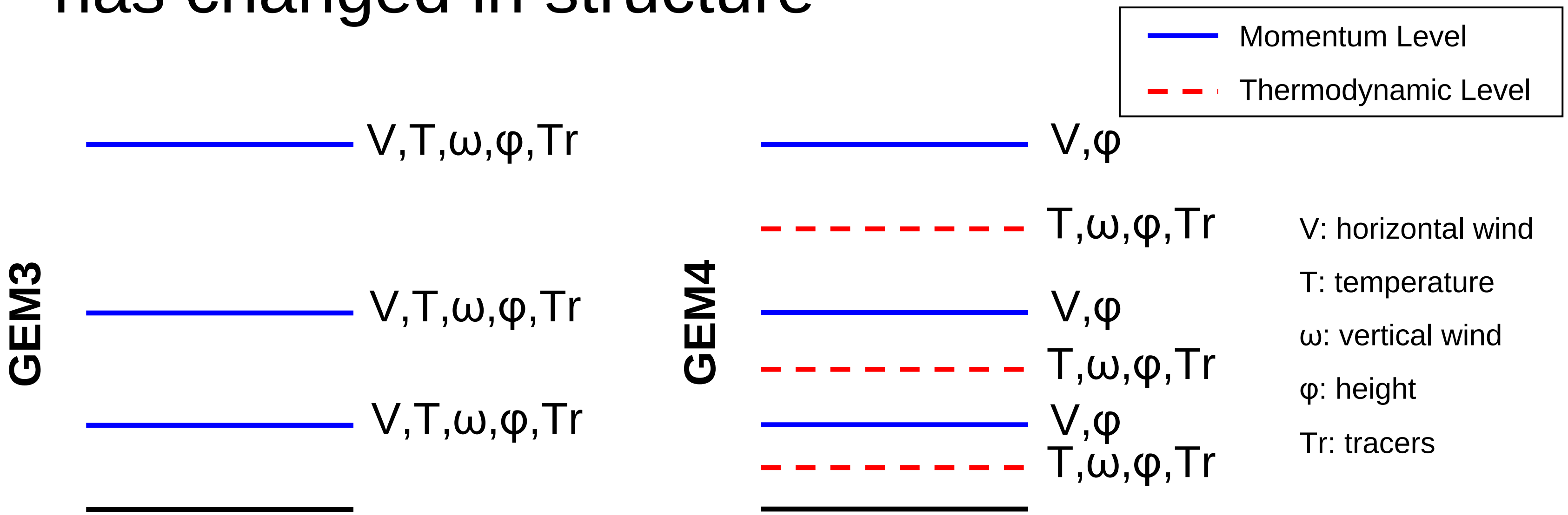
GEM3 versus **GEM4**

using operational **moistke**



What's happening in GEM4?

- The **main change in GEM4** that has a direct impact on the physics is the **vertical staggering of variables**
- The physics sees a "physical world" state that has changed in structure



Does Staggering Affect the PBL?

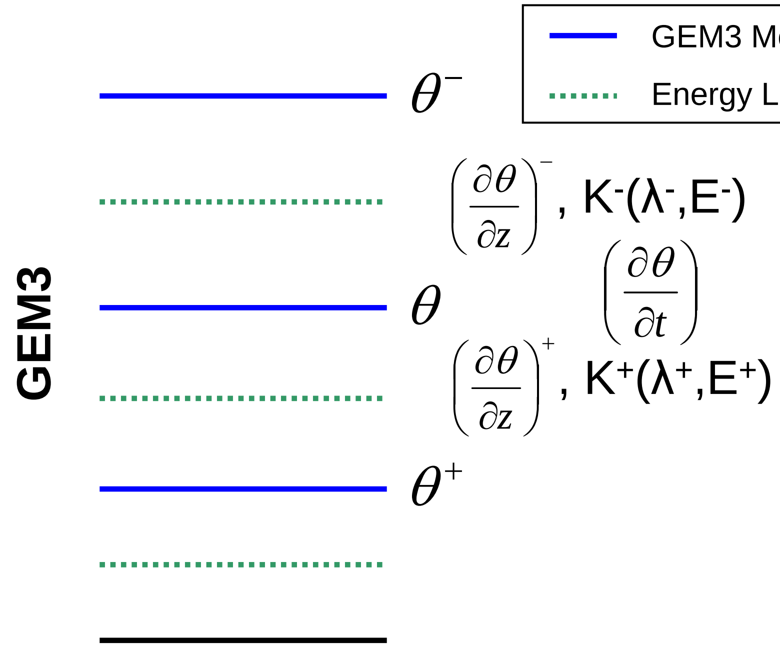
- The PBL scheme solves a **diffusion equation** of the form

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left(K_T \frac{\partial \theta}{\partial z} \right)$$

- The solution of this equation is relatively simple once the **diffusion coefficient** and the **boundary conditions** are known

Does Staggering Affect the PBL?

- To maximize the accuracy of the diffusion equation, the **K coefficients should be valid on "energy" levels** between the diffused quantity

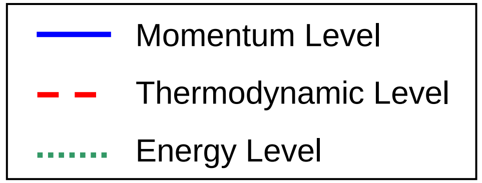


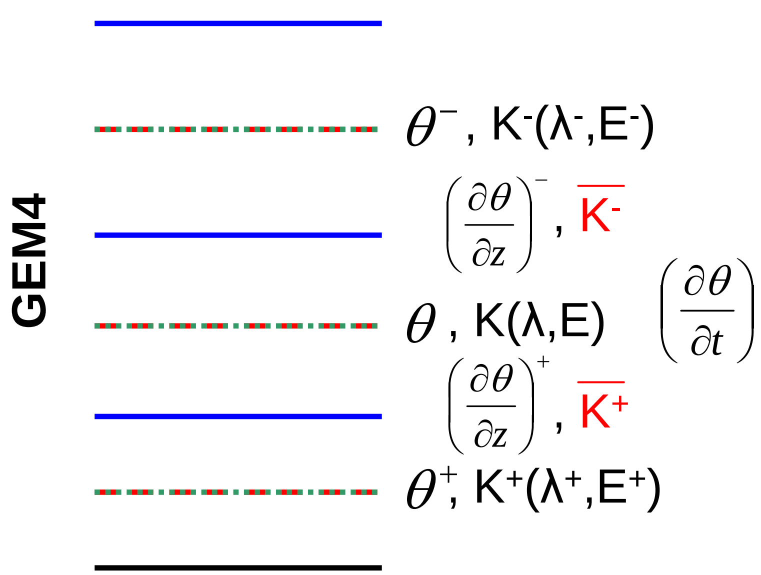
$$\boxed{\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left(K_T \frac{\partial\theta}{\partial z}\right)}$$

Since the K coefficients are functions of the mixing length (λ) and turbulent kinetic energy (E), these values are also computed on energy levels

Does Staggering Affect the PBL?

- In GEM4, the thermodynamic variables are now staggered onto levels that generally coincide with the existing energy levels





$$\boxed{\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left(K_T \frac{\partial\theta}{\partial z}\right)}$$

Because of staggering, the computation of time tendencies of variables on thermodynamic levels, a vertical averaging of the diffusion coefficients onto momentum levels is required

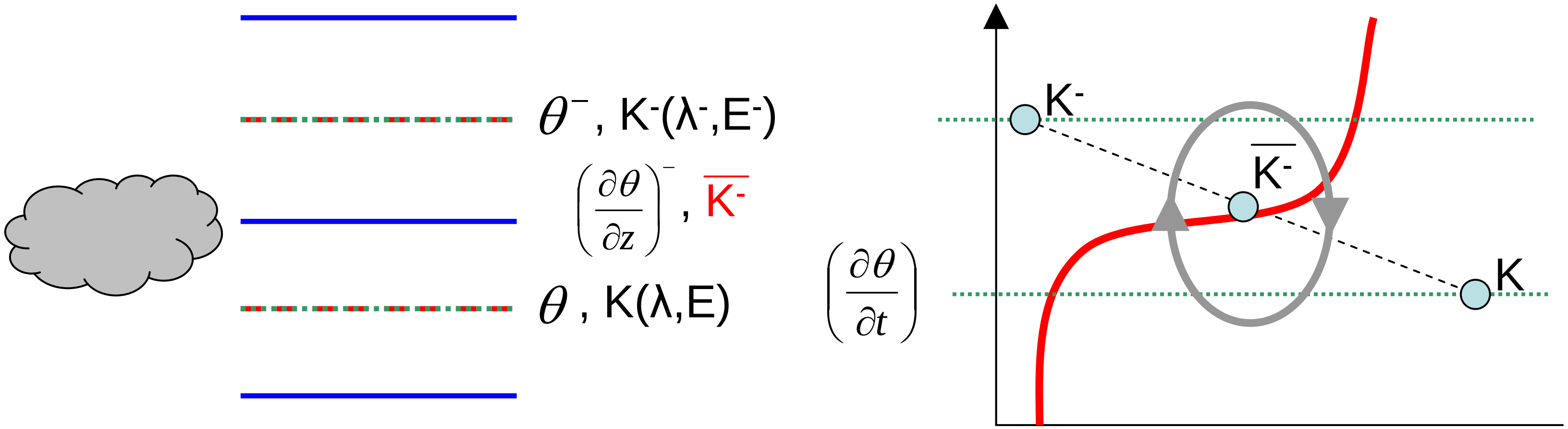
Clouds in the PBL Scheme

- The PBL scheme contains its own diagnostics of subgrid clouds. In a layer where such clouds are diagnosed, heat fluxes are amplified -- using a ***flux enhancement factor*** – possibly leading to destabilization.

- The flux enhancement factor **can increase the K coefficients by up to two orders of magnitude within cloud layers**

Clouds in the PBL Scheme

- The resulting sharp gradients in the K profiles make **vertical averaging problematic**, especially at the top of the cloud layer (i.e. the inversion)



Comparison of PBL Structures without the flux enhancement factor

Single Column Model (SCM) simulations

- Time step: **45s**
- Duration: **3h**
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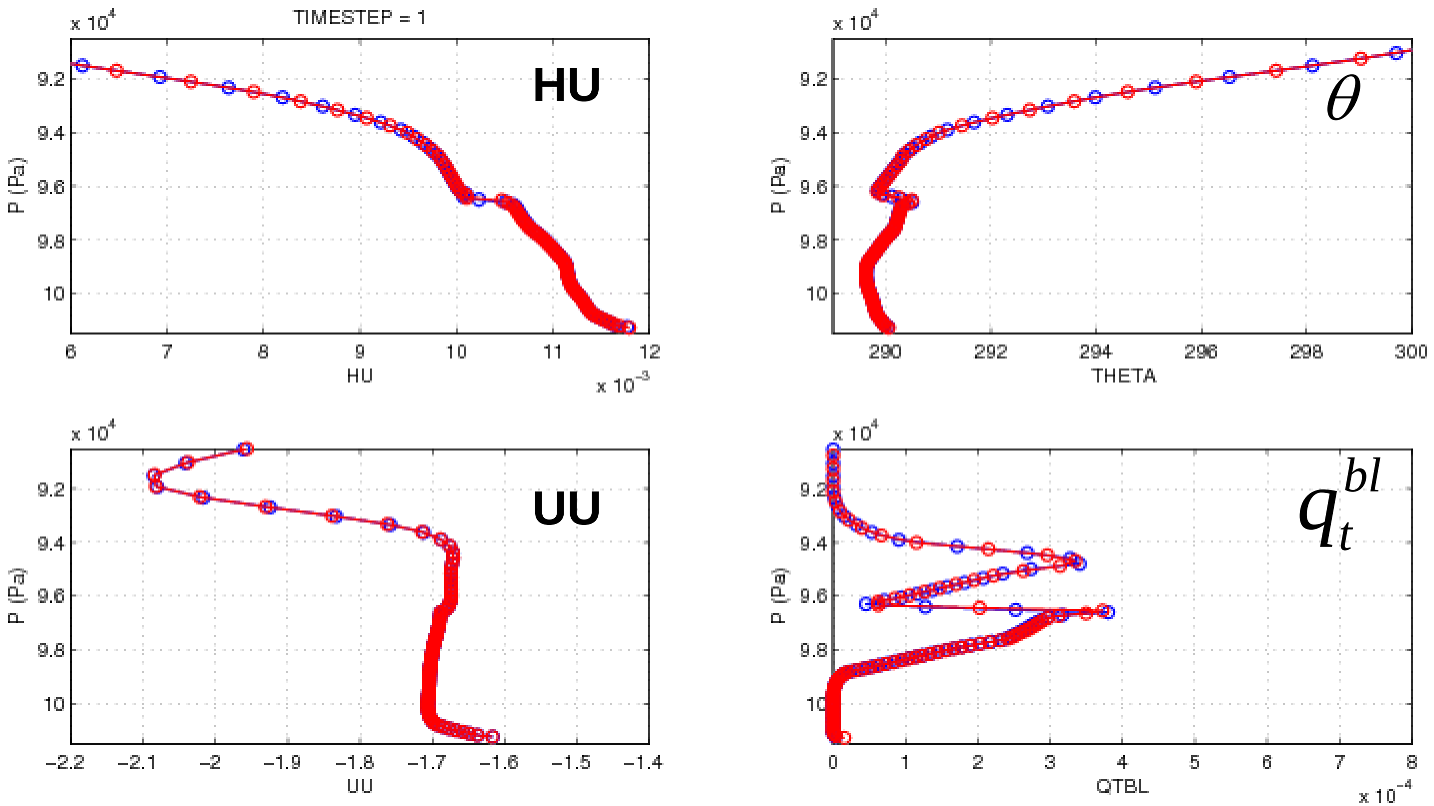
- Initial conditions: **grid point over north-east Pacific**,
- No forcings; only active scheme is **moistke**
- **Surface fluxes: constant** sensible and latent heat fluxes

GEM3 versus GEM4

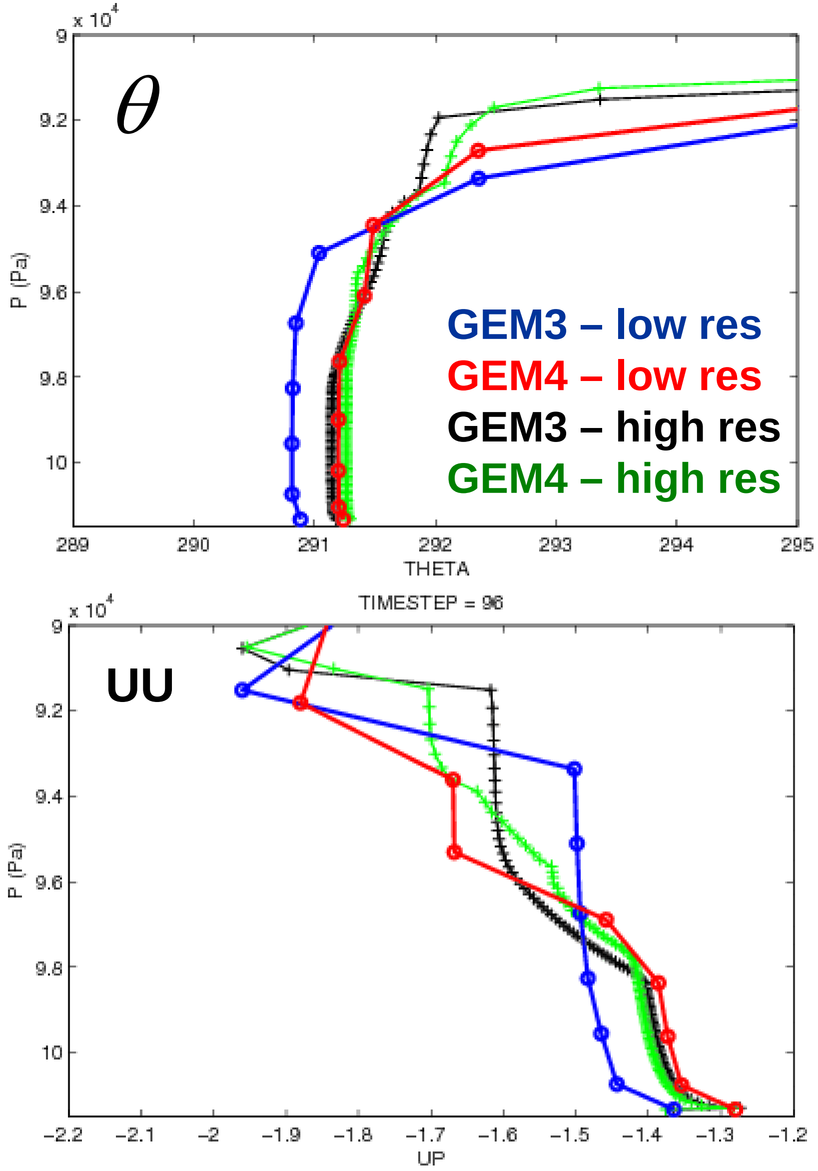
using operational **moistke**

without the flux enhancement factor



Complication: Scheme Convergence

- The plots shown on the previous slide are from a Single Column Model (SCM) simulation at high vertical and temporal resolution
- In the GDPS (GEM3 and GEM4), the **solution from the PBL scheme has not converged**: it is sensitive to time and space resolution
- In the RDPS, the **moistke scheme fails to converge even at high resolutions** (figures)



Possible Solutions

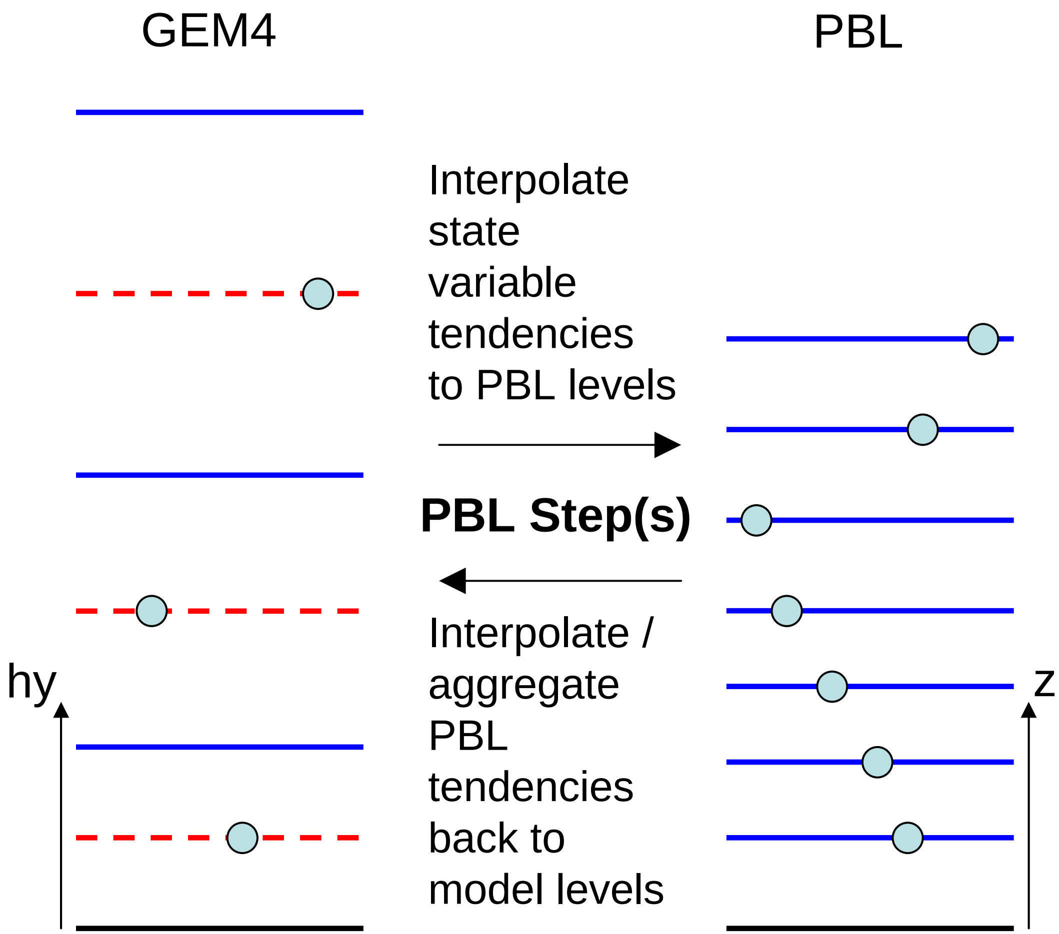
- Once the source of the unphysical PBL expansion was identified, **numerous attempts were made** to limit this process:
  - Change averaging for K (geometric, harmonic, nearest-neighbor)
  - De-stagger the physics / PBL scheme
  - Deactivate flux enhancement (e.g. no shallow convection in GDPS)
- Each of these modifications either **failed** to suppress PBL growth or caused other major problems in the integration

We need a solution that will simultaneously remove the need for averaging and run with higher resolution

Coupling the PBL Scheme

- Removing the restriction of running the PBL scheme with the same discretization as the rest of the model would allow us to address these problems directly
- As an analog, consider horizontal grid coupling (e.g. to an ocean model):
  - PBL runs with its own **unstaggered** vertical grid (no K coefficient averaging and improved resolution)
  - PBL runs with a split timestep to improve temporal resolution
  - PBL retains its own state and communicates with the rest of the model via tendencies at model timesteps

Coupling the PBL Scheme



The PBL scheme retains its own state from step-to-step, allowing it to develop a sharper profile

More appropriate unstaggered height coordinates can be used in the PBL scheme only

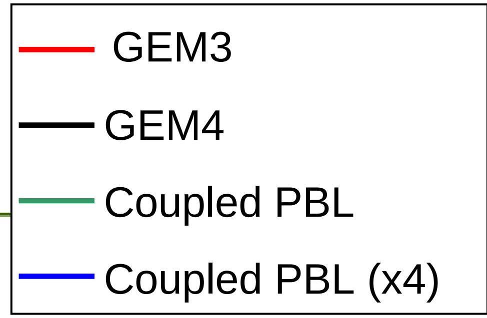
PBL scheme can work in the lower atmosphere only

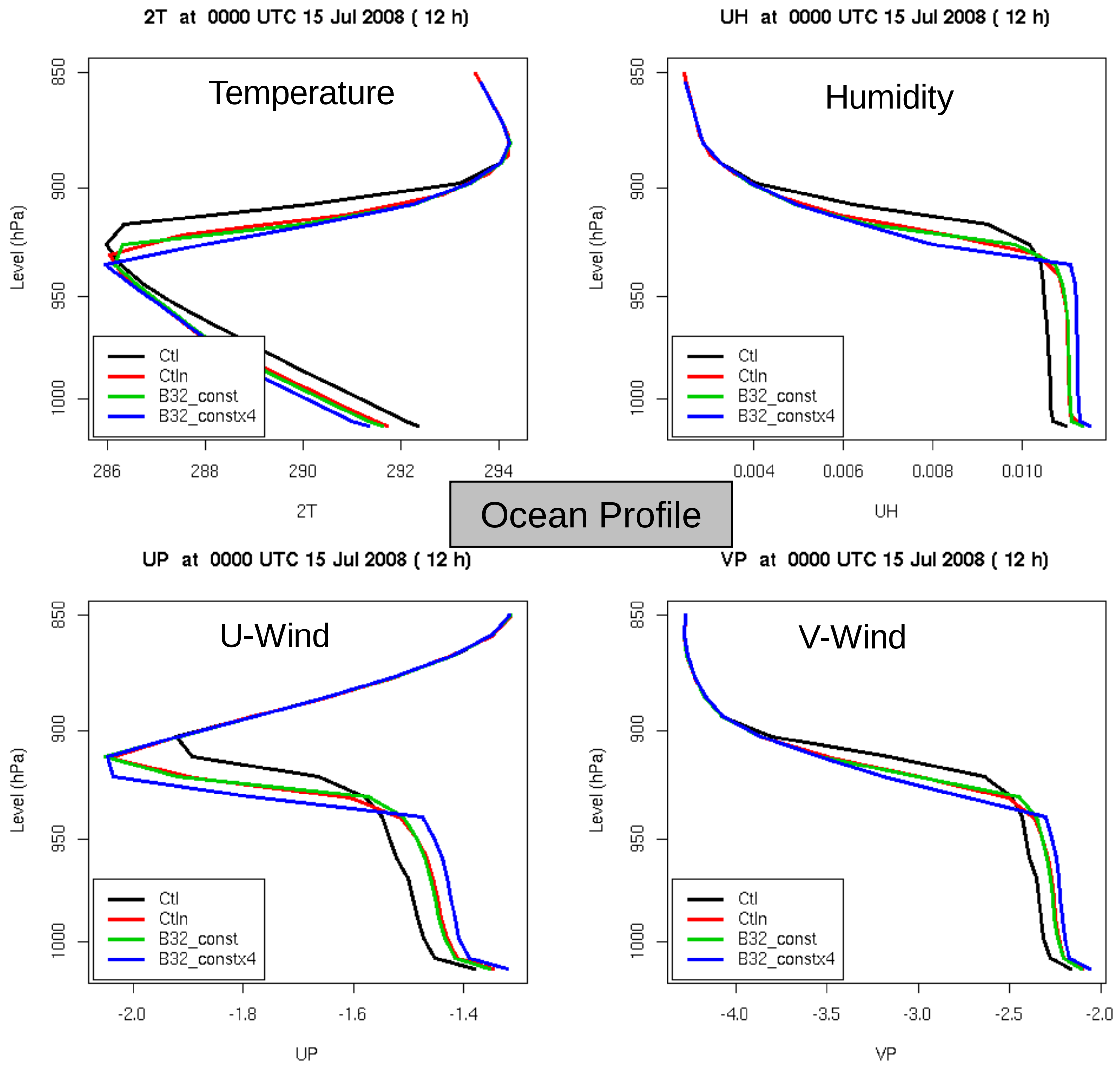
○ Temperature

Current Status of PBL Coupling

- Coupled PBL scheme uses model hybrid coordinate as a basis, with a minimum of doubled resolution such that all model levels (momentum and thermo) coincide with a PBL level (PBL_ZSPLIT=1)
- Tendencies are sampled from the PBL scheme onto model coordinates
- Split time-stepping is unimplemented
- The tropical sponge (implemented as enhanced K-coefficients at upper levels) has been moved to the dynamics to allow the coupled PBL to extend only to the PBL_KTOP model level for efficiency

Does it fix the problem(s)?





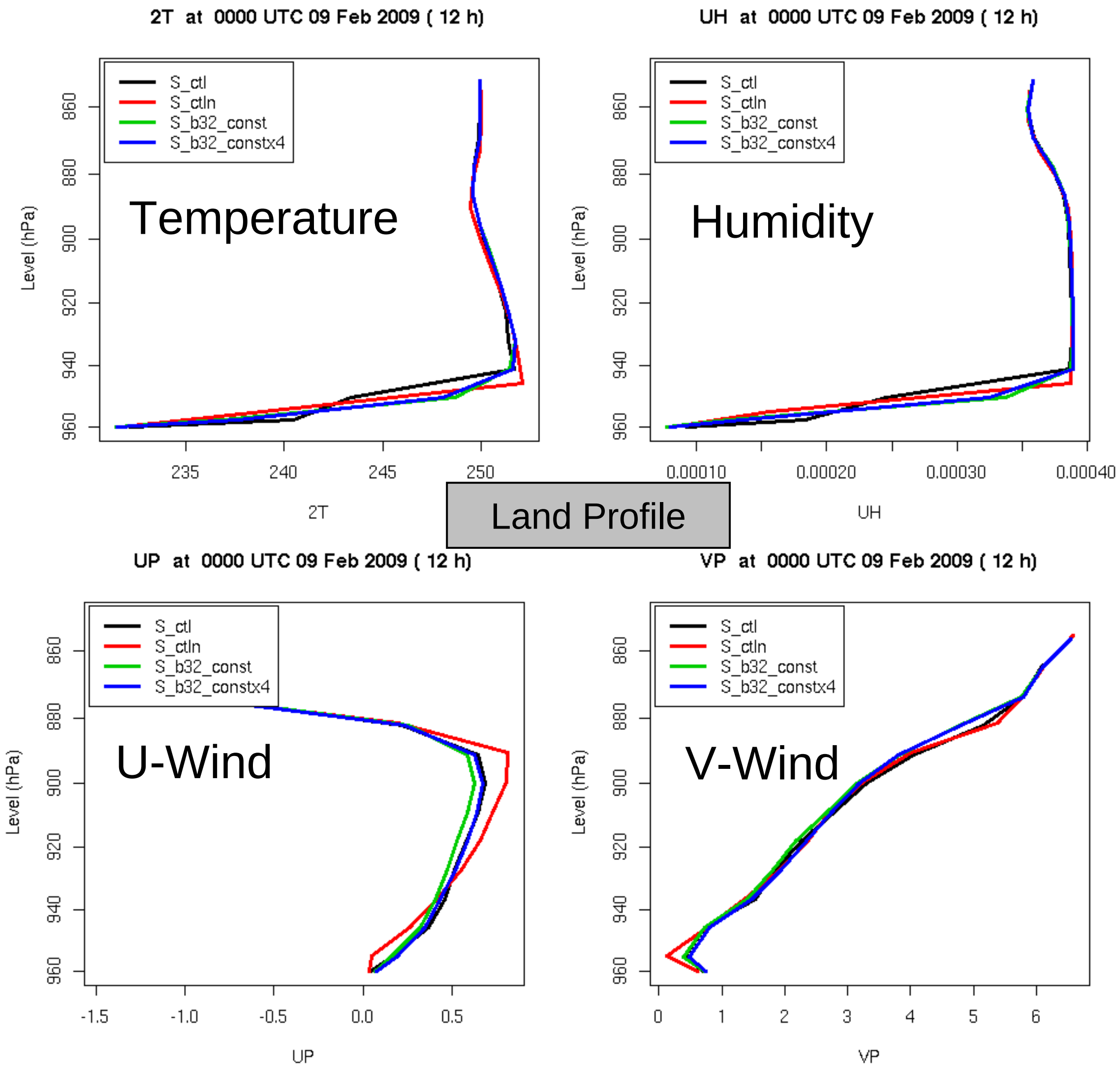
For an unstable ocean profile, the coupled PBL scheme successfully limits PBL growth and results in a PBL structure very similar to the unstaggered GEM3

Increased resolution further sharpens the profile

Profiles of state variables (as labelled) after 12h of SCM integration for a typical unforced subtropical maritime profile. SCM is run in an operational configuration (vertical levelling and timstep)

Does it fix the problem(s)?

- GEM3
- GEM4
- Coupled PBL
- Coupled PBL (x4)



For an stable winter profile, the PBL scheme seems relatively insensitive to vertical discretization

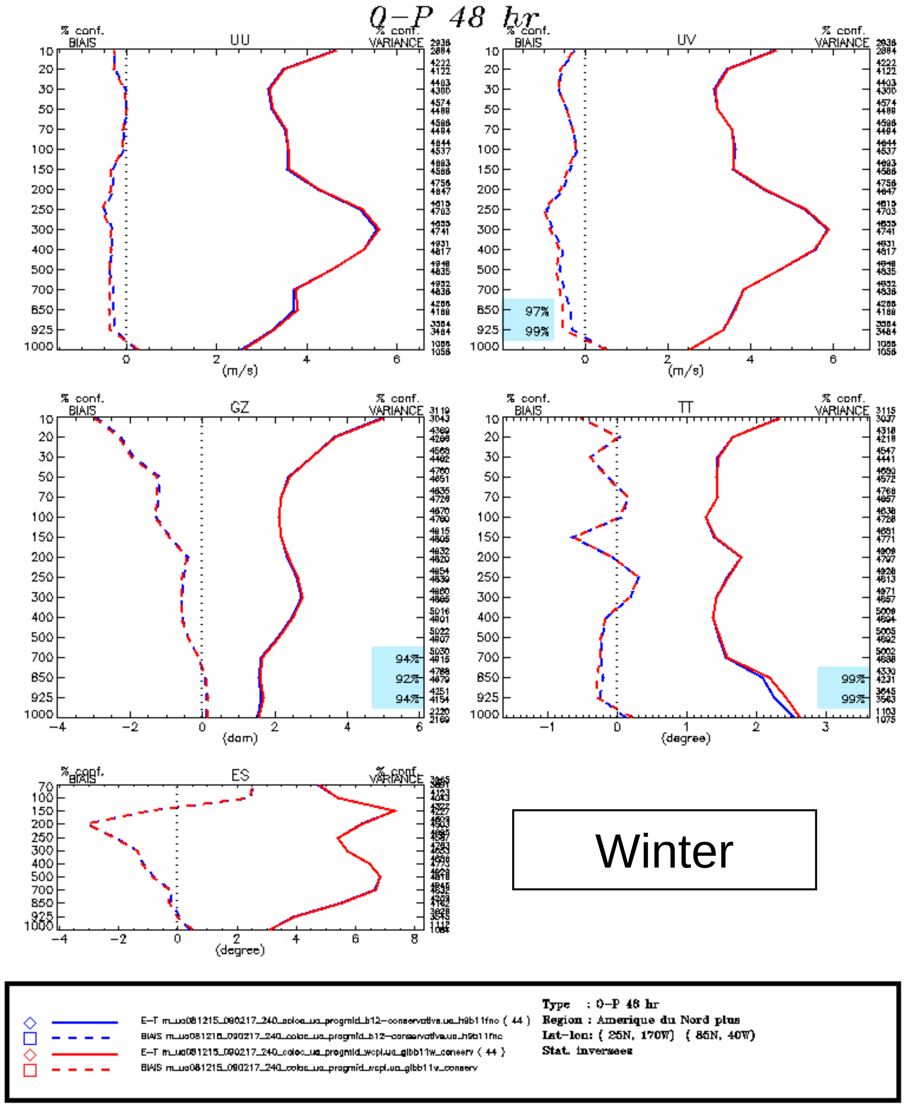
However, the GEM4 temperature profile does show an unusual pair of stable layers instead of a uniform inversion

Profiles of state variables (as labelled) after 12h of SCM integration for a typical high latitude winter profile. SCM is run in an operational configuration (vertical levelling and timstep)

Coupling Complications

- In the original GEM4 configuration, the lowest thermo level is below the lowest momentum level, implying extrapolation for the base of the profile:
  - Constant extrapolation leads to excessive cooling under extreme inversion conditions (only valid for the unstable case)
  - Log-based extrapolation is only strictly valid for the neutral case
  - Use of stability function diagnosis yields poor results in the maritime subtropical profile of interest
- A modification to the discretization allows for a co-location of the lowest thermo and momentum levels (Schm_TLift=1), eliminating the need for extrapolation

Epic Fail



- Results from the 44 winter cases of the GDPS show a serious degradation of forecast skill in PBL temperatures
- A reduction in near-surface wind speeds is also observed
- Possible origins of this problem include:
  - Conceptual error in coupling strategy (SCM results suggest that this is not the case)
  - Error in the implementation of the coupling strategy
  - Sensitivity to sampling of tendencies on return to model levels
- Results from the 44 summer cases suggest that strongly stable conditions exacerbate coupled PBL errors

Arcad evaluation scores against North American radiosondes after 48 h of integration for 44 Winter cases. Statistics are inverted.

So, where do we go from here?

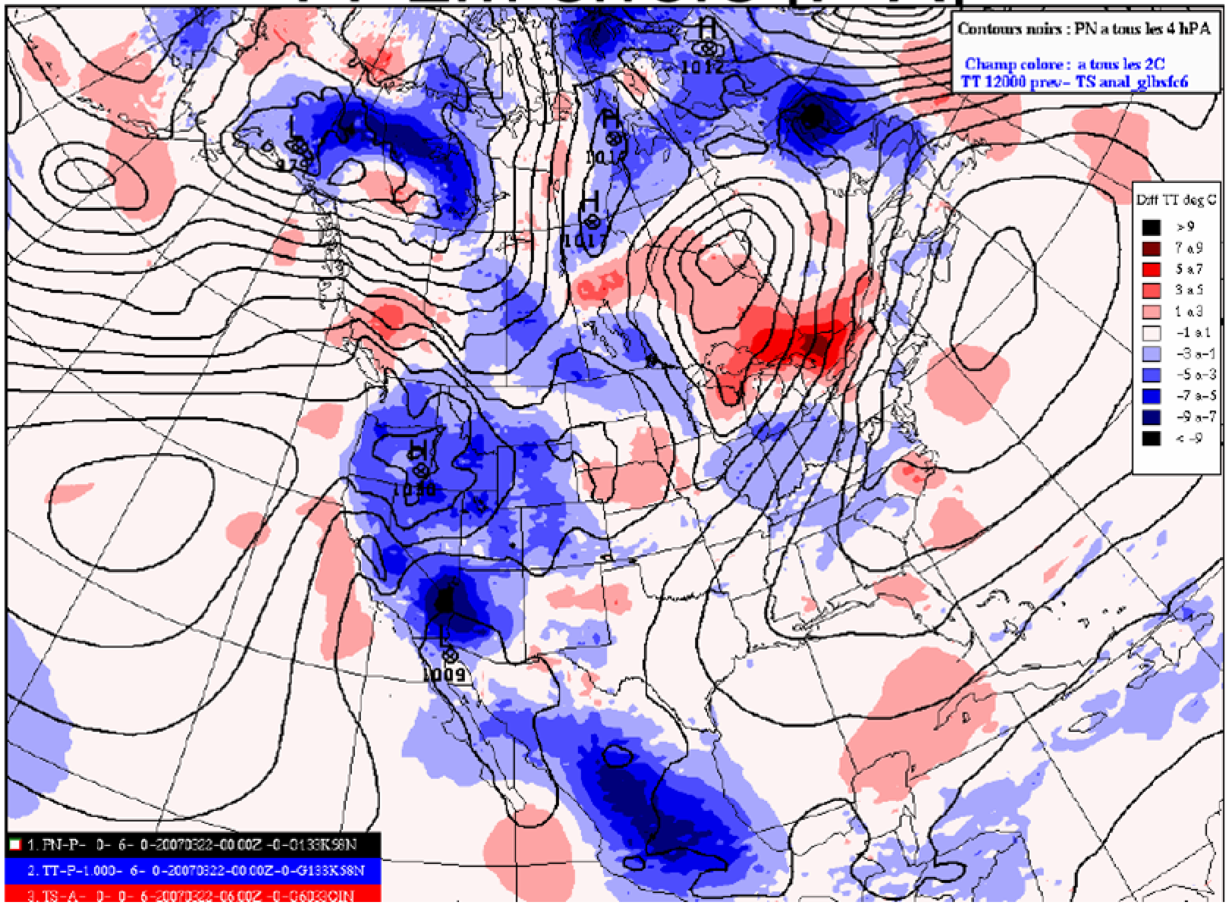
- Further work on PBL coupling is clearly needed, and is an open-ended project with important potential benefits:
  - Allows us to focus resources on high resolution (temporal and spatial) where it is needed near the surface for the PBL scheme
  - Would allow us to obtain a converged PBL solution without increasing model resolution or decreasing the model timestep
  - A type of “superparameterization” (Grabawski 2004) that could be generalized to other schemes
- Time constraints forced the RDPS – where the problems were most serious – back to GEM3
- For the GDPS, we chose to refocus the PBL project on addressing the “warm episode” error, a known issue that appears to be related to vertical diffusion

“Warm Episodes” in GEM

- The “warm episode” error is a problem that affects all GEM configurations (noted particularly in GDPS/RDPS)
- It has been identified by forecasters as one of the most serious guidance problems:
  - Large near-surface temperature errors (approaching 10 K) can appear at very short lead times
  - Tends to occur in regions with precipitation, making phase forecasts difficult
  - Freezing rain profiles are particularly affected, leading to under-forecasting of freezing rain events during warm episodes
- Considerable effort has already gone into diagnosing the source of this problem (P. Vaillancourt / A.-M. Leduc), identified to be associated with over-mixing in the PBL scheme

Warm Episode Case Study

Case study: march 22nd 2007 TT-2m errors [P-A]

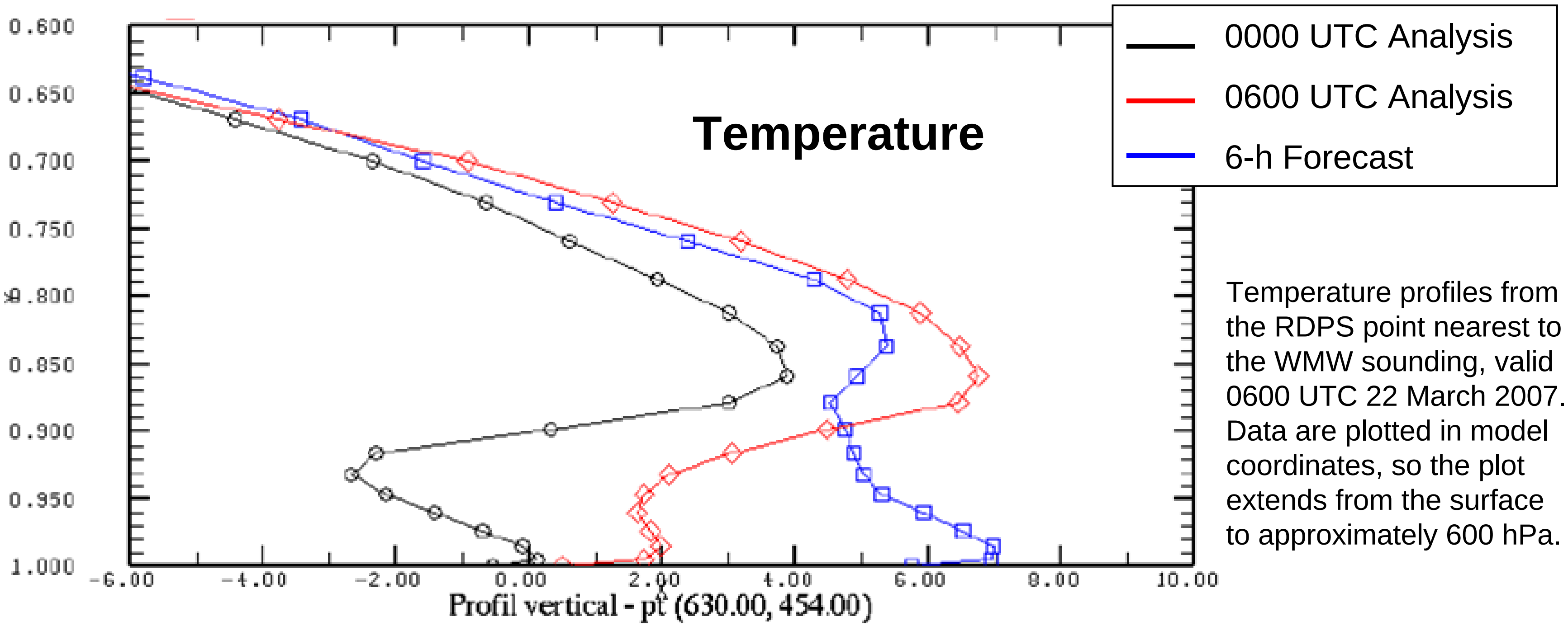


The canonical warm episode case occurs in the warm advection region of a winter continental cyclone

In this case, a warm error of >7 K is apparent in the 6 h forecast over southern Ontario and Quebec

Near-surface temperature errors (forecast – analysis, colour-shaded as indicated on the colour bar) and MSLP (contoured at 4 hPa intervals) n the 6 h forecast initialized at 0000 UTC 22 March 2007. (Courtesy P. Vaillancourt.)

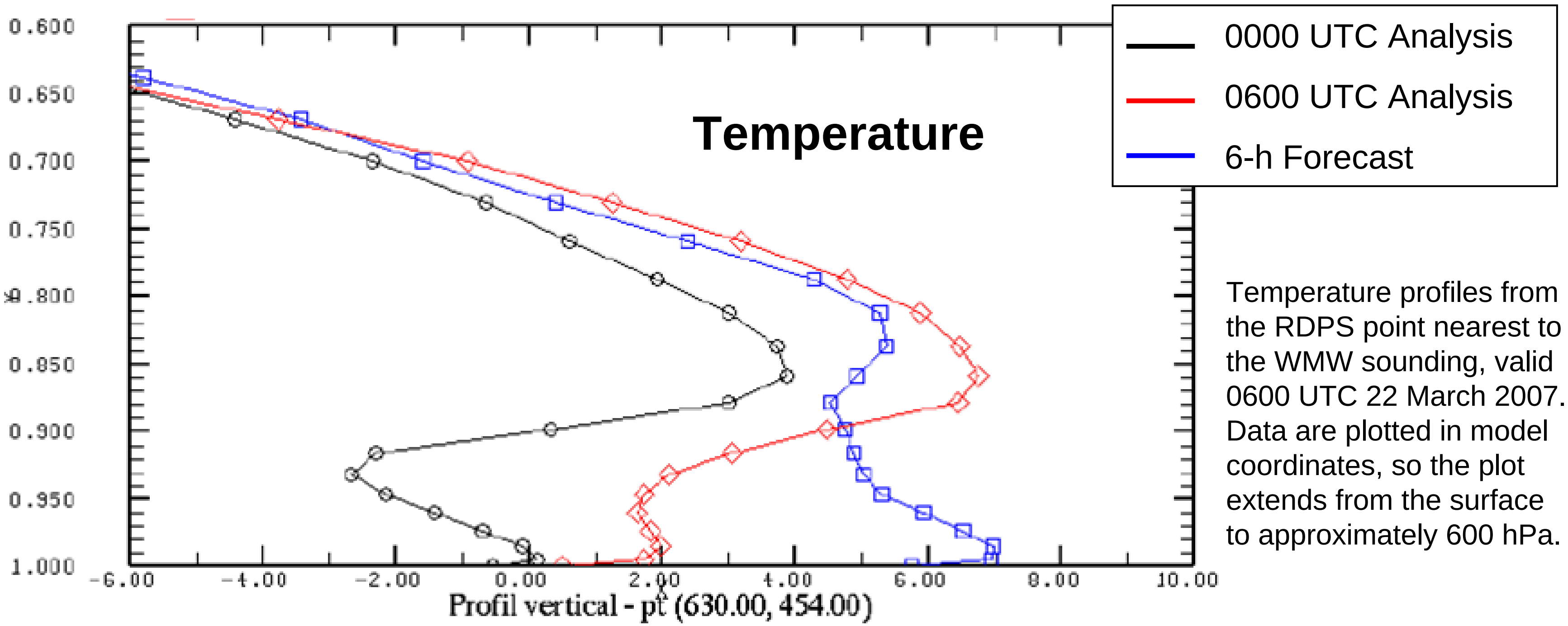
Warm Episode Case Study



Temperature profiles from the RDPS point nearest to the WMW sounding, valid 0600 UTC 22 March 2007. Data are plotted in model coordinates, so the plot extends from the surface to approximately 600 hPa.

- The warm nose in the 0600 UTC analysis (red) - created and maintained by strong warm advection around 850 hPa - is almost completely eliminated in the 6-h forecast (blue)
- Cooling aloft and warming below (approximate conservation of equivalent potential temperature) suggests that vertical diffusion is responsible for this profile error, instead of it being a response to an surface source/sink

Warm Episode Case Study



Temperature profiles from the RDPS point nearest to the WMW sounding, valid 0600 UTC 22 March 2007. Data are plotted in model coordinates, so the plot extends from the surface to approximately 600 hPa.

So why are the PBL diffusion coefficients too large?

Vertical Diffusion Revisited

- With its TKE closure, the PBL scheme estimates the diffusion (K_M, K_T) coefficients using,

$$K_M = c\lambda_{\text{mix}}\sqrt{E} \qquad\qquad K_T = \frac{1}{\Pr}K_M$$

$\Pr$ Prandtl Number

λ_{mix} Mixing length (vertical scale of turbulent eddies)

c Constant of proportionality (currently 0.516)

E Turbulent kinetic energy (TKE)

- Both Pr and the mixing length depend diagnostically on the Richardson Number (Ri)

Vertical Diffusion Revisited

- The TKE is a prognostic quantity that is updated at each timestep using the tendency equation,

(shear generation – buoyant suppression) (viscous dissipation) (TKE diffusion)

$$\frac{\partial E}{\partial t} = BE^{1/2} - CE^{3/2} + \frac{\partial}{\partial z}\left(K_M \frac{\partial E}{\partial z} \right)$$

$$B = (1 - Ri_f) \cdot \left| \frac{\partial V}{\partial z} \right|^2 \cdot c\lambda_{\text{mix}}$$

$$C = {0.14}/{\lambda_{\text{diss}}}$$

Dissipation length scale (function of Ri)

- The first term in the tendency equation (B-coefficient) generally leads to the most rapid changes in TKE

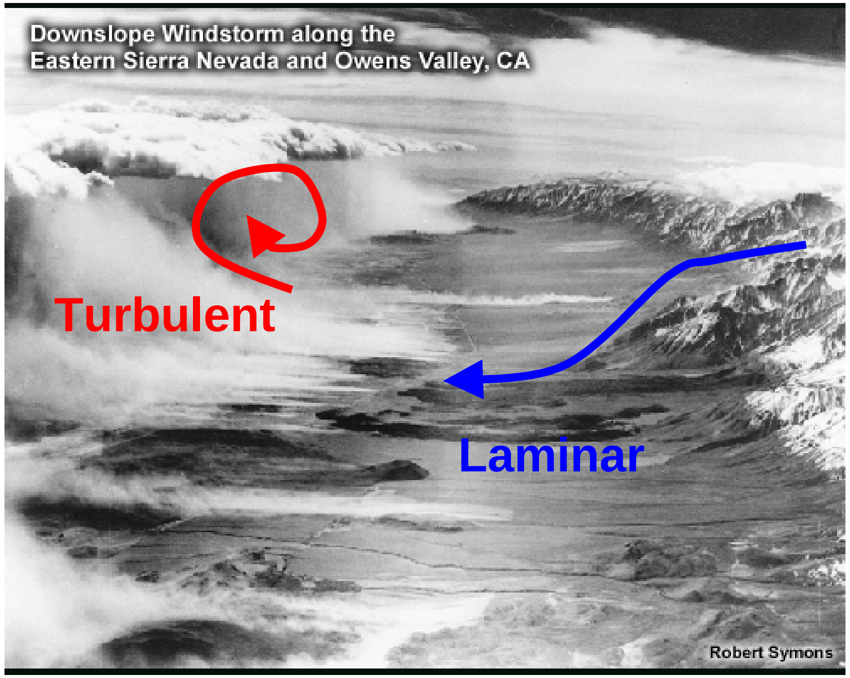
Vertical Diffusion Revisited

- The wind and virtual temperature profiles control growth and decay of TKE (coefficients B, C and K_m in the tendency equation) through Ri

$$\mathrm{Ri} = \frac{\text{(buoyant suppression)}}{\text{(shear generation)}}$$

- The form of $B = (1 - Ri_f) \cdot \left|\partial V / \partial z\right|^2 \cdot c\lambda_{\mathrm{mix}}$ suggests that something interesting happens when Ri = 1, such that B = 0 and the leading term in the tendency equation changes from a source (Ri < 1) to a sink (Ri > 1)
- $Ri_c = 1$ is the critical Richardson number in this formulation and identifies the transition point between turbulent ($Ri < Ri_c$) and laminar ($Ri > Ri_c$) regimes

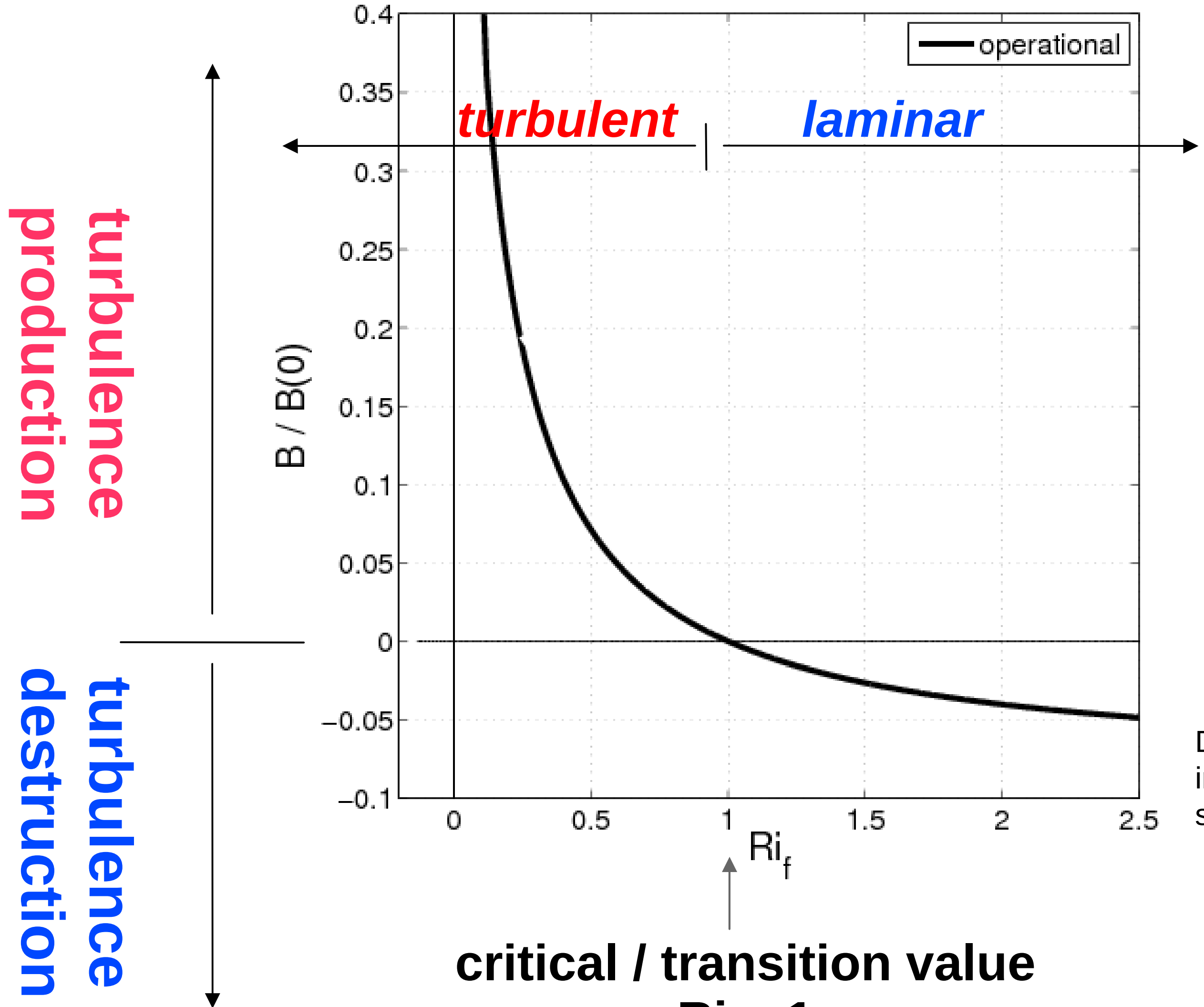
Turbulent / Laminar Transitions



Dust plumes during a downslope windstorm in the Sierra Nevada Mountains of California. The flow on the right side of the image is laminar, and the transition to turbulence occurs near the left edge of the image. Note the stratocumulus cap on the unstable PBL, related to the flux enhancement factor described earlier (Courtesy MetEd.)

- The transition from laminar to turbulent flow is associated with a rapid increase in TKE
- Since the K-coefficients are related to $TKE^{1/2}$ this causes a sudden enhancement of vertical diffusion and the homogenization of conserved quantities in the profile
- Reliably predicting the transition between turbulent and laminar regimes is therefore an important element of the PBL scheme

Turbulent / Laminar Transitions



Dependence of B on Ri in the operational PBL schemes at CMC.

critical / transition value
Ri = 1

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Richardson Number Hysteresis

- Despite the importance of Ri_c, its value depends on the context in which it is used:
  - Linear stability theory suggests a value of 0.25
  - Observations have found values between <0.2 and 0.25
  - The nonlinear governing equations suggest 1

KH wave clouds in Birmingham, AL. (Courtesy alabamawx)

- To further complicate matters, observations suggest that laminar flows do not spontaneously become turbulent until Ri < ~0.25 and that some initially turbulent flows remain turbulent even when Ri > 1 (Woods 1969, Lettau 1979, Canuto et al. 2001, and others)

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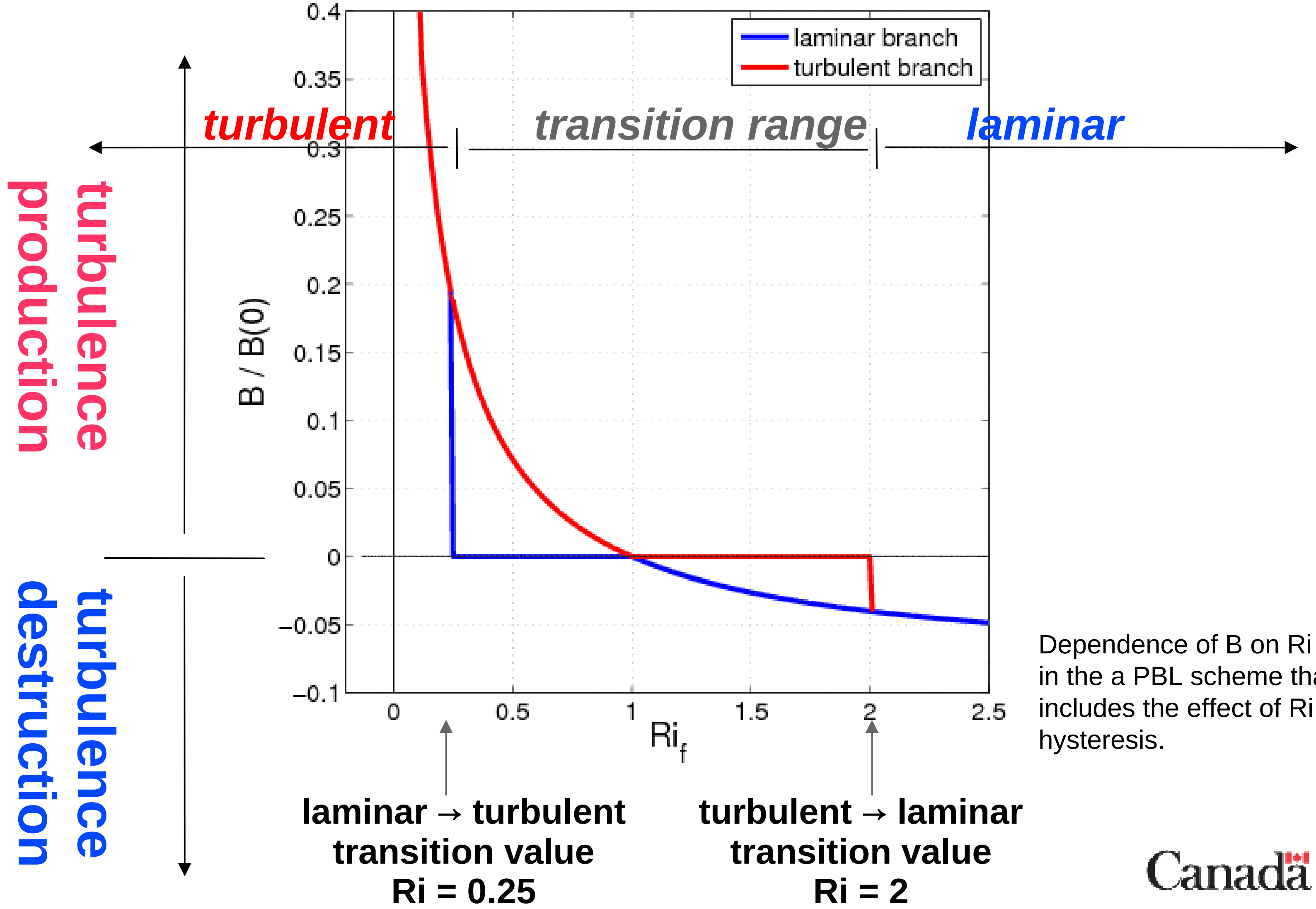
Richardson Number Hysteresis

- With a single Ri_c=1, both operational PBL schemes do not take the effect of Ri hysteresis into account when evolving the TKE profile
- However, since both schemes make the same closure assumptions, this effect can be added relatively easily
- Extrema of the hysteretic region may be expected to lie somewhere in the range of 0.2 and 2 (Woods 1969, Canuto et al. 2001)
- The precise values should be determined based on the model’s performance given uncertainty in discretized Ri profiles

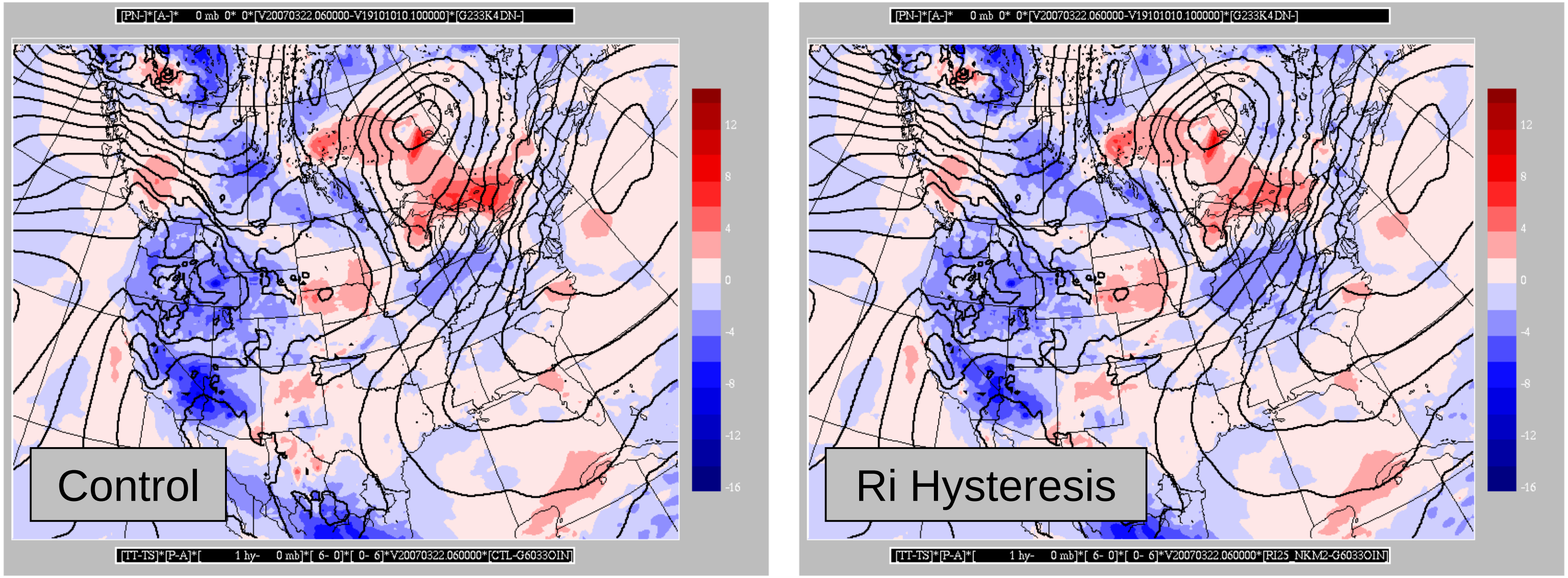
Richardson Number Hysteresis



Dependence of B on Ri in the a PBL scheme that includes the effect of Ri hysteresis.

Warm Episode Case Study

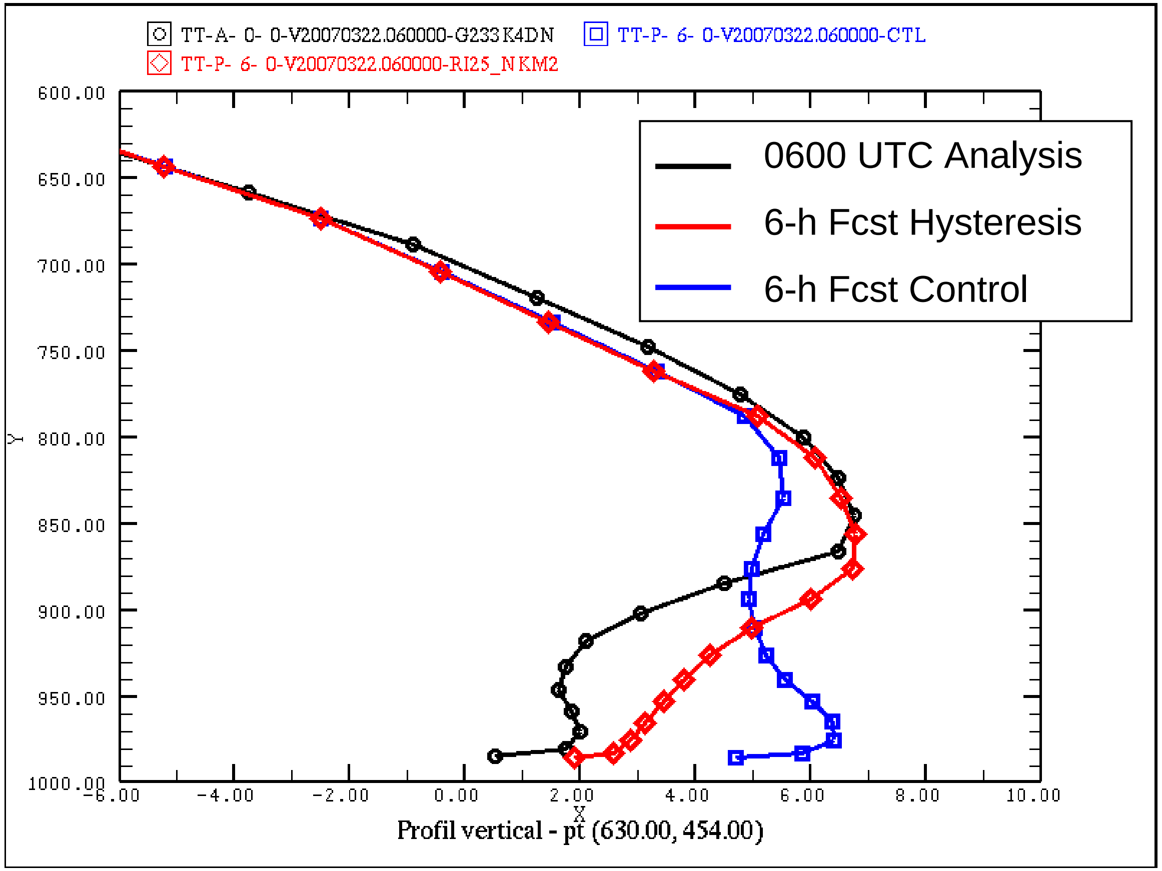
- The introduction of turbulent hysteresis reduces near-surface temperature errors by 2-3 K in the warm advection region without degrading guidance elsewhere in NA
- Complete correction of the problem should not be expected in this case since the analysis contains remnants of previous over-mixing in the background state



Temperature errors (colours) and MSLP (contoured at 4 hPa intervals) after 6h of integration valid 0600 UTC 22 March 2007 in the control (left panel) and the RI Hysteresis (aggressive) simulations (right panel).

Warm Episode Case Study

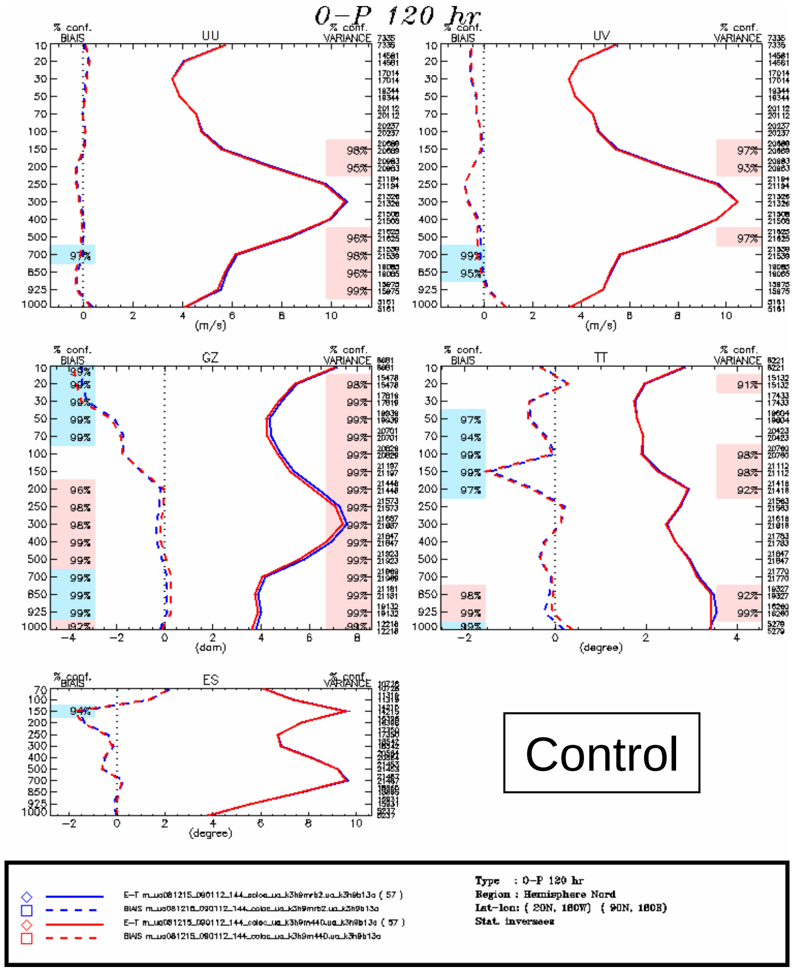
- The profile of Ri lies close to the operational Ri_c=1 (not shown), with subcritical layers triggering intense TKE generation and mixing (blue)
- When Ri hysteresis is included, TKE generation is reduced and the nose of the temperature profile near 850 hPa is maintained (red)
- Since the warm air stays aloft, near-surface warming is dramatically reduced

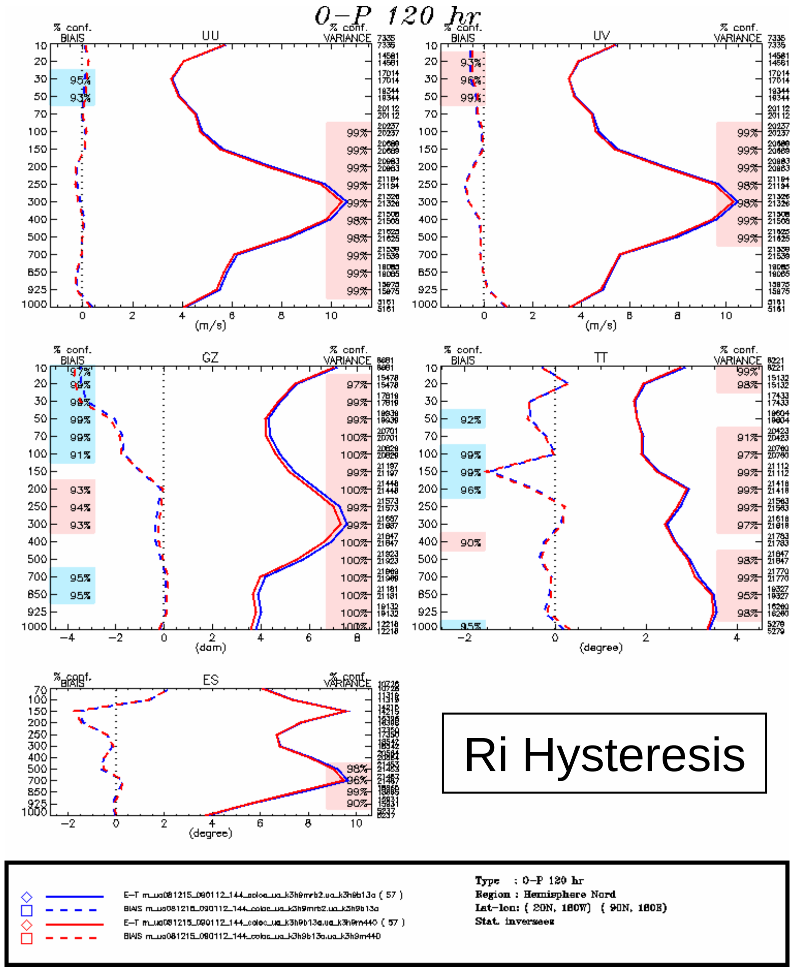


Temperature profiles from the GDPS point nearest to WMW after 6h of integration, valid 0600 UTC 22 March 2007. The verifying analysis (black), control (blue) and the Ri Hysteresis (red, aggressive) simulations are shown.

Turbulent Hysteresis in Action

Northern Hemisphere 120 h Scores





Northern Hemisphere 120 h upper-air scores against radiosonde observations for two 3Dvar cycles of proposed GDPS configurations (33 km), one without (left,) and one with (right) Ri hysteresis. Statistics are inversed in both plots.

Turbulent Hysteresis Discussion

- Tests of classic “warm episode” cases and forecast cycles suggest that the addition of a hysteretic effect on turbulence is useful
- Hysteresis has the effect of limiting TKE (and thus mixing coefficient) growth for laminar flows whose Ri values drop below 1; similarly, TKE destruction by buoyancy is eliminated for turbulent flows that have not yet reached the upper Ri bound
- In this way, we are better able to retain the warm nose in warm advection regions during freezing rain events, where Ri values are less than 1, but greater than the lower limit (0.15 or 0.25 in the tests shown here)
- Furthermore, the overall improvement of scores shows that this effect may be important more generally than for just infrequent freezing rain events

Summary of Recent PBL Changes

- Unexpected sensitivities in PBL structure were found when the RDPS and GDPS attempted to move to GEM4
  - Progressive deepening of PBL
  - Changes in oceanic heat fluxes and cloud cover
- To address the issues of diffusion coefficient averaging and solution convergence a coupled PBL was implemented for testing
  - Successfully limits sensitivities to staggering
  - Degrades guidance in stable winter conditions
- To limit warm episode errors, Richardson Number hysteresis was introduced and tested
  - Improves PBL profiles during warm episodes
  - Improves overall scores, particularly in winter cycles

Ongoing / Planned Work

- The strategy of coupling physical parameterizations to the model offers the possibility of tailoring vertical and temporal resolutions to the needs of each scheme individually:
  - Ri profiles are known to be highly sensitive to vertical resolution and appear to be at least partially responsible for the forecast degradation seen in the coupled PBL simulations
  - As a testbed for profile coupling, more effort will be put into attempting to diagnose and fix the coupled PBL approach
- Modernization of the PBL code:
  - Consideration of replacing TKE with total energy (Mauritsen 2007)
  - Consider alternative PBL formulations, including higher order closures, parameterized PBL, eddy diffusivity mass flux (Neggers et al. 2009)
  - Recombination of the CLEF and MOISTKE parameterizations
- Implementation of distributed drag to change lower boundary condition for the PBL scheme

Acknowledgements

Lots of this outstanding work was done by other excellent people, including (in reverse alphabetical order because otherwise Paul never gets to go first):

Paul Vaillancourt, Michel Roch, Andre Plante, Alain Patoine, Jocelyn Mailhot, Anne-Marie Leduc, Claude Girard, Michel Desgagné, Martin Charron

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