# The dependence of Indian monsoon rainfall on Arabian Sea moisture fluxes and the impact of coupled model biases

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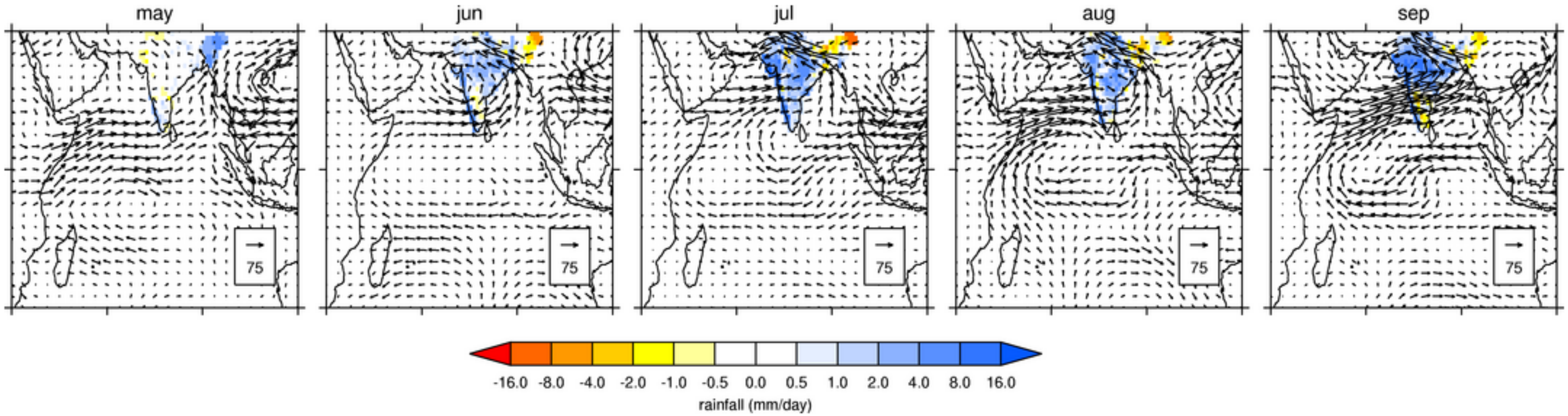
- Arabian Sea-monsoon relationship in observations
- Role of systematic coupled model SST biases in HadGEM3, with focus on Arabian Sea
- SST bias development and monsoon impact in initialised coupled experiments
- Effect on future predictions?

# Arabian Sea-monsoon relationship in observations

# In observations strong monsoon years rely on additional moisture fluxes across the Arabian Sea




*Anomaly of vertically integrated ERA40 moisture flux (vectors) and IITM/IMD rain-gauge rainfall (colours) for composites of strong minus weak monsoon rainfall years (1958-2001)*



*from Levine and Turner, Clim Dyn, 2011*

# Contemporaneous relationship between total monsoon rainfall and Arabian Sea SST is less clear

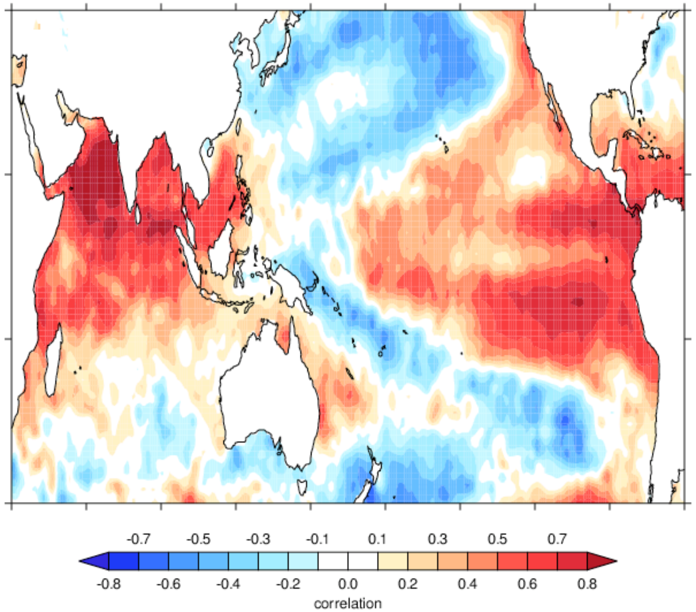
(see various other studies, e.g. Clark et al, 2000)

**reasons:** compensating impacts on land-sea gradient and moisture / strong air-sea coupling / dominating impact of ENSO

- SST-AIR correlations during monsoon season are weak and/or negative

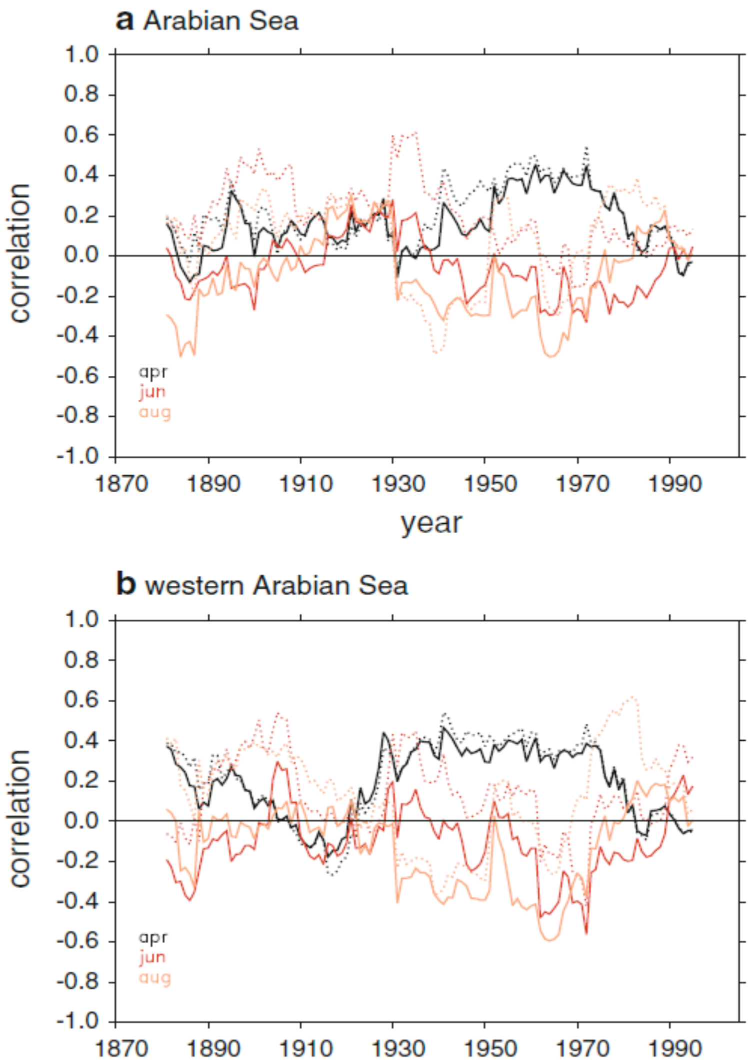
**note:** more positive correlations exist with smaller-scale regions such as W Arabian Sea SST-W Ghat rainfall (Vecchi and Harrison 2004; Izumo et al. 2008)

- removing effect of ENSO makes correlations more positive in recent decades




correlations of area-averaged Arabian Sea SST with SST elsewhere






*from Levine and Turner, Clim Dyn, 2011*

# Impact of coupled model Arabian Sea SST biases in HadGEM3

# HadGEM3 model
## development version of MetUM

- **Atmospheric model**

- horizontal resolution: N96 (1.25° x 1.75°)
- 38 levels in vertical
- Physical formulation: Mass flux convection with CMT (Gregory and Rowntree, 1990), Prognostic cloud PC2 (Wilson et al, 2008), etc.

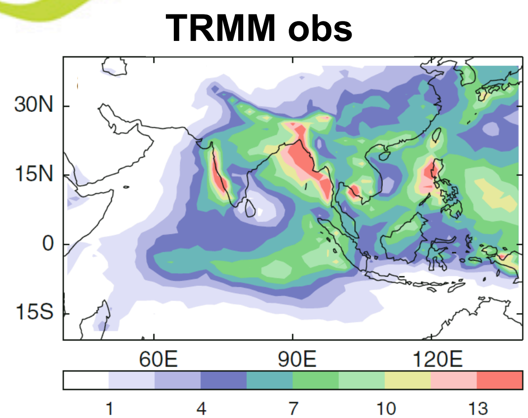
- **NEMO ocean model**: ORCA tripolar grid with nominal 1° resolution (up to 1/3° in the tropics), and 42 levels in vertical

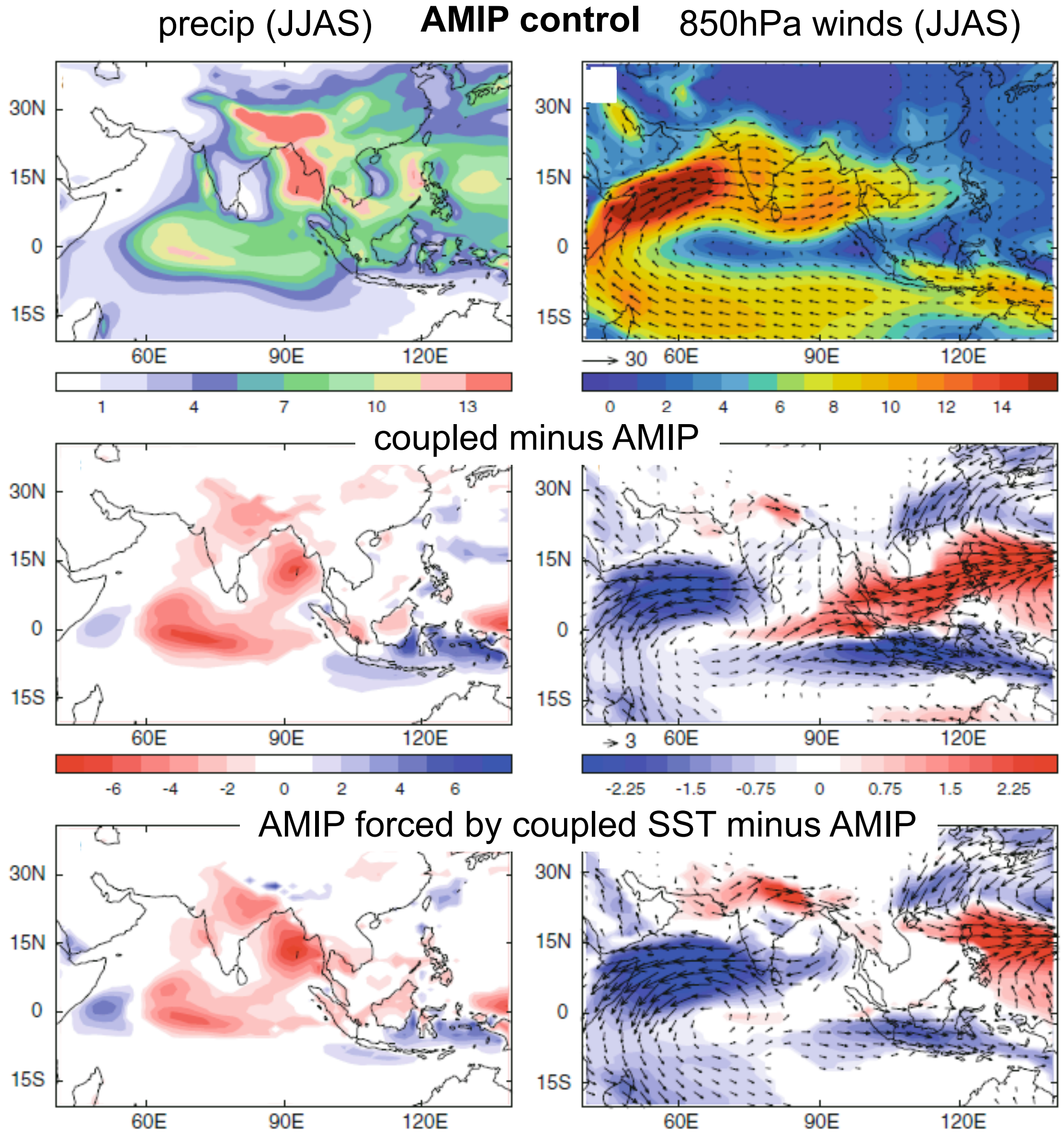
- **CICE sea-ice model**

Atmosphere-only configuration, including sensitivity experiments, run for 20-year period (1979-1998)

Coupled configuration run for 40-year period (present day control)

# Comparison of atmosphere-only and coupled model simulations of monsoon




HadGEM3 coupled model has **~30%** less monsoon rainfall compared to equivalent AMIP run

AMIP has realistic total JJAS (6.5 vs 6.8 mm/day in obs) and seasonal cycle of All-India rainfall

Observed AIR interannual variability is **only ~10%**

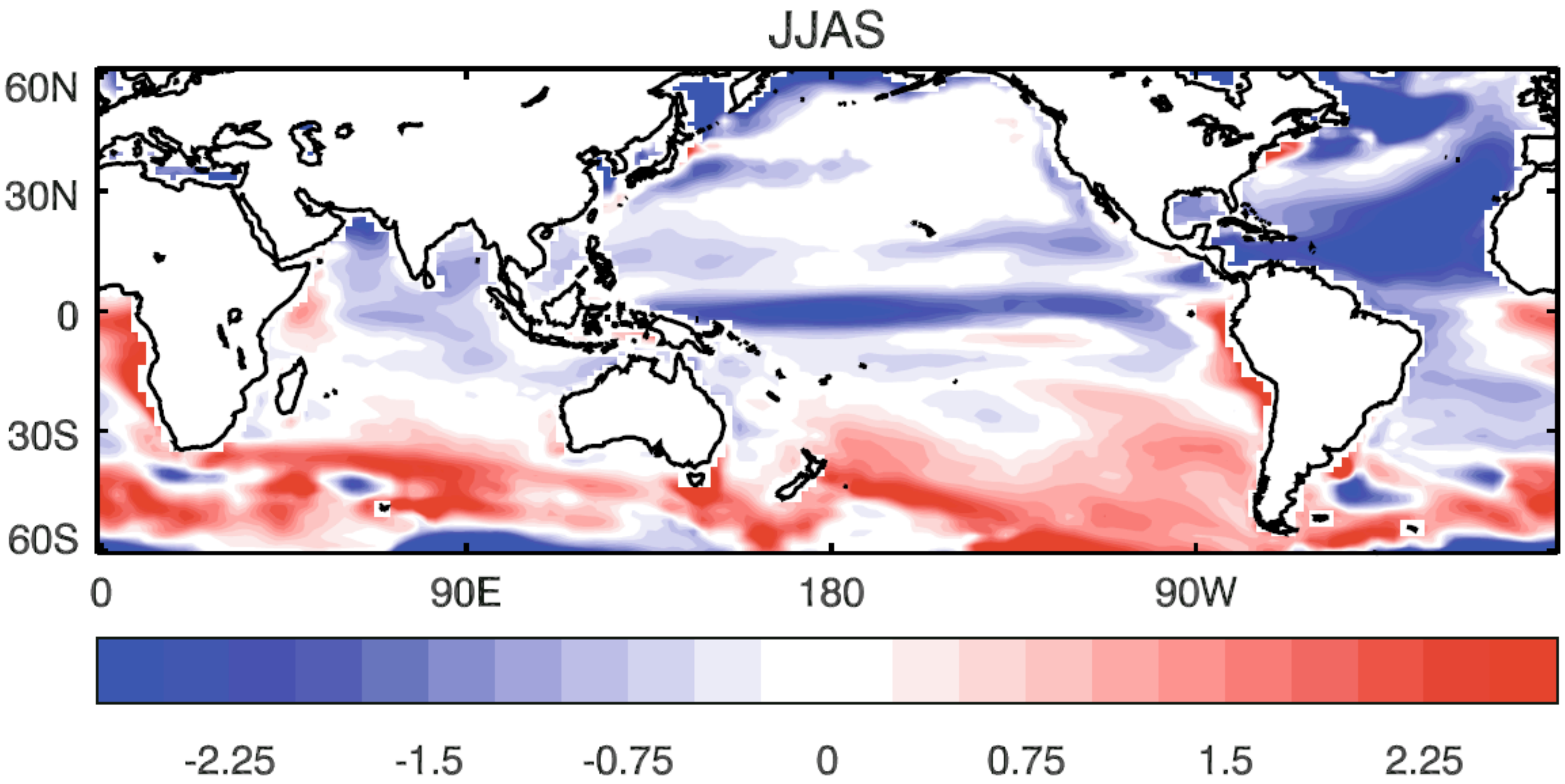
**Reduction caused by coupled model SST biases:** similar pattern and size of rainfall change in AMIP model forced by coupled model derived SST



*from Levine and Turner, Clim Dyn, 2011*

# HadGEM3-AO SST biases

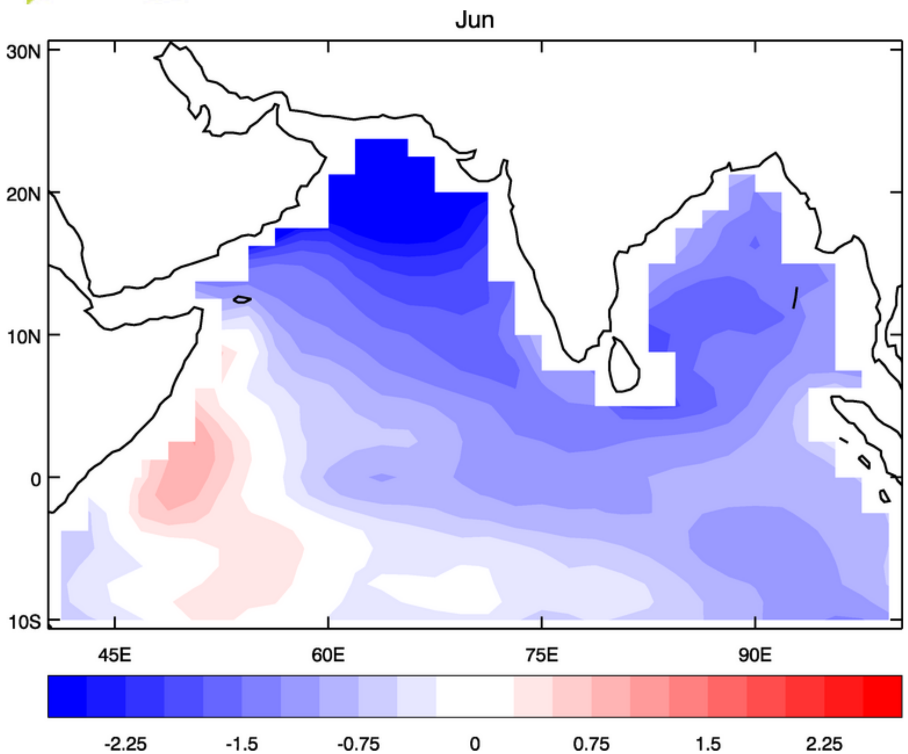
model has both local (e.g. Arabian Sea) and remote (e.g. equatorial Pacific) biases which may affect Indian monsoon

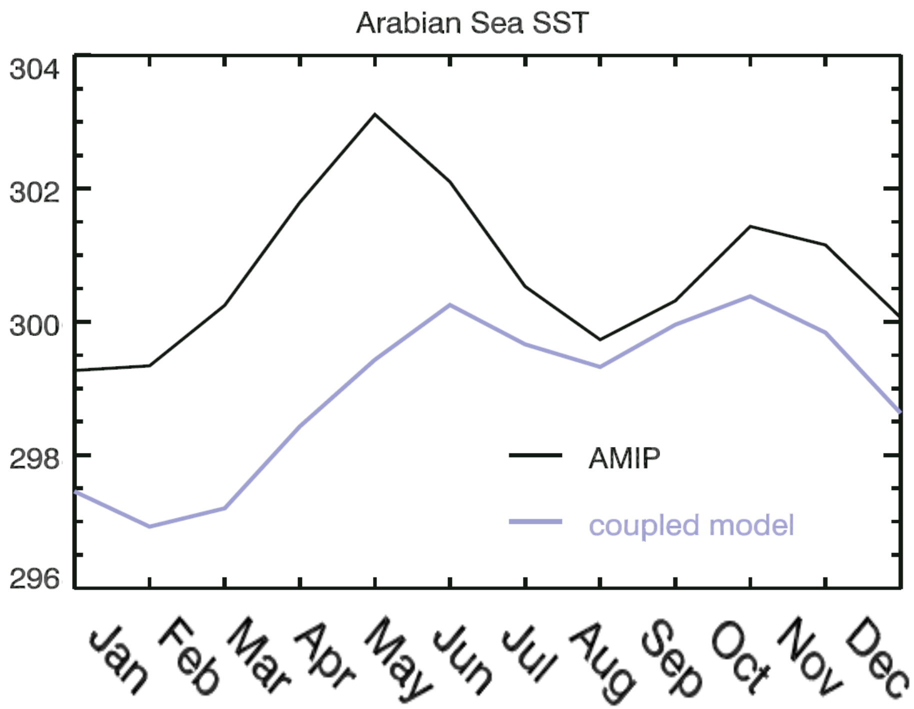





*from Levine and Turner, Clim Dyn, 2011*

# Arabian Sea cold SST bias is long-term systematic error in HadGEM3-AO




- cold Arabian Sea SST bias develops in winter due to strong wind stress

  (1) cold continental surface temperatures increasing meridional temperature gradient
  (2) strong equatorial convection forcing excessive convergence

- SST bias weakens in monsoon season due to reduced evaporative cooling
  (delayed monsoon onset, weaker flow, colder SST)

- **similar SST biases are also present in many CMIP3 / CMIP5 models**



*from Levine and Turner, Clim Dyn, 2011*

# Effect of applying coupled model style SST anomalies in AMIP experiments

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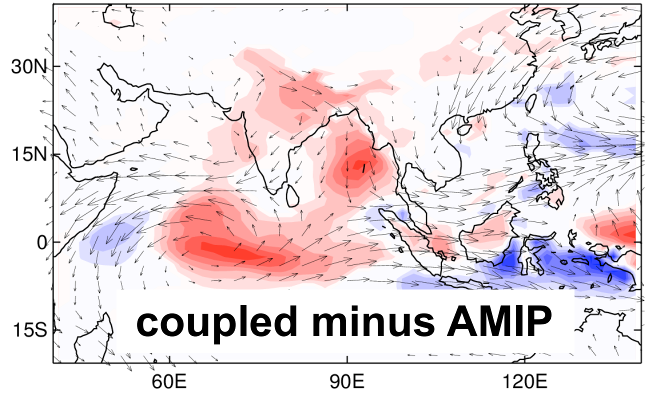
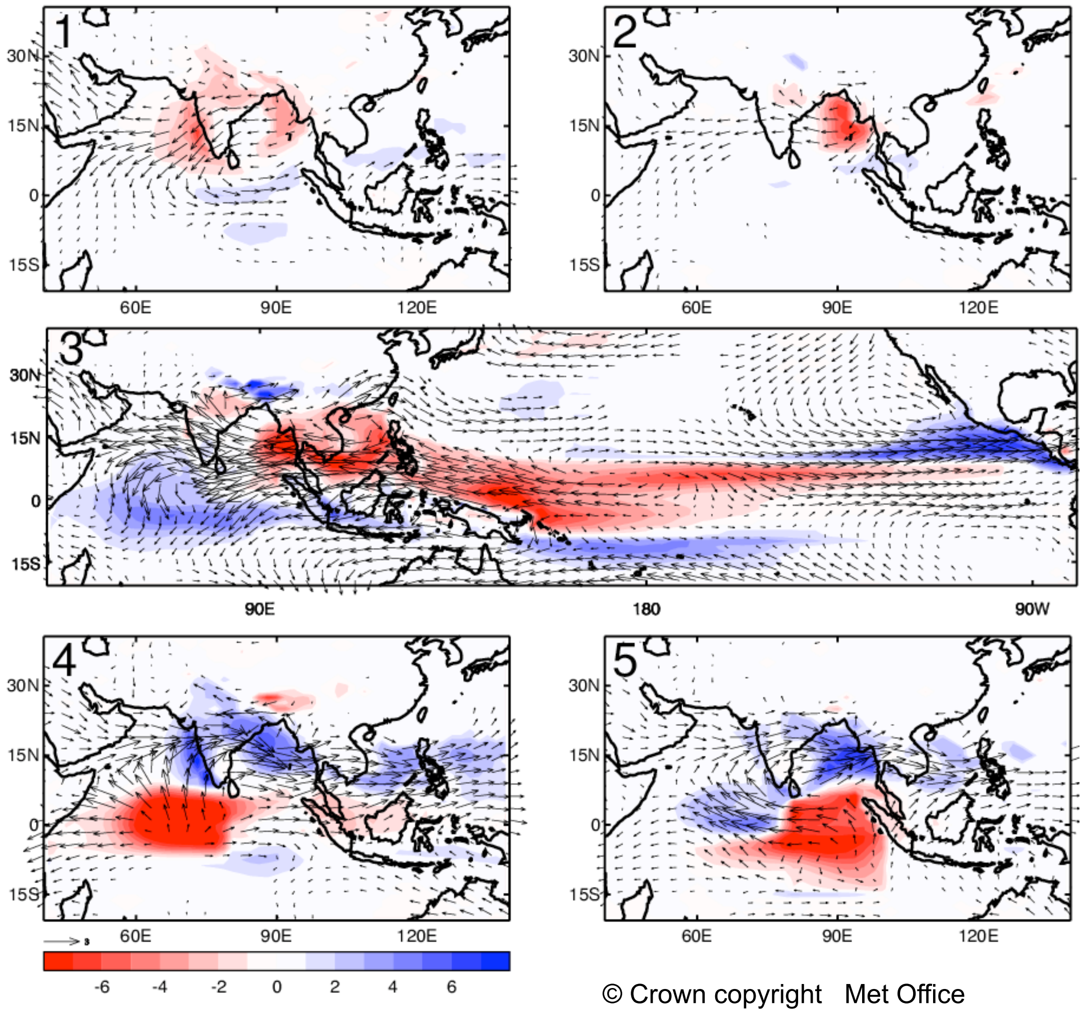
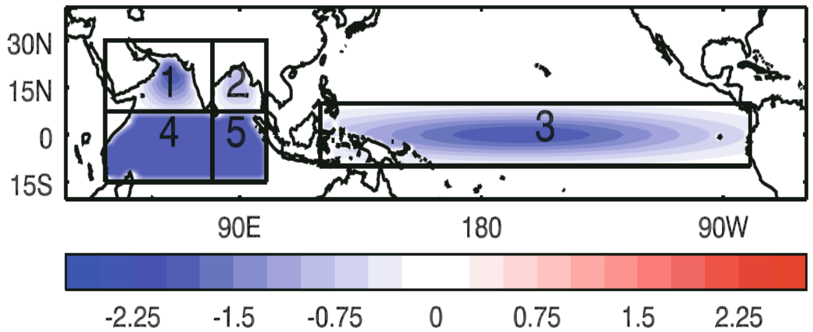



**rainfall (colours) and 850hPa wind (vector) anomalies**




- pattern / timing of change over India and Maritime Continent most consistent with local Arabian Sea / Bay of Bengal combination, and equatorial extension
- equatorial Indian Ocean cold bias has opposite effect by strengthening land-sea thermal contrast

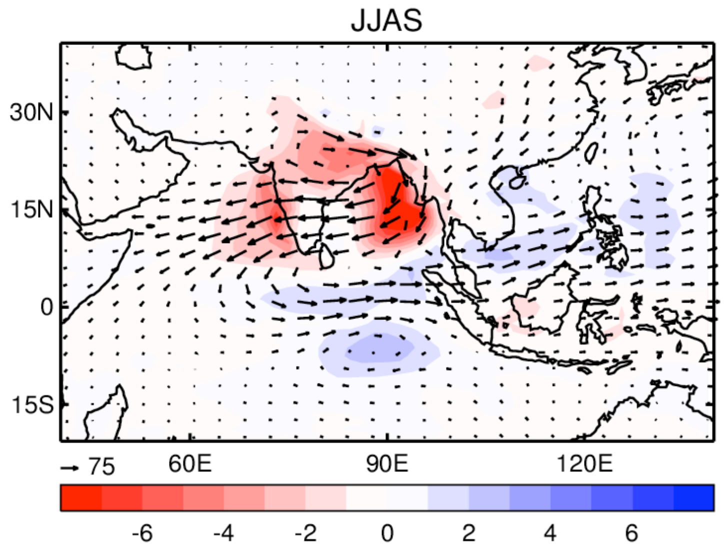
**SST anomalies applied to idealised AMIP tests throughout year**




*from Levine and Turner, Clim Dyn, 2011*

# Combined Arabian Sea and Bay of Bengal bias in AMIP experiment

**rainfall (colours) and vertically integrated moisture flux (vector) anomalies**

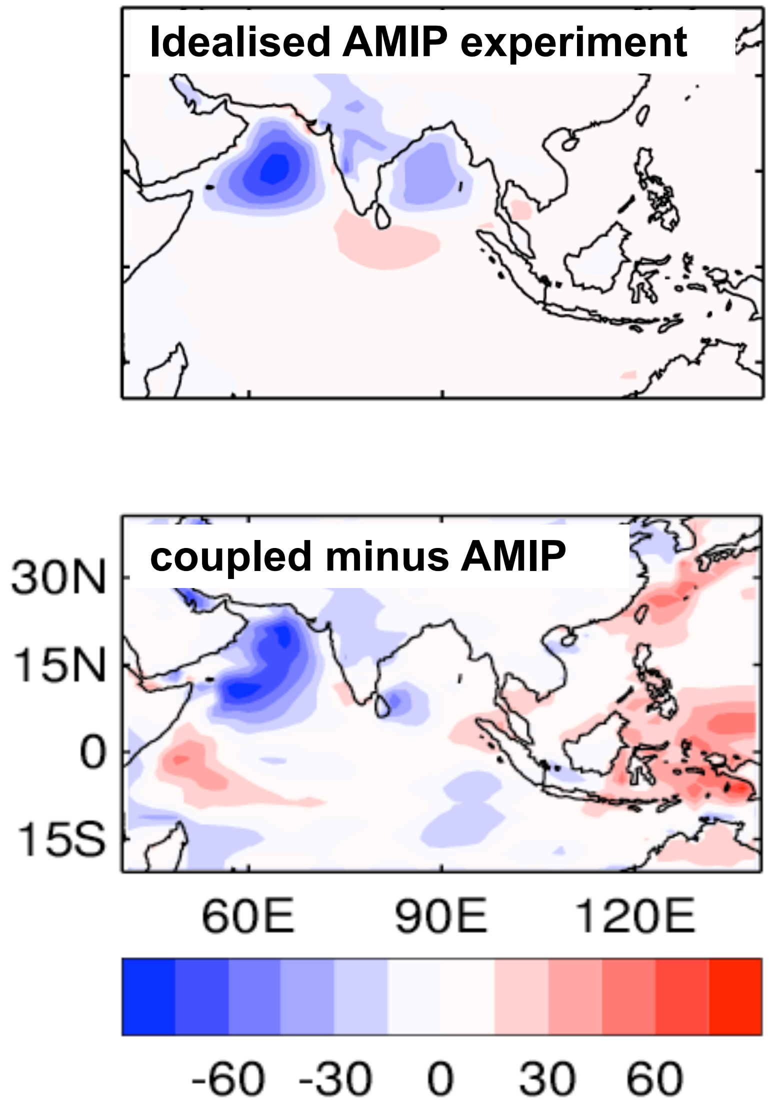



Combined bias results in 32% reduction in AIR, compared to 29% for coupled model

Monsoon rainfall varies linearly with magnitude of applied Arabian Sea SST anomaly in AMIP tests

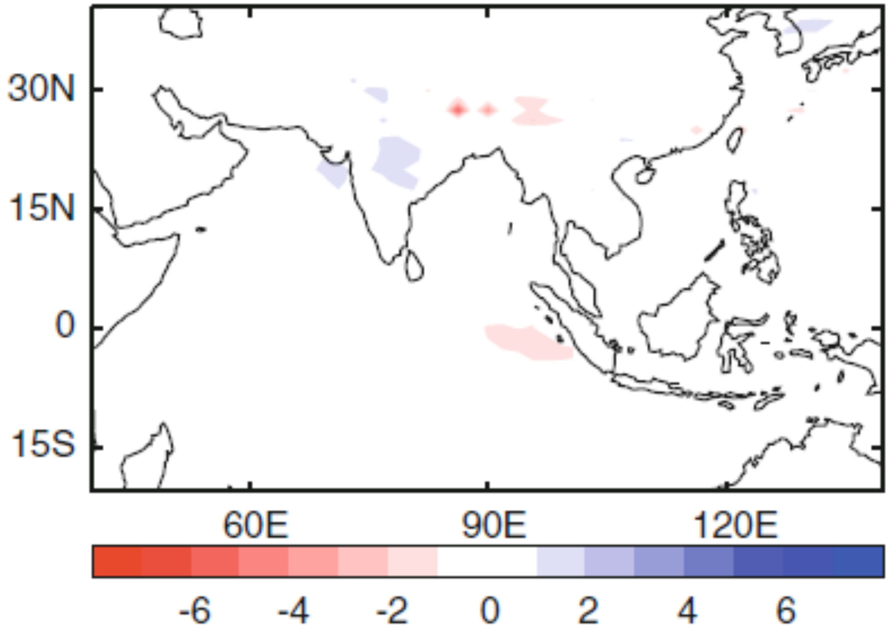
Impact in AMIP tests is **direct** and **local** effect of SST bias by weakening evaporation and moisture fluxes during monsoon season

**surface latent heat flux anomaly (W/m$^2$)**




*from Levine and Turner, Clim Dyn, 2011*

# Combined Arabian Sea and Bay of Bengal bias applied only prior to monsoon (Jan-May)




**Applying Arabian Sea and Bay of Bengal SST biases prior to start of monsoon season has virtually no impact in AMIP test:**

local biases impact coupled model during monsoon season through direct impact on moisture fluxes



*from Levine and Turner, Clim Dyn, 2011*

# Effect of Arabian Sea SST bias in initialised coupled simulations

# GloSEA4

## seasonal forecasting configuration of MetUM

Configuration used for analysis here:

- based on latest version of HadGEM3 (GA3.0):
  N96 (1.25° x 1.75°) in horizontal and 85 levels in vertical
- NEMO ocean, CICE sea-ice
- Seasonal hindcasts for 1996-2009, run for 7 months, initialised in Feb, Apr, May, Jun
- Atmosphere initialised from ECMWF re-analysis
- Ocean and sea-ice initialised from GloSEA4 ocean data assimilation (ODA) (parallel version of UKMO-FOAM ODA suite)
- 3 ensemble members (SKEB2 stochastic physics) per start date

# Arabian Sea SST bias reduced by ~1°C in latest version of HadGEM3

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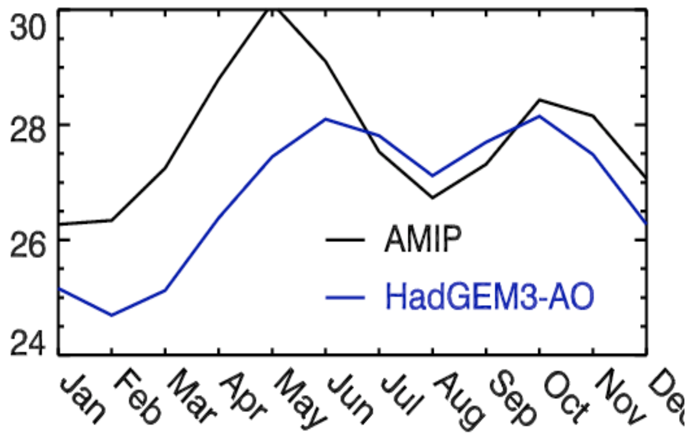
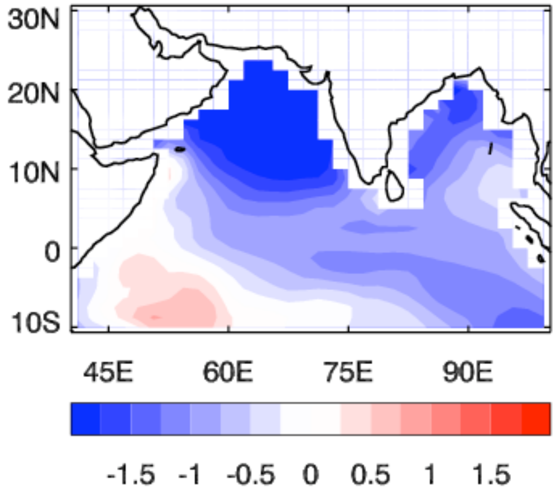
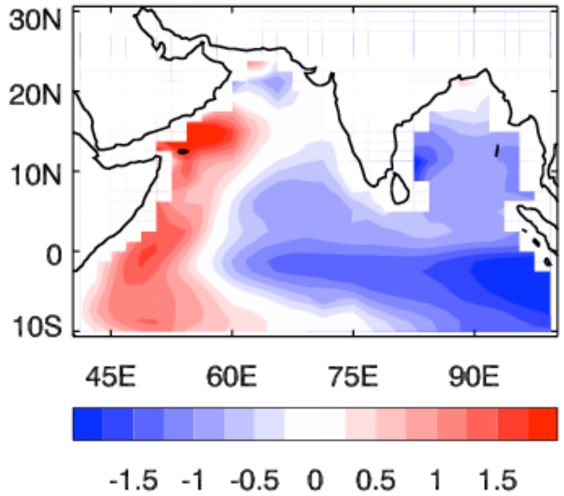
Arabian Sea SSTs




coupled minus obs



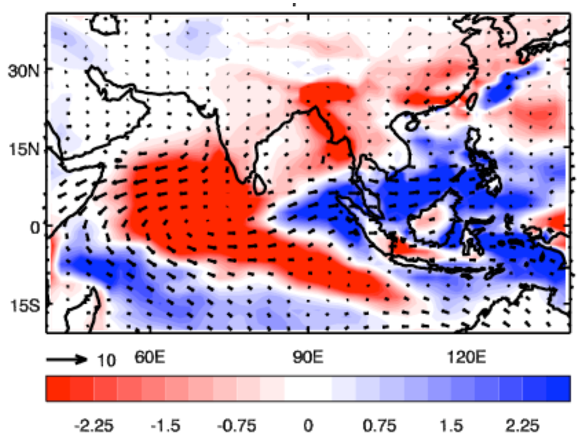

coupled minus obs



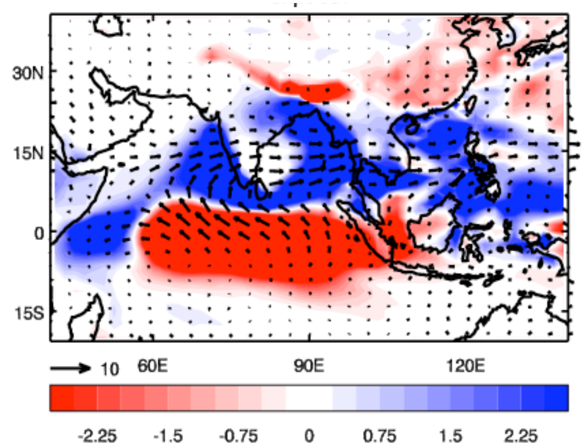

- Arabian Sea cold SST bias dominates in May-June, but weakens from July
- (E) equatorial Indian Ocean cold SST bias strengthens land-sea thermal contrast from July (c.f. cold equatorial AMIP tests)

balance of these biases determines impact on monsoon

**May-Jun mean**




**Jul-Sep mean**



# Arabian Sea SST bias weakens with reduced lead time in GloSEA4 hindcast set (1996-2009)

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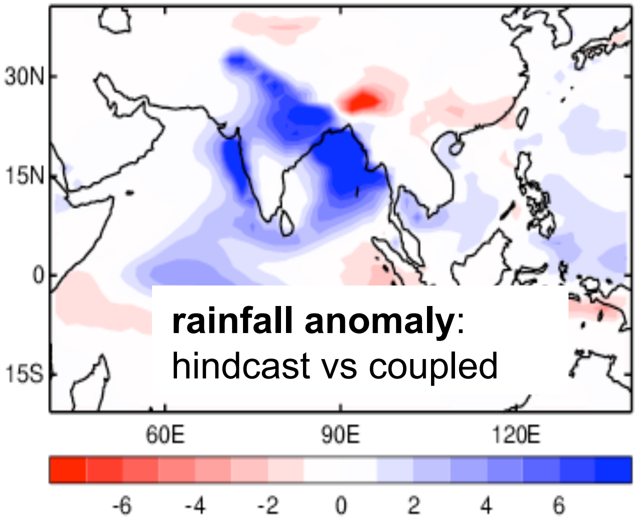
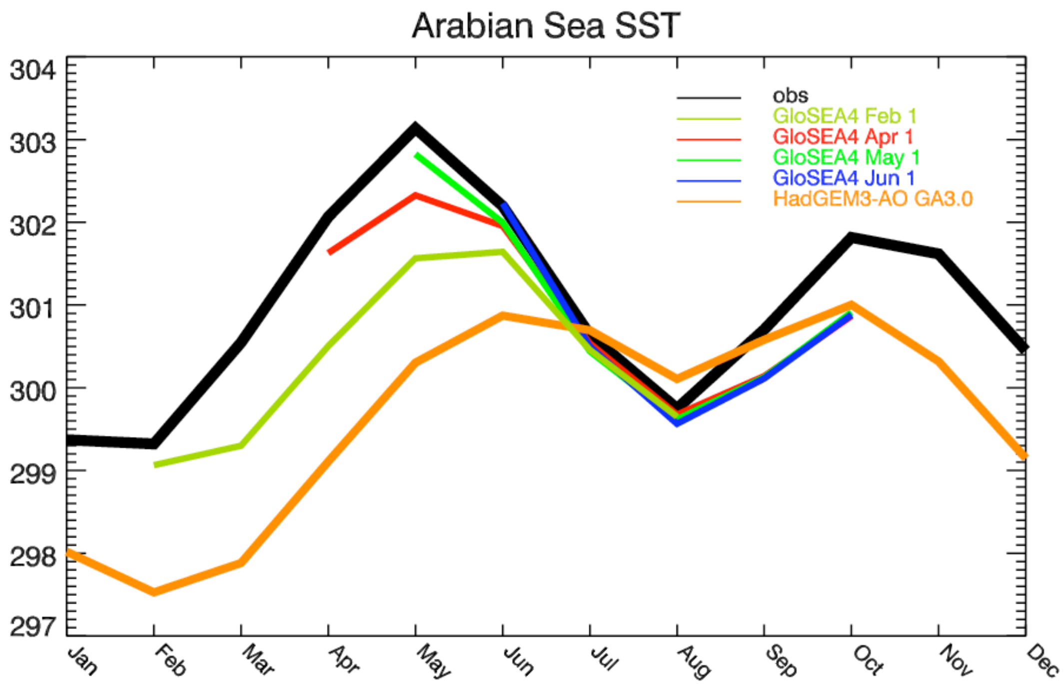
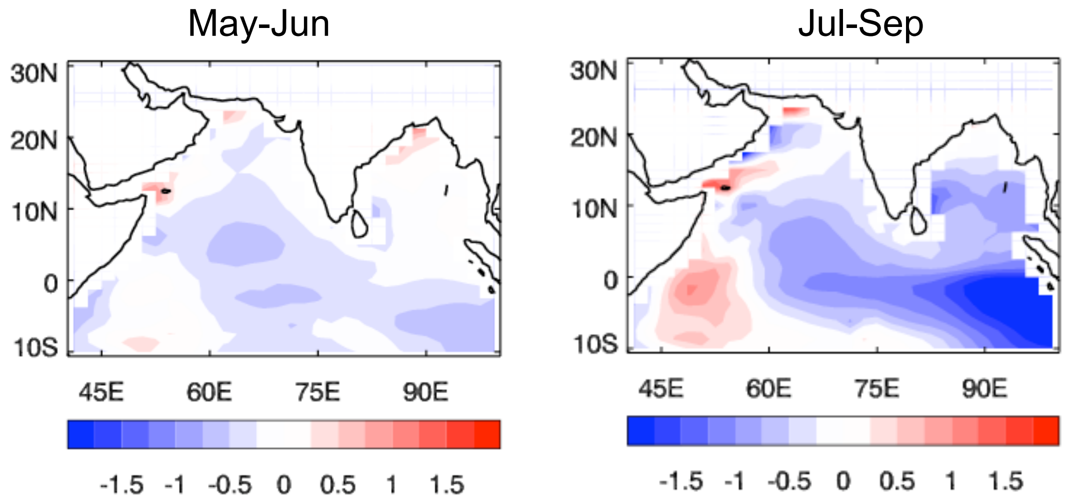
- Initialisation after the end of winter does not allow development of Arabian Sea cold SST bias
- Cold equatorial SST bias remains, developing as a result of excessive equatorial convection during monsoon, also enhances northwards progression
- Removing Arabian Sea SST bias with May initialisation strengthens monsoon



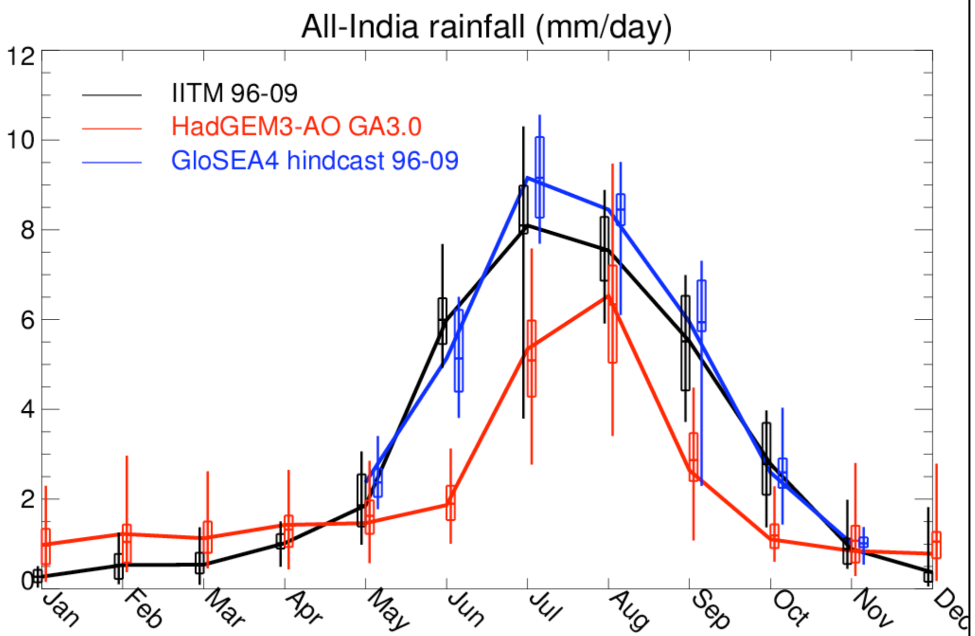



**GloSEA4 May initialisation SST bias:**



# Improvements to mean state coincide with improved seasonal cycle and aspects of intra-seasonal variability

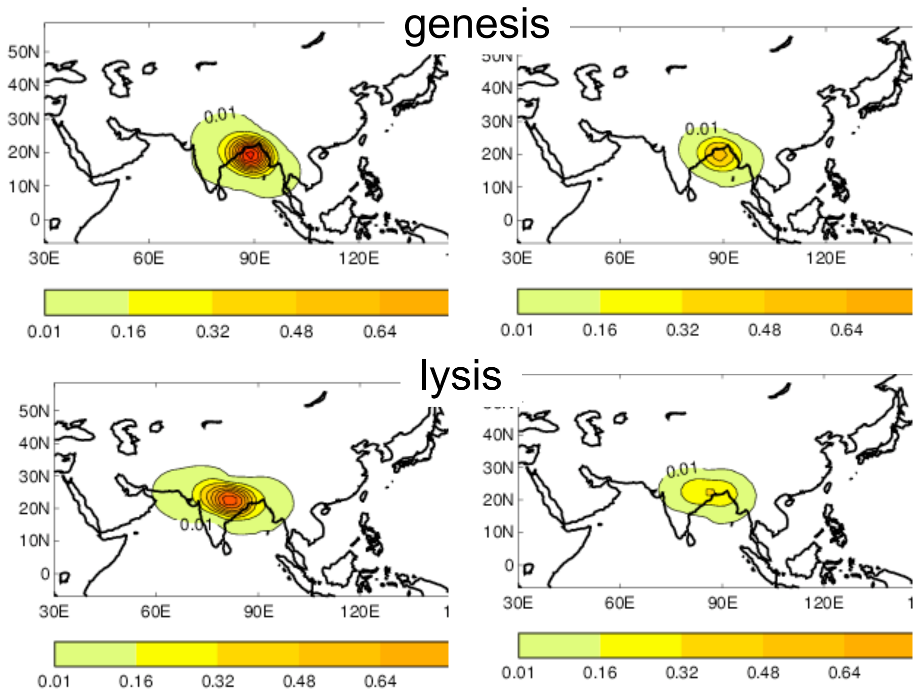



**All-India rainfall**
seasonal cycle significantly improved in GloSEA4 hindcast: improvements for all years

however, errors remain in predictability of small-scale indices (such as AIR), for example due to problems with simulating ENSO

**Monsoon depressions**
number and trajectories of depressions in GloSEA4 drastically improved compared to coupled model, and help bring rainfall to India interior

**GloSEA4 hindcast** **HadGEM3 coupled**



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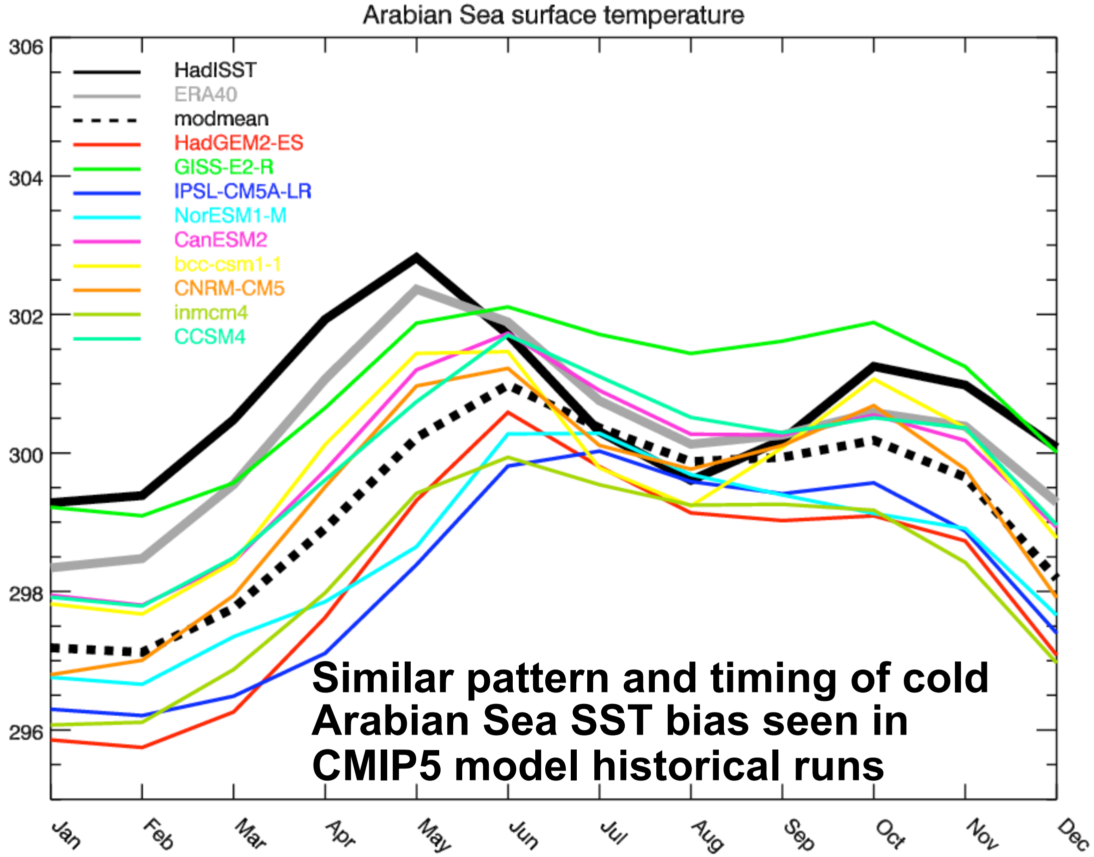
# Potential to affect future predictions: CMIP5 models

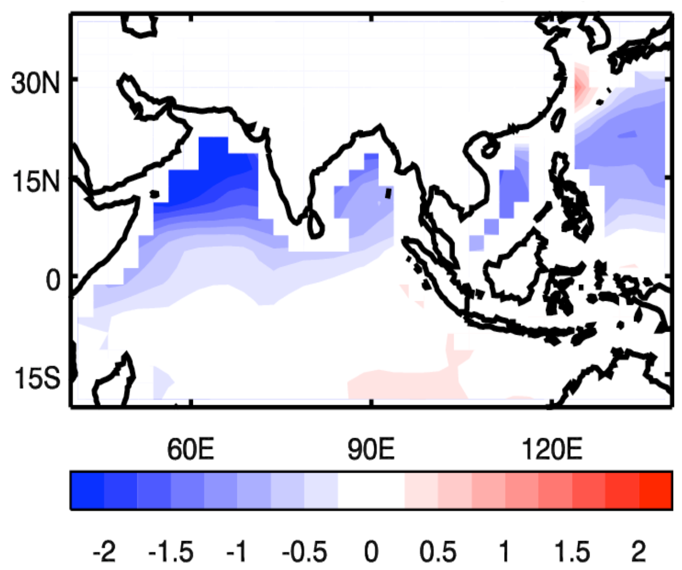
state-of-art models have problems simulating monsoon, and also have systematic errors in Arabian Sea

# Do Arabian Sea SST bias affect future predictions for monsoon?

- **CMIP5 mean:** small increase in future monsoon rainfall
- SST bias same order of magnitude as expected Indian Ocean warming over next 100 years
- This warming increases moisture available for monsoon rainfall, *however*, if cold SST bias removed would acceleration of moisture increase be larger due to nonlinear Clausius-Clapeyron relationship?




**CMIP5 multi-model mean SST bias (MAM)**



# CMIP5 historical:
## monsoon rainfall

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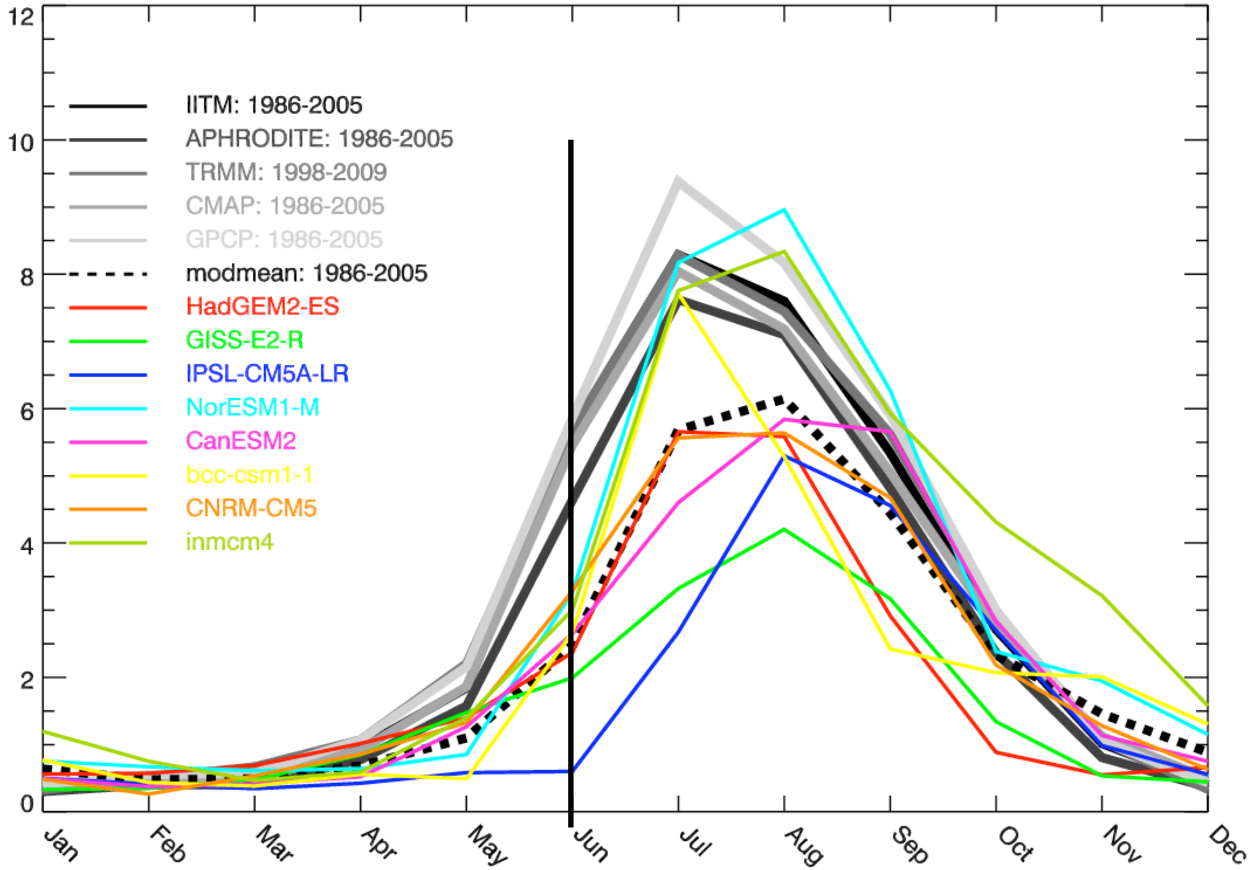
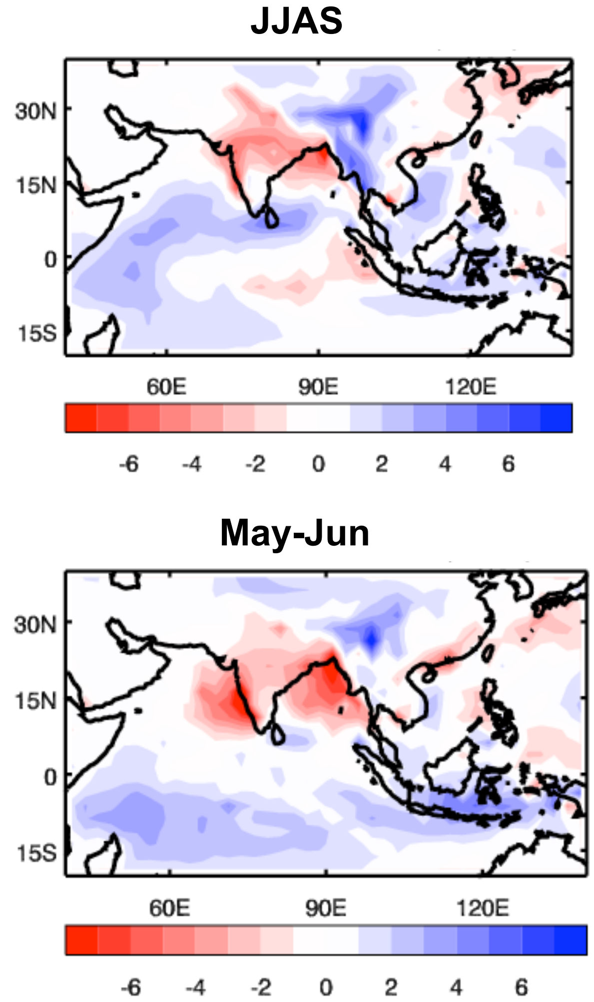
**Weak monsoon rainfall, particularly at beginning of monsoon, problem in almost all CMIP5 models, similar to effect of Arabian Sea SST bias in latest HadGEM3 version**




**CMIP5 multi-model mean rainfall bias**



# Common mechanism for CMIP5 Arabian Sea SST development?

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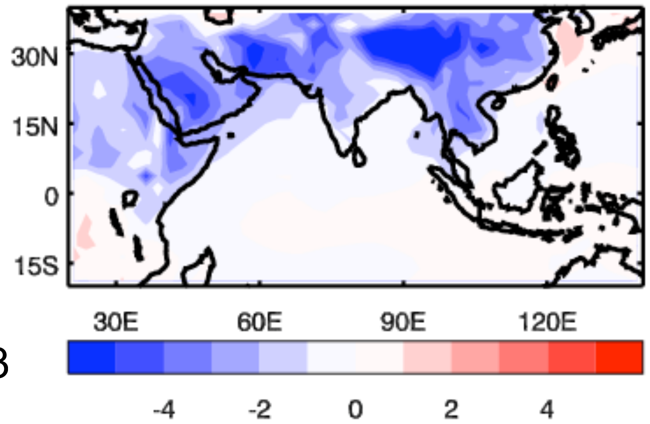
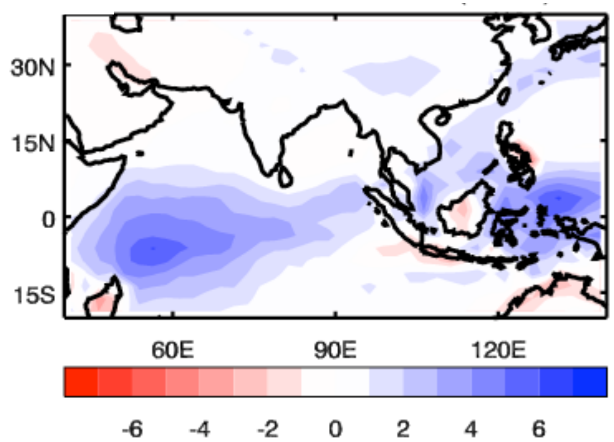
Continental surface cold bias in winter, and excessive equatorial rainfall / convergence is common amongst CMIP5 models, suggesting similar mechanism may operate as in HadGEM3

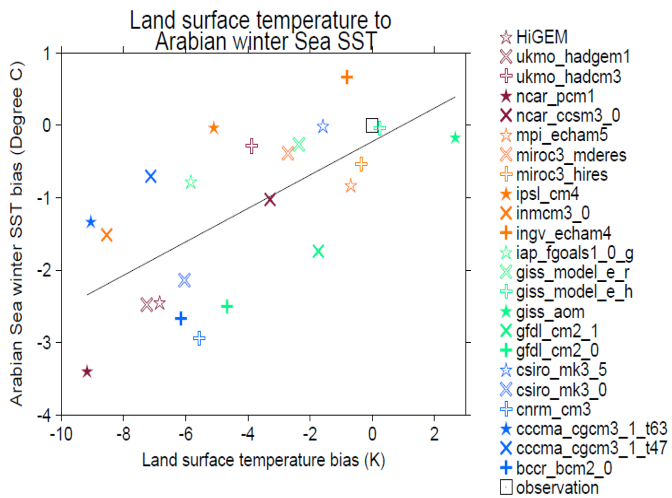
CMIP3 models show similar signal: from **Marathayil et al (in preparation)**

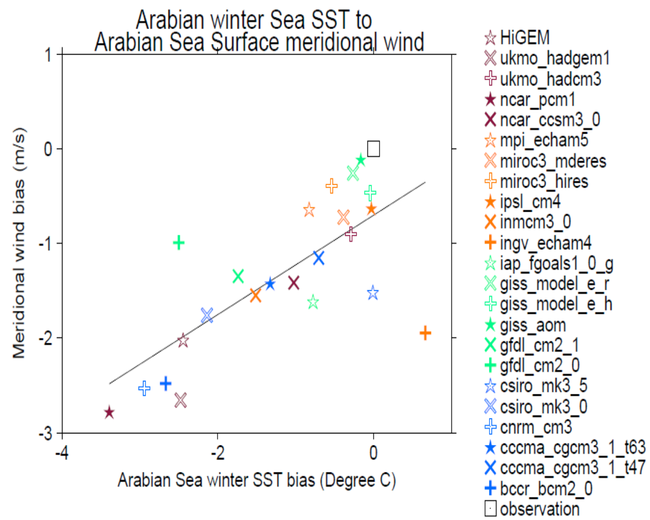
**CMIP5 multi-model mean T 1.5m bias (DJF) compared to ERA reanalysis**




**CMIP5 multi-model mean rainfall bias (DJF) compared to GPCP**



# Conclusions

# Conclusions

- Arabian Sea SST biases are common amongst state-of-the-art models, including in HadGEM3, where the bias significantly affects mean state monsoon rainfall
- In HadGEM3 cold Arabian Sea SST bias develops in **winter** through excessive monsoon northerlies, similar biases are found in CMIP5 models
- Arabian Sea SST bias affects monsoon through direct impact in **summer**, by weakening local evaporation and transport of moisture towards India
- Initialised forecasts, if initialised in May or later, do not allow Arabian Sea bias to develop, and significantly increase monsoon rainfall
- In coupled framework the impact of Arabian Sea SST bias can be counteracted by equatorial processes (excessive convection and subsequent cold bias) when Arabian Sea bias is weakened
- **Future work:** determine if mean state bias limits acceleration of moisture availability, and monsoon rainfall, in future climate predictions

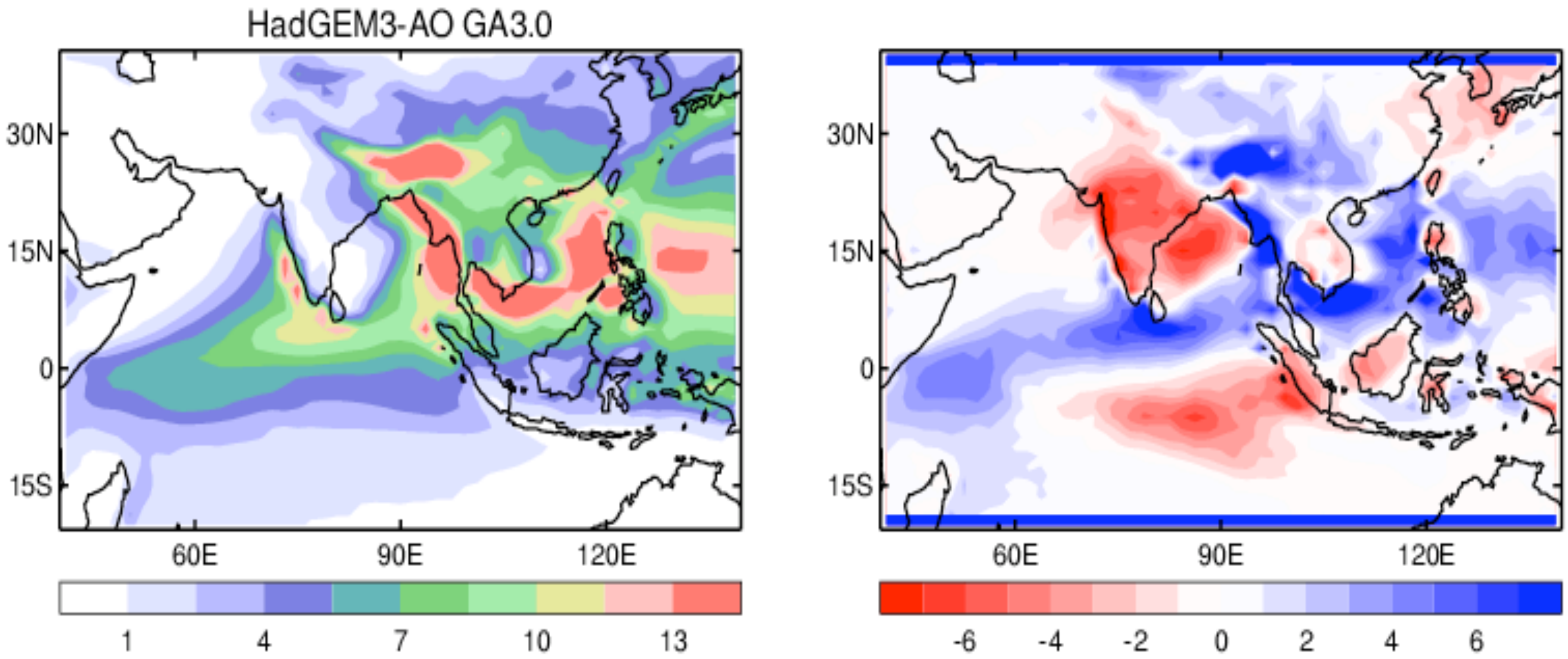
**References:**

RC Levine, AG Turner (2011), Dependence of Indian monsoon rainfall on moisture fluxes across the Arabian Sea and the impact of coupled model sea surface temperature biases, Climate Dynamics, *in press, doi:10.1007/s00382-011-1096-z*

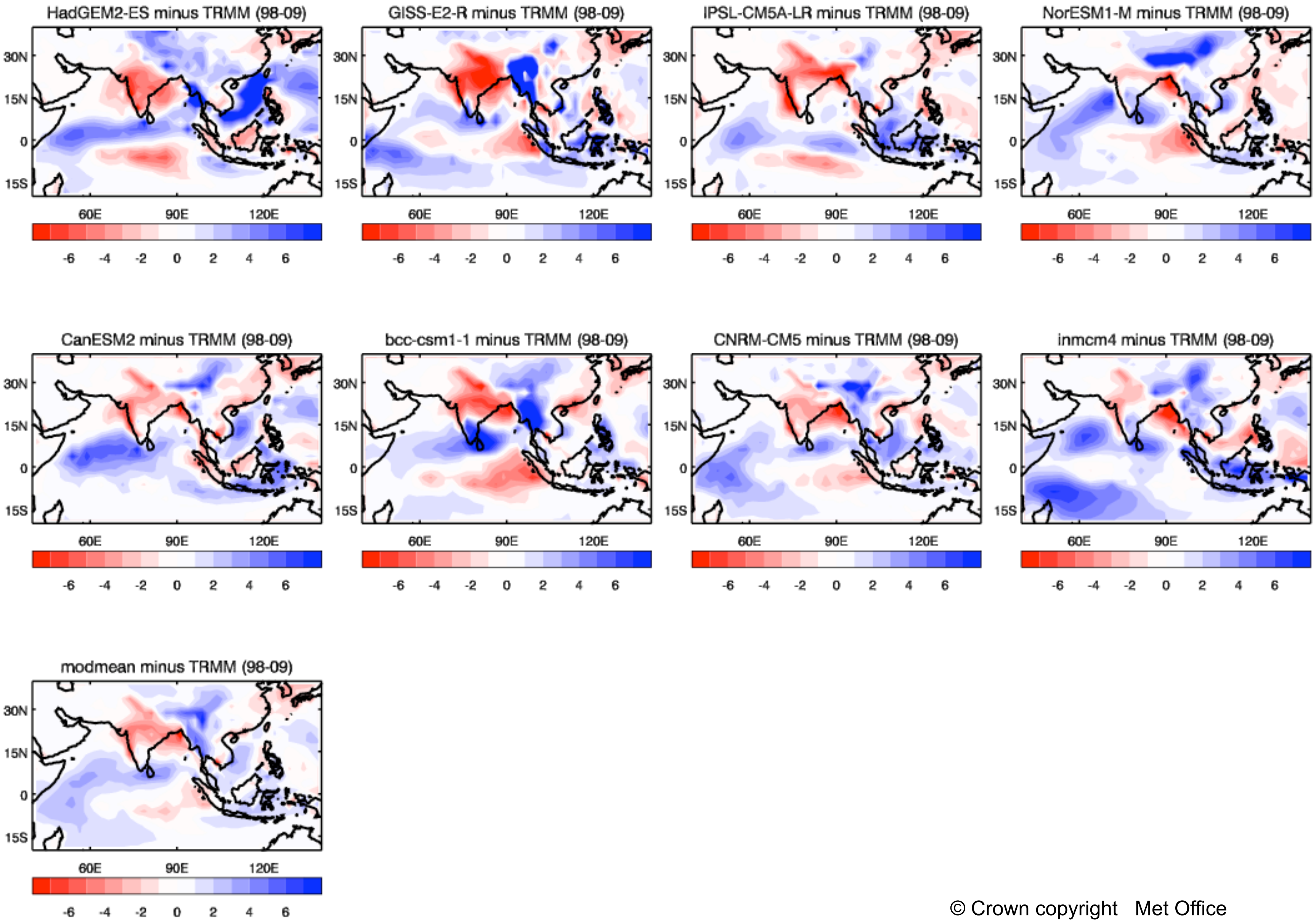
D Marathayil, L Shaffrey, A Turner, J Slingo, Examination of Arabian Sea SST biases in the HiGEM high resolution coupled climate model and the CMIP3 multi-model dataset, in preparation

# The end

# HadGEM3-AO (GA3.0) rainfall anomalies compared to obs



# CMIP5 historical rainfall (JJAS) bias



# GloSEA4 hindcast
## (May initialisation)

May-Jun mean latent heat flux anomalies