ERA-CLIM2
University of Reading, UK

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Task 2.5: Research towards development of fully coupled data assimilation methods

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(1) **Analysis and inter-comparison of coupled error covariances (MetO, UREAD)**

•*Objective*: to assess strengths and weaknesses of weakly coupled data assimilation schemes, and to develop techniques for calculating coupled error covariances.

•Investigate and assess case studies of particular coupled phenomena, and develop methods and carry out the calculation of coupled covariances using the outputs of weakly coupled DA systems (eg. CERA).

(2) **Model bias correction in coupled data assimilation (UREAD)**

•*Objective*: development of bias correction methods explicitly designed to achieve more balanced atmosphere and ocean states as part of a coupled reanalysis system.

•Develop new advective approaches for correcting ocean biases in the tropical thermocline and mid-latitude boundary currents which are critical for atmospheric responses. New approaches will also be tested to reduce coupled model drifts in wind stress, buoyancy fluxes, and ocean thermocline.

(3) ***Fully coupled data assimilation in simplified model systems (INRIA)***

•*Objective: to explore advanced methods for fully coupled data assimilation, using the ECMWF OOPS framework.*

•*Develop the methodology by which some aspects of fully coupled data assimilation will be implemented. Investigate possibility of controlling the interfaces between the different components of the coupled system together with their initial conditions. Use a simplified coupled system in the OOPS framework, which would allow its extension to a realistic framework.*

UREAD: Deliverables

- D2.8 Report on strengths and weaknesses of weakly coupled data assimilation methods for Earth system reanalysis. UREAD 18
- D2.9 Report on techniques for calculating coupled error covariances from outputs of a weakly coupled data assimilation experiment. METO+UREAD 18
- D2.10 Report on assessment of coupled-model drift and approaches for obtaining consistent ocean and atmospheric bias corrections. UREAD 34 +12 =46
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Atmosphere-Ocean Coupled Covariances
eg. SST v. T2m(or winds)

Popular approaches for Background error covariances: B

Method	Description and references
"Canadian quick" method	$\mathbf{x_f} - \mathbf{x_t} \sim (\mathbf{x_f}(t+T) - \mathbf{x_f}(T))/\sqrt{2}$. Take population from one long time run. Polavarapu S., Ren S., Rochon Y., Sankey D., Ek N., Koshyk J., Tarasick D., Data assimilation with the Canadian middle atmosphere model. Atmos.-Ocean 43: 77–100 (2005).
Analysis of innovations $\mathbf{d} = \mathbf{y} - \mathbf{H}\mathbf{x_f}$ "Hollingsworth and Lonnberg" also more recently Desroziers et al	Choose a pair of direct and independent obs separated by r: $[y(r) - x_f(r)]\,[y(r+\Delta r) - x_f(r+\Delta r)] =$ $[\{y(r) - x_t(r)\} - \{x_f(r) - x_t(r)\}]\,[\{y(r+\Delta r) - x_t(r+\Delta r)\} - \{x_f(r+\Delta r) - x_t(r+\Delta r)\}]$ $\langle[\epsilon^y(r) - \epsilon^{x_f}(r)]\,[\epsilon^y(r+\Delta r) - \epsilon^{x_f}(r+\Delta r)]\rangle = \langle\epsilon^y(r)\epsilon^y(r+\Delta r)\rangle + \langle\epsilon^{x_f}(r)\epsilon^{x_f}(r+\Delta r)\rangle$, (above assumes obs and bg errors are uncorrelated). Take population from many pairs with same Δr. Furthermore if $\Delta r > 0$: $\langle\epsilon^y(r)\epsilon^y(r+\Delta r)\rangle = 0$. Rutherford I.D. 1972. Data assimilation by statistical interpolation of forecast error fields. J. Atmos. Sci. 29: 809–815. Hollingsworth A., Lönnberg P., The statistical structure of short-range forecast errors as determined from radiosonde data. Part I: The wind field. Tellus 38A: 111–136 (1986). Järvinen H., Temporal evolution of innovation and residual statistics in the ECMWF variational data assimilation systems. Tellus 53A: 333–347 (2001).
NMC method	Choose pairs of lagged forecasts valid at the same time, e.g.: $\mathbf{x_f} - \mathbf{x_t} \sim (\mathbf{x_f^{48}}(t) - \mathbf{x_f^{24}}(t))/\sqrt{2}$. Take population from difference at many times. Parrish D.F., Derber J.C., The National Meteorological Center's spectral statistical interpolation analysis system. Mon. Wea. Rev. 120 1747–1763 (1992). Berre L., Ştefănescu S.E., Pereira M.B., The representation of the analysis effect in three error simulation techniques. Tellus 58A 196–209 (2006).
Ensemble method	If you have an ensemble that is correctly spread: $\mathbf{x_f} - \mathbf{x_t} \sim \mathbf{x_f^{(i)}} - \langle\mathbf{x_f}\rangle$ or $\mathbf{x_f} - \mathbf{x_t} \sim \left(\mathbf{x_f^{(i)}} - \mathbf{x_f^{(j)}}\right)/\sqrt{2}$. Take population from ensemble members and over many times. Houtekamer P.L., Lefaivre L., Derome J., Ritchie H., Mitchell H.L., A system simulation approach to ensemble prediction. Mon. Wea. Rev. 124, 1225–1242 (1996). Buehner M., Ensemble derived stationary and flow dependent background error covariances: Evaluation in a quasi-operational NWP setting. Q.J.R. Meteorol. Soc. 131, 1013–1043 (2005).

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CERA Increments not Innovations available

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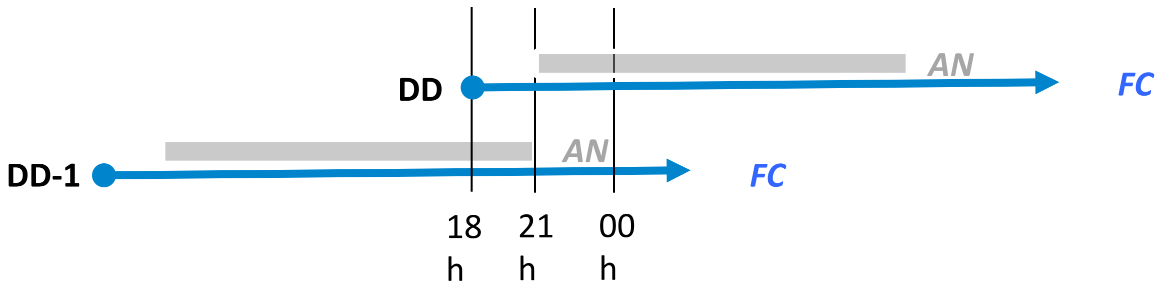
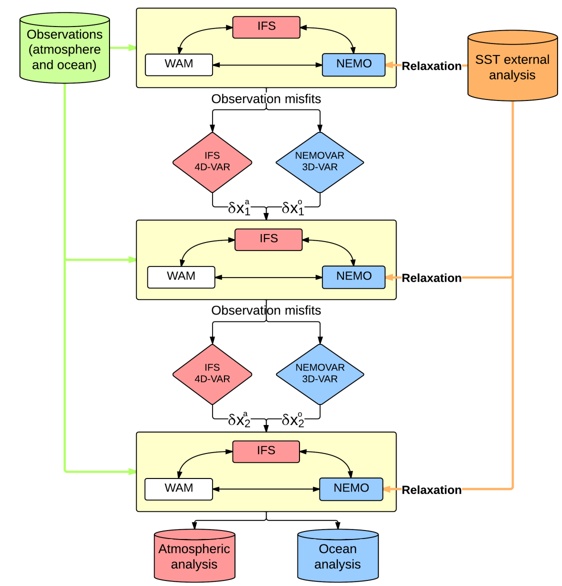
Increment Calculations

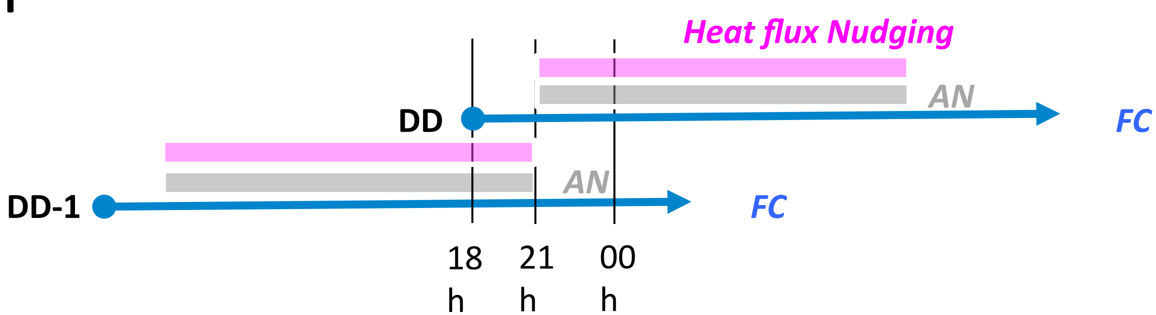
- **Atmosphere (4DVar) + Ocean(3DVar+FGAT/Direct Ins.)**





AN(start=21hr) – FC(start=18hr, lead=3hr)

- **SST**



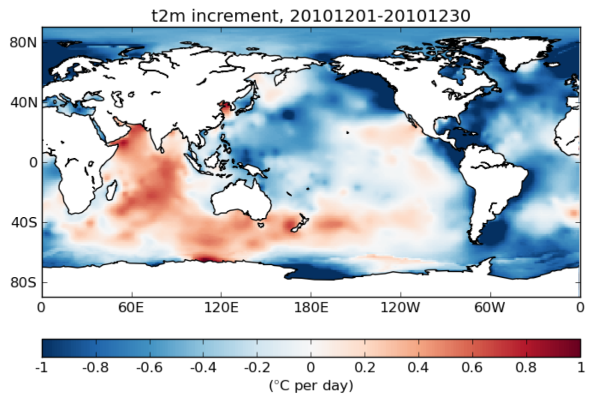
AN(start=21hr)] + heat flux nudging(21hr –> (21hr+1d)) – *FC(start=18hr, lead=3hr)*

Due to sublayer ocean DA and feedbacks of atm DA

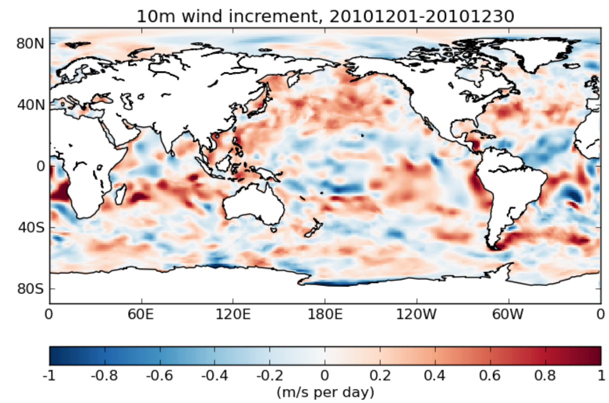
Due to SST relaxation

Mean Atmosphere increments Dec 2010: T2m and 10m wind

2m temperature

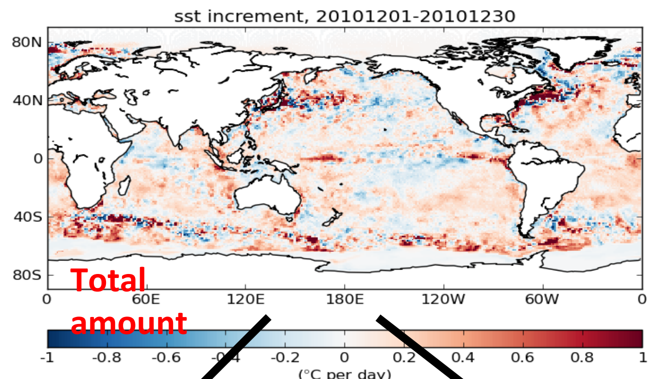


10m wind speed

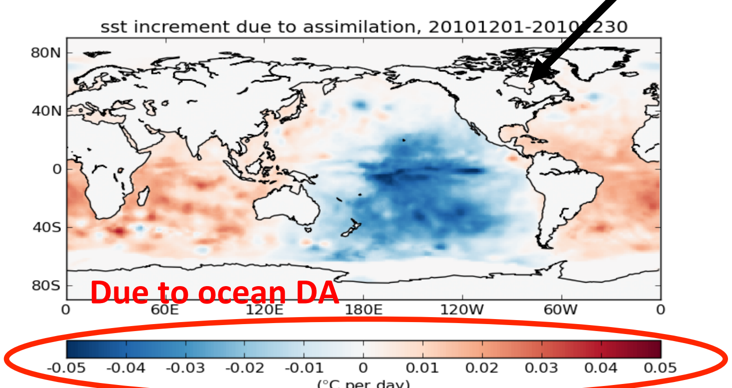


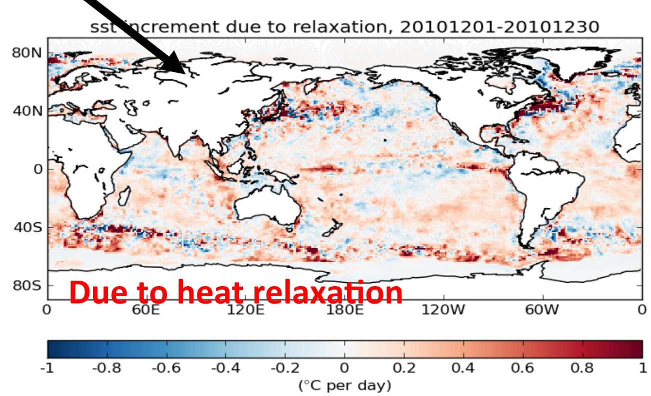
Mean over Dec 2010 ‘g541’ CERA-20C test

SST increments



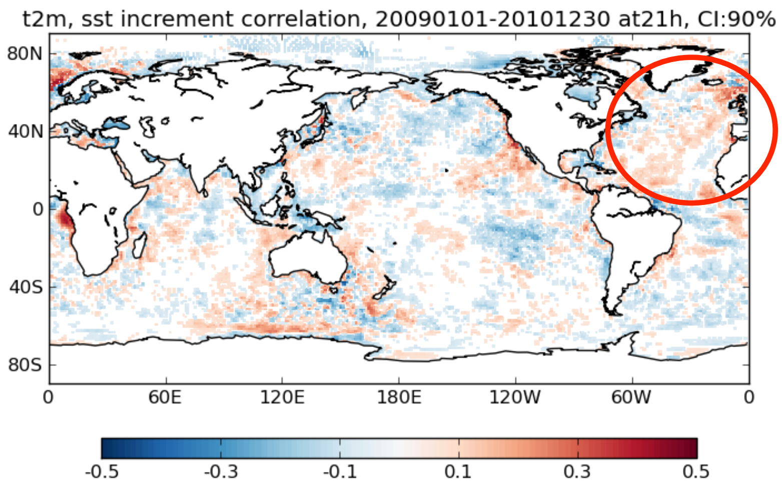
- *Little changes when ‘g6gm’ CERA-Sat test data used.*

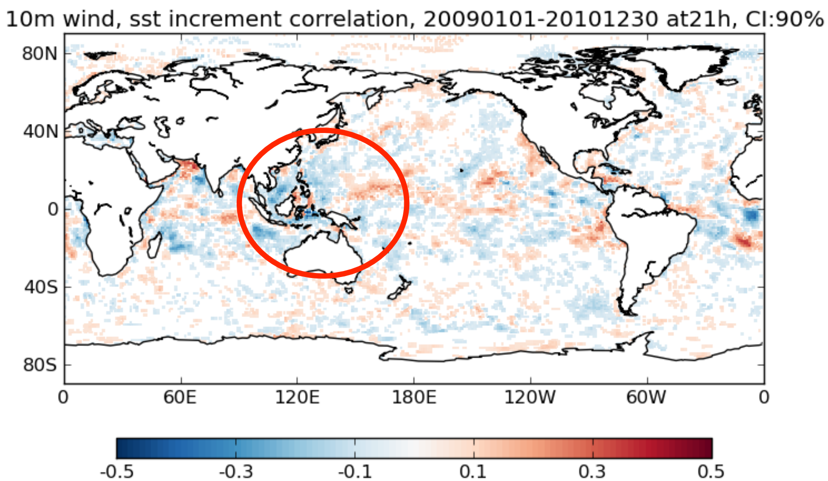




Correlation between detrended SST and atmosphere increments

When using increments from ‘g541’ over longer period (2 years)





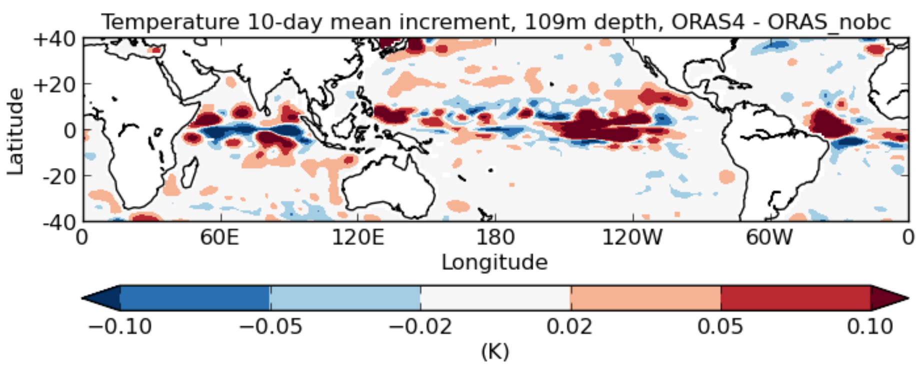
Further covariance work

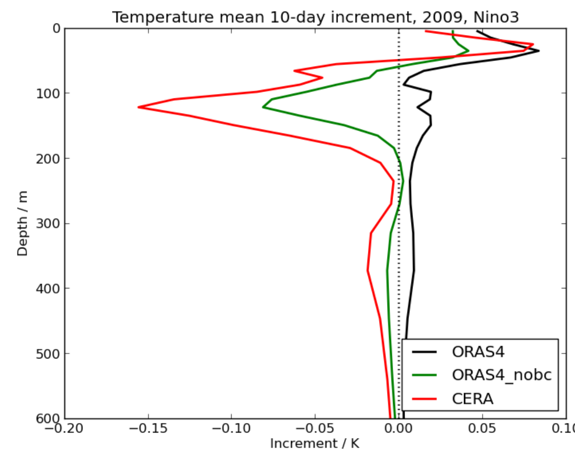
- Check CERA increments
- Investigate whether CERA Innovations calculable
- Increment and Innovation coupled covariances
- Comparison with Met Office results (preferably equivalent period)

Bias Correction and impact on forecasts

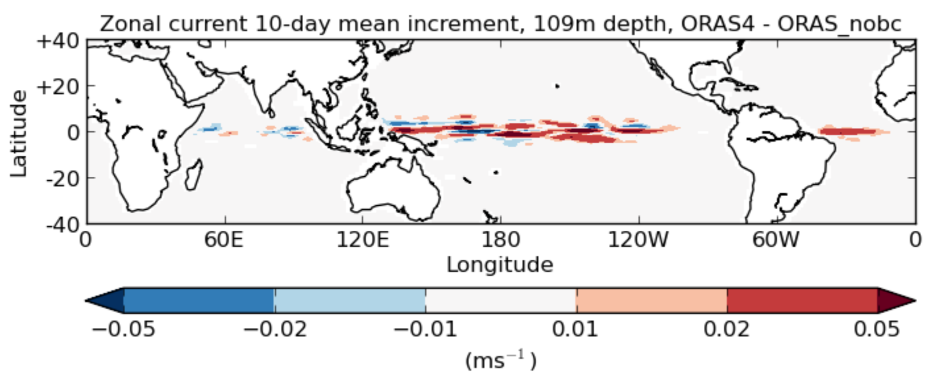
- Equatorial bias correction is necessary to reduce spurious circulations in ocean/coupled analysis

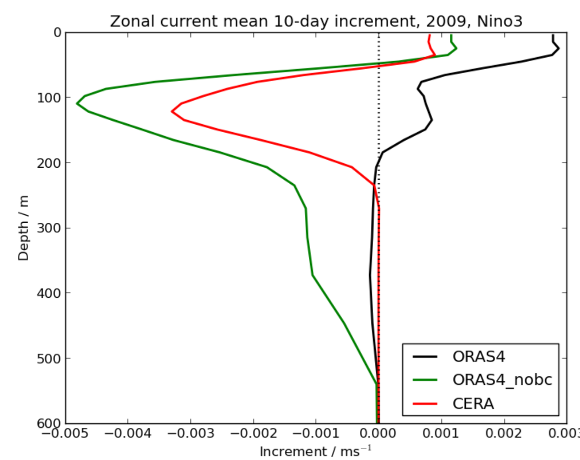
Mean Nino3 profile increments. T and U





T increment 100m, ORAS4 – ORAS4_nobc and Nino3 profiles incl. CERA

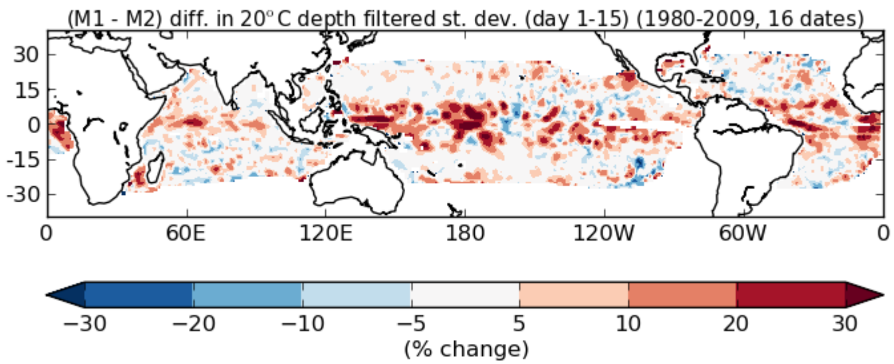




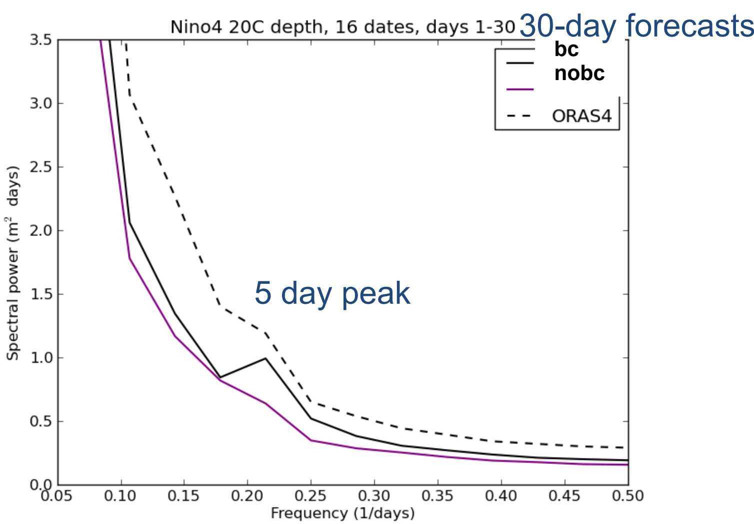
U increment 100m, ORAS4 – ORAS4nobc and Nino3 profiles incl. CERA

Coupled Hindcast Experiments

- System: IFS-40R3(ERA-I) + NEMO3.4(ORAS4/nobc)
- 16 start dates (1980-2009 all 4 seasons); 5 member ensembles; 7-month forecasts
- Sudden absence of bias correction in forecasts excites oscillations in Eq. Pac. (Mulholland et al 2015)
- Non-linear interactions within forecasts?

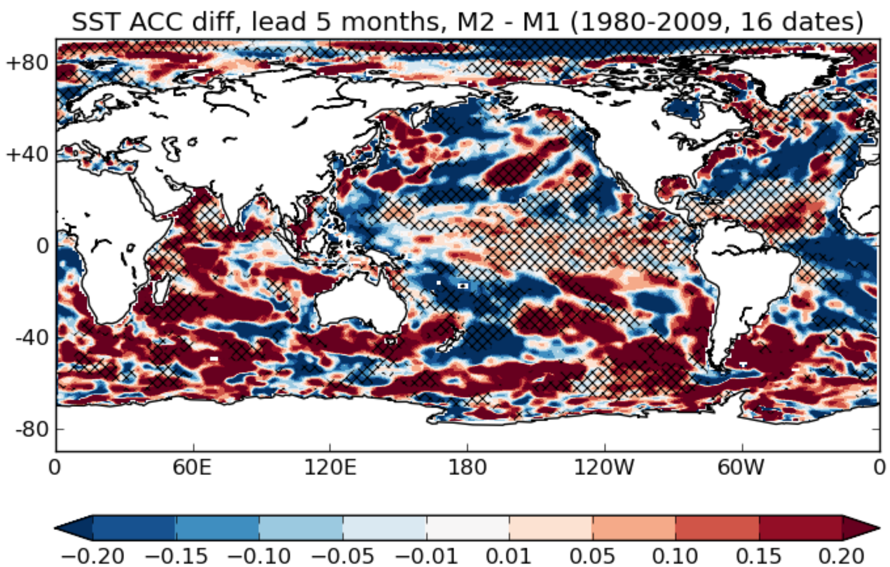


Increase in 20C depth temporal variability,
***ORAS4-init – nobc-init**, days 1-15*

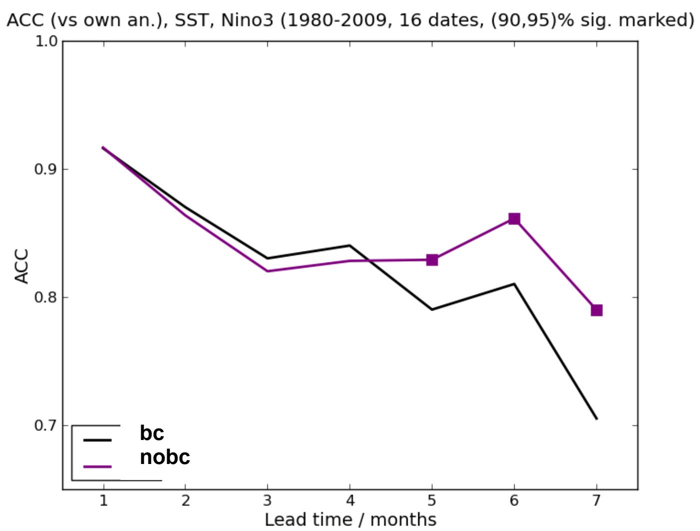


Nino4 20C depth frequency spectrum

- BC affects SST forecast skill after a few months
  - nobc-init performs better in areas where significant seasonal skill exists (esp. E Pacific)

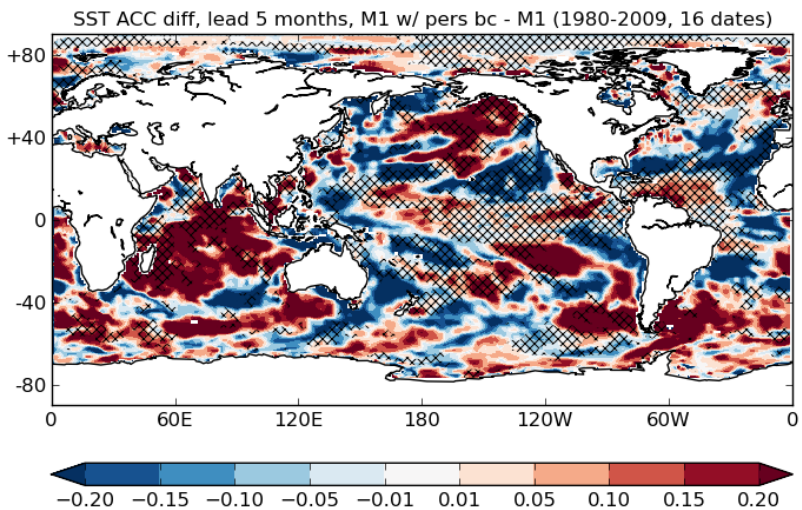


*SST ACC at 5 months' lead, **nobc-init** – **ORAS4-init**;*
hatching where either ΔACC is >0.5

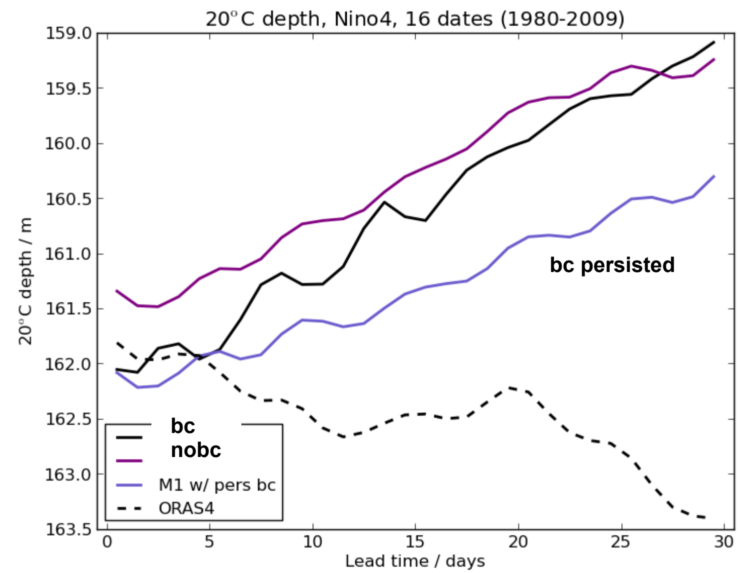


Nino3 SST ACC, months 1-7.
***nobc-init** skill is higher at 95% significance in months 5-7*

- Forecasts initialised from ORAS4 but persisting bias correction => decreased shock, slight increased skill (ACC)
  - Prevents spurious oscillations in west Pacific thermocline



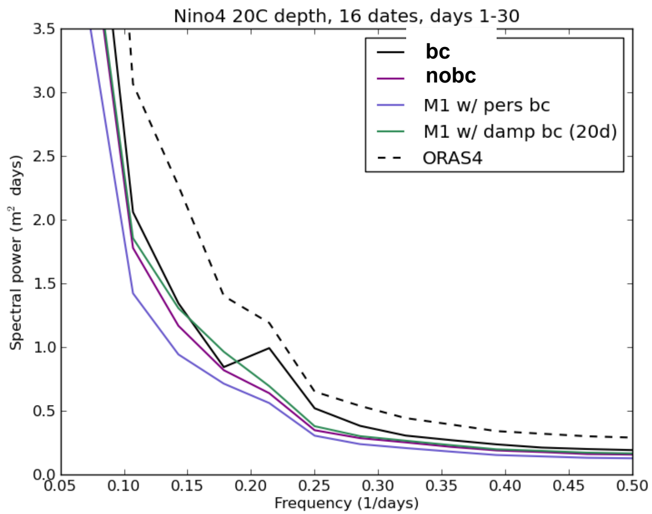
*SST ACC at 5 months' lead, **pers-bc** – **ORAS4-init**; hatching where either ΔACC is >0.5*



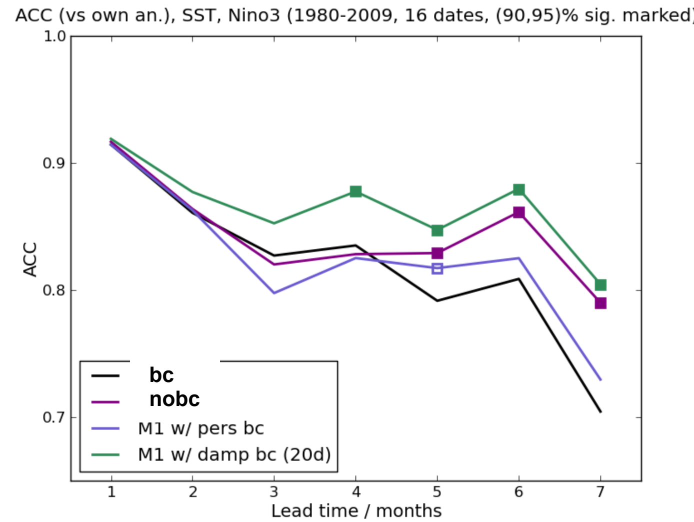
*Nino4 20C depth forecast time series, showing **ORAS4-init**, **nobc-init**, **pers-bc** and ORAS4 (dashed)*

Damped BC : Linear ramp to nobc over 20 days

- Thermocline oscillations still mostly prevented
- Nino3 SST ACC skill highest of all cases



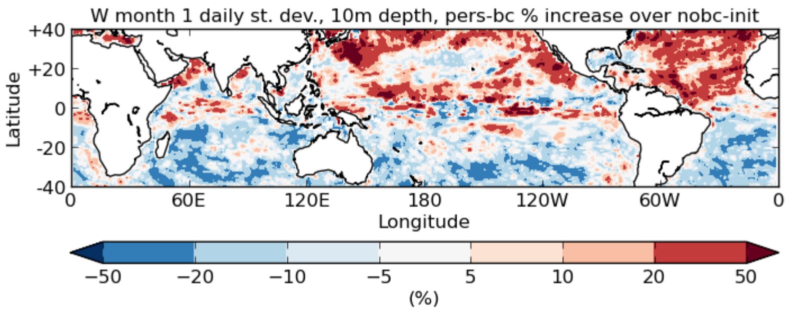
Nino4 20C frequency spectrum
Spurious peak is avoided in both ***pers-bc*** *and* ***damp-bc***

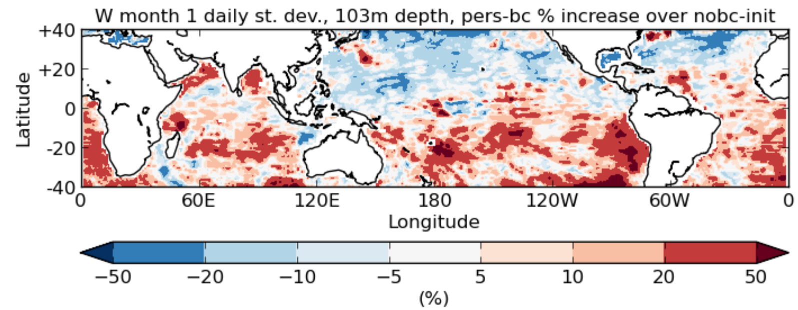


Nino3 SST ACC, months 1-7
damp-bc (green) *skill is signif. >* ***ORAS4-init***

- Likely to work better with CERA-initialised forecasts as (wind) drifts are slower
- Pressure bias correction in CERA with slow removal in forecast may be the best approach

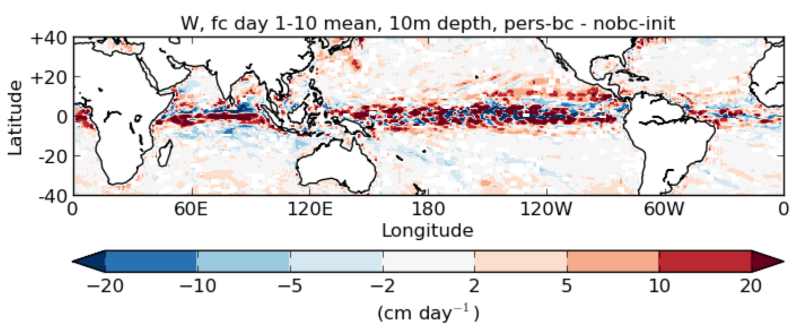
Forecast W results (surprising?)

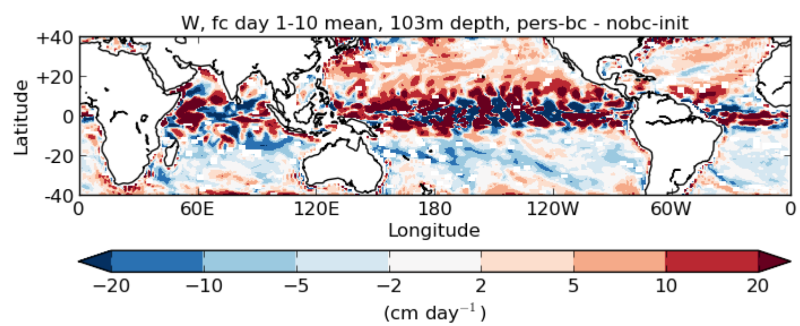




persbc-init – nobc-init (fc month 1) W daily st. dev., 10m and 100m depth (i.e. W st. dev. Initialised from ORAS4 minus initialised from ORAS4_nobc)

8 date (4 season) average. Higher variability along equator but why the N/S pattern?





Persbc-init – nobc-init fc day 1-10 means
Bias corr clearly affects upwelling along equator.

Further bias correction work

- Need further testing as looks v. important
- Larger set of hindcast start dates
- Test duration of improved skill
- Extend bias corrections to CERA system
  - Variability of 20C isotherm depth
  - Test different bias correction methods (eg. MetO are testing more temporal variability in bc)
  - Hindcasts from CERA initial conditions!