Solar cycle - modeling and predicting

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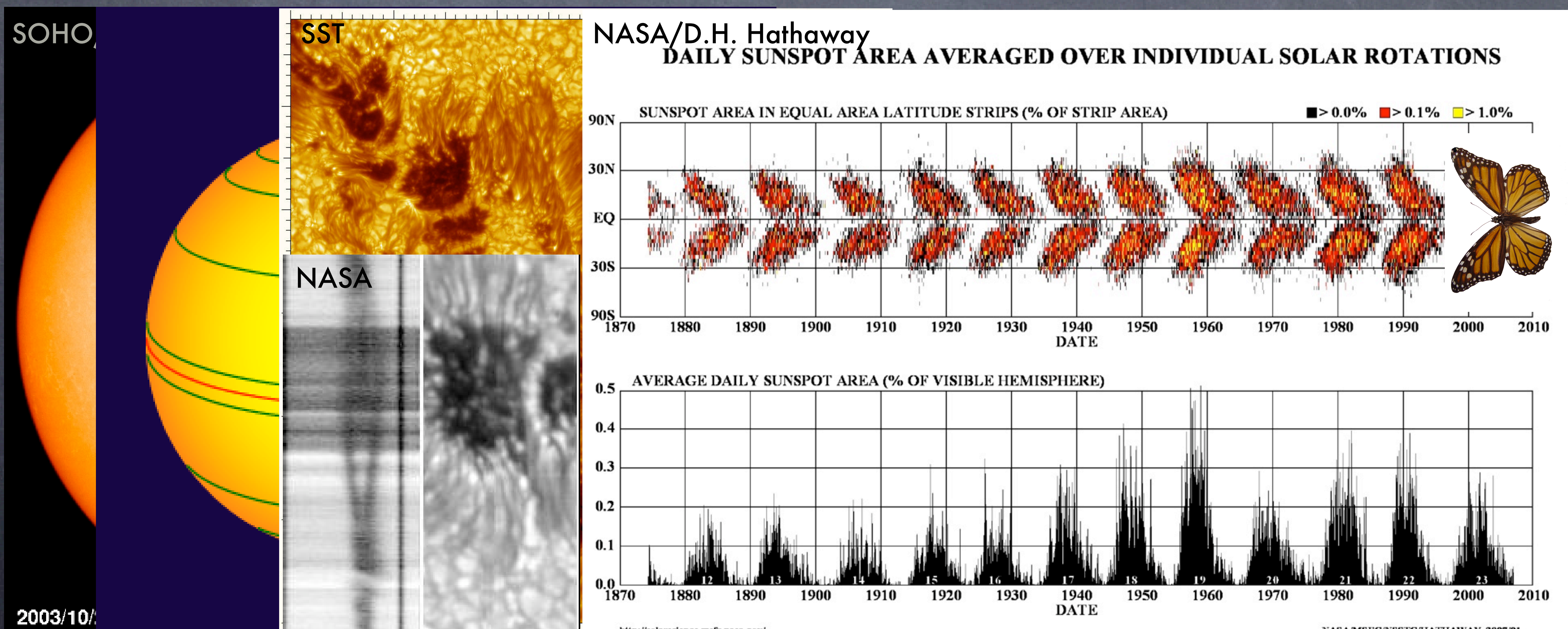

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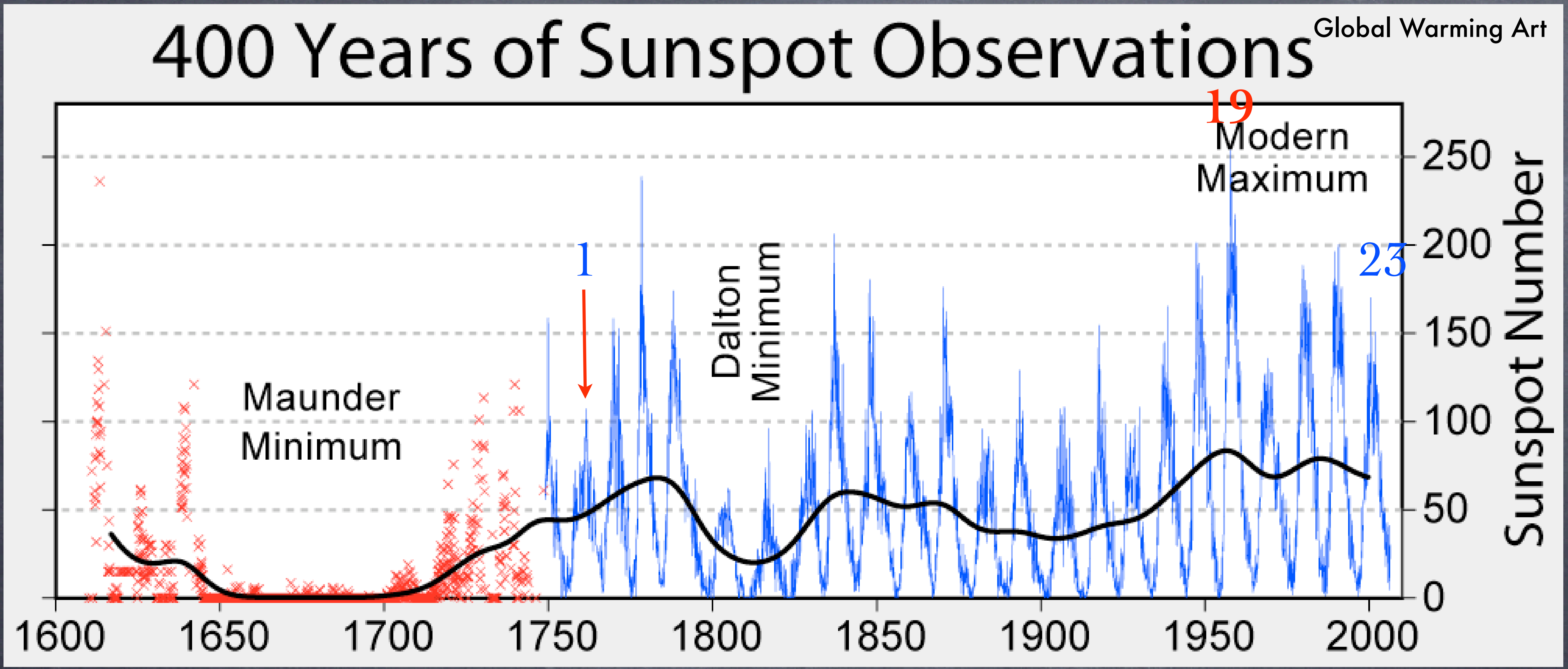
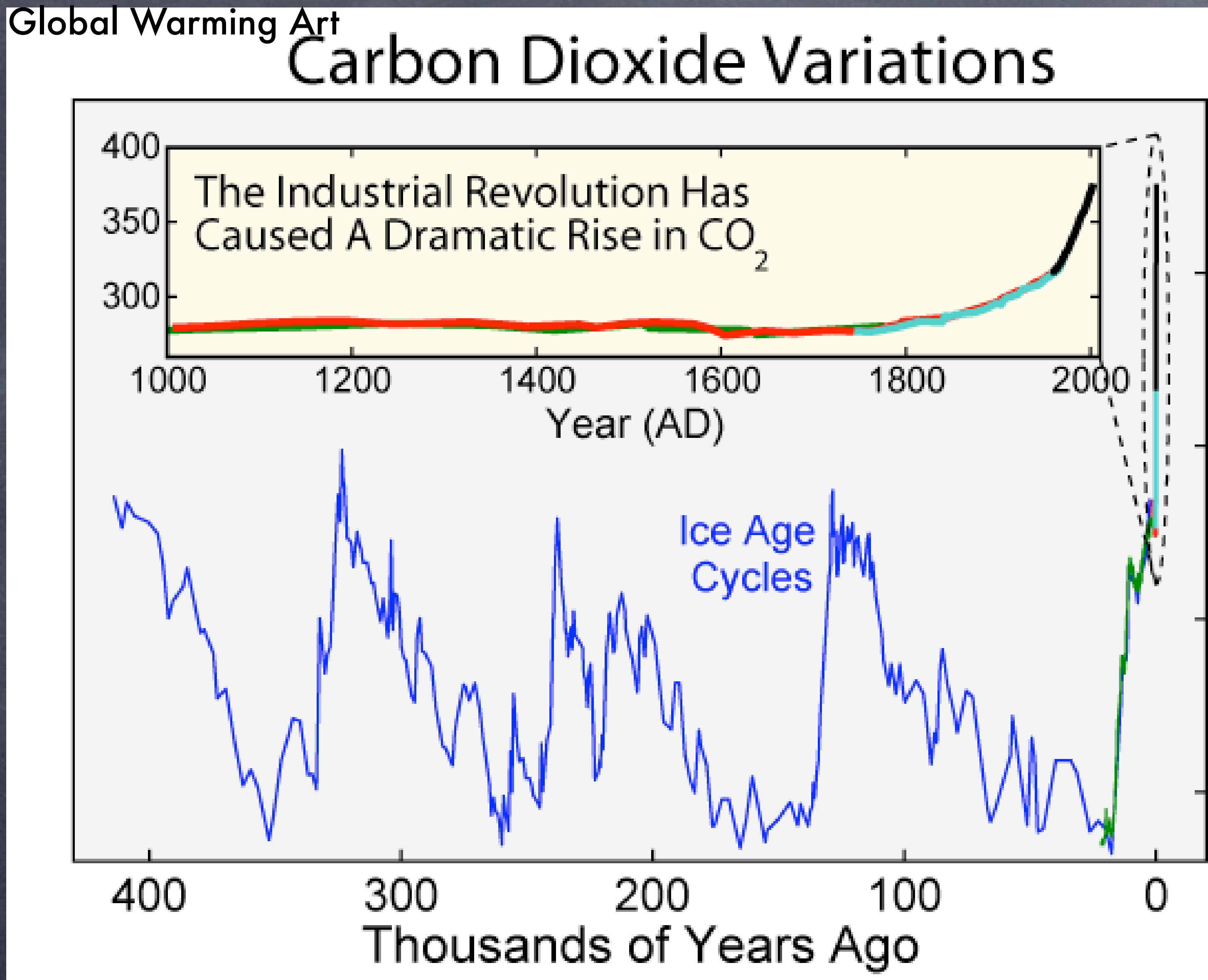
Sunspot observations

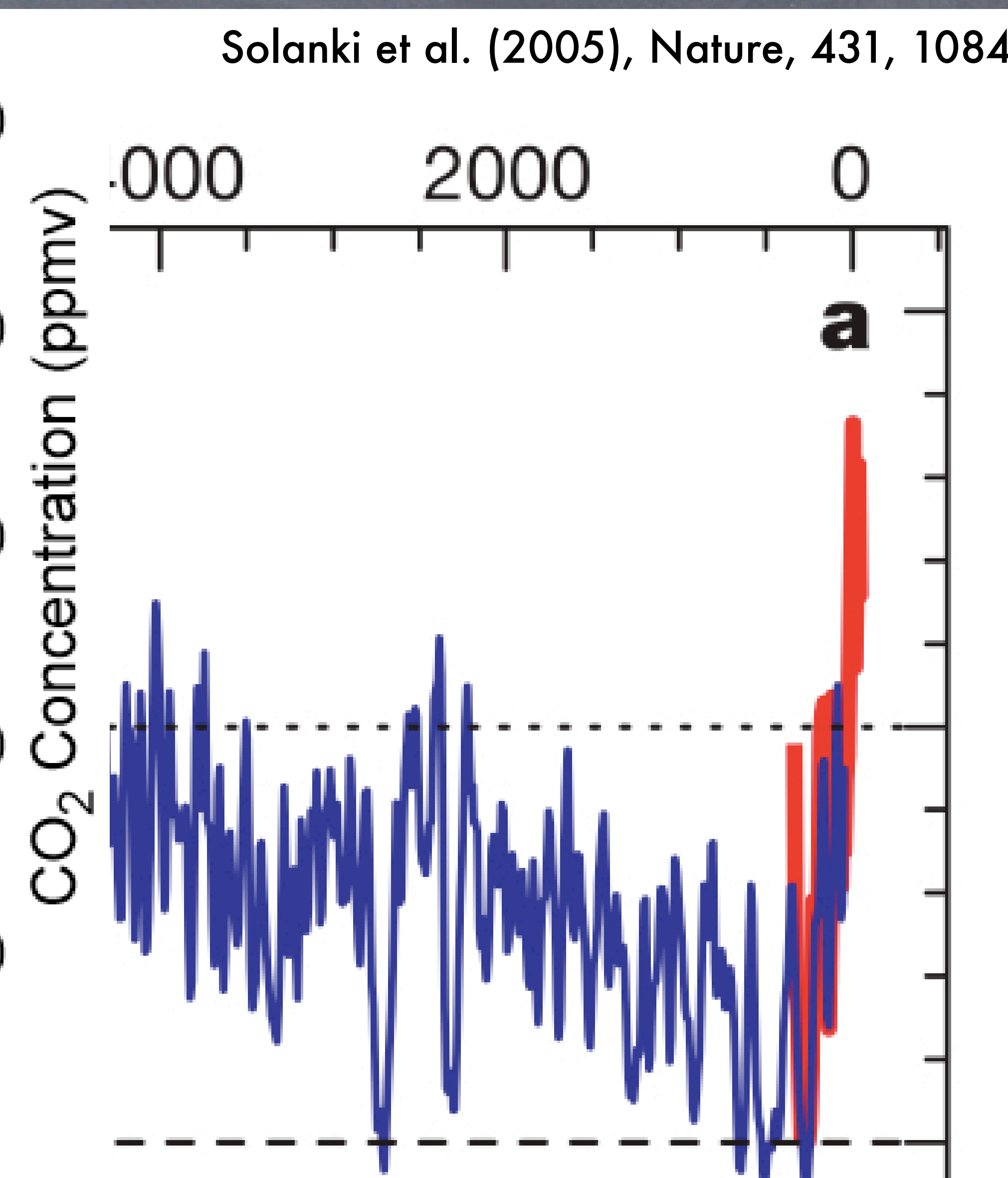


11-year Schwabe cycle/22-year Hale cycle

87-year Gleissberg cycle

Solar cycle deductions

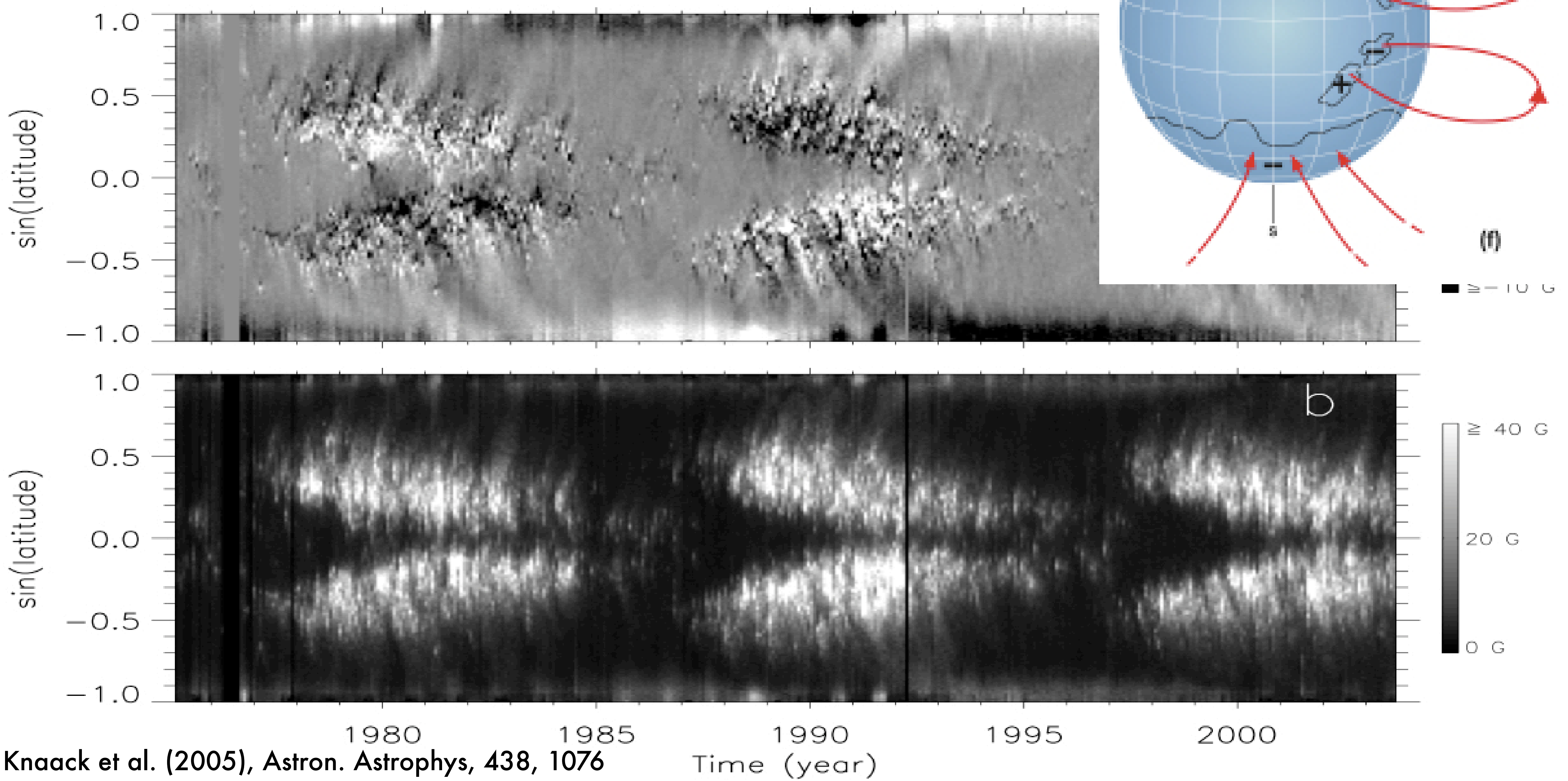




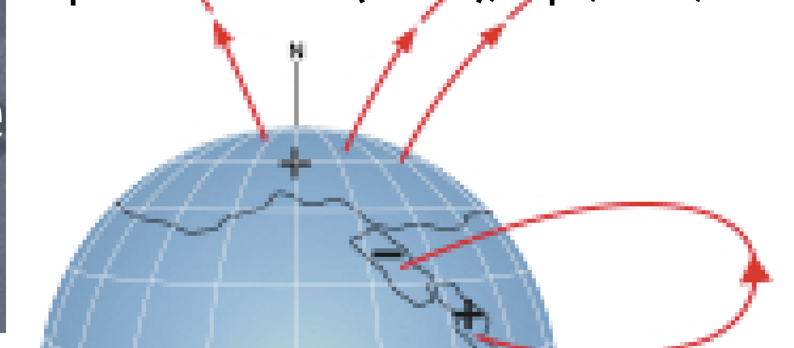
The Sun is now more active than any time in the past 8000 years

230 year Suess/2300 year Hallstatt cycles

Typical solar cycle

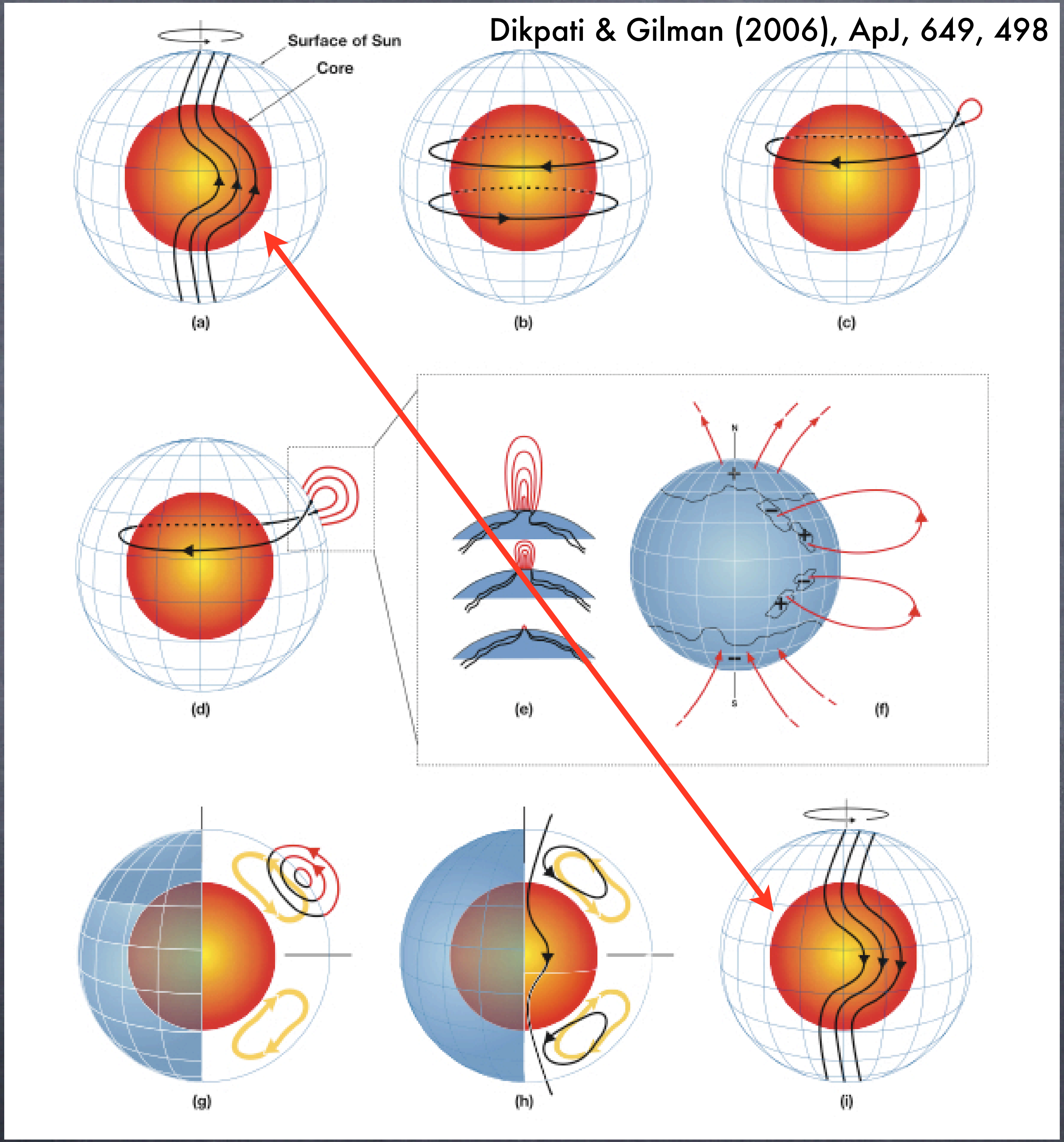


Knaack et al. (2005), Astron. Astrophys, 438, 1076



Dikpati & Gilman (2006), ApJ, 649, 498

Schematic flux transport dynamo cycle



Quantitative model of the solar cycle

The induction equation	$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{U} \times \mathbf{B} - \eta \nabla \times \mathbf{B})$
Separating the mean and the fluctuation, the mean-field induction equation is obtained	$\mathbf{B} = \overline{\mathbf{B}} + \mathbf{b} \qquad \mathbf{U} = \overline{\mathbf{U}} + \mathbf{u}$ $\frac{\partial \overline{\mathbf{B}}}{\partial t} = \nabla \times (\overline{\mathbf{U}} \times \overline{\mathbf{B}} + \overline{\mathbf{u} \times \mathbf{b}} - \eta \nabla \times \overline{\mathbf{B}})$
Turbulent quantities enter via the emf which needs to be expressed in terms of the mean field	$\mathcal{E} = \overline{\mathbf{u} \times \mathbf{b}}$ $\mathcal{E}_i = a_{ij} \overline{B}_j + b_{ijk} \frac{\partial \overline{B}_k}{\partial x_j} + \cdots$
Consider isotropic (non-mirror symmetric) turbulence as a first approximation	$\mathcal{E} = \alpha \overline{\mathbf{B}} - \eta_{\mathbf{t}} \nabla \times \overline{\mathbf{B}}$ $\frac{\partial \overline{\mathbf{B}}}{\partial t} = \nabla \times [\overline{\mathbf{U}} \times \overline{\mathbf{B}} + \alpha \overline{\mathbf{B}} - (\eta_{\mathbf{t}} + \eta) \nabla \times \overline{\mathbf{B}}]$

How to model...cont'd

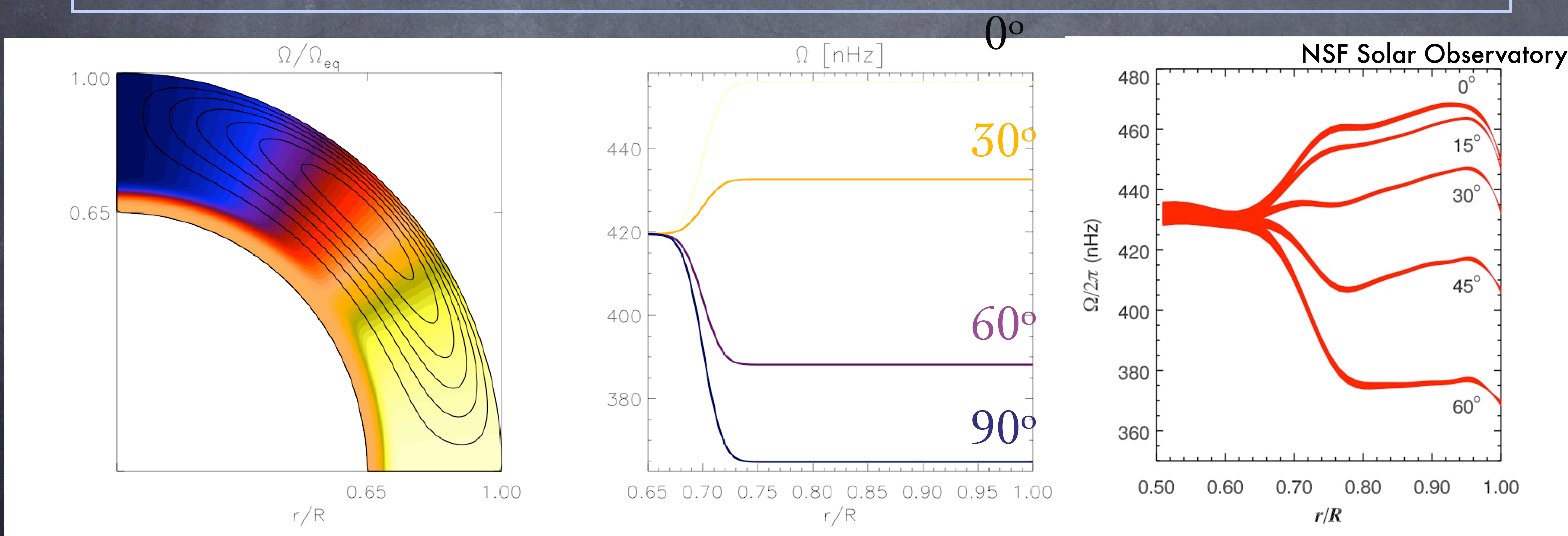
Assume axisymmetry

$$\overline{\mathbf{B}} = \overline{B_\phi}(r,\theta,t)\hat{\mathbf{e}}_\phi + \nabla \times \overline{A_\phi}(r,\theta,t)\hat{\mathbf{e}}_\phi$$

Adopt idealized descriptions of the large-scale velocity field

$$\overline{\mathbf{U}} = \overline{\mathbf{U}}_{\rm mer}(r,\theta) + r\sin\theta\,\Omega(r,\theta)\hat{\mathbf{e}}_\phi$$

$$\rho\overline{\mathbf{U}}_{\rm mer} = \nabla \times (\psi\hat{\mathbf{e}}_\phi)$$



What about α and η_t?

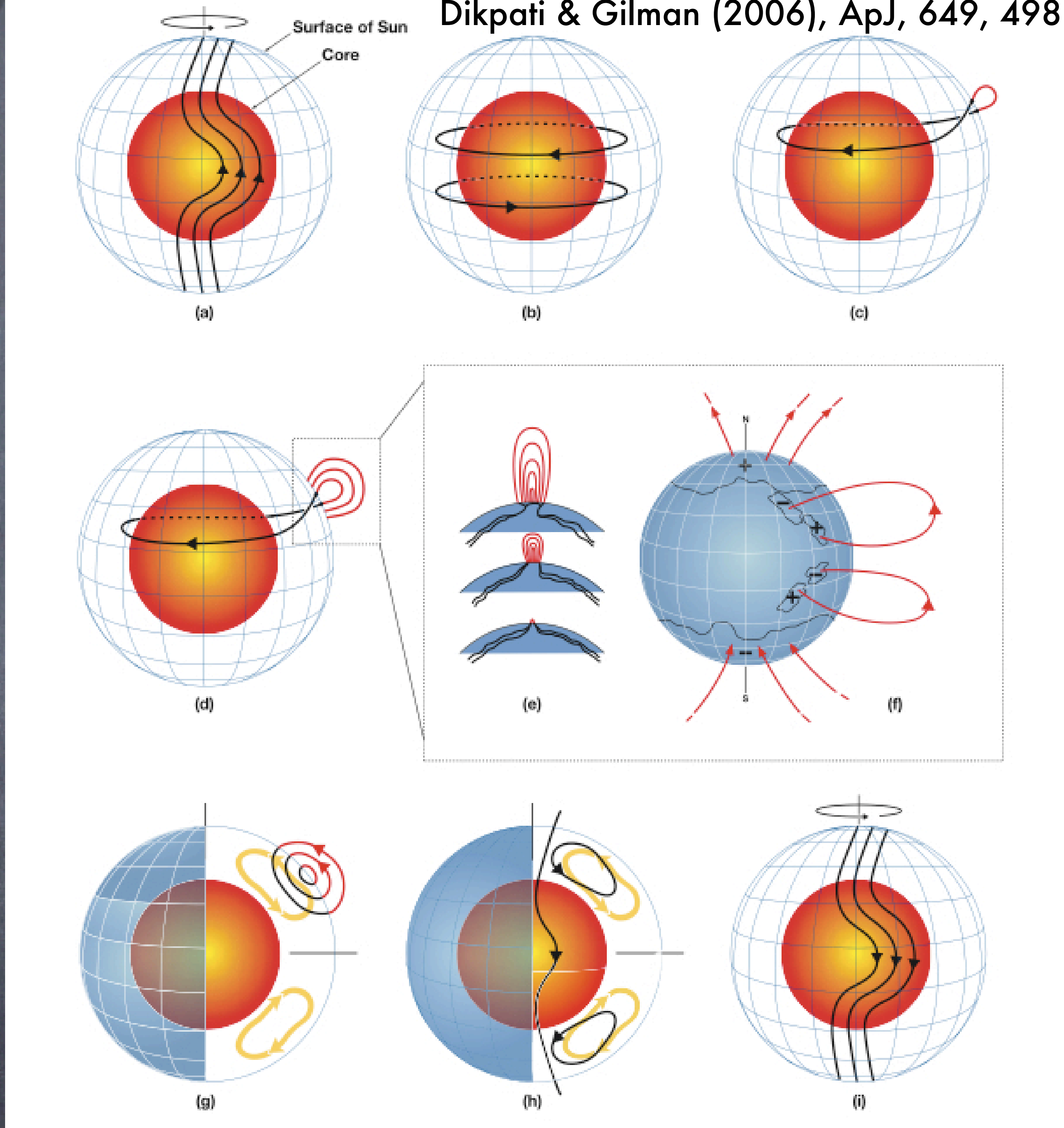
Turbulence parameters are tricky to estimate for the Sun

- α-effect present at the surface but proportional to toroidal field at the *base* of the convection zone $\alpha \approx 10^{-4}\ u_{\rm MLT}$

- Turbulent diffusivity at the surface from observations, fine-tuned (low) value within the convection zone

$$\eta_t^{\rm (surf)} \approx u_{\rm MLT} l_{\rm MLT}$$

$$\eta_t^{\rm (bulk)} \approx 10^{-2} u_{\rm MLT} l_{\rm MLT}$$



Dikpati & Gilman (2006), ApJ, 649, 498

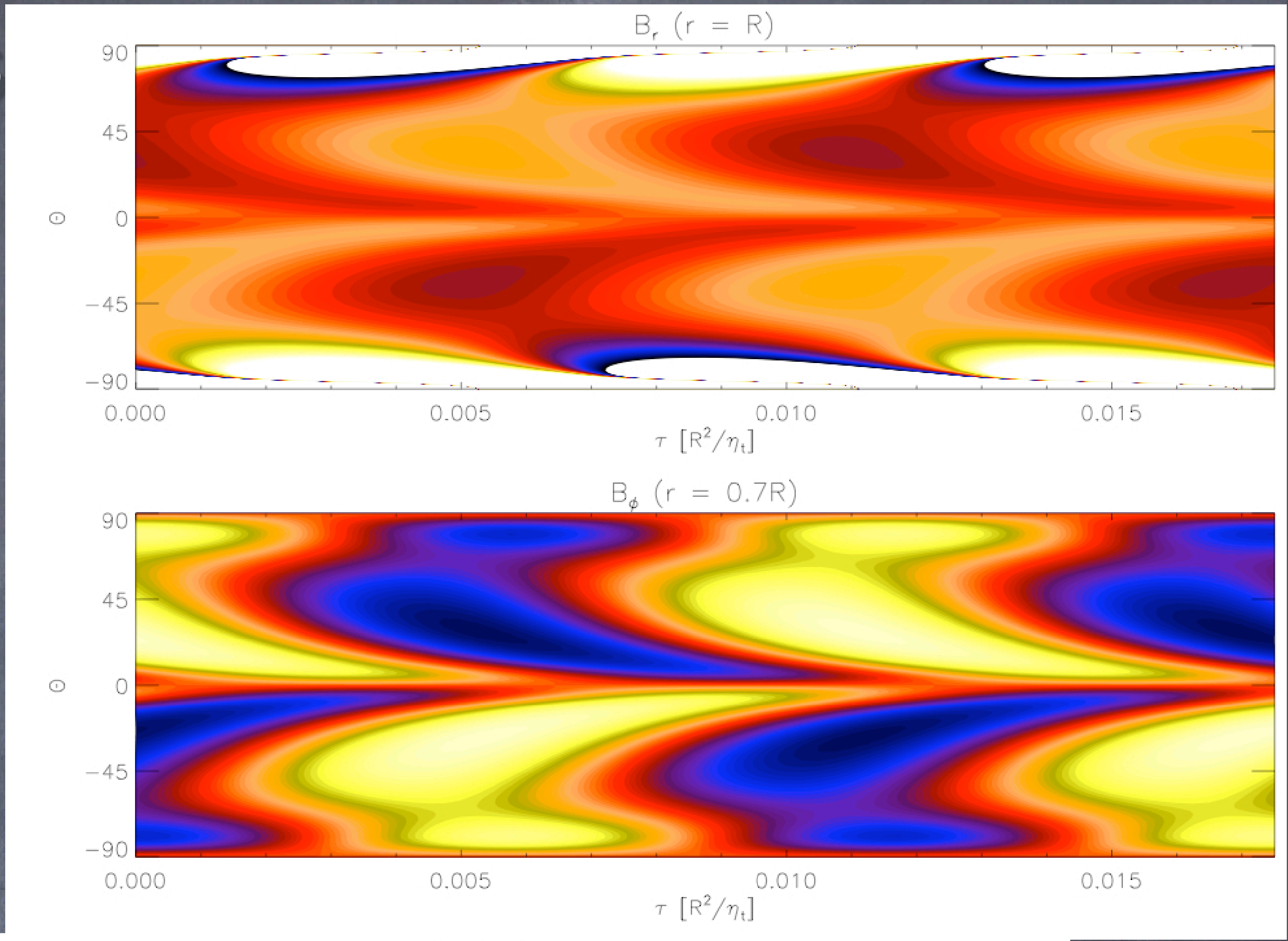
Representative results

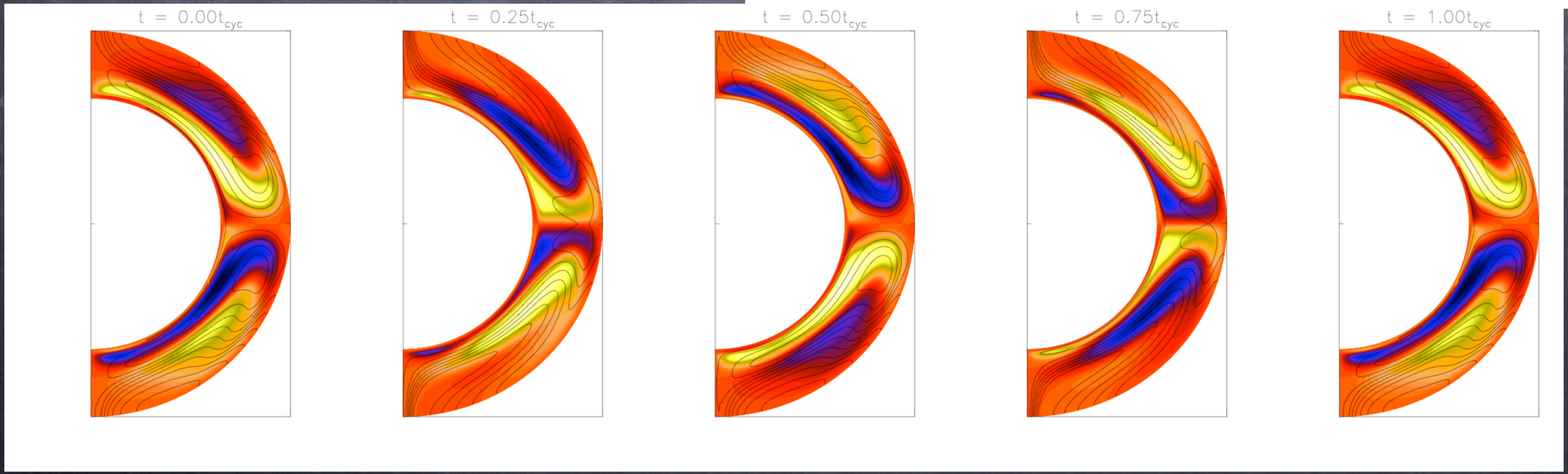
Results from an ongoing *dynamo benchmark project*

$$\eta_t^{(\text{surf})} = \eta_t^{(\text{bulk})} = 10^7 m^2 s^{-1}$$

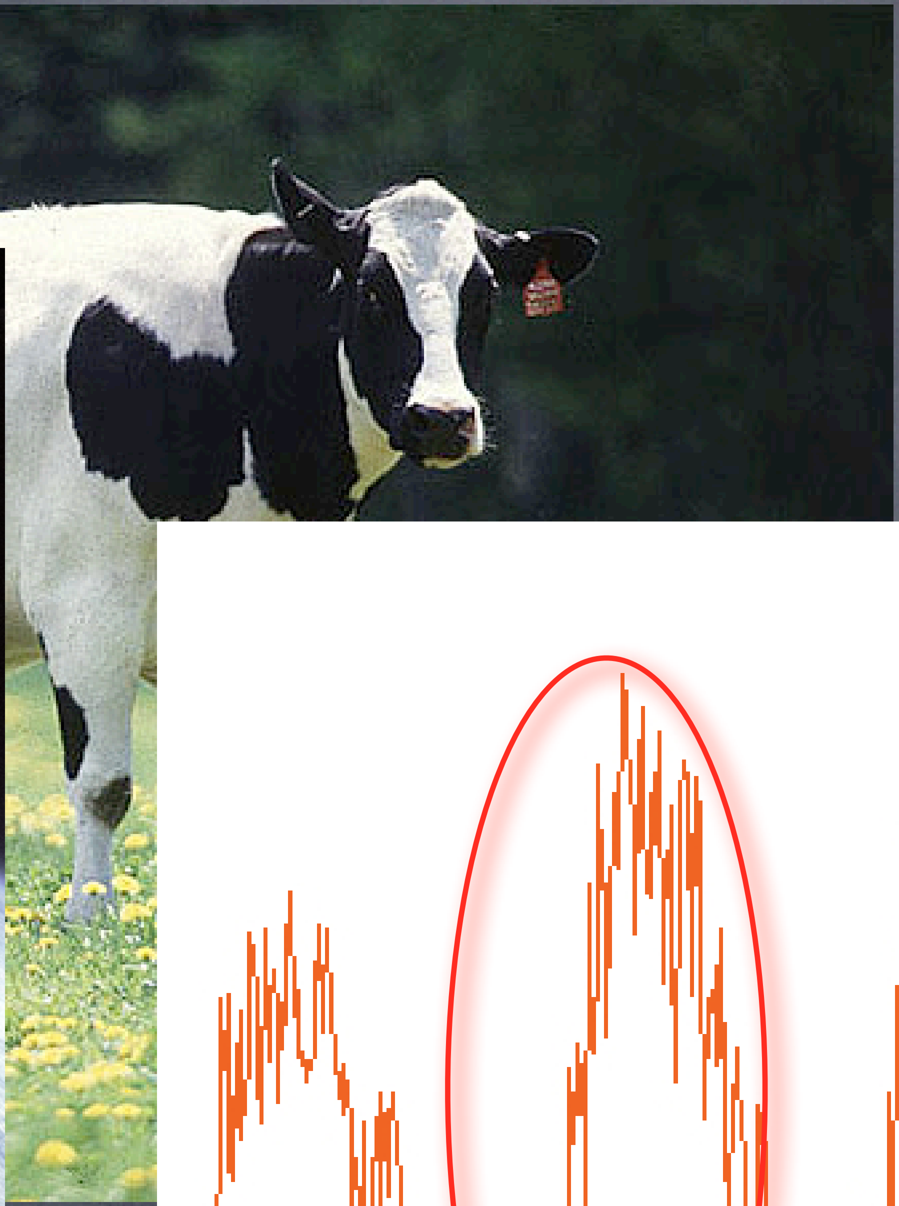
$$\alpha = 0.24\ m\ s^{-1}$$

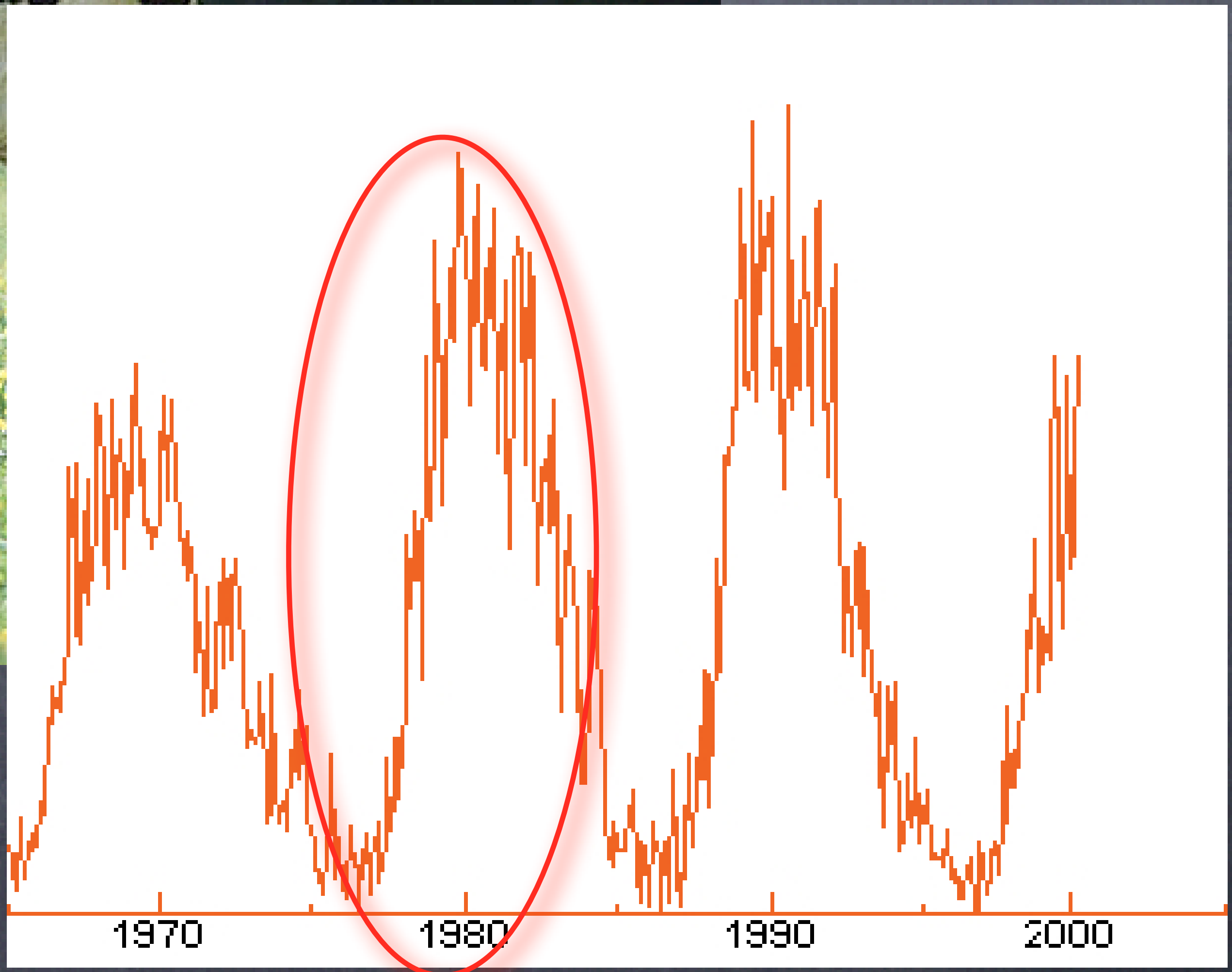
$$t_{\text{cyc}} = 0.012\tau_{\text{D}} \approx 19yr$$





How the Sun killed a cow





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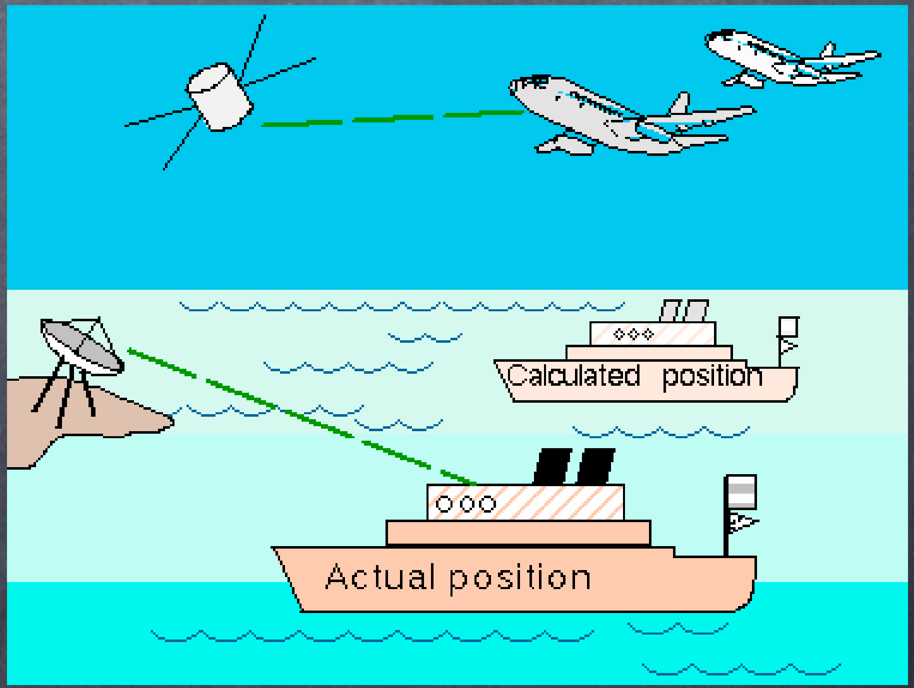
Other possible casualties of space weather

- Terrestrial communications (including homing pigeons)

- Satellite navigation systems (e.g. GPS)

- Health hazards for spaceborne human beings



- Power and oil supply

- Geomagnetic storms can be helpful for finding oil and minerals

How to predict the next solar cycle?

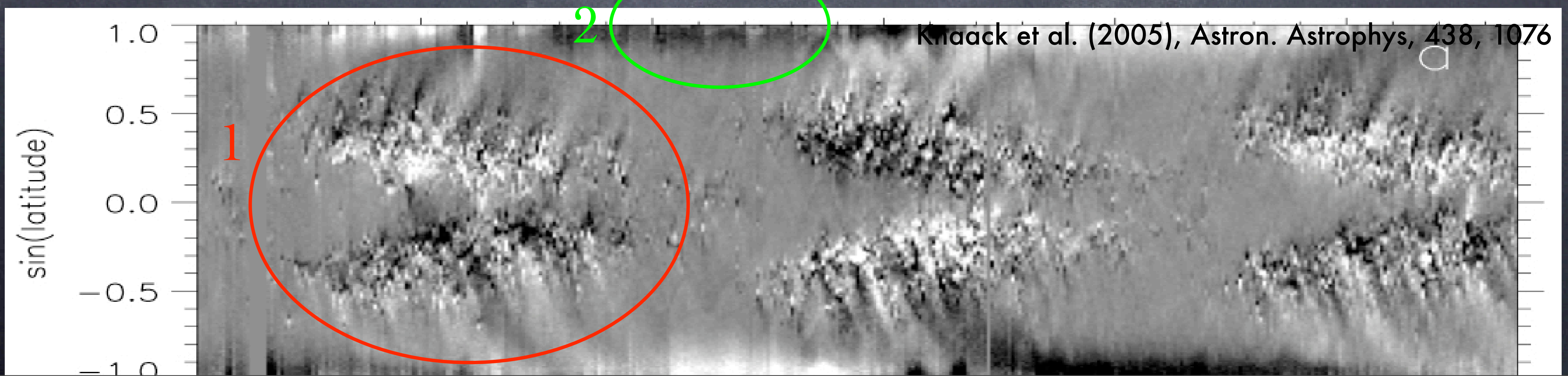
Purely statistical treatment relying on past observations (e.g. neural networks)

Precursors in the declining phase of the cycle as estimates of the dipole moment (DM)

- Radial field at the poles
- Flux crossing the equator or residing near the equator
- Geomagnetic indices

Dynamo models taking guidance from observed quantities

- 1.Observed sunspot area during the whole solar cycle
- 2.Radial field at the poles at solar minimum



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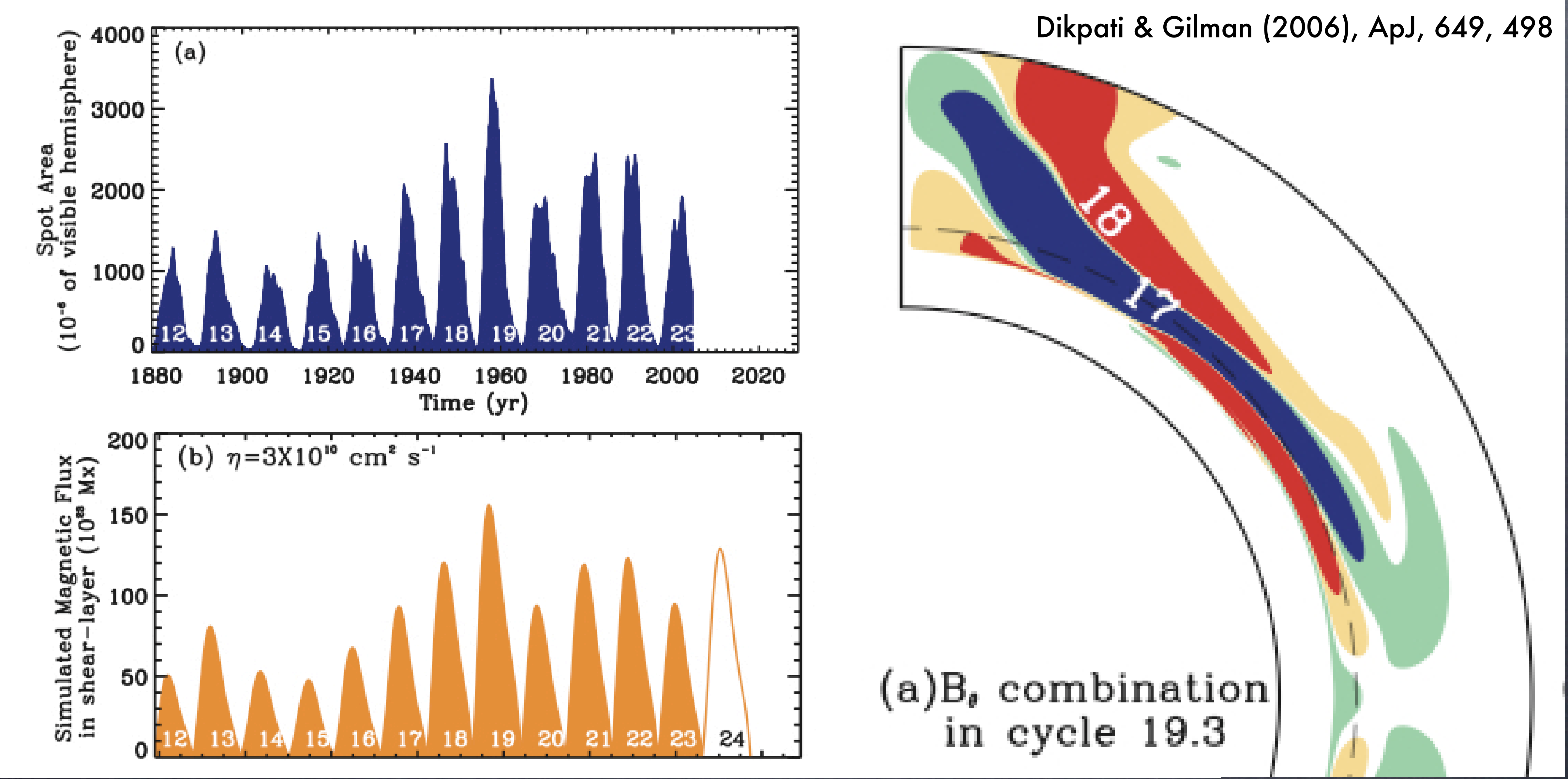
Predictions from dynamo models I (DG06)

1. Sunspot area as a proxy of the α-effect

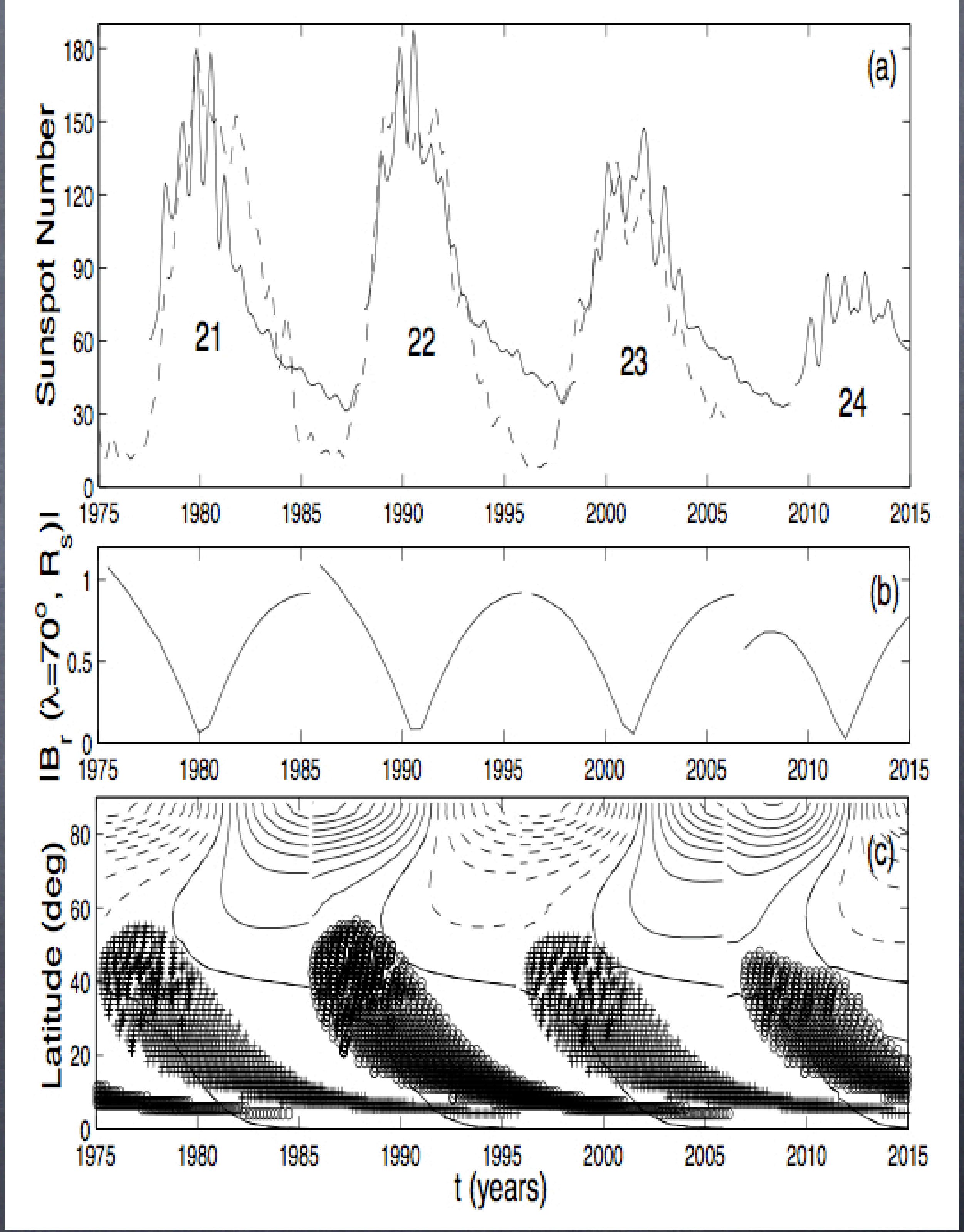
- Shows very good skill in `predicting' past cycles 16 to 23
- Cycle n depends mostly on cycle n-2
- Predicts a very strong cycle 24

Dikpati & Gilman (2006), ApJ, 649, 498



Predictions from dynamo models II (CCJ07)

Choudhuri et al. (2007), submitted to PhRvL (astro-ph/0701527)



2. Polar magnetic field at minimum as a proxy of the dipole moment

- Reliable polar field data available only from the end of cycle 20 onwards
- Adjusting the polar field strength at minima \`predicts' cycles 21-23
- Predicts a very weak cycle 24

What are the differences?

	DG06	CCJ07
Solar input	Sunspots, B_ϕ especially at maximum	Polar field, B_{pol} from minimum
α-effect	Proportional to sunspots	const.
Meridional flow	Within CZ	Penetrates into the core

Conclusions

- The solar cycles had implications for past climate and present space weather

- Mean-field theory gives a qualitative description of the cycle but models have internal difficulties

- Predictions can be based on cycle maximum (sunspots, DG06) or minimum (dipole moment, CCJ07) properties

- Predictions based on *sunspots* do not seem to characterize the next cycle well (strong cycle 24?)

- *Polar field* as a precursor seems more robust: acted upon only by differential rotation (weak cycle 24?)