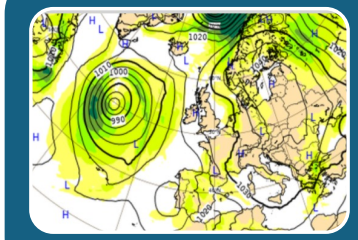
Seasonal forecasting at ECMWF

Predictability training course lecture, 2026

Stephanie Johnson

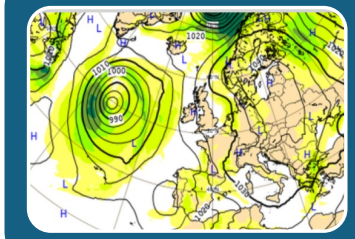
With thanks to Tim Stockdale, Dan Befort, Eduardo Penebad and Anca Brookshaw

Ensemble Forecast systems at ECMWF



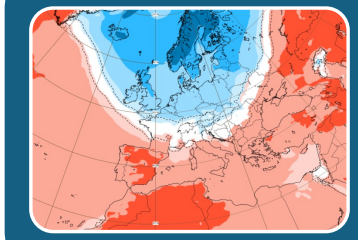
IFS: Medium range

- 0-15 days
- 9 km resolution, 137 levels
- 51 ensemble members, run twice daily
- Upgraded approximately once a year



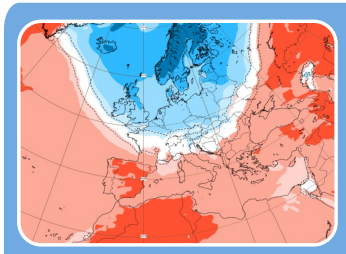
AIFS: Medium range

- 0-15 days
- ~0.25 degree resolution
- Deterministic (AIFS-single) and ensemble (AIFS-ENS) versions
- Upgraded as developments are ready



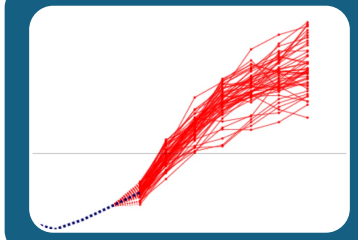
IFS: Sub-seasonal

- 0-46 days
- 35 km, 137 levels
- 101 ensemble members, run once daily
- Upgraded approximately once a year, with medium range



AIFS: Sub-seasonal

- 0-46 days
- ~1 degree resolution
- Modified version of AIFS-ENS
- Running in experimental real-time mode



IFS: SEAS5

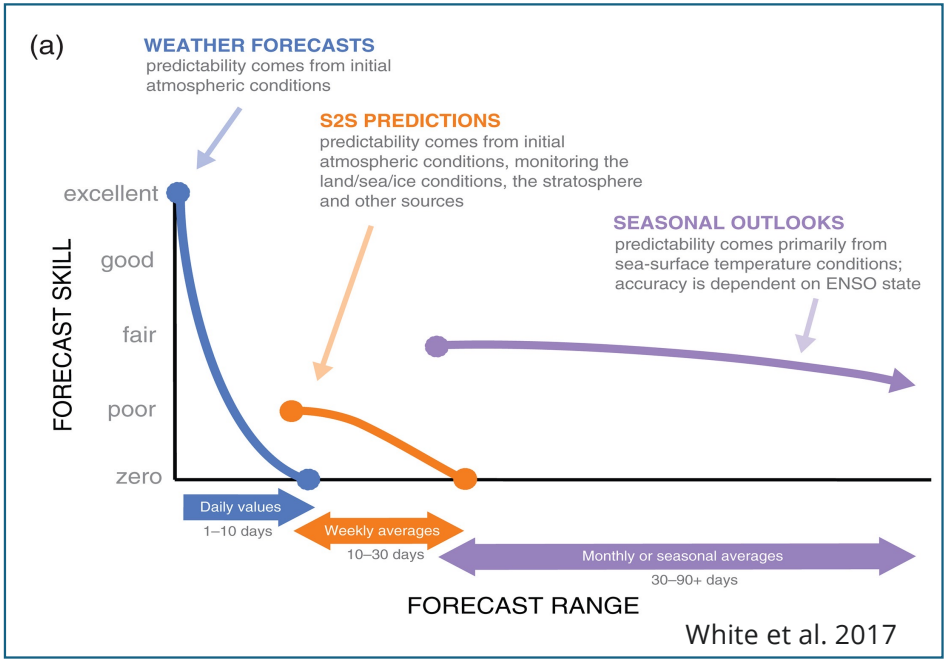
- 0-7 months
- 35 km, 137 levels
- 51 ensemble members, run once a month
- Four times a year, the forecast is run out to 13 months
- Last upgraded in 2017 (Cy43r1), next upgrade in 2027

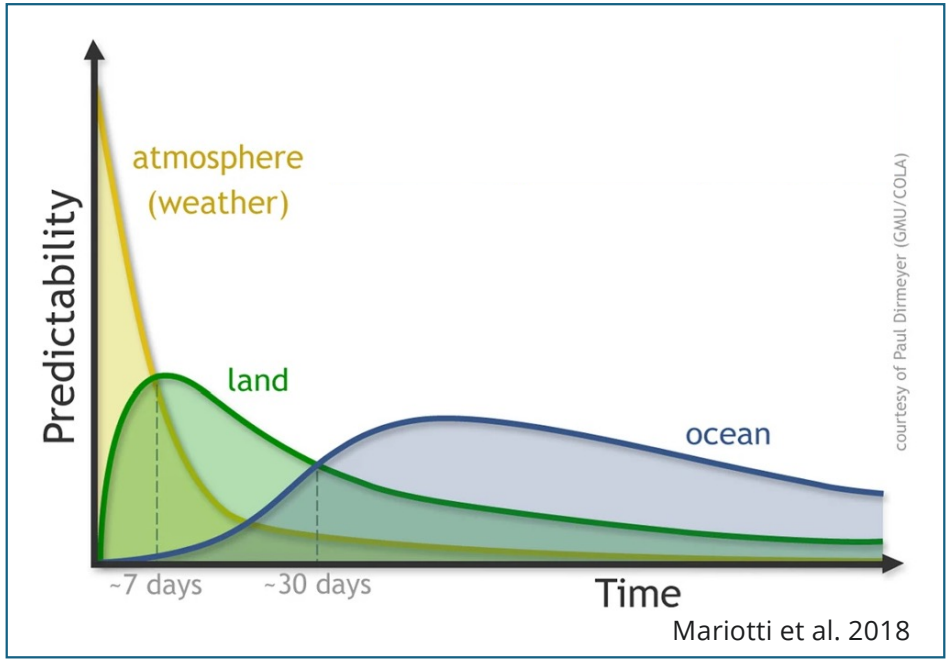
A seamless forecast model underpins all dynamical systems (at implementation).

Overview

- The basis for seasonal forecasting
- Components of a seasonal forecast system
- ECMWF's seasonal forecast system
  - SEAS5 configuration
  - SEAS5 products and calibration
- Future developments in seasonal forecasting
  - SEAS6 development
  - Beyond SEAS6

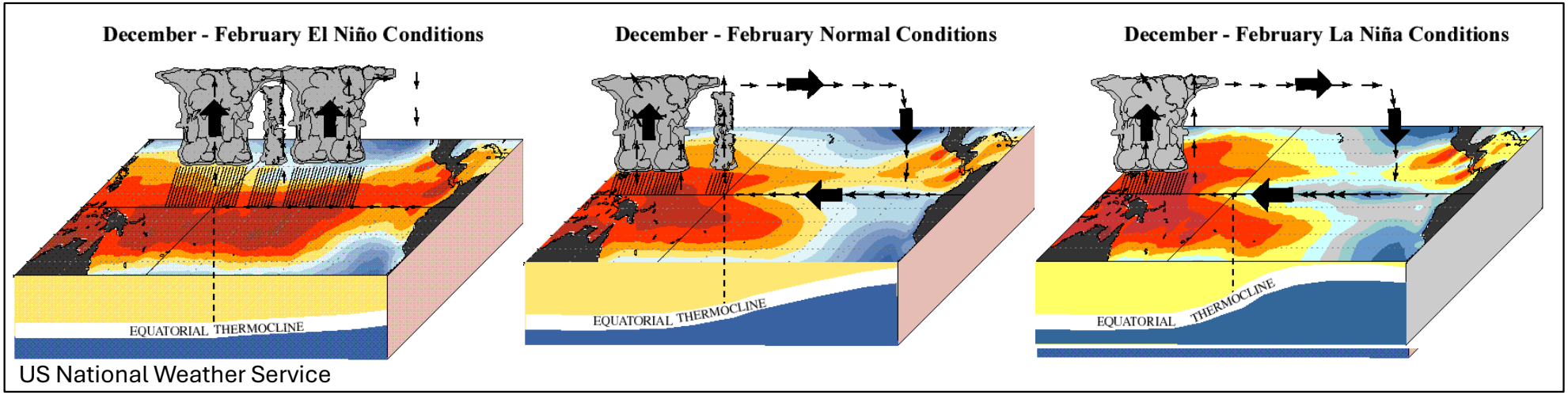
The basis for seasonal forecasting





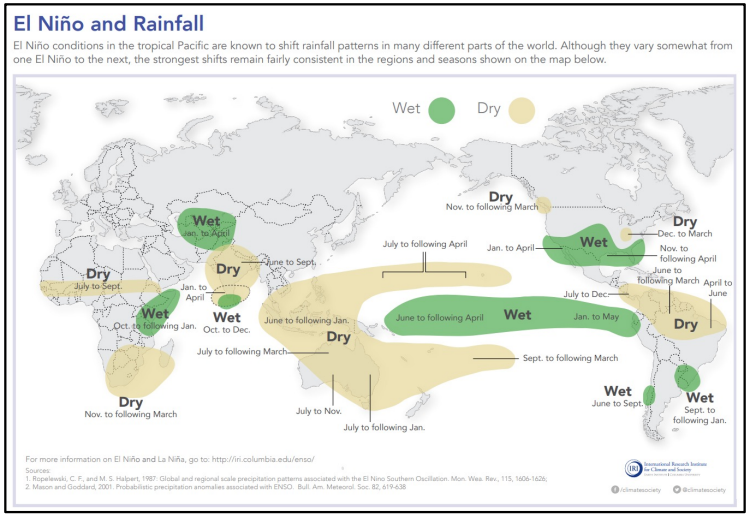
- Unlike NWP, which relies on predictability from the atmosphere initial conditions, seasonal forecasting relies on the slower evolving boundary conditions to the atmosphere that are predictable at longer timescales. Forecasts are usually issued for monthly or seasonal means.
- The dominant source of predictability at seasonal timescales are predictable modes of the tropical oceans which impact global circulation through changes in tropical precipitation.

The importance of ENSO

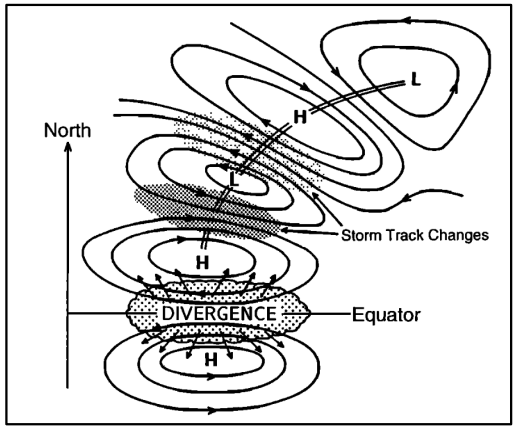


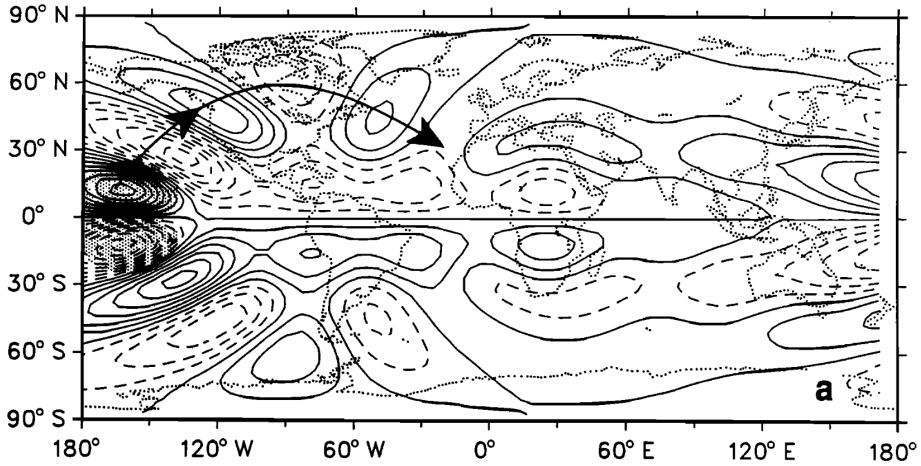
US National Weather Service

- The El-Nino southern oscillation is the leading mode of interannual SST variability.
- ENSO changes the location of the convection in the tropical Pacific warm pool, altering the Walker circulation.
- Impacts are pronounced in the tropics, for example, ENSO is the dominant predictable driver of South Asian Monsoon rainfall (JJA).



The importance of ENSO





Trenbeth et al. 1998

- Anomalous convection also excites Rossby waves that propagate to the extratropics.
- ENSO teleconnections affect the PNA and North American continent and, to a lesser extent, the European sector.
- Correctly predicting these complex processes is a challenge for seasonal forecast models.

Sources of seasonal predictability

- Known sources of predictability
  - 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 less prominent sources of predictability
  - 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. Arctic fires in summer 2019 ????

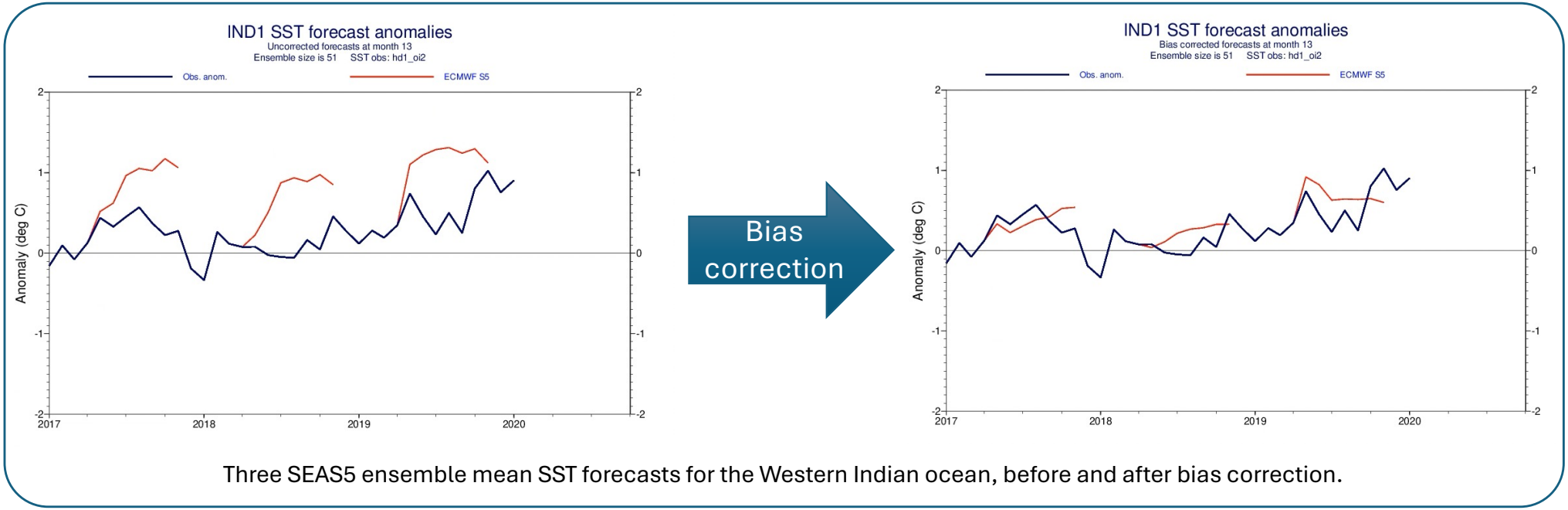
Thanks to T. Stockdale

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Why do we need a re-forecast set?

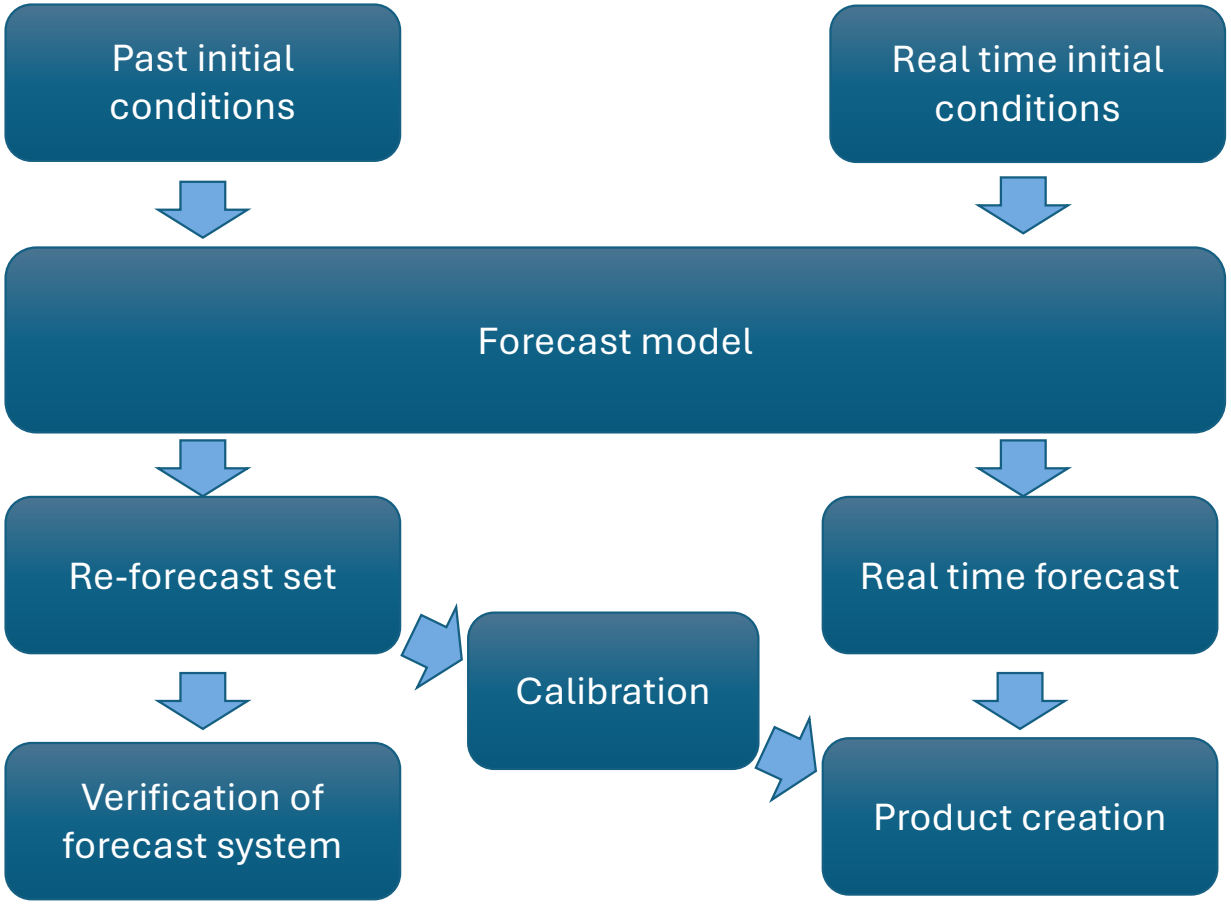
- Climate models drift substantially over the longer timescale of seasonal forecasts, giving errors in the model climate that can be comparable to interannual variability.
- Consequently, forecasts need to be calibrated. A set of retrospective forecasts, or re-forecasts/hindcasts are used to calculate corrections that are applied to calibrate the real-time forecast.
- This re-forecast set is typically 20-30 years of forecasts - far more computationally expensive than the forecast.



Three SEAS5 ensemble mean SST forecasts for the Western Indian ocean, before and after bias correction.

Components of a seasonal forecast system

- Real-time atmosphere, ocean, land, and sea ice initialization is needed to initialize real-time forecasts.
- Quality historical reanalysis of atmosphere, ocean, land, and sea ice is needed to initialize reforecasts.
- Reforecast set also used for verification. This can be challenging to interpret - because of the limited number of cases in the re-forecast set (20-30 years), sampling error is often comparable to true impacts from changes to the system.



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SEAS5 initial conditions

	Re-forecasts	Real time
Atmosphere	ERA-Interim	ECMWF operational analysis
Ocean	ORAS5 reanalysis	OCEAN5-RT
Land	Offline LDAS driven by ERA-Interim	ECMWF operational analysis

Initial condition perturbations sample uncertainty in initial state

Atmosphere (singular vectors, EDA)

Ocean: ocean sub-surface (5 member analysis) and additional SST perturbations (50 perturbations)

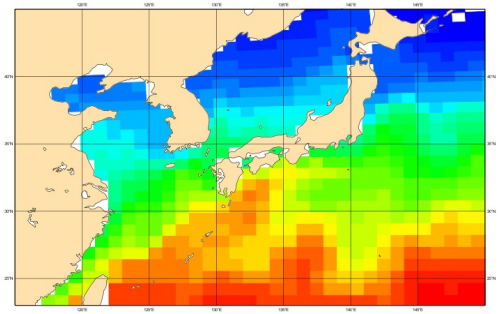
Issue of consistency

Differences between real-time analyses and re-analyses must be minimised

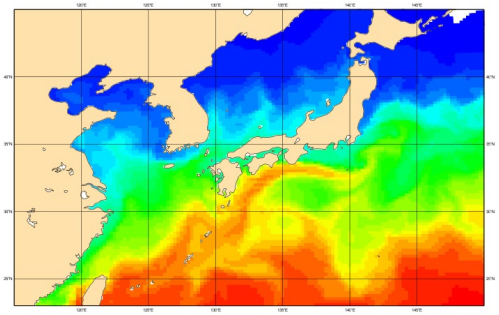
SEAS5 forecast model

- SEAS5 is a **state of the art coupled seasonal forecasting system**:
  - IFS (atmosphere and land surface)
    - $T_{CO}319L91$ Cy43r1, 36km 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 (ERA5) 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 (prognostic sea-ice)
    - Single category ice, solved on same grid as ocean model

NEMO ORCA1 Z42



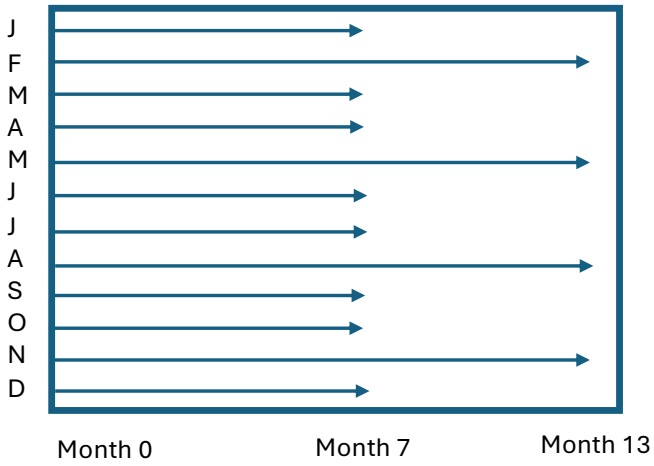
NEMO ORCA025 Z75



Thanks to T. Stockdale

SEAS5 forecasts and re-forecasts

- Forecasts initialized on the first of the month
  - “Long range forecast”: 51 members integrated for 7 months
  - ”ENSO outlook”: 15 of those members integrated for 13 months in Feb, May, Aug, Nov
- Re-forecasts initialized from 1981 to 2016 (36 years)
  - 25 members integrated for 7 months
  - 15 of those members integrated for 13 months in Feb, May, Aug, Nov
  - For operational charts, 1993 to 2016 used for bias correction (24 years, consistent with C3S)
  - Whole period used for verification



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Ensemble mean anomaly

Forecast anomaly = forecast − model climatology

1 Average over the target season

For each ensemble member, calculate the mean over the chosen months, for example December–February.

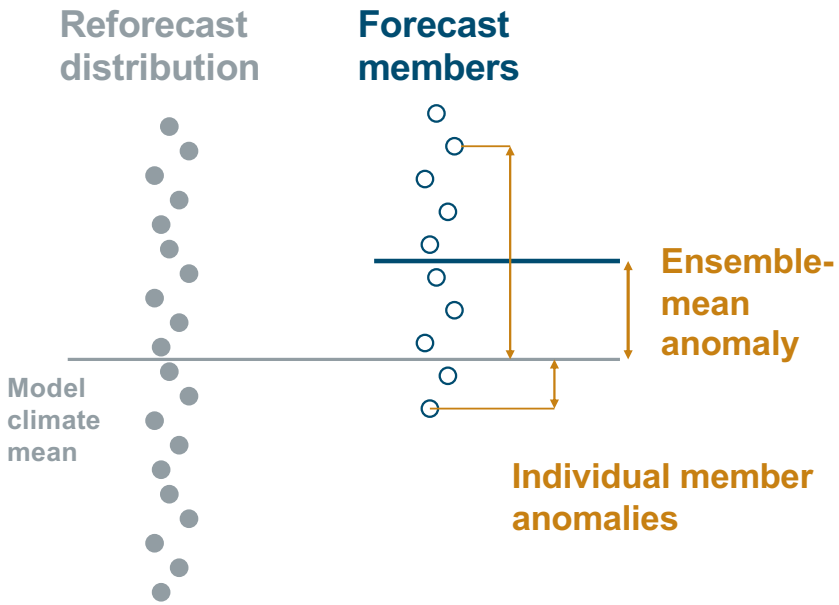
2 Calculate the model's normal climate

Average reforecasts for the same model, start month and lead time. Standard SEAS5 maps use the 1993–2016 baseline.

3 Subtract the matched climatology

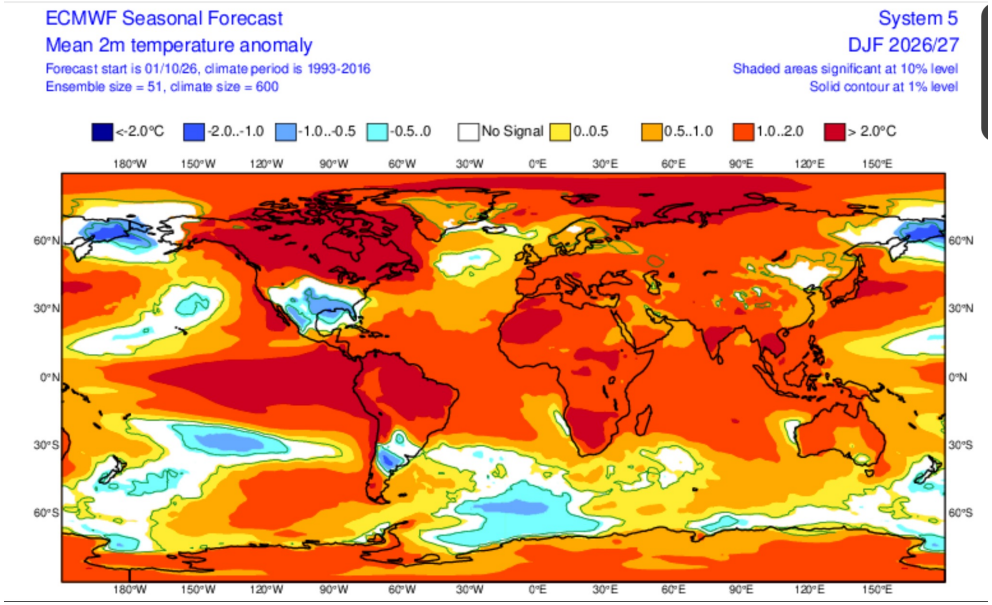
Subtract that baseline from each forecast member. Average the anomalies for an ensemble-mean map, or retain the ensemble spread.

This corrects for average error in the forecast with time

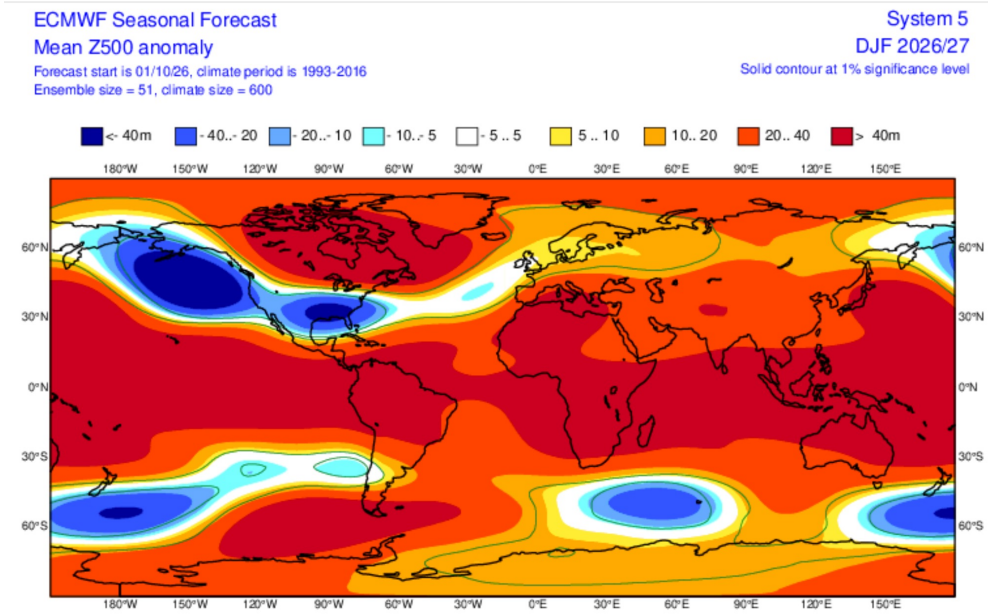


Ensemble mean anomaly example

2-metre temperature

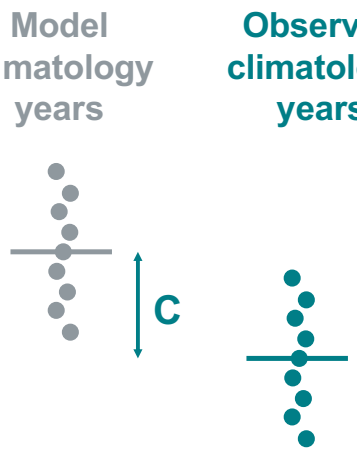


500 hPa geopotential height



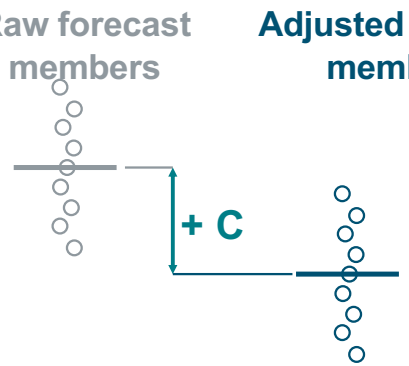
How bias-adjusted forecast anomalies are calculated

1 Estimate the correction



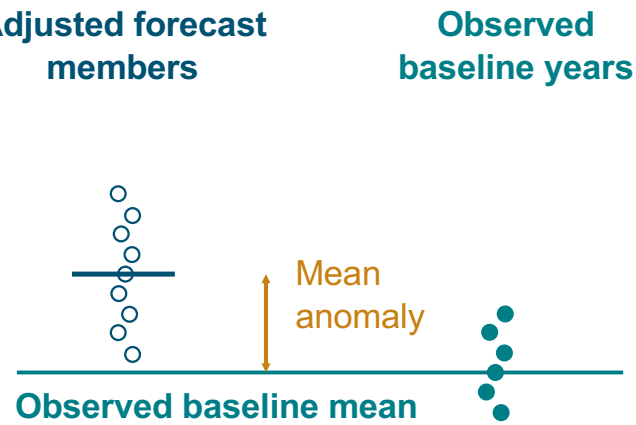
C = observed mean − model mean over calibration period

2 Shift every member by C



Adjusted member = raw member + C

3 Calculate anomalies



Anomaly = adjusted forecast − observed mean over baseline period

Match season, location and forecast lead time when estimating and applying C.
The baseline may use different years from calibration, for example more recent observed years.

Bias-adjusted forecast anomaly example

Correction: 1993–2016

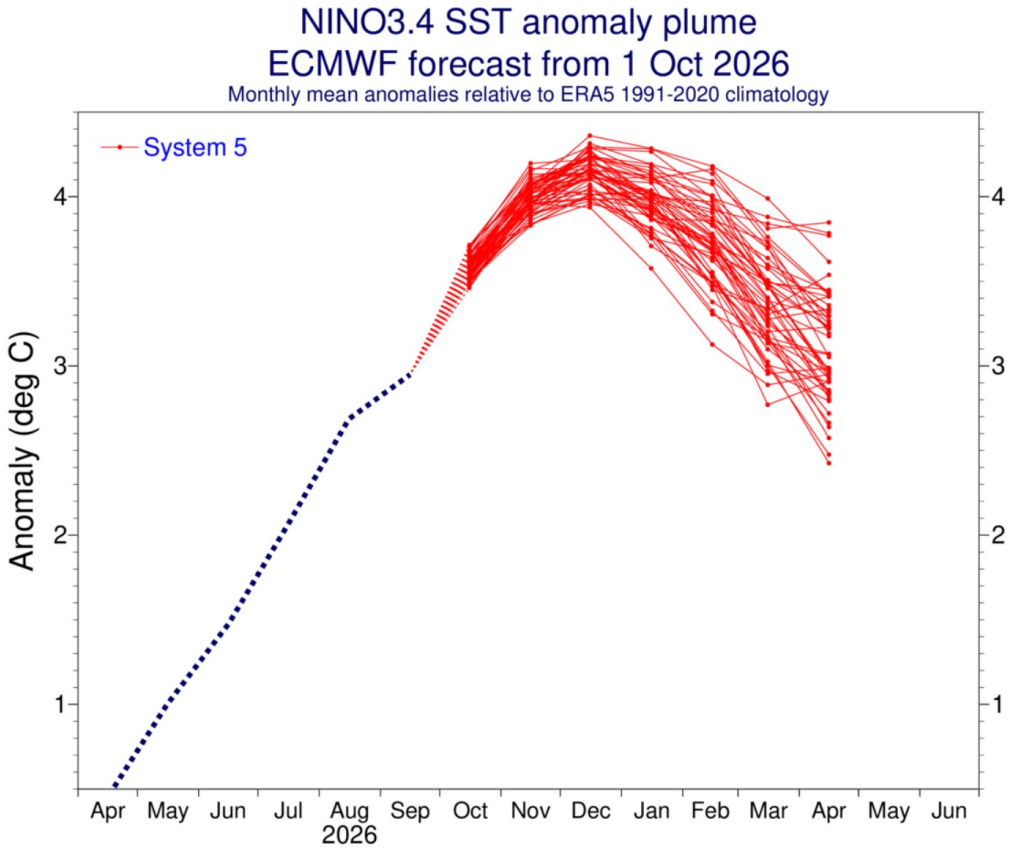
Calculate the bias correction over this calibration period, then apply it to the forecast plumes.

Anomaly: 1991–2020

Express the corrected forecast relative to the more recent observed climatology shown in the plot.

Why use two periods?

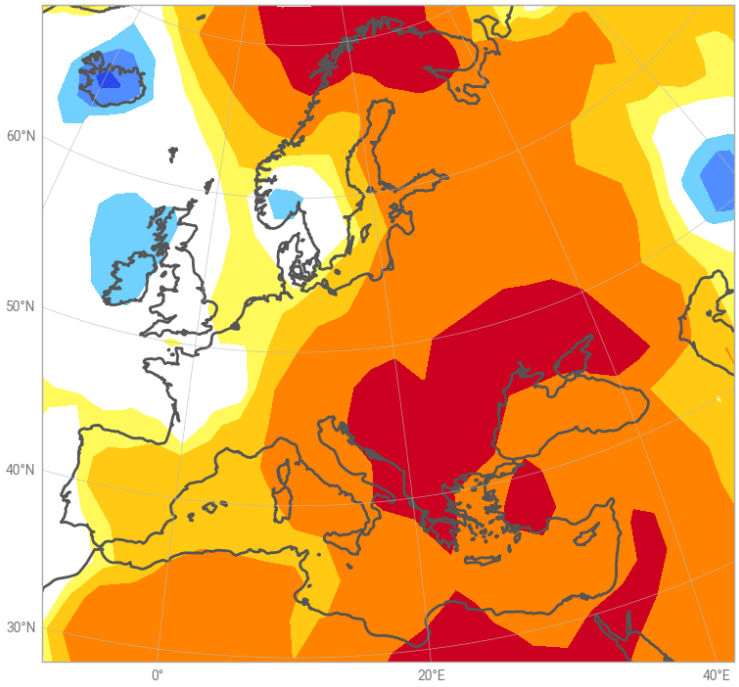
More calibration years improve sampling of the correction. Here – they don't differ much, but the anomaly baseline can now be shifted to suit the application.



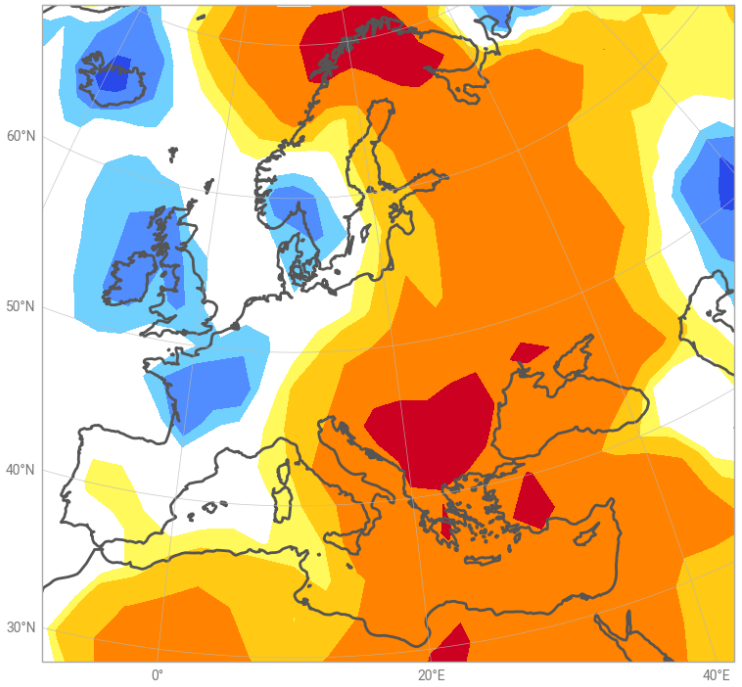
Sensitivity to reference period: summer 2024

ERA5 2-metre temperature JJA anomalies

Relative to 1993-2016* climatology



Relative to 2014-2023





1993-2016* is the currently used baseline/reference period for C3S seasonal products

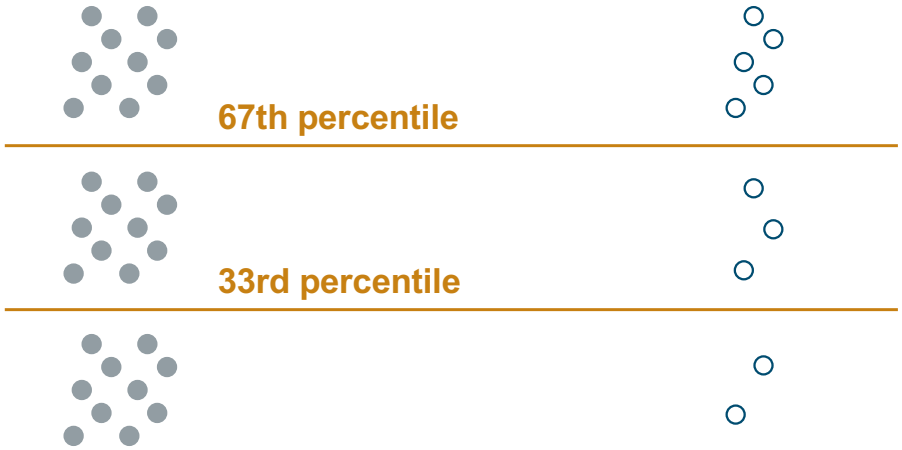
Thanks to D. Befort

How quantile probabilities come from an ensemble

Tercile example at one location, for one target season

1 Define climate thresholds

Re-forecast distribution



Each climate category contains one third of the reference distribution.

2 Classify each member

10 forecast seasonal means

Use the same thresholds for the forecast.

3 Count and divide

Upper third	5 / 10 = 50%
Middle third	3 / 10 = 30%
Lower third	2 / 10 = 20%

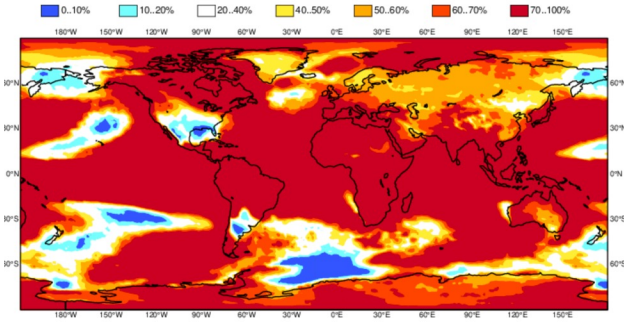
P(category) = members in category / total members

Illustrative 10-member ensemble with 6 year 5 member hindcast set. Match season, location and lead time.

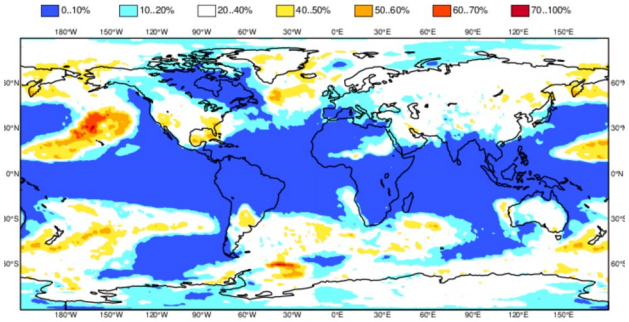
Example tercile forecast

2m temperature October 2026 forecast for December 2026–February 2027

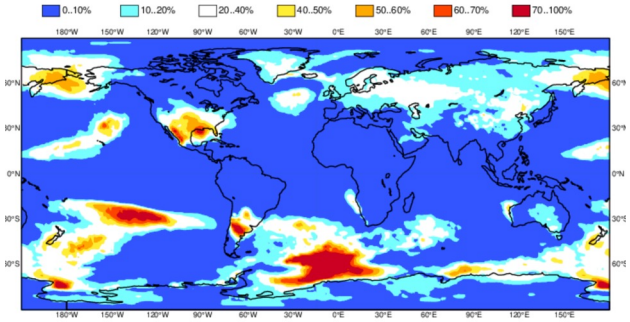
Upper third



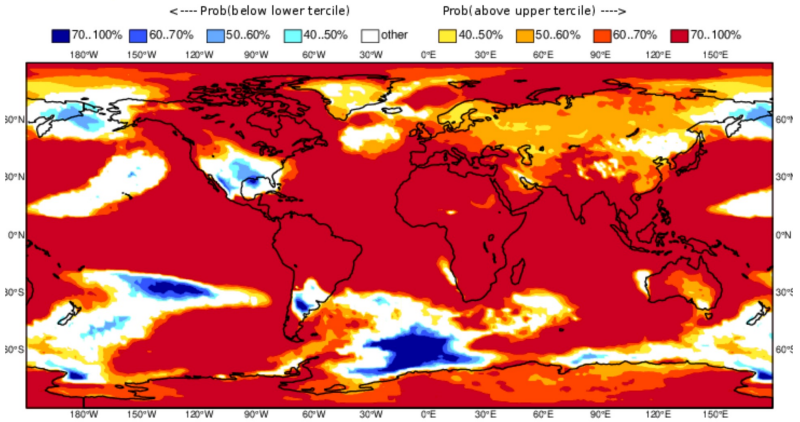
Middle third



Lower third



Tercile summary



The tercile summary is made only from the upper and lower third terciles, the colour indicates the most likely tercile and its probability.

White (“other”) can mean the middle tercile is more likely, or can mean the probabilities are all about equal.

Available products

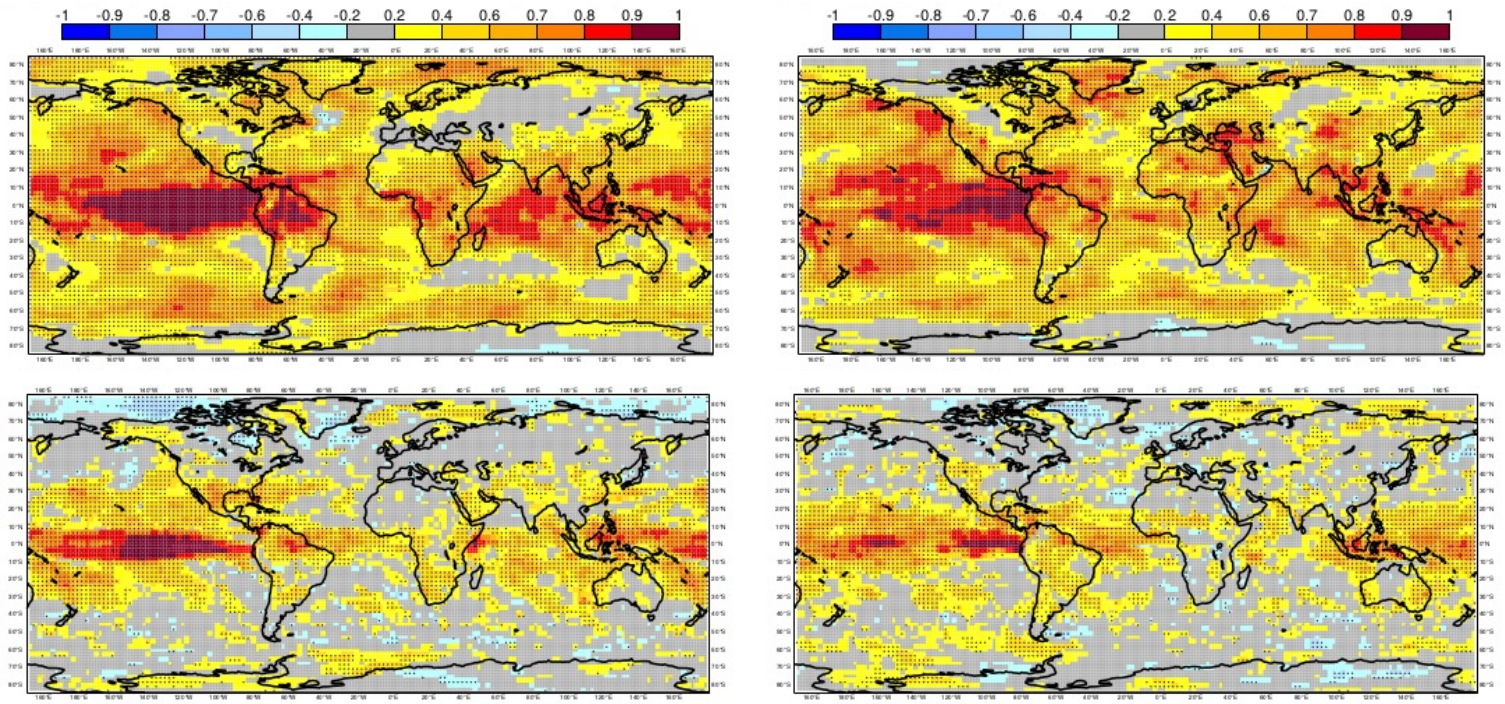
- tercile summary
- Ensemble mean
- Probability exceeding median
- Prob for lower third of distribution
- Prob for middle third of distribution
- Prob for upper third of distribution
- Prob for lowest 20%
- Prob for highest 20%

SEAS5 anomaly correlation (1981-2016)

DJF (month 2-4) | **JJA (month 2-4)**

2 m T verified with ERA-Interim

Precip verified with GPCP2.2



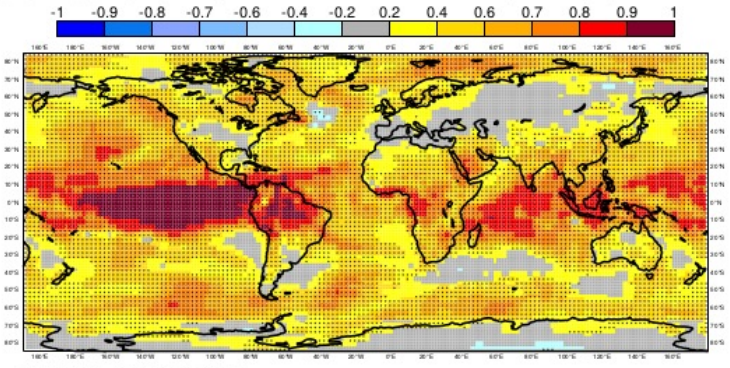
- Skill can vary substantially with season
- Skill in 2m temperature and precipitation present over tropical oceans.
- Skill in 2m temperature extends to the extratropics. For example, over Europe in summer.

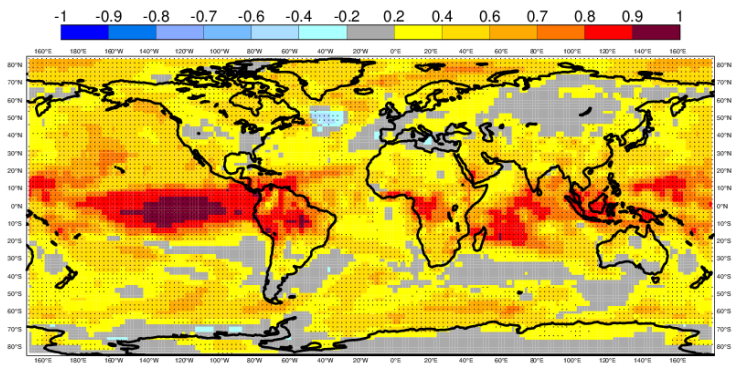
SEAS5 anomaly correlation (1981-2016)

DJF (month 2-4)

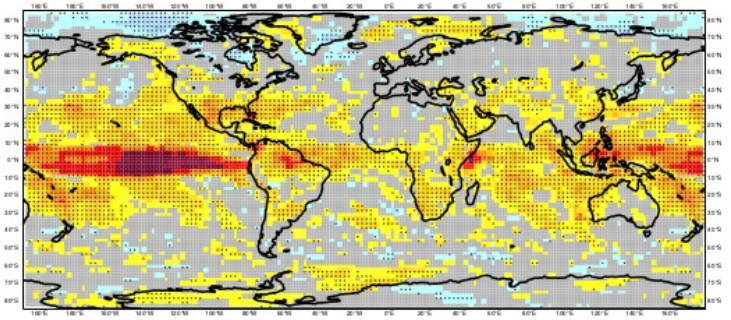
DJF (month 5-7)

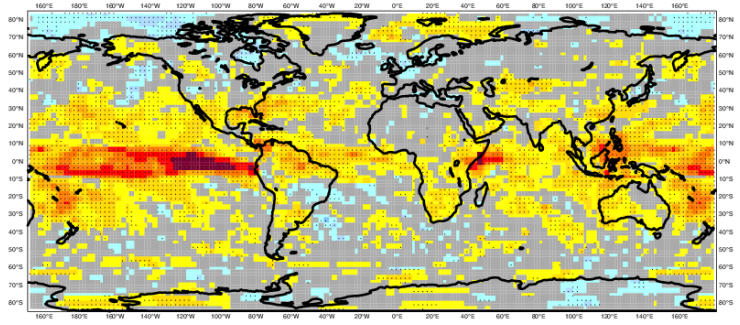
2 m T
verified with
ERA-Interim





Precip
verified with
GPCP2.2





ENSO outlooks maintain significant skill throughout the 13 months of the forecast.

Nino3.4 verified with OIv2

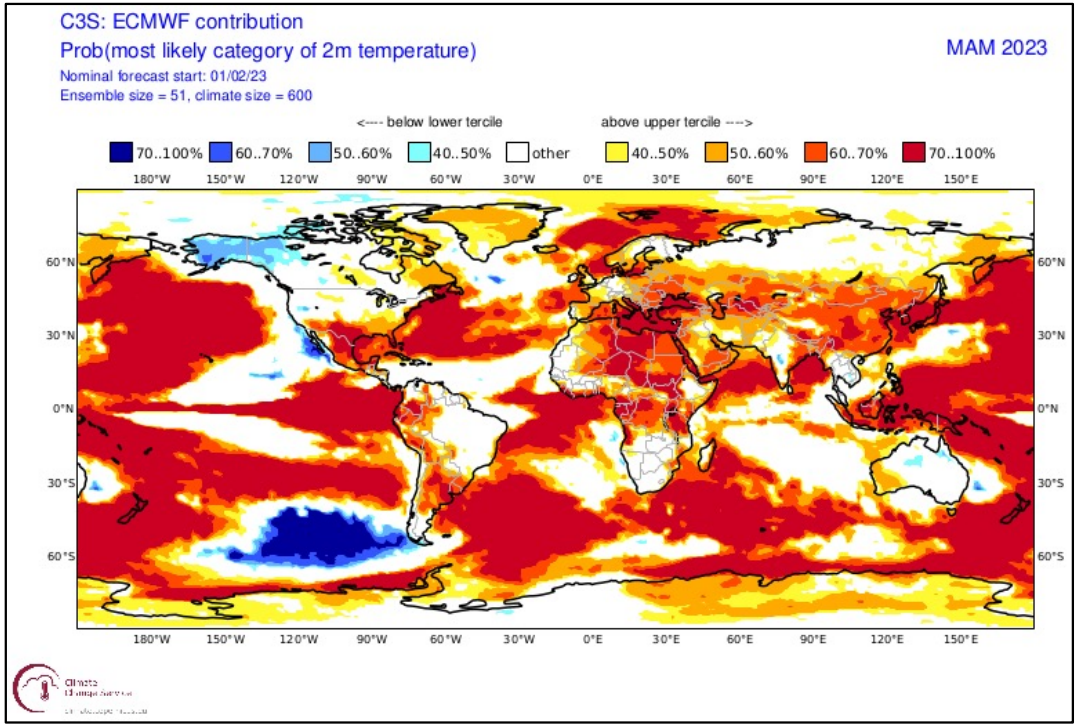
	January			July		
Forecast lead month	Forecast start month	SEAS5	SEAS4	Forecast start month	SEAS5	SEAS4
2	Nov	0.98	0.97	May	0.88	0.86
5	Aug	0.93	0.88	Feb	0.71	0.72
8	May	0.89	0.76	Nov	0.52	0.60
11	Feb	0.78	0.59	Aug	0.52	0.58

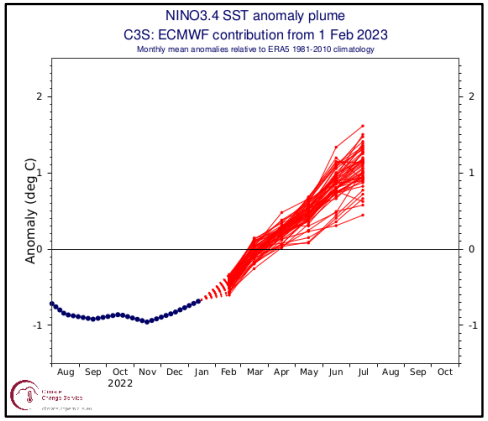
Products available through C3S

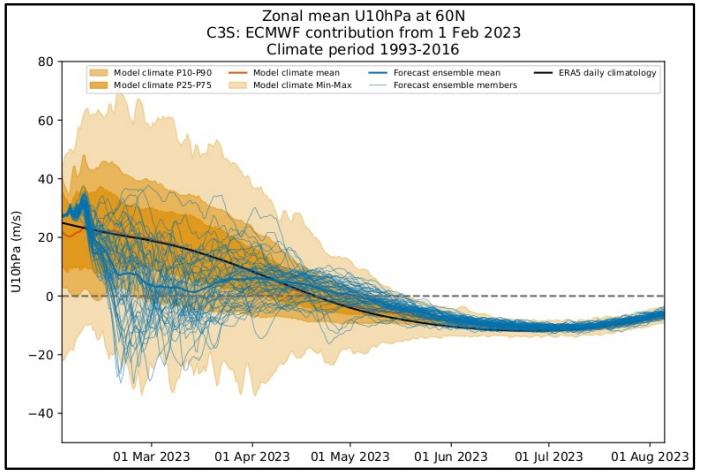
SEAS5 graphical products and data are publicly available through the **C3S climate change service**

Climate Change Service

climate.copernicus.eu







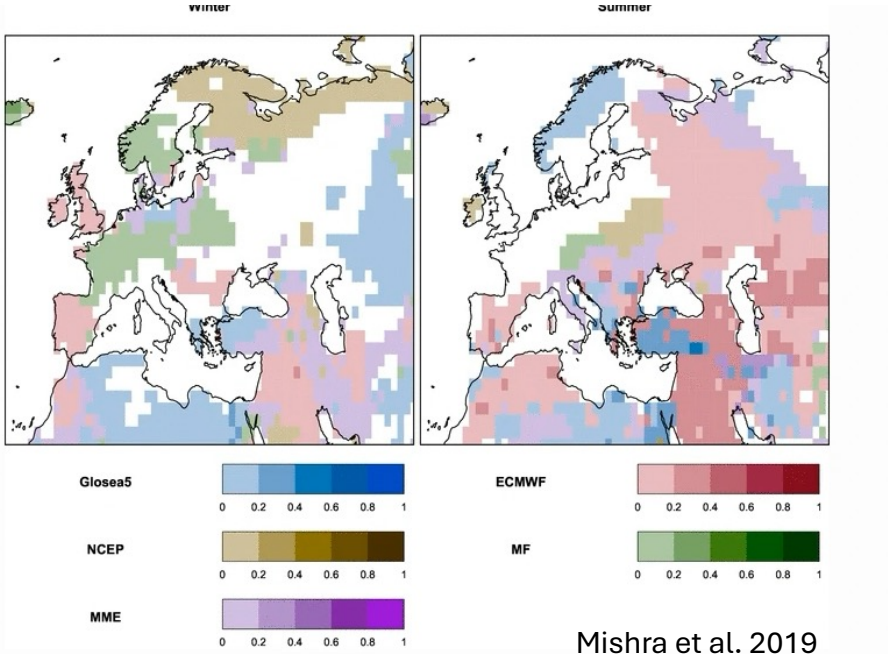
Improved skill through multi-model forecasts

RPS for winter 2mT in Europe from C3S models



Buontempo et al. 2022, BAMS

Maximum positive CRPSS amongst the four EUROSIPP models and the multi-model mean



Mishra et al. 2019

While individual model skill can exceed multi-model skill at individual grid-points, at a regional scale, a multi-model ensemble often improves on individual model skill, especially in the noisy extratropics.

Overview

- The basis for seasonal forecasting
- Components of a seasonal forecast system
- ECMWF's seasonal forecast system
  - SEAS5 configuration
  - SEAS5 products and calibration
- Future developments in seasonal forecasting
  - SEAS6 development
  - Beyond SEAS6

SEAS6 development strategy

- **Ocean and atmosphere model upgrades**
  - Particular focus on the stratosphere
- **New initialization datasets**
- **Improved forcings**
- **Addressing known errors in SEAS5**

Seamlessness has been a priority in SEAS6 development:
Developments needed for seasonal are contributed to IFS cycles and tested in medium and extended range forecasts.

Introducing SEAS6

SEAS6 represents nearly 10 years of model development and upgrades every part of the forecast system, including transitioning to single precision forecasts in the ocean and atmosphere, and archiving data in GRIB2 format.

Model

Atmosphere cycle	CY43r1 → **Cy49r2**
Stochastic physics (atmosphere only)	SPPT → **SPP**
Atmosphere resolution	**TCo319 (~35 km)**, L91→ **L137**
Ocean/sea ice model	NEMO3.4 LIM2 → **NEMO4 SI^3**
Ocean/sea ice model resolution	ORCA025 L75 → **eORCA025 L75**

Initialization

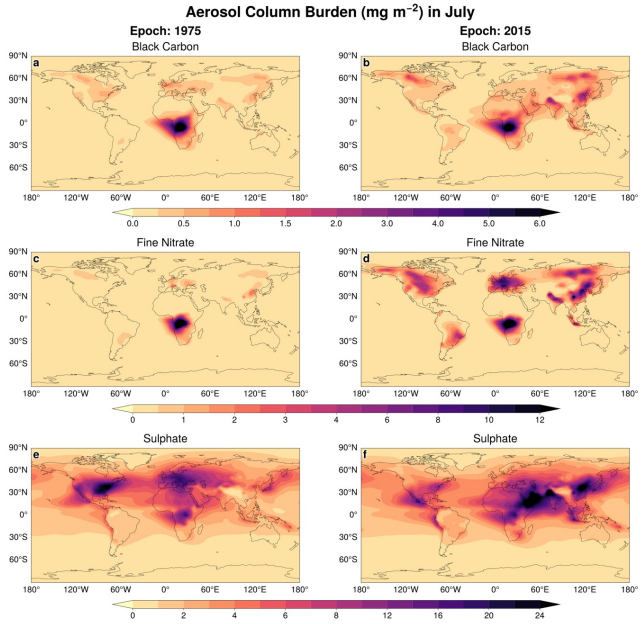
	Reforecast	Real-time
Atmosphere	ERA5 / ERA5.1	Real-time operational analysis
	EDA and singular vector perturbations	
Ocean	ORAS6	Real-time operational analysis
	Initialised from 11 member ocean analysis	
Land	Offline LDAS	Real-time offline LDAS

Introducing SEAS6: Forcings

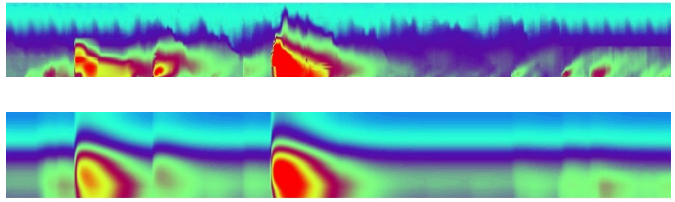
A lot of work has gone into improved forcings for SEAS6

Troposphere aerosol	Time-varying aerosol generated by IFS-COMPO Cy48r1 up to 2019 - held constant afterwards
Volcanic aerosol	EVA_H model (Aubry et al. 2020) driven by prescribed sources up to forecast start
GHG	CMIP7 historical/medium low scenario concentrations
Solar	CMIP7 annual TSI

Time-varying aerosol climatology

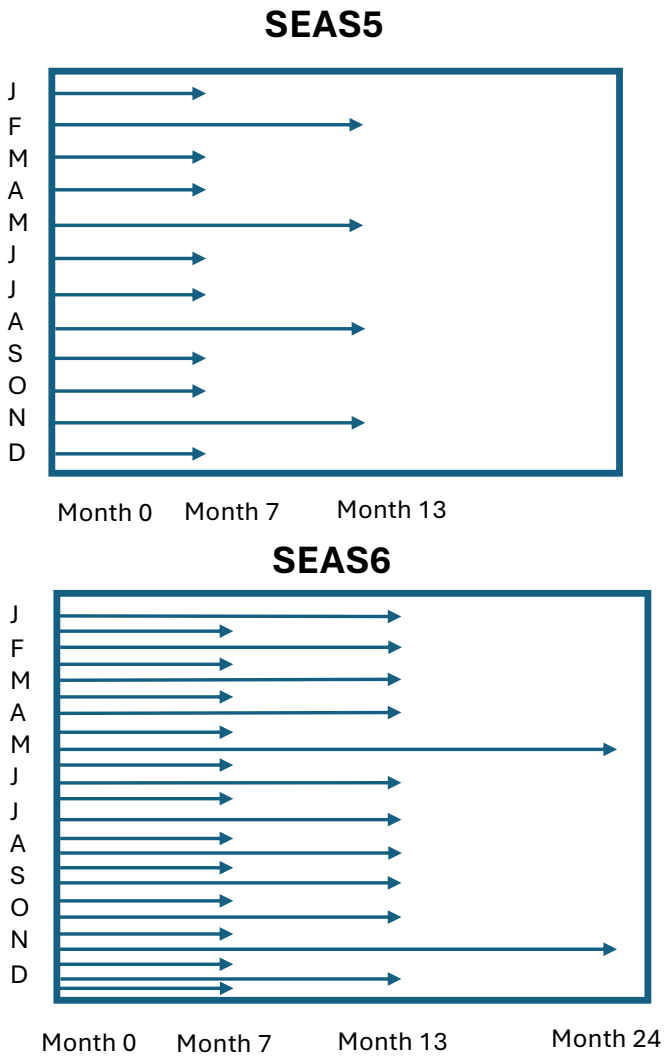


Volcanic aerosol extinction,
from GloSSACv2 (top) and EVA_H (bottom)



Introducing SEAS6: configuration

- **Enhancement 1: Real-time 101 member ensemble**
  - Currently 51 members
- **Enhancement 2: Issue SEAS twice per month**
  - Initial date 1st and 16th of each month
- **Enhancement 3: Expand annual-range ENSO forecasts**
  - Issue forecast monthly not quarterly
  - Twice per year, increase range to 24 months
- **Enhancement 4: More comprehensive reforecasts**
  - Larger ensemble sizes and larger set of years
  - Some reforecasts will extend to the 1960s for enhanced analysis of past performance (Not all years will be used for calibration and product creation)



Highlight: Stratosphere

Since SEAS5, many improvements have been targeted at improving the stratosphere:

- New radiation scheme
- Higher resolution in the stratosphere – L137
- Quintic vertical interpolation
- Hybrid linear ozone scheme
- Reduced vertical diffusion in the stratosphere

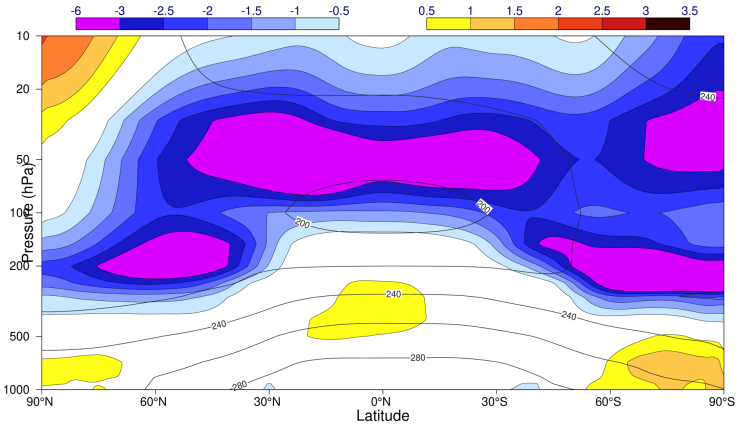
These have improved the stratosphere climate and variability:

- Large cold bias in the stratosphere in SEAS5 is reduced by up to 3 degrees.
- Amplitude and phase of the QBO is improved throughout the stratosphere, in some cases RMS error reduced by half.

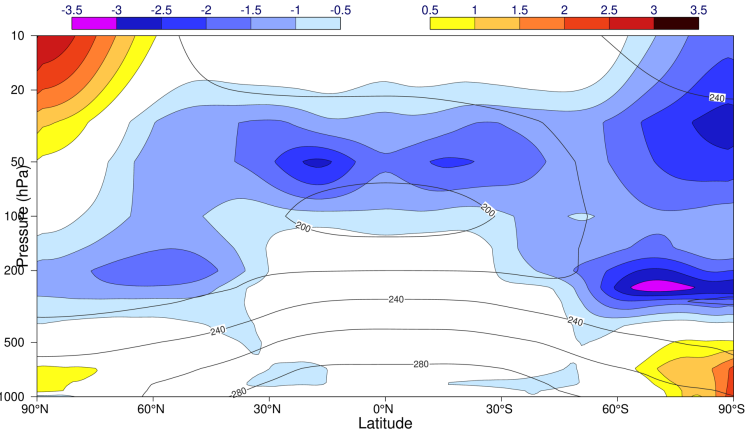
For more information see ECMWF Technical Memorandum 824: "Report on the Stratosphere Task Force"

DJF Zonally averaged T profile

SEAS5 – ERA5



SEAS6 prototype – ERA5



Reforecasts from 1993-2024, 10 ensemble members, initialized on Nov. 1, month 2-4

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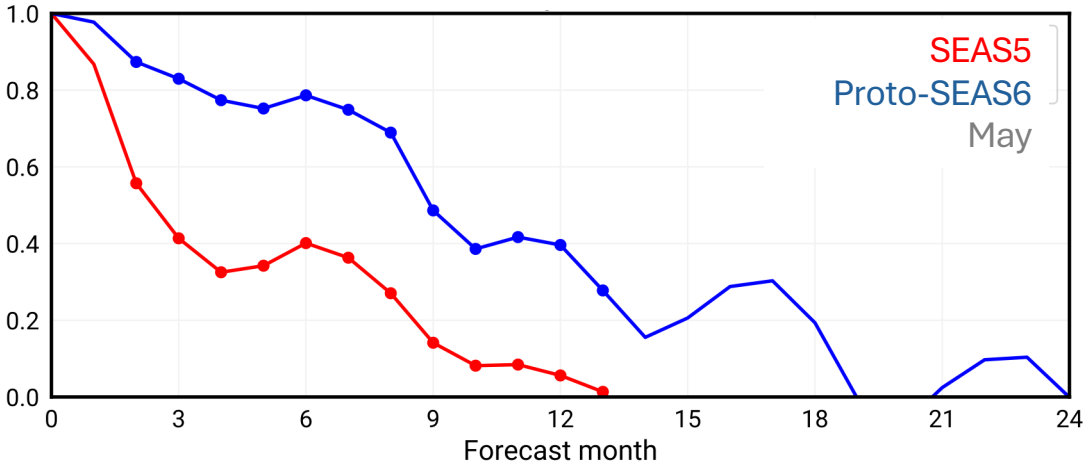
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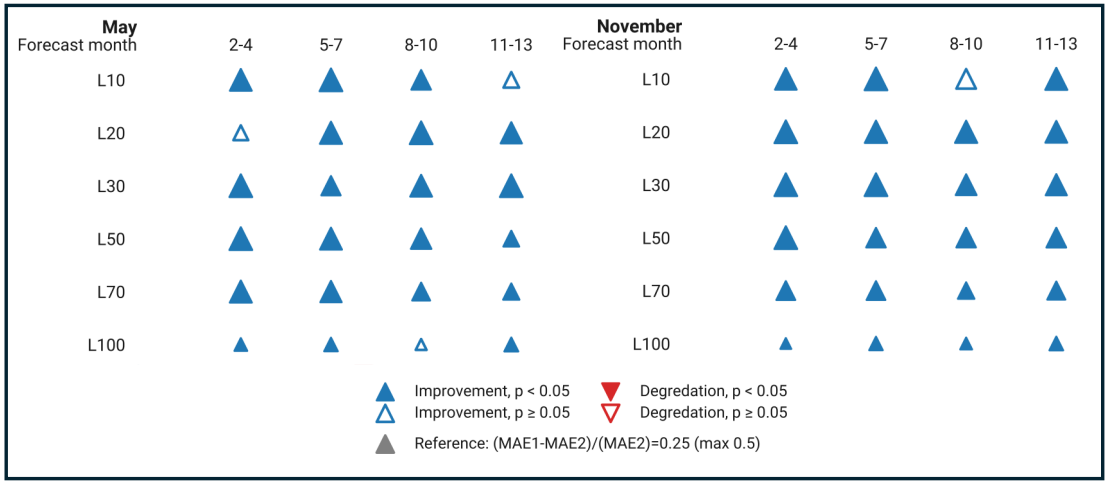
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QBO Mean square skill score

U70, zonally averaged, 5N-5S





Reforecasts from 1993-2024, 22 ensemble members, initialized on May 1 and Nov 1

Highlight: Western Pacific

The ocean model has also undergone significant development:

- ORAS6 upgrades include SST assimilation with Ensemble 3DVar and Hybrid B approach
- Improved formulation of upper ocean mixing in the ocean model

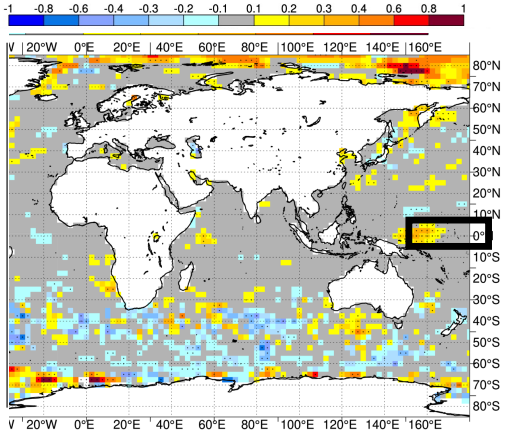
Which has resulted in several improvements:

- Improved variability in the Western Pacific, particularly JJA/SON
- ENSO skill maintained; longer and more frequent forecasts will add value
- Improved gulf stream separation area
- Improved equatorial upwelling in the eastern Pacific (Nino 1+2)

For more information see ECMWF Newsletter 180:
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"ECMWF's next ensemble reanalysis system for ocean and sea ice: ORAS6"

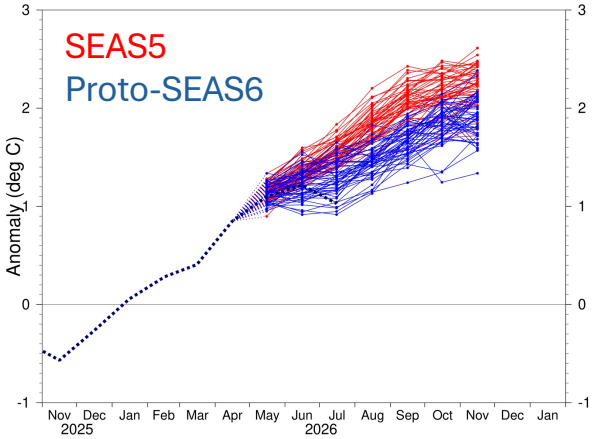
JJA SST ΔACC

protoS6-S5 wrt ERA5



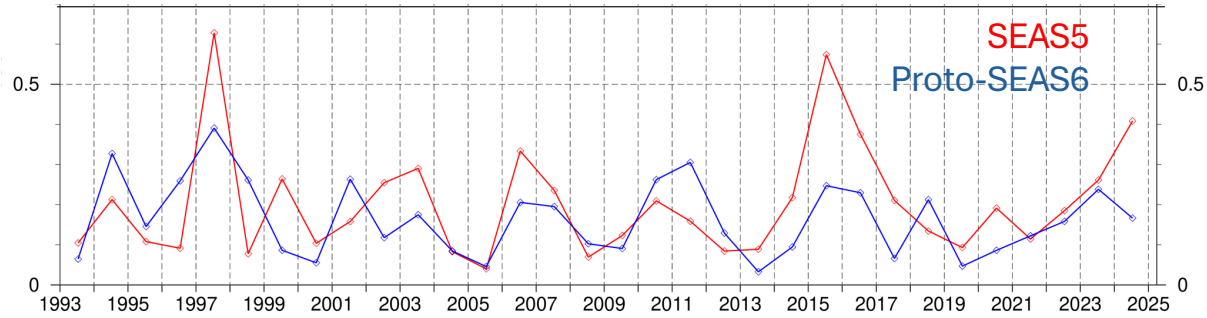
NINO4 SST forecast

1 May 2026



Equatorial Western Pacific JJA absolute error (ºC)

wrt ESA-CCI, 5N-5S, 150-190E (ºC)



Reforecasts from 1993-2024, 51 ensemble members, initialized on May. 1, month 2-4

Highlight: 24-month forecasts

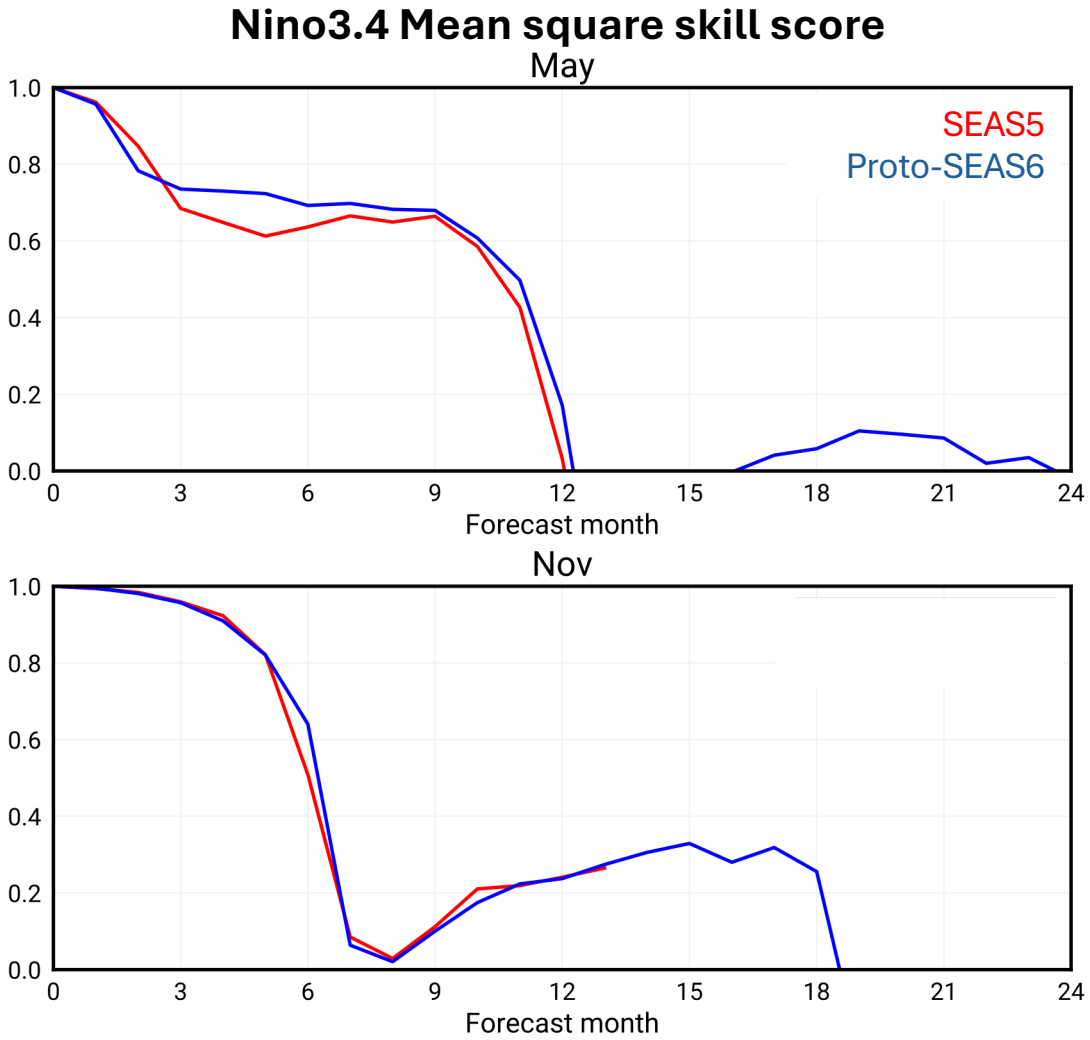
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Summary – operational aspects

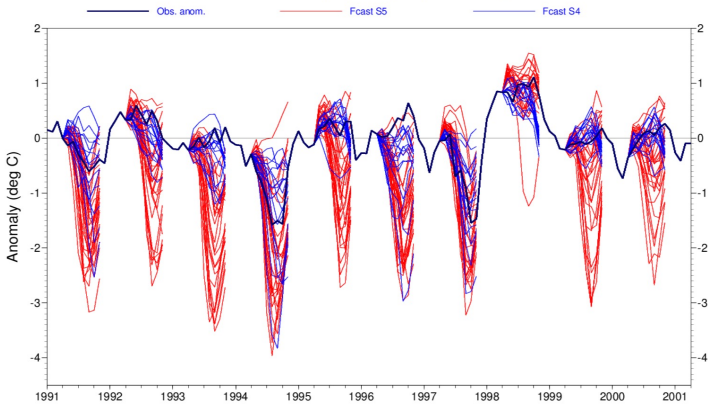
- ECMWF seasonal forecasting is largely **seamless** with medium/extended range configurations
  - A very small number of adaptions important for longer timescales
- Seasonal forecast configuration includes extensive re-forecast set
  - Dominates cost of system, only updated at intervals of several years
  - Allows many types of calibration and estimation of skill
- Multi-model seasonal forecasts are provided by C3S
  - These can be better than any single model, and should always be consulted
- SEAS6 developments
  - More forecast members and more frequent forecasts
  - Upgraded ocean, atmosphere and land surface models and improved forcings
  - Upgraded atmosphere and ocean initial conditions
  - Better representation of stratosphere climate and variability

Overview

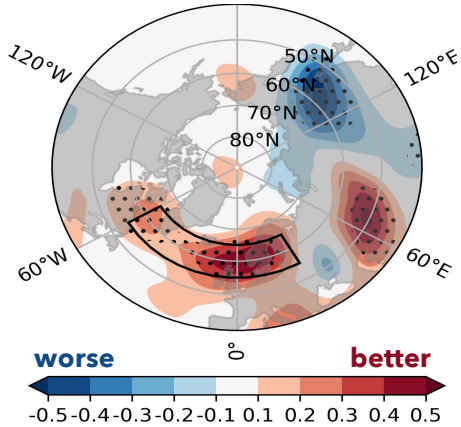
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Future development of physical models

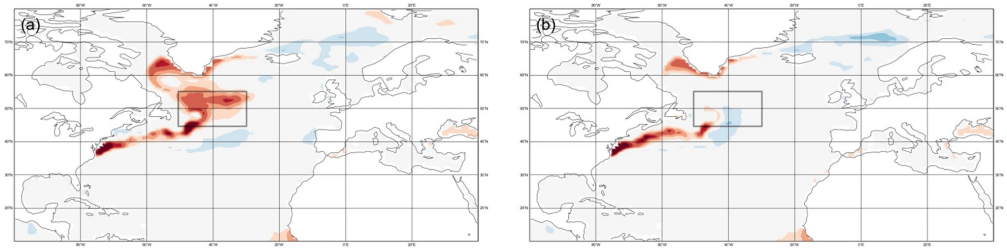
- Increased realism of the model
  - Possible developments:
    - SPP in sea ice and ocean
    - Cloud aerosol interactions – particularly important for correctly simulating the response to long-term evolution in aerosol
- Some known errors remain outstanding challenges
  - Indian ocean problem still a priority
  - North Atlantic subpolar gyre particularly challenging to initialize (especially pre-ARGO)



Eastern Indian ocean SST anomalies in SEAS5



Initial experiments introducing seas ice SPP show improved atmospheric skill on seasonal time scales, possibly mean-state induced.
Strommen et al. 2026 in WCD



SEAS5 SST drift in 1981-1996 and 2001-2016
Tietsche et al. 2020

Machine learning for seasonal forecasting

Data driven seasonal forecasting presents unique challenges:

- Climate change means empirical modelling on past data may not lead to reliable future prediction.
- Limited independent seasons means limited data for training and verification.

Studies of data driven forecasting at the seasonal timescales are still in their infancy:

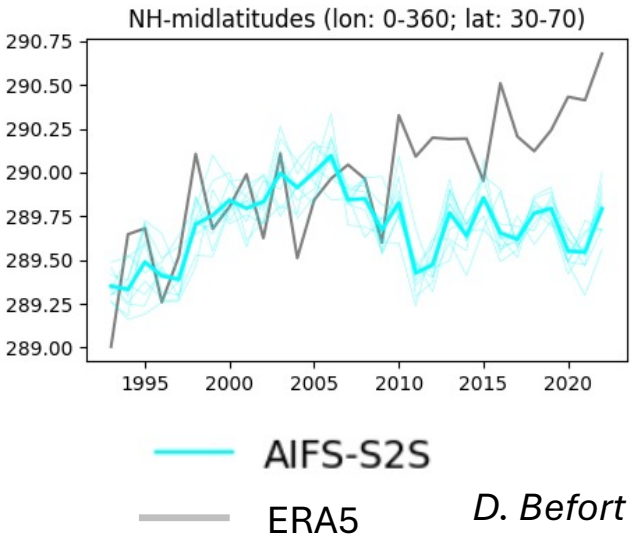
- Usually opportunistically using what is available.
- Often verifying within the training period.

Themes of work in the literature:

- Rolling out data driven NWP models to seasonal timescales using persisted SST, with promising initial results (Kent et al. 2025, Antonio et al. 2025)
- Climate model emulation to allow cheap climate integrations (e.g. Watt-Meyer et al. 2025)
- Prediction specific phenomenon, e.g. ENSO, NAO (Fraile et al. 2026, Ham et al. 2019)

Watch this space!

T2M NH midlatitudes



Reforecasts from 1993-2023, 10 ensemble members, initialized on May 1, month 2-4, training data until 2010. Older version of AIFS-S2S.

Thank you!



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