第七章:

大气环流模式

(General Circulation Model)

授课教师：张洋

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Introduction

The climate system is too complex for the human brain to grasp with simple insight. No scientist managed to devise a page of equations that explained the global atmosphere's operations. With the coming of digital computers in the 1950s, a small American team set out to model the atmosphere as an array of thousands of numbers…

Adapted from Paul Edwards, *A Vast Machine: Computer Models, Climate Data, and the Politics of Global Warming* (Cambridge, MA: MIT Press, 2010).

- Models:
  - **Full model** (i.e. full GCM, weather model), mainly for prediction
  - **Simplified/idealized model** (i.e. two-layer model, dry model, aqua-planet model...), for understanding

Introduction

- Governing equations:

Given the initial condition

Integrate over time

Equations of motion:

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} = 2\mathbf{\Omega} \times \mathbf{u} - \frac{1}{\rho}\nabla p + \mathscr{F}.$$

Hydrostatic equation:

$$\frac{\partial p}{\partial z} = -\rho g$$

Equation of continuity:

$$\frac{1}{a\cos\phi}\frac{\partial u}{\partial \lambda} + \frac{1}{a\cos\phi}\frac{\partial(v\cos\phi)}{\partial \phi} + \frac{1}{\rho_R}\frac{\partial(\rho_R w)}{\partial z} = 0.$$

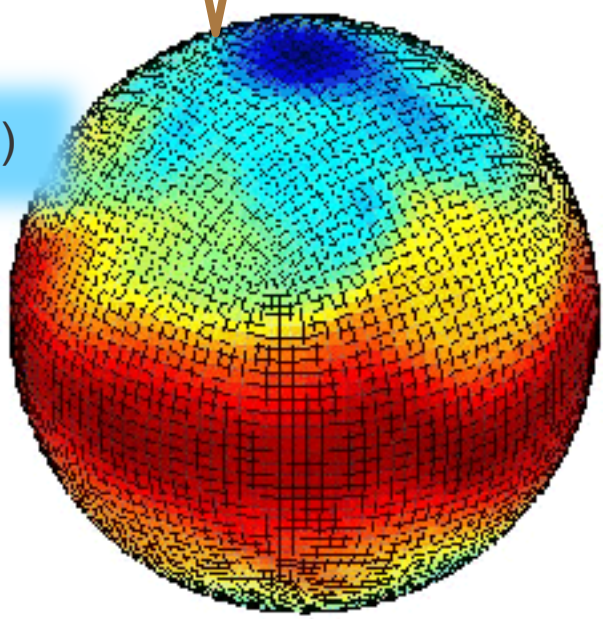
Thermodynamic equation:

$$\frac{\partial \theta}{\partial t} + \frac{u}{a\cos\phi}\frac{\partial \theta}{\partial \lambda} + \frac{v}{a}\frac{\partial \theta}{\partial \phi} + w\frac{\partial \theta}{\partial z} = \mathscr{Q}.$$

$$\frac{\partial r}{\partial t} + \mathbf{u} \cdot \nabla r = E - P.$$

u(x,y,z)

u(i,j,k)



Outline

- Introduction
- A historical review of GCMs

  from the numerical wether prediction, idealized model to full GCMs
- Uncertainties of full GCMs
- A hierarchy of GCMs
- Some examples

A Historical review of GCMs

Before the emergence of digital computers

↓

coming of digital computer in 1940s-1950s

Numerical weather prediction (1945-1955)

↓

Emergence and development of GCMs (1955-1965)

↓

Credible Climate prediction (1965-1979)

↓

Atmosphere-Ocean coupled model (1979-1988) → After 1988

A Historical review of GCMs

- Before the emergence of digital computers
  - Early in the 20th century, V. Bjerknes argued that weather forecasts can be calculated from the basic physics of the atmosphere. He developed a set of seven “primitive equations” of heat, air motion and moisture.
  - In 1922, L. Richardson, published a more complete numerical system of weather prediction
    - use simplified versions of Bjerknes’ “primitive equation”
    - divide up a territory into a grid of cells
    - solve the equation using finite difference solutions of PDE
    - with pencil and paper

A Historical review of GCMs

- Numerical weather prediction
  - In 1946, soon after his computer ENIAC become operational, Von Neumann advocate of using computer for numerical weather prediction
  - Charney began the simplification of Richardson's equation
    - By 1949, a channel model is developed
    - Meanwhile, upper air observation networks were built; observation data are available for the initial condition and comparison with model results
    - In 1950, first serious numerical weather simulation was completed
      - 2-dimensional, grid cell
      - cover North America, 270 points 700km apart
      - take 24 hr calculation for a 24 hour weather prediction
  - In May 1955, US weather Bureau began issuing real-time forecast in advance of weather; Dec. 1954, Univ of Stockholm delivered weather forecast to the Royal Swedish Air Force Weather Service

A Historical review of GCMs

- From the weather forecasting models to the general circulation models of climate
  - Early weather forecasting models were regional, not global in scale
  - Weather and climate models are fundamentally different type of problem from forecasting
    - Weather prediction is essentially an “initial value” problem
    - Climate model is essentially a “boundary layer” problem

A Historical review of GCMs

- The first true General Circulation Model:

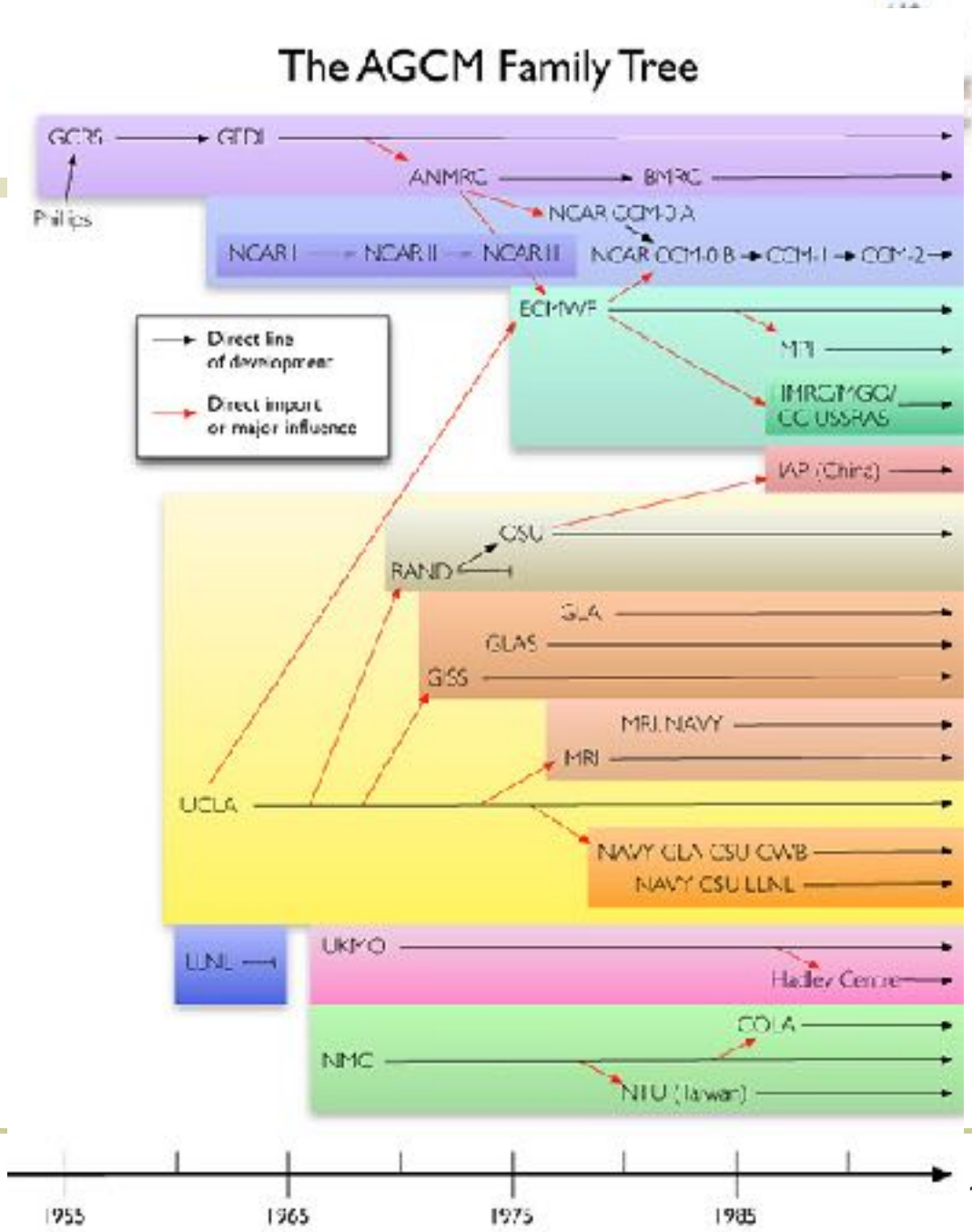
  Norman Phillip's classic experiments in 1955

  - Two-layer model
  - grid covered a cylinder (beta plane) in stead of a hemisphere
  - 17 x 16 in circumference
  - results show plausible jet stream and evolution of realistic-looking weather disturbance

A Historical review of GCMs

- Launch of GCM projects
  - Smagorinsky, 1955: a general circulation model of the entire three-dimensional global atmosphere built directly from the primitive equations.
    - 1958, Syukuro (Suki) Manabe joint the lab and built one of the most vigorous and long-lasting GCM development programs in the world. (More physical processes put into the model, e.g. an atmosphere with water vapor, CO2, ozone and rainfall...);
    - 1965, a nine-level, 3-D atmospheric model was built.
  - In the 1950s, Mintz at UCLA, also launched a long-term GCM develop project.
    - Akio Arakawa, developed his scheme and parameterization for computing fluid flow
    - 1964, a two-layer GCM but including realistic geography
  - In 1964, another major effort got underway at National Center for Atmospheric Research (NCAR) in Boulder, Colorado under Warren Washington and yet another Tokyo University graduate, Akira Kasahara.

AGCM


The AGCM Family Tree
GCRS
GFDL
Philips
ANMRC
BMRC
NCAR CCM0A
NCAR I
NCAR II
NCAR III
NCAR CCM0B
CCM-1
CCM-2
ECMWF
MPI
IMRG/MGO/
CC USSRAS
IAP (China)
CSU
RAND
GLA
GLAS
GISS
MRI NAVY
MRI
UCLA
NAVY GLA CSU CWB
NAVY CSU LLNL
LLNL
UKMO
Hadley Centre
COLA
NMC
NTU (Taiwan)
Direct line of development
Direct import or major influence
1955
1965
1975
1985

A Historical review of GCMs

- After 1988, the research front move from
  - atmospheric models to atmosphere-ocean coupled models
  - stable system to transient response to changes in condition
  - global planet variation to regional response
  - modelers work more closely, community models, multi-model comparisons

A Historical review of GCMs

- Now, “GCM”

  stood from the

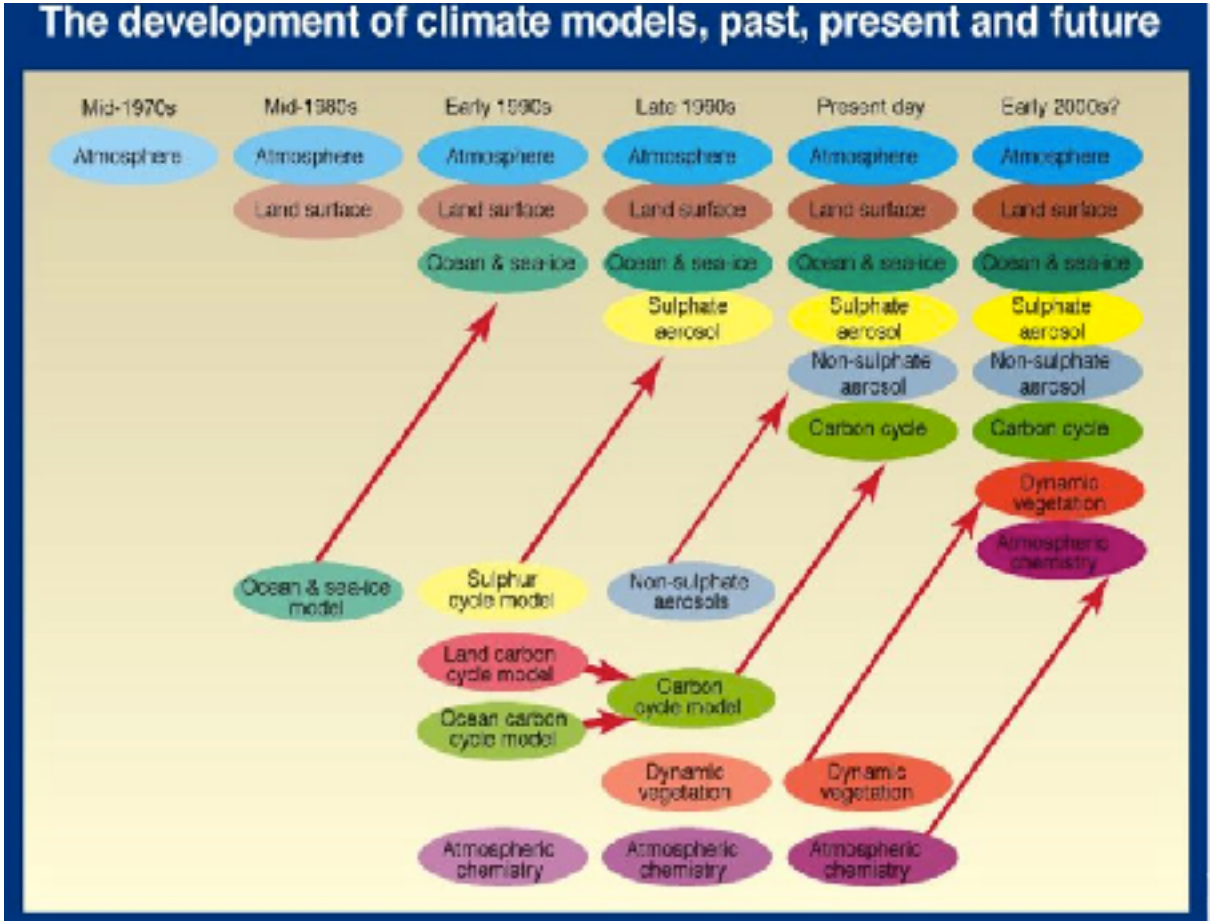
  “**G**eneral **C**irculation **M**odel”

  to

  “**G**lobal **C**limate **M**odel”

  or

  “**G**lobal **C**oupled **M**odel”



A Historical review of GCMs

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Credible Climate prediction (1965-1979)

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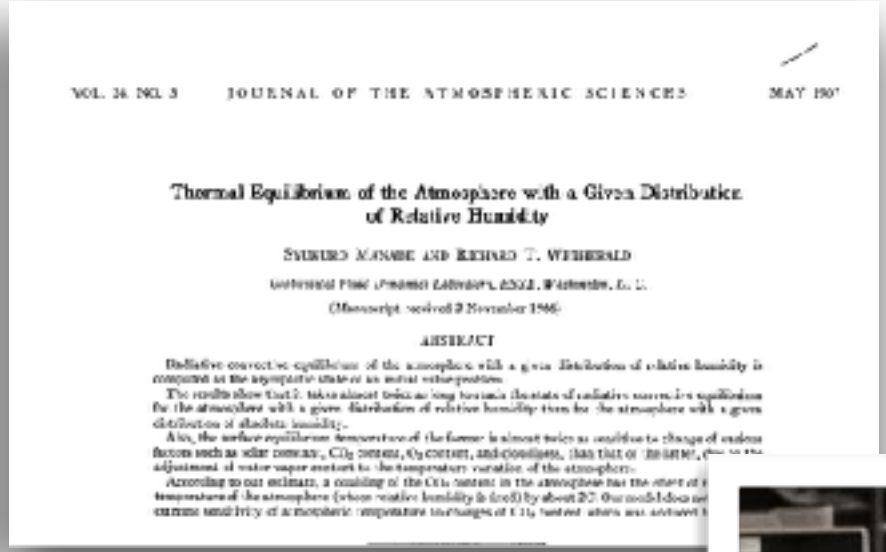
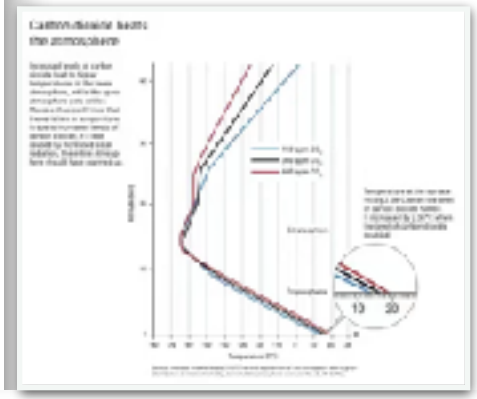
awareness of green house effects from model simulation

Atmosphere-Ocean coupled model (1979-1988) → After 1988

A Historical review of GCMs





Uncertainties of full GCM

- From the governing equations (physical laws)

Equations of motion:

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} = 2\mathbf{\Omega} \times \mathbf{u} - \frac{1}{\rho}\nabla p + \mathscr{F}.$$

Hydrostatic equation:

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Equation of continuity:

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Water budget equation:

$$\frac{\partial r}{\partial t} + \mathbf{u} \cdot \nabla r = E - P.$$

#1

A deep understanding of these physical processes is lacking.

Uncertainties of full GCM

- From the governing equations to numerical simulations

Equations of motion:

Hydrostatic equation:

Equation of continuity:

$$\frac{1}{a\cos\phi}\frac{\partial u}{\partial\lambda}+\frac{1}{a\cos\phi}\frac{\partial(v\cos\phi)}{\partial\phi}+\frac{1}{\rho_R}\frac{\partial(\rho_R w)}{\partial z}=0.$$

Thermodynamic equation:

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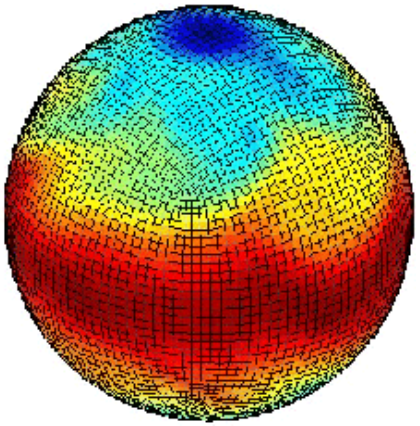
Water budget equation:

$$\frac{\partial r}{\partial t}+\mathbf{u}\cdot\nabla r=E-P.$$

Model can only simulate fluid flow with space and time scales that greater than the model truncations.



#2

Parameterizations of the subgrid-scale processes, e.g. clouds

Uncertainties of full GCM

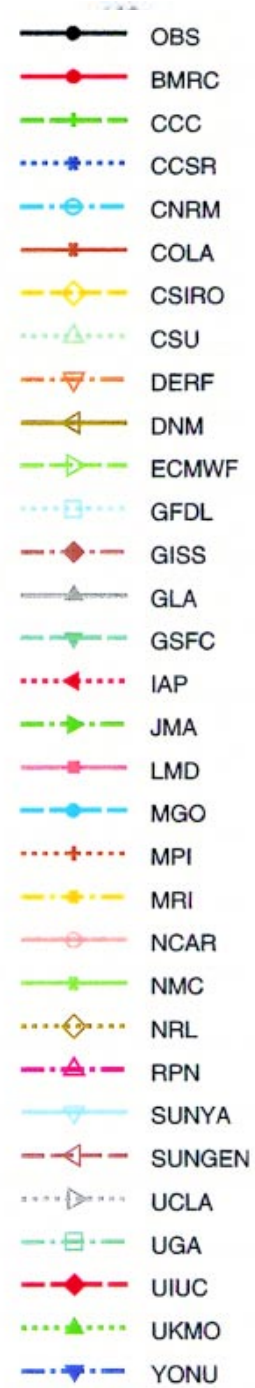
- Model Inter-comparison Projects (e.g. AMIP, CMIP)

The Atmospheric Model Inter-comparison Project (AMIP), initiated in 1989 under the auspices of the World Climate Research Programme, undertook the systematic validation, diagnosis, and intercomparison of the performance of atmospheric general circulation models.

- Taken AMIP I as an example
  - all models were required to simulate the evolution of the climate during the decade 1979–88;
  - under the observed monthly average temperature and sea ice and a common prescribed atmospheric CO2 concentration and solar constant;
  - 31 modeling groups, representing virtually the entire inter- national atmospheric modeling community, had attended the project.

Uncertainties of full GCM

AMIP group	Location
Bureau of Meteorology Research Centre (BMRC)	Melbourne, Australia
Canadian Centre for Climate Modelling and Analysis (CCC)	Victoria, Canada
Center for Climate System Research (CCSR)	Tokyo, Japan
Center for Ocean–Land–Atmosphere Studies (COLA)	Calverton, Maryland
Centre National de Recherches Météorologiques (CNRM)	Toulouse, France
Colorado State University (CSU)	Fort Collins, Colorado
Commonwealth Scientific and Industrial Research Organisation (CSIRO)	Mordialloc, Australia
Department of Numerical Mathematics (DNM)	Moscow, Russia
Dynamical Extended Range Forecasting (DERF at GFDL)	Princeton, New Jersey
European Centre for Medium-Range Weather Forecasts (ECMWF)	Reading, United Kingdom
Geophysical Fluid Dynamics Laboratory (GFDL)	Princeton, New Jersey
Goddard Institute for Space Studies (GISS)	New York, New York
Goddard Laboratory for Atmospheres (GLA)	Greenbelt, Maryland
Goddard Space Flight Center (GSFC)	Greenbelt, Maryland
Institute of Atmospheric Physics (IAP)	Beijing, People's Republic of China
Japan Meteorological Agency (JMA)	Tokyo, Japan



Adapted from Gates et al, 1999

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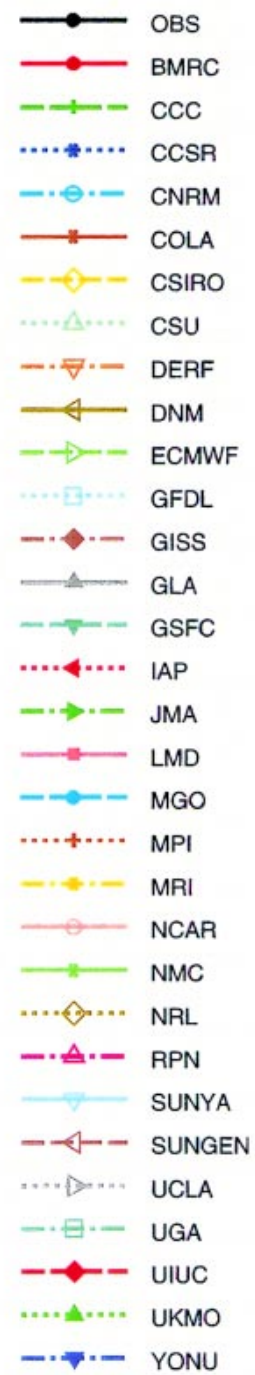
Uncertainties of full GCM

AMIP group	Location
Laboratoire de Météorologie Dynamique (LMD)	Paris, France
Main Geophysical Observatory (MGO)	St. Petersburg, Russia
Max-Planck-Institut für Meteorologie (MPI)	Hamburg, Germany
Meteorological Research Institute (MRI)	Ibaraki-ken, Japan
National Center for Atmospheric Research (NCAR)	Boulder, Colorado
National Meteorological Center (NMC)	Suitland, Maryland
Naval Research Laboratory (NRL)	Monterey, California
Recherche en Prévision Numérique (RPN)	Dorval, Canada
State University of New York at Albany (SUNYA)	Albany, New York
State University of New York at Albany/National Center for Atmospheric Research (SUNYA/NCAR)	Albany, New York/ Boulder, Colorado
University of California, Los Angeles (UCLA)	Los Angeles, California
The UK Universities' Global Atmospheric Modelling Programme (UGAMP)	Reading, United Kingdom
University of Illinois, Urbana–Champaign (UIUC)	Urbana, Illinois
United Kingdom Meteorological Office (UKMO)	Bracknell, United Kingdom
Yonsei University (YONU)	Seoul, Korea



Adapted from Gates et al, 1999

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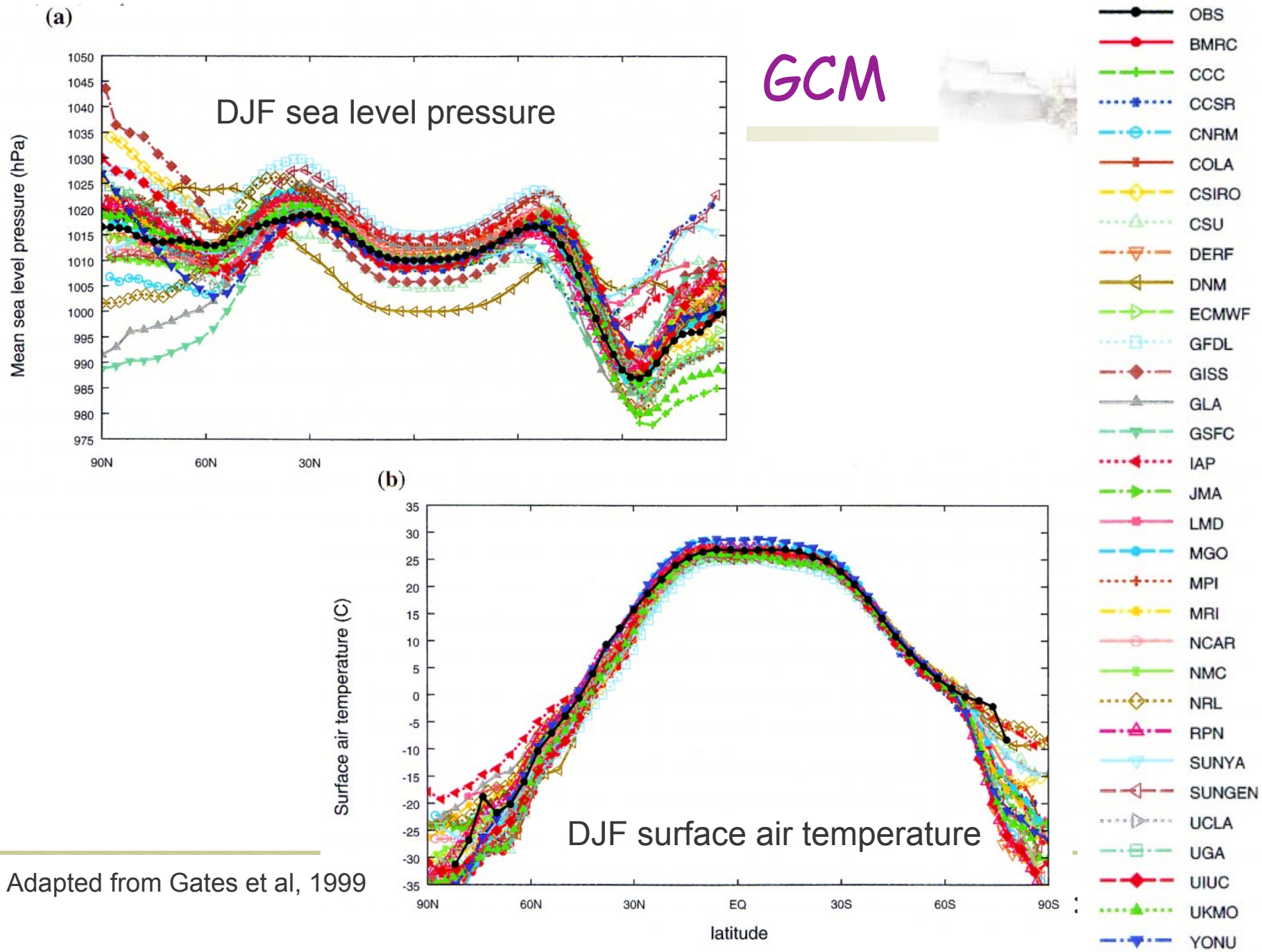
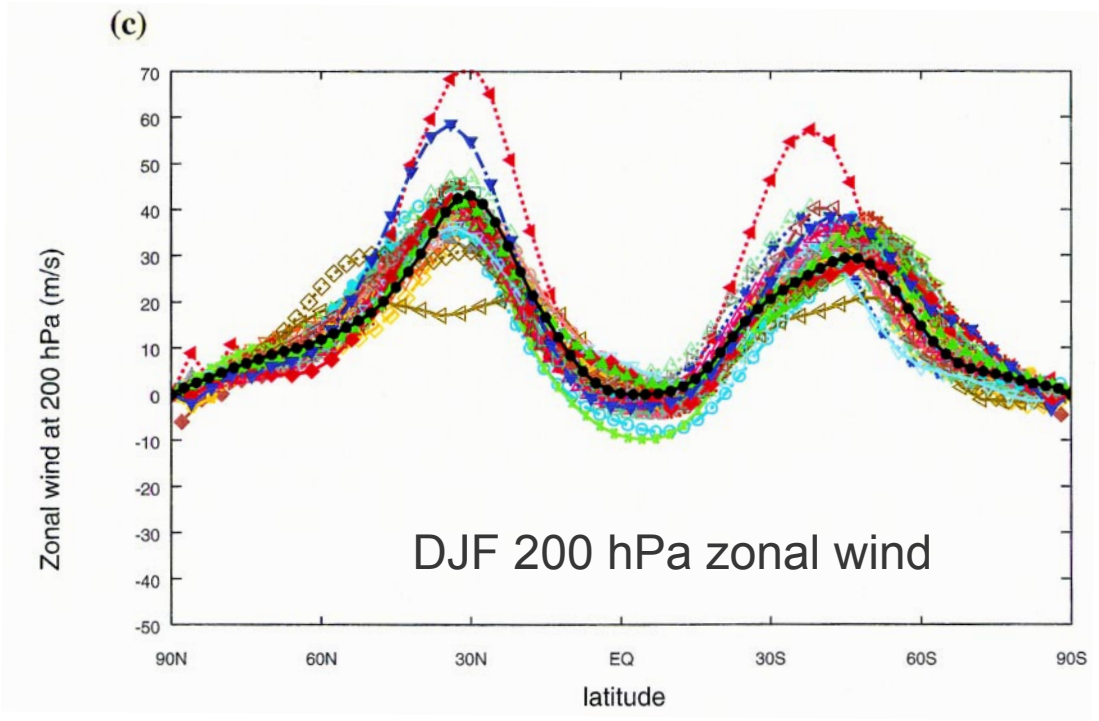
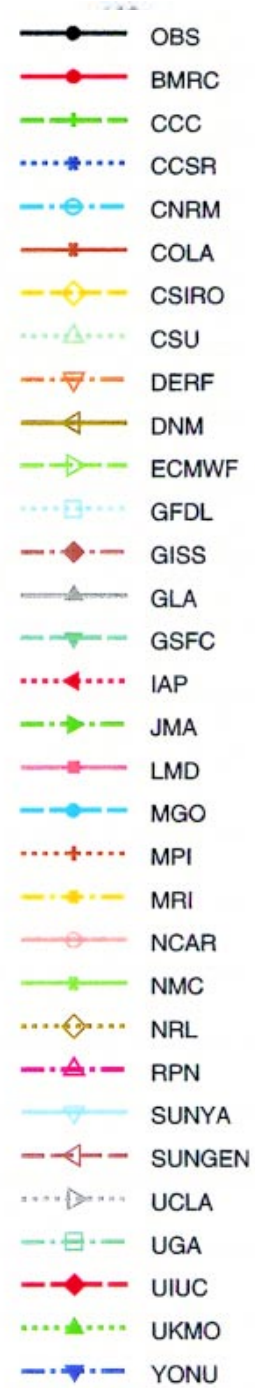
GCM



Adapted from Gates et al, 1999

Uncertainties of full GCM





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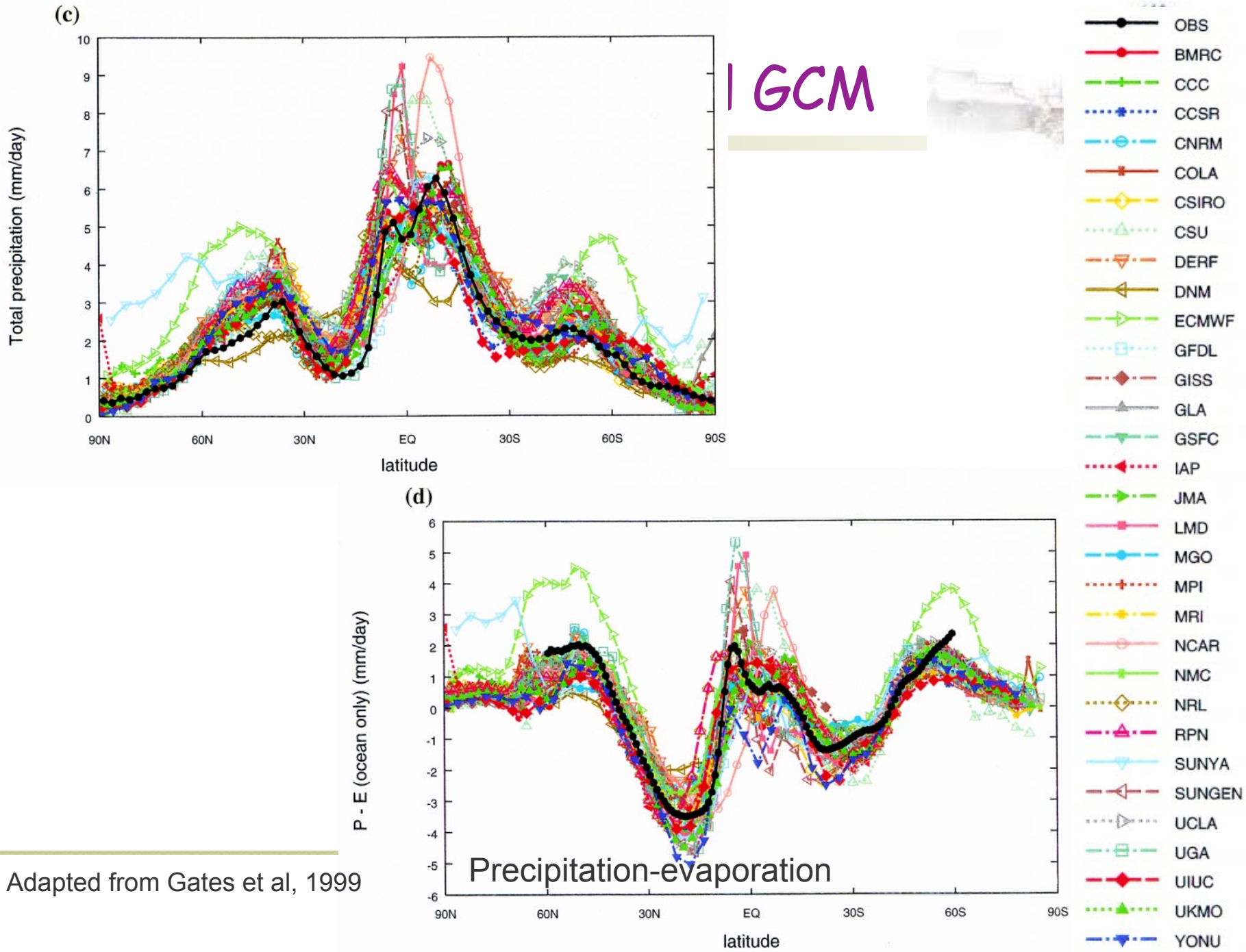

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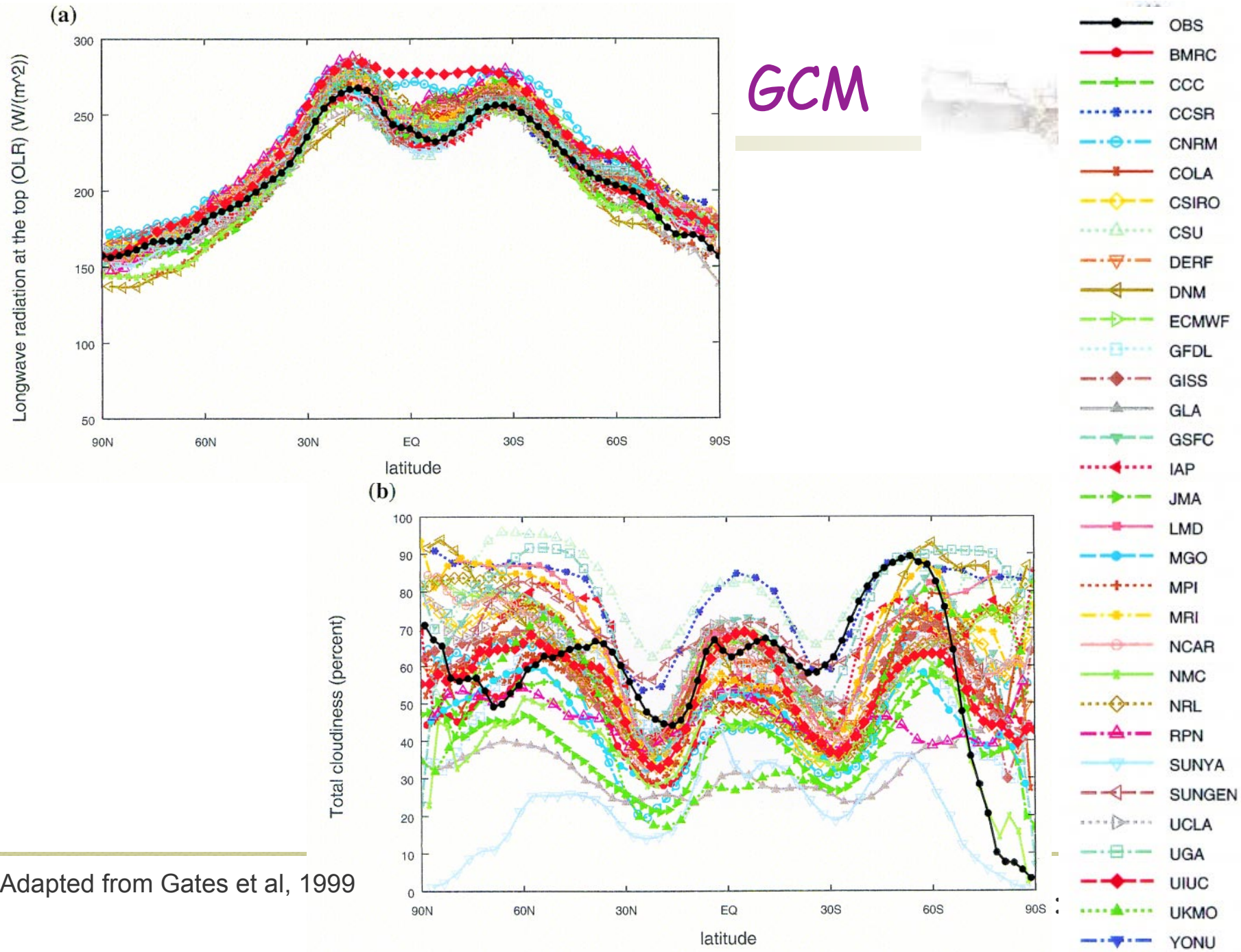
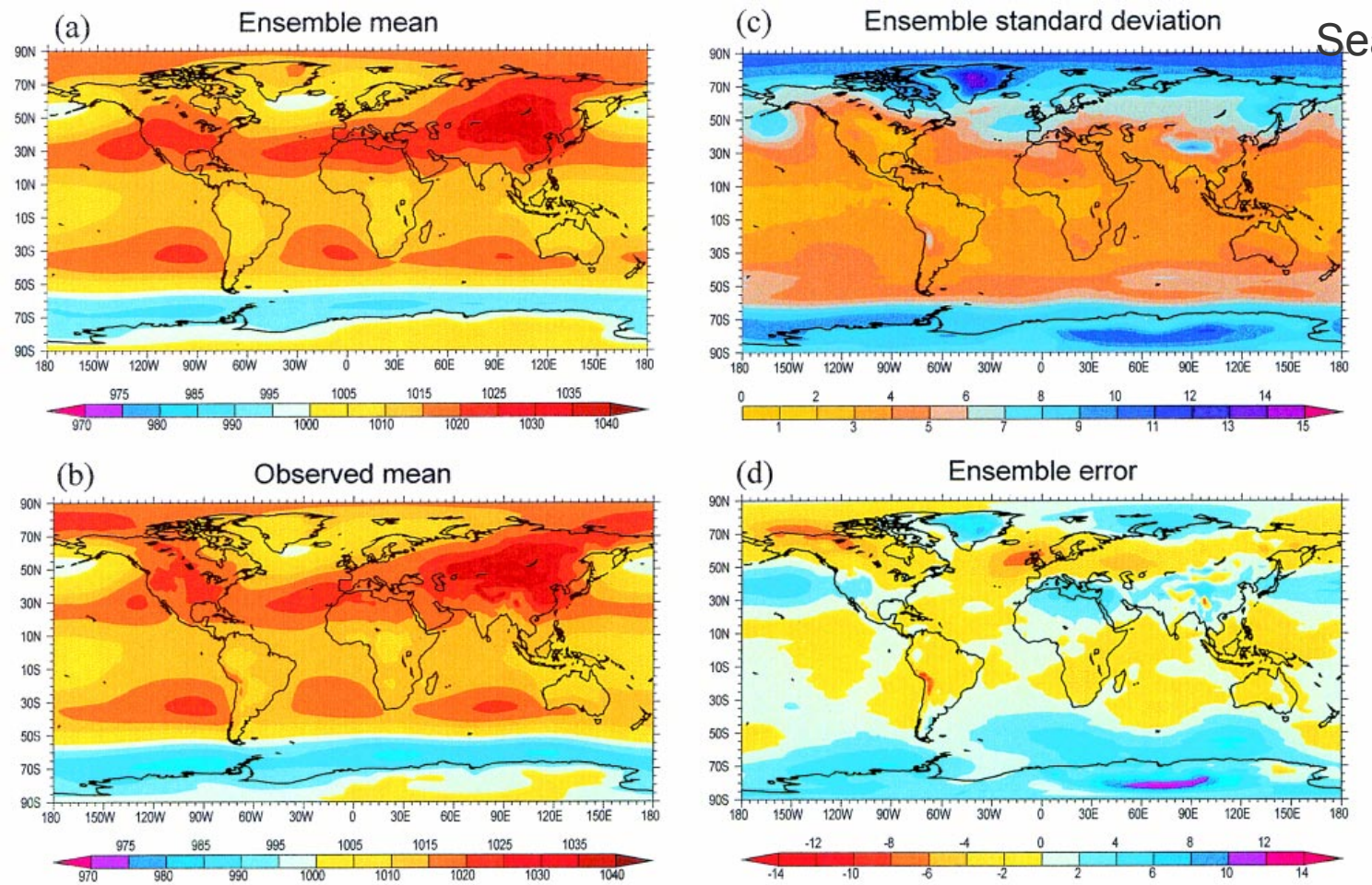
GCM



Adapted from Gates et al, 1999

Uncertainties of full GCM

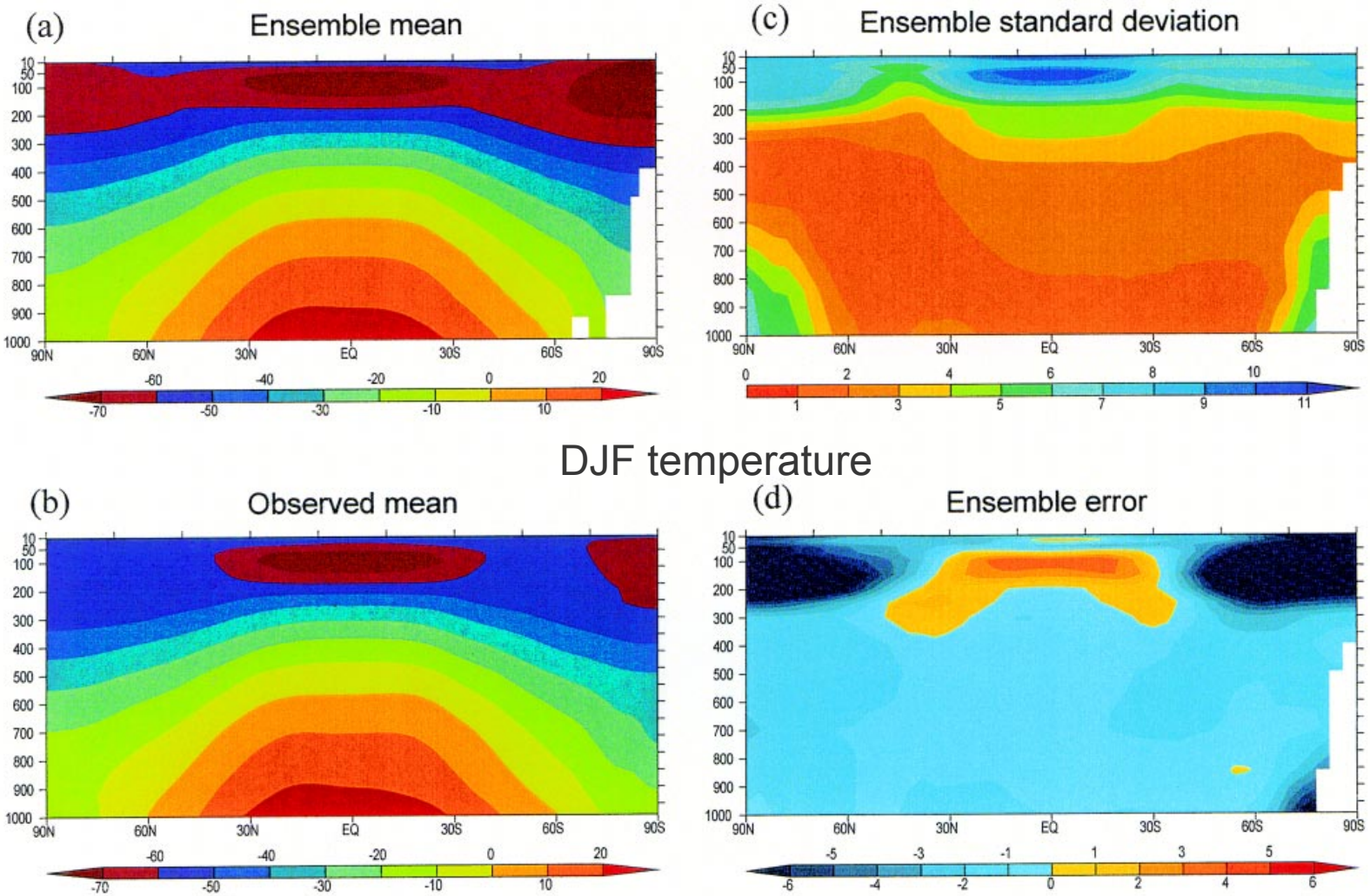


Sea level pressure in DJF

Gates et al, 1999

FIG. 1. The geographical distribution of mean sea level pressure (hPa) in DJF of 1979–88 given by (a) the AMIP ensemble mean, and (b) by data from the ECMWF reanalysis (Gibson et al. 1997) for 1979–88. (c) The standard deviation (hPa) of the model ensemble, and (d) the error (ensemble mean minus observation; hPa).

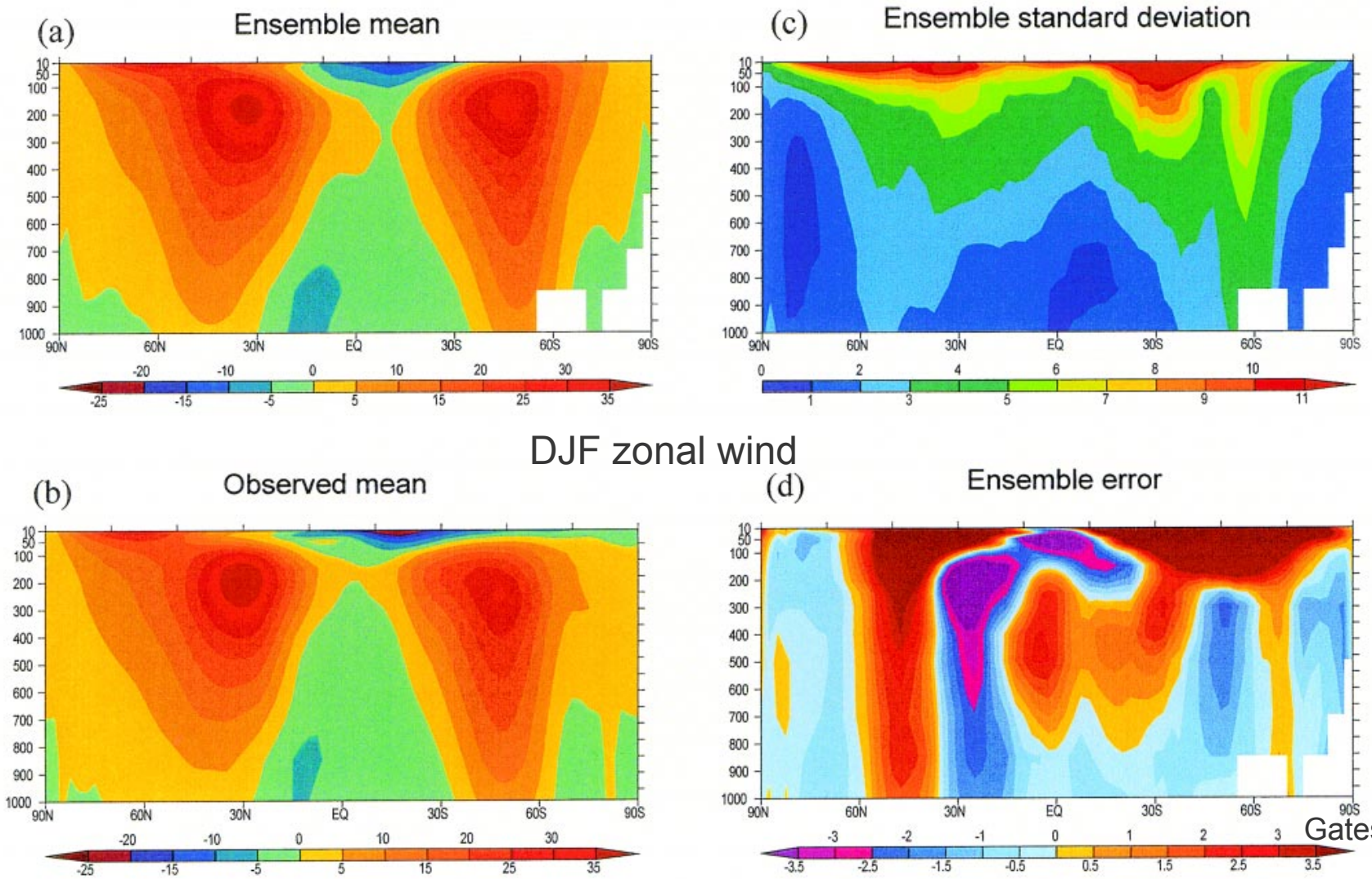
Uncertainties of full GCM



Gates et al, 1999

FIG. 8. (a) The latitude–pressure meridional section of the temperature (°C) given by the AMIP ensemble mean and (b) the observed data from the ECMWF reanalysis (Gibson et al. 1997). (c) The standard deviation of the ensemble mean and (d) the ensemble error. The pressure units are hPa.

Uncertainties of full GCM

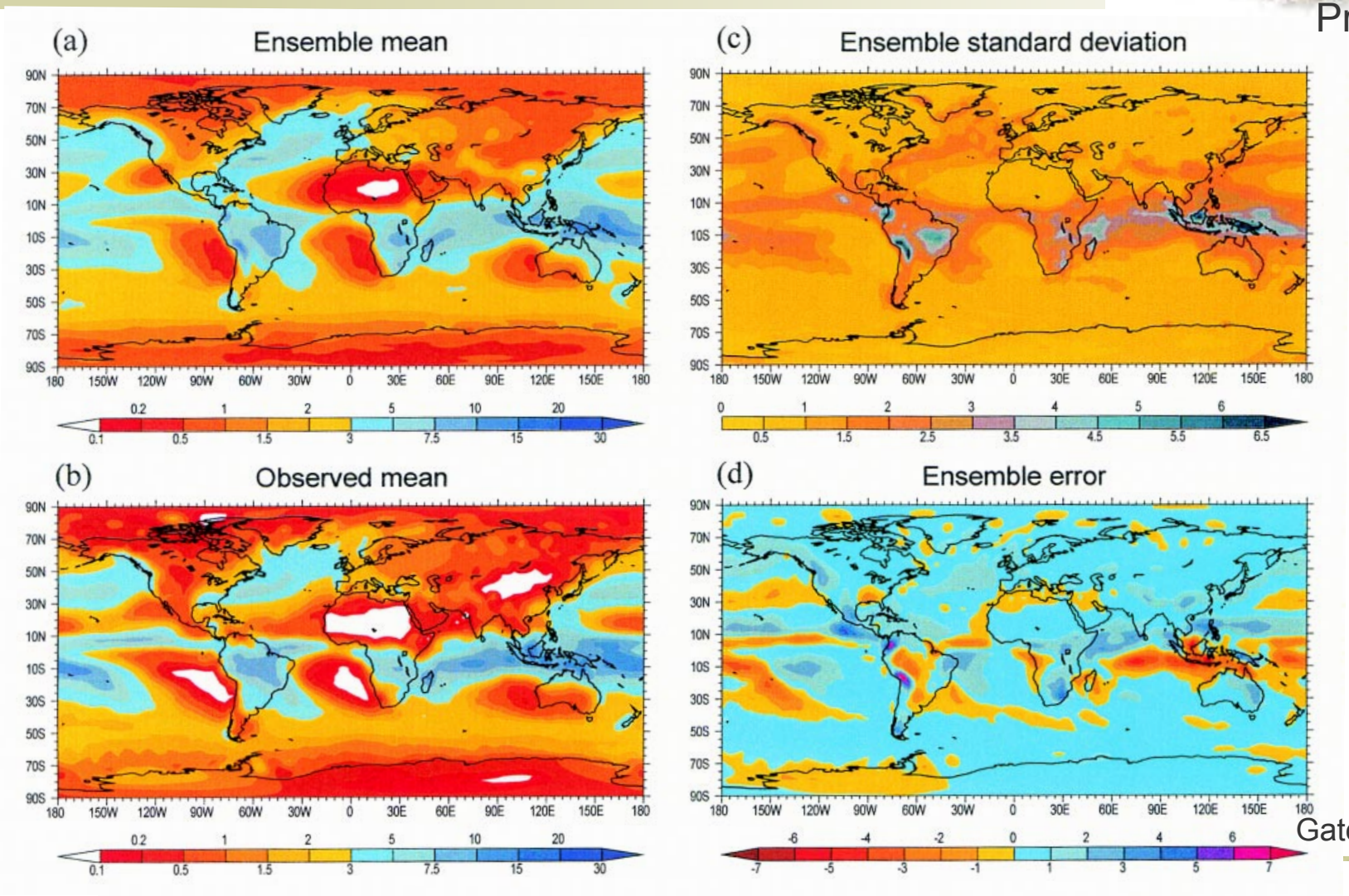


Gates et al, 1999

FIG. 9. As in Fig. 8 except for the zonal wind (m s^{-1}), with the observed estimate taken from the ECMWF reanalysis (Gibson et al. 1997).

Uncertainties of full GCM

Precipitation in DJF

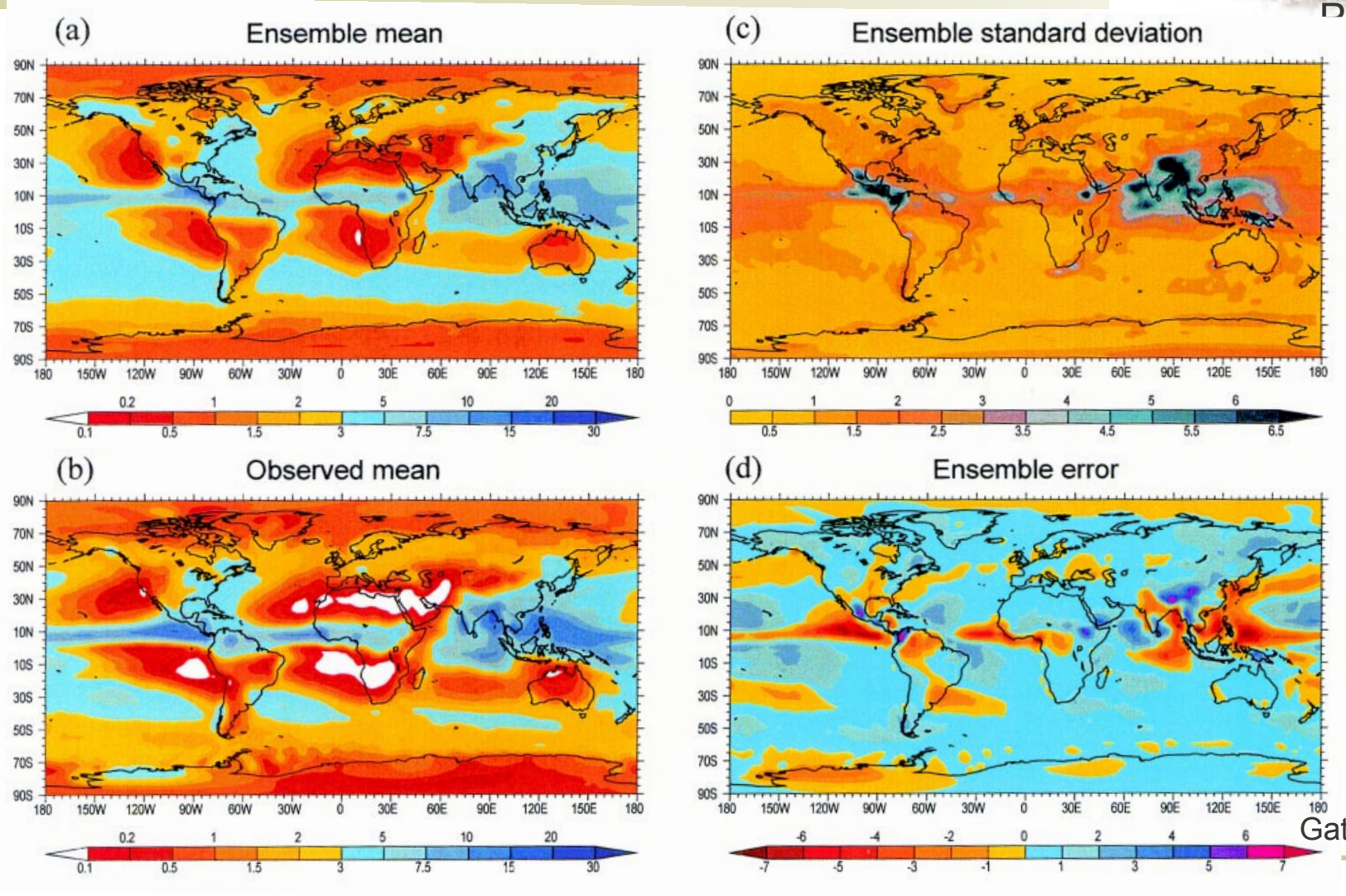


Gates et al, 1999

FIG. 3. As in Fig. 1 except for precipitation (mm day^{-1}), with observations for 1979–88 from the NCEP database (Xie and Arkin 1997). Note the nonlinear scale in (a) and (b).

Uncertainties of full GCM

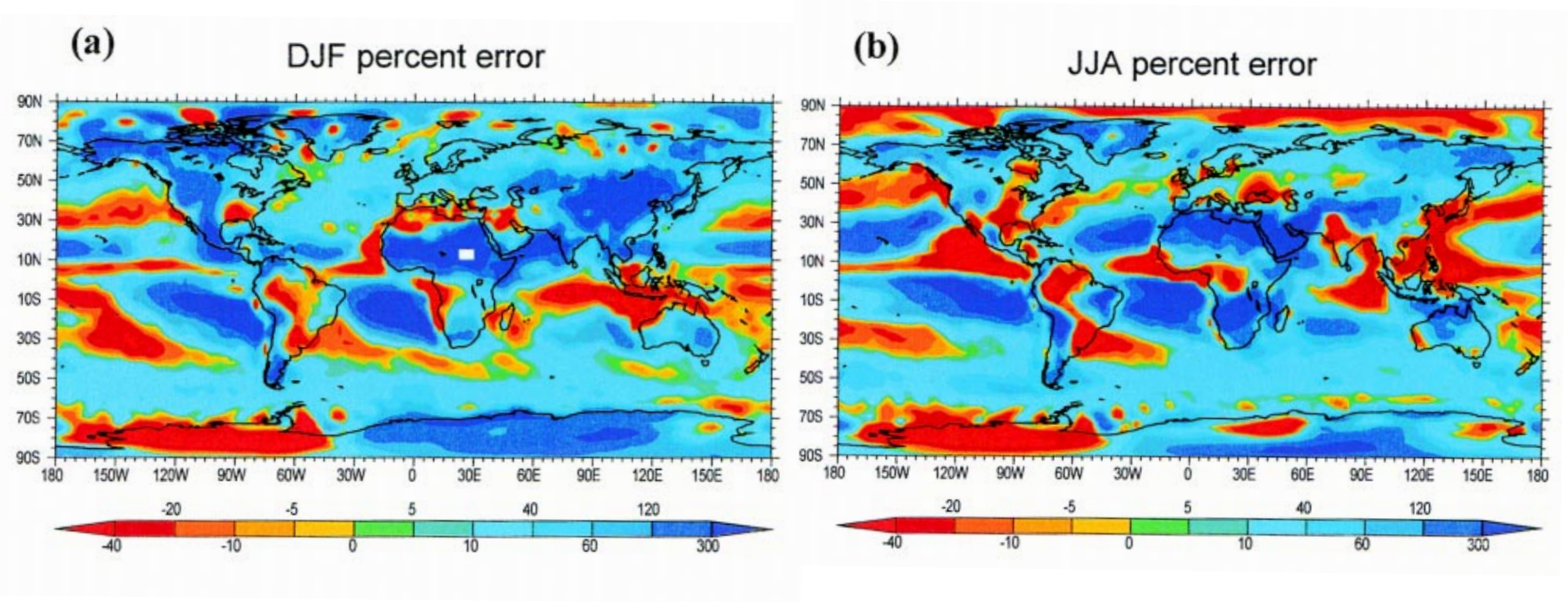
Precipitation in JJA



Gates et al, 1999

FIG. 4. As in Fig. 3 except for JJA.

Uncertainties of full GCM



precipitation

Gates et al, 1999

Uncertainties of full GCM

- A summary from the AMIP I results:
  - Ensemble mean shows that the average large-scale seasonal distributions of pressure, temperature, and circulation are reasonably close to what are believed to be the best observational estimates available;
  - The average large-scale distributions of pressure, temperature and circulation shows relatively large intermodel differences in high/polar latitudes compared to low/mid latitudes.
  - The large-scale structure of the ensemble mean precipitation also resembles the observed estimates but show particularly large intermodel differences in low latitudes.
  - The total cloudiness, on the other hand, is rather poorly simulated.

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  from the numerical wether prediction, idealized model to full GCMs
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A hierarchy of GCMs: From idealized model to full GCM

The need for model hierarchies

The complexity of the climate system presents a challenge to climate theory, and to the manner in which theory and observations interact, eliciting a range of responses. On the one hand, we try to *simulate* by capturing as much of the dynamics as we can in comprehensive numerical models. On the other hand, we try to *understand* by simplifying and capturing the essence of a phenomenon in idealized models, or even with qualitative pictures.

Constructing a hierarchy

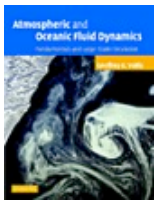
The simpler the model that explains some aspect of climate dynamics the better! But the claim is that there are sources of complexity in the climate system that prevent us from generating convincing simple quantitative theories for many of the questions that interest us. My concern here is with models that attack some of the core sources of complexity in the climate system, that allow one to address questions of climate maintenance and sensitivity...

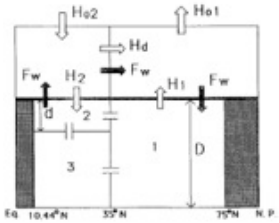
From Issac Held, *The Gap between Simulation and Understanding in Climate Modeling*, BAMS, 2005.

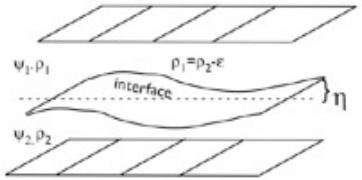
A hierarchy of GCMs: From idealized model to full GCM

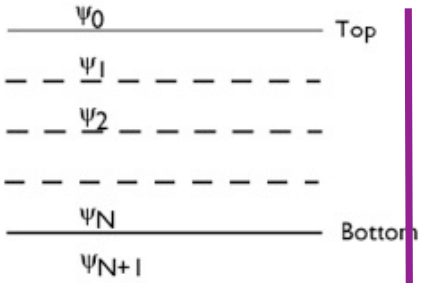
- An example for using hierarchy of models to study the role of eddies

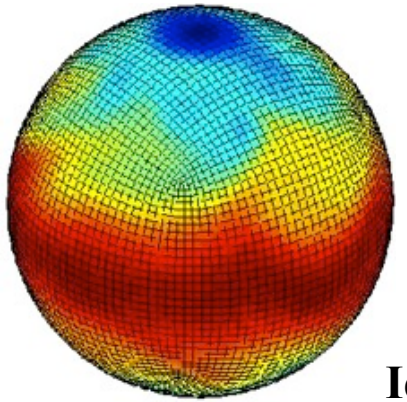
GFD → **Box model** → **Quasi-geostrophic model** → **Multi-layer modified QG model**



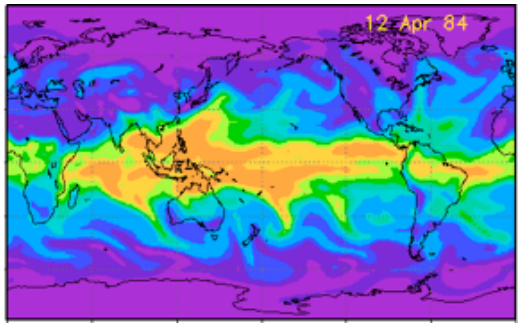








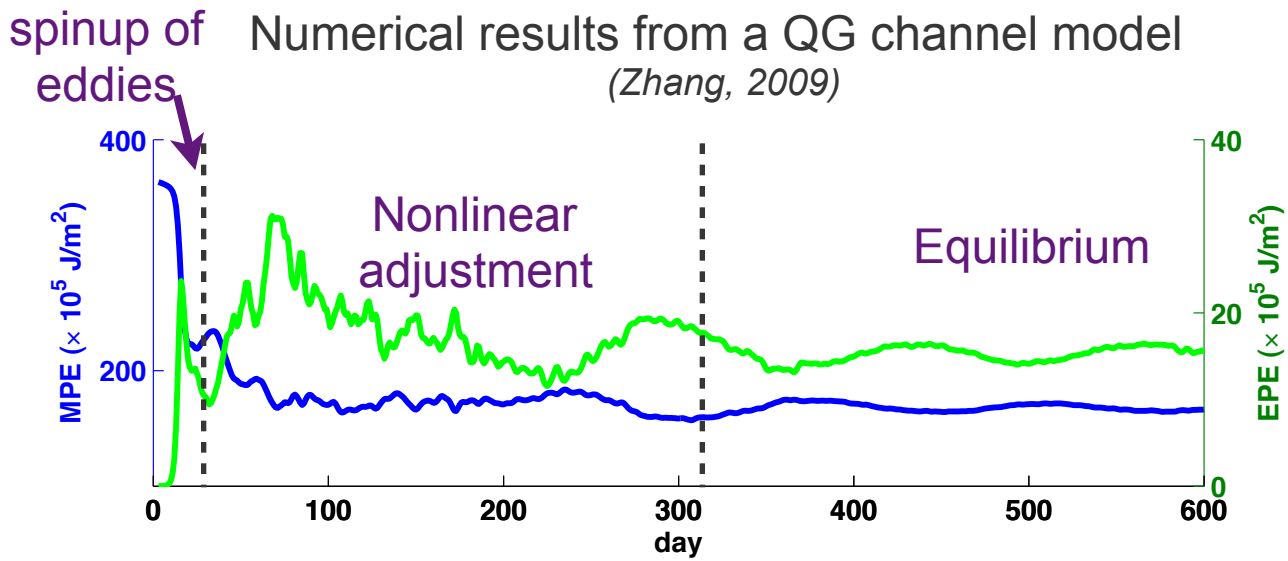
Idealized GCM



Full GCM

QG channel model

From Chap4.3, baroclinic eddies



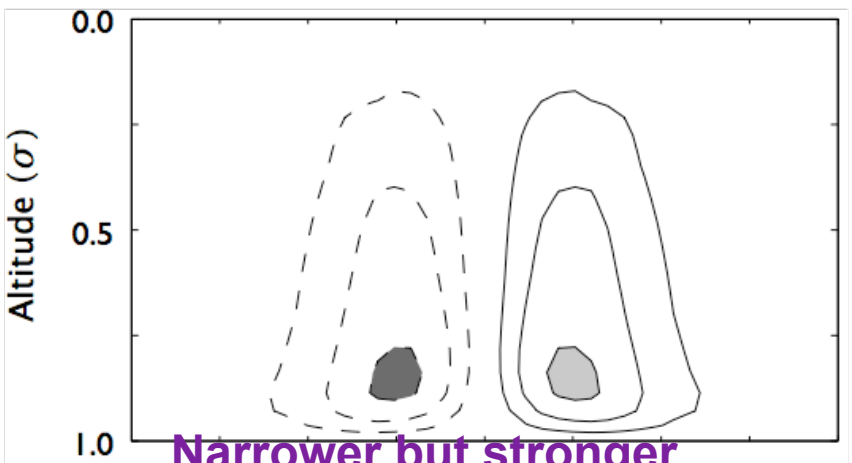
Some examples of idealized model

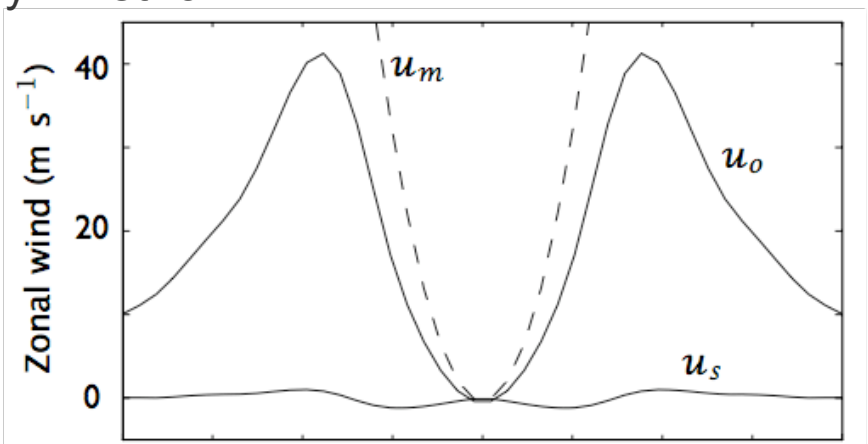
Dynamical core

From Chap3.2, Hadley Circulation

Vallis, 2006,
numerical results from idealized GCM

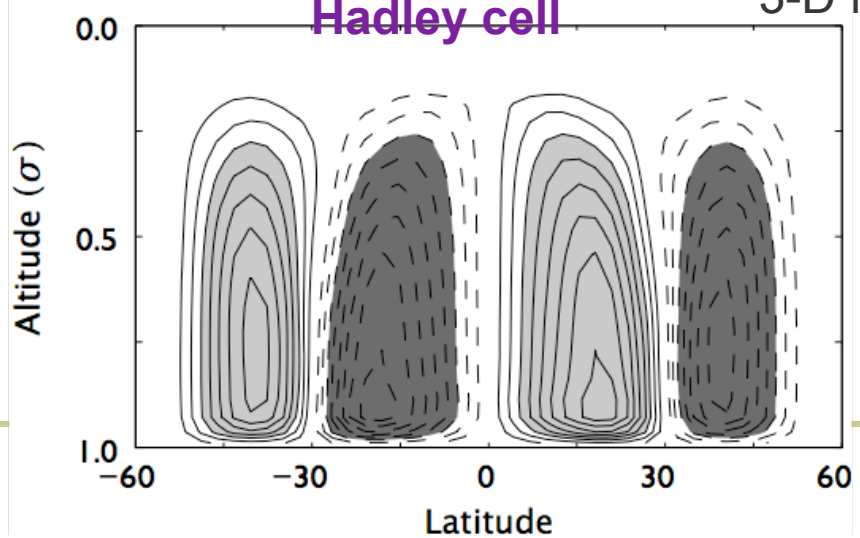
axisymmetric

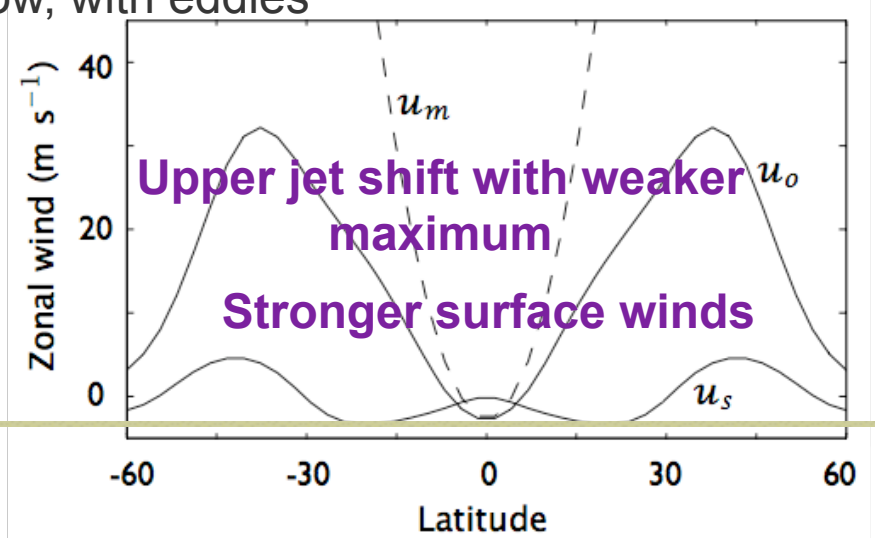




Narrower but stronger Hadley cell

3-D flow, with eddies



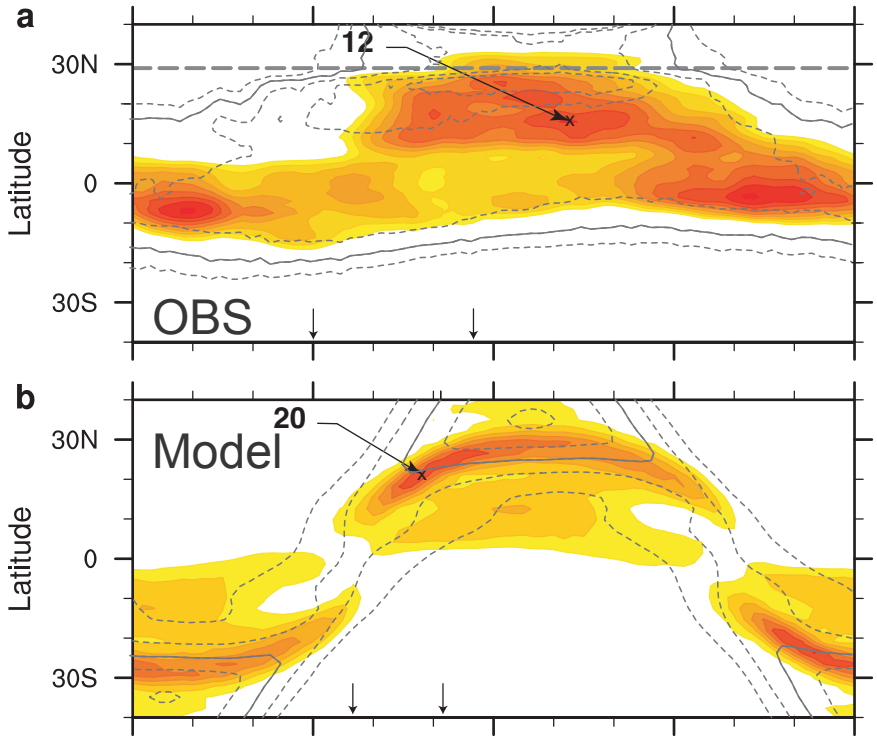


Upper jet shift with weaker maximum

Stronger surface winds

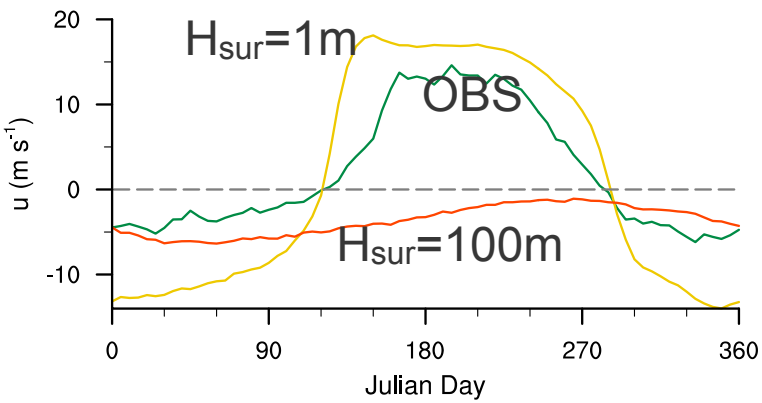
Some examples of idealized model

Aqua-planet model



Numerical results from idealized aqua-planet model:

- ocean surface all the globe
- no orography
- only vary depth of the ocean mixed layer



(Bordoni and Schneider, 2010)

From Chap 6.2, monsoonal circulation