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Karlsruhe Institute of Technology

Impacts of global warming on the development of extratropical cyclones in idealized simulations

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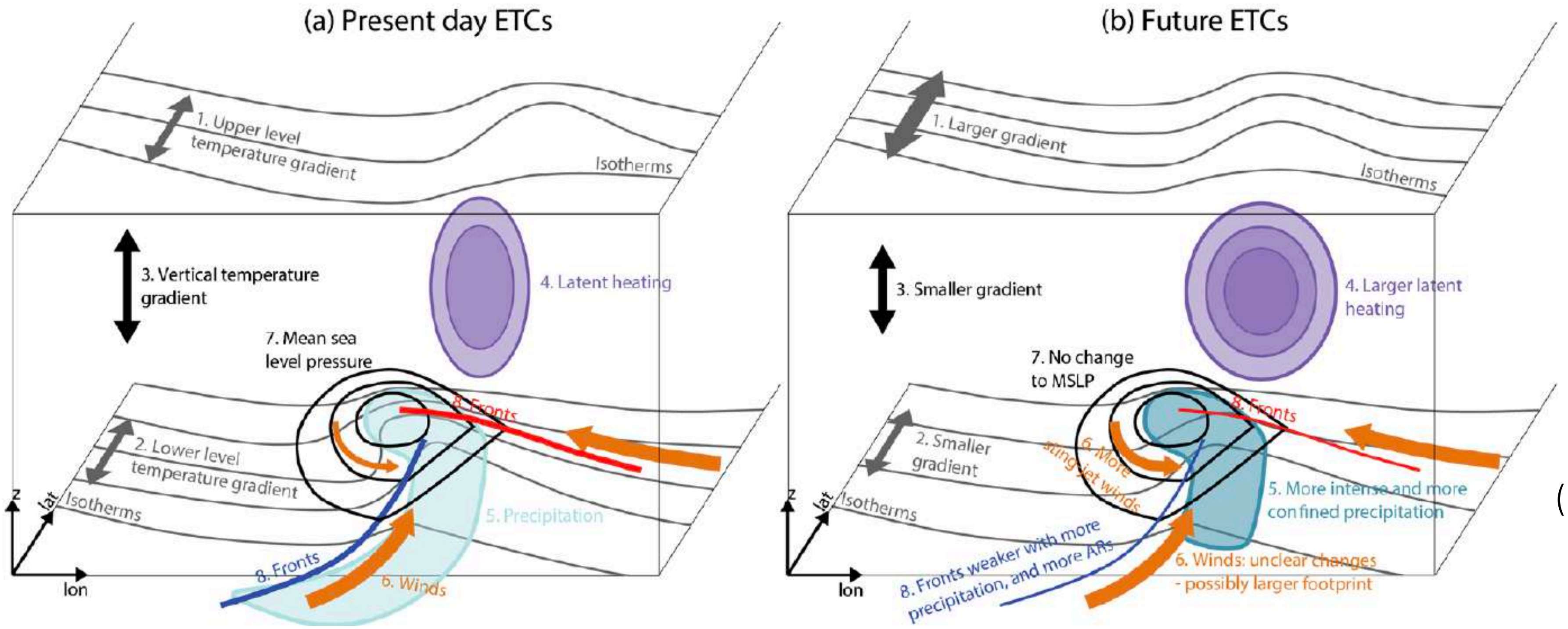
FONA Research for sustainability

CLIMXTREME Climate Change and Extreme Events

How will the development, structure and impact of extreme extratropical cyclones (ETC) change in a future warmer climate?



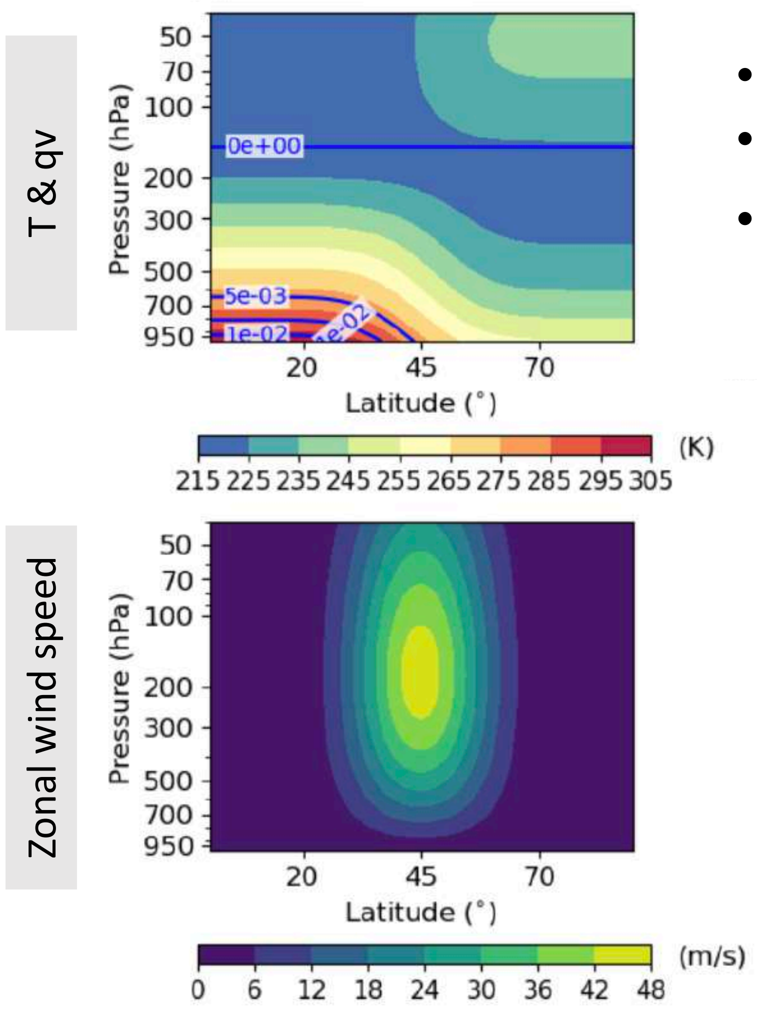
- Uncertainty remains in the opposing influences of factors 1, 2, 3, & 4 on ETC development in a warmer climate.

(Catto et al. 2019)

How will the role of **diabatic processes** change and feed back on to the central pressure?
Does the **model resolution** notably impact on GCM projections?

Model setup

CTL



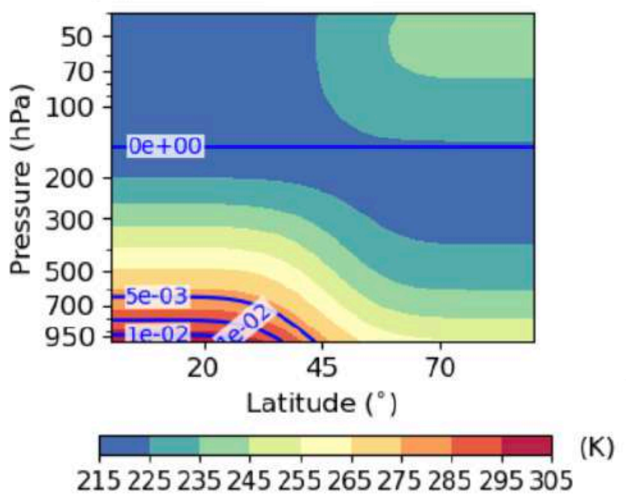
- **Idealized baroclinic life cycle simulations**
- **ICON-NWP** (version 2.6.2.2)
- Model configuration (Keshtgar et al., 2023):

Limited-area, f-plane, aquaplanet channel setup (periodic zonal boundaries)		
Domain size	4000 km (Lx) x 9000km (Ly)	
Initialization	Life cycle type 1 configuration (Polvani and Esler, 2007) Relative humidity 80%	
Perturbation	A sinusoidal thermal wave with 1K at all levels; a wavelength = Lx	
Grid spacing	**80 km** (fully physics with deep convection scheme activated)	**2.5 km** (fully physics with shallow but not deep convection)

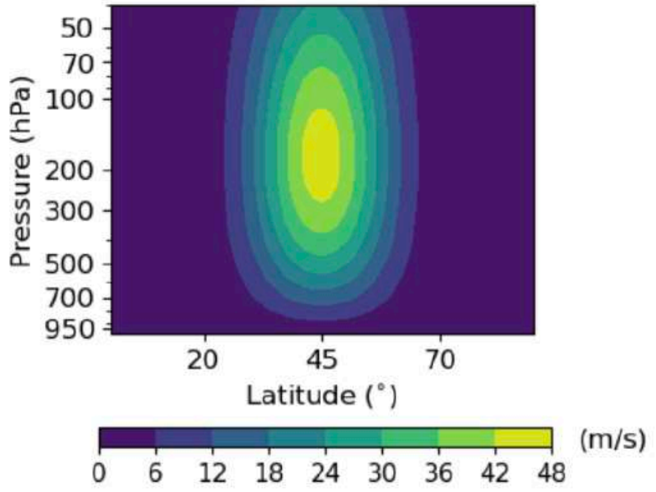
Model setup

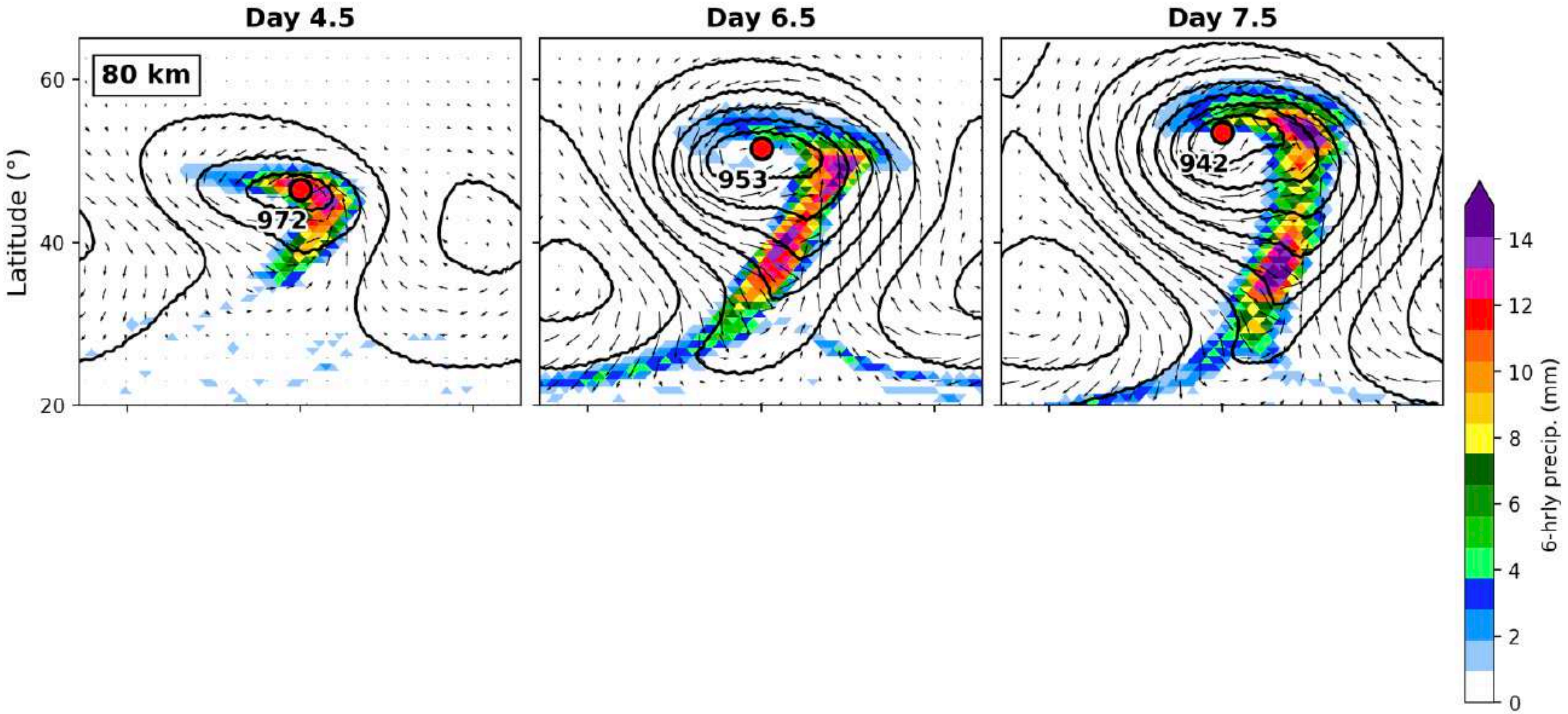
T & qv

CTL

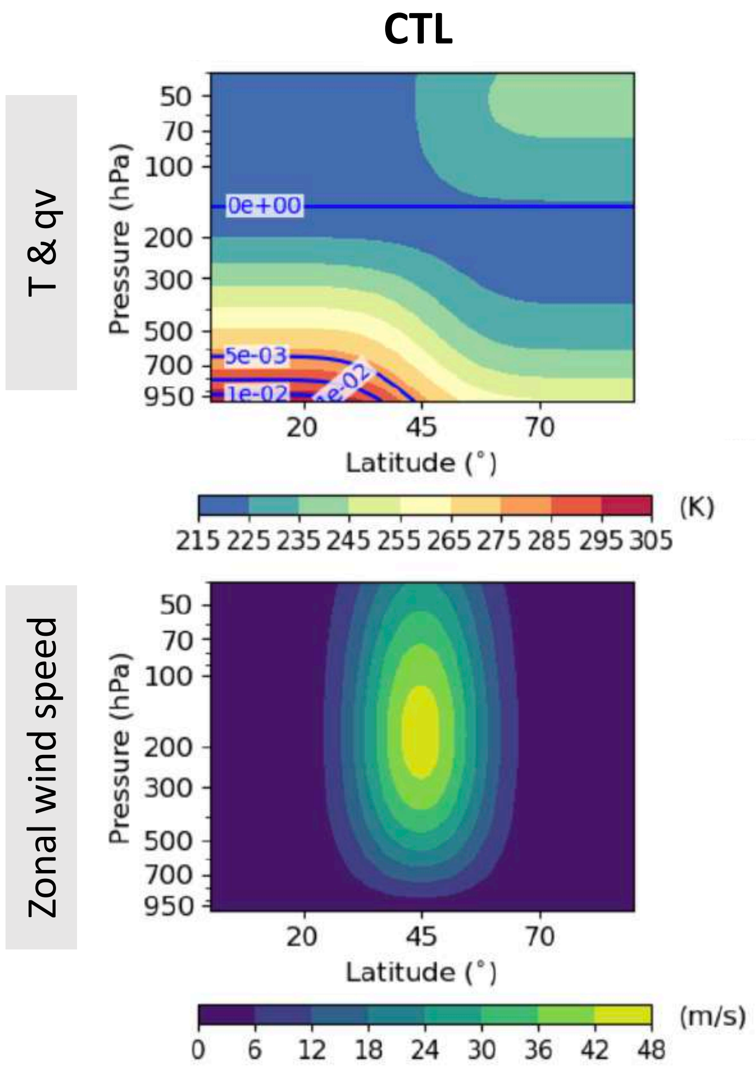


Zonal wind speed

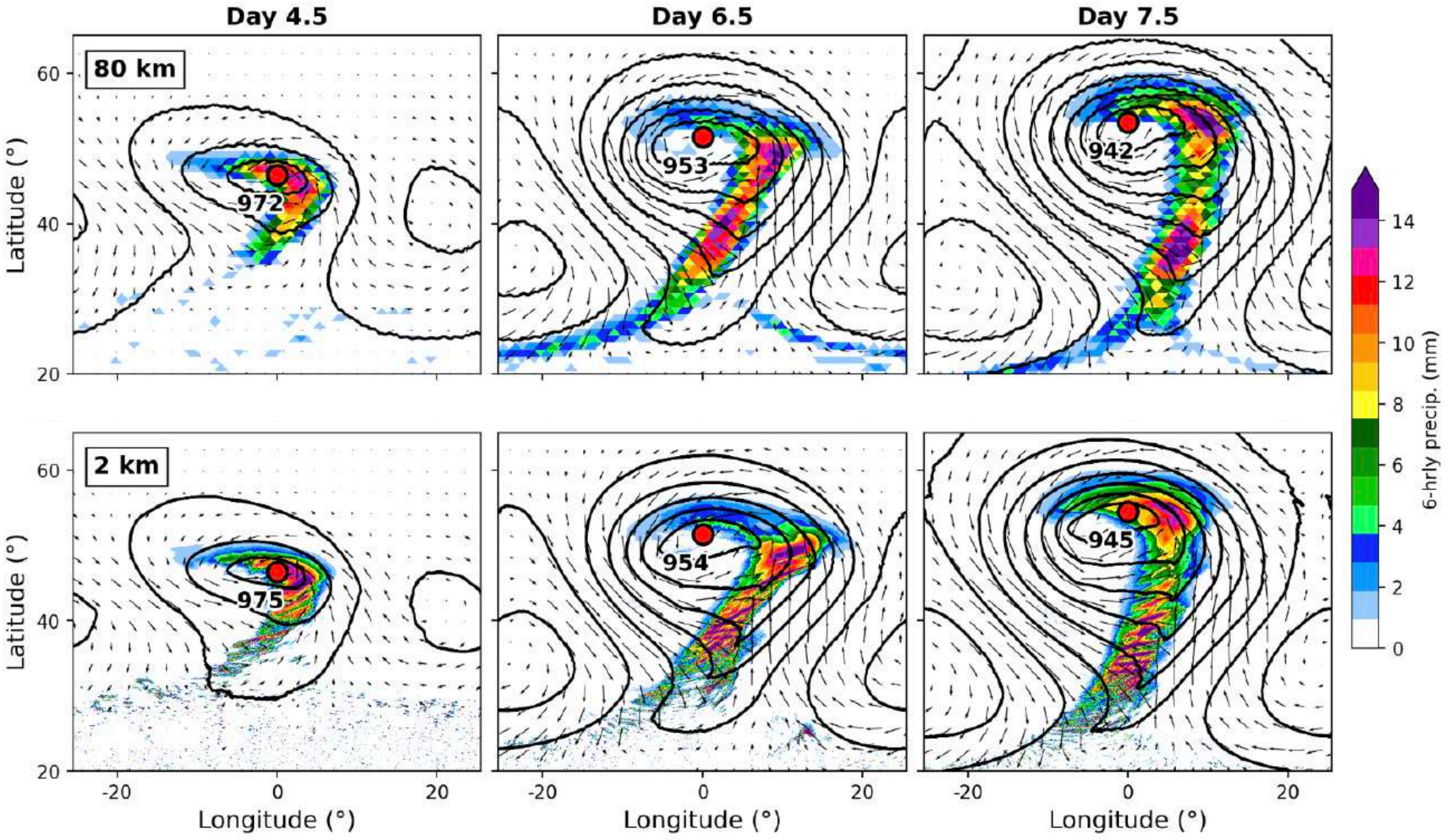




Model setup

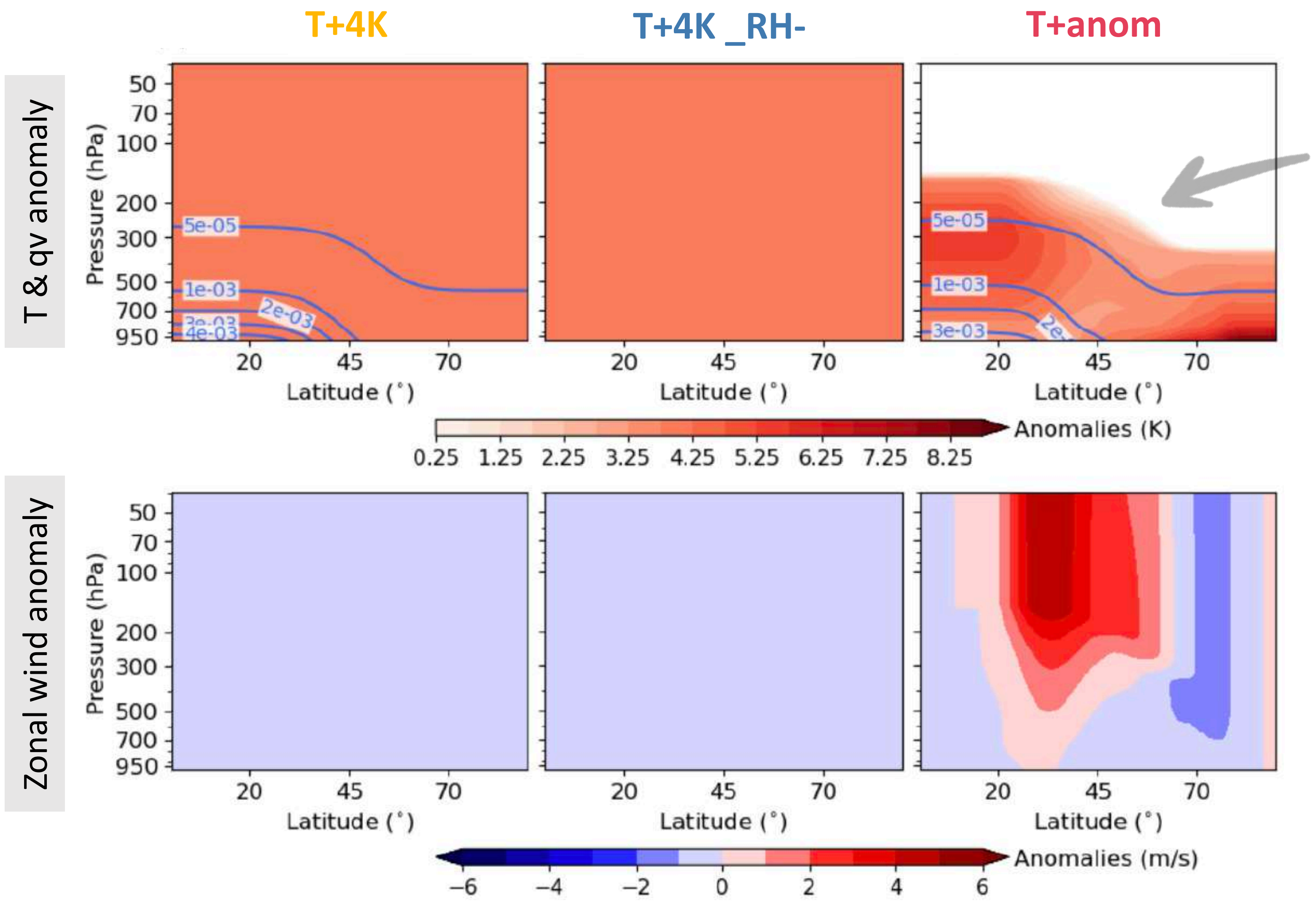


CTL
T & qv
Pressure (hPa)
Latitude (°)
0e+00
5e-03
1e-02
(K)
215 225 235 245 255 265 275 285 295 305
Zonal wind speed
(m/s)
0 6 12 18 24 30 36 42 48



Day 4.5
Day 6.5
Day 7.5
80 km
2 km
972
953
942
975
954
945
Latitude (°)
Longitude (°)
6-hrly precip. (mm)

Model setup – warmer climate scenarios



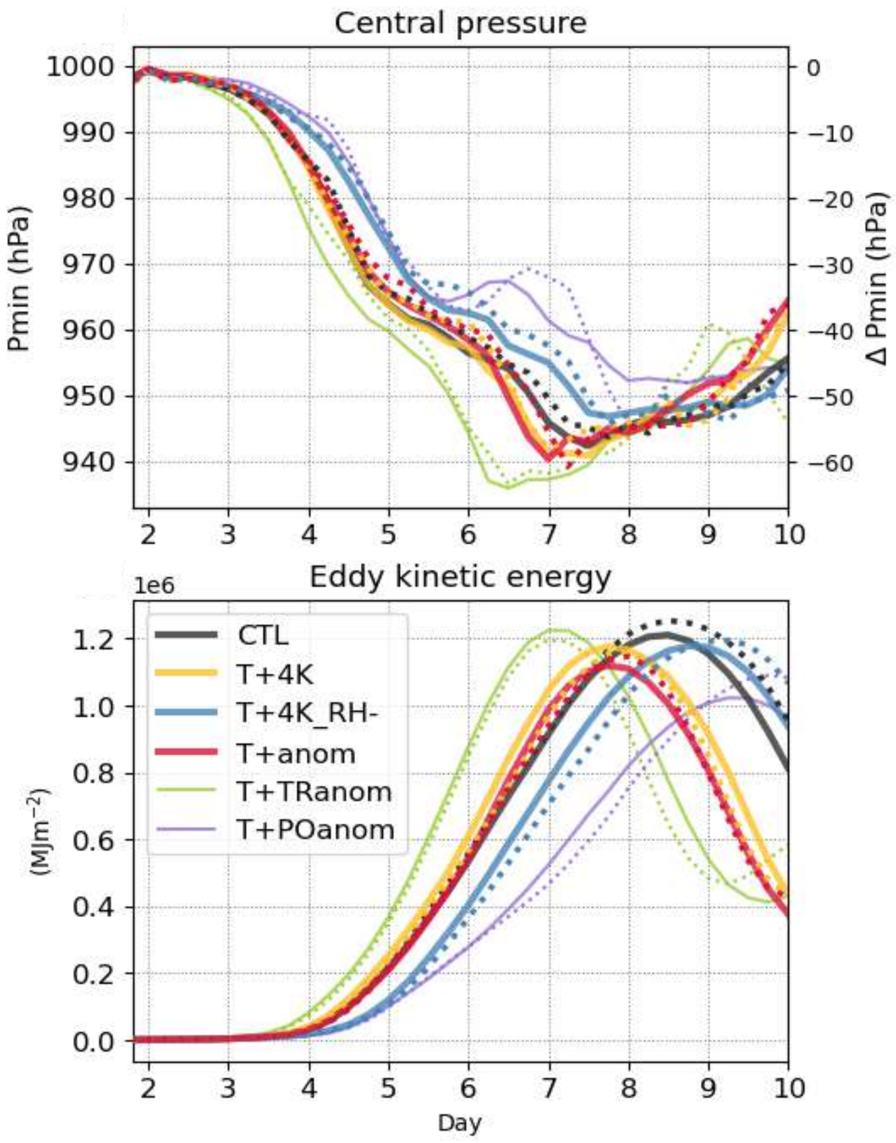
Future **(winters 2070-2099)**–
Historical **(winters 1980-2009)**
from MPI-ESM1-2-LR, SSP 5-8.5

qv is increased to keep RH same as CTL

Warmer & Moister : **T+anom**, **T+4K**

Warmer: **T+4K_RH-**

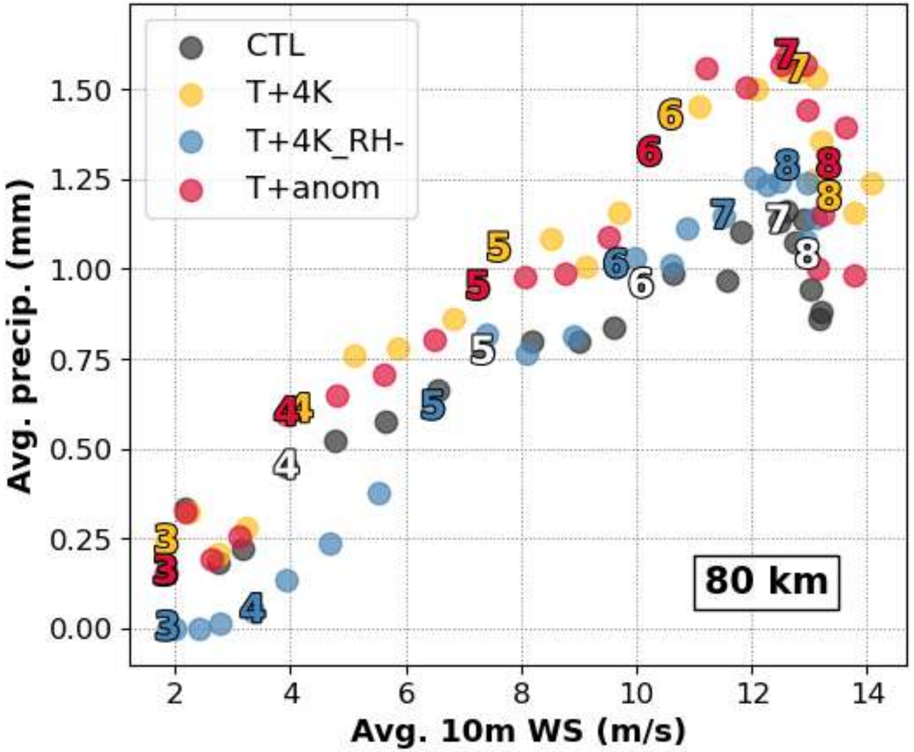
Cyclone intensity



80-km	CTL	T+anom	T+4K	T+4K_RH-
		Diff with CTL		
Pressure (hPa)	942.3 (total drop of 57.7 hPa)	-2	-1.5	+4.5
Time reached	7.5 day	-0.5 day	0 day	+0.25 day
EKE (MJm^{-2})	1.21	-0.09	-0.03	-0.03
Time reached	8.5 day	-0.5 day	-0.75 day	-0.75 day

- **Slightly deeper cyclone core** at maturity: central pressure drops by 2 hPa more (total drop increases by 3.4%)
- **Faster** development (peak time hastens by 12 hours)
- **Lower** spatially-integrated **EKE** by 7.4%

Near-surface impacts



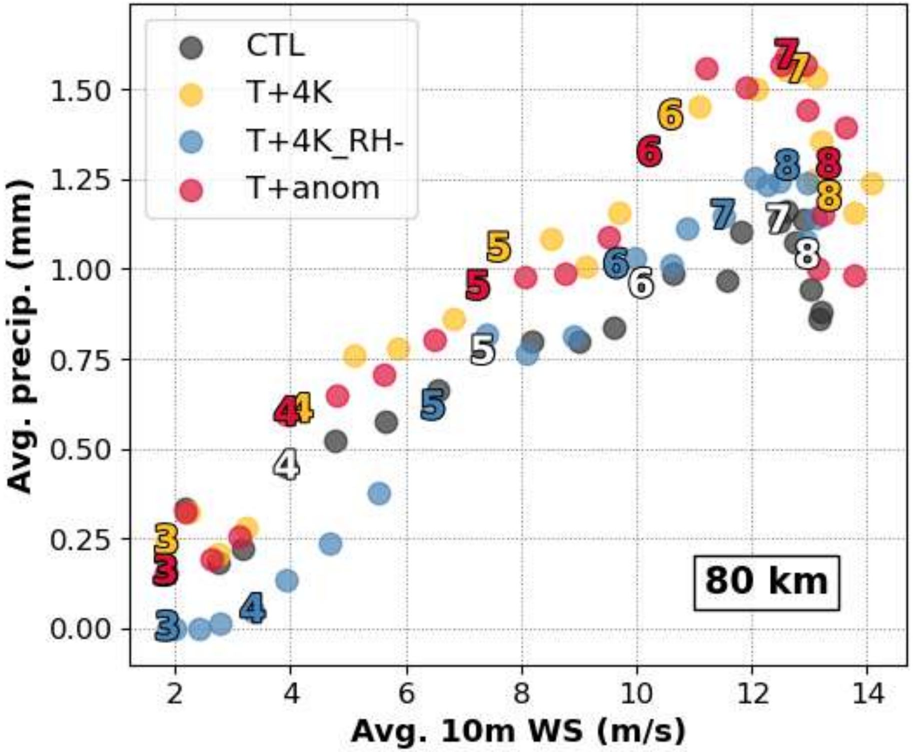
T+anom, **T+4K** *(Warmer & Moister climate)*

- Peak-time domain-average precip. increases by 37%
- Peak-time near-surface wind speed increases by 5% for domain average

T+4K_RH- *(Warmer climate)*

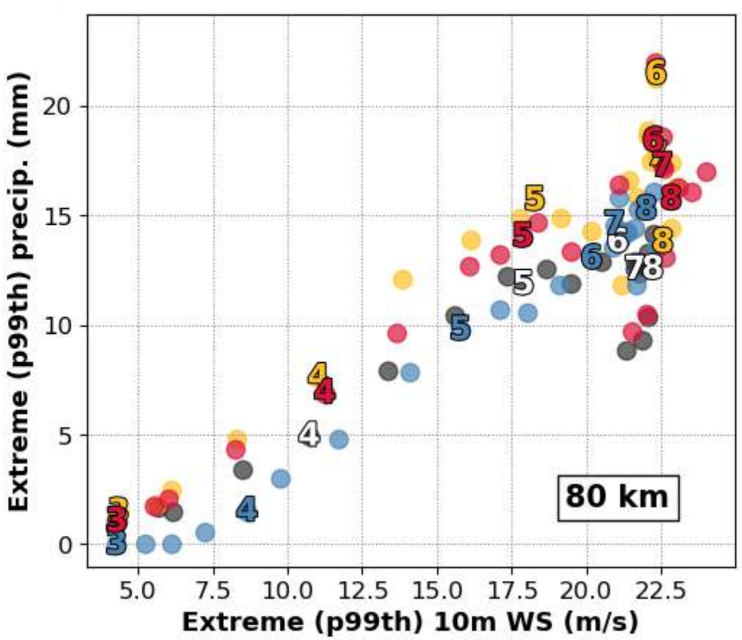
- lower precip. in early time due to lower RH but exceeds CTL at mature stage (increases by 10%)
- Almost no changes in wind speed

Near-surface impacts

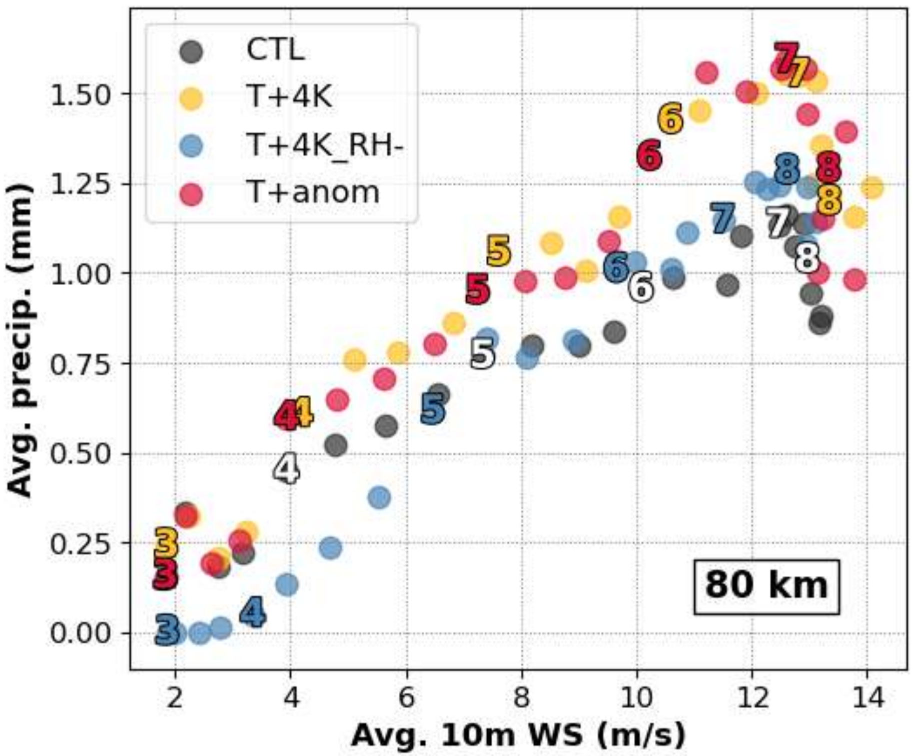


T+anom, T+4K *(Warmer & Moister climate)*

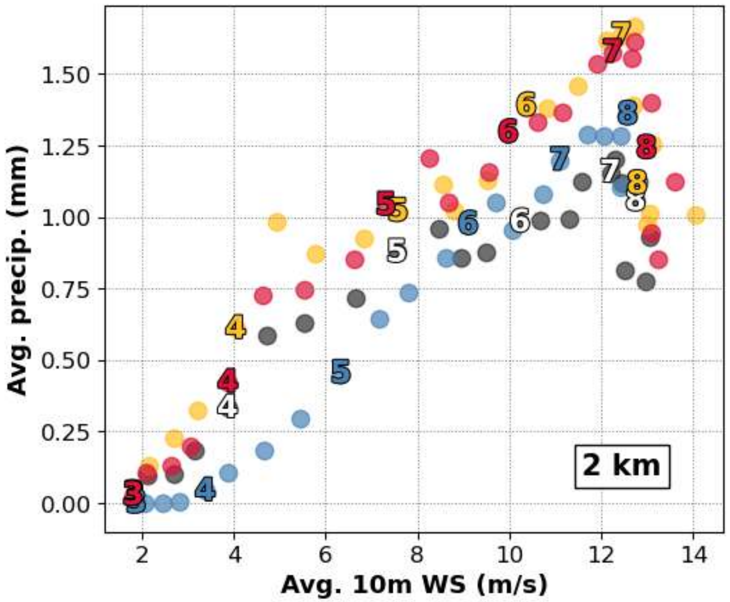
- Peak-time domain-average precip. increases by 37% (extreme grid-point value increases by 51%)
- Peak-time near-surface wind speed increases by 5% for domain average (7% for local spatial extreme)

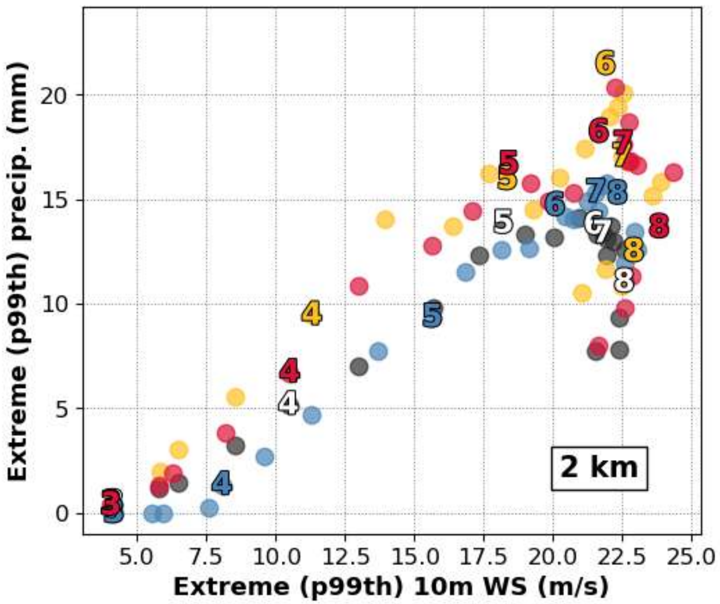


Near-surface impacts



- 2-km simulations exhibit similar responses to different warmer climate scenarios.

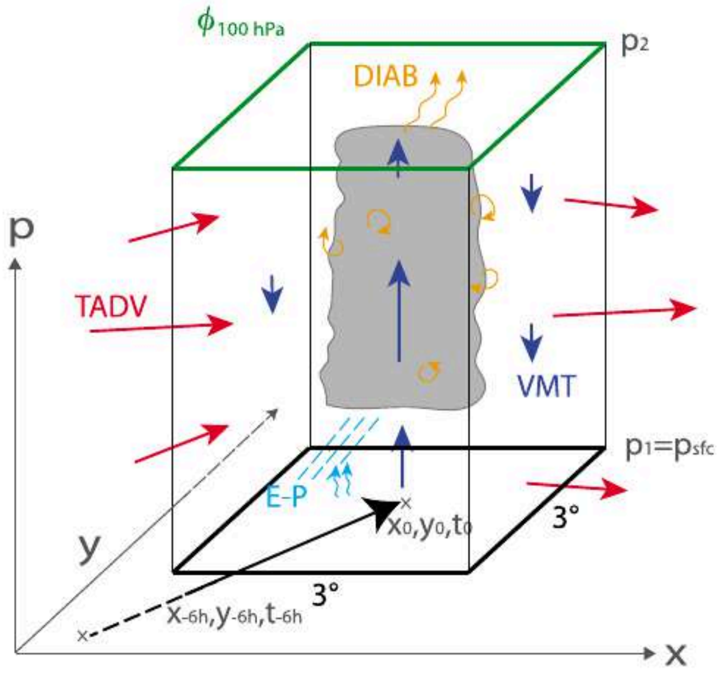




Pressure tendency equation (PTE) analysis

$$\frac{\partial p_{sfc}}{\partial t} = \rho_{sfc}\frac{\partial \phi_{p2}}{\partial t} + \rho_{sfc}R_d\int_{sfc}^{p_2}\frac{\partial T_v}{\partial t}\mathrm{dln}p + g(E-P) + residual$$

Surface pressure drop	Lifts/falls of upper lid (p2)	Column net temp. tendency	Mass change due to precipitation & evaporation	
Dp	**Dfi**	**ITT**	**EP**	**Eq 1**



Fink et al. (2012)

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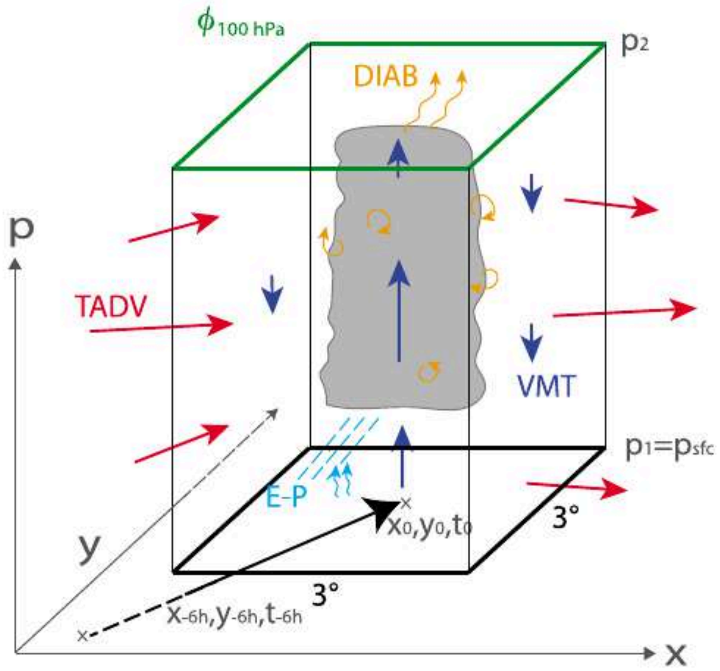
Dp	Dfi	ITT	EP

Eq 1

$$\mathrm{ITT} = \rho_{sfc}R_d\left[\int_{sfc}^{p_2} -\vec{v}\cdot\vec{\nabla}_p T_v \mathrm{dlnp} + \int_{sfc}^{p_2}\left(\frac{R_d T_v}{C_p p} - \frac{\partial T_v}{\partial p}\right)\omega \mathrm{dlnp} + \int_{sfc}^{p_2}\frac{T_v\dot{Q}}{C_p T}\mathrm{dlnp}\right] + residual$$

TADV	VMT	DIAB
Horizontal temp. advection	Adiabatic cooling/warming due to vertical motion	(Latent heat, radiation, diffusion, turbulent mixing)

Eq 2

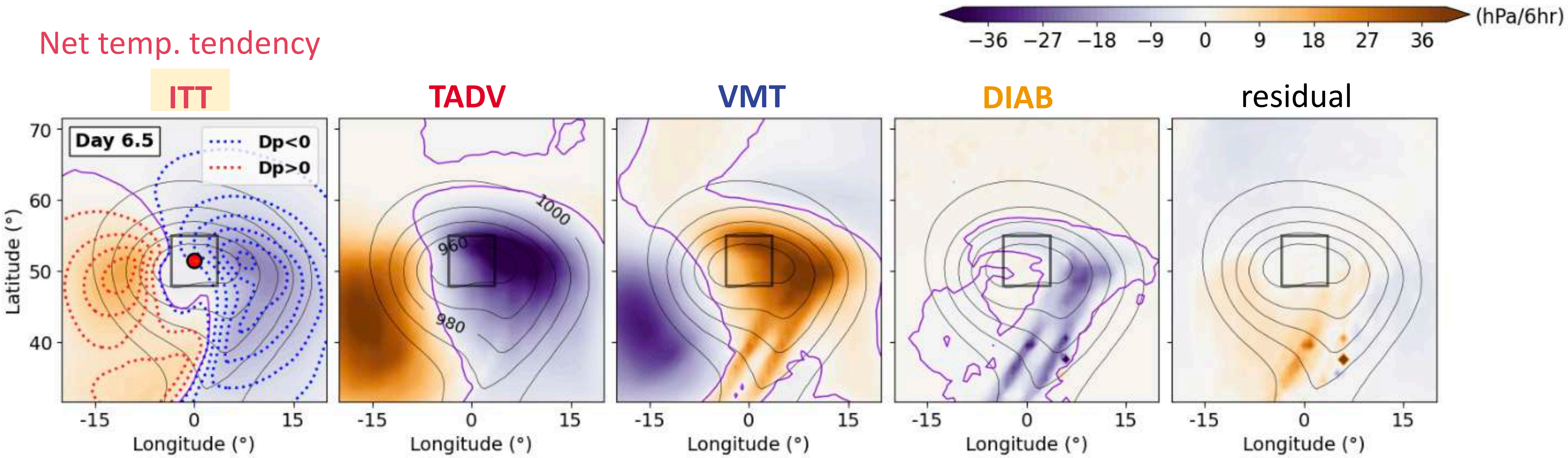


Fink et al. (2012)

Diagnosis is applied at 6 h interval.

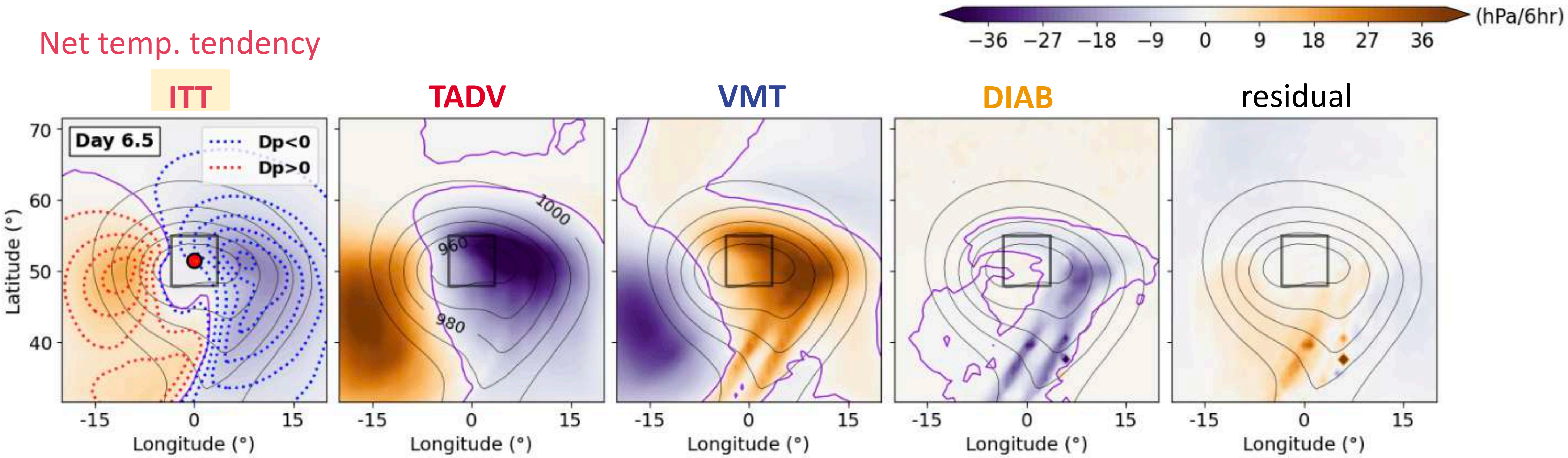
Pressure tendency equation (PTE) analysis An example of 80-km CTL (Eq.2)

Net temp. tendency

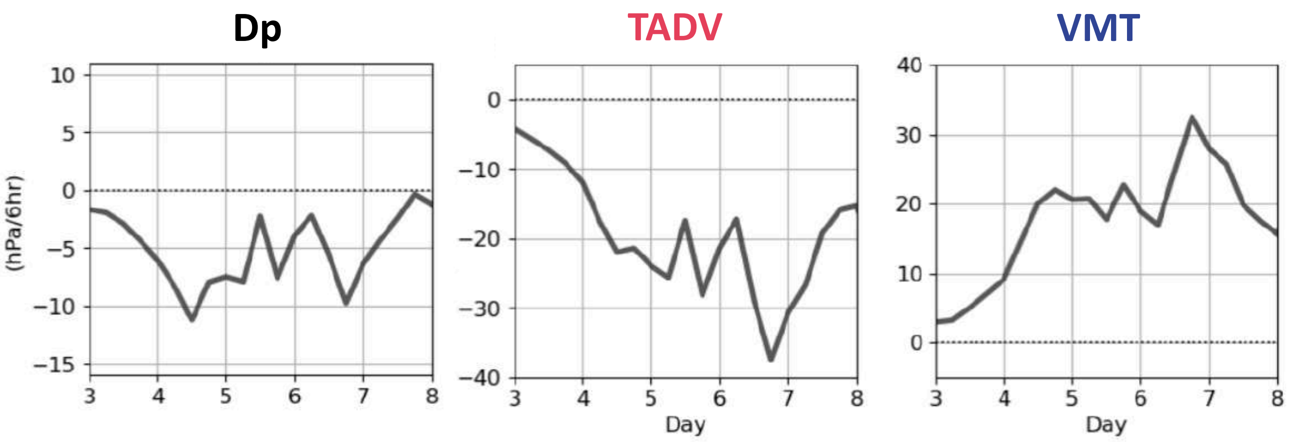


Pressure tendency equation (PTE) analysis

An example of 80-km CTL (Eq.2)



Take spatial averages over a 6°x6° box around the cyclone center



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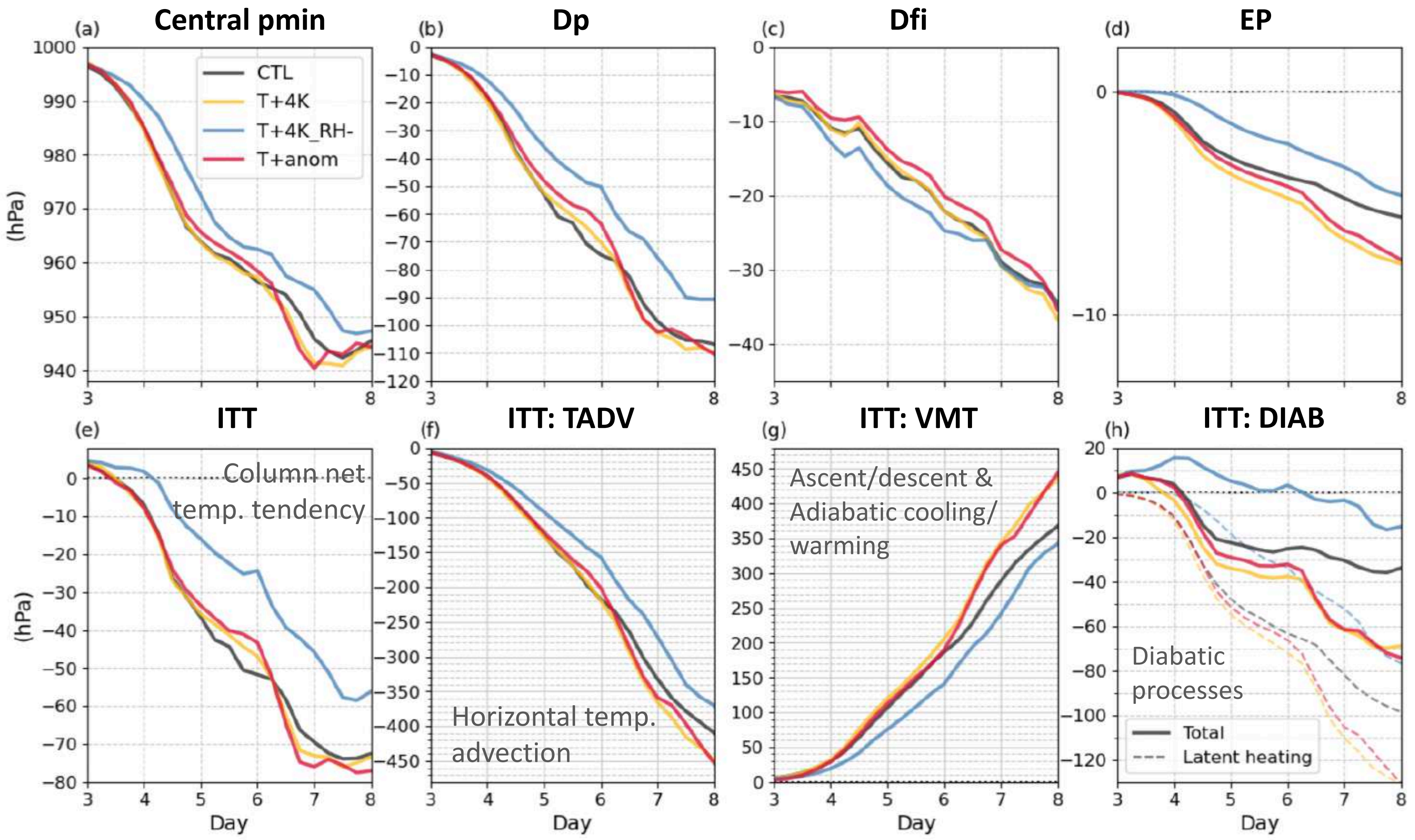
Time-integrated PTE analysis: CTL vs. warmer (&moister) climates

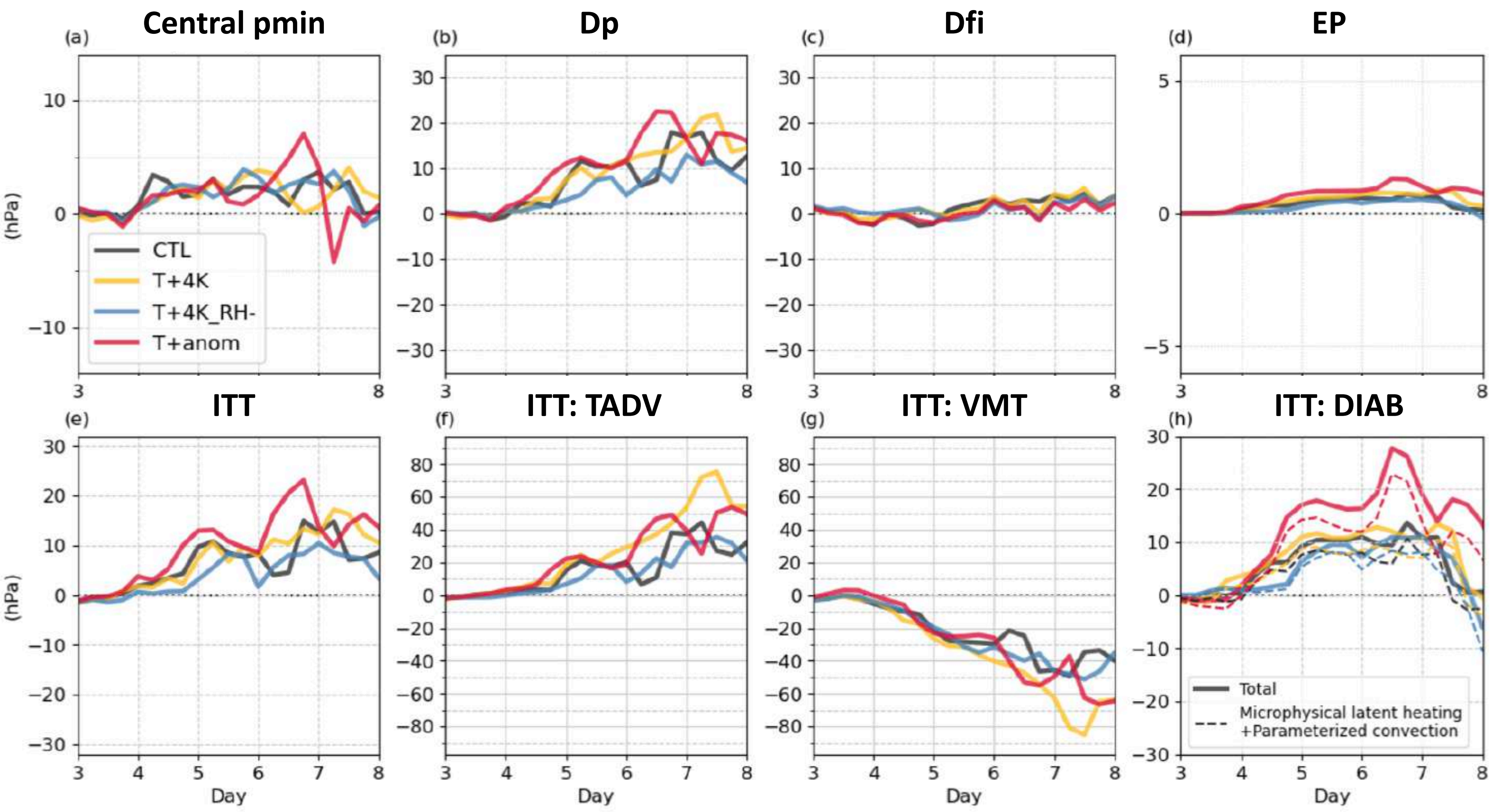


CTL → T+anom, T+4K:

DIAB: -30 → -60 hPa
TADV: -335→-365 hPa
VMT: 290→ 340 hPa
by day 7

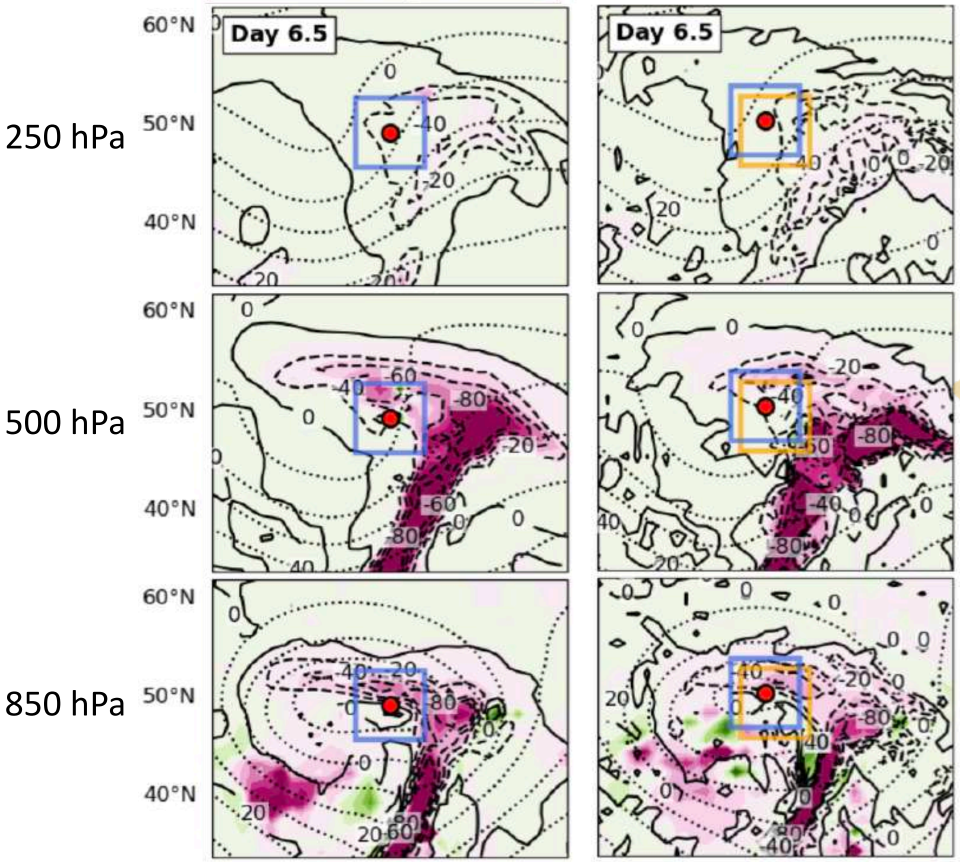
Change in DIAB precedes that in TADV!

Time-integrated PTE analysis: Difference (2km − 80km)



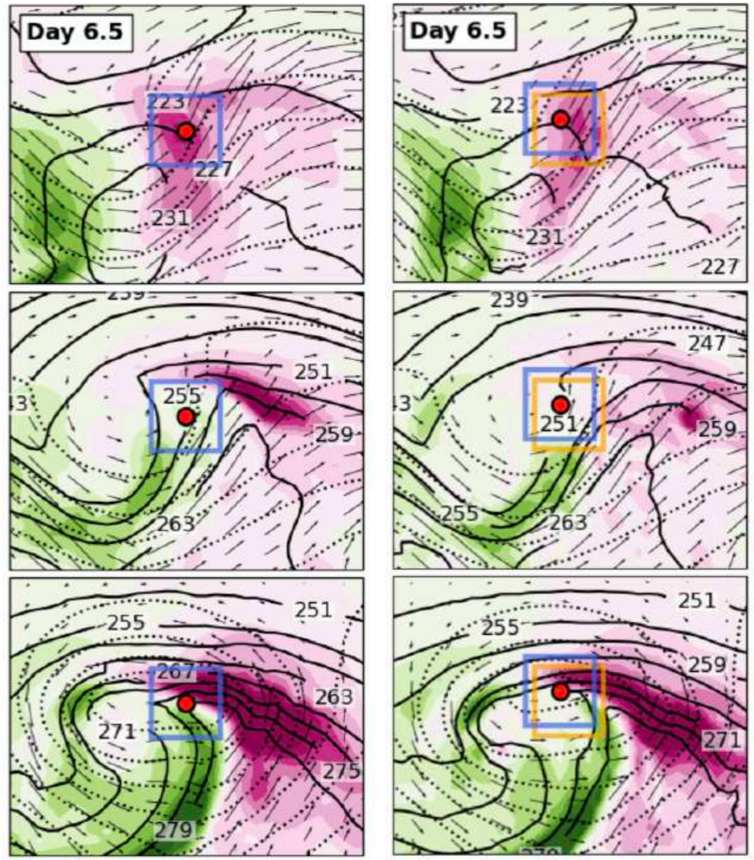
- 2km simulations exhibit systematically weaker cyclones (higher central pressure) than their 80km counterparts.
- Supported by PTE: all temp. tendency effects get weaker in magnitude.

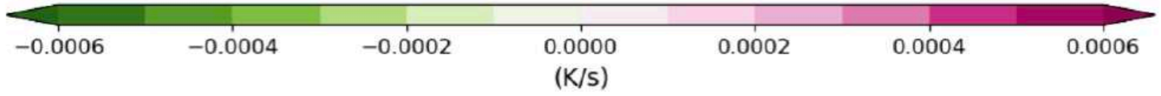
An example of major heating processes in T+anom



2 km: weaker diabatic heating near cyclone center

Feedback?





Concluding remarks

From our idealized initial-value experiments using ICON-NWP model:

- **ETC develops similarly in two different warmer and moister climate scenarios, T+anom and T+4K:**

  Development ↑ by 12 hours; pmin ↓ by 2 hPa (marginal; only 3% of total deepening in CTL); EKE ↓ by 7%.

  Near-surface impact ↑ (by 37% & 51% in averaged & local extreme precipitation; 5% & 7% for wind speeds).

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- **Contribution to cyclone pressure drop via pressure tendency equation (PTE) analysis:**

	DIAB	**TADV**	VMT
Response to warming & moistening (increase in magnitude % of CTL)	-30 hPa (+100%) Gradually starts on day 4	-30 hPa (+9%) On day 6	+50 hPa (+17%) On day 6

Indirect feedback (DIAB → TADV)

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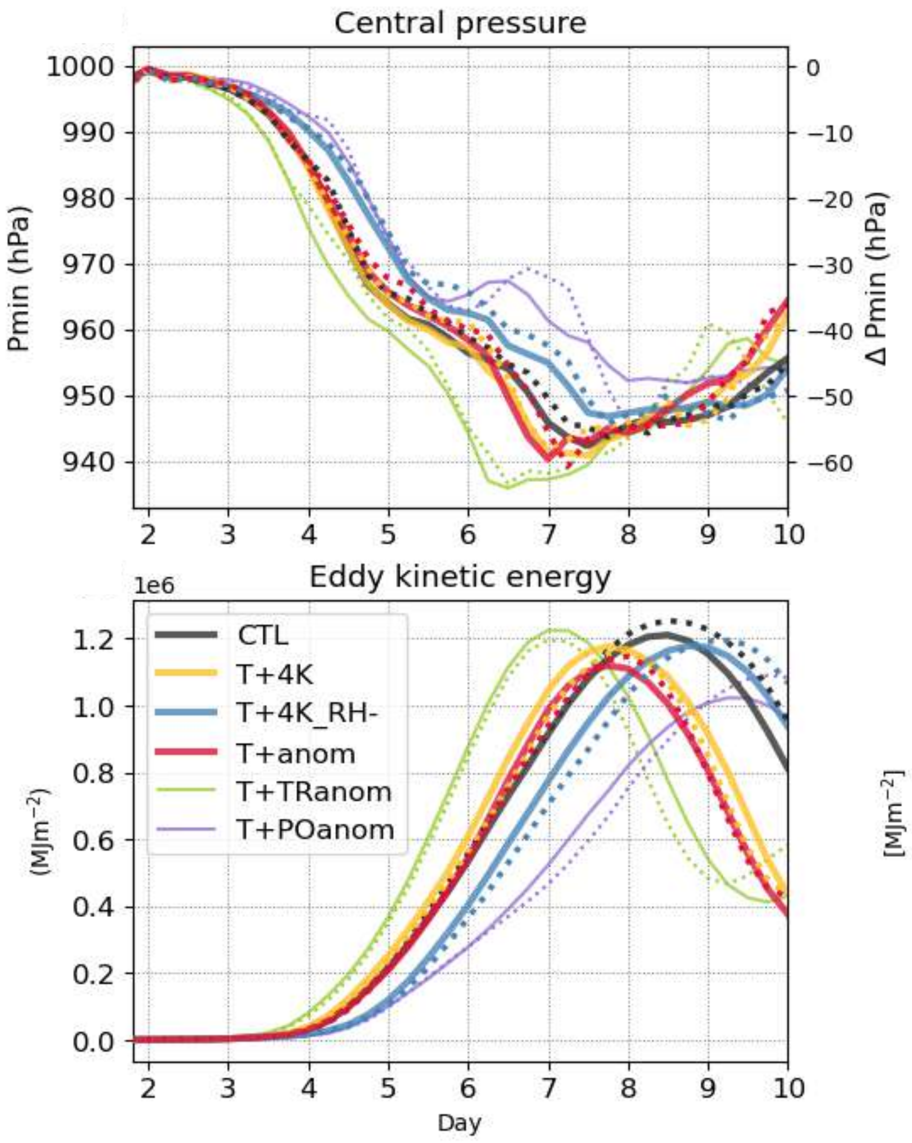
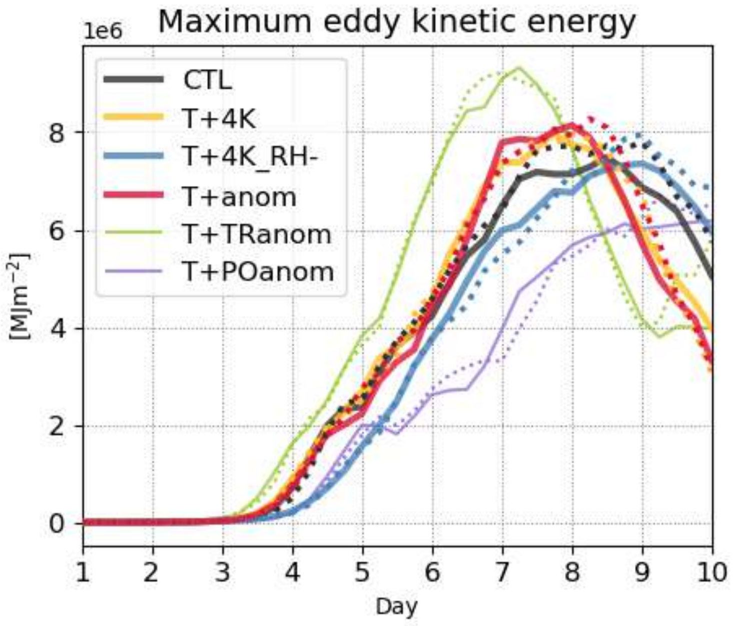
Indirect feedback

- Convection-permitting 2.5km simulations suggest a potential overestimation for *cyclone deepening* (not the *response to global warming*) in coarser-grid GCMs.

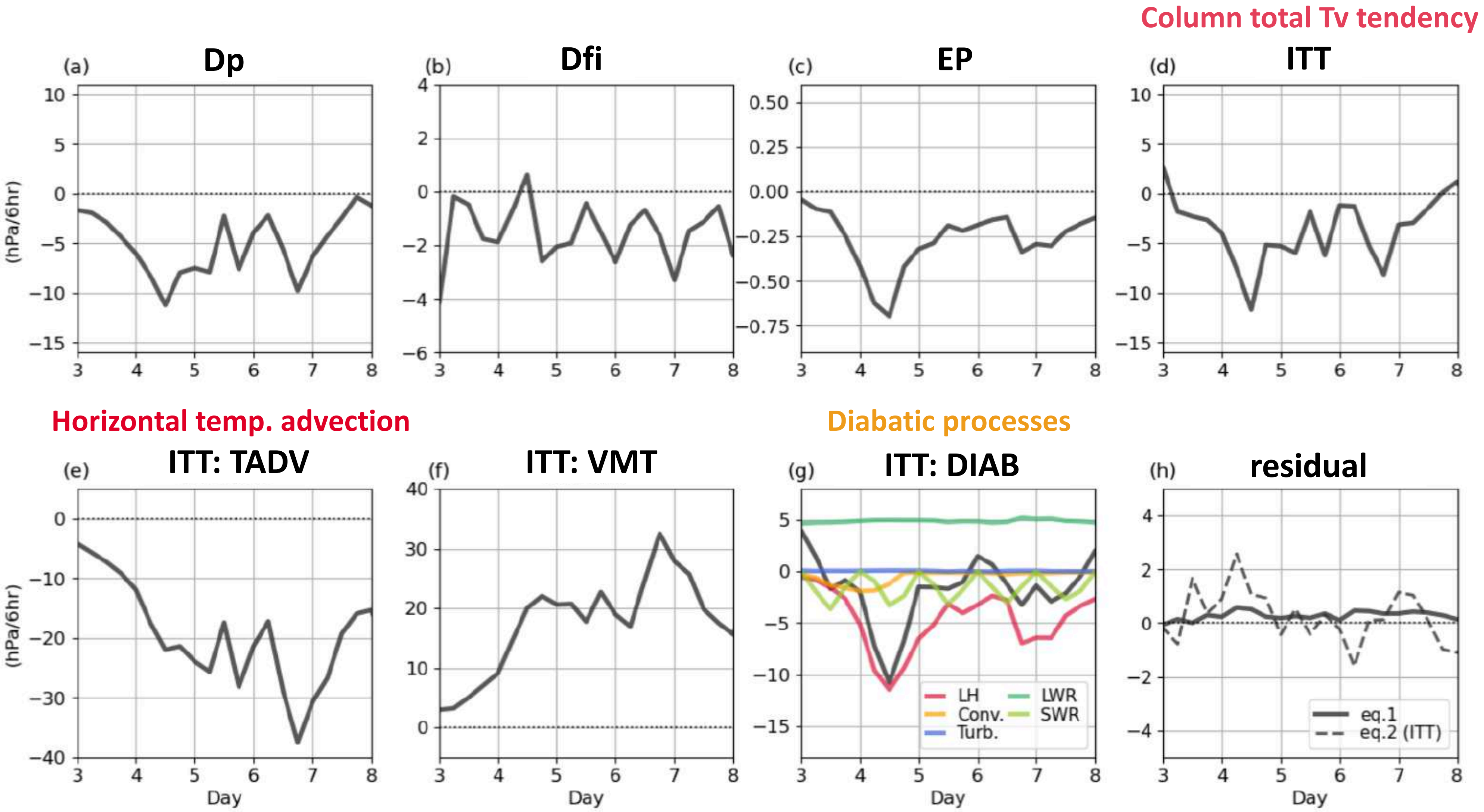
- Future work: conduct more realistic setup/experiments using historical cases.

Cyclone intensity





PTE analysis following cyclone tracks with time An example for 80-km CTL



Eq 1

Eq 2

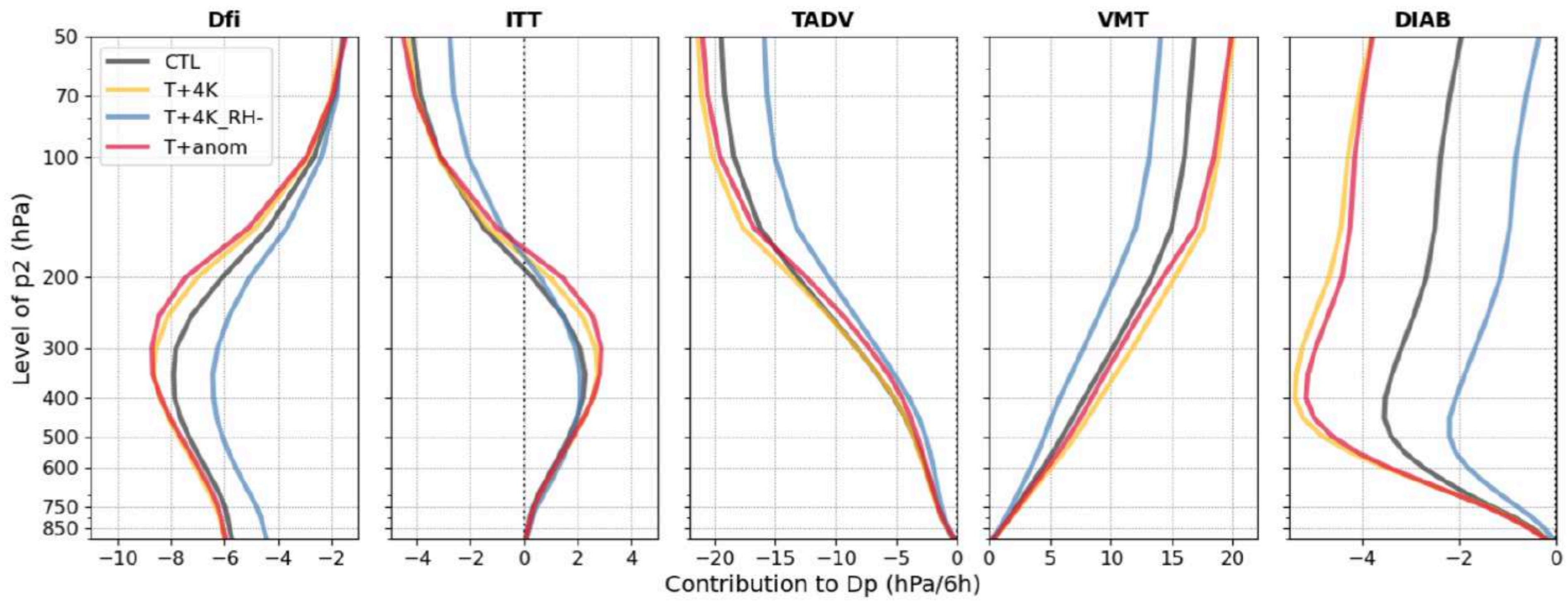


Fig. E1. Time-averaged profiles of selected PTE analysis terms as a function of the upper integration boundary (p2): Dfi, ITT, TADV, VMT, and DIAB (from left to right). Values in x-axis are averages over day 3 to day 7.

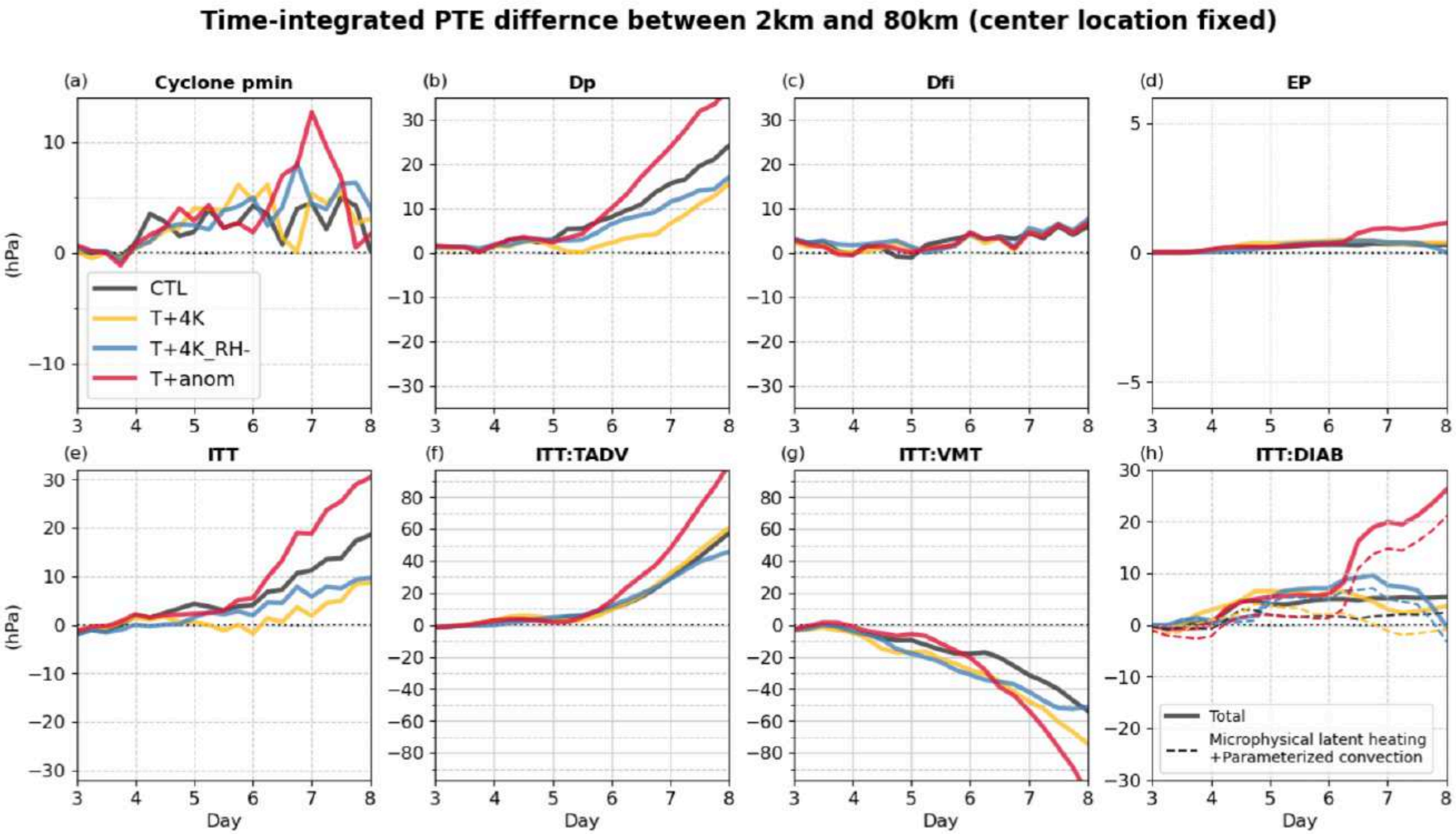


Fig. B1. Same as Fig. 10, but the location of cyclone center used for averaging PTE are based on the 80-km runs universally.

PTE analysis

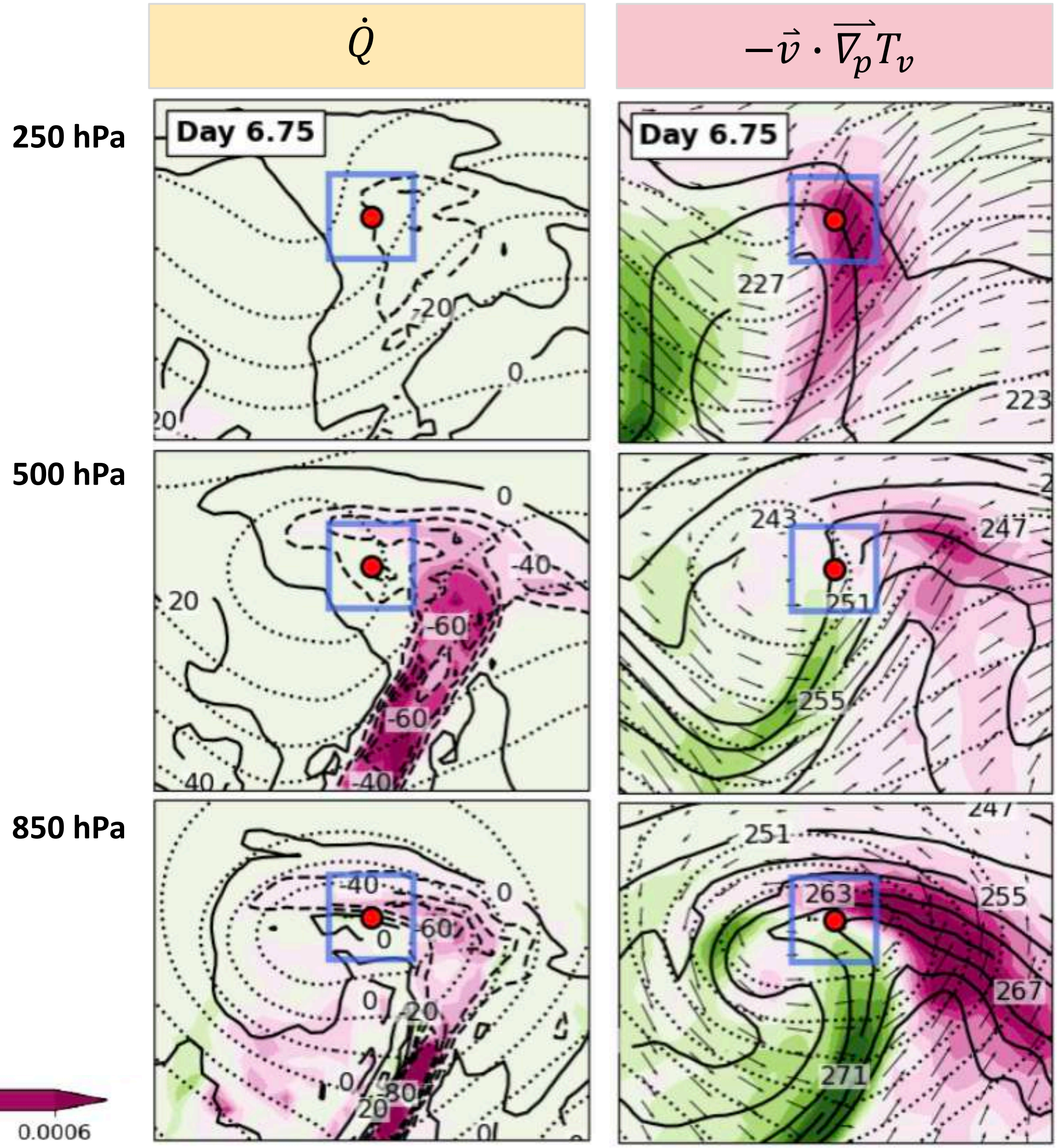
ITT $=$

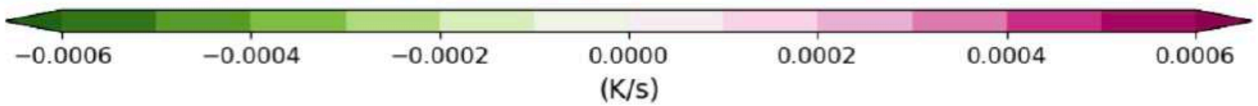
$$\rho_{sfc} R_d \int_{sfc}^{p_2} -\vec{v}\cdot\vec{\nabla}_p T_v \, d\ln p$$ Horizontal temp. advection **TADV**

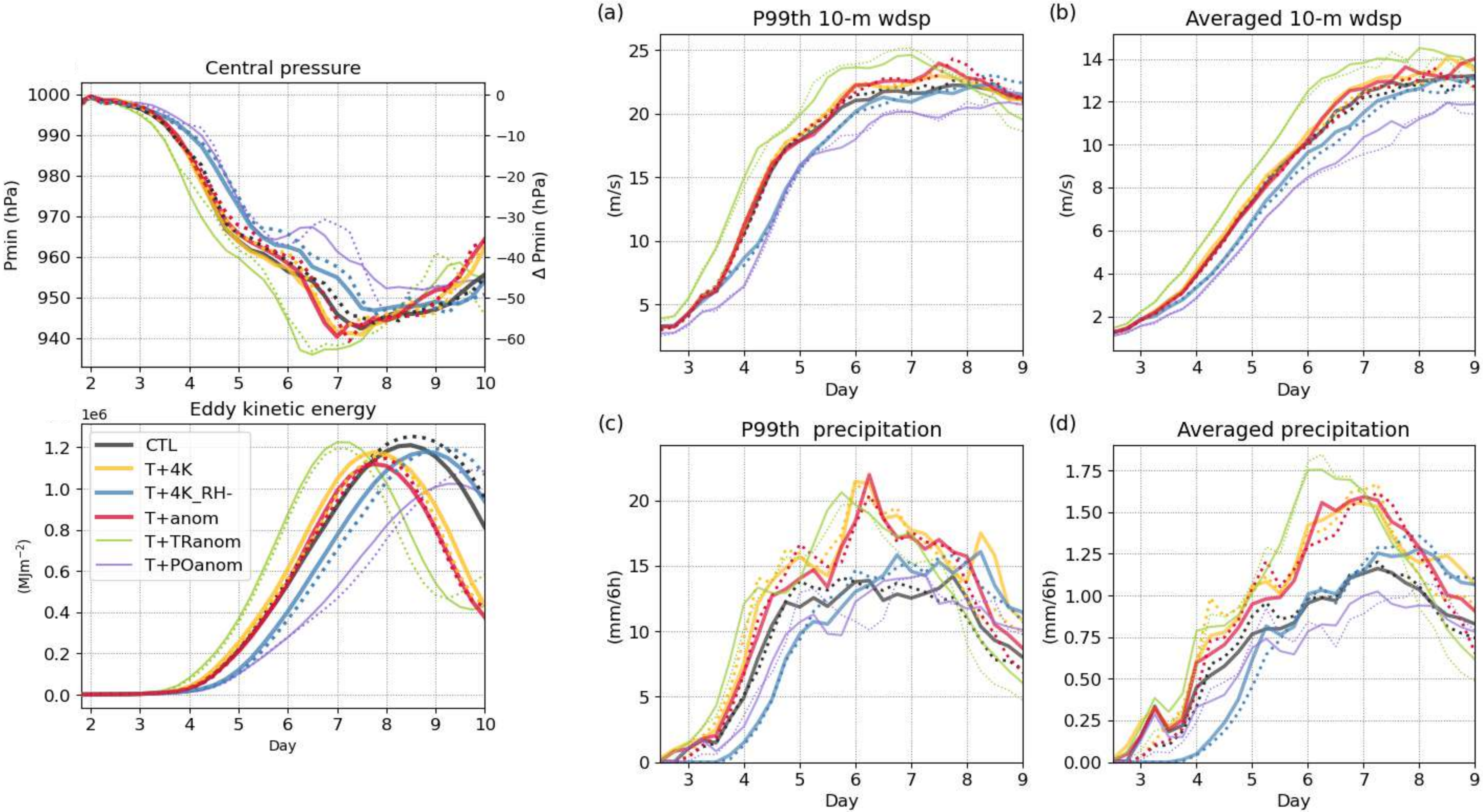
$$+\rho_{sfc} R_d \int_{sfc}^{p_2} \left(\frac{R_d T_v}{C_p p} - \frac{\partial T_v}{\partial p}\right) \omega \, d\ln p$$ Adiabatic cooling/ warming due to vertical motion **VMT**

$$+\rho_{sfc} R_d \int_{sfc}^{p_2} \frac{T_v \dot{Q}}{C_p T} \, d\ln p$$ (Latent heat, radiation, diffusion, turbulent mixing) **DIAB**

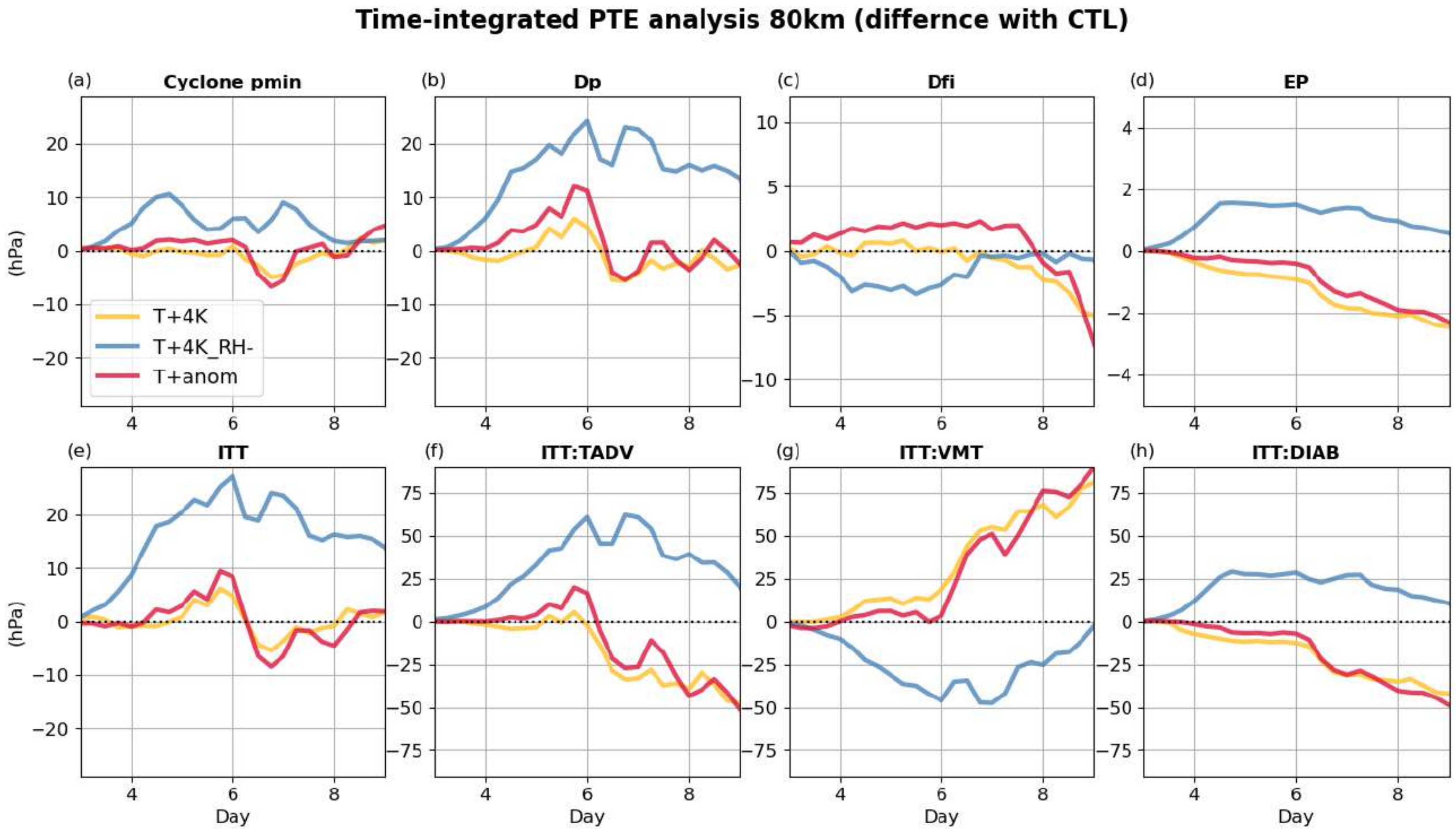
$$+\,residual$$







Central pressure
Pmin (hPa)
Δ Pmin (hPa)
Eddy kinetic energy
1e6
(MJm^{-2})
Day
CTL
T+4K
T+4K_RH-
T+anom
T+TRanom
T+POanom
(a)
P99th 10-m wdsp
(m/s)
Day
(b)
Averaged 10-m wdsp
(m/s)
Day
(c)
P99th precipitation
(mm/6h)
Day
(d)
Averaged precipitation
(mm/6h)
Day


Time-integrated PTE analysis 80km (differnce with CTL)
(a) Cyclone pmin
(b) Dp
(c) Dfi
(d) EP
(e) ITT
(f) ITT:TADV
(g) ITT:VMT
(h) ITT:DIAB
(hPa)
Day
T+4K
T+4K_RH-
T+anom

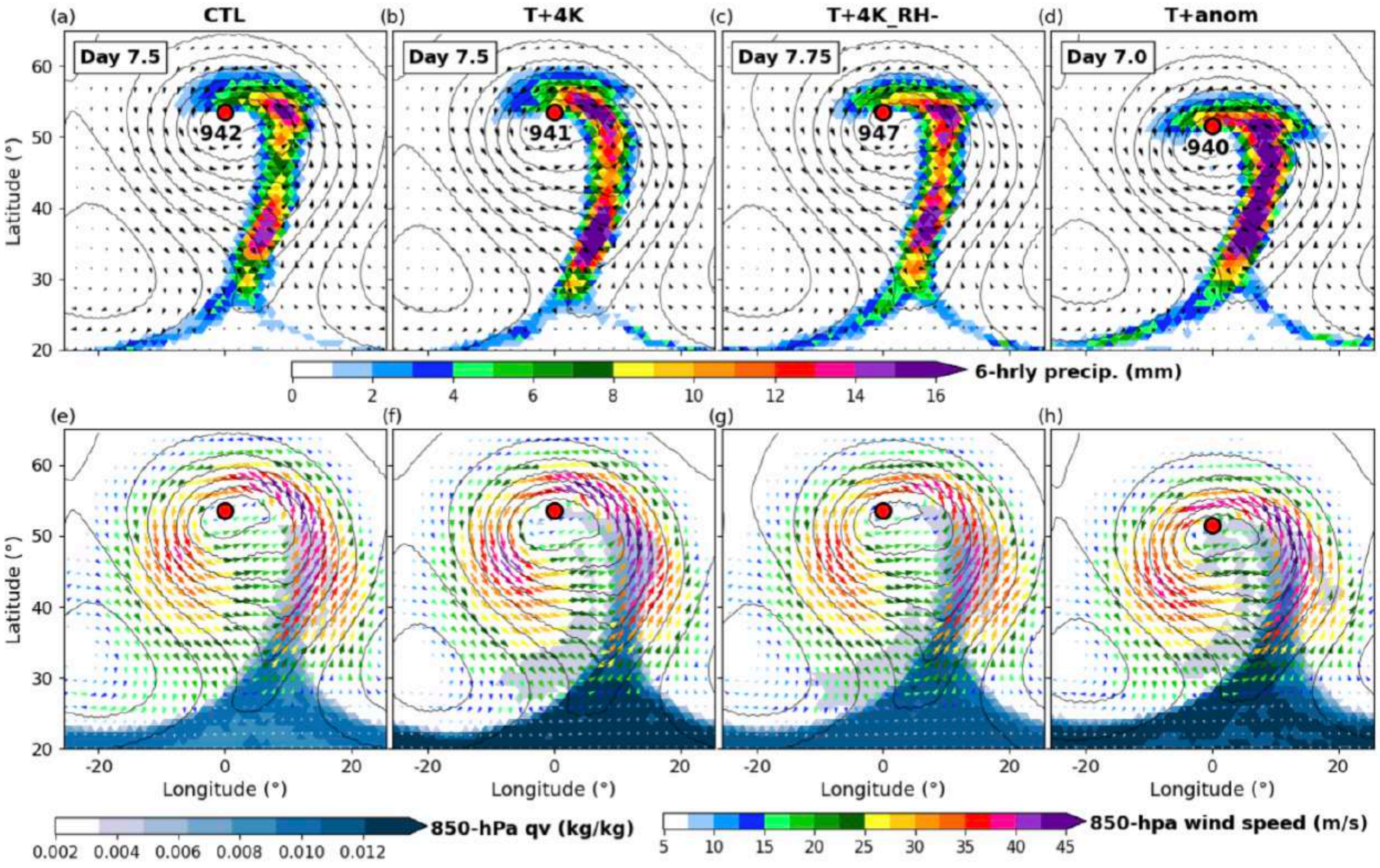


FIG. 5. Snapshots of cyclone features at its peak intensity for 80-km (a) CTL, (b) T+4K, (c) T+4K_RH-, and (d) T+anom. Upper row shows 6-hrly precipitation (shades; mm), mean sea level pressure (contours), and 10-m wind (arrows). Bottom row same as upper row but for specific humidity at 850-hPa level (shades; kg/kg), and 850-hPa wind (colored arrows). Red circle indicates the cyclone center with the minimum pressure specified.