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Research Article

Keywords: climate model design, parameterisation, precipitation, planetary boundary layer (PBL), regional climate model (RCM), ACM2, MYNN2, NARClIM2.0

Posted Date: August 12th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10558667/v1>

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Impacts of Planetary Boundary Layer schemes on ERA5-NARClIM2.0 convection-permitting climate simulations over southeastern Australia

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Abstract

Planetary boundary layer (PBL) parameterisations are major sources of uncertainty in climate modelling because they regulate land–atmosphere exchanges of heat, moisture, and momentum. This study evaluates the influence of two PBL schemes on the seasonal climatology of southeastern Australia using ERA5-forced Weather Research and Forecasting regional climate models (RCM) at 4-km resolution: the local Mellor–Yamada–Nakanishi–Niino (MYNN2) scheme and hybrid local–nonlocal Asymmetric Convective Model version 2 (ACM2). Although both RCMs exhibit biases in seasonal-mean daily maximum and minimum temperatures, daily maximum temperature is more sensitive to PBL parameterisation. Compared with MYNN2, ACM2 reduces the cold bias in daily maximum temperature while producing a generally warmer climate. Additionally, MYNN2 overestimates seasonal precipitation during most seasons, whereas ACM2 shows substantially smaller biases except during summer.

We show that a positive land–atmosphere feedback can explain the warmer and drier climate simulated by the ACM2 RCM. Stronger nonlocal turbulent mixing in the ACM2 scheme deepens the PBL, enhancing the entrainment of dry free-tropospheric air. The resulting reduction in boundary-layer humidity suppresses cloud liquid water, allowing more shortwave radiation to reach the surface. Increased surface heating raises near-surface temperature and promotes further PBL growth, which in turn strengthens entrainment and reinforces the drying and cloud reduction. Reduced precipitation further decreases soil moisture, sustaining the warm–dry feedback. These findings highlight the strong sensitivity of RCM simulations to PBL parameterisation, thus providing process-based guidance for future high-resolution climate modelling.

Key words: climate model design, parameterisation, precipitation, planetary boundary layer (PBL), regional climate model (RCM), ACM2, MYNN2, NARClIM2.0

1. Introduction

Turbulent mixing in the planetary boundary layer (PBL) plays an important role in the vertical transport of moisture, heat and momentum, thus determining how thermodynamic and kinematic profiles evolve, which in turn influences the formation of deep convection, vertical pollution transport and surface wind gusts (Garratt 1994). Therefore, the performance of numerical weather prediction and climate models relies on accurate representation of PBL effects and their interactions with other components of the earth system. However, turbulent mixing mostly occurs at spatiotemporal scales that cannot be explicitly resolved in most climate models, such that PBL parameterisation schemes are used. The main functions for a PBL parameterisation include (1) the estimation of the surface fluxes of prognostic variables, (2) the determination of the process of cloud formation in the PBL, and (3) the formulation of the interactions between the PBL and the free atmosphere (Konor et al. 2009).

Over recent decades, PBL parameterisation schemes have been improved in terms of atmospheric stability, closure methods, mixing approaches, and numerical techniques (Mantovani Júnior et al. 2023). These schemes are broadly categorised by their turbulence closure method, specifically whether considering local or nonlocal processes. Local PBL schemes assume vertical transport is mainly driven by small-scale eddies that only occur between adjacent model layers and that are related to local turbulent kinetic energy (TKE). Consequently, local PBL schemes are often suitable for stable atmospheric conditions where mixing is confined to the immediate vicinity of the surface (Cohen et al. 2015; Xie et al. 2012). However, they may not accurately represent the effects of large-scale, convective eddies that can penetrate the top of the mixed layer and lead to counter-gradient fluxes. In contrast, nonlocal PBL schemes use multiple vertical levels to determine covariance at a given grid point through a mixing approach based on either a counter-gradient term, a grid-size dependency function, or a transilient matrix (i.e., a convective mass-flux formulation). They allow transport between distant layers by large-scale eddies, which can penetrate the entire PBL and mix air across multiple levels. Hence, they are better suited for simulating convective boundary layers and to accurately represent counter-gradient fluxes, where heat and moisture can be transported upwards even when the local temperature profile is stable (Pleim 2007a).

The Weather Research and Forecasting (WRF) model (Skamarock et al. 2019) is a non-hydrostatic mesoscale atmospheric model widely used for numerical weather prediction and regional climate simulations, with flexible parameterisation schemes for key atmospheric and land–surface processes. WRF provides a range of PBL parameterisation schemes, whose impacts on simulated weather and climate have been extensively evaluated across diverse climatic regions and at various spatial and temporal scales (e.g., Gibbs et al. 2011; Huang et al. 2013; Cohen et al. 2015; Milovac et al. 2015; Ma et al. 2024). Gibbs et al. (2011) found that the nonlocal Yonsei University scheme (YSU; Hong et al. 2006) and the hybrid local–nonlocal Asymmetrical Convective Model version 2 scheme (ACM2; Pleim 2007a, b) produce drier PBLs in a dry convective boundary layer and better depict the observed PBL than the local Mellor–Yamada–Janjić (MYJ; Janjić 1994; Mesinger 1993) scheme. The use of nonlocal PBL parameterisation schemes can enhance the model’s simulation of heat extraction from the surface while still representing fluxes associated with the convectively induced secondary circulation (Ching et al. 2014). Garcia-Diez et al. (2013) examined the performance of three WRF PBL schemes (YSU, MYJ, and ACM2) in simulating European seasonal-mean temperatures. They found that model biases depend heavily on the season—producing a warm bias in winter due to misrepresented cold extremes and a systematic cold bias in summer. They also pointed out that the nonlocal YSU scheme generally produces warmer surface temperatures

than the local closure schemes because it mixes heat more efficiently through a deeper daytime boundary layer. A recent study using WRF by Ma et al. (2024) showed that the nonlocal YSU scheme generally outperformed the local MYJ scheme in simulating the weather along the tropical coastal region of China. Although both schemes underestimated temperature and PBL height and overestimated wind speed and turbulent fluxes, these biases were reduced by increasing horizontal resolution from 27 to 9 km. Prein et al. (2022) conducted sensitivity tests to investigate how mesoscale convective systems in the US Southern Great Plains and Amazon are influenced by the choices of microphysics and PBL schemes. They found that the Amazon cases are more sensitive to the PBL scheme—the local Mellor–Yamada–Nakanishi–Niino Level 2.5 (MYNN2; Nakanishi and Niino 2004) scheme simulates a deeper and strongly mixed PBL than the YSU and MYJ schemes, which consequently supports the development of widespread convection in the Amazon basin. Mantovani Júnior et al. (2023) also found that the local MYNN2 scheme showed the overall best performance for PBL height prediction, mainly at night for the Amazon.

Although the impacts of PBL parameterisations have been studied in simulating the climate of many regions globally, comparatively fewer studies have assessed their impacts on climate simulations over Australia. Kala et al. (2015) conducted a suite of sensitivity tests using the WRF regional climate model (RCM) to investigate how the choices of driving data and physical parameterisation impact temperature and precipitation. They found that minimum temperatures over the southwest of Western Australia are more sensitive to the choice of PBL schemes than other parameterisations. Evans et al. (2012) evaluated the performance of 36 combinations of WRF physical parameterisations on the simulation of rainfall events over southeastern Australia, including the local MYJ and nonlocal YSU PBL schemes. They concluded that no single member of these parameterisation combinations is universally the best for all locations and variables. However, their study did not isolate the impacts from individual parameterisations; hence, it was not possible to disentangle the effect of individual parameterisation from their combined impact on the climate simulations.

As is clear from previous studies, the choice of PBL scheme remains a key area of interest in regional climate modelling. In this study, we explicitly isolate the impacts of PBL parameterisation on climate over southeastern Australia and investigate the physical mechanisms underlying the differences. The two WRF simulations used in this study, selected from the seven RCM configurations evaluated by Di Virgilio et al. (2025b) based on their performance, are both driven by the fifth-generation European Centre for Medium-Range Weather Forecasts Reanalysis v5 (ERA5; Hersbach et al. 2020) and only differ in their PBL schemes: one employs the local MYNN2 scheme, while the other uses the hybrid local–nonlocal ACM2 scheme. These ERA5-driven simulations serve as the “benchmark simulations” for CMIP6-forced (Coupled Modelling Intercomparison Project Phase 6) historical and future climate simulations over Australia conducted as part of the NARClIM2 (New South Wales and Australian Regional Climate Modelling version 2.0) project (Di Virgilio et al. 2025a). By focussing on these ERA5-driven simulations, this study assesses the implications of PBL scheme selection which will help inform the interpretation of CMIP6-driven WRF simulations from NARClIM2.0. Specifically, this study aims to (1) quantify the impact of the MYNN2 and ACM2 PBL schemes on the simulation of temperature, precipitation, and boundary-layer characteristics over southeastern Australia; and (2) diagnose the physical mechanisms responsible for the simulated differences. Consequently, this study provides insights to better understand the role of PBL processes in Australian regional climate modelling and help inform future RCM model design choices.

2. Model and Datasets

2.1 Model

In this study, two RCM simulations, which are configured with identical physics parameterisations except for their PBL schemes, have been used for comparison. The details of physics parameterisations can be found in Table 1. As these two simulations are a subset of seven RCM simulations from Ji et al. (2024) and Di Virgilio et al. (2025a, b), we use the same naming system for consistency, namely R3 (i.e., the 3rd RCM) and R5 (i.e., the 5th RCM), respectively. In this study, the RCMs use the WRF version 4.1.2 with Advanced Research dynamical core and are driven by ERA5 reanalysis. The “one-way” nesting method is employed—that is, a parent domain (d01) over Australasia provides the lateral boundary conditions as inputs to drive a nested domain (d02) over southeast Australia, and there is no feedback from d02 to d01. The d01 domain follows specifications for the Australasia region in the Coordinated Regional Climate Downscaling Experiment (CORDEX; <https://cordex.org/domains/region-9-australasia/>) and uses a quasi-regular grid spacing of approximately 20 km (i.e., $0.176^\circ \times 0.176^\circ$ on a rotated coordinate system), while the d02 domain uses a resolution of approximately 4 km (i.e., $0.0352^\circ \times 0.0352^\circ$ on a rotated coordinate system) covering southeastern Australia (Fig. 1). There are 45 vertical levels configured for both domains—the highest level is at 50 hPa and there are ~9 levels within the lowest 1-km above ground level. The cumulus parameterisation is turned off in d02 because, at a 4 km horizontal resolution, these RCMs resolve convection explicitly and are therefore considered convection-permitting models. Urban physics is activated to capture surface energy balance in urban areas via a single-layer urban canopy model. Both simulations are run for a 42-year period from January 1979 to December 2020, and the first year was discarded in our analyses due to spin-up. Further details on the design and set-up of these RCMs can be found in Di Virgilio et al. (2025a).

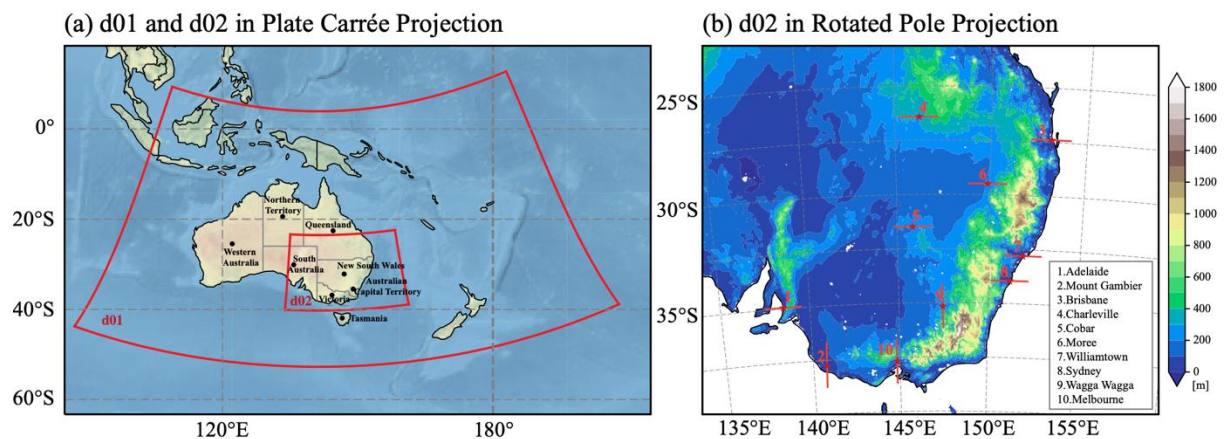


Fig. 1 (a) The domains d01 and d02 projected in the Plate Carrée projection. The parent domain d01 over CORDEX-Australasia with a resolution of ~20 km, and the nested domain d02 over southeastern Australia with a resolution of ~4 km. (b) The southeastern Australia domain d02 projected in our native Rotated Pole projection with the land topography shown. Ten sounding sites (see Table 2) used in Section 3.2 are marked as red stars. The red lines demonstrate the cross-sections centred at sounding sites and extending 1° on both sides, which are used in the cross-section analyses in Section 3.5.

155 **Table 1** The major parameterisation schemes used in the two RCM simulations

RCM	PBL Physics/ Surface Layer Physics	Microphysics	Cumulus Physics	Shortwave and Longwave radiation physics	Land Surface	Land option
R3	Mellor-Yamada-Nakanishi-Niino Level 2.5 (MYNN2)	Thompson	BMJ	RRTMG/RRTMG	Noah-MP	Dynamic vegetation
R5	Asymmetric Convective Model 2 (ACM2)	Thompson	BMJ	RRTMG/RRTMG	Noah-MP	Dynamic vegetation

156

157 2.2 Evaluation Datasets

158 The Australian Gridded Climate Data (AGCD; Australian Bureau of Meteorology 2020; Evans et al. 2020)
 159 from the period of 1980–2019 has been used to evaluate the performance of the simulated means of daily
 160 maximum/minimum 2-metre air temperatures ($T_{\max}/T_{\min}$) and precipitation (pr) over land. The AGCD dataset,
 161 interpolated from station observations across the Australian continent, has a resolution of 0.05° . Given that Di
 162 Virgilio et al. (2025b) has completed essential evaluations over the CORDEX Australasia domain (d01), this study
 163 focuses on the southeastern Australian domain (d02). We apply a quality mask to the AGCD dataset to mask out
 164 the northwestern area in d02 due to sparse observations in this region. Apart from the AGCD observational data,
 165 we include the ERA5 reanalysis with a horizontal resolution of 0.25° (~31 km) as reference, including PBL height
 166 (PBLH), atmospheric temperature (T), zonal (u) and meridional (v) winds, vertical velocity (w), and specific
 167 humidity (q) at pressure levels from 1000 to 500 hPa. As ERA5 reanalysis has no equivalent surface specific
 168 humidity to our RCM simulations, we calculate the surface specific humidity (q_{2m}) using surface air pressure and
 169 2-m dewpoint temperature. All observational and reanalysis data were re-gridded to match the RCM data on their
 170 native grids using a conservative area-weighted re-gridding scheme.

171 To evaluate the simulated seasonal-mean vertical profiles of potential temperature (θ), q and wind speed
 172 ($wspd = \sqrt{u^2 + v^2}$), three years of observational sounding data gathered by radiosondes from the Australian Bureau
 173 of Meteorology during the period of 2018–2020 are used. These sounding data underwent a comprehensive
 174 quality-control procedure. Profiles with missing near-surface observations, insufficient vertical coverage or
 175 resolution, unrealistic lapse rates, or surface discontinuities were rejected. Instances of supersaturation (dewpoint
 176 > temperature) were removed by setting dewpoint equal to temperature, while gaps and unrealistic spikes in the
 177 temperature and dewpoint profiles were interpolated. The profiles were then linearly interpolated to fixed 100-m
 178 height intervals from the surface to 20 km above ground level (AGL) and smoothed using a Gaussian filter with
 179 a standard deviation of 100 m. In a final step, temperature and dewpoint below 1 km AGL were adjusted where
 180 needed to eliminate extreme lapse rates while avoiding supersaturation.

181 We adopt sounding data from ten sites that are covered in this domain (See Fig. 1b and Table 2). The sounding
 182 data are irregularly measured per day, and all stations have most samples collected at 1100 or 2300 UTC

(Coordinated Universal Time) except for Sydney where most samples are collected at 1900 or 2000 UTC. As our simulation outputs were only available at a 3-hour interval and the timesteps may not match with the sounding data time, we choose the closest timesteps from simulations to compare with the sounding data. For better understanding the profiles from a local perspective, the UTC is converted to AEST (Australian Eastern Standard Time) by adding 10 hours.

Table 2 Details of sounding data used in this study. DJF = December–January–February (austral summer); MAM = March–April–May (austral autumn); JJA = June–July–August (austral winter); SON = September–October–November (austral spring).

No.	Sites	Coordinates	Time (AEST)	No. of Samples			
				DJF	MAM	JJA	SON
1	Adelaide	34.95°S, 138.52°E	0900–1000	163	127	116	134
			2100–2200	154	97	107	139
2	Mount Gambier	37.75°S, 140.77°E	0900–1000	30	38	39	41
3	Brisbane	27.39°S, 153.13°E	0900–1000	199	164	183	169
			0300–0400	182	162	186	165
4	Charleville	26.41°S, 146.26°E	0900–1000	111	113	160	124
5	Cobar	31.48°S, 145.83°E	0900–1000	29	30	42	46
6	Moree	29.49°S, 149.85°E	0900–1000	70	43	48	69
7	Williamstown	32.79°S, 151.84°E	0900–1000	48	67	73	81
8	Sydney	33.95°S, 151.17°E	1300–1600	31	34	26	49
			0400–0700	183	206	189	169
9	Wagga Wagga	35.16°S, 147.46°E	0900–1000	99	75	104	83
10	Melbourne	37.67°S, 144.83°E	0900–1000	157	110	140	159
			2100–2200	159	93	147	142

2.3 Descriptions of PBL Schemes

The NARCLiM2.0 R3 simulation uses the local MYNN2 PBL scheme (Nakanishi and Niino 2004; hereafter R3-MYNN2), which uses a 1.5-order closure method that predicts TKE as an extra prognostic variable. The TKE-based mixing produces relatively uniform turbulent diffusion throughout the mixed layer, promoting entrainment across the boundary-layer top and resulting in a less distinct transition between the PBL and the free atmosphere. The mixing length scale is calculated as a harmonic average among the turbulent, surface, and buoyant length scales. PBL height (PBLH) is computed as the height at which TKE first falls below a threshold value ($10^{-6} \text{ m}^2 \cdot \text{s}^{-2}$).

The NARCLiM2.0 R5 RCM uses the ACM2 PBL scheme (Pleim 2007a, b; hereafter R5-ACM2). ACM2 is a first-order, hybrid local–nonlocal PBL scheme with nonlocal upward mixing and local downward mixing explicitly defined. The ACM2 scheme applies the transilient matrix to manage the contribution of nonlocal fluxes. PBLH in the ACM2 scheme is diagnosed using a method based on the bulk Richardson number method, with explicit treatment of the entrainment layer at the PBL top. Because turbulence associated with wind shear and thermal penetration extends above the diagnosed PBL, different approaches are used under stable and unstable

conditions. Under stable conditions, the PBLH is determined using the conventional incremental bulk Richardson number method, whereas under unstable conditions it is defined as the height above the level of neutral buoyancy where the bulk Richardson number within the entrainment layer exceeds the critical threshold of 0.25. ACM2 extends the original ACM scheme (Pleim and Chang 1992) by incorporating local subgrid-scale turbulent mixing between adjacent model layers in addition to nonlocal convective transport. This enhancement produces more realistic entrainment and smoother vertical profiles of atmospheric variables.

2.4 Evaluation and Diagnostic Methods

2.4.1 Evaluation Metrics

To quantify RCM accuracy, several statistical metrics are applied to seasonal means of T_{max} , T_{min} and pr on a grid cell basis, including the mean absolute error (MAE) and spatial (rs) and temporal (rt) Pearson correlations, calculated as

$$MAE = \frac{1}{N} \sum_{i=1}^N |x_i - y_i| \quad (1)$$

$$r_s = \frac{\sum_{i=1}^N (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^N (x_i - \bar{x})^2 \sum_{i=1}^N (y_i - \bar{y})^2}} \quad (2)$$

$$r_t = \frac{\sum_{t=1}^T (x_t - \bar{x})(y_t - \bar{y})}{\sqrt{\sum_{t=1}^T (x_t - \bar{x})^2 \sum_{t=1}^T (y_t - \bar{y})^2}} \quad (3)$$

where, in Equation (1) and (2), N is the total number of land grid points; x_i and y_i are the seasonal-mean values at grid point i from the model and observation, respectively; $\bar{x} = \frac{1}{N} \sum_{i=1}^N x_i$ and $\bar{y} = \frac{1}{N} \sum_{i=1}^N y_i$ denote the spatial mean values of the model and observation averaged over d02, respectively. In Equation (3), T is the total number of years; x_t and y_t are the seasonal-mean values for year t from the model and observation at each grid point of d02, respectively; $\bar{x} = \frac{1}{T} \sum_{t=1}^T x_t$ and $\bar{y} = \frac{1}{T} \sum_{t=1}^T y_t$ denote the temporal mean values of the model and observation averaged over the period of 1980–2019 at each grid point of d02, respectively.

Significant tests with a significance level of 0.05 are applied on seasonal means of temperatures and pr over the period—Student’s t -test for T_{max} and T_{min} and Mann–Whitney U test for pr as rainfall data is not normally distributed.

The PBLH is strongly influenced by topography, moisture, temperature, and winds. For different WRF PBL parameterisations, the definition of the PBLH differs. As described in Section 2.3, the R3-MYNN2 uses a TKE threshold, while R5-ACM2 mostly uses the bulk Richardson number. Consequently, it is not appropriate to directly compare the PBLH values from the WRF output. To investigate the sensitivity of seasonal-mean PBLHs to PBLH definition, we manually calculate the PBLH for the period of 2018–2020 for both RCMs using a common method based on virtual potential temperature (θ_v). PBLH is defined as the altitude where θ_v first exceeds the minimum value from surface by +1.5 K (e.g., Nielsen-Gammon et al. 2008; Hu et al. 2010). To distinguish the PBLH from different sources, the PBLHs that are determined using θ_v method are labelled as “reconstructed PBLHs” (R-PBLH), while the ones from WRF outputs are labelled as “diagnostic PBLHs” (D-PBLH). The comparisons will be shown in Section 3.3.

2.4.2 Metrics for Sub-daily Data

As the PBL is characterised by strong diurnal variations, some diagnostic analyses are carried out using sub-daily data. In Section 3.4, we calculate the diurnal PBLH range—defined as the difference between daily maximum and minimum PBLHs—to show the spatial distribution of single-day variations of the PBLH over the domain of interest.

Additionally, cross-section analysis is used to visualise vertical mixing and the horizontal transport of heat and moisture. In Section 3.5, seasonal-means of u or v , w , θ , q and horizontal moisture fluxes (qu or qv) are projected to ten cross-sections (Fig. 1b), which are selected along either the west-east or south-north axis. Each cross-section is centred on one of the sounding sites and extends 1° on either side, which is sufficient to capture the land–sea breeze circulation for those sounding sites located near the coast.

To analyse the surface heat budget, we break down the net surface heat flux (Q_{net}) into four components: net surface shortwave flux (Q_{sw}), net surface longwave flux (Q_{lw}), net surface sensible heat flux (Q_{sh}), and net surface latent heat flux (Q_{lh}). For all heat fluxes, positive values indicate downward fluxes. Q_{net} is then given by:

$$Q_{net} = Q_{sw} + Q_{lw} + Q_{sh} + Q_{lh} \quad (4)$$

3. Results

3.1 Evaluations of seasonal means

It is essential to assess the RCMs' skill in simulating temperature and precipitation as these variables provide important information on long-term climate variability and change. We first evaluate the simulated seasonal-averaged daily T_{max} and T_{min} and pr against observational AGCD data over land. ERA5 reanalysis data are also included in this evaluation to assess how the WRF simulations differ from the driving data and to evaluate the effects of dynamical downscaling.

In Fig. 2, the observed T_{max} shows clear seasonal and spatial variations, with temperatures exceeding 40°C across northwest inland regions during DJF (Fig. 2a-1), and below 10°C over the Australian Alps in the southeast of the domain during JJA (Fig. 2c-1). The ERA5 reanalysis shows significant cold biases in T_{max} , especially during DJF (Fig. 2a-2) and SON (Fig. 2d-2), with $MAEs$ greater than 3°C . Such large cold biases are largely reduced in R3-MYNN2 (Figs. 2a-3 and 2d-3) and R5-ACM2 (Figs. 2a-4 and 2d-4), indicating that overall, the RCMs show improved performances in simulating T_{max} . The comparisons between the biases of two RCMs (Figs. 2a-3, 2b-3, 2c-3, and 2d-3 versus Figs. 2a-4, 2b-4, 2c-4, and 2d-4) show that R3-MYNN2 has larger cold biases in T_{max} than R5-ACM2 in general. Therefore, it is expected to see warmer T_{max} in R5-ACM2 than R3-MYNN2, especially during DJF (Fig. 2a-5) and SON (Fig. 2d-5) across the whole domain.

Likewise, the observed seasonal T_{min} is characterised by pronounced spatiotemporal variations, with larger values ($> 25^\circ\text{C}$) over the northwestern inland regions during DJF (Fig. 3a-1) and the lowest values ($< 0^\circ\text{C}$) over the Australian Alps in JJA (Fig. 3c-1). ERA5 underestimates the DJF-mean T_{min} , with MAE exceeding 1°C (Fig. 3a-2), and slightly underestimates the SON-mean T_{min} (Fig. 3d-2), but exhibits a slight warm bias during the other two seasons with $MAEs$ exceeding 1°C (Figs. 3b-2 and 3c-2). Compared with ERA5, the RCMs demonstrate substantial improvements in simulating seasonal-mean T_{min} with largely reduced biases during DJF (Figs. 3a-3 and 3a-4 versus Fig. 3a-2), more marginal improvements during JJA (Figs. 3c-3 and 3c-4 versus Fig. 3c-2), but

show poorer performances during MAM (Figs. 3b-3 and 3b-4 versus Fig. 3b-2) and SON (Figs. 3d-3 and 3d-4 versus Fig. 3d-2). The two RCMs show similar spatial patterns of T_{min} biases in each season. During DJF (Fig. 3a-3 versus Fig. 3a-4) and SON (Fig. 3d-3 versus Fig. 3d-4), significant warm biases occur along the inland side of the Great Dividing Range, whereas significant cold biases are found in the central part of the domain. During MAM (Fig. 3b-3 versus Fig. 3b-4) and JJA (Fig. 3c-3 versus Fig. 3c-4), significant warm biases extend across the entire domain. Significant differences in T_{min} between R5-ACM2 and R3-MYNN2 are only evident over land during DJF (Fig. 3a-5) and SON (Fig. 3d-5), indicating that R5-ACM2 generally simulates warmer seasonal-means of T_{min} than R3-MYNN2 during these seasons.

Regarding the seasonal-mean pr , AGCD shows that the southeastern region is more prone to seasonal variation. In DJF and MAM, pr greater than $5 \text{ mm} \cdot \text{day}^{-1}$ is generally found along the eastern coast (Figs. 4a-1 and 4b-1), with values progressively decreasing further inland towards the northwest of the domain. For other seasons, pr greater than $5 \text{ mm} \cdot \text{day}^{-1}$ is found over the Australian Alps (Figs. 4c-1 and 4d-1). ERA5 reproduces the mean seasonal pr well, with almost no significant biases over land. Notable exceptions include some significant dry biases along the coast in DJF, MAM and JJA and wet biases over the southern region in SON (Figs. 4a-2 and 4b-2). The two RCMs perform differently in representing seasonal-mean pr . In DJF, R3-MYNN2 shows significant dry biases over central Queensland, whereas significant wet biases are evident along the east coast and over the southern regions of Victoria and South Australia (Fig. 4a-3). In contrast, R5-ACM2 shows an overall significant dry bias over land in DJF (Fig. 4a-4). For the other three seasons, R3-MYNN2 (Figs. 4b-3, 4c-3, and 4d-3) shows significant wet biases, especially over South Australia and western regions of Victoria, but these are largely reduced in R5-ACM2 (Figs. 4b-4, 4c-4, and 4d-4). The differences between RCMs indicate more intense seasonal-mean precipitation in R5-ACM2 than in R3-MYNN2 across most of the domain, particularly during DJF (Figs. 4a-5) or over South Australia, Victoria and southern and eastern New South Wales (Figs. 4b-5, 4c-5, and 4d-5). Overall, R5-ACM2 is more accurate than R3-MYNN2 in simulating mean pr for these seasons.

The spatial correlations between models and observations can quantify how well the patterns of simulated variables match observations. Table 3 lists the spatial correlation coefficients for T_{max} , T_{min} , and pr between ERA5/RCMs and the observations. It is evident that the r_s between RCMs and AGCD are very close to those between ERA5 and AGCD. In all cases, values of r_s range from 0.67 to 0.85 for T_{max} , 0.83 to 0.89 for T_{min} , and 0.96 to 0.98 for pr , suggesting strong spatial correlations between ERA5/RCMs and AGCD. This reflects that two RCMs can represent the spatial patterns of the seasonal means of temperature and precipitation as well as ERA5.

However, the temporal correlations between RCMs and AGCD show overall smaller values than those between ERA5 and AGCD across almost all seasons and variables, except for T_{min} and T_{max} in SON (Supplementary Figs. S1–S3). In particular, the absolute mean values of r_t averaged over the land for pr are only 0.11 between AGCD and R3-MYNN2 and 0.03 between AGCD and R5-ACM2, due to large areas with negative r_t along with positive r_t smaller than 0.4 (Figs. S3a-1 and S3a-2). This indicates that the RCMs have limited skills in capturing interannual variations in temperature and precipitation. The finding is consistent with previous studies (Teng et al. 2024).

In summary, compared with R3-MYNN2, R5-ACM2 substantially reduces cold biases in both T_{max} and T_{min} during the warm season, especially in DJF, and reduces wet biases in pr across all seasons, although there is a

significant dry bias occurs in DJF. Compared with the simulated seasonal-mean T_{max} and T_{min} , seasonal-mean pr simulated by both RCMs exhibit stronger spatial correlations but weaker temporal correlations with observation. Overall, R5-ACM2 simulates a warmer and drier seasonal climate over southeaster Australia than R3-MYNN2. The differences between the two RCMs are most pronounced during DJF, when the largest contrasts in T_{max} , T_{min} and pr occur.

Table 3 The spatial correlation coefficients (r_s) of T_{max} , T_{min} and pr between reanalysis/models and AGCD for each season.

	DJF			MAM			JJA			SON		
	T_{max}	T_{min}	pr	T_{max}	T_{min}	pr	T_{max}	T_{min}	pr	T_{max}	T_{min}	pr
ERA5	0.68	0.84	0.97	0.72	0.85	0.96	0.85	0.88	0.96	0.80	0.89	0.97
R3-MYNN2	0.67	0.84	0.96	0.70	0.85	0.97	0.82	0.83	0.97	0.78	0.86	0.98
R5-ACM2	0.67	0.83	0.96	0.70	0.85	0.97	0.82	0.83	0.96	0.77	0.86	0.98

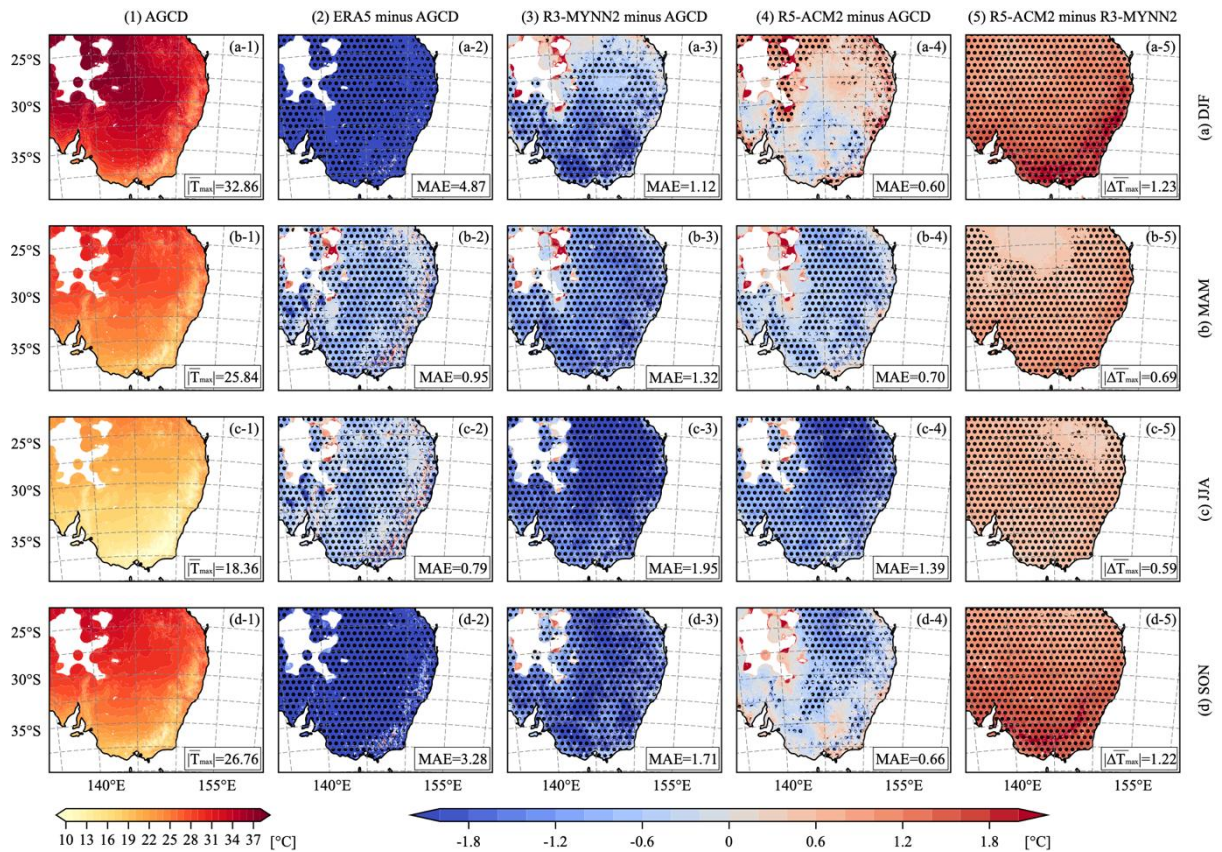


Fig. 2 Seasonal means of daily maximum near-surface temperature (T_{max}) for observational AGCD data and the model biases relative to AGCD. The panels from top to bottom show the four seasons: (a) DJF, (b) MAM, (c) JJA, and (d) SON, while the columns from left to right represent the seasonal means of T_{max} from (1) AGCD, (2) ERA5 minus AGCD, (3) R3-MYNN2 minus AGCD, (4) R5-ACM2 minus AGCD and (5) R5-ACM2 minus R3-MYNN2, respectively. All seasonal means are averaged over the common period of 1980–2019. The areas with statistically significant differences (p -values less than 0.05) are stippled in each panel. The blank area in the northwest is due to missing or poor-quality data in AGCD.

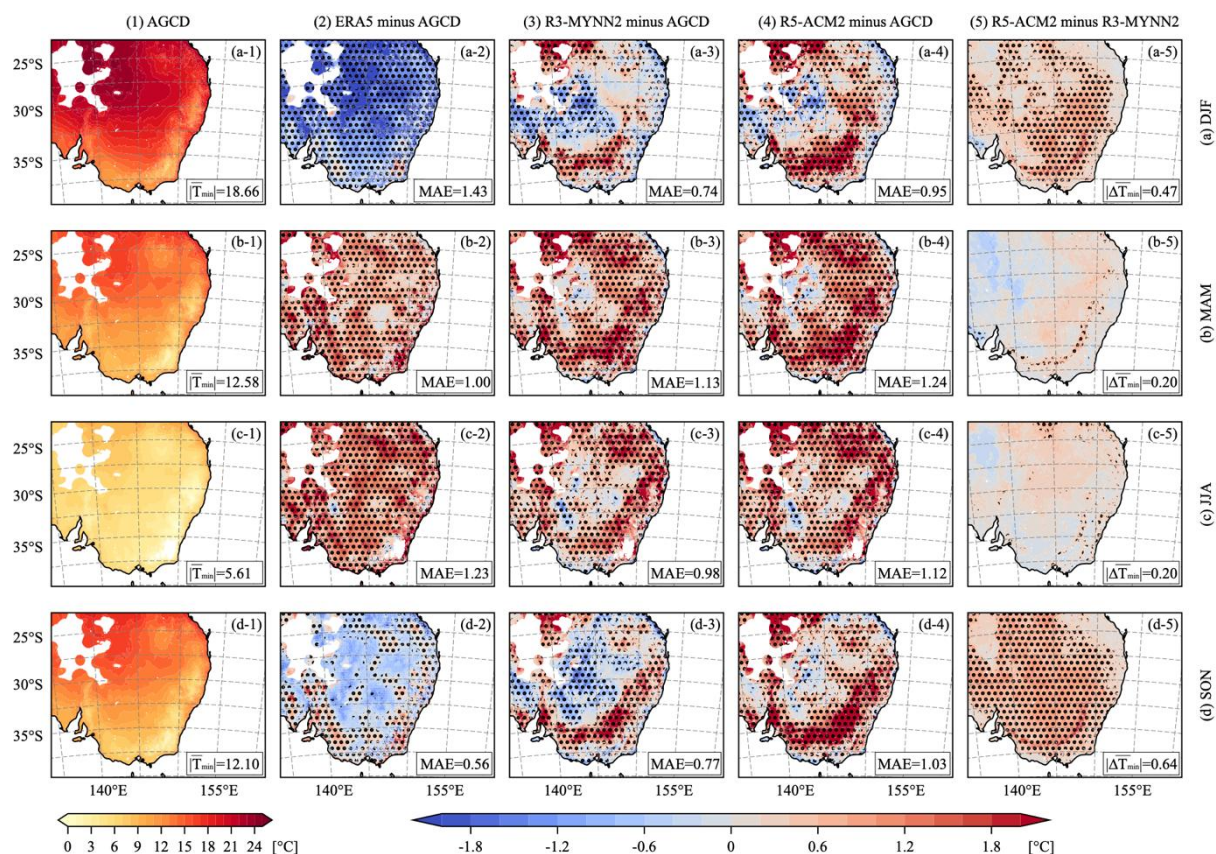


Fig. 3 Same as Fig. 2, but for seasonal T_{min} means.

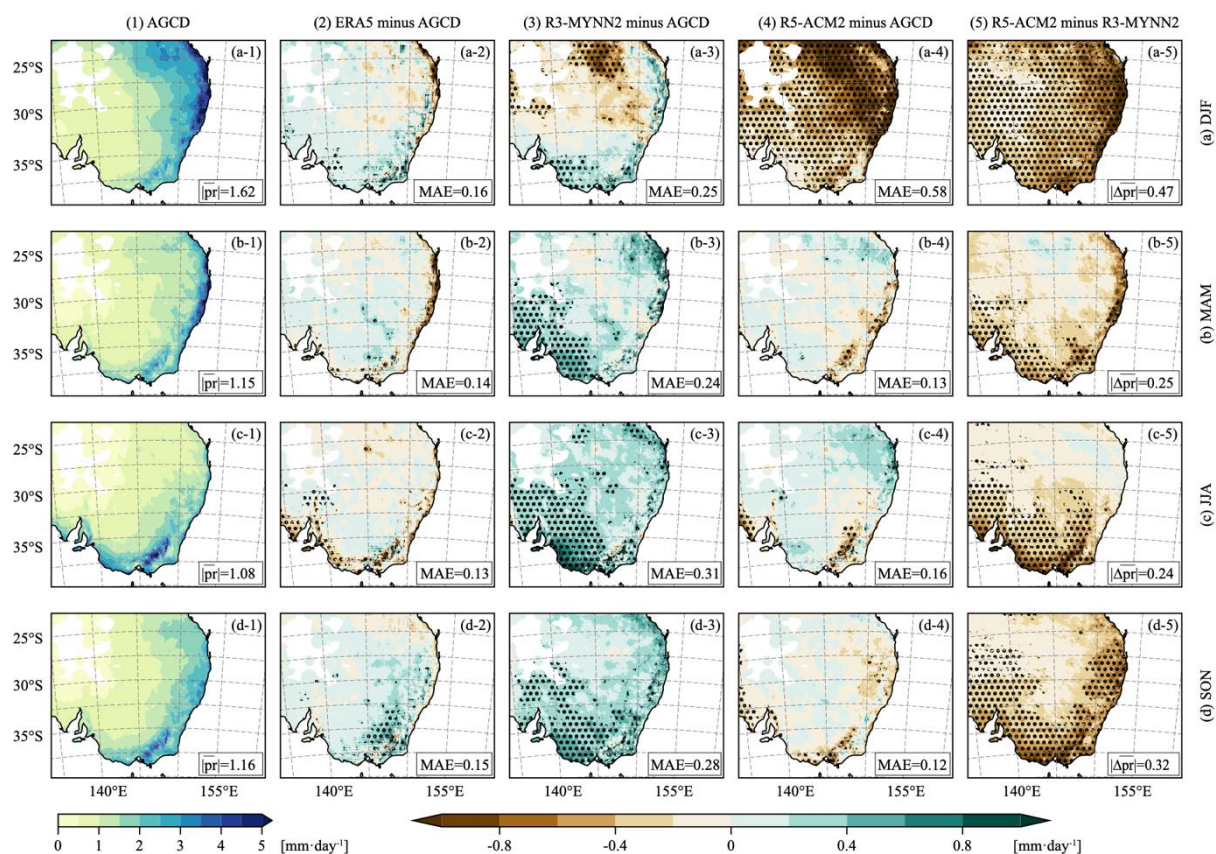


Fig. 4 Same as Fig. 2, but for seasonal pr means.

3.2 Evaluation of vertical profiles

The vertical profiles of temperature, specific humidity, and wind are important to the evolution of the PBL. Fig. 5 shows the DJF-mean vertical profiles of θ , q and $wspd$ averaged from the timesteps as described in Section 2.2. From Figs. 5a-1 to 5a-10, the observed surface θ varies among sounding sites owing to their geographic locations, ranging from 290 to 305K. R3-MYNN2 and R5-ACM2 simulate similar vertical profiles of θ —the θ from surface to ~ 1000 m AGL is overestimated for almost all sites except for Sydney where simulations underestimate θ throughout the atmospheric column during the daytime from 1300 to 1600 AEST. For those sites with two vertical profiles, both RCMs simulate weaker static stability during nighttime or early morning (i.e., smaller vertical θ gradients) than observed (dashed lines in Figs. 5a-1, 5a-3, 5a-8, and 5a-10). For all sites, R5-ACM2 simulates warmer θ at the surface but a slower increase in θ with height (i.e., weaker static stability) than R3-MYNN2 during daytime (solid lines in Fig. 5a). Above ~ 1000 – 1500 m, the θ in R5-ACM2 becomes slightly cooler than R3-MYNN2. The smaller vertical θ gradient in R5-ACM2 indicates a well-mixed boundary layer with stronger turbulent mixing.

The observed surface q shows strong geographic variations. Given that Brisbane (Fig. 5b-3), Williamstown (Fig. 5b-7) and Sydney (Fig. 5b-8) are located along the eastern coast in the vicinity of the Pacific Ocean, the observed surface q is greater than that of other sites. The other sites are either far inland or near to the Southern Ocean where cooler water restricts evaporation and lowers the maximum moisture capacity of the atmosphere, leading to a relatively lower surface q . The R3-MYNN2 and R5-ACM2 simulations are able to capture such geographic variations but they generally underestimate surface q by up to $1 \text{ g}\cdot\text{kg}^{-1}$. At lower heights (of approximately 1000-1500 m), the vertical q profiles simulated by R3-MYNN2 are generally closer to the observed q as compared to R5-ACM2. Overall, compared to R3-MYNN2, R5-ACM2 shows an overall drier vertical profile and a smaller q gradient. This suggests that the atmosphere is less vertically stratified in moisture for R5-ACM2.

Although simulated $wspd$ vertical profiles vary across the sites, both simulations show a general overestimation of $wspd$ throughout the atmospheric column for most sites (Fig. 5c). The simulations capture the signature of a nocturnal low-level jet for those sites with nighttime soundings (particularly Adelaide). Over Sydney, they also show enhanced low-level winds during the afternoon, presumably associated with the sea breeze. The vertical profiles for the other seasons are similar to those for DJF and are presented in Supplementary Figs. S4–S6.

In summary, the RCM simulations represent reasonable vertical profiles of temperature, humidity and wind speed in most cases. However, simulations generally overestimate θ and $wspd$, and underestimate q throughout the atmospheric column. In addition, R5-ACM2 shows a smaller positive vertical θ gradient and negative vertical q gradient, indicating a more well-mixed boundary layer, characterised by reduced static stability and weaker moisture stratification than R3-MYNN2.

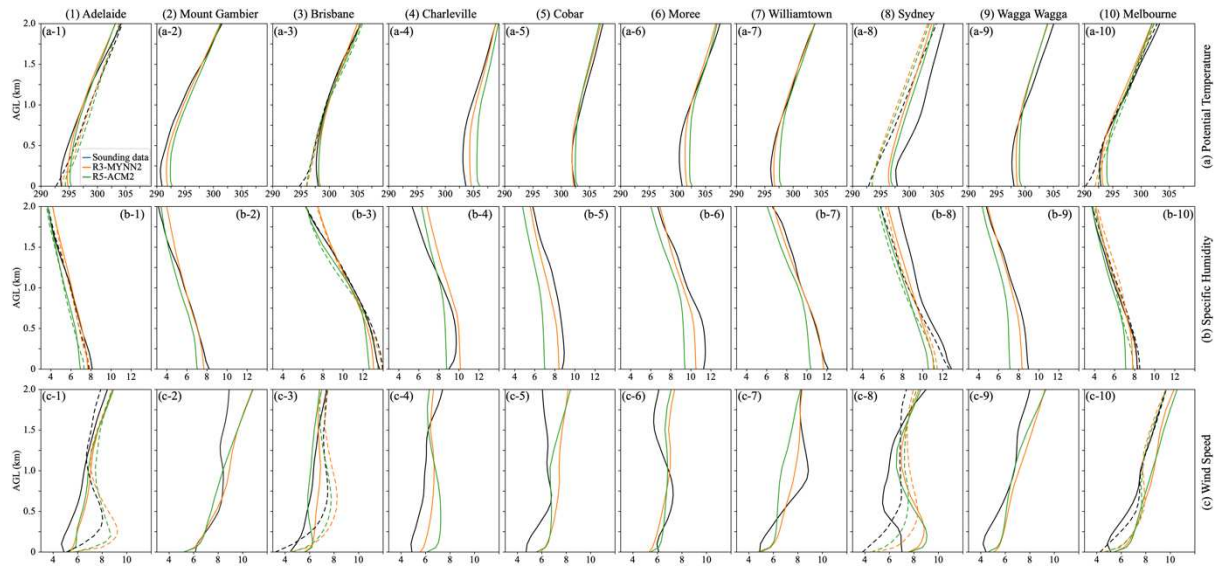


Fig. 5 DJF-mean profiles of (a) potential temperature (θ ; unit: K), (b) specific humidity (q ; unit: $\text{g}\cdot\text{kg}^{-1}$) and (c) wind speed ($wspd$; unit: $\text{m}\cdot\text{s}^{-1}$) for sounding sites of (1) Adelaide, (2) Mount Gambier, (3) Brisbane, (4) Charleville, (5) Cobar, (6) Moree, (7) Williamtown, (8) Sydney, (9) Wagga Wagga, and (10) Melbourne, respectively. All seasonal means are averaged over the common period of 2018–2020. For panels with only solid lines, all lines represent the averages from 0900 to 1000 AEST. For Sites (1) and (10), solid lines represent the averages from 0900 to 1000 AEST and dashed lines represent the averages from 2100 to 2200 AEST. For Site (3), solid lines represent the averages from 0900 to 1000 AEST and dashed lines represent the averages from 0300 to 0400 AEST. For Site (8), solid lines represent averages from 1300 to 1600 AEST and dashed lines represent the averages from 0400 to 0700 AEST.

3.3 Evaluation of PBLHs Estimated by Different Methods

To evaluate whether differences in PBLH definitions contribute to discrepancies in PBLH estimates, this section compares the seasonal-mean PBLH derived from different methods for both RCM simulations. The definitions of R-PBLH and D-PBLH are described in Section 2.4.1. Fig. S7 presents the seasonal-mean R-PBLH and D-PBLH for R3-MYNN2 and R5-ACM2, together with their differences. Overall, both simulations exhibit similar spatial distributions regardless of the PBLH definition, with relatively shallow PBLs over the coastal region and progressively deeper PBLs inland. For both R3-MYNN2 and R5-ACM2, R-PBLH is generally higher than D-PBLH over the ocean. Over land, however, the choice of PBLH definition produces contrasting effects between the two simulations. In R3-MYNN2, the θ_v method (R-PBLH) yields slightly lower PBLH than the TKE-based method (D-PBLH). In contrast, for R5-ACM2, the θ_v method produces substantially higher PBLHs than the bulk Richardson number method (D-PBLH).

Different PBLH definitions can produce substantial differences in PBLH estimates for the same RCM, which in turn affect the inferred differences between R3-MYNN2 and R5-ACM2. Fig. 6 compares the seasonal-mean PBLH differences (Δ denotes R5-ACM2 minus R3-MYNN2) using the same PBLH definition for both simulations. When PBLH is estimated using the θ_v method (R-PBLH), R5-ACM2 exhibits consistently higher PBLHs than R3-MYNN2 in all seasons, particularly over land (Figs. 6a-1, 6b-1, 6c-1, and 6d-1). In contrast, the model-diagnosed PBLH (D-PBLH) indicates that R5-ACM2 generally simulates shallower PBLs than R3-MYNN2 over most land areas, except along the Great Dividing Range and over most coastal land regions during DJF and SON (Figs. 6a-2 and 6d-2).

These contrasting results raise an important question: which PBLH differences are physically relevant to the simulated differences in other climate variables, such as the warmer and drier conditions simulated by R5-ACM2? In WRF, the model-diagnosed PBLH is not merely an output variable but is also used internally by other model components, including the cloud and land-surface schemes, thereby influencing the simulation of surface fluxes, clouds, and other atmospheric processes. Therefore, D-PBLH is used in the following analyses to interpret differences in PBL structure and their impacts on other simulated climate variables between R3-MYNN2 and R5-ACM2. For simplicity, hereafter the term PBLH refers to D-PBLH, unless otherwise stated.

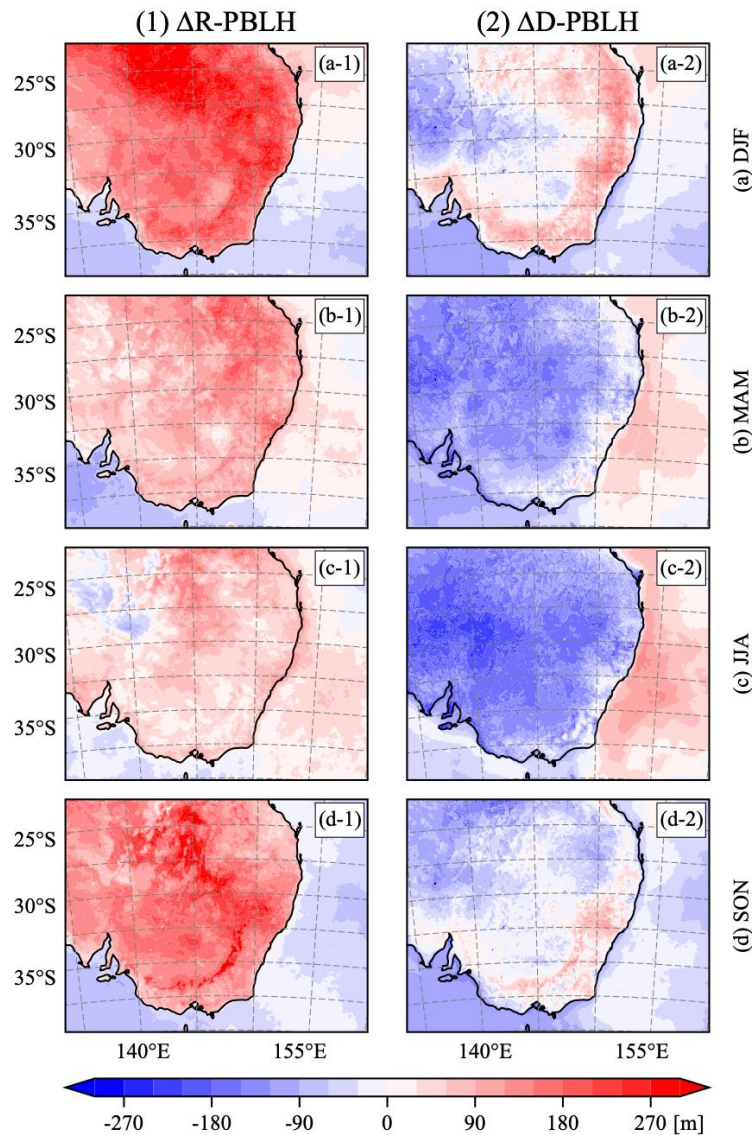


Fig. 6 The seasonal means of (1) ΔR -PBLH and (2) ΔD -PBLH for seasons of (a) DJF, (b) MAM, (c) JJA, and (d) SON. The Δ denotes R5-ACM2 minus R3-MYNN2. The R-PBLH (reconstructed PBLH) is calculated using the same method for both R3-MYNN2 and R5-ACM2, while D-PBLH (diagnosed PBLH) refers to the WRF-diagnosed PBLH, which uses different methods for R3-MYNN2 and R5-ACM2.

3.4 DJF-Mean Variables Related to PBL Processes

Based on the results presented in Section 3.1, the differences between R5-ACM2 and R3-MYNN2 are most pronounced for T_{max} , T_{min} and pr during DJF. Therefore, the following sections focus on DJF to investigate the physical mechanisms responsible for these differences in greater detail.

Fig. 7a-1 shows the DJF-mean PBLH from ERA5. The PBL is generally deeper over inland regions, where stronger surface heating (Fig. 7b-1) promotes more vigorous thermal convection and turbulent mixing. The deeper PBL facilitates greater downward transport of momentum from aloft, resulting in stronger near-surface winds (Fig. 7c-1). In contrast, shallower PBLs are found along the coast, consistent with lower surface temperatures and weaker near-surface winds associated with the moderating influence of the ocean. Both R3-MYNN2 and R5-ACM2 simulate deeper mean PBLs over land than ERA5, particularly across inland regions (Figs. 7a-2 and 7a-3). However, these deeper PBLs are not always accompanied by correspondingly higher near-surface temperatures. For example, the DJF-mean T_{2m} simulated by R3-MYNN2 is generally lower than that in ERA5 except over Queensland (Fig. 7b-2). This apparent inconsistency is likely attributable, at least in part, to differences in how PBLH is diagnosed. In ERA5, the PBLH is defined as the lowest level at which the bulk Richardson number reaches the critical value of 0.25, whereas the RCM simulations diagnose PBLH using methods specific to their respective PBL parameterisations. In R3-MYNN2, the PBLH is determined using a TKE threshold, which represents the depth of the turbulent layer rather than a thermodynamic boundary. Consequently, a deeper TKE-defined PBLH does not necessarily imply higher near-surface air temperatures. By contrast, the PBLH diagnosed by R5-ACM2 is based on the Richardson number, making it more comparable to the method used in ERA5. As a result, the relationship between PBLH and near-surface temperature is more consistent between R5-ACM2 and ERA5, with the deeper PBLs in R5-ACM2 generally corresponding to warmer T_{2m} (Fig. 7b-3).

Compared with R3-MYNN2, R5-ACM2 simulates deeper PBLs along the coast but shallower PBLs over most inland areas (Fig. 7a-4). Despite the generally shallower inland PBL, R5-ACM2 exhibits consistently warmer mean near-surface temperatures than R3-MYNN2, with differences exceeding 1.5 °C in some regions (Fig. 7b-4). In contrast, differences in near-surface wind speed are small over most land areas. Localised increases are evident over southeastern Queensland, where a stronger sea-breeze circulation enhances onshore winds (Fig. 7c-4). Over the adjacent coastal waters, R5-ACM2 also simulates stronger north-easterly near-surface winds, with wind speed differences exceeding 0.2 m·s⁻¹ (Fig. 7c-4).

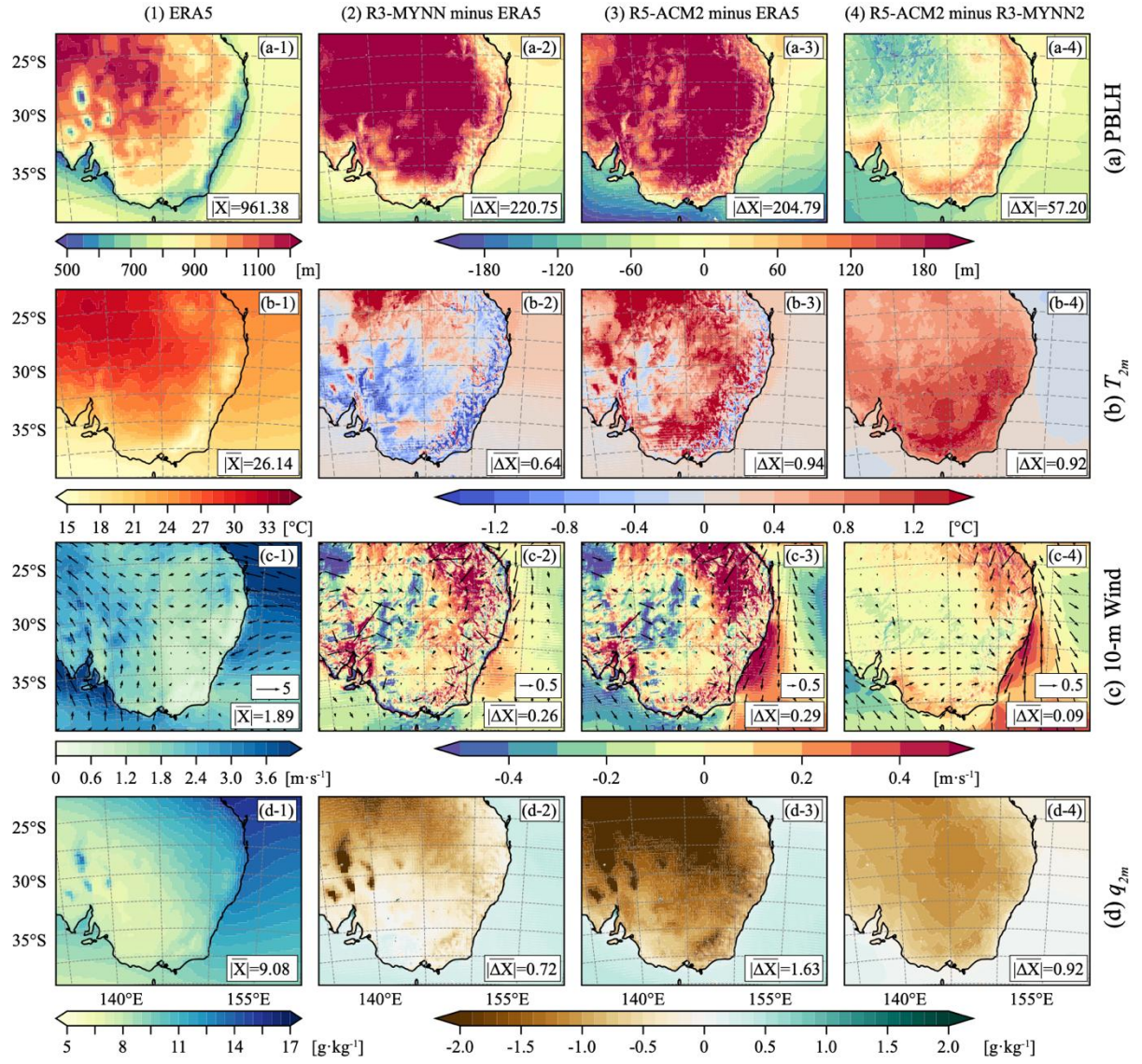


Fig. 7 DJF means of several variables averaged over the period of 1980–2020. The rows from top to bottom show (a) planetary boundary layer height (PBLH), (b) air temperature at 2-metre (T_{2m}), (c) surface wind at 10 m (10-m Wind), and (d) specific humidity at 2-metre (q_{2m}), and the columns from left to right represent (1) ERA5, (2) R3-MYNN2 minus ERA5, (3) R5-ACM2 minus ERA5, and (4) R5-ACM2 minus R3-MYNN2, respectively. The absolute mean over land is shown in the bottom right of each panel.

In addition to temperature and wind, near-surface humidity is an important factor in explaining the precipitation differences between R3-MYNN2 and R5-ACM2. Fig. 7d-1 shows that the seasonal-mean q_{2m} in ERA5 is highest over the northeastern part of the domain and gradually decreases towards the southwest with the lowest values are over the arid inland parts of South Australia and New South Wales. Compared with ERA5, R3-MYNN2 exhibits only slightly lower q_{2m} over the northwestern region (Fig. 7d-2), whereas R5-ACM2 simulates a widespread dry bias over land (Fig. 7d-3). Consequently, R5-ACM2 produces lower q_{2m} than R3-MYNN2 across most land areas, with a domain-mean difference of 0.92 $g \cdot kg^{-1}$ (Fig. 7d-4).

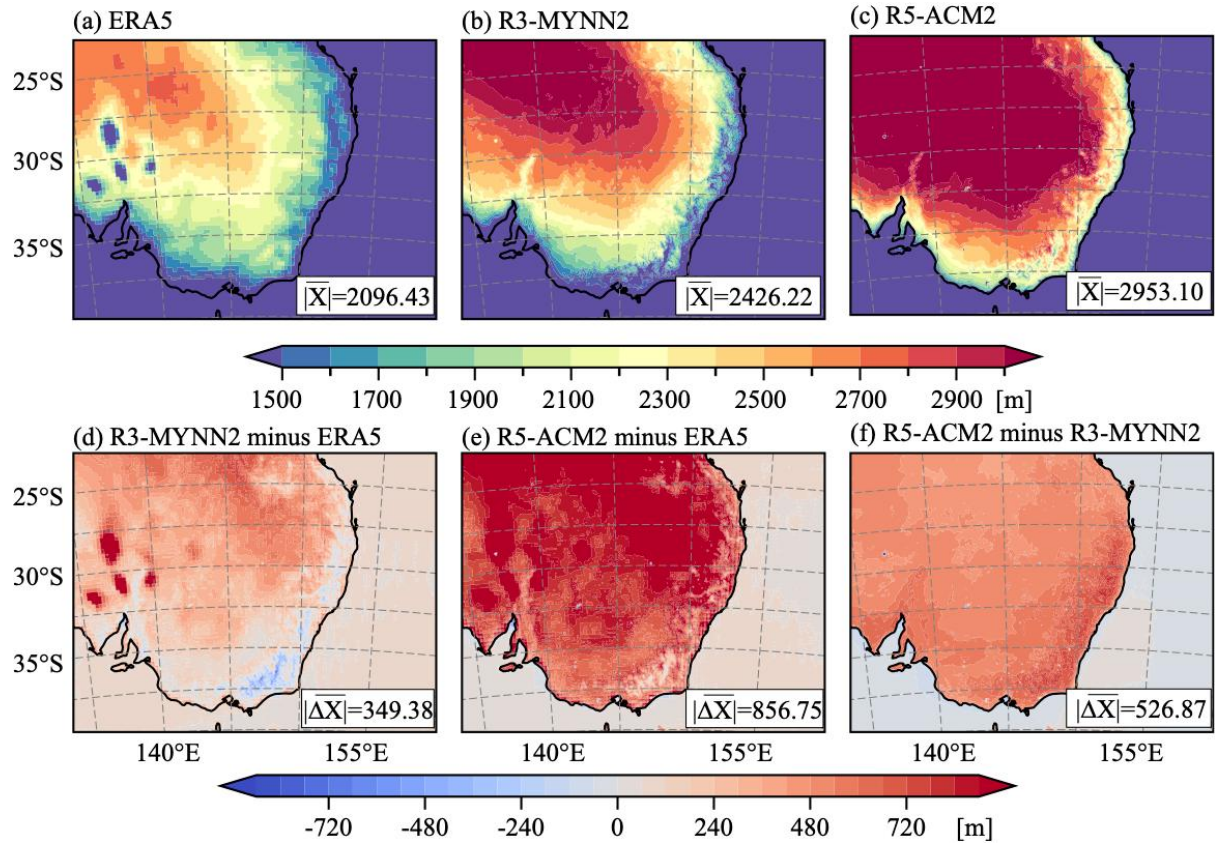


Fig. 8 The DJF-averaged diurnal ranges of D-PBLH for (a) ERA5, (b) R3-MYNN2, (c) R5-ACM2, (d) R3-MYNN2 minus ERA5, (e) R5-ACM2 minus ERA5, and (f) R5-ACM2 minus R3-MYNN2. The absolute mean over land is shown in the bottom right of each panel.

Because the seasonal-mean PBLH is strongly influenced by its diurnal evolution, we further examine the DJF-mean diurnal range of PBLH (Fig. 8). ERA5 and both RCM simulations reproduce similar spatial patterns, with smaller diurnal variations in PBLH along the coast that gradually increase inland (Figs. 8a–8c). These patterns are consistent with the spatial distribution of the DJF-mean PBLH in ERA5 (Fig. 7a-1). Relative to ERA5, both R3-MYNN2 and R5-ACM2 simulate enhanced diurnal variations in PBLH across most of the domain, although the magnitude of the increase differs between the two simulations (Figs. 8d and 8e). Overall, R5-ACM2 exhibits substantially stronger diurnal variations than R3-MYNN2, with the mean difference exceeding 500 m (Fig. 8f). The largest differences are distributed along the Great Dividing Range, which runs parallel to the eastern coastline (Fig. 8f), coinciding with the region where R5-ACM2 also simulates a deeper DJF-mean PBL (Fig. 7a-4).

In summary, R5-ACM2 simulates a warmer and drier DJF climatology than R3-MYNN2. Compared with R3-MYNN2, R5-ACM2 produces deeper mean PBLs along the coastal region but shallower PBLs over inland areas, broadly consistent with the spatial pattern of near-surface temperature differences. Despite the shallower inland mean PBLs, R5-ACM2 exhibits a larger diurnal PBLH range, indicating stronger daytime boundary-layer growth followed by greater nocturnal collapse. This enhanced diurnal cycle may contribute to the reduced seasonal-mean PBLH over inland regions. The widespread reduction in near-surface humidity and increase in near-surface temperature simulated by R5-ACM2 suggest that changes in boundary-layer processes play an important role in shaping the simulated climate differences. Potential mechanisms include differences in

horizontal moisture transport, which affect the advection of moisture from the ocean, and vertical turbulent mixing, which influence the redistribution of heat and moisture within the boundary layer and exchanges with the free atmosphere.

3.5 DJF-Mean Diurnal Evolution of Cross-Sectional Fields

To understand the horizontal transport and vertical mixing of heat and moisture, we examine selected snapshots of the sub-daily vertical distributions of q and θ along ten cross-sections (Fig. 1b). Fig. 9 presents the pressure–longitude cross-section of qu and zonal wind circulation across Sydney, spanning the mountain range, coastal plain, and adjacent ocean. As the sign of qu follows that of the u , negative values represent onshore moisture flux, whereas positive values indicate offshore moisture flux.

ERA5 captures a pronounced land–sea breeze circulation, with weak onshore moisture flux developing during the early morning (Fig. 9a-1) and strengthening to a maximum in the evening (Fig. 9a-3). Compared with ERA5, both R3-MYNN2 (Figs. 9b-1–9b-4) and R5-ACM2 (Figs. 9c-1–9c-4) simulate a stronger diurnal circulation, characterised by enhanced offshore moisture transport near 700 hPa and stronger onshore moisture transport within the near-surface layer. The differences between R5-ACM2 and R3-MYNN2 reveal stronger offshore zonal winds and moisture flux at 0100 AEST (Fig. 9d-1) and 0700 AEST (Fig. 9d-2). During the afternoon, the prevailing offshore flow aloft persists, while a shallow local circulation develops over the coastal land area (Figs. 9d-2 and 9d-3). Although this circulation enhances the onshore moisture transport near the surface, the imported moisture is rapidly transported upward by stronger vertical mixing, reducing its retention within the near-surface layer. Consequently, compared with R3-MYNN2, R5-ACM2 exhibits stronger near-surface onshore moisture transport but also enhanced offshore moisture transport aloft, resulting in a drier near-surface atmosphere.

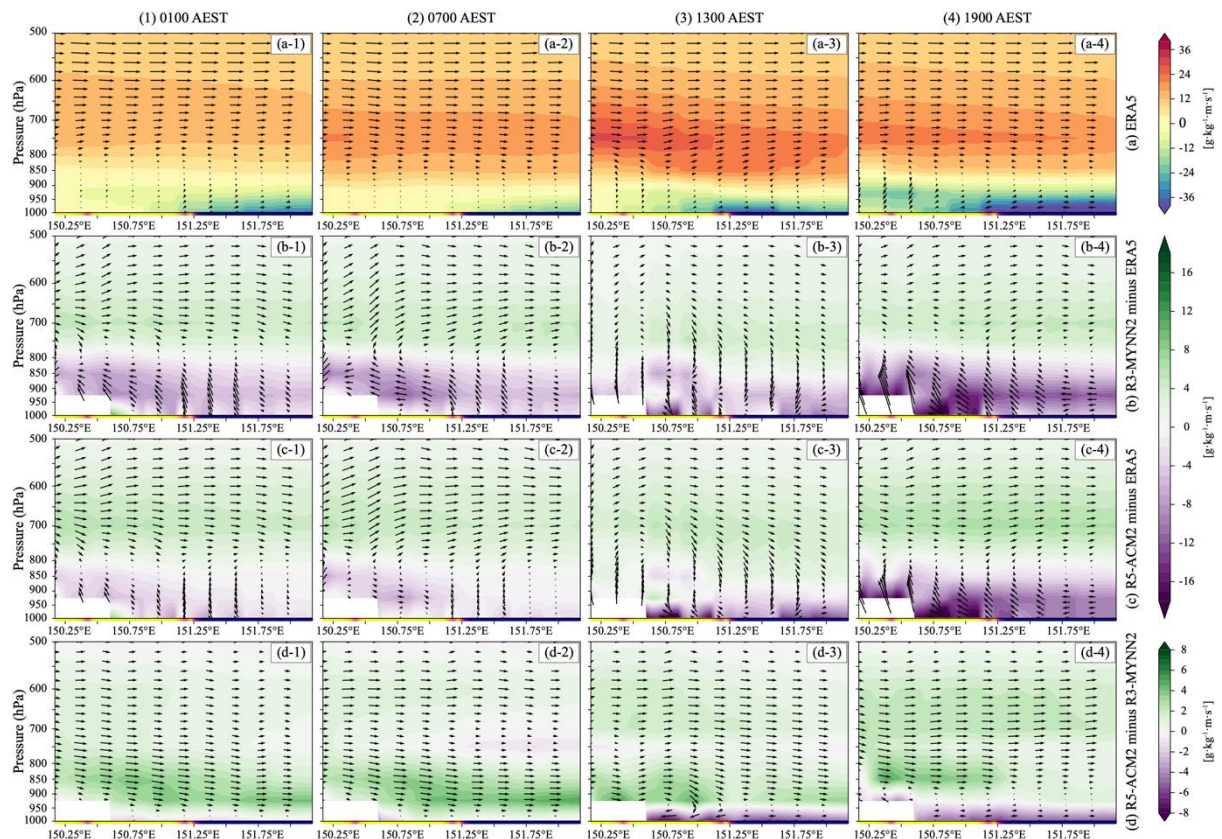


Fig. 9 DJF-averaged vertical profiles of zonal moisture flux (calculated using the formula of qu ; shading) and wind circulation (derived from u and w , with w multiplied by a factor of 10 for visualisation; vector) along the cross-section passing Sydney shown in **Fig. 1b**. The rows from top to bottom show (a) ERA5, (b) R3-MYNN2 minus ERA5, (c) R5-ACM2 minus ERA5, and (d) R5-ACM2 minus R3-MYNN2, and the columns from left to right represent the times of (1) 0100, (2) 0700, (3) 1300, and (4) 1900 Australian Eastern Standard Time (AEST), respectively. The pressure levels below the surface are masked in the RCM simulations but extrapolated in ERA5, and the white space in the panels represents the location of the Great Dividing Range. The land fraction along the cross-section is indicated at bottom of each panel with yellow=1 (i.e., 100% of land), blue=0 (i.e., 100% of ocean) and other colours representing fractions between 0 and 1.

Fig. 9 illustrates the horizontal moisture transport and air vertical mixing along the selected cross-section, while Fig. 10 shows the corresponding vertical distributions of q and θ throughout the diurnal cycle. In ERA5, evaporation from the ocean during the late night and early morning (Figs. 10a-1 and 10a-2) increases moisture within the marine boundary layer. As the sea breeze develops, the moist air is advected inland and lifted over the coastal mountains during the afternoon (Fig. 10a-3), before gradually weakening in the early evening (Fig. 10a-4). This diurnal evolution is consistent with the moisture transport shown in Figs. 9a-1–9a-4.

Compared with ERA5, R3-MYNN2 simulates reduced moisture in the PBL and increased moisture in the free atmosphere (particularly around 700 hPa) throughout the diurnal cycle (Figs. 10b-1–10b-4), indicating stronger vertical redistribution of moisture within the boundary layer. A similar but more pronounced pattern is evident in R5-ACM2, which exhibits substantially lower moisture in the lower atmosphere, centred near 850 hPa over the ocean and within the near-surface layer over land, together with enhanced moisture around 700 hPa (Figs. 10c-1–10c-4).

The differences between R5-ACM2 and R3-MYNN2 further show that R5-ACM2 simulates lower moisture content near the surface over land and around 850 hPa over the ocean. These drier conditions become more pronounced during the afternoon, accompanied by a slight increase in moisture near 700 hPa. This vertical redistribution of moisture is consistent with the enhanced vertical mixing and stronger offshore transport aloft shown in Figs. 9d-1–9d-4, which reduce moisture retention within the near-surface layer.

The differences identified along the Sydney cross-section are also evident in the other cross-sections (Supplementary Figs. S8–S11). For cross-sections adjacent to the ocean, moisture advected inland by the onshore flow is transported more rapidly upward during the daytime in R5-ACM2 owing to enhanced vertical turbulent mixing. In addition, offshore moisture transport during the nighttime and early morning is stronger in R5-ACM2 than in R3-MYNN2. Across all cross-sections, R5-ACM2 exhibits a drier lower free troposphere (approximately 800–850 hPa) during the nighttime and early morning. During the daytime, the boundary layer and near-surface atmosphere become progressively drier, accompanied by stronger wind circulations. These results suggest that, in R5-ACM2, enhanced entrainment of dry free-tropospheric air into the growing boundary layer, together with more vigorous turbulent mixing that transports moisture upward from the near-surface layer, contributes to the daytime drying of the boundary layer.

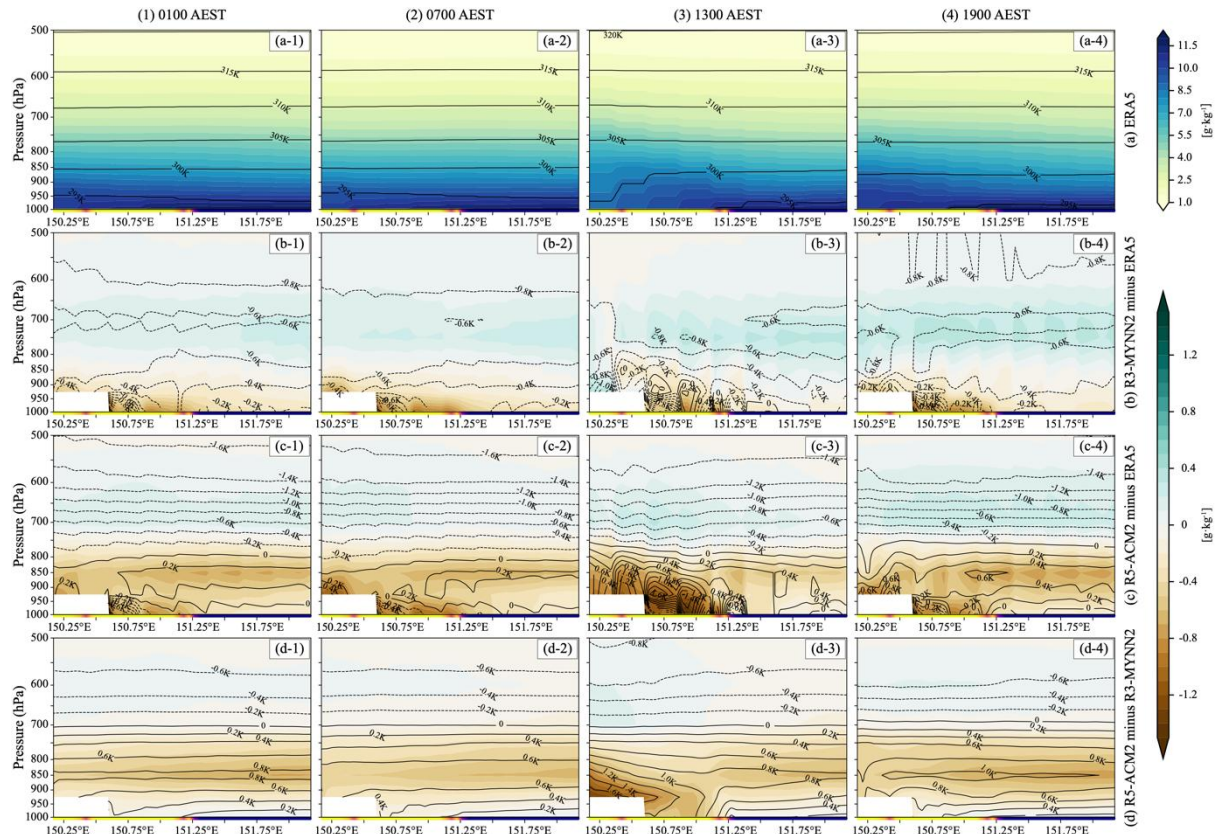


Fig. 10 Same as Fig. 9, but for the DJF-averaged vertical profiles of q (shading) and θ (contours) along the cross-section passing Sydney.

3.6 DJF-Mean Diurnal Evolution of Surface Energy Balance and PBL Processes

Because the PBL exhibits a pronounced diurnal cycle, developing rapidly during the daytime and decaying after sunset, we investigate the diurnal variations of PBL-related variables to understand how they contribute to differences in the mean climate. As shown in Fig. 4a-5, significant differences in the DJF-mean pr between the two RCMs are evident over land. To investigate the factors contributing to these differences, we identify clusters of grid points where the absolute difference in DJF-mean pr exceeds $1 \text{ mm} \cdot \text{day}^{-1}$ (based on Fig. 4a-5). These selected grid points also show significant differences in the DJF-mean T_{max} (Fig. 2a-5), which can be largely explained by differences in the diurnal evolution of net surface heat fluxes (Q_{net}).

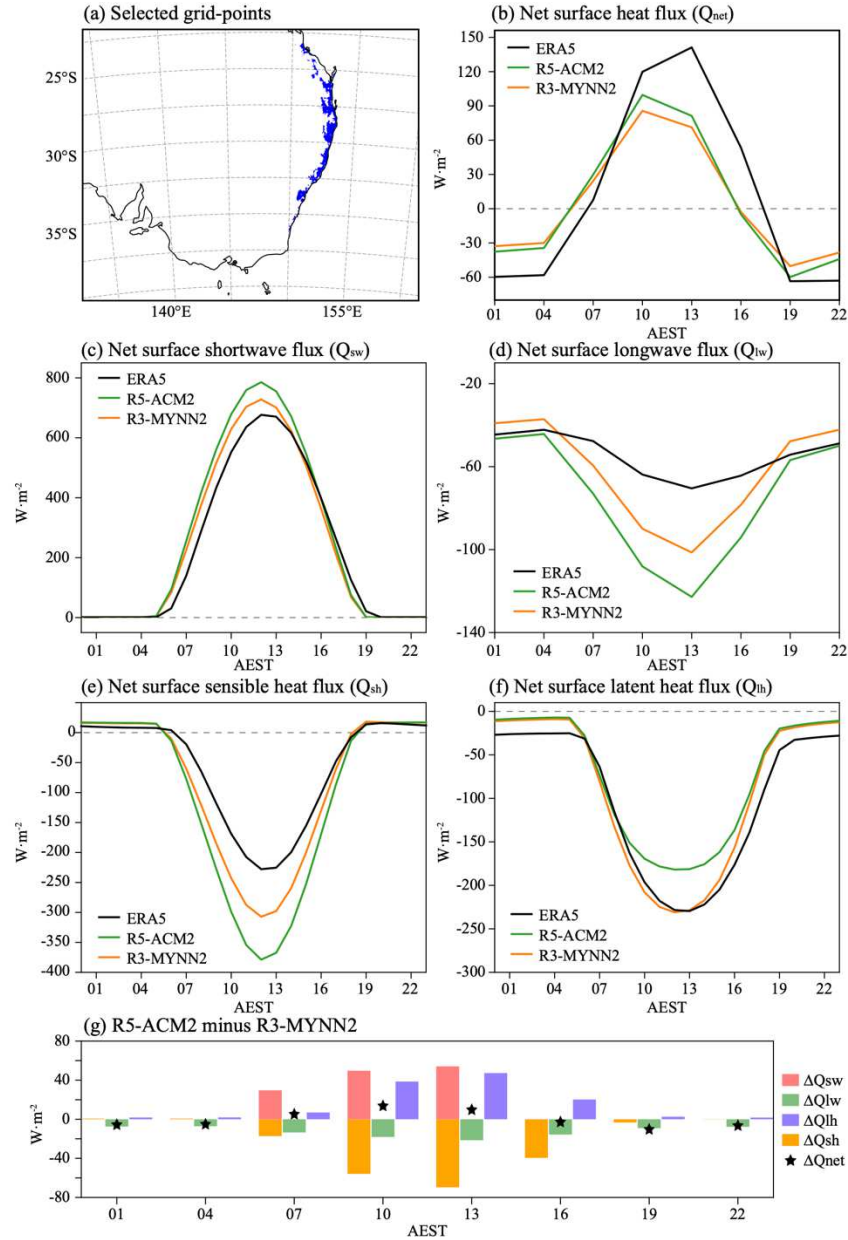


Fig. 11 DJF-averaged diurnal cycles of (b) net surface heat fluxes (Q_{net}), (c) net surface shortwave flux (Q_{sw}), (d) net surface longwave flux (Q_{lw}), (e) net surface sensible heat flux (Q_{sh}) and (f) net surface latent heat flux (Q_{lh}) averaged over the selected grid points shown in (a). In (b)–(f), ERA5, R3-MYNN2 and R5-ACM2 are presented in black, orange and green lines, respectively. All heat fluxes are positive downward. In (g), Δ denotes R5-ACM2 minus R3-MYNN2.

Fig. 11 shows the DJF-mean diurnal cycles of Q_{net} and its components averaged over all selected grid points (locations shown in Fig. 11a). ERA5 shows that Q_{net} reaches its maximum ($\sim 140 \text{ W m}^{-2}$) at 1300 AEST (Fig. 11b). In contrast, R3-MYNN2 and R5-ACM2 simulate diurnal cycles of Q_{net} with a peak occurring at 1000 AEST, which is ~ 3 hours earlier than ERA5. Additionally, the daily maximum Q_{net} from R5-ACM2 is higher than R3-MYNN2 by $\sim 20 \text{ W m}^{-2}$, suggesting more net energy gained in R5-ACM2 during the day, which consequently leads to a higher surface temperature. Among all surface heat flux components, Q_{sw} is the primary contributor to Q_{net} . Both RCMs and ERA5 reach their maximum Q_{sw} at 1200 AEST, with R5-ACM2 showing the largest peak, followed by R3-MYNN2 and ERA5 (Fig. 11c). The surface emits Q_{lw} throughout the day, with the maximum emission occurring at ~ 1300 AEST. ERA5 shows lower Q_{lw} emission, followed by R3-MYNN2 and R5-ACM2

(Fig. 11d). Although R5-ACM2 emits approximately $20 \text{ W}\cdot\text{m}^{-2}$ more Q_{lw} than R3-MYNN2, it still receives a larger net radiative flux ($Q_{sw} + Q_{lw}$) at the surface. Q_{sh} in ERA5 and the RCM simulations peak at 1200 AEST, coinciding with the maximum Q_{net} . Among ERA5 and the RCMs, R5-ACM2 simulates the highest Q_{sh} but the lowest Q_{lh} (Fig. 11e), whereas R3-MYNN2 shows the opposite behaviour, producing the lowest Q_{sh} and the highest Q_{lh} (Fig. 11f).

Fig. 11g quantifies differences between R5-ACM2 and R3-MYNN2 (R5-ACM2 minus R3-MYNN2, denoted as Δ) for all surface energy fluxes. ΔQ_{net} becomes positive at 0700 AEST, reaches a maximum of approximately $20 \text{ W}\cdot\text{m}^{-2}$ at 1000 AEST, and then gradually decreases during the afternoon. At 0700 AEST, ΔQ_{sw} is the primary contributor to the positive ΔQ_{net} . As the day progresses, the contributions of ΔQ_{sh} and ΔQ_{lh} become increasingly important in the surface energy balance. Throughout the daytime, ΔQ_{sh} remains negative and ΔQ_{lh} remains positive, indicating enhanced sensible heat loss and reduced latent heat loss in R5-ACM2. This behaviour is consistent with the hotter and drier near-surface conditions simulated by R5-ACM2. The higher surface temperature enhances the sensible heat flux through a larger surface–air temperature gradient, while the reduced surface moisture limits evapotranspiration, thereby suppressing the latent heat flux.

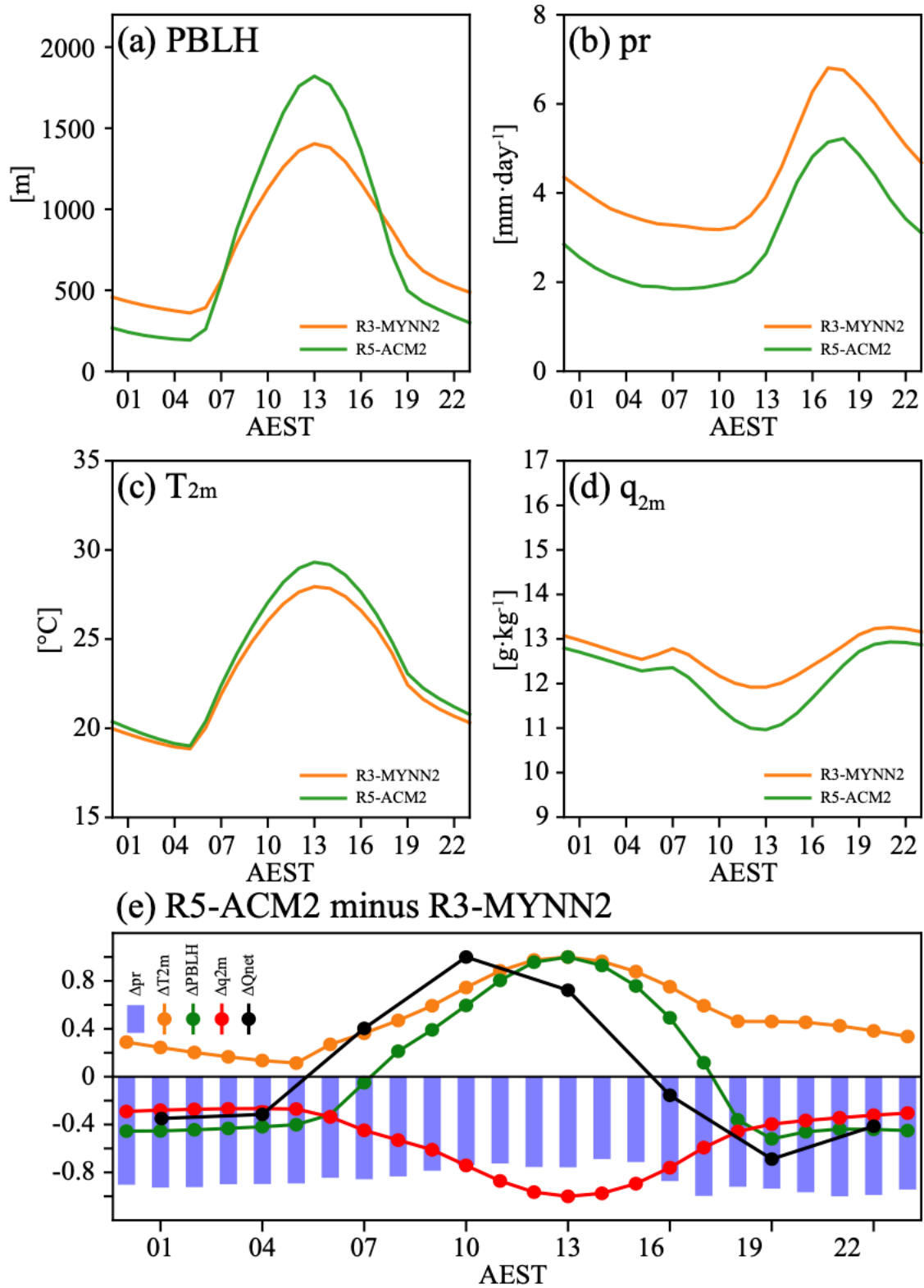


Fig. 12 The DJF-mean diurnal cycles for (a) PBLH, (b) pr , (c) T_{2m} and (d) q_{2m} for R3-MYNN2 and R5-ACM2. (e) shows the normalised DJF-mean diurnal cycles of Δpr , ΔT_{2m} , $\Delta PBLH$, Δq_{2m} and ΔQ_{net} . The Δ denotes R5-ACM2 minus R3-MYNN2. All diurnal cycles are the DJF means for the period of 1980–2020 averaged from selected grid points shown in Fig. 11a.

Beyond the surface energy fluxes, Fig. 12 presents the diurnal cycles of four additional variables that help explain the mechanisms responsible for hotter and drier DJF-mean conditions simulated by R5-ACM2. Fig. 12a

shows that both RCM simulations reach their maximum PBLH at 1300 AEST. However, R5-ACM2 exhibits a larger diurnal variation in PBLH over the selected area, with an amplitude of approximately 1500 m between the nighttime minimum and daytime maximum, compared with about 1000 m in R3-MYNN2. The simulated pr peaks at 1700 AEST in R3-MYNN2, whereas the peak in R5-ACM2 occurs one hour later, at 1800 AEST. Nevertheless, R3-MYNN2 consistently simulates higher pr than R5-ACM2 throughout the diurnal cycle. Both RCM simulations reach their highest T_{2m} (Fig. 12c) and lowest q_{2m} (Fig. 12d) at 1300 AEST. Throughout the diurnal cycle, R5-ACM2 consistently simulates higher T_{2m} and lower q_{2m} than R3-MYNN2, though differences are largest at 1300 AEST.

Fig. 12e shows normalised differences in the four variables together with the normalised ΔQ_{net} to examine their lead-lag relationships. To facilitate comparison of their temporal evolution, all variables were normalised to the range of 0–1 using Max Scaling (i.e., $x_{norm} = \frac{x}{|x_{max}|}$). Consistent with the previous results, ΔT_{2m} remains positive throughout the day, whereas Δpr and Δq_{2m} remain negative, reflecting the persistently hotter and drier surface conditions simulated by R5-ACM2. In contrast, $\Delta PBLH$ and ΔQ_{net} exhibit pronounced diurnal variations, with negative values during the nighttime and positive values during the daytime. The maximum ΔQ_{net} occurs at 1000 AEST, approximately three hours before the maximum $\Delta PBLH$ and ΔT_{2m} and the minimum Δq_{2m} . The minimum Δpr occurs at 1700 AEST, approximately four hours after the peaks in $\Delta PBLH$ and ΔT_{2m} and the minimum Δq_{2m} . This temporal sequence suggests that the enhanced net surface heating precedes surface warming and the deepening of the PBL, while the reduction in surface moisture occurs almost simultaneously with the PBL deepening. These changes are subsequently followed by changes in precipitation.

We next investigate the diurnal evolution of the vertical profiles of q and θ (Fig. 13) to explore the differences in vertical mixing over the selected area. Both RCM simulations exhibit similar diurnal variations in the vertical profiles of q and θ (Figs. 13a and 13b). Near-surface q gradually decreases from around 0700 AEST, reaching a minimum at approximately 1300 AEST. Meanwhile, q increases in the overlying atmosphere, indicating that vertical mixing transports moisture upward from the surface into the boundary layer and the lower free troposphere. This mixing process persists for approximately 3 hours, reaching up to around 700 hPa by 1600 AEST. Thereafter, the intensity of vertical mixing gradually weakens, and the atmosphere becomes increasingly stratified during the nighttime. The vertical profile of θ shows a progressively weaker vertical gradient from around 1000 AEST, reaching a minimum at approximately 1300 AEST. This reduction in the θ gradient indicates the development of a well-mixed and convectively unstable boundary layer, consistent with enhanced daytime turbulent mixing.

The difference in the vertical profiles of q and θ between R5-ACM2 and R3-MYNN2 exhibits distinct patterns during nighttime (1900–0700 AEST) and daytime (0700–1900 AEST). During the nighttime, Δq is most negative between approximately 800 and 850 hPa, coinciding with positive $\Delta \theta$, indicating that the free atmosphere in R5-ACM2 is drier and warmer than in R3-MYNN2. The stable nocturnal boundary layer suppresses turbulent mixing, allowing moisture to accumulate close to the surface. The relatively small Δq near the surface at nighttime indicates that this accumulated moisture is comparable between the two RCM simulations. After sunrise, increased surface heating initiates convective turbulence and promotes the rapid development of the PBL. During this period, the largest negative Δq shifts downward to the surface–900 hPa layer, accompanied by positive $\Delta \theta$ near the surface. These changes indicate that enhanced turbulent mixing in R5-ACM2 transports more moisture upward while entraining warm, dry air from the free atmosphere into the growing PBL. Consequently, the near-surface

atmosphere becomes warmer and drier than in R3-MYNN2. The stronger vertical redistribution of heat and moisture suggests that R5-ACM2 simulates more vigorous daytime boundary-layer mixing than R3-MYNN2.

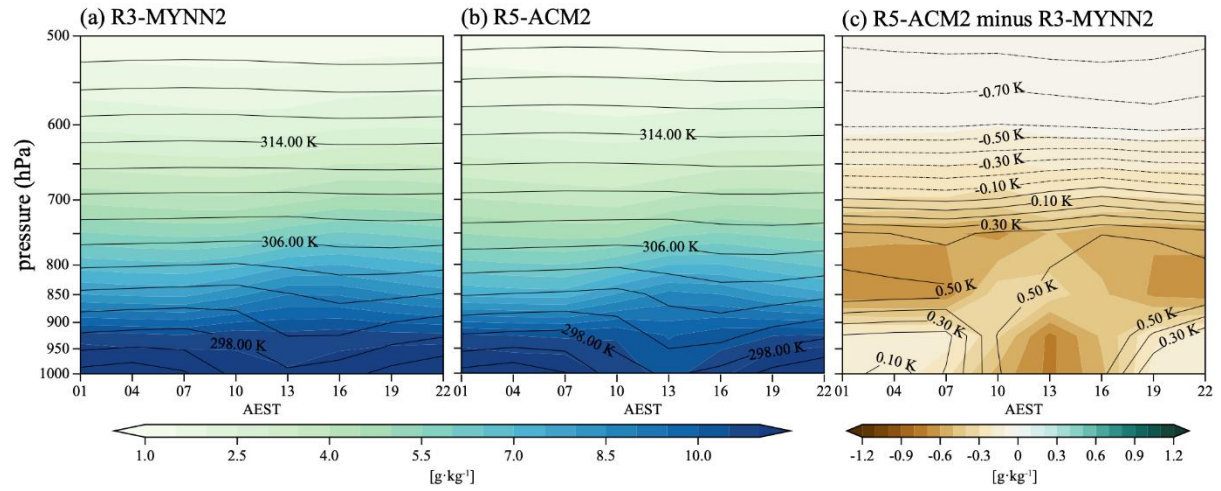


Fig. 13 The diurnal evolutions of the vertical profiles of q (shading) and θ (contours) for (a) R3-MYNN2, (b) R5-ACM2 and (c) R5-ACM2 minus R3-MYNN2. All fields represent mean values in DJF season from 1980–2020 averaged from selected grid points shown in **Fig. 11a**.

3.7 Proposed Mechanisms Underlying the Differences between the RCM Simulations

The analyses over the selected region indicate that R5-ACM2 simulates enhanced daytime Q_{net} , primarily driven by increased Q_{sw} , leading to higher surface temperature. The warmer surface promotes the development of a deeper PBL and stronger vertical mixing, which transports moisture upward while entraining warmer and drier air from the free atmosphere into the boundary layer.

To examine whether these mechanisms operate across the broader domain rather than only over the selected region, Fig. 14 shows the daytime evolution of the differences in key variables presented in previous analyses over the entire domain, together with the differences in total cloud fraction (Δclt), vertically integrated cloud condensed (i.e., liquid and ice) water ($\Delta clwvi$) and downward Q_{sw} ($\Delta Q_{sw\downarrow}$) that help explain why R5-ACM2 simulates greater solar irradiance than R3-MYNN2.

During the early morning (0700 AEST), the PBL has not yet fully developed, and $\Delta PBLH$ remains small (Fig. 14a-1). Nevertheless, $\Delta clwvi$ is negative over almost the entire domain (Fig. 14b-1), with the largest reductions occurring along the east coast of New South Wales. This indicates reduced cloud condensate within the atmosphere column in R5-ACM2, suggesting less extensive and/or optically thinner clouds than in R3-MYNN2. Consistent with this, Δclt is also reduced over land (Fig. 14c-1). The decrease in cloud cover allows more incoming solar radiation to reach the surface, resulting in positive $\Delta Q_{sw\downarrow}$ (Fig. 14d-1). Consequently, ΔQ_{net} becomes positive at this time (Fig. 11g), leading to positive ΔT_{2m} (Fig. 14e-1). In response to the rising ΔT_{2m} , ΔQ_{sh} begins to increase (Fig. 14f-1), particularly along the coast. In contrast, ΔQ_{lh} remains negative (Fig. 14g-1), consistent with the negative Δq_{2m} (Fig. 14h-1) and reduced soil moisture (not shown).

As solar heating intensifies after sunrise, $\Delta PBLH$ becomes positive, reaching a maximum at approximately 1300 AEST (Figs. 14a-2–14a-4), consistent with the diurnal evolution over the selected region (Fig. 12a). This deeper PBL indicates persistently stronger vertical mixing in R5-ACM2 between 1000 and 1600 AEST,

631 accompanied by consistently negative Δchl_{wvi} (Figs. 14b-2–14b-4). Consequently, although Δclt gradually
632 transitions from negative to positive (Figs. 14c-2–14c-4), $\Delta Q_{sw\downarrow}$ remains positive across the entire domain until
633 1600 AEST (Figs. 14d-2–14d-4). This suggests that the clouds simulated by R5-ACM2 contain less condensed
634 water and are therefore optically thinner, allowing more incoming shortwave radiation (i.e., $\Delta Q_{sw\downarrow}$ is positive) to
635 reach the surface despite the increase in cloud cover. As a result, positive ΔT_{2m} continues to intensify and peaks at
636 approximately 1300 AEST (Figs. 14e-2–14e-4), consistent with the earlier diurnal analyses (Fig. 12c). During this
637 period, ΔQ_{sh} increases (Figs. 14f-2–14f-4) because the enhanced surface warming strengthens the surface–air
638 temperature gradient, whereas ΔQ_{lh} decreases (Figs. 14g-2–14g-4) owing to the reduced near-surface moisture
639 availability, consistent with negative Δq_{2m} (Figs. 14h-2–14h-4).

640 At 1900 AEST, $\Delta PBLH$ transitions from positive to negative (Fig. 14a-5), indicating a more rapid collapse of
641 the daytime convective PBL in R5-ACM2 after sunset. Meanwhile, Δchl_{wvi} remains negative (Fig. 14b-5),
642 suggesting that the atmospheric column continues to contain less condensed cloud water than in R3-MYNN2.
643 Consistent with this, Δclt becomes negative (Fig. 14c-5), indicating reduced cloud cover over land. This decrease
644 in cloud cover favours stronger nocturnal radiative cooling by allowing more outgoing longwave radiation to
645 escape to space, contributing to a shallower nocturnal PBL in R5-ACM2. As shown in Fig. 11g, the nighttime
646 surface energy balance is dominated by ΔQ_{lw} , with persistently negative ΔQ_{lw} indicating greater net longwave
647 radiative loss in R5-ACM2 and, consequently, more efficient nocturnal cooling. Throughout the day, the Δq_{2m}
648 shows negative values over land (Figs. 14h-1–14h-5), likely reflecting persistently drier soil moisture conditions
649 (not shown). The accompanying reduction in precipitation (not shown) further limits soil moisture replenishment.

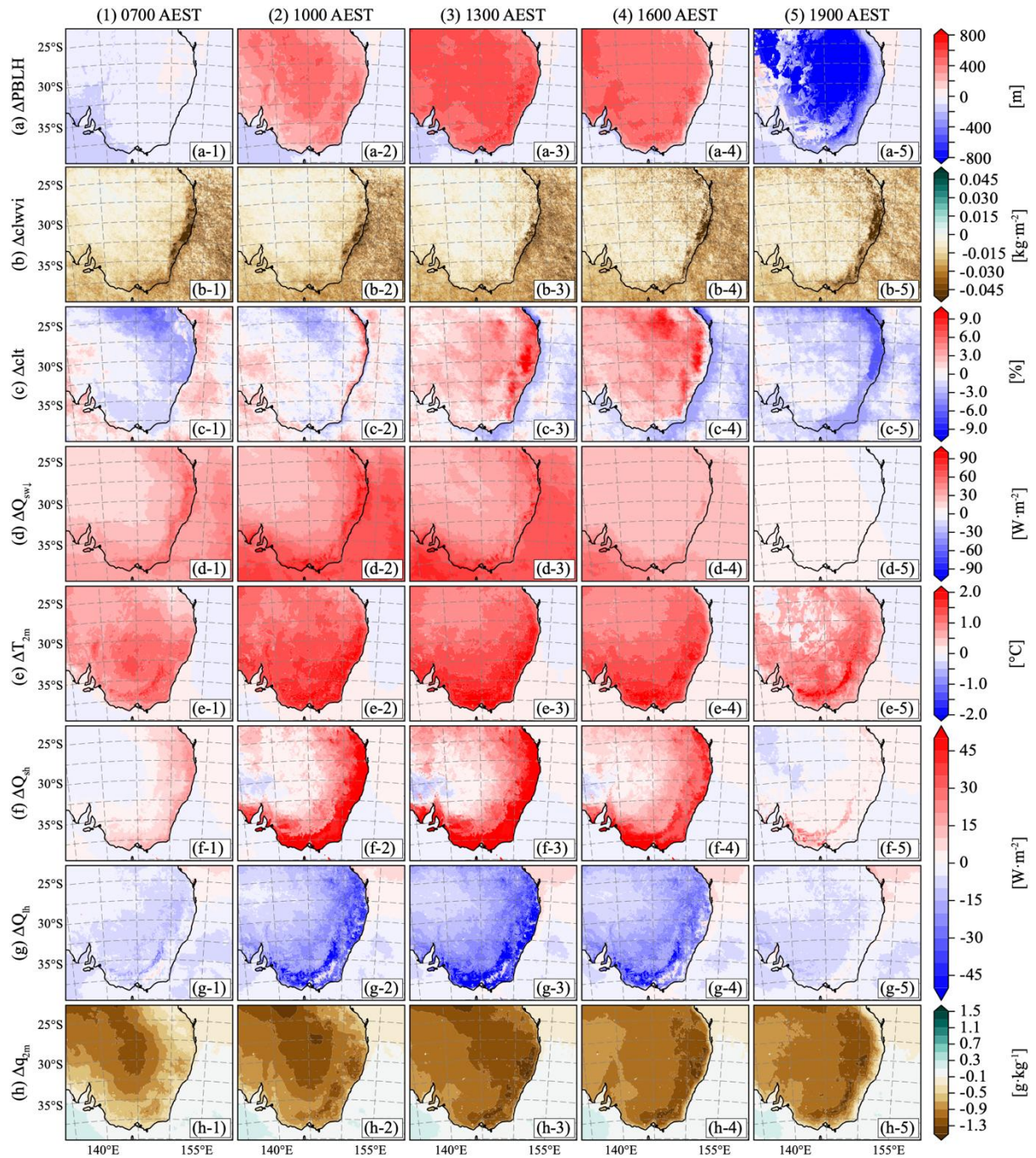


Fig. 14 The diurnal evolutions of R5-ACM2 minus R3-MYNN2 during daytime at (1) 0700, (2) 1000, (3) 1300, (4) 1600, and (5) 1900 AEST. The variables from top to bottom are the differences of (a) PBLH ($\Delta PBLH$), (b) vertically integrated cloud condensed water content ($\Delta chlwwi$), (c) total cloud fraction (Δclt), (d) surface downwelling shortwave radiation flux (ΔQ_{swl}), (e) near-surface temperature at 2 m (ΔT_{2m}), (f) surface sensible heat flux (ΔQ_{sh}), (g) surface latent heat flux (ΔQ_{lh}) and (h) specific humidity at 2 m (Δq_{2m}).

4. Discussion and Conclusion

This study first evaluated the fidelity of two ERA5-driven WRF RCM simulations at 4-km convection-permitting resolution in reproducing the seasonal climatology over southeastern Australia. Although both simulations exhibit significant biases in the seasonal means of daily maximum and minimum near-surface temperatures, the daily maximum temperature is more sensitive to the choice of PBL parameterisation than the daily minimum temperature. Compared with the R3-MYNN2, the R5-ACM2 scheme reduces the cold bias in

daily maximum temperature while showing little improvement in daily minimum temperature. In addition, R5-ACM2 simulates higher near-surface temperatures than R3-MYNN2. This result is consistent with previous studies. For example, García-Díez et al. (2013) found that local PBL schemes, such as the MYJ scheme, generally produce larger cold biases than the nonlocal YSU scheme and the hybrid local–nonlocal ACM2 scheme. The relatively smaller cold bias associated with ACM2 has been attributed to stronger entrainment at the top of the boundary layer.

The two RCMs also differ markedly in their ability to reproduce seasonal-mean precipitation. During austral summer, R3-MYNN2 exhibits smaller precipitation biases than R5-ACM2, suggesting that the local MYNN2 PBL scheme more effectively represents precipitation under conditions characterised by strong convective activity and heavy rainfall than the hybrid local–nonlocal ACM2 scheme. The larger dry biases simulated by R5-ACM2 are likely associated with its stronger vertical mixing, which reduces boundary-layer moisture availability. Outside austral summer, however, R3-MYNN2 significantly overestimates seasonal precipitation, particularly over South Australia and Victoria, whereas R5-ACM2 exhibits only limited regions with statistically significant precipitation biases relative to observations. Nevertheless, these improvements are not consistently statistically significant along the eastern coast of New South Wales, where both simulations show significant biases. Austral summer not only exhibits the largest precipitation biases in R5-ACM2 but also the most extensive areas of statistically significant differences between the two RCMs over land. In the remaining seasons, R5-ACM2 consistently simulates less precipitation than R3-MYNN2, with the largest and most statistically significant reductions occurring over South Australia, Victoria, and the eastern coast of New South Wales.

Evaluation of the vertical profiles of temperature and moisture at ten radiosonde sites indicates that both RCMs reasonably reproduce the observed thermodynamic structure of the atmosphere. However, both simulations underestimate the vertical humidity gradient, implying stronger vertical turbulent mixing, with the difference being more pronounced in R5-ACM2.

The analyses based on the diurnal evolution of PBL-related variables reveal a positive land–atmosphere feedback that helps explain the hotter and drier climate simulated by R5-ACM2. Previous studies have shown that the differences between local and nonlocal PBL schemes arise primarily from their representation of turbulent mixing. For example, Coniglio et al. (2013) found that the local MYJ scheme tends to produce a boundary layer that is too cool and moist during the daytime because of insufficient turbulent mixing in convective conditions, whereas the nonlocal YSU scheme often generates overly warm and dry boundary layers. Our study also showed that the hybrid local–nonlocal ACM2 scheme simulates a warmer and drier boundary layer than the local MYNN2 scheme during the day due to stronger vertical mixing. The vertical mixing plays a key role in this positive feedback by modulating the amount of solar radiation reaching the surface and, consequently, the partitioning of surface energy, PBL development, and atmospheric moisture.

- 1) During the nighttime, R5-ACM2 simulates greater outgoing longwave radiation, resulting in stronger radiative cooling and a shallower, more stable PBL. The reduced nighttime cloud cover and cloud-condensed water persist into the early morning.

- 2) The reduced morning cloud cover allows more downward shortwave radiation to reach the surface. During the afternoon, although cloud fraction becomes higher in R5-ACM2, the cloud condensed water content

remains lower, suggesting that the clouds are optically thinner and therefore transmit more incoming shortwave radiation than those in R3-MYNN2.

3) The enhanced downward shortwave radiation increases the daytime net radiation, leading to higher surface temperature.

4) Although R5-ACM2 receives more net radiation, lower soil moisture and reduced precipitation limit evapotranspiration, suppressing the latent heat flux. Consequently, a larger proportion of the available energy is partitioned into sensible heat, which further increases near-surface air temperature, deepens the PBL, and strengthens daytime turbulent mixing.

5) Enhanced turbulent mixing transports more moisture upward while entraining potentially warm, dry air from the free atmosphere into the boundary layer, producing a warmer and drier near-surface atmosphere. The resulting reduction in precipitation by R5-ACM2 likely contributes to maintaining these drier soil conditions, suppresses evapotranspiration, and limits atmospheric moisture available for thick cloud formation.

Throughout the diurnal cycle, R5-ACM2 consistently exhibits lower soil moisture, reduced near-surface humidity, lower column-integrated cloud-condensed water and less precipitation than R3-MYNN2. Because both RCM simulations are driven by the same initial and lateral boundary conditions, the differences arise primarily from the contrasting PBL schemes. The persistently drier soil conditions in R5-ACM2 result from the cumulative effects of stronger vertical mixing produced by the hybrid local–nonlocal ACM2 scheme in conjunction with the Noah-MP land surface model throughout the simulation period.

In a previous study focusing on the Amazon, Hu et al. (2023) suggested that enhanced vertical mixing within the PBL simulated by the ACM2 scheme transports moisture from the surface to the top of the boundary layer, promoting cloud development and supplying moisture to a thicker cloud layer. This resulting increase in cloud cover reduces the amount of shortwave radiation reaching the surface, leading to weaker surface heating, reduced convective available potential energy (CAPE), and consequently less precipitation. These findings appear to contrast with our results, which indicated that reduced precipitation simulated by the ACM2 scheme over southeastern Australia is accompanied by increased surface radiative heating. However, these contrasting responses likely reflect differences in regional moisture availability rather than inconsistencies in the PBL scheme itself. The climatic response to enhanced boundary-layer mixing depends strongly on the dominant moisture source or related to the moisture content of the free troposphere. In moisture-rich environments, such as the Amazon rainforest examined by Hu et al. (2023), abundant evapotranspiration provides a continuous supply of atmospheric moisture. Enhanced turbulent mixing redistributes this moisture throughout the boundary layer, maintaining or even enhancing cloud development despite reduced surface heating. Furthermore, the relatively moist free troposphere over the Amazon allows the entrainment of moisture into the growing PBL, promoting cloud formation at the top of the boundary layer. In contrast, southeastern Australia is a moisture-limited environment during austral summer, where atmospheric moisture is supplied primarily by advection from the adjacent ocean. The air at free atmosphere is also considerably drier over southeastern Australia. Under these conditions, enhanced vertical mixing redistributes a limited moisture supply through a deeper boundary layer while entraining dry air from the free troposphere. The resulting dilution of boundary-layer moisture suppresses cloud formation and precipitation, allowing more shortwave radiation to reach the surface and reinforcing the warm, dry land–atmosphere feedback.

Given that the two RCM configurations form key components of the NARClIM2.0-CMIP6 simulations, the mechanisms proposed in this study provide a physical basis for understanding the diverging hindcasts and projections produced by the NARClIM2.0-CMIP6 ensemble (e.g., Di Virgilio et al. 2025b; Ji et al. 2026a, b). These findings provide useful information for the selection of PBL schemes in future high-resolution regional climate modelling applications.

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Data Availability

The RCM simulation data are published through the Australian National Computational Infrastructure (NCI). On NCI, ERA5-driven NARClIM2.0 is available from <https://doi.org/10.25914/ysxb-rt43>; AGCD data is the CSIRO's commercially licensed version of the Bureau's AGCD dataset, which is available from <http://dx.doi.org/10.25914/6009600304b02>; and ERA5 reanalysis is available from <https://dx.doi.org/10.25914/5fb115b82e2ba>.

Statements and Declarations

Funding: This research was supported by the New South Wales Department of Climate Change, Energy, the Environment and Water as part of the NARClIM2.0 dynamical downscaling project contributing to CORDEX Australasia. Funding was provided by the NSW Climate Change Adaptation Strategy and NSW Climate Change Fund for NSW and Australian Regional Climate Modelling (NARClIM) Project. This research was undertaken with the assistance of resources and services from the National Computational Infrastructure (NCI), which is supported by the Australian Government. J.P.E. acknowledges the support of the Australian Research Council Centre of Excellence for 21st Century Weather (CE230100012) and the Climate Systems Hub of the Australian Governments National Environmental Science Program. **Competing Interests:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. **Author Contributions:** Y.L. designed the methodology, conducted the evaluation and diagnostic analyses, interpreted the results, prepared the figures, and wrote the original manuscript. G.V.D and J.F supervised the study and reviewed and edited the manuscript. E.T. performed the WRF simulations, managed the model output, provided technical support, and reviewed the manuscript. J.K. and R.W. contributed to the study design, assisted with interpretation of the results, and reviewed and edited the manuscript. J.E., S.W., J.A. D.C., R.G., Y.K. and L.N. reviewed and edited the manuscript. All authors approved the final manuscript.

Supplementary Figures

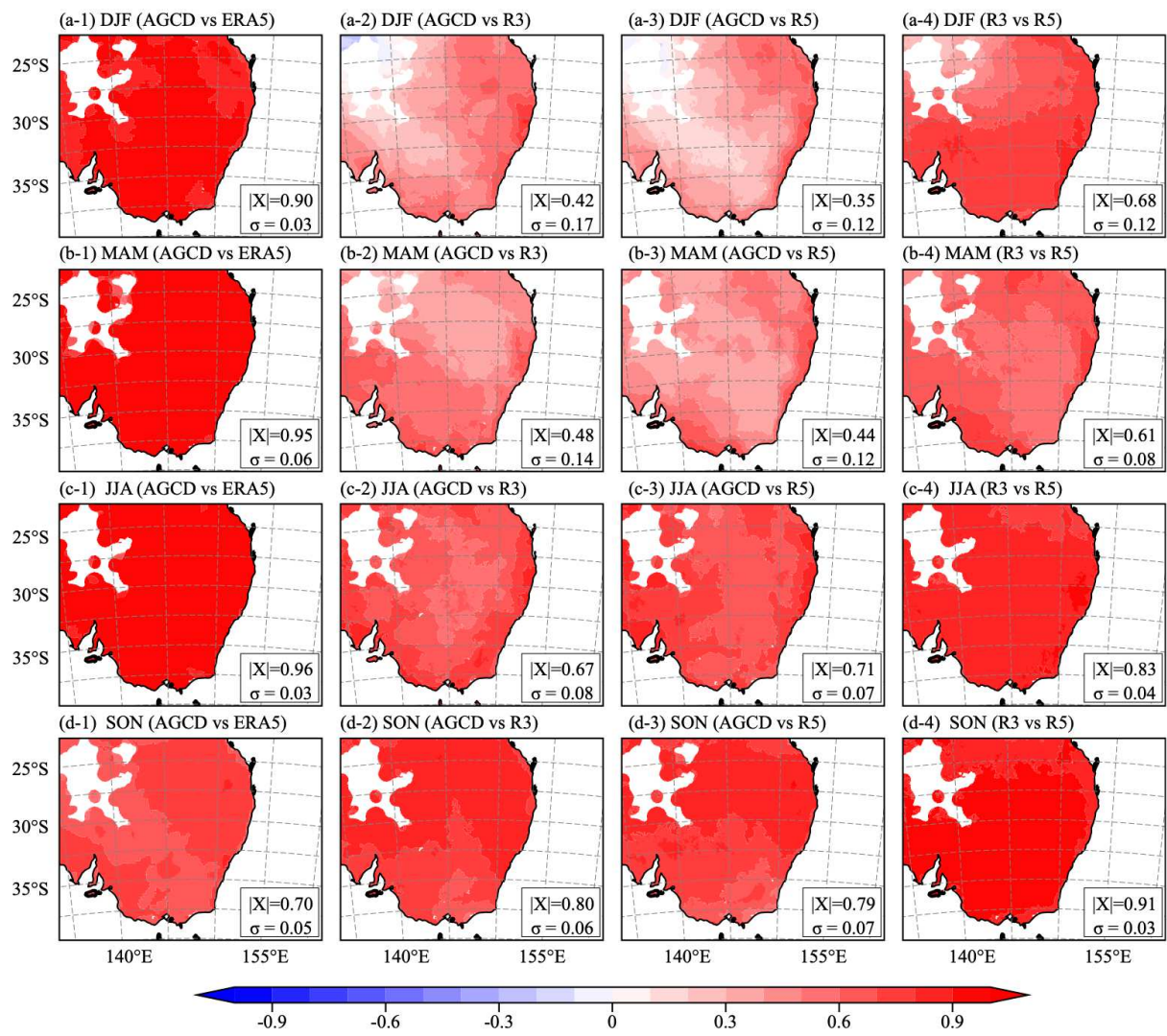


Fig. S1 The seasonal correlations of T_{max} between AGCD and ERA5, between AGCD and R3-MYNN2, between AGCD and R5-ACM2, and between R3-MYNN2 and R5-ACM2 for DJF, MAM, JJA and SON, respectively. The spatial mean correlation and its standard deviation over land are shown in the bottom right of each panel.

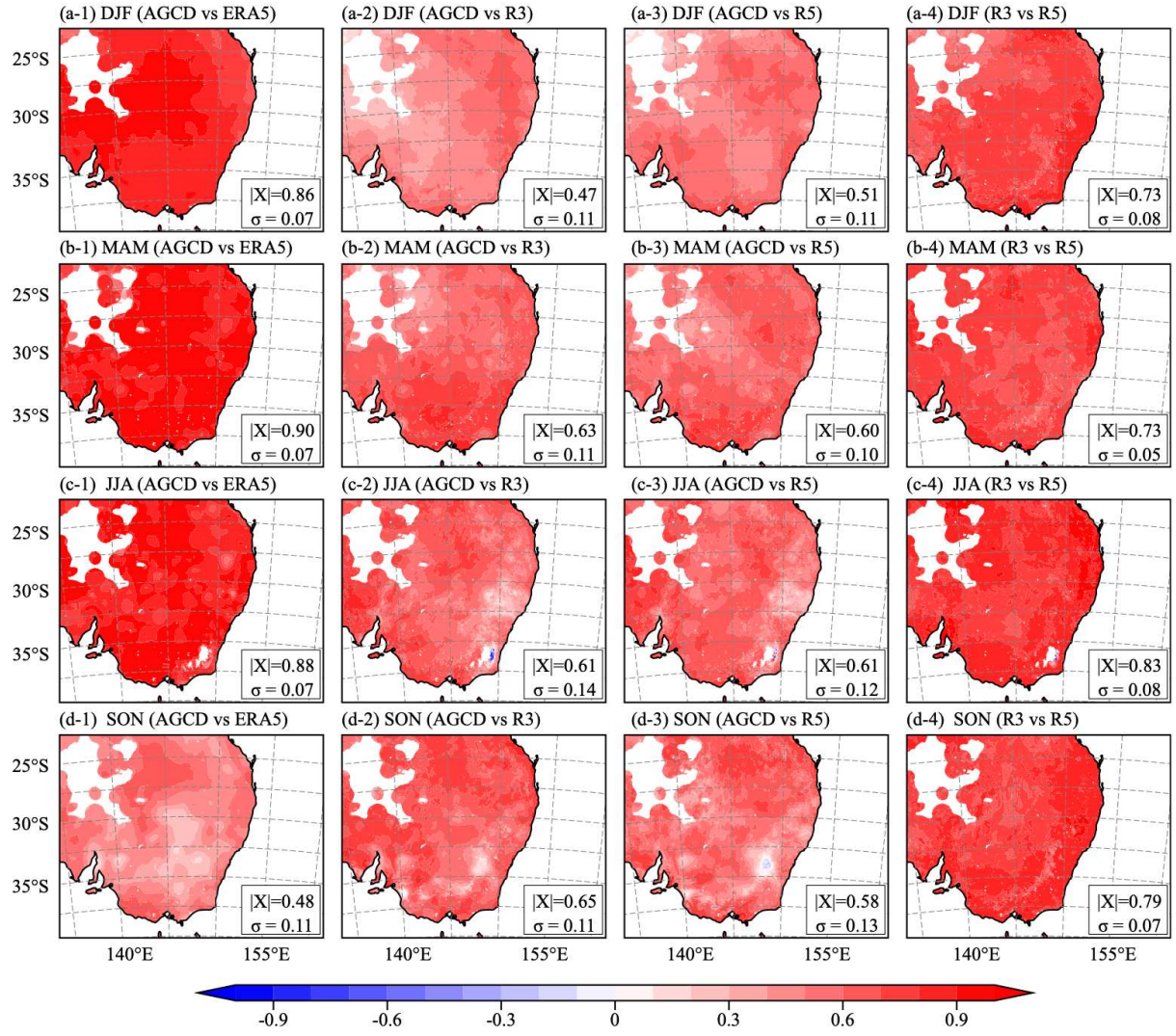


Fig. S2 Same as Fig. S1, but for T_{min} .

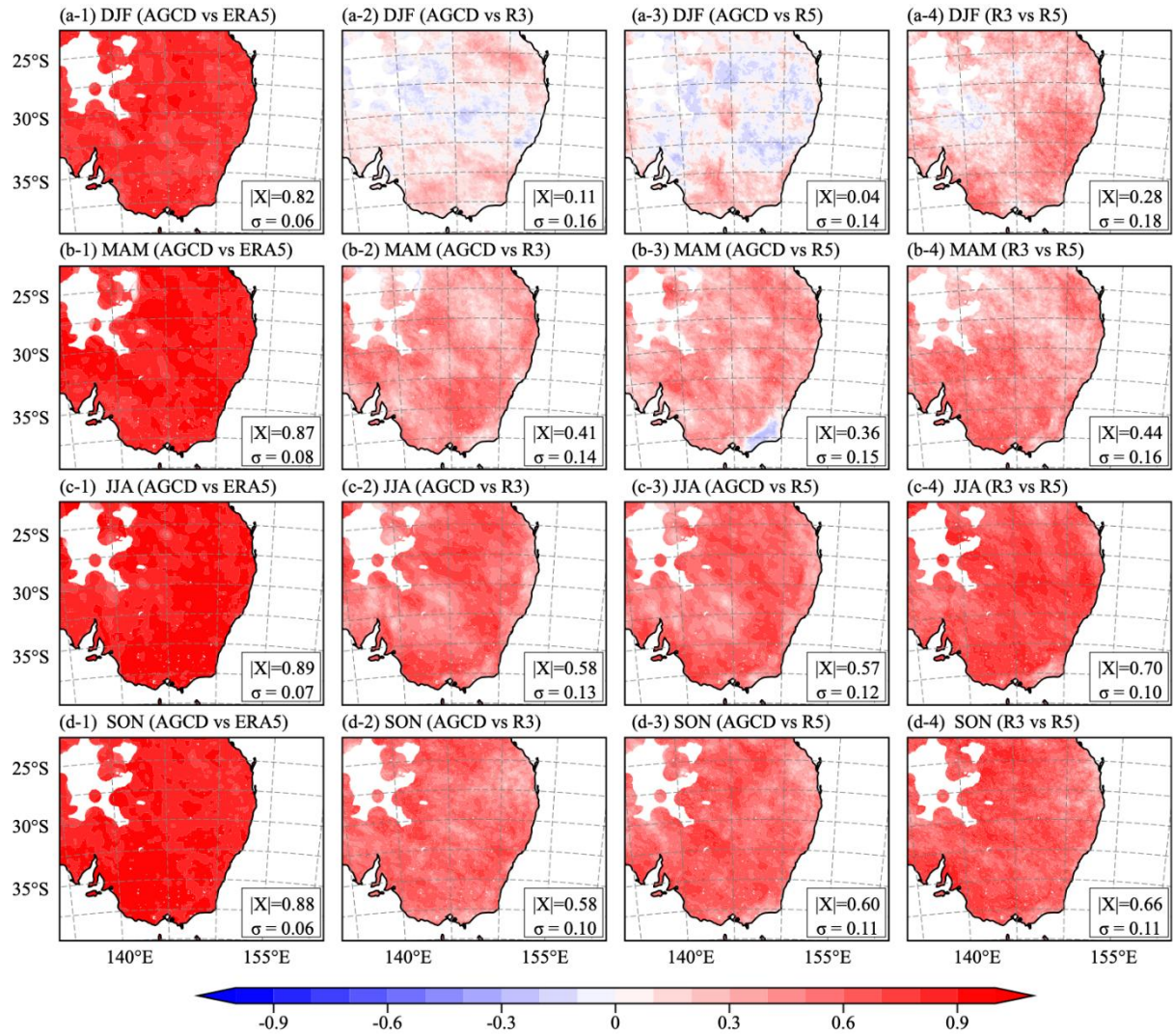


Fig. S3 Same as Fig. S1, but for *pr*.

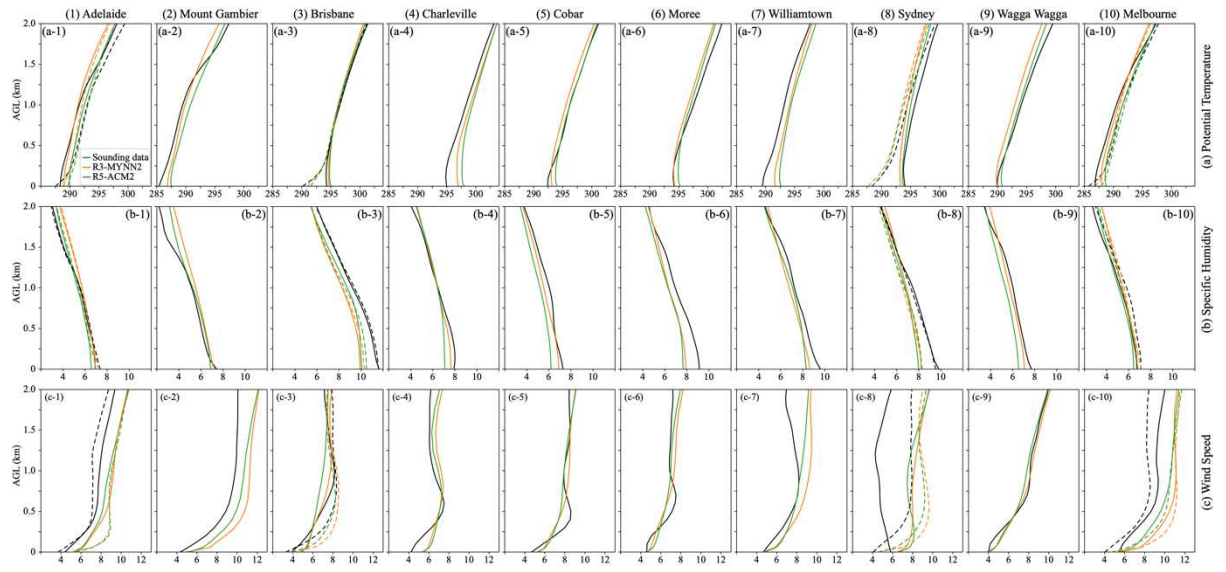


Fig. S4 The rows from top to bottom show the MAM means of vertical profiles of (a) potential temperature (θ ; unit: K), (b) specific humidity (q ; unit: $\text{g} \cdot \text{kg}^{-1}$) and (c) wind speed ($wspd$; unit: $\text{m} \cdot \text{s}^{-1}$), and the columns from left to right represent the MAM-means from sounding sites of (1) Adelaide, (2) Mount Gambier, (3) Brisbane, (4) Charleville, (5) Cobar, (6) Moree, (7) Williamtown, (8) Sydney, (9) Wagga Wagga, and (10) Melbourne, respectively. All seasonal-means are averaged over the common period of 2018–2020. For panels with only solid lines, all lines represent the averages from 0900 to 1000 AEST. For Sites (1) and (10), solid lines represent the averages from 0900 to 1000 AEST and dashed lines represent the averages from 2100 to 2200 AEST. For Site (3), solid lines represent the averages from 0900 to 1000 AEST and dashed lines represent the averages from 0300 to 0400 AEST. For Site (8), solid lines represent averages from 1300 to 1600 AEST and dashed lines represent the averages from 0400 to 0700 AEST.

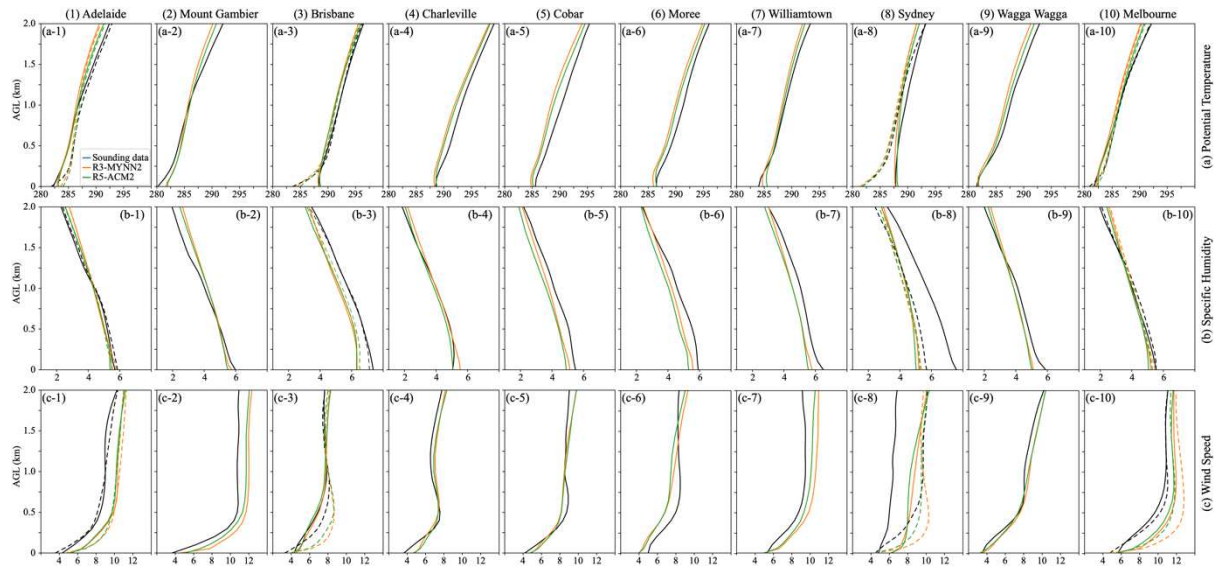


Fig. S5 Same as Fig. S4, but for JJA season.

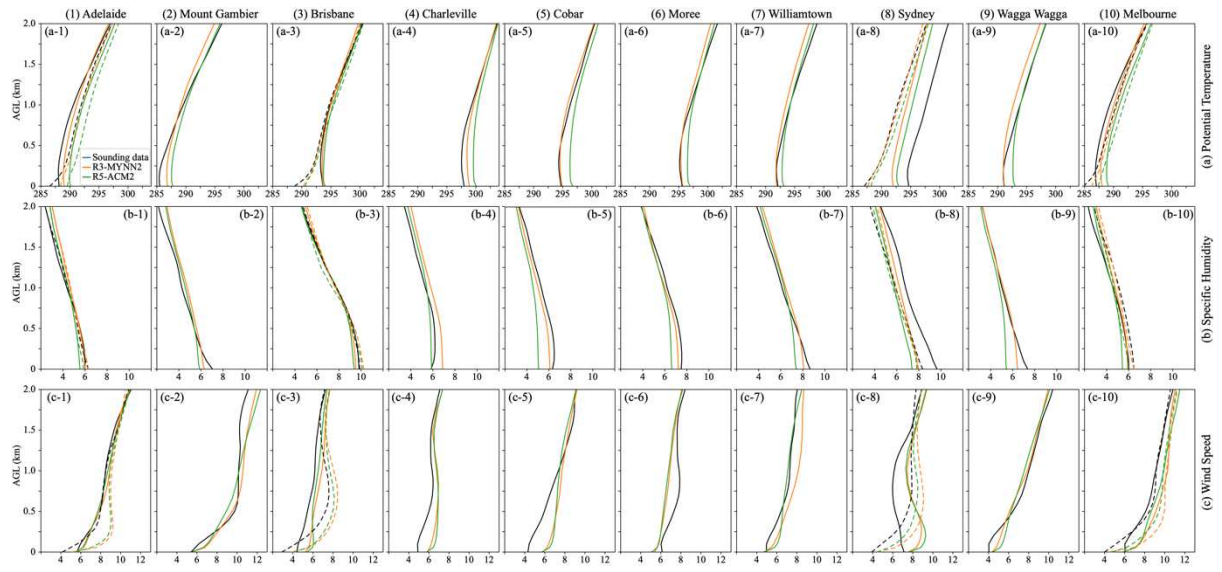


Fig. S6 Same as **Fig. S4**, but for SON season.

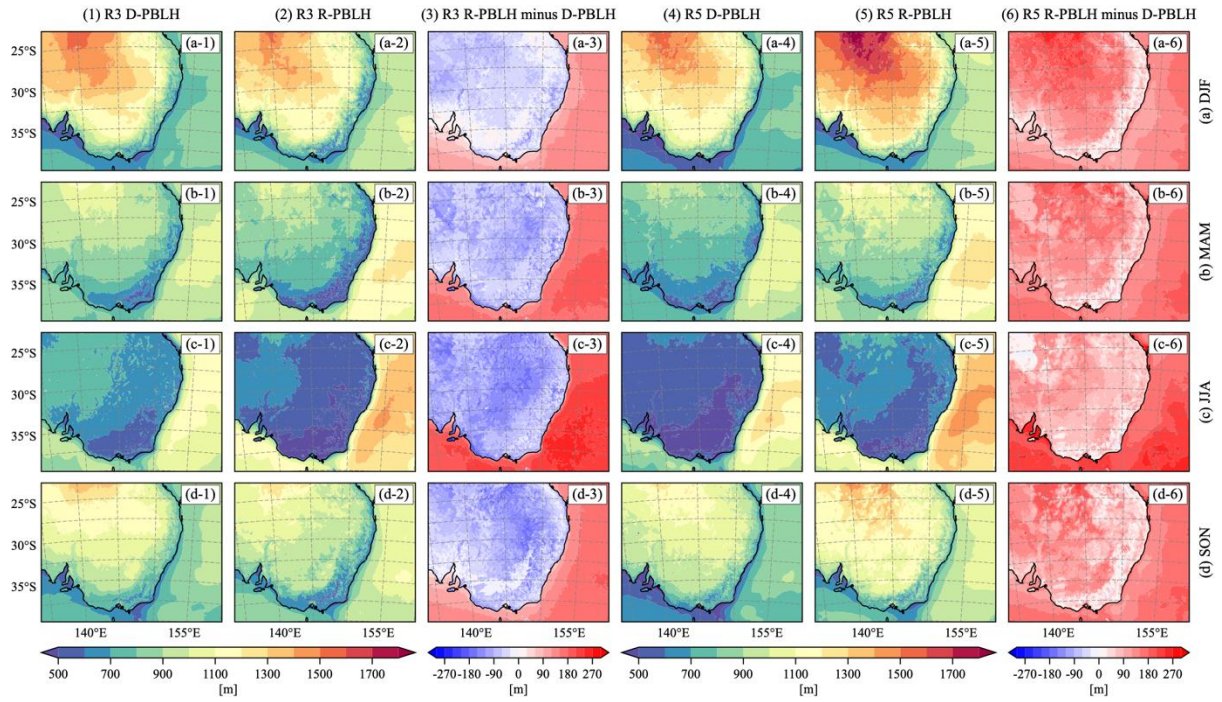


Fig. S7 The seasonal means of reconstructed and diagnosed PBLHs for R3-MYNN2 and R5-ACM2. The differences of R-PBLH minus D-PBLH are also followed. The reconstructed PBLH (R-PBLH) is calculated using the same theta-increase definition for both R3-MYNN2 and R5-ACM2, while the diagnostic PBLH (D-PBLH) refers to the PBLH diagnosed by WRF. The rows from top to bottom show the seasons of (a) DJF, (b) MAM, (c) JJA, and (d) SON, and the columns from left to right represent the means of (1) R3 D-PBLH, (2) R3 R-PBLH, (3) R-PBLH minus D-PBLH for R3, (4) R5 D-PBLH, (5) R5 R-PBLH, and (6) R-PBLH minus D-PBLH for R5, respectively.

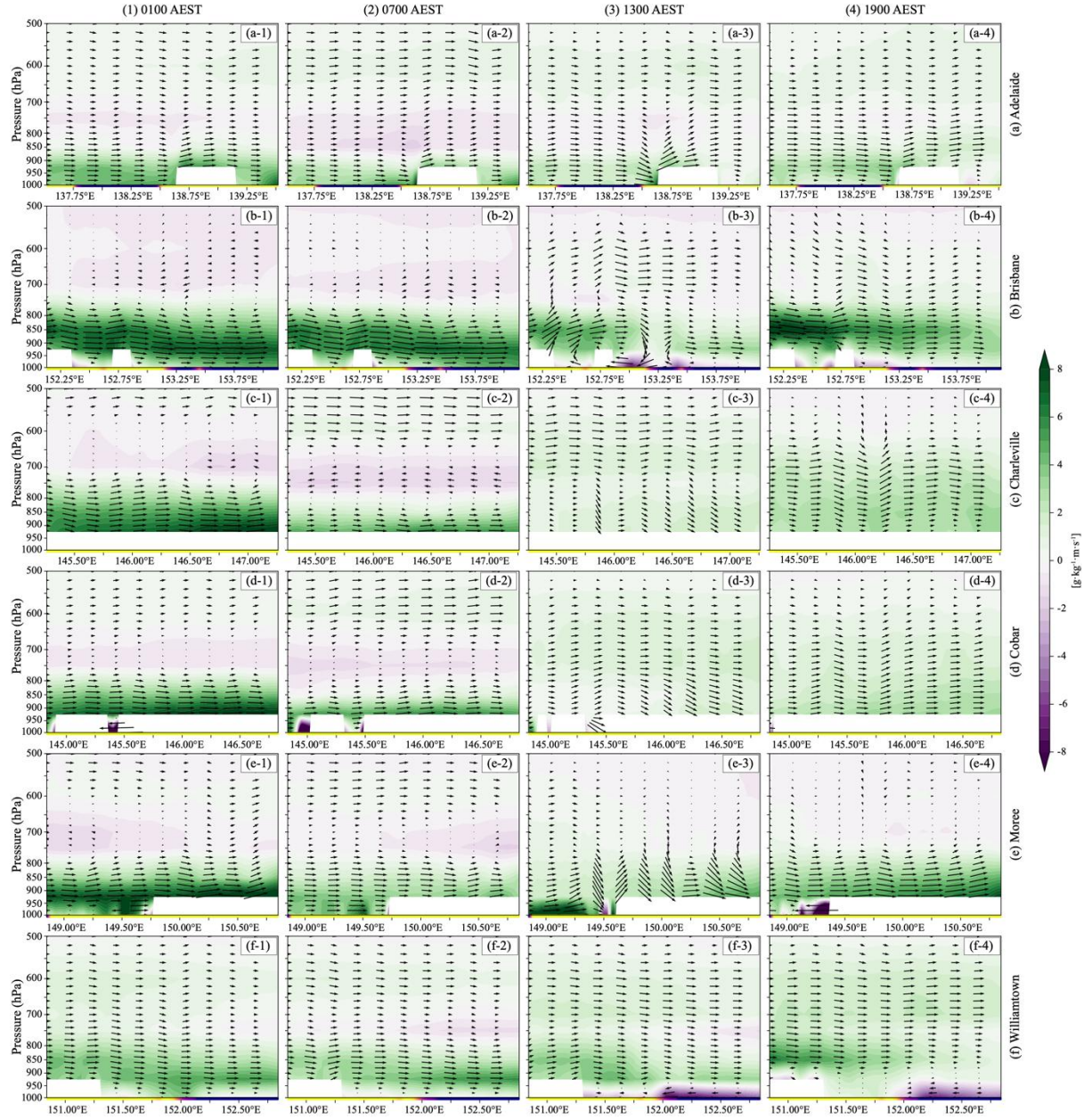


Fig. S8 DJF-averaged vertical profiles differences between R5-ACM2 and R3-MYNN2 in terms of zonal moisture flux (calculated using the formula of qu ; shading) and wind circulation (derived from u and w , with w multiplied by a factor of 10 for visualisation; vector) along the cross-sections passing (a) Adelaide, (b) Brisbane, (c) Charleville, (d) Cobar, (e) Moree, and (f) Williamtown (see Fig. 1b). The columns from left to right represent the times of (1) 0100, (2) 0700, (3) 1300, and (4) 1900 Australian Eastern Standard Time (AEST), respectively. The white space in the panels represents high rise terrain. The land fraction along the cross-section is indicated at bottom of each plot with yellow=1 (land) and blue=0 (ocean) and other colours representing fractions between 0 and 1.

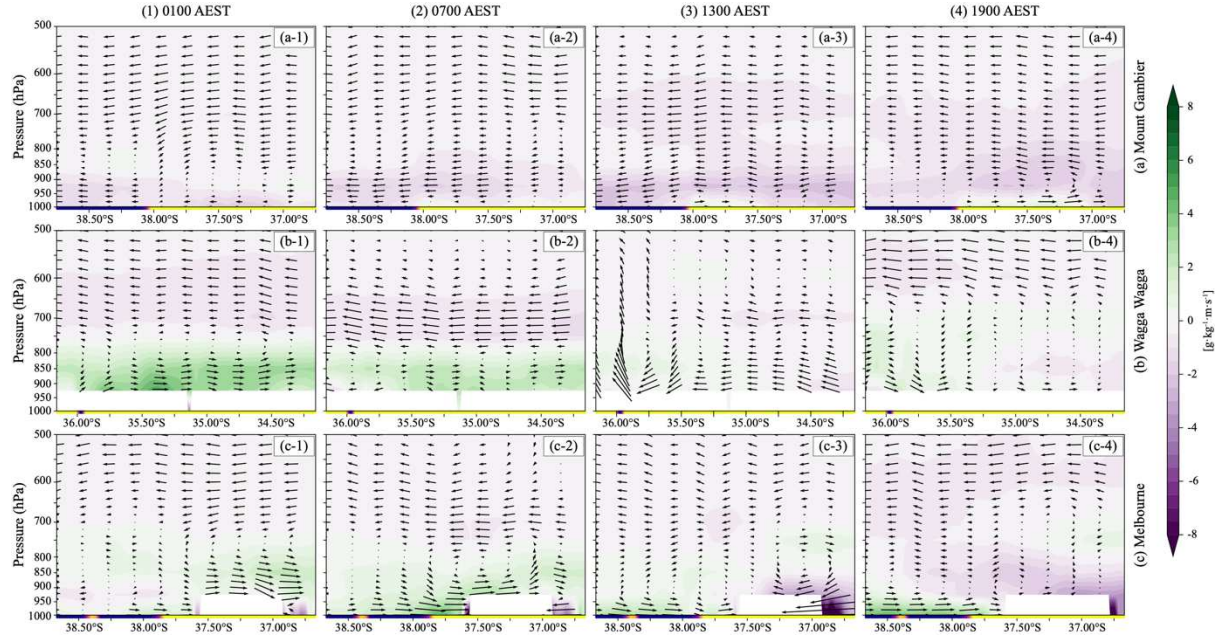


Fig. S9 DJF-averaged vertical profiles differences between R5-ACM2 and R3-MYNN2 in terms of meridional moisture flux (calculated using the formula of q_v ; shading) and wind circulation (derived from v and w , with w multiplied by a factor of 10 for visualisation; vector) along the cross-sections passing (a) Mount Gambier, (b) Wagga Wagga, and (c) Melbourne (see Fig. 1b). The columns from left to right represent the times of (1) 0100, (2) 0700, (3) 1300, and (4) 1900 AEST. The white space in the panels represents high rise terrain. The land fraction along the cross-section is indicated at bottom of each plot with yellow=1 (land) and blue=0 (ocean) and other colours representing fractions between 0 and 1.

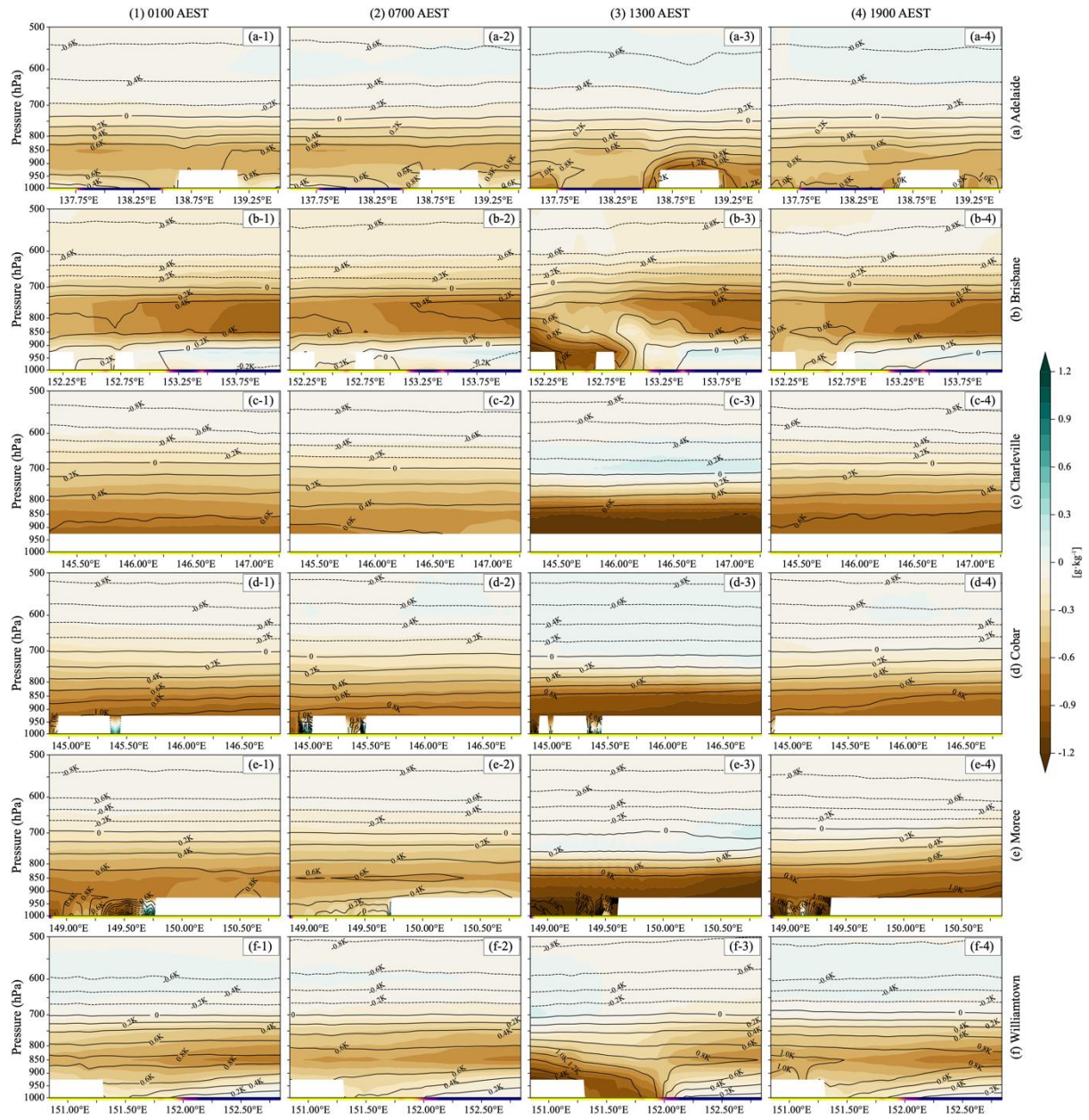


Fig. S10 Same as Fig. S8, but for the specific humidity (q ; shading) and potential temperature (θ ; contour).

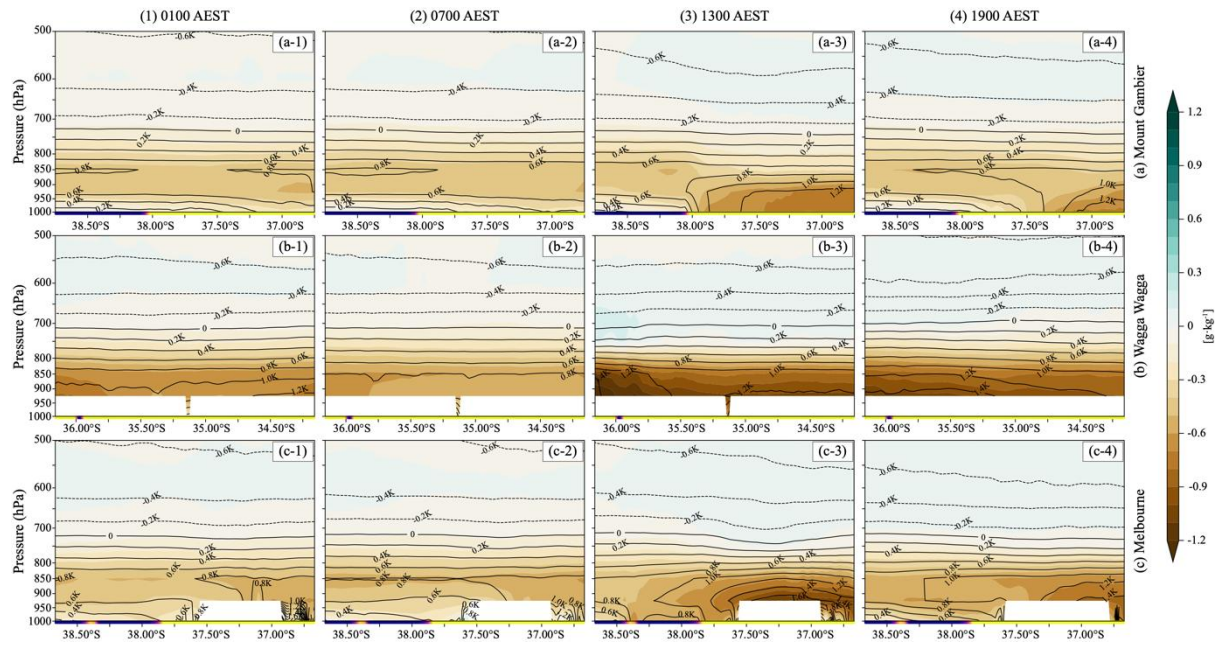


Fig. S11 Same as **Fig. S9**, but for the specific humidity (q ; shading) and potential temperature (θ ; contour).

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [Supp.Fig.10DJFcrossectionqwiththetastation03.png](#)
- [Supp.Fig.11DJFcrossectionqwiththetastation46.png](#)
- [Supp.Fig.1Seasonaltasmaxcorrelationv2.png](#)
- [Supp.Fig.2Seasonaltasmincorrelationv2.png](#)
- [Supp.Fig.3Seasonalprcorrelationv2.png](#)
- [Supp.Fig.4Verticalprofile10stationsMAM20182020v2copy.png](#)
- [Supp.Fig.5Verticalprofile10stationsJJA20182020v2copy.png](#)
- [Supp.Fig.6Verticalprofile10stationsSON20182020v2copy.png](#)
- [Supp.Fig.7PBLHseasonalmeancomparison20182020.png](#)
- [Supp.Fig.8DJFcrossectionquwithwindPRGnv2copy.png](#)
- [Supp.Fig.9DJFcrossectionqvwithwindPRGnv2copy.png](#)