



第七章:

大气环流模式 (General Circulation Model)

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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:

Equations of motion:

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

Hydrostatic equation:

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

Equation of continuity:

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

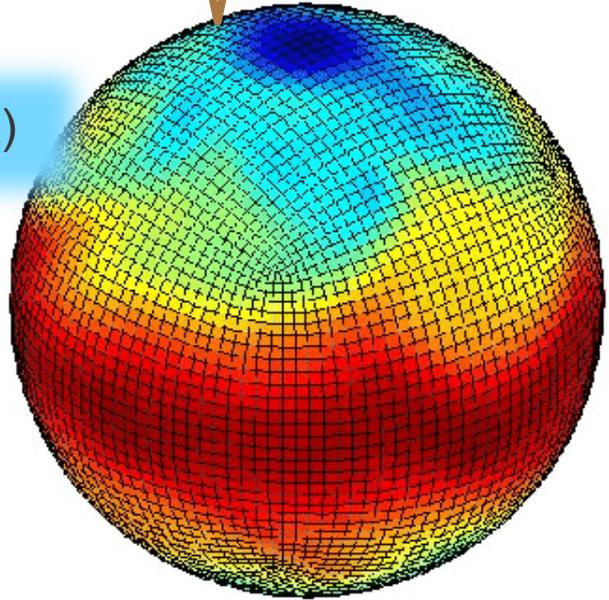
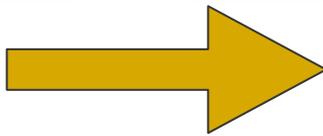
Thermodynamic equation:

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

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

Given the initial condition
Integrate over time

$u(x,y,z)$ → $u(i,j,k)$





Outline



- Introduction
- A historical review of GCMs
 - from the numerical weather 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



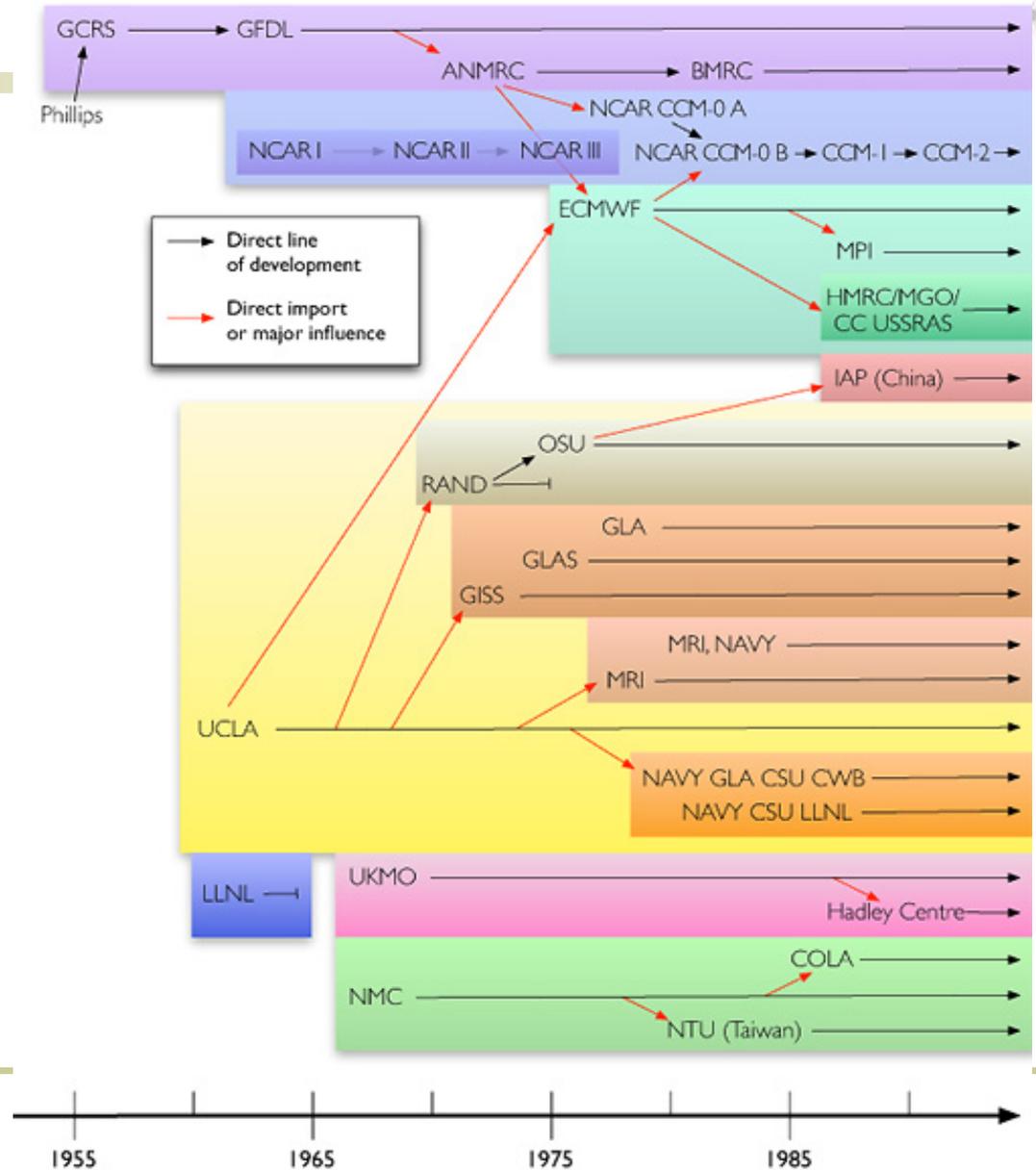
■ Launch of GCM projects

- 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





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

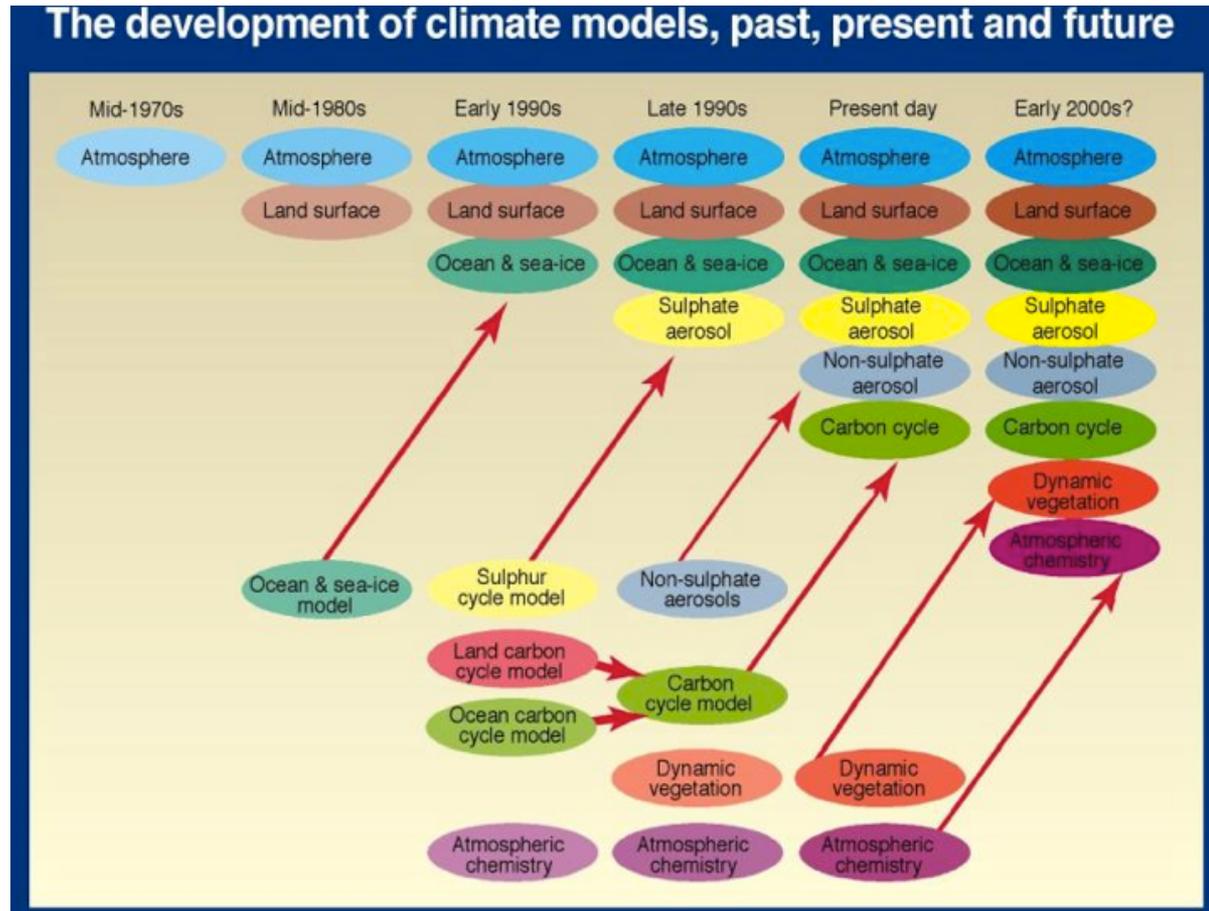
“General Circulation Model”

to

“Global Climate Model”

or

“Global Coupled Model”





A Historical review of GCMs



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After 1988



awareness of green house
effects from model simulation



Uncertainties of full GCM



- From the governing equations (physical laws)

Equations of motion:

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

Hydrostatic equation:

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Equation of continuity:

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Thermodynamic equation:

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

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:

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

Hydrostatic equation:

Equation of continuity:

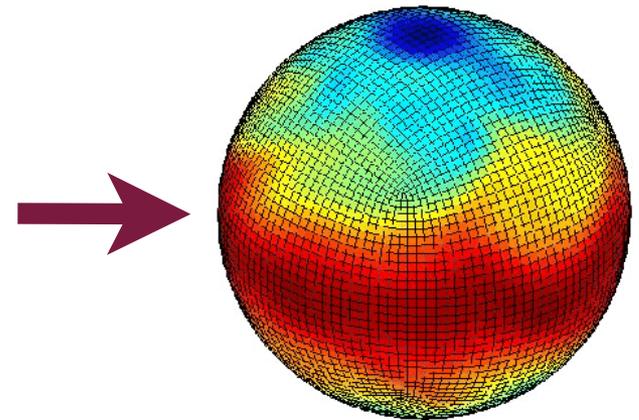
$$\frac{1}{a \cos \phi} \frac{\partial u}{\partial \lambda} + \frac{1}{a \cos \phi} \frac{\partial (v \cos \phi)}{\partial \phi} + \frac{1}{\rho_R} \frac{\partial (\rho_R w)}{\partial z} = 0.$$

Thermodynamic equation:

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

Water budget equation:

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



#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 international 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 |

- OBS
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- CCC
- CCSR
- CNRM
- COLA
- CSIRO
- CSU
- DERF
- DNM
- ECMWF
- GFDL
- GISS
- GLA
- GSFC
- IAP
- JMA
- LMD
- MGO
- MPI
- MRI
- NCAR
- NMC
- NRL
- RPN
- SUNYA
- SUNGEN
- UCLA
- UGA
- UIUC
- UKMO
- YONU

Adapted from Gates et al, 1999

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Uncertainties of full GCM

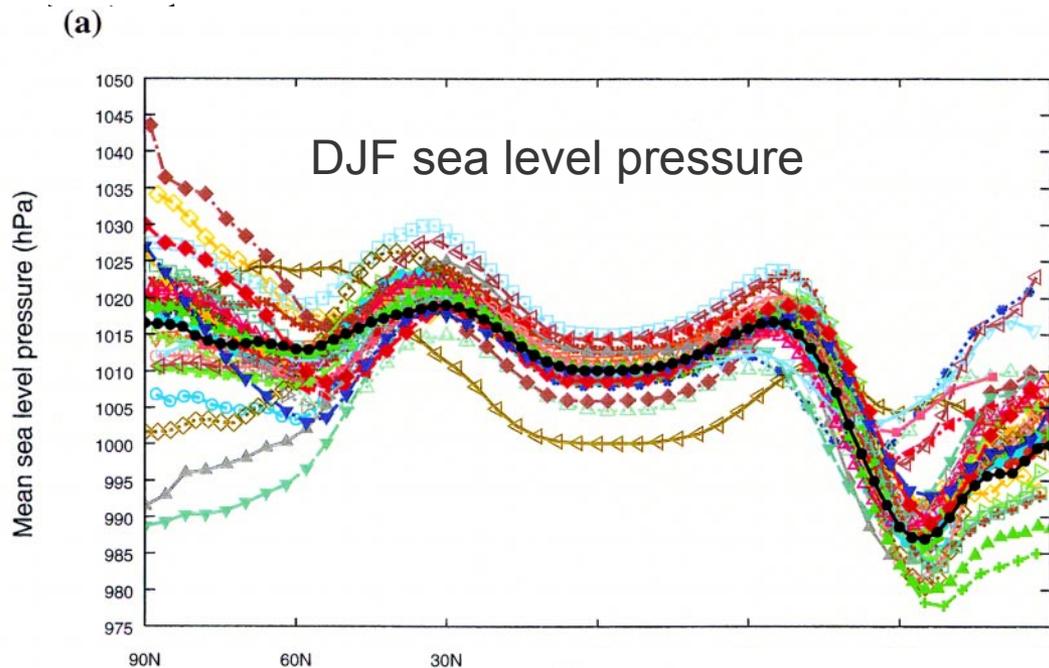


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| AMIP group | Location |
|--|--|
| Laboratoire de Météorologie Dynamique (LMD) | Paris, France |
| Main Geophysical Observatory (MGO) | St. Petersburg, Russia |
| Max-Planck-Institut für Meteorologie (MPI) | Hamburg, Germany |
| Meteorological Research 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

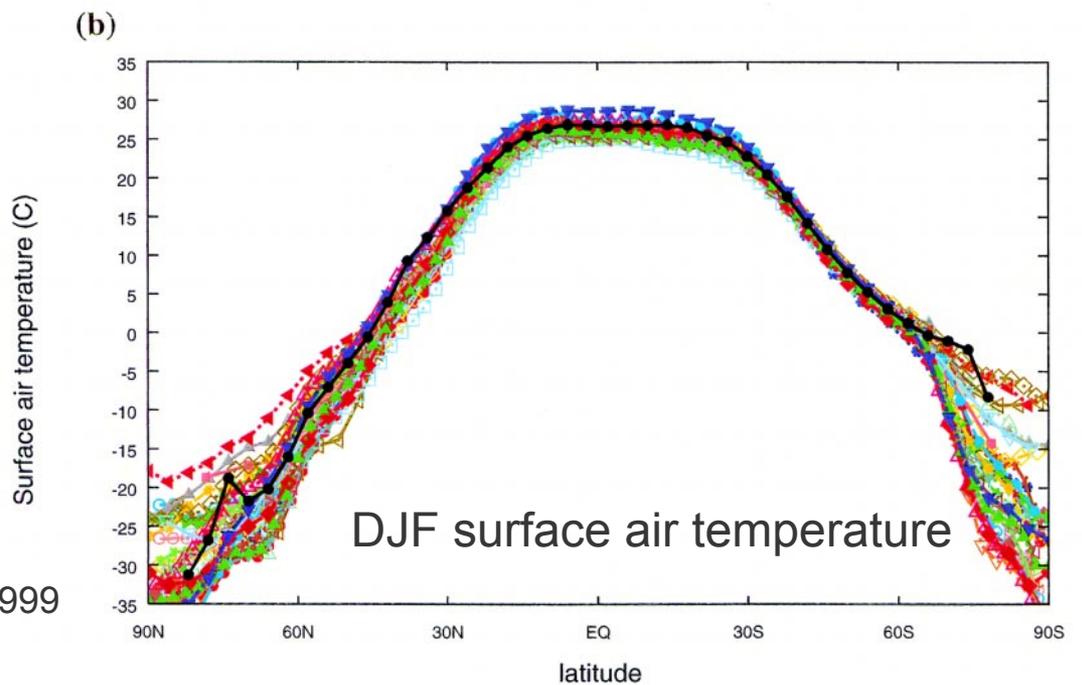
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GCM



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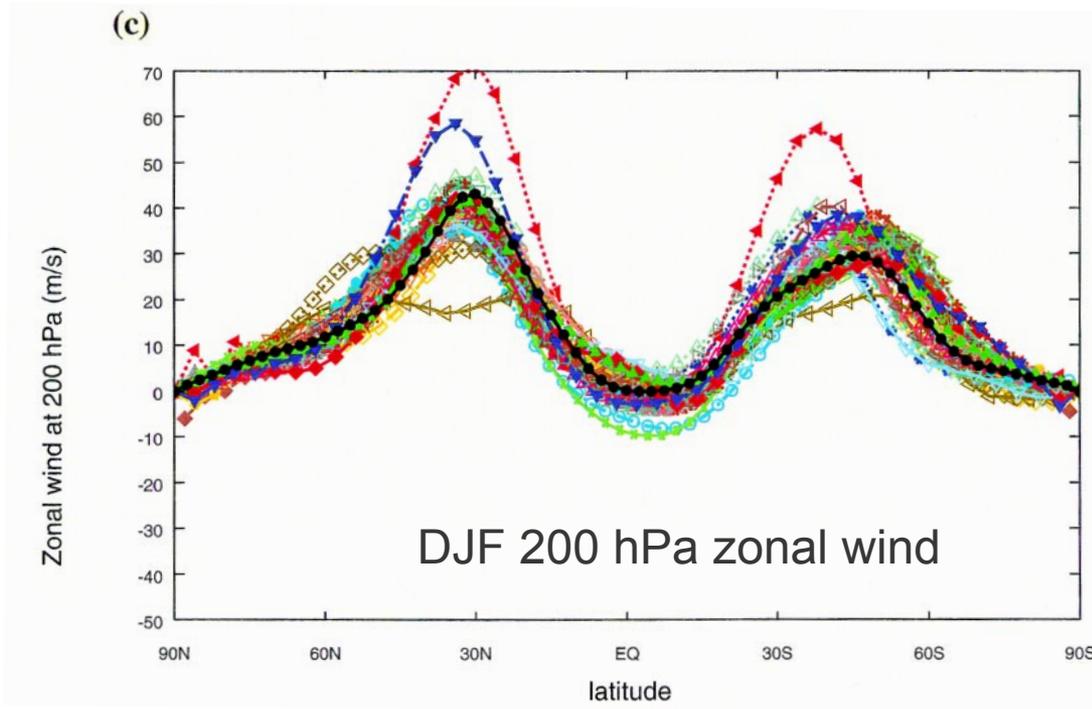
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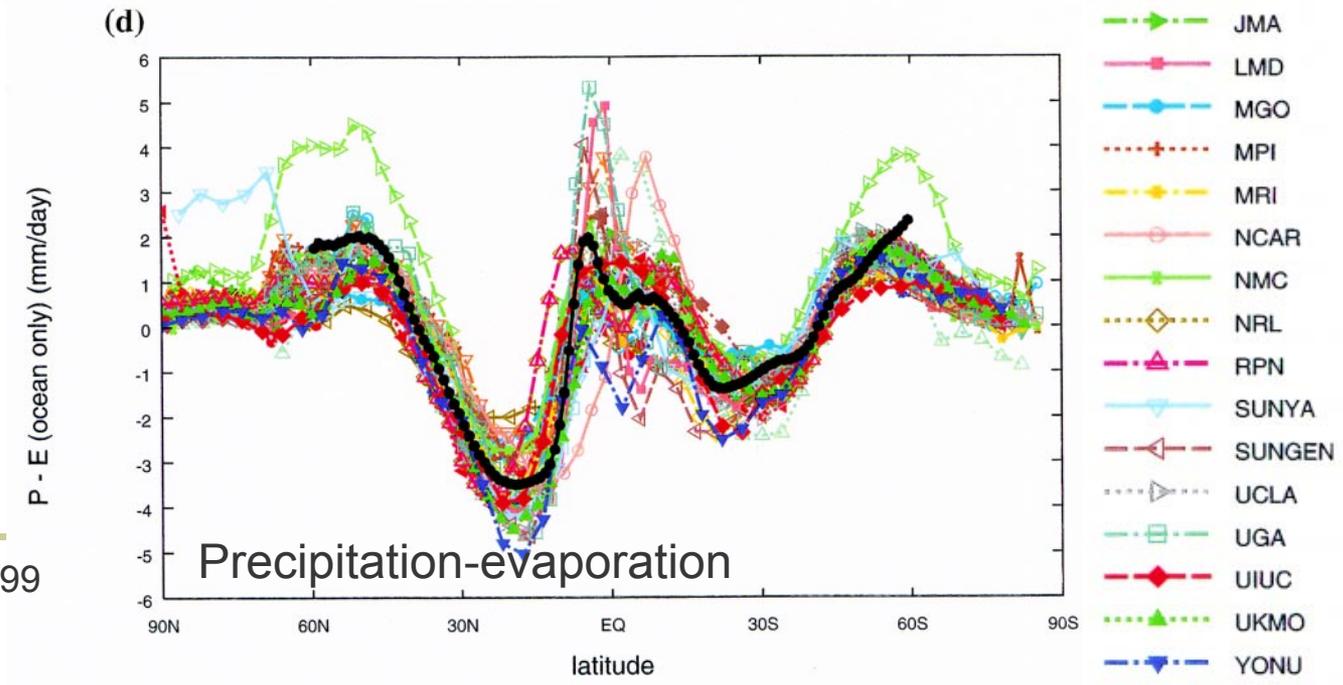
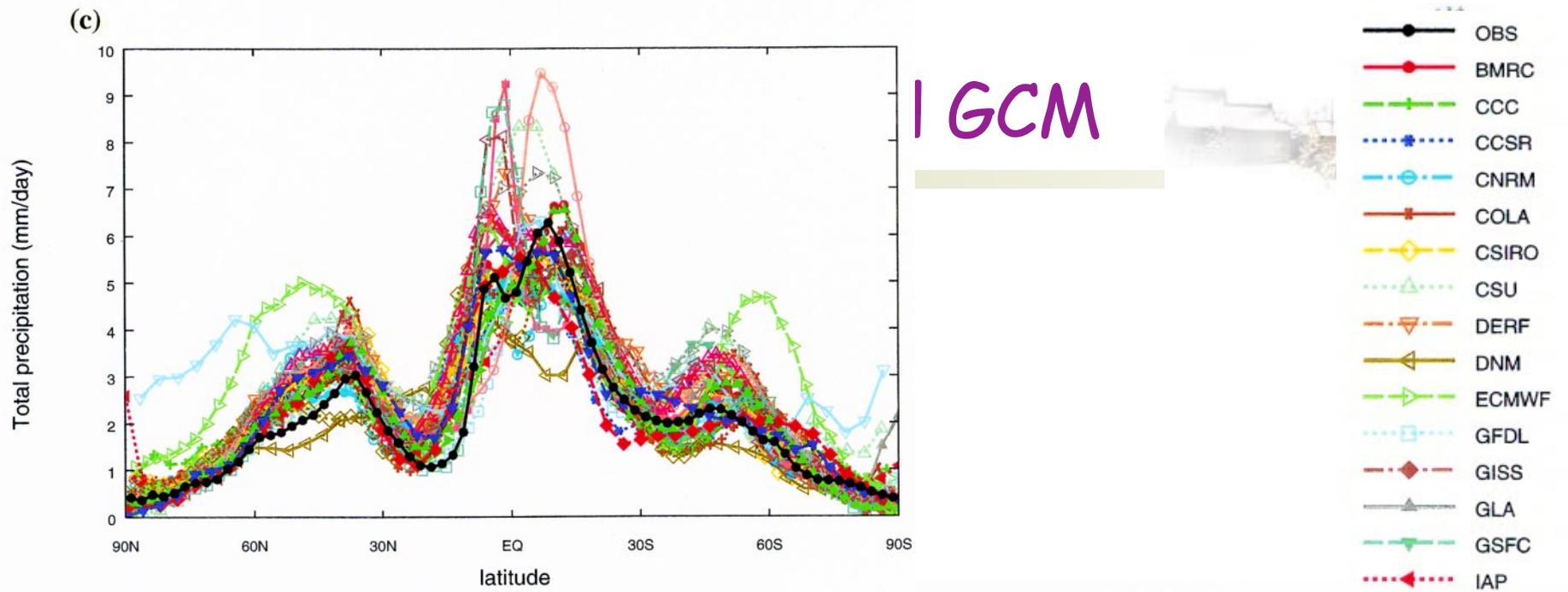


Uncertainties of full GCM

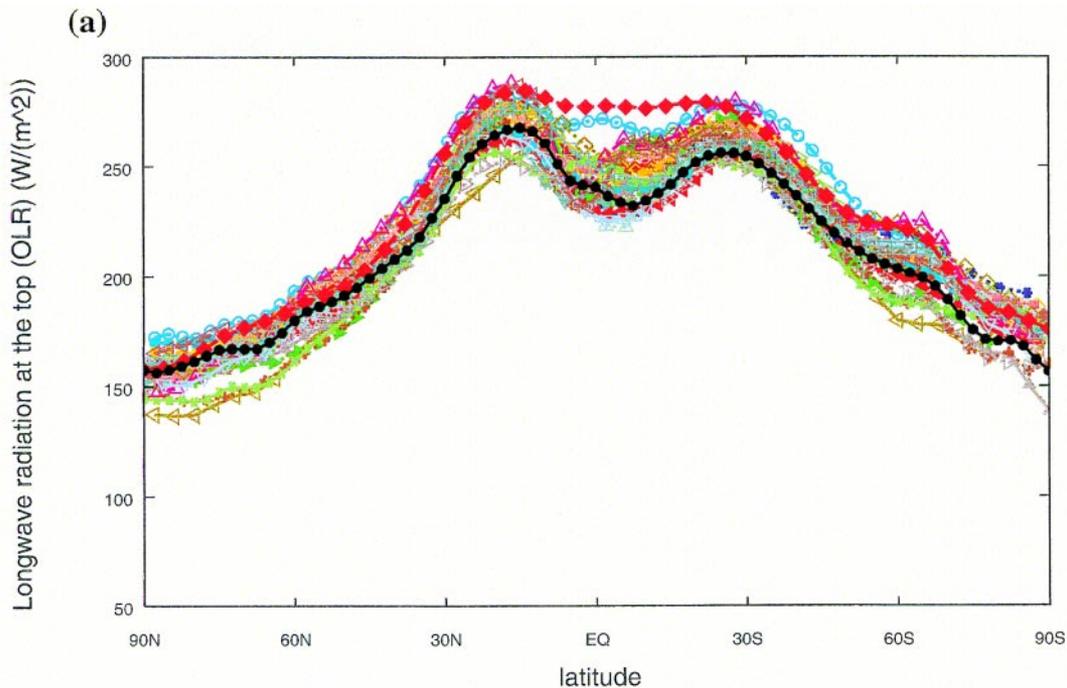


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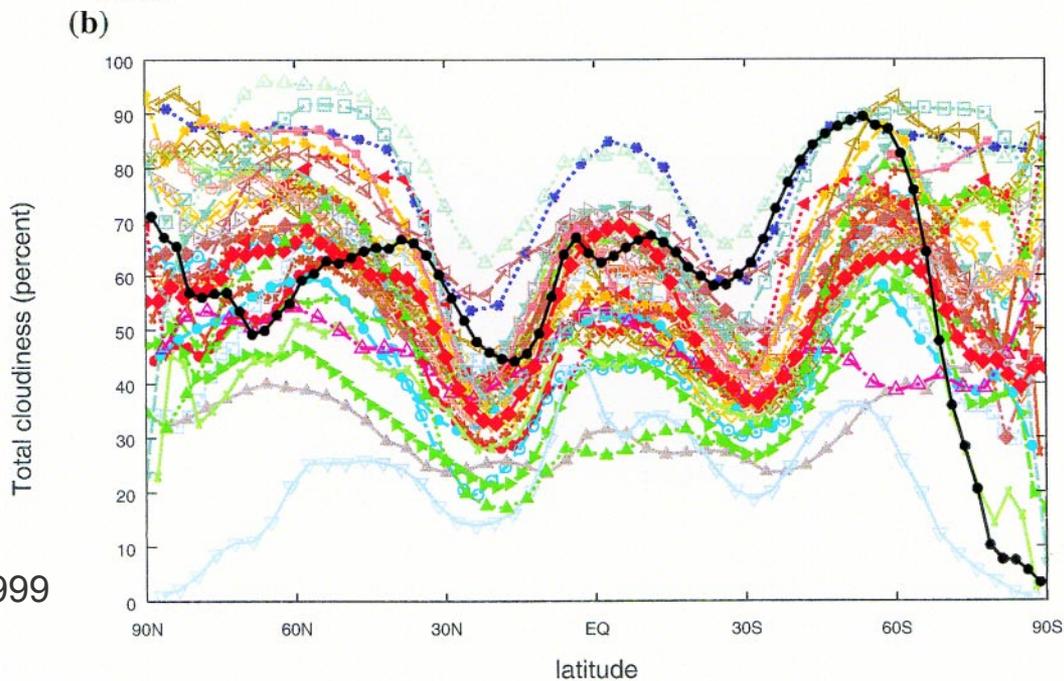
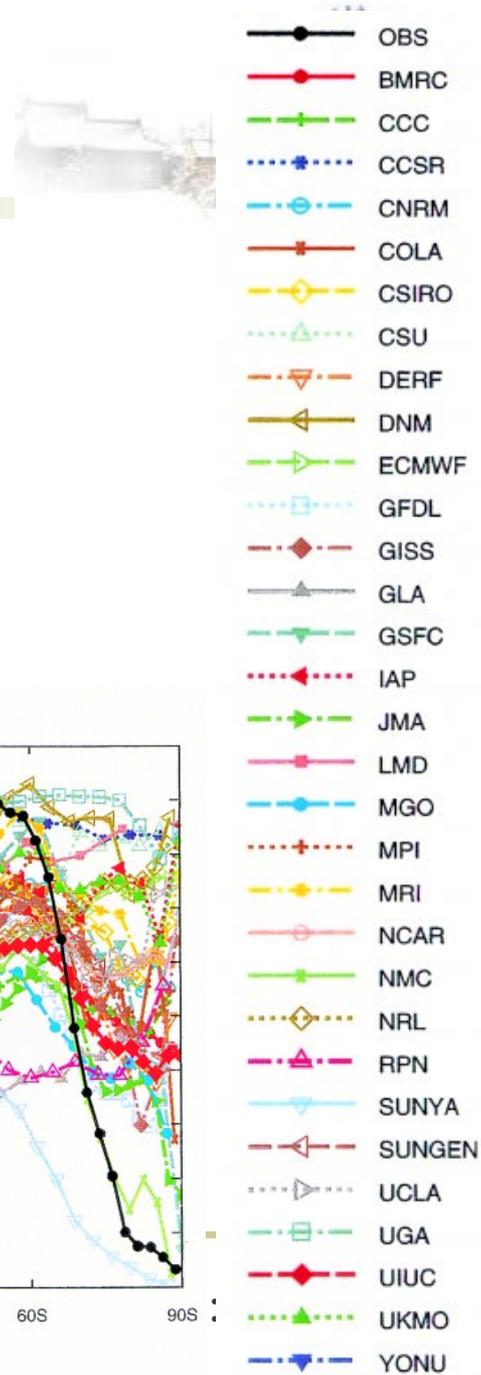




Adapted from Gates et al, 1999



GCM



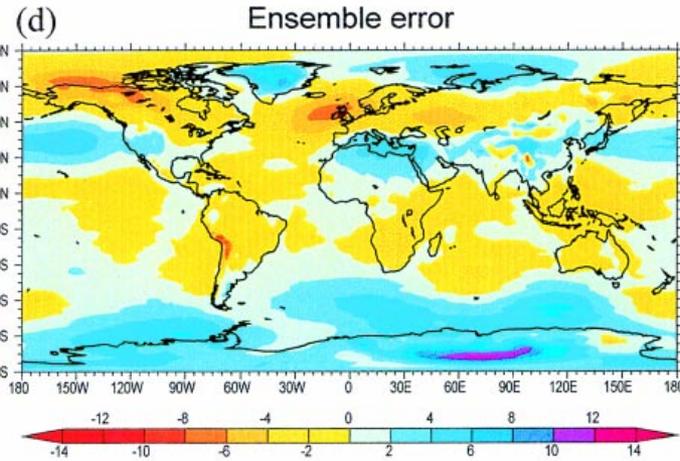
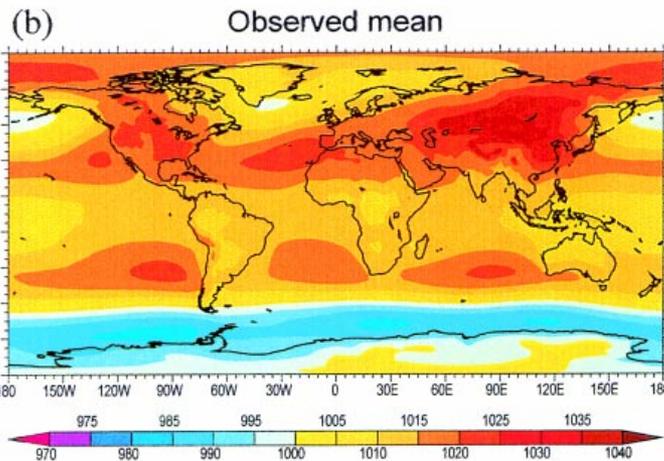
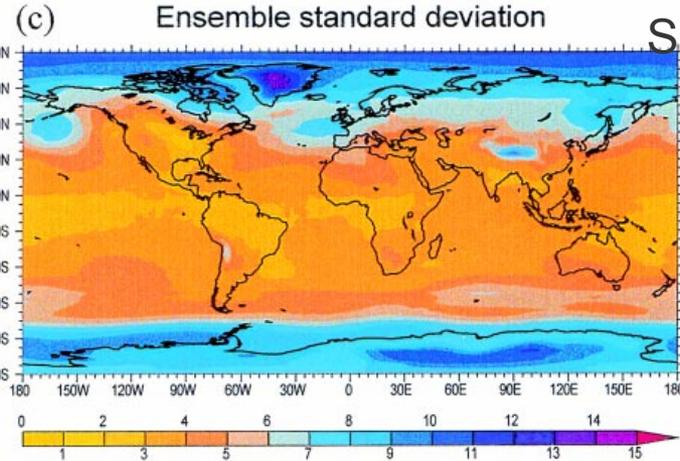
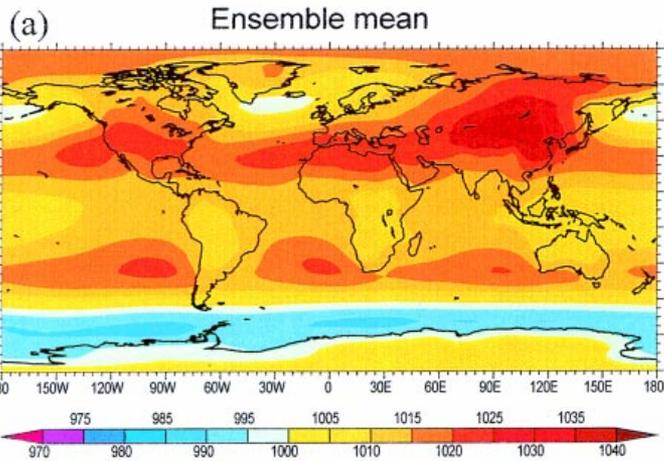
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Uncertainties of full GCM



Sea level pressure
in DJF

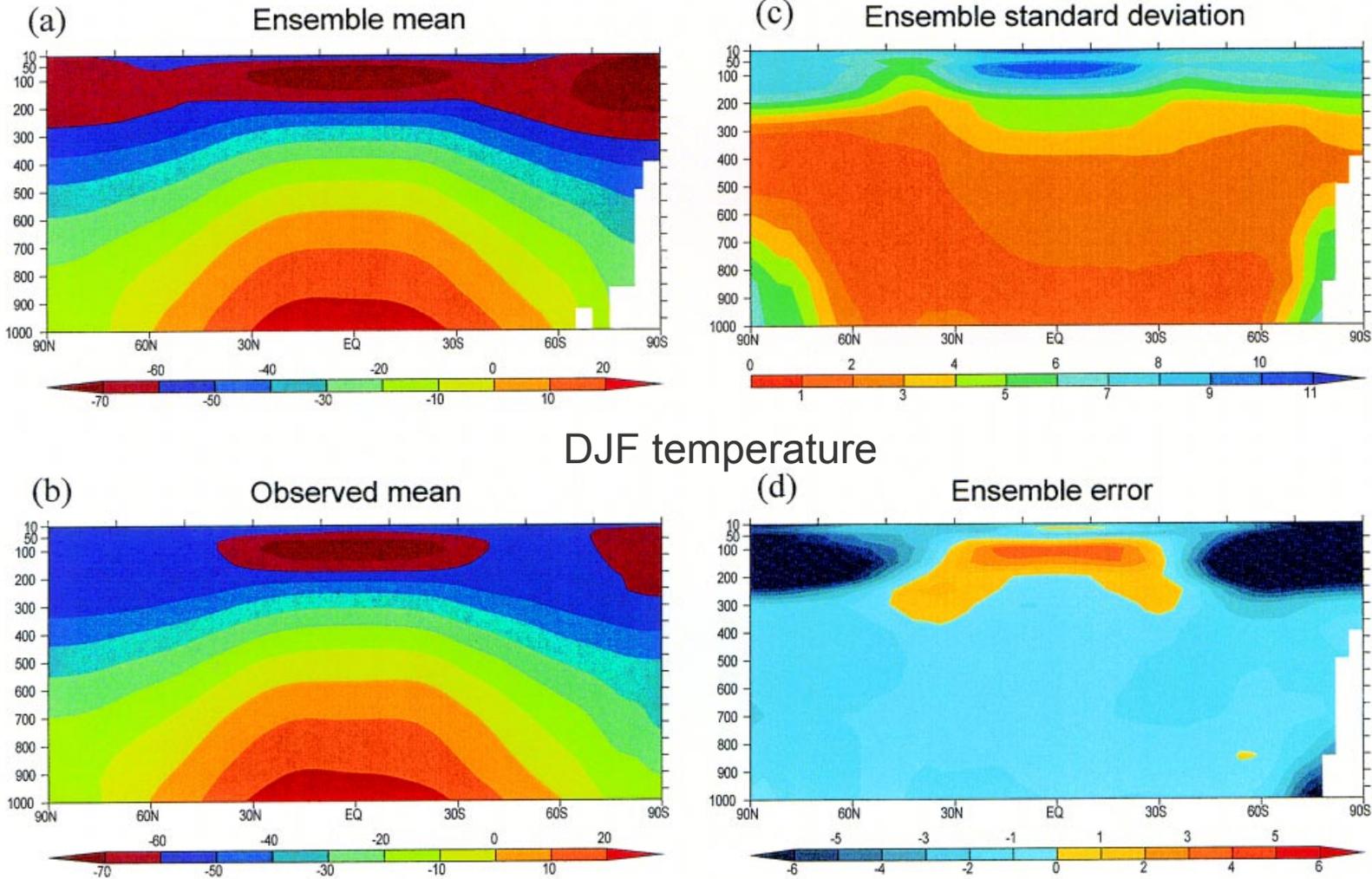


Gates et al, 1999

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

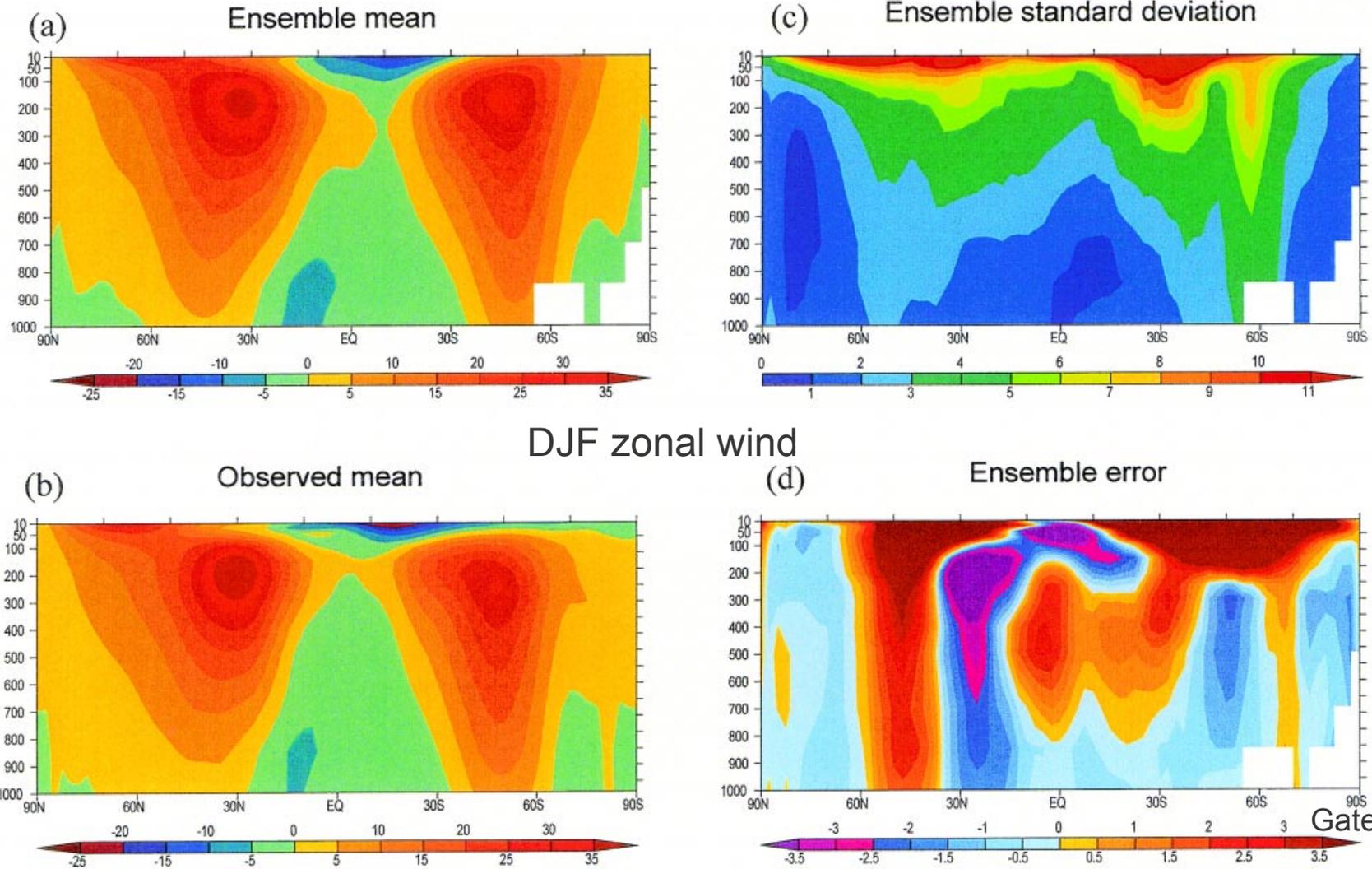


Gates et al, 1999

FIG. 8. (a) The latitude–pressure meridional section of the temperature ($^{\circ}\text{C}$) 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. (d) The ensemble error. The pressure units are hPa.



Uncertainties of full GCM



Gates et al, 1999

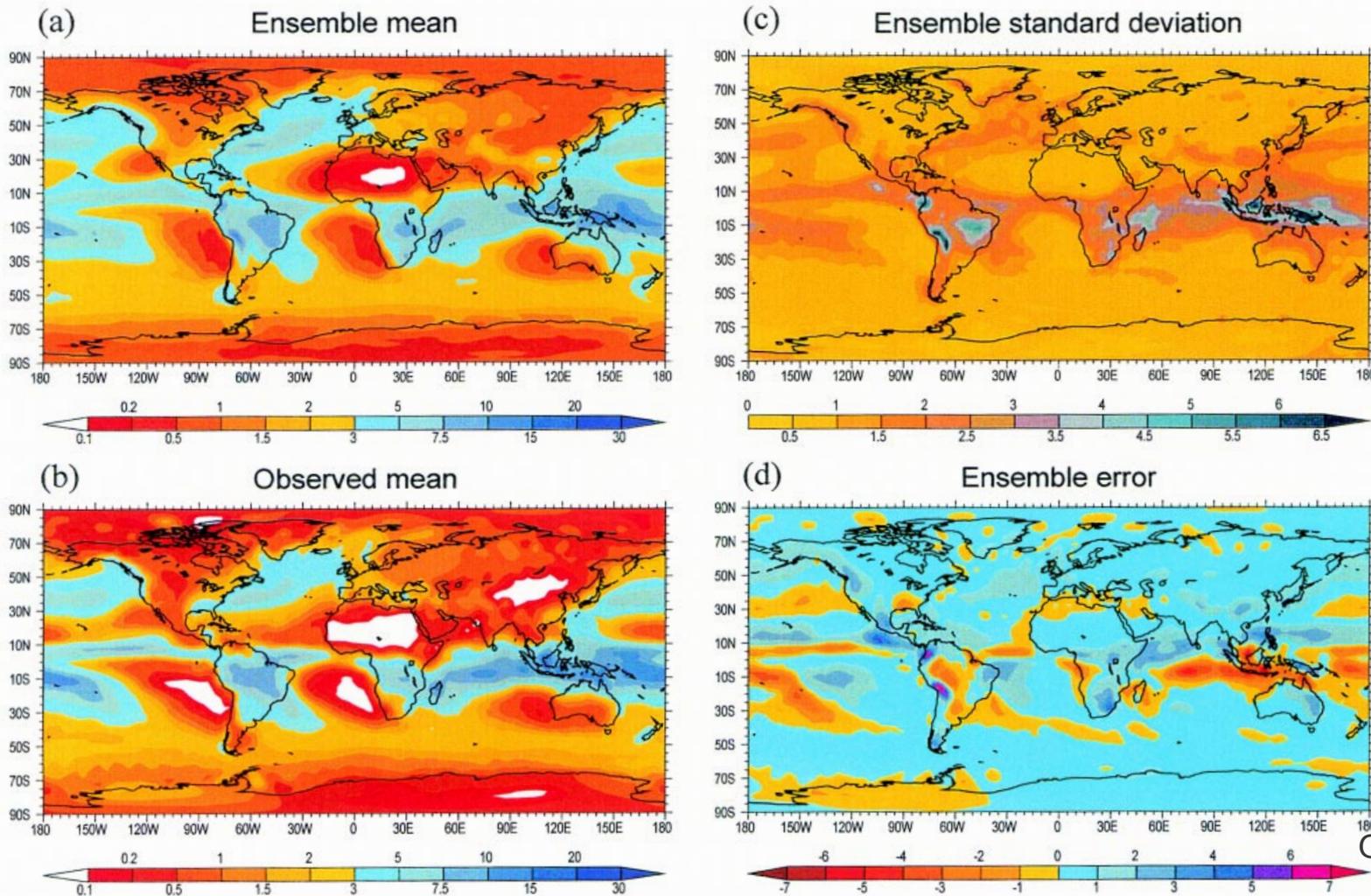
FIG. 9. As in Fig. 8 except for the zonal wind (m s^{-1}), with the observed estimate taken from the ECMWF reanalysis (Gibson et al. 1997).



Uncertainties of full GCM



Precipitation
in DJF



Gates et al, 1999

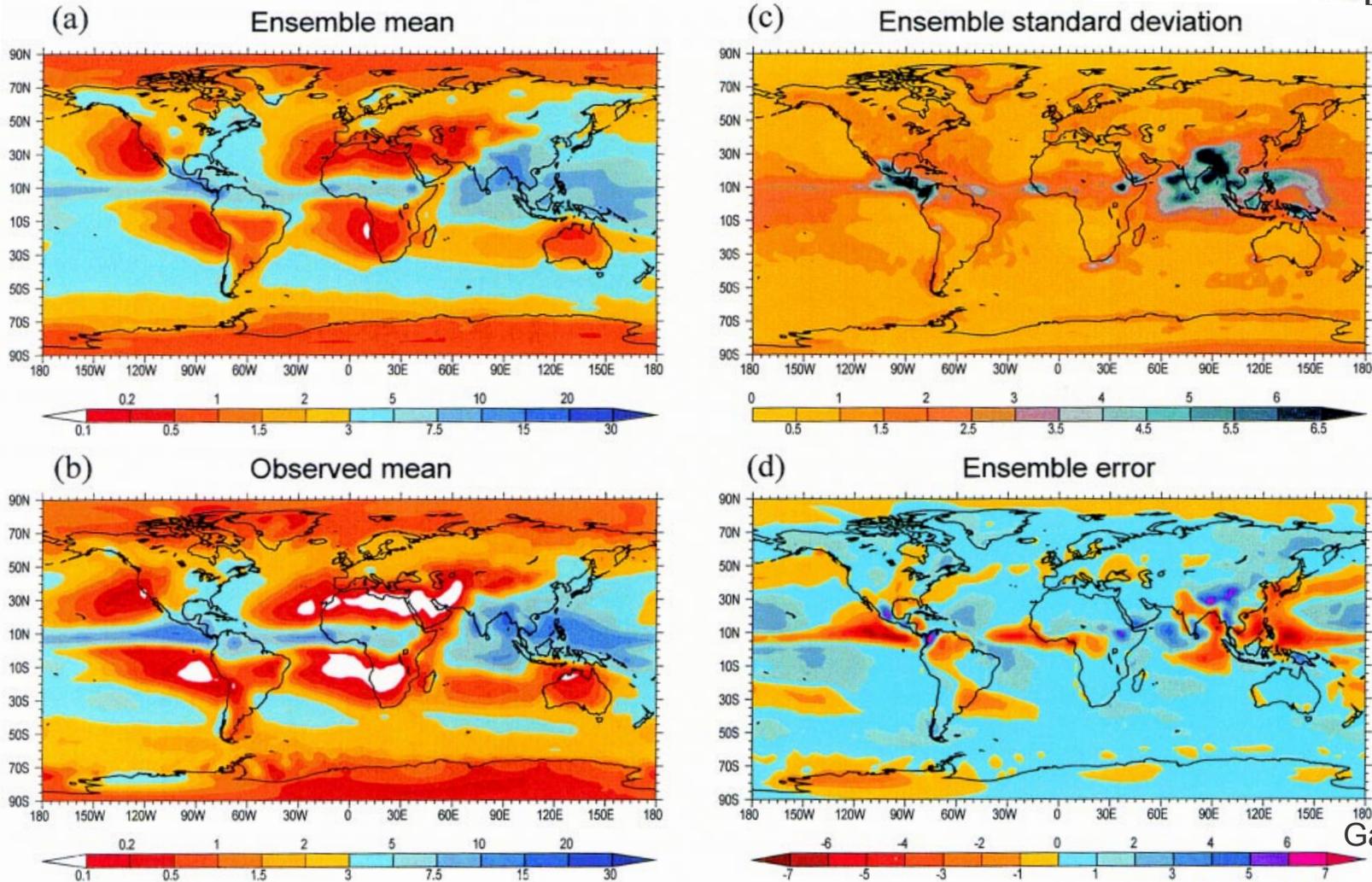
FIG. 3. As in Fig. 1 except for precipitation (mm day^{-1}), with observations for 1979–88 from the NCEP database (Arkin and Meade 1997). Note the nonlinear scale in (a) and (b).



Uncertainties of full GCM



Precipitation
in JJA



Gates et al, 1999

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

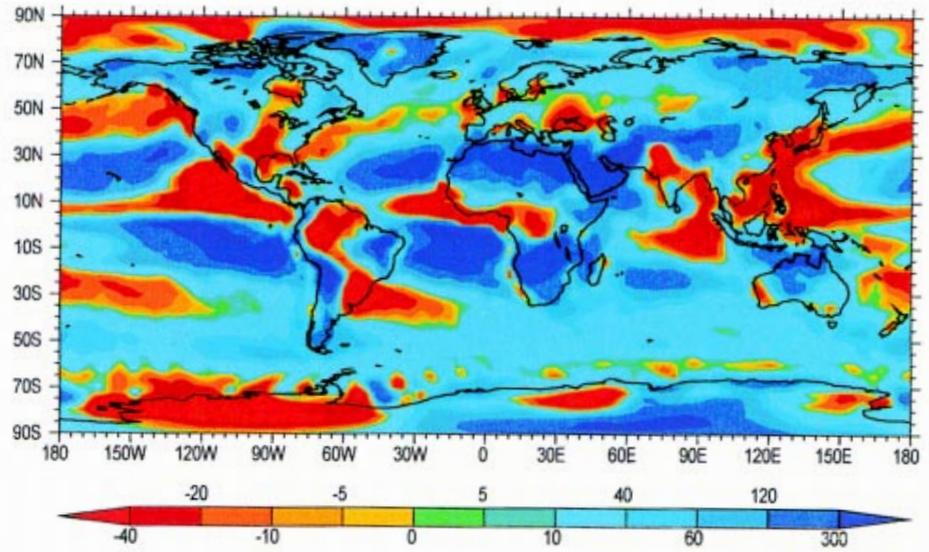
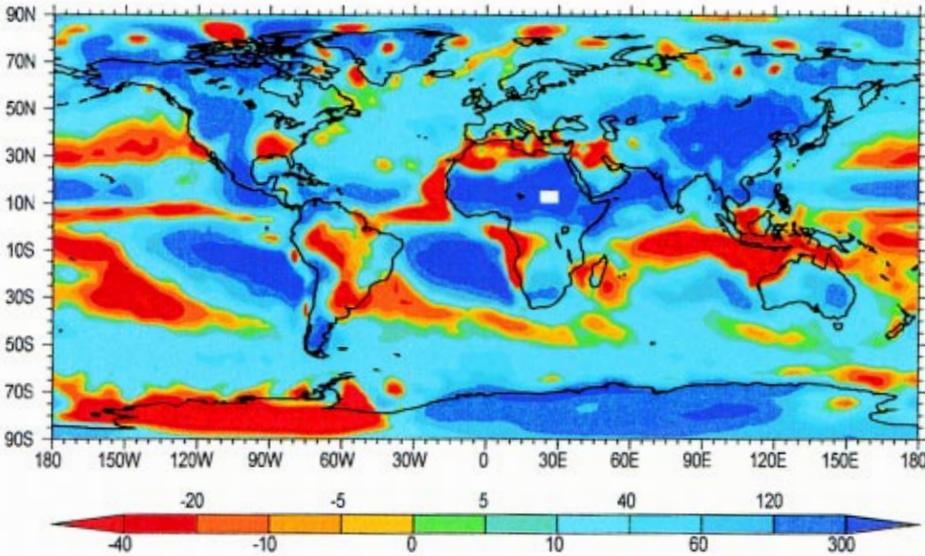


Uncertainties of full GCM



(a) DJF percent error

(b) JJA percent error



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.



Outline



- Introduction
- A historical review of GCMs
 - from the numerical weather prediction, idealized model to full GCMs
- Uncertainties of full GCMs
- A hierarchy of GCMs
- Some examples



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...

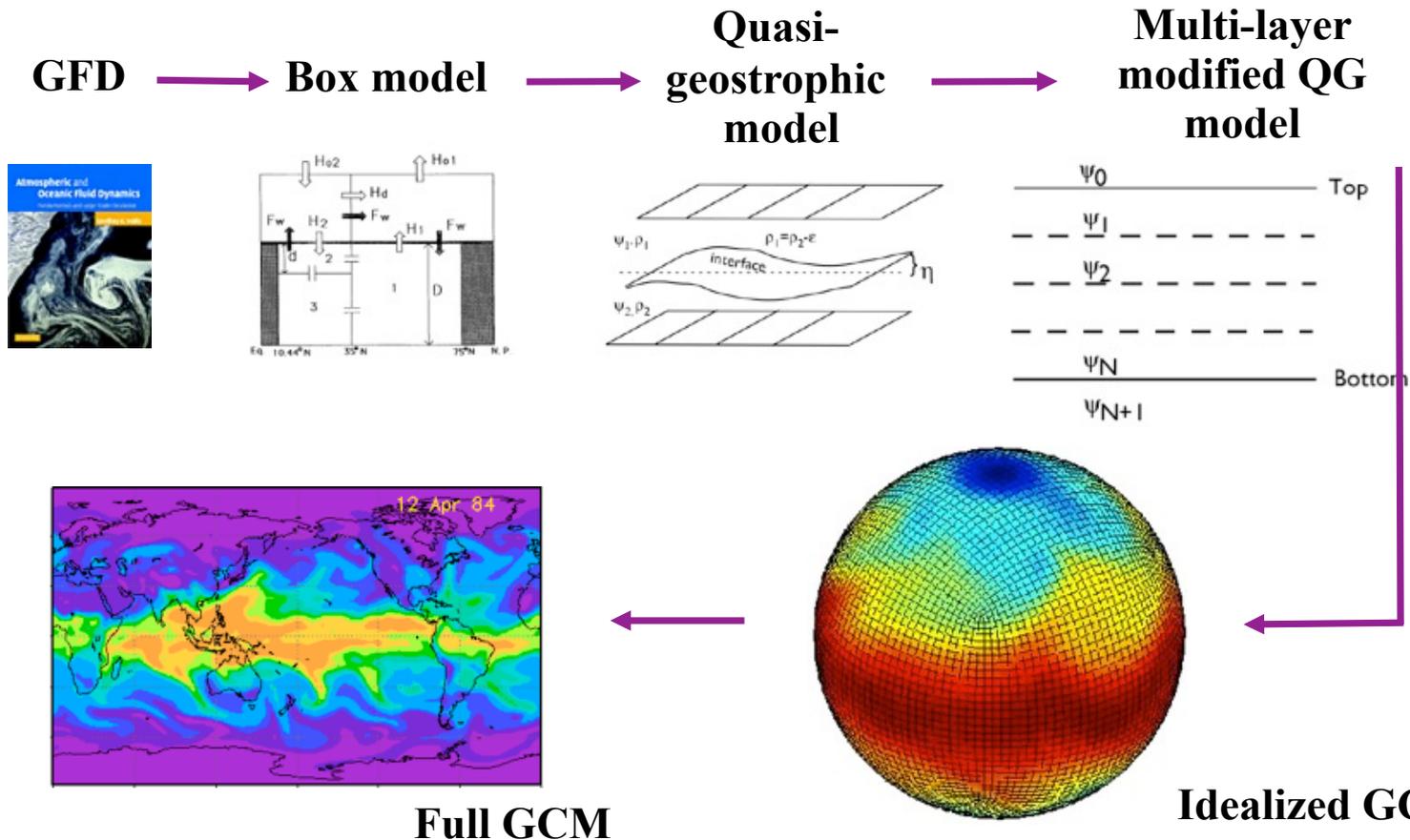
From Issac Held, *The Gap between Simulation and Understanding in Climate Modeling*, BAMS, 2005.



A hierarchy of GCMs: From idealized model to full GCM



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

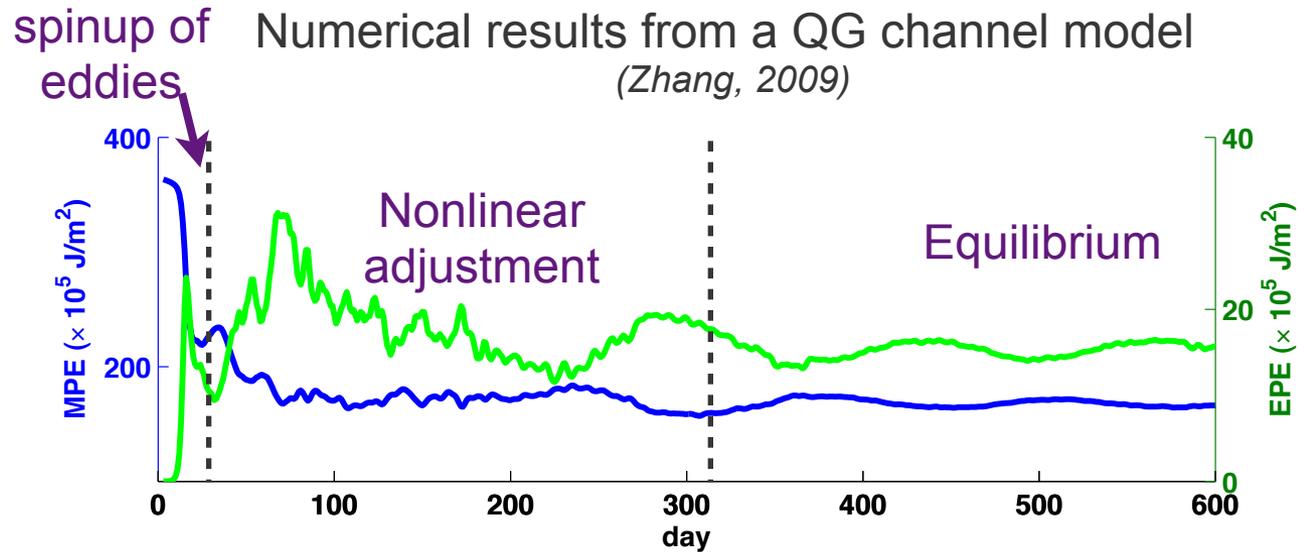




Some examples of idealized model QG channel model



From Chap4.3, baroclinic eddies





Some examples of idealized model Dynamical core

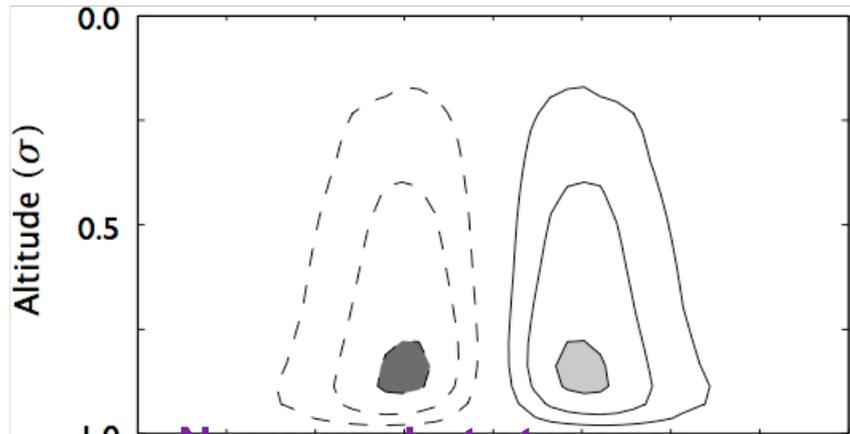


From Chap3.2, Hadley Circulation

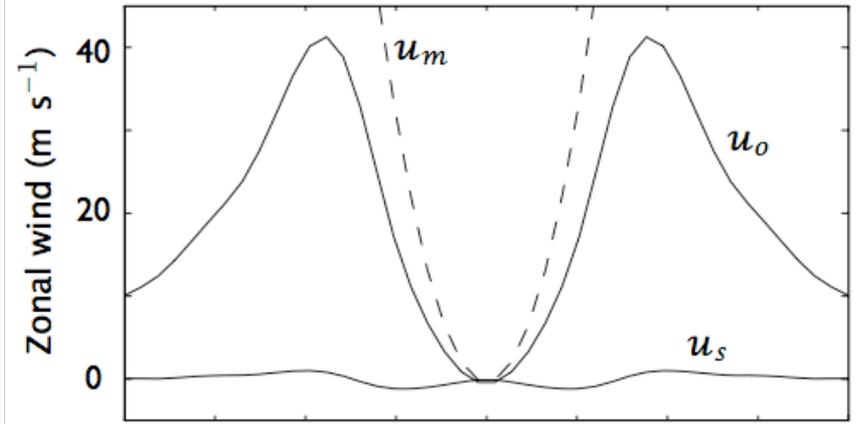
Vallis, 2006,

axisymmetric

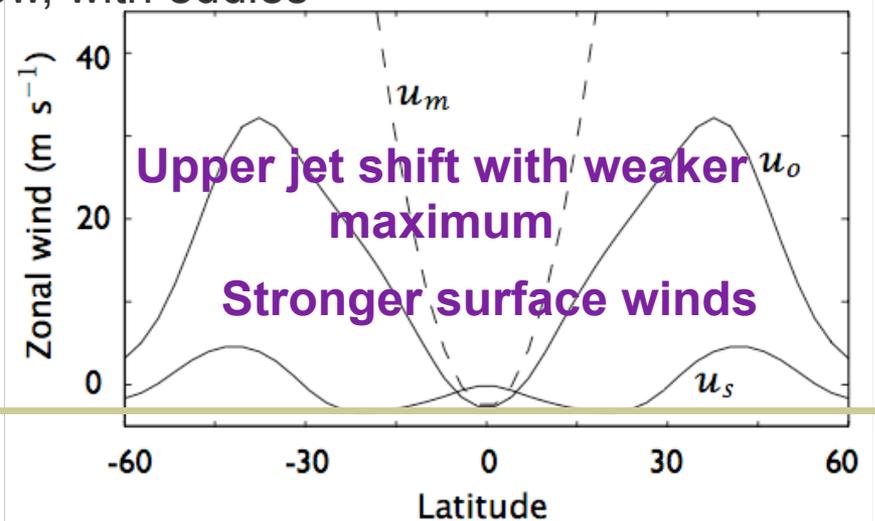
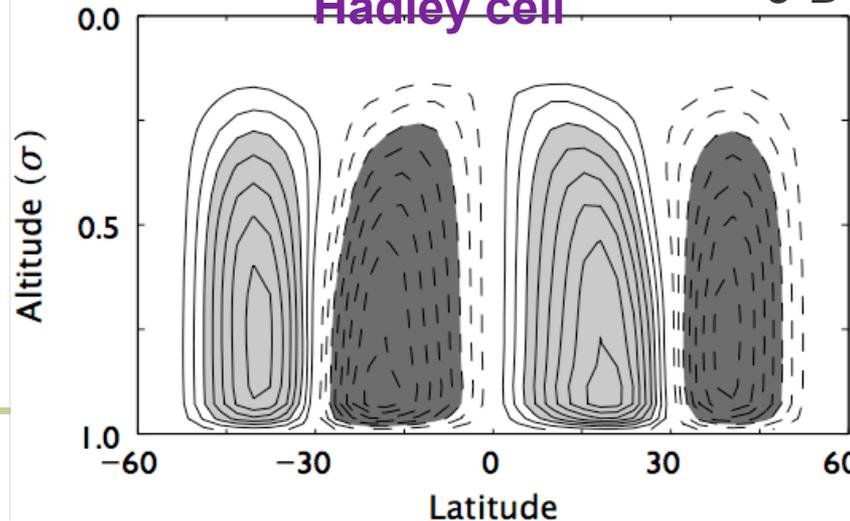
numerical results from idealized GCM



**Narrower but stronger
Hadley cell**



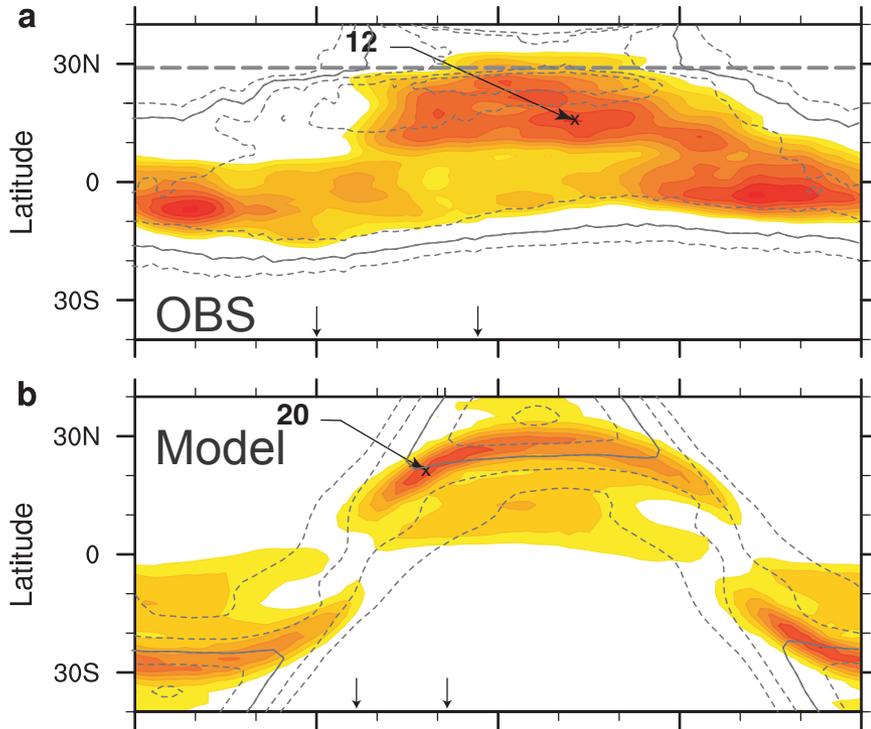
3-D flow, with eddies



**Upper jet shift with weaker
maximum
Stronger surface winds**

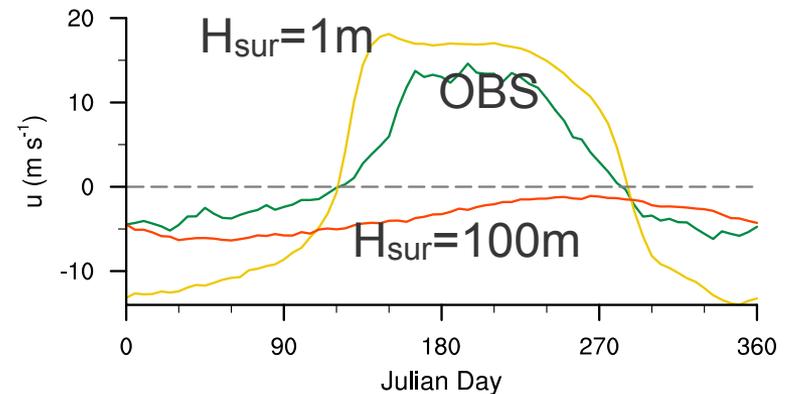


Some examples of idealized model Aqua-planet model



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