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Global coupled NWP: recent research progress at the Met Office

Presentation to CAWCR Workshop, Melbourne, Australia

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Overview

- ➢Introduction
- ➢Coupled NWP research phases
  - With GA3 science version (pre-ENDGame)
  - With GC2 (most recent)
- ➢Results
  - Atmospheric forecast skill (coupled vs. uncoupled) and unravelling differences
  - Examples of coupled phenomena/variability
    - MJO, diurnal SST, Arctic sea ice
- ➢Next steps and challenges

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Introduction

- Coupled air-sea-ice interaction is fundamental to the climate system; seasonal prediction and climate models have long recognised its role by using coupled model formulations
- The Met Office's strategy for seamless model science across prediction timescales has – in part – motivated our interest in exploring coupled NWP in research mode over recent years
- It's arguable that even on short to medium range NWP timescales improvements to forecast accuracy may benefit from a coupled formulation as opposed to prescribed SST/ice BCs
- The Met Office's has existing requirements to serve NWP as well as marine sector customers – so economies of scale could result from moving to coupled NWP systems for both output streams
- A further motivation for this work is that coupled NWP provides a useful modelling framework in which to investigate the origins of coupled systematic errors – in order to link error characteristics between NWP and longer (seasonal/climate) timescales
- The work described here has run alongside global coupled model development efforts (D. Walters talk at this meeting) and links also with work on coupled data assimilation (Lea et al. 2015; also described by D. Walters at this meeting)

Coupled NWP systems (June 2015)

System	Model resolution	Initialisation/ characteristics	Status
Coupled MyOcean forecasts	N216L85 ORCA025L75	Global Uncoupled DA ➔ operational NWP 4DVAR + FOAM NEMOVAR	Operational 7-day ocean forecast products via web (from single GloSea5 forecast member)
Coupled NWP case studies / hindcasts This talk	**N216L85 ORCA025L75**	**Global Uncoupled DA (Analyses of opportunity)**	**R&D Integrated with GC model evaluation and development**
Coupled NWP from coupled DA D. Walters' talk	**N216L85 ORCA025L75**	**Global Weakly coupled DA (Native analyses)**	**R&D Moving towards operational suite demo phase in 2016**
Coupled Environmental Prediction	1.5 km atmos and ocean	Regional for UK Regional DA	In initial development and prototyping phase

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Coupled NWP research phases

Model version/ Phase	Experimental design	References/comments
Phase 1 – early configuration of HadGEM3	6 winter and 6 summer start dates thro' 2007-08, each run to 30 days. 3-hourly coupling. Includes parallel atmosphere-only and ocean-only controls.	Shelly et al. 2011 (tech report)
GA3/GO1 - Phase 2	Over 100 start dates thro' 2008-10, each run to 15 days. 3-hourly coupling. Includes parallel forced atmosphere-only and ocean-only controls.	Johns et al. 2012 (tech report); Shelly et al. 2014; Johns et al. (in preparation)
GC2	Annual cycle of daily start dates Aug 2011-Sept 2012, run to 15 days, including parallel forced atmosphere-only controls. Feb 2010 daily start dates, run to 6 days. Hourly coupling as standard.	Analysis currently in progress; also used as a basis for CNWP sensitivity tests and science development

All research phases have used MetUM/NEMO/CICE Global Coupled physical model configurations at 'standard' resolutions of N216L85 (atmos) and ORCA025L75 (ocean)

GA3 (Phase 2) experimental design

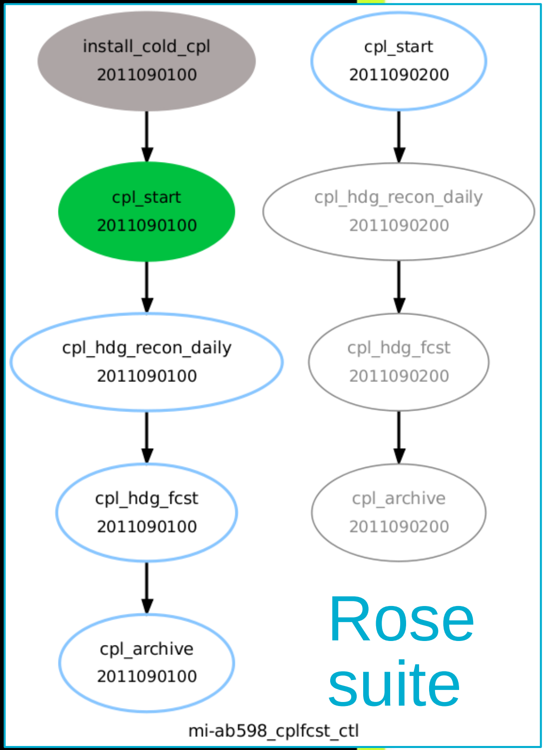
Coupled NWP 15-day initialised hindcasts

- 3-hourly atmosphere-ocean coupling
- Atmosphere/land initial conditions: Met Office operational NWP analyses at 12z from the archive (represents pre-GA3 science)
- Ocean/sea ice initial conditions: 12h ocean forecast from FOAM–NEMOVAR analyses at 00z

Control atmos-only NWP and ocean-only 15-day initialised hindcasts

- Same resolution and setup as coupled
- Persisted SST anomaly for atmos-only, 3h mean fluxes from coupled used to force ocean-only
- Ocean-only controls for a subset of start dates

GC2 experimental design



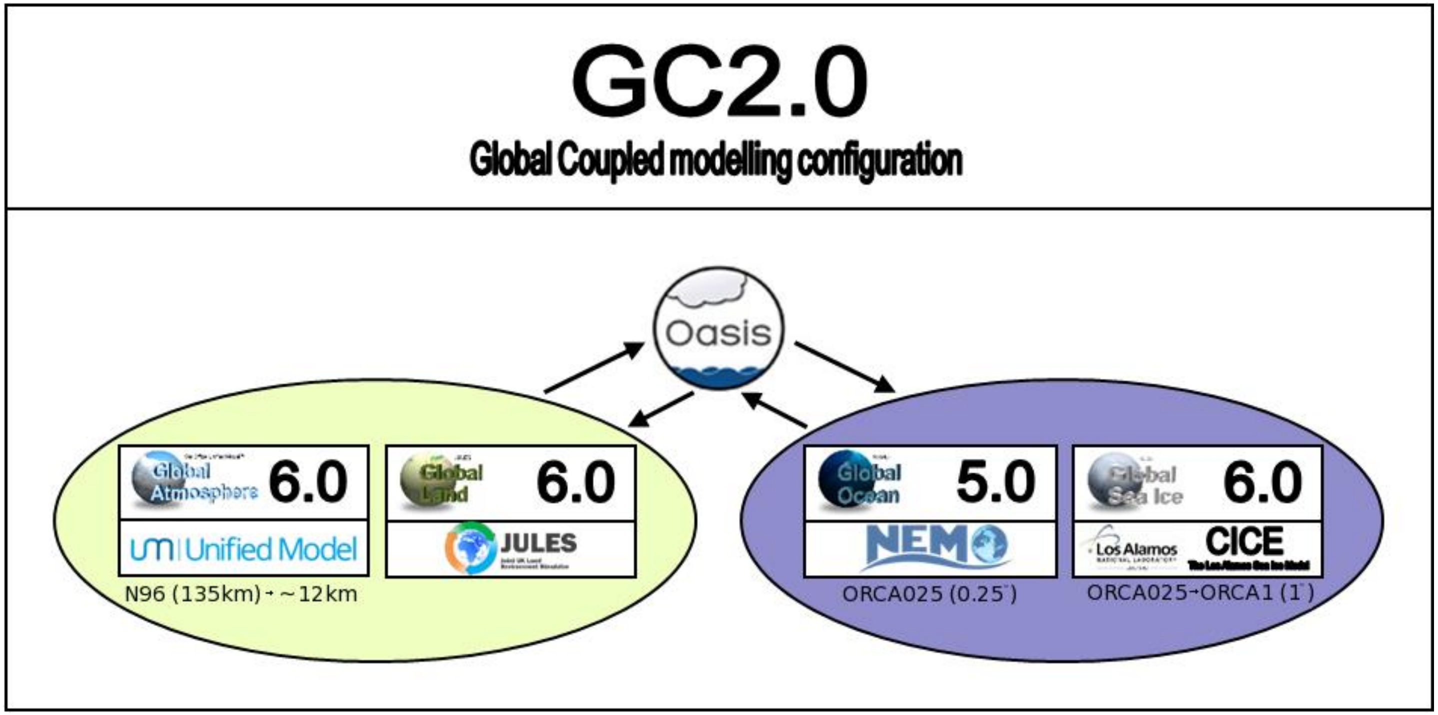
Coupled NWP 15-day initialised hindcasts

- 1-hourly atmosphere-ocean coupling
- Complete annual cycle with daily starts from mid-August 2011 to mid-Sept 2012 (*a few failed*)
- Atmosphere/land initial conditions: Met Office operational NWP analyses at 00z from the archive (represents pre-GC2 science)
- Ocean/sea ice initial conditions from: FOAM(v13)–NEMOVAR reanalyses at 00z (GO5-like ocean science: Megann et al. 2014)

Control atmos-only NWP 15-day initialised hindcasts

- Complete annual cycle with daily starts from mid-August 2011 to mid-Sept 2012 in parallel
- Same resolution and setup as coupled
- No ocean-only controls (yet)

GC2 – Global Coupled Model 2.0



[D. Walters - talk on Thursday]

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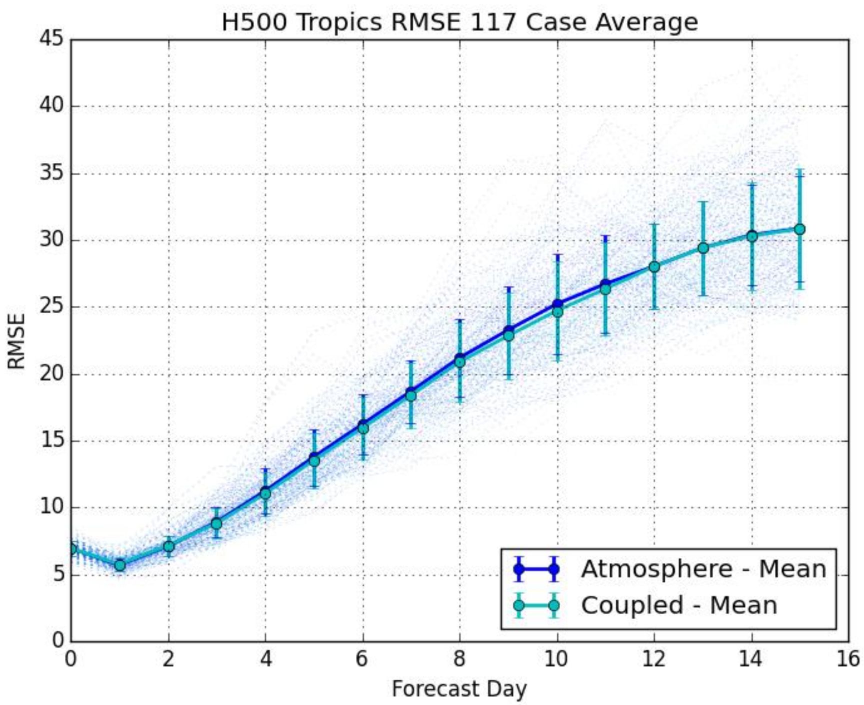
- Next steps and challenges

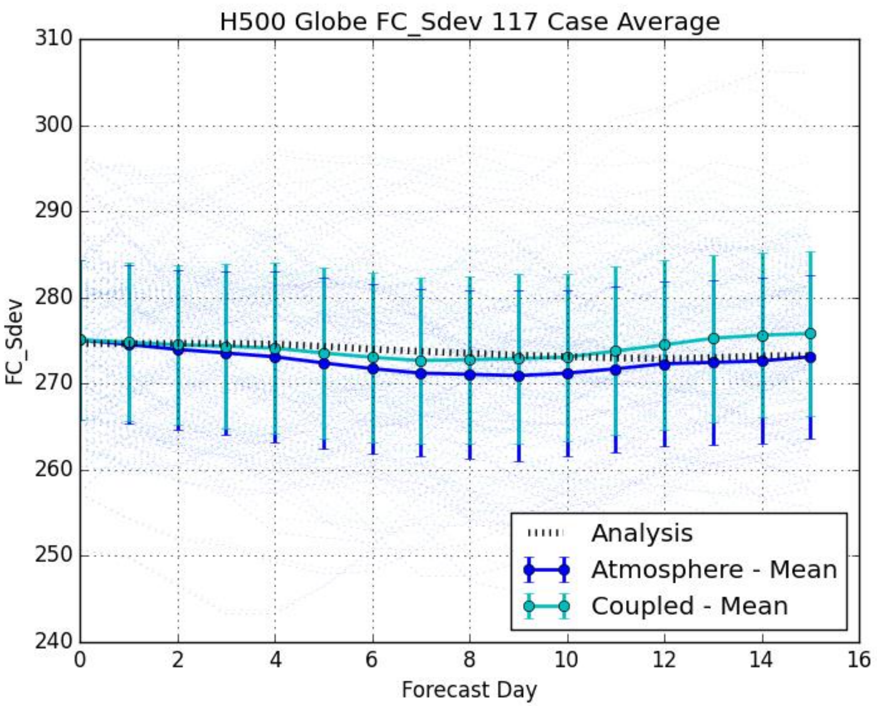
Coupled (C) versus Uncoupled (A) verification vs ECMWF analyses for 117 GA3 hindcasts

H500 Tropics - RMSE



C ~ A at most lead times (similar skill)
C has slightly lower RMSE at 4-12 days

H500 Global – Spatial stdev



C retains more spatial variance than A beyond day 2 lead time (better?)

[Johns et al. in prep]

Coupled vs. uncoupled skill

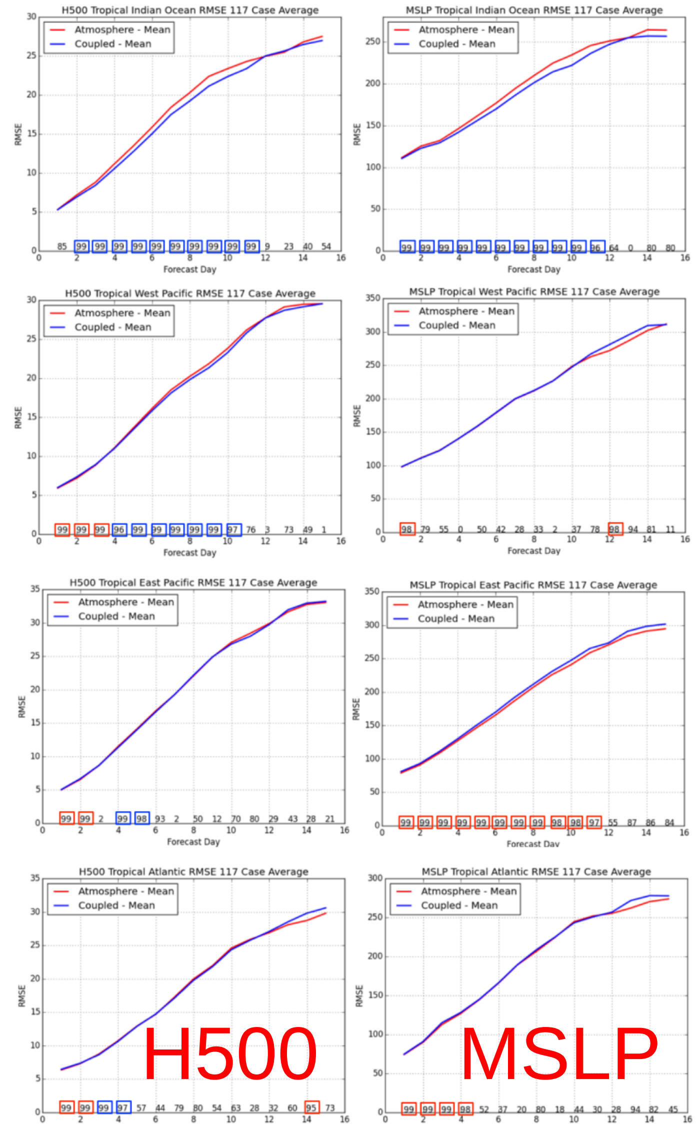
RMSE vs. EC analyses – Phase 2 expts:117 cases

Indian Ocean

West Pacific

East Pacific

Atlantic



[Johns et al., in prep]

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Coupled vs. uncoupled skill

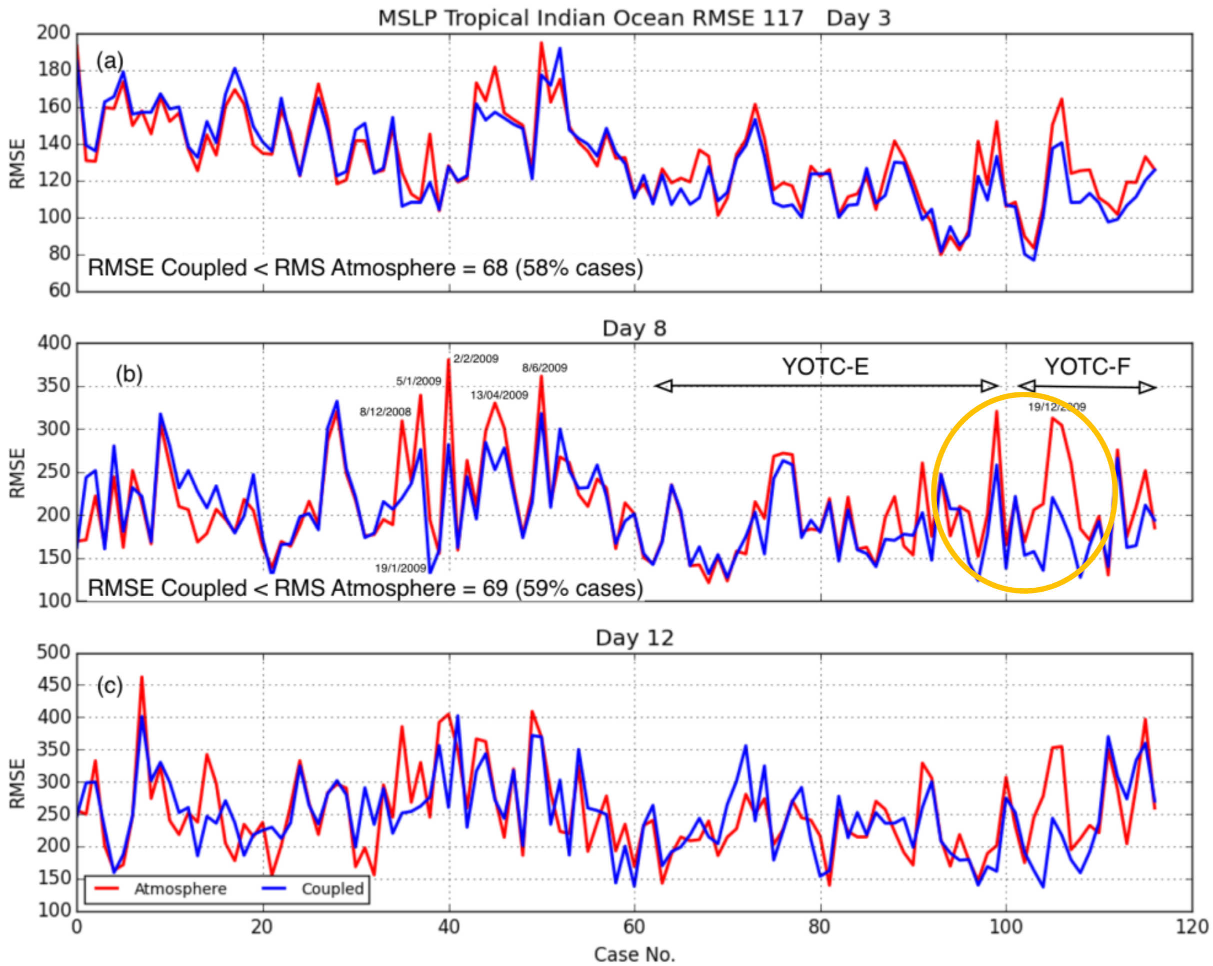
Indian Ocean MSLP RMSE – Phase 2 expts: 117 cases

[Johns et al., in prep]

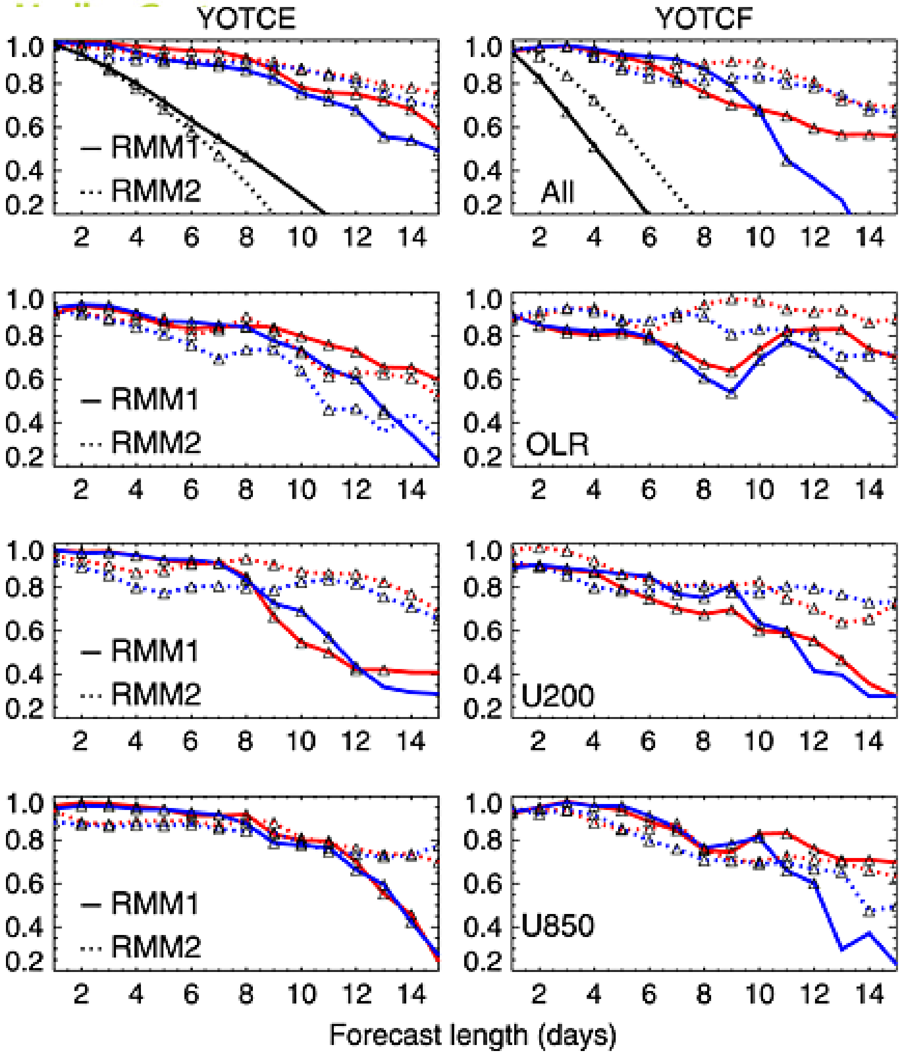
Day 3

Day 8

Day 12



MJO results – anomaly correlation scores of RMM1 and RMM2 during YOTCE & YOTCF



[Shelly et al., 2014]

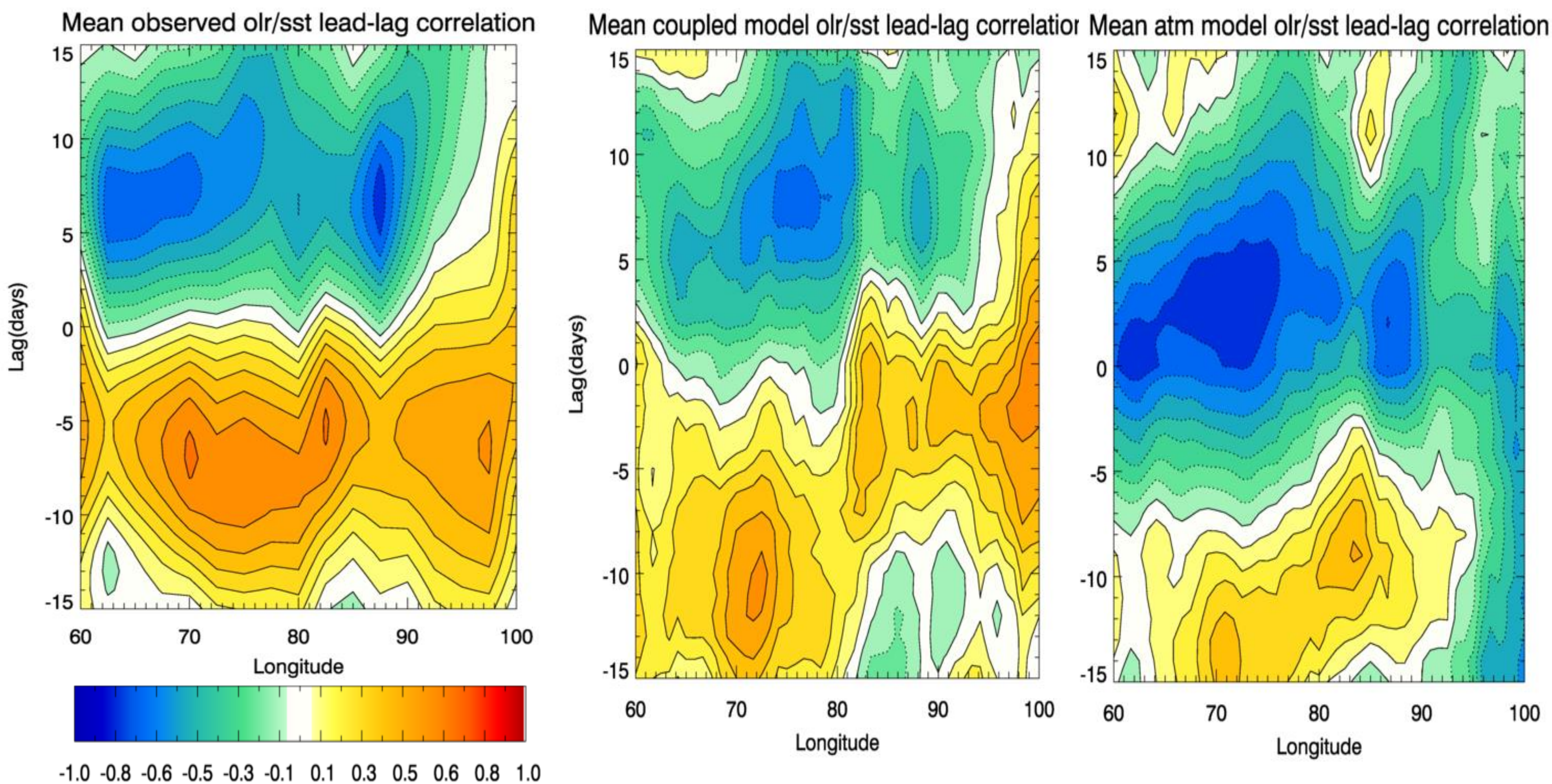
Similar skill out to day 11 for RMM2, after which coupled is slightly more skilful.

Persistence rapidly diverges from the dynamical hindcasts (top), with a rapid loss of predictability.

During YOTCF (right), atmosphere has greater RMM1 predictability from days 5 to 10, after which the score rapidly deteriorates. Coupled scores remain above 0.6 at these later lead times (right), extending predictability by ~5 days in the case of RMM1 for combined fields (top). However, little difference between coupled and atmosphere scores for RMM2.

OLR/SST phase relationship : Indian Ocean

Observed state	Coupled model	Atmosphere control



Warm SST's lead enhanced convection by ~5-10days

[Shelly et al., 2014]

Day 5

MJO related fluxes have no influence on SST so convection adjusts to a location where SST is favourable Results in an in-phase relationship

Coupled model maintains phase lagged relationship

Links between ocean wave and MJO activity in the Indian Ocean in YOTCE period

- Shelly et al. (2014) also show that enhanced convection and strong surface winds likely associated with preceding MJO activity in mid-October 2009 in YOTCE excites an oceanic Kelvin wave which propagates eastward along the equator reaching the Maritime Continent in late November.

- There are then signals of westward propagating, downwelling Rossby waves in the period between October 2009 and January 2010 . The latest observed wave, triggered in late Nov, coincides with YOTCE MJO propagation into the Maritime Continent, and from early Dec moves West reaching 80 deg E by mid-Jan.

- The phase 2 hindcasts over this period capture these features reasonably well (at lead times of 1 and 14 days).

Diurnal SST

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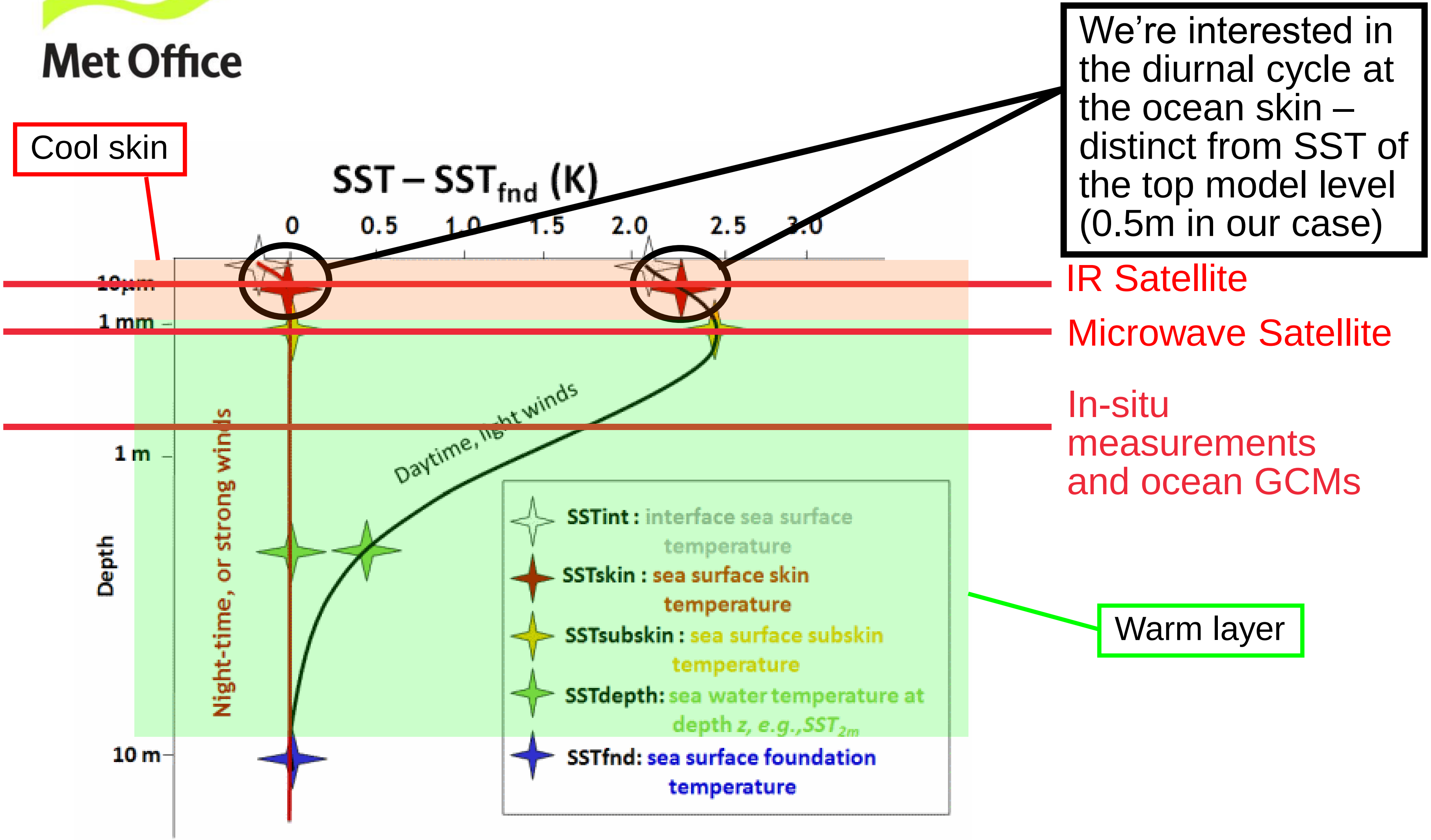
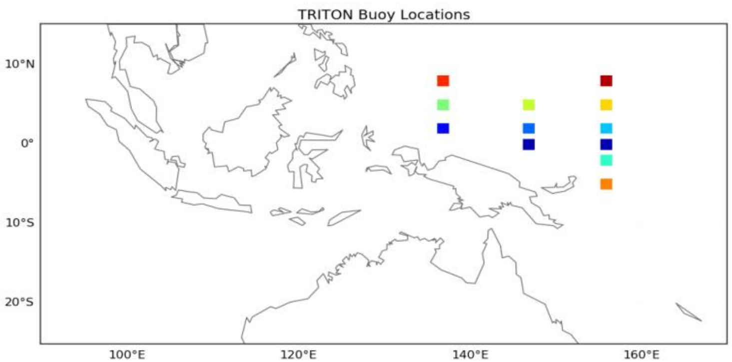


Picture courtesy of the GHRSST consortium

[James While]

Evaluation of dSST (0.5m) in GC2 coupled NWP experiments (in-situ measurements)



Simulations:
Coupled NWP hindcasts using GC2 at N216ORCA025.

5-day hindcast run starting every day of February 2010.

Observations:
12 TRITON moored buoys, on the tropical West Pacific. Measurements at ~1m.

SST minima and maxima in each day determined using the algorithm of Sykes et al. (2011)

	MIN			MAX			RANGE		
FCST	R (ANOM)	BIAS	RMS	R (ANOM)	BIAS	RMS	R	BIAS	RMS
Day 1	0.78	-0.03	0.18	0.86	0.34	0.44	0.79	0.37	0.46
Day 2	0.69	0.01	0.23	0.78	0.33	0.48	0.69	0.31	0.45
Day 5	0.53	-0.04	0.28	0.49	0.07	0.41	0.23	0.11	0.35

Evaluation of dSST (at 0.5m) in GC2 hindcasts against satellite skin SST data

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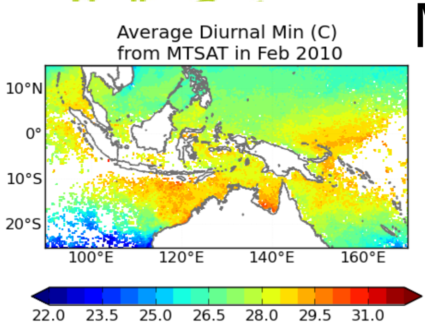
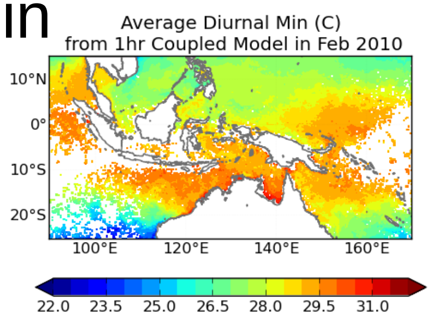
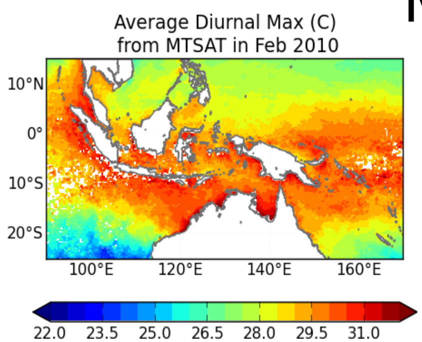
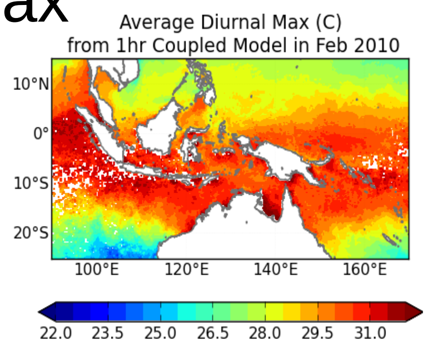
Min



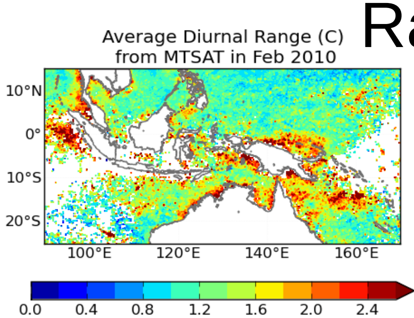


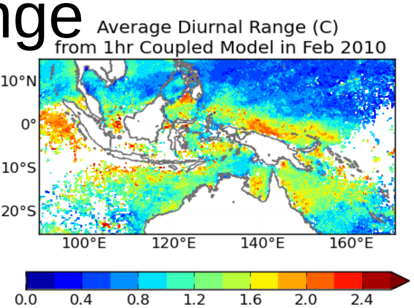
Max





Range





MTSAT-1R SST skin dataset (left) over the tropical Warm Pool (TWP+ dataset)

Minima and maxima in each day determined using the algorithm of Sykes et al (2011)

Model (right) overestimates the diurnal minima for most of the TWP+ domain. Maxima are relatively well represented.

Consequently, dSST range is underestimated in most of the TWP+ region: average bias of ~ -0.33C.

Modelled dSST range is insensitive to coupling frequency (1h vs. 3h) but 1h coupling moves min and max forward in time by ~ 1 and 2 hrs respectively.

Coupling frequency	minima	maxima
3hr	3.50	0.61
1hr	2.50	-1.60

Average timing bias (hrs)

Simple prognostic skin SST scheme in GC2

Met Office Hadley Centre

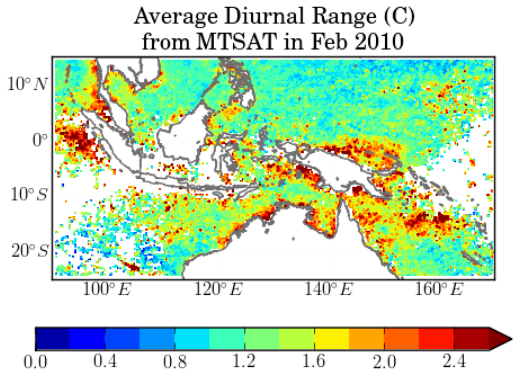
$$F_{\text{surf}} = \frac{2K_e}{h}(T_{\text{skin}} - T_{\text{surface layer}})$$

Sensitivity tests of scheme with constant effective thermal conductivity, K_e.

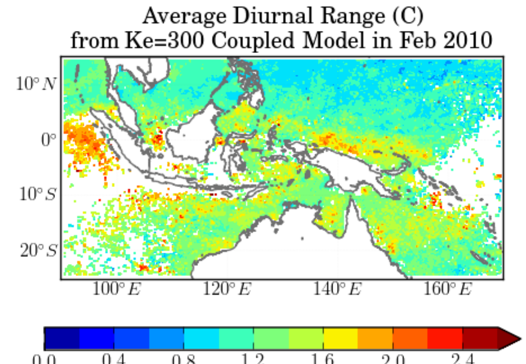
Evaluation of coupled NWP hindcasts on TWP+ region with hourly coupling.

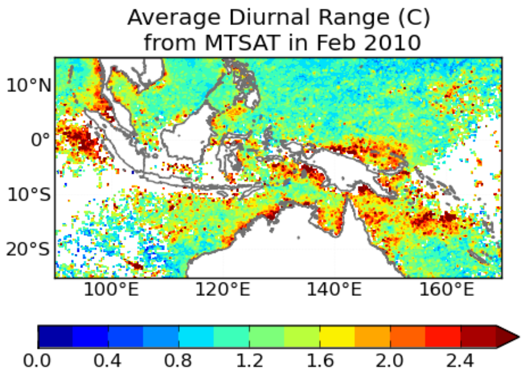
K_e = 300 W/mK: average dSST–range bias ~ -0.08C

MTSAT

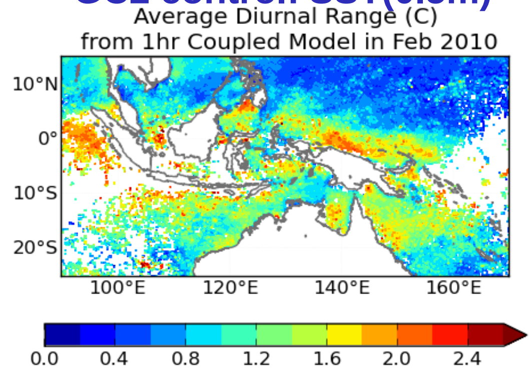


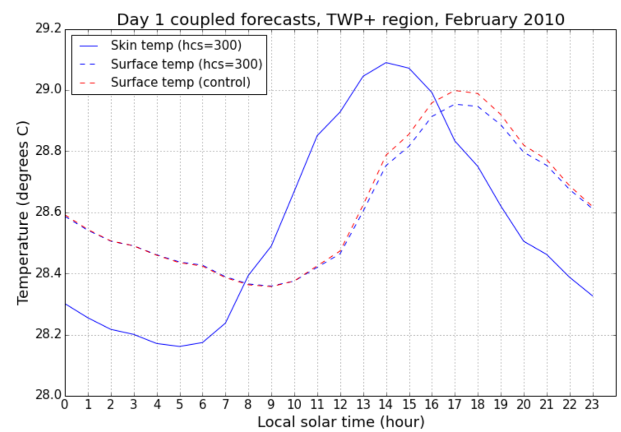
GC2: K_e=300 W/mK





GC2 control: SST(0.5m)





Diurnal cycle:
Scheme reduces temperature of the uppermost layer in the ocean at time of maxima.
Skin temperature : maximum warmer and minimum cooler ➔ larger dSST range.
Timings: minimum moved forward by ~ 4hr (good), maximum moved forward by ~ 3hr (bad).

Warm Layer Model

- Embedded warm layer model within NEMO-FOAM ocean forecast model

- Based on the Takaya (2010) diurnal model.
  - Computationally cheap.
  - Continuous in time.

$$\frac{\partial T}{\partial t} = \underbrace{\frac{Q(\nu+1)}{D_T \rho c_p \nu}}_{\text{Bulk thermal heating of a layer}} - \underbrace{\frac{(\nu+1)k u_w^* f(L_a)}{D_T \Phi\left(\frac{D_T}{L}\right)}}_{\text{Turbulent damping}} T$$

T:- ΔT_{WL}
t :- Time
Q:- Thermal energy flux
D_T:- Layer depth
ρ:- Water density
c_p:- Heat capacity
ν:- Structure parameter
u_w*:- Friction velocity
L_a:- Langmuir number
k:- Von Karman's constant
g:- Acceleration due to gravity
α_w:- Thermal expansion coefficient

$$f(L_a) = \max(1, L_a^{\frac{2}{3}}) \qquad L = \frac{\rho c_p {u_w^*}^3}{\kappa g \alpha_w Q} \qquad \Phi(\zeta) = \begin{cases} 1 + \frac{5\zeta + 4\zeta^2}{1 + 3\zeta + 0.25\zeta^2} & (\zeta \geq 0) \\ (1 - 16\zeta)^{-\frac{1}{2}} & (\zeta < 0) \end{cases}$$

- These equations are solved using an implicit scheme

[James While]

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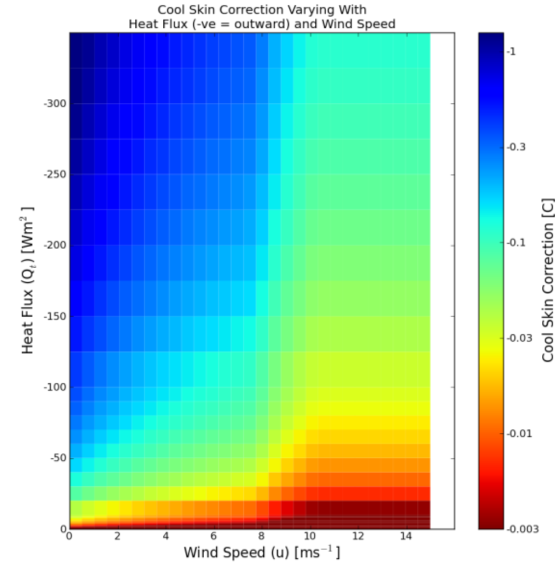
Cool Skin



Have also implemented in NEMO-FOAM the Artale et al. (2002) cool skin model, which is based upon the Saunders equation.

According to Tu and Tsuang (2005), this model provides the best parameter values at both low and high wind-speed:

$$\Delta T_{cs} = \frac{Q_T \lambda \nu}{k_t u_*}$$

Layer thickness (~1mm)

$$\lambda = \frac{u_* k_t C}{\rho_w c_w h \nu \gamma}$$

$$\gamma = \begin{cases} 0.2u + 0.5, & u \le 7.5 ms^{-1} \\ 1.6u - 10, & 7.5 < u < 10 ms^{-1} \\ 6, & u \ge 10 ms^{-1} \end{cases}$$

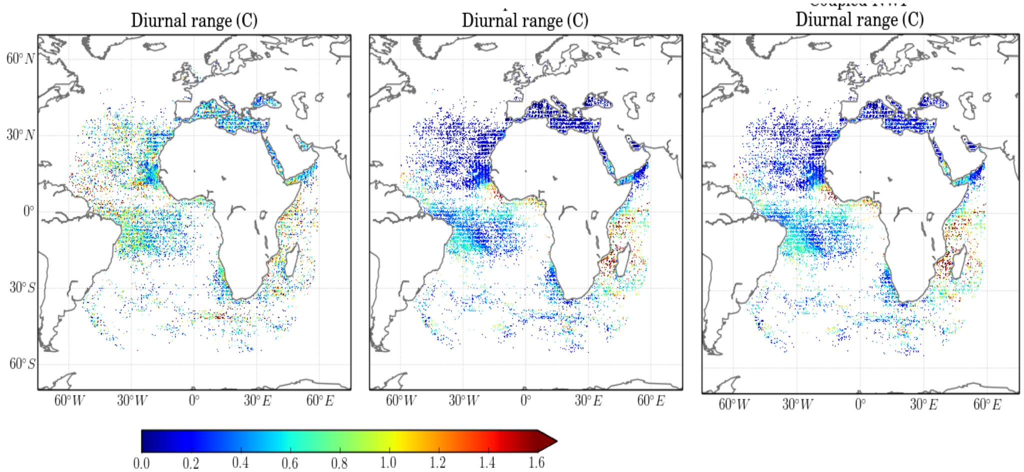
ΔT_{cs} = the skin and bulk difference
Q_t = Total heat flux (-ve in cool skin)
ν = kinematic viscosity of seawater
k_t = thermal conductivity of seawater
u_* = friction velocity of surface water
$= \sqrt{\tau_u / \rho_w}$
τ_u = wind stress
ρ_w = seawater density
λ = a constant of proportionality
$C = 86400s$ (number of secs in 1 day)
c_w = specific heat capacity of seawater at constant pressure
h = a reference depth
γ = dimensionless function of wind speed
u = wind speed

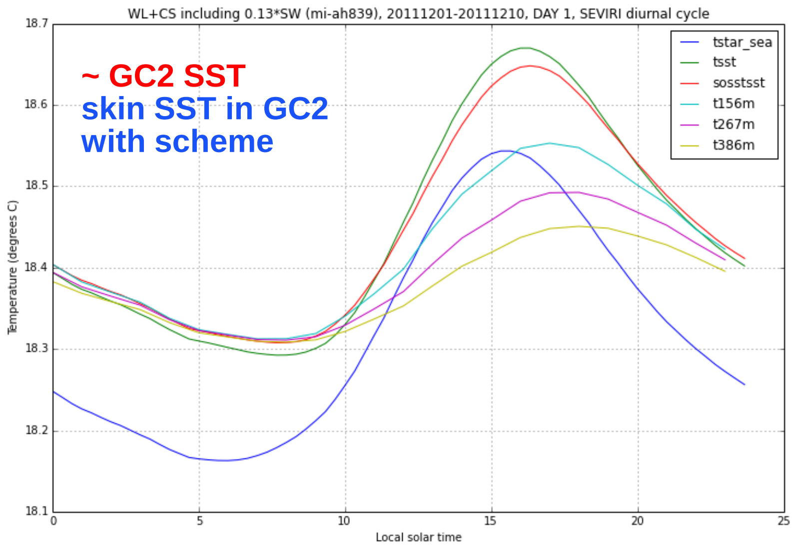
[James While]

Cool skin+warm layer schemes in GC2

Comparison with SEVIRI satellite

SEVIRI | GC2 | GC2 with scheme





•SEVIRI skin SST dataset (Atlantic).

•Small set of coupled NWP hindcasts: 10 members.

Amplitude:

•In most of the domain, GC2 model overestimates the diurnal minima and underestimates the minima. As a consequence, the diurnal amplitude is underestimated in most of the region.

•The scheme lowers the minimum values, reducing the bias in the area. It also lowers the maxima (to a lesser extent). As a result, the diurnal amplitude is slightly increased.

Timing:

Average timing bias (hrs)

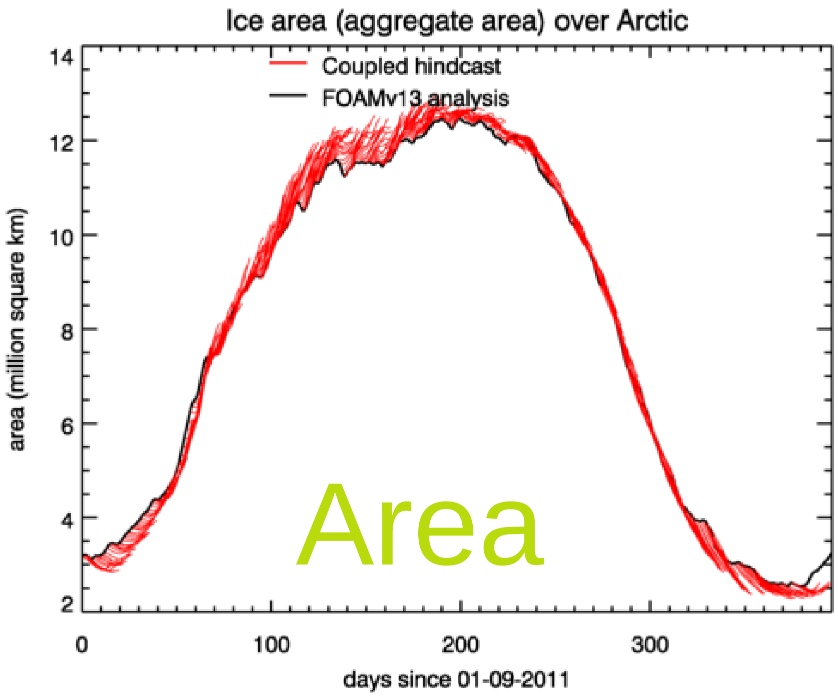
simulation	minima	maxima
GC2	2.34	0.20
GC2 with scheme	-0.78	-0.85

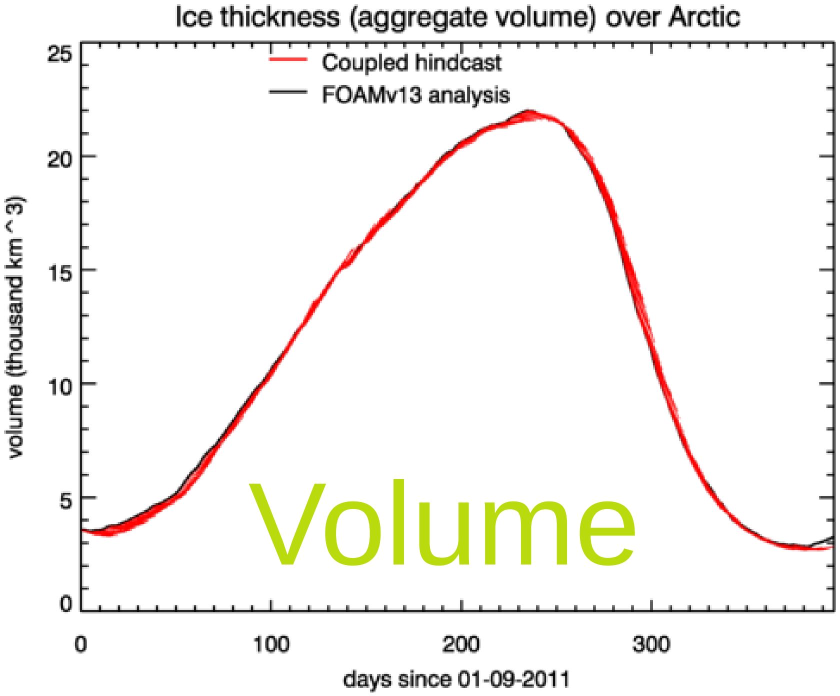
[Scheme being evaluated and tuned]

Arctic sea ice: area and volume

Shelly et al. 2015, Fig 11

*Time series of **daily mean** integrated total Arctic sea ice <u>area</u> (left) and volume (right) from FOAM(v13)–NEMOVAR reanalysis (black solid line) and each 15-day GC2 Coupled NWP hindcast (thin red lines) for start dates from 1 Sept 2011 to mid Sept 2012*





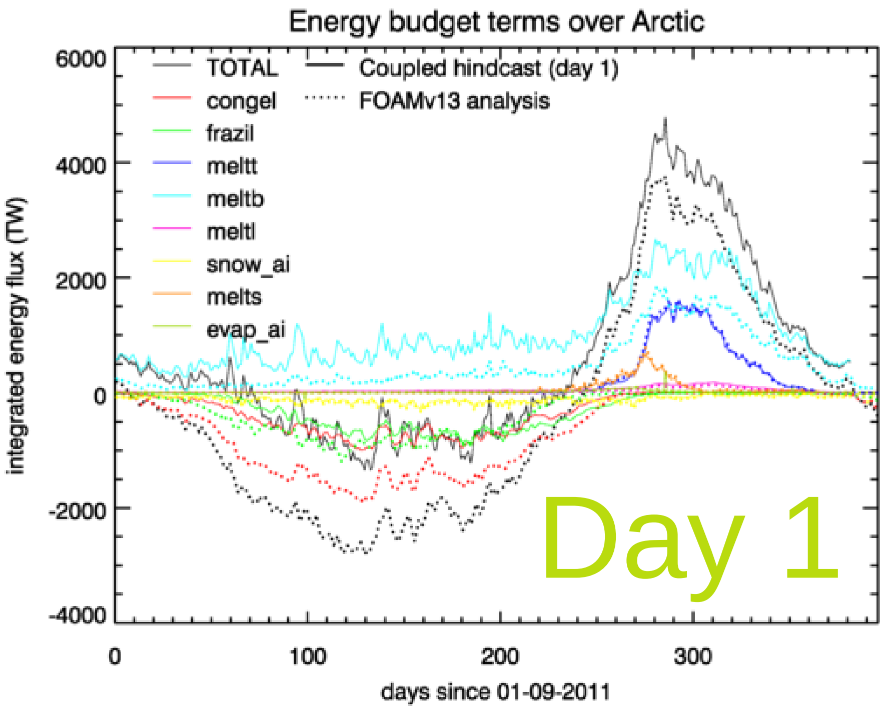
Hindcasts overshoot analysed winter max and summer min <u>area</u>, delaying minima relative to true dates (Sept 2011 and 2012)

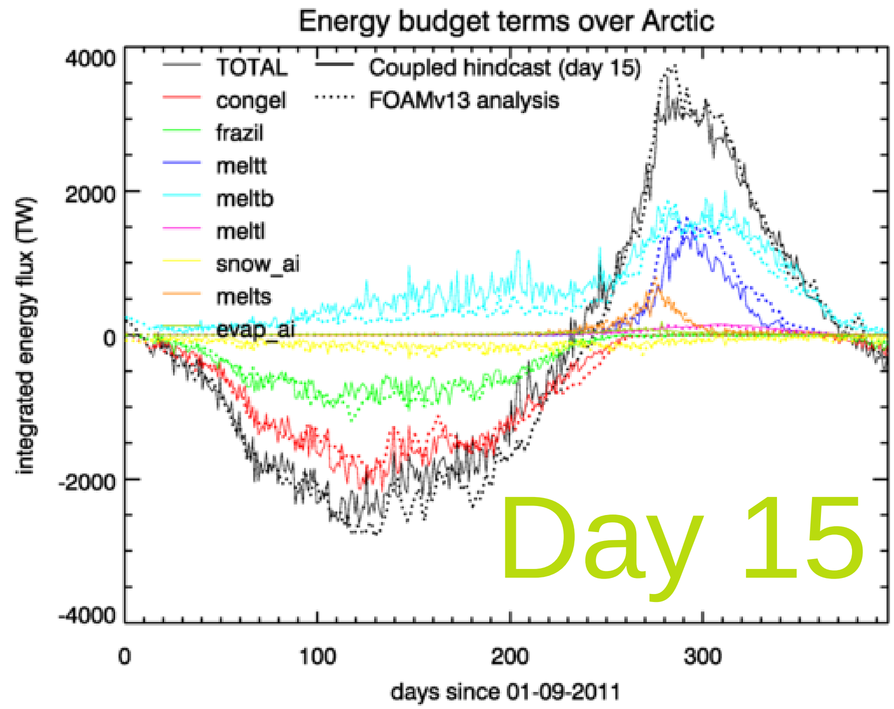
Hindcasts track analyses more closely than is the case for <u>area</u> (left), but still tend to slightly undershoot min

Arctic sea ice: energy budget

Shelly et al. 2015, Fig 12

Daily mean sea ice energy budget terms and total at 1 day (left) and 15 day (right) lead times from GC2 coupled NWP hindcasts (solid lines), compared with corresponding budget terms from FOAM(v13)–NEMOVAR reanalysis (dotted lines). Positive values imply heat energy into the ice (i.e. net melting)





Large differences between analyses and hindcasts at <u>day 1 lead time</u>, largest being meltb (all year) and congel (winter-spring)

Closer convergence between analyses and hindcasts at <u>day 15 lead time</u>, but meltb still somewhat higher and meltt becomes lower (spring-summer) in hindcasts

Reduced sea ice initialisation shock

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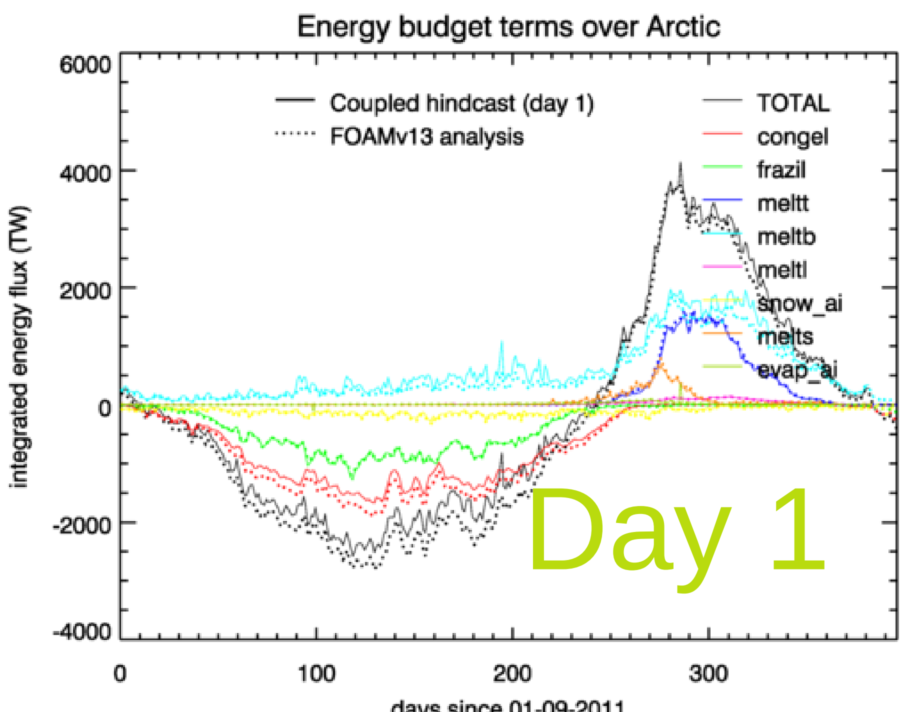
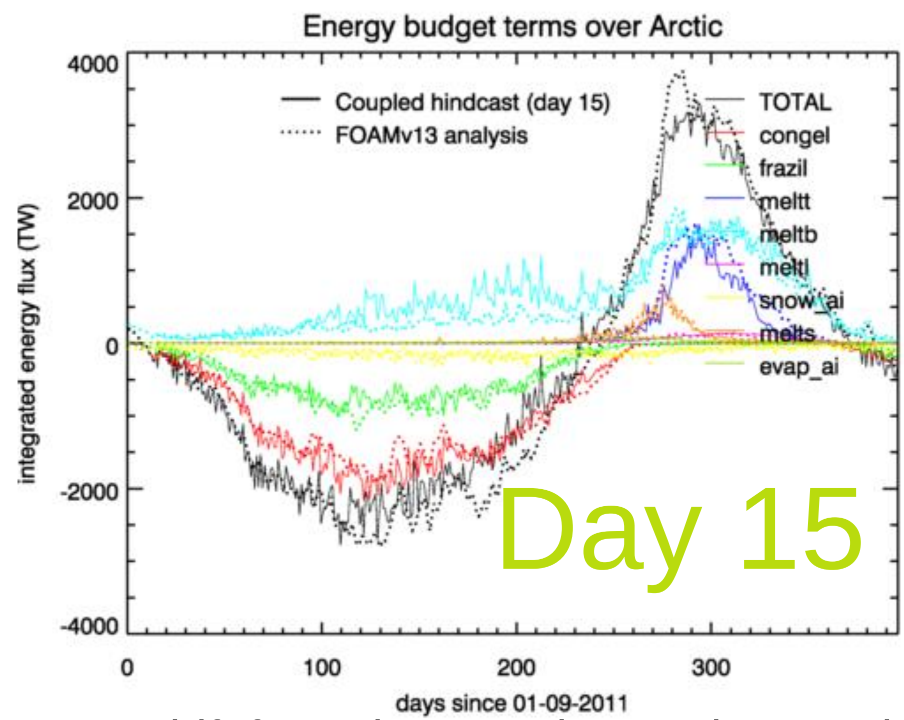
A sensitivity experiment has been run including salinity-dependent freezing temperature for sea water (standard GC2 uses a constant value, which is a different formulation to FOAM-NEMOVAR). With this change the model now sees the ocean-ice ICs as closer to 'native' analyses, reducing initial shock.



Closer agreement between analyses and hindcasts at <u>day 1 lead time</u> for most individual terms and the total



Some drift from day 1 to day 15, but much less adjustment than in standard GC2 setup, reflecting reduced initial shock

Conclusions

- Our results reinforce the expectation that coupled NWP will ultimately deliver improved forecast skill to short-medium range predictions
- Tropical Indian Ocean region is of particular note in our results as a region of enhanced skill (linked with MJO)
- Large CNWP hindcast sets are needed to generate significant results in standard verification analysis
- Process studies are important to evaluating the performance of CNWP
- Initialisation shock is potentially an issue (but can probably be alleviated to an extent with coupled DA)

NEXT STEPS AND CHALLENGES

Next steps

- Transition to the new Cray HPC (already up and running)
- Evaluate GC3 performance in coupled NWP mode – aiming for Jun 2016 UM User Workshop in Exeter (dependent on GC3 seasonal hindcast analyses for ocean initialisation)
- Improve coupled NWP hindcast test/trialling system and integrate with verification and assessment, permitting a faster assessment of GC model performance and evaluation of science changes in coupled NWP mode
- Evaluate sensitivity to use of coupled DA for initialisation (link to demonstration operational coupled DA system which is expected to start mid-late 2016)
- Investigate coupled NWP performance at higher resolution (N1024/N1260-ORCA025/ORCA12)

Science Challenges/Opportunities

- Coupled initialisation shock, SST drift/bias, and forecast signal/noise
- Tropical variability: MJO, IOD, tropical cyclones, tropical and extratropical teleconnections
- Diurnal cycle (SST, skin SST, air-sea fluxes, land-sea interaction)
- Air-sea coupled feedbacks at ocean eddy-resolving resolution (links to Charisma/PRIMAVERA projects)
- Mid-latitude air-sea coupling (Gulf Stream impact on atmospheric frontogenesis, convection, storms)
- Polar performance (sea ice, heat budget, meteorology)
- Other coupling developments (wave model, sea spray LH+SH, ...)

-> A lot of work to do to develop diagnostics and methods for coupled NWP verification and process-based assessment to advance our understanding of coupled systematic error development

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Selected references

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Thank-you for your attention!

QUESTIONS?