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Dynamics of active region flux tubes in the solar convection zone

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Abstract. I review recent results on modeling the buoyant rise of active region scale flux tubes in the solar convective envelope based on both a thin flux tube model incorporating the effects of giant-cell convection as well as direct 3D spherical-shell anelastic MHD simulations. It is found that the dynamic evolution of the flux tube changes from magnetic buoyancy dominated to convection dominated as the initial field strength of the flux tube varies from about 100 kG to 15 kG. Mid-range field strengths of about 40 - 50 kG seem to produce emerging loops that best match the observed properties of solar active regions. The initial twist of the tube cannot be too high in order for the tilt of the emerging loops to be dominated by the effect of the Coriolis force and be consistent with the mean tilt of solar active regions. Future high resolution (low diffusivity) global-scale MHD simulations in a rotating, fully convecting spherical shell representative of the solar convective envelope are needed to self-consistently study the formation and dynamic rise of active region scale flux tubes in the solar convection zone.

Keywords : MHD – Sun: dynamo – Sun: interior

1. Introduction

Active regions on the solar surface are generally thought to originate from a strong toroidal magnetic field generated at the base of the solar convection zone by a deep-seated solar dynamo. Understanding the dynamic rise of active region flux from the base of the convection zone to the surface is therefore a crucial component for the study of the solar cycle dynamo. There has be a great deal of modeling effort to study the dynamic rise of active region scale flux tubes in the solar convective envelope, starting from the pioneering work based on the thin flux tube approximation in the

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80's (e.g. Spruit 1981; Moreno-Insertis 1986; Choudhuri & Gilman 1987). Several detailed reviews exist on this subject (see e.g. Fisher et al. 2000; Fan 2009). Here in this paper, I focus on discussing some of the recent results from 3D anelastic MHD simulations of rising flux tubes in a rotating spherical shell, both with and without convection, as well as the results from a recent thin flux tube model incorporating the effect of giant-cell convection and the associated mean flows computed separately from a global convection simulation. Modeling active region scale flux tubes in a 3D global-scale MHD simulation of the solar convective envelope is still very difficult because of the limited numerical resolution and the effect of numerical diffusion which can significantly impact the magnetic buoyancy. Thus these 3D simulations typically assume initially buoyant toroidal flux tubes with high initial field strengths ($\gtrsim 10^5$ G), such that the rise time is short compared to the diffusive time scale of the flux tube. On the other hand, the thin flux tube model takes the approach of following the Lagrangian evolution of individual tube segments, which preserves the magnetic frozen-in condition, and the 1D nature of the model is much less computationally demanding. Thus it can be applied to study toroidal flux tubes originating from the bottom of the solar convective envelope with a wide range of relevant initial field strengths, from 10^4 G to 10^5G, and initially in mechanical equilibrium, which is a more natural initial state than artificially prescribing an initial buoyancy distribution.

2. 3D spherical-shell anelastic MHD simulations

Fan (2008) has carried out a set of 3D anelastic MHD simulations of the buoyant rise of active region scale flux tubes in the solar interior in a rotating spherical shell geometry (see Figs 1 and 2). These simulations have considered twisted, buoyant toroidal flux tubes at the base of the solar convection zone with an initial field strength of 10^5 G, which is $\sim$ 10 times the field strength in equipartition with convection, and thus have neglected the effect of the convective flows. The main finding from these simulations is that the twist of the tube induces a tilt at the apex of the rising Ω-tube that is opposite to the direction of the observed mean tilt of solar active regions, if the sign of the twist follows the observed hemispheric preference (see Fig.1). It is found that in order for the tilt driven by the Coriolis force to dominate, such that the emerging Ω-tube shows a tilt consistent with Joy's law of active region mean tilt, the initial twist rate of the flux tube needs to be smaller than about a half of that required for the tube to rise cohesively. Under such conditions, the buoyant flux tube is found to undergo severe flux loss during its rise, with less than 50% of the initial flux remaining in the final Ω-tube that rises to the surface (see Fig.2a). Furthermore, it is found that the Coriolis force drives a retrograde flow along the apex portion of the emerging tube, resulting in a relatively greater stretching of the field lines and hence a stronger field strength in the leading leg of the tube (Fan, Fisher & DeLuca 1993; Fan 2008). With a greater field strength, the leading leg is more buoyant with a greater rise velocity, and remains more cohesive compared to the following leg (see Fig. 2c).

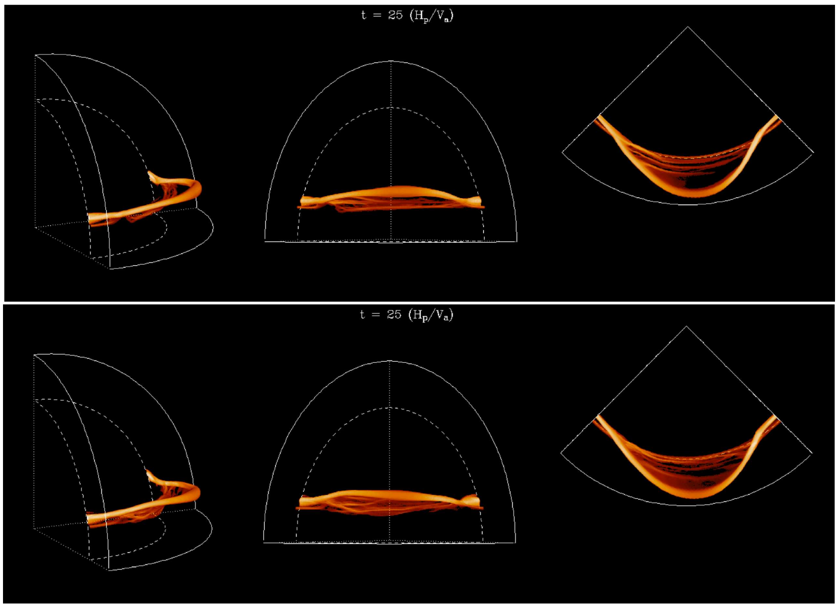

Figure 1. Top row: 3D volume rendering of the magnetic field of a final rising Ω-shaped tube as it approaches the top boundary, resulting from a simulation described in Fan (2008, see the NT run in that paper) where the initial buoyant flux tube has a left-handed initial twist. Bottom row: same as the top row except that the emerging tube results from a simulation where the sign of the initial twist is reversed (i.e. with a right-handed initial twist, see the PT run in Fan 2008).

Fan, Tian & Alexander (2009) further studied the consequence of such asymmetry in field strength and cohesion between the leading and following sides of the emerging tube in the simulation. It is found that field lines in the leading leg of the tube show more coherent values of local twist rate α, defined as $\alpha \equiv (\nabla \times \mathbf{B}) \cdot \mathbf{B}/B^2$, whereas the α values in the following leg show large fluctuations and are of mixed signs. On an average, however, the field lines in the leading leg do not show a systematically greater mean twist rate compared to the following. However, the higher rise velocity of the leading leg as well as the greater Alfvén speed in the leading tube due to the stronger magnetic field can result in a greater helicity injection rate into the corona from the interior through the leading polarity of an emerging active region. Such an asymmetry in helicity injection rate between the leading and the following polarities has been observed (Tian & Alexander 2009; Tian et al. 2011).

Jouve & Brun (2009) have carried out the first set of global anelastic MHD simulations of the buoyant rise of an initially toroidal flux ring in a rotating, fully convective spherical shell, possessing self-consistently generated mean flows such as meridional circulations and differential rotation representative of the conditions of the solar convective envelope, using the ASH (Anelastic Spherical Harmonics) code. Due to

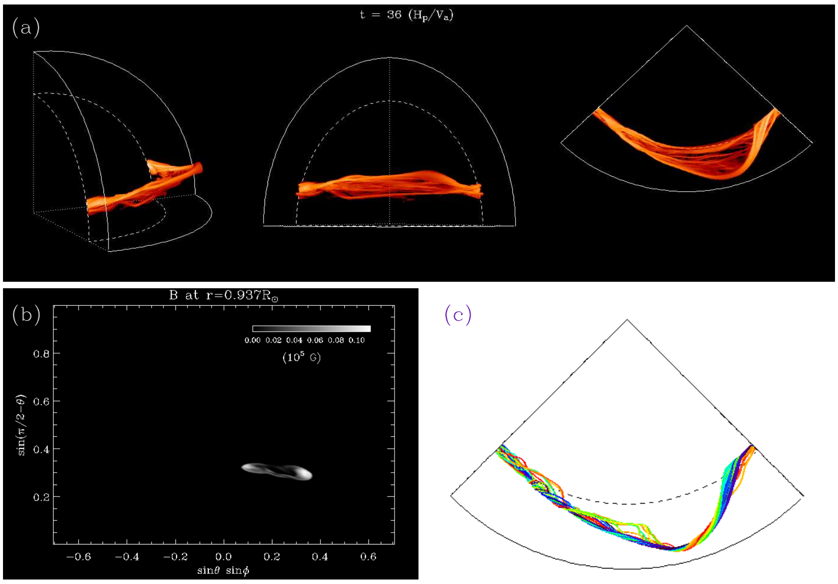

Figure 2. (a) 3D volume rendering of the magnetic field strength of a weakly twisted, rising Ω-tube whose apex is approaching the top boundary, resulting from a simulation described in (Fan 2008, see the LNT run in that paper); (b) A cross section of B near the top boundary at $r = 0.937R_{\odot}$, showing a tilt of the emerging tube that is consistent with the observed mean tilt of solar active regions; (c) Selected field lines threading through the coherent apex cross-section of the Ω-tube, where field lines in the leading leg are twisting about each other in a more coherent fashion, whereas the field lines in the following leg are fraying more severely. .

limited numerical resolution and relatively high magnetic diffusivity and viscosity in these simulations, they have considered initially buoyant flux tubes with a large initial field strength, ranging from 1.5×10^5 to 6×10^5 G, such that the rise time of the flux tubes are smaller than the diffusive time scale of about 14.5 days. So in most of the cases studied, the evolution is essentially in the magnetic buoyancy dominated regime, and as a result, the rising toroidal flux ring develops only moderate undulations by the influence of the convective flows, and the simulations recovered many of the findings obtained from previous simulations in the absence of convective flows. These include the dependence of poleward deflection of the flux tube on the initial field strength (e.g. Choudhuri & Gilman 1987), the critical dependence on the initial twist for the cohesion of the rising flux tubes (e.g. Emonet & Moreno-Insertis 1998; Abbett et al. 2000); and also the dependence of the tilt angle of the emerging tube on the sign of the twist (Fan 2008). It is also found that flux tubes introduced at lower latitudes (e.g. at 15°), have difficulty reaching the top of the domain (even with a strong field strength of 3×10^5 G), and the authors attributed the cause to the differential rotation. In the weakest field strength case, it is found that portions of the flux tube are pinned down by convection and eventually the tube loses its buoyancy and is unable to rise to the top. Clearly, simulations with reduced magnetic diffusion are needed to model the dynamic evolution of active region scale flux tubes in more realistic field strength regimes subjecting to the convective flows in the rotating solar convective envelope.

3. A thin flux tube model with giant-cell convection

As a first step towards this, Weber, Fan & Miesch (2011) have used the thin flux tube model, with the inclusion of a (separately computed) 3D turbulent convective velocity field in a rotating model solar convective envelope, to study its effects via the aerodynamic drag force, together with the forces of magnetic buoyancy, tension, and the Coriolis force, on the dynamic evolution of the emerging Ω-loops. They have performed these thin flux tube simulations for a range of initial toroidal magnetic fields (15 kG to 100 kG) from near-equipartition to super-equipartition initial field strengths at varying initial latitudes from 1° to 40° in both the northern and southern hemispheres. The initial toroidal flux rings are placed just above the base of the convective envelope, initially in mechanical equilibrium. The external time-dependent convective velocity field that the flux tube is subject to, shows giant-cell convection under the influence of solar rotation (see Fig. 3). Throughout most of the convection zone, except near the bottom, the convection has a mean kinetic helicity that is negative in the northern hemisphere and positive in the southern hemisphere. The mean zonal flow shows a solar like differential rotation profile.

It is found that the development and the evolution of the rising Ω-loops change from convection dominated to magnetic buoyancy dominated as the initial field strength of the tube varies from 15 kG to 100 kG (see Fig. 4). At 100 kG, the development of Ω-shaped rising loops are mainly controlled by the growth of the magnetic buoyancy instability, with only the strongest convective downdrafts producing some moderate perturbations to the final emerging loops. The mean properties of the final emerging loops are in agreement with previous thin flux tube models in the absence of convection. On the other hand, at a low field strength of 15 kG, the development of the emerging flux loops is largely controlled by the convective flows. Both the average up-flows and down-flows can significantly affect the rise of the flux tube. The properties of the emerging loops are significantly changed compared to the previous results in the absence of convection. With convection, the rise times are drastically reduced for the weak field strength cases (from years to a couple of months for 15kG cases). The previous issue of 15 kG - 30 kG flux tubes being significantly deflected poleward by the Coriolis force during their rise is resolved: loops can emerge at low latitudes all the way to the equator. The main reasons for this are the anchoring of the emerging flux loops by the convective downdrafts and also the faster rise of the loops propelled by the up-flows.

Using thin flux tube simulations in the absence of convection, D'Silva & Choudhuri (1993) were the first to show that active region tilts as described by Joy's law can be explained by the Coriolis force acting on the rising flux loops and that the best agreement with observations is obtained for flux tubes with an initial field strength

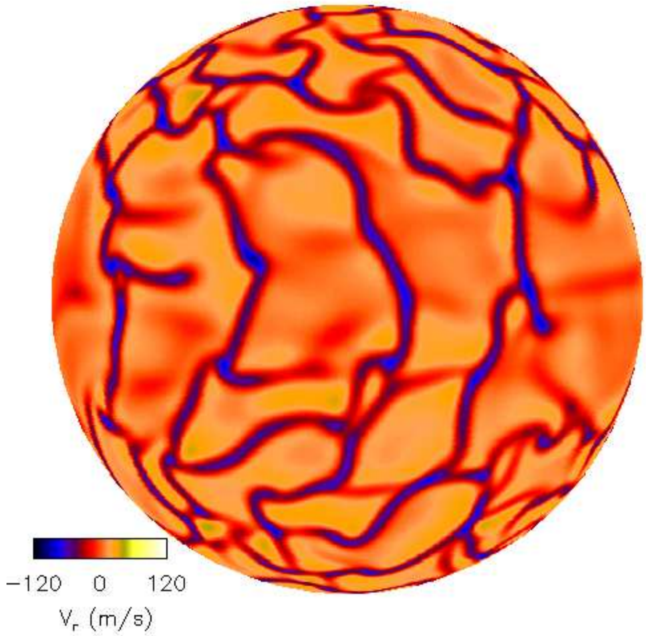

Figure 3. From Weber, Fan & Miesch (2011). A snapshot of the radial velocity of the giant-cell convective flow field (used for the thin flux tube simulations) at a depth of 25 Mm below the solar surface.

of about 100 kG at the base of the solar convection zone. With the inclusion of convection, the simulations of Weber, Fan & Miesch (2011) found that convection produces random scatters in the tilts of the emerging loops, especially for the weaker field strength cases where the scatters are greater (see Fig. 5). Furthermore, because the convective flow in the rotating spherical envelope possesses a mean kinetic helicity that is negative (positive) in the northern (southern) hemisphere, it on an average tends to drive clockwise (anti-clockwise) tilts for the rising loops in the northern (southern) hemisphere, consistent with the sign of the active region mean tilt. As a result, the inclusion of convection increases the slope of the linear Joy's Law fit of the tilt angles of the emerging loops as a function of emerging latitudes (see Fig. 4). It is found that flux tubes with initial field $\gtrsim$ 40 kG and $\lesssim$ 100 kG produce a mean tilt angle dependence on latitude that is consistent with the observed Joy's Law (see Fig. 4). At weaker field strengths (below 40 kG), it is found that the random scatters produced by the convection dominate the tilts, and they do not show a significant systematic dependence on latitude as described by Joy's law. More thin flux tube simulations with the flux tube subjecting to independent time spans of the convective flows are needed to improve the statistics in these weak field cases to see if a Joy's law like dependence emerges.

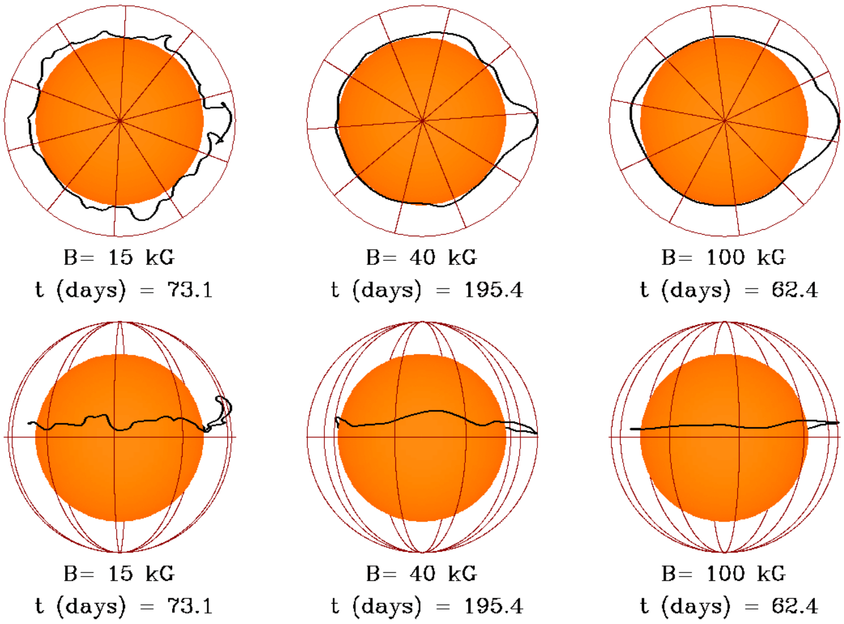

Figure 4. From Weber, Fan & Miesch (2011). Polar (top row) and equatorial (bottom row) views of the final rising flux tube, developed from an initial toroidal flux ring at a latitude of 6°, at a time when its apex is approaching the top boundary, with an initial magnetic field strength of 15 kG, 40 kG, and 100 kG respectively, subjected to the external time dependent convective flow field.

Previous thin flux tube simulations in the absence of convection have found other asymmetries of the emerging loop that arise due to the effect of the Coriolis force. One is the field strength asymmetry with the leading side of the emerging loop having a stronger field strength than the following side due to the differential stretching of the loop by the Coriolis force (e.g. Fan, Fisher & DeLuca 1993; Fan 2008) as discussed in the previous section. This provides an explanation for the observed more coherent and less fragmented morphology for the leading polarity of an active region (e.g. Bray & Loughhead 1979). However, Caligari, Moreno-Insertis & Schussler (1995) and Caligari, Schussler & Moreno-Insertis (1998) found that this asymmetry depends on the initial condition of the toroidal flux tube. For toroidal flux tubes initially in mechanical equilibrium, the emerging loop that develops has a stronger field strength in the leading side only if the initial field strength of the toroidal tube is below 60 kG. For flux tubes with higher initial field strengths, the field strength asymmetry reverses at the top of the emerging loop. Similar results are found from thin flux tube simulations with the inclusion of the convective flow (Weber, Fan & Miesch 2011): loops with initial field strengths $\leq$ 50 kG tend to emerge with a stronger field strength in the leading leg. Caligari, Moreno-Insertis & Schussler (1995) have also found a geometric asymmetry of the emerging loop where the leading side of the apex of the loop

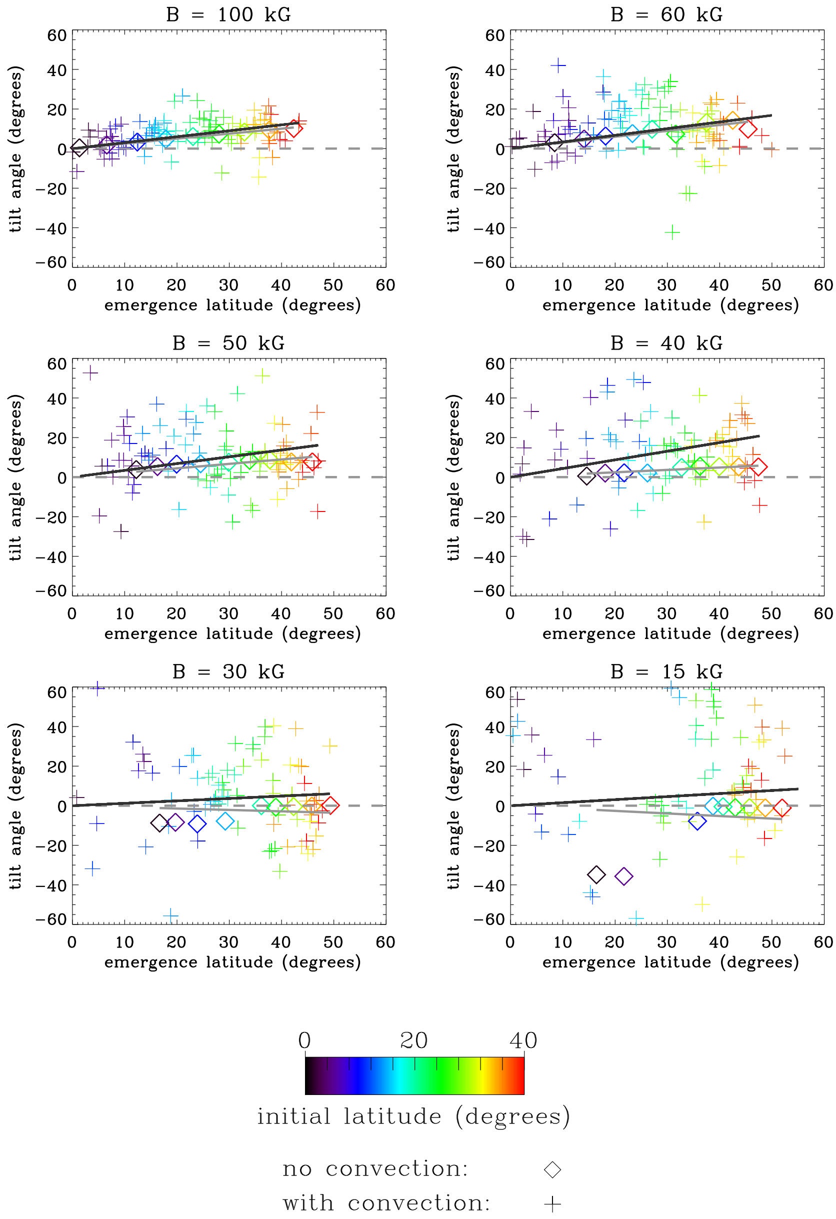

Figure 5. From Weber, Fan & Miesch (2011). Tilt angle as a function of emergence latitude for initial magnetic field strengths of 100 kG, 60 kG, 50 kG, 40 kG, 30 kG, and 15 kG respectively, and for cases with (plus signs) and without (diamond points) the influence of convection. The gray line is the least squares fit for flux tubes in the absence of convection. The black line is the fit to the cases subjected to the convective flow.

tends to incline more horizontally than the following side. The emergence of such an asymmetric loop may provide an explanation for the observed apparent asymmetric east-west proper motions of the two polarities of am emerging active region (e.g. Moreno-Insertis et al. 1994; Caligari, Moreno-Insertis & Schussler 1995; Caligari, Schussler & Moreno-Insertis 1998). With convection, it is found that for all field strengths, the majority of the emerging loops still develop a more shallow inclination on the leading side of the apex of the loop than the following side, although the inclination angle differences are overall reduced with the inclusion of convection (Weber, Fan & Miesch 2011).

Taking the above results together, the thin flux tube model suggests that mid-range field strength of ∼ 40 - 50 kG produces emerging loops that best match the observed properties of solar active regions.

4. Discussions

Initial results from a thin flux tube model incorporating the effect of solar-like giant-cell convection suggest that solar convection may play an important role in defining the properties of emerging flux tubes responsible for the formation of solar active regions. Overall, the effect of the convective flow is found to allow mid to weak field strength range flux tubes (∼ 15 kG - 50 kG) to develop emerging loops with properties that are more consistent with the observed properties of solar active regions. For these flux tubes, the convective flow is found to reduce the rise time, reduce the latitude of emergence through anchoring by downdrafts, and promote tilt angles that are consistent with the observed mean tilt of solar active regions because of the mean kinetic helicity in the flow. As a result, weaker fields can reproduce Joy's law. So far the simulations show that mid-range field strength of ∼ 40 - 50 kG produces emerging loops that best match the observed properties of solar active regions. More simulations that sample independent time spans of the convective flows may improve the statistics for the even weaker field strength cases (< 40 kG), and see whether a Joy's law like dependence for the tilt angles as a function of emerging latitudes exists for these field strengths. Recent solar cycle dynamo models which take into account the dynamic effects of the Lorentz force from the large-scale mean fields have suggested that the toroidal magnetic field generated at the base of the solar convection zone is ∼ 15 kG, and most likely cannot exceed 30 kG (Rempel 2006a,b). Thus it is important to understand whether toroidal flux tubes at these field strengths can produce emerging loops that are consistent with the observed properties of solar active regions under the influence of convection.

The main limitation of the thin flux tube approach is that the model assumes the tube remains cohesive, and does not address the dynamic effect of the twist of the flux tube. 3D spherical shell simulations of the buoyant rise of twisted flux tubes have shown that the twist of the tube cannot be too high in order for the tilt of the emerging loop to be dominated by the effect of the Coriolis force so as to be consistent with the mean tilt angles of solar active regions (Fan 2008). Furthermore, it has been suggested that a significant twist of the tube may no longer be required to obtain reasonably cohesive emerging tubes. This is because the generation of strong vortex tubes by magnetic buoyancy is suppressed due to the anchoring of the flux tube at short intervals by the convective downdrafts, for weak field strength flux tubes in the convection dominated regime (Fan, Abbett & Fisher 2003). All these possibilities need to be examined self-consistently by high resolution (low diffusivity) 3D spherical-shell simulations of rising flux tubes in a rotating, fully convecting spherical shell representative of the solar convective envelope.

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