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310/1749-41

ICTP-COST-USNSWP-CAWSES-INAF-INFN
International Advanced School
on
Space Weather
2-19 May 2006

Solar Influences on Climate - II

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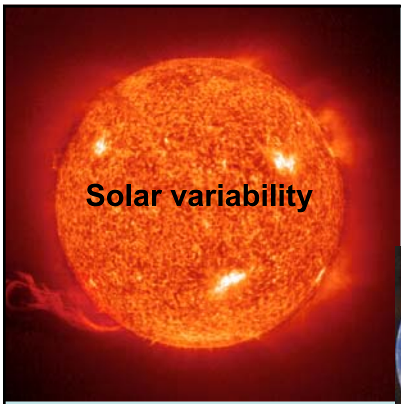
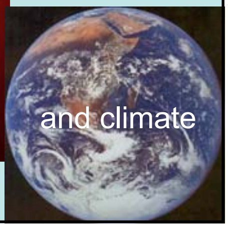


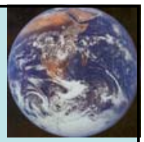


Joanna D. Haigh

Department of Physics
Imperial College London

2. Evidence and mechanisms

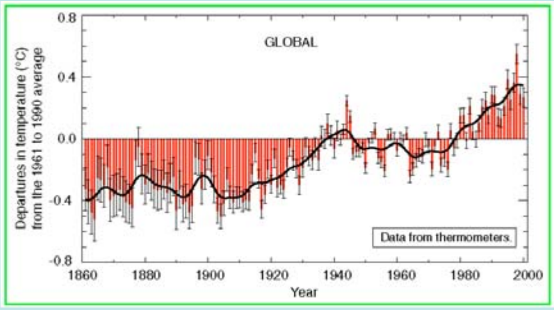
Outline of lecture



1. Observed climate variability and trends.
2. Evidence for influence of solar variability on the lower atmosphere.
3. Mechanisms of solar influence on climate.

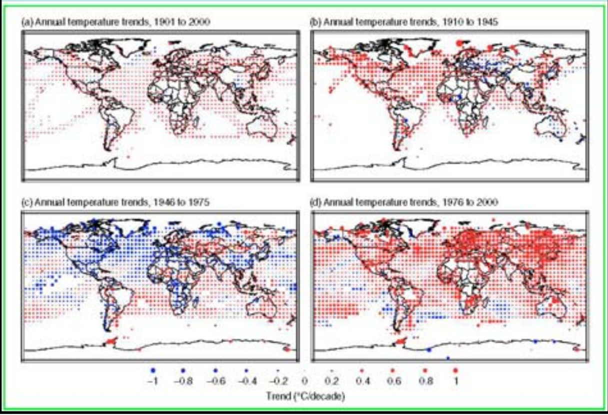
Observations of climate variability and trends

Measured global temperature record

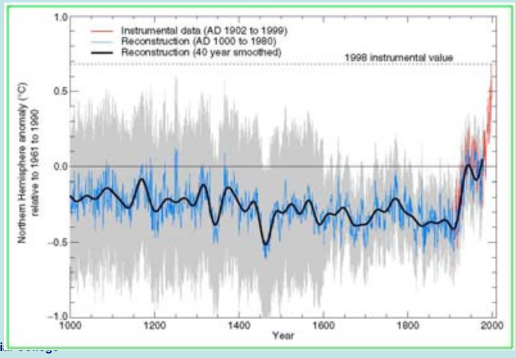


IPCC (2001)

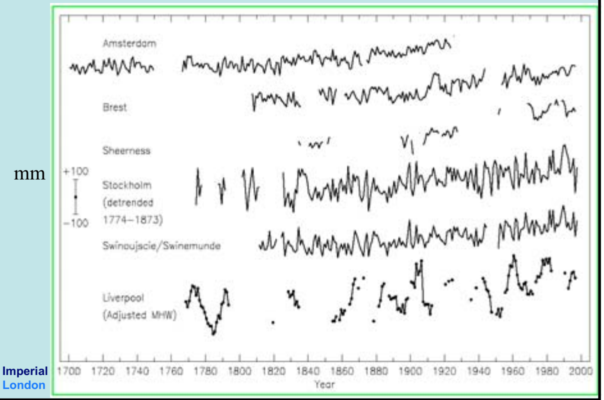
Surface temperature trends

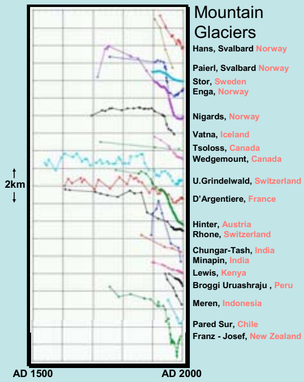


N. Hemis. temperature from proxies



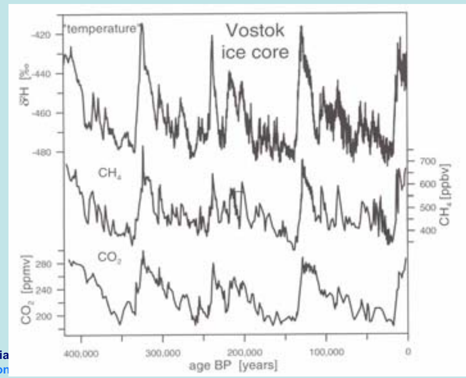
N.W. Europe sea level height





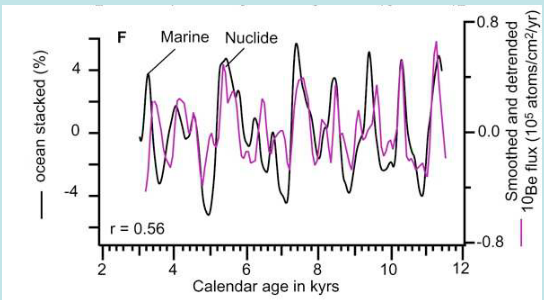
UK Hadley Centre

Ice age temperature, CH_4 and CO_2



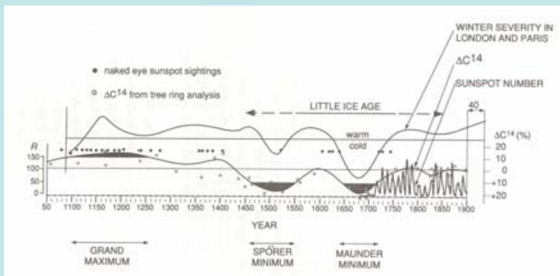
Evidence for the influence of solar variability on climate

Solar influences on climate (?) : N. Atlantic ice flows



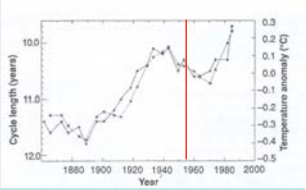
Bond et al (2002)

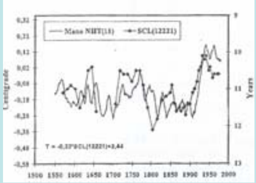
Temperature in NW Europe

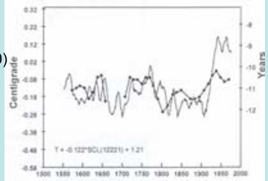


Eddy (1976)

Solar cycle length and N. H. temperature







above: Friis-Christensen and Lassen (1991)

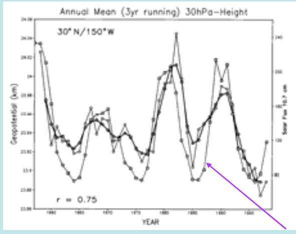
top right: Lassen and Friis-Christensen (2000)

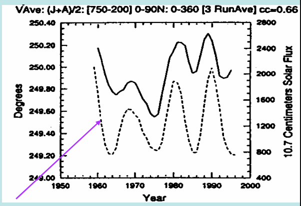
right: Laut and Gundermann (2000)

30 hPa geopotential height (annual mean, Hawaii)

Upper troposphere temperatures (NH Jul-Aug)

3-year running averages



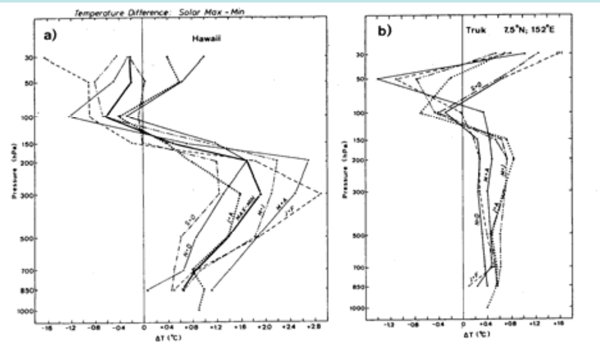


solar 10.7cm flux

Labitzke and van Loon (1995)

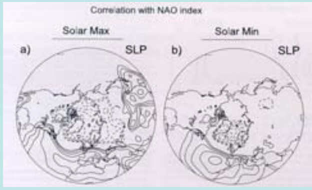
van Loon and Shea (2000)

Temperature profiles



Labitzke and van Loon (1986)

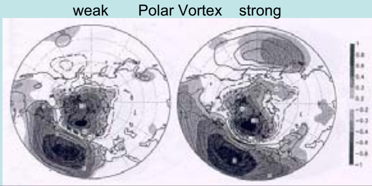
North Atlantic Oscillation



Correlation between NAO index and sea level pressure.

Kodera *G.R.L.* 2002

weak Polar Vortex strong



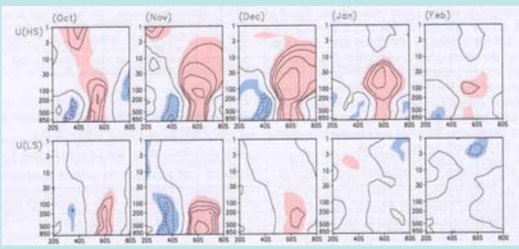
Castanheira and Graf *J.G.R.* 2003

Southern Annular Mode

high

Solar F10.7

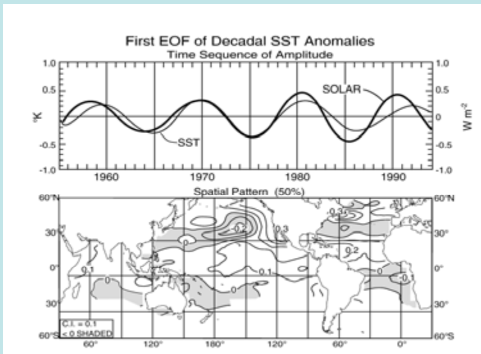
low



Lagged correlation between Oct/Nov SAM index and geopotential height.

Kuroda and Kodera *G.R.L.* 2005

Sea surface temperatures



White et al (1997)

Multiple regression analysis

$$y(x,t) = \sum_i \beta_i(x) f_i(t) + noise$$

- $y(x,t)$ are data
- $f_i(t)$ is time-dependent climate factor i
- $\beta_i(x)$ is weight of contributing factor i at point x
- y and f are known, β are to be estimated
- noise is represented by an AR(1) model

10 factors are taken into account:
trend
solar irradiance
volcanic aerosol
ENSO
NAO
QBO
amplitude & phase of annual cycle
amplitude & phase of semi-annual cycle

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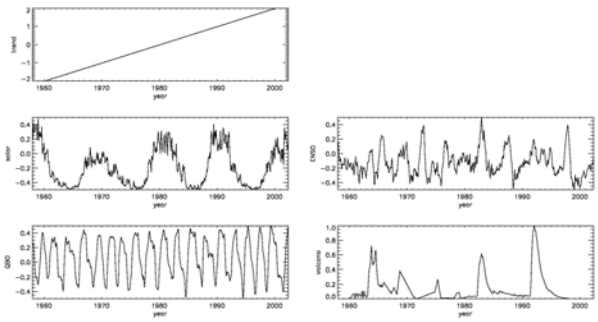
Forcing factors



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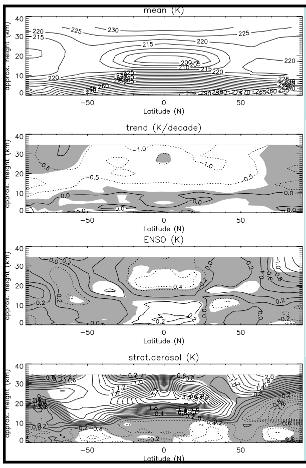
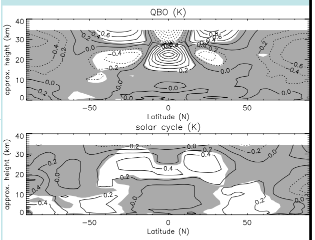
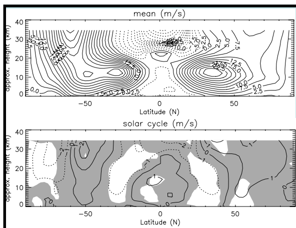
Analysis of NCEP/NCAR zonal mean temperatures (1979-2002)



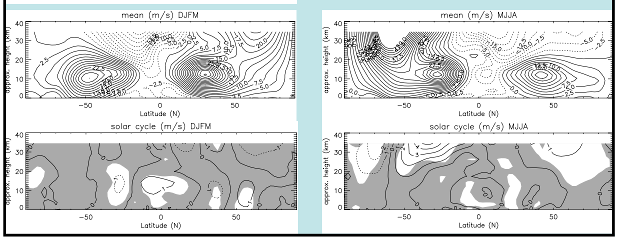


shaded areas not significant at 5% level

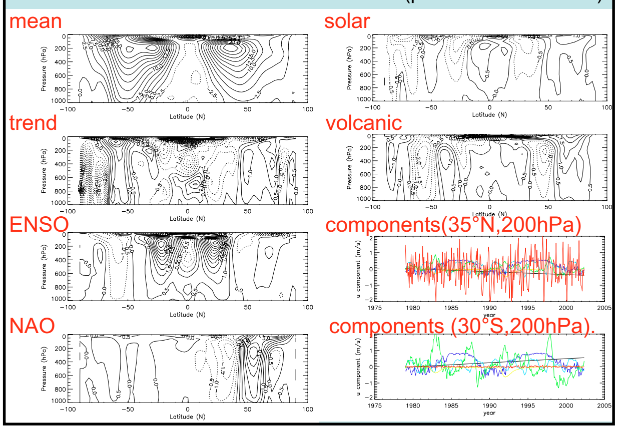
Analysis of NCEP/NCAR zonal mean zonal wind (1979-2002)



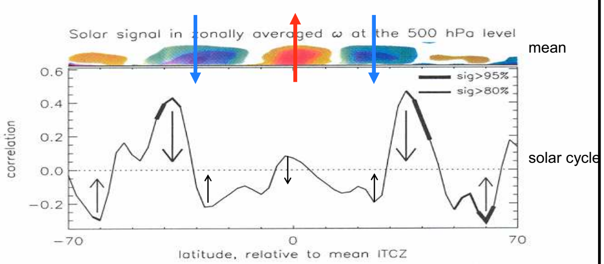
Mid-latitude jets weaker and shifted poleward when Sun more active.



NCEP zonal mean zonal wind (pressure as ordinate)



Solar signal in vertical velocity from NCEP data



(Gleisner and Thejll, 2003)

Hadley cells weaker and broader when Sun more active.

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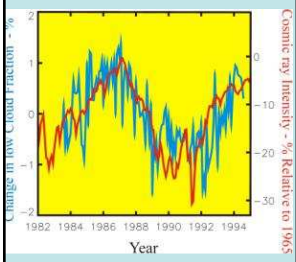
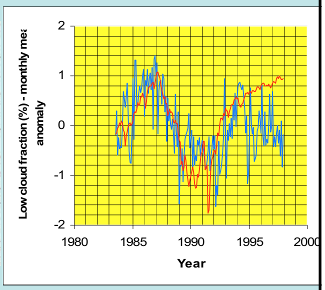
Low cloud and galactic cosmic rays

Marsh & Svensmark 2000

updated





Mechanisms involved in the influence of solar variability on climate

How might solar activity influence weather and climate?

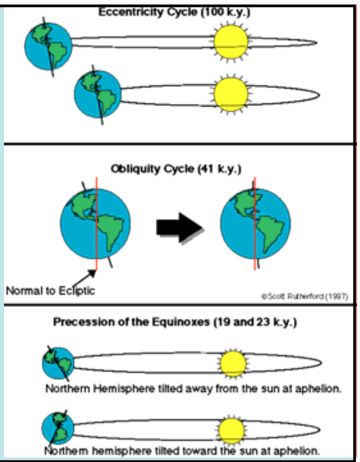
Total solar irradiance:	Modulate energy input to the Earth.
UV irradiance:	Heating stratosphere, O_3 photochemistry.
Solar energetic particles:	Ionisation & chemistry (upper atmosphere).
Galactic cosmic rays:	Ionisation (lower stratosphere).

Total solar irradiance mechanisms

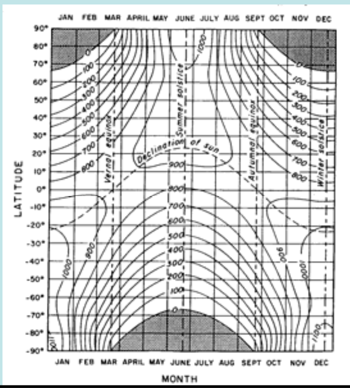
- Variations in Earth's orbit around the Sun (>10,000 year timescales).
- Variations in solar radiative output (decadal to millennial timescales).

Variations in Earth's orbit around the Sun

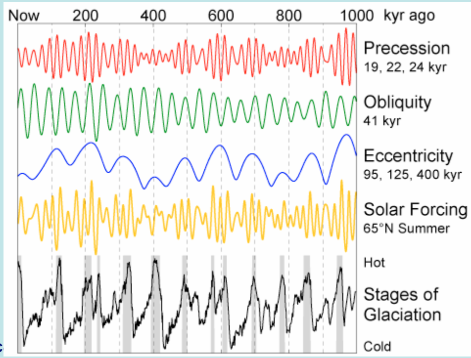
"Milankovitch cycles" in climate

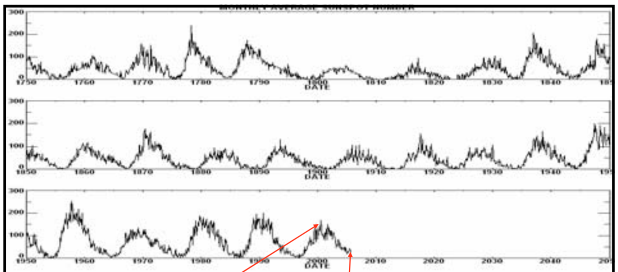


Geographical distribution of solar irradiance



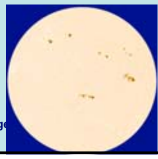
Earth orbital parameters - temporal variation





20 March 2000

9 May 2006



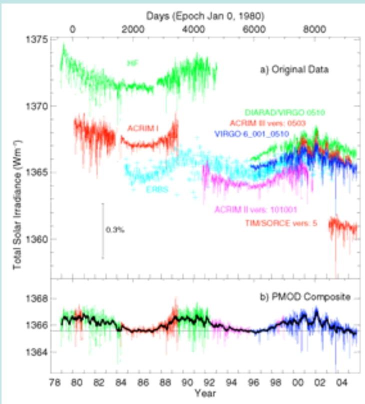
Sunspot cycle

(Images courtesy University of Hawaii)

Total solar irradiance (TSI) measurements from satellites

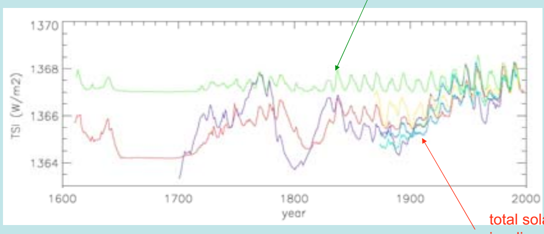
courtesy Claus Fröhlich

Poor agreement on absolute value; better on variation.



TSI and radiative forcing

sunspot no.

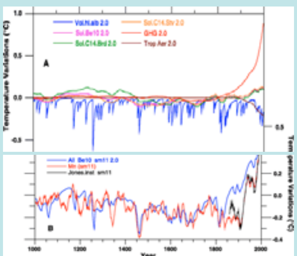


total solar irradiance estimates

N.B. $RF = \frac{1}{4}(1-\alpha)\Delta TSI$

Large uncertainties in TSI reconstructions.

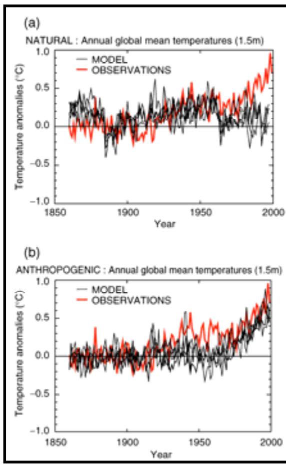
Energy Balance Model



Forcings

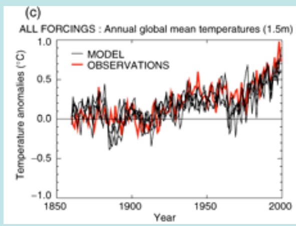
Response:
obs.
proxy obs.
model

Crowley (2000)

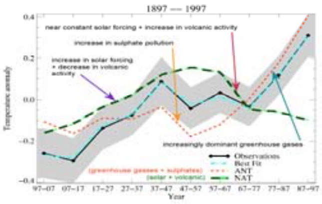


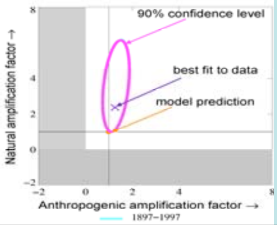
GCM global mean surface temperature simulations

IPCC 2001



All is explained?



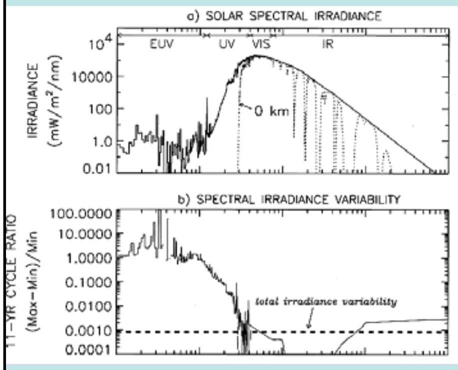


Detection/attribution of surface temperature trends

No!
Model underestimates response to natural forcing by a factor of 2 or 3

Stott et al 2003

Solar spectrum



Larger variability in UV than in visible (or total) irradiance.

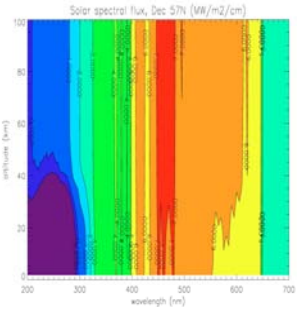
Lean & Rind (1998)

UV mechanisms

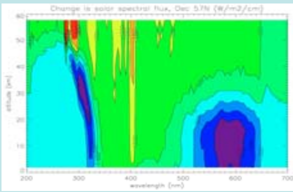
- Stratospheric ozone and solar radiative forcing.
- UV heating of the middle atmosphere and dynamical coupling to lower atmosphere.

Profile of solar spectral irradiance

Non-linear effect on radiative forcing



Solar minimum



Max-min

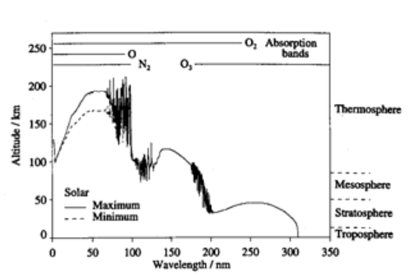
Haigh, *Nature*, 1994

Ozone feedback on solar radiative forcing

author	solar change	ΔS RF (toa)	ΔS RF (tpse)	ΔO_3	O_3 SW effect	O_3 LW effect	net O_3 effect	RF amp (%)
Haigh 1994	11-year amp	0.13	0.11	+ve peak near 40km	-0.03	+0.02	-0.01	-9
Hansen et al 1997	11-year amp	0.13	0.11	+ve 10-150hPa			+0.05	+45
Myhre et al 1998	11-year amp	0.13	0.11	+ve	-0.08	+0.06	-0.02	-18
Wuebbles et al 1998	c1680-c1990	0.49<0.70	0.42<0.60	+ve peak near 40km			-0.13	-21 < -30
Larkin et al 2000	11-year amp	0.13 0.13	0.11 0.11	+ve (as H94) +ve (SBUV/TOMS)	-0.06 -0.03	+0.11 +0.08	+0.05 +0.05	+45 +45
Shindell et al 2001	1680-1780	0.30<0.39	0.26<0.33	-ve (upper strat) +ve (lower strat)			+0.02	+6 < +8

No agreement on sign let alone amplitude!

Altitude of unit optical depth



(Andrews, 2000)

Simulations of impacts of varying solar UV using General Circulation Models

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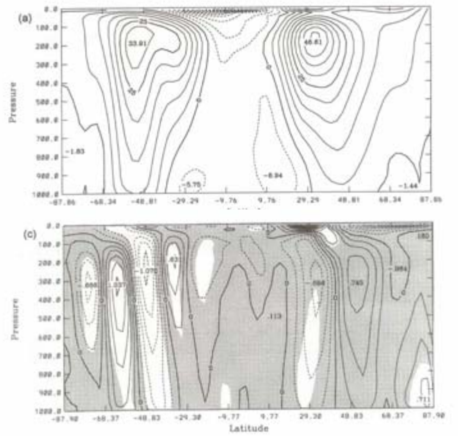


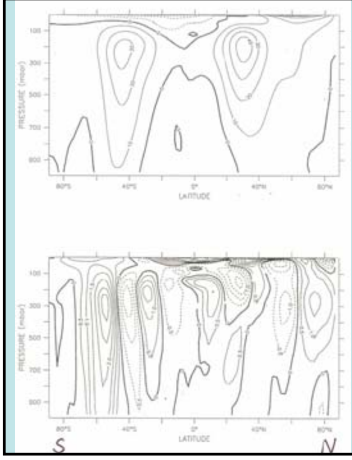
UGCM zonal wind

January

solarmax-solarmin

(2D model ΔO_3)

Haigh (*Science*1996; *QJRMS* 1999)



UM zonal wind

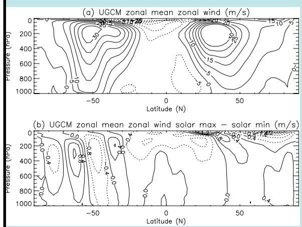
January

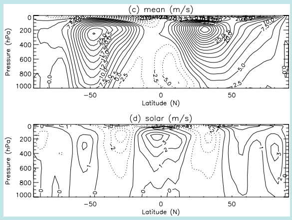
solarmax-solarmin

Similar results using two very different GCMs (UGCM and UM).

Larkin et al (2000)

Solar signal in zonal mean zonal wind





Model (Jan) (Haigh, 1999)

NCEP data (DJF) (Haigh et al, 2005)

Similar results for solar signal in zonal wind found in GCM and observations.

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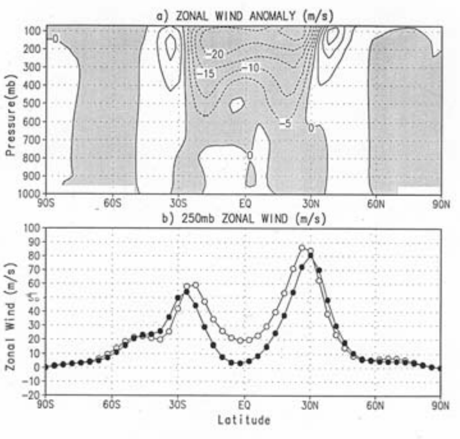
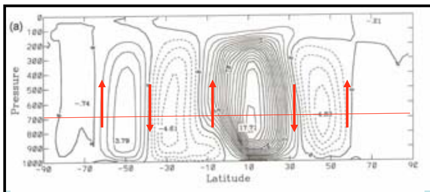
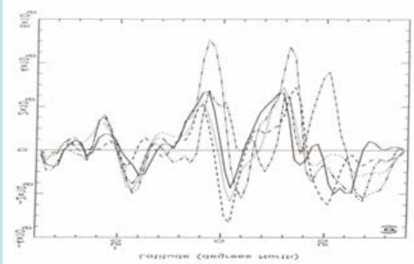


Hou (2000) GCM response in zonal wind to “artificial” ΔO_3

Response qualitatively similar to solar signal found in GCMs and obs.





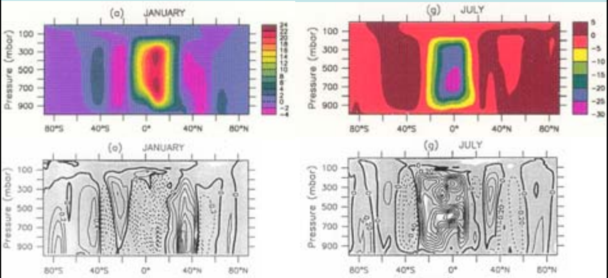
UGCM mean meridional circulation

January

change in MMC at 682hPa

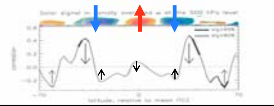
Haigh (1999)

UM mean meridional circulation



Larkin (2000)

Hadley cells weaker and broader when Sun more active in UGCM and UM, as in obs:



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So GCMs with increased UV appear to simulate the observed solar impact in the troposphere

But how does the UV produce the observed effects?

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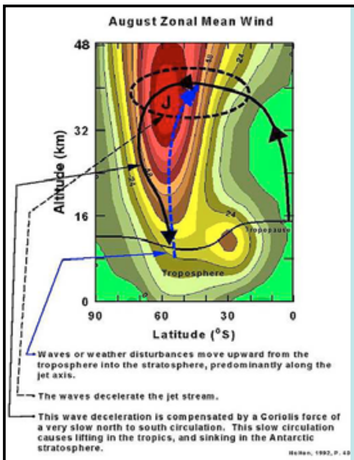
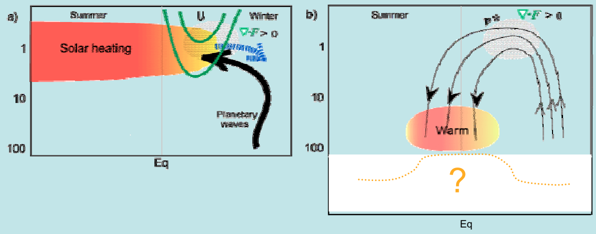


Wave – mean flow interactions in the stratosphere

ICTP Lecture 2 51

Observed modulation of Polar Night Jet and Brewer-Dobson Circulation



Solar heating → increase in zonal wind → planetary wave refraction → weaker Brewer-Dobson circulation → warmer tropical lower stratosphere → impact on troposphere?

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Matthes (2006) after Kodera and Kuroda (2002)

ICTP Lecture 2 52

Stratosphere-troposphere coupling: potential mechanisms

- Increased static stability (due to warming of lower stratosphere) weakens tropical upwelling and Hadley cells.
- Changes in zonal wind in stratosphere affect growth/propagation/reflection of planetary waves in troposphere.
- Baroclinic lifecycles (mid-latitude weather patterns) modified.

Possibly all of these (in different locations and/or seasons).

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ICTP Lecture 2 53

Simplified GCM - “dynamical core” model

Based on University of Reading spectral model:
Full dynamics T42 L20.
No orography.
Newtonian cooling - equinoctal radiative equilibrium temperatures T_e(lat.,ht.).
Rayleigh friction.

Experiments:
1. Equilibrium response to perturbations to stratospheric T_e.
(Haigh, Blackburn & Day, *J.Clim.*, 2005)
2. Spin-up ensemble.

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ICTP Lecture 2 54

Simplified GCM perturbation experiments

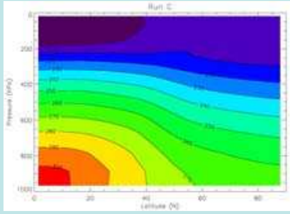
Run C — Control: T_e distribution of Held and Suarez (1994).

Run U5 — Stratospheric only T_e increased uniformly by 5K.

Run E5 — Stratospheric only T_e increased by 5K at the equator, decreasing with $\cos^2$(latitude) to 0K at the poles.

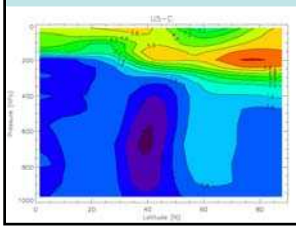
Simplified GCM perturbation runs:

temperature (K)

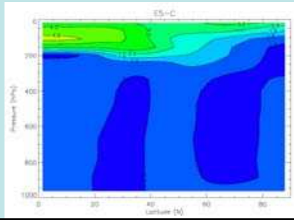


Run C

U5 – C

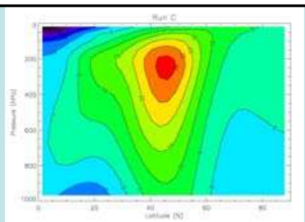


E5 - C



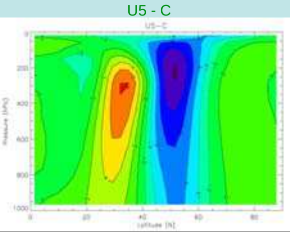
Simplified GCM perturbation runs:

zonal wind (m/s)

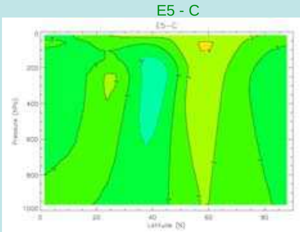


Run C

U5 - C

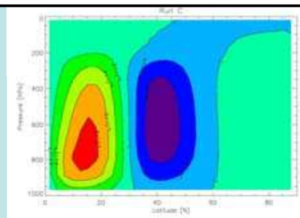


E5 - C



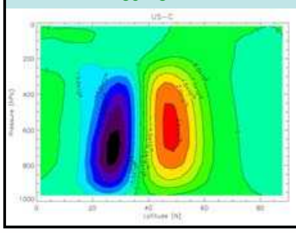
Simplified GCM perturbation runs:

mean meridional circulation (kg/s)

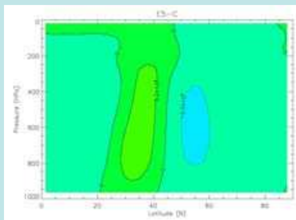


Run C

U5 – C

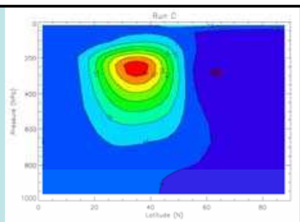


E5 - C



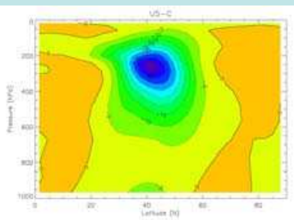
Simplified GCM perturbation runs:

horizontal eddy momentum flux $[u'v']$ (m^2/s^2)

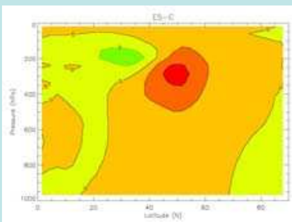


Run C

U5 – C



E5 - C



Vertically-integrated budget of zonal momentum

Zonally-averaged zonal momentum equation:

$$\frac{\partial [u]}{\partial t} = -\frac{1}{a\cos^2\phi}\frac{\partial}{\partial \phi}\{[uv]\cos^2\phi\} - \frac{\partial}{\partial p}[u\omega] + f[v] + [F_\lambda]$$

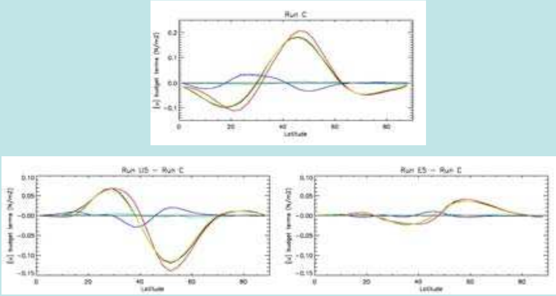
Integrated through depth of atmosphere:

$$\frac{\partial}{\partial t}\int_0^{p_s}[u]\,dp = -\frac{1}{a\cos^2\phi}\frac{\partial}{\partial \phi}\left\{\cos^2\phi \int_0^{p_s}\left([u][v]+[u'v']\right)dp\right\} + \int_0^{p_s}[F_\lambda]\,dp$$

or:

$$\frac{1}{g}\frac{\partial}{\partial t}\int_0^{p_s}[u]\,dp = C_{ZONAL} + C_{EDDY} - [\tau_{S\lambda}]$$

Vertically-integrated budget of zonal momentum

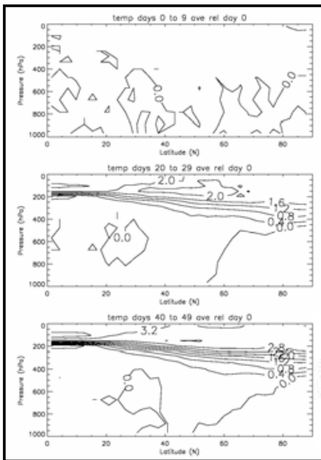


$$\frac{1}{g}\frac{\partial}{\partial t}\int_0^{p_s}[u]\,dp = C_{ZONAL} + C_{EDDY} - [\tau_{S\lambda}]$$

Spin-up ensemble

Ensemble of 200 50-day runs each starting from different initial conditions acquired from the control run.

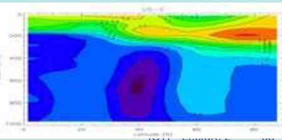
For each ensemble member the U5 heating perturbation is switched on at day 0.

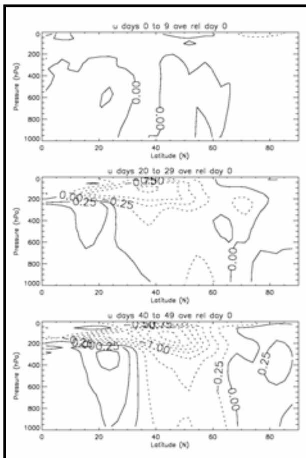


Spin-up ensemble

evolution of temperature

equilibrium response

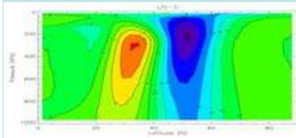


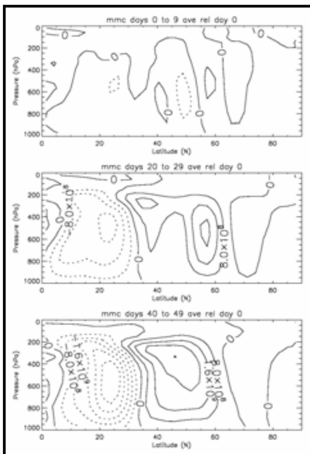


Spin-up ensemble

evolution of zonal wind

equilibrium response

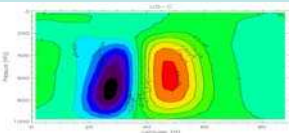


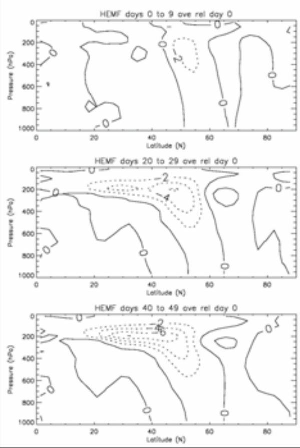


Spin-up ensemble

evolution of MMC

equilibrium response

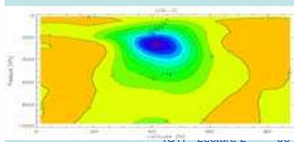


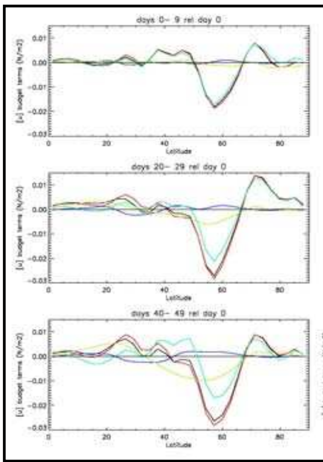


Spin-up ensemble

evolution of $[u'v']$

equilibrium response



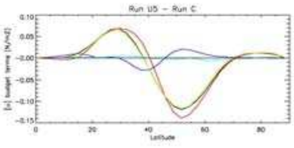


Spin-up ensemble

evolution of vertically-integrated momentum budget

$$\frac{1}{g}\frac{\partial}{\partial t}\int_0^{p_s}[u]dp = C_{ZONAL} + C_{EDDY} - [\tau_{S\lambda}]$$

equilibrium response



Conclusions 1/3

- The Earth has warmed over the past 150 years but not uniformly in space or time.
- The increase in greenhouse gas concentrations is predominantly responsible but the Sun probably influenced early 20th century warming.
- The effects of solar variability are seen in a variety of meteorological parameters on a wide range of time scales, although care has to be taken in attribution.
- The response is not spatially uniform. The troposphere shows vertical bands of warming in mid-latitudes and weakened and broadened Hadley cells.

Conclusions 2/3

- Variations in total solar irradiance due to changes in the Earth's cause significant impact on climate on long timescales.
- The Sun's total irradiance varies by ~0.1% over an 11-year cycle but changes over longer periods are not well established.
- Variations in the UV portion of the spectrum are much larger than in TSI.
- The vertical structure of the apparent ozone response is not well understood.
- GCMs with imposed variations of UV can produce a response in the lower atmosphere similar to that observed.

Conclusions 3/3

- (Any) thermal perturbations to the lower stratosphere exert a dynamical influence on the circulation of the lower atmosphere.
- Solar influence on climate provides an interesting test-bed for theories of stratosphere-troposphere coupling.
- The geographical pattern of the solar influence can only be understood via dynamical feedbacks.
- Stratospheric influence starts with modification to wave convergence at tropopause.

Hershel, Phil.Trans.Roy.Soc. 1801

… more or less light and heat from the sun [may] be liable to produce a great variety in the severity or mildness of the seasons …

Before we can generalize the influence of a certain cause, we ought to confine our experiment to one permanent situation, where local circumstances may be supposed to act nearly alike at all times, which will remove a number of difficulties.

… when many things which are already known to affect the temperature of different countries … come to be properly combined with the results we propose to draw from solar observations, we may possibly find this subject less intricate than we might apprehend …