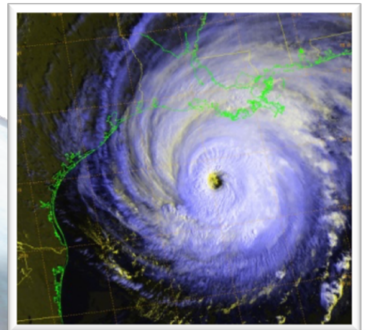
Atmospheric Angular Momentum related to Earth Rotation studies: History and modern developments

Atmospheric and Environmental Research
Lexington, MA, USA

Journees 2019

L'observatoire de Paris
October 8, 2019



Dedication -- to Prof. Barbara Kolaczek

With whom I collaborated for many years – I was inspired by her scientific insight and curiosity, determination, and genuine kindness.

Outline

History of Atmospheric angular momentum and relation to Earth rotation
Modeling of the atmosphere (and the ocean): equations based on physics

Variable Earth rotation: relationship to atmosphere
Atmospheric angular momentum (AAM)--how it is measured and its
climate signals
Seasonal, subseasonal, intraseasonal, interannual time scales

Dynamical relations: torques change rotation rate

Long-period models (20^{th} century +)
Coupled model intercomparison project (CMIP), global change results, and relationship to AAM

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

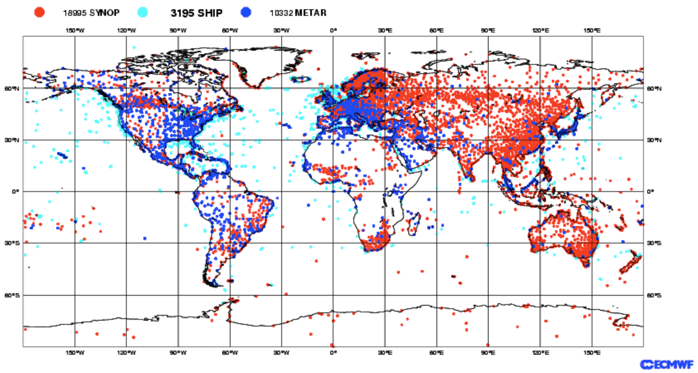
1. Observations, from surface, air, space, and sea

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

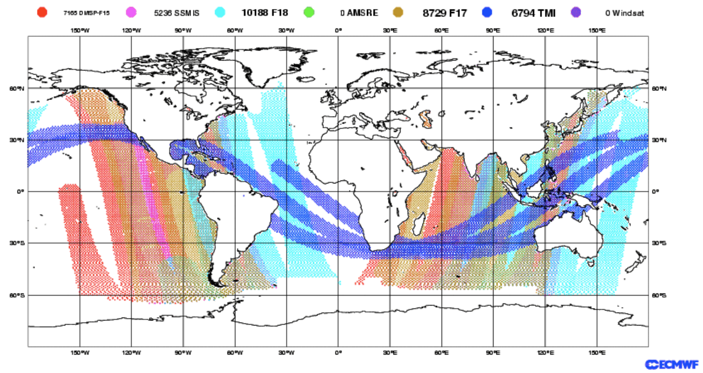
3. How to construct a model of the atmosphere

1.Raw meteorological data

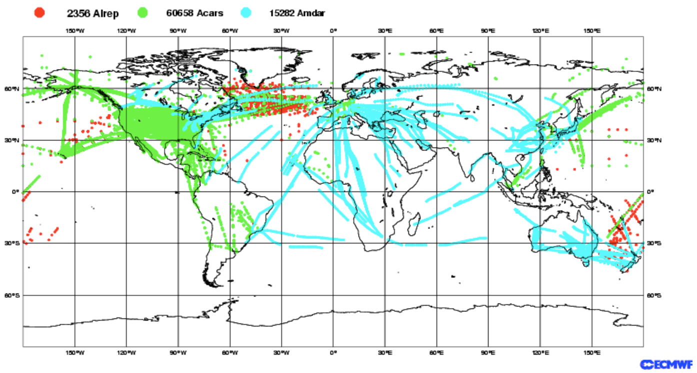
RAOBS, SURFACE



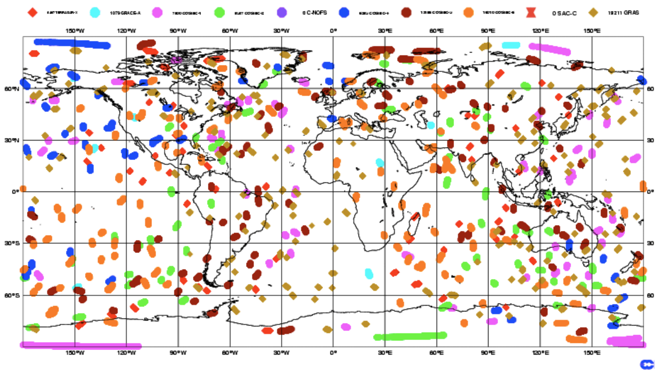
Microwave, (PO+OO)



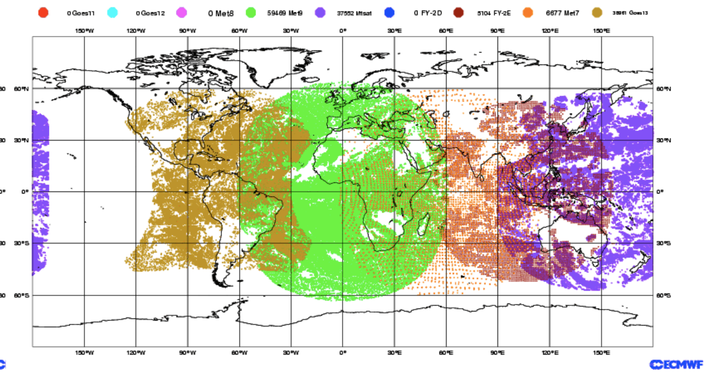
AIRCRAFT



GPS

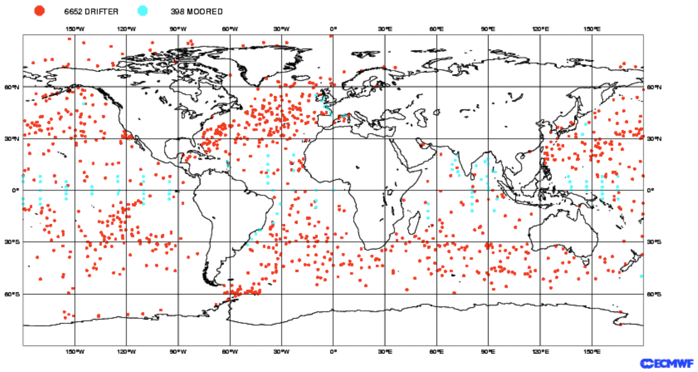


IR (Geostationary)

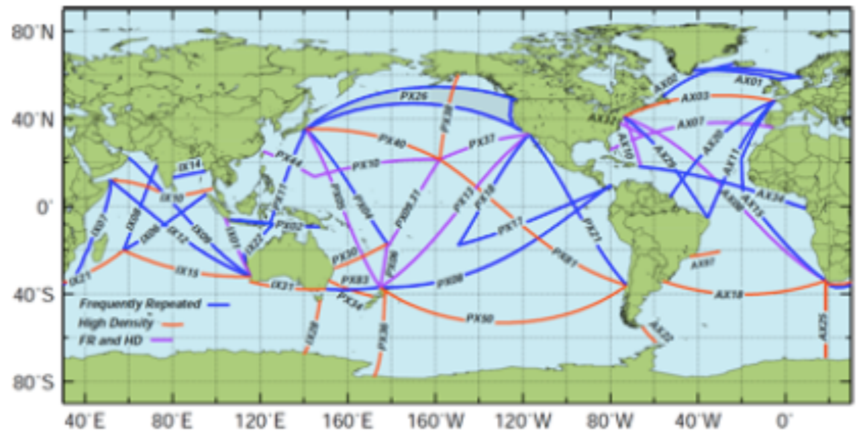


Some more ocean observations

BUOYS



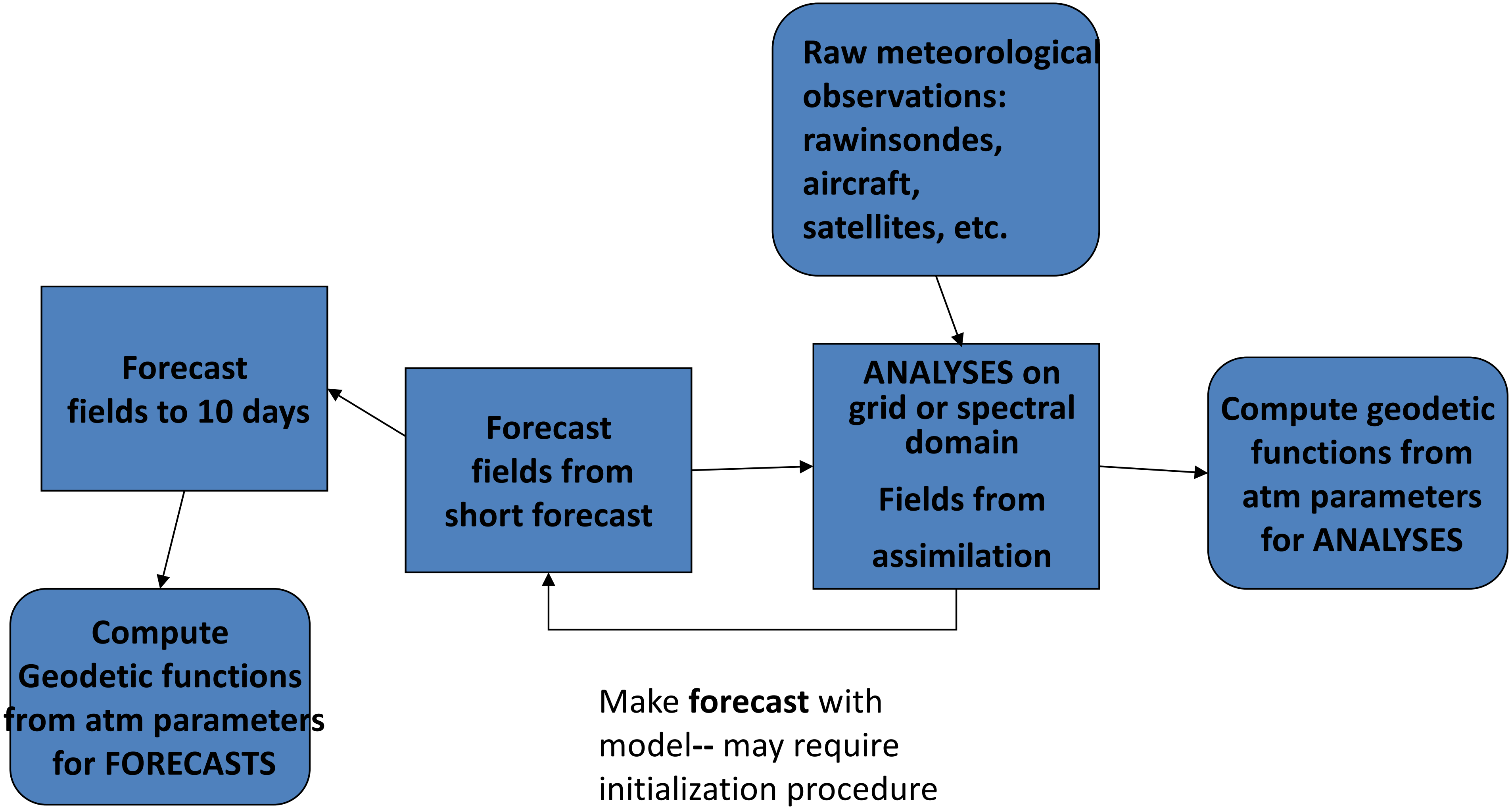
XBTs



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

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 Friction Body gravity

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

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

Angular momentum fluxes in atmosphere

From: **Physics of Climate**, J.P. Peixoto and A.H. Oort, 1992

angular momentum =

mass x velocity x

distance to axis

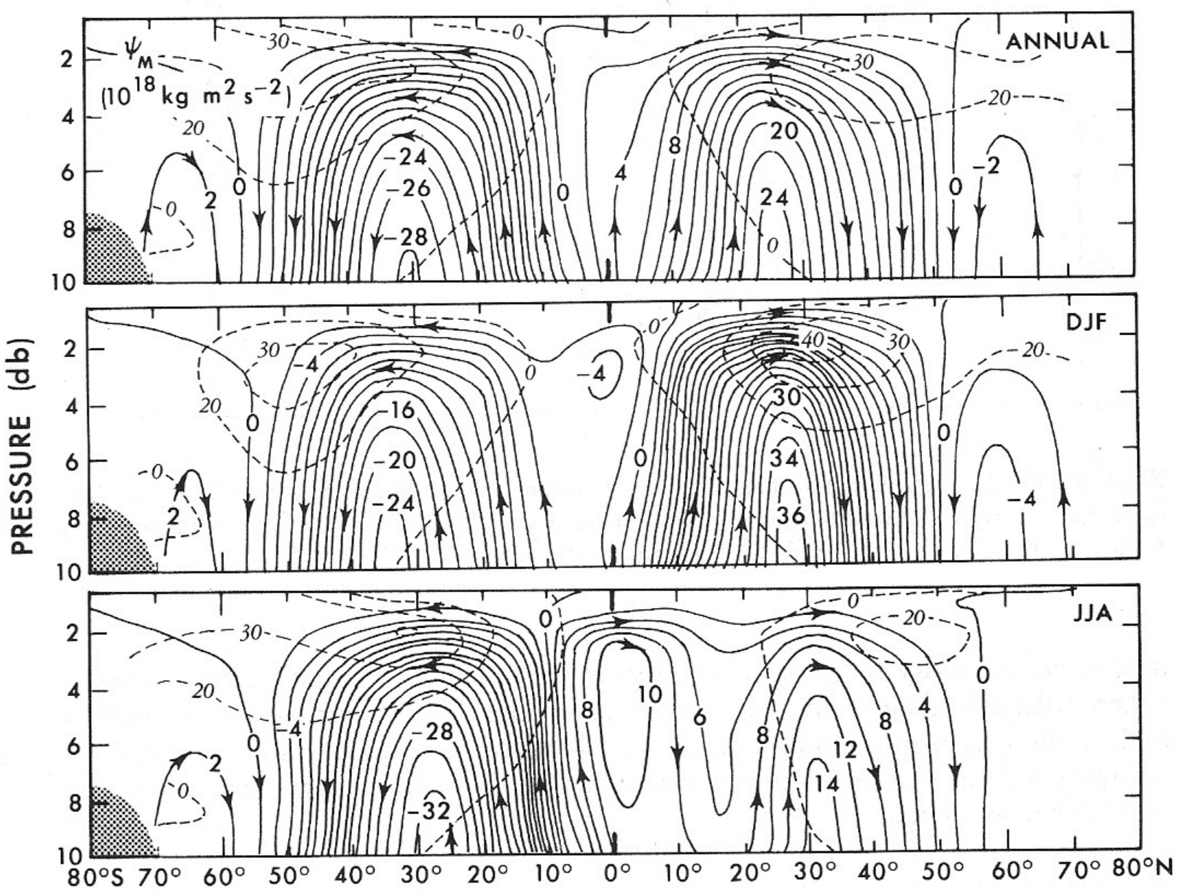


FIGURE 11.13. Streamlines of the nondivergent component of the zonal-mean transport of relative angular momentum in the atmosphere for annual, DJF, and JJA mean conditions in 10^{18} kg m^2 s^{-2}. Added are some dashed contours of $[u]/\cos\phi$ in units of m s^{-1}, which show the counter-gradient nature of the eddy transports (from Oort and Peixoto, 1983).

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Variable Earth rotation/atmospheric angular momentum (1)

Stoyko and Stoyko (1936): Annual variation of length of day: tied to air masses
Paris Observatory

Starr (1948): Statement that the atmosphere need not conserve angular momentum, and could share it with the Earth below.
Victor Starr started the "General Circulation Project" at the Massachusetts Institute of Technology (MIT)

Walter Munk and collaborators in the early 1950s: Calculations of atmospheric angular momentum [Munk and MacDonald 1960]

Lambeck and Cazenave (1973) Earth's rotation and atmospheric variations [Lambeck 1980]. At Paris Obs. Data from MIT

Intraseasonal variations: Feissel and Gambis (1980) (Paris Obs) for geodetic, followed by Langley et al. (1981) for AAM (MIT)

Variable Earth rotation/atmospheric angular momentum (2)

Hide et al. (1980) and Barnes, R. Hide, et al. (1983): codified the theory with relationship to lod and polar motion, using atmospheric models

-- combining atmosphere calculations and Earth responses (Love numbers etc.)

Sub-bureau for Atmospheric Angular Momentum set up as an agency of the IERS in 1989. (Salstein et al. 1993) at AER and NOAA. Since 1999 called: Special Bureau for the Atmosphere of the Global Geophysical Fluids Center (GGFC/IERS)

-- Angular momentum from the following centers:

US National Centers for Environmental Prediction (analysis AND reanalysis)
European Centre for Medium-Range Weather Forecasts
United Kingdom Meteorological Office
Japan Meteorological Agency

Updated by Zhou et al. (2006) -- better integration techniques, updated Earth parameters
From Eubanks

Variable Earth rotation/atmospheric angular momentum (3)

Efforts to use analysis and forecasts of AAM and as proxy for LOD:

At US NOAA and AER: Rosen et al. (1987, 1991)

At USNO: Johnson et al. (2005), Stamatakos et al. (2011 -)

-- combine US Navy Products of NAVGEM atmosphere model and HYCOM ocean model

At GFZ: Dill et al. (2017; 2019) using ECMWF models, with ocean, land hydrology and sea-level models

At Vienna University of Technology: Archive of atmosphere excitations for many Geodetic purposes / GGOS Atmosphere (Schindelegger et al., 2011, 2013, 2014)

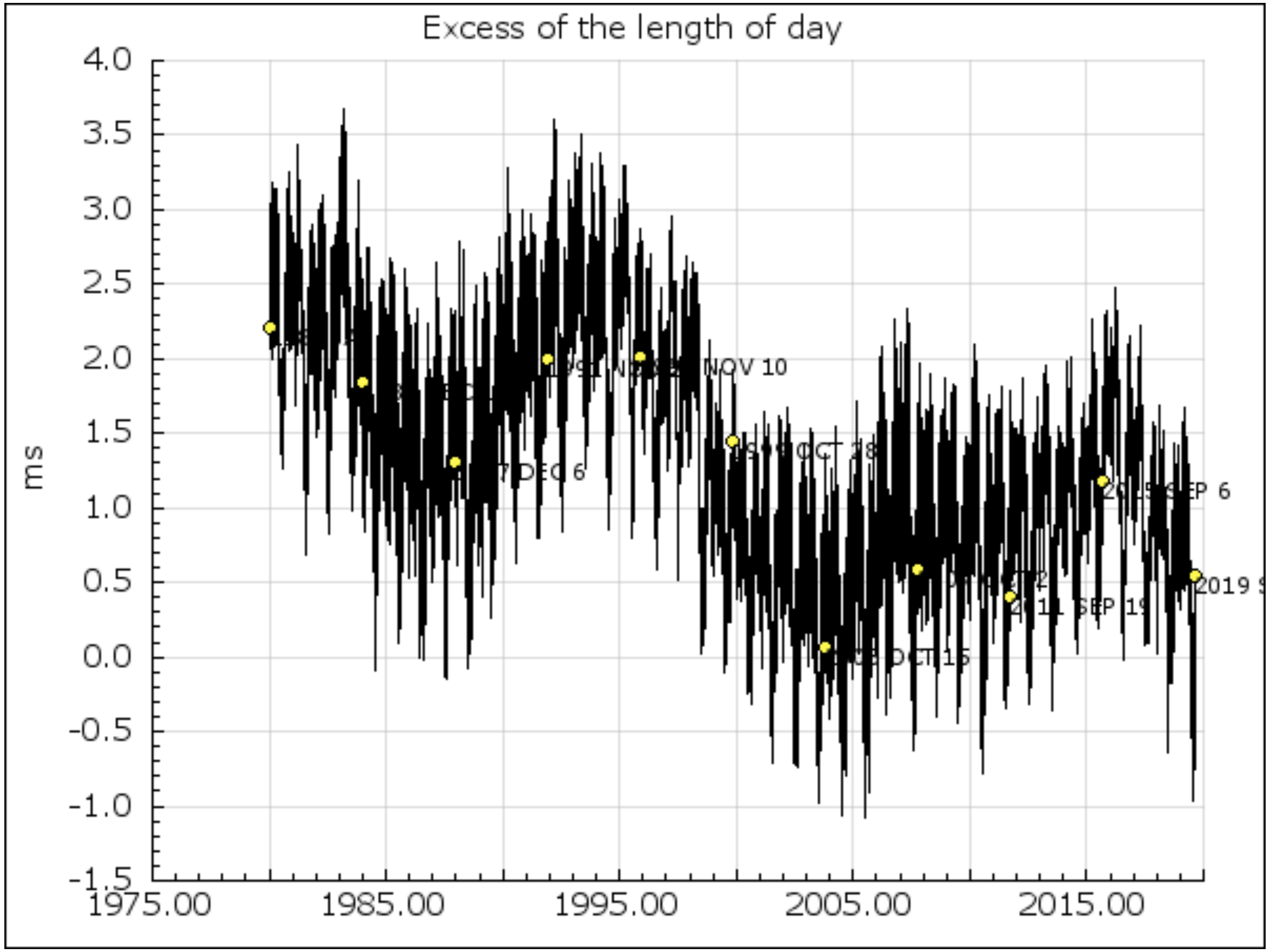
Seasonal: J. Hopfner (2000) at GFZ, showing LOD, four different Met. Centers agreement

Interannual variations: Quasi-biennial signals (~2.2 years) and El Nino/Southern Oscillation (~3-4 years)

Works by several groups, including JPL (Dickey et al.) Eubanks et al. AER, Rosen et al.(1984 …)

Russian Hydromet. Center: Sidorenkov (…, 2009,) exhaustive survey of agreements

LOD: 1980-2019



C04 series of LOD, from Paris Observatory

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

Polar motion (1,2)

mass

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

motion

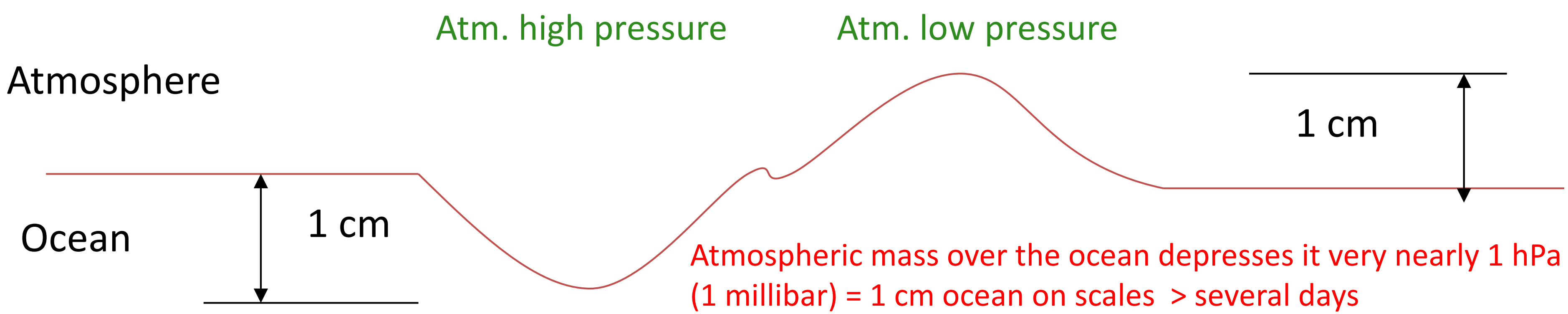
$$\chi^W = \chi_1^W + i\chi_2^W = \frac{-1.5913R^3}{\Omega(C-A)g}\iiint (u\sin\phi + iv)\cos\phi\, e^{i\lambda}\, dp\, d\lambda\, d\phi$$

Earth rotation: Length-of-Day (3)

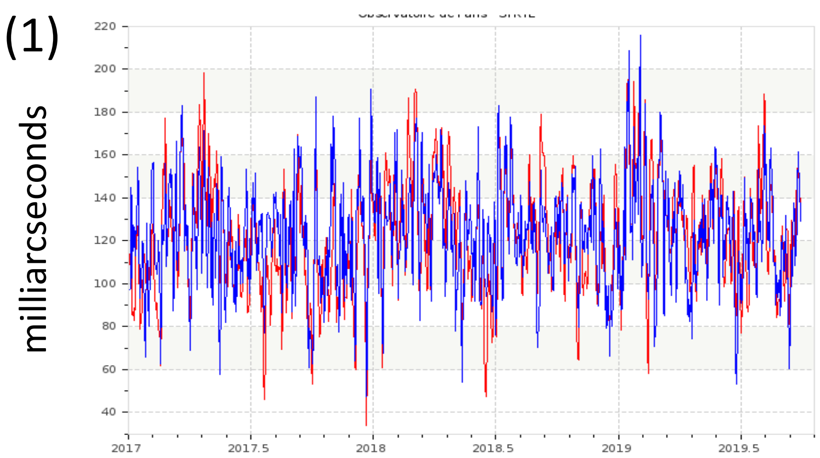
$$\chi_3^P = \frac{0.753R^4}{C_m g}\iint p_s \cos^3\phi\, d\lambda\, d\phi$$

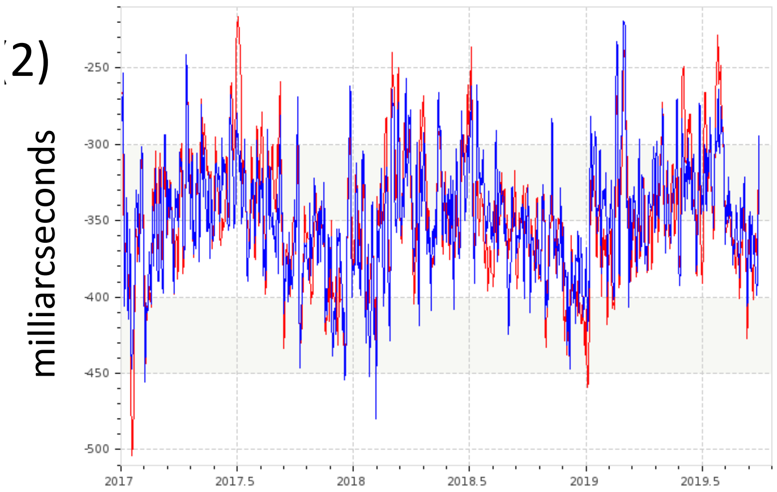
$$\chi_3^W = \frac{0.998R^3}{C_m \Omega g}\iiint u \cos^2\phi\, dp\, d\lambda\, d\phi$$

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

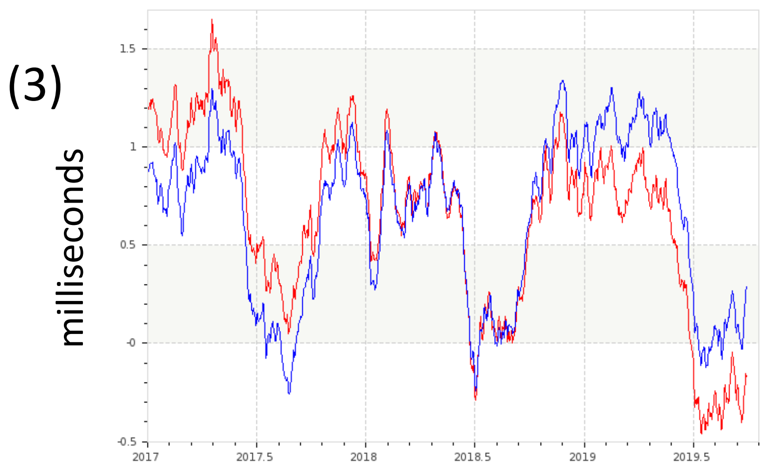


AAM (NCEP-NCAR Reanalyses) and Earth Rotation Parameters (01/2017 – 09/2019)





Polar motion



Length-of-day

— AAM

— ERP (geodetic)

ERP data and software: Paris Observatory

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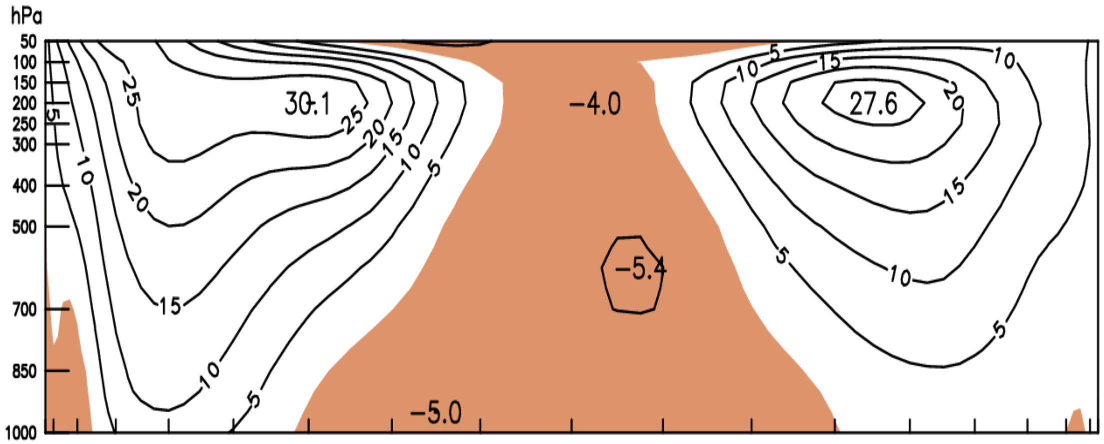
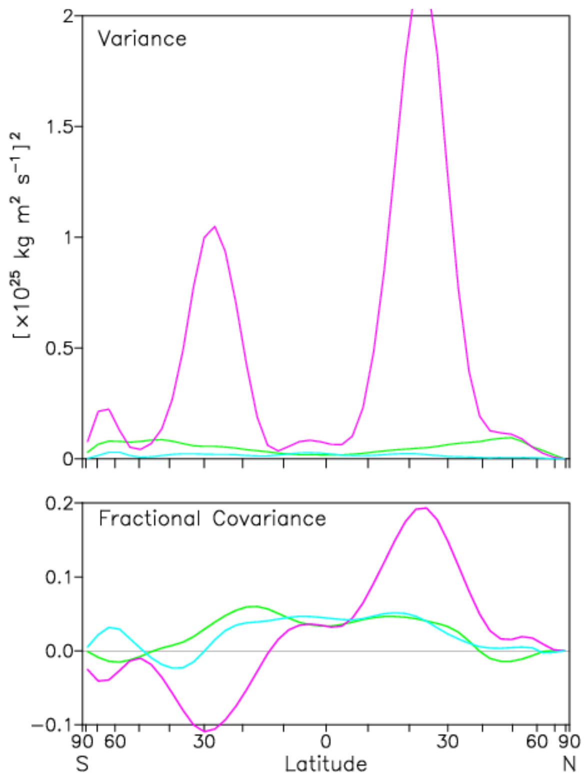
Where are changes coming from in the atmosphere (l.o.d.)?

Zonal winds



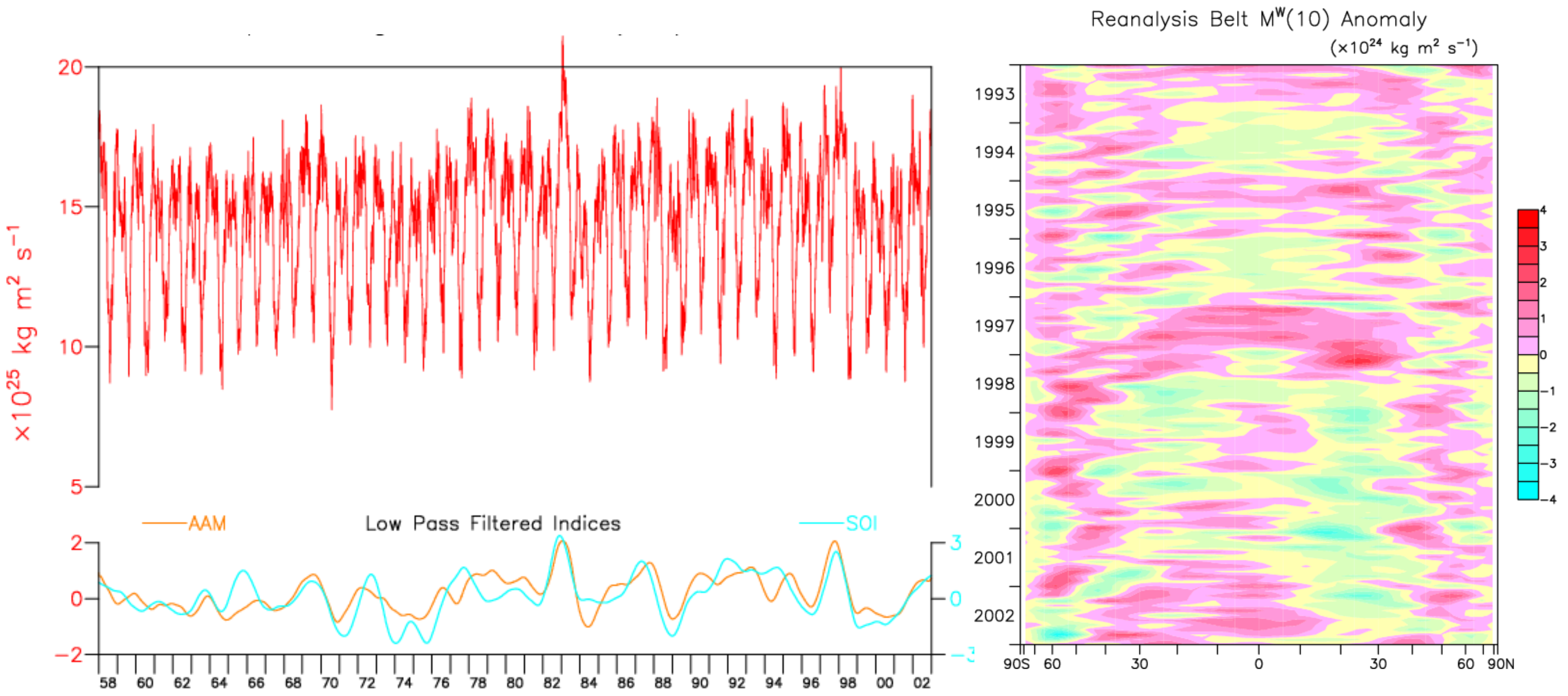
90S

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

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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

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

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

Mountain and friction torques

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

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

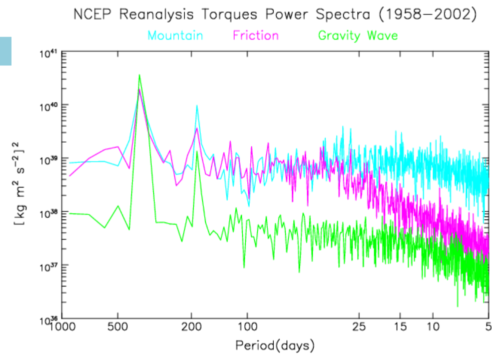
$T_{gravity-wave} =$ Frictional related to sub-grid scale
Action in the atmospheric model

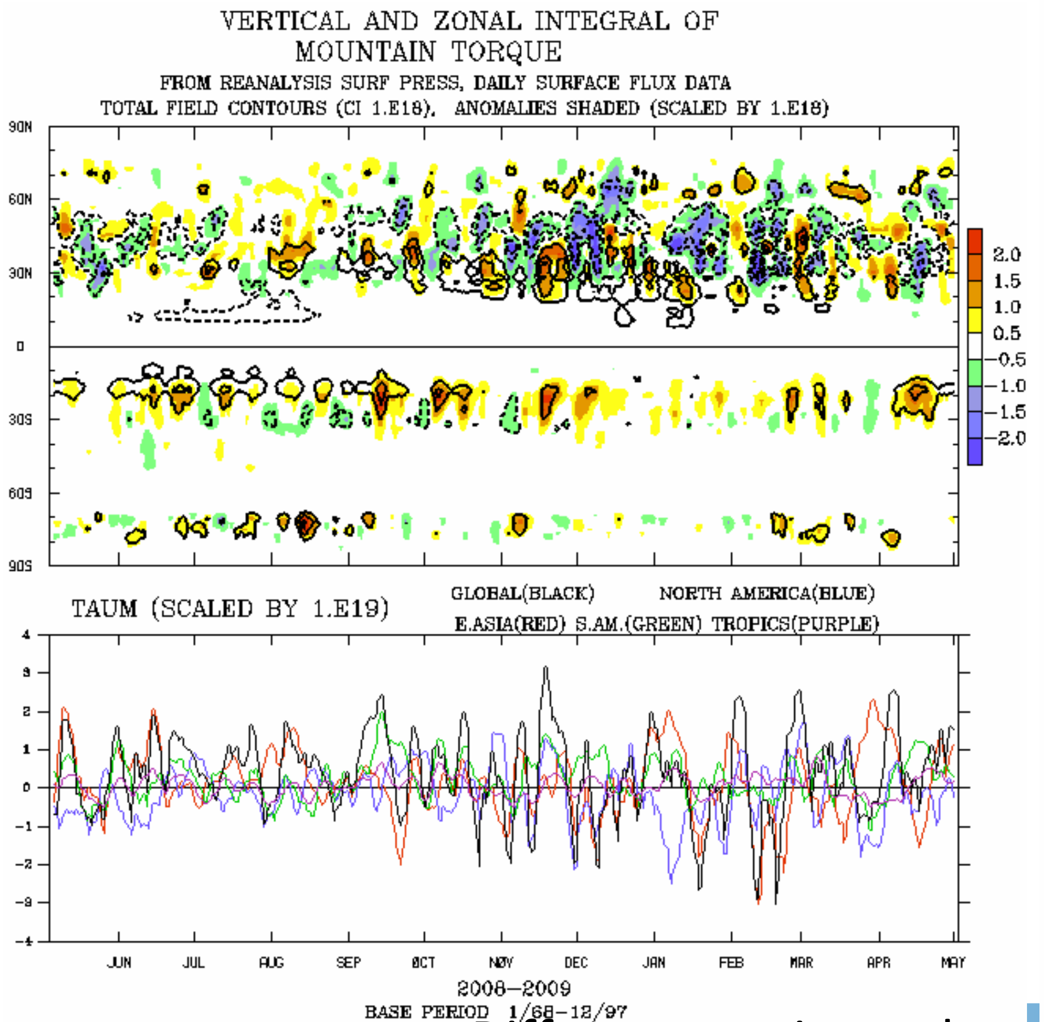
R=Earth radius, $\mathbf{p_s}$=surface pressure, **Z**=topographic height

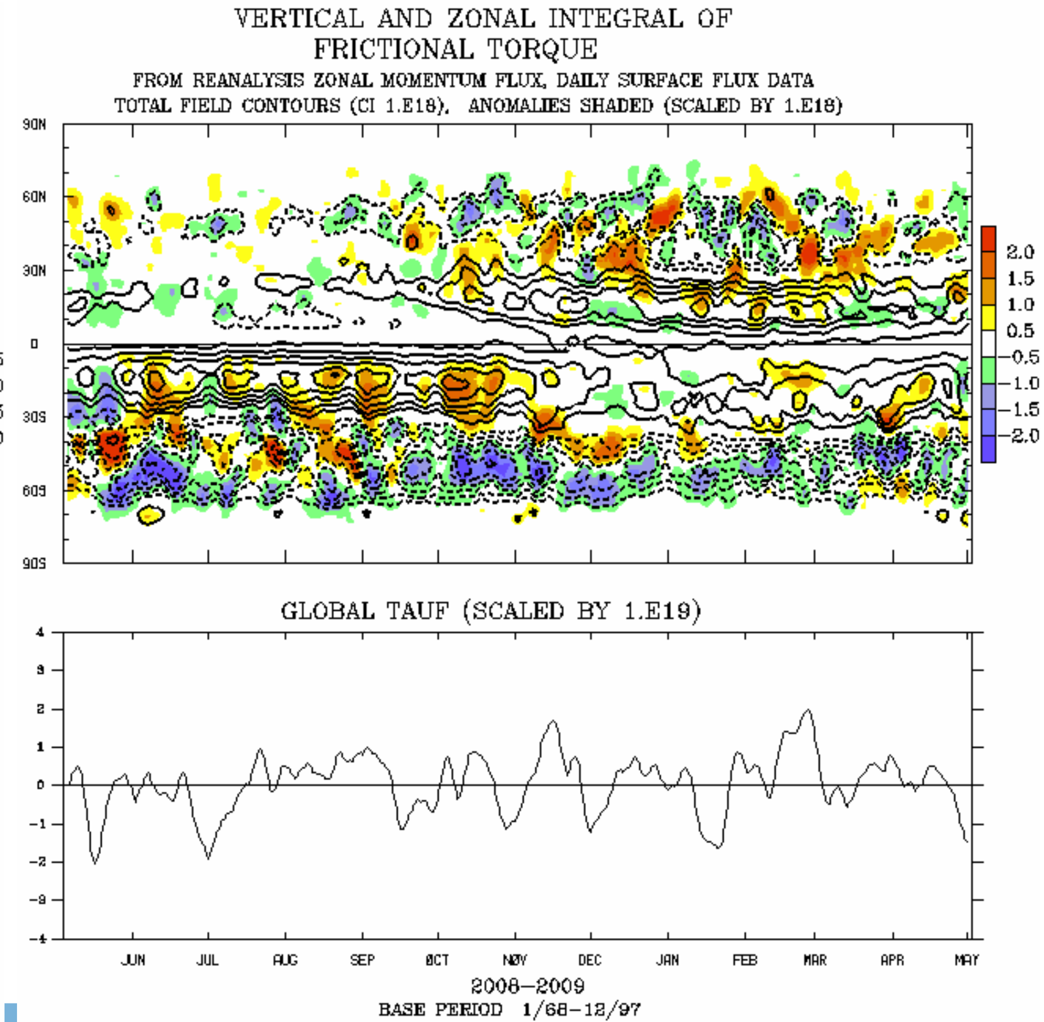
τ=frictional stress, related to winds and roughness (model)

ϕ=longitude λ=latitude

Mountain and friction torques
4 May 08 - 3 May 09







Different continental areas

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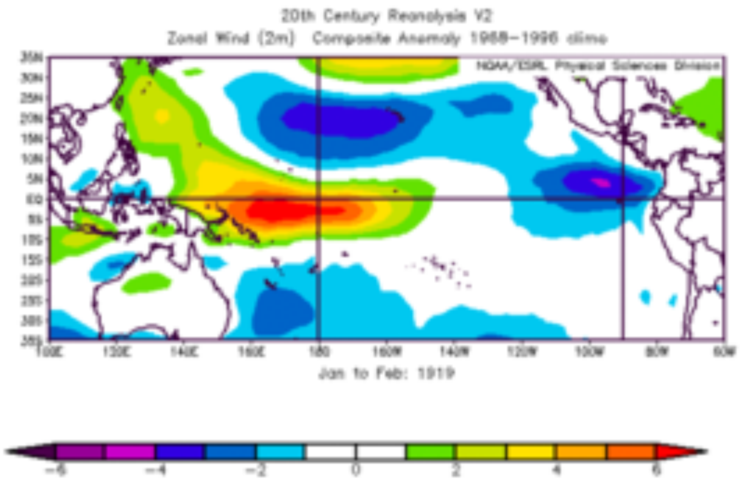
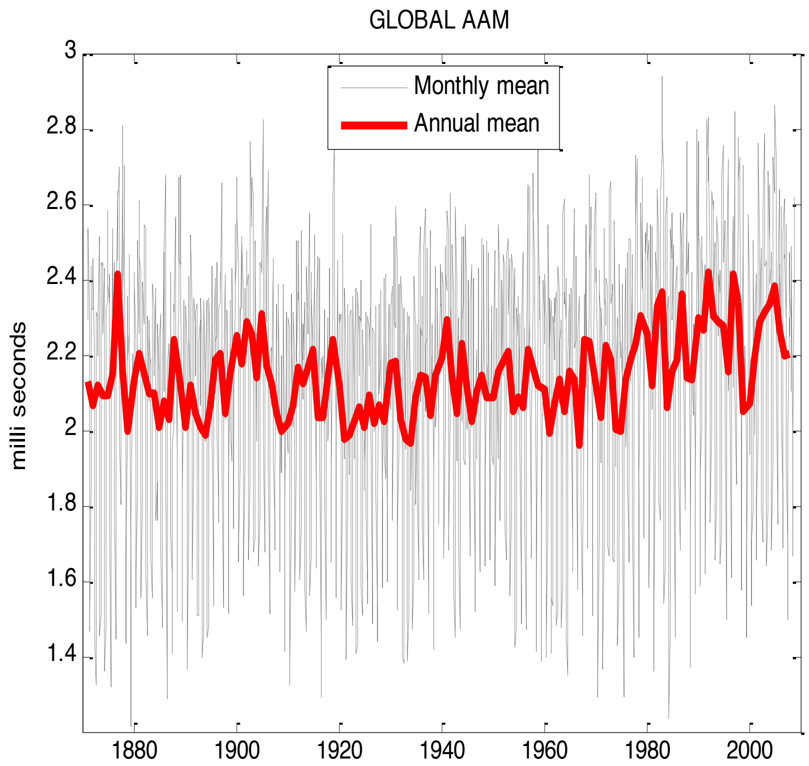
US NOAA, following Iskenderian and Salstein, and Weickmann et al.

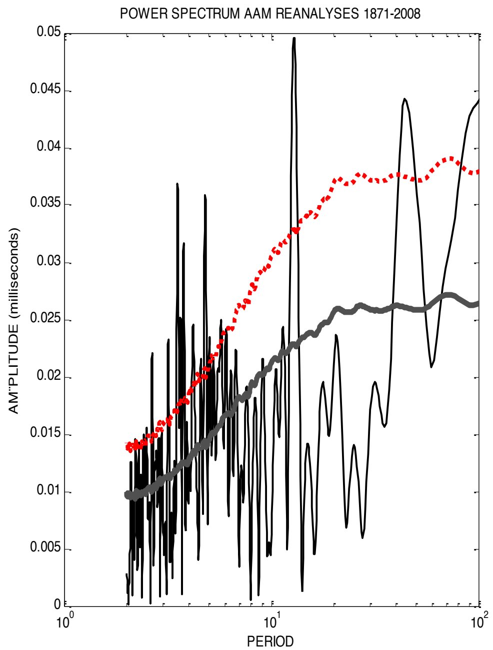
Climate of the 20th Century, based on surface pressure

El Nino of 1919, wind anomaly →



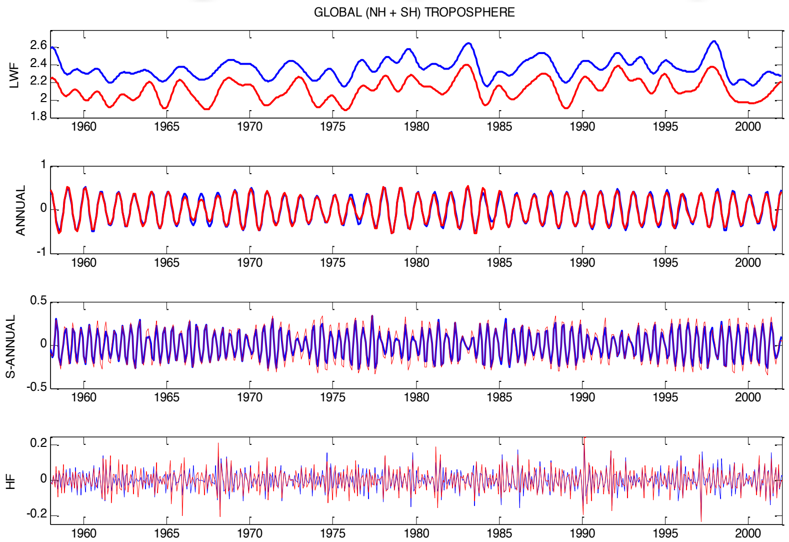
Compo, G.P., et al, 2011:The Twentieth Century Reanalysis Project. Quarterly J. Roy. Meteorol. Soc., 137, 1-28. DOI: 10.1002/qj.776.

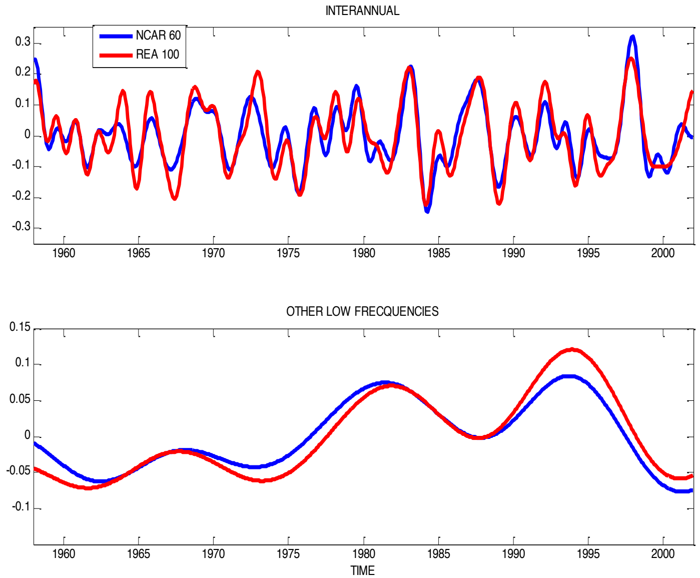


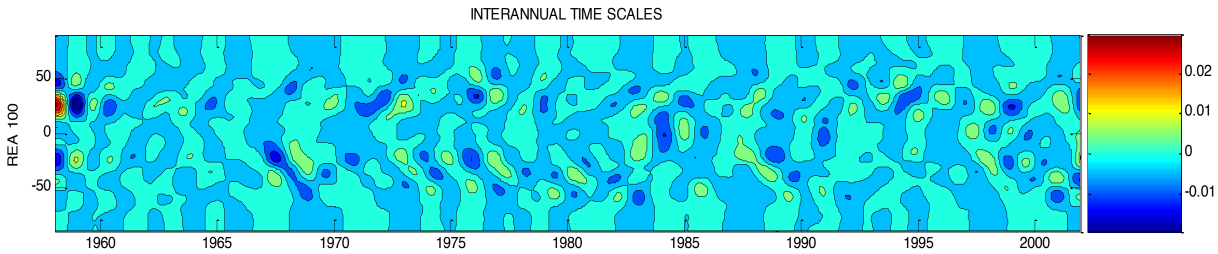


Abarca del Rio and Salstein, 2011

Climate of the 20th Century vs. NCEP-NCAR reanalysis (NCAR) 1958-2010







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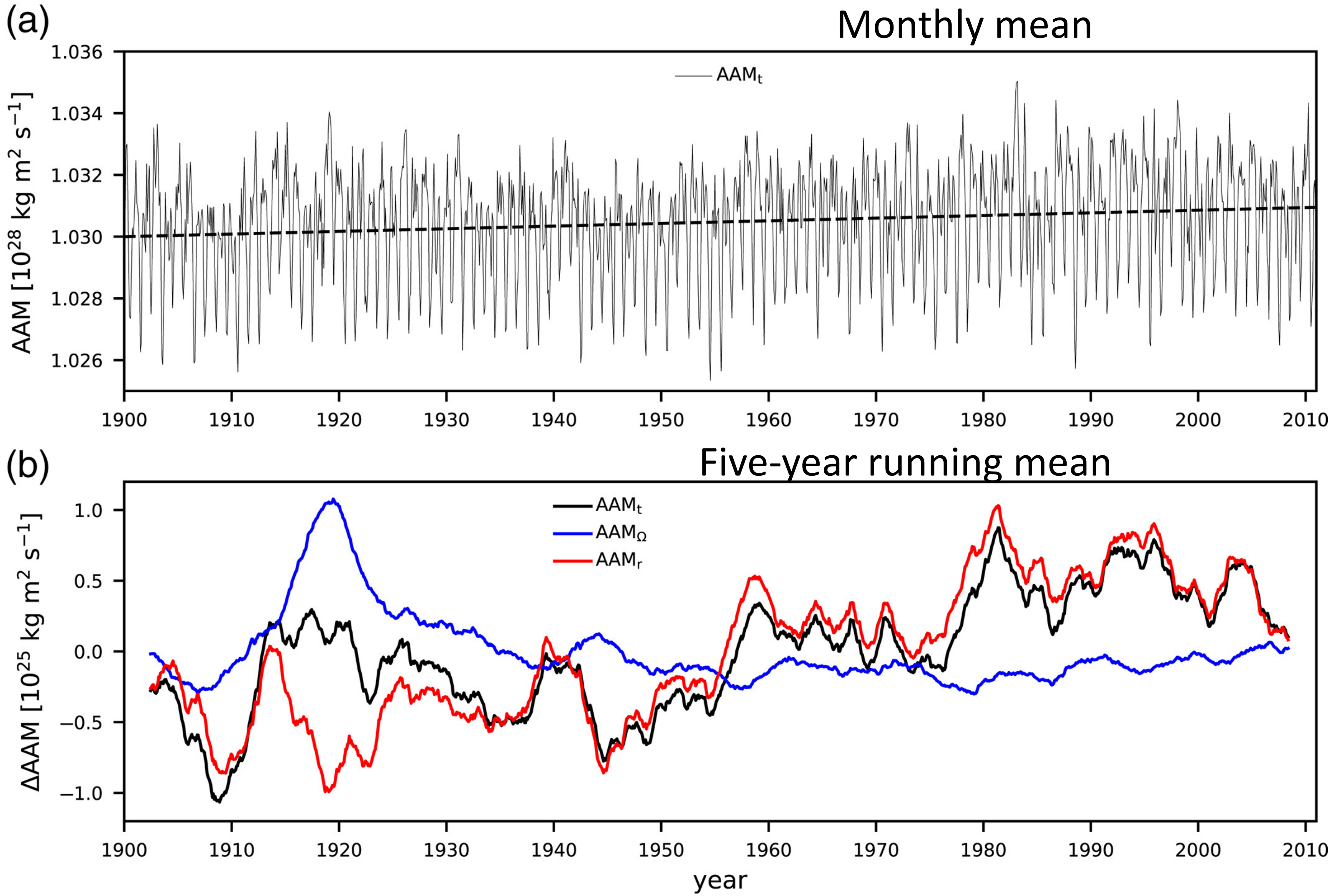
AAM of the 20th century (ERA-20C data)



Veerman and van Heerwaarden, 2019)

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.

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

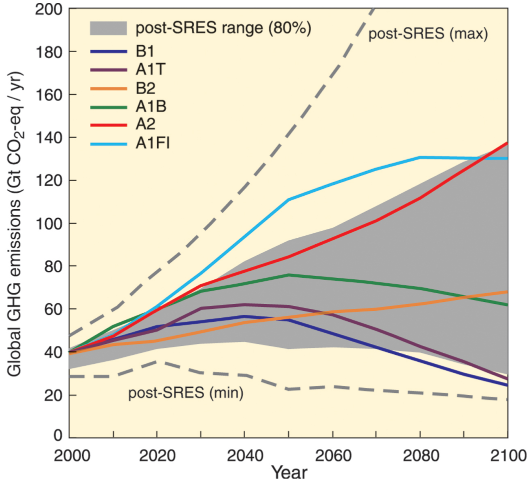
CMIP5

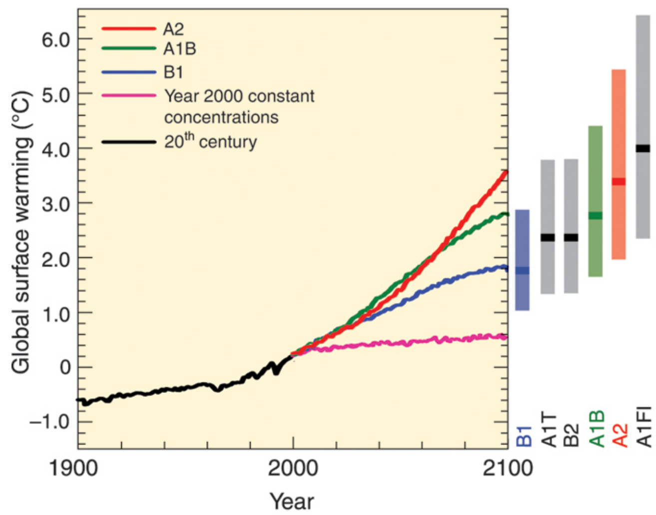
Updated IPCC scenarios have quantitative RCP’s (Representative Concentration Pathways) that span the climate space of radiative forcing: RCP 2.6, 4.5, 6.0,8.5

CMIP6

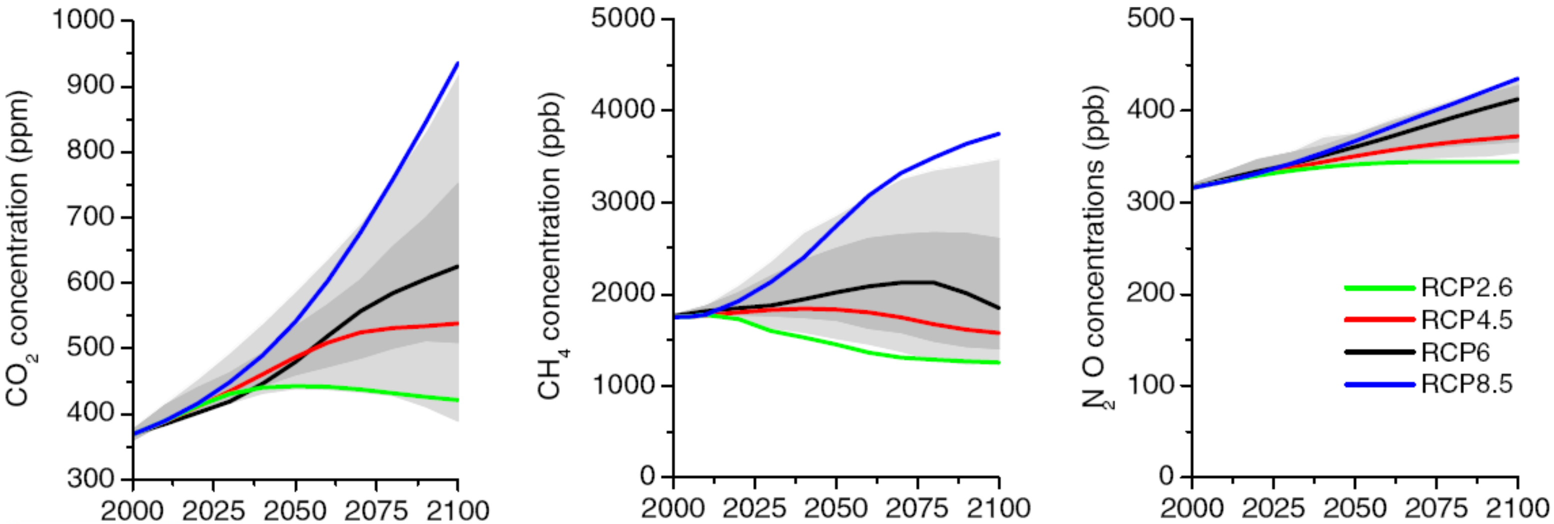
SSPs: Shared societal pathways (combination: Bohm and Salstein, poster, this meeting)

Greenhouse gas and warming scenarios from CMIP models





CMIP3



CMIP5

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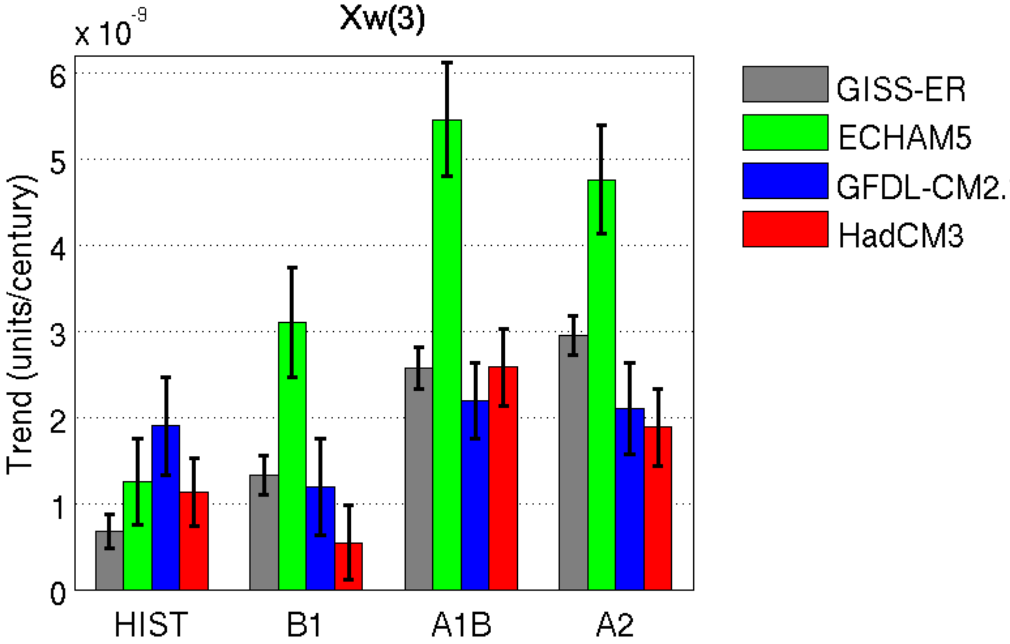
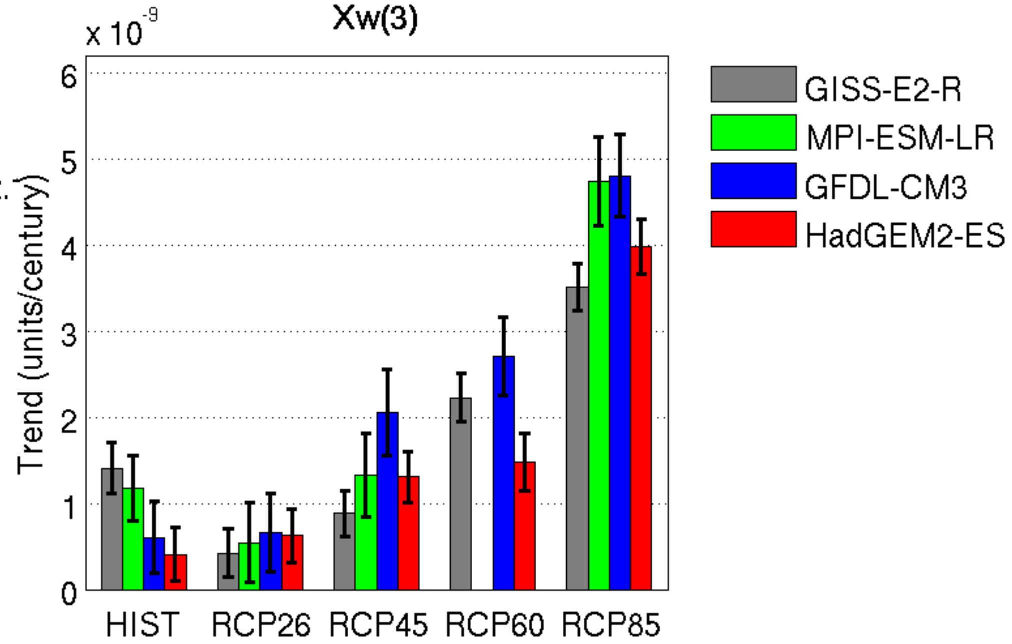
Trend in Earth rotation excitation by winds, CMIP3 and CMIP5





Salstein and Quinn

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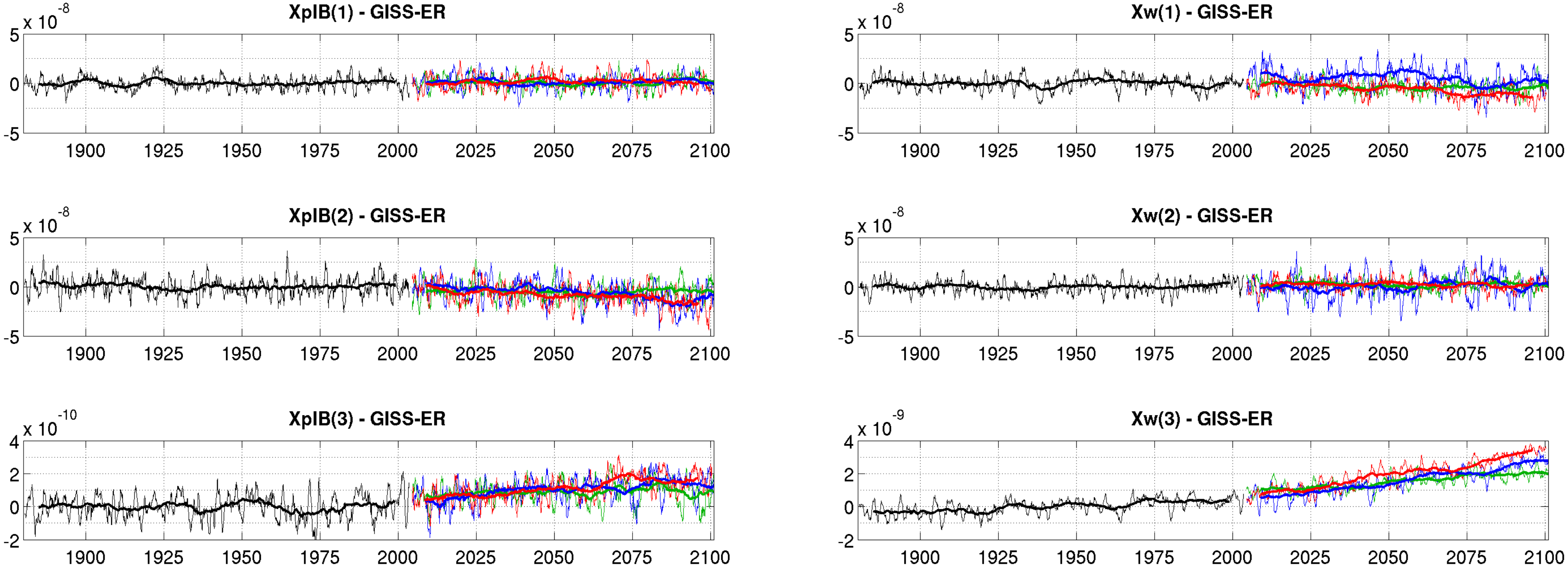
Atmospheric excitation functions under different scenarios (CMIP3)



Pressure-IB *Wind*

A2, A1B, B1

Salstein and Quinn

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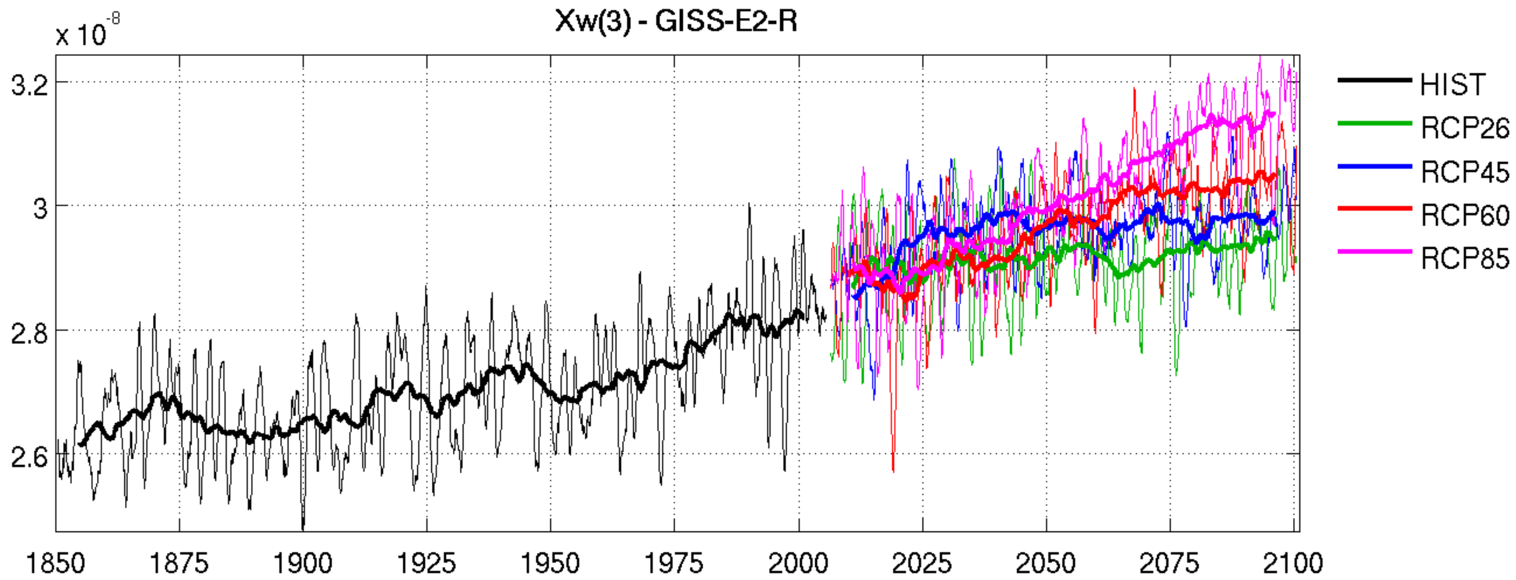
Atmosphere component, coupled model CMIP5, chi 3-wind



Salstein and Quinn

More on this topic in updated experiments: Poster of Bohm and Salstein

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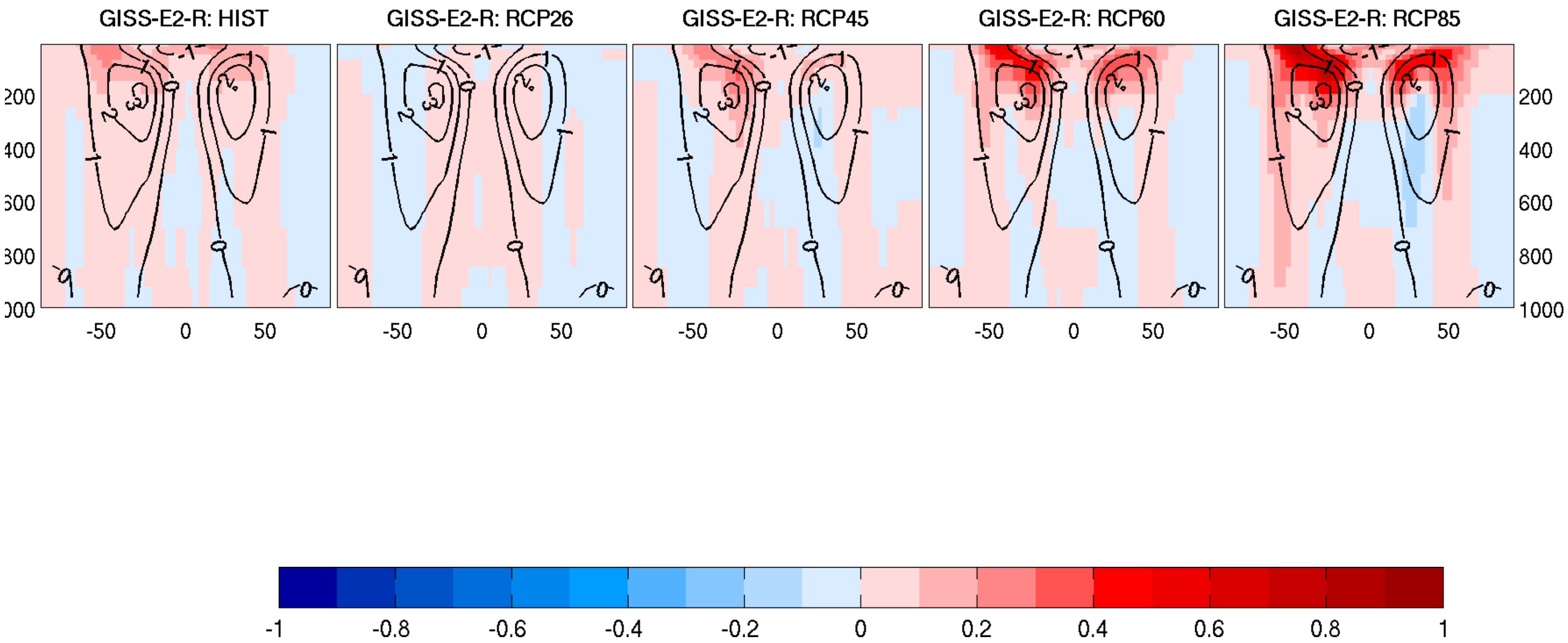
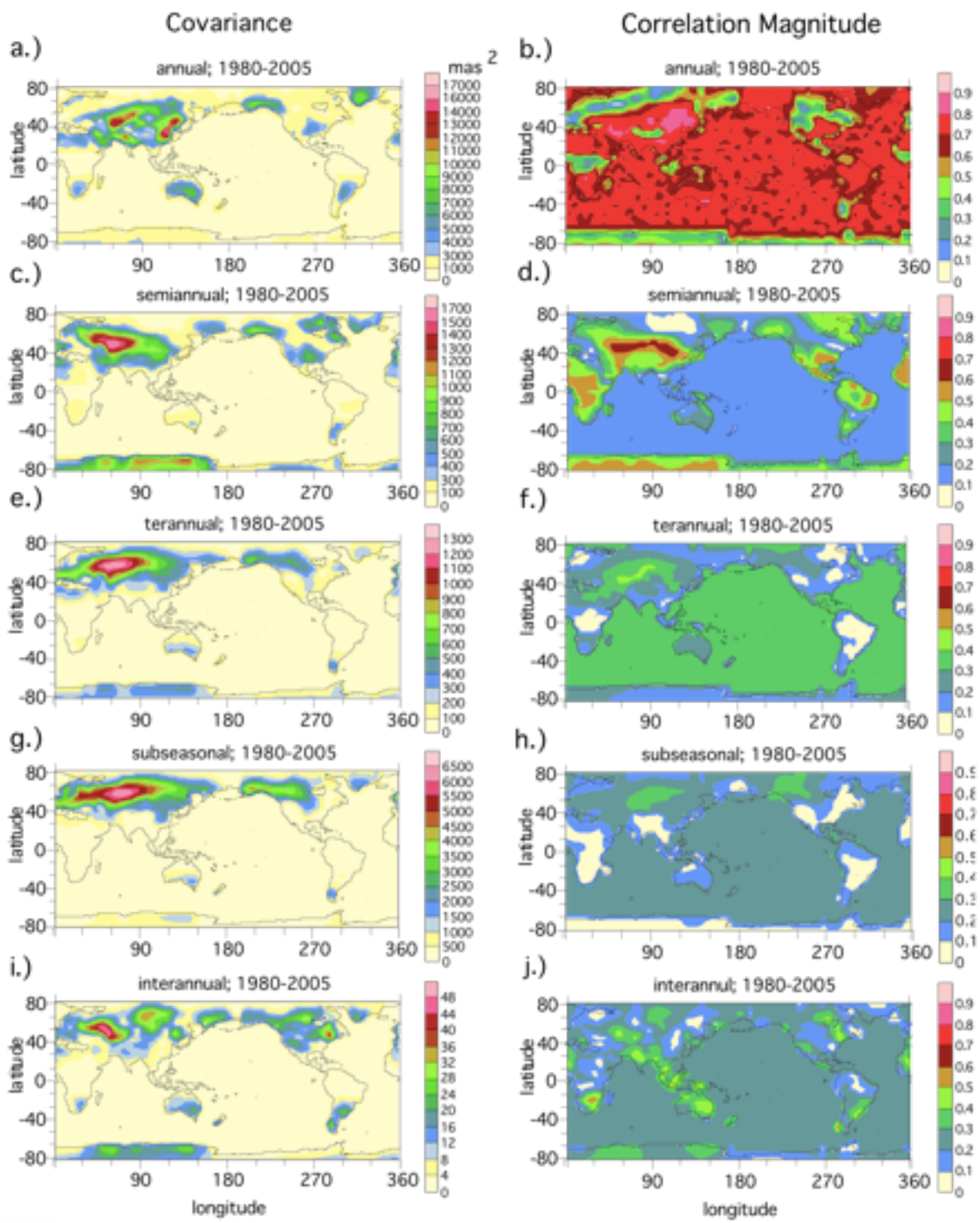
Trends in zonal means – χ3w Height-Latitude cross section



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

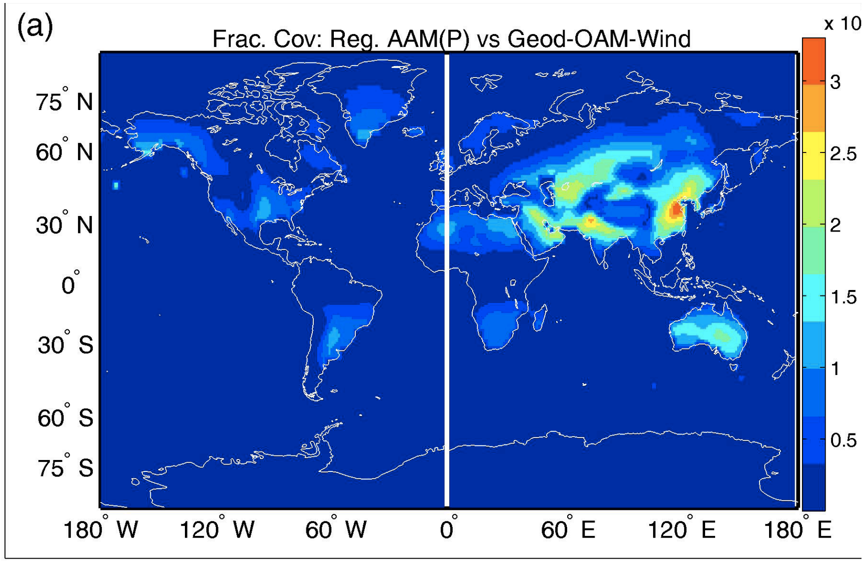


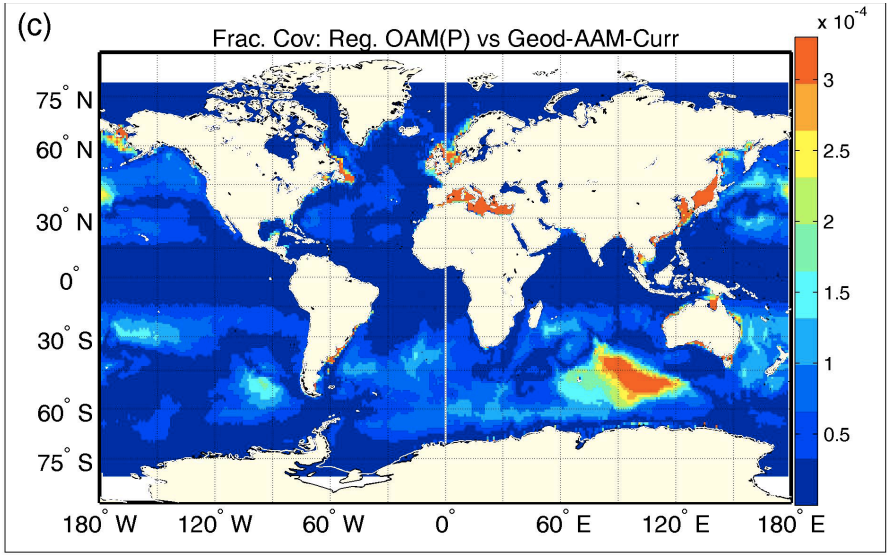
Nastula, Salstein, Kolaczek (2009)

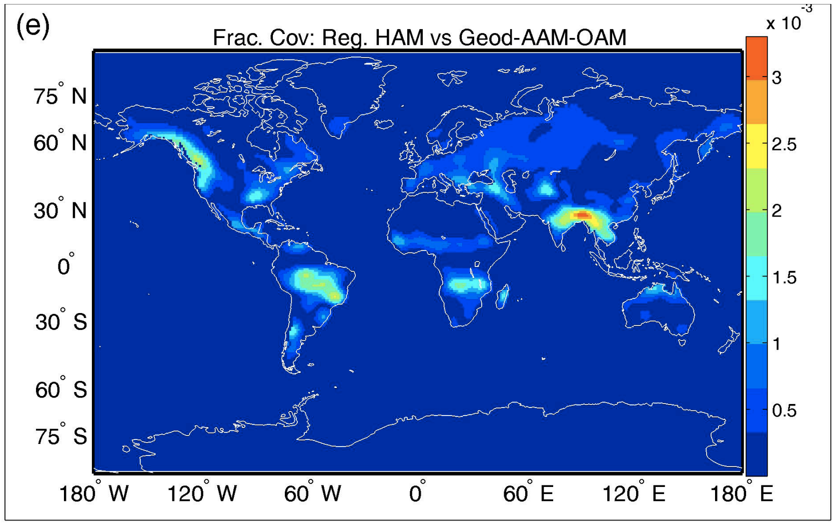
Regional contributions to polar motion at different time scales: from the NCEP/NCAR Reanalyses

Excitation polar motion by mass: Annual – Atmosphere, ocean, land hydrology masses

Nastula, Salstein Gross (2012)







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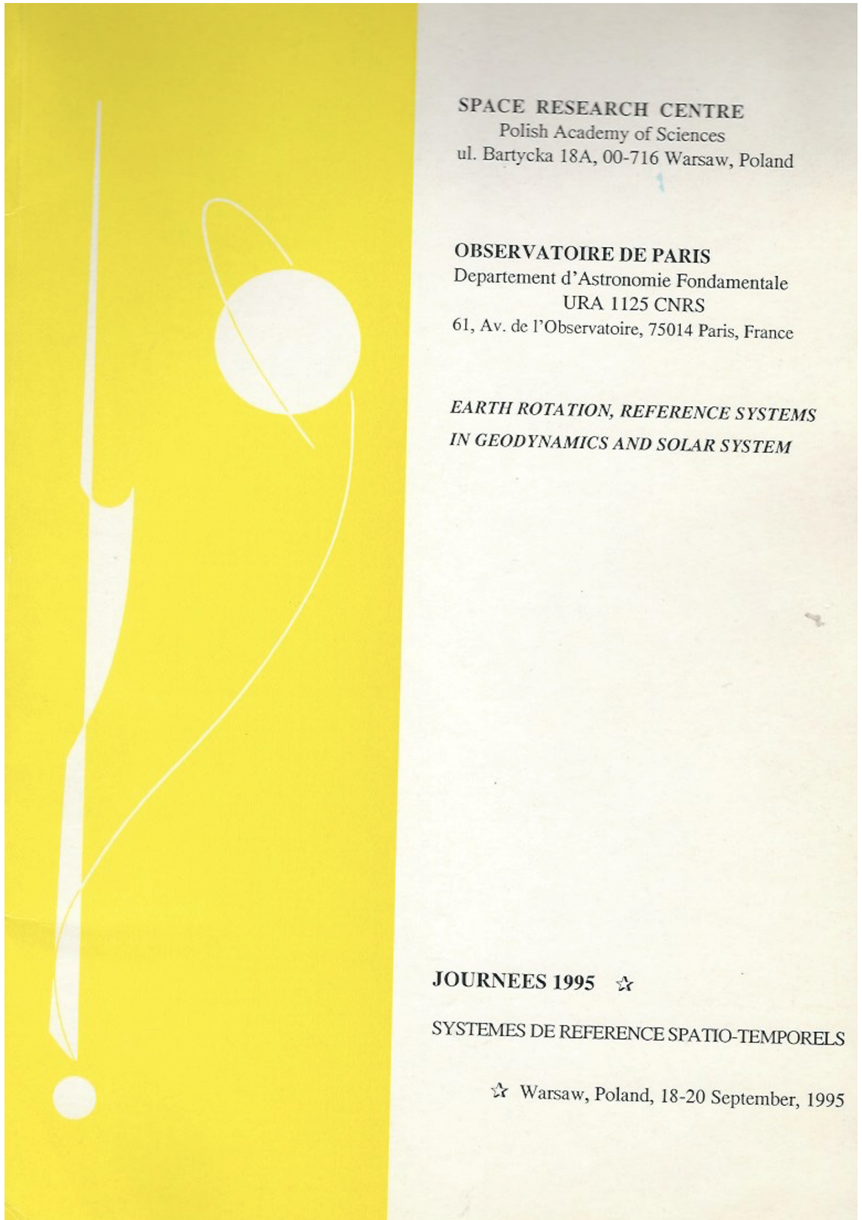
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61, Av. de l'Observatoire, 75014 Paris, France

EARTH ROTATION, REFERENCE SYSTEMS IN GEODYNAMICS AND SOLAR SYSTEM

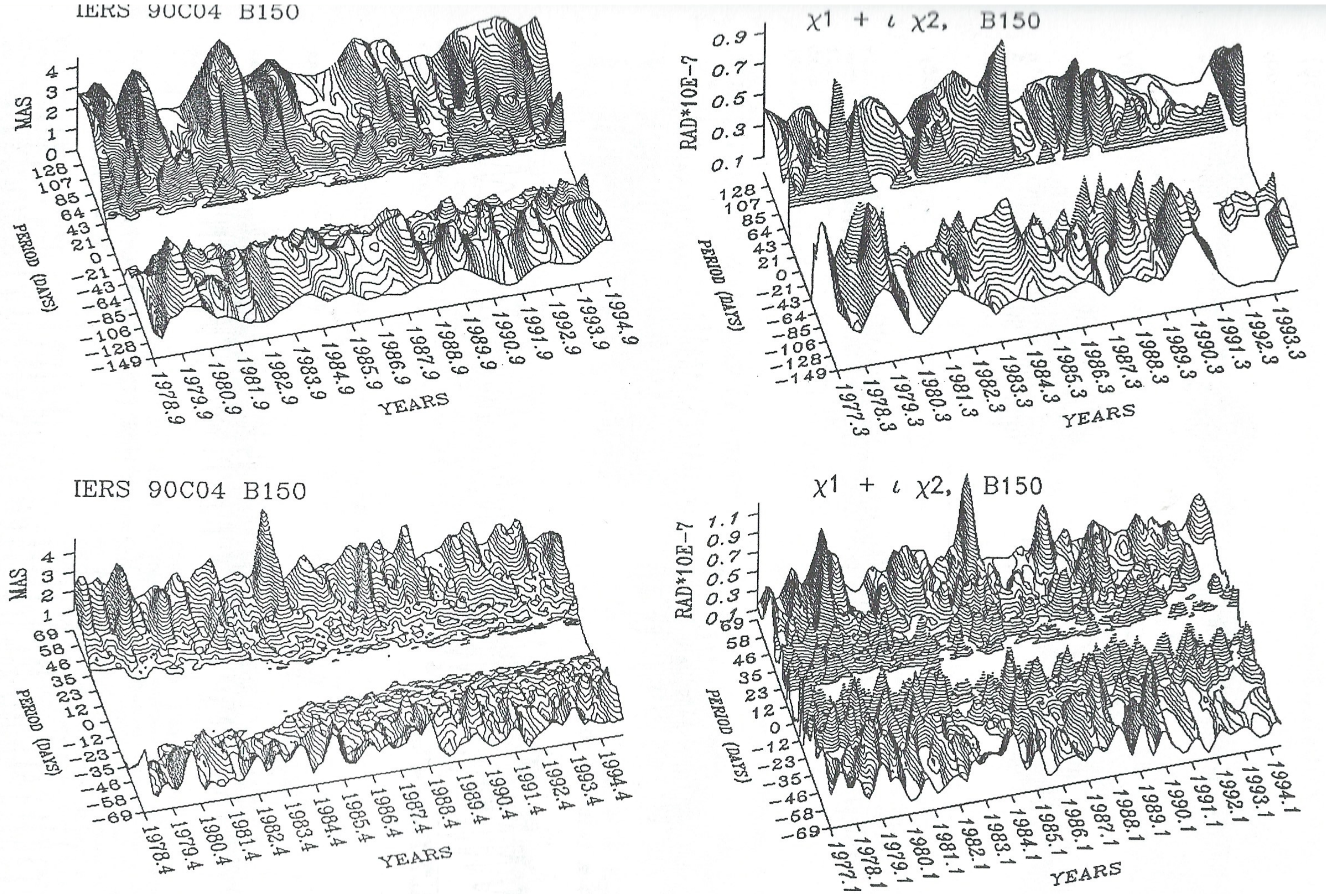
JOURNEES 1995 ☆

SYSTEMES DE REFERENCE SPATIO-TEMPORELS

☆ Warsaw, Poland, 18-20 September, 1995

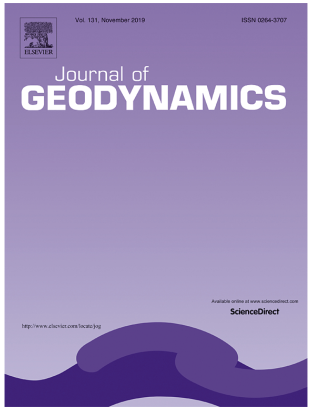
Barbara Kolaczek contributions

Short period variations of Earth Rotation (B.Kolaczek, Journees 1995)



The impact of El Niño and other low-frequency signals on Earth rotation and global Earth system parameters

David A. Salstein, Barbara Kolaczek, Daniel Gambis (eds.).(IERS Technical Note ; 26), 1999



Journal of Geodynamics

↗

Earth Rotation and Episodic Processes

D. Gambis, B. Kolaczek, D. A. Salstein Volume 36, Issue 3, Pages 341-444 (October 2003)

Summary

- Atmosphere angular momentum is an important driver of Earth rotation variations, given conservation of angular momentum in the Earth system
- Atmospheric angular momentum (AAM) is a fundamental measure of the atmosphere, relating to seasonal and climate signatures and Earth rotation measurements
- Atmosphere and ocean can be modeled based on the equations of physics and forecast in time. With data assimilation → series of AAM from models
- Torques are the means of angular momentum transfer between atmosphere and Earth -- normal force against mountains, and tangentially by friction
- 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
- Many researchers were involved in AAM over the last decades

- FOND MEMORY OF AND GRATITUDE TO BARBARA K !

State, thermodynamic, conservation equations

$$p = \rho R_d T$$

Equation of state

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

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/r
v	velocity
q	spec. humidity
S	water source

Can model changes in time from equations

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

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

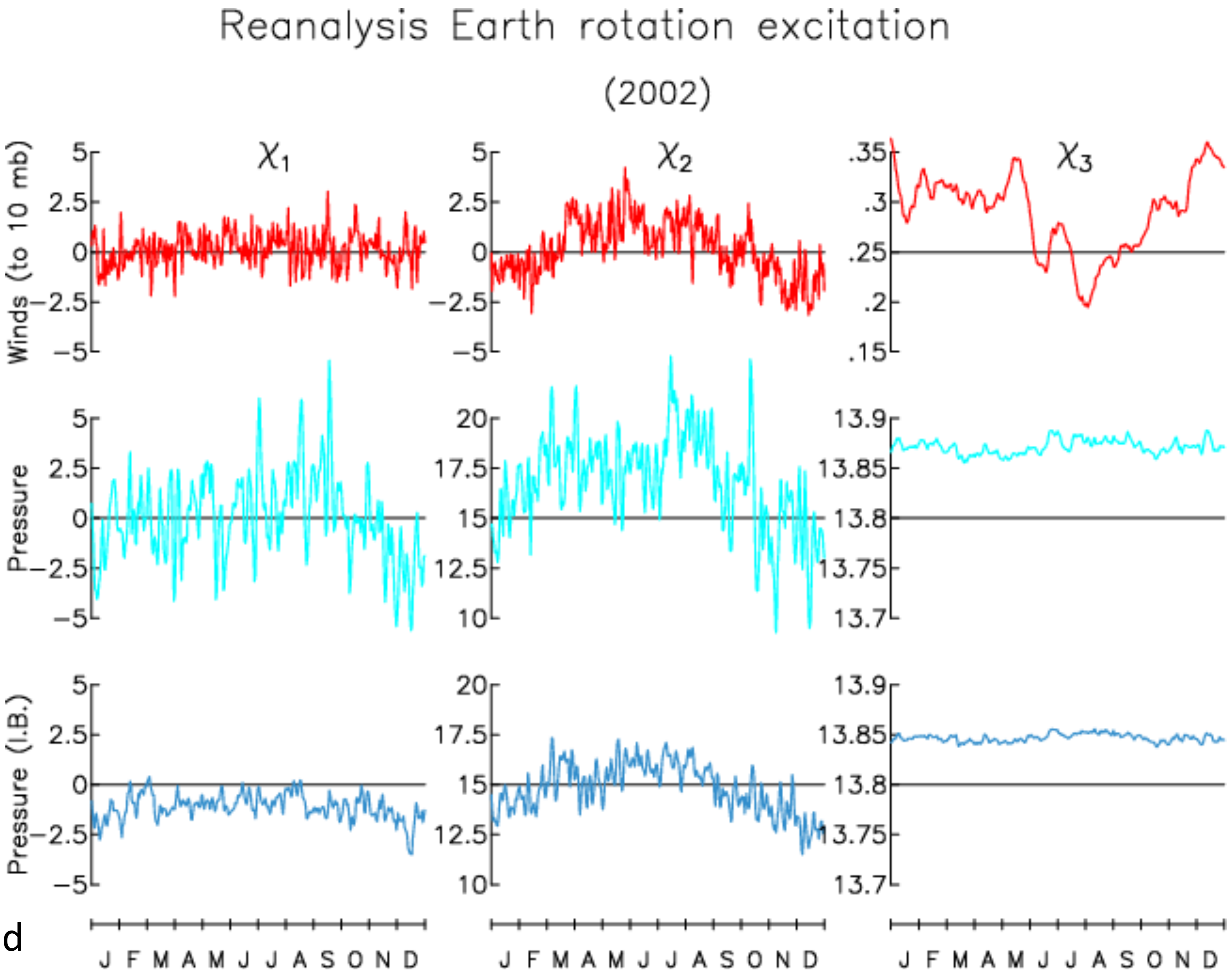
For M = u (zonal wind, from west to east))
v (meridional wind, from south to north
T (temperature)
q (water vapor)

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

Atmospheric and Environmental Research



motion

mass

Mass--
IB

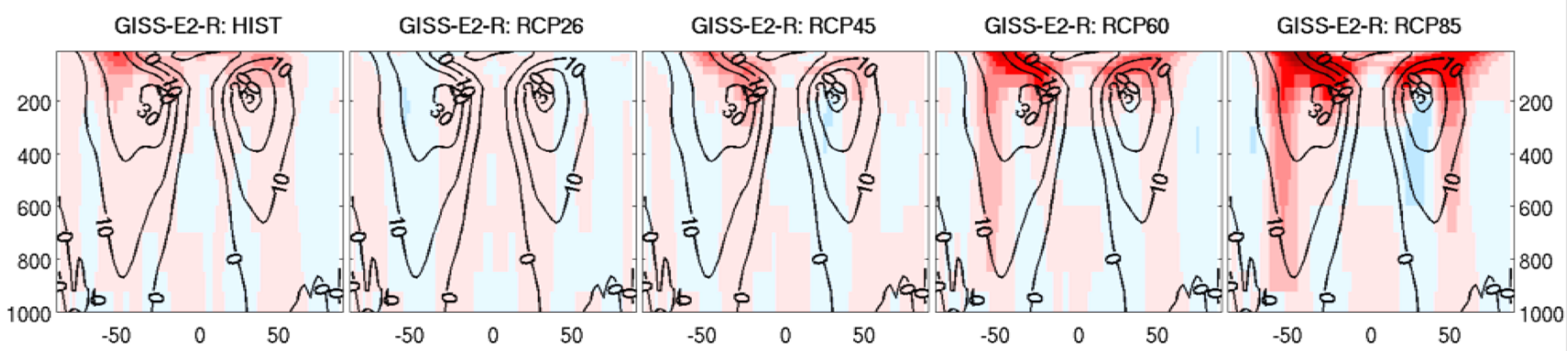
IB=Inverted
Barometer

Polar motion

Length of day

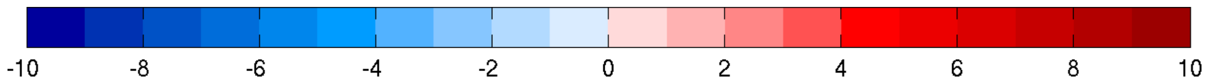
Atmospheric and
Environmental Research

Trends in zonal means – zonal winds



Units: m/s/century

Contour units mean over 20th century in m/s



Salstein and Quinn
also Paek and Huang