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The impact of gradient wind imbalance on tropical cyclone intensification

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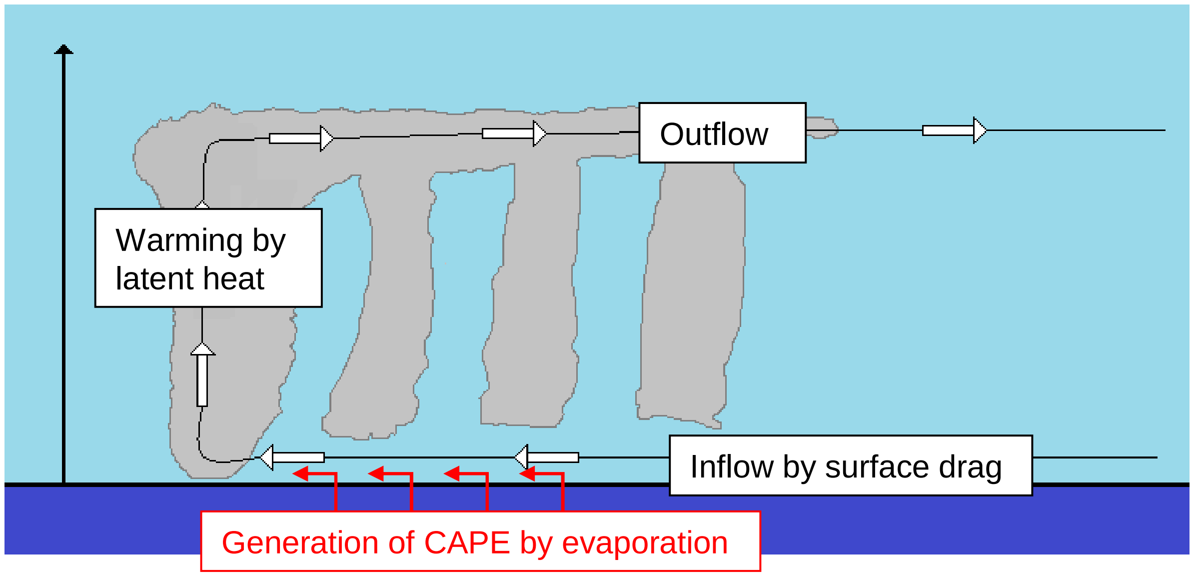
1 Introduction

Conceptual model for intensification



Feedback loop:

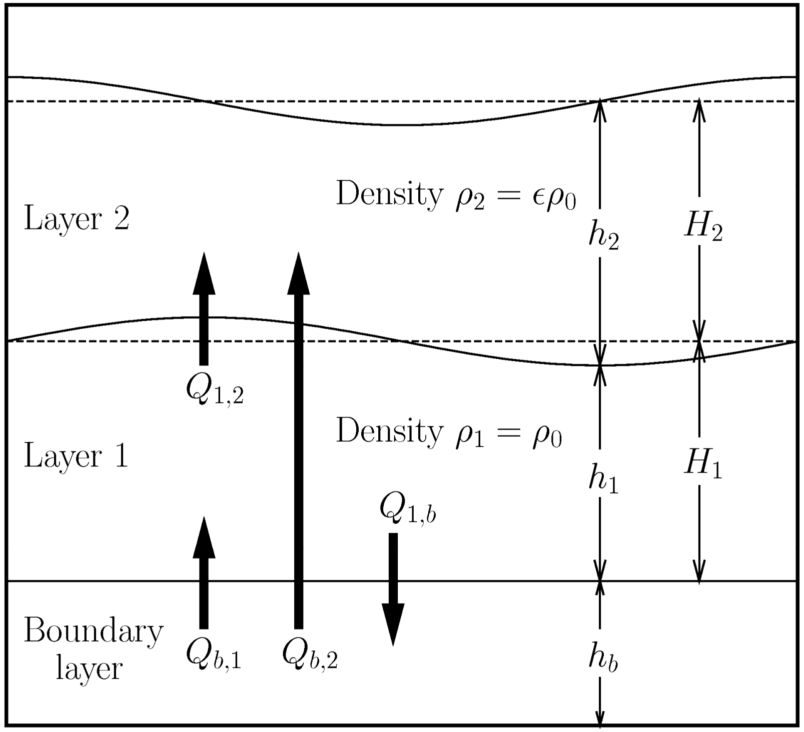
1. Inflow by drag ⟶ 2. Evaporation ⟶ 3. Latent heat release ⟶ 4. Wind intensification

Question: How important is gradient wind imbalance for this process?

2 Model and experimental design

The effect of gradient wind imbalance is analyzed within Ooyama‘s axisymmetric three layer model

Figure: Schematic showing the design of Ooyama’s three-layer model.



Experiments

REF: Standard simulation as in the original paper by Ooyama (1969)

UNBAL: Neglect of the balance assumption in all layers

UNBALBL: Neglect of the balance assumption in the boundary layer only

BALBL: Neglect of the balance assumption in the upper two free atmosphere layers only

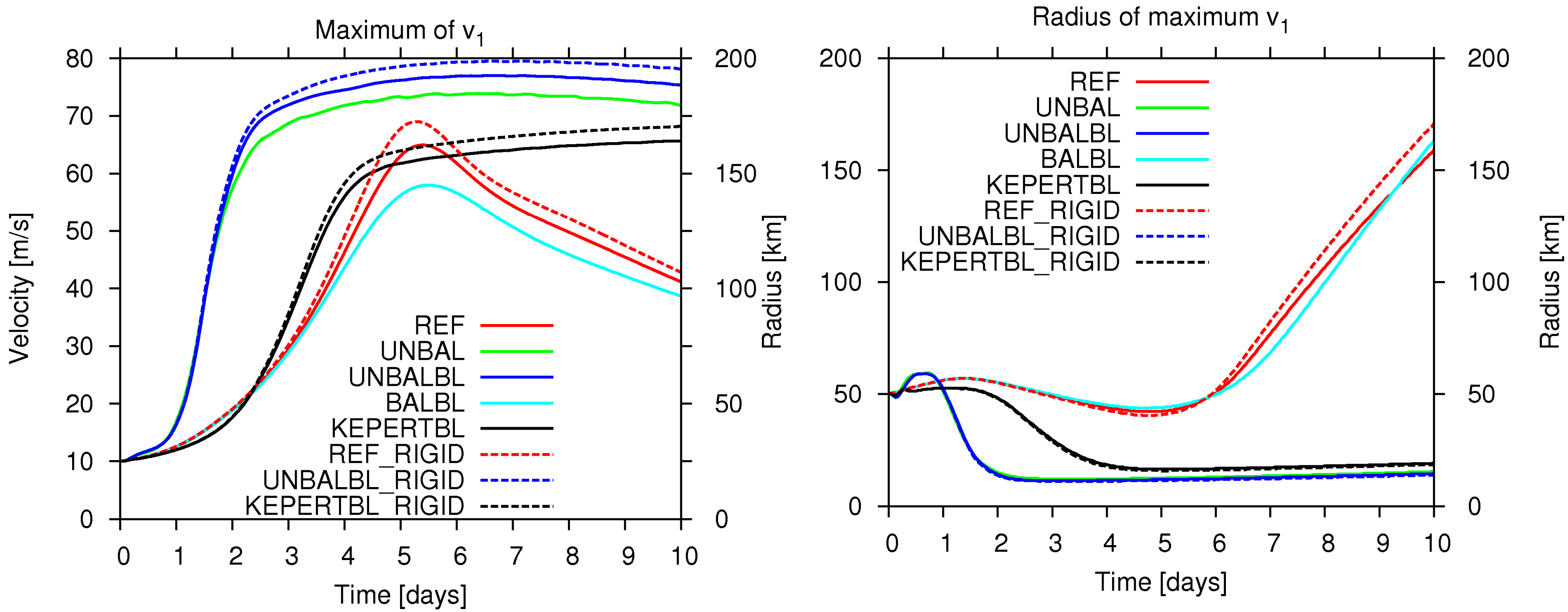
KEPERTBL: Replacement of the slab-boundary layer by Kepert‘s height parameterized boundary layer model (Kepert 2010)

XXX_RIGID: As experiment XXX but with a rigid lid

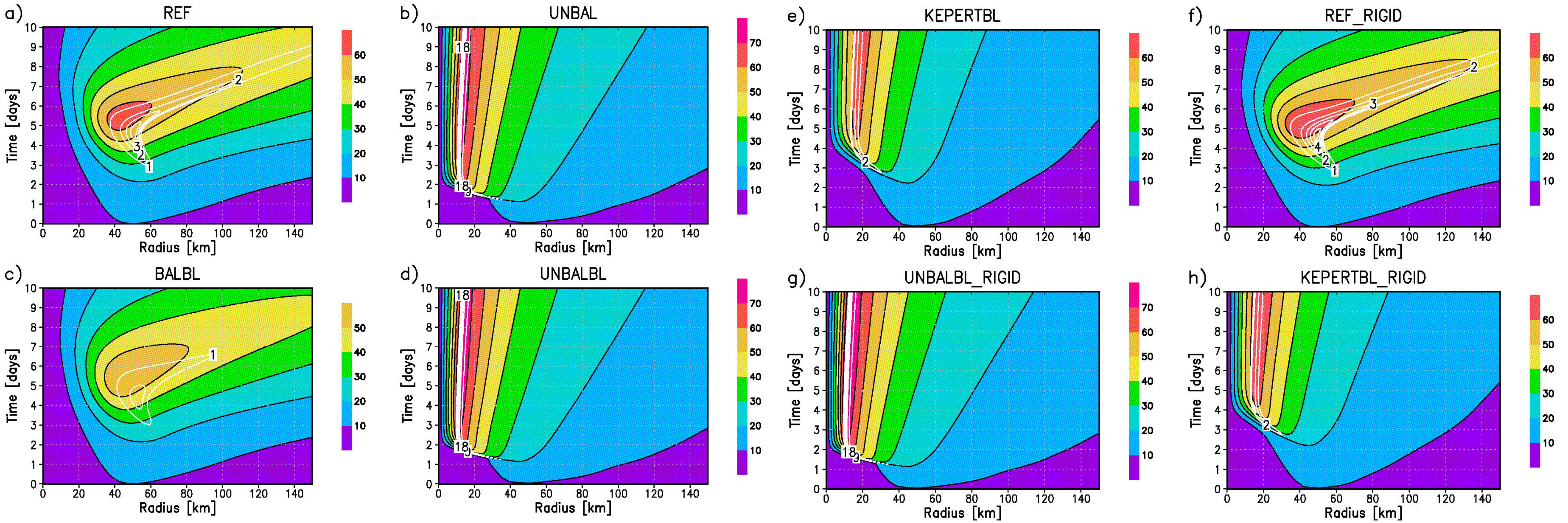
The model is initialized as in the original study by Ooyama (1969) and the model simulations cover 240 hours (10 days).

3 Results

Time evolution of middle-layer tangential wind maximum and its radius



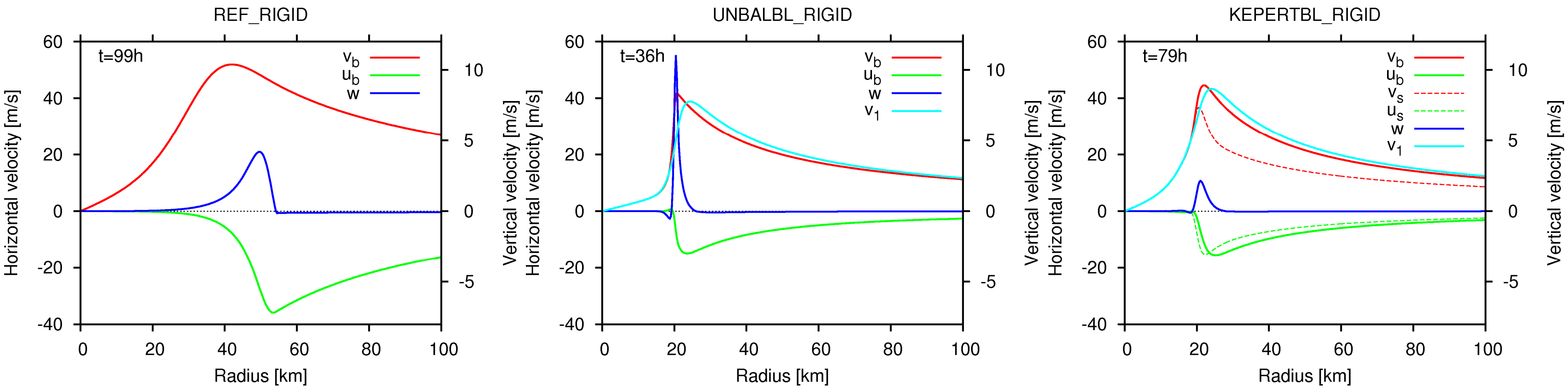
Radius time diagram of middle-layer tangential wind (coloured shadings) and vertical wind at the top of the boundary layer (white isolines)



Obviously, the time evolution is mainly sensitive to the chosen boundary layer model.

UNBALBL and KEPERTBL exhibit convective ring contraction during intensification while all experiments with a balanced boundary layer do not.

Radial profiles of boundary layer tangential wind (red) and radial wind (green), vertical velocity at the boundary layer top (blue) and middle-layer tangential wind (light blue) at the time of maximum intensification. The dashed lines in KEPERTBL display the respective surface wind components.



In the balanced boundary layer case (REF_RIGID) the maximum vertical wind and associated heating occurs outside of the radius of maximum gradient wind (RMGW). In UNBALBL_RIGID and KEPERTBL_RIGID the opposite is true.

4 Analysis of the intensification process

The balance-assumption in the free-atmosphere layer and the rigid lid have little impact on intensification. Therefore, both assumptions are reasonable for the analysis of the intensification process.

With these assumption a diagnostic equation for the radial mass flux Ψ_1 in the middle layer can be derived (the two-layer pendant to the Sawyer-Eliassen equation):

$$\boxed{\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial \Psi_1}{\partial r}\right) - S\,\Psi_1 = E + L + U + D + M}$$

where r denotes the radius and S the inertial stability.

The terms on the right hand side are source terms resulting from:

Ekman pumping (E) Latent heat release (L) Upper layer intensification (U)

Momentum diffusion (D) Vertical momentum flux (M)

By the radial mass flux Ψ_1 one can determine the time tendency of middle-layer tangential wind, v_1 since this quantity results from the following equation:

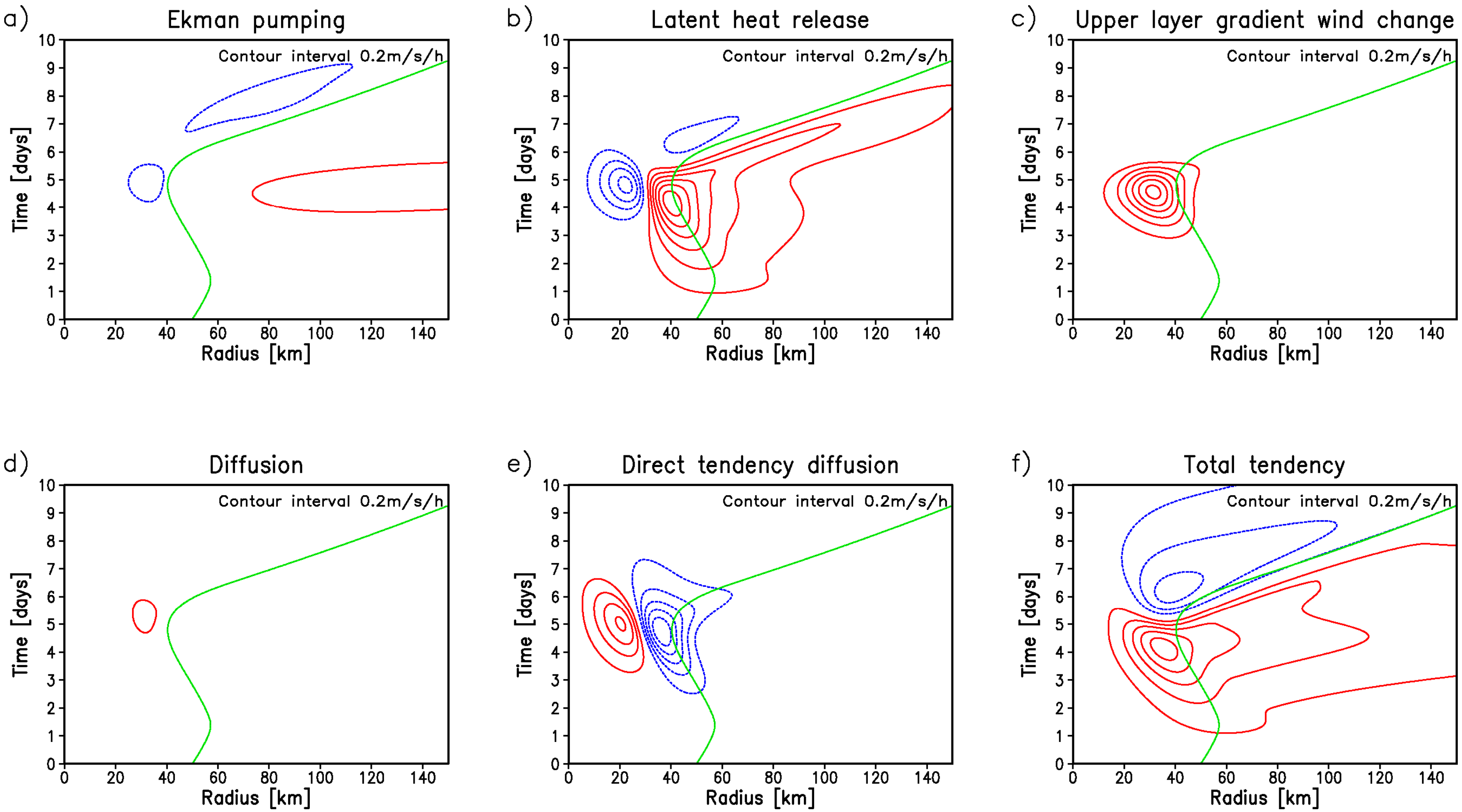
$$\frac{\partial v_1}{\partial t} = \underbrace{\frac{\zeta_1}{h_1 r}\Psi_1}_{\substack{\text{Inward flux} \\ \text{of angular momentum}}} + \underbrace{Q_{b,1}\frac{v_b - v_1}{h_1}}_{\substack{\text{Upward momentum} \\ \text{flux}}} + \underbrace{\frac{\nu_h}{h_1 r^2}\frac{\partial}{\partial r}\left[h_1 r^3 \frac{\partial}{\partial r}\left(\frac{v_1}{r}\right)\right]}_{\text{Radial momentum diffusion}}$$

where ζ_1 denotes the middle-layer vorticity and ν_h the diffusion coefficient.

- The last two processes have a direct effect on the v_1 momentum budget and also an indirect via the diagnostic equation for Ψ_1.
- Due to the linear form of the equation for Ψ_1 the contributions of the various processes to intensification can be deduced.
- The upward momentum flux has little impact and, therefore, it is not shown in the subsequent analysis.

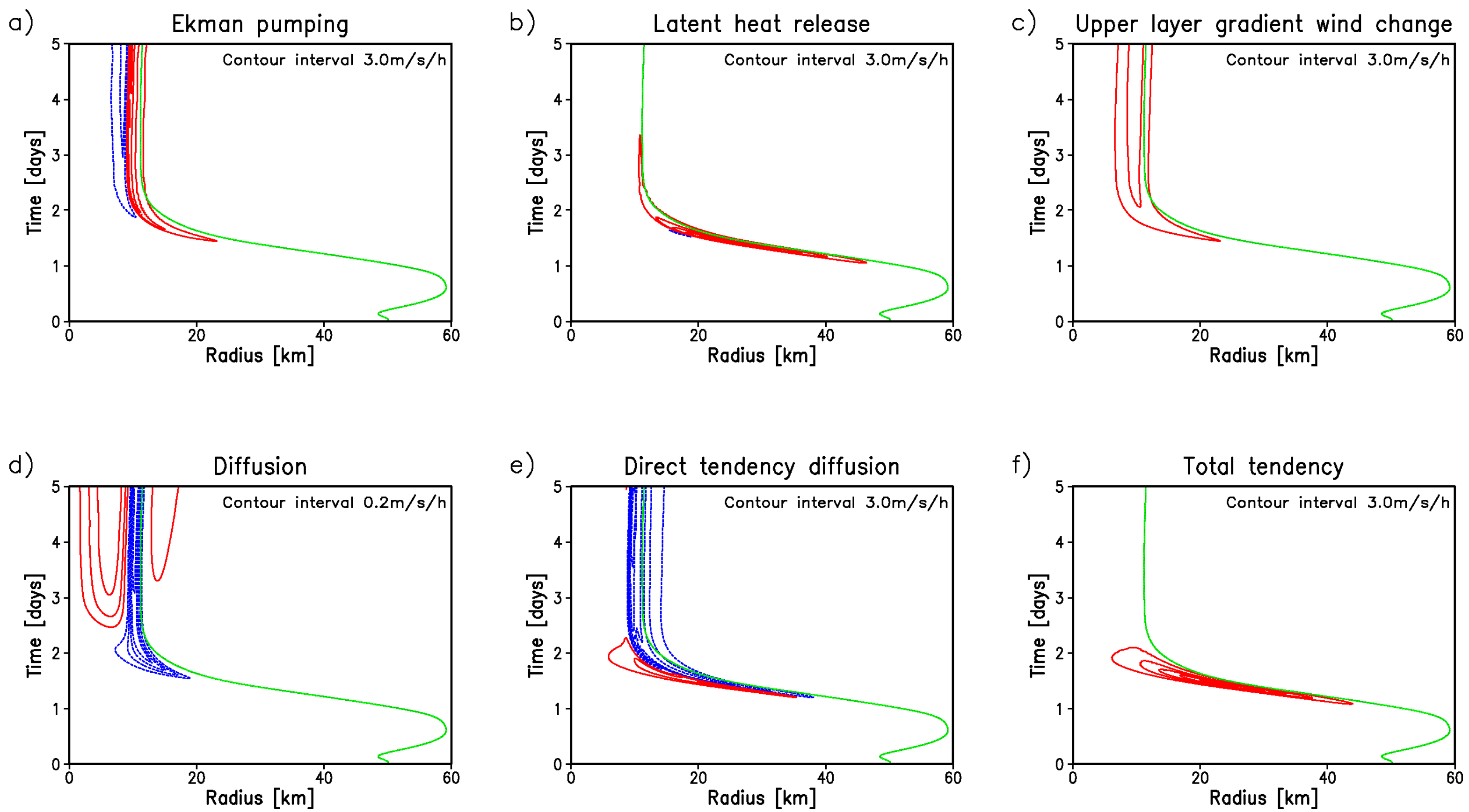
Radius time diagram of middle-layer tangential wind tendencies (green line = RMGW)

Experiment REF_RIGID



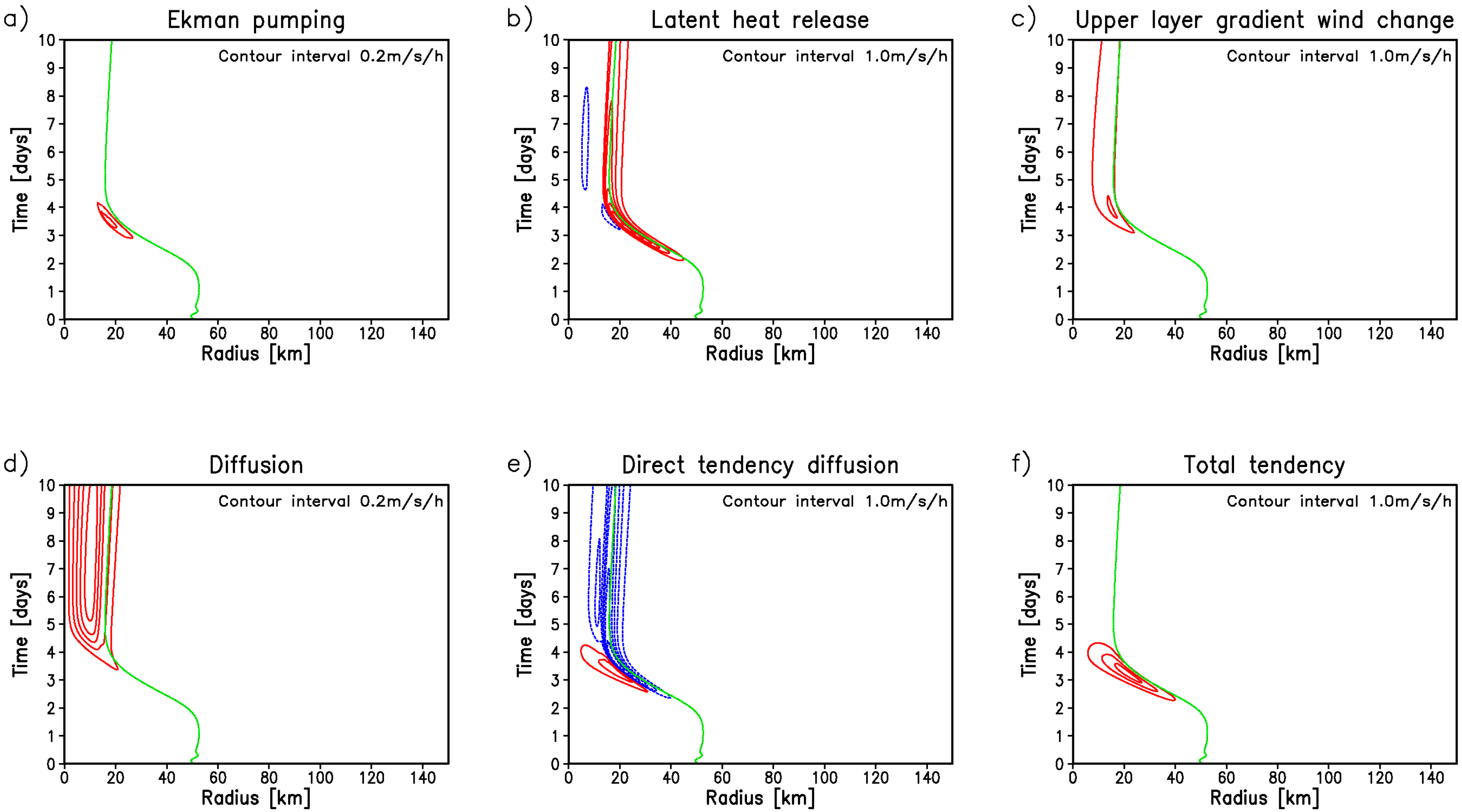
Radius time diagram of middle-layer tangential wind tendencies (green line = RMGW)

Experiment UNBALBL_RIGID



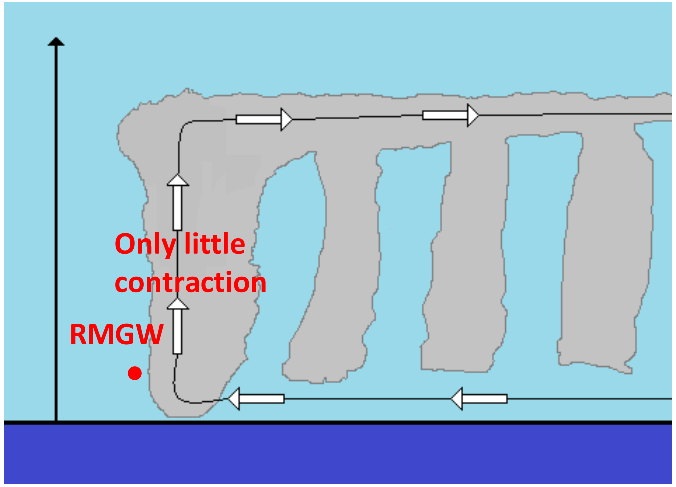
Radius time diagram of middle-layer tangential wind tendencies (green line = RMGW)

Experiment KEPERTBL_RIGID

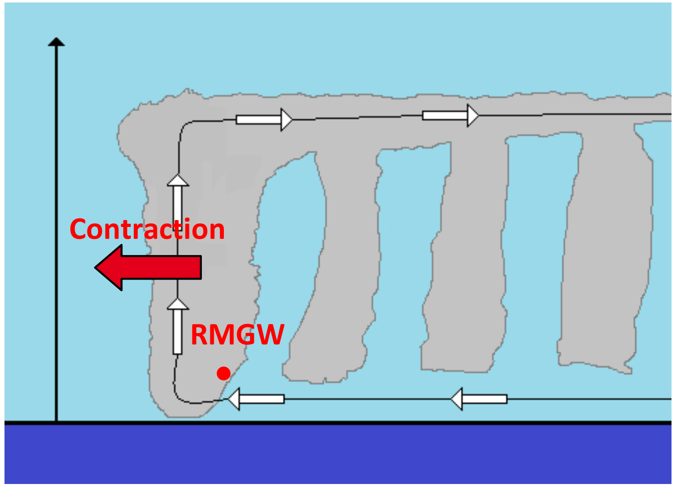


- It seems that the position of the latent heat maximum (eyewall) relative to the RMGW is essential for intensification and vortex contraction.
- The inertia of the boundary layer air is likely responsible for the inflow beyond the RMGW and it brings about that the latent heating takes place inside of the RMGW in the unbalanced cases.

Balanced boundary layer



Unalanced boundary layer



4 Conclusion

- Tropical cyclone intensification is very sensitive to the boundary layer parameterization in Ooyama‘s three layer model.
- The balance approximation of the free-atmosphere layers and the rigid lid assumption do not alter the intensification significantly.
- The most realistic boundary layer profiles are found with Kepert‘s height-parameterized boundary layer model.
- Analysis of the diagnostic equation for the middle-layer mass flux reveal that the latent heat release mainly causes intensification and contraction.
- It turns out that the position of the convective ring inside or outside of the RMGW is of vital importance for vortex contraction and can explain the large impact of boundary layer imbalance.

Acknowledgments

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