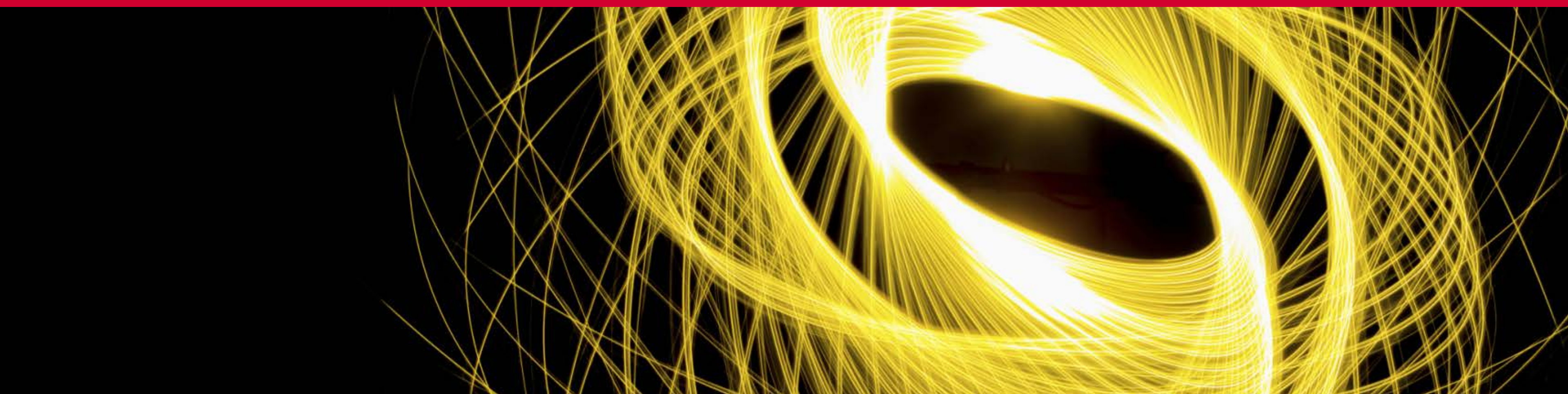
Department of Meteorology
School of Mathematical, Computational and Physical Sciences

University of Reading

Weather, climate and energy



David Brayshaw

With thanks to students, postdocs and collaborators: Hannah Bloomfield, Dan Drew, Dirk Cannon, Kieran Lynch, Caroline Dunning, Caroline Holmes (nee Ely), Emma Suckling, Dan Hdidouan, John Methven, Len Shaffrey, Andrew Charlton-Perez, Iain Staffell, Chris Dent, Stan Zachary, Alberto Troccolli and others

National Centre for Atmospheric Science
NATURAL ENVIRONMENT RESEARCH COUNCIL

Walker INSTITUTE

Power systems and meteorology

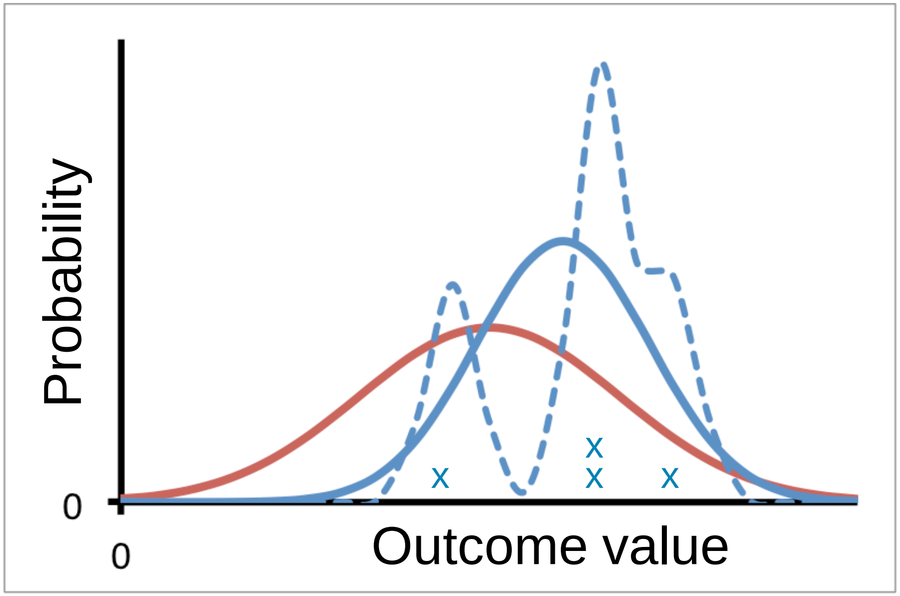
- Many impacts of weather on power (damage, demand, transmission, supply)
- Use of renewables: *Increasing sensitivity* to weather on generation side
- Climate variability and change: *Changing weather*

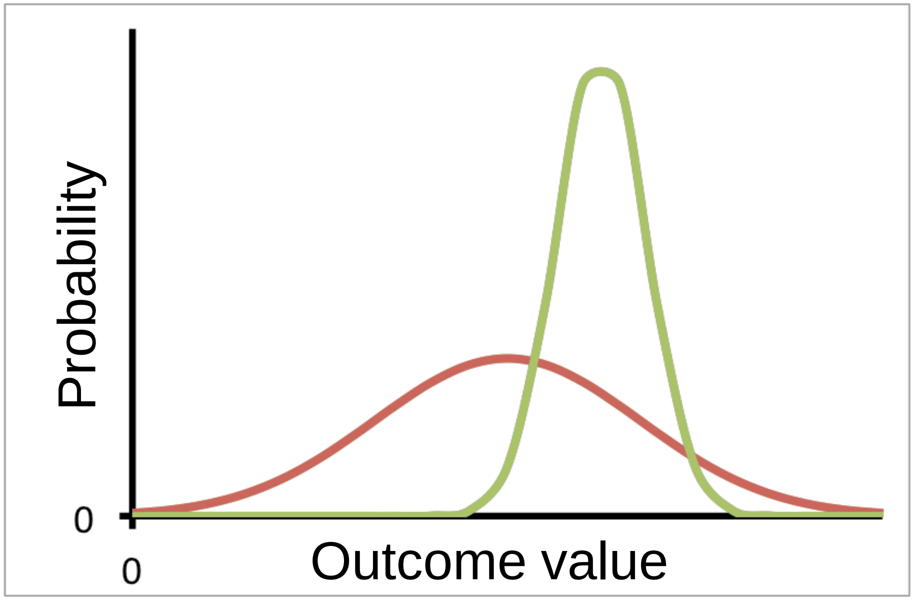
Operational (seconds –few days)	• Day to day operations (e.g., grid management, plant sched) • Anticipating extreme weather
Trading (days – 1 year)	• Longer-term wholesale energy contracts • Maintenance planning • Medium term resource planning
Strategic (long term climate)	• Characterising demand/supply • Impacts of climate change
Extremes (disrupting weather)	• Risk and impact of extreme disruptive weather • Local and far-field

- Key challenge: how to use weather/climate data effectively to understand behaviour of impacted system and develop risk management strategies
- Today: three examples – operational, strategic and, if time permits, trading
- Power-, Euro-, Renewables- centric (please ask about other areas!)

Types of climate information

- **Type 1 – climatologies of risk: understanding range of the possible (blue → red)**
  - **Reanalysis**
  - **Climate model projections (GCMs)**
- Type 2 – forecasting risk: anticipating outcomes (**red** → **green**)
  - Ensemble prediction (subseasonal, seasonal and decadal)





Climatologies of risk

- **Wind-power variability**
  - Reserve holding, system planning, system management
  - Risks: persistent-high, persistent-low and rapid ramps in wind power
- Example 1: Can historical meteorological data better characterize these three risks? (now and into the future)

- **Climate impacts on "integrated" power systems**
  - Load duration and operating opportunity for conventional plant
- Example 2: Are economic "system planning" models robust to climate variations?

- National-aggregate

Wind power climatologies

(Cannon et al, 2015; Drew et al 2015; Canon et al, accepted MetZet)

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- Insufficient direct power observation records (few years)

- Previous work largely based on met-station data (Sinden, Leahy, Earl, Fruh, …)
  - Spatially sparse, inhomogenous (spatial, temporal)
  - Wrong height (10m), wrong location (relative to wind farms)
  - → Conversion to "power" problematic

- Reanalysis
  - Full, gridded, homogenous coverage
  - Greater homogeneity, multiple vertical heights
  - Freely available, no need for additional simulations
  - NASA MERRA (Reinecker et al 2011); similar results with ERA-Interim (Dee et al, 2011)

- See also excellent recent work by Ed Sharp, Iain Staffell, Stefan Pfenninger, Lucy Cradden and others

Conversion to wind power

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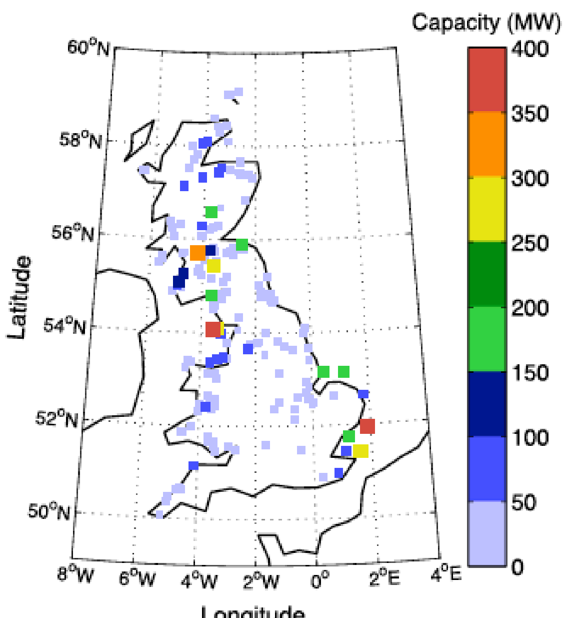
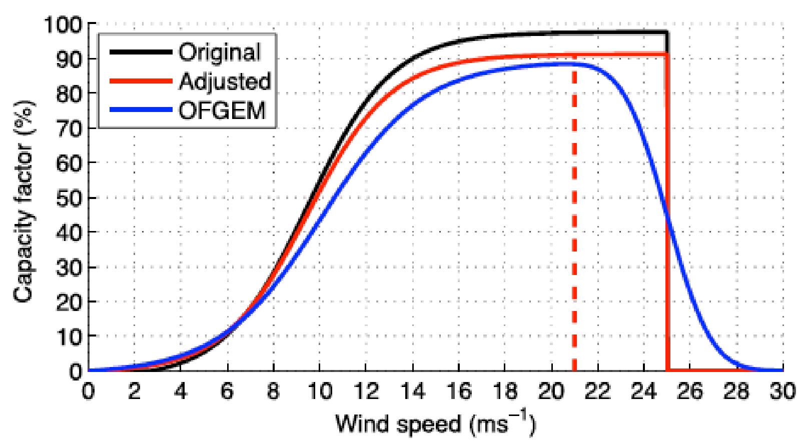
- Interpolate hourly wind-speed to each site in 2012 wind-farm list (2, 10, 50m)
- Extrapolate to turbine height using a fitted logarithmic profile
- Applying simple power curve to estimate capacity factor
- Weight by local installed capacity and aggregate nationally
- Calibrate power curve using observed 2012 wind-power records

(a) September 2012 wind farm distribution



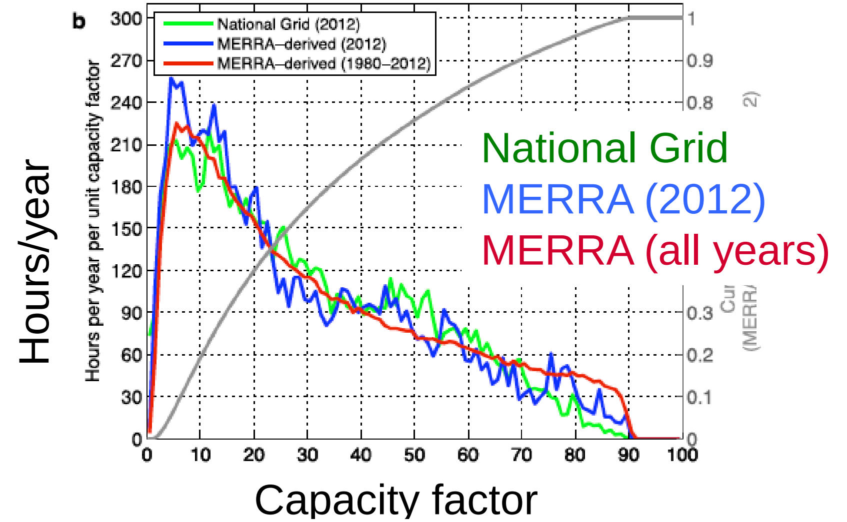
(b) Wind speed to power generation transformations

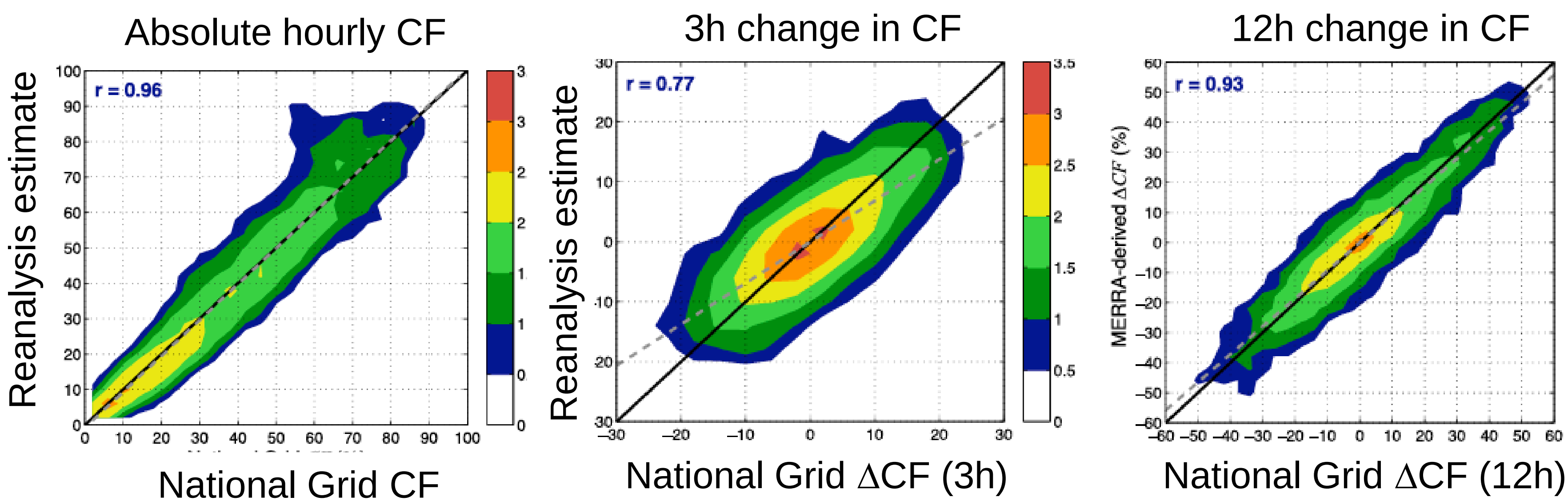


Cannon et al (2015)

Wind power – 2012 period

- Calibration performs well
- Good representation of hourly values
- Under estimates ramping < 3-6h
- Good estimation of ramping > 12h
  - Care required at finer spatio-temporal scales





Cannon et al (2015)

Aside: The limits of reanalysis

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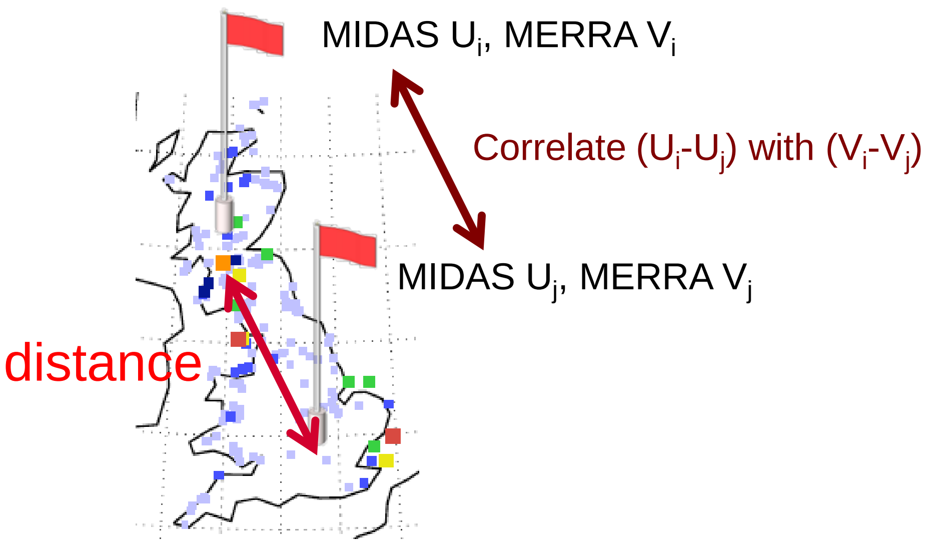
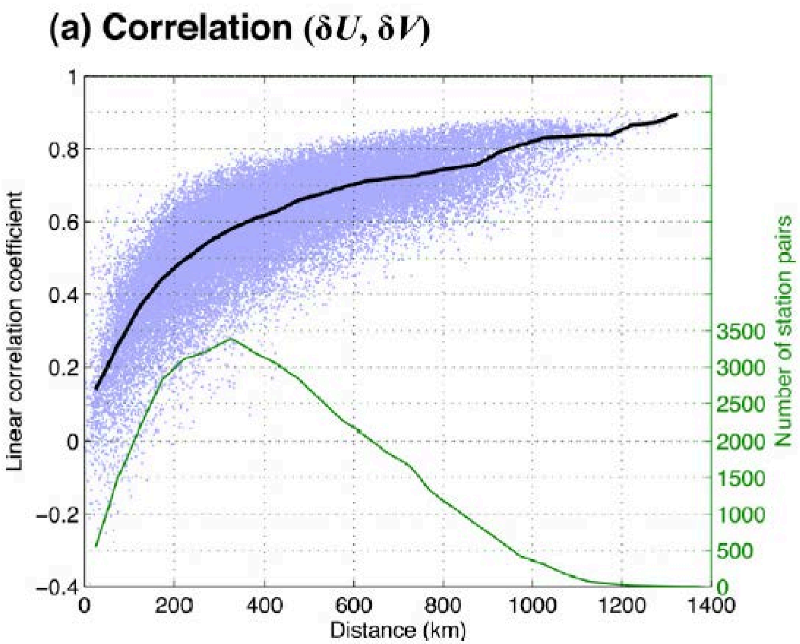
GB wind strongly spatially correlated, decreasing with distance ~100's km (Sinden, 2007)

Question: how well does MERRA capture *differences between sites*?





Correlation ~0.6 @ 300 km

Interpretation:

- dU contains contribution from "local situation" and "large-scale weather"
- MERRA captures the contribution from "large-scale" but "local" is unresolved
- Effective resolution on scale ~ 300km

Cannon et al (2015)

Wind power synthetic record
(Cannon et al, 2015, Renewable Energy)

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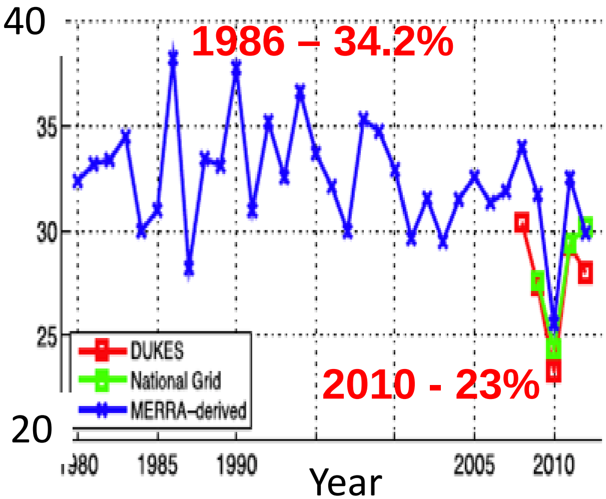
30+ year "synthetic history" of wind power

- **Model and data freely available: www.met.reading.ac.uk/~energymet**

Key points:

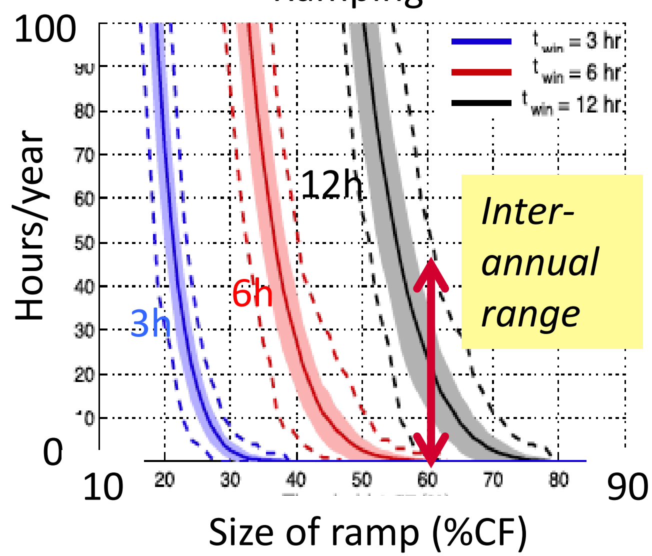
- Better quantification of risks associated with inter-annual climate variability
- Annual-mean capacity factor higher than previous estimates (32.5%) but *highly variable* (15pp range)
- Persistent high/low wind events approximately Poisson-like (exponential decay with persistence)
- Very large ramps can occur – but caution required

Annual mean CF

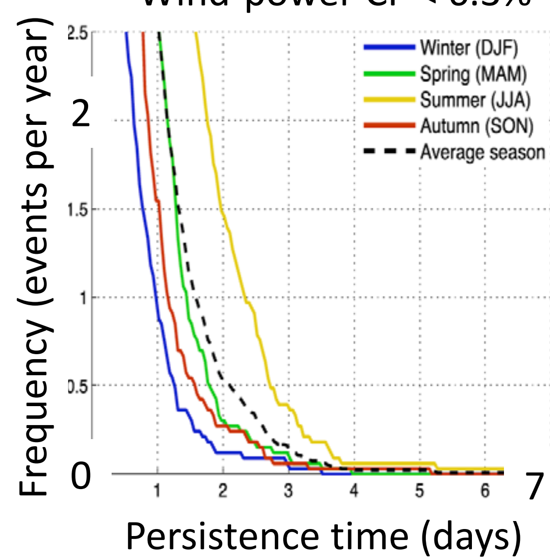


Mean – 32.5%

Ramping



Wind-power CF < 6.3%



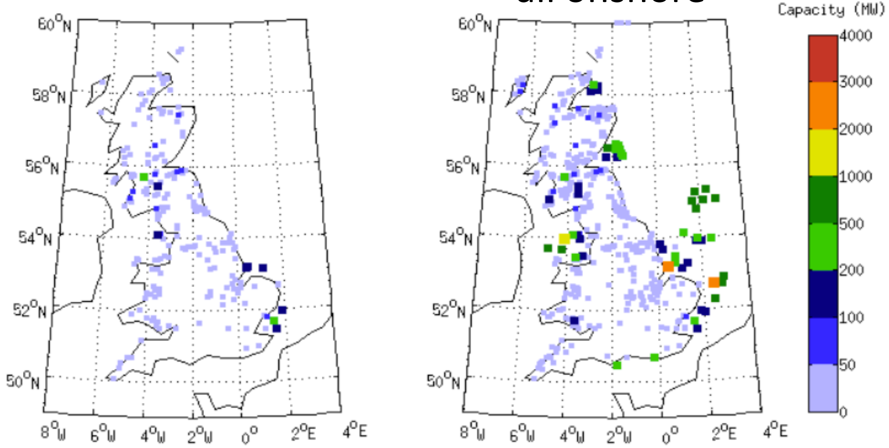
Future wind power installation
(Drew et al, 2015, Resources)

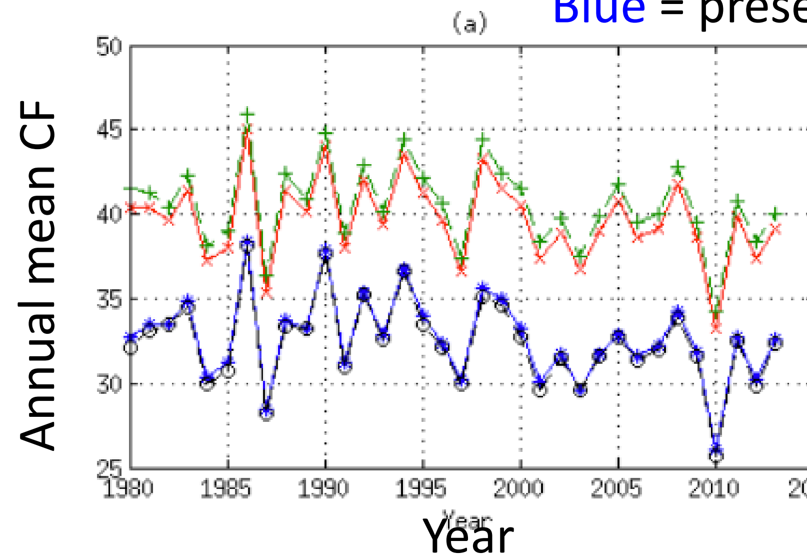
- "What if" scenarios: characteristics of future power systems
- Identify contributions from offshore/onshore

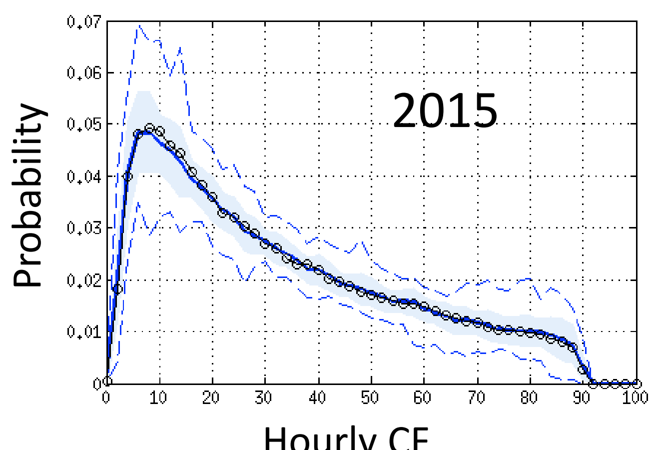
Red = "future"
Blue = present

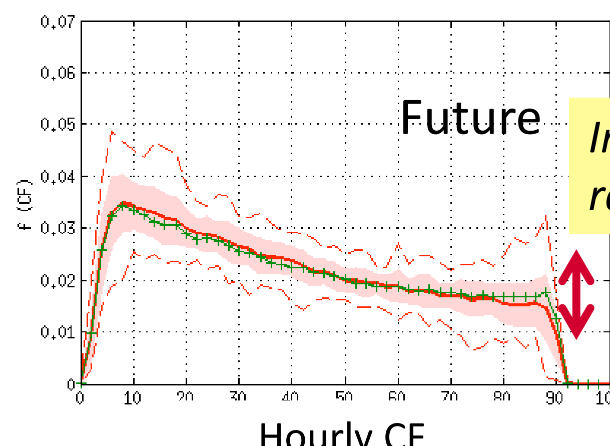
2015

"Future" = Round 3 + all onshore







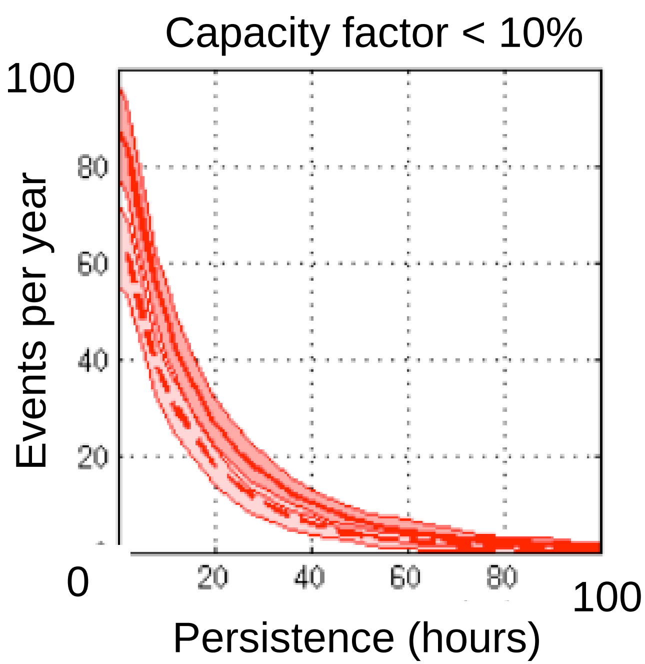


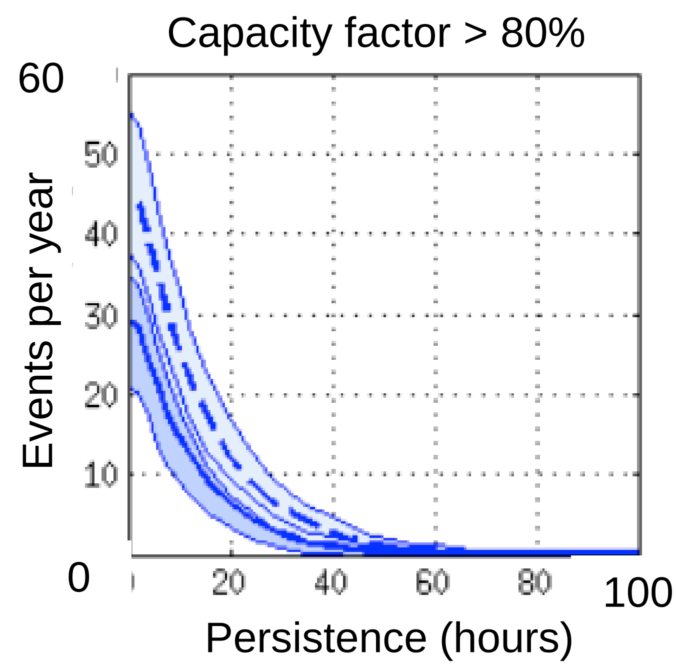
Interannual ranges

Drew et al (2015)

Future wind power installation
(Drew et al, 2015, Resources)

- Fewer persistent low CF events → much fewer in terms of GW output
- More persistent high CF events → much more in terms of GW output
- Ramps same size in CF terms → larger ramp in GW





Solid lines = present
Dotted = future
Shading = 1 std. dev.

Drew et al (2015)

Integrated power systems
(mainly work by Hannah Bloomfield, PhD student)

- Integration of renewables: more sensitive to weather
  - … but climate impact work usually considers "ingredients", not power "systems"
- Perspective: two particular "classes" of problem

Short run	**Long run**
Operation of a "fixed" power system	Design of "best" power system
E.g., unit commitment, power flow, loss of load probability	E.g., capacity mix, policy choices, economic optimality

- Both challenging, both important, both focus of much energy-system research
- Highly complex, often drawing on numerical simulation (typically optimisation-based)

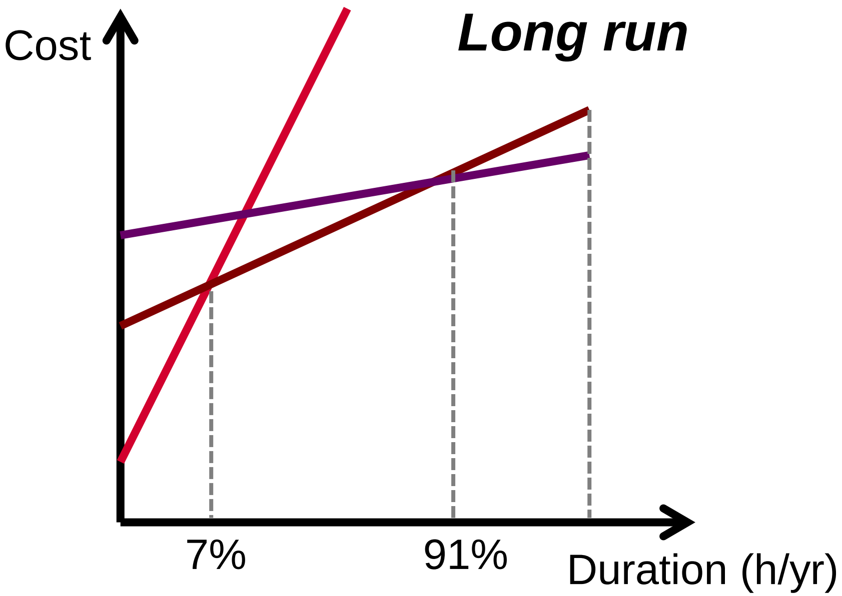
- However, many influential studies use short weather/climate records, e.g. (for long-run):
  - Grunewald 2011; Poyry 2009; Green 2010; Gerber 2012; Widen 2011; Buttler 2016; Schaber 2013; Macdonald (in press); EWITS, WWSIS

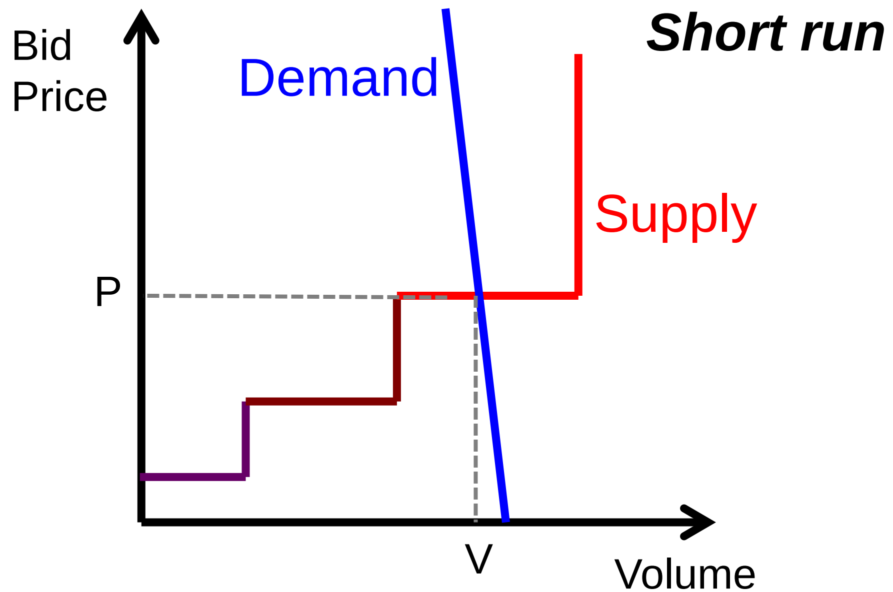
- **Question: How robust are the results to long-term climate variability?**

Integrated power systems

(work by Hannah Bloomfield, PhD student)

- Simplified approach, based on “merit-order” principles
- Enables approximation of economic decision-making in power sector
- Intention to explore how climate information can/should be used…
- … not to replace “more complex” power models, or to produce precise predictions



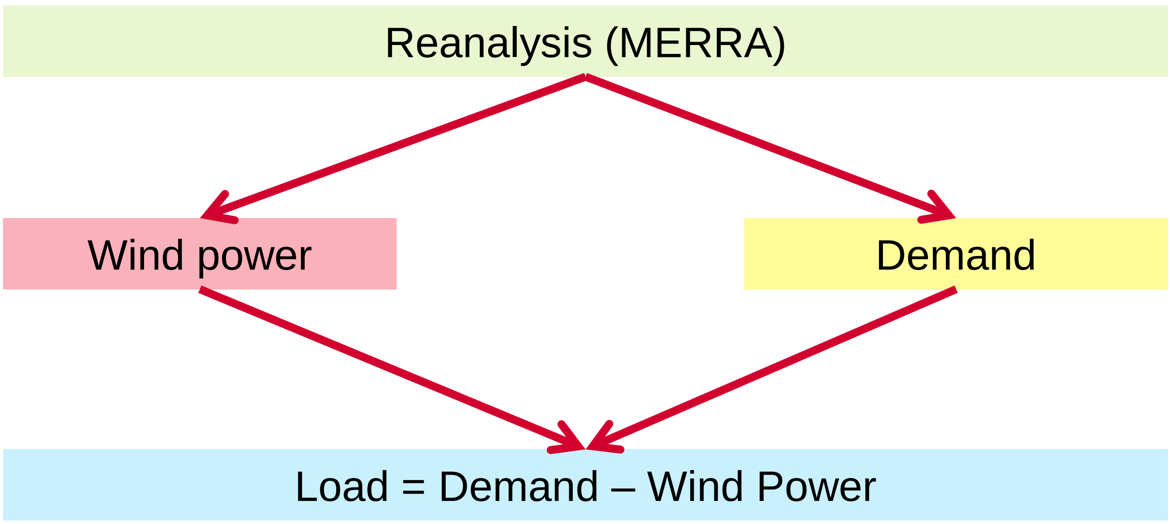


Type	Capital cost	Operating cost	Example
Peaking	Low	High	OCGT, oil
Mid-merit	Medium	Medium	CCGT, coal
Baseload	High	Low	Nuclear

See, e.g., Stoft (2002)
7% and 91% thresholds based on DECC 2013

“Model” concept

- Consider a one-zone (copper plate) model of the GB power system
- No transmission constraints, interconnectors, storage or ramping constraints
- Self-consistent weather impact scenarios from reanalysis



Bloomfield et al, Nature Energy (submitted)

“Model” concept

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- Consider a one-zone (copper plate) model of the GB power system
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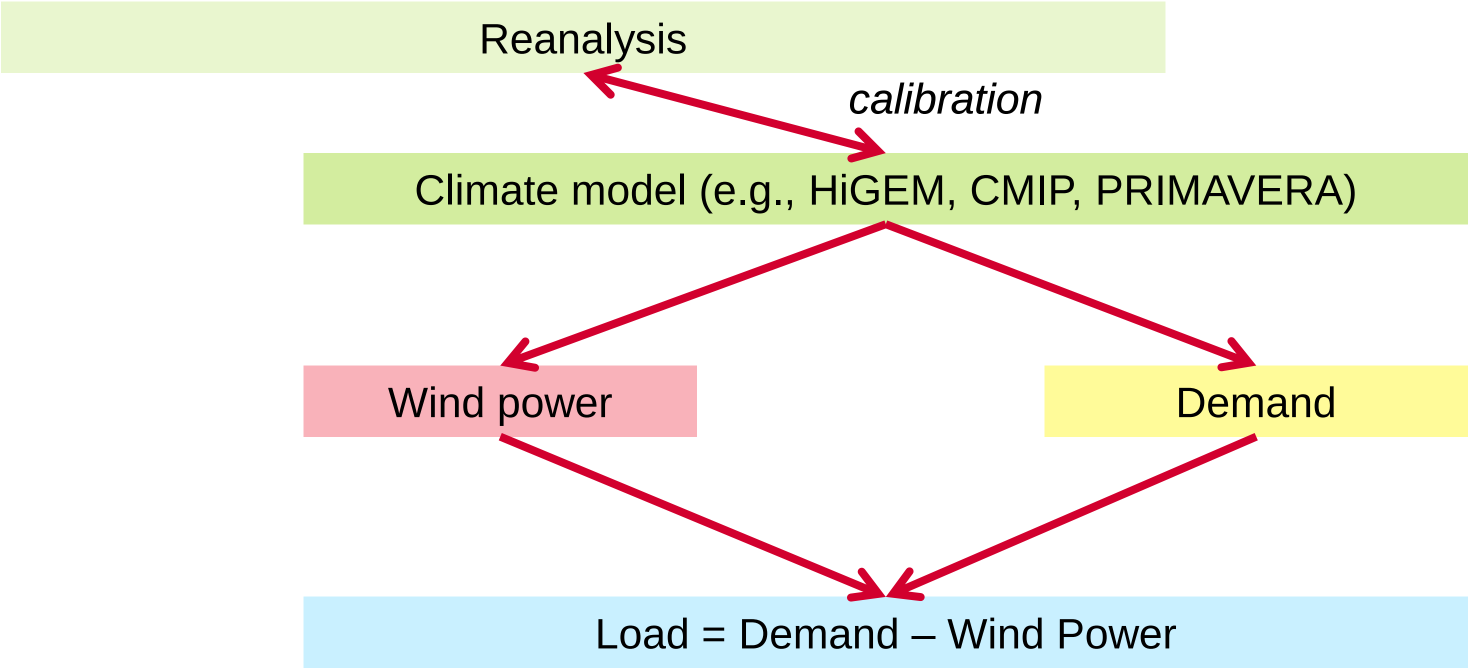
- Self-consistent weather impact scenarios from reanalysis or **climate model**



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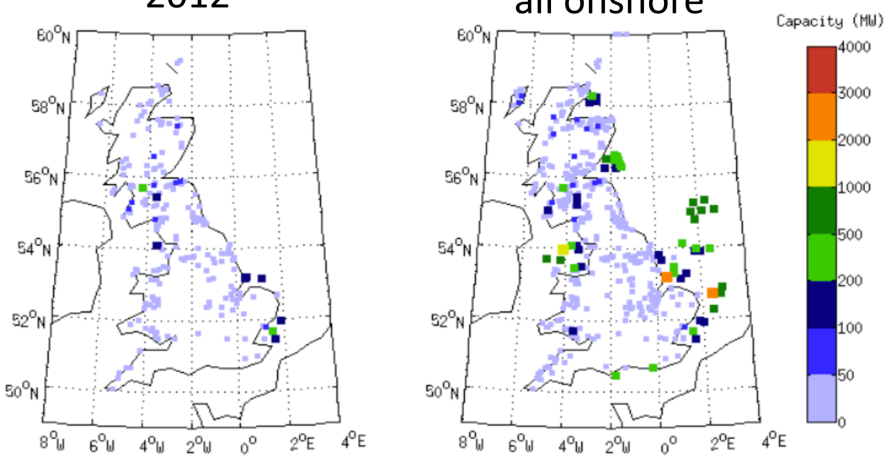
Wind power scenarios/model

- Constructed as previously, but using four different capacity scenarios:

Scenario	WP capacity	Distribution	Interpretation
NOWIND	0 GW		No use of wind power
LOW	15 GW	2012	Present day (2015)
MED	30 GW	2012	National Grid GG 2025
HIGH	45 GW	Future (Rd3)	National Grid GG 2035

2012

“Future” = Round 3 + all onshore



Bloomfield et al, Nature Energy (submitted)

GG = National Grid Future Energy Scenarios “Gone Green” (2015)

Note: interpretive comparisons indicate approximate consistencies, not precise definitions

Demand model

Three step approach:

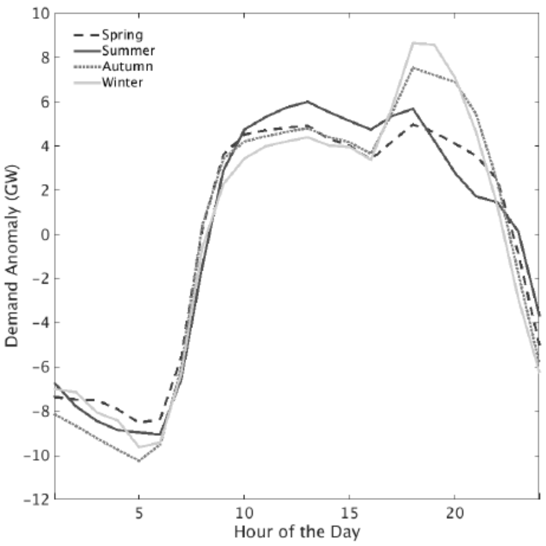
1. Daily demand: multiple linear regression on temperature, c.f. Taylor & Buizza (2003)
   - Trained on recorded national demand 2006-2010; good fit R^2 ~ 0.93

$$Demand(t) = \alpha_1 + \alpha_2(t) + \alpha_3 sin(\omega t) + \alpha_4 cos(\omega t) + \alpha_5 Te(t) + \alpha_6 Te^2(t) + \sum_{k=7}^{8} \alpha_k WE(t) + \sum_{l=9}^{12} \alpha_l WD(t) + \alpha_{13} HOL(t)$$

1. Simplify demand: remove "special days" with no meteorological significance

$$Demand = \alpha_1 + \alpha_3 sin(\omega t) + \alpha_4 cos(\omega t) + \alpha_5 T(t) + \alpha_6 T^2(t)$$

1. Simplified hourly demand:
   - "Downscaling" using observed diurnal curves
   - One curve per season



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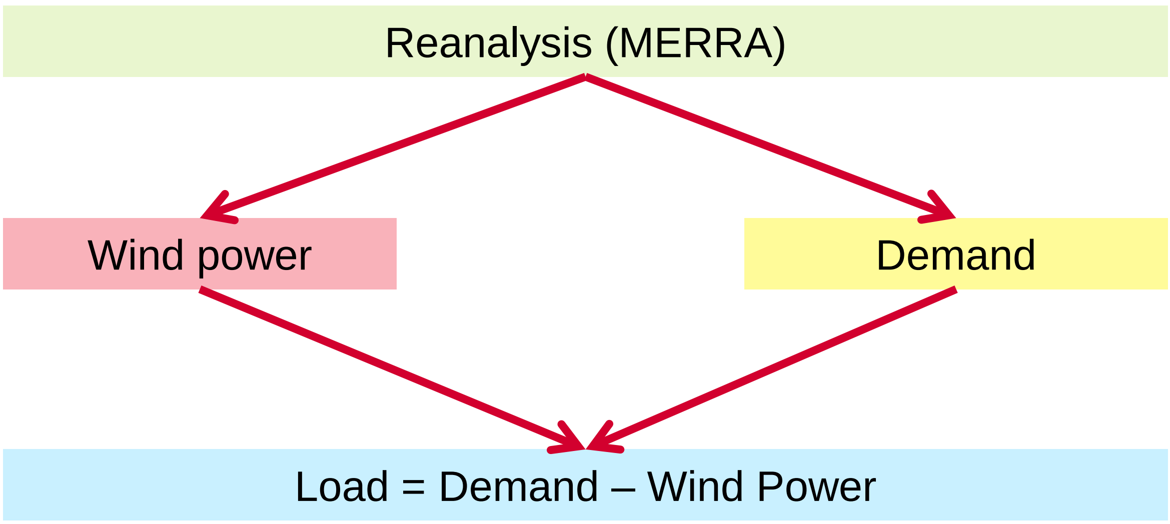
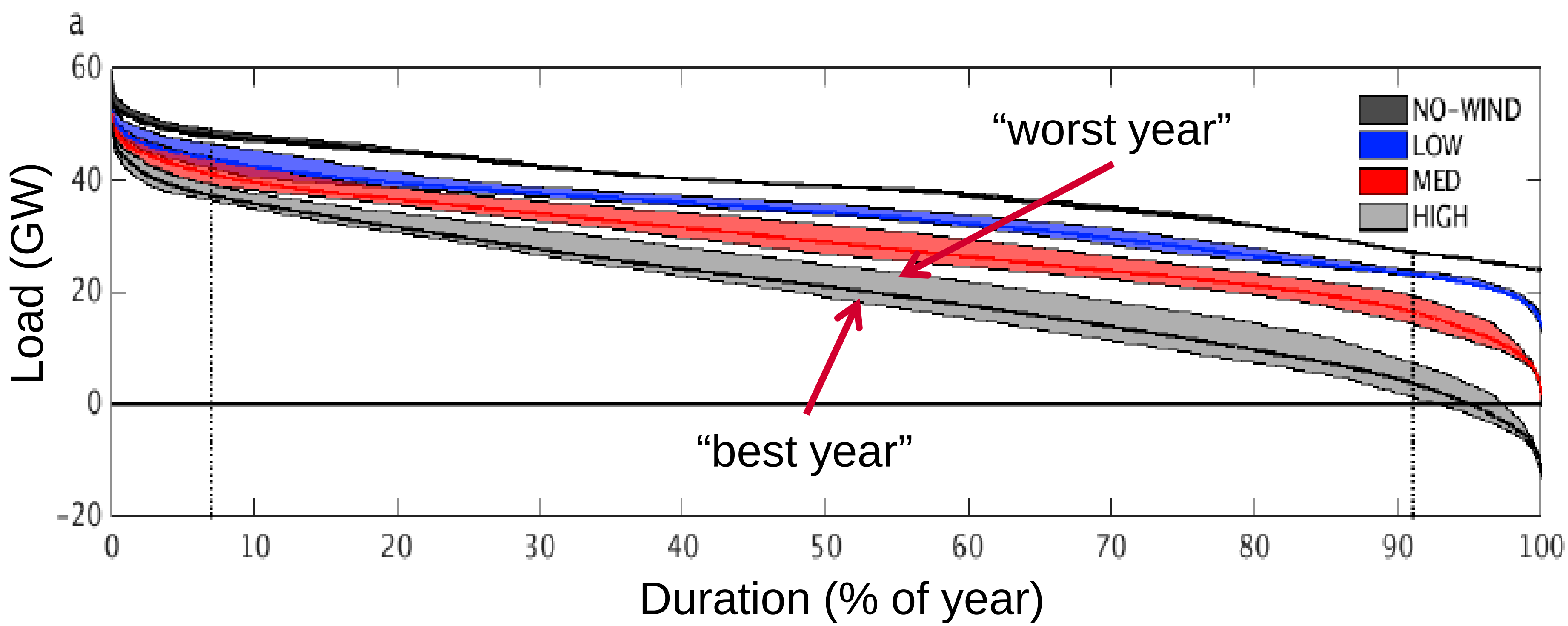


Bloomfield et al, Nature Energy (submitted)

Power system "model" concept

Bloomfield et al, Nature Energy (submitted)

- Result:
  - 4 x 36 year scenarios (NO-WIND, LOW, MED, HIGH); hourly resolution
  - Convenient to display as annual load duration curves (→ 36 LDCs per scenario)



Power system metrics

Bloomfield et al, Nature Energy (submitted)

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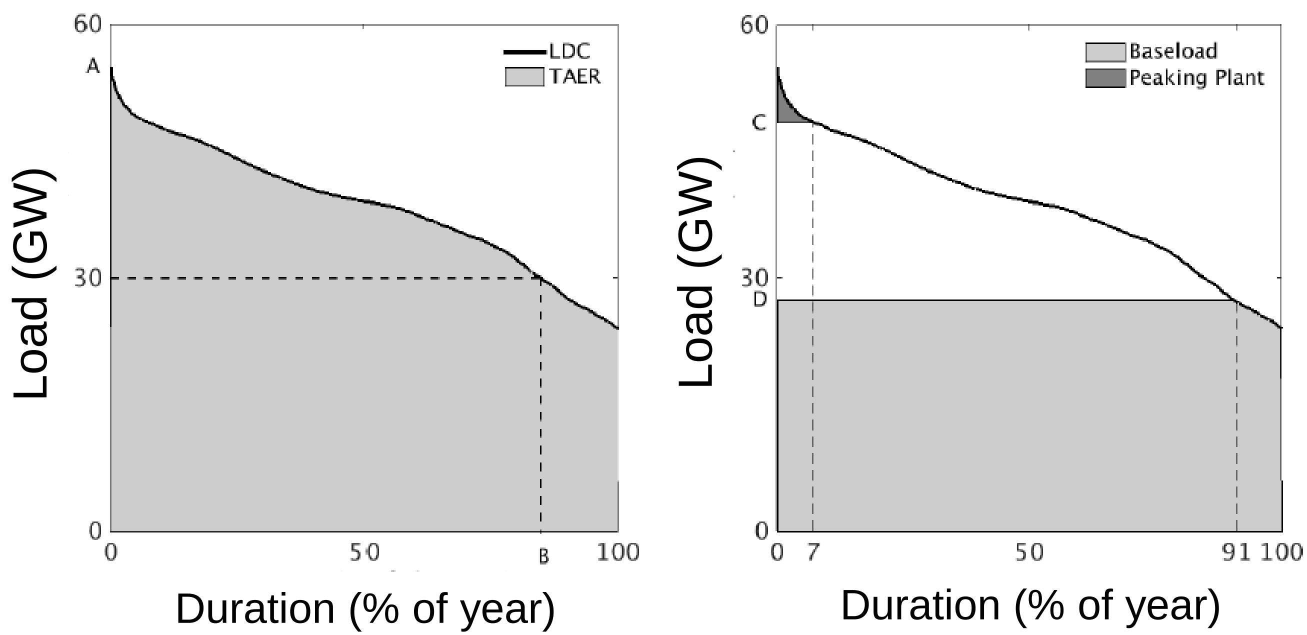
- Assume "load" must be met by schedulable plant (either peaking, mid-merit, or baseload)
- Six power system "impact metrics" defined
  - Total annual energy required
  - Peak load
  - Curtailed wind energy
  - Threshold of economic opportunity for 7% peaking plant (or volume of energy opportunity)
  - **Threshold of economic opportunity for 91% baseload plant** (or volume of energy opportunity)
  - **Annual operating hours of 30GW marginal mid-merit plant**

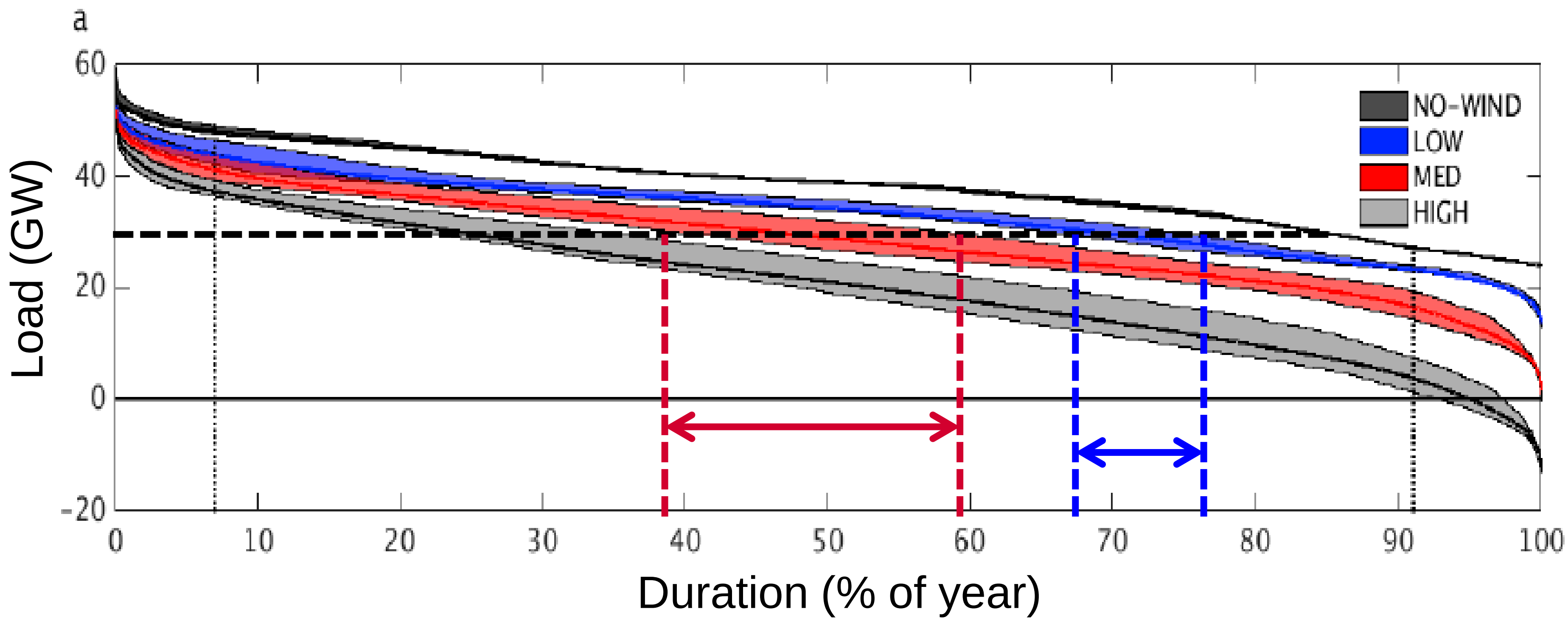


Mid-merit operating hours

Bloomfield et al, Nature Energy (submitted)

Perspective: "Short run" problem

- Substantial decrease in number of hours where load exceeds 30GW (from ~73% to ~50%)
- Also: increase in the year-to-year range
  - Doubling from ~10pp (750h/yr) to ~20pp (1350h/yr)
  - Significantly increased impact of climate on the operation opportunity



Baseload threshold of opportunity

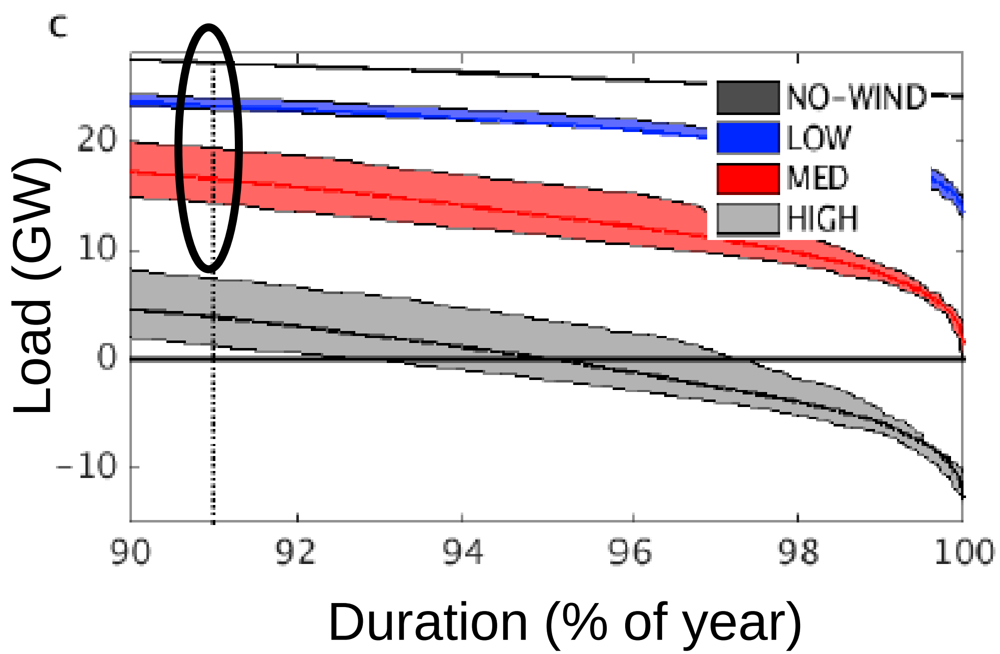
Bloomfield et al, Nature Energy (submitted)

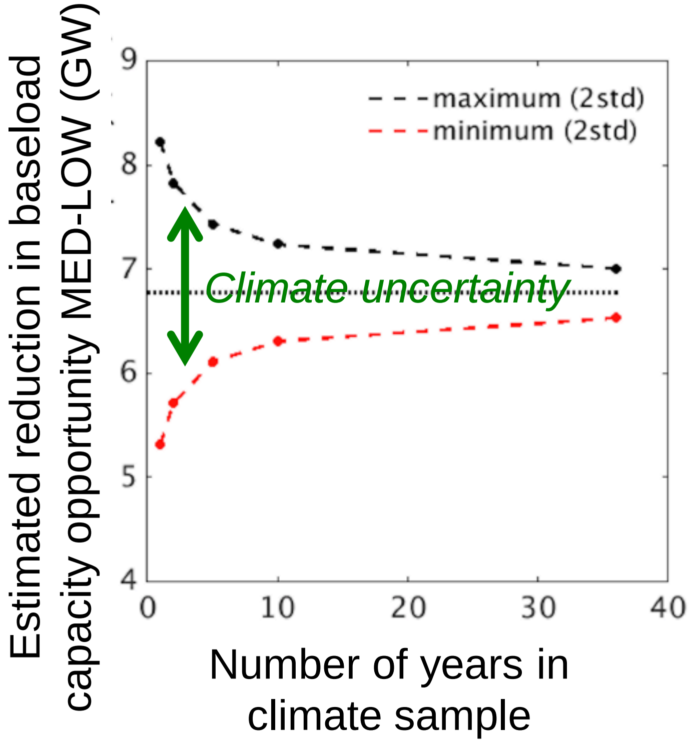
Perspective: "Long run" problem - optimal amount of "baseload type" plant capacity

- Mean decreases dramatically → less opportunity for this type of generation
- Inter-annual range significantly increases → more climate uncertainty

→ Estimates of the economically "optimal" opportunity for baseload which are reliant on short-data may be significantly in error:

- Recall many studies use between 1 and 10 years of data
- 50% error in the change in optimal capacity for single year; 15% error for 10-year

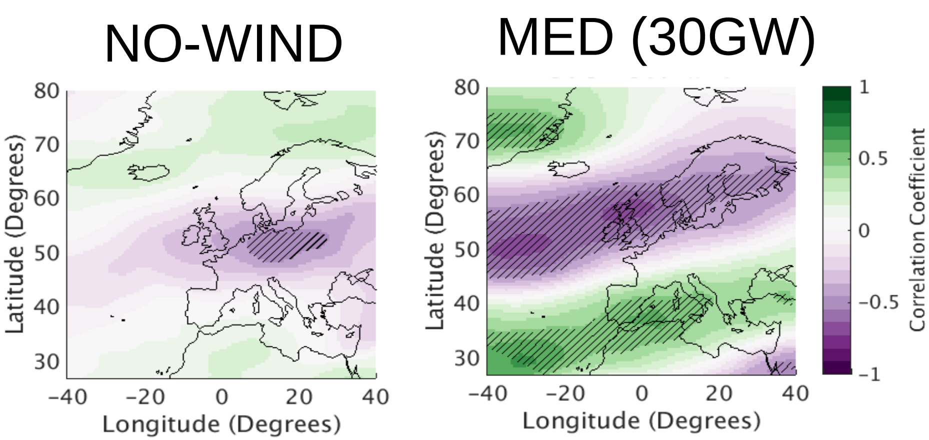




Climate drivers

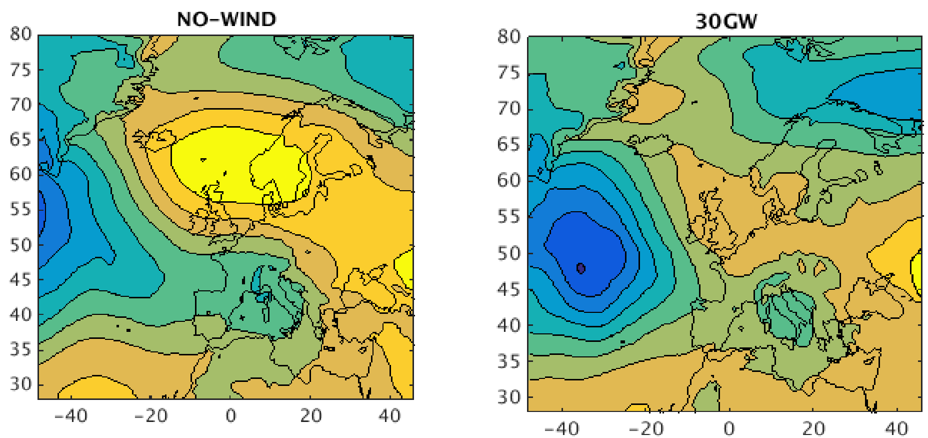
(Hannah Bloomfield, PhD thesis in prep)

- Exploration of what *causes* climate impacts (work in progress)
  - Meteorological drivers sensitive to construction of power system
  - See also Brayshaw, Dent and Zachary (2012) for wind-during-peak-demand



Baseload energy opportunity

Correlation with zonal wind U850



Peak Load

Composite MSLP
(Top 10, 5d separation)

Climate change

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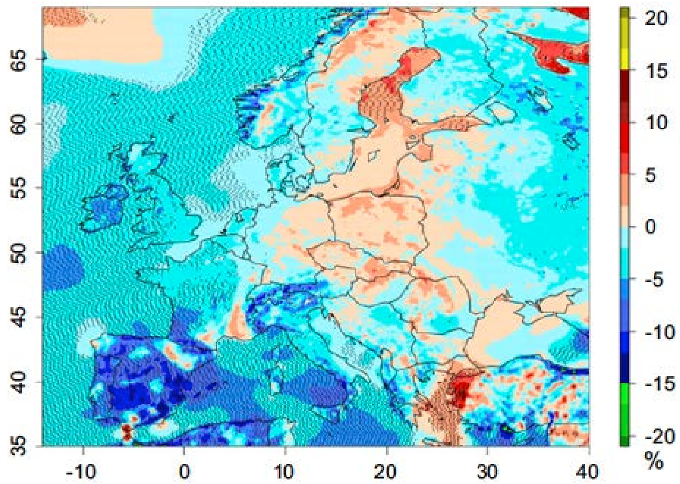
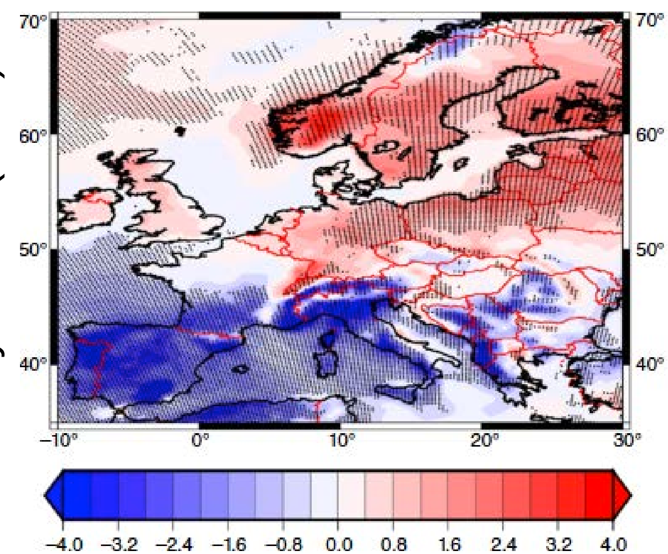
- Growing number of studies addressing climate change on energy systems
- General consensus for wind:
  - Changes are “fairly small”
  - Increases in N. Europe
  - Decreases in S. Europe
  - Significant differences between models
  - Differences between studies – even using same model archive!
- See, e.g., Bonjean-Stanton et al (2016) for a recent review across many technologies

RCP8.5 late C21 ENS mean
Change in wind power potential

Tobin et al (2016)



Reyes et al (2016)



A note on climate change…

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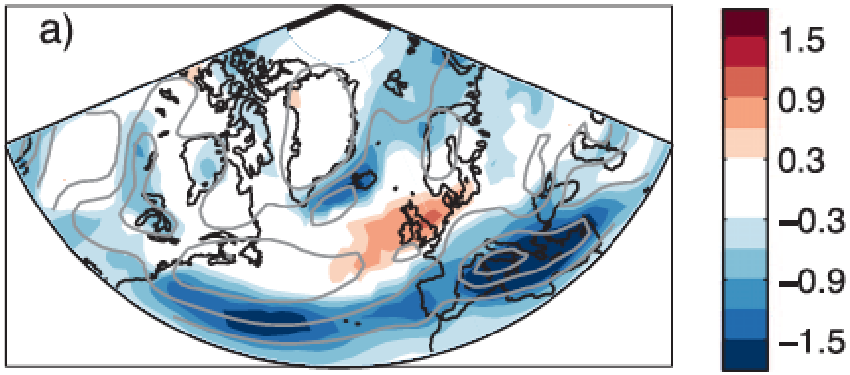
- Understanding the meteorological drivers is important…
- … forced regional climate change signals can be quite uncertain (note: colour scales!)

"Climate response"
RCP8.5-HIST Track density DJF
Ensemble mean



Figures: Zappa et al 2013

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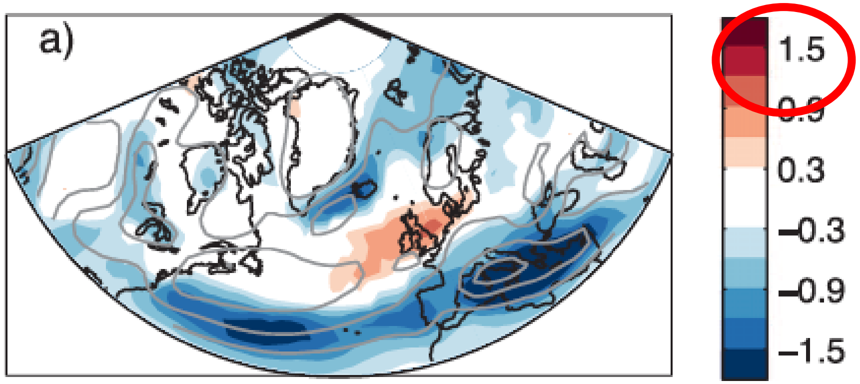
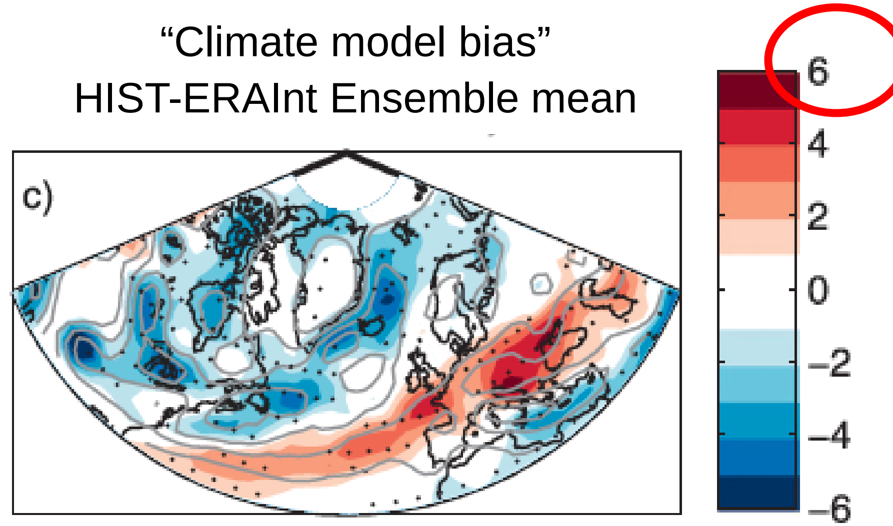


"Climate model bias"
HIST-ERAInt Ensemble mean



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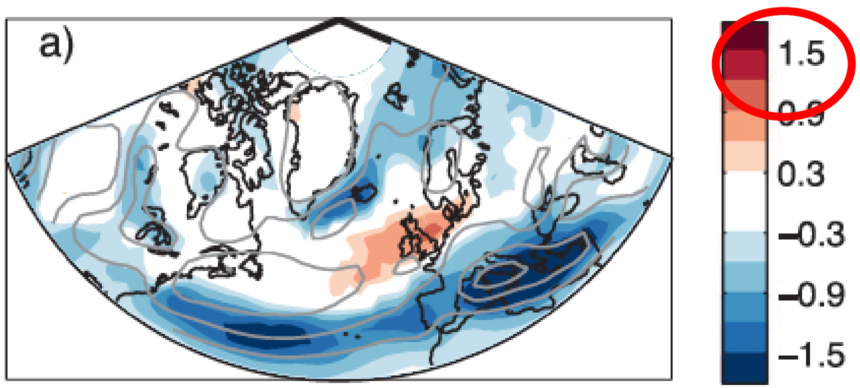

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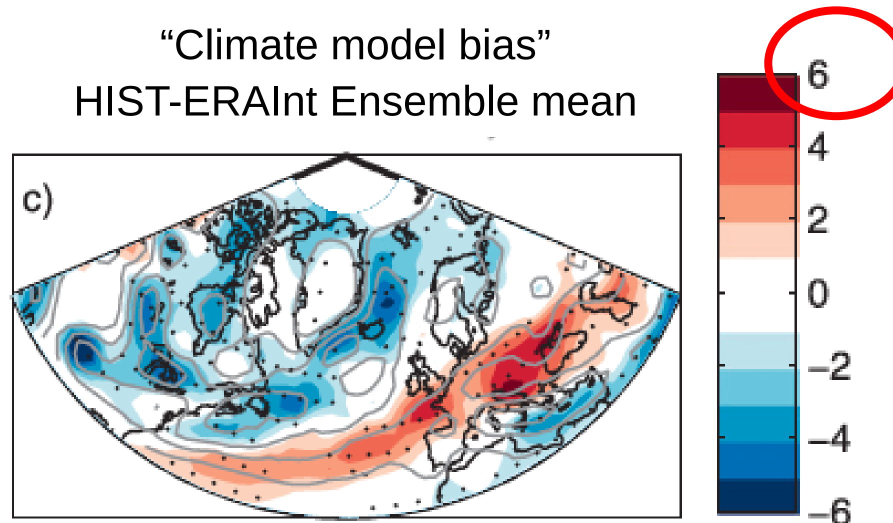

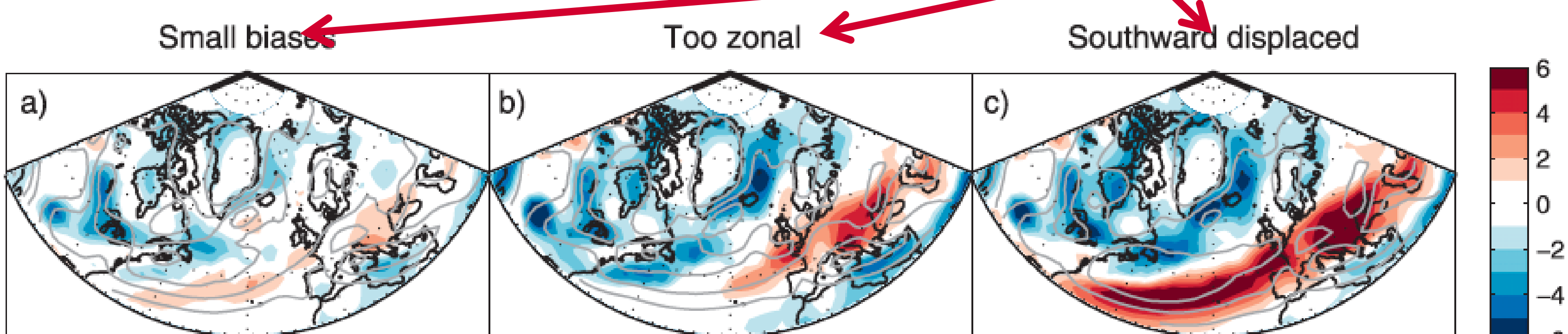

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Types of climate information

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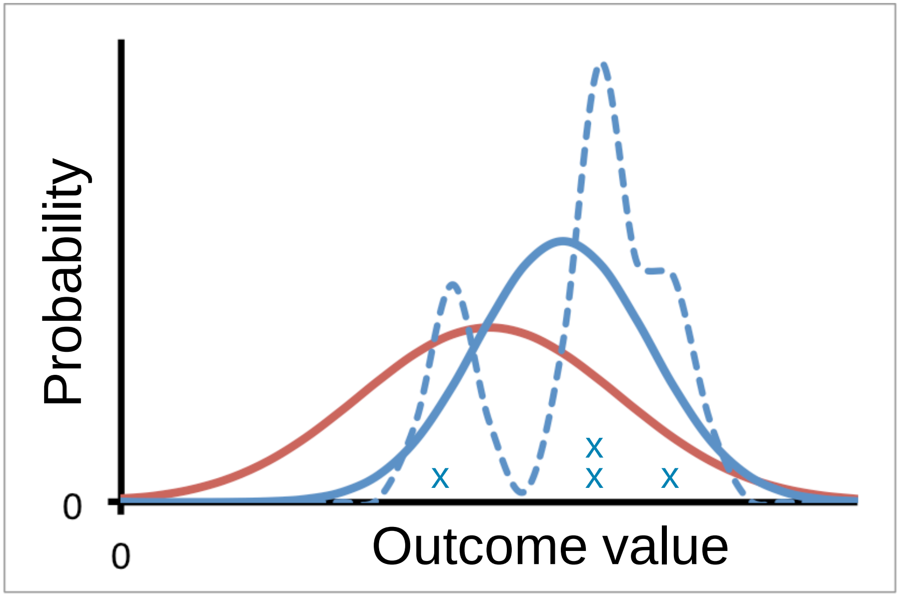
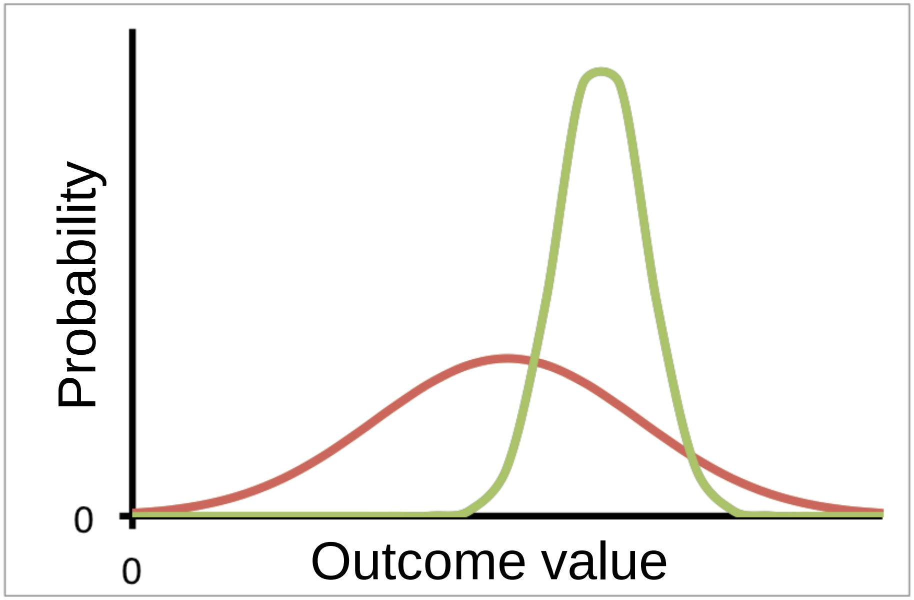
- Type 1 – climatologies of risk: understanding range of the possible (blue → red)
  - Reanalysis
  - Climate model projections (GCMs)
- **Type 2 – forecasting risk: anticipating outcomes (red → green)**
  - **Ensemble prediction (subseasonal, seasonal and decadal)**





Subseasonal and seasonal forecasting

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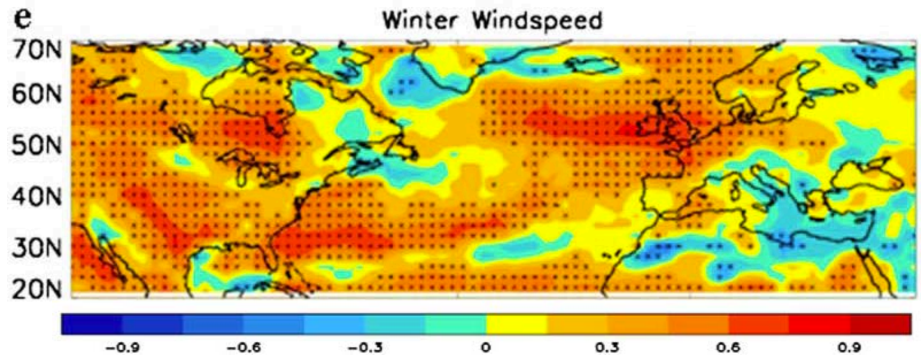
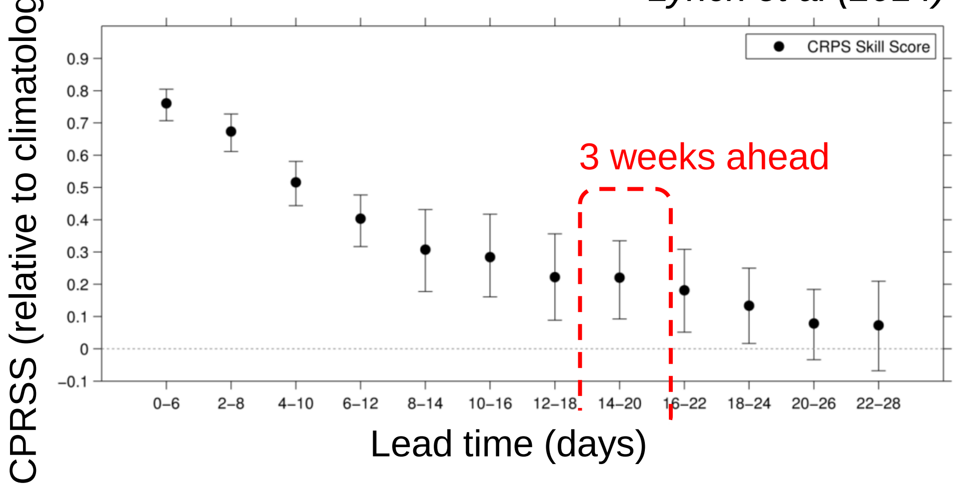
- Ensemble forecasts
- 3 weeks – 4 months
- Skill at large scales (space & time)
- Inherently probabilistic

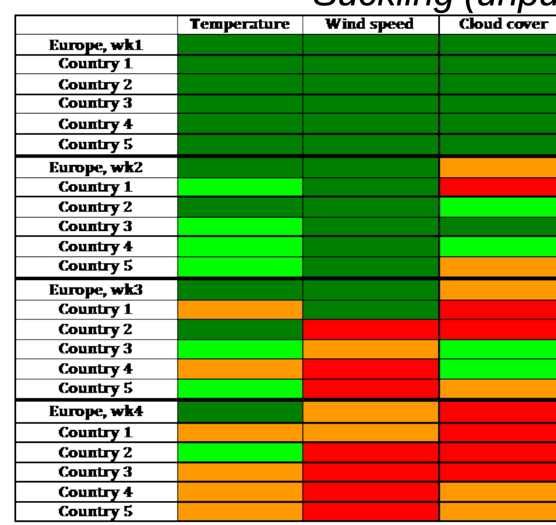


3-month average skill in winter wind speed in Met Office seasonal forecast
Scaife et al 2014

ECMWF ensemble forecast
UK-average 7-day mean 10m windspeed
Lynch et al (2014)



Country-average weekly-mean forecast skill for Temperature, wind and solar
Suckling (unpublished)



Using climate forecasts
(Lynch et al 2014; Lynch PhD thesis 2016)

- Similar issues to short-range but often more challenging (calibration etc)
- Acting on probabilistic information

Ensemble weather forecast

Wind

Temperature

Wind power

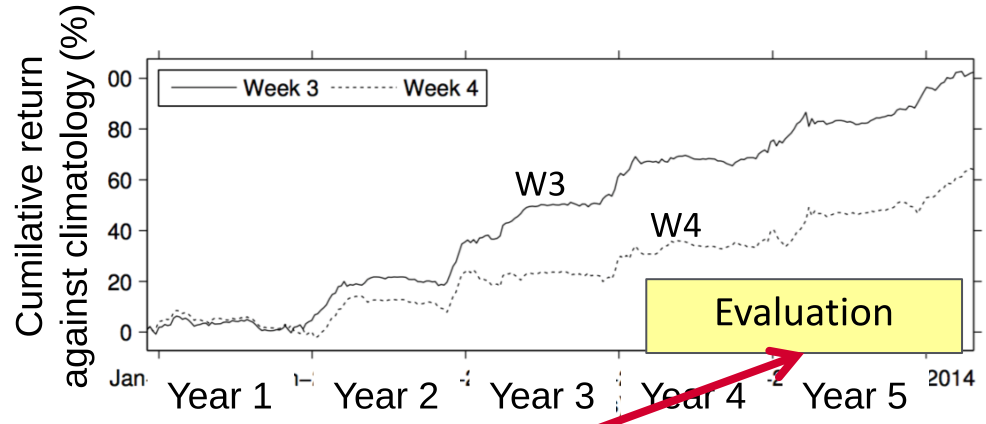
Demand

Power model (stack; EnKF)

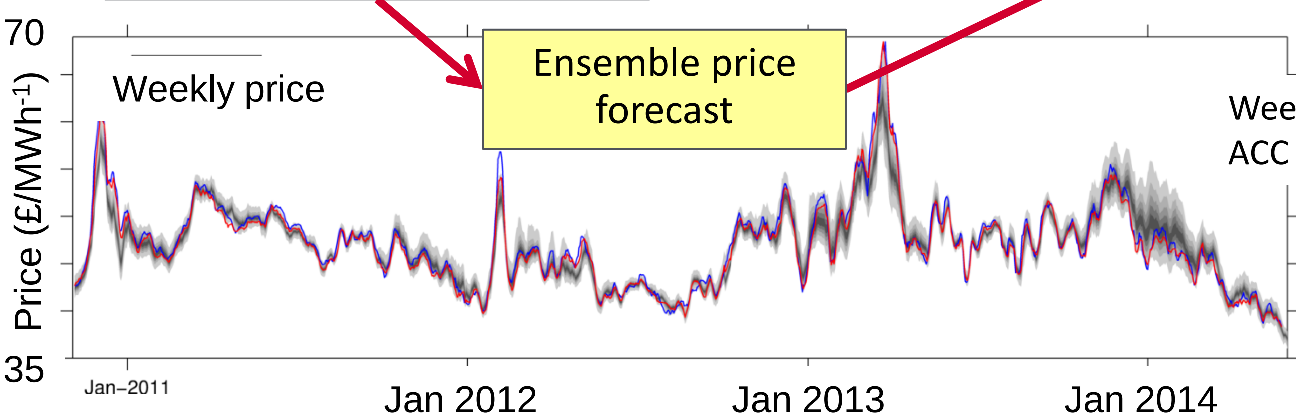
Ensemble price forecast

Optimize trading strategy

Evaluation



Lynch et al (thesis submitted)



Weekly price 3-week ahead forecast: ACC 0.53; CRPS 0.15 (99% confidence)

It **is** likely possible to extract more skill

Summary

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- Weather and climate risk matters for energy applications
  - **Climate variability and change (years-to-decades) produces significant uncertainty**
  - Impacts all parts of the power system, not just renewables
  - Influence on both “short-run” (fixed system) and “long-run” (investment/planning) perspectives
  - Has not been adequately addressed in many previous studies: CIPSMIP?

- Opportunties to better manage the risks… but need for interdisciplinary collaboration
  - Reanalysis and GCMs are powerful tools: **but must be used appropriately**
  - Climate drivers need to be understood: **does dataset/model include the relevant processes?**
  - Sub-seasonal, seasonal and decadal forecast systems: **need to integrate with decision-making**

Impact complexity ↓

Simple	Single variable Single timestep Single location	Wind at a site
Complicated	Multi-variable Multi-timestep Multi-location	Demand net renewables
Complex	Multiple-sensitivity Time trajectory Geographic network	Integrated power systems

Citations and upcoming

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Major projects ongoing:

- ECEM climate services for energy
- PRIMAVERA climate-energy impacts

Recruiting postdoc now!

Contact:

- Website (models and data): www.met.reading.ac.uk/~energymet
- Email: d.j.brayshaw@reading.ac.uk

Citations:

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