Duration and size of blocking events: Future changes and impacts on weather extremes

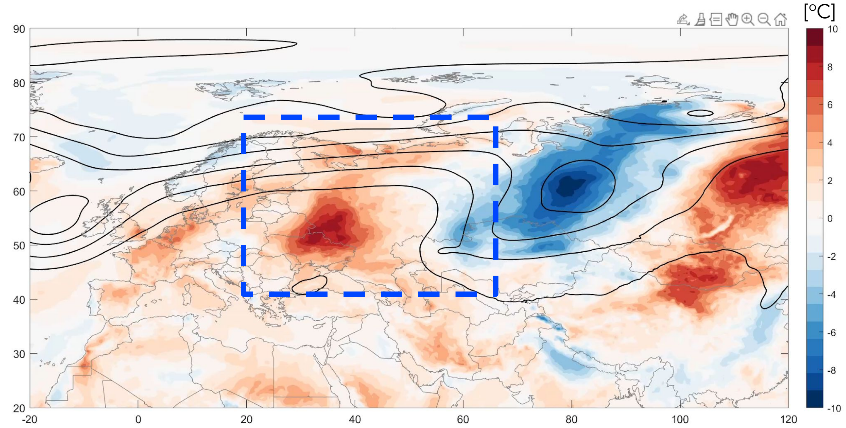
Pedram Hassanzadeh[1], Ebrahim Nabizadeh[2] & Sandro Lubis[3]

[1]University of Chicago, [2]VERSIK Analytics, [3]PNNL

Supported by

Blocking events can drive or exacerbate weather extremes

How will blocking events change as climate warms?



2010
Russian
blocking &
heat wave

55000 deaths
$15B loss

nature
COMMUNICATIONS

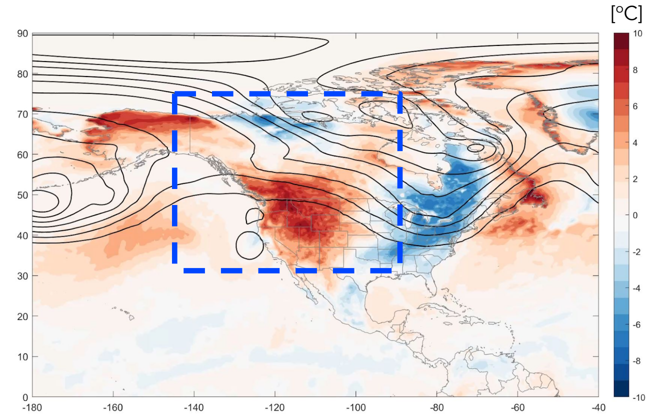
ARTICLE

Check for updates

https://doi.org/10.1038/s41467-020-17130-7 OPEN

Effects of climate change on the movement of future landfalling Texas tropical cyclones

Pedram Hassanzadeh[1,2✉], Chia-Ying Lee[3], Ebrahim Nabizadeh[1], Suzana J. Camargo[3], Ding Ma[4] & Laurence Y. Yeung[2]

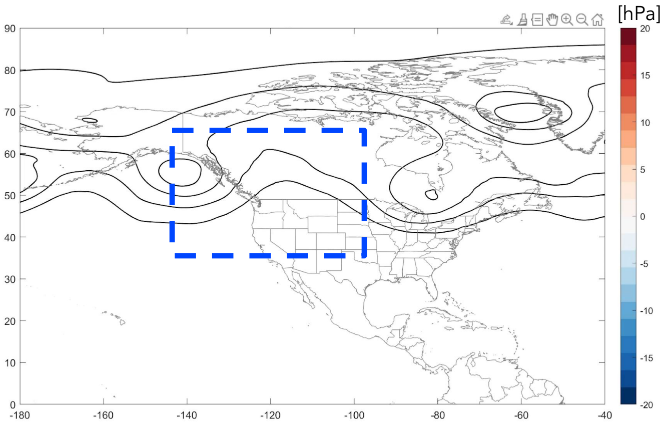


2021 Pacific
North-West
heat wave

1500 deaths
$9B loss

2017
Hurricane
Harvey

107 deaths
$125B loss



Movies: ERA5 reanalysis data

Changes in key characteristics of blocking events

Connections between these characteristic and those of extreme events?

Key blocking characteristics:

- Frequency
- Size
- Duration
- Intensity
- 3D structure
- Location …

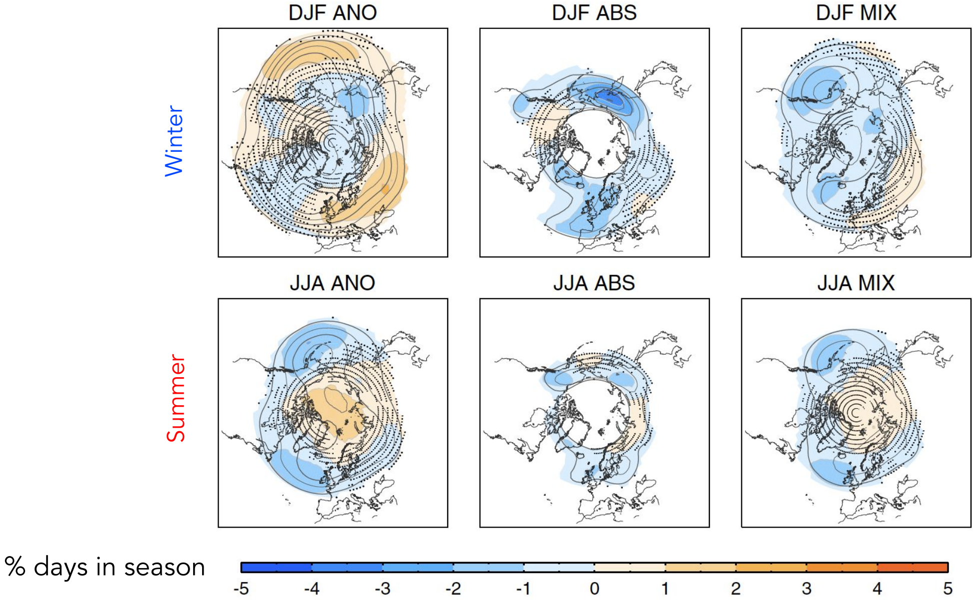
Key extreme events' characteristics?

- Blocking-extreme event relationship

Change in blocking *frequency* in a warming climate?

Frequency will generally decrease but there are high uncertainties and index/GCM dependency

Woollings et al. (2018, Curr. Clim. Change Rep.)



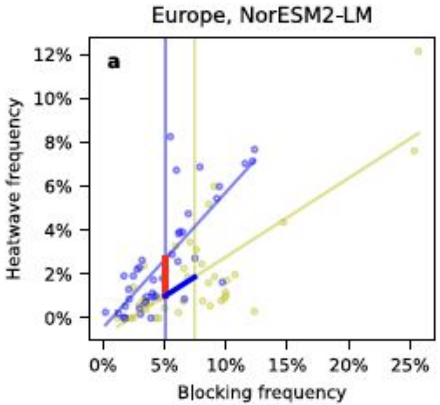
CMIP5 multi-model-mean
RCP 8.5

2061-2090 (Future) period vs. 1961–1990 (Historical) period

Dots: less than two thirds of the models displaying the same sign

Change in blocking *frequency* in a warming climate?

Fewer blocks may not mean fewer heat waves: blocking-heat wave relationship may change too!



Geophysical Research Letters 2019

Evaluating Indices of Blocking Anticyclones in Terms of Their Linear Relations With Surface Hot Extremes

Pak-Wah Chan[1], Pedram Hassanzadeh[2], and Zhiming Kuang[1,3]

[1]Department of Earth and Planetary Sciences, Harvard University, Cambridge, MA, USA, [2]Department of Mechanical Engineering, and Department of Earth, Environmental and Planetary Sciences, Rice University, Houston, TX, USA, [3]John

"There are several examples supporting changing relationships between blocking and its impacts."

Woollings et al. (2018, Curr. Clim. Change Rep.)

npj | climate and atmospheric science 2022

ARTICLE OPEN

Heatwave–blocking relation change likely dominates over decrease in blocking frequency under global warming

Pak Wah Chan[1]✉, Jennifer L. Catto[1] and Matthew Collins[1]

"Over Europe, with a historical heatwave frequency of 2.5%,
less blocking will cause 0.6% fewer heatwaves,
steepened heatwave–blocking relation will cause 1.4% more heatwaves …."

Changes in key characteristics of blocking events

Connections between these characteristic and those of extreme events?

Key blocking characteristics:

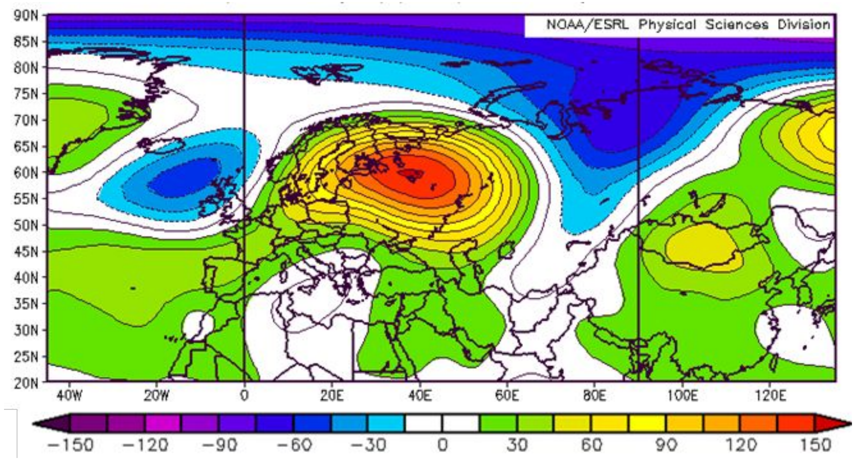
- Frequency
- Size
- Duration
- Intensity
- 3D structure
- Location …

Key extreme events' characteristics?

- Blocking-extreme event relationship

Change in blocking *size* in a warming climate?

Size: area, spatial extent



Larger block →
More impactful block
- Larger heat waves (?)
- Increase in mixing length (?)

Z500 anomaly [m]

Geophysical Research Letters 2019

RESEARCH LETTER
10.1029/2019GL084863

Size of the Atmospheric Blocking Events: Scaling Law and Response to Climate Change

Ebrahim Nabizadeh[1], Pedram Hassanzadeh[1,2], Da Yang[3,4], and Elizabeth A. Barnes[5]

[1]Department of Mechanical Engineering, William Marsh Rice University, Houston, TX, USA, [2]Department of Earth, Environmental and Planetary Sciences, William Marsh Rice University, Houston, TX, USA, [3]Department of Land, Air and Water Resources, University of California, Davis, CA, USA, [4]Lawrence Berkeley National Laboratory, Berkeley, CA, USA, [5]Department of Atmospheric Science, Colorado State University, Fort Collins, CO, USA

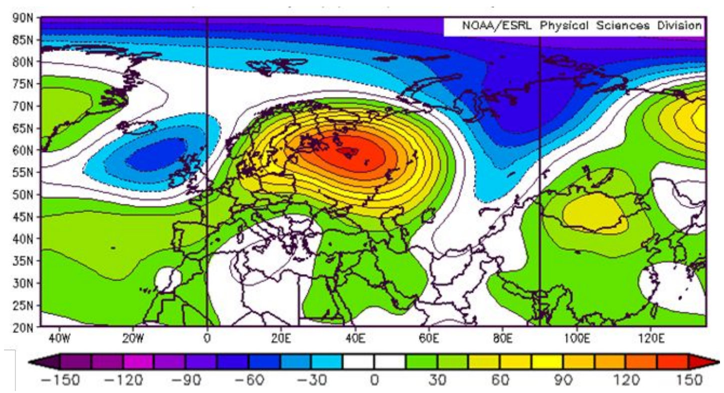
Key Points:
- Size of blocking events robustly increases with climate change in most regions in two sets of large-ensemble fully coupled GCM simulations
- A scaling law for blocking area is derived in a QG model using

Change in blocking *size* in a warming climate?

Using large-ensemble simulations from comprehensive GCMs

Two large-ensemble fully coupled GCM datasets:
NCAR's large-ensemble CESM1 (LENS): 40 members per period
GFDL's large-ensemble CM3 (CM3-LE): 20 members per period

Current period: Historical (1979-2005)
Future period: RCP8.5 (2074-2100)



Blocking index (Dole-Gordan):
Z500 anomaly ≥ 1.5 standard deviation
for ≥ 7 days

Blocking area:
Computed daily area inside closed 1 standard deviation contourline

Blocking events are getting bigger with climate change!

Larger increases in Northern Hemisphere summer

	Sector	Change in blocking area	
		LENS	CM3-LE
Summer	North Atlantic	+8%	+10%
	North Pacific	+10%	+13%
	Russia	+10%	+11%
	Southern Hemisphere	-3%	0%
Winter	North Atlantic	+3%	+1%
	North Pacific	+4%	+10%
	Russia	+4%	+5%
	Southern Hemisphere	+2%	+6%

Scaling for the *size* of midlatitude features?

Synoptic eddies: Rossby deformation radius or Rhines scales

- **Two-layer QG:** Stone (1969); Panetta (1993); Held & Larichev (1996)

Idealized dry GCMs: Schneider & Walker (2006); Kidston et al. (2011); Jansen & Ferrari (2012); Chemke & Kaspi 2016; Chan et al. (2022)

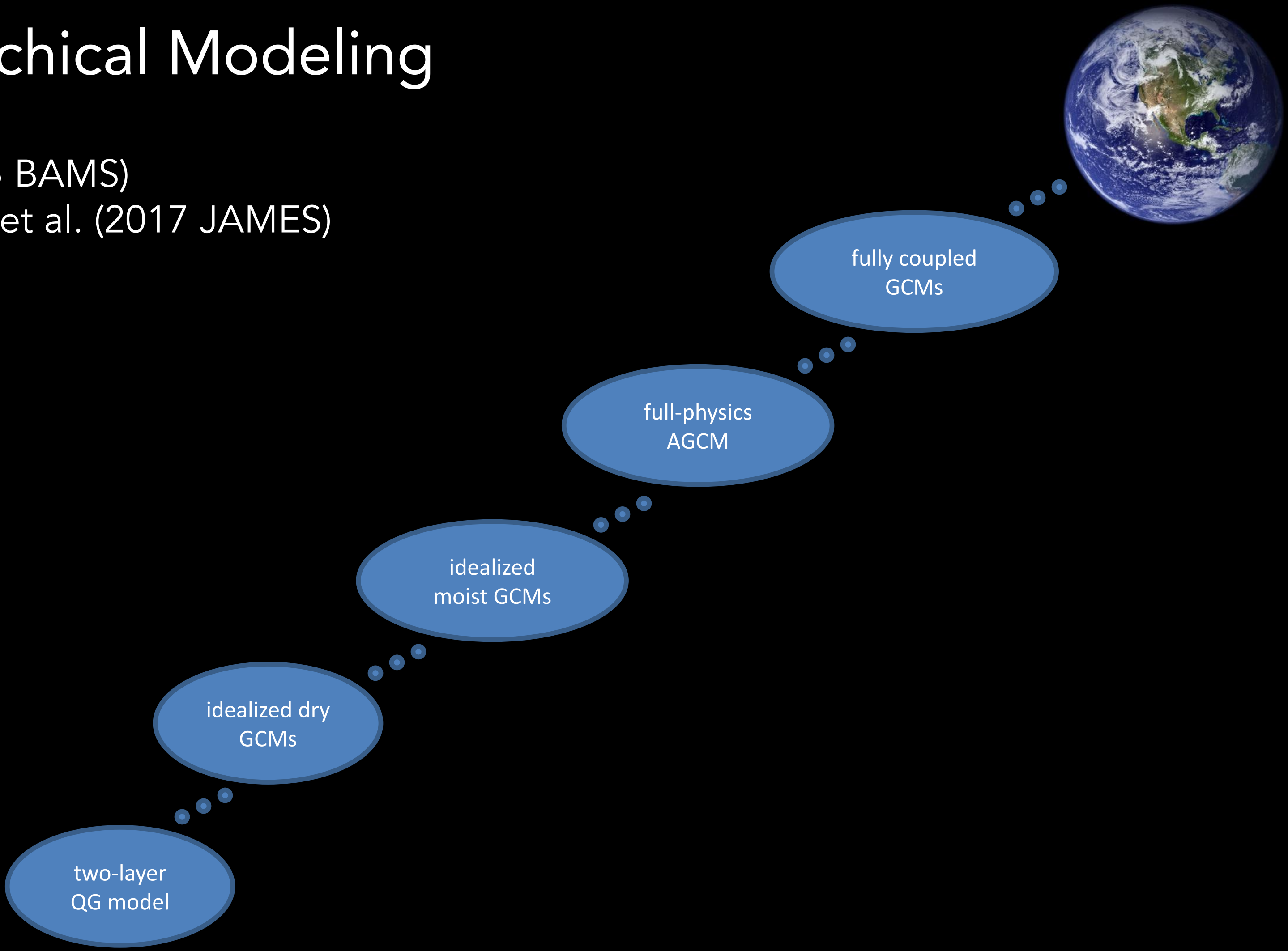
Idealized moist GCMs: Frierson et al. (2006); O'Gorman & Schneider (2008)

Rossby deformation radius: $\lambda = 2\pi \frac{NH}{f}$

Rhines scale: $L_R = 2\pi \sqrt{\frac{u_{rms}}{\beta}}$

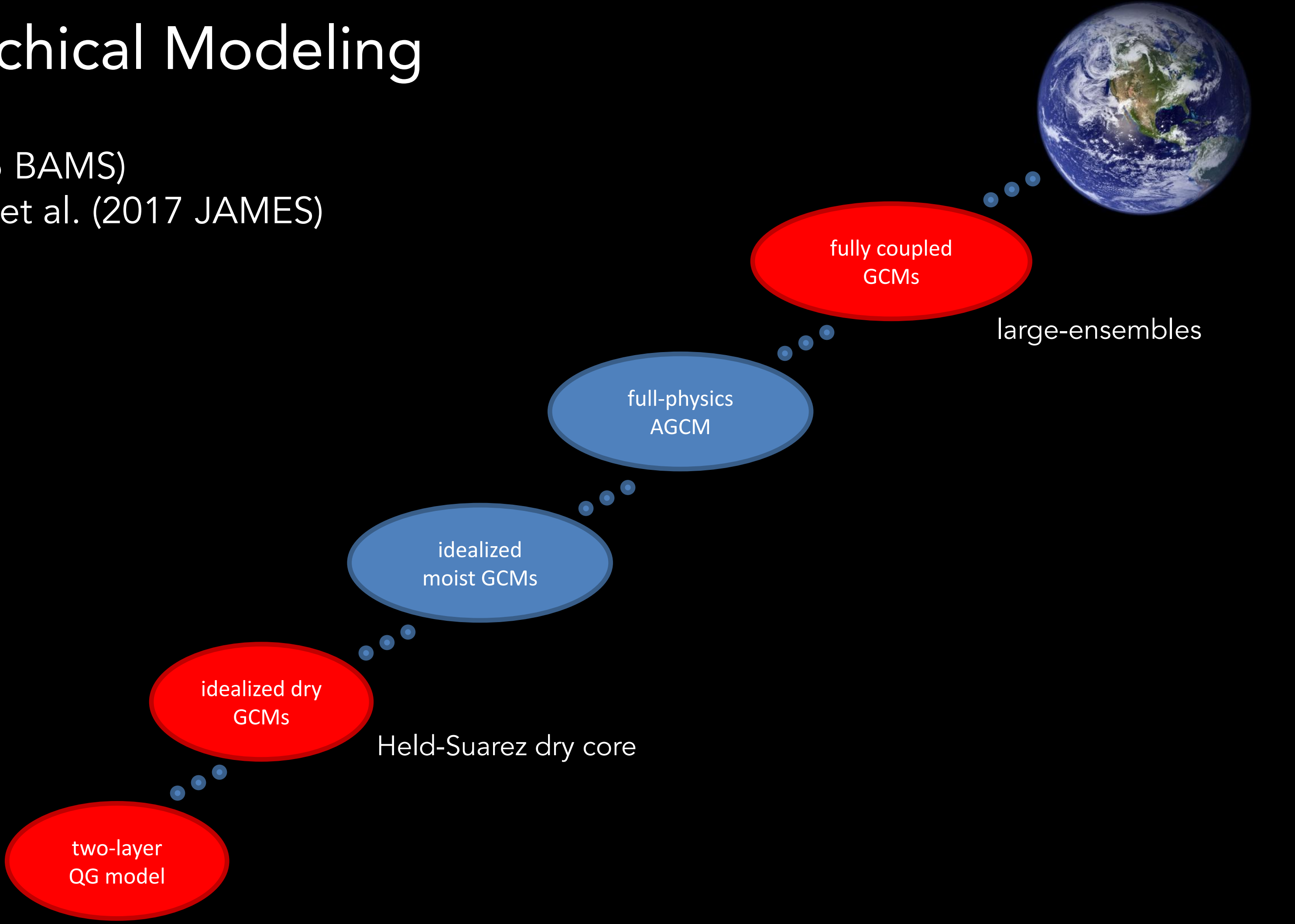
Hierarchical Modeling

Held (2005 BAMS)
Jeevanjee et al. (2017 JAMES)



Hierarchical Modeling

Held (2005 BAMS)
Jeevanjee et al. (2017 JAMES)



Two-layer quasi-geostrophic (QG) model

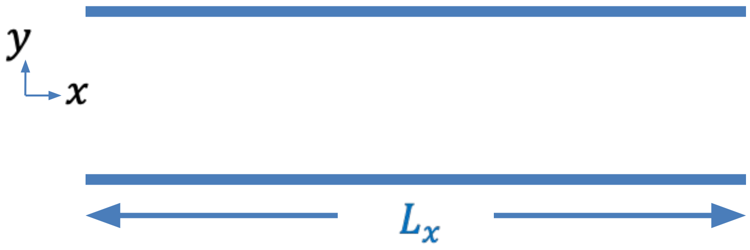
There are 7 parameters

$$\frac{\partial q_n}{\partial t} + \mathrm{J}(\psi_n, q_n) = -\frac{(-1)^n}{\tau_d}\frac{\psi_1 - \psi_2 - \psi_R}{\lambda^2} - \delta_{n2}\frac{\nabla^2\psi_n}{\tau_f}$$

$$n = 1,2$$

$$q_n = \nabla^2\psi_n(-1)^n\frac{\psi_1 - \psi_2 - \psi_R}{\lambda^2} + \beta y$$

$$\frac{\partial \psi_R}{\partial y} = -U\,\mathrm{sech}^2(y/\sigma)$$



Systematic dimensional analysis:

Buckingham-π Theorem (Buckingham 1915 PRL)

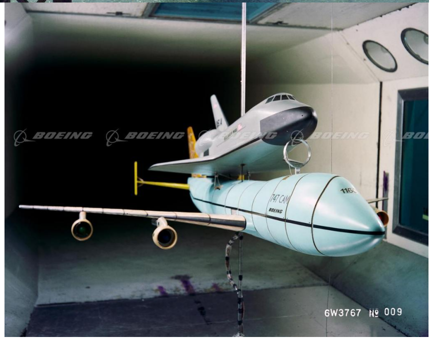
- All parameters (7): $\lambda, U, \sigma, \beta, \tau_d, \tau_f, L_x$

Fundamental dimensions (2): time & lengt

The system can be fully described by 7-2=

Length: λ

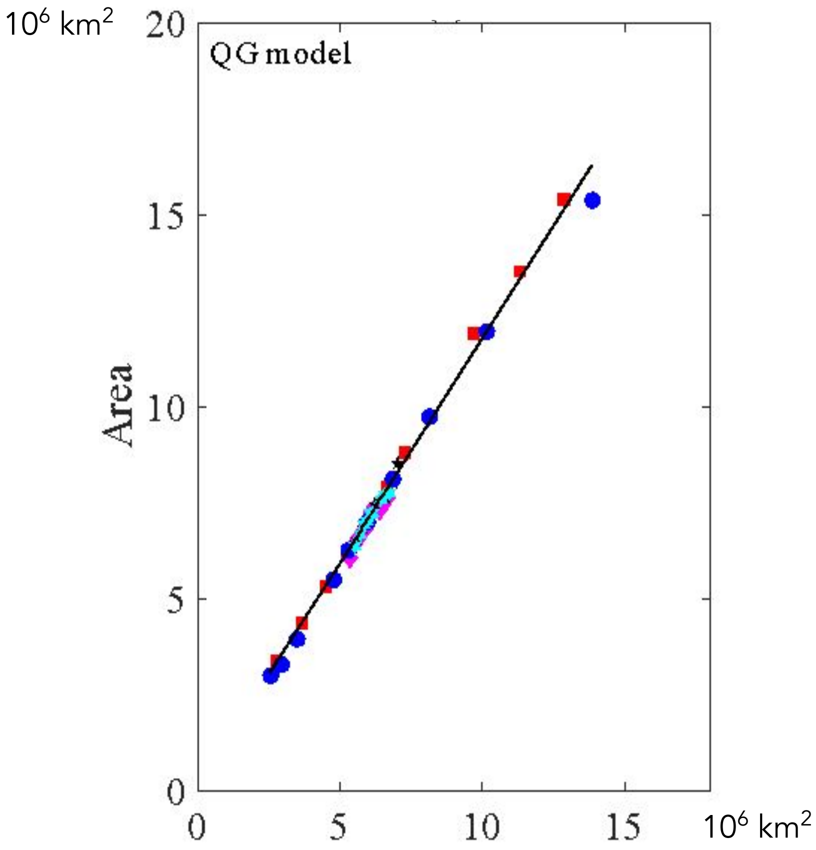
Time: λ / U



$$\frac{A}{\lambda^2} \sim \left[\frac{\beta\lambda^2}{U}\right]^a \left[\frac{\sigma}{\lambda}\right]^b \left[\frac{U\tau_d}{\lambda}\right]^c \left[\frac{U\tau_f}{\lambda}\right]^d \left[\frac{L_x}{\lambda}\right]^f$$

Scaling law based on the common use of Buckingham-$\boldsymbol{\pi}$ Theorem works well

But involves variables that are hard to diagnose from data



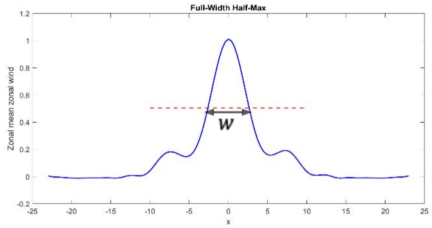
$$\lambda^2 \left[\frac{\beta\lambda^2}{U}\right]^{-0.77} \left[\frac{\sigma}{\lambda}\right]^{0.7} \left[\frac{U\tau_f}{\lambda}\right]^{0.15} \left[\frac{U\tau_d}{\lambda}\right]^{-0.1} \left[\frac{L_x}{\lambda}\right]^{0.1}$$

$$\frac{A}{\lambda^2} \sim \left[\frac{\beta\lambda^2}{U}\right]^{-0.77} \left[\frac{\sigma}{\lambda}\right]^{0.70} \left[\frac{U\tau_f}{\lambda}\right]^{0.15} \left[\frac{U\tau_d}{\lambda}\right]^{-0.10} \left[\frac{L_x}{\lambda}\right]^{0.10}$$

$$\frac{L_R}{\lambda} \sim \left[\frac{\beta\lambda^2}{U}\right]^{-0.52} \left[\frac{\sigma}{\lambda}\right]^{0.33} \left[\frac{U\tau_f}{\lambda}\right]^{0.20} \left[\frac{U\tau_d}{\lambda}\right]^{-0.10} \left[\frac{L_x}{\lambda}\right]^{0.01}$$

$$L_R = 2\pi\sqrt{\frac{u_{rms}}{\beta}}$$

$$\frac{w}{\lambda} \sim \left[\frac{\beta\lambda^2}{U}\right]^{-0.61} \left[\frac{\sigma}{\lambda}\right]^{0.38} \left[\frac{U\tau_f}{\lambda}\right]^{-0.09} \left[\frac{U\tau_d}{\lambda}\right]^{-0.02} \left[\frac{L_x}{\lambda}\right]^{-0.01}$$



$$\frac{L_K}{\lambda} \sim \left[\frac{\beta\lambda^2}{U}\right]^{-0.29} \left[\frac{\sigma}{\lambda}\right]^{0.27} \left[\frac{U\tau_f}{\lambda}\right]^{0.22} \left[\frac{U\tau_d}{\lambda}\right]^{-0.11} \left[\frac{L_x}{\lambda}\right]^{0.01}$$

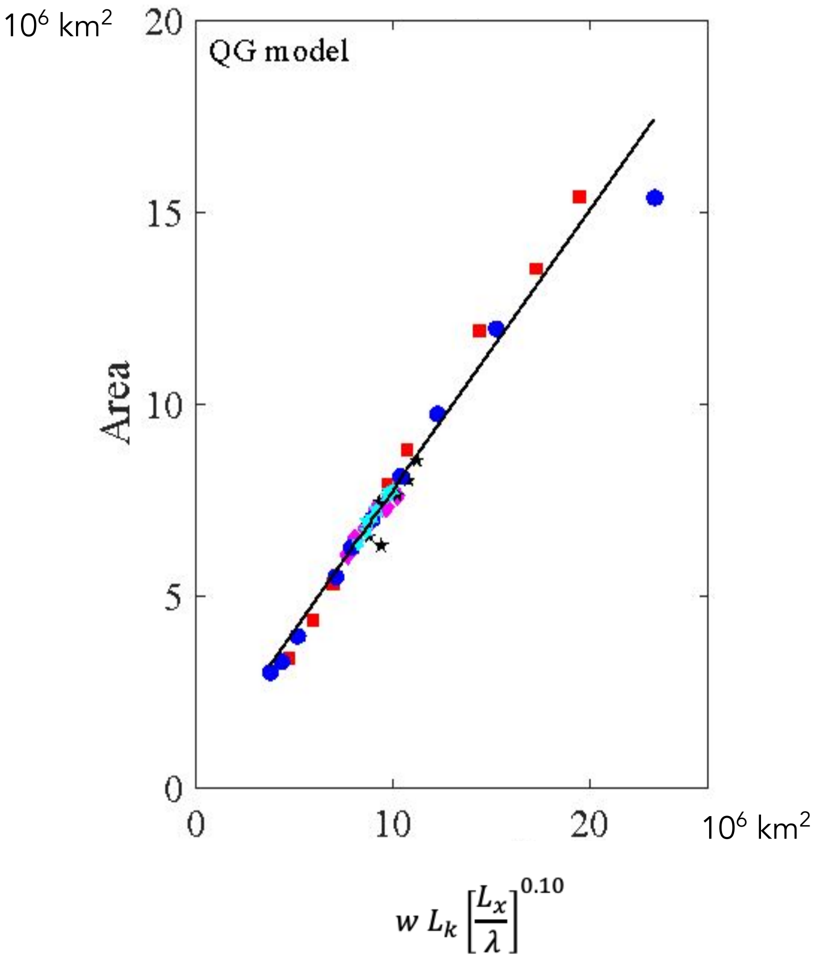
$$c = U - \frac{\beta}{k^2 + l^2}$$

$$L_K = 2\pi\sqrt{\frac{U}{\beta}}$$

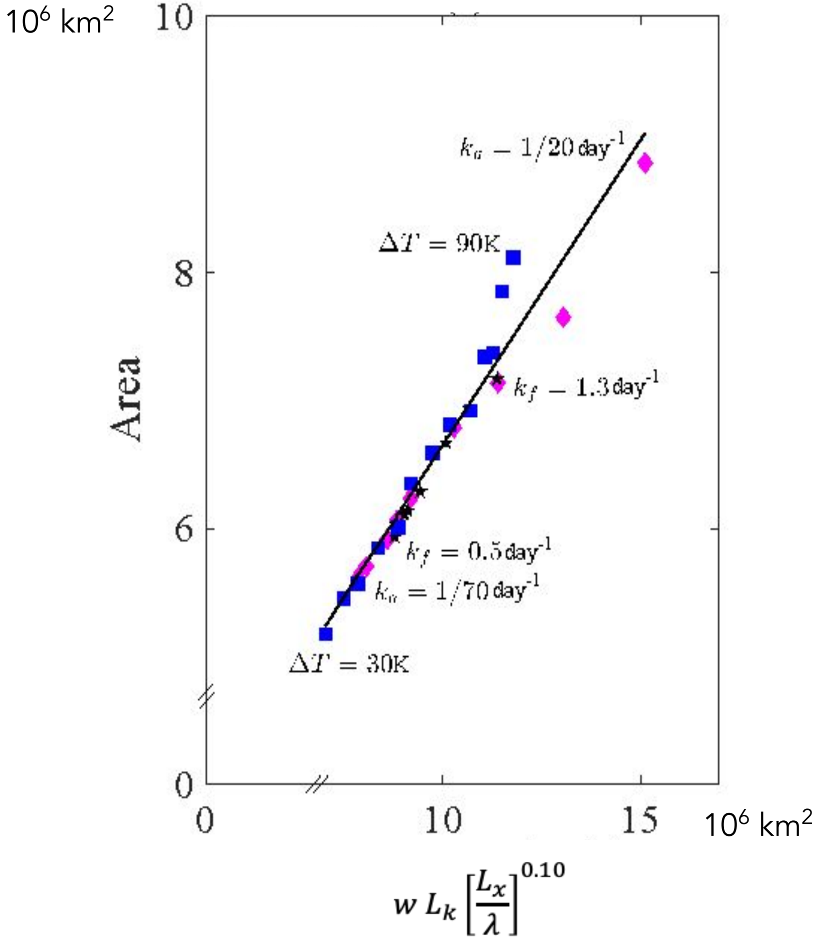
$$A \sim w\, L_k \left[\frac{L_x}{\lambda}\right]^{0.10}$$

The new scaling law works well in QG

Involves variables that can be diagnose from data



The new scaling law works well in Held-Suarez idealized GCM



Idealized dry GCM:

GFDL dry dynamical core

T85 resolution

Aquaplanet

The scaling wall works well (overall) in winters

RCP8.5 vs Historical

Sector				
	Area	*w*		
North Atlantic	+3% 1%	-6% +5%	+6% 0%	-1% +4%
North Pacific	+4% +10%	+2% +4%	+3% +4%	+4% +8%
Russia	+4% +5%	+3% +4%	+1% +2%	+3% +5%
Southern Hemisphere	+2% +6%	-2% -2%	+5% +7%	+2% +5%

The scaling law does not work in summers

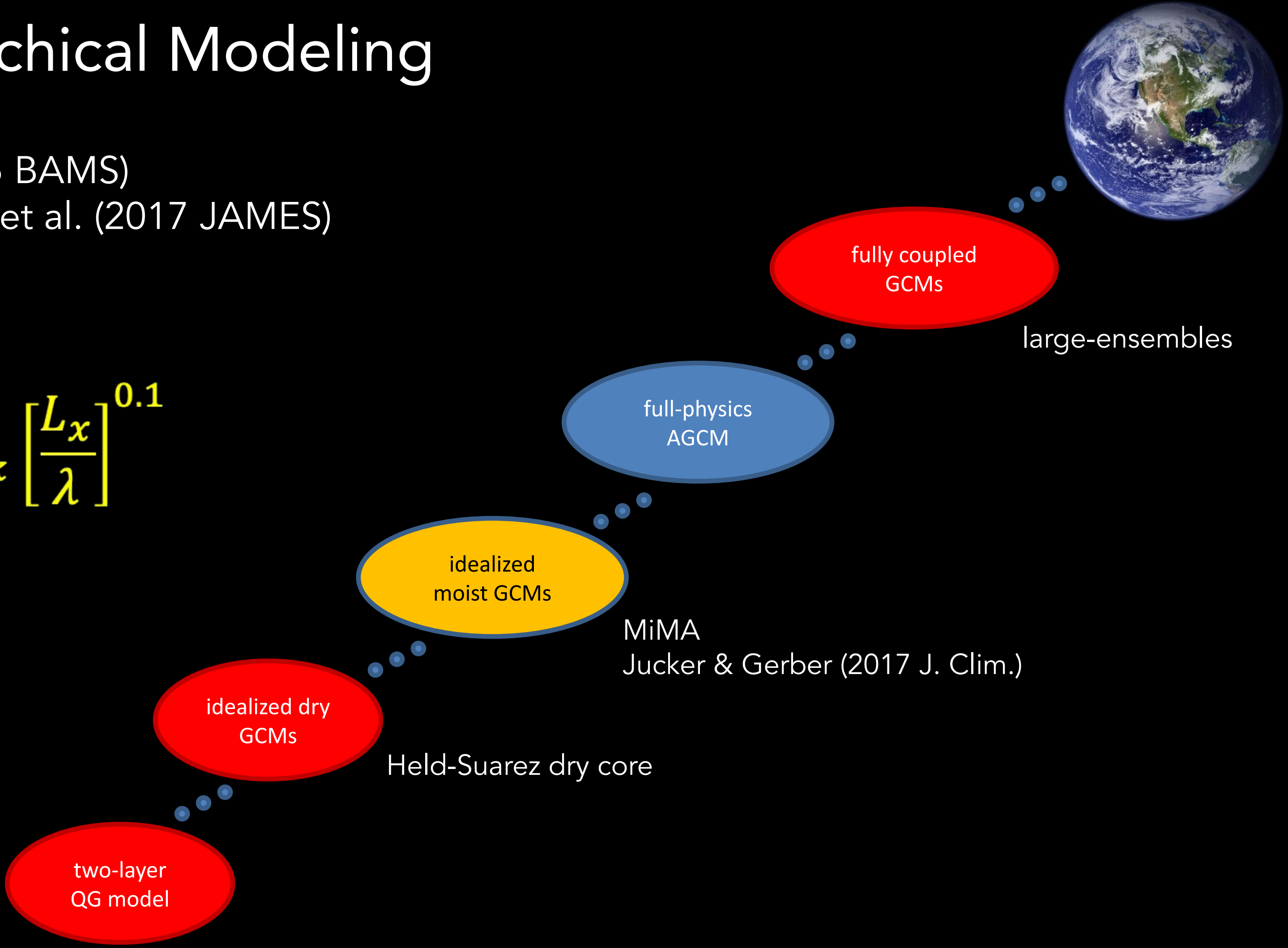
RCP8.5 vs Historical

Sector				
	Area	*w*		
North Atlantic	+8% +10%	+8% +4%	+2% +12%	+9% +16%
North Pacific	+10% +13%	? +6%	-8% -5%	? 1%
Russia	+10% +11%	-3% -2%	-2% 0%	-5% -2%
Southern Hemisphere	-3% 0%	+2% +13%	+5% +6%	+6% +20%

Hierarchical Modeling

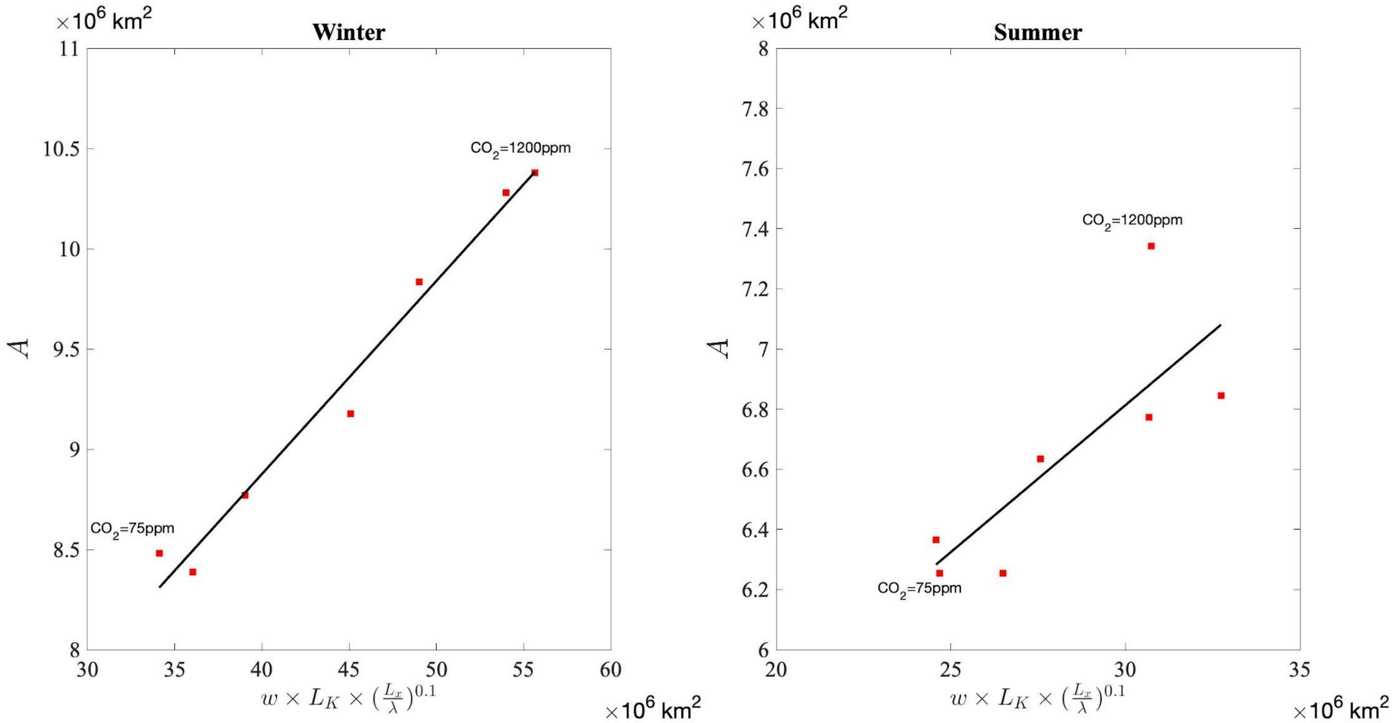
Held (2005 BAMS)
Jeevanjee et al. (2017 JAMES)

$$w\, L_k \left[\frac{L_x}{\lambda}\right]^{0.1}$$



Experiments with MiMA (aquaplanet, with seasonal cycle)

The scaling law works well in winters but does not work in summers



Change in blocking *duration* in a warming climate?

Using large-ensemble simulations from comprehensive GCMs

NCAR's CESM1 (LENS1): 40 members per period
NCAR's CESM2 (LENS2): 50 members per period
GFDL's CM3: 20 members per period

Historical period: Historical (1975-2000)
Future period: RCP8.5/SSP370 (2075-2100)

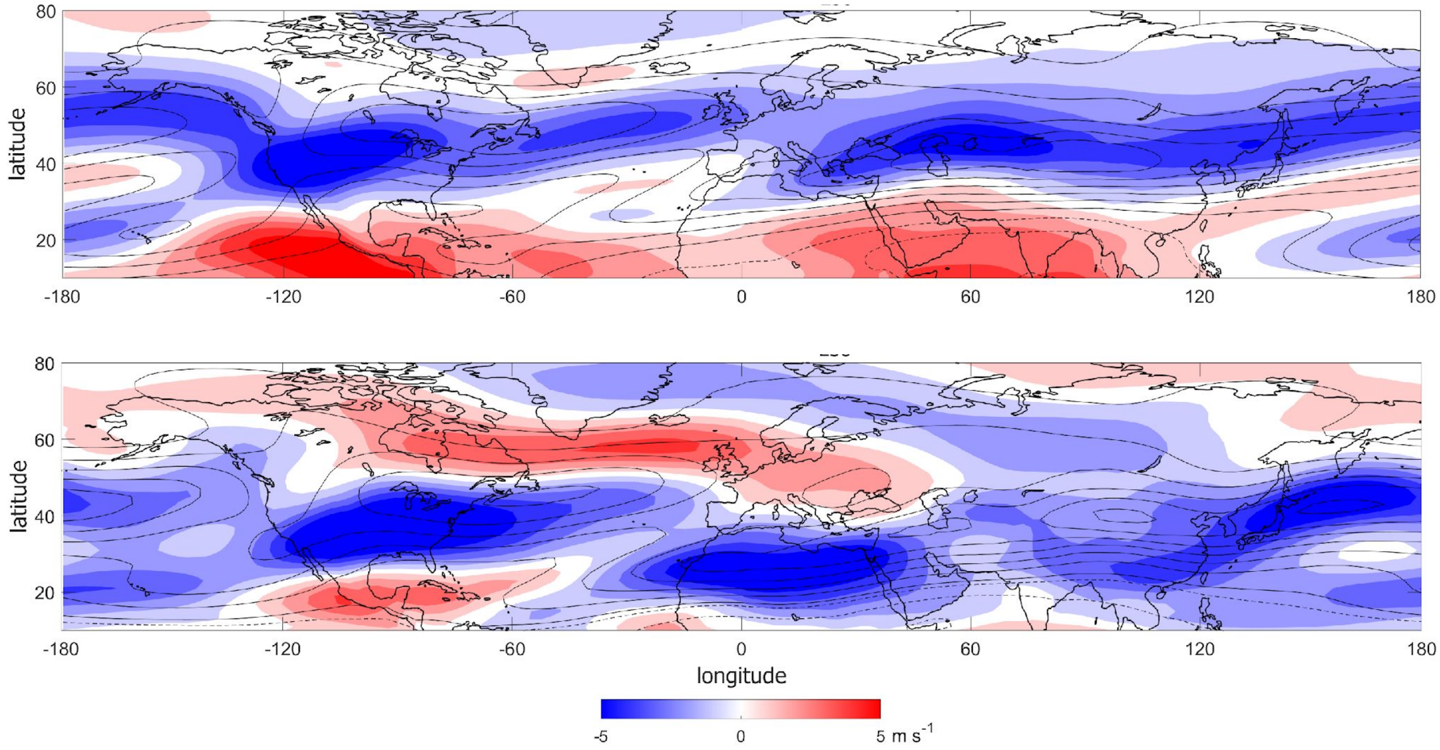
Dole & Gordon index:
Z500 anomaly > 1.5 standard deviation for ≥ 5 days

Scherrer et al. index:
Reversal of Z500 meridional gradient for ≥ 5 days

~20% slower summertime jet stream in a warming climate

Would lead to longer blocking and extreme events (?)

Shading: Response of 250 mb zonal winds



NCAR's LENS2
50 members

GFDL's CM3-LE
20 members

No change in average blocking duration under climate change

Robust w.r.t. region, season, land vs ocean, index, other studies, model hierarchy

Season	Sector	Average duration of *long* blocks (days) Historical vs Future periods	
		LENS2	CM3-LE
Summer	North Atlantic	11.4 vs 11.3	12.1 vs 12.2
Summer	North Pacific	11.6 vs 11.4	12.0 vs 12.2
Summer	Russia	11.9 vs 11.4	11.9 vs 12.5
Winter	North Atlantic	11.8 vs 12.0	12.1 vs 12.1
Winter	North Pacific	12.5 vs 12.3	13.4 vs 14.0
Winter	Russia	12.1 vs 12.1	12.5 vs 12.7

Same conclusion:

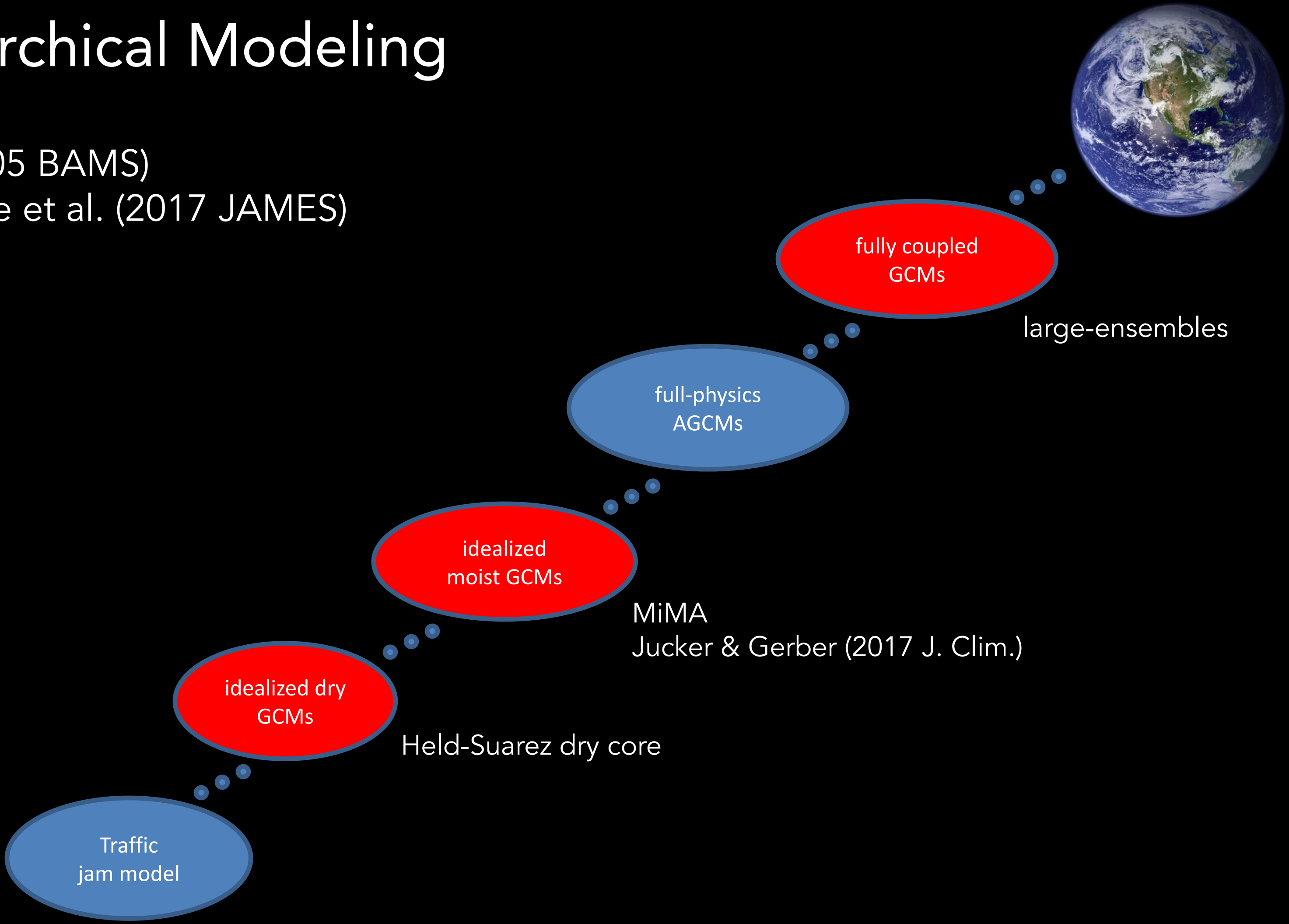
- for all blocks (+5 days)

- another index

- other studies using CMIP3 & 5
  (Barnes et al. 2012 Clim. Dyn.;
  Dunn-Sigouin & Son 2013 JGR;
  Huguenin et al. 2020 GRL)

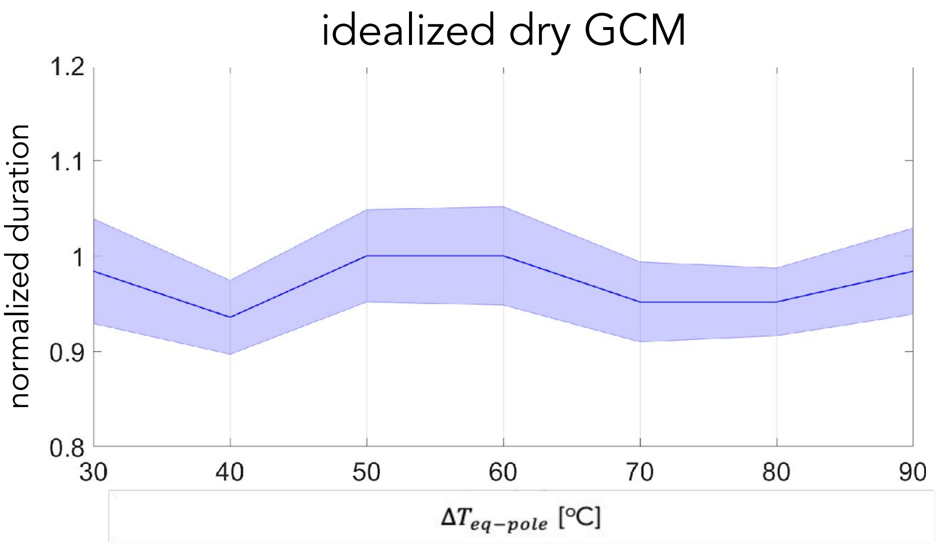
Hierarchical Modeling

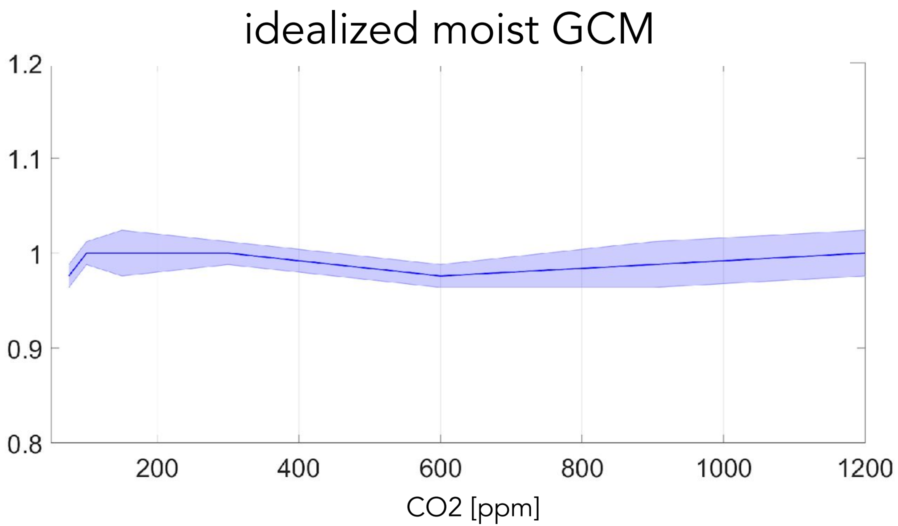
Held (2005 BAMS)
Jeevanjee et al. (2017 JAMES)



No change in average blocking duration under climate change

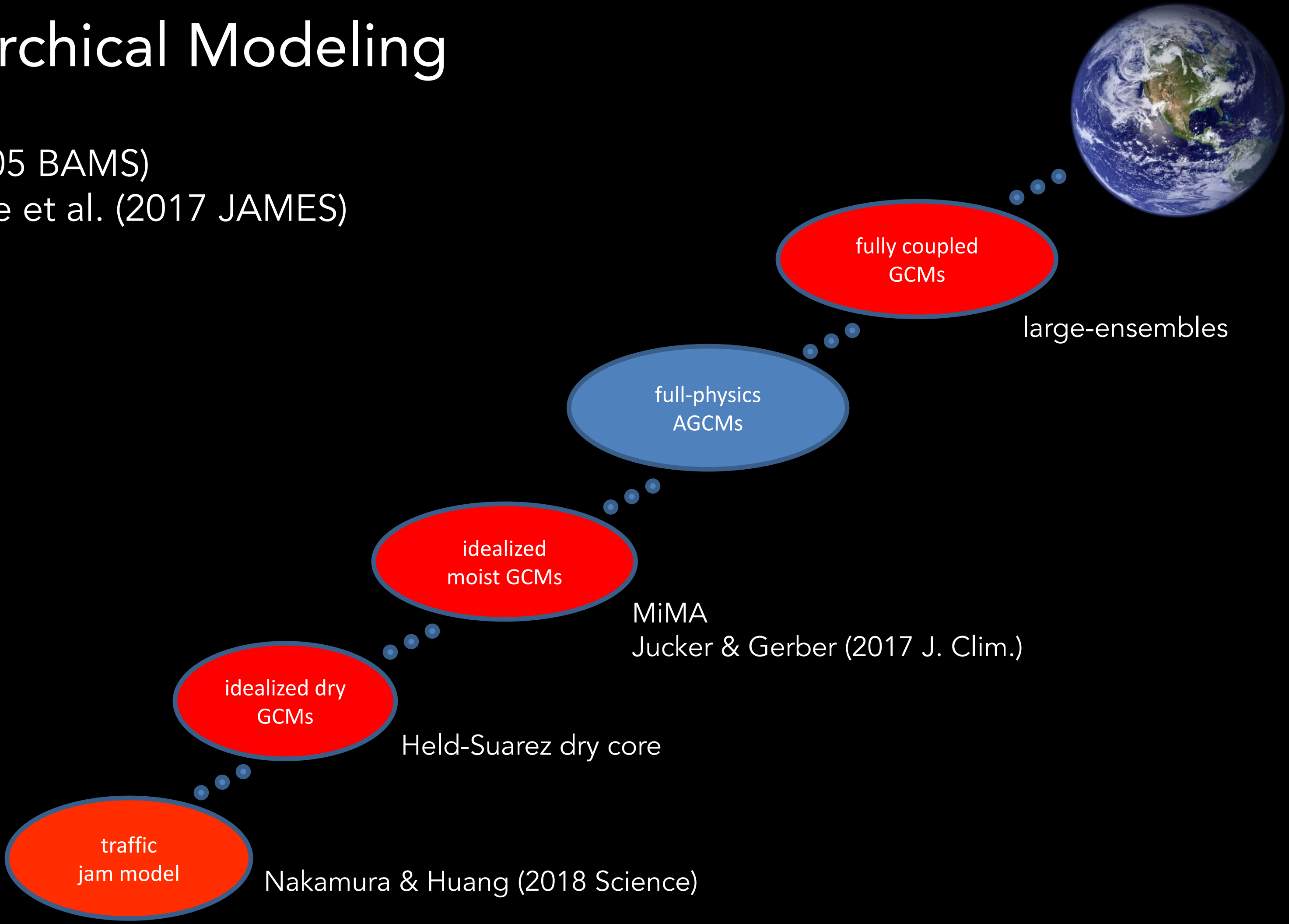
Idealized dry & moist GCMs isolate the role of large-scale atmospheric circulation





Hierarchical Modeling

Held (2005 BAMS)
Jeevanjee et al. (2017 JAMES)



Average blocking duration in the 1D traffic jam model

Provides a quantitative framework for the eddy-blocking feedback

$$\frac{\partial A}{\partial t} = -U_{ref}\frac{\partial A}{\partial x} + \left[\frac{\partial}{\partial x}A^2 + S(x,t)\right] + \text{damping} + \cdots$$

zonal advection

nonlinear feedback

transient eddies

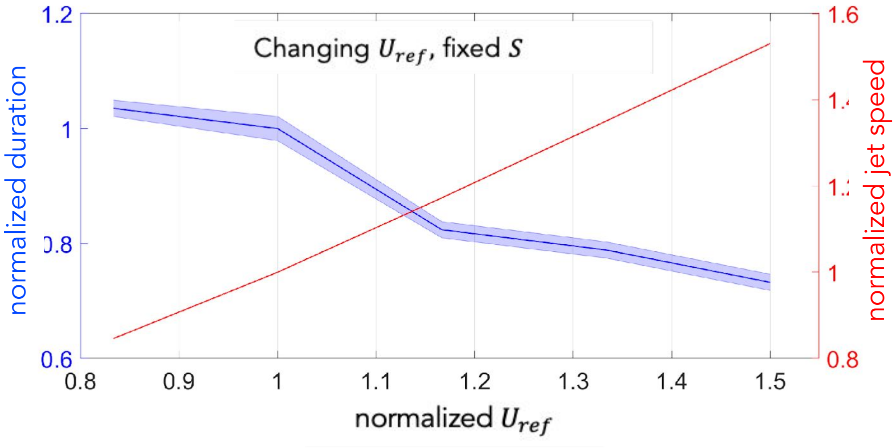
$A(x,t)$: finite-amplitude wave activity

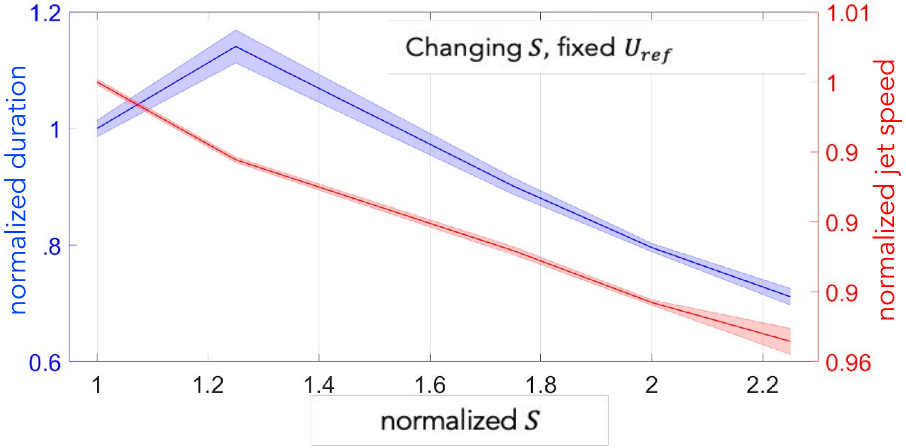
x: longitude

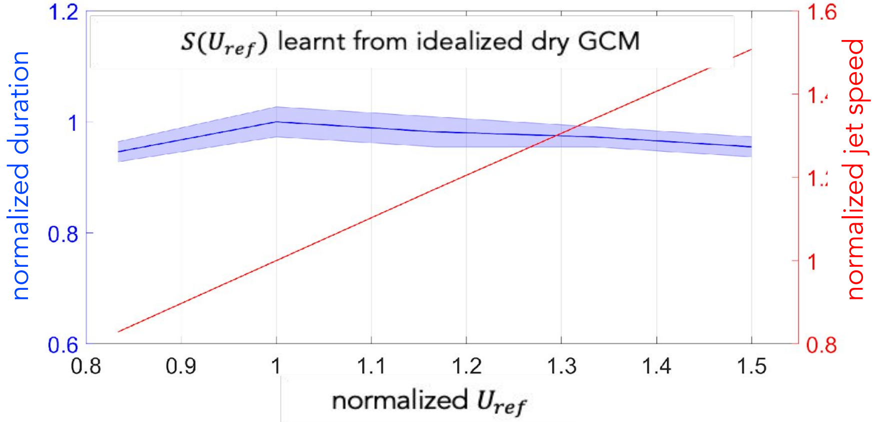
Nakamura & Huang (2018 Science)
Parasdise et al. (2019 JAS)
Valva & Nakamura (2021 JGR)

Average blocking duration in the 1D traffic jam model

No change IF the relationship between mean flow & eddies is accounted for







No change in the average blocking duration under climate change

Due to proportional change of the mean jet speed and eddy feedback

One implication:
Increase in duration of future midlatitude heat waves is not directly due to dynamics (so, it is due to thermodynamics)

Li & Thompson (2021 Nature):
Increase in duration of future heat waves can be mainly explained by thermodynamics
Major source of uncertainty: changes in blocking duration

Chan et al. (2023, npj Climate & Atmos. Sci.): Heat wave-blocking relationship changes
Zhang & Boos (2023, PNAS): Convective instability sets max midlatitude temperature

Change in blocking *structure & intensity* in a warming climate?

Analysis of ERA5 and model hierarchy, T tendency equation budget

15 December 2021 NABIZADEH ET AL.

The 3D Structure of Northern Hemisphere Blocking Events: Climatology, Role of Moisture, and Response to Climate Change

Ebrahim Nabizadeh,[a] Sandro W. Lubis,[a] and Pedram Hassanzadeh[a]

[a] *Rice University, Houston, Texas*

- Latent heating plays a role in setting the 3D structure (e.g., creating a westward tilt)
- Vertical wind structure: complicated
- Blocking intensity response-land temperature anomaly do not always have the same sign

Changes in key characteristics of blocking events

Connections between these characteristic and those of extreme events?

Key blocking characteristics:

- Frequency
- Size
- Duration
- 3D structure
- Location …

Key extreme events' characteristics?

- Blocking-extreme event relationship

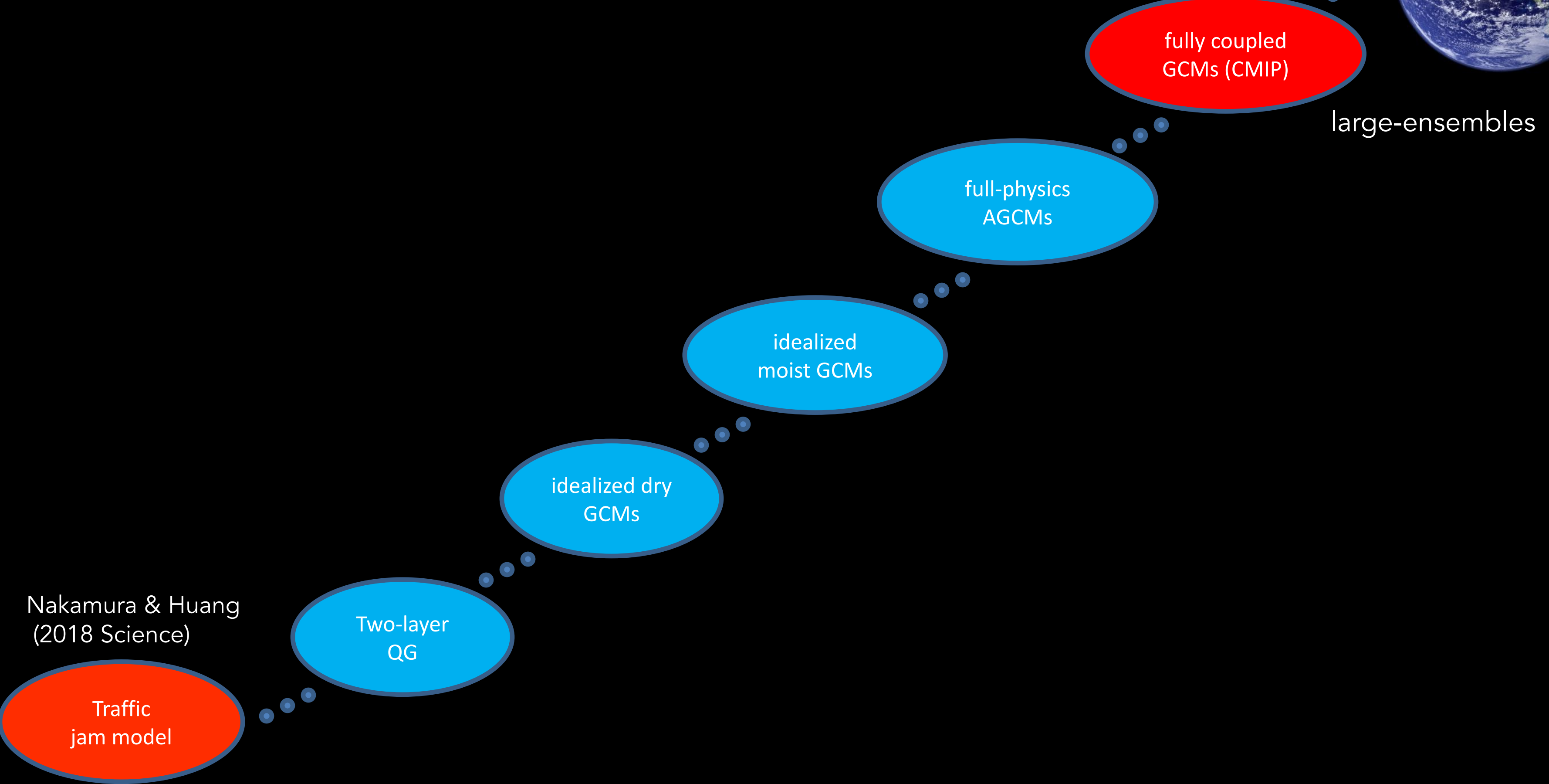
- Model/data hierarchy
Large ensembles to 1D traffic-jam model

- Scaling laws: blocks & extreme events
Accelerated with ML?

- (Integrated ?) Metrics for blocking characteristics weather extreme characteristics

- Integrated conceptual models
Blocking + extreme event

Hierarchical modeling for blocking events



Effects of blocking size on size/impact of extreme events?

CrossMark

LETTER

Projected increase in the spatial extent of contiguous US summer heat waves and associated attributes

OPEN ACCESS

RECEIVED
22 February 2019

REVISED
3 October 2019

ACCEPTED FOR PUBLICATION
4 October 2019

PUBLISHED
8 November 2019

Bradfield Lyon[1,5], Anthony G Barnston[2], Ethan Coffel[3] and Radley M Horton[4]

[1] Climate Change Institute and School of Earth and Climate Sciences, University of Maine, Orono, ME, United States of America
[2] The Earth Institute, Columbia University, New York, NY, United States of America
[3] Neukom Institute and Department of Geography, Dartmouth College, Hanover, NH, United States of America
[4] Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY, United States of America
[5] Author to whom any correspondence should be addressed.