Overview of the ECMWF long-range forecasting system

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Approaches to seasonal forecasting

- Empirical, low-order model or ML-based forecasting
  - Use past observational record and statistical methods
  - Works with reality instead of error-prone numerical models ☺
  - Aim to extract predictable signals, and represent uncertainty in outcome ☺
  - Limited number of past cases: works best when observed variability is dominated by a single source of predictability ☹
  - Limited quality of past data is a problem for some sources of predictability ☹
  - A non-stationary climate is problematic ☹
- Full-physics numerical forecasts
  - Include comprehensive range of sources of predictability ☺
  - Non-linear interactions of oceanic, land and atmospheric sources of predictability ☺
  - Benefit from latest observing systems, use all information about the present state ☺
  - Ensemble forecasts map uncertainty in initial state to uncertainty in outcome ☺
  - Model errors are an issue! ☹

Sources of seasonal predictability

– KNOWN TO BE IMPORTANT:
  - El Nino variability - biggest single signal
  - Other tropical ocean SST - important, but multifarious
  - Climate change - impact is substantial, especially in temperature forecasts, and must be accounted for
  - Local land surface conditions - e.g. soil moisture in spring: dry soil warms up more quickly and is more prone to drought

– OTHER FACTORS:
  - Volcanic eruptions - definitely important for large events, gives global cooling plus sometimes a winter warming in parts of the northern hemisphere
  - Mid-latitude ocean temperatures - Convergence near SST fronts
  - Remote soil moisture/ snow cover - Unclear how large the effects might be
  - Sea ice anomalies - definitely local effects, also weaker remote impacts
  - Dynamic memory of atmosphere - most important for first month
  - Stratospheric influences - polar vortex, QBO, solar cycle, ozone, …
  - Aerosols - natural and anthropogenic

– Unknown or Unexpected - e.g. smoke from forest fires, other unexpected events ??

SEAS5 forecast model

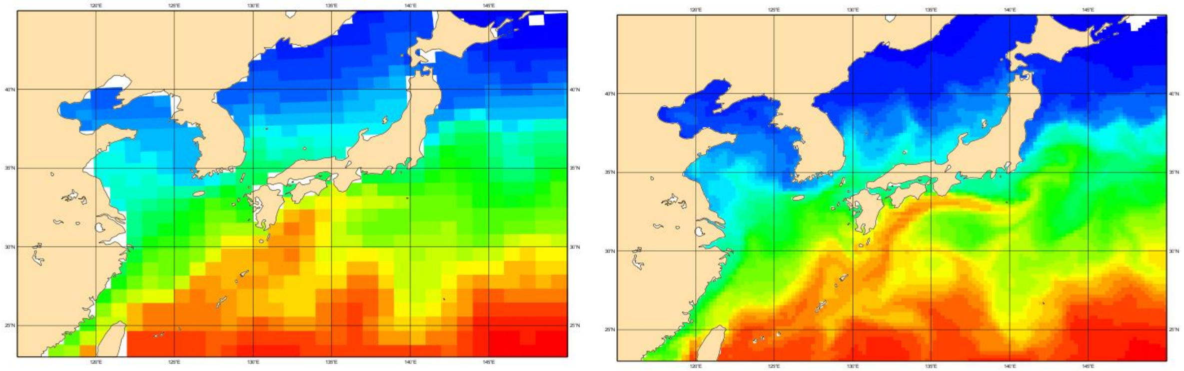
- IFS (atmosphere and land surface)
  - TCo319L91 Cy43r1, 35km grid for physics, full stratosphere
  - All of the physical and dynamic processes of a world-class NWP model
  - Land surface model, multiple soil layers, different soil types, different vegetation types, snow, glaciers
  - Lake model with variable depths, variable mixed layer, surface and bottom temperatures, lake ice
  - Time varying tropospheric sulphate aerosol and stratospheric aerosol from volcanoes
- Wave model
  - Ocean surface waves modify the interaction between ocean and atmosphere. Runs at 0.5 deg resolution.
- NEMO (ocean)
  - Global ocean model, 0.25 deg resolution (eddy permitting), 75 vertical levels
- LIM (sea-ice)
  - Single category ice, solved on same grid as ocean model

SEAMLESS STRATEGY: SAME MODEL AS MEDIUM/EXTENDED RANGE FORECASTS*

*in reality, almost identical, when introduced

SEAS5 – ocean component

- Ocean model resolution upgraded from previous 1x1 deg to 0.25x0.25 deg
- Ocean vertical resolution improved from previous 42 levels to 75 levels
- High ocean resolution is needed to represent ocean eddies, and to better resolve the boundary currents that are important in the ocean, such as the Kuroshio in the Pacific (shown here) and the Gulf Stream in the Atlantic.

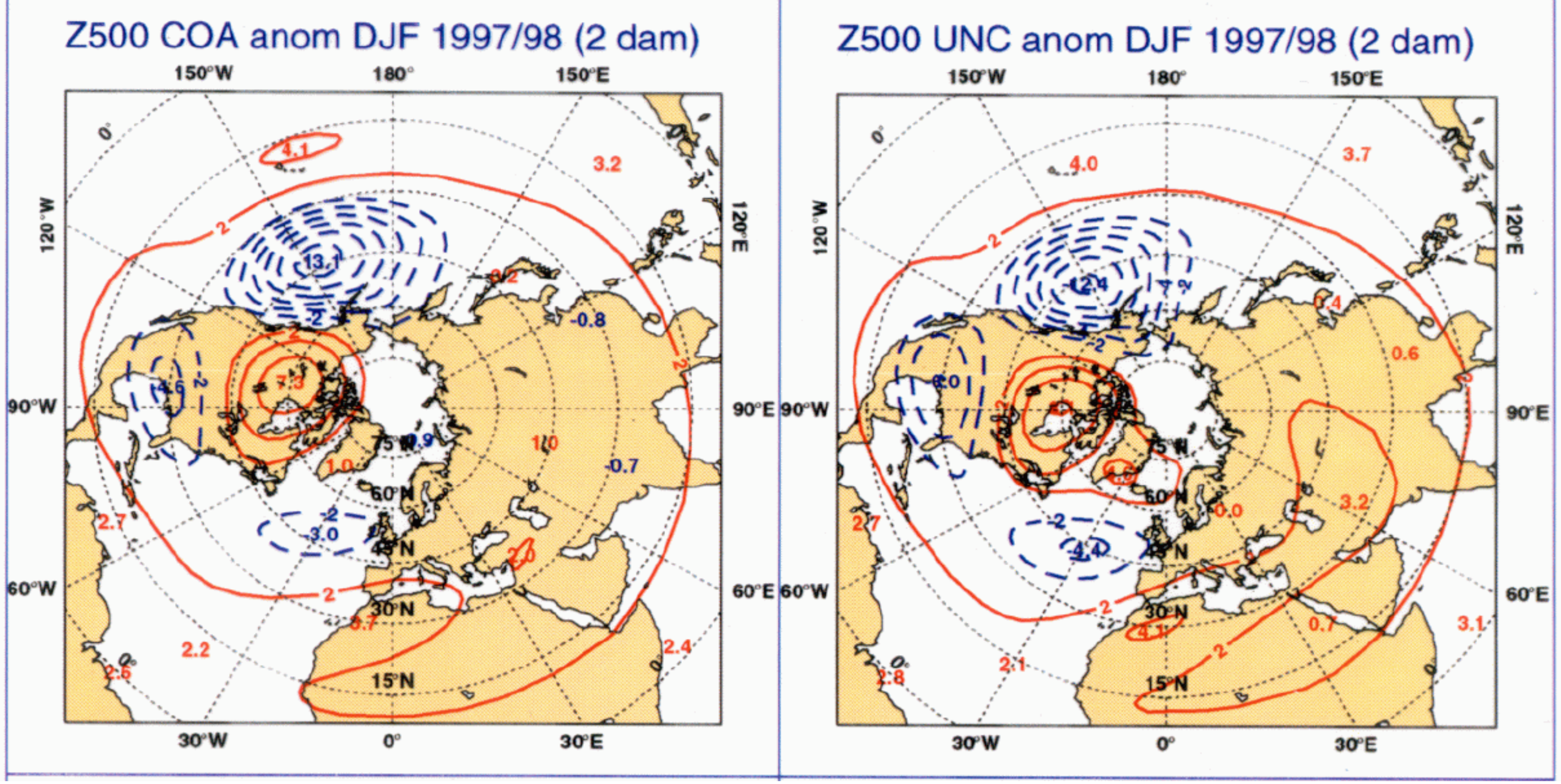


NEMO ORCA1 Z42 NEMO ORCA025 Z75

Note: ¼ degree ocean resolution is not enough to resolve eddies or boundary currents properly.

1/12 degree would be nice, but is unaffordable

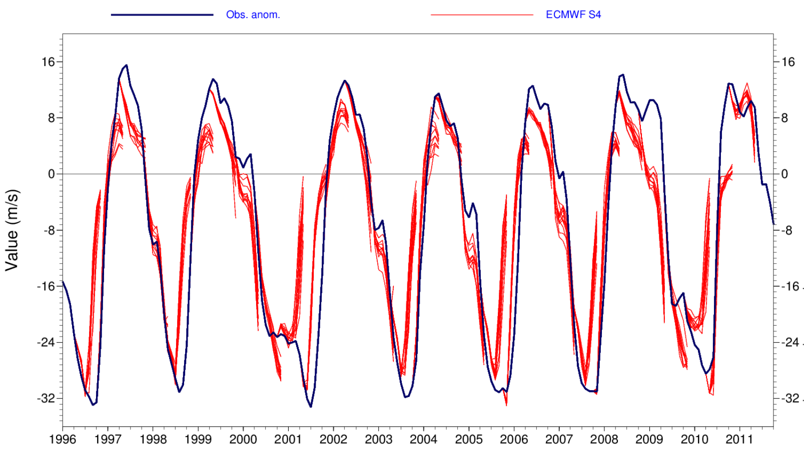
Despite SST bias and other errors, anomalies in the coupled system can be remarkably similar to those obtained using observed (unbiased) SSTs …..



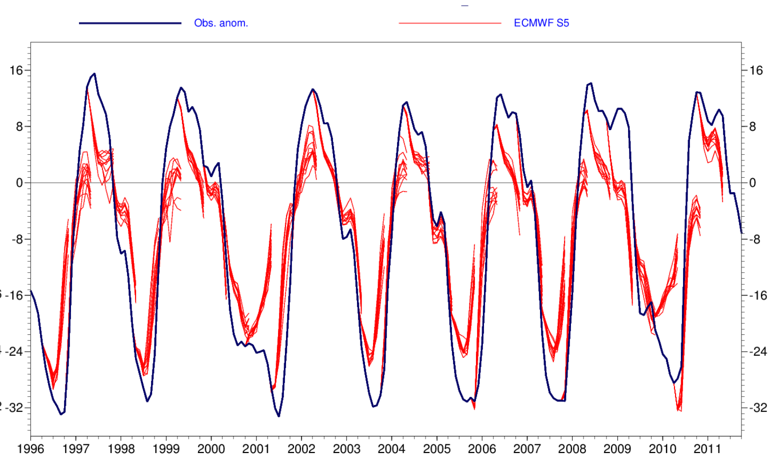
Historic plot, showing results from our first real-time seasonal forecast system in 1997. This system had large cold SST biases, but established that mid-latitude seasonal forecasting was viable even with an imperfect ocean and an imperfect model.

Stratosphere - the QBO

System 4

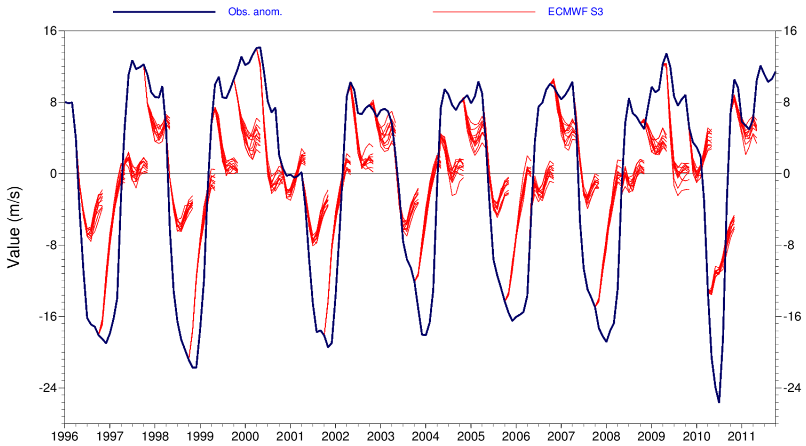


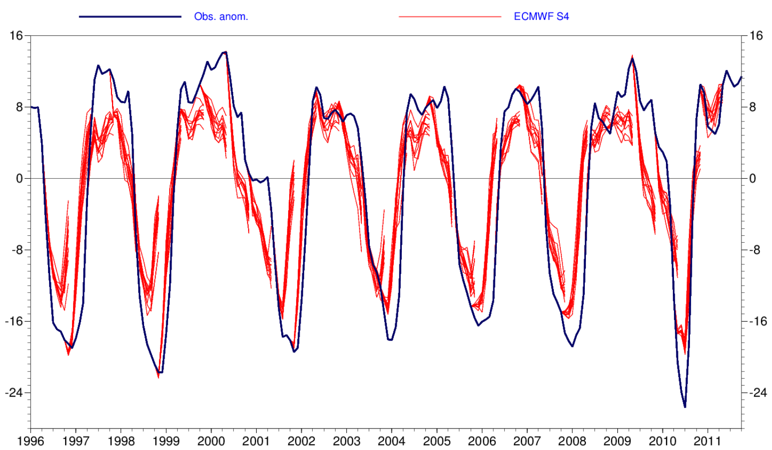
SEAS5

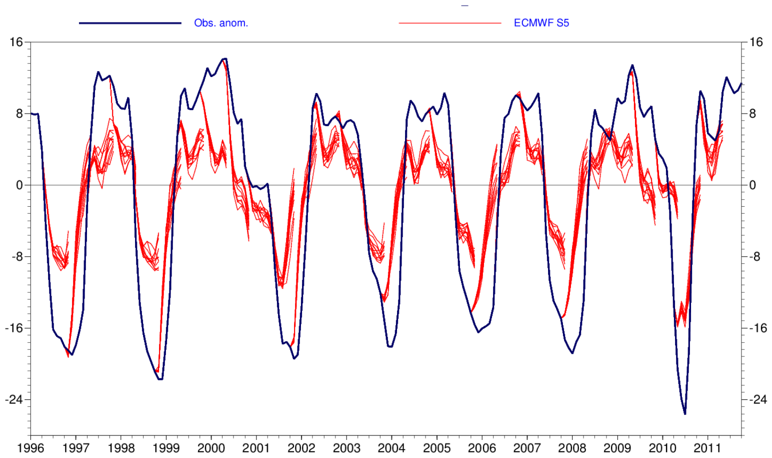


30hPa

System 3



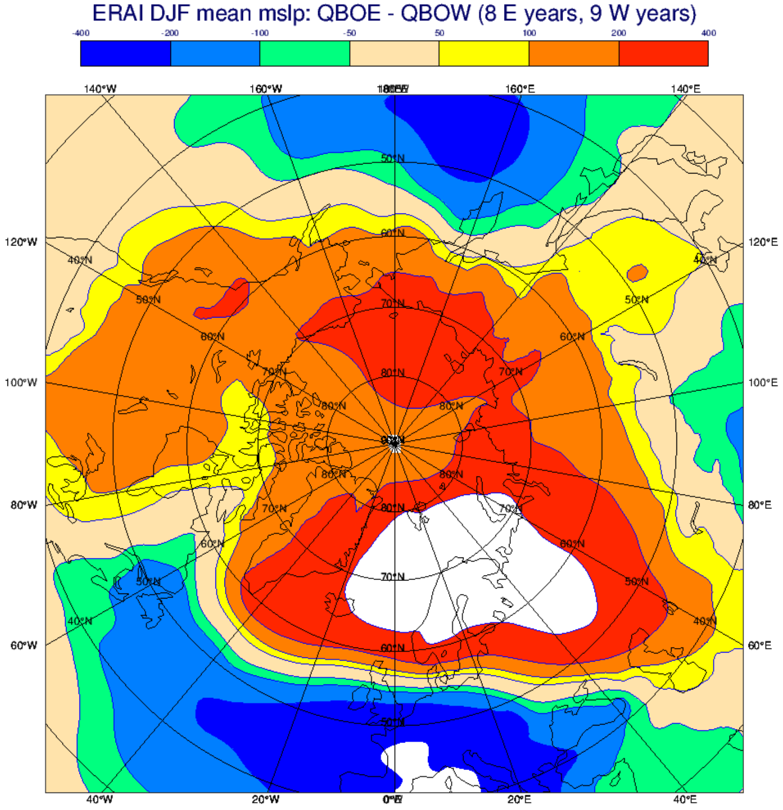


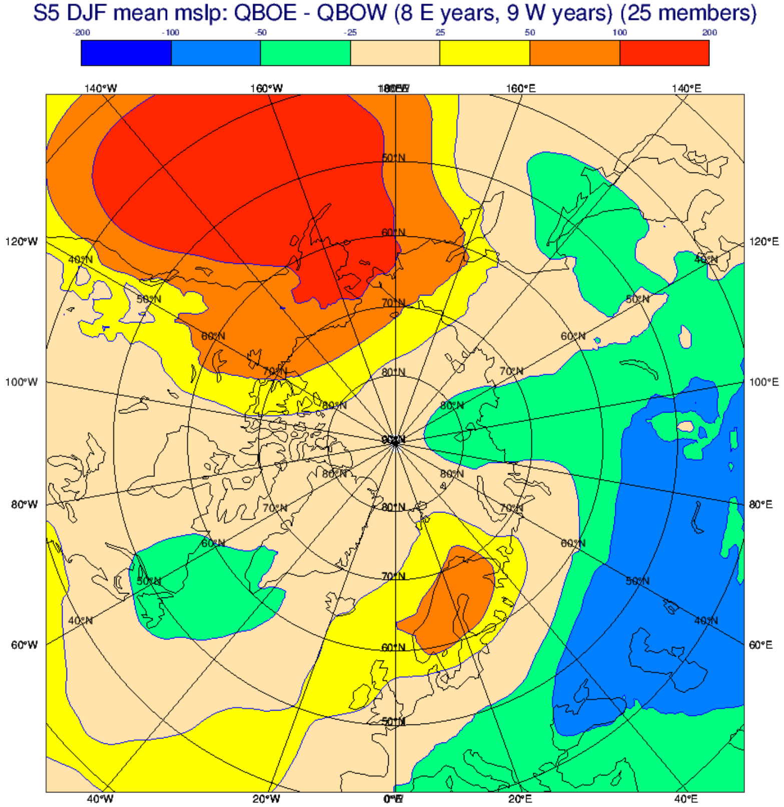


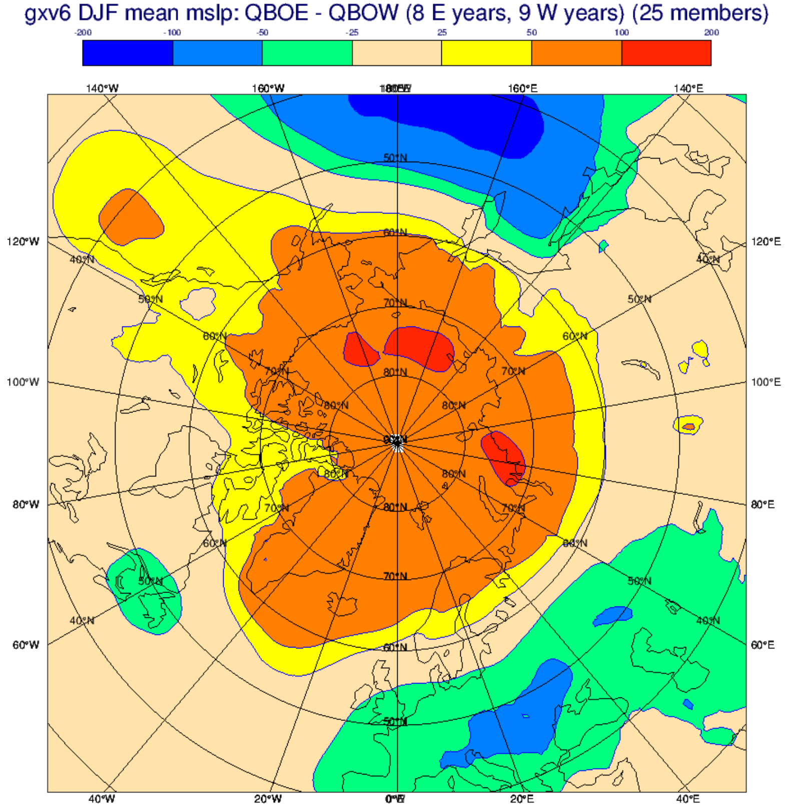
50hPa

QBO teleconnections – NH winter MSLP

SEAS5 | SEAS5 L137







Contour intervals: double

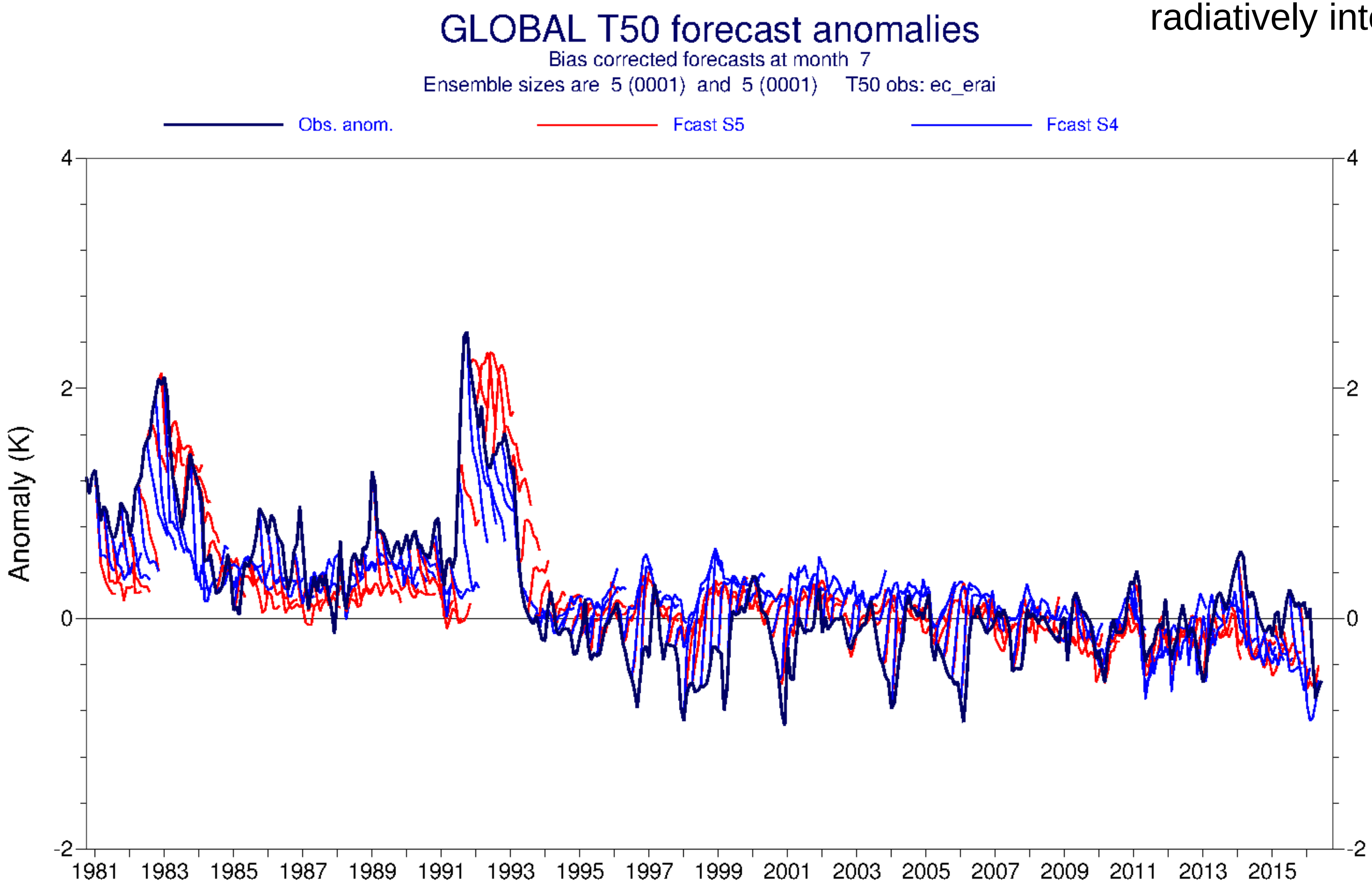
<- Contour intervals: single ->

QBO composite years for 1981-2016, following Martin Andrews, defined to maximize NAO teleconnection, equivalent to ~20 hPa level, approx 90 degree phase shift to previous definition. Contour interval is 0.5 hPa for ERAI, 0.25 hPa for model. Model composites based on 25 member ensemble. Note slightly smaller sample despite longer period.

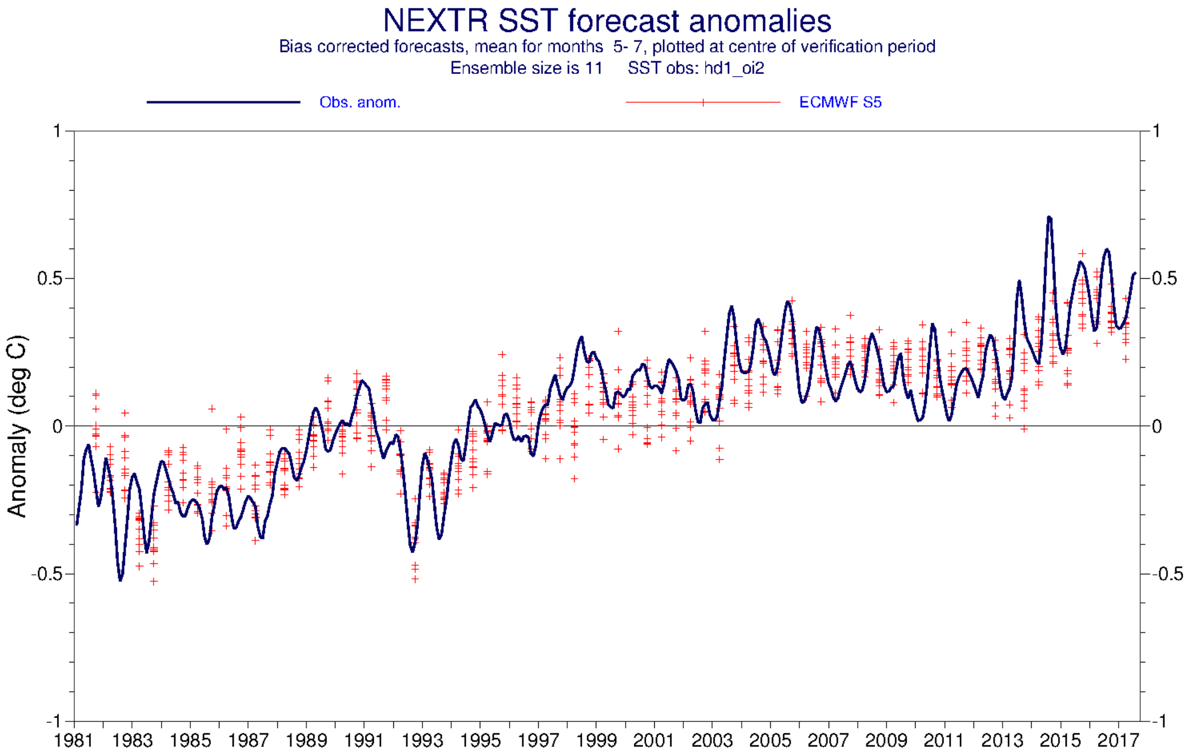
NB: QBO phase chosen to optimize observed NAO, possibility of overfitting.

Stratosphere – volcanic aerosols

SEAS5 does **not** have radiatively interactive ozone

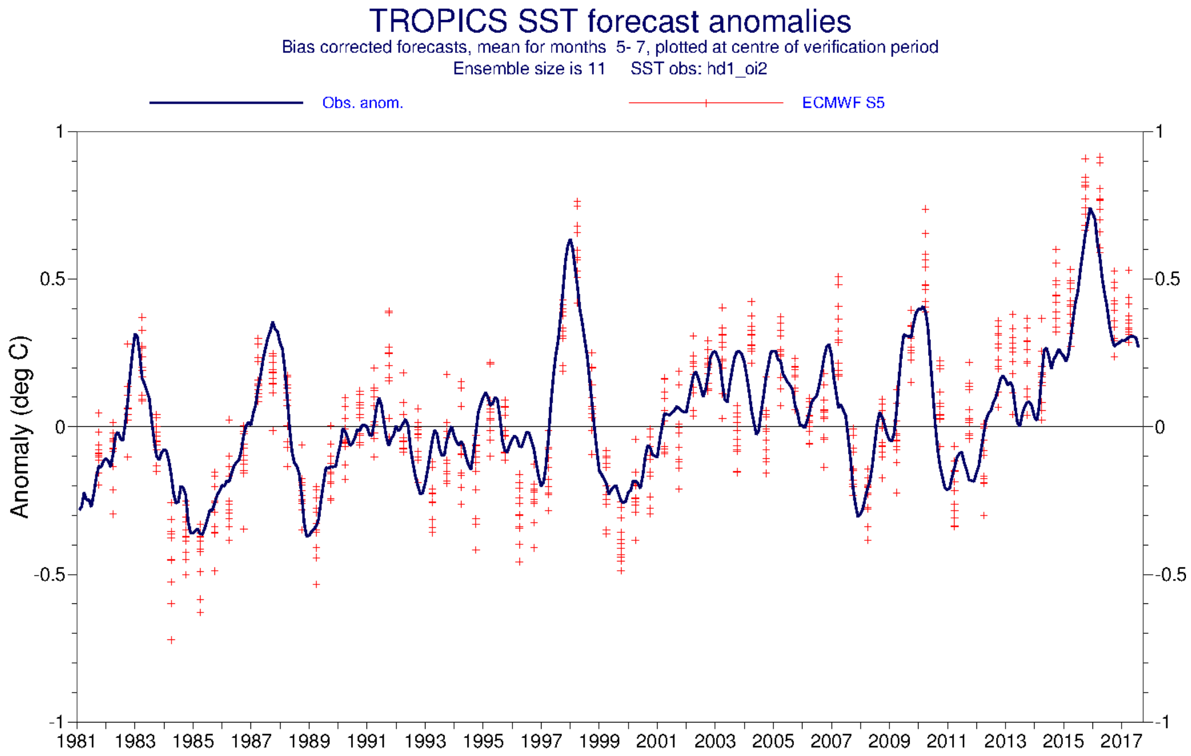


Trends

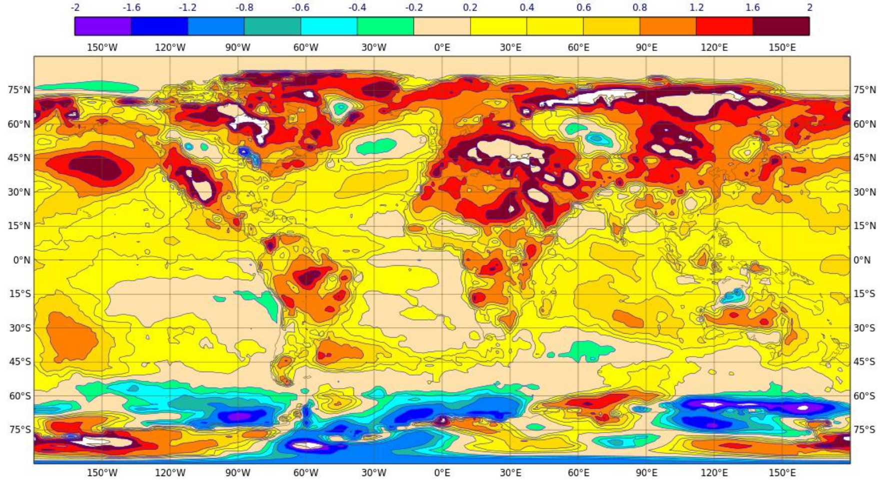


Capturing trends is important. Time-varying CO_2 and other factors are important in this.

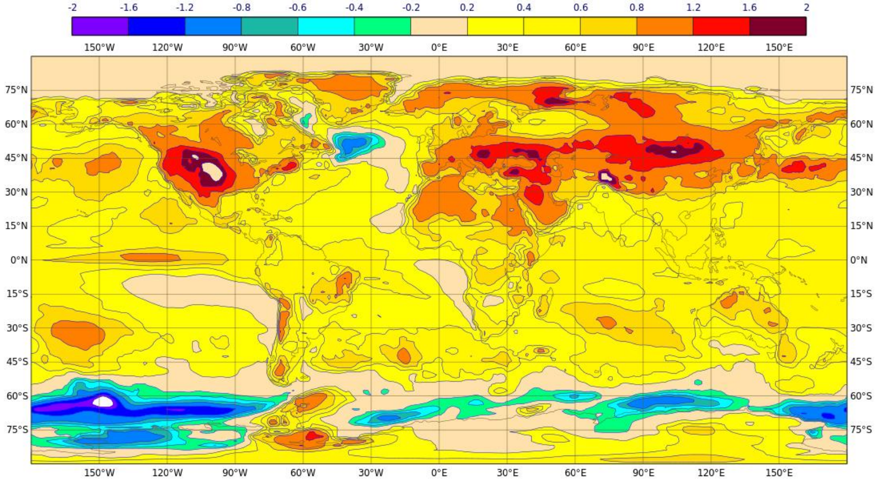
There is a strong link between seasonal prediction and decadal/ multi-decadal climate prediction.



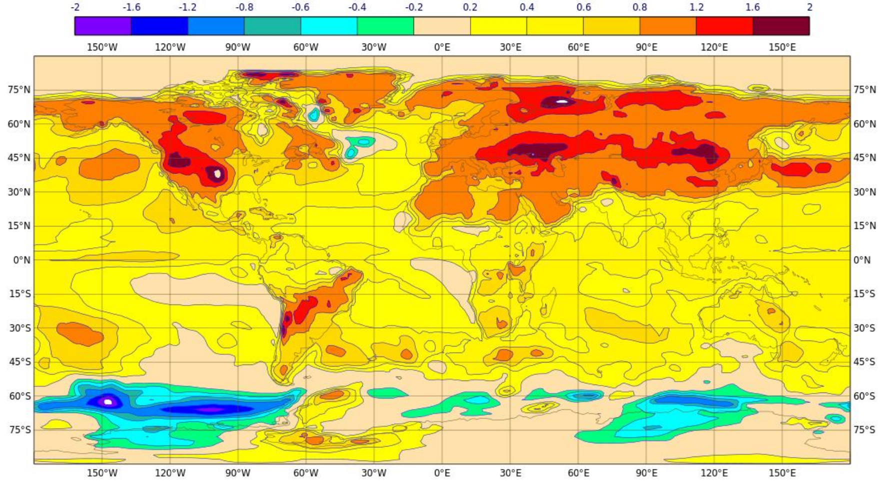
era5: 2-metre temperature, JJA mean
Difference (2011-20) - (1981-90)
mean: 0.52 rms: 0.77 stddev: 0.57



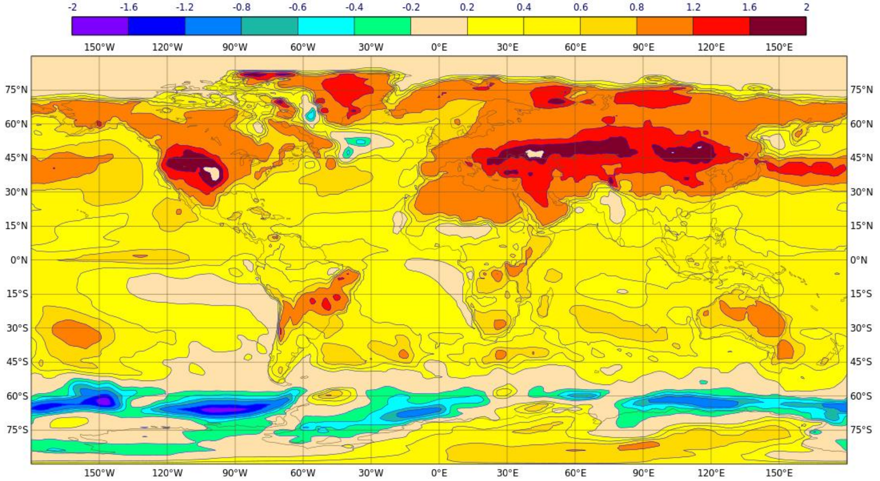
seas5: 2-metre temperature, JJA mean
Difference (2011-20) - (1981-90)
mean: 0.46 rms: 0.60 stddev: 0.39

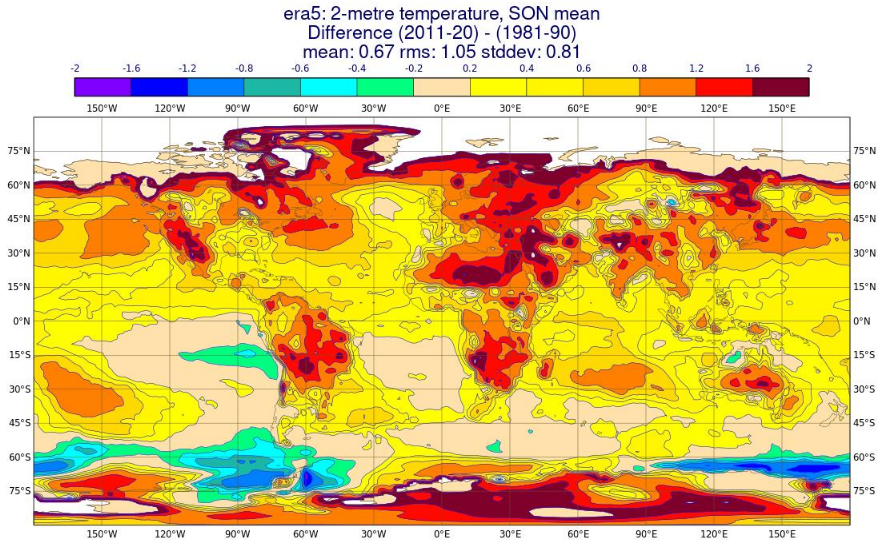


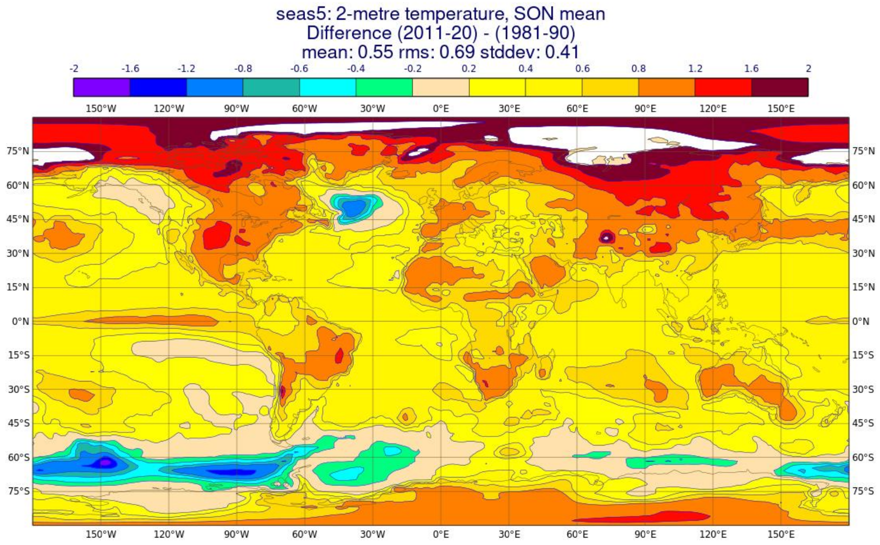
i5gs: 2-metre temperature, JJA mean
Difference (2011-20) - (1981-90)
mean: 0.48 rms: 0.62 stddev: 0.39

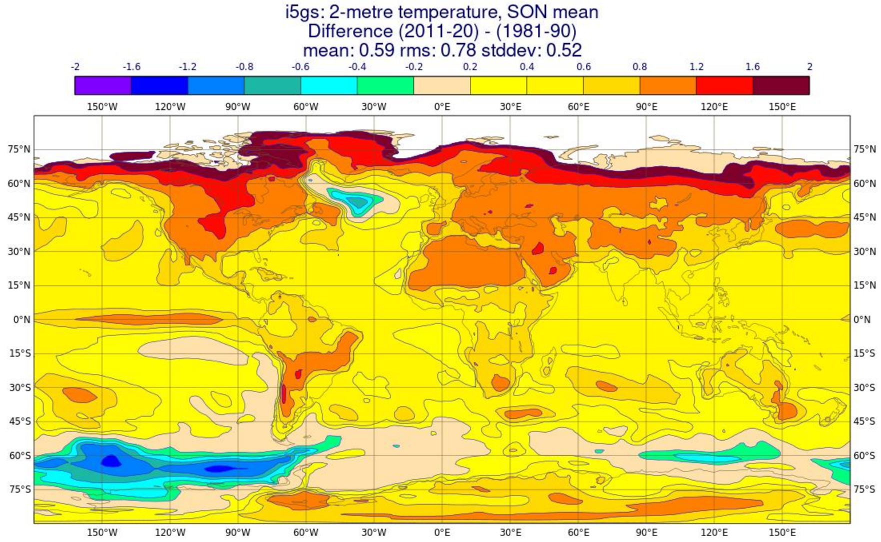


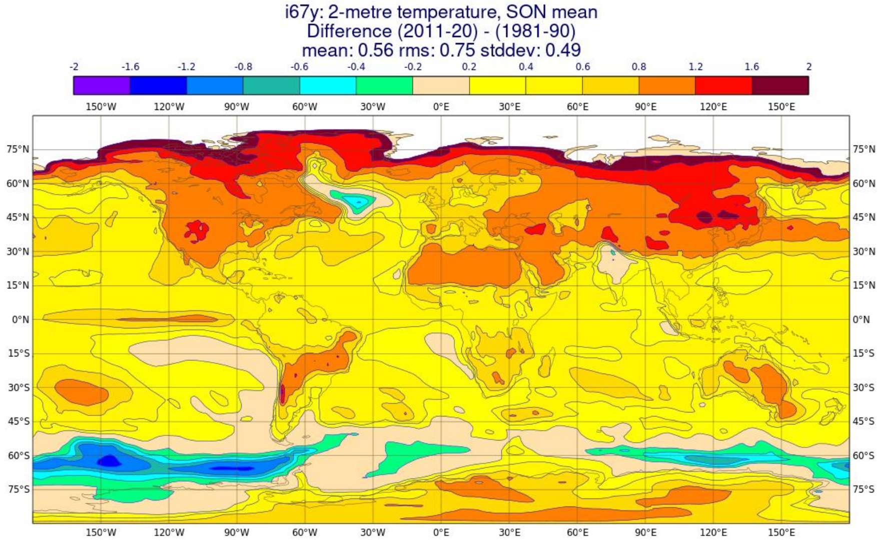
i67y: 2-metre temperature, JJA mean
Difference (2011-20) - (1981-90)
mean: 0.50 rms: 0.65 stddev: 0.42




era5: 2-metre temperature, SON mean
Difference (2011-20) - (1981-90)
mean: 0.67 rms: 1.05 stddev: 0.81


seas5: 2-metre temperature, SON mean
Difference (2011-20) - (1981-90)
mean: 0.55 rms: 0.69 stddev: 0.41


i5gs: 2-metre temperature, SON mean
Difference (2011-20) - (1981-90)
mean: 0.59 rms: 0.78 stddev: 0.52

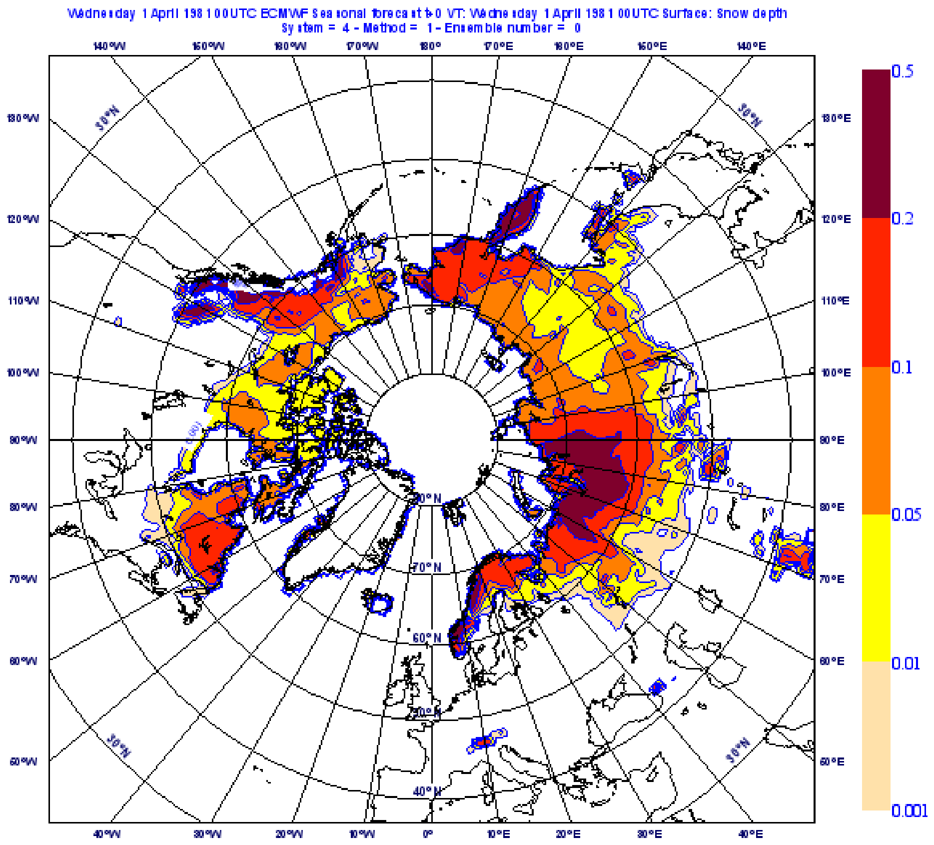

i67y: 2-metre temperature, SON mean
Difference (2011-20) - (1981-90)
mean: 0.56 rms: 0.75 stddev: 0.49

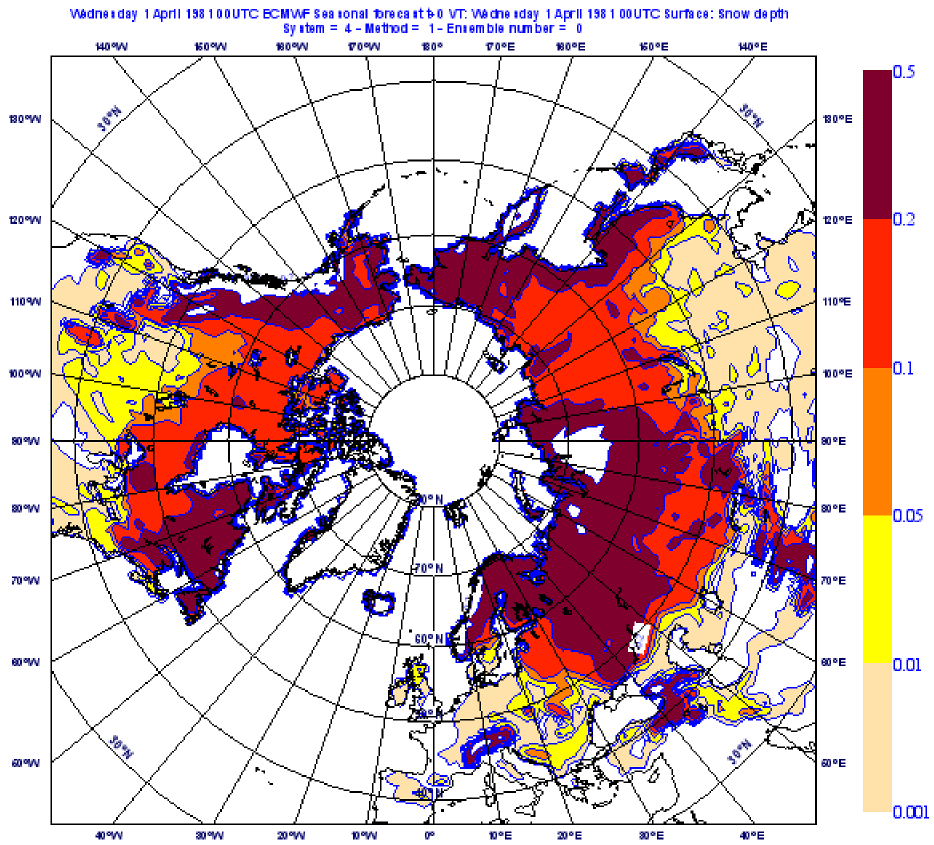
SEAS5 initial conditions

- Issue of consistency
  - Differences between real-time analyses and re-analyses must be minimised
  - Not easy, given evolution of observing system and practical constraints

- Issue of uncertainty
  - Attempt to sample uncertainty in initial state
    - SST (50 perturbations)
    - ocean sub-surface (5 member analysis)
    - atmosphere (singular vectors, EDA)
    - … but not yet land

Initial conditions - land surface





Snow depth limits, 1st April

Used as a safeguard to ensure consistency between real-time and re-forecast initial states.
Applied to soil moisture, snow, lakes, soil temperatures. Specific to seasonal configuration.

ECMWF SEAS5 forecasts and re-forecasts

- Real time forecasts:
  - **51 member ensemble forecast to 7 months**
  - SST and atmosphere initial perturbations (SV, EDA) added to each member

  - **15 member ensemble forecast to 13 months**
  - Designed to give an ‘outlook’ for ENSO
  - Only runs once per quarter (Feb, May, Aug and Nov starts)

- Re-forecasts from 1981-2016 (**36 years**)
  - **25 member** ensemble every month
  - 15 members extended to 13 months once per quarter

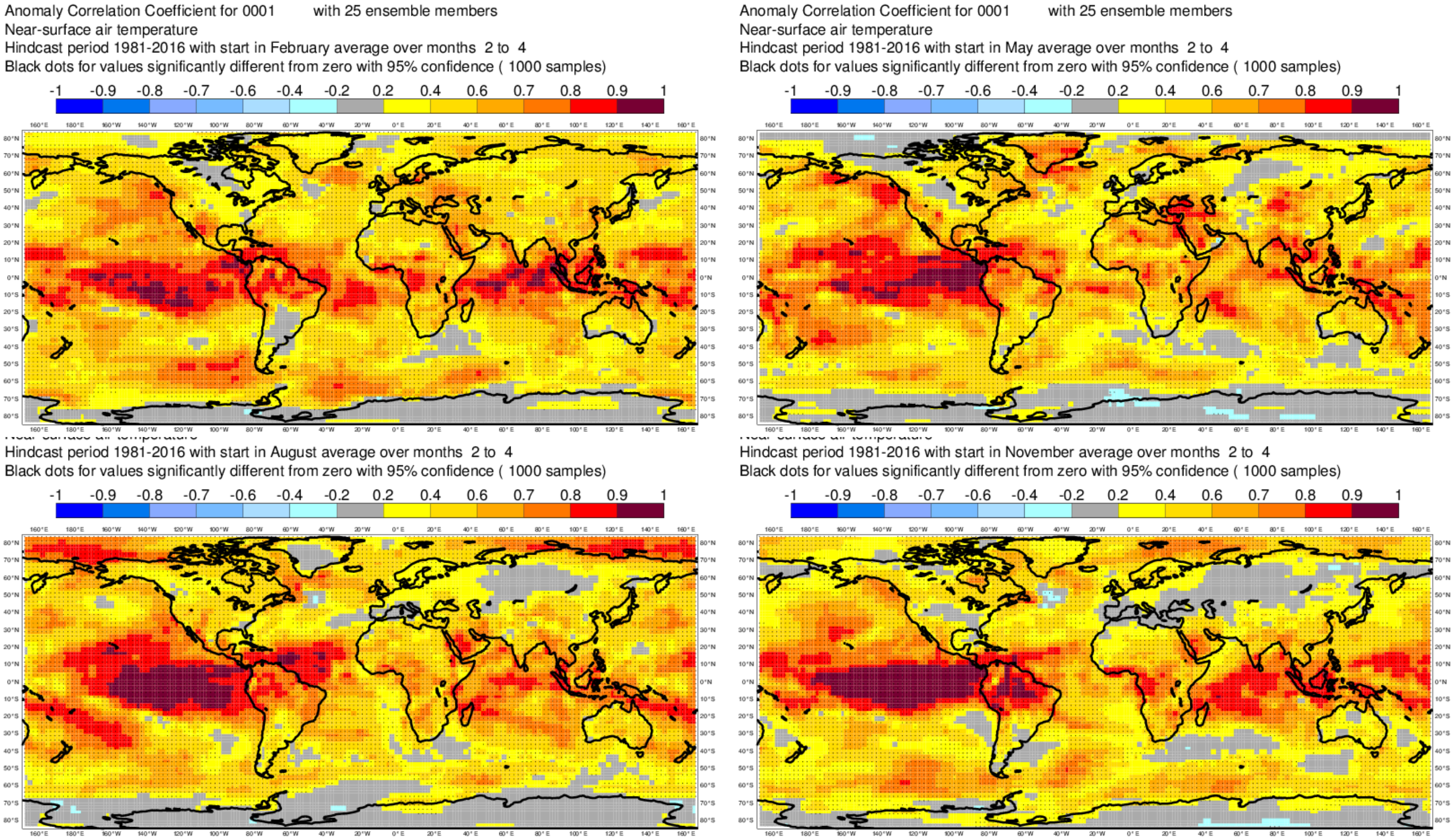
How many re-forecasts?

- Re-forecasts dominate total cost of system
  - SEAS5: 10800 re-forecasts (must be in first year)
    612 real-time integrations (per year)
- Re-forecasts define model climate
  - Need both climate mean and the pdf, latter needs large sample
  - May prefer to use a “recent” period (SEAS5 has 36 years available, but uses only last 24 years for web products)
  - SEAS5 has 600 member climate (25 members * 24 years) for web products, so sampling is basically OK
- Re-forecasts provide information on skill
  - A forecast cannot be used unless we know (or assume) its level of skill
  - Observations have only 1 member, so large ensembles are less helpful than large numbers of cases.
  - Care needed e.g. to estimate skill of 51 member ensemble based on past performance of 25 member ensemble
  - For regions of high signal/noise, SEAS5 gives adequate skill estimates
  - For regions of low signal/noise (eg <= 0.5), need hundreds of years, 36 years available is not enough

Skill can vary a lot with season ……

MAM

JJA

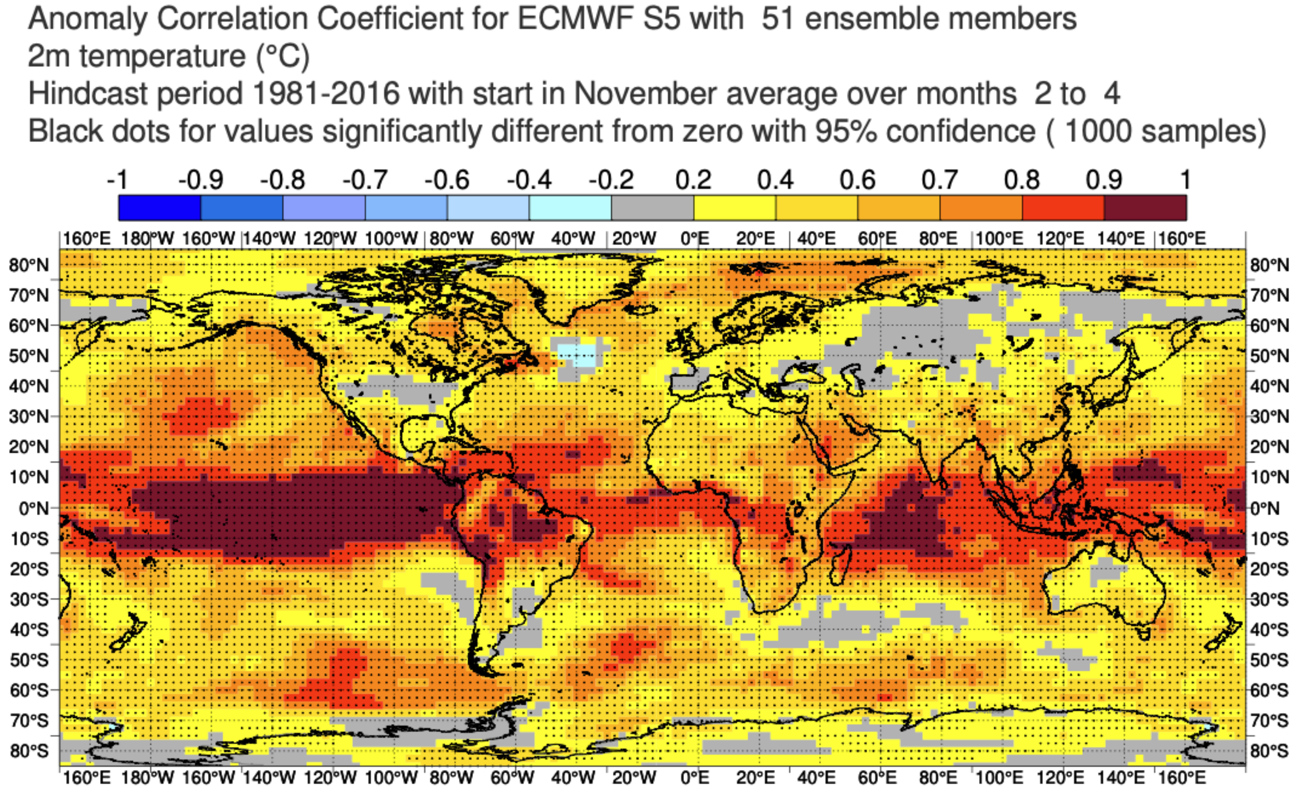


SON

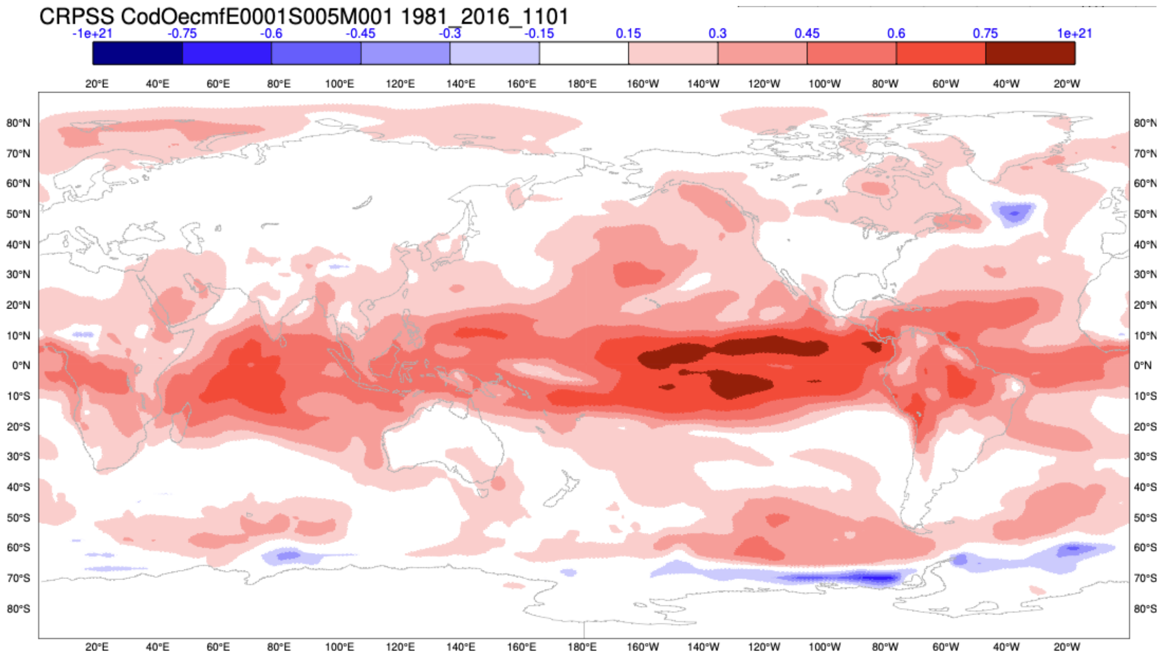
DJF

Skill estimates vary with ensemble size

Here we plot some DJF scores calculated from 51 member reforecasts – we can only do this from certain dates



SEAS5 correlation skill in N Europe is around 0.5, statistically significantly >0. But skill is much higher in the tropics, as always.



Probabilistic scores such as CRPSS against climatology remain small for Europe in winter.

A much wider set of scores is given on the web but are based on 25-member ensembles. They thus underestimate both skill and reliability of the 51-member real-time ensemble forecast.

ECMWF

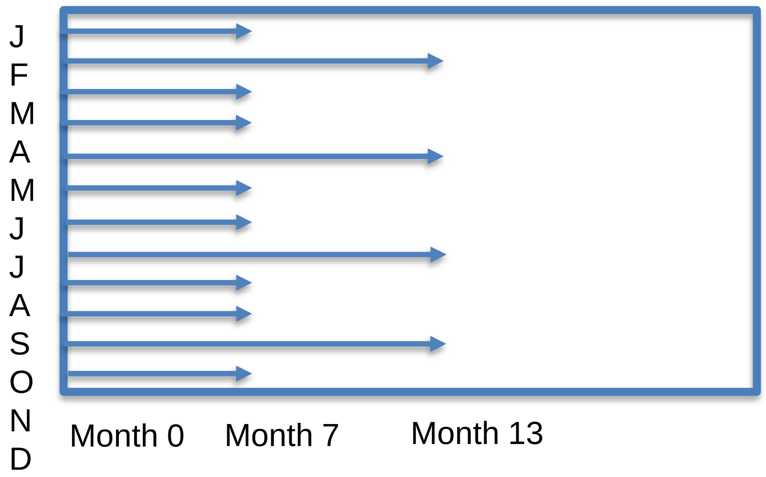
SEAS5 operational; SEAS6 planned for 2024/2025

- **Scientific improvements**
  - New IFS version (Cy49r2 vs Cy43r1)
  - New ocean model (NEMO4 SI3 vs NEMO3.4 LIM2)
  - New ocean re-analysis
  - New offline land surface re-analysis / real-time analysis
- **Resolution improvements**
  - Horizontal resolution unchanged
  - IFS vertical resolution L91 -> L137
  - IFS and NEMO from double to single precision, overall cost neutral
- **Configuration improvements**
  - This is where we have used extra HPC resources

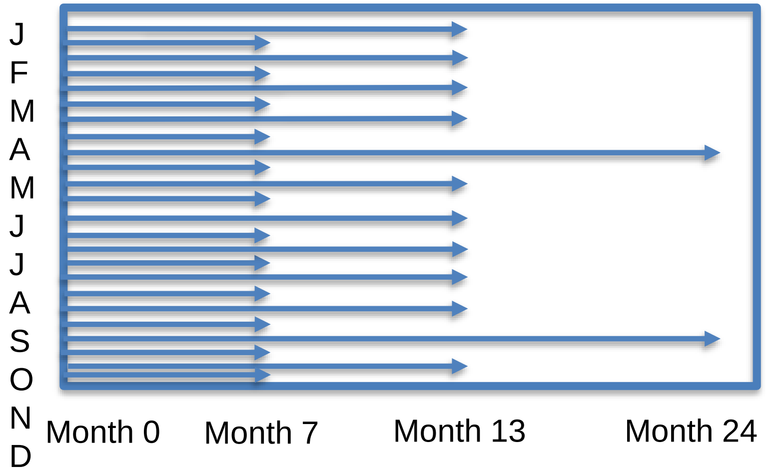
SEAS6 configuration summary

- **Enhancement 1: Real-time 101 member ensemble**
- **Enhancement 2: Issue SEAS twice per month**
  - Initial date 1st and 16th of each month
- **Enhancement 3: More comprehensive reforecasts**
  - Larger ensemble sizes and larger set of years
- **Enhancement 4: Expand annual-range ENSO forecasts**
  - Issue forecast monthly not quarterly
  - Twice per year, increase range to 24 months

SEAS5

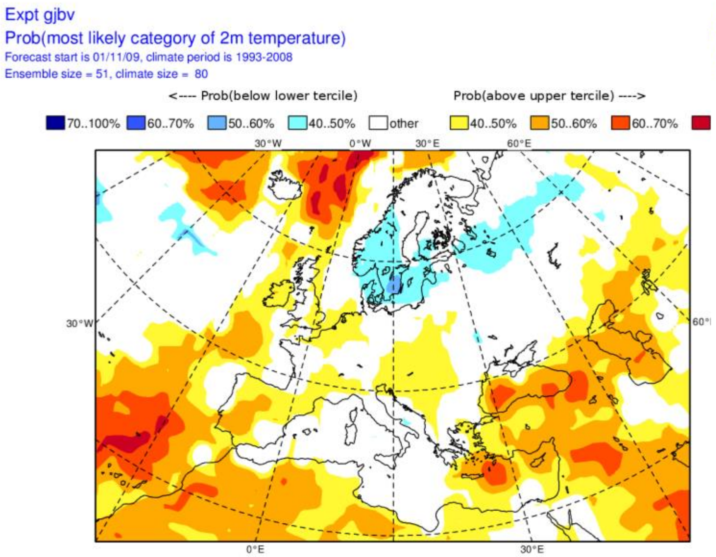


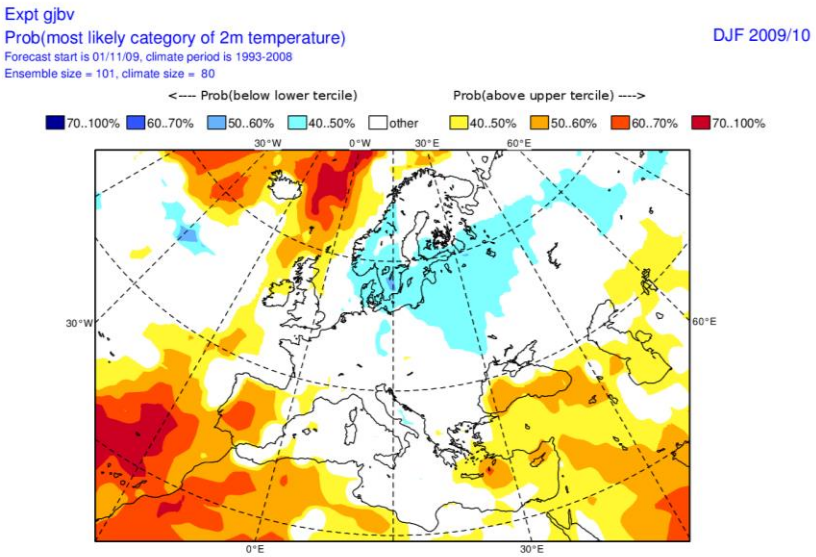
SEAS6

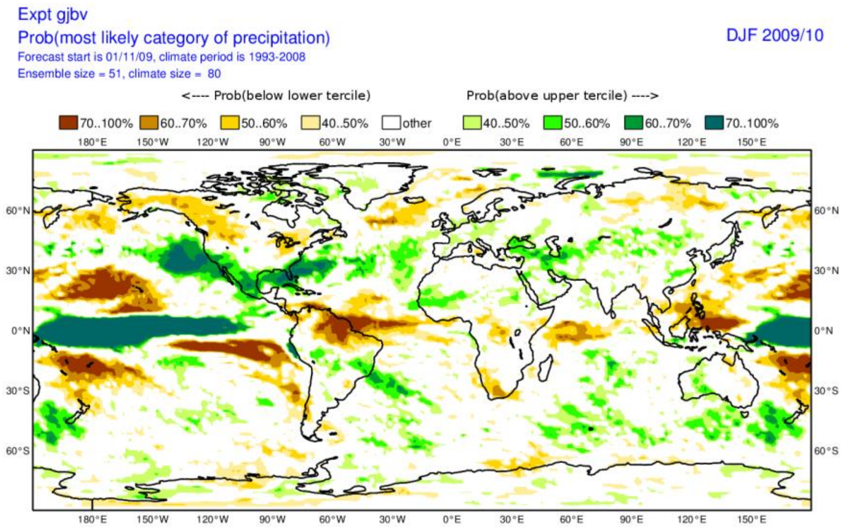


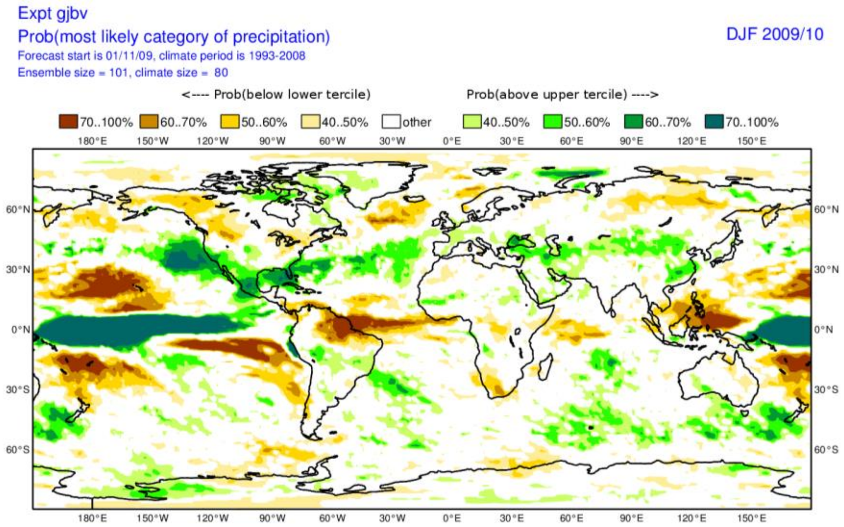
SEAS6 enhancement 1: 101 member ensembles

- Reduced noise and improved accuracy in forecasts





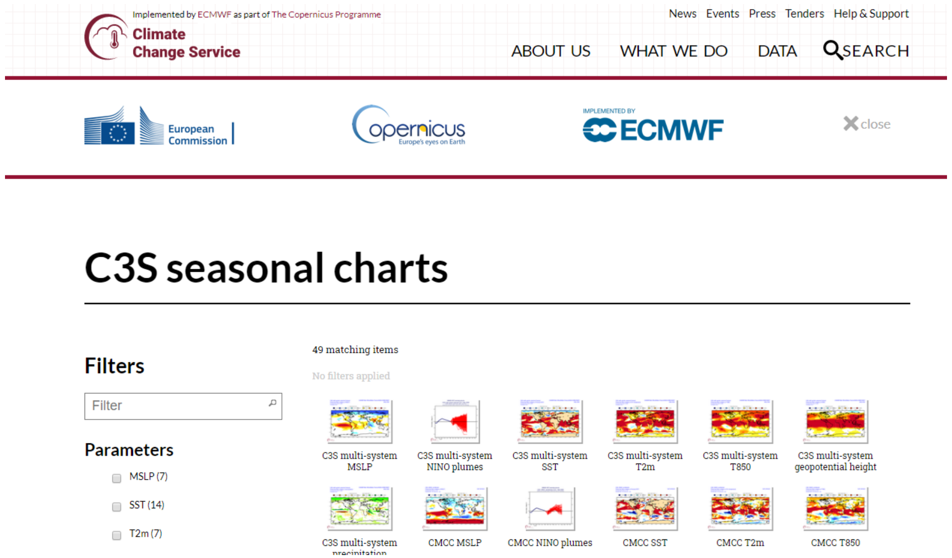




- Consistent with recent increase in EXT
- For SEAS5, real-time is only 5.4% of seasonal cost in first year, so doubling this is relatively cheap.

Alternative approach to reducing impact of model errors: multi-model

- First operational system: EUROSIP
- New incarnation: C3S from COPERNICUS
- More comments in tomorrow's lecture on calibration



Summary – operational aspects

- ECMWF seasonal forecasting is largely **seamless** with medium/extended range configurations
  - A very small number of adaptions important for longer timescales
  - Aim is to incorporate these into medium-range configuration to have a completely unified system
- Seasonal forecast configuration includes extensive re-forecast set
  - Dominates cost of system, only updated at intervals of several years
  - Allows many types of calibration and estimation of skill
- Seasonal forecast product set includes large range of graphical products
  - Fundamental rule is that all products should be provided alongside estimates of skill and/or reliability
- Multi-model seasonal forecasts are provided by C3S
  - These are considered to be better than any single model, and should always be consulted

Summary – scientific considerations

- Forecasting models are fairly realistic in many ways, but remaining errors are enough to substantially impact forecast skill and reliability, even after calibration
- Creating consistent initial conditions for past and present is a challenge, due in particular to the lack of observational data in the past. Observing systems are better now, but still need some improvements.
- Limited predictability and limited past data prevent us being sure about the skill levels of today's forecast systems, and assessment of improvements in forecast skill is difficult.
- Changing climate is a challenge
  - are our trends right?
  - how do we assess uncertainty in a real-time forecast?
  - how do we communicate the forecast?
- Multi-model ensembles are helpful, **but** they only partially span the space of model errors.
- In the end, the only way to achieve high reliability is to build trustworthy models

References and further reading

SEAS5 forecasts on www.ecmwf.int/en/forecasts/charts and https://climate.copernicus.eu/seasonal-forecasts

ECMWF Seasonal Forecast User Guide

SPECS fact sheets http://www.specs-fp7.eu/Fact%20sheets on seasonal forecasting

Boer, G.J. and K. Hamilton, 2008: QBO influence on extratropical predictive skill. Clim. Dyn. 31:987–1000. doi: 10.1007/s00382-008-0379-5

Hagedorn, R., F.J. Doblas-Reyes and T.N. Palmer, 2005: The rationale behind the success of multi-model ensembles in seasonal forecasting. Part I: Basic concept. *Tellus*, 57A, 219-233.

Molteni, F., Stockdale, T., Balmaseda, M., Balsamo, G., Buizza, R., Ferranti, L., Magnusson, L., Mogensen, K., Palmer, T., and Vitart, F, 2011: The new ECMWF seasonal forecast system (System 4), ECMWF Tech. Memo 656., DOI:10.21957/4nery093i

Johnson, S. J., Stockdale, T. N., Ferranti, L., Balmaseda, M. A., Molteni, F., Magnusson, L., Tietsche, S., Decremer, D., Weisheimer, A., Balsamo, G., Keeley, S., Mogensen, K., Zuo, H., and Monge-Sanz, B., 2018: SEAS5: The new ECMWF seasonal forecast system, Geosci. Model Dev. DOI: 10.5194/gmd-2018-228

Stockdale, T., Alonso-Balmaseda, M, Johnson, S, Ferranti, L, Molteni, F, Magnusson, L, Tietsche, S, Vitart, F, Decremer, D, Weisheimer, A, Roberts, CD, Balsamo, G, Keeley, S, Mogensen, K, Zuo, H, Mayer, M, and Monge-Sanz, BM, 2018: SEAS5 and the future evolution of the long-range forecast system. ECMWF Tech Memo 835, DOI: 10.21957/z3e92di7y