Climate and statistics

Outline

Anomalies

Comparing climate models to data

Downscaling and bias correction

The fit of models

Climate is the distribution of weather

To reasonably estimate a distribution (from data or from models) need a relatively long stretch of data–WMO suggests at least 30 years

How well does the CMIP5 experiment used in the recent IPCC assessment work for describing annual global mean temperature?

The greenhouse effect

Joseph Fourier (1768-1830) realized that Earth ought to be a lot cooler than it is.

John Tyndall (1820-1893) found that water vapor and CO_2 are greenhouse gases

Svante Arrhenius (1859-1927) calculated how changes in CO_2 can heat the planet

A simple climate model

What comes in

$$S\pi r^2(1-a)$$

Solar constant
1365 W/m²

Earth's albedo
0.3

must go out

$$4\pi r^2\varepsilon\sigma T^4$$

Effective emissivity
(greenhouse, clouds)
0.61

Stefan's constant
5.67×10^{-8} W/(K$^4\cdot$m^2)

Solution

$$T^4 = \frac{1365 \times 0.7}{4 \times 0.61 \times 5.67} \times 10^8$$

Average earth temperature is T=288K (15°C)

One degree Celsius change in average earth temperature is obtained by changing

solar constant by 1.4%

Earth's albedo by 4.5%

effective emissivity by 1.4%

But in reality…

The solar constant is not constant

The albedo changes with land use changes, ice melting and cloudiness

The emissivity changes with greenhouse gas changes and cloudiness

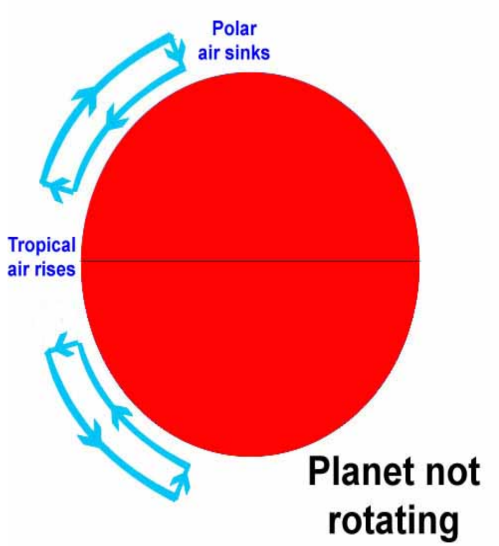
Need to model the three-dimensional (at least) atmosphere

But the atmosphere interacts with land surfaces…

…and with oceans!

The climate engine I

If Earth did not rotate:
tropics get higher solar radiation
hot air rises, reducing surface pressure
and increasing pressure higher up
forces air towards poles
lower surface pressure at poles
makes air sink
moves back towards tropics



The climate engine II

Since earth does rotate, air packets do not follow longitude lines (Coriolis effect)

Speed of rotation highest at equator

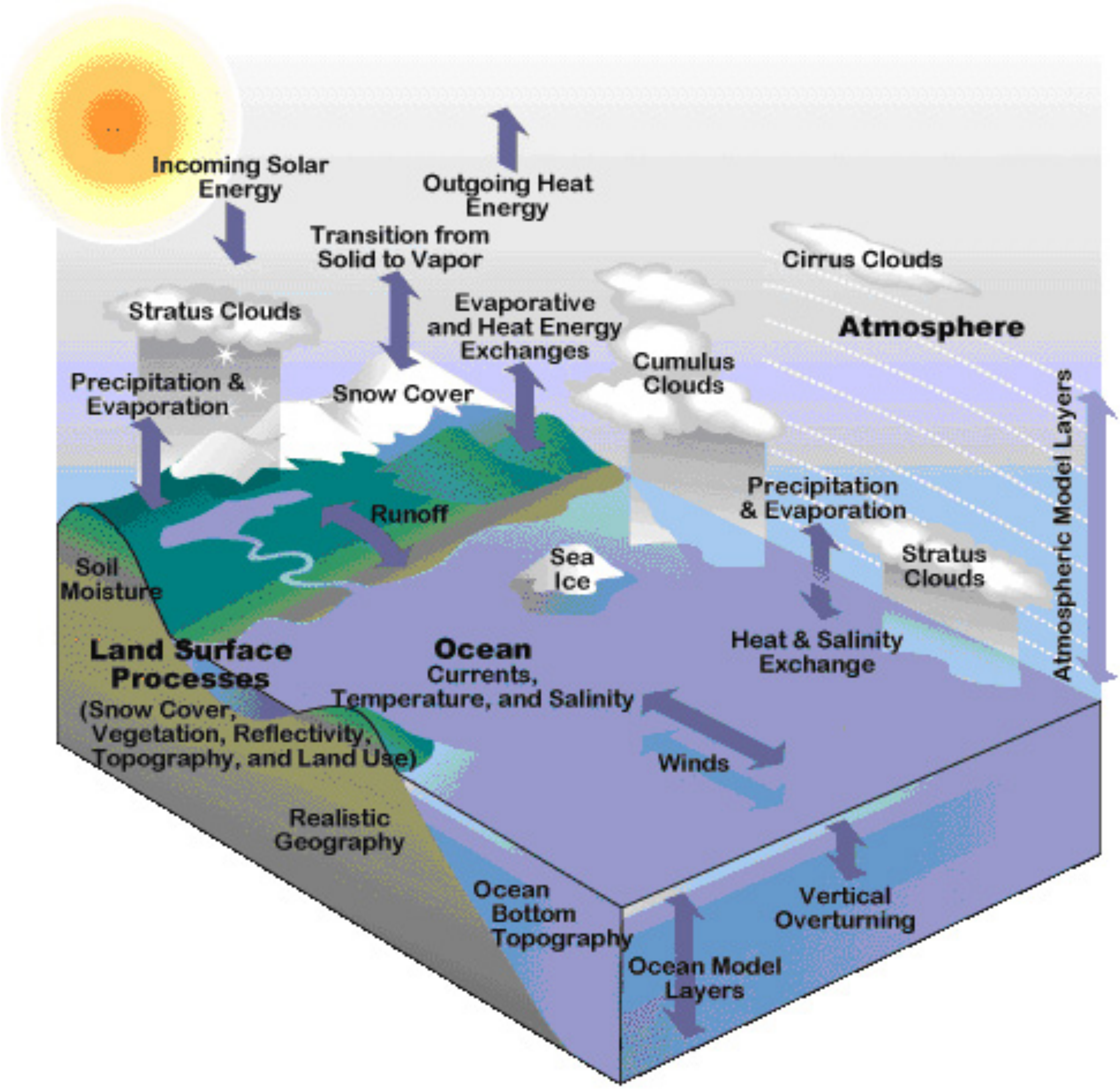
Winds travelling polewards get a bigger and bigger westerly speed (jet streams)

Air becomes unstable

Waves develop in the westerly flow (low pressure systems over Northern Europe)

Mixes warm tropical air with cold polar air

Net transport of heat polewards


Incoming Solar Energy
Outgoing Heat Energy
Transition from Solid to Vapor
Cirrus Clouds
Stratus Clouds
Evaporative and Heat Energy Exchanges
Atmosphere
Cumulus Clouds
Precipitation & Evaporation
Snow Cover
Atmospheric Model Layers
Precipitation & Evaporation
Runoff
Sea Ice
Stratus Clouds
Soil Moisture
Heat & Salinity Exchange
Land Surface Processes
(Snow Cover, Vegetation, Reflectivity, Topography, and Land Use)
Ocean
Currents, Temperature, and Salinity
Winds
Realistic Geography
Ocean Bottom Topography
Vertical Overturning
Ocean Model Layers

Modeling the atmosphere

Lagrangean approach

Conservation of mass:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial p} = 0$$

height is pressure

Conservation of momentum:

$$\frac{dc}{dt} = \underbrace{-2\Omega \times c}_{\text{Coriolis effect}} - \frac{\text{grad}(p)}{\rho} + \underbrace{\text{grad}(\phi)}_{\text{apparent gravity}} + \underbrace{F}_{\text{friction}}$$

c=(u,v,w); ρ is geopotential; φ is density

Material derivative $\frac{\partial}{\partial t} + u\frac{\partial}{\partial x} + v\frac{\partial}{\partial y} + w\frac{\partial}{\partial p}$

Modeling, cont.

Net heating rate/unit mass

Thermodynamics:

$$\frac{dT}{dt} = \frac{Q}{c_p} + \kappa \frac{T\omega}{p}$$

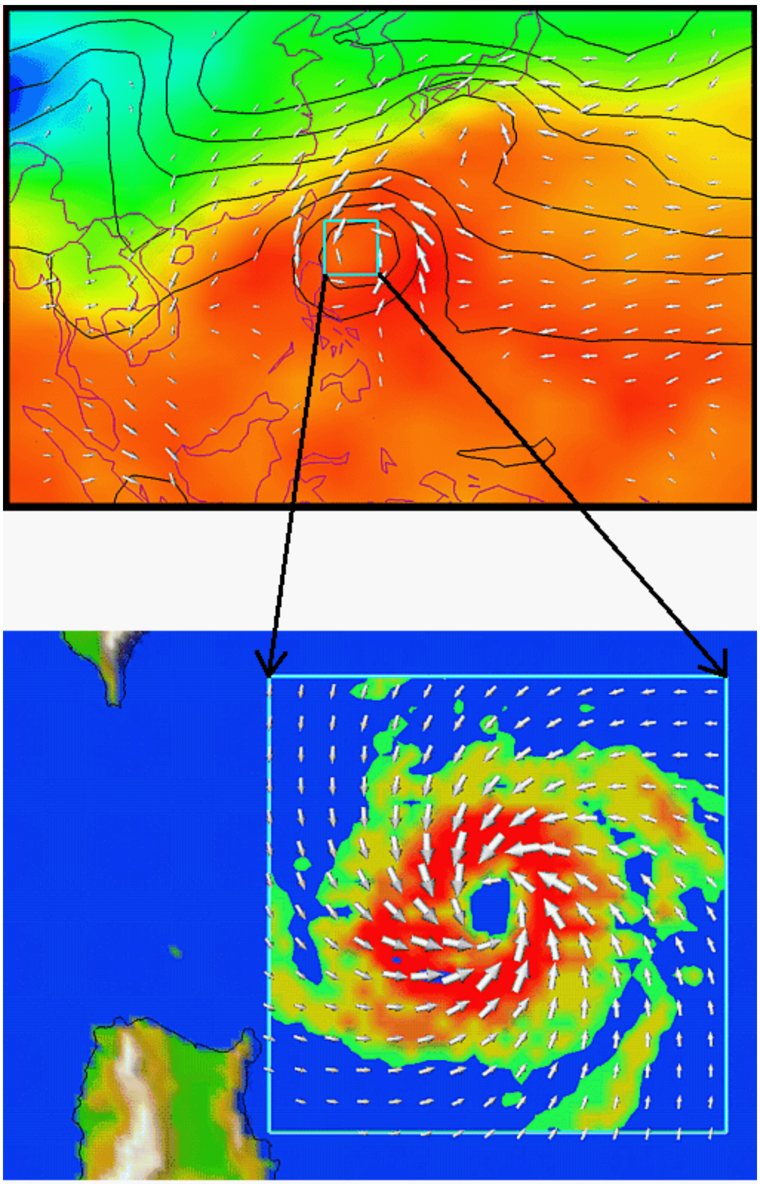
Conservation of water vapor:

$$\frac{dq}{dt} = s(q) + D$$

Hydrostatic equilibrium:

$$\frac{\partial \phi}{\partial p} = -\frac{RT}{p}$$

The issue of gridding



Hurricanes
Clouds
Glaciers

Comparing two distributions

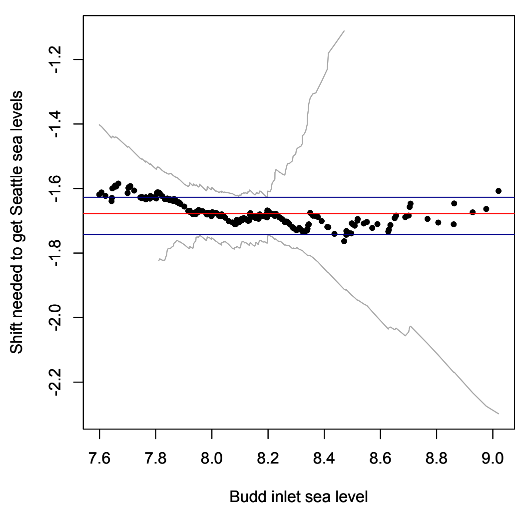
Location shift: $X + \delta \sim Y$

Location-scale: $\alpha X + \delta \sim Y$

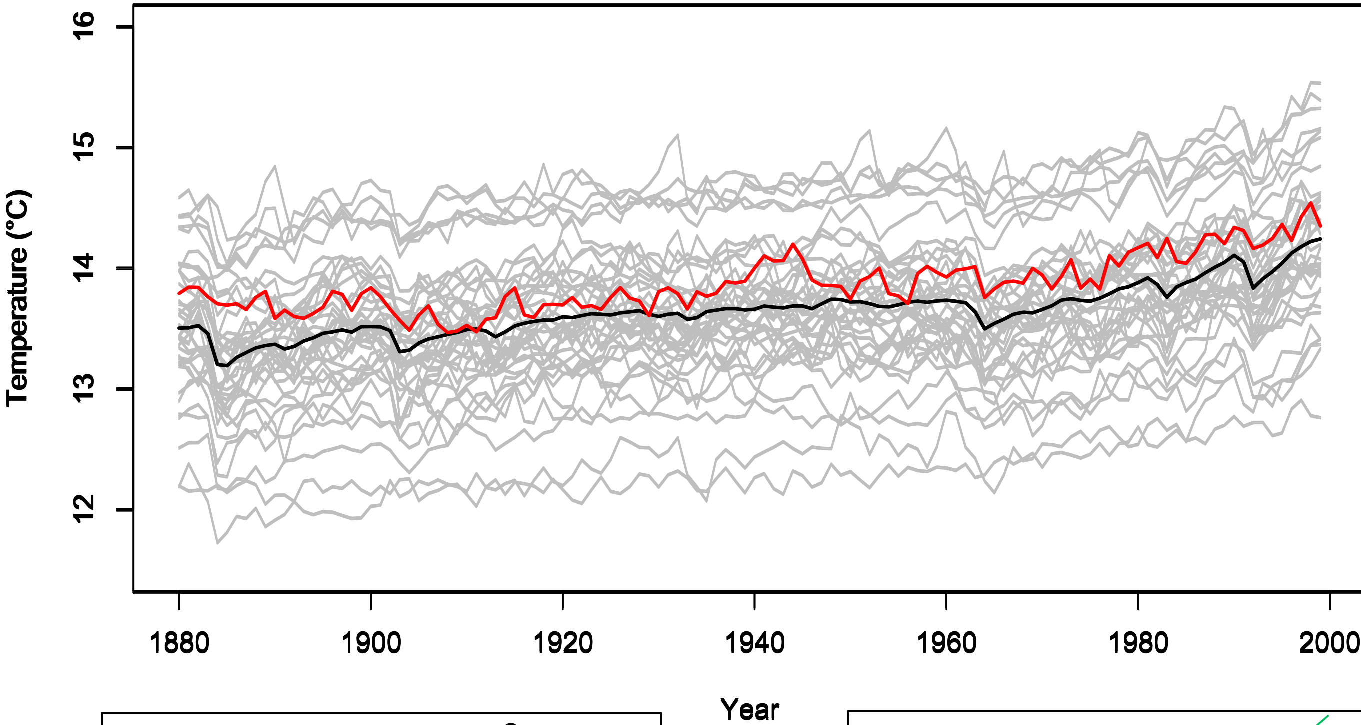
More general: $X + \Delta(X) \sim Y$

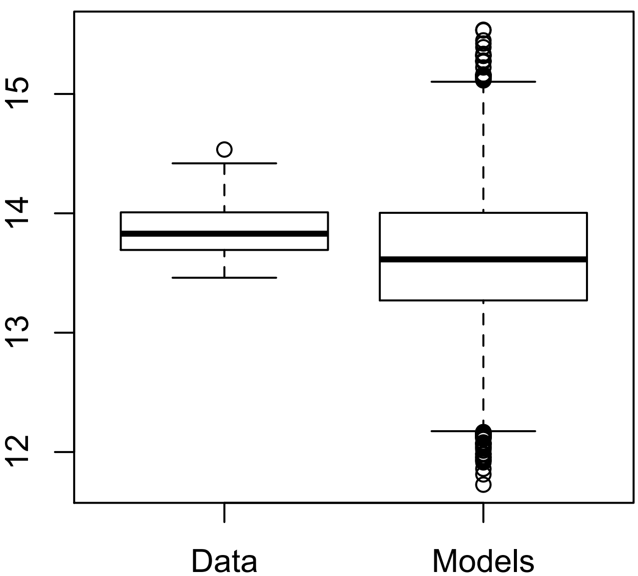
Having m observations from Y and n observations from X we estimate

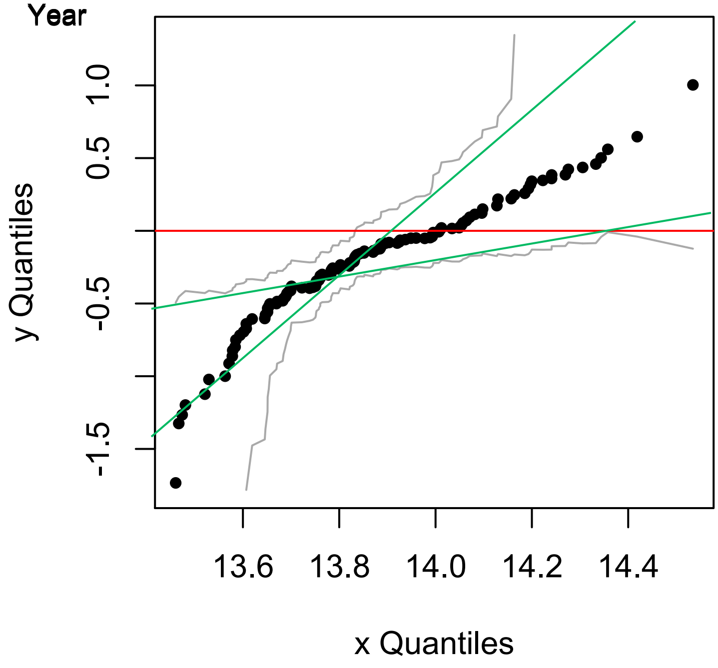
$$\hat{\Delta}(x) = G_m^{-1}(F_n(x)) - x$$



Comparing global climate models to data







Anomalies

Comparison to “normal”

Normal = 30 yr average

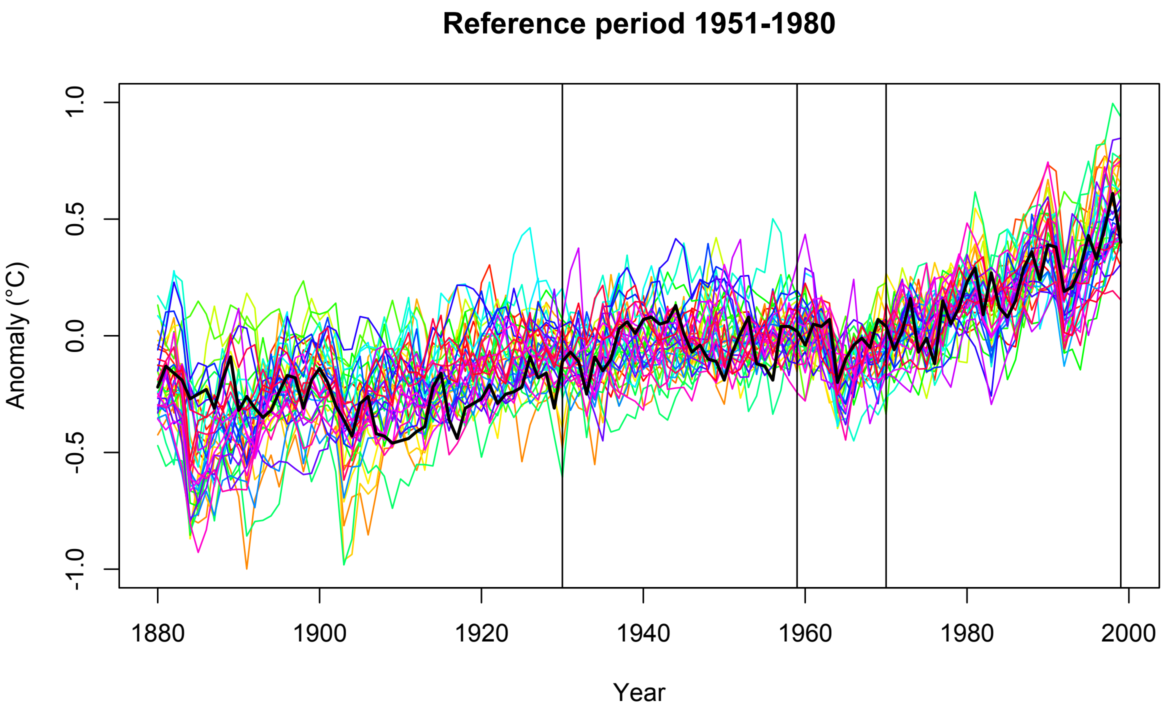
Different baselines

Helps for regional trends

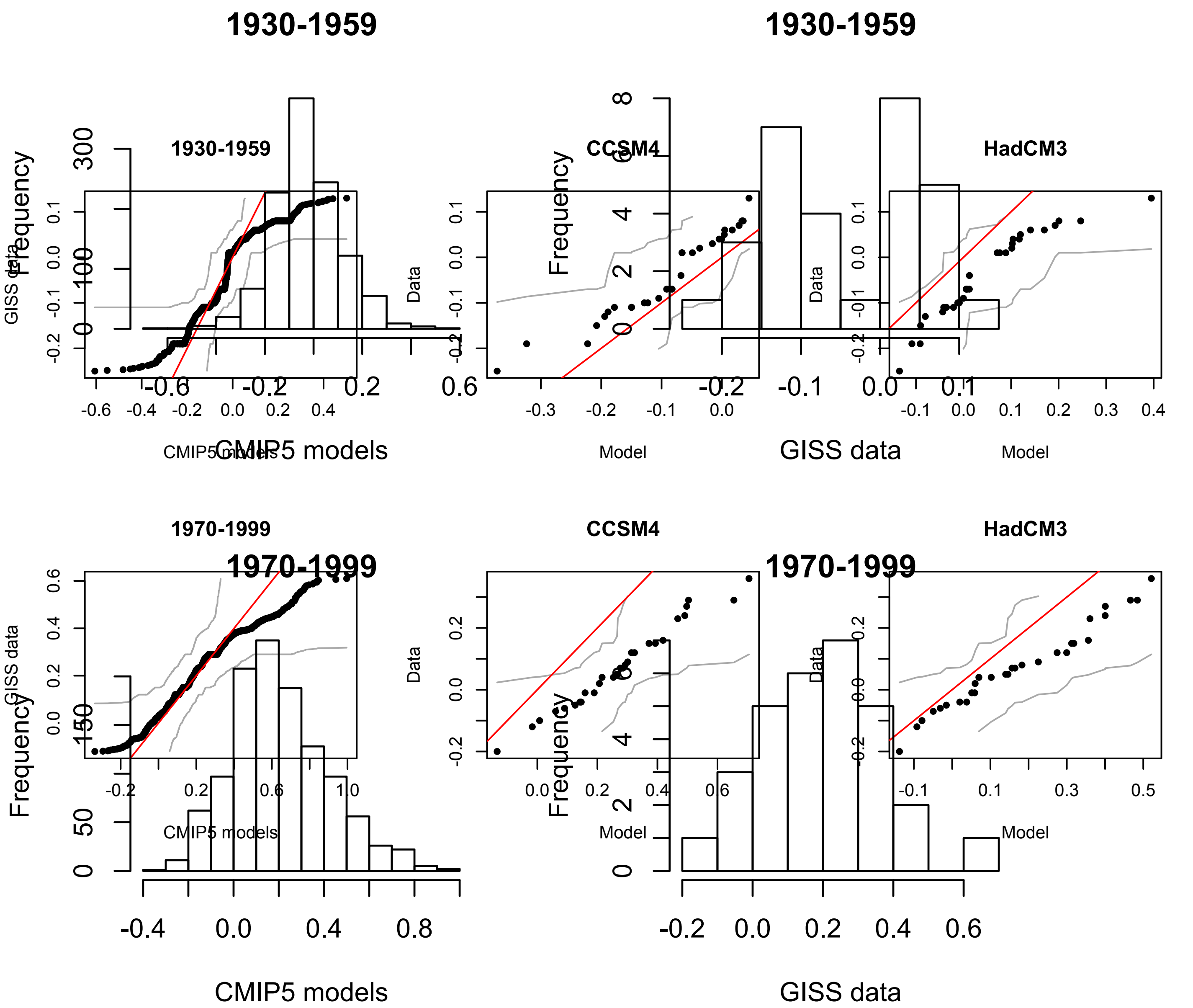
Really residuals

So fit a model (trend + seasonal + covariates+variability)

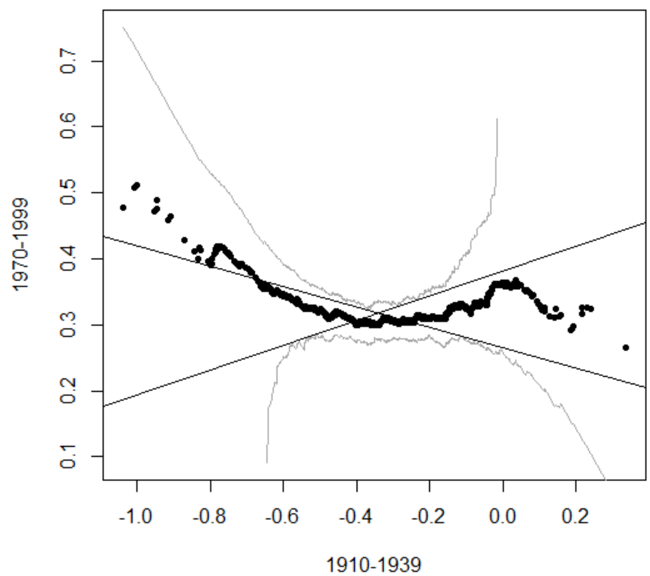
Global mean temperature

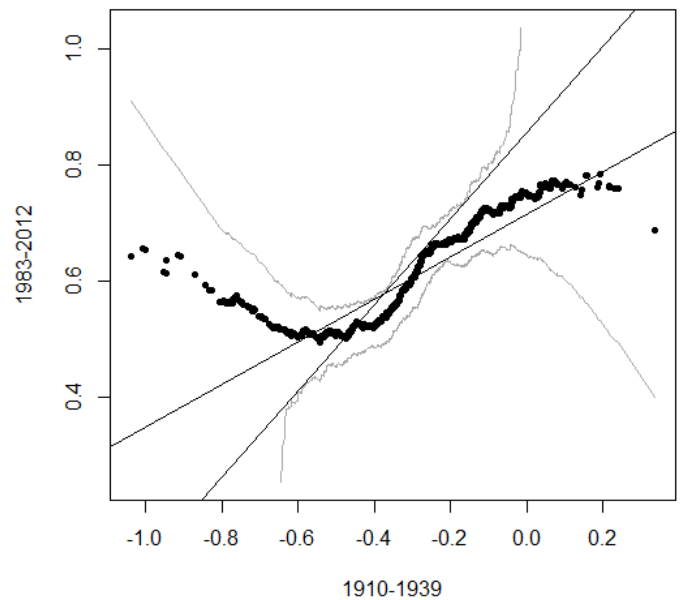


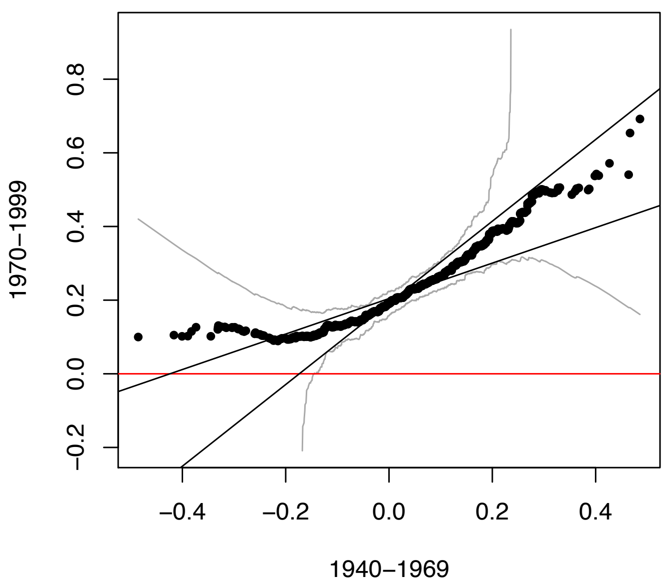
30-year distributions

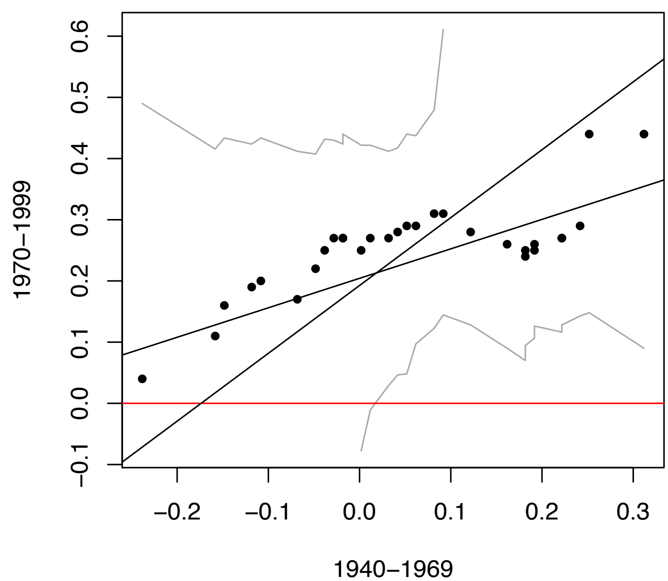


Comparing location and spread

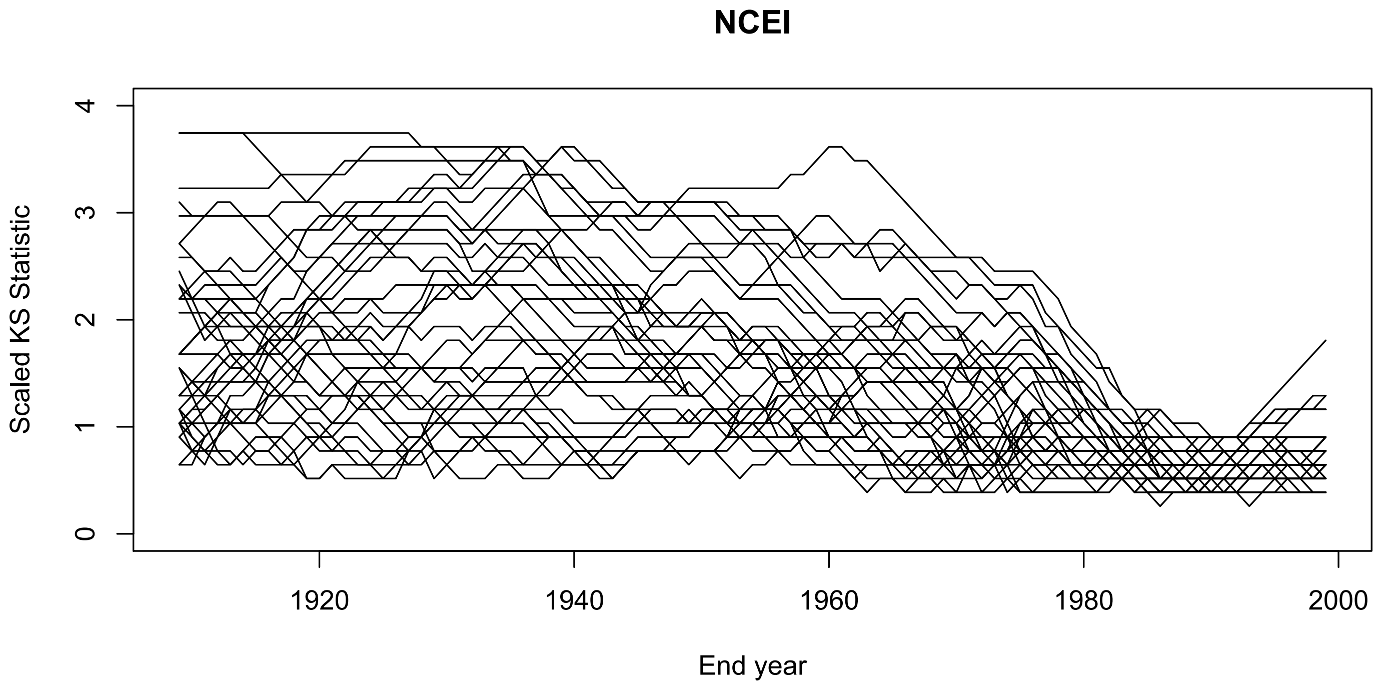


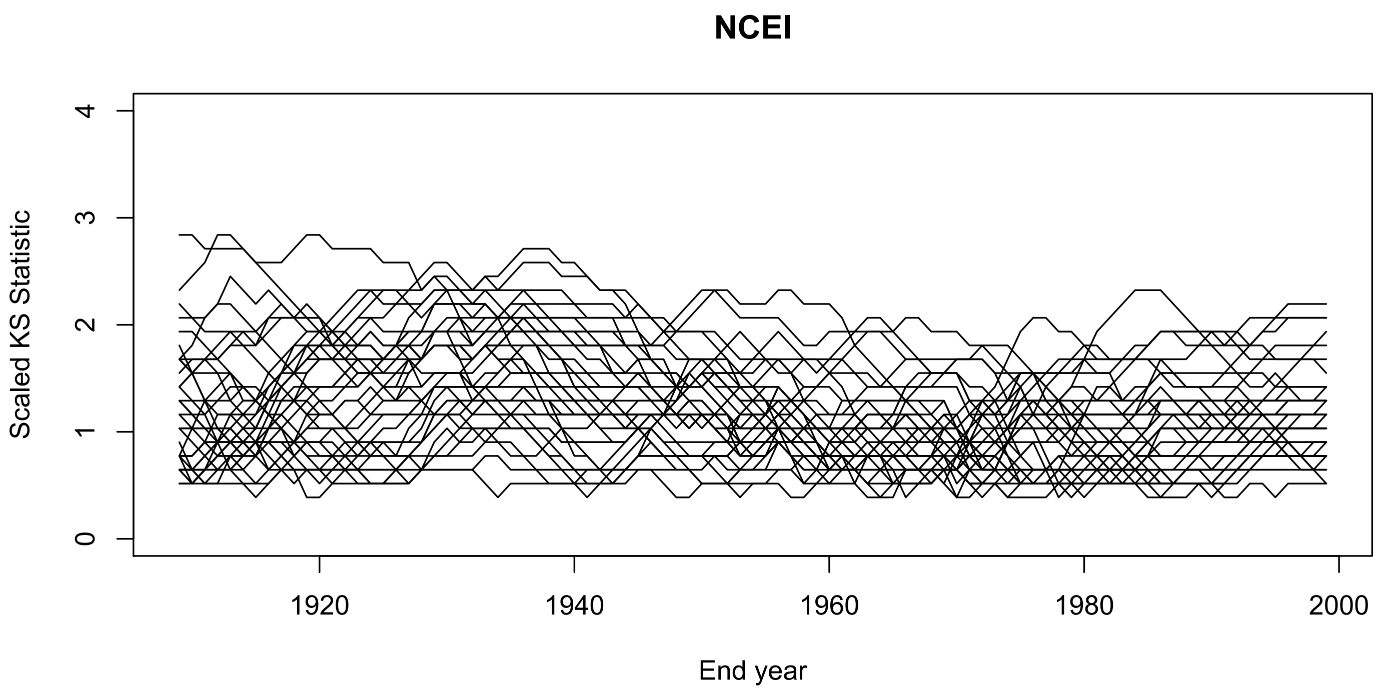






Effect of anomalies

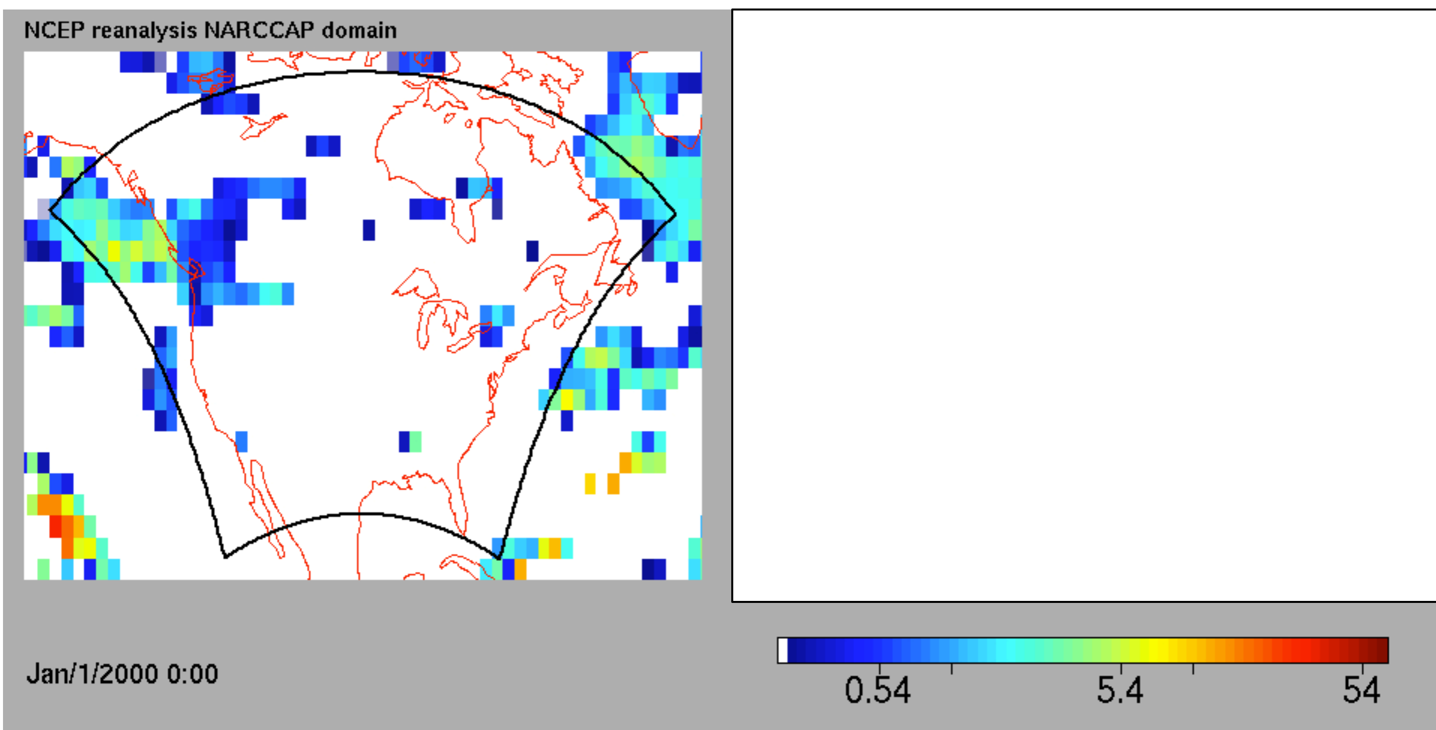




Dynamical downscaling

Global models are very coarse

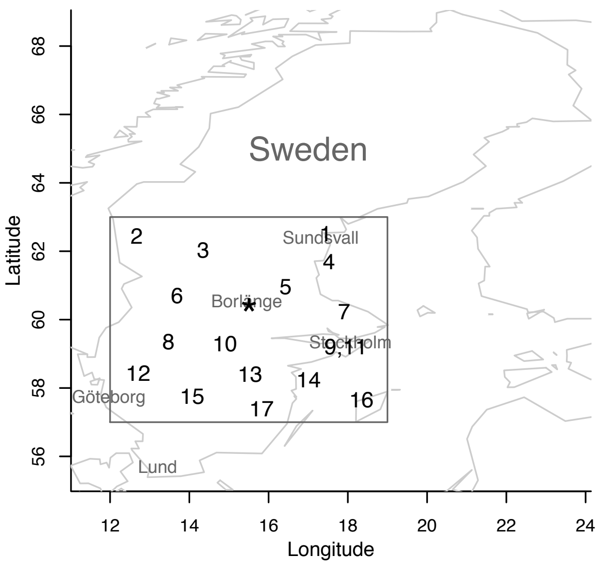
Regional models are driven by boundary conditions given by global model runs

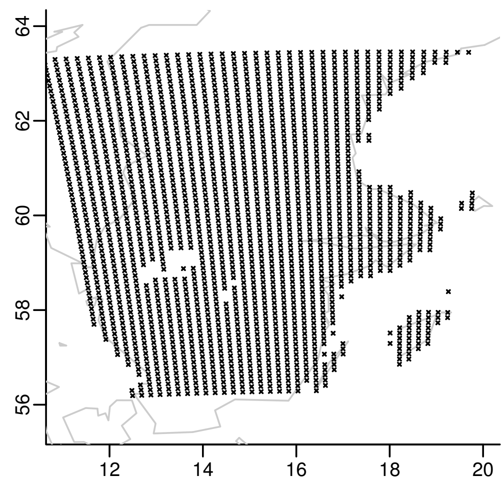


Swedish temperature minima

SMHI synoptic stations in south central Sweden, 1961-2008. SMHI regional model (open air & snow)

Seasonal minima (d=1 DJF, d=2 MAM, d=3 JJA, d=4 SON).





Spatial models

$$-m_t(s) \sim \mathrm{GEV}(\mu_t(s), \sigma(s), \xi)$$

where

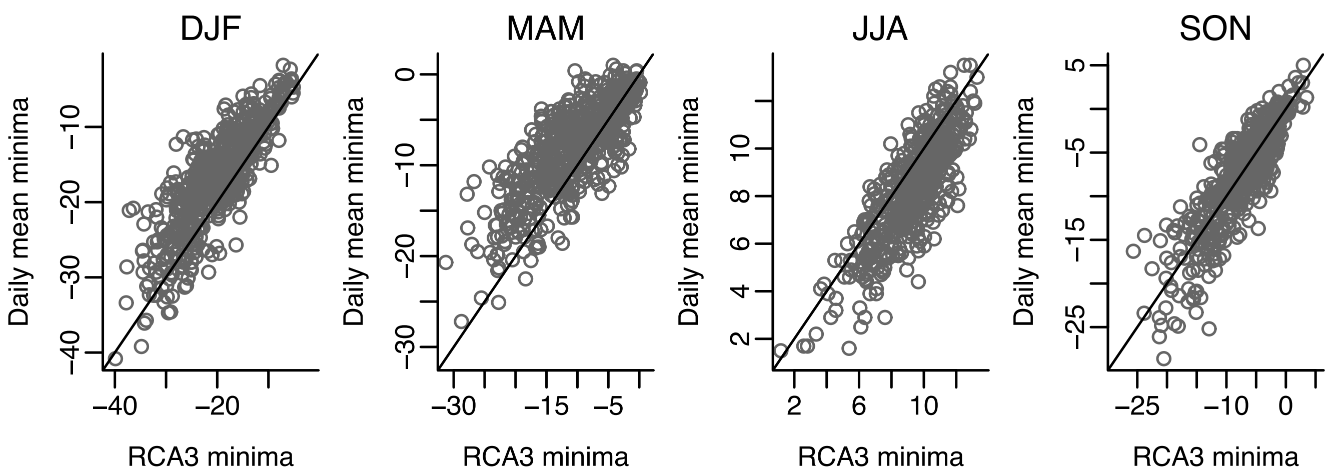
$$\mu_t(s) = \beta_0(s) + \beta_1(s)\left(t - 1961\right)/50 + \sum_{d=2}^{4} \beta_d(s) 1(d_t = d)$$

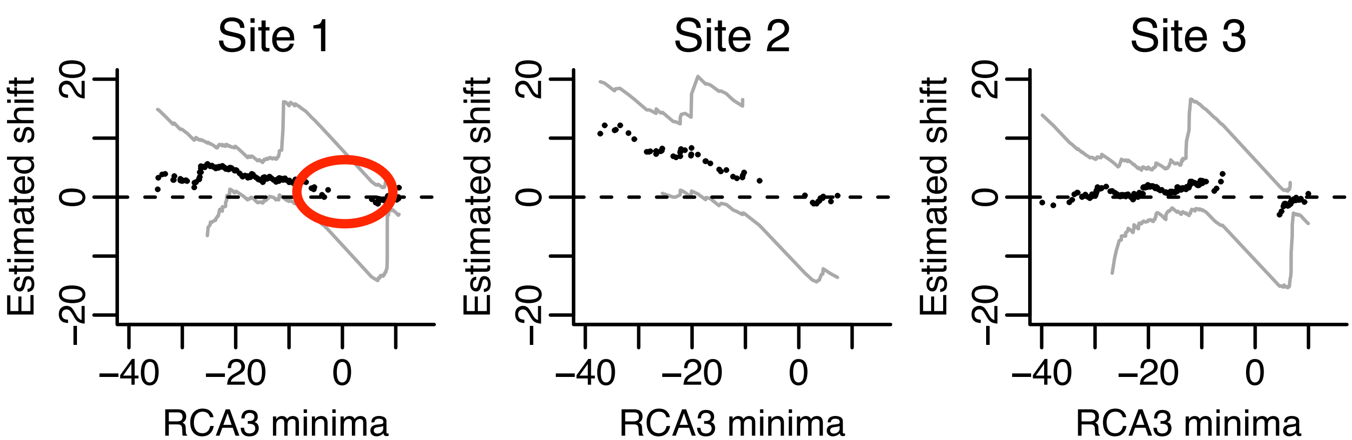
$$\beta_i(s) \sim \mathrm{GP}(\mu_i, \sigma_i(1 - \exp(-\theta_i d(s))$$

$$\log\sigma(s) \sim \mathrm{GP}(\mu, \sigma(1 - \exp(-\theta d(s))$$

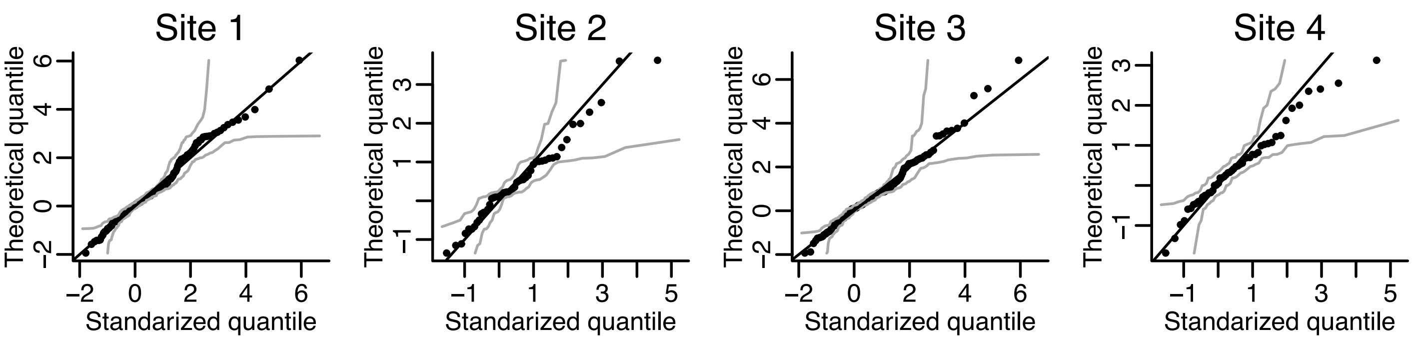
Both for data and model output.

RCM temperature minima

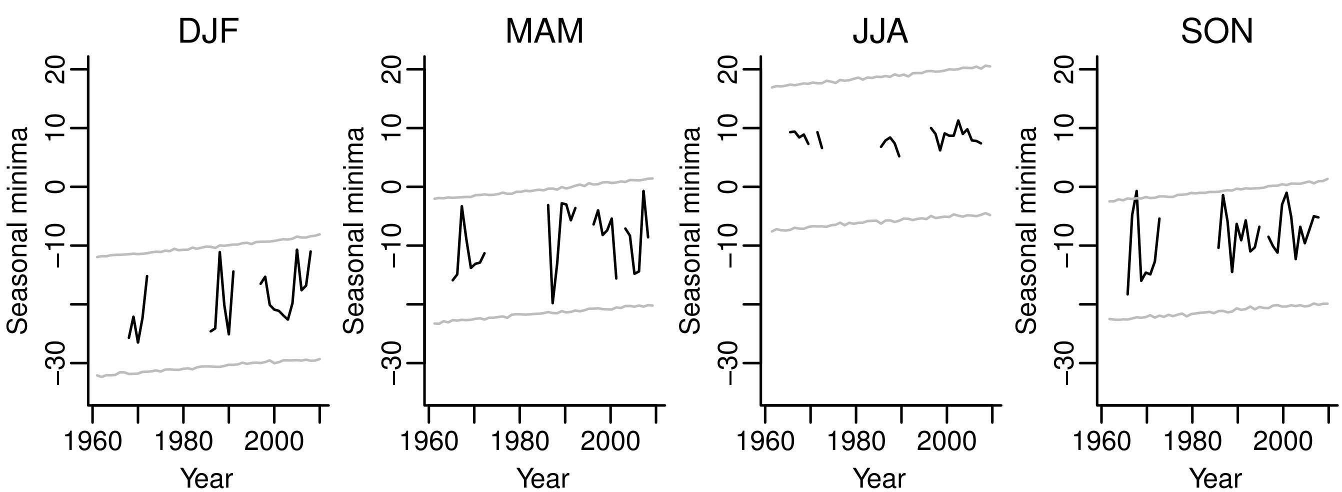




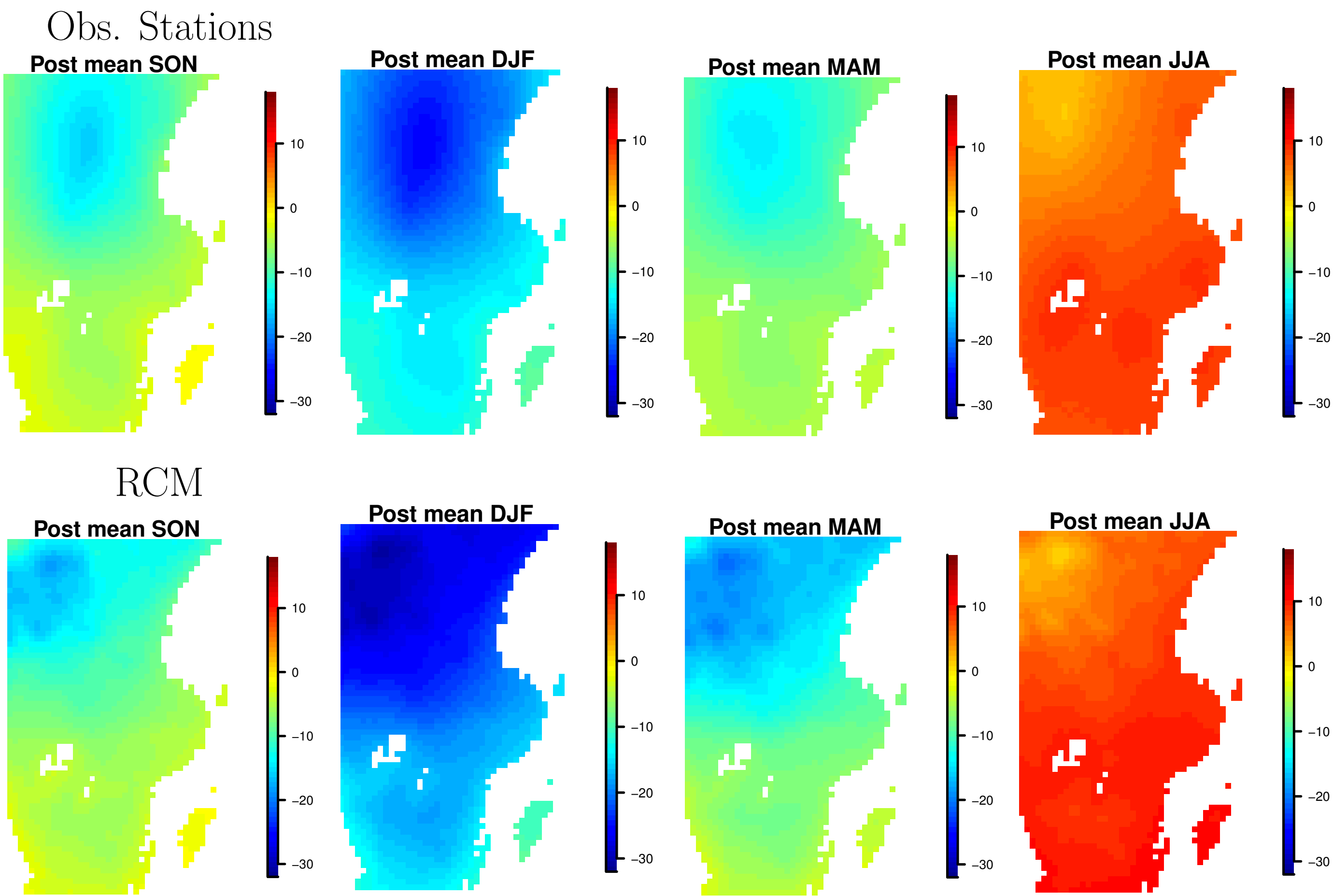
Fit of GEV-distribution



Fit is better when σ depends on s.

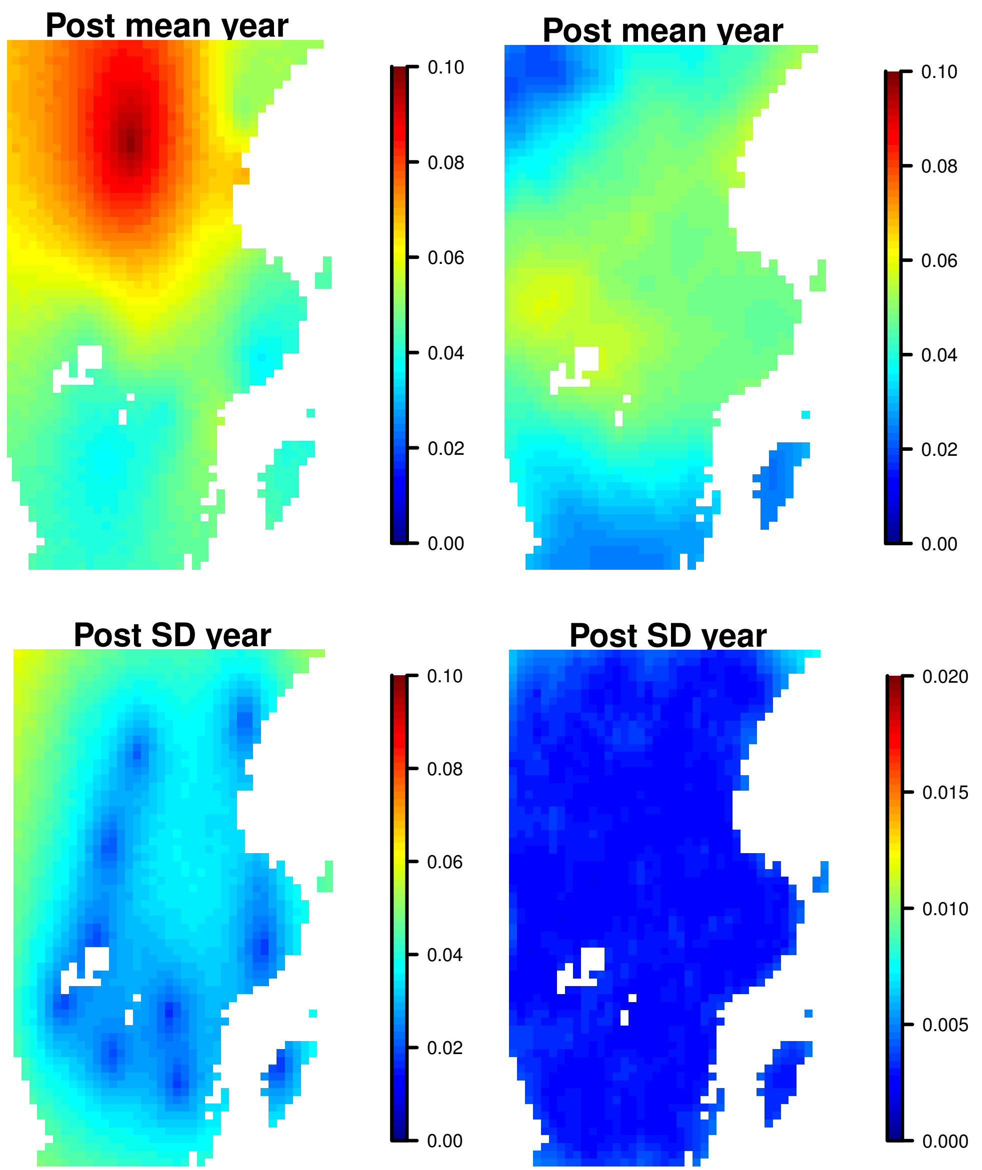


Seasonal fits



Trend fits

Observed stations RCM



(Dis)agreement between RCM and data

Seasonal effects quite similar

Similar spatial scale

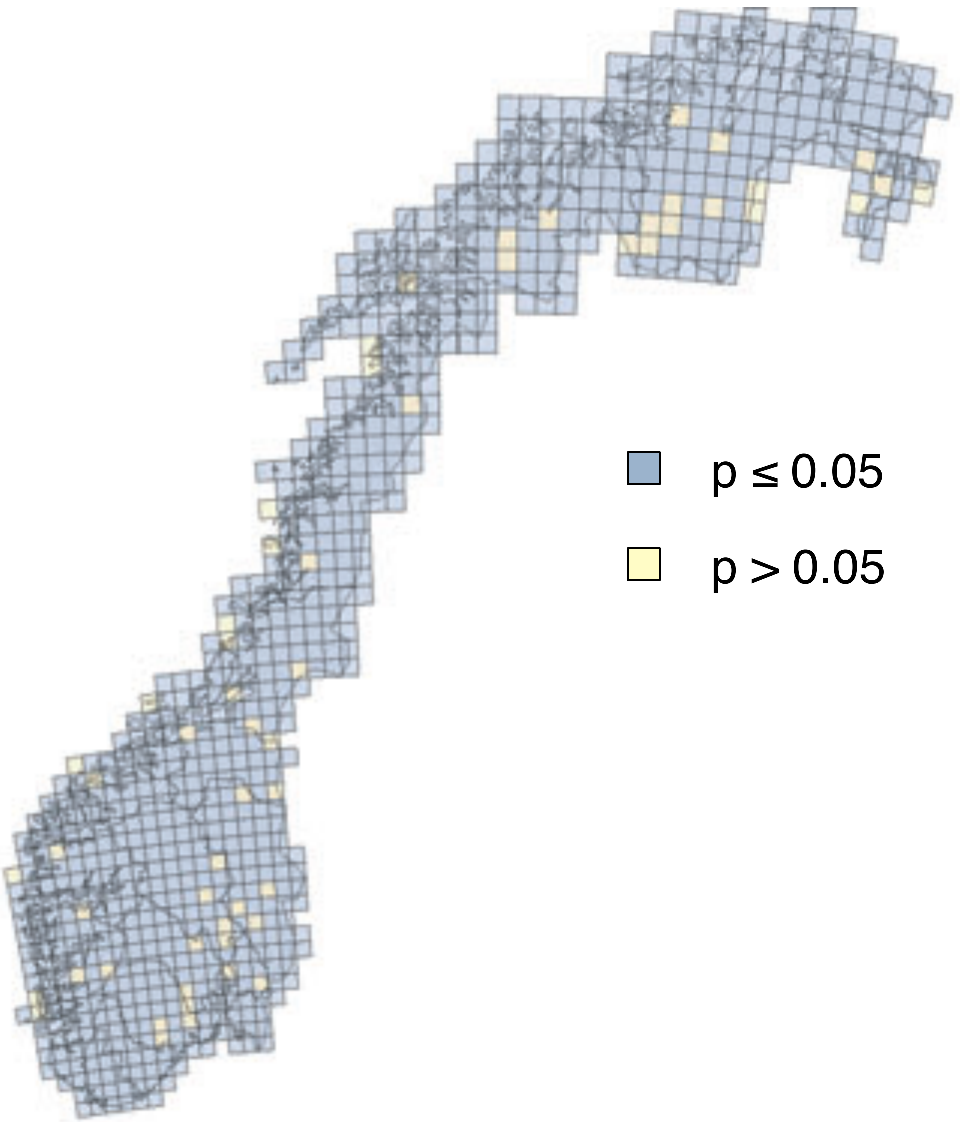
Similar shape parameter

Temporal trend substantially lower in model output

Data trend about 0.4-1°C /decade

(lower than the annual model)

Norwegian winter precip



Bias correction

Need downscaled precipitation projections for adaptation plans

Bias correction for downscaled reanalysis

Apply to downscaling historical GCM

If works, apply to downscaling GCM projections

Correction more important for large quantiles than for entire distribution

Full quantile correction

Applying the Doksum shift we get

$$
\begin{aligned}
z_{it'}^{cal} &= z_{it'}^{H} + \hat{\Delta}_i(z_{it'}^{H}) \\
&= z_{it'}^{H} + \hat{G}_i^{-1}(\hat{F}_i(z_{it'}^{H})) - z_{it'}^{H} \\
&= \hat{G}_i^{-1}(\hat{F}_i(z_{it'}^{H}))
\end{aligned}
$$

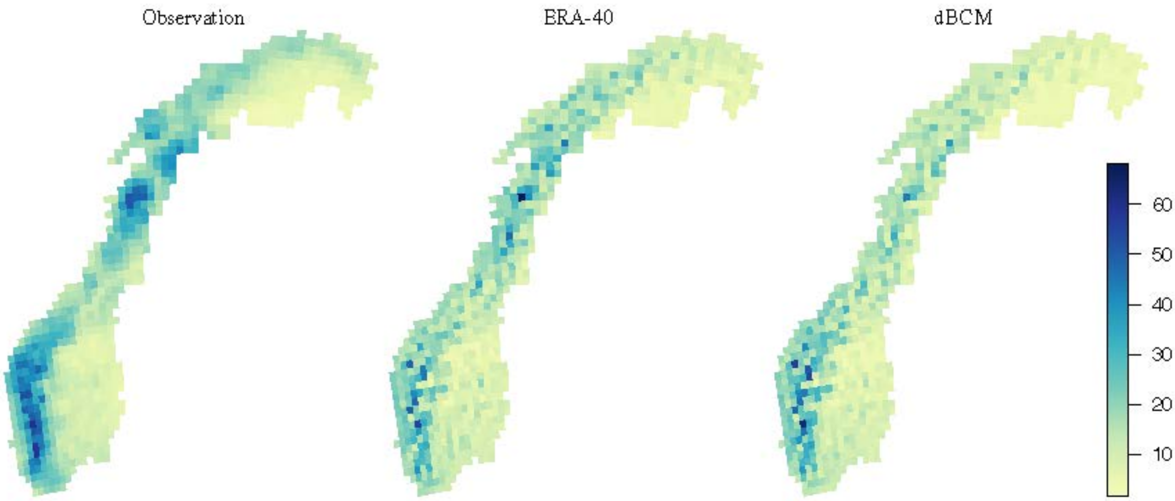
Rejections (fit to 80%, tested on 20%):

Raw 77%

Corrected 18%

Corrected GCM 79%

Single quantile correction



$$\log(Y^q) = \alpha + \text{diag}(\log(X^q))\beta + \varepsilon$$

$$\beta \sim GP(0, \Sigma(\nu, \kappa, \phi))$$

Replace with smoothed version

Bias-correction of 95th precipitation percentile