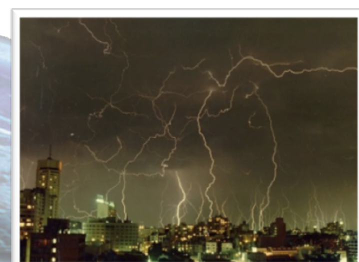
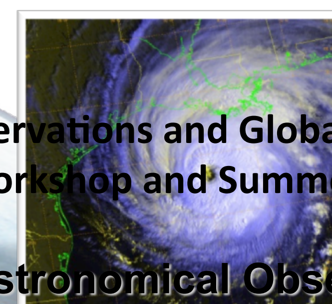
Atmospheric and
Environmental Research

Atmosphere and Ocean Circulation Models and Global Change

David Salstein

Atmospheric and Environmental Research
Lexington, MA, USA
and
Visiting Professor for Senior International Scientists of the Chinese Academy of Sciences





The 2014 Spaceborne Earth Observations and Global Change Workshop and Summer School

Shanghai Astronomical Observatory
July 15, 2014

Outline

Modeling of the atmosphere and the ocean: equations based on physics

Uses of atmospheric information for geodetic science

Earth rotation variability and methods to measure it
--vector: Polar motion (about two equatorial axes) and "Length of day" (axial) -- (LOD)

Atmospheric angular momentum (AAM)--how it is measured and its climate signals

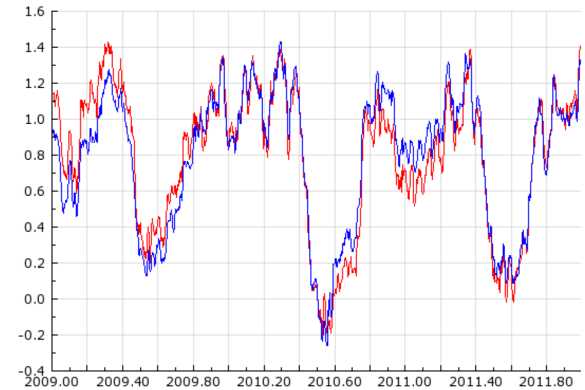
Dynamical relations: torques change rotation rate

Coupled model intercomparison project (CMIP), global change results, and relationship to AAM

Conclusions

Need for atmospheric information in geodetic science

Atmospheric angular momentum (AAM), along with ocean angular momentum, changes are "Excitations" to changes in Earth rotation. (Changes in Length of Day and polar motion)



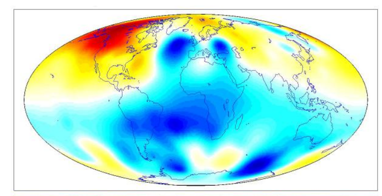
---Length of day ----AAM ms

Atmospheric information needed for path delays of signals from geodetic satellites. (GNSS and VLBI)

Sun, <--> atmosphere (dry, wet) <--> Land Satellite

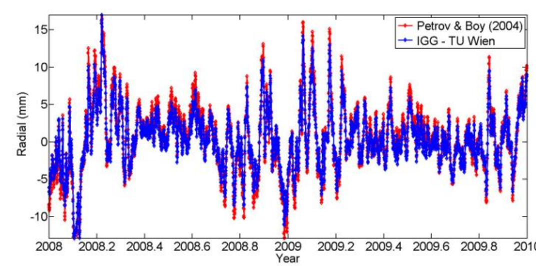
Atmosphere and ocean mass contributes to the gravity field. (removed from gravity sensing satellites)

Geoid height Variations from Atmosphere, mm



Atmosphere and ocean pressure "load" the Earth, with compression effects.

Atmospheric displacement, Station Wettzell, mm



What do we need to know about the atmosphere (and ocean)?

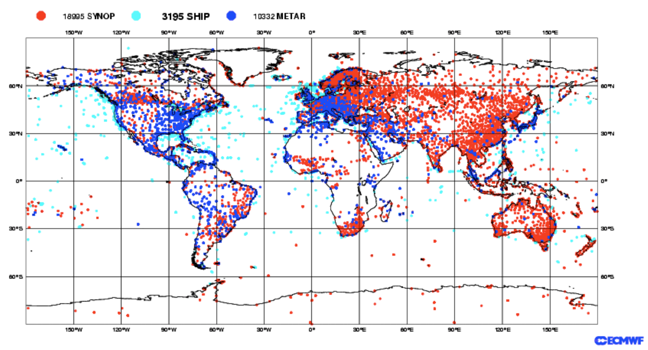
1. Observations, from surface, air, space, and sea

2. Methods of combining observations with each other and with modeled information

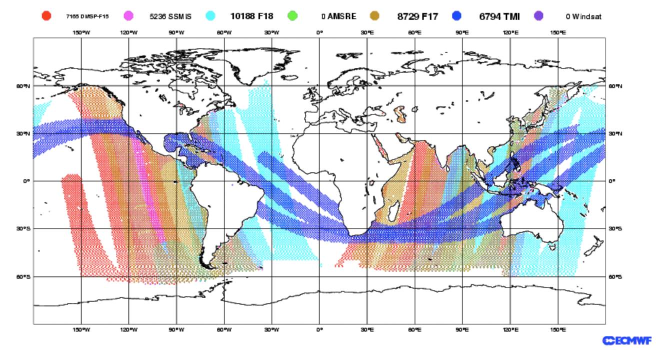
3. How to construct a model of the atmosphere

1.Raw meteorological data (e.g. 00.18.04.12)

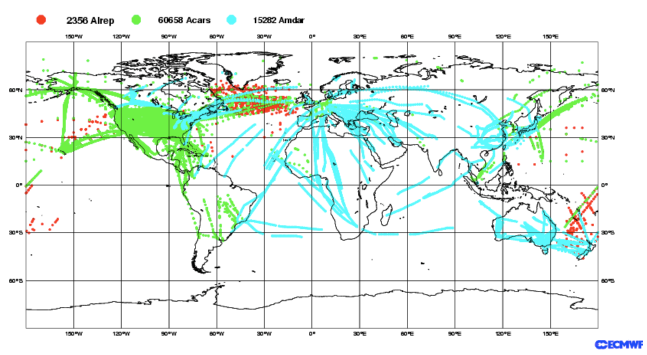
RAOBS, SURFACE



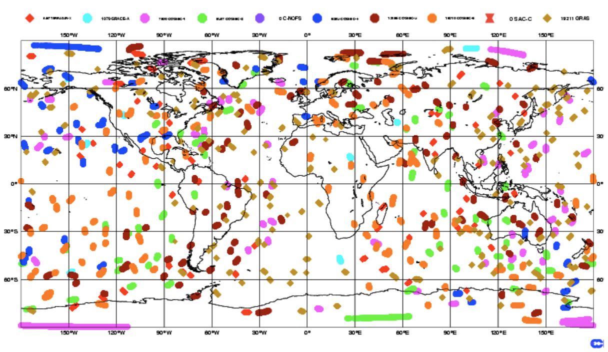
Microwave, (PO+OO)



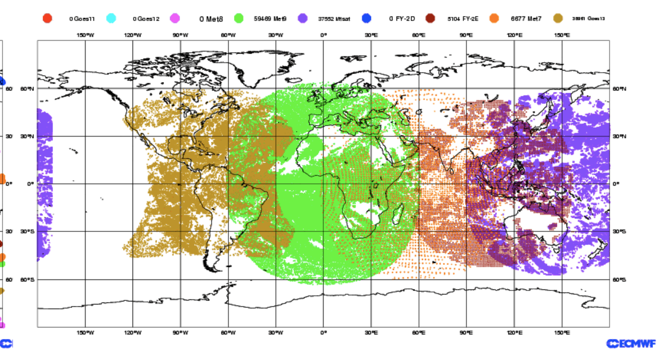
AIRCRAFT



GPS



IR (Geostationary)



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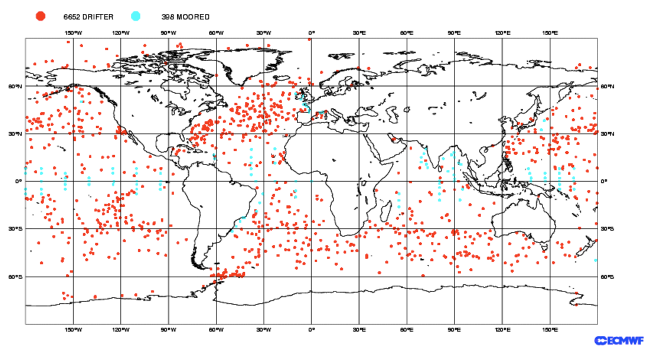
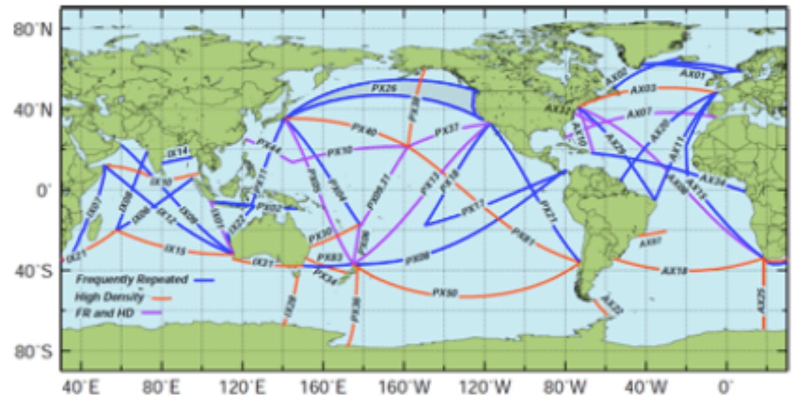
Some more ocean observations

BUOYS



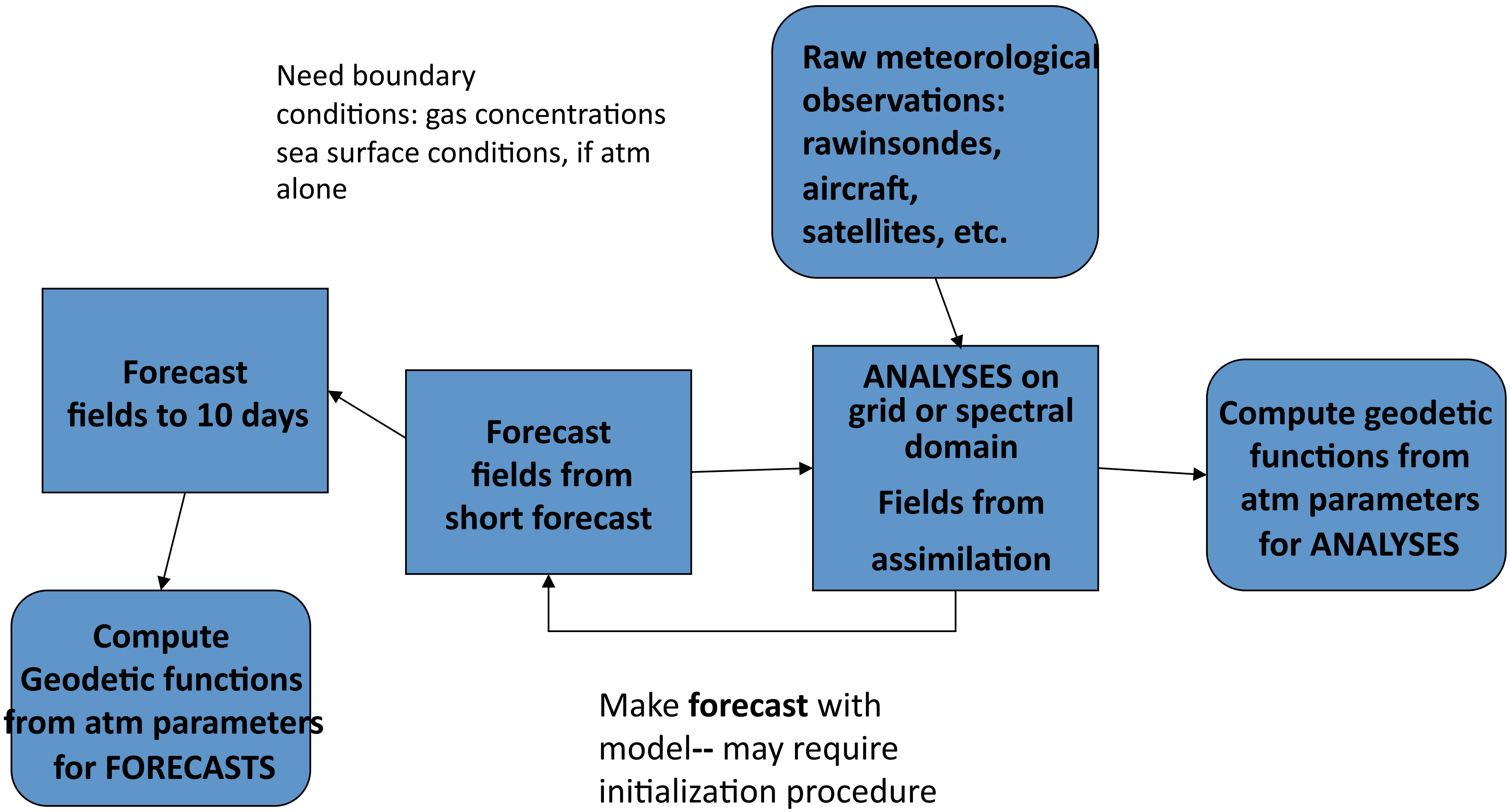
XBTs



View map of XBT lines

(eXpendable BathyThermographs)

2. METEOROLOGICAL DATA ASSIMILATION and FORECAST SYSTEM



3. Atmospheric and ocean models: Equations of fluid motion

Expressed from physical principles:

Equation of motion (Force = Mass x acceleration) about an axis:
in rotating frame:
Torque = Moment of inertia x angular acceleration

Equation of thermodynamics (Heat = increase in temperature x specific heat + work done by expansion)

Conservation of mass* (inflows of mass balanced by divergence out)

*both DRY air and WATER vapor

Equation of motion in fluid

$\mathbf{v}$	velocity(u,v,w)
∇	**i** d/dx +**j** d/dy
ρ	density
Ω	rotation ang. vel
p	pressure
T	stress tensor
f	body force

$$\frac{D}{Dt} = \frac{\partial}{\partial t} + \mathbf{v} \bullet \nabla$$

Substantial derivative, follows the flow

$$\rho\left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \bullet \nabla \mathbf{v} + 2\Omega \times \mathbf{v}\right) = -\nabla p + \nabla \bullet \mathbf{T} + \mathbf{f}$$

Mass Acceleration Forces

$$\frac{\partial \mathbf{v}}{\partial t} = -\mathbf{v} \bullet \nabla \mathbf{v} - 2\Omega \times \mathbf{v} - \frac{\nabla p}{\rho} + \frac{\nabla \bullet \mathbf{T}}{\rho} + \frac{\mathbf{f}}{\rho}$$

Velocity change Advection Coriolis accel Pressure gradient Edge Body

Friction gravity

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Two equations in horizontal: du/dt = … dv/dt = …

Hydrostatic balance in vertical: 0 = (1/ρ) dp/dz = g No vertical accel.

State, thermodynamic, conservation equations

$$p = \rho R_d T$$

Equation of state

$$c_v \frac{dT}{dt} + p\frac{d\alpha}{dt} = heating$$

Thermodynamic eq.

$$\frac{D\rho}{Dt} = -\rho \nabla \bullet \mathbf{v}$$

Continuity of dry air

$$\frac{Dq}{Dt} = S$$

Change in water = sources

$$\frac{\partial q}{\partial t} = -u\frac{\partial q}{\partial x} - v\frac{\partial q}{\partial y} + Evaporation - Condensation$$

p	pressure
ρ	density
Rd	gas constant
T	temperature
cv	specific ht
a	1/ρ
v	velocity
q	spec. humidity
S	water source

Heating=radiation
+latent

3.Can model changes in time from equations

We showed that from physics we have, for property M:

$$\frac{\partial M}{\partial t} = M_{rate}$$

For M = u (zonal wind, from west to east)
v (meridional wind, from south to north)
T (temperature)
q (water vapor)

So we can the relationship as the basis of a "**Forecast model**":

$$M_{t+\Delta t} = M_t + \Delta t * M_{\mathrm{rate}}$$

Perform this sequentially at points on a grid

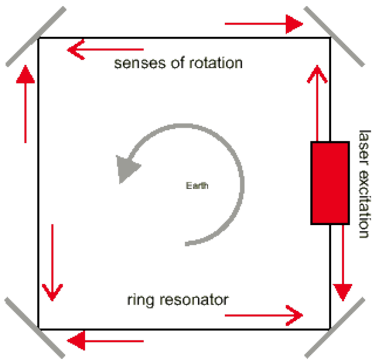
Methods of detection of Earth’s variable rotation

1. Traditional

- Eclipse records (since ancient days)
- Astronomic records, including lunar occultations of stars (since 1600s)

2. Inertial system

- Ring laser (HeNe) - detects Earth rotation independently--by Sagnac effect of splitting of the two directional beams
- Demonstrated, but not routine (Wettzell, Germany geodetic station)
- Current capability: 1 part in 10**8, 1 millisecond in LOD and 10 cm in polar motion



3. Space-geodetic methods (since 1970s)

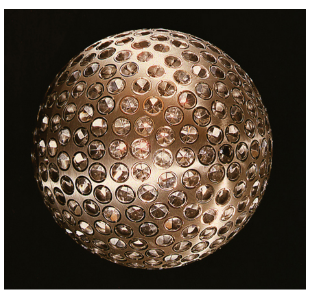
services

Laser ranging -- 1. To moon: lunar retroreflectors (Apollo mission) and 2. To very stable artificial satellites — ILRS

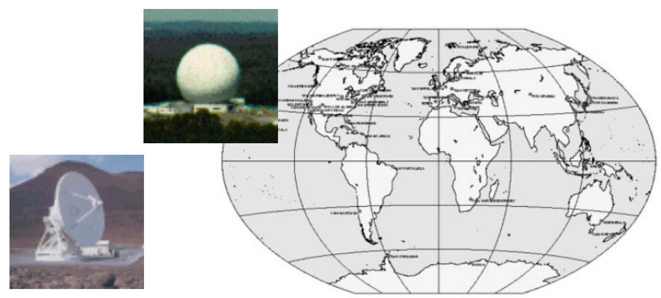
Very-long baseline interferometry (VLBI) radiotelescope to quasars-- compare radio source signals from different ends of baselines — IVS

GNSS - Global positioning system (constellation of >24 satellites) — IGS

Doppler orbitography and radio-positioning integrated from space(DORIS) — IDS



LAGEOS satellite



VLBI radio-telescope network

These four services produce are combined optimally at the International Earth Rotation and Reference Systems Service (IERS) to produce Earth rotation

Physics of Earth rotation

a. Angular momentum (**M**) approach

Atmospheric angular momentum = AAM

$$\frac{dM_{solid.Earth}}{dt} = -\frac{dM_{fluid.layer}}{dt}$$

b. Torque (**T**) approach

$$\frac{dM_{solid.Earth}}{dt} = T_{fluid.layer}$$

$$\frac{dM_{fluid.layer}}{dt} = -T_{fluid.layer}$$

AAM: excitation (χ) vector for Earth rotation: polar motion (1,2) and rotation rate (3)

Polar motion (1,2)

mass

$$\chi^{\mathbf{P}} = \chi_1^P + i\chi_2^P = \frac{-1.098R^4}{(C-A)g}\iint p_s \sin\phi \cos^2\phi \, e^{i\lambda} d\lambda d\phi$$

motion

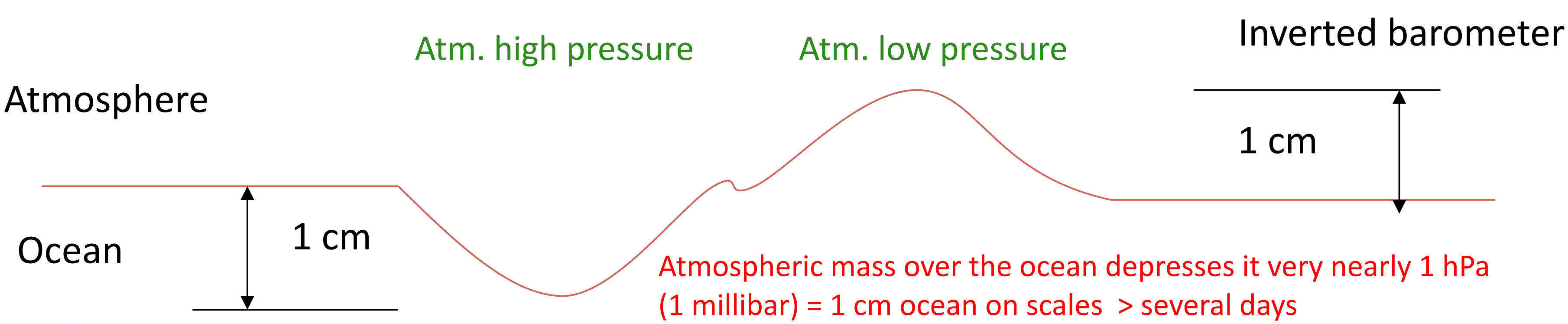
$$\chi^{\mathbf{W}} = \chi_1^W + i\chi_2^W = \frac{-1.5913R^3}{\Omega(C-A)g}\iiint (u\sin\phi + iv)\cos\phi \, e^{i\lambda} \mathrm{d}p\mathrm{d}\lambda\mathrm{d}\phi$$

Earth rotation: Length-of-Day (3)

$$\chi_3^P = \frac{0.753R^4}{C_m g}\iint p_s \cos^3\phi \, d\lambda d\phi$$

$$\chi_3^W = \frac{0.998R^3}{C_m \Omega g}\iiint u\cos^2\phi \, \mathrm{d}p\mathrm{d}\lambda\mathrm{d}\phi$$

Zhou, Salstein, Chen, (2006), updates Barnes et al. (1983)



Atmospheric mass over the ocean depresses it very nearly 1 hPa (1 millibar) = 1 cm ocean on scales > several days

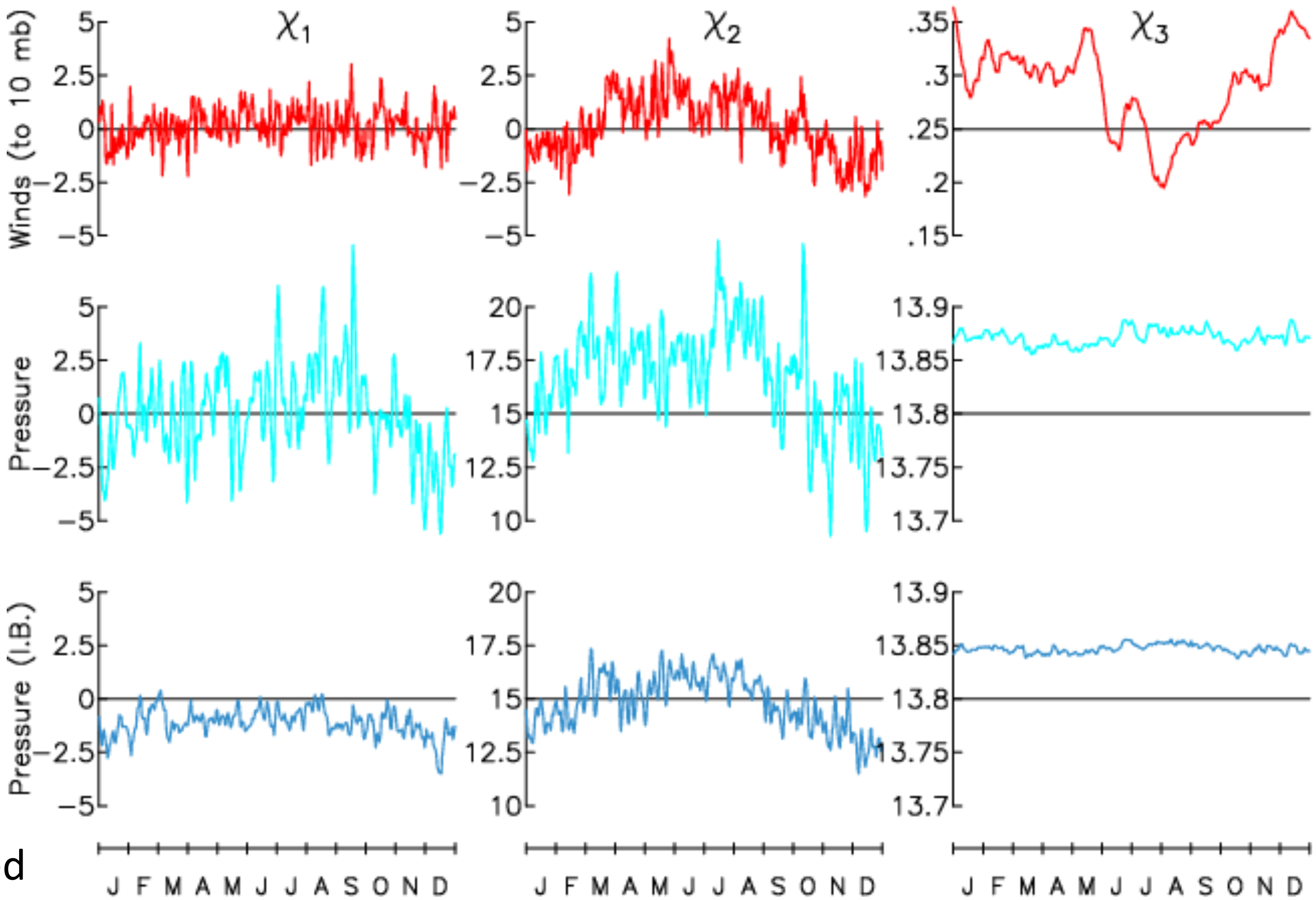
Reanalysis Earth rotation excitation

(2002)

motion

mass

Mass--
IB



IB=Inverted
Barometer

Polar motion

Length of day

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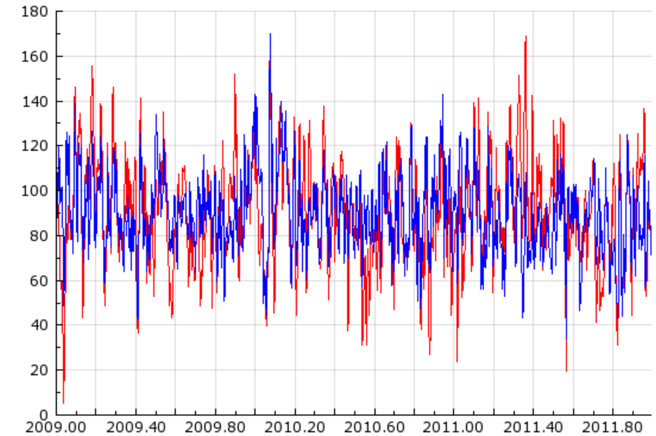
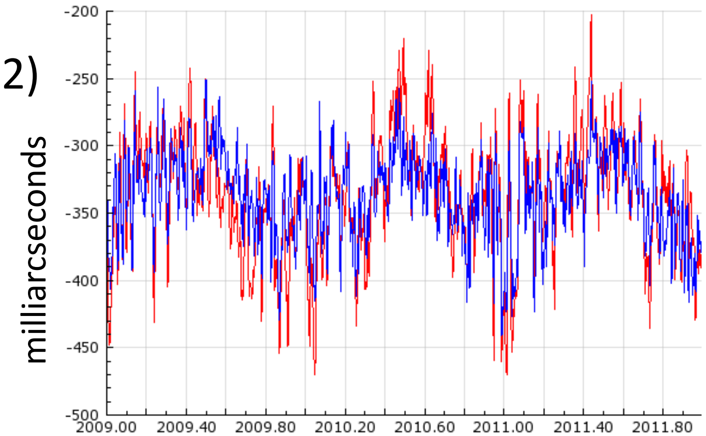
AAM (NCEP-NCAR Reanalyses) and Earth Rotation Parameters (01/2009 – 12/2011)

(1)

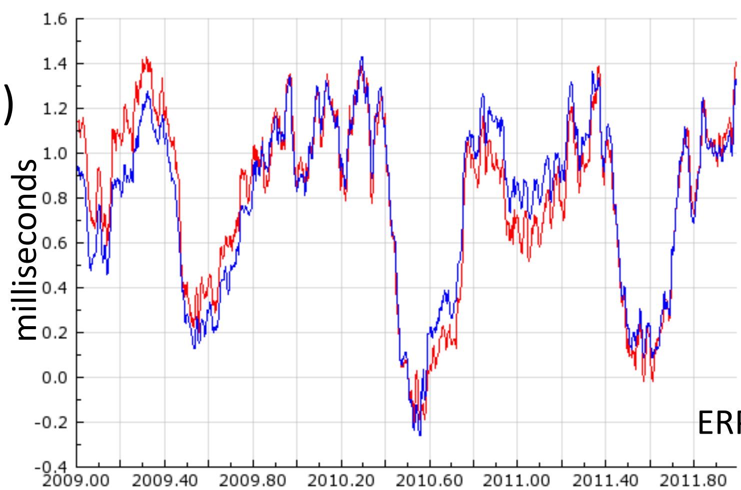


(2)



Polar motion

(3)



Length-of-day

AAM

ERP (geodetic)

ERP data and software: Paris Observatory

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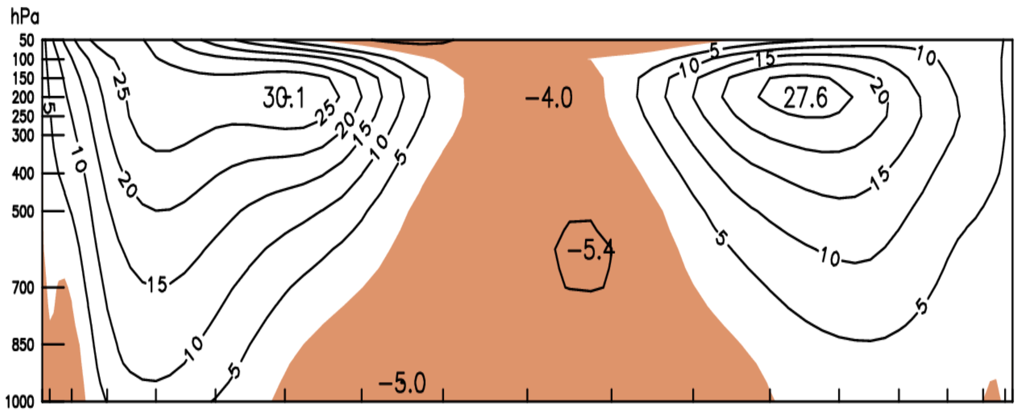
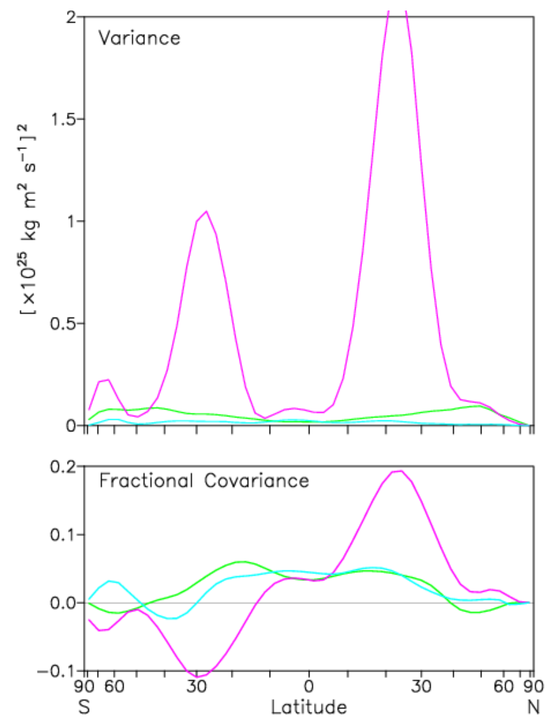
Where are changes coming from in the atmosphere (l.o.d.)?

Zonal winds



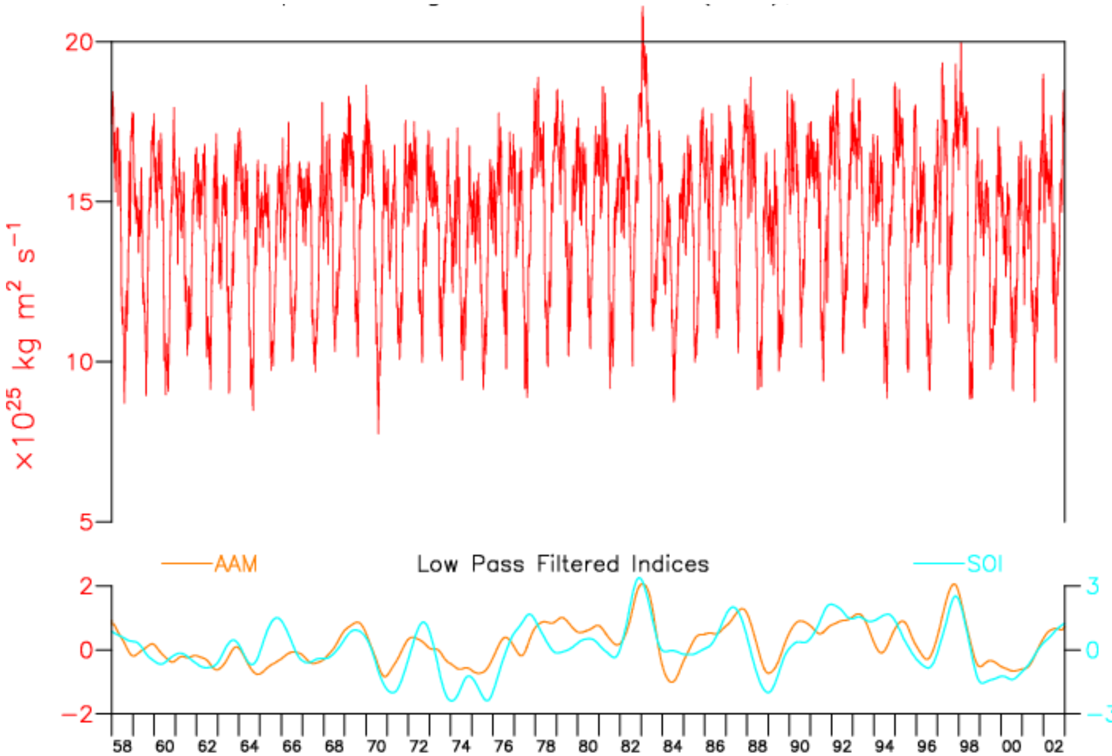
90S

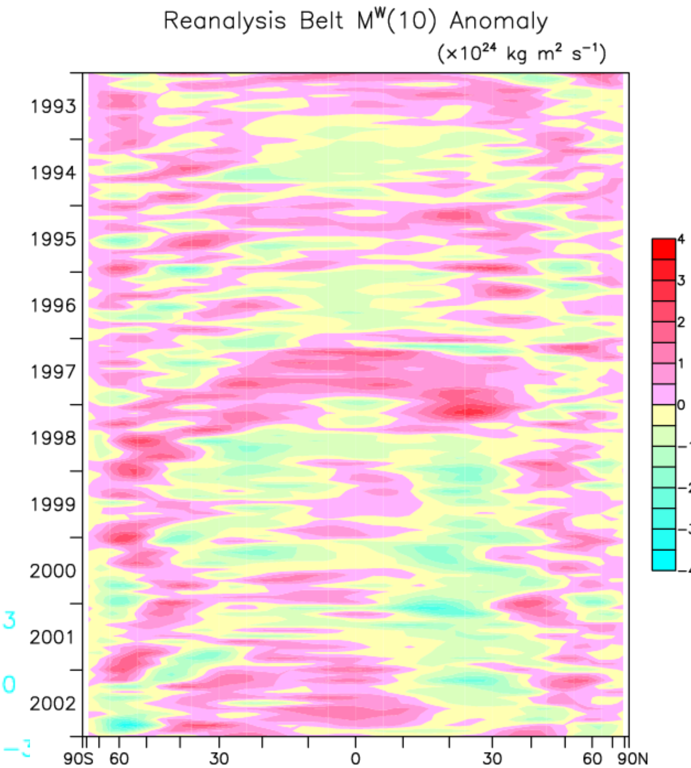
90N



Variance and fractional covariance by latitude

Relevance to climate parameters (ENSO)

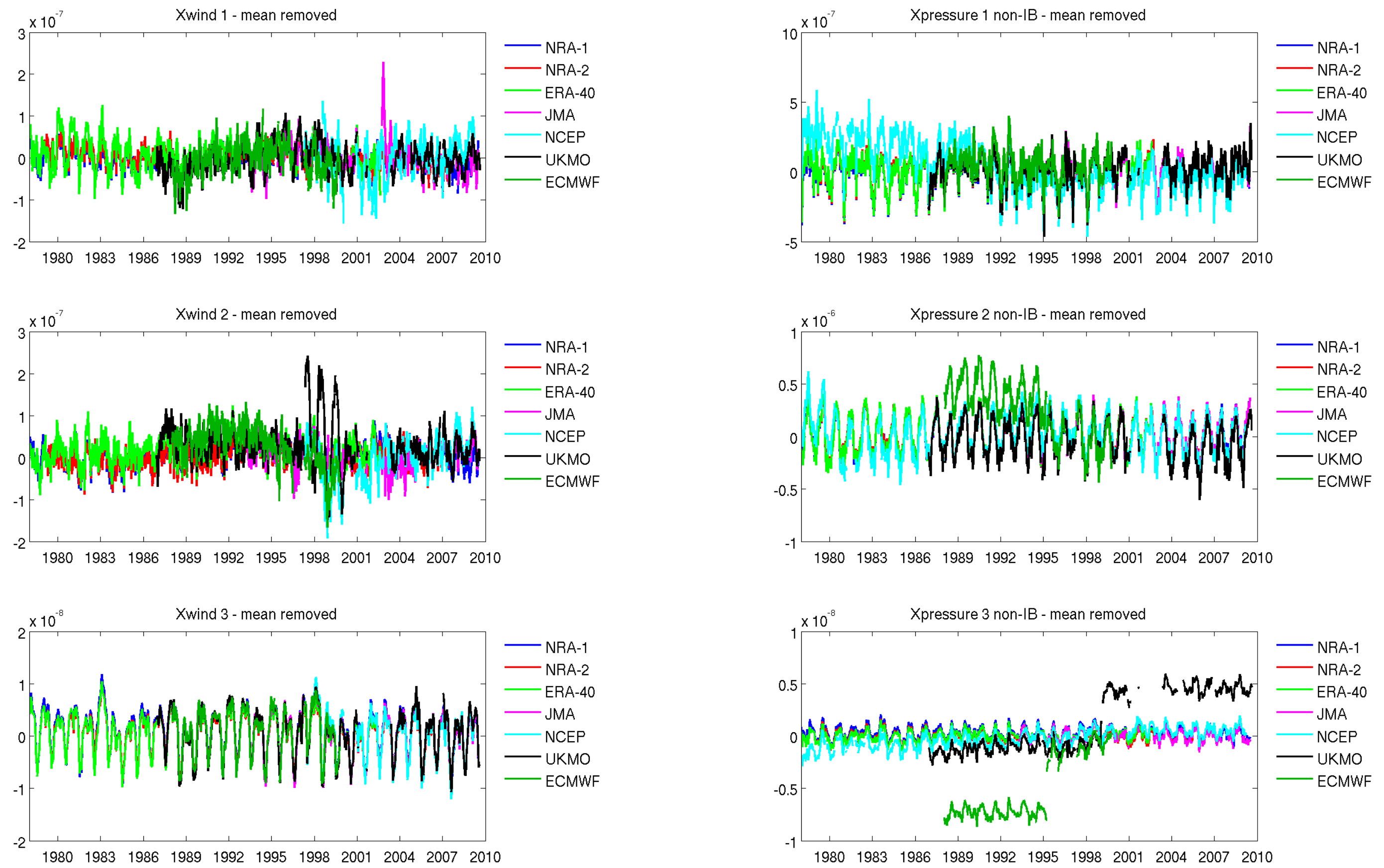




SOI = Southern Oscillation Index; the standardized difference between p_s over Tahiti (central Pacific) and Darwin, Australia. Peaks are El Nino events

ENSO= El Nino/Southern Oscillation

Excitation (AAM) series from the Special Bureau for the Atmosphere of the IERS* (30 day mean removed)



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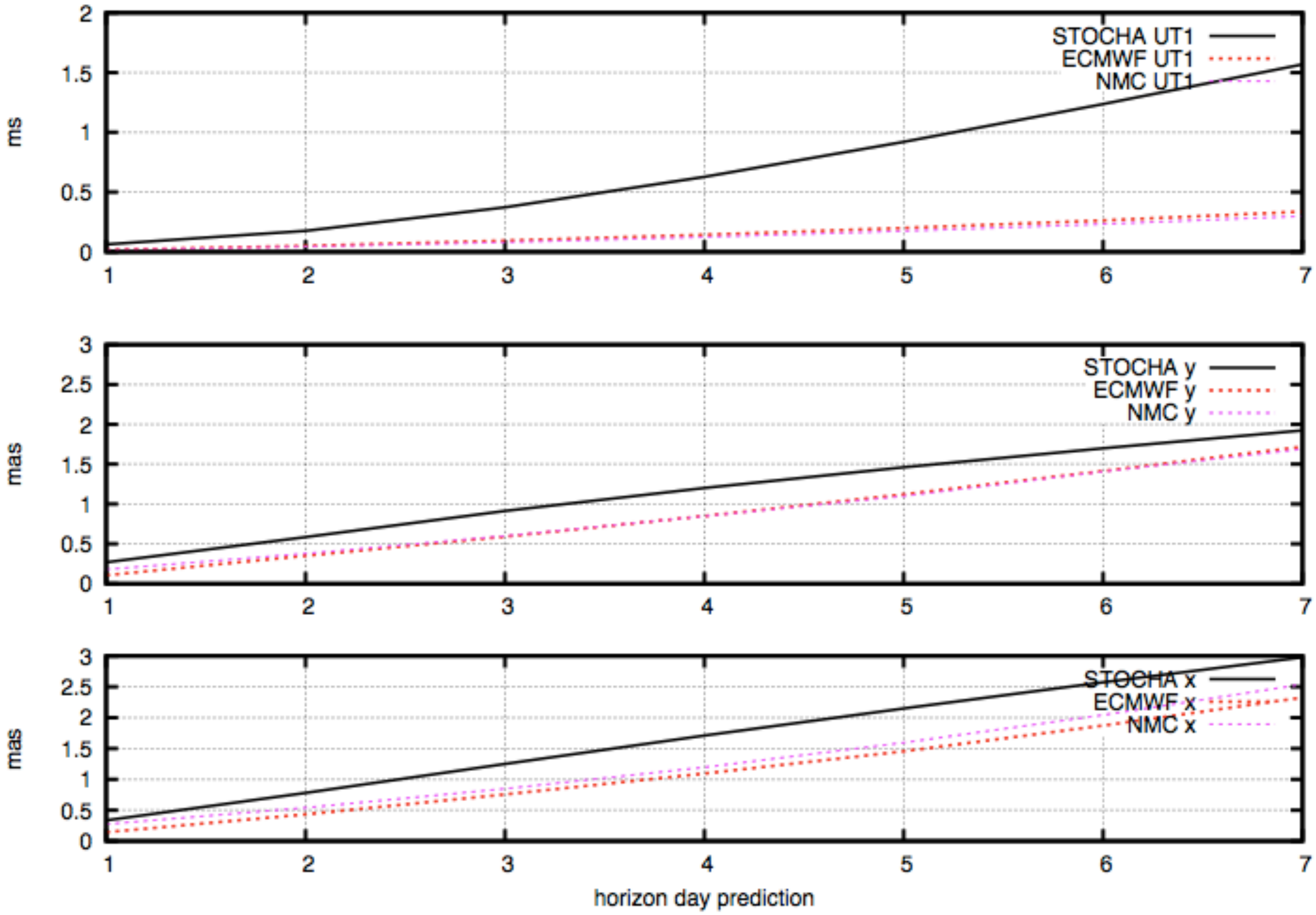
*International Earth Rotation and Reference Systems Service

Forecasts of lod, pm, including AAM



with C. Bizouard,
D. Gambis,
Paris Observatory

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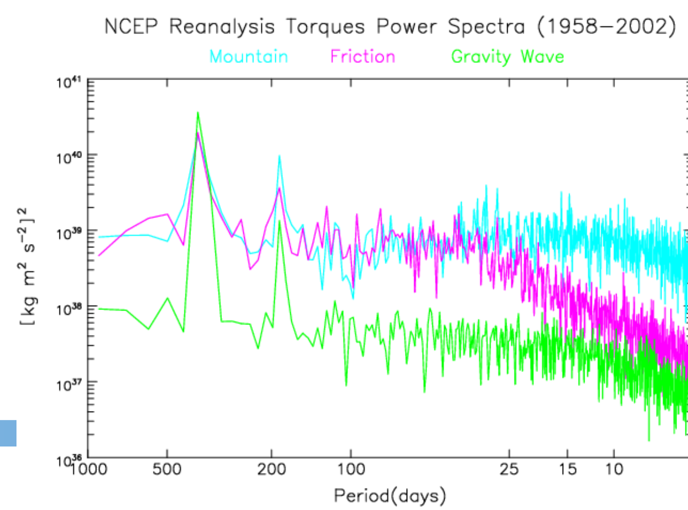
Mountain and friction torques

$$T_{mountain} = -R^2 \iint p_s \frac{\partial Z}{\partial \lambda} \cos\phi \, d\phi \, d\lambda$$

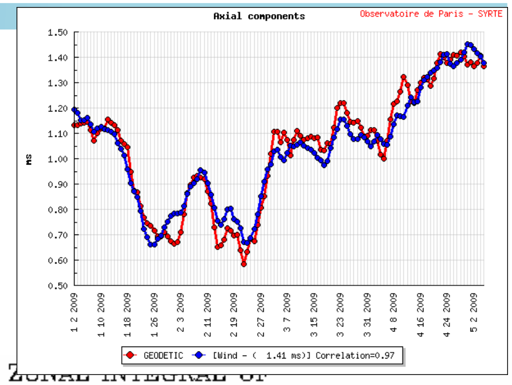
$$T_{friction} = R^3 \iint \tau \cos^2\phi \, d\phi \, d\lambda$$

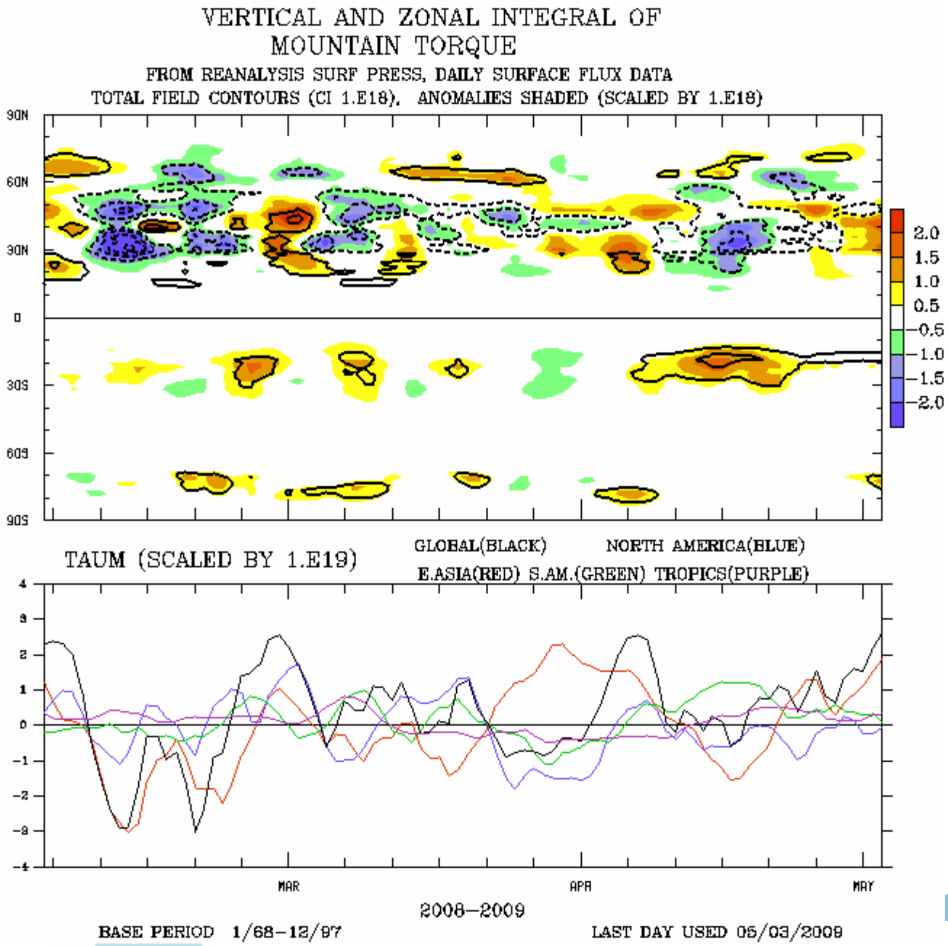
$T_{gravity-wave} =$ Frictional related to sub-grid scale Action in the atmospheric model

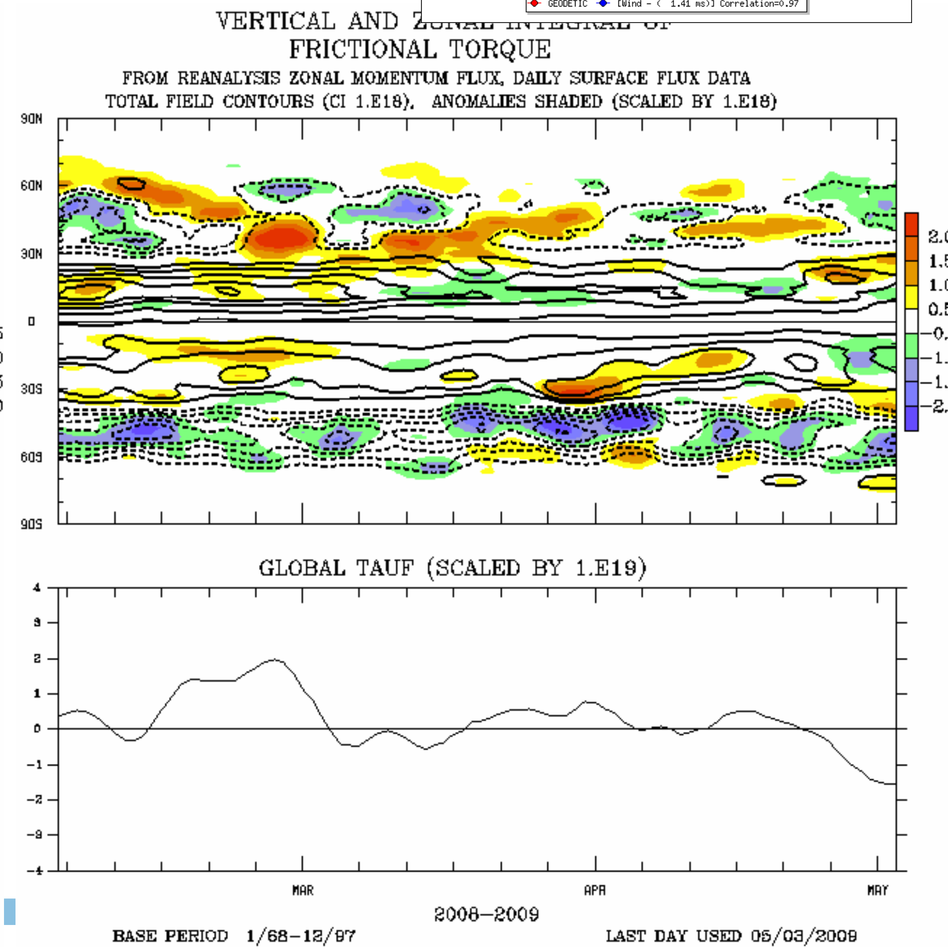
R=Earth radius, **p_s**=surface pressure, **Z**=topographic height
τ=frictional stress, related to winds and roughness (model)
ϕ=longitude λ=latitude



Mountain and friction torque
4 Feb 09 - 3 May 09







US NOAA, following Iskenderian and Salstein, and Weickmann et al.

Coupled model intercomparison project

Uses climate models with Greenhouse gas and other forcing: basis of the assessment reports by the Intergovernmental Panel on Climate Change.

Many climate models available, but we chose these to focus on models from MPI (Max Planck Inst.), US NASA Goddard (GISS), US GFDL, Hadley Center (UK)

CMIP 3

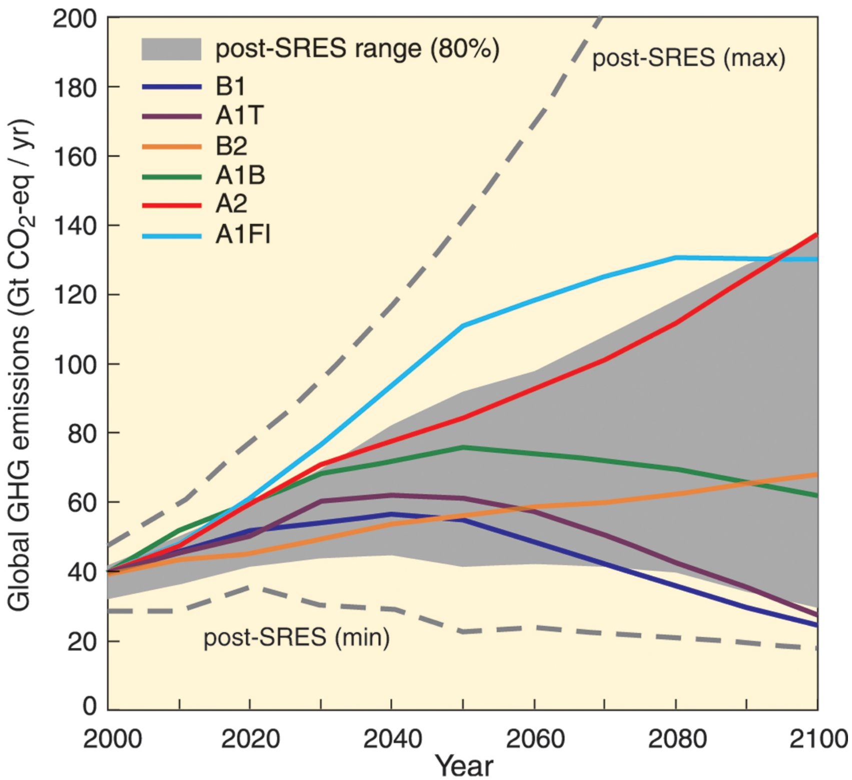
Previously IPCC scenarios were chosen based on population, economic growth, and technological developments:

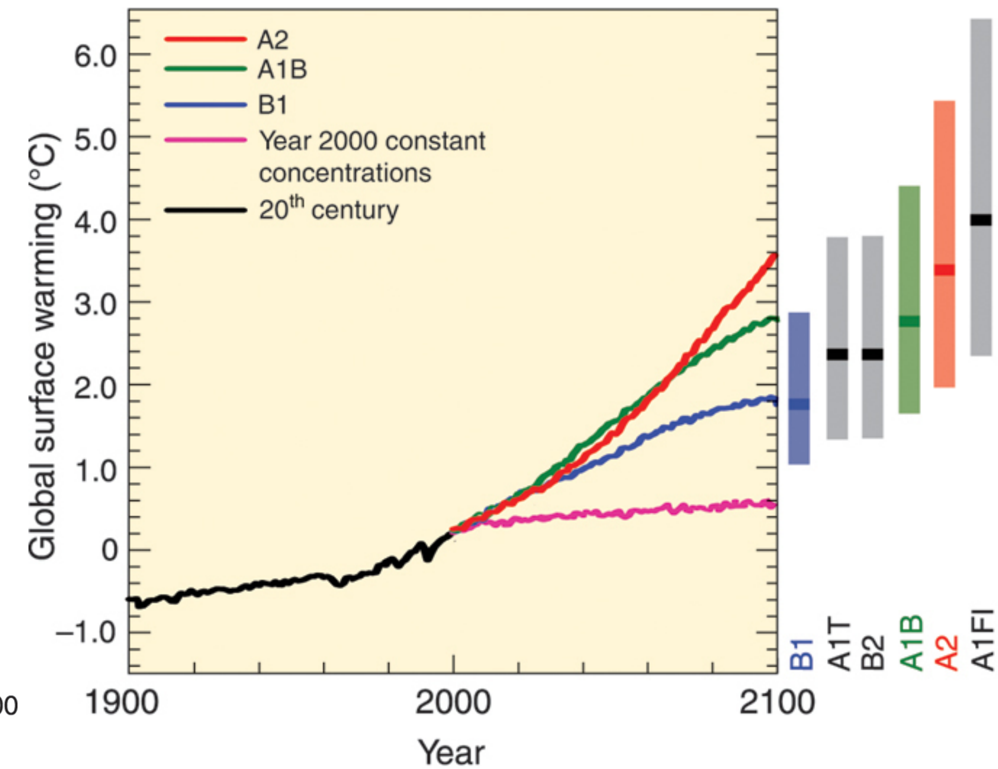
A2: Rapid growth
A1B: “Middle of the road” scenario
B1: GHG emissions stabilized

CMIP5

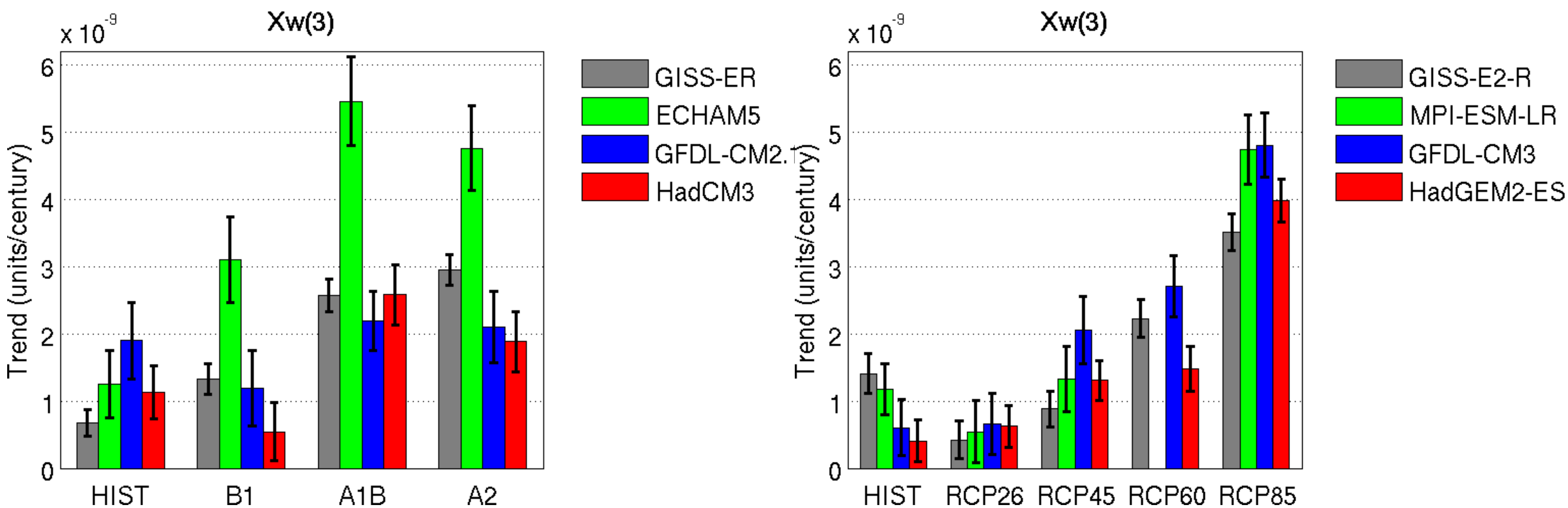
Updated IPCC scenarios have quantitative RCP’s (Representative Concentration Pathways) that span the climate space of radiative forcing: RCP 2.6, 4.5, 6.0,8.5

Greenhouse gas and warming scenarios from CMIP models



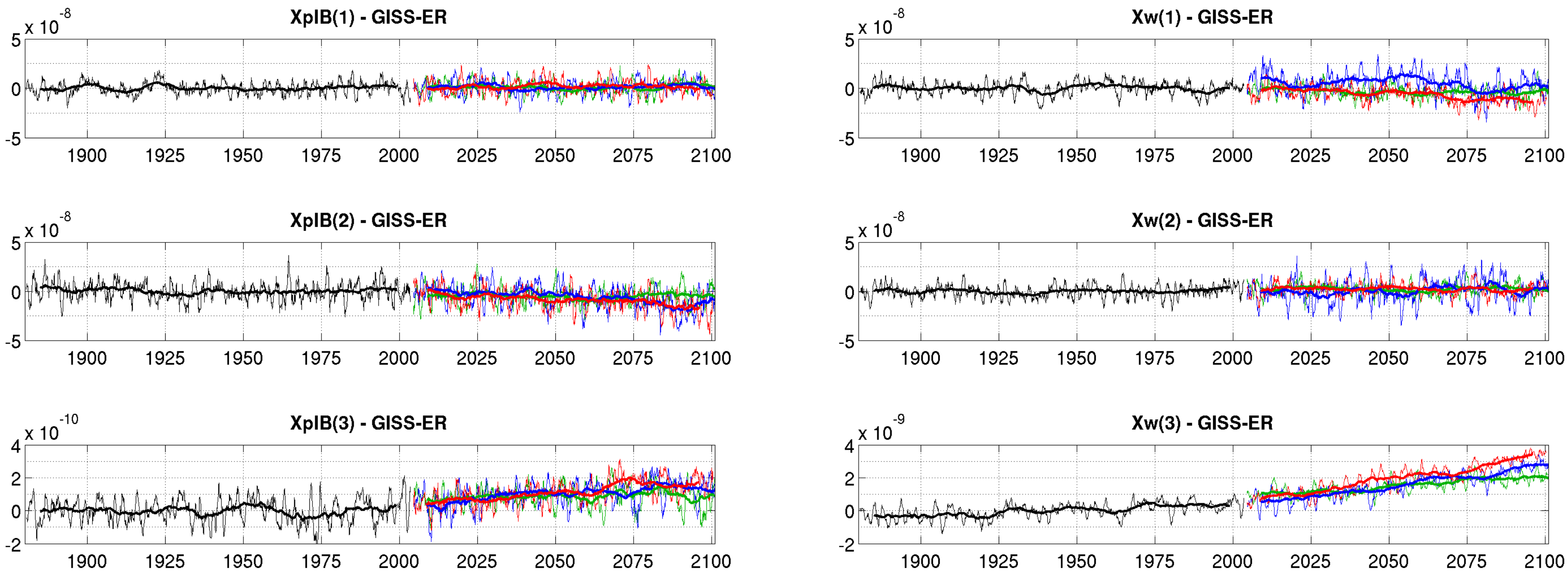


Trend in Earth rotation excitation by winds, CMIP3 and CMIP5



Salstein and Quinn

Atmospheric excitation functions under different scenarios (CMIP3)



Pressure-IB *Wind*

A2, A1B, B1

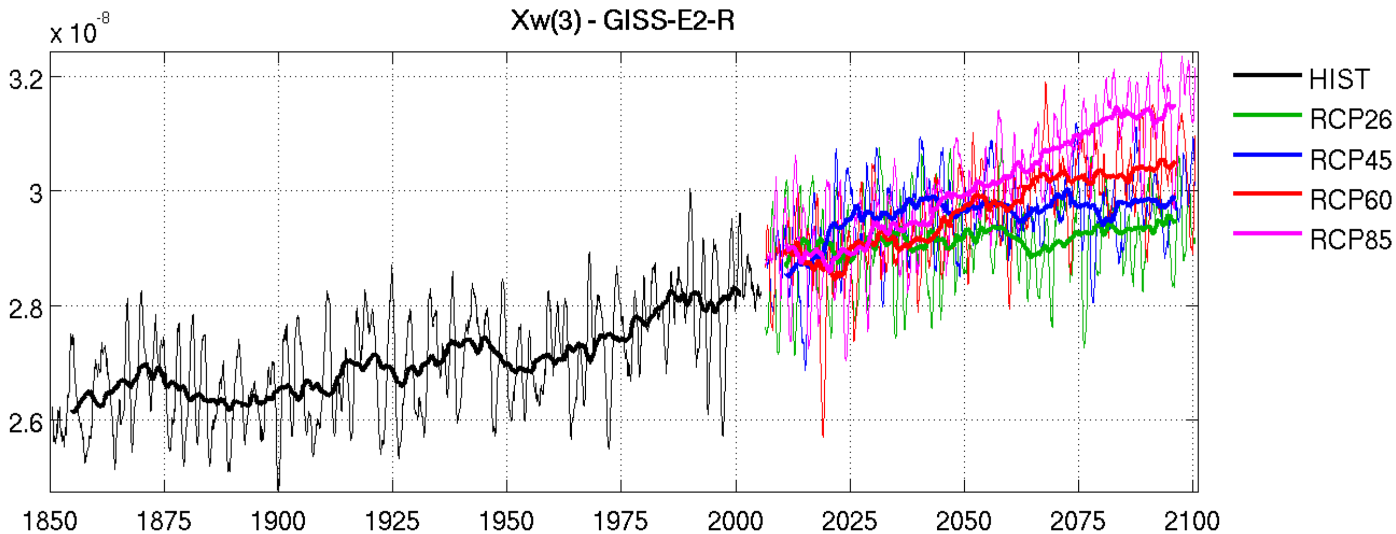
Salstein and Quinn

Atmosphere component, coupled model

Uses climate models with Greenhouse gas and other forcing: basis of the assessment reports of climate change by the Intergovernmental Panel on Climate Change.

CMIP 5

Updated IPCC scenarios have quantitative RCP's (Representative Concentration Pathways) that span the climate space of radiative forcing



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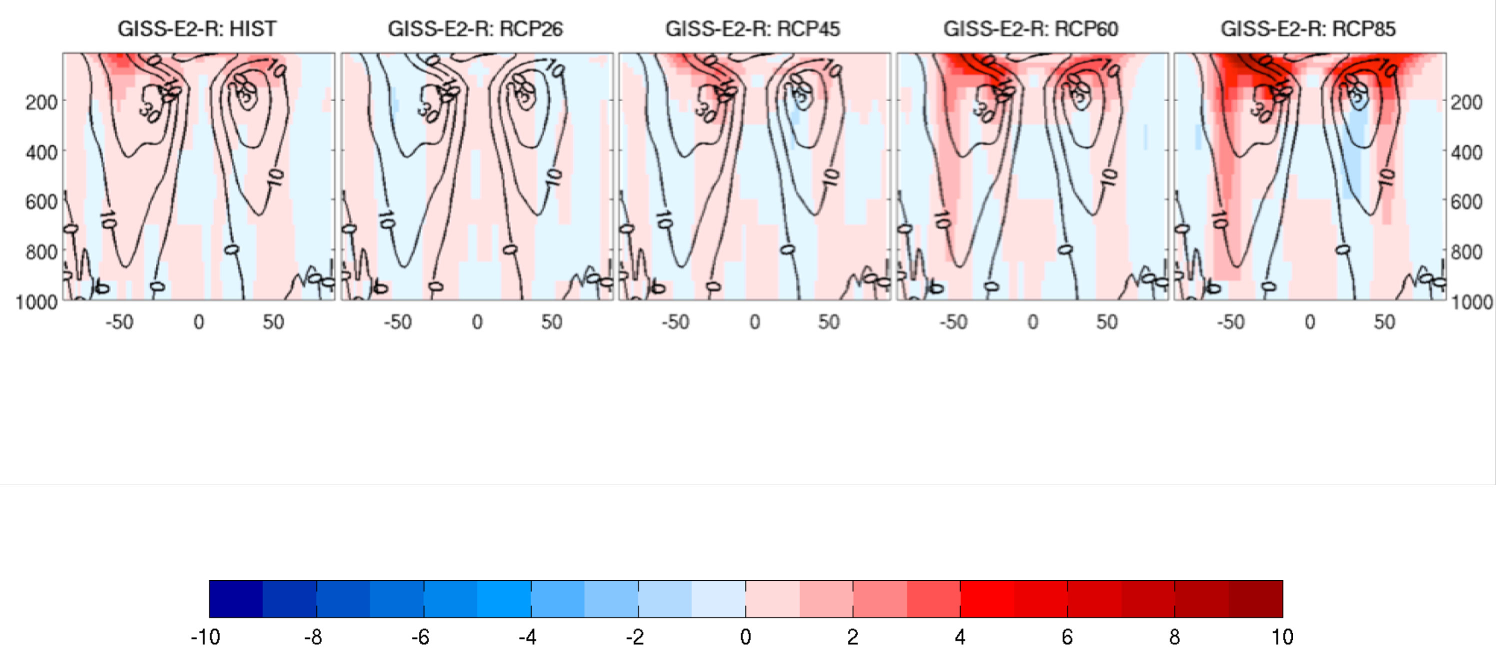
Trends in zonal means – zonal winds



Units: m/s/ century

Contour units mean over 20th century in m/s

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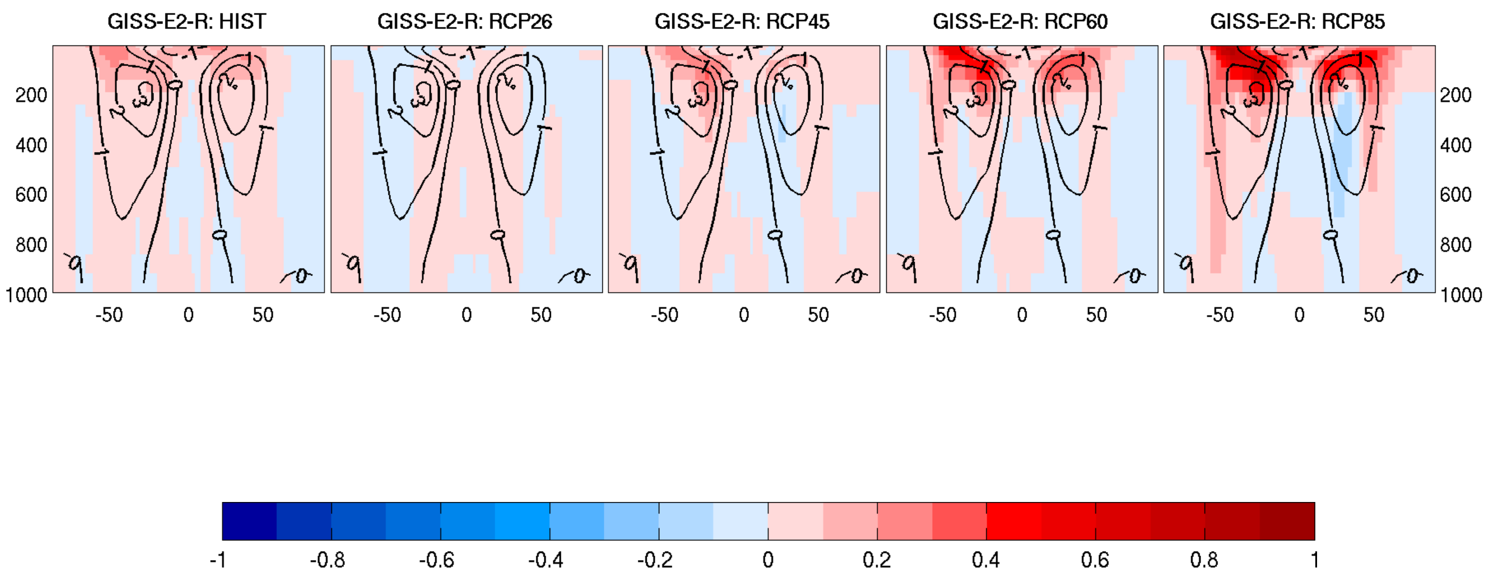
Trends in zonal means – χ3w

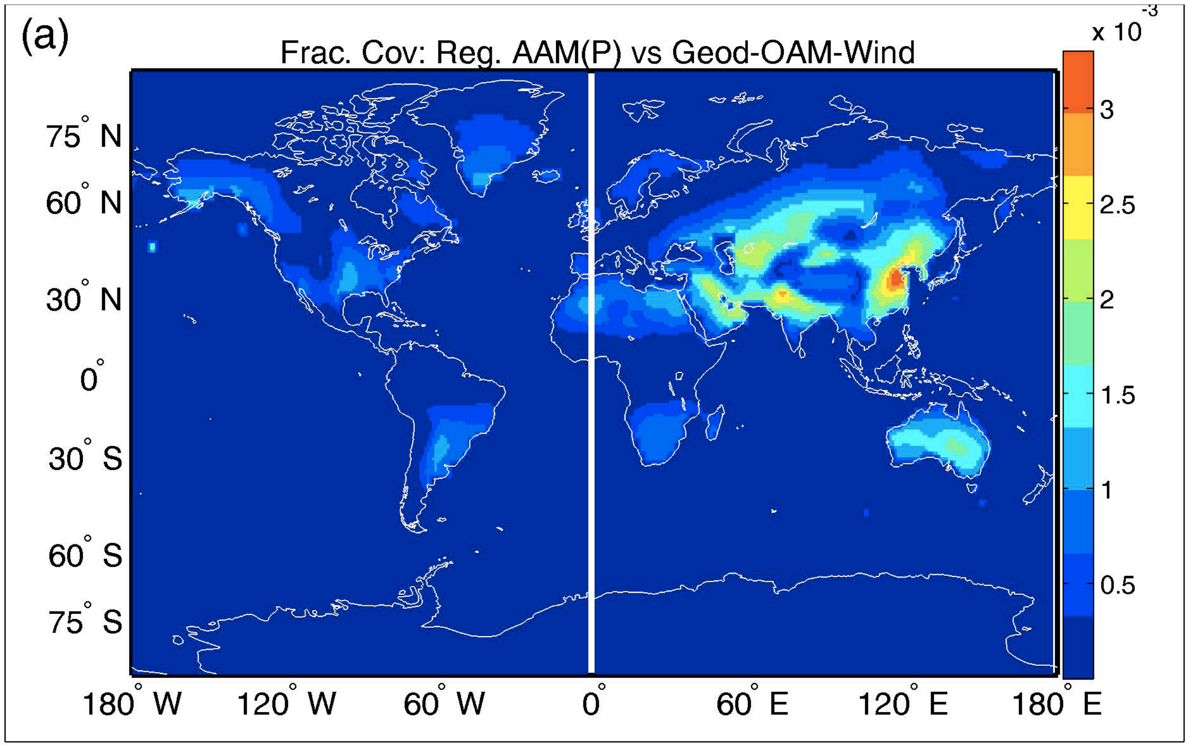


Zonal mean trend (per century) by latitude and pressure level (hPa), weighted by zonal area and pressure: (10^-25/m^2/hPa/century). Contour lines: 20C3M zonal mean χ3w, similar weighting 10^-25/m^2/hPa).

Salstein and Quinn

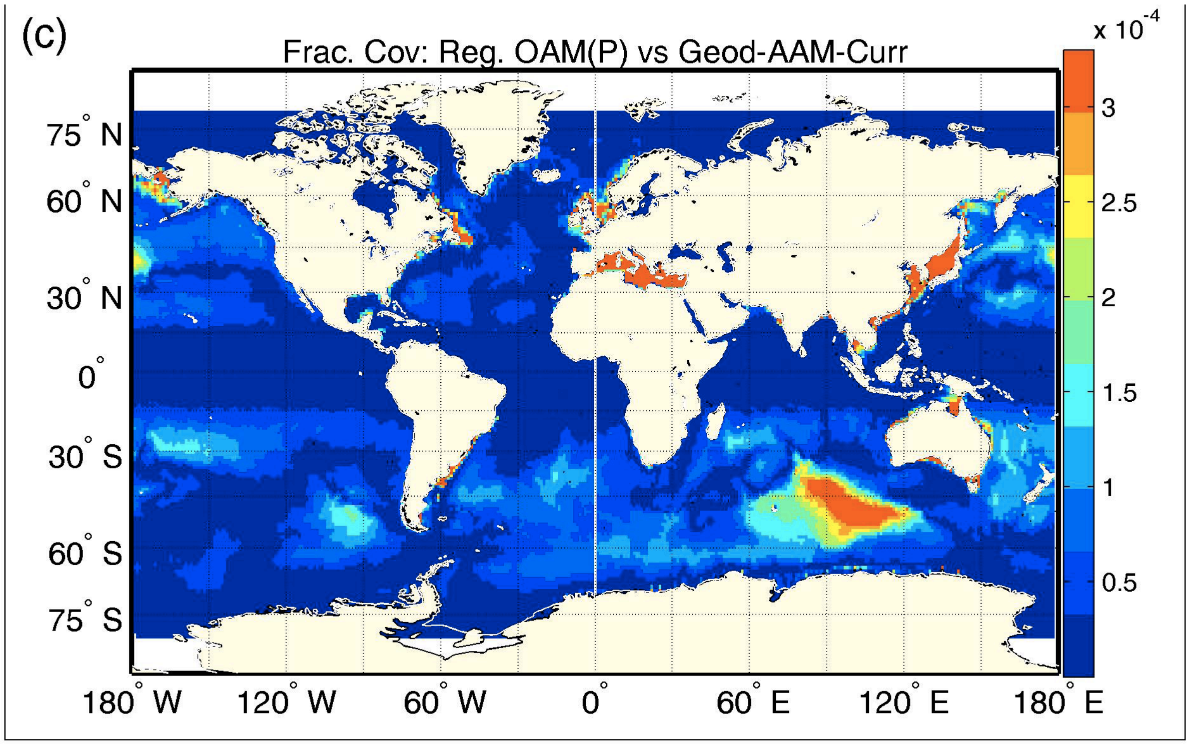
Excitation polar motion, annual – Atmosphere mass

Nastula, Salstein Gross (2012)



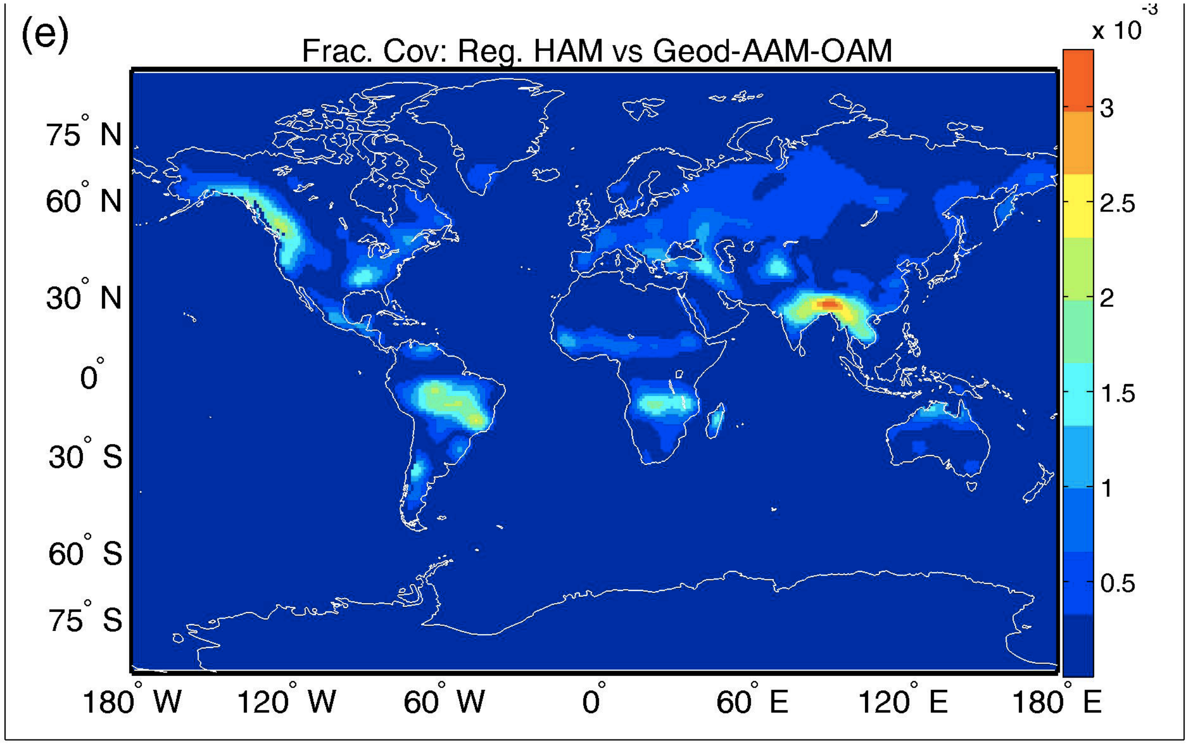
Excitation polar motion, annual – Ocean mass

- Nastula, Salstein, Gross (2012)



Excitation polar motion, annual – Land hydrology mass

- Nastula, Salstein, Gross (2012)

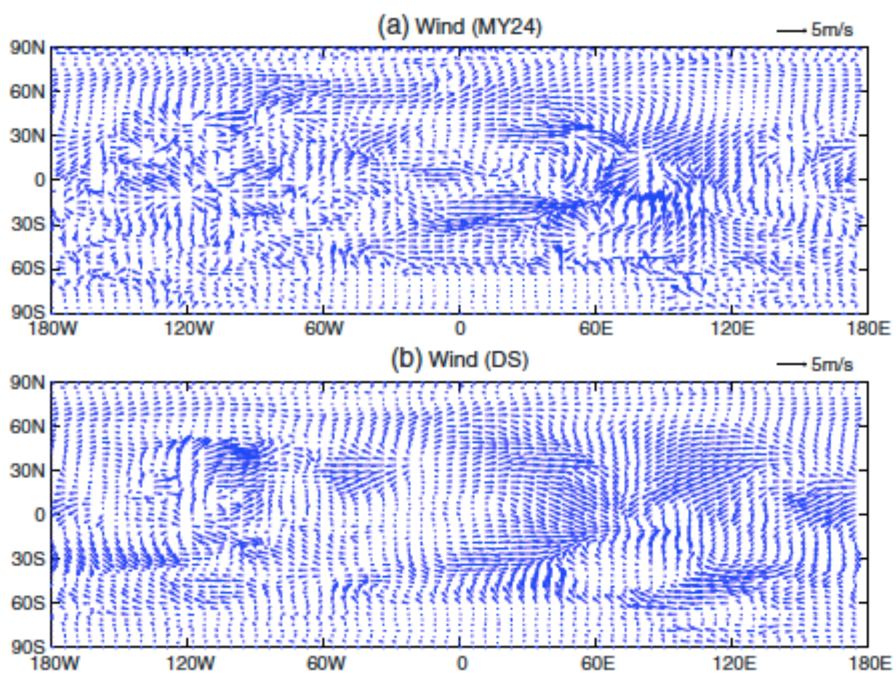


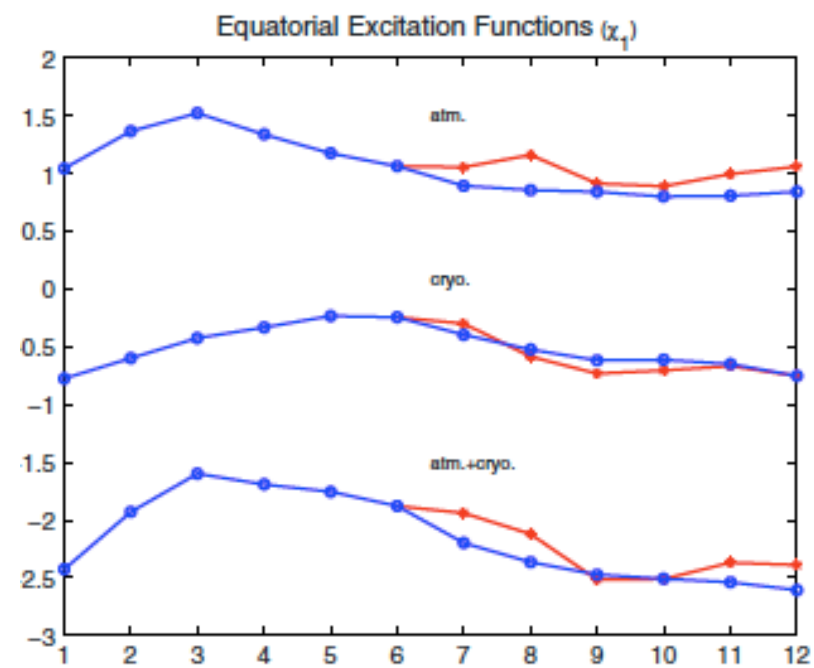
What about AAM on other planets/ satellites?

- Earth: atmosphere medium density, 1000 hPa
- Mars: atmosphere very low density, 600 Pa, CO2
- Venus: atmosphere very high density, fast superrotation of 4 Earth days), compared to 243 Earth day rotation, retrograde
- Titan: atmosphere medium density, 1500 hPa

Mars – impact of dust storm on AAM and rotation

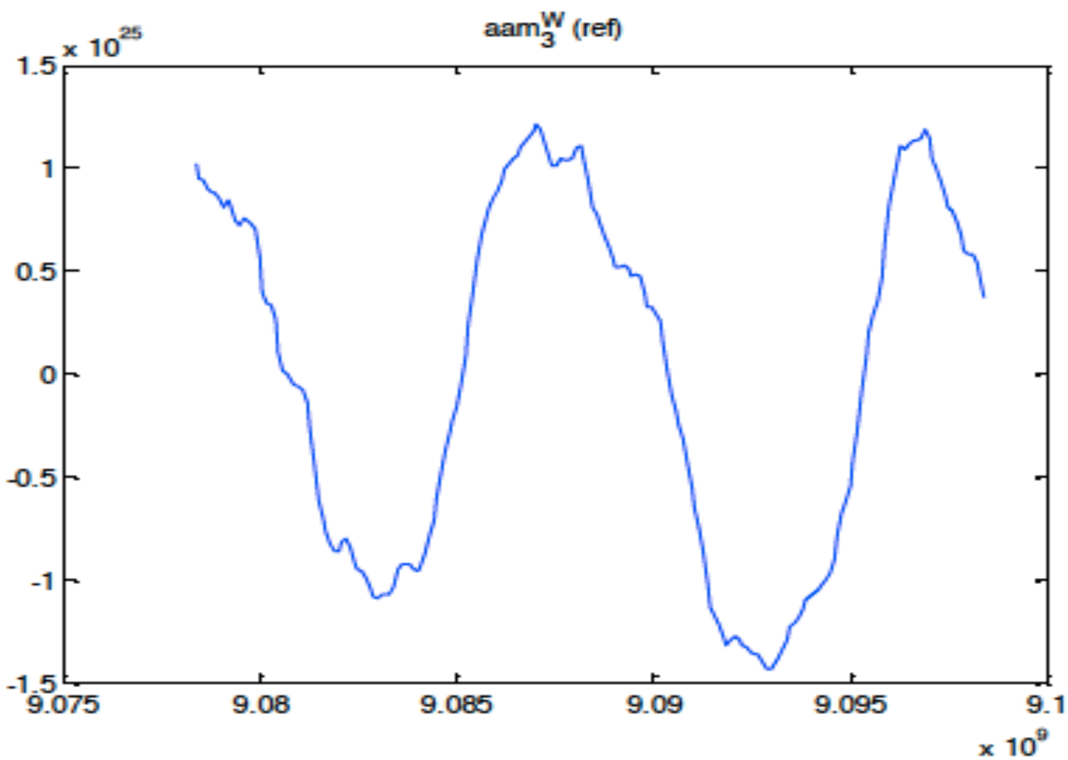
- **Global dust storm signal in the meteorological**
- **excitation of Mars' rotation, 2013: JGR**
- **Y. H. Zhou,1 D. A. Salstein,2 X. Q. Xu,1 and X. H. Liao1**





Venus: super-rotation with great mass

- Topic of current work with Y. Zhou
- AAM from winds over 2 Venus Days



Using data from LMD model, as analyzed by Lebonnois et al. 2010

Summary

- Atmosphere is important for for a number of geodetic purposes (AAM, loading, gravity, delays.) Recognized by the IERS.

- Atmospheric angular momentum (AAM) is a fundamental measure of the atmosphere, relating to both climate signatures and Earth rotation measurements; from *reanalyses* and models, useful for forecasts.
- Atmosphere and ocean can be modeled based on the equations of physics and forecast in time.

- CMIP: Modeled trend in AAM increased somewhat in the 20th century and expected to increase more in the 21st century depending upon the warming scenario. Source: zonal wind changes in upper troposphere/ lower stratosphere in the subtropics.

Program, acknowledgments

- We maintain a range of atmospheric data for the geodetic and astronomical communities, in additional to the application to climate/weather science, as part of the Global Geophysics Fluid Center of the “International Earth Rotation and Reference Systems Service”
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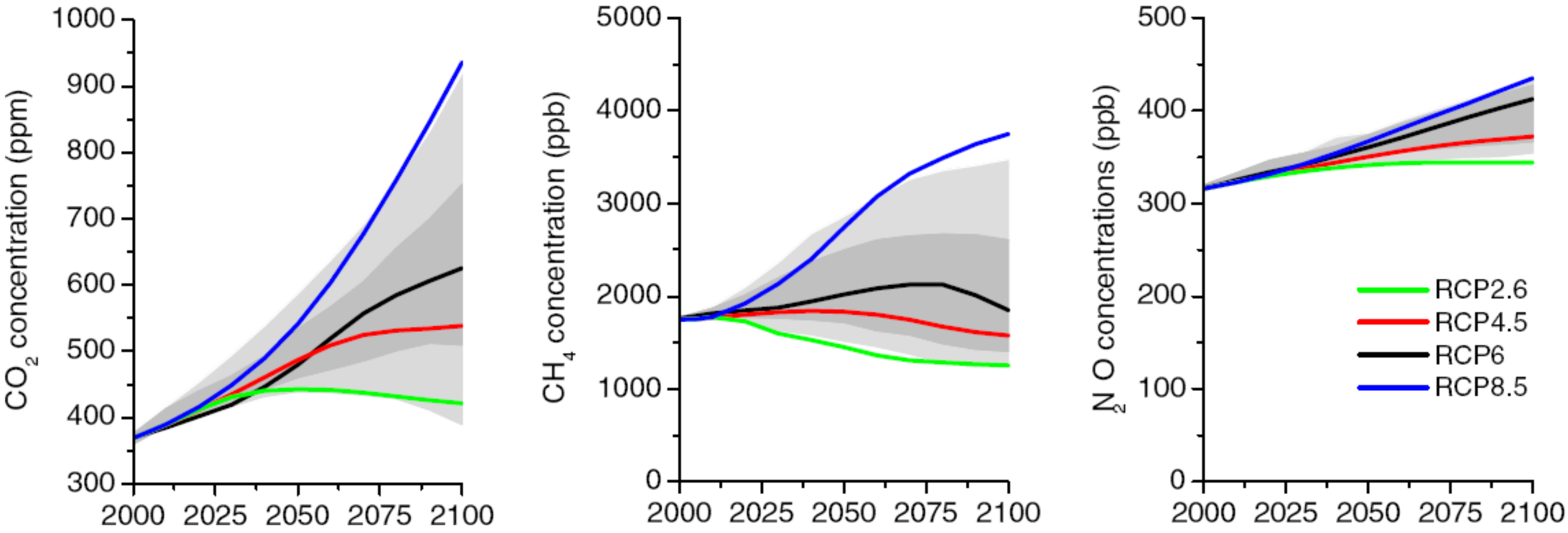
Trends in concentration of GHG



(Clark et al. , 2010)

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