The atmospheric boundary layer and its impact on the general circulation

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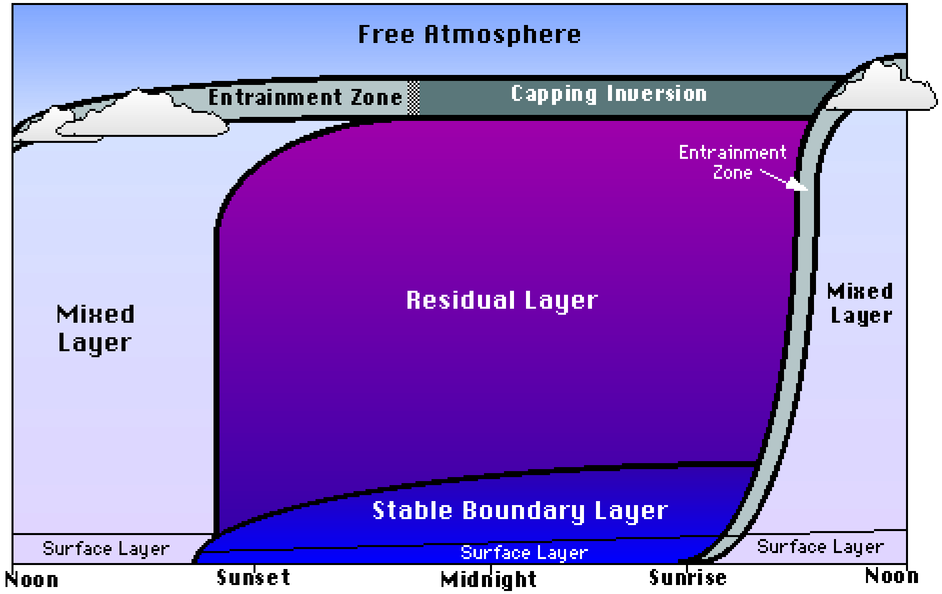
Planetary boundary layer

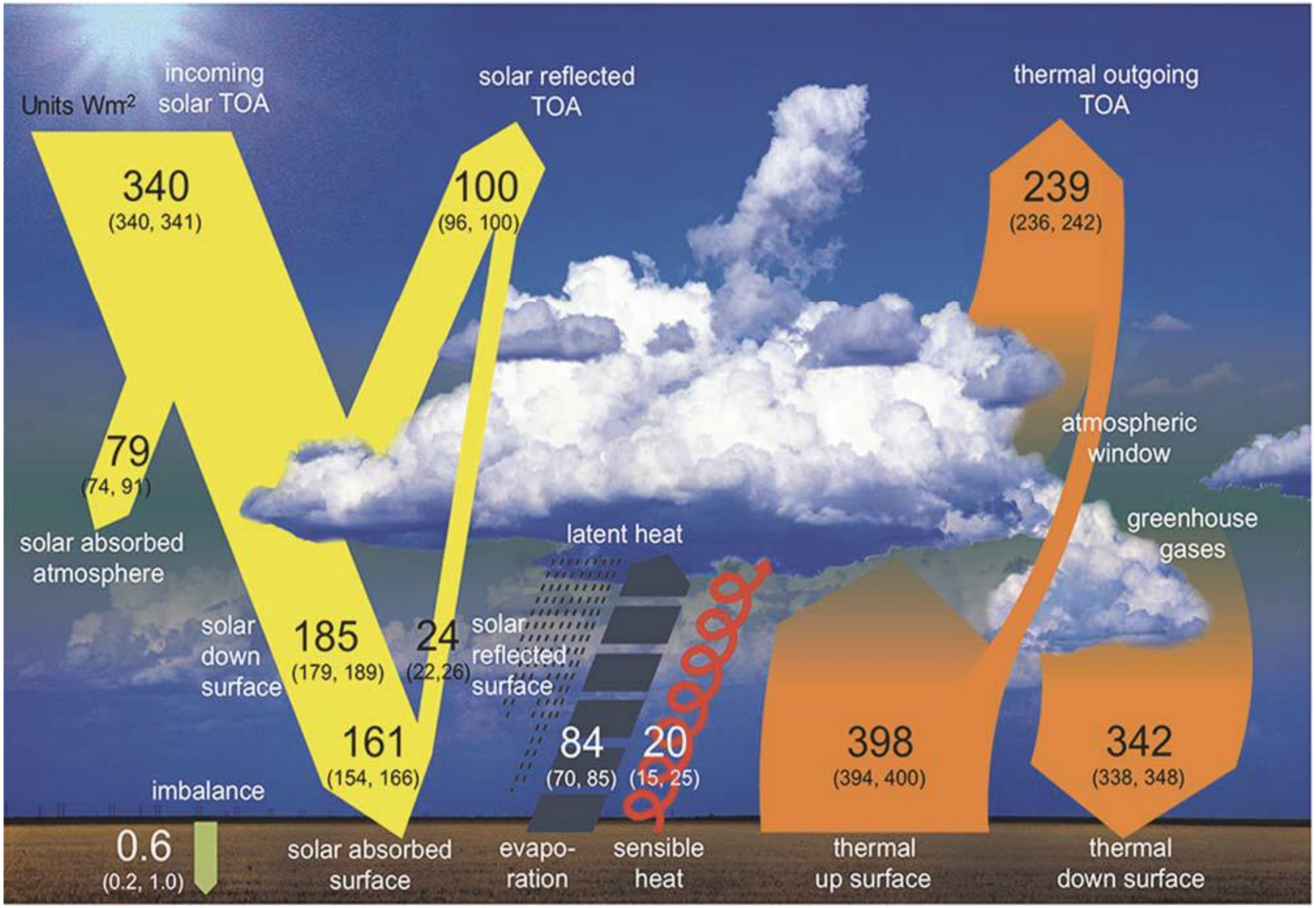
PBL



Structure of Planetary Boundary Layer
adapted from Stull, 1988.

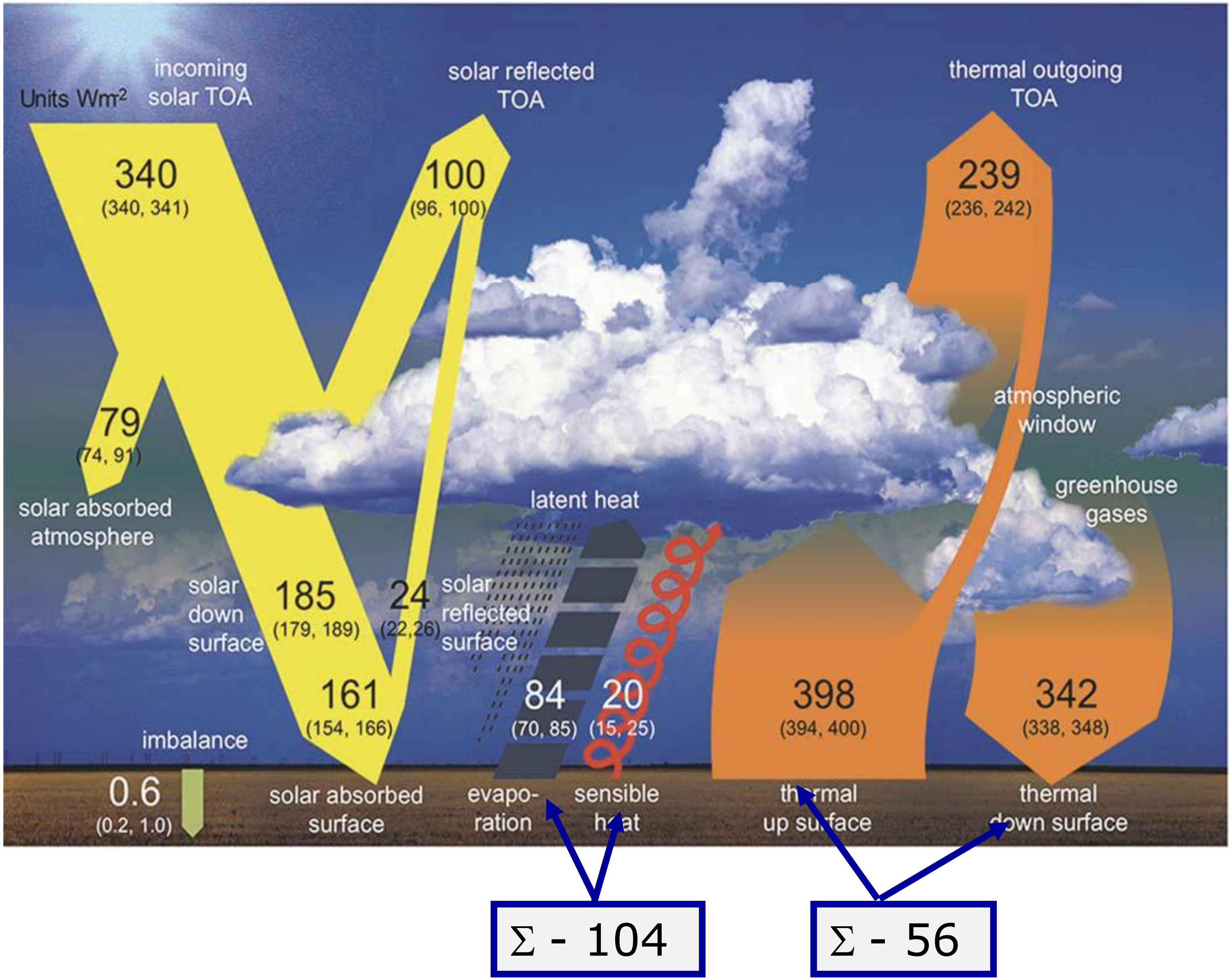
- Lowest part of the atmosphere that controls the exchange of heat, moisture, momentum etc at the surface interface
- Depth varies between O(m) and O(km)
- Always turbulent
- Characteristics, diurnal cycles and strong vertical gradients

Climate system

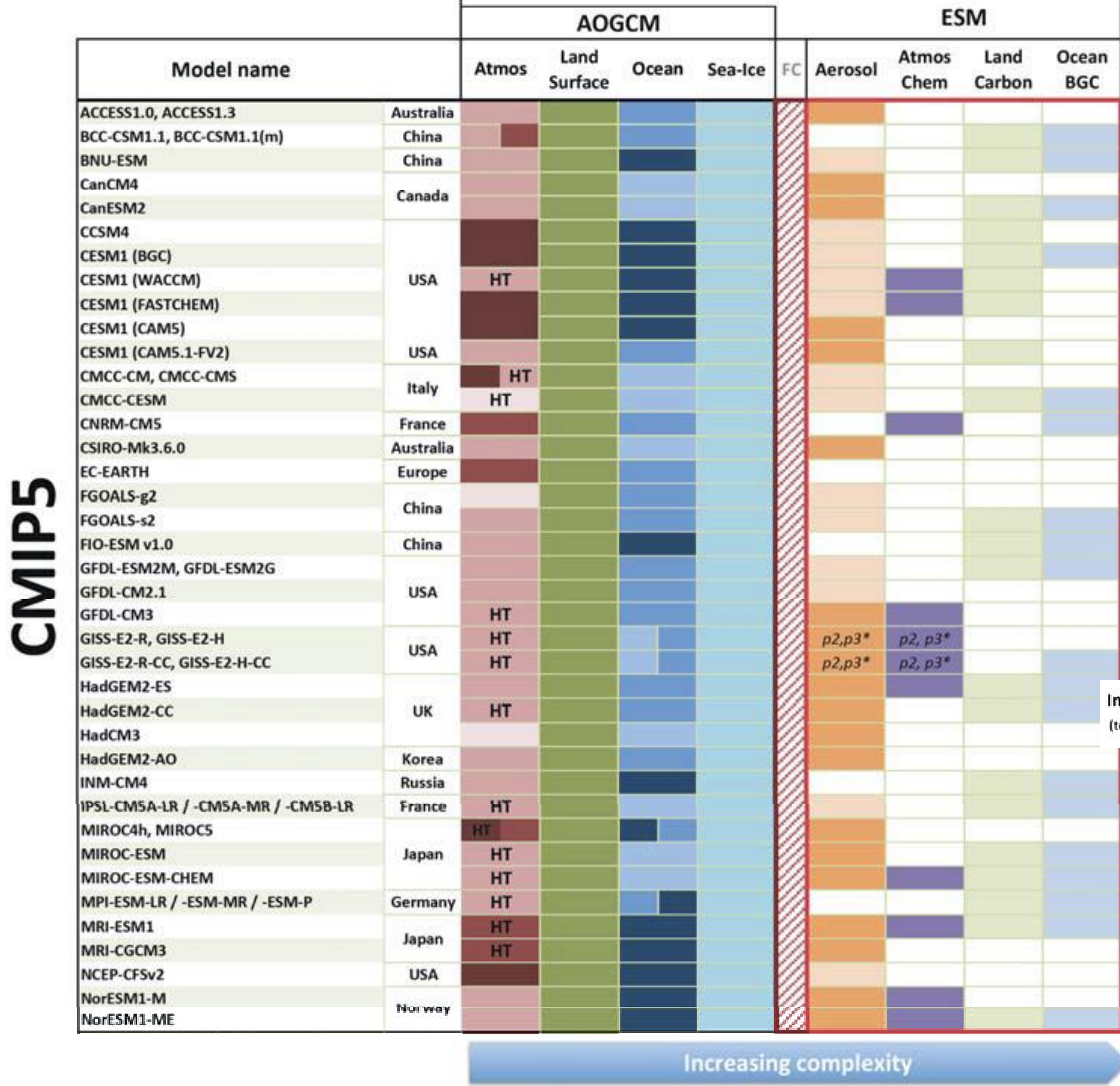


IPCC, 2013

Climate system



IPCC, 2013



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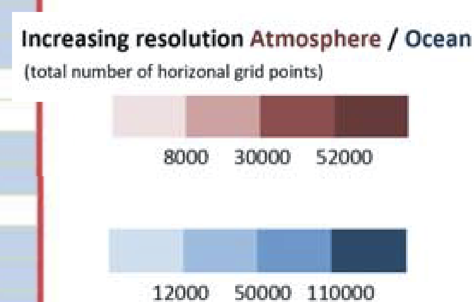
Coupled Model Intercomparison Project Phase 5 (2010 – 2011)
CMIP5 data federated archive:
>3 PB

Phase 6 (2016 – 2020)
CMIP6: **>150 PB**



18-95 vertical levels

CMIP5 model evaluation

T_{2m} (1980-2001)

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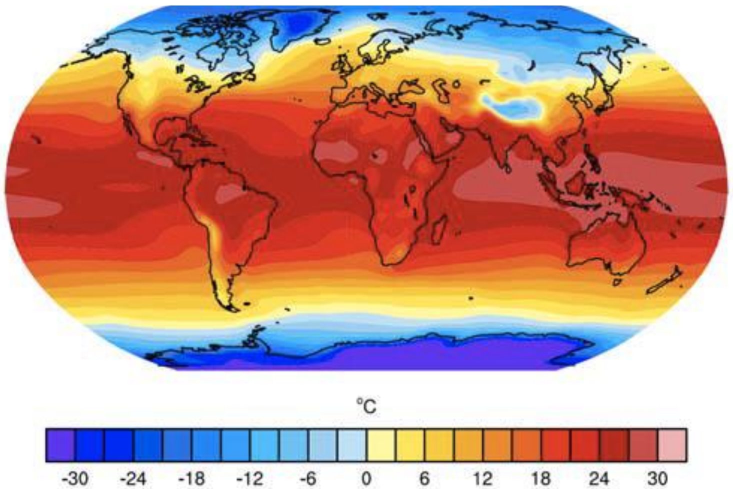
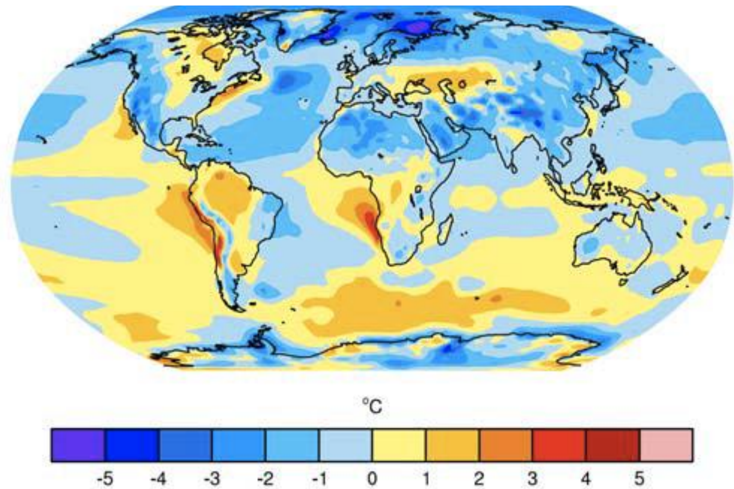
Multi-model mean

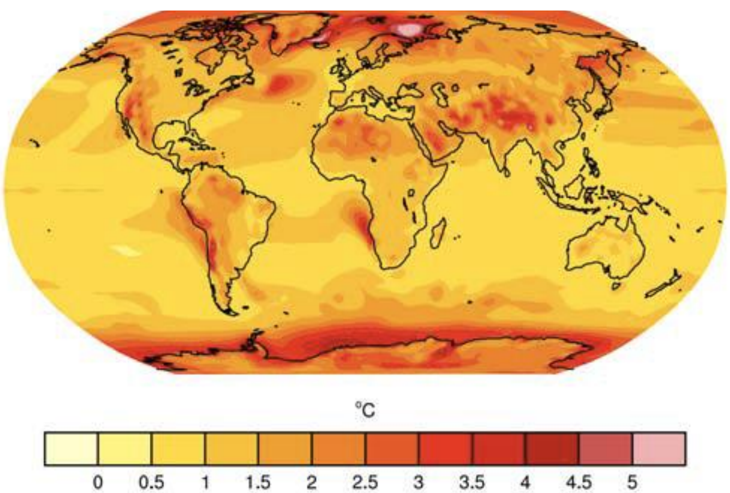


Multi-model mean bias

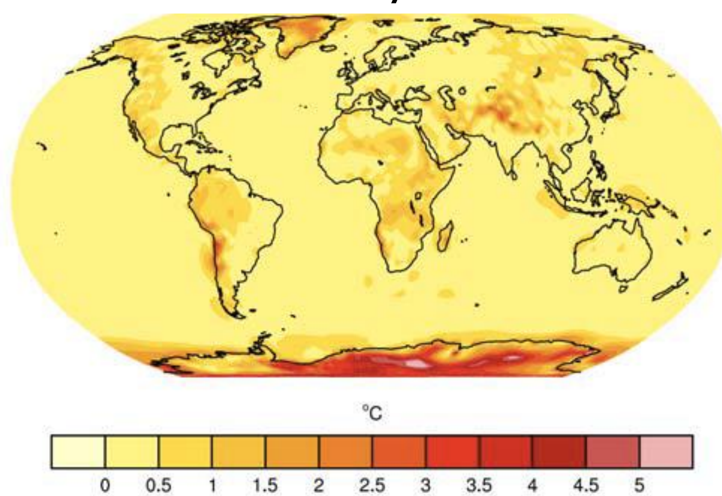


ERA-Interim

Multi-model mean of absolute error

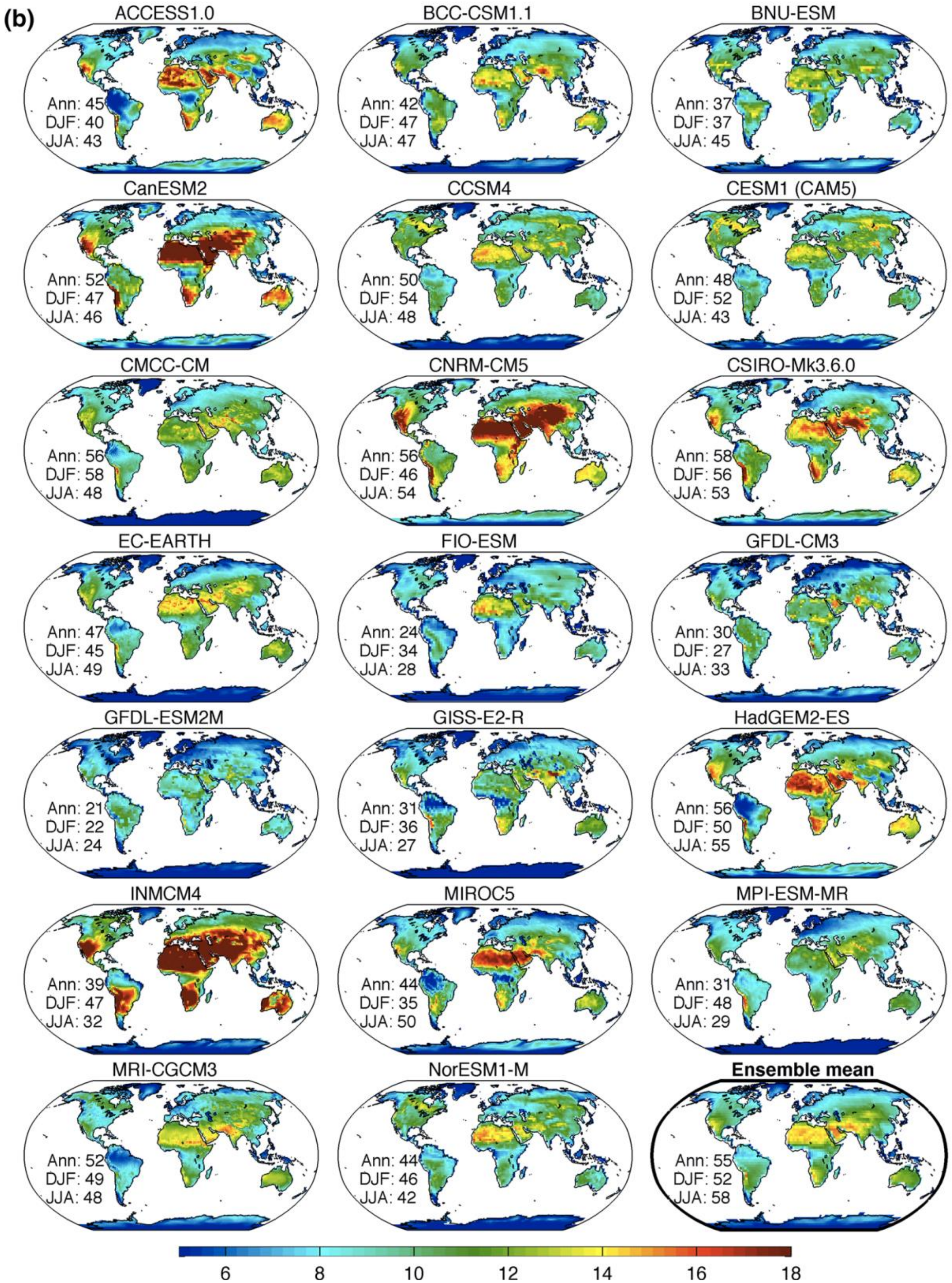


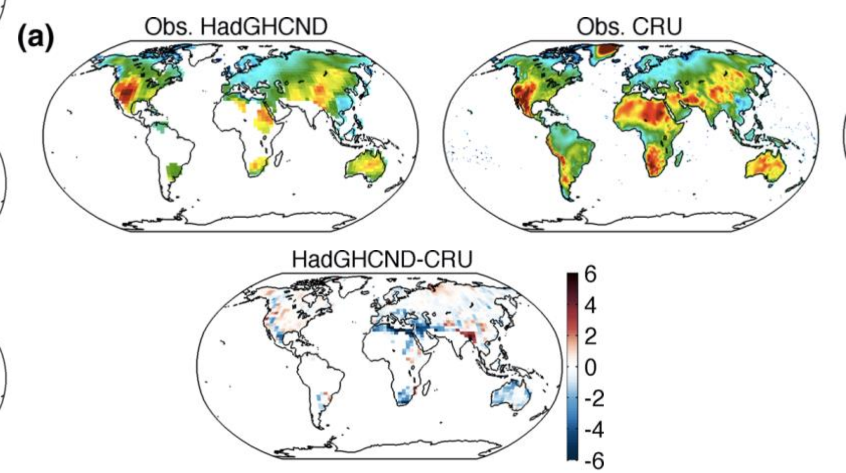
Mean reanalysis inconsistency



ERA-Interim
ERA-40
JRA-25

CMIP5: Diurnal temperature range T_{max}-T_{min}

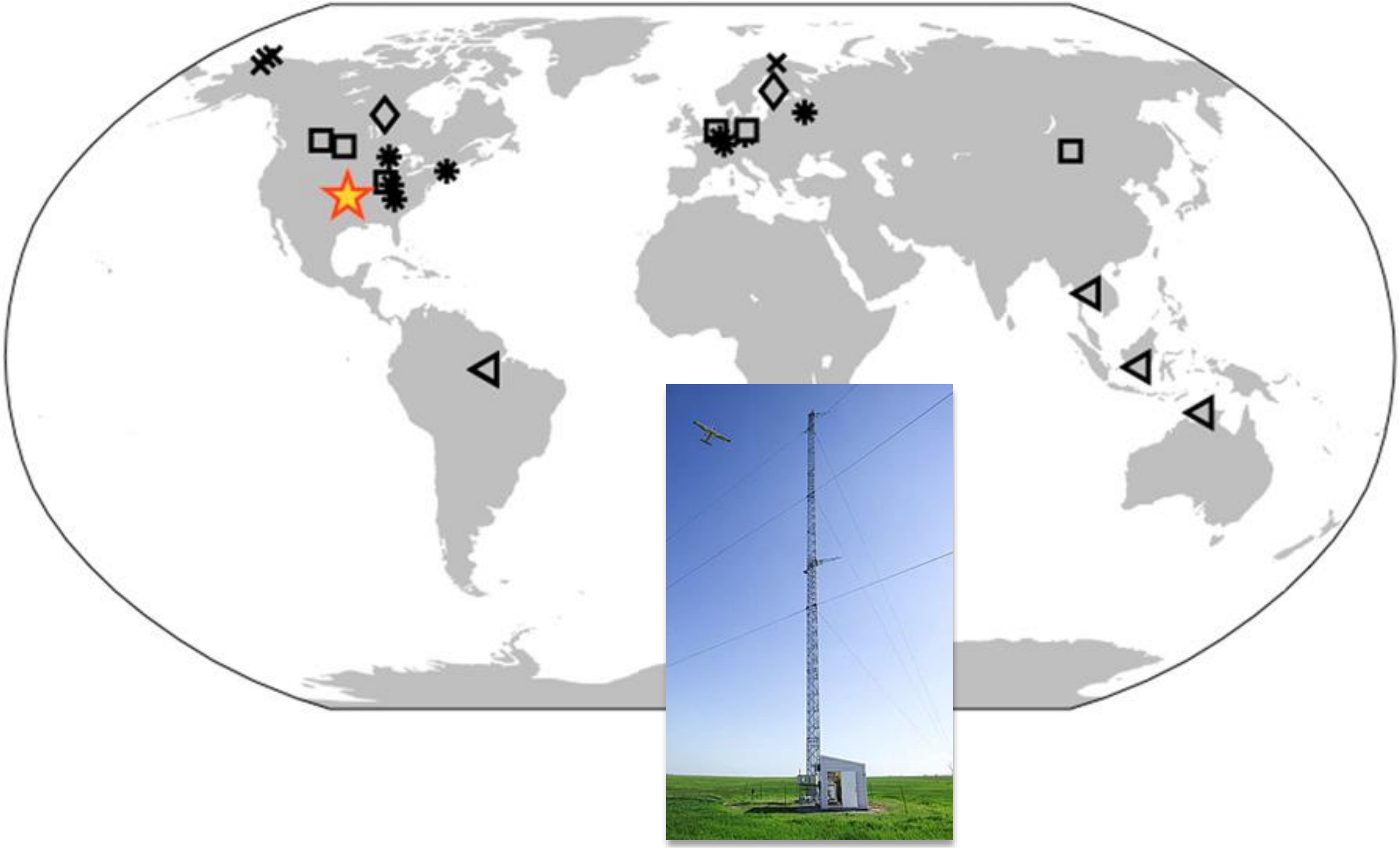




(Lindvall and Svensson 2014)

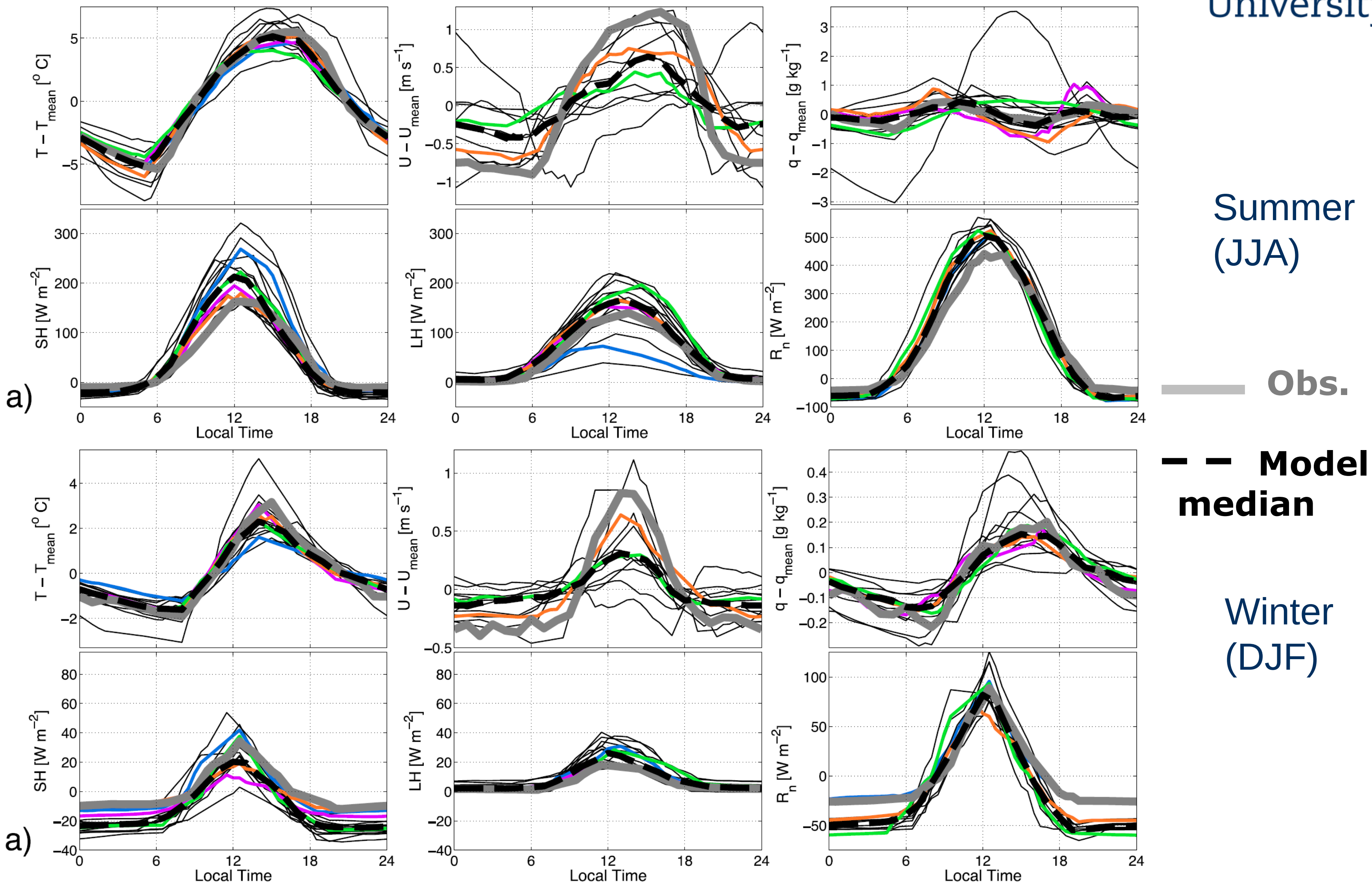
Evaluation of CMIP5 models

Carbon flux network, 26 sites used here
Long-term surface flux observations



(Svensson and Lindvall 2015)

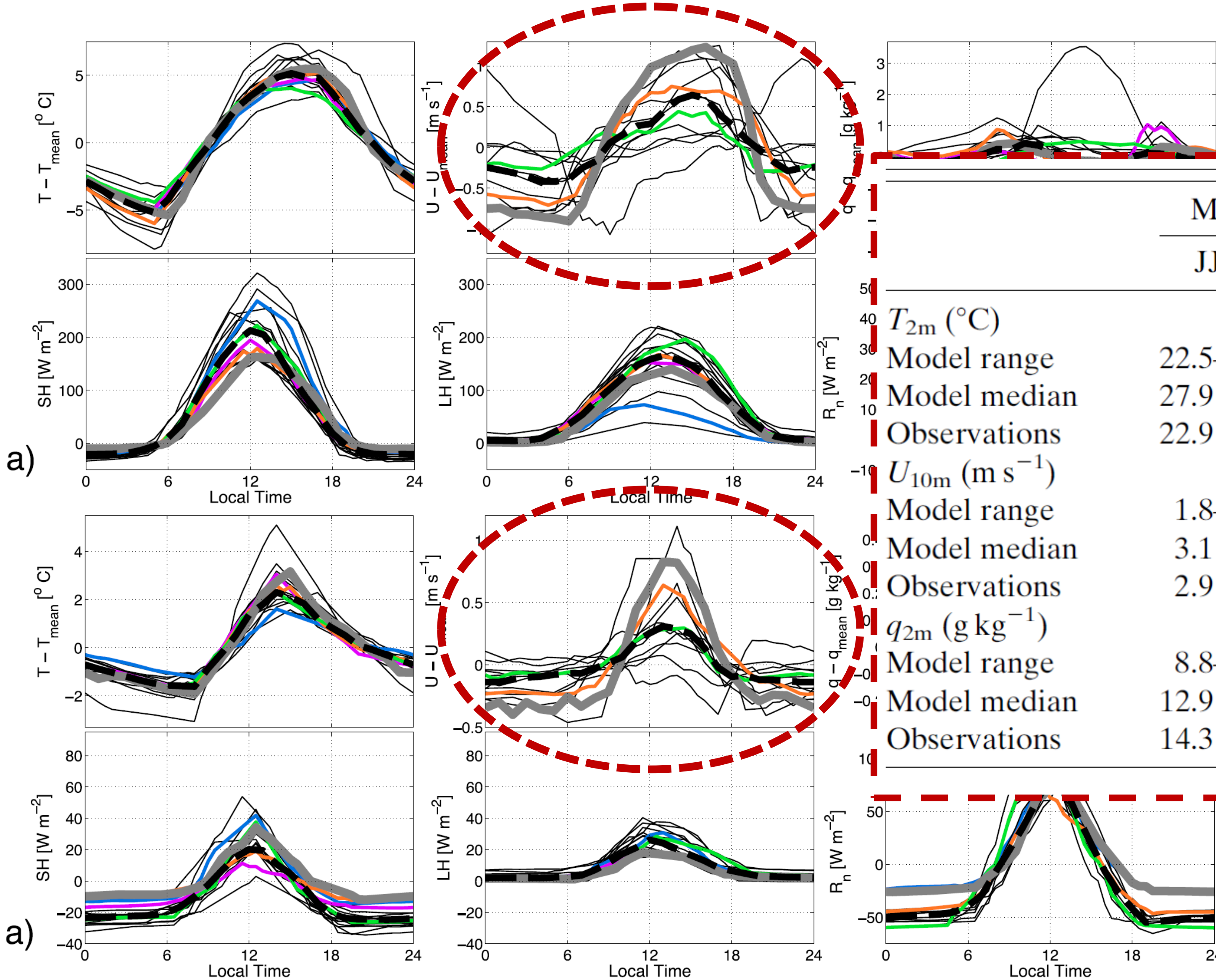
Evaluation of CMIP5 models
Diurnal cycle, midlatitude grassland, 7 sites



(Svensson and Lindvall 2015)

Evaluation of CMIP5 models

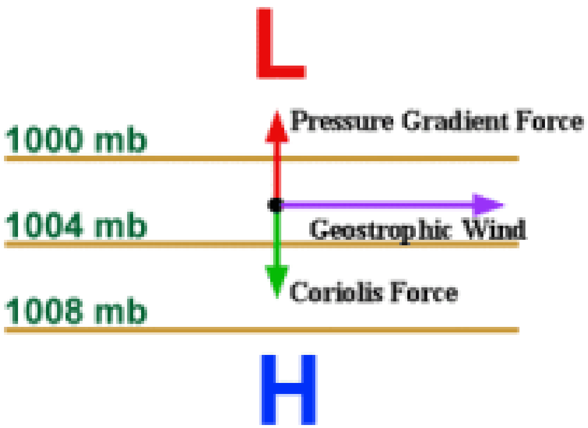
Diurnal cycle, midlatitude grassland, 7 sites



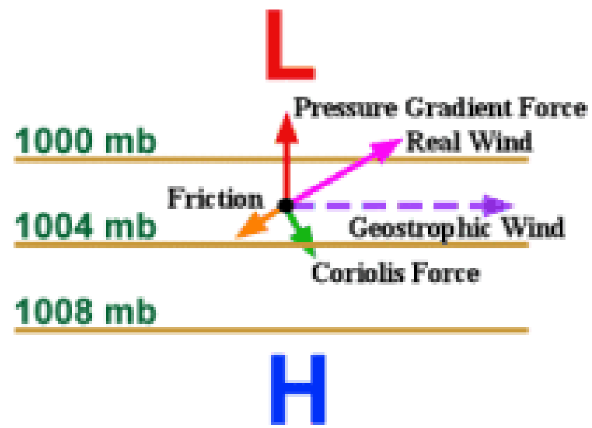
	Midlatitude grassland	
	JJA	DJF
T_{2m} (°C)		
Model range	22.5–32.2	−2.5 to 1.4
Model median	27.9	−1.3
Observations	22.9	−0.68
U_{10m} ($m\,s^{-1}$)		
Model range	1.8–6.4	2.8–7.5
Model median	3.1	4.5
Observations	2.9	4.9
q_{2m} ($g\,kg^{-1}$)		
Model range	8.8–17.8	2.3–3.7
Model median	12.9	2.6
Observations	14.3	3.2

(Svensson and Lindvall 2015)

PBL winds



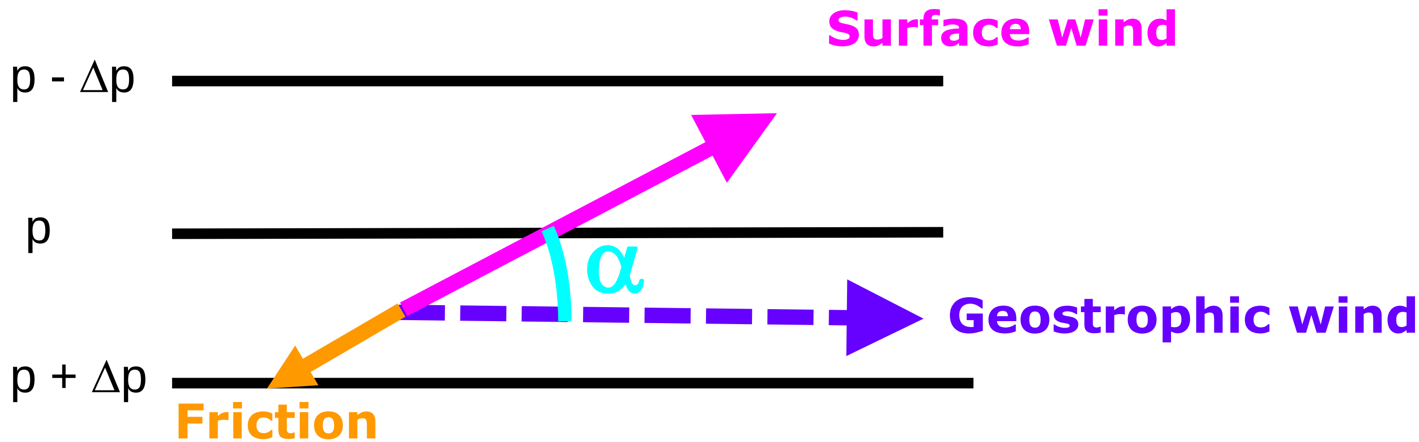
Above the PBL



In the PBL

PBL winds are ageostrophic

Cross-isobaric angle



$$\vec{\boldsymbol{\tau}}: \left(\tau_x, \tau_y\right) = \left(-\overline{u'w'}, -\overline{v'w'}\right)$$

What determines the cross-isobaric angle (α) and the magnitude $\tau = \sqrt{\left(\tau_x{}^2 + \tau_y{}^2\right)}$ of the friction?

PBL in climate & NWP models

parameterizations: turbulence models

The boundary-layer surface stress vector is provided by similarity theory (e.g. Monin-Obukhov theory), assuming a constant flux layer, relating the gradients from the lowest model level to the surface fluxes, corrected by stability functions using stability parameter Monin-Obukhov lenght (z/L) or Richardson gradient number

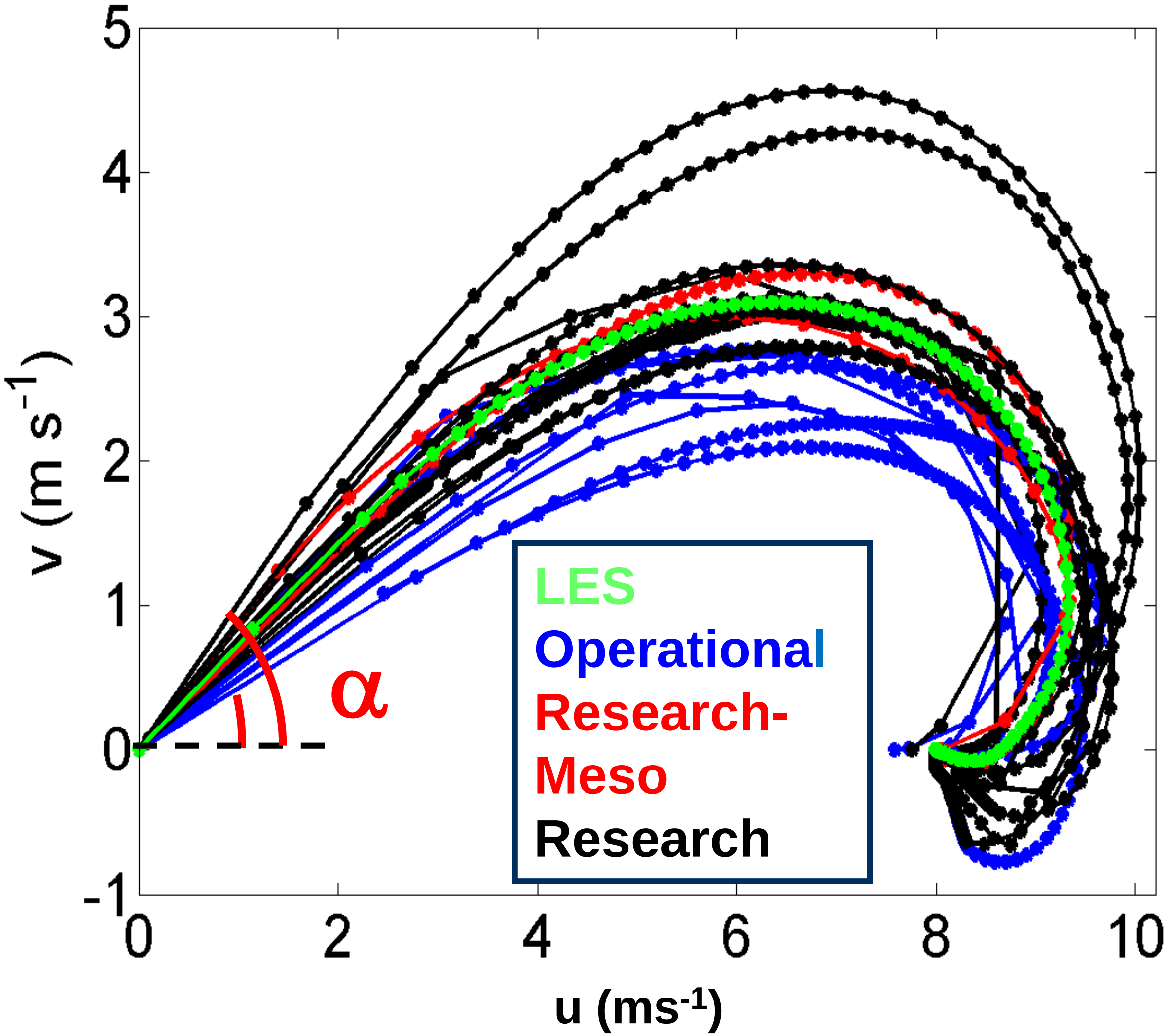
Stability functions are determined from carefully designed experimental campaigns

Lack of global wind observations to constrain models:

- over ocean scatterometer observations provide estimates of the near surface wind
- over land at midlatitudes, reanalysis constrained by radiosoundings using geostrophic (mass – flow) balance

GABLS1

PBL scheme intercomparison



LES: 36°

Operational models: 23 – 36°

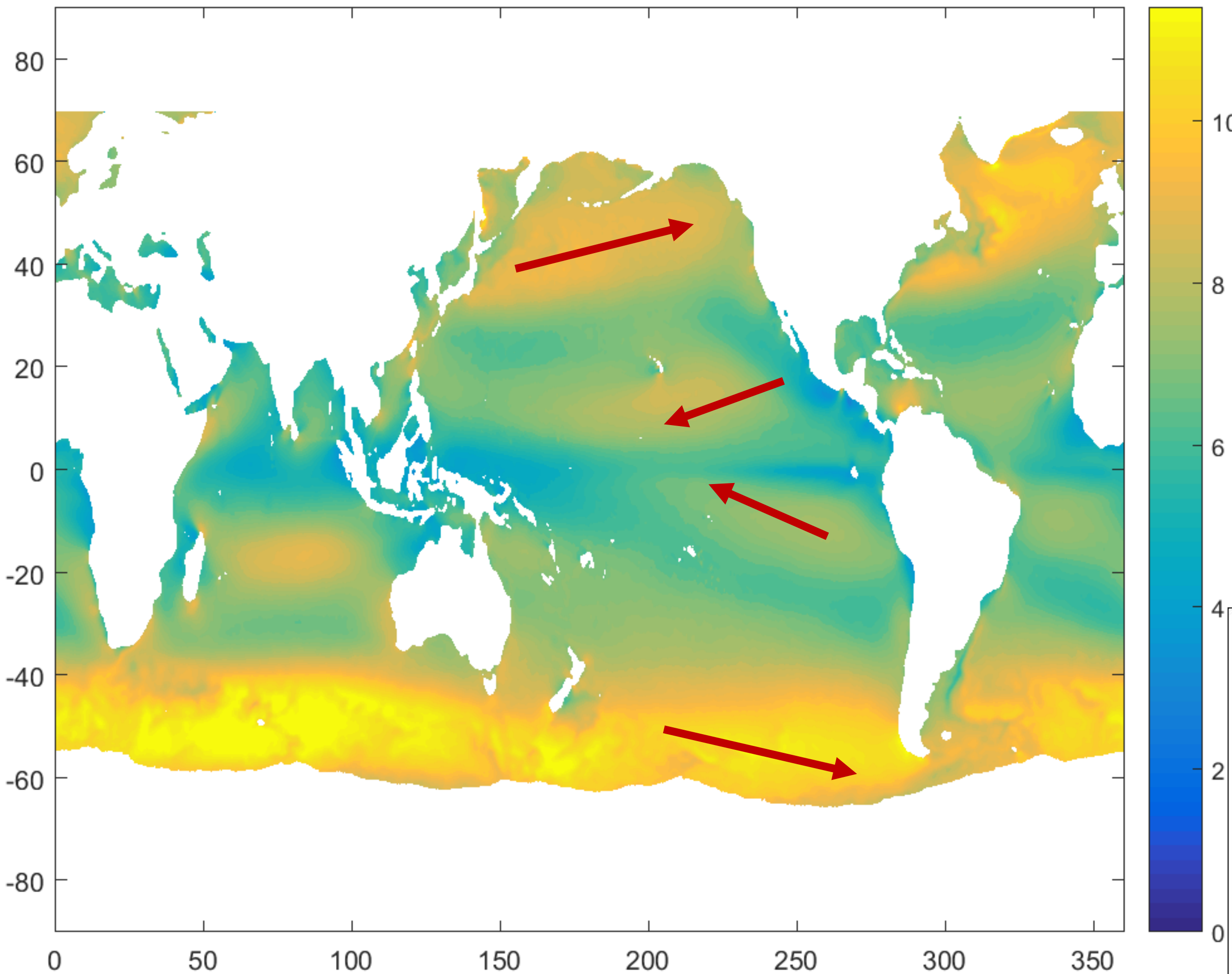
Research models: 27 – 46°

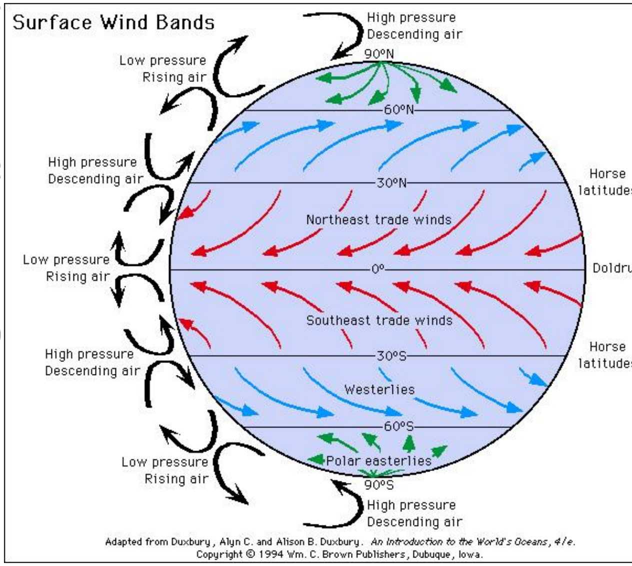
(Ekman spiral: 45°)

(Cuxart et al.2006; Beare et al. 2006; Svensson and Holtslag 2009)

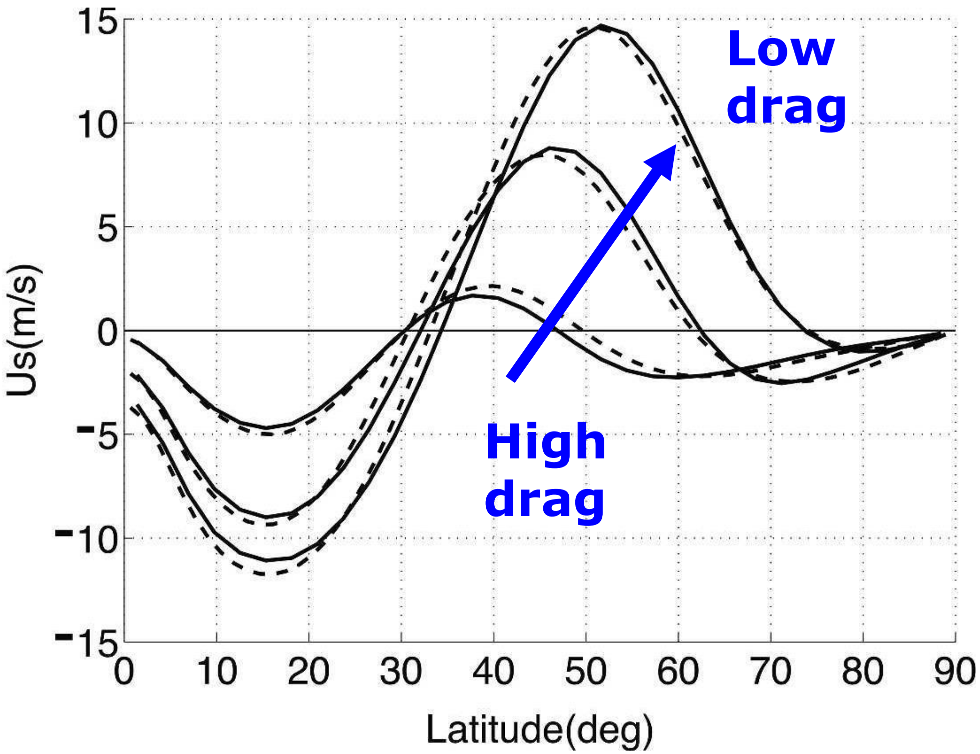
Satellite observations of wind
10-m wind speed (m s^{-1})

Stockholm University





Idealized global experiments

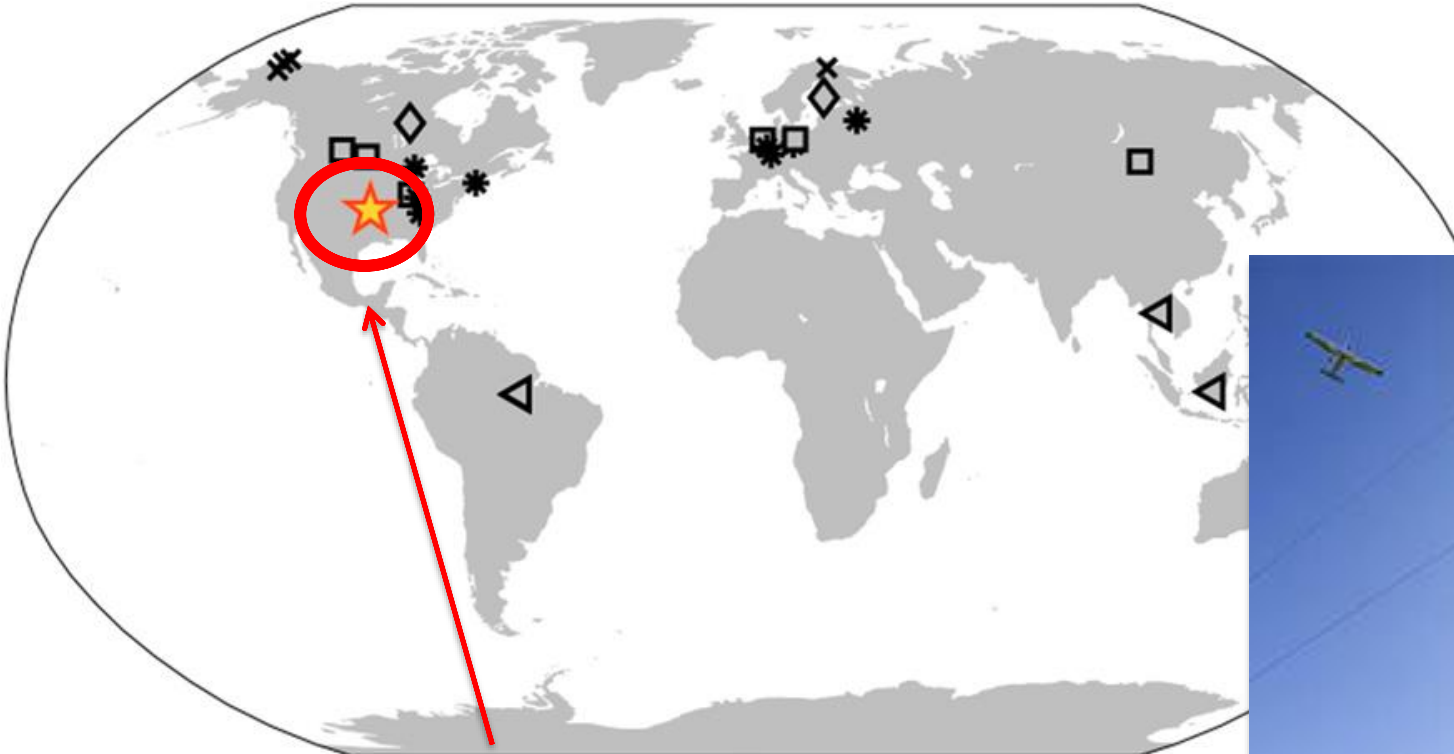


In idealized AGCMs, surface jet strength and latitude are highly sensitive to surface drag, via feedback on baroclinic eddies

Chen et al., 2007

ARM Southern Great Plains site

Stockholm University

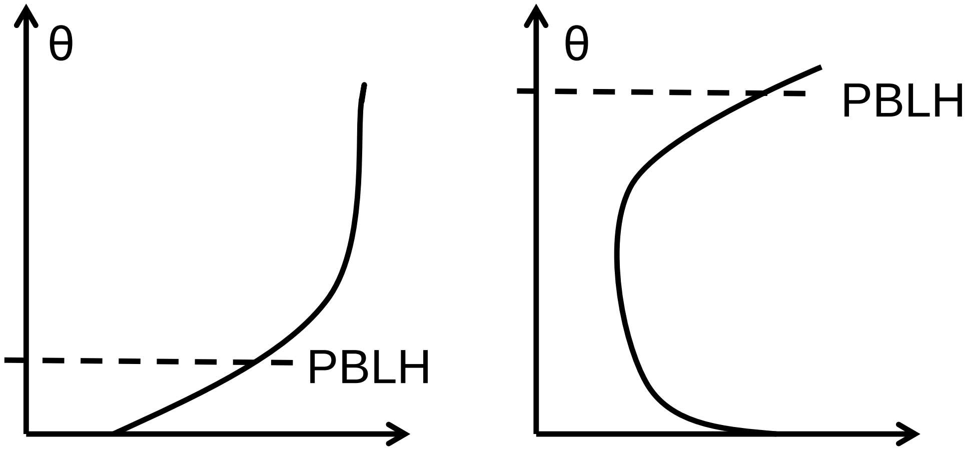


ARM Southern Great Plains site

Six years of measurements
Radiosondes are released four times daily

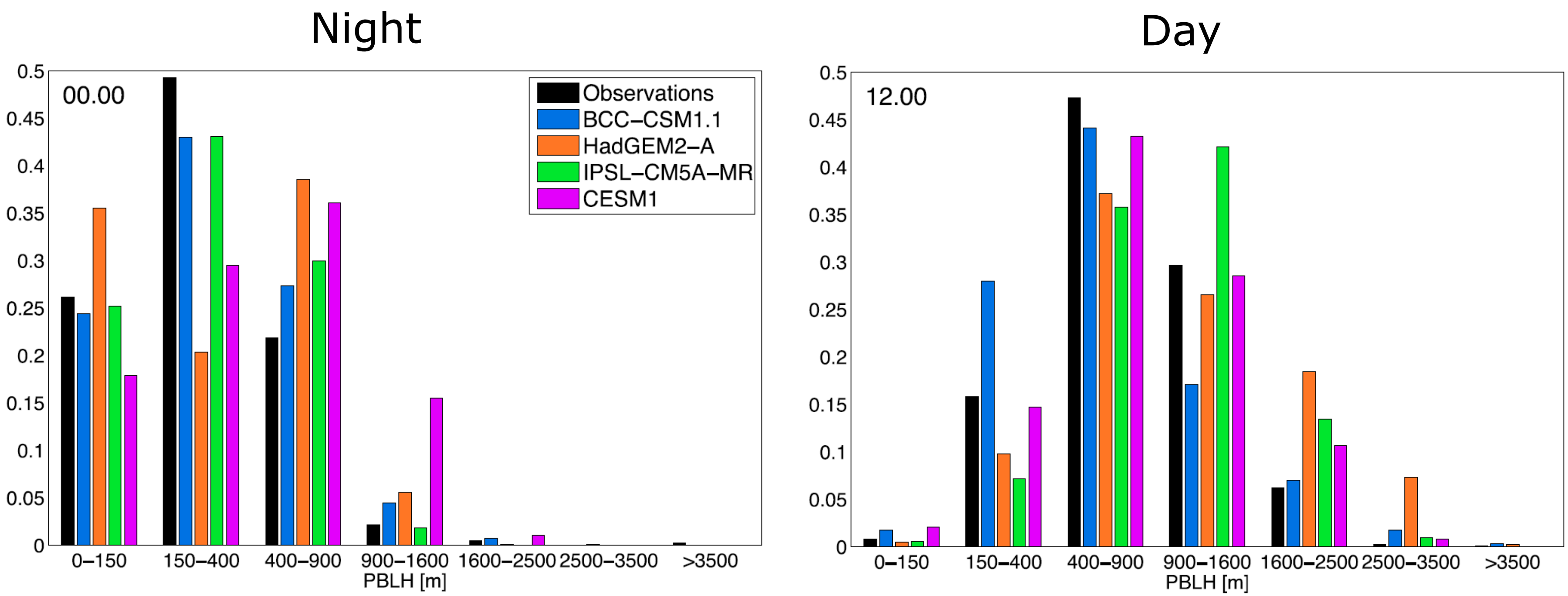
PBL depth estimation

- Diagnosed using a bulk Richardson number (finding first level where $Ri_{bulk} > 0.25$ or 0.30)
- When possible, use friction velocity to improve the estimate following Vogelezang and Holtslag (1996)
- For a fair comparison, the same method is used to calculate the PBL depth in the models and observations



Evaluation of CMIP5 models

ARM Southern Great Plane



PBL height (m) overestimated by the models

(Svensson and Lindvall 2015)

Evaluation of CMIP5 models

Vertical structure, Southern Great Plains

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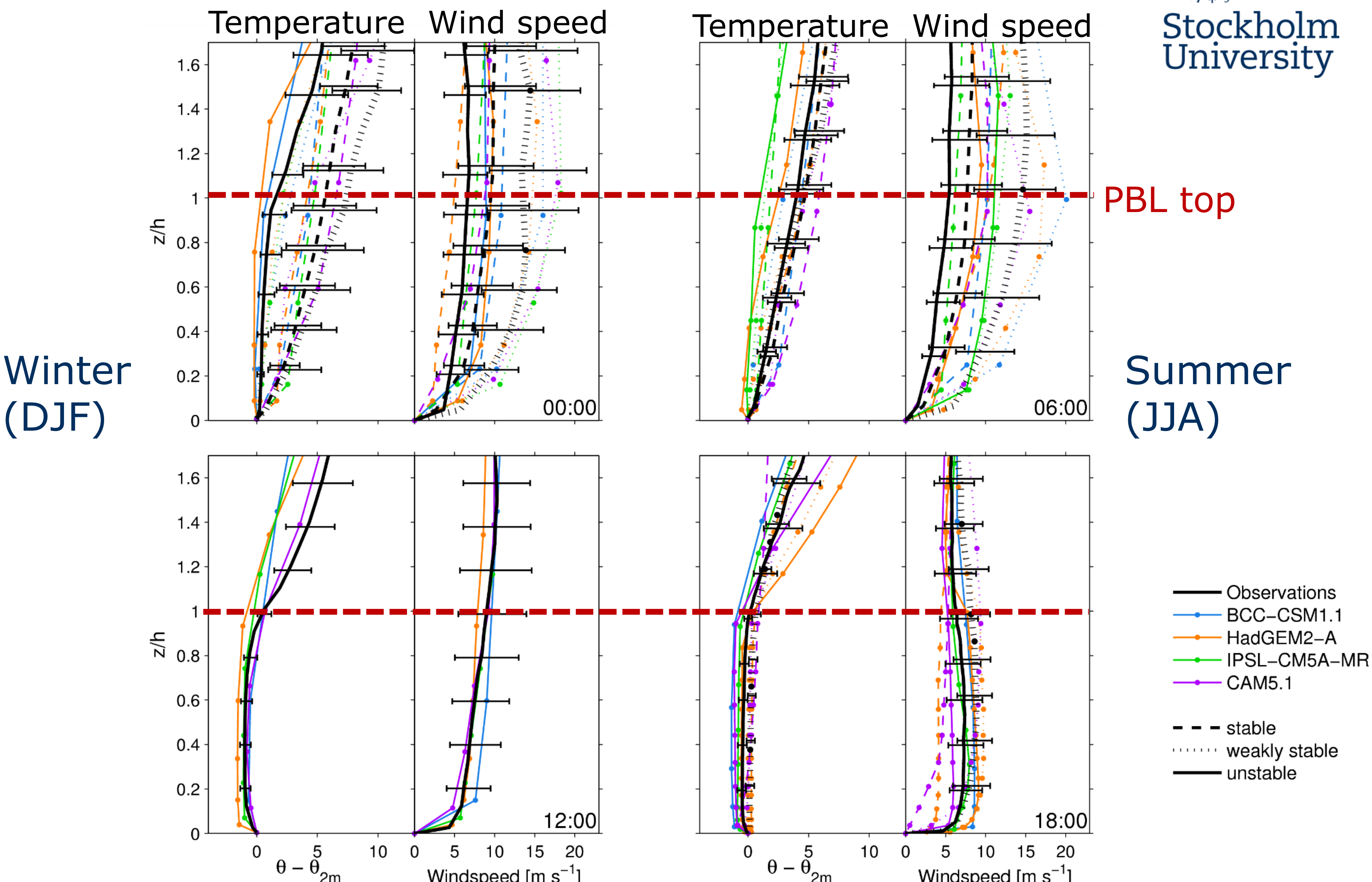

(Svensson and Lindvall 2015)

NWP models
Tricks to improve circulation in weather forecasts

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Long-tail functions - enhanced mixing in stably stratified conditions

- Increase PBL depth
- Increased heat fluxes
- Biases include too strong surface winds and warm bias
- Mixes out gradients e.g. Low-level jets are damped

Rotating the surface stress angle – results in more ageostrophic flow in the PBL

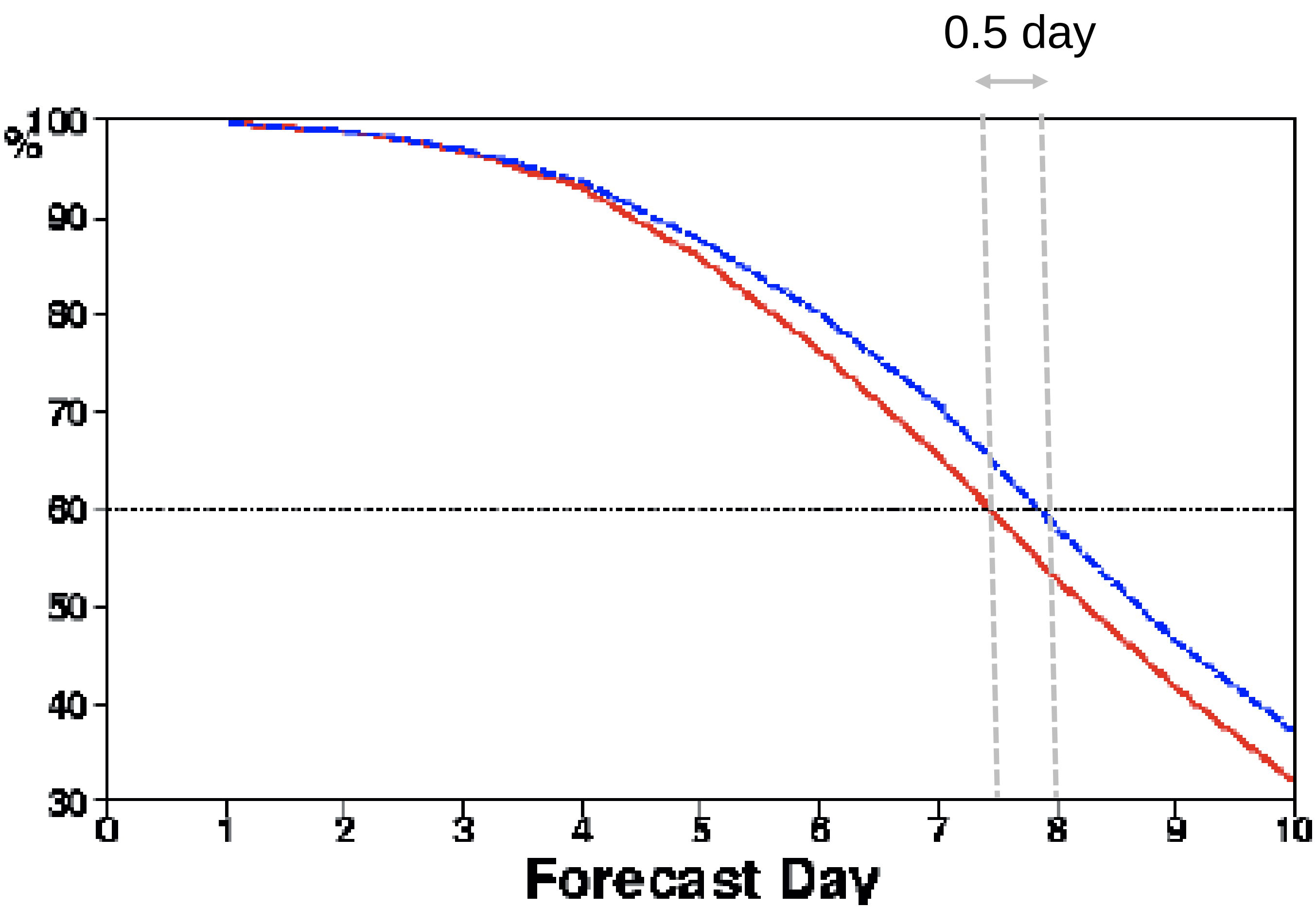
- Magnitude of stress is not changed
- Heat fluxes not changed
- Not consistent with constant flux layer theory

In addition, enhanced surface roughness is often used to account for sub-grid orography (or an alternative parameterization is used)

These methods improve the weather forecast but not necessarily the PBL structure!

Global forecast model

Stability functions affect the large scale forecast scores



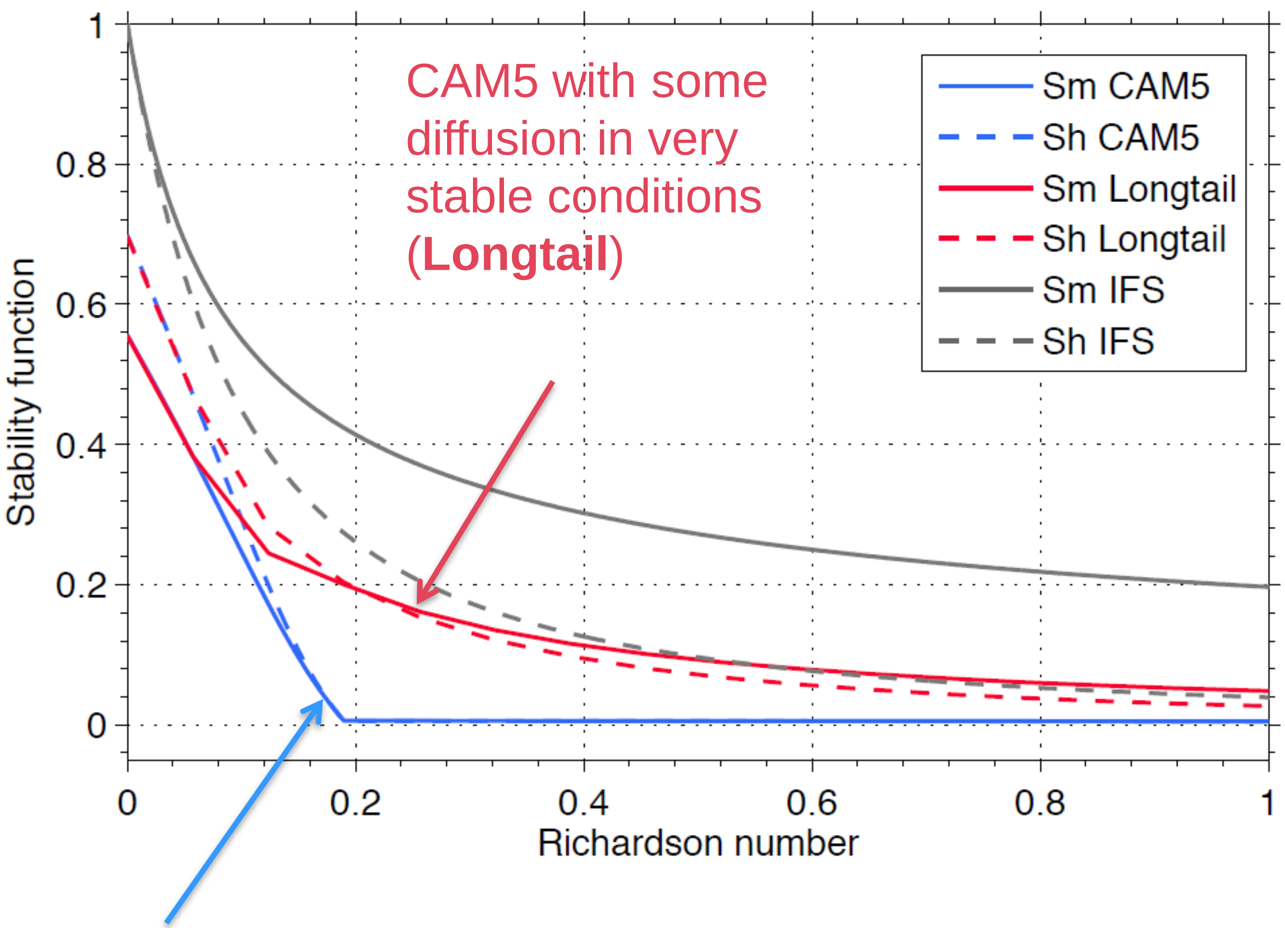
Effect of MO-stability functions (reduced diffusion) instead of operational formulation, on 500hPa NH height scores

ECMWF IFS Courtesy A. Beljaars

Experiments in CAM5.3

10-year AMIP-type experiments

Stockholm University



Default CAM5 (**CONTROL**)
No atmospheric turbulence when Ri > 0.19

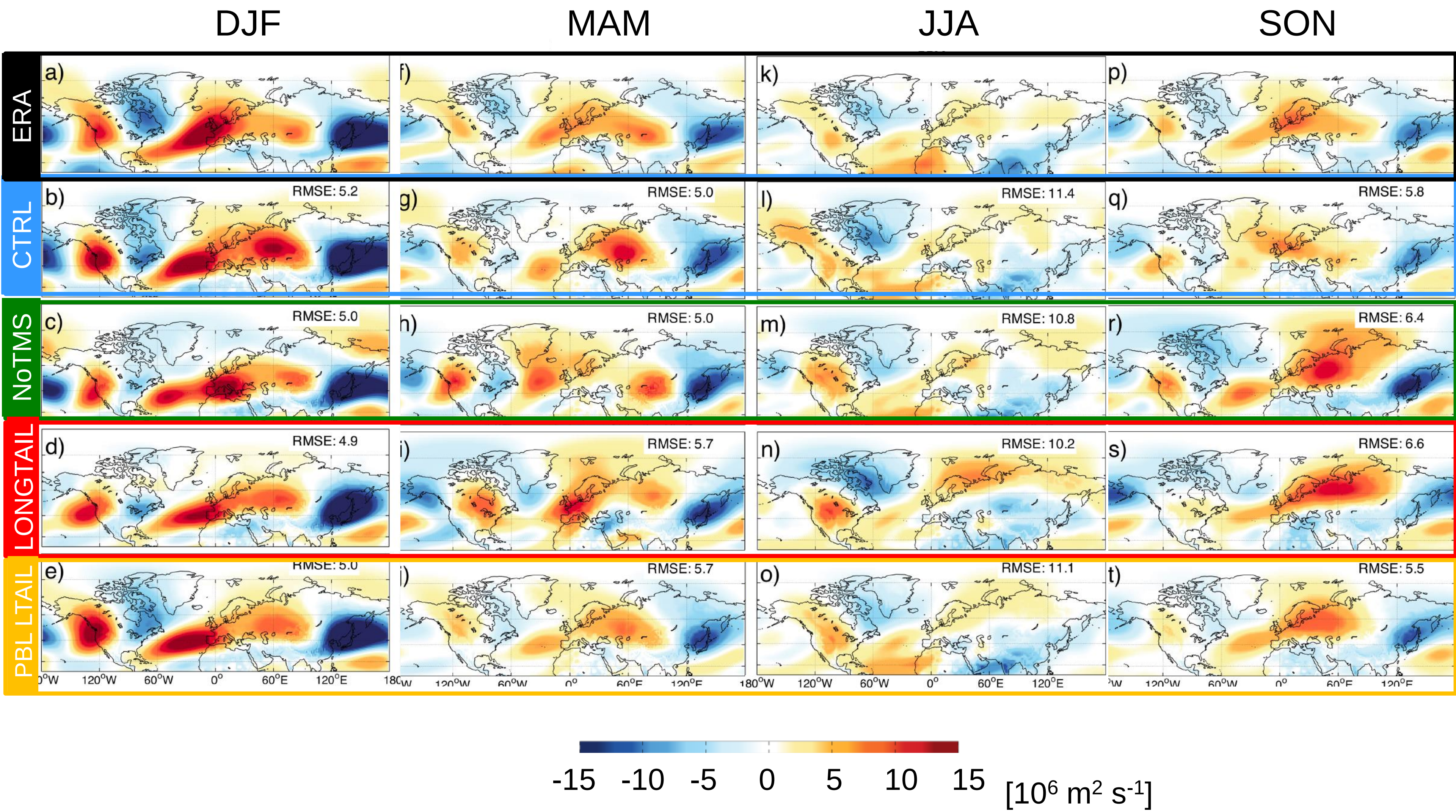
1 degree resolution
&
30 vertical layers

PBL scheme:
Bretherton and Park, (2009)

Land model use long-tail functions

(Lindvall, Svensson and Caballero, 2016)

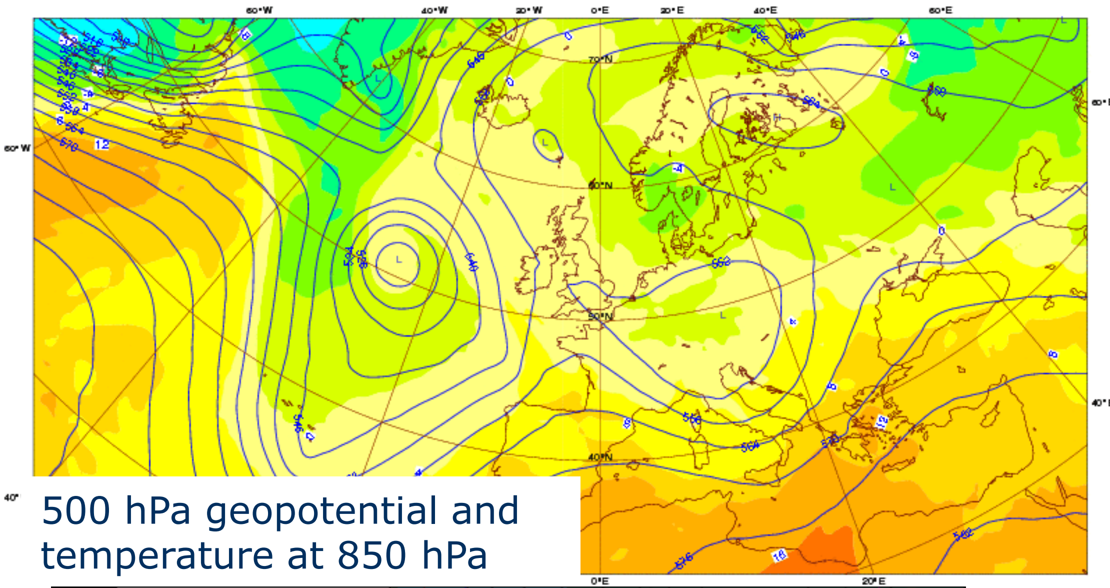
Zonal anomaly of the 500hPa streamfunction



(Lindvall, Svensson and Caballero, 2016)

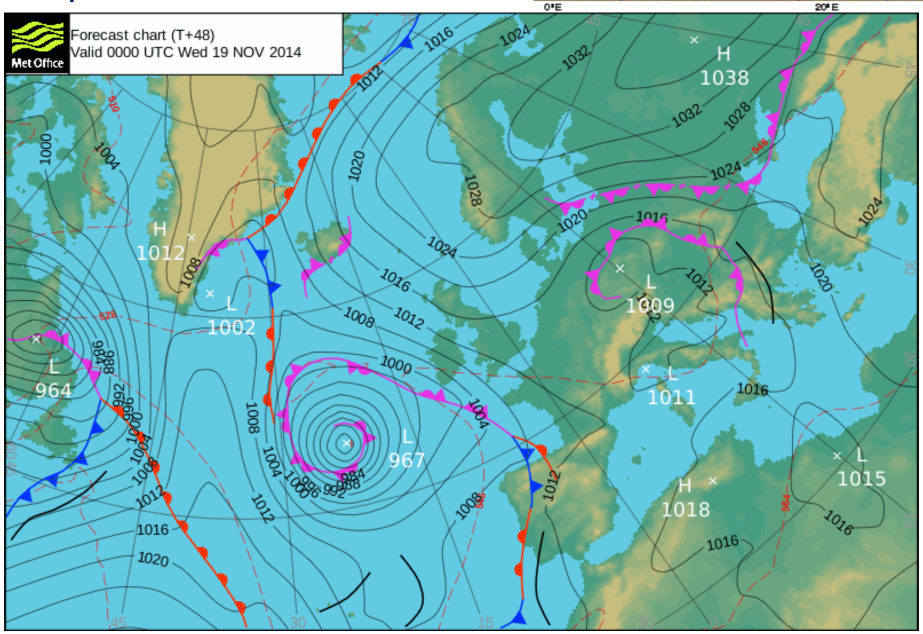
Atmospheric blockings

00:00 UTC, November 19, 2014



500 hPa geopotential and temperature at 850 hPa

ecmwf.int



metoffice.gov.uk

Quasi-stationary highs that persist for more than ~5 days

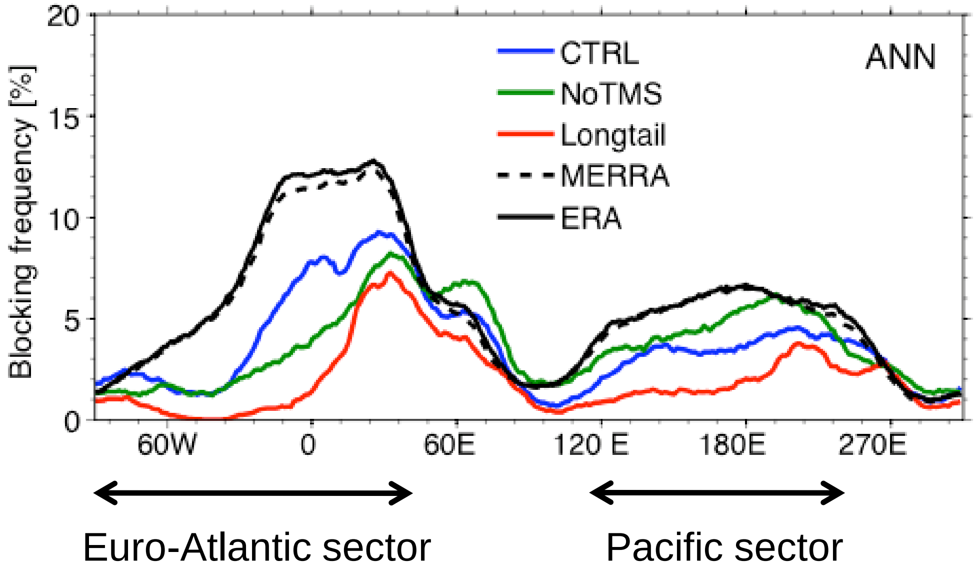
Increase in the meridional energy transport

Anomalies in temperature and precipitation

What will happen with these in a warmer climate?

Atmospheric blocking frequency

All model versions have too few blockings, specially for the Euro-Atlantic sector



Lindvall, Svensson and Caballero, 2016

Atmospheric blocking frequency

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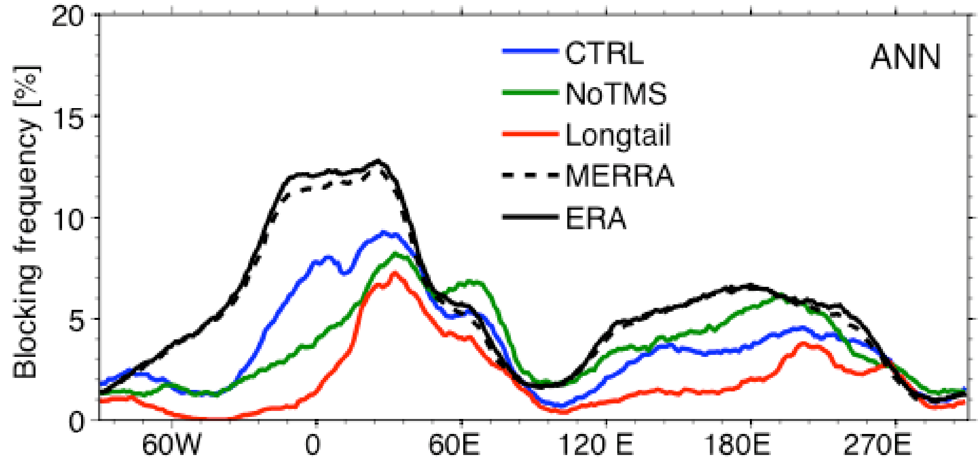
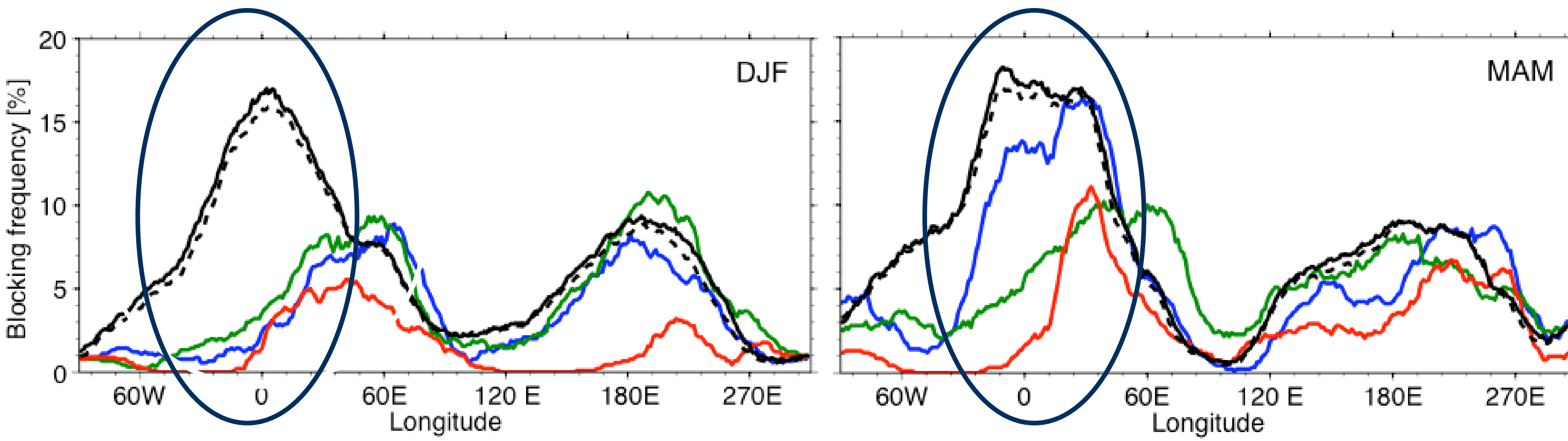
No version captures the Atlantic blockings in winter



Control is closer to observations than both NoTMS and Longtail in spring



CONTROL – With TMS (subgrid scale turbulent orographic drag)
NoTMS - Without TMS (no subgrid scale turbulent orographic drag)
LONGTAIL - Higher diffusivity in stably statitified conditions + no turbulent orographic drag

Lindvall, Svensson and Caballero, 2016

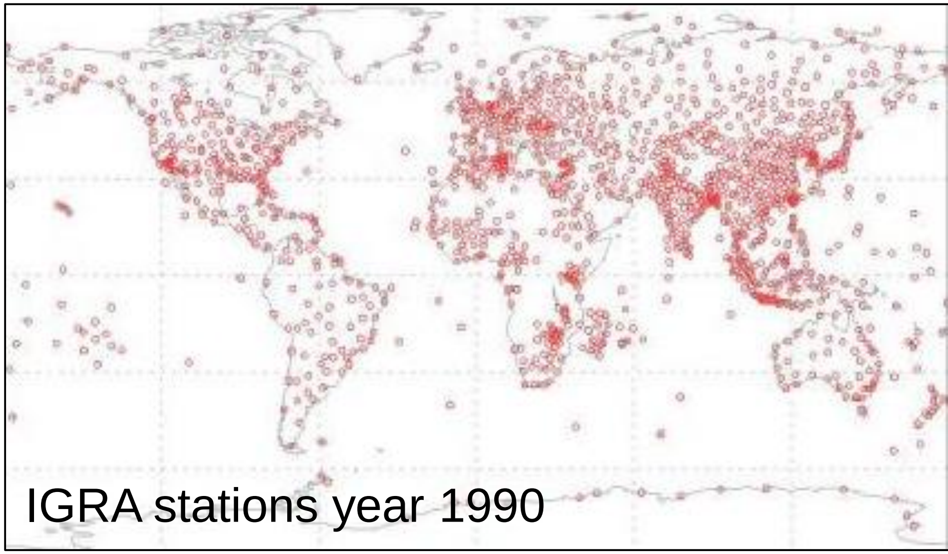
Observations

IGRA

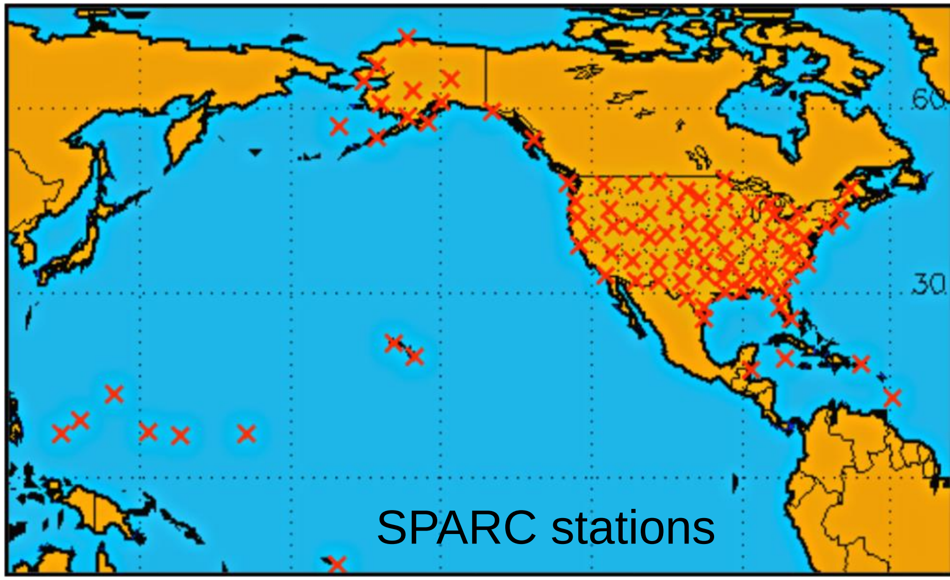
- Soundings at over 1000 locations (681 included)
- Limited vertical resolution
- PBLH from Seidel et al, 2010 (1971-2010)

SPARC

- High vertical resolution (6 or 1 s)
- Fewer points (US only)
- 1998-2011



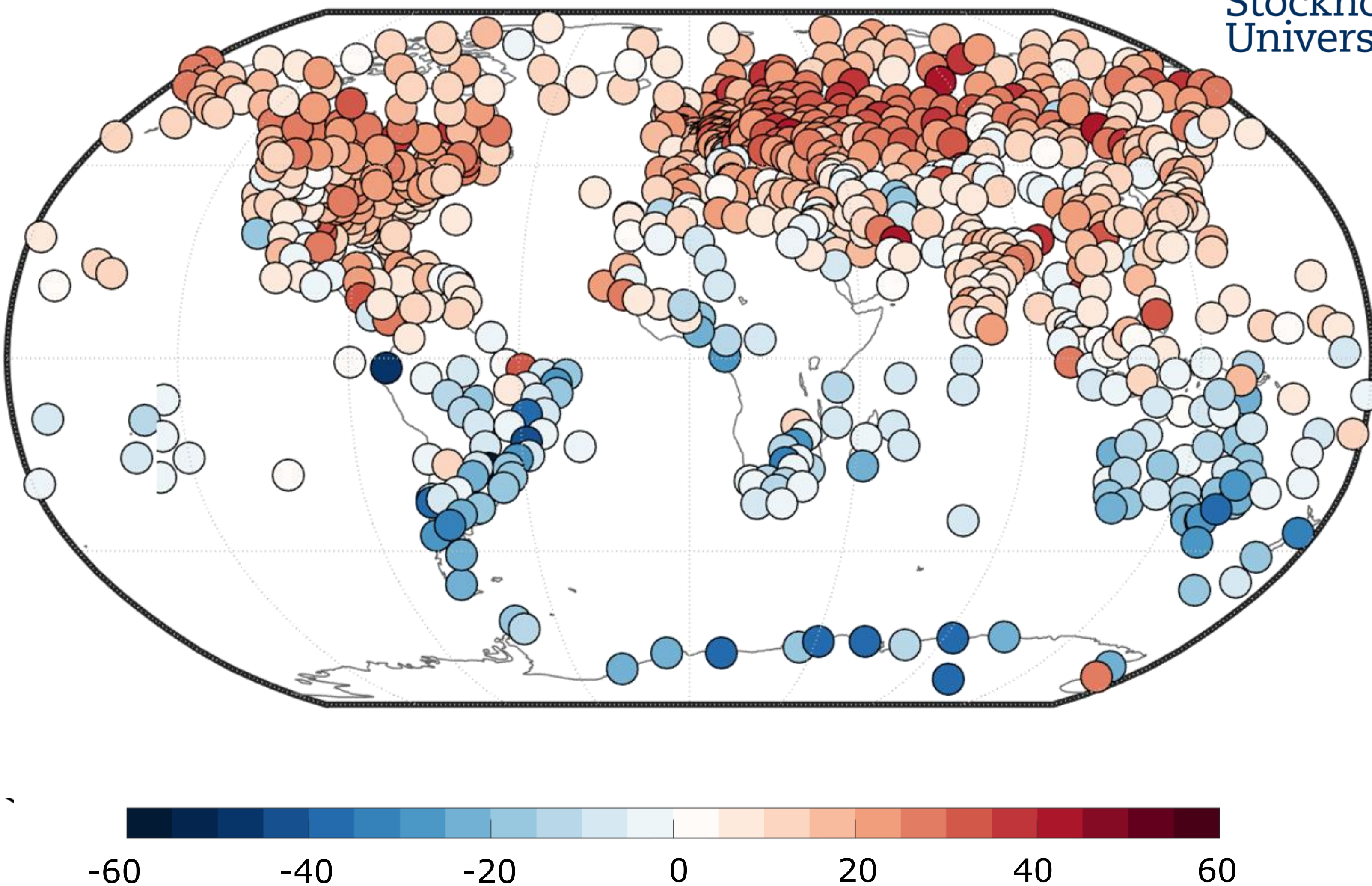
IGRA stations year 1990



SPARC stations

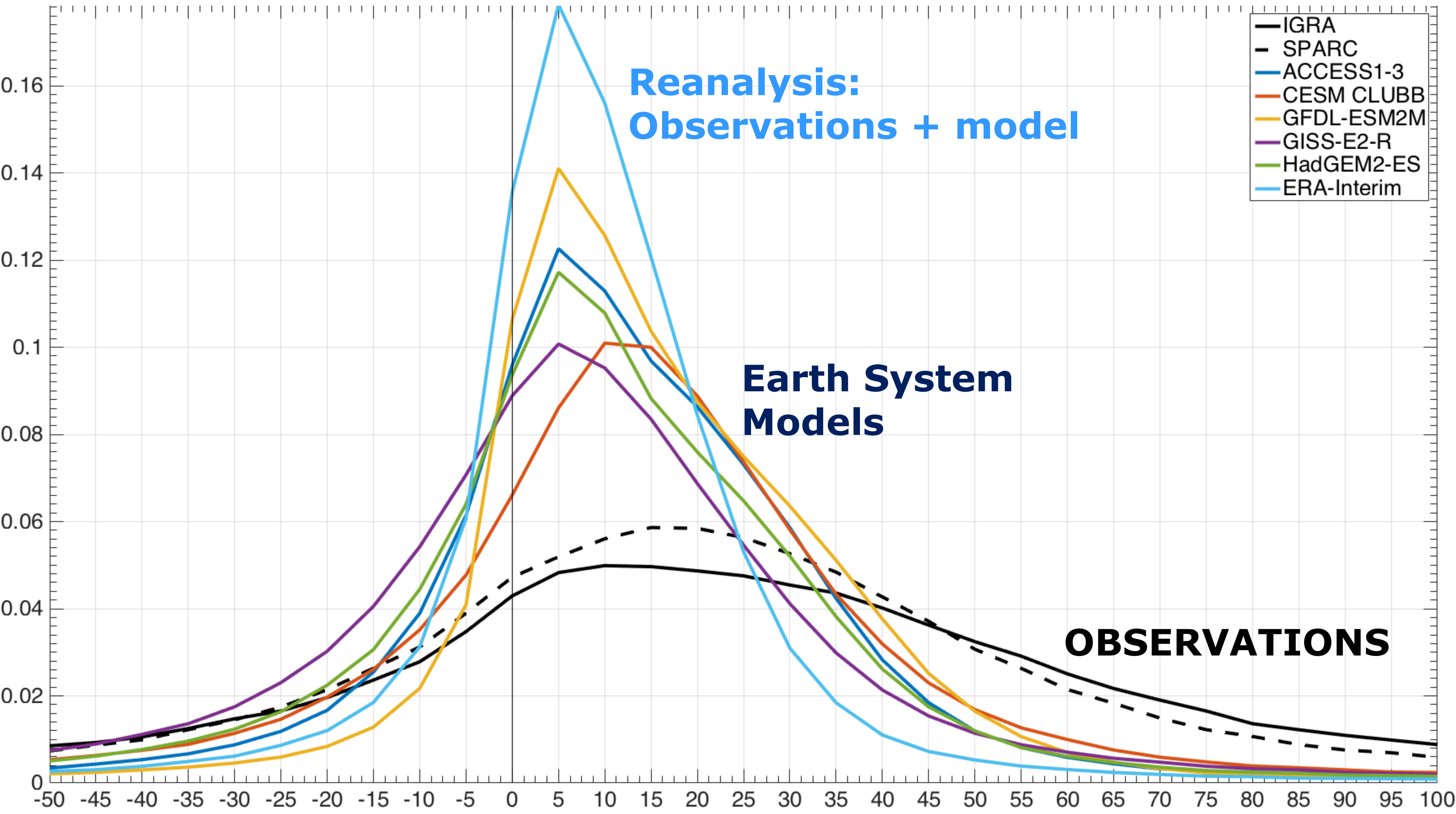
Wind turning over PBL

Annual mean



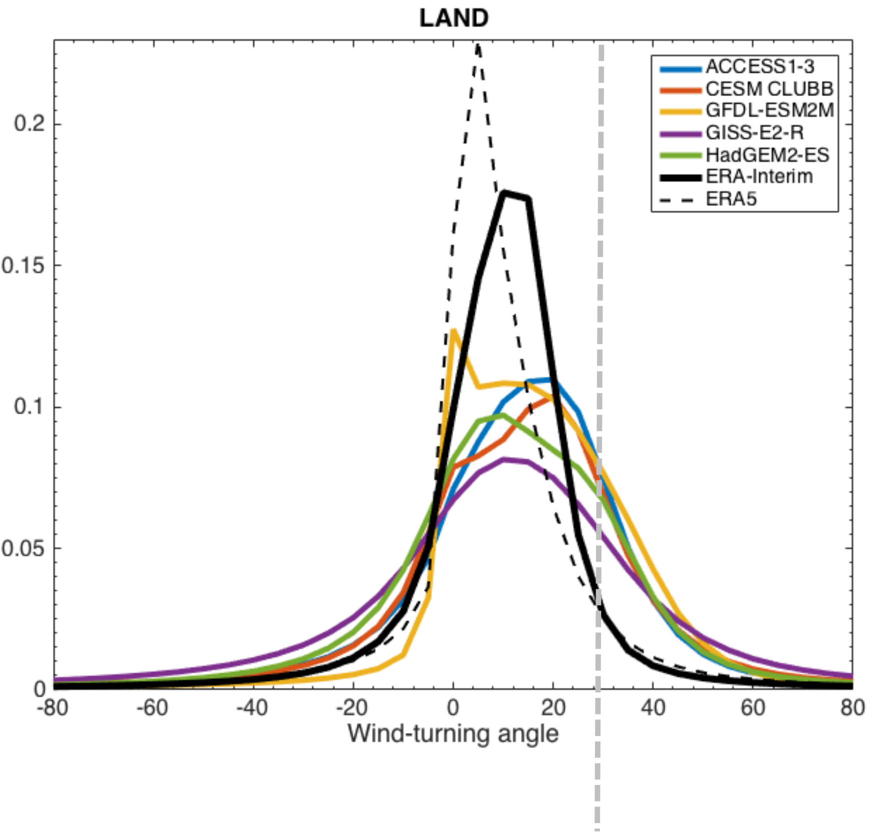
Wind turning at the SPARC sites

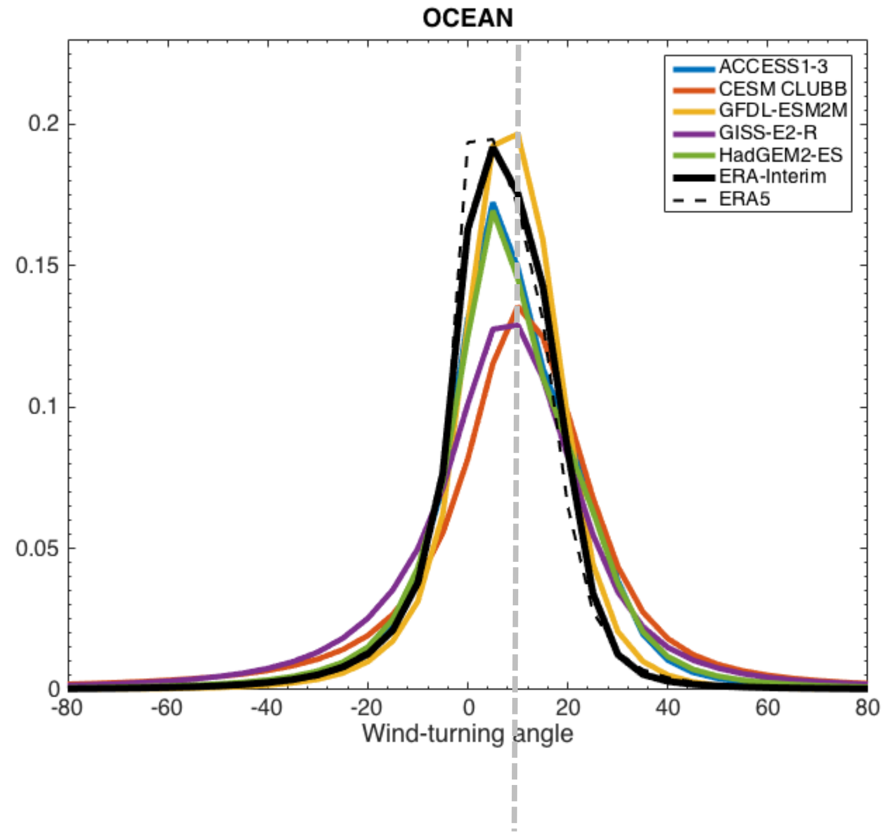
CMIP5 models, CESM(CLUBB) and ERA-Interim
5-years of 6-hourly data



Cross-isobaric angle

Era-Interim and CMIP5 models





Early studies using sounding data

~30 degrees Gray (1969) up to 850 hPa

8-12 degrees Gray (1972) over 1 km

Conclusions

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Evaluation of CMIP5 models:

- Large intermodel spread in diurnal temperature range (DTR) and diurnal cycle of near-surface variables and surface fluxes
- Boundary layer depth is generally overestimated
- Vertical structure of planetary boundary layer is not represented very well;Temperature is generally better represented than winds
- Wind turning over the boundary layer, or cross-isobaric angle, is generally smaller in models and reanalysis products than observations show

CAM5 experiments:

- Large-scale circulation is very sensitive to surface drag
- Difficult to evaluate drag and near-surface wind due to lack of global datasets, cross-isobaric angel could be a useful measure