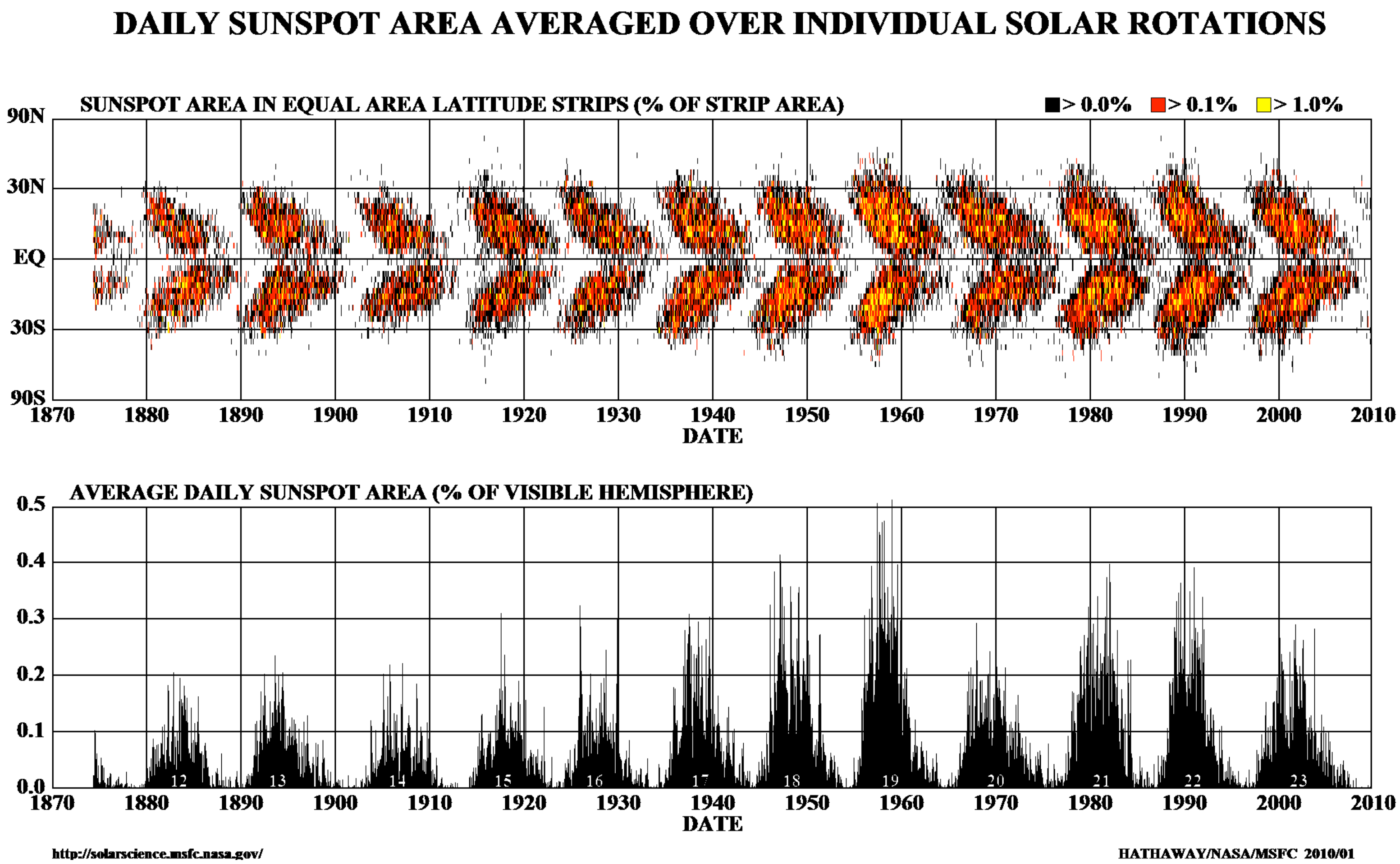
Solar-like cycles on a global large eddy simulation of solar convection

The GRPS MHD simulation gang:
Mihai Ghizaru, Paul Charbonneau, Piotr Smolarkiewicz (NCAR),
Jean-François Cossette, Étienne Racine(CSA), Patrice Beaudoin (>May)
Département de Physique, Université de Montréal

1. The simulation model
2. Convection and small-scale magnetic fields
3. Large-scale magnetic field and cycles
4. Mode of dynamo action
5. Cycle imprint on energy transport
6. Conclusion

PICARD science meeting, 03/10

The sunspot cycle



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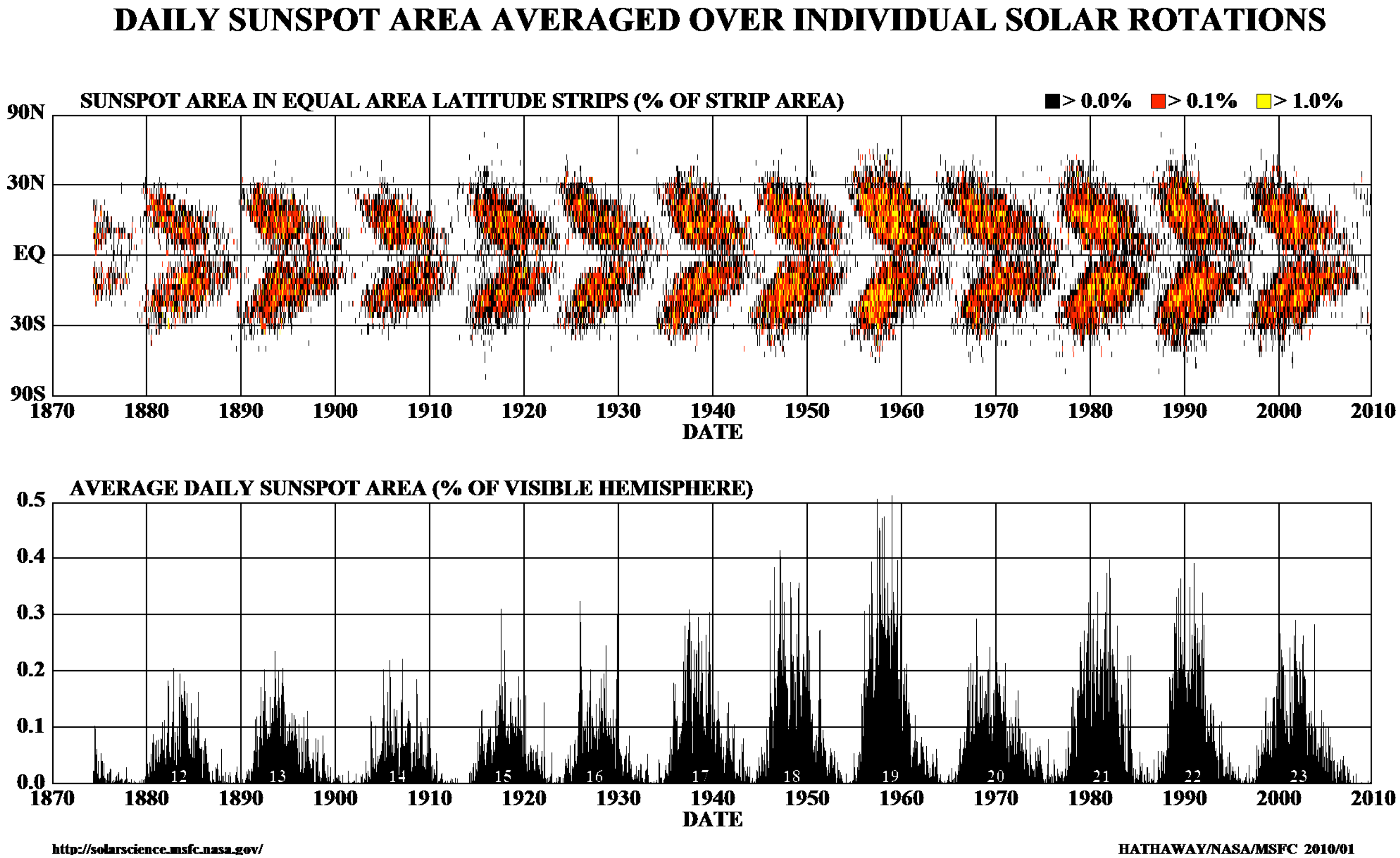

Is the large-scale magnetic field responsible for the solar activity cycle
Influencing convective energy transport through the solar envelope ?.

The simulation model (1)

$$\frac{D\mathbf{v}}{Dt} = -\nabla\pi - \mathbf{g}\frac{\theta'}{\theta_o} + 2\mathbf{v}\times\boldsymbol{\Omega} + \frac{1}{\mu\rho_o}(\mathbf{B}\cdot\nabla)\,\mathbf{B} + \mathcal{D}_\mathbf{v}\ ,$$

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$$\nabla\cdot(\rho_o\mathbf{v}) = 0\ ,\quad \nabla\cdot\mathbf{B} = 0\ ,$$

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Solution domain is a thick, rotating stratified shell of electrically conducting fluid spanning 0.61 to 0.96 of the solar radius, with solar luminosity forced across the shell:

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Simulations presented in what follows: on spatial meshes of longitude X latitude X radius = 128X64X47 and 256X128X93; very long temporal integrations (up to 175 yr!)

Convection and small-scale magnetic fields

Turbulent convection, in itself, produces a lot of magnetic field,
but very little net magnetic flux on the larger spatial scales

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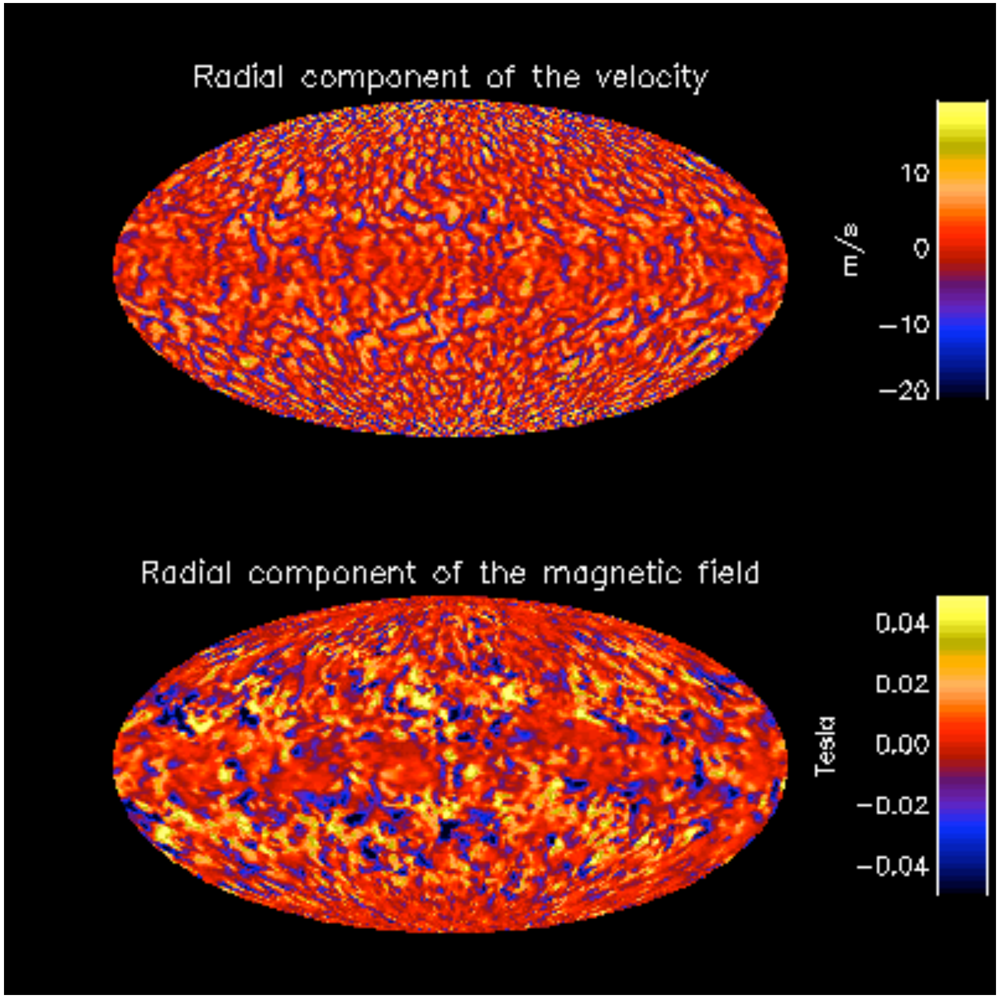

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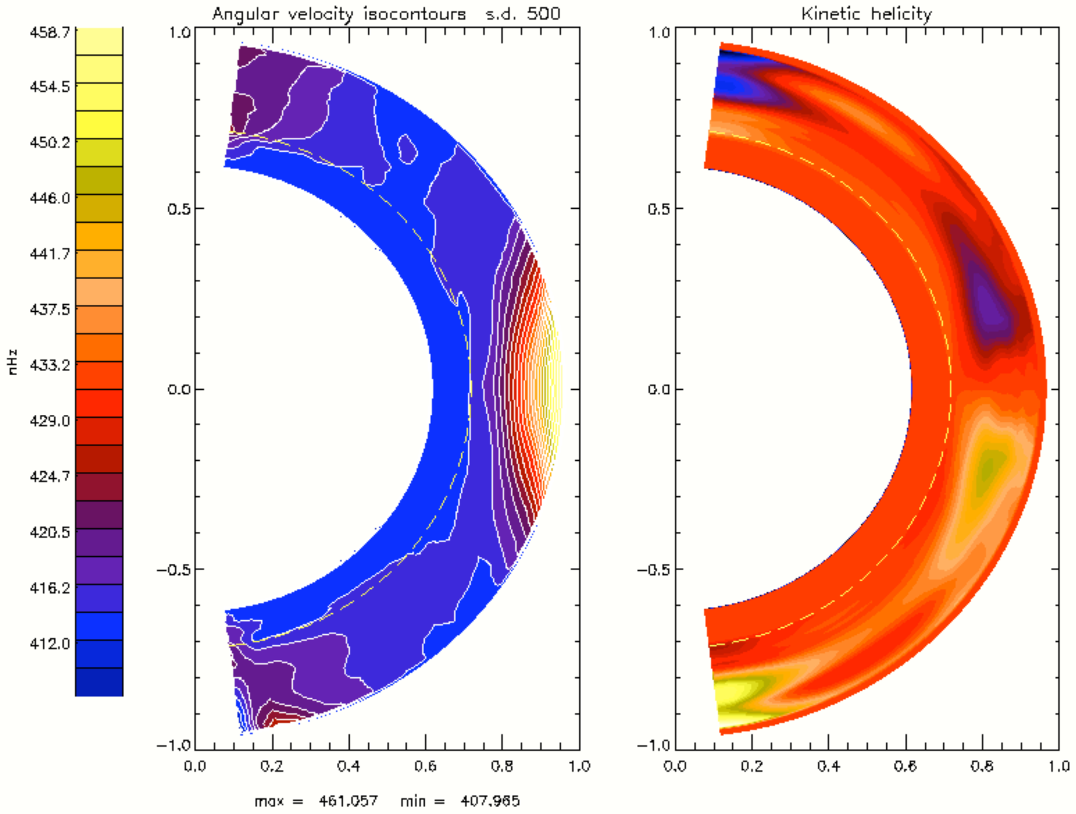
Differential rotation and kinetic helicity



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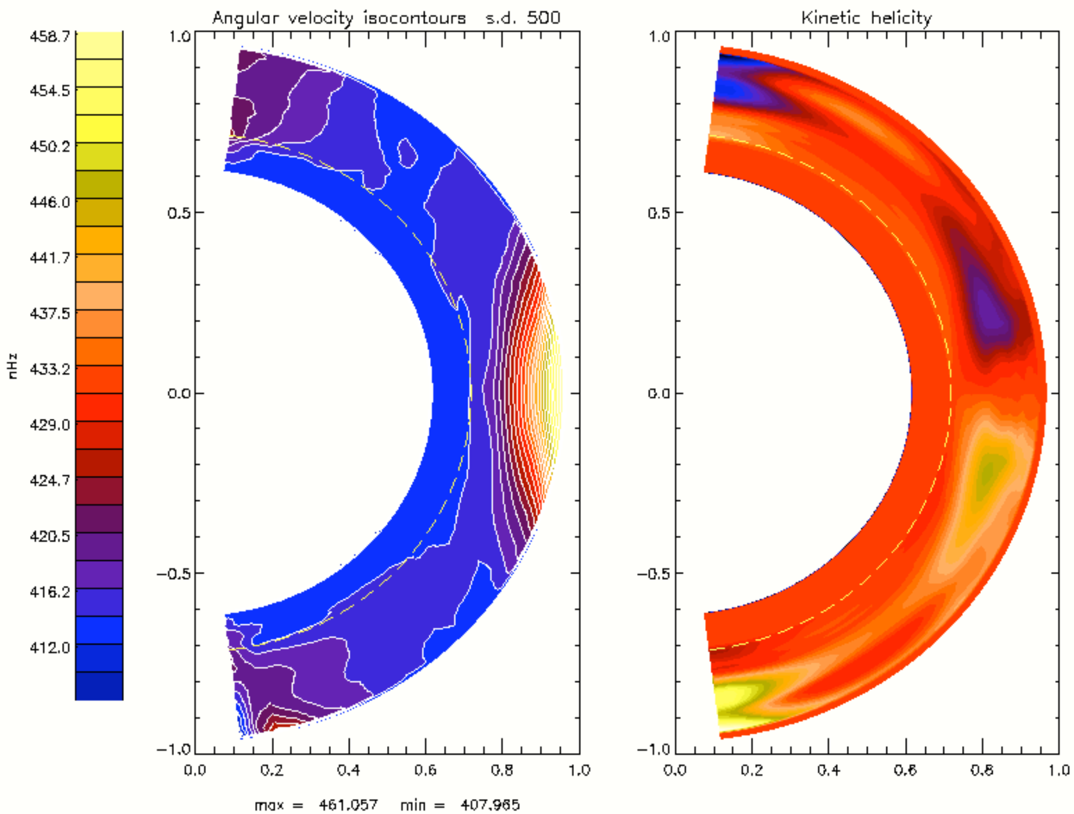

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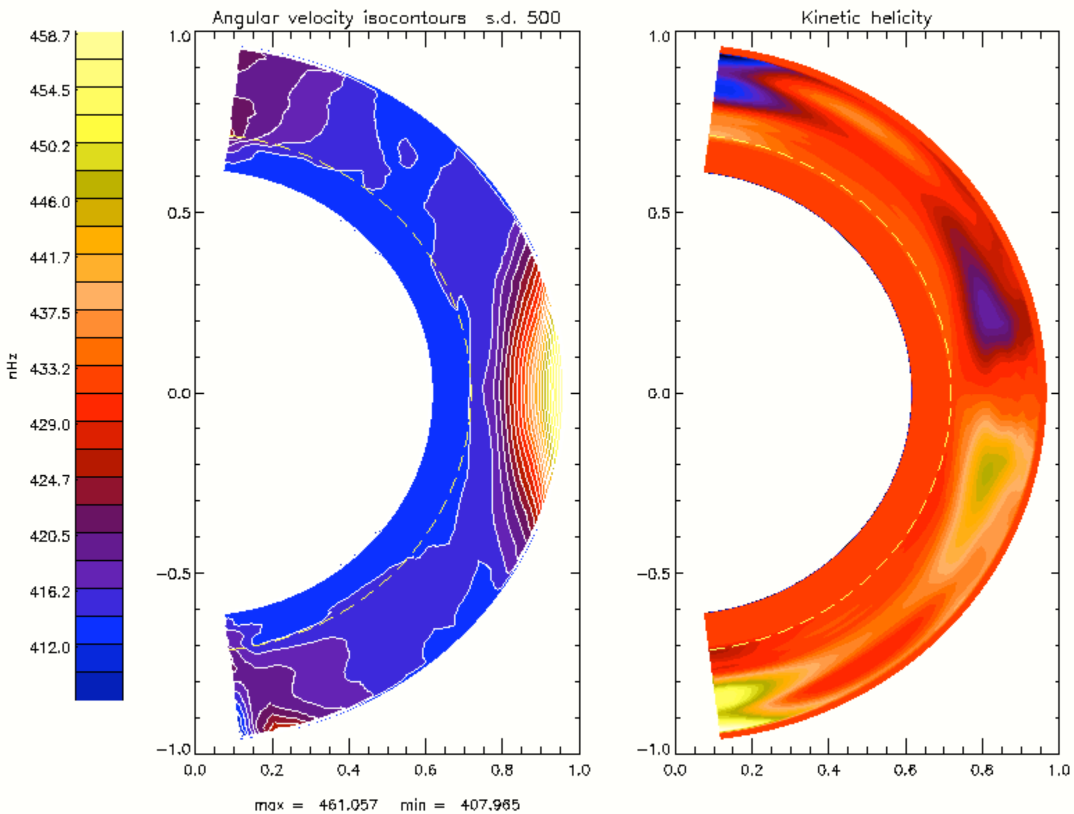

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Kinetic helicity is negative in bulk of N-hemisphere, as expected from action of Coriolis force.

The large-scale magnetic fields

Mollweide projection of toroidal magnetic component immediately beneath core-envelope interface

Field is very « turbulent », due to convective undershoot;

Fairly well-defined axisymmetric component, antisymmetric about equatorial plane;

Hemispherically synchronous polarity reversals on ~32 yr timescale.

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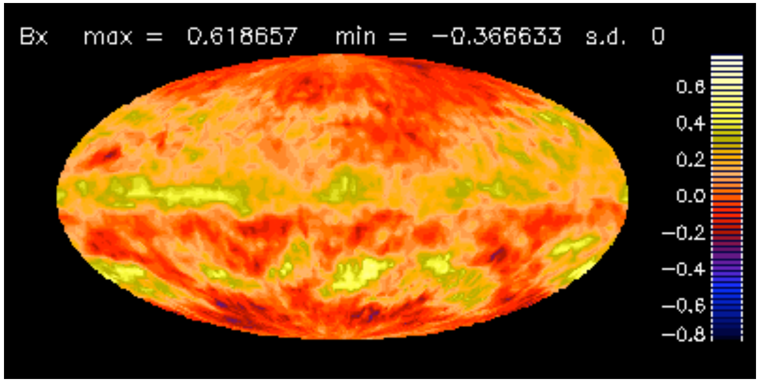

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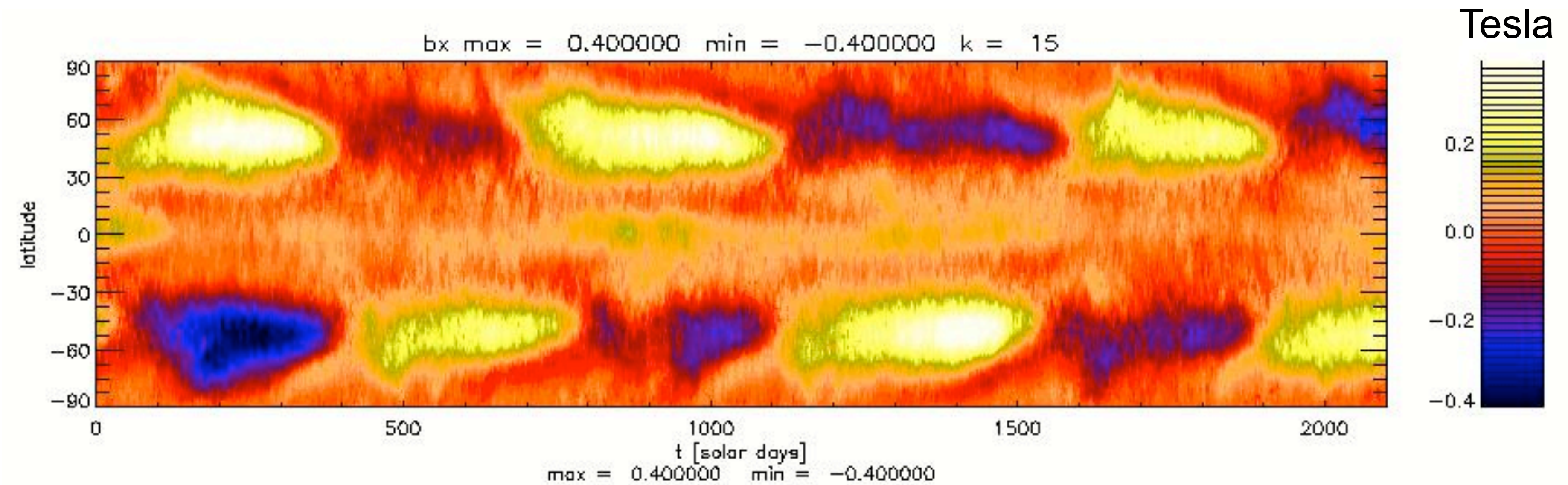
Magnetic cycles (1)

Time-latitude diagram of zonally-averaged toroidal Component at core-envelope interface (r/R=0.718)



IF flux rope formation is proportional to toroidal field strenths, and **IF** flux ropes rise radially through convective envelope, then this is the simulation's analog to the sunspot butterfly diagram

Magnetic cycles (2)

Surface radial magnetic field over
North and South polar caps

Magnetic field is very intermittent spatiotemporally

Nonetheless, there is a clear axisymmetric component on the larger spatial scales.

Pattern of polar cap B_r shows a very well-defined dipole moment, very well aligned with rotation axis.

Polarity reversals begin at mid-latitude and proceeds towards pole.

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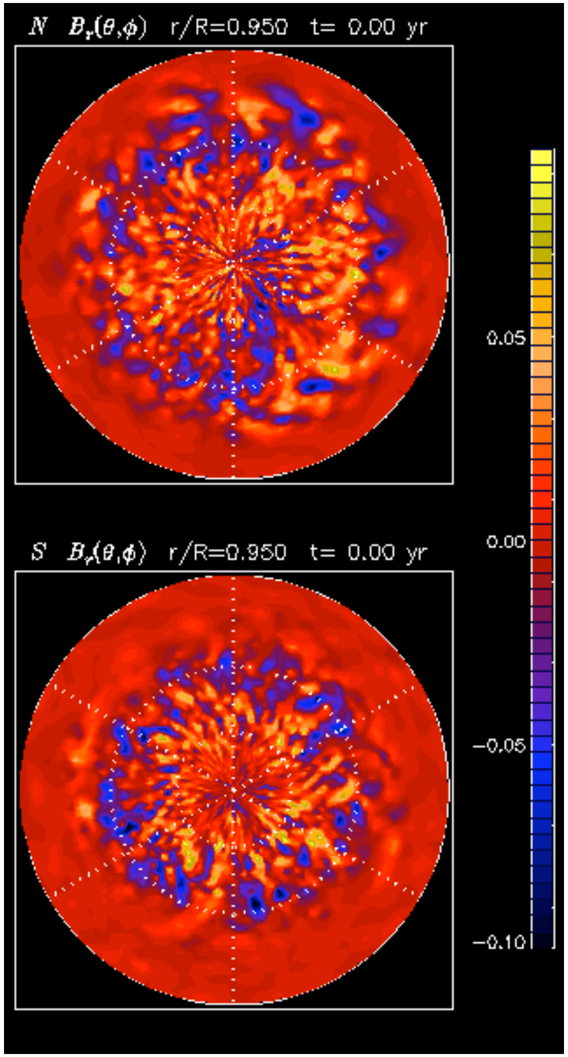

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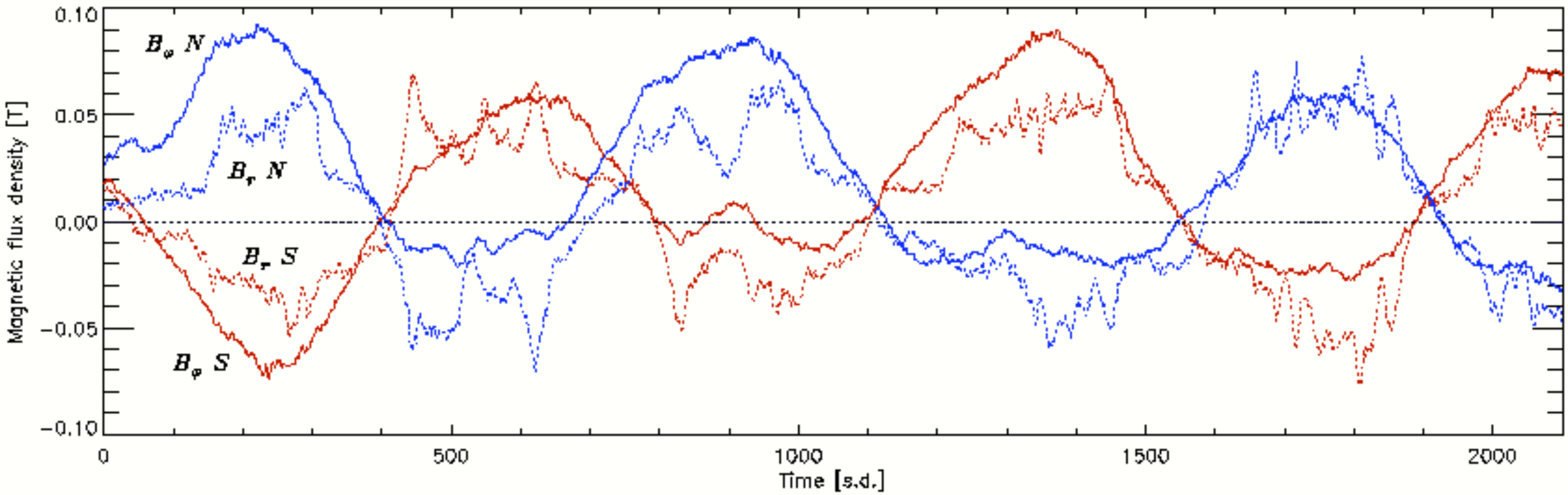
Magnetic cycles (3)

Polar cap magnetic flux (dotted lines), interface toroidal flux (solid lines)

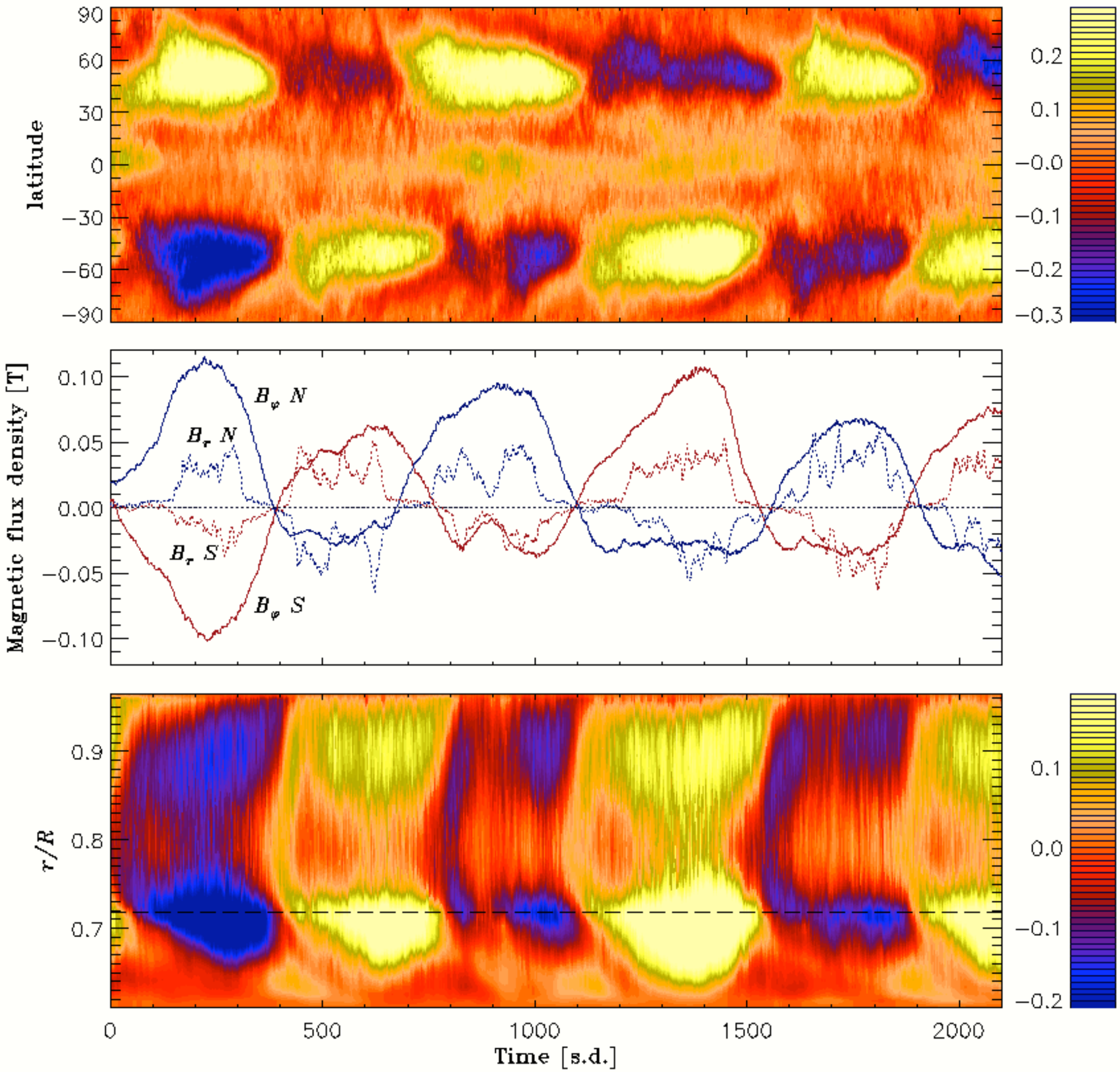


Good hemispheric synchrony, despite strong cycle-to-cycle fluctuations

Well-defined dipole moment, oscillating in phase with toroidal component

Cycle period is fairly regular, here ~32 yr instead of the solar 11

Magnetic cycles (4)



Cycle originates in bottom half of convective envelope;

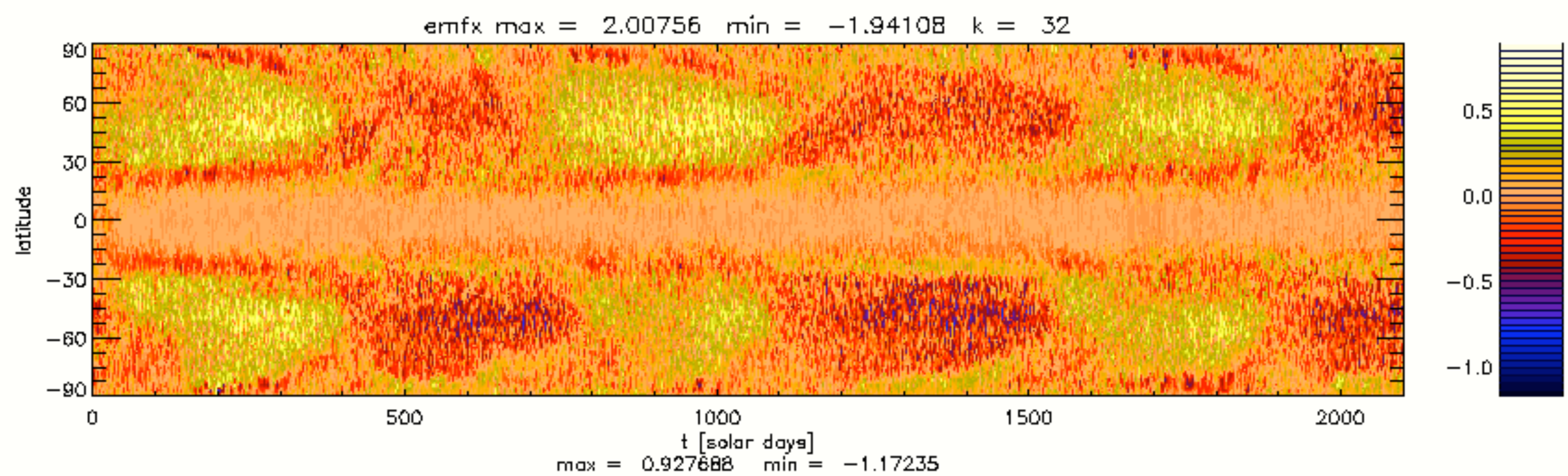
Turbulent pumping below interface, and further amplification by angular velocity shear.

Cycle pervades whole convective envelope.

Positive toroidal field in N-hemisphere breeds a positive dipole moment.

Mode of dynamo action
[Lead: Étienne Racine]

Time-latitude diagram of phi-component of the turbulent emf < **u**' x **b** '> at mid-depth in the convective envelope.



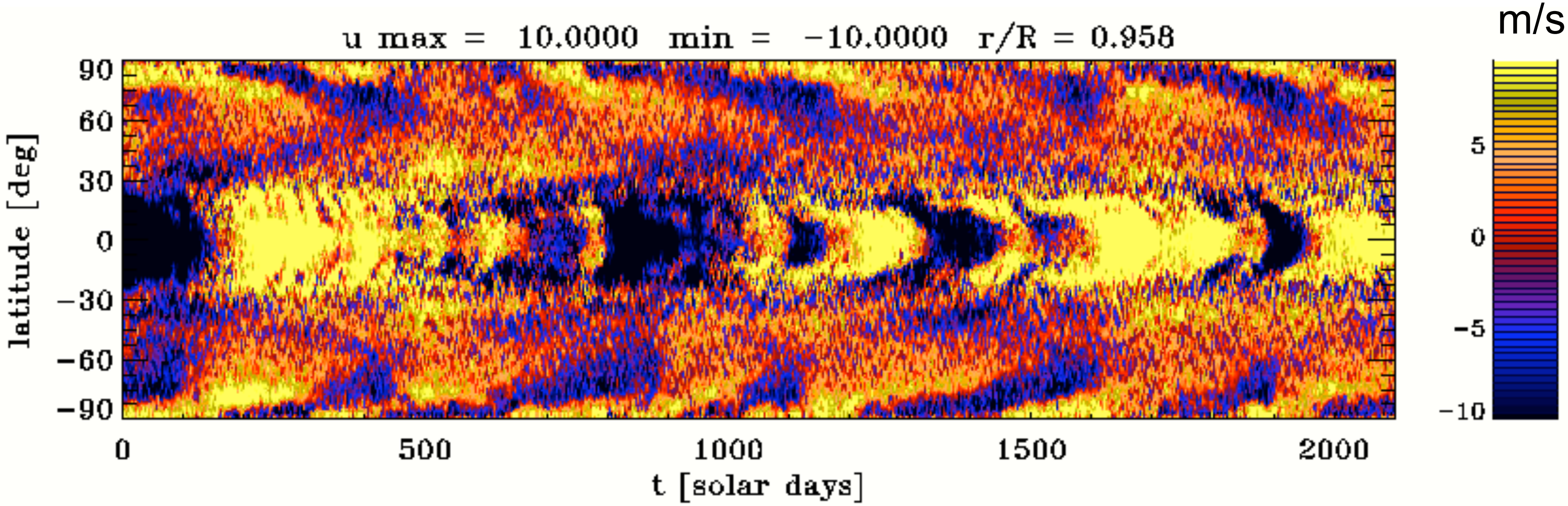
Turbulent emf has same sign in each hemisphere

Turbulent emf changes sign from one cycle to the next

This is consistent with the idea of a turbulent alpha-effect producing the observed dipole moment

Torsional oscillations

[Lead: Mihai Ghizaru]



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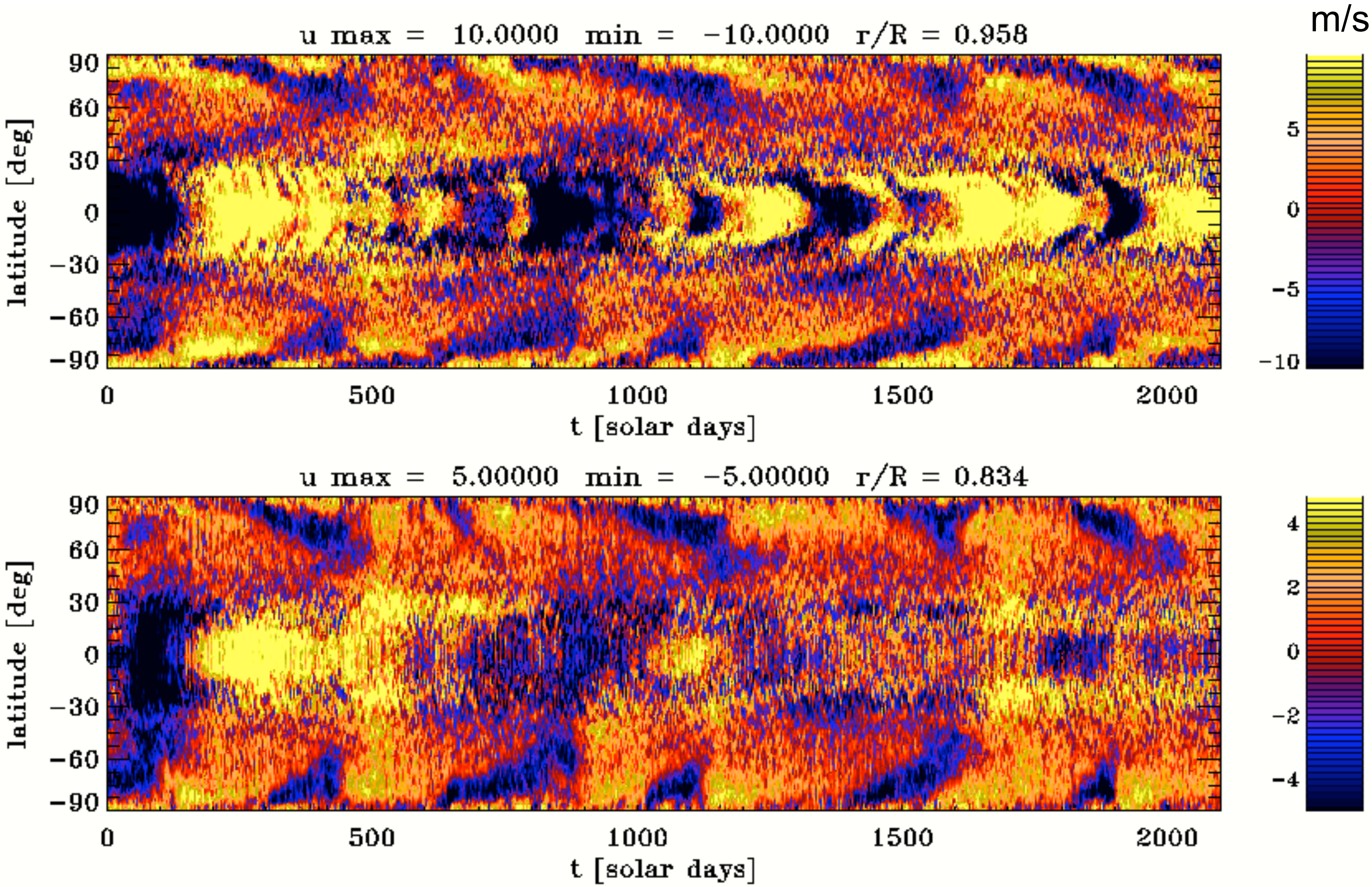

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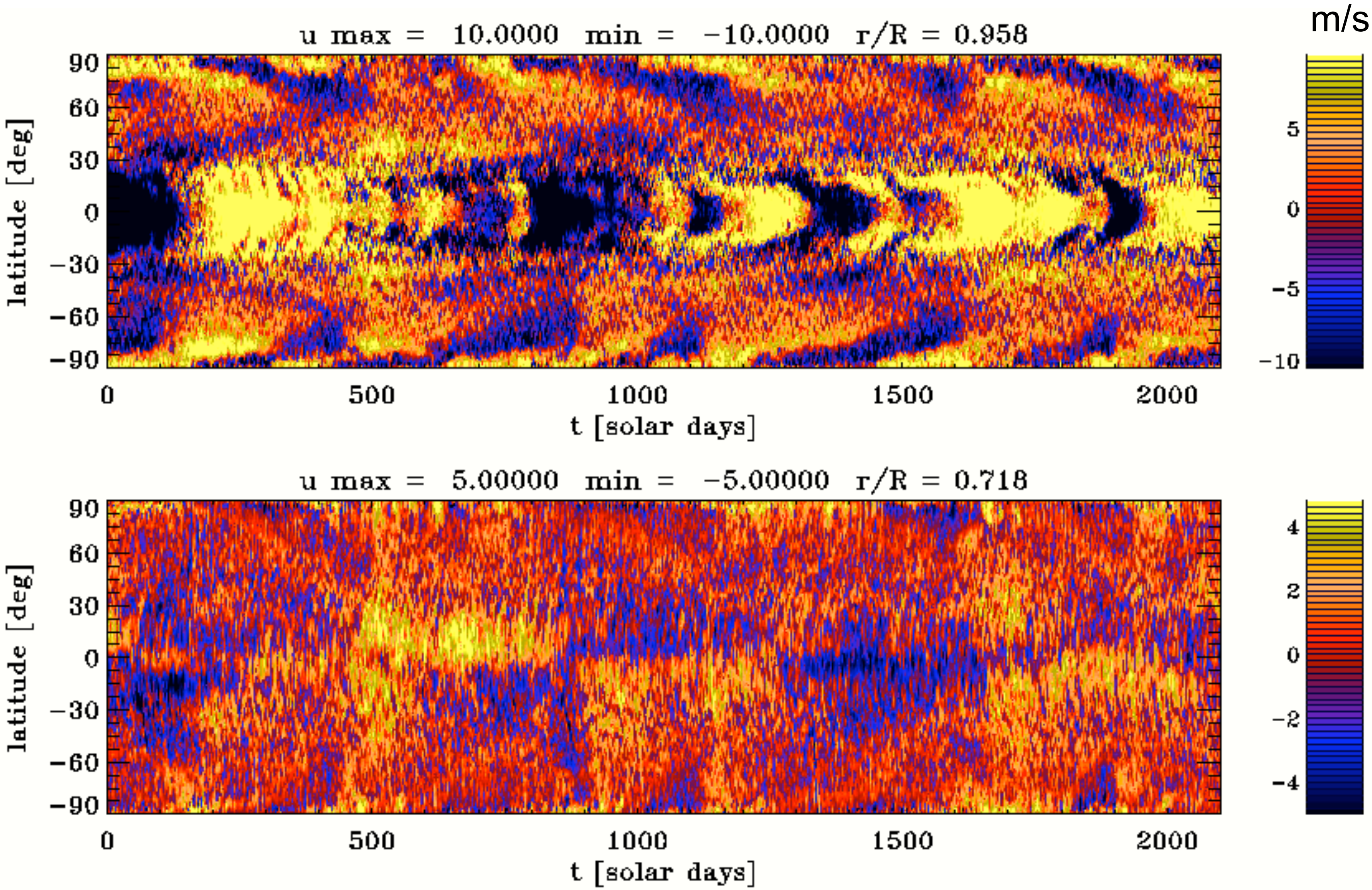
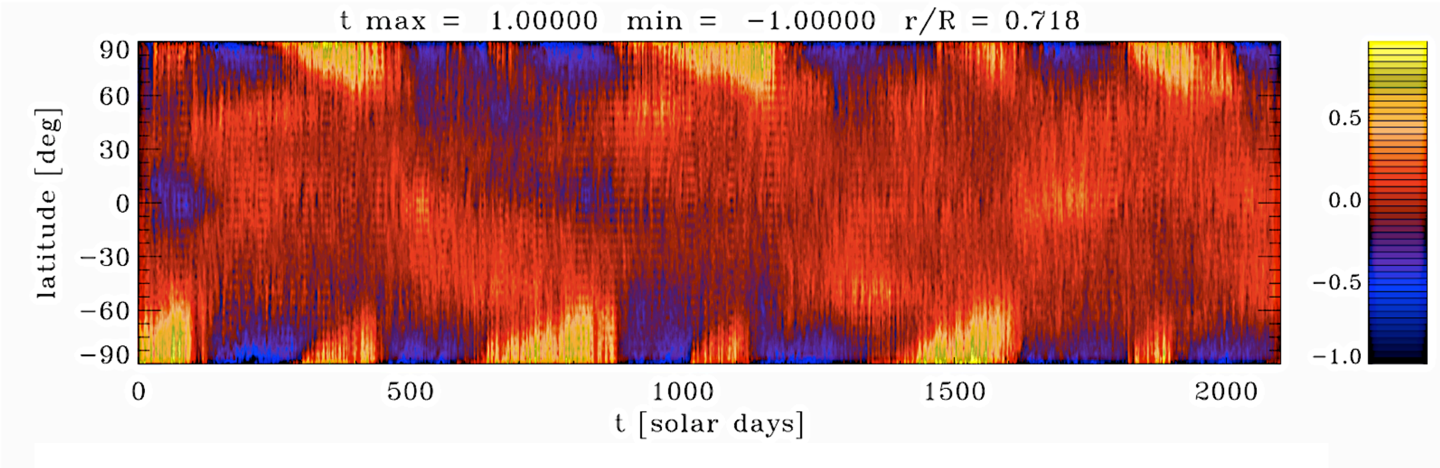
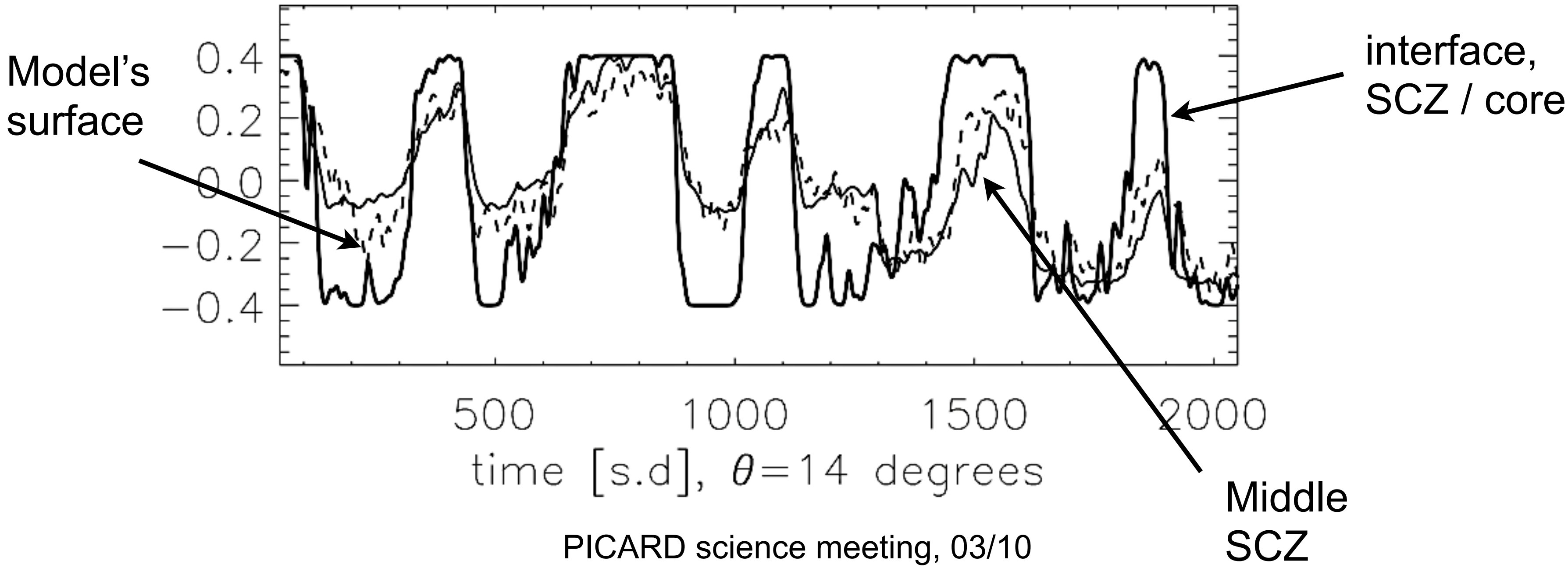


Modulation of convective energy transport
[Lead: Jean-François Cossette]





Conclusions (for now…)

We have a global turbulent MHD simulation of the solar convection zone that produces a large-scale magnetic component undergoing polarity reversals on decadal timecales; this is a first !!

In addition, these magnetic cycles show a number of solar-like features: equatorial migration of deep-seated toroidal component, well-defined rotationally-aligned dipole moment, torsional oscillations.

Based on analyses carried out to date, it appears that this large-scale dynamo operates as what as known as an alpha-Omega dynamo in mean-field electrodynamics.

We detect a weak but clear signature of the magnetic cycle in the convective transport of energy, all the way to the outer layers.

Future directions (1)

Currently extending existing runs and carrying out runs at higher spatial resolution;

Currently measuring components of the alpha-tensor, including antisymmetric components corresponding to turbulent pumping;

Currently trying to estimate effective diffusivities in the simulations; based on turbulent spectrum, Reynolds number is ~300-1200, depending on spatial resolution and manner of estimating energy injection scale.

Need to understand if rotational shear is primary source of toroidal magnetic component, or if turbulent emf also contributes significantly.

Need to understand what sets the length of the cycle period (sensitivity to parameter regime, forcing, etc.)

Need to understand why we get cycles, but the ASH group (Brun, Browning, Miesch, Toomre, etc…) by all appearances doesn't.

Future directions (2)

More specifically in relation to PICARD:

Need to understand the physical origin of observed cycle-mediated modulation of convective energy transport.

Need to build gray outer-envelope and atmosphere over the simulation in order to assess the impact of cyclic modulation of convective energy flux on limb profiles, latitudinal variations of radiative emissivity, etc.

Need to activate grid deformation in EULAG to try to model cycle-induced radius variations; requires very careful consideration of how outer boundary condition on outgoing energy flux is implemented.

Looking for additional postdoctoral (wo)manpower !!
(and money to pay them…)

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MAGNETIC CYCLES IN GLOBAL LARGE EDDY SIMULATIONS OF SOLAR CONVECTION

Mihai Ghizaru**, Paul Charbonneau*, Piotr K. Smolarkiewicz**
*Département de Physique, Université de Montréal,
C.P. 6128 Succ. Centre-ville, Montréal, Qc, H3C-3J7 CANADA
**National Center for Atmospheric Research, Boulder, CO 80307, USA
Draft version February 19, 2010

ABSTRACT

We report on a global magnetohydrodynamical simulation of the solar convection zone, which succeeds in generating a large-scale axisymmetric magnetic component, antisymmetric about the equatorial plane and undergoing regular polarity reversals on decadal timescales. We focus on a specific simulation run covering 175 yr, during which 5 polarity reversals are observed, with a mean period of 32 yr. Time-latitude slices of the zonally-averaged toroidal magnetic component at the base of the convecting envelope show a well-organized toroidal flux system building up in each solar hemisphere, peaking at mid-latitudes and migrating towards the equator in the course of each cycle, in remarkable agreement with inferences based on the sunspot butterfly diagram. The simulation also produces a large-scale dipole moment, varying in phase with the internal toroidal component, suggesting that the simulation may be operating as what is known in mean-field theory as an $\alpha\Omega$ dynamo.

Subject headings: Convection — MHD — Sun: magnetic fields — Sun: cycle

Preprint available at:
http://www.astro.umontreal.ca/~paulchar/eulag/apjlsubmit.pdf
For updates on simulation results, see GRPS Web Page:
http://www.astro.umontreal.ca/~paulchar/grps

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