Process-based diagnostics using atmosphere budget analysis and nudging technique to identify sources of model systematic errors in global MetUM

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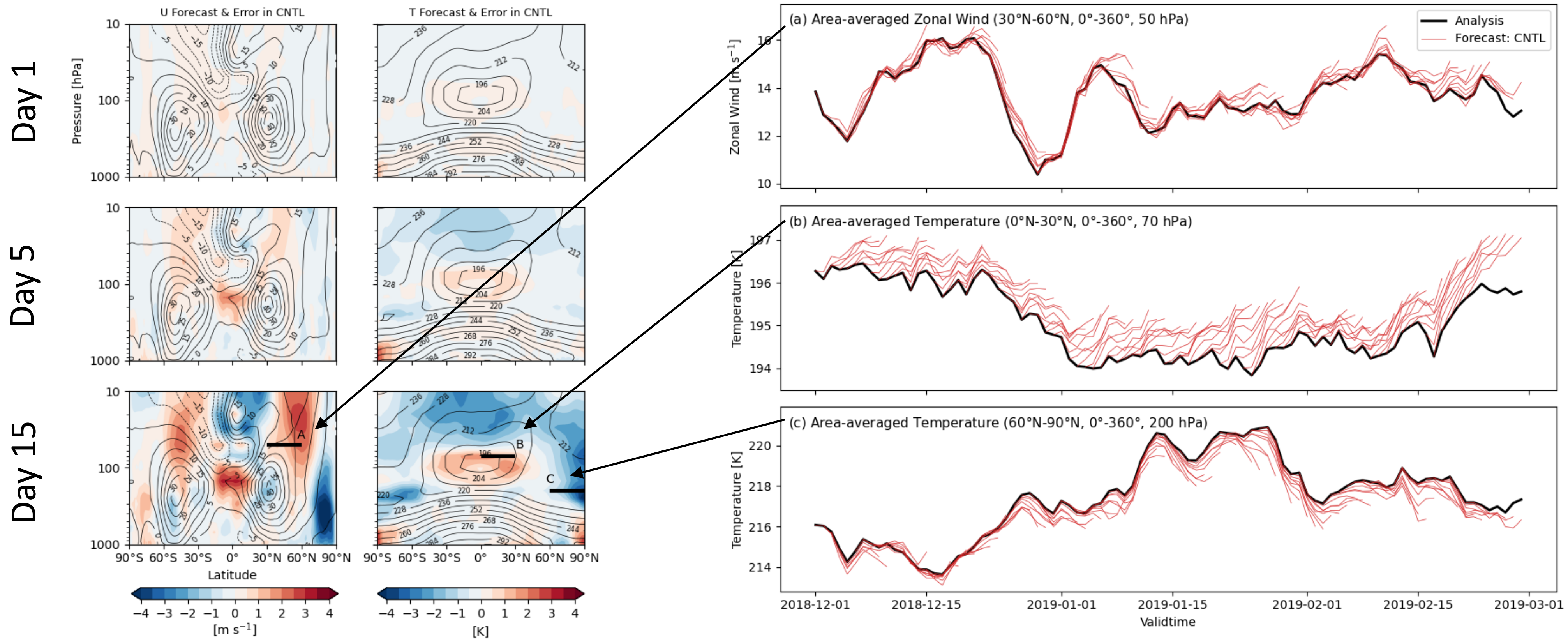
Motivations: model systematic errors in NWP timescale

- MetUM GAL9 N320L70 (approx. 40 km) atmosphere-only NWP hindcast experiments for DJF 2018/2019 (90 cases)
  - NH mid-latitude westerly bias, Tropical tropopause warm bias, High-latitude tropopause cold bias

→ Identifying sources of model systematic errors using process-based diagnostics

Zonal mean U&T biases

Area-averaged time series of analysis and forecasts up to Day 7



Error Diagnostics

- Forecast error against analysis

$$\underbrace{\phi_e(t_i; \Delta t)} \equiv \underbrace{\phi_f(t_i; \Delta t) - \phi_a(t_i + \Delta t)}$$

Error at a forecast lead time of Δt initialized at t_i

Difference between forecast at a forecast lead time of Δt initialized at t_i and analysis at $t_i + \Delta t$

$$= \left\{\phi_f(t_i; \Delta t) - \phi_f(t_i; 0)\right\} - \{\phi_a(t_i + \Delta t) - \phi_a(t_i)\} \qquad \because \phi_f(t_i; 0) = \phi_a(t_i)$$

$$= \underbrace{\left\{\overline{\left(\frac{\partial \phi}{\partial t}\right)_{f,t_i}} - \overline{\left(\frac{\partial \phi}{\partial t}\right)_{a,t_i}}\right\}}\Delta t$$

$\overline{}$: temporal mean over a given forecast length Δt in a single case

Error of forecast tendency against analysis tendency

- Diagnostics Method
  1. Atmospheric zonal momentum & thermal budget analysis – to diagnose forecast and analysis tendencies
  2. Nudging techniques – to produce a proxy of analysis fields

1. Zonal Momentum & Thermal Budgets Analysis

Zonal-mean zonal momentum & thermal budgets in spherical and pressure coordinates:

Unresolved processes (Residual)

$$\frac{\overline{\partial[u]}}{\partial t} = -\left(\frac{[\bar{v}]}{a\cos\phi}\frac{\partial[\bar{u}]\cos\phi}{\partial\phi} + [\bar{\omega}]\frac{\partial[\bar{u}]}{\partial p}\right) - \left(\frac{1}{a\cos^2\phi}\frac{\partial[\bar{u}^*\bar{v}^*]\cos^2\phi}{\partial\phi} + \frac{\partial[\bar{u}^*\bar{\omega}^*]}{\partial p}\right) - \left(\frac{1}{a\cos^2\phi}\frac{\partial[\overline{u'v'}]\cos^2\phi}{\partial\phi} + \frac{\partial[\overline{u'\omega'}]}{\partial p}\right) + f[\bar{v}] + [\bar{F_u}]$$

$$\frac{\overline{\partial[T]}}{\partial t} = -\left(\frac{[\bar{v}]}{a}\frac{\partial[\bar{T}]}{\partial\phi} + [\bar{\omega}]\left(\frac{\partial[\bar{T}]}{\partial p} - \frac{R_d}{pc_p}[\bar{T}]\right)\right) - \left(\frac{1}{a\cos\phi}\frac{\partial[\bar{v}^*\bar{T}^*]\cos\phi}{\partial\phi} + \frac{\partial[\bar{\omega}^*\bar{T}^*]}{\partial p} - \frac{R_d}{pc_p}[\bar{\omega}^*\bar{T}^*]\right) - \left(\frac{1}{a\cos\phi}\frac{\partial[\overline{v'T'}]\cos\phi}{\partial\phi} + \frac{\partial[\overline{\omega'T'}]}{\partial p} - \frac{R_d}{pc_p}[\overline{\omega'T'}]\right) + \frac{[\bar{Q}]}{c_p}$$

Total Tendency

Resolved processes (mean stationary flow, stationary eddy fluxes, transient eddy fluxes, Coriolis)

- To what extent the individual components in the equation contribute to the total tendency of the corresponding variable

- Total tendency and individual resolved processes diagnosed using forecast/analysis data
- Unresolved processes (i.e., mechanical forcing & thermal forcing) subsequently deduced as a residual and referred to as "residual term"

u: zonal wind velocity
v: meridional wind velocity
ω: vertical pressure velocity
T: temperature
a: radius of the earth
ϕ: latitude
p: pressure
f: Coriolis parameter
R_d: Gas constant
c_p: specific heat of air at constant pressure
F_u: mechanical forcing term
Q: diabatic heating rate

$\bar{\ }$: temporal mean (over a given forecast length in a single case)
$'$: deviation from temporal mean
[ ]: zonal mean
*: deviation from zonal mean

1. Zonal Momentum & Thermal Budgets Analysis

Zonal-mean zonal momentum & thermal budgets in spherical and pressure coordinates:

Unresolved processes (Residual)

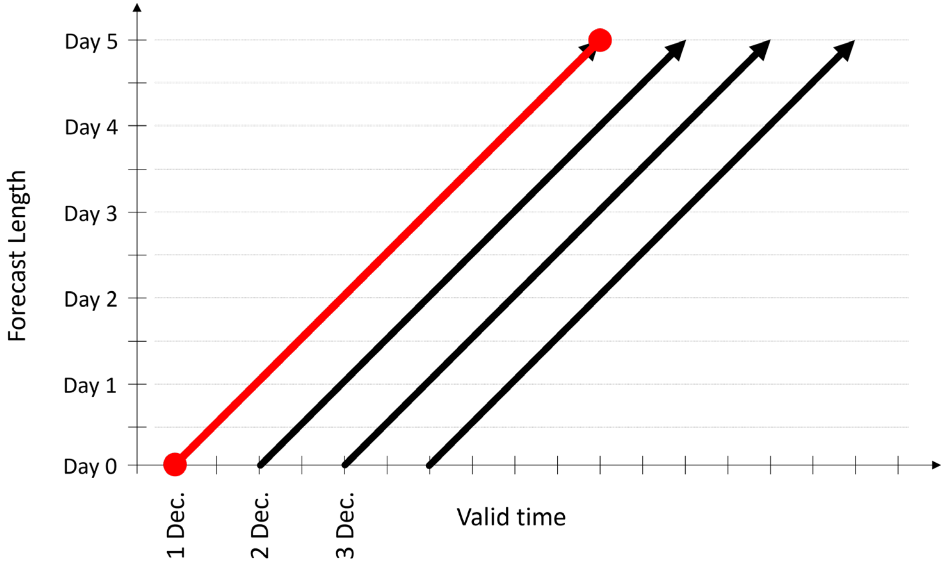
$$\frac{\partial\overline{[u]}}{\partial t} = -\left(\frac{[\bar v]}{a\cos\phi}\frac{\partial[\bar u]\cos\phi}{\partial\phi} + [\bar\omega]\frac{\partial[\bar u]}{\partial p}\right) - \left(\frac{1}{a\cos^2\phi}\frac{\partial[\bar u^*\bar v^*]\cos^2\phi}{\partial\phi} + \frac{\partial[\bar u^*\bar\omega^*]}{\partial p}\right) - \left(\frac{1}{a\cos^2\phi}\frac{\partial[\overline{u'v'}]\cos^2\phi}{\partial\phi} + \frac{\partial[\overline{u'\omega'}]}{\partial p}\right) + f[\bar v] + [\bar F_u]$$

$$\frac{\partial\overline{[T]}}{\partial t} = -\left(\frac{[\bar v]}{a}\frac{\partial[\bar T]}{\partial\phi} + [\bar\omega]\left(\frac{\partial[\bar T]}{\partial p} - \frac{R_d}{pc_p}[\bar T]\right)\right) - \left(\frac{1}{a\cos\phi}\frac{\partial[\bar v^*\bar T^*]\cos\phi}{\partial\phi} + \frac{\partial[\bar\omega^*\bar T^*]}{\partial p} - \frac{R_d}{pc_p}[\bar\omega^*\bar T^*]\right) - \left(\frac{1}{a\cos\phi}\frac{\partial[\overline{v'T'}]\cos\phi}{\partial\phi} + \frac{\partial[\overline{\omega'T'}]}{\partial p} - \frac{R_d}{pc_p}[\overline{\omega'T'}]\right) + \frac{[\bar Q]}{c_p}$$

Total Tendency   Resolved processes (mean stationary flow, stationary eddy fluxes, transient eddy fluxes, Coriolis)

- Overbar is defined as a temporal mean over the given forecast length Δt in a single case, $\bar\phi_i \equiv \left(\langle\phi\rangle_{t_0}^{t_0+\Delta t}\right)_i$, (rather than the whole experimental period) and computed using fields at each model time step

- Zonal momentum and thermal budget is calculated for individual cases, and then averaged over the cases if mean error and mean budget are examined



Trajectory of one single case

1. Zonal Momentum & Thermal Budgets Analysis

Zonal-mean zonal momentum & thermal budgets in spherical and pressure coordinates:

Unresolved processes (Residual)

$$\frac{\partial[u]}{\partial t} = -\left(\frac{[\bar{v}]}{a\cos\phi}\frac{\partial[\bar{u}]\cos\phi}{\partial\phi} + [\bar{\omega}]\frac{\partial[\bar{u}]}{\partial p}\right) - \left(\frac{1}{a\cos^2\phi}\frac{\partial[\bar{u}^*\bar{v}^*]\cos^2\phi}{\partial\phi} + \frac{\partial[\bar{u}^*\bar{\omega}^*]}{\partial p}\right) - \left(\frac{1}{a\cos^2\phi}\frac{\partial[\overline{u'v'}]\cos^2\phi}{\partial\phi} + \frac{\partial[\overline{u'\omega'}]}{\partial p}\right) + f[\bar{v}] + [\bar{F_u}]$$

$$\frac{\partial[T]}{\partial t} = -\left(\frac{[\bar{v}]}{a}\frac{\partial[\bar{T}]}{\partial\phi} + [\bar{\omega}]\left(\frac{\partial[\bar{T}]}{\partial p} - \frac{R_d}{pc_p}[\bar{T}]\right)\right) - \left(\frac{1}{a\cos\phi}\frac{\partial[\bar{v}^*\bar{T}^*]\cos\phi}{\partial\phi} + \frac{\partial[\bar{\omega}^*\bar{T}^*]}{\partial p} - \frac{R_d}{pc_p}[\bar{\omega}^*\bar{T}^*]\right) - \left(\frac{1}{a\cos\phi}\frac{\partial[\overline{v'T'}]\cos\phi}{\partial\phi} + \frac{\partial[\overline{\omega'T'}]}{\partial p} - \frac{R_d}{pc_p}[\overline{\omega'T'}]\right) + \frac{[\bar{Q}]}{c_p}$$

Total Tendency

Resolved processes (mean stationary flow, stationary eddy fluxes, transient eddy fluxes, Coriolis)

Zonal-mean model tendencies:

$$\left[\frac{\partial u}{\partial t}\right] = \left[\left(\frac{\partial u}{\partial t}\right)_{\mathrm{Dyn1}}\right] + \left[\left(\frac{\partial u}{\partial t}\right)_{\mathrm{Dyn2}}\right] + \cdots + \left[\left(\frac{\partial u}{\partial t}\right)_{\mathrm{Dyn}N}\right] + \left[\left(\frac{\partial u}{\partial t}\right)_{\mathrm{Phys1}}\right] + \left[\left(\frac{\partial u}{\partial t}\right)_{\mathrm{Phys2}}\right] + \cdots + \left[\left(\frac{\partial u}{\partial t}\right)_{\mathrm{Phys}N}\right] + \left[\left(\frac{\partial u}{\partial t}\right)_{\mathrm{Nudging}}\right]$$

$$\left[\frac{\partial T}{\partial t}\right] = \left[\left(\frac{\partial T}{\partial t}\right)_{\mathrm{Dyn1}}\right] + \left[\left(\frac{\partial T}{\partial t}\right)_{\mathrm{Dyn2}}\right] + \cdots + \left[\left(\frac{\partial T}{\partial t}\right)_{\mathrm{Dyn}N}\right] + \left[\left(\frac{\partial T}{\partial t}\right)_{\mathrm{Phys1}}\right] + \left[\left(\frac{\partial T}{\partial t}\right)_{\mathrm{Phys2}}\right] + \cdots + \left[\left(\frac{\partial T}{\partial t}\right)_{\mathrm{Phys}N}\right] + \left[\left(\frac{\partial T}{\partial t}\right)_{\mathrm{Nudging}}\right]$$

Dynamics:
- Solver, Advection, Advection Correction

Physics Parametrizations:
- U: Convection, Gravity wave(+Subgrid-scale orography), Boundary layer
- T: Radiation, Cloud, Microphysics, Convection, Gravity wave dissipation, Boundary layer

➢ Resolved and unresolved processes are expected to correspond to model dynamics and physics, respectively

➢ Residual term contains effects of unresolved processes, numerical diffusion, diagnostics errors, etc.

2. Nudging Technique

$$\phi_F = \phi_M + \frac{\Delta t}{\tau}(\phi_A - \phi_M)$$

additional increments due to nudging

ϕ_F : prognostic variables after nudging
ϕ_M : prognostic variables before nudging
ϕ_A : prognostic variables used as a forcing
Δt : time interval of the model integration
τ : relaxation time scale of nudging

- Relaxing the prognostic variables ϕ_M (U, V, θ) back towards the forcing data ϕ_A (temporally interpolated MetUM analysis) at the very end of each time step (Telford et al. 2008)
- Nudging increments are comparable to forecast errors at a particular timescale with the reversed sign
- Nudging tendencies are comparable with the model tendencies due to the dynamics and physics

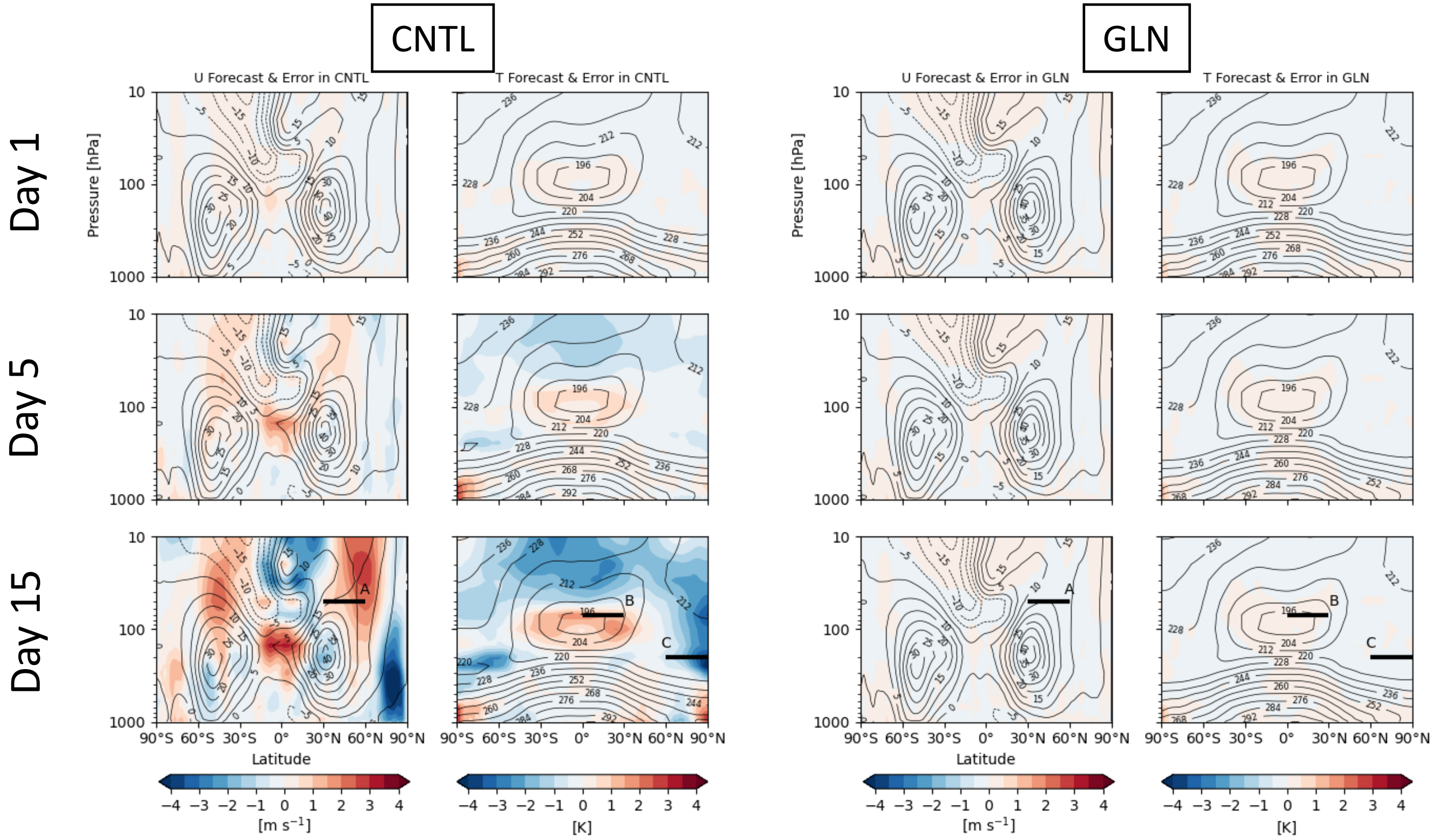
Use of nudging experiments:

- **Global UVθ nudging experiment (GLN)** with the same experimental design as CNTL **to provide a best possible estimate of analysis tendency** (in place of analysis due to data availability)

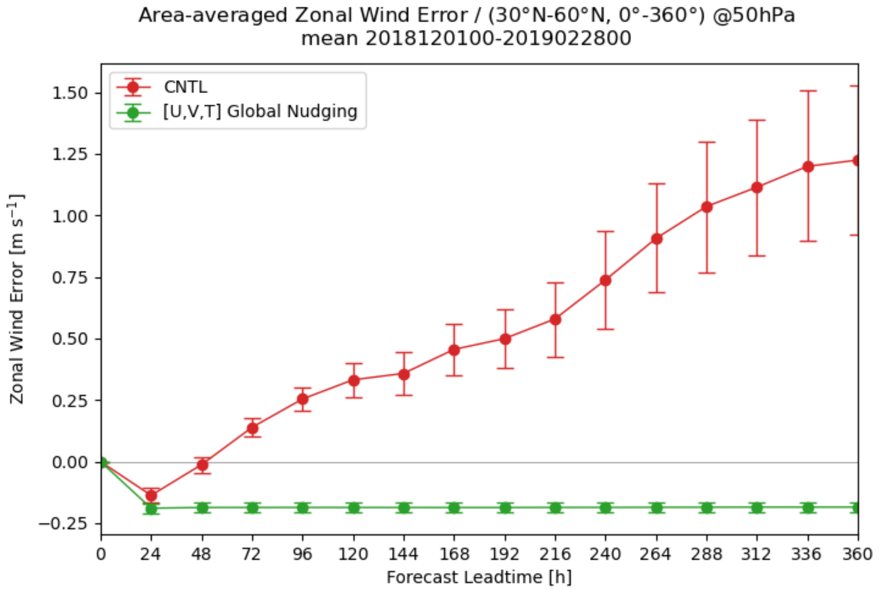
→ Budget components in GLN are used to validate those in CNTL

Model Systematic Errors

- MetUM GAL9 N320L70 (approx. 40 km) atmosphere-only NWP hindcast experiments up to Day 15 for DJF 2018/2019 (90 cases)
  - CNTL : Non-nudging control experiment
  - GLN : Global UVθ nudging experiment



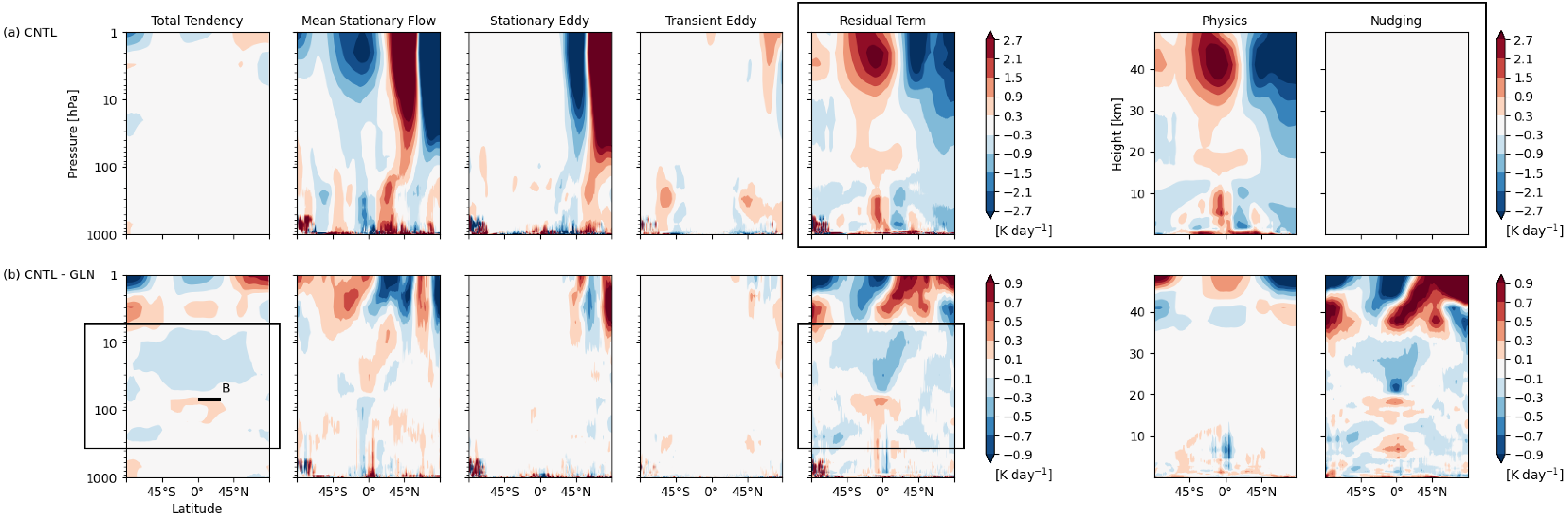
- NH mid-latitude zonal wind bias in the lower stratosphere, characterized by an initial easterly bias and subsequent westerly bias
- Properly nudged in GLN, but small error remains



Zonal-mean Thermal Budgets

CNTL & GLN zonal-mean thermal budget up to Day 5 averaged over the 90 cases for DJF 2018/2019

Budget residual term corresponds to sum of the model physics tendencies (Radiation, GWD, Cloud, Microphysics, Convection, and BL) and nudging tendency.



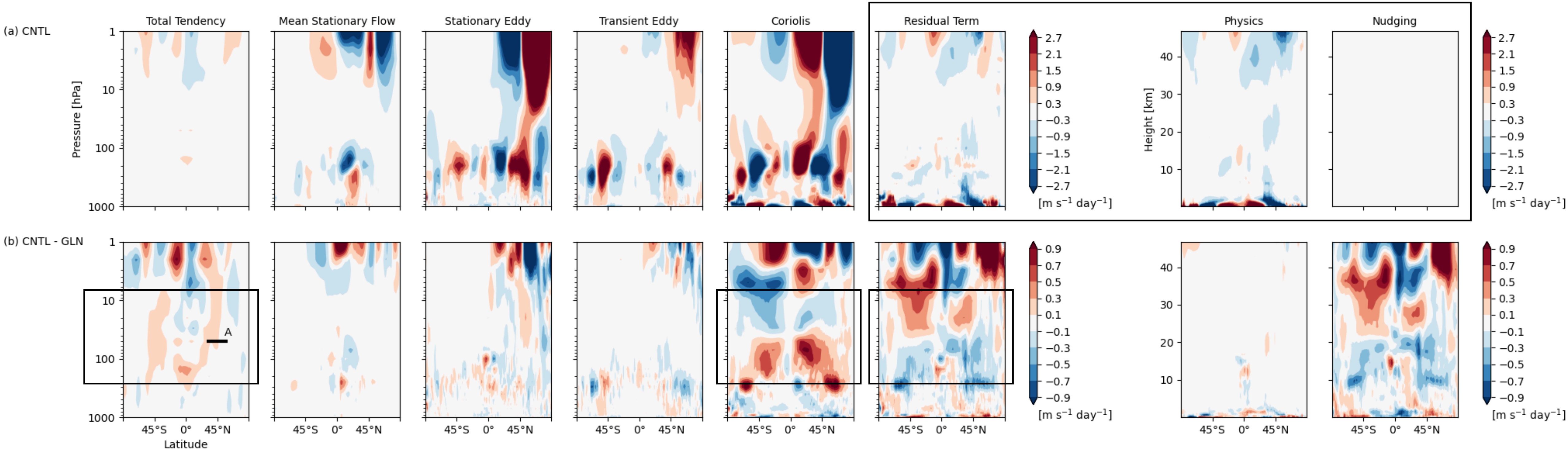
Error in T total tendency against GLN accounted for by the residual term.

→ Mean forecast error in zonal-mean temperature is expected to be caused by incorrect representations of unresolved processes parametrized in the model.

Zonal-mean Zonal Momentum Budgets

CNTL & GLN zonal-mean zonal momentum budget up to Day 5 averaged over the 90 cases for DJF 2018/2019

Budget residual term corresponds to sum of the model physics tendencies (GWD+SSO, Convection, and BL) and nudging tendency.



Error in U total tendency against GLN contributed by the Coriolis forcing and the residual term.

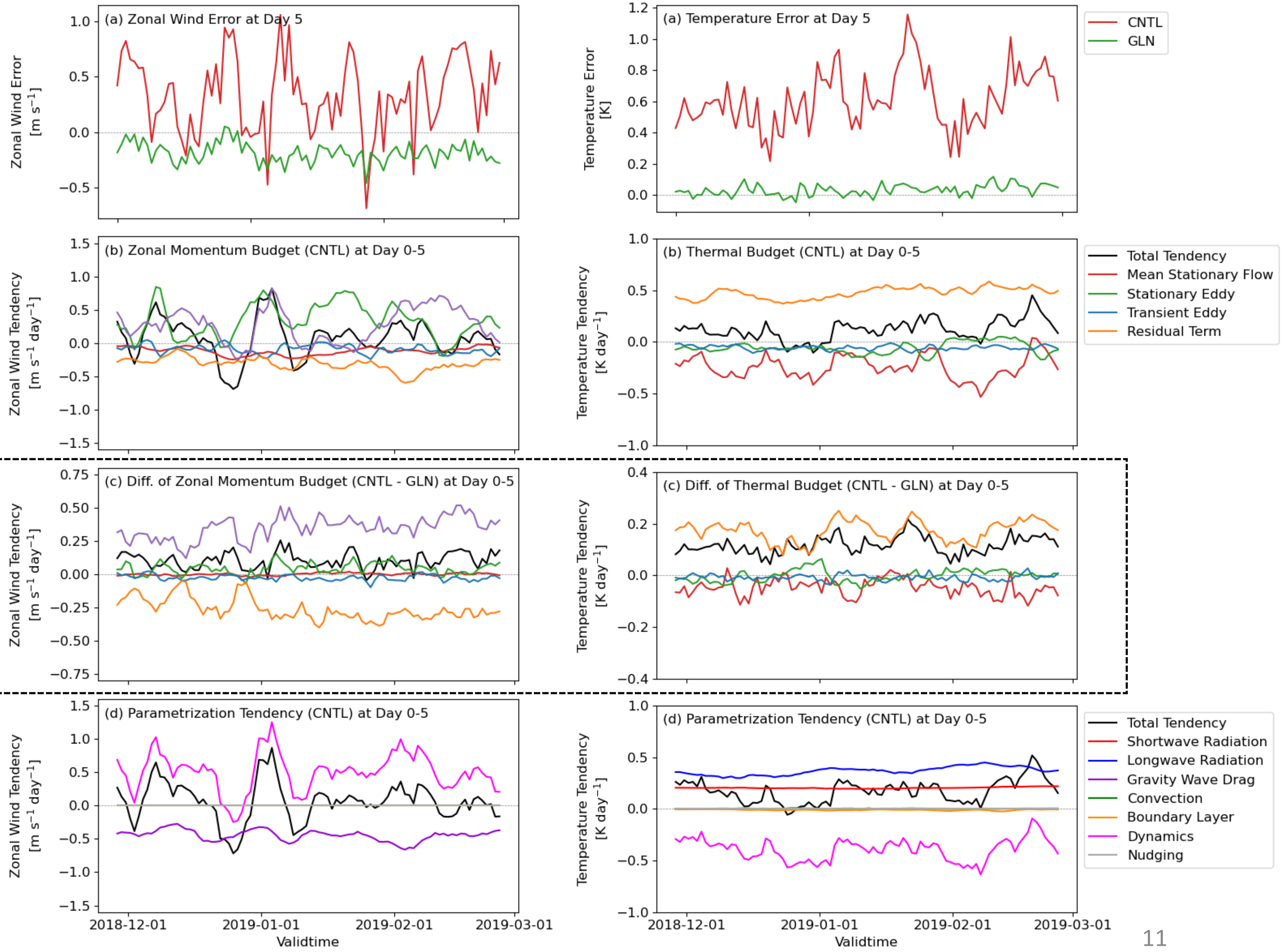
→ Mean forecast error in zonal-mean zonal wind is caused by incorrect mechanical forcing and a dynamical response to incorrect thermal forcing.

Timeseries of Momentum & Thermal Budgets

- Warm temperature error contributed by residual term (unresolved processes)
- Westerly wind error resulting from excessive westward forcing in residual term and counteracting excessive eastward forcing in Coriolis term

→ Error compensations in NH mid-latitude wind bias between mechanical westward forcing and dynamical responses to thermal forcing

Left : A. U error & Zonal momentum budgets averaged in NH midlatitude (30N-60N) at 50 hPa
Right : B. T error & Thermal budgets averaged in NH tropics (0-30N) at 70 hPa



Summary & Ongoing Work

- Process-based diagnostics to identify sources of model systematic errors in Met Office Unified Model at global NWP timescale
  - Model systematic errors:
    A. Zonal wind initial easterly bias and subsequent westerly bias in NH mid-latitude lower stratosphere
    B. Temperature warm bias near the tropical tropopause
  - Atmospheric zonal-mean zonal momentum & thermal budget analysis
    - Global UVθ nudging experiment (GLN) to produce a best possible estimate of analysis budget
    - Budget contributions to the total tendency in CNTL validated against those in GLN
- Error mechanisms and sources in NH mid-latitude lower stratospheric zonal wind
  - Mechanical forcing causes the easterly error (at least at approx. 40 km horizontal resolution)
  - Thermal forcing is the source of the westerly error through the Coriolis forcing
- Ongoing work
  - Investigations on horizontal resolution sensitivity
  - Diagnostics for various experiments