# East Asian atmospheric water cycle and monsoon circulation in the Met Office Unified Model

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## Introduction

- In this study we evaluate the performance of the latest generation of Met Office Unified Model (MetUM) in simulating the East Asian water cycle and representing the Asian Pacific monsoon flow [1]. We assess its climatological behaviour and explore the impacts of increased horizontal resolution and atmosphere-ocean coupling.
- The atmosphere-only configurations correspond to MetUM GA6 [2] and were produced with the same surface temperature, sea-ice fractions and other external forcings as in the AMIP framework of CMIP5.
- The coupled simulations correspond to MetUM GC2 [3]. The climate models were run at 3 horizontal resolutions, N96, N216 and N512. Information on model resolution for each simulation is summarised in Table 1.

| Type | Horizontal resolution (30°) | Vertical levels (Ocean) | Timestep (minutes) |
|---|---|---|---|
| AMIP N96 | 181 Km ×139 Km | NA | 20 |
| AMIP N216 | 80 Km ×62 Km | NA | 15 |
| AMIP N512 | 34 Km ×26 Km | NA | 10 |
| Coupled N96 | 181 Km ×139 Km | 75 | 20 |
| Coupled N216 | 80 Km ×62 Km | 75 | 15 |

**Table 1.** Climate model horizontal and vertical resolutions and time steps. All MetUM models are run with 85 vertical levels in the atmospheric component.

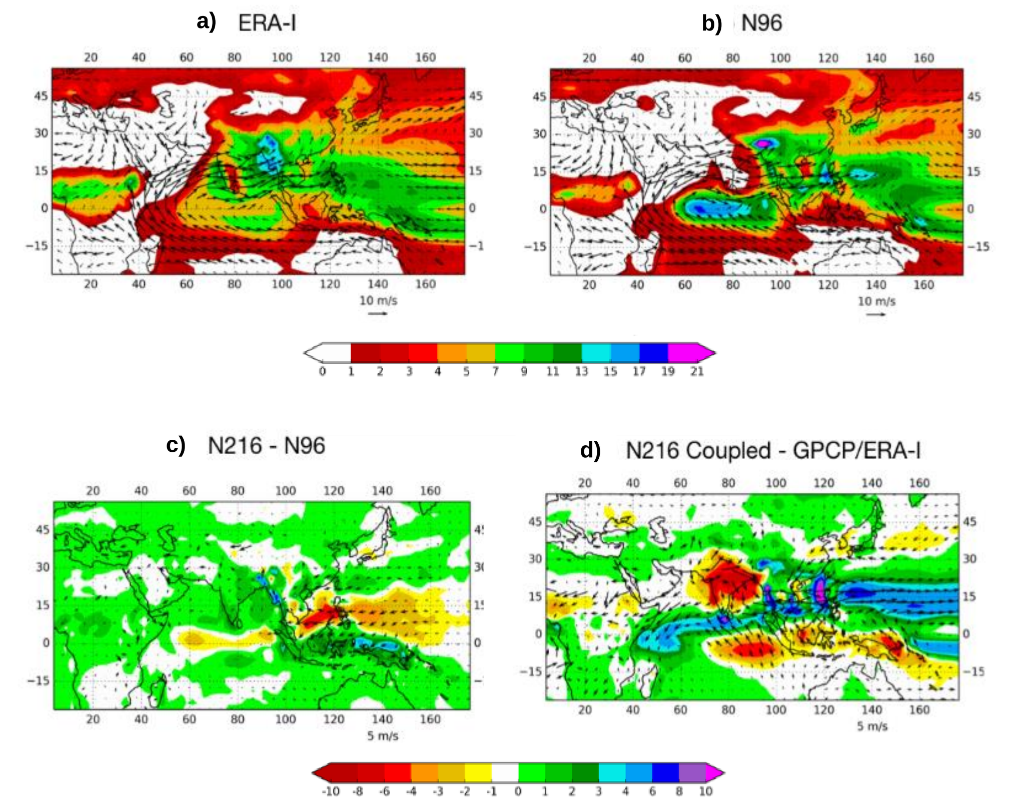

**Figure 1.** June-August 1982-2007 precipitation and 859hPa wind vectors for (a) ERA-Interim and (b) MetUM AMIP at N96. Model differences for (c) N216-N96. Mean errors relative to GPCP precipitation and ERA-Interim winds for N216 coupled model (d). Precipitation is in mm day$^{-1}$ and winds in ms$^{-1}$. The coupled run is for 100 years of a present day simulation.

## Asian summer monsoon precipitation and 850 hPa circulation

### Mean precipitation

- ERA-I: Main *P* centres over west coast of India, Bay of Bengal and over countries of mainland East Asia and into south China.
- MetUM: -Too much *P* over equatorial Indian Ocean and too little over India and its surrounding oceans. Too little *P* over the islands of Maritime Continent and too much over the Western Pacific (15° N). Mean P over east Asian land is better represented, although too wet over south China and too dry over the Korean peninsula.

### Low-level circulation

- ERA-I850 hPa winds: easterly flow along the equator in the Indian Ocean curving northward at the African coast (Somali jet) and then flowing eastward over India and south east Asia. Over east Asia the flow turns northward around the west Pacific subtropical high (**WPSH**). Intensity and location of WPSH modulates east Asian summer monsoon evolution.
- MetUM: WPSH is too weak and located too far east. This results in an anomalous cyclonic circulation that weakens the northward low-level flow over China and excessive westerly flow over the west Pacific Ocean. This error implies a dry bias north of 30 N and over the Yellow Sea and land areas of Korea and southern Japan.

### Effect of horizontal resolution and air-sea coupling

- In principle, increased horizontal resolution allows better representation of the spectrum of atmospheric eddy/wave motions ant their interactions with the mean flow. Detail in the orography and land surface representation also improves.
- South Asia: increased resolution brings a reduction in the excessive *P* over the equatorial Indian Ocean and beneficial increase over India. East Asia: N216 reduces the cyclonic circulation error in the WPSH and increases the south-westerly flow over eastern China. This reduces the dry biases over north East China, but makes the wet bias over southern China larger. The wet biases and excessive westerly flow in tropical west Pacific and south China Sea are improved. Across the Maritime Continent the dry biases at N96 are reduced at N216.
- Coupled simulations: the dry bias over India is still present, but P biases over the Indian ocean are modified (too much *P* in the west and too little in the east). The wet bias over the western tropical Pacific is larger than in the AMIP simulation. The WPSH is weaker compared to AMIP with an erroneous north-easterly flow over China.
- Sensitivity to horizontal resolutions in coupled simulations (not shown) is less than that in AMIP simulations. This suggests that circulations errors forced from SST drifts outweigh the benefits seen in the atmosphere alone.

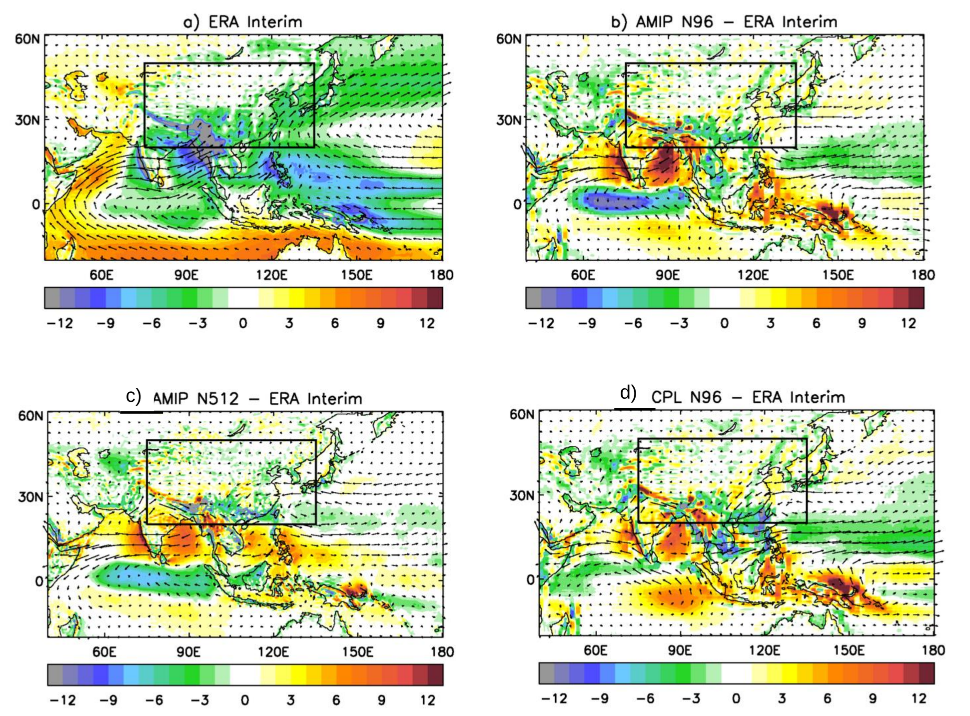

**Figure 2.** June-august water vapour divergence (shaded, $10^5$ Kgm$^{-2}$s$^{-1}$) superimposed with water vapour flux vector (arrows). ERA-Interim climatological mean is shown in a). Climate model simulations minus reanalysis data are shown in the rest of the panels for the following cases: b) AMIP-N96, c) AMIP-N512, d) coupled-N96. The figures also show the rectangular region used to calculate regional water vapour fluxes and precipitation recycling.

### Summer Vertically-integrated moisture transport

- Water vapour divergence links sources and sinks of moisture in the atmosphere to evaporation and precipitation. Divergent regions correspond to places predominantly evaporative. Precipitation dominates in convergent areas.
- The patterns of vertically-integrated moisture transport closely reflect the large-scale monsoon circulation in the lower troposphere.
- Moisture fluxes into the region (see box in Figure 2a) come from 4 main sources: moisture from the Arabian Sea and Bay of Bengal, transported by the Indian monsoon; moisture from the western tropical Pacific, transported by the South East Asian monsoon; cross equatorial transport (100-150 E); and a small flux from mid latitude westerlies.
- Errors in convergence in the east Asian monsoon region (see box) resemble *P* biases discussed above: an excess of moisture convergence over south China and lack of convergence over East China Sea and north-east China. The south westerly moisture flux entering South China Sea (crossing the south side of box) tends to be too zonal, with less moisture penetrating the land area. This error is partly explained by circulation errors associated with a weak WPSH mentioned above.

### Water vapour fluxes and precipitation recycling

- A negative net outgoing flux in the area represented by the box in Figure 2 indicates that, as a whole, and in an annual basis, there is an excess of precipitation over evaporation in the region. Model simulations exhibit a higher precipitation surplus compared with ERA-I. This bias intensifies as the resolution increases.
- Most of the water vapour advected into the region by the general circulation comes from fluxes across the west and south borders. Part of that moisture is moved out of the region over the east border. A weaker export of water vapour across this border in MetUM is the main source of the precipitation excess bias mentioned above.
- The annual cycle of outgoing water vapour fluxes across the different borders (see Figure 3) matches the East Asian monsoon evolution. Most pronounced seasonal variability occurs at the southern border, where moisture is imported from February to September and exported from September to February. MetUM underestimates the strength of the import peak (June) and the change from import to export, associated with the end of the summer monsoon is too abrupt. Strength and timing improve with resolution. Moisture across the east border is exported all year round (maximum in June and minimum in September). MetUM simulations underestimate the moisture flow out of the region across this border, consistent with the low level circulation biases discussed above.
- Annual mean **precipitation recycling**: 0.32 in ERA-I and 0.32 to 0.34 in model simulations. Its seasonal cycle goes in hand with the annual cycle of moisture imported into the region. It oscillates between an minimum of 0.18 during the peak of the summer monsoon to a maximum of 0.48 on December. MetUM reproduce this cycle, although their values are higher than ERA-I from July to December and smaller from January to May.

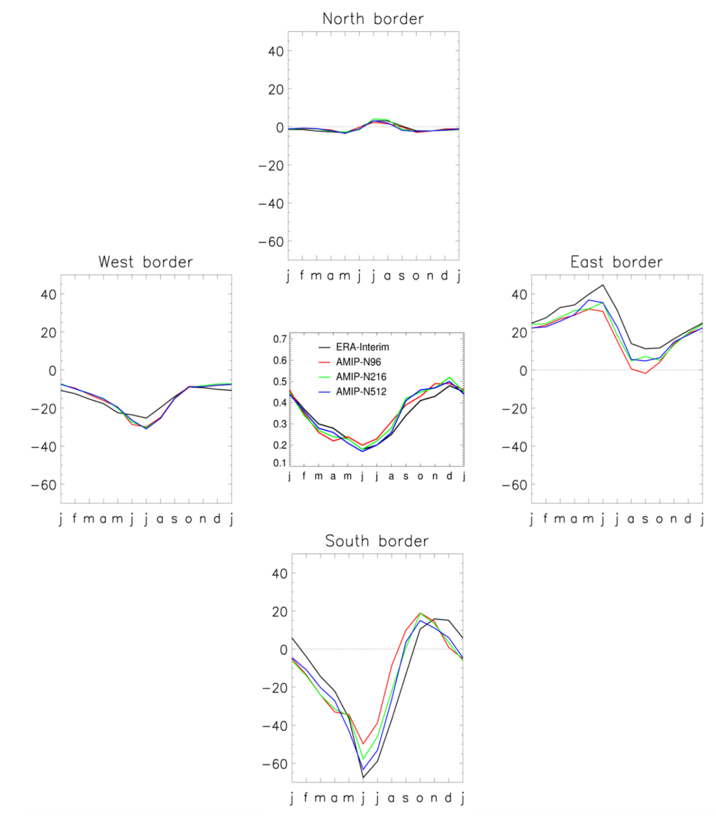

**Figure 3**. Sources of moisture in east Asia's hydrological cycle. Outer panels: annual cycle of water vapour fluxes across the area borders ($10^{12}$ Kg day$^{-1}$). Negative values indicate water vapour flowing into the region. Middle panel: precipitation recycling ration within the area. Borders are defined by the box in Figure 2.

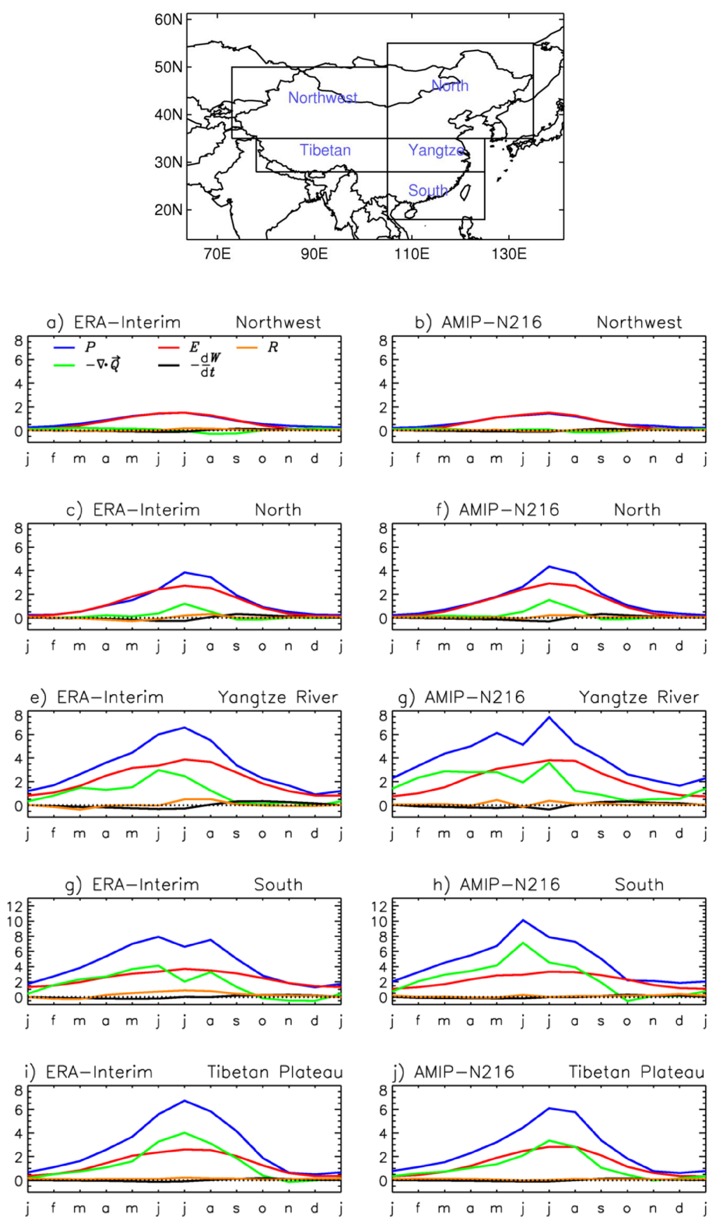

**Figure 4.** Monthly mean water budget terms over 5 east Asia domains shown in the top panel. The various terms in the budgets are represented as follows: precipitation in blue, moisture convergence in green, evaporation in red and the rate of change of column moisture in black. Residual non-conservation errors are shown in orange. Values of precipitation in the plots are equal to the sum of the other terms in the budget. Al quantities are spatial averages in land points over the 5 regions. Values are expressed in mm day$^{-1}$.

### Water budgets over 5 land domains

- Precipitation over land comes from three sources: moisture already present in the atmosphere, convergence of water vapour advected into the region by atmosphere circulation, and water vapour supplied by local evaporation from the land surface (recycling of fallen precipitation).
- Precipitation in Northwest and North regions comes mainly from local evaporation. In the Northwest domain the source of the small amount of precipitation comes almost entirely from local evaporation. There is a general good agreement between MetUM and ERA-I for all components in these regions. Large-scale moisture convergence is the main source of precipitation in the South and Tibetan plateau regions.
- Precipitation in the Yangtze river basin originates mostly from local evaporation, although its peak during the summer months is caused by a significant increase in moisture convergence. MetUM simulations fail to properly reproduce the seasonal cycle of moisture convergence in this region. They show too much convergence all year round and the transition to the summer monsoon starts too early in the simulations (an extra peak in April not seen in ERA-I).
- In the South region MetUM simulations show an excess of moisture convergence that increase at higher resolutions. As a consequence, the excessive precipitation error is exacerbated by increased resolution.

## References

[1] Rodríguez, J. M., S. F. Milton and C. Marzin, The East Asian Atmospheric Water Cycle and Monsoon Circulation in the Met Office Unified Model (2016), *Submitted*.

[2] Walters, D., et al. (2016), The Met Office Unified Model Global Atmosphere 6.0/6.1 and JULES Global Land 6.0/6.1 configurations, *Geoscientific Model Development Discussions*, doi:10.5194/gmd-2016-194.

[3] Williams, K., et al. (2015), The Met Office Global Coupled Model 2.0 (GC2) configuration, *Geoscientific Model Development Discussions*, **8** (1), 521-565.

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