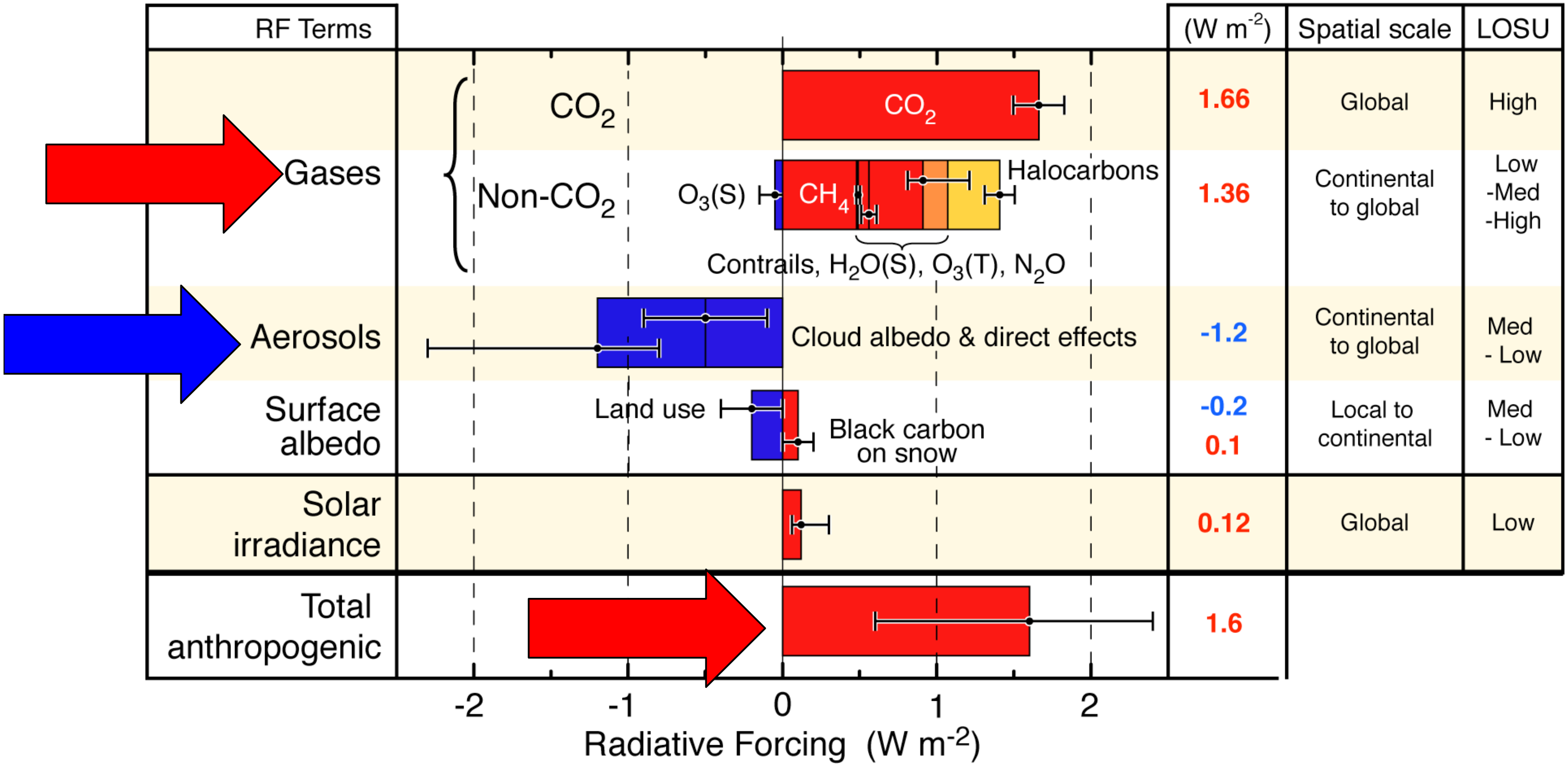
15.023J / 12.848J / ESD.128J Global Climate Change: Economics, Science, and Policy
Spring 2008

THE CLIMATE MACHINE II : Greenhouse Gas Exchange Rates and Dynamics of the Atmosphere and Oceans

R. PRINN, February 25, 2008

1. Multiple greenhouse gases and their exchange rate
2. Horizontal Circulations
3. Vertical Circulations
4. Ocean-atmosphere Coupling
5. Fundamental Equations & Model Integration
6. Accuracy of Coupled Models

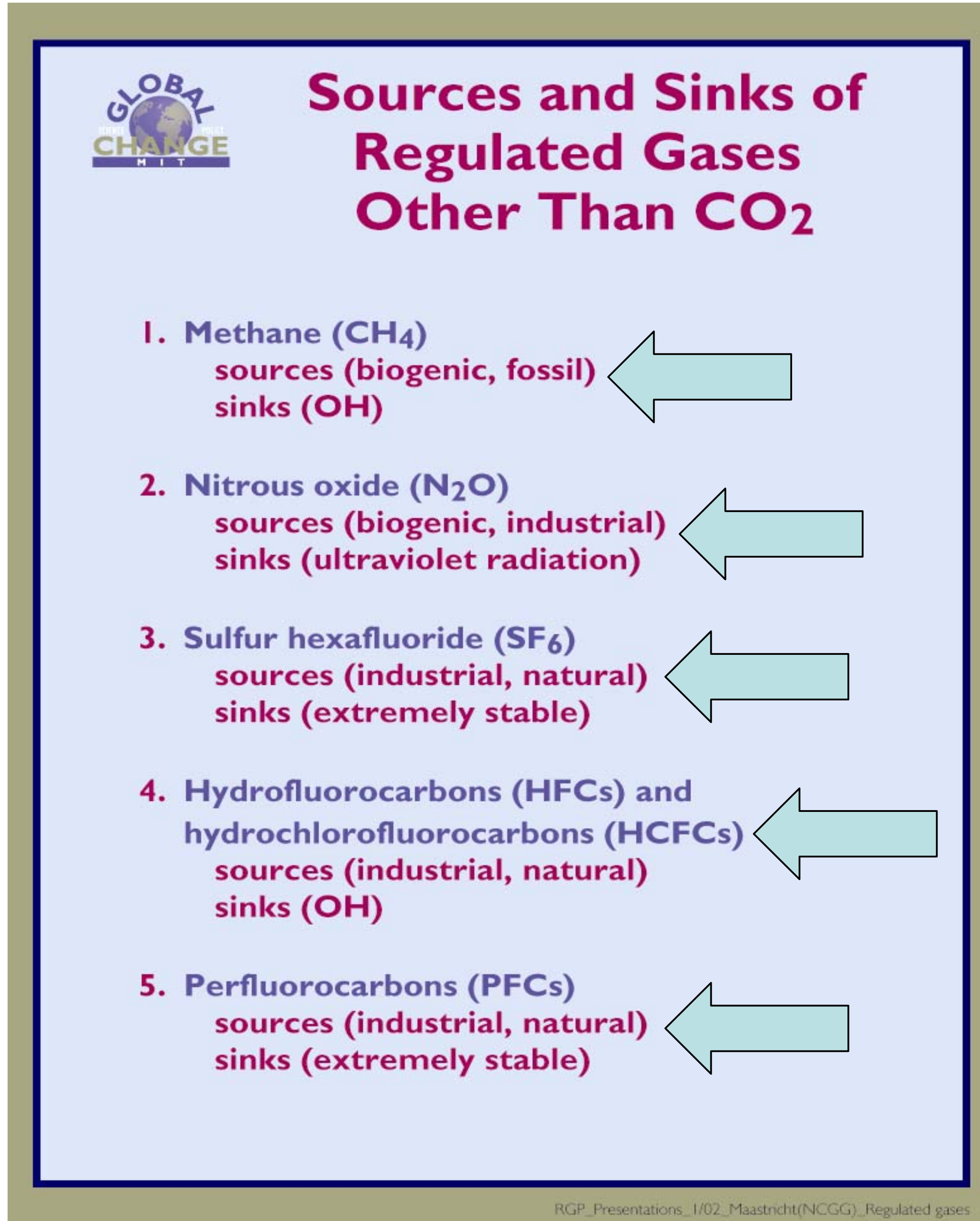
WHAT ARE THE MAJOR HUMAN & NATURAL ACTIVITIES FORCING CLIMATE CHANGE IN THE INDUSTRIAL ERA (1750-2005)?



$1.6\ W\ m^{-2} \times 5.1 \times 10^{14}\ m^2 = 8.16 \times 10^{14}\ W$ = 816 TW (about 52 times current global energy consumption)!

Ref: adapted from IPCC 4th Assessment, Summary for Policymakers, Feb. 2, 2007

THE KYOTO PROTOCOL REGULATES EMISSIONS OF CARBON DIOXIDE AND FIVE OTHER GREENHOUSE GAS CATEGORIES



HOW CAN WE COMPARE EMISSION REDUCTIONS OF NON-CO_2 GASES TO CO_2 FOR POLICY PURPOSES?

THE KYOTO PROTOCOL HAS ADOPTED GLOBAL WARMING POTENTIALS TO DEFINE THE "EXCHANGE RATES" BETWEEN GASES FOR EMISSION REDUCTION PURPOSES

Global Warming Potentials (GWPs)

$$GWP = \frac{\int_0^T I_{gas} M_{gas}\, dt}{\int_0^T I_{CO_2} M_{CO_2}\, dt}$$

I_{gas} = instantaneous radiative forcing by gas at time t [depends on basic molecular properties and on atmospheric composition (gases, clouds, aerosols)]

M_{gas} = amount of added gas still remaining at time t [depends on lifetime of the gas, which in turn usually depends on amounts of the gas itself and of other gases (indirect effects)]

T = time horizon for integration [gases with lifetimes (longer/shorter) than CO_2 have GWPs (increasing/decreasing) with T]

Notes

1. Corrections must be made to account for effects of added gas on amounts of other greenhouse gases (e.g., effects of added CH_4 on O_3 and H_2O)
2. M_{CO_2} depends on assumptions regarding oceanic and terrestrial CO_2 sinks

TABLE 3: Direct Global Warming Potentials (GWPs) relative to carbon dioxide (for gases for which the lifetimes have been adequately characterised). GWPs are an index for estimating relative global warming contribution due to atmospheric emission of a kg of a particular greenhouse gas compared to emission of a kg of carbon dioxide. GWPs calculated for different time horizons show the effects of atmospheric lifetimes of the different gases . [Based upon Table 6.7]

Gas		Lifetime (years)	Global Warming Potential (Time Horizon in years)		
			20 yrs	100 yrs	500 yrs
Carbon dioxide	CO_2		1	1	1
Methane[a]	CH_4	12.0[b]	62	23	7
Nitrous oxide	N_2O	114[b]	275	296	156
Hydrofluorocarbons					
HFC-23	CHF_3	260	9400	12000	10000
HFC-32	CH_2F_2	5.0	1800	550	170
HFC-41	CH_3F	2.6	330	97	30
HFC-125	CHF_2CF_3	29	5900	3400	1100
HFC-134	CHF_2CHF_2	9.6	3200	1100	330
HFC-134a	CH_2FCF_3	13.8	3300	1300	400
HFC-143	CHF_2CH_2F	3.4	1100	330	100
HFC-143a	CF_3CH_3	52	5500	4300	1600
HFC-152	CH_2FCH_2F	0.5	140	43	13
HFC-152a	CH_3CHF_2	1.4	410	120	37
HFC-161	CH_3CH_2F	0.3	40	12	4
HFC-227ea	CF_3CHFCF_3	33	5600	3500	1100
HFC-236cb	$CH_2FCF_2CF_3$	13.2	3300	1300	390
HFC-236ea	CHF_2CHFCF_3	10	3600	1200	390
HFC-236fa	$CF_3CH_2CF_3$	220	7500	9400	7100
HFC-245ca	$CH_2FCF_2CHF_2$	5.9	2100	640	200
HFC-245fa	$CHF_2CH_2CF_3$	7.2	3000	950	300
HFC-365mfc	$CF_3CH_2CF_2CH_3$	9.9	2600	890	280
HFC-43-10mee	$CF_3CHFCHFCF_2CF_3$	15	3700	1500	470
Fully fluorinated species					
SF_6		3200	15100	22200	32400
CF_4		50000	3900	5700	8900
C_2F_6		10000	8000	11900	18000
C_3F_8		2600	5900	8600	12400
C_4F_{10}		2600	5900	8600	12400
$c\text{-}C_4F_8$		3200	6800	10000	14500
C_5F_{12}		4100	6000	8900	13200
C_6F_{14}		3200	6100	9000	13200
Ethers and Halogenated Ethers					
CH_3OCH_3		0.015	1	1	<<1
HFE-125	CF_3OCHF_2	150	12900	14900	9200
HFE-134	CHF_2OCHF_2	26.2	10500	6100	2000
HFE-143a	CH_3OCF_3	4.4	2500	750	230
HCFE-235da2	$CF_3CHClOCHF_2$	2.6	1100	340	110
HFE-245fa2	$CF_3CH_2OCHF_2$	4.4	1900	570	180
HFE-254cb2	$CHF_2CF_2OCH_3$	0.22	99	30	9
HFE-7100	$C_4F_9OCH_3$	5.0	1300	390	120
HFE-7200	$C_4F_9OC_2H_5$	0.77	190	55	17
H-Galden 1040x	$CHF_2OCF_2OC_2F_4OCHF_2$	6.3	5900	1800	560
HG-10	$CHF_2OCF_2OCHF_2$	12.1	7500	2700	850
HG-01	$CHF_2OCF_2CF_2OCHF_2$	6.2	4700	1500	450

[a] The methane GWPs include an indirect contribution from strato... H_2O an... productio...
[b] The values for methane and nitrous oxide are adjustment times, ... incorpor...e indirect effects of emission of each gas on its own lifetime.

http://www.ipcc.ch

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GWP's VERY DEPENDENT ON THE GAS's **INSTANTANEOUS RADIATIVE FORCING**, LIFETIME & CHOSEN TIME HORIZON

KYOTO PROTOCOL ADOPTS A 100-YEAR TIME HORIZON

IS THIS SCIENTIFICALLY JUSTIFIABLE? (e.g. methane)

THE ATMOSPHERE AND OCEAN ARE CIRCULATING FLUIDS WHICH CAN TRANSPORT HEAT, MOMENTUM, MASS, GREENHOUSE GASES AND PARTICLES (cloud droplets, ice crystals, aerosols) OVER GREAT DISTANCES.

THE DYNAMICS OF THESE FLUIDS AND THE EXCHANGES BETWEEN THEM PLAY A MAJOR ROLE IN CLIMATE.

WHAT ARE THE HORIZONTAL CIRCULATIONS?

ATMOSPHERE

(lines are height (m) of 1 bar surface)

Images removed due to copyright restrictions. See Figure 7.1a and Figure 8.1 in:

Peixoto, Jose, and Abraham Oort. *Physics of Climate*. New York, NY: Springer, 1992. ISBN: 9780883187128.

OCEAN

WHAT ARE THE VERTICAL CIRCULATIONS?

Images removed due to copyright restrictions. See Figure 10.2 in:

Peixoto, Jose, and Abraham Oort. *Physics of Climate*. New York, NY: Springer, 1992. ISBN: 9780883187128.

ATMOSPHERE

OCEAN

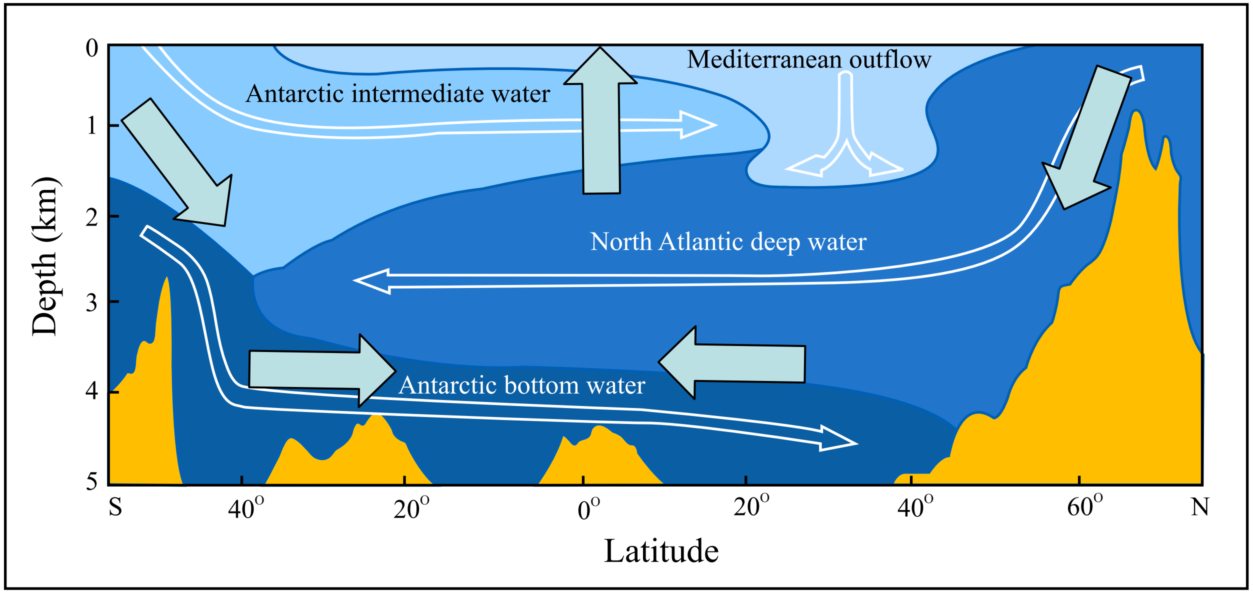
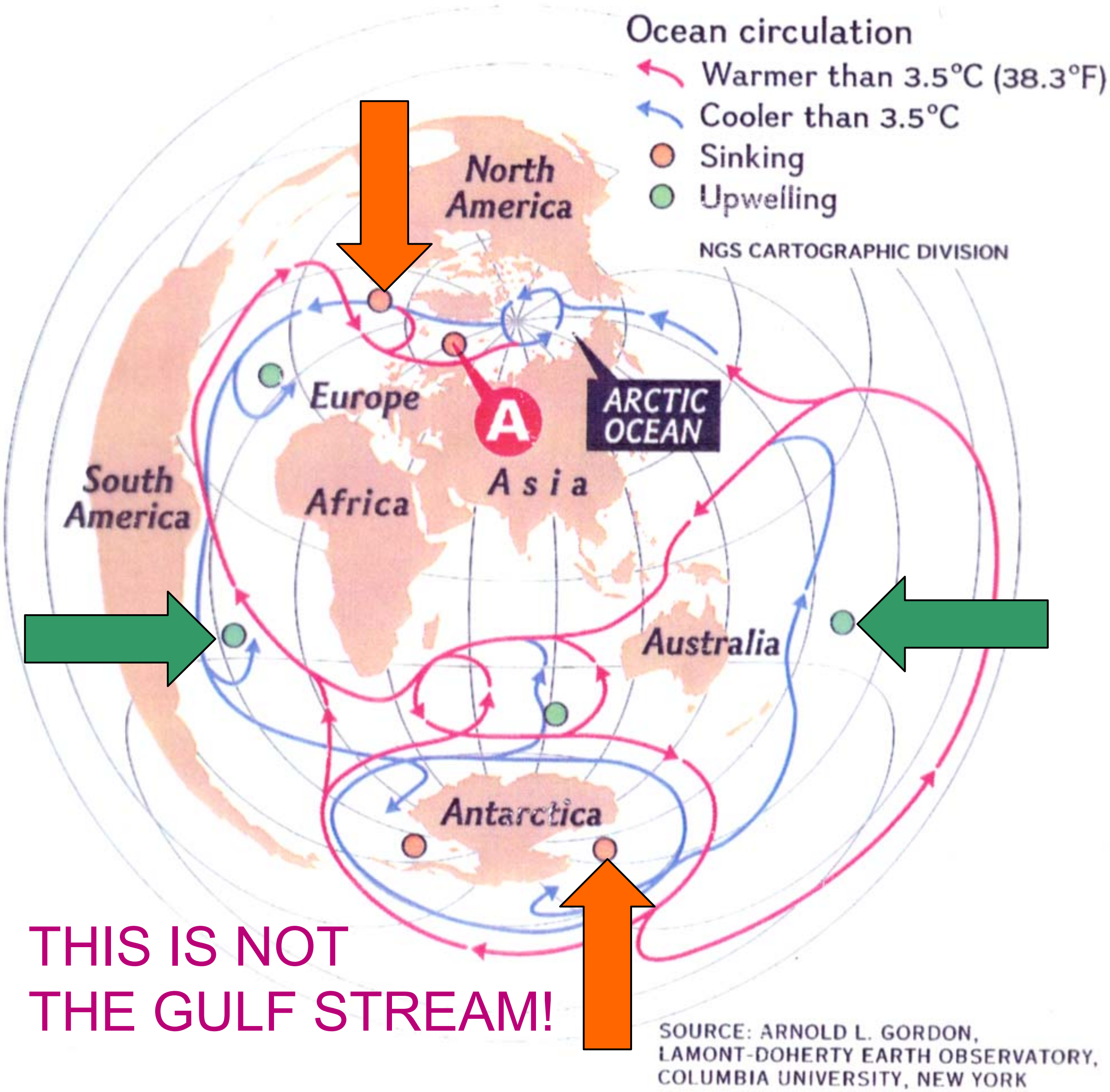


Figure by MIT OpenCourseWare.

Deep Atlantic circulation; water filling the North Atlantic basin comes from sources in the high-latitude North Atlantic, the Southern Ocean near Antarctica, and (at shallower depths) the Mediterranean Sea. (Adapted from E. Berner and R. Berner, Global Environment [Englewood Cliffs, N.J. Prentice -Hall, 1996].)

DEEP OCEAN OVERTURNING (THERMOHALINE) CIRCULATION



VERY IMPORTANT AS A HEAT AND CARBON DIOXIDE SINK

COMPRISES SINKING WATER IN THE POLAR SEAS (Norwegian, Greenland, Labrador, Weddell, Ross) AND RISING WATER ELSEWHERE

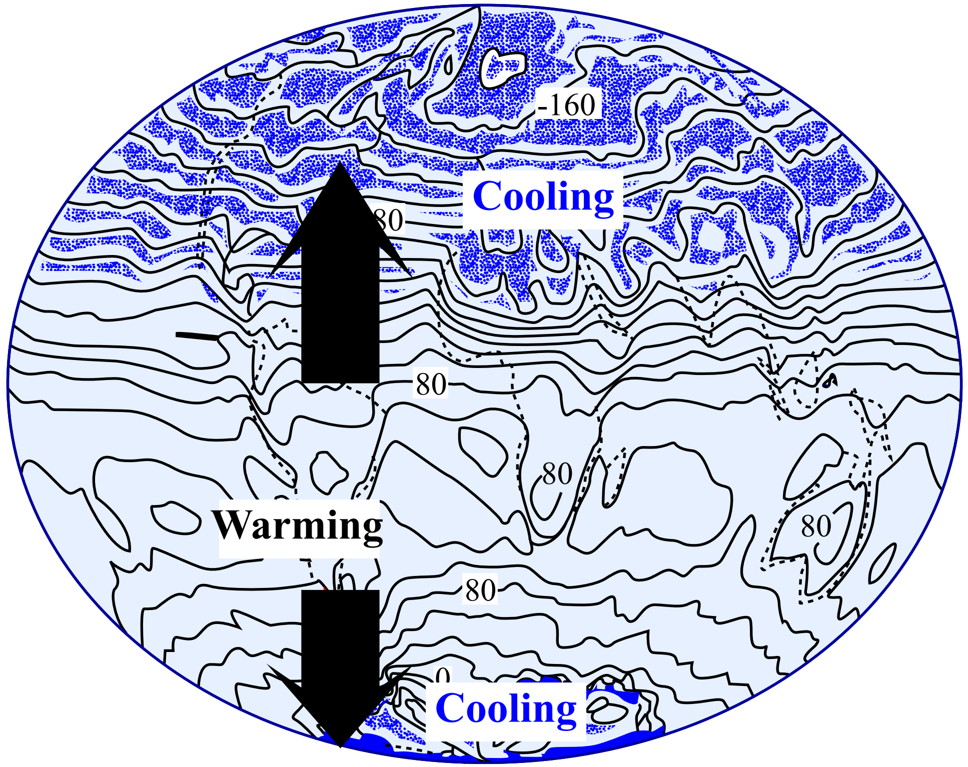
SLOWED BY DECREASED SEA ICE & INCREASED FRESH WATER INPUTS INTO THESE SEAS

INCREASED RAINFALL, SNOWFALL & RIVER FLOWS, & DECREASED SEA ICE, EXPECTED WITH GLOBAL WARMING!

RADIANT HEATING OR COOLING AND INFERRED HORIZONTAL HEAT TRANSPORT

AS A RESULT OF THESE CIRCULATIONS, WHERE DOES RADIANT HEAT ENTER AND LEAVE THE EARTH?

USE SATELLITES TO MEASURE DIFFERENCE (IN WATT/M²) BETWEEN INCOMING SOLAR & OUTGOING INFRARED RADIATION



Net radiation (SW absorbed - LW emitted to space) for December-February, adapted from Hartmann et al., (1986).

Figure by MIT OpenCourseWare.

Fundamental Equations

Models of the earth's climate are based on laws of physics:

- Conservation of energy (sensible (temp.), latent (evap./cond.), radiation)
- Conservation of momentum (north-south,east-west,up-down)
- Conservation of mass
- Equation of state (relates pressure, density and temperature)
- Conservation of chemical elements

Express the changes in the variables by "budget" or "continuity" equations:

$$\left(\frac{\partial \Phi}{\partial t}\right) = \frac{d\Phi}{dt} - \frac{\partial}{\partial x}(u\Phi) - \frac{\partial}{\partial y}(v\Phi) - \frac{\partial}{\partial z}(w\Phi)$$

The local change (rate of accumulation) of ( ) in the box

Actual production or destruction of ( ) within the box

Change in ( ) due to loss to downstream boxes or arrival of ( ) from an upstream box (called advection or convection)

COUPLING OF GENERAL CIRCULATION MODELS (GCM's) OF THE OCEAN & ATMOSPHERE

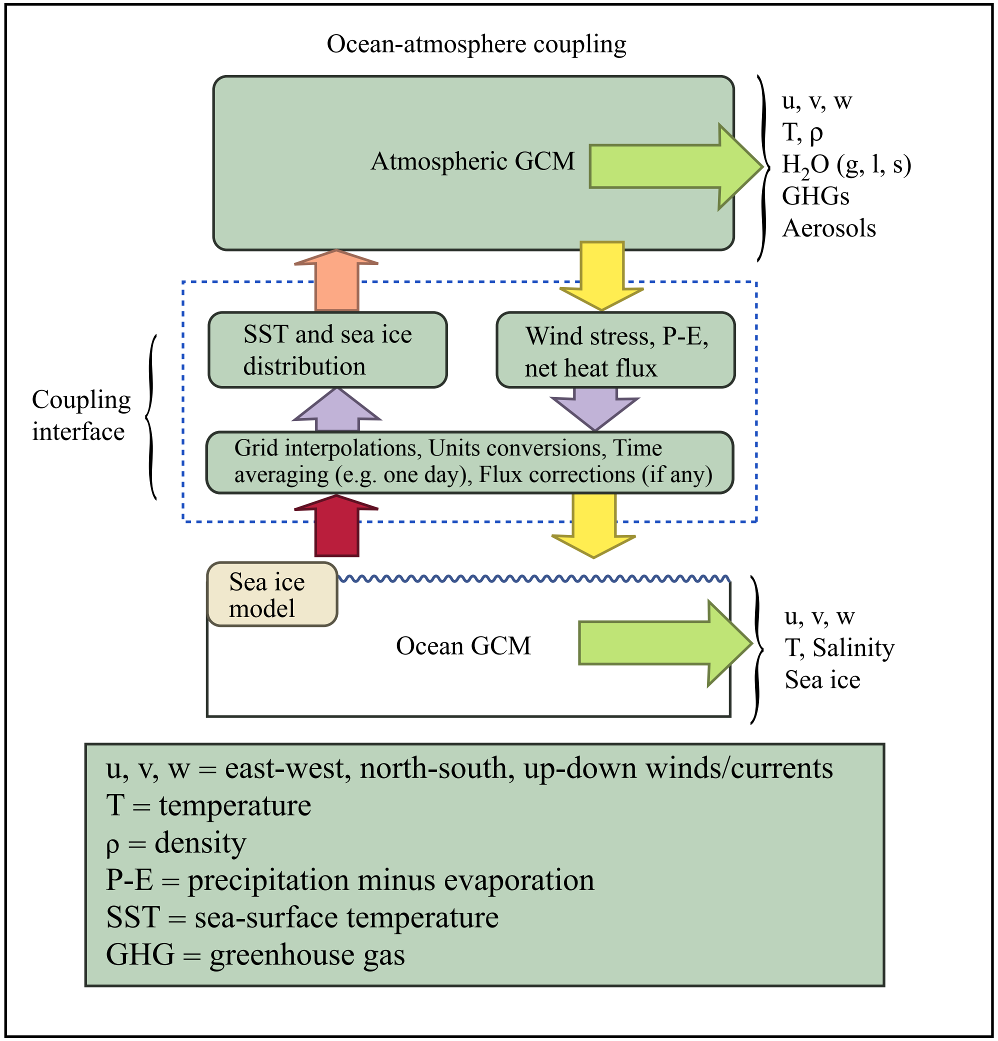
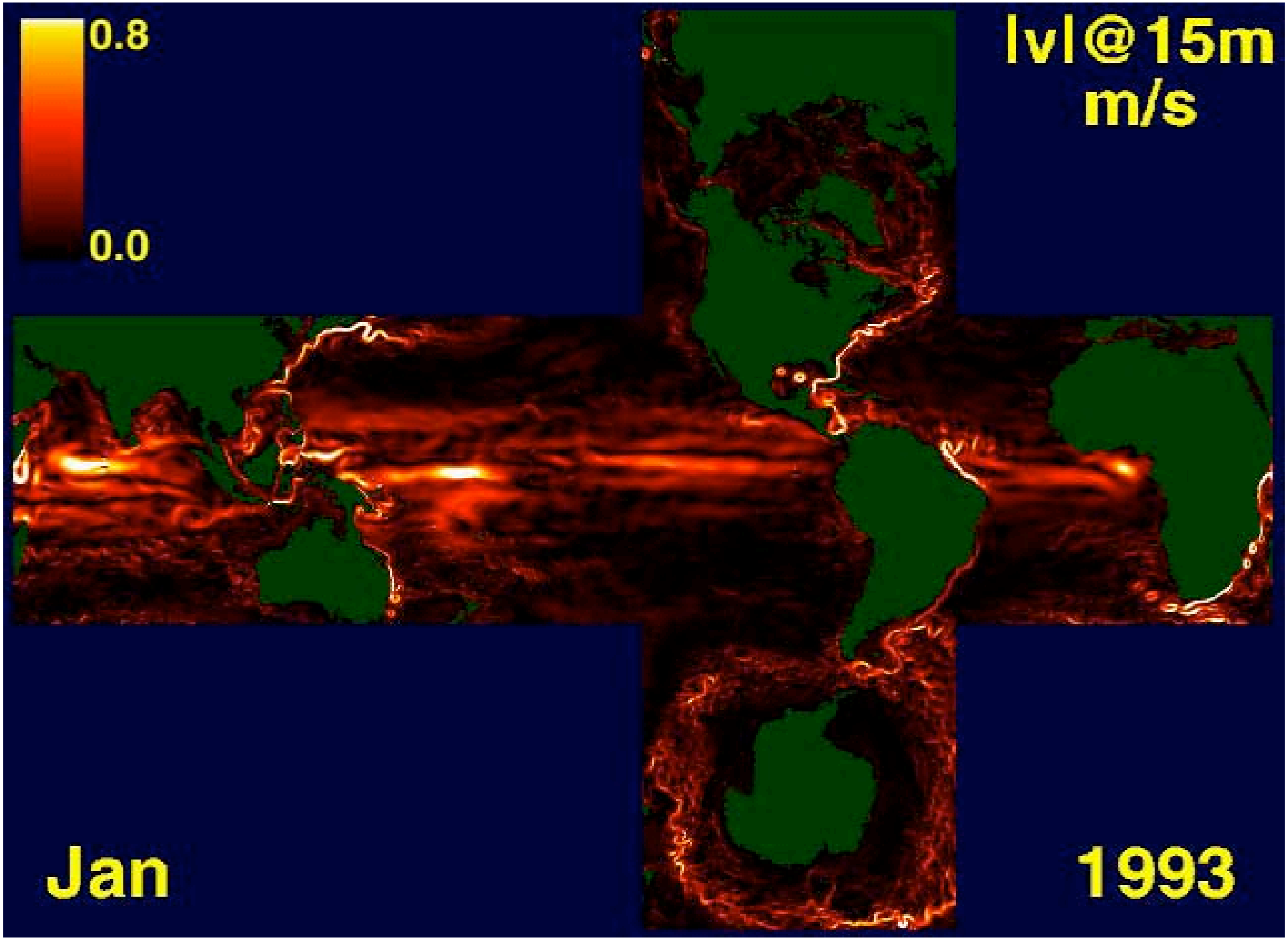


Figure by MIT OpenCourseWare.

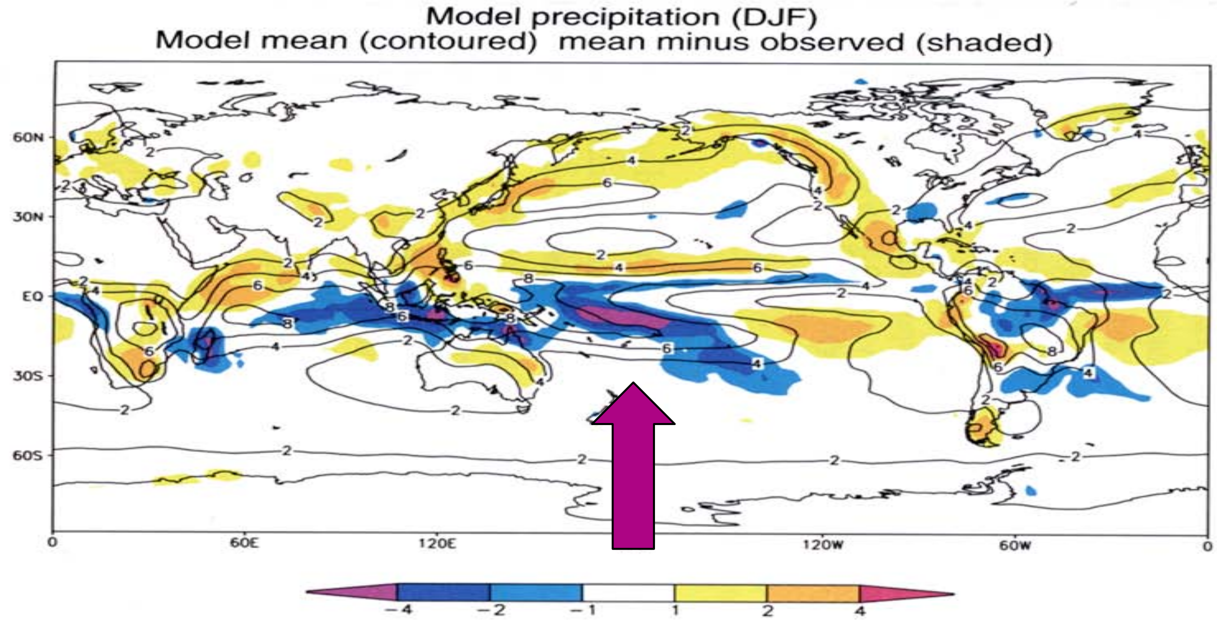
AN EXAMPLE: OCEAN CIRCULATION MODEL (CGCS CLIMATE MODELLING INITIATIVE)



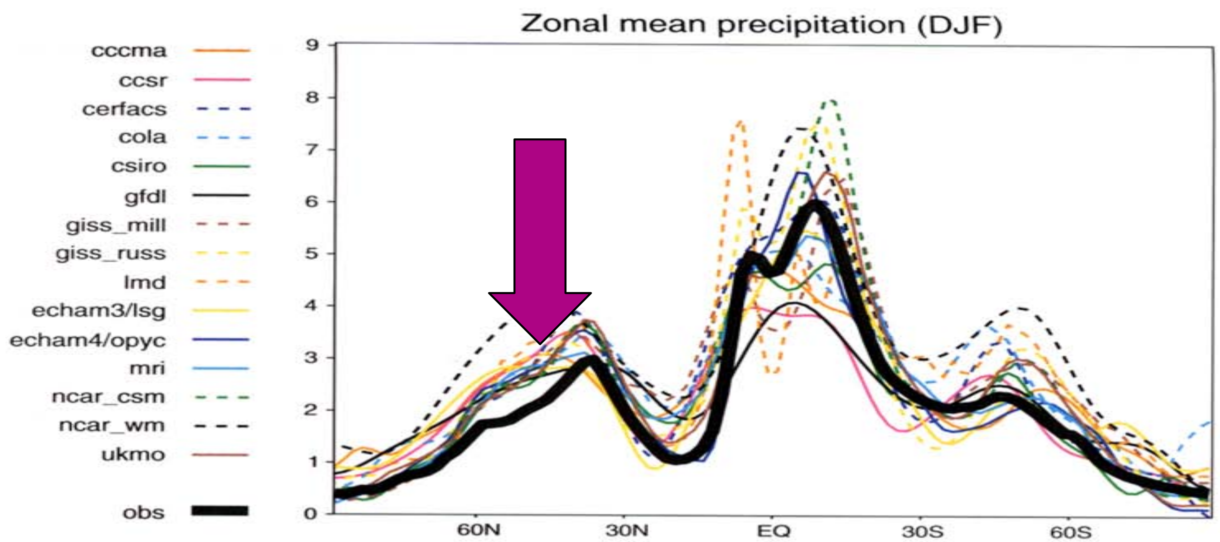
USES NOVEL CUBED SPHERE GRID

CURRENTS AT 15 METERS DEPTH

PROBLEMS WITH CONVECTION & CLOUDS



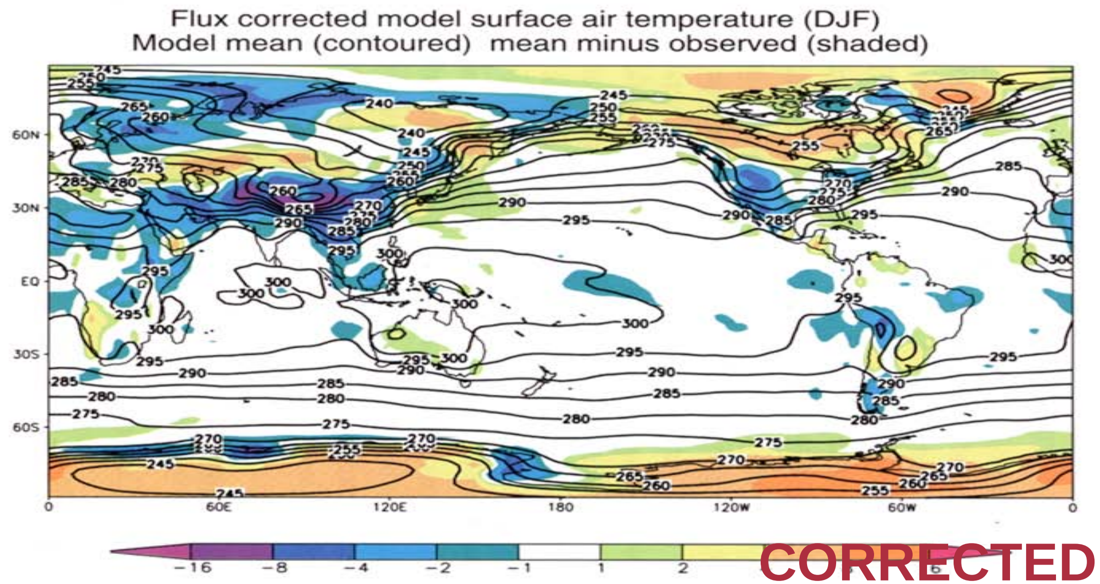
ERRORS CAN EXCEED 4MM/DAY (1.5M/YEAR)!



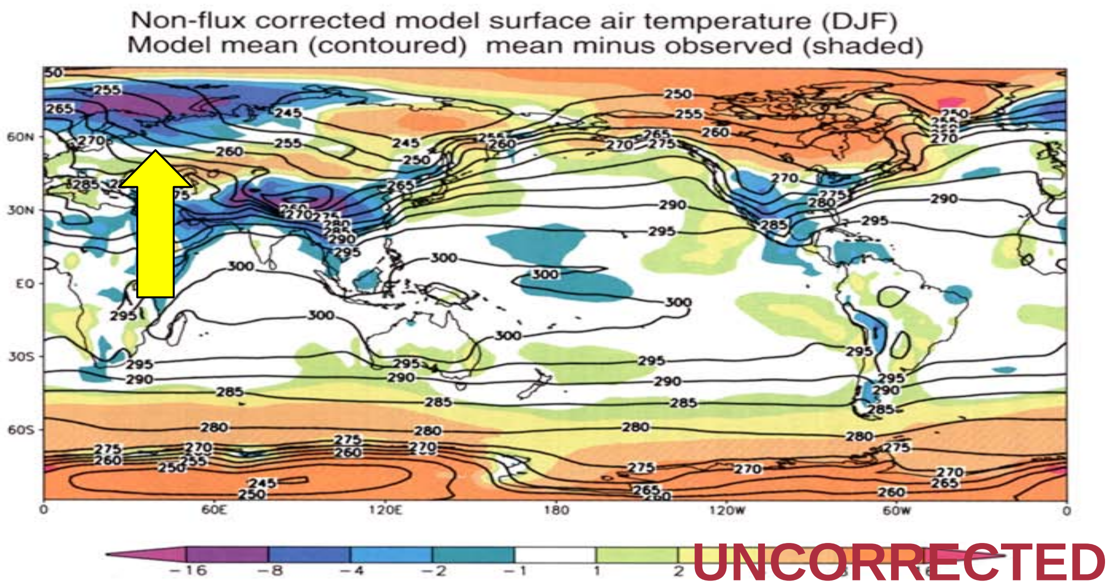
Courtesy of the Intergovernmental Panel on Climate Change. Used with permission.

(precipitation in mm/day)

PROBLEMS IN COUPLING (Flux adjustments)



WITHOUT THESE ADJUSTMENTS CAN HAVE REGIONAL TEMPERATURE ERRORS EXCEEDING 16^{o}C!



(temperatures in degrees Kelvin)

HAVE MODELS IMPROVED OVER THE PAST SIX YEARS?

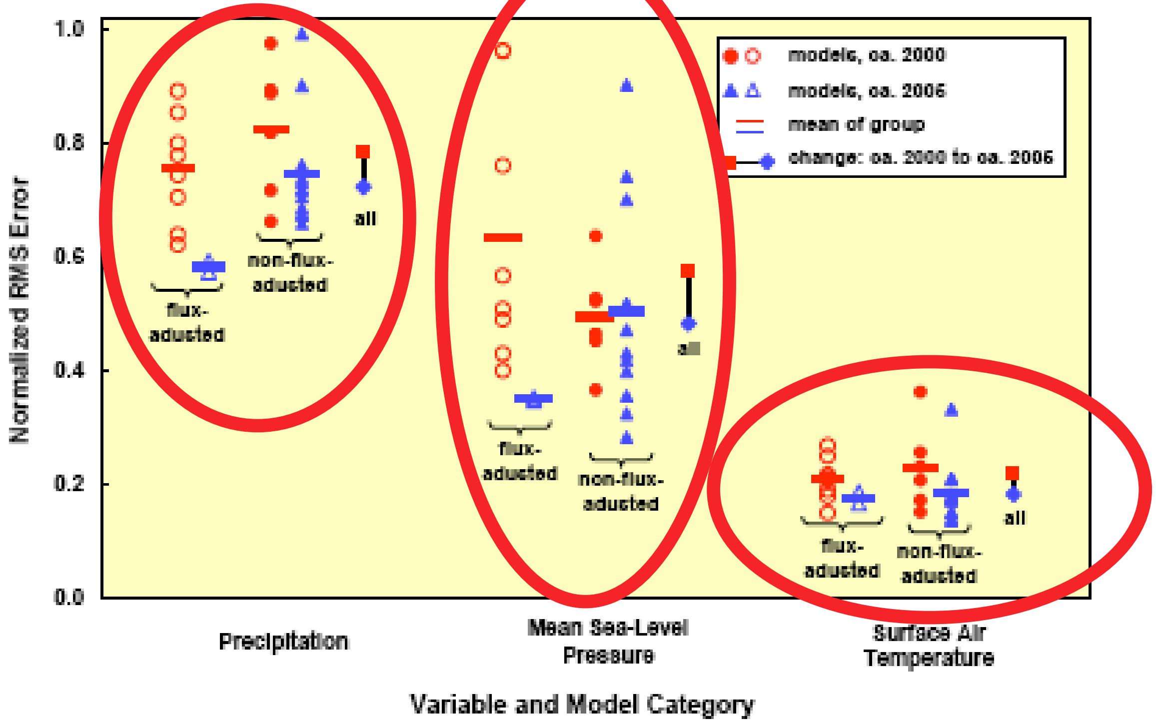


Figure 8.11. Normalized root-mean-square error in simulation of climatological patterns of monthly precipitation, mean sea-level pressure, and surface air temperature. Recent AOGCMs (ca. 2005) are compared to their predecessors (ca. 2000, and earlier). Models are categorized based on whether or not any flux adjustments were applied. The models are gauged against the following observation-based datasets: CMAP (Xie and Arkin, 1997) for precipitation (years 1980–1999), ERA40 (Uppala et al., 2005) for sea-level pressure (years 1980–1999), and CRU (Jones et al., 1999) for surface temperature (years 1961–1990). Before computing the errors, both the observed and simulated fields were mapped to a uniform 4 x 5 degree latitude-longitude grid. For the earlier generation of models, results are based on the archived output from control runs (specifically, the first 30 years, in the case of temperature, and the first 20 years for the other fields), and for the recent generation models, results are based on the 20th Century simulations with climatological periods selected to correspond with observations. (In both groups of models, results are insensitive to the period selected.)

Ref: IPCC 4th Assessment, Chapter 8, 2007