Convection and Irradiance Variations

By PETER A. FOX[1] AND SABATINO SOFIA[2]

[1]High Altitude Observatory, National Center for Atmospheric Research, Boulder CO 80307, USA

[2] Center for Solar and Space Research, Yale University New Haven, CT 06511, USA

In the outer layers of the Sun ($\approx 30\%$ by radius), energy is transported by convection. The nature of the highly stratified and compressible convective flow is determined from the components of the energy flux (internal, kinetic, viscous, magnetic and radiative). Local suppressions or enhancements of any of these components may give rise to measurable changes in the emergent radiation.

On the solar surface there is direct evidence for modulation of the emerging heat flux covering a large range in spatial and temporal scales, particularly associated with concentrated magnetic fields (e.g. sunspots, plages). Associated with these surface features is the observation that the characteristics of convective motions are also modified. In the deeper layers, the interaction of convection and magnetic fields will play an important role in readjusting the local emerging heat flux and thus should contribute to the modulation of the total solar irradiance.

The task of calculating the response of the convection zone structure to developing active regions, and the solar activity cycle in general is difficult and complex due to the highly non-linear nature of the interaction of convection and magnetic fields. Theoretical work has ranged from empirical and global structure models, all the way to fine scale compressible convection simulations. This paper will highlight some recent theoretical advances that may have a direct bearing on the understanding of solar luminosity and irradiance variations and outline the important problems that must be addressed and what observational constraints may be used.

1. Introduction

When the Sun is viewed in terms of its main sequence evolution (timescales on the order of billions of years), processes in the convective envelope zone can be viewed as instantaneous. However, if the timescale of interest is reduced to centuries or decades, many of the physical processes become distinct and exhibit their own characteristic time variation. Examples of these timescales are those of radiative relaxation, thermal diffusion, convective turnover, and hydrostatic readjustment. The study of solar variability amounts to determining the response of the solar convection zone to disturbances. In general the resulting variability depends on the location, size, strength, and nature of the perturbation.

To date, the primary solar variability that is observed and can be largely explained, is that associated with short term surface modulations, (sunspots, faculae, and most likely the magnetic network) which have timescales ranging from hours to days, to months. The next established timescale is that of the solar cycle (decadal) variation of the solar irradiance (from Nimbus 7 and ACRIM I/II, for example). Nevertheless a complete theoretical explanation for the measurements is still lacking. Beyond these observed timescales, there is an inferred secular variation (on the order of centuries, or longer) which arises from statistical studies of global solar and geophysical parameters. It is reasonable to assume that these changes are associated with long term internal modulation of the solar heat flux, and thus the convective energy transport.

Convection is also likely to play a role in the conversion between the solar luminosity

https://doi.org/10.1017/S0252921100024787 Published online by Cambridge University Press

and irradiance; which involves a knowledge of the radiance of solar surface structures (sunspots, plage, etc). These issues will not be addressed in this paper.

As added motivation, there now exists increasing observational evidence for changes in convective energy transport within the Sun. In regions of enhanced magnetic field there is a noticeable change in both the surface pattern and the lifetime of granulation which is the dominant energy carrying scale in the surface layers. More quantitatively, the changes in solar absorption line bisectors both over the solar cycle and in/out of plage (Livingston 1990), gives some measure of the change in the convective flows. Even though these observations relate only to the surface layers, it seems reasonable to assume that convection motions in the deeper interior are also affected by concentrations of magnetic flux. More global variations in the convective heat transport are suggested by observations of limb temperature excesses (Kuhn 1989) whose location varies with the solar cycle.

An even more abrupt change in the Sun has been observed to occur around 2–3 years after solar cycle maximum (McIntosh 1994; White 1994), where all proxies of solar activity suddenly decrease and do not return to the previously high levels. Accompanying this effect in the most recent cycle (January 1992), is the tantalizing hint that a thermal shadow effect may be present in the ERBS irradiance measurements (corrected for sunspots) exactly at this time (White 1994). An observational limit for ground–based photometry of shadows, or bright rings localized around active regions is 0.1 to 0.3% (Fowler *et al.* 1983), whereas the irradiance measure is weighted across the solar disk. If confirmed, or established, this implies a submergence of active regions on a large scale, and thus a modification of the solar luminosity. To date all observational support for changes in the convective nature of the Sun is limited to timescales up to decades.

Even though this paper will only focus on recent advances in convection theory there is an existing body of numerical work on global solar perturbations (see Endal *et al.* 1985) in the solar convection zone which provides a strong incentive to advance our understanding of convective energy transport.

2. Convective energy transport

2.1. *Equations*

The basic equations which govern magnetized convective energy transport in a star like the Sun can be written:

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot \mathbf{M}, \quad \frac{\partial \mathbf{M}}{\partial t} = -\nabla \cdot \mathbf{P} + \rho \mathbf{g}, \quad \frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E}, \quad \frac{\partial \varepsilon}{\partial t} = -\nabla \cdot \mathbf{F}_{\text{total}},$$

where ρ is the density, ε is the total energy $\mathbf{M}$ is the momentum vector, $\mathbf{P}$ is the momentum flux tensor, $\mathbf{g}$ represents the gravitational field, $\mathbf{F}_{\text{total}}$ is the total heat flux vector, $\mathbf{B}$ is the magnetic field, and $\mathbf{E}$ is the electric field. The ancillary relations, such as the equation of state of the gas, the Ohm's law, etc., are not relevant to the following discussion, and rotational effects have been neglected at present although are certainly important over longer timescales.

Consider a particular layer in the Sun where the incident heat flux is uniform in the statistical sense, i.e. time averaged (in reality the boundary between the convection zone and radiation zone is unlikely to have uniform flux at a given instant). In the absence of any perturbations, that incident heat flux will be propagated through the convective layer until it reaches the surface. In doing so, it will be distributed according to the following components of the heat flux:

$$\mathbf{F}_{\text{total}} = \mathbf{F}_{\text{ep}} + \mathbf{F}_{\text{ke}} + \mathbf{F}_{\text{rad}} + \mathbf{F}_{\text{B}} + \mathbf{F}_{\text{visc}} + \mathbf{F}_{\text{turb}}, \tag{2.1}$$

https://doi.org/10.1017/S0252921100024787 Published online by Cambridge University Press

which are the enthalpy flux, kinetic energy flux, radiative flux, Poynting flux, viscous flux and the turbulent flux, respectively. One of the problems then, is to determine how convection redistributes the emerging solar heat flux in response to magnetic (or other) variations, and over what timescale. Another key question is to determine the role of horizontal fluxes of energy which are not usually considered in mean structure models.

2.2. *Standard stellar structure*

Models of the spherically symmetric solar structure utilize an expression for the total heat flux to determine the radial thermodynamic profiles, and thus the effective temperature (luminosity). For example in Mixing Length Theory (MLT; Vitense 1953), the expression is $F_{\rm total} = F_{\rm conv} + F_{\rm rad}$, and radiation is modeled with the diffusion approximation. MLT provides an expression for $F_{\rm conv}$ in terms of local quantities and a number of adjustable parameters which are usually all expressed in terms of the mixing length to pressure scale height ratio, α. The primary drawback with this free parameter (which, to first order, is selected so that the model has the correct solar radius) becomes apparent when studying solar variability, i.e. relative changes in radius and luminosity.

An essential ingredient of solar structure models is that the physics be as realistic as possible, i.e equation of state, opacity, chemical composition, atmosphere model, etc. In any case, for the purpose of study solar variability, these models are viewed as instantaneous representations of the state of the convection zone of a star. When timescale of the internal changes become comparable to the characteristic times for convection, the assumption of instant adjustments needs to be examined carefully.

2.3. *Numerical simulations*

A long standing concern for simplified models of convective energy transport is how well they would capture the features of time dependent, three dimensional motions that actually take place within a star such as the Sun (the only star whose surface motions we can observe in detail, and whose structure we can reliably probe with helioseismology). Because of the highly turbulent nature of the solar convection zone, numerical simulations are not expected to accurately represent the real Sun either, however they do give a guide to the features that must be present and what the essential physics is. In this section we will highlight some recent results of numerical simulations that have a direct bearing on understanding solar variability.

Since the physical conditions in the solar convection zone vary considerably throughout the zone (that of a highly compressible and stratified gas, with the effects of partial ionization and radiation, etc.), numerical simulations/experiments have focused primarily on three distinct regions: the shallow layers – which are highly superadiabatic (with a radiative layer on top), the deeper layers – which are marginally superadiabatic or adiabatic, and the lower convection zone–radiation zone interface (also known as the overshoot region).

2.3.1. *Topology*

One of the very important results of turbulent compressible convection calculations is that the topology of the flow is quite unlike the cellular patterns reminiscent of Benard-type convection. The upflows are broad and extend over a scale height or two, whereas the downflow regions are narrow and often extend over multiple scale heights (Chan & Sofia 1986; Chan & Sofia 1989; Stein & Nordlund 1989; Cattaneo *et al.* 1991) with velocities comparable to the local sound speed.

These results strongly suggest that the energy carrying vertical scale of convection is that on the order of a pressure scale height whereas the surface horizontal scale naturally divides itself into granular, mesogranular and supergranular domains.

In addition to these general features, Chan & Sofia (1989) found that the vertical velocity autocorrelation function (whose FWHM is a measure of the so-called mixing length) scaled with the local pressure scale height and not the density scale height in agreement with standard MLT models. They also found that the mean vertical velocity, $\bar{v}$, was non-zero over most of the layer, in contrast with the MLT assumption.

2.3.2. *Energy fluxes*

Another extremely important result arises from studying the horizontally averaged energy flux components (in eq. (2.1)). The work of Chan & Sofia (1989; Figure 13) and Cattaneo *et al.* (1991) indicates the dominance of enthalpy and kinetic energy fluxes and the very minor role played by diffusive/turbulent fluxes. This result has also been confirmed by many authors and is now regarded as a robust feature of these flows.

Further, Chan & Sofia (1989) found that, although the creation can be described in terms of local quantities, the dissipation of kinetic energy flux is a non-local process.

2.3.3. *The role of downflows*

In the analysis of mean structure models of convection, the horizontal averaging provides the net fluxes. Since there is a marked asymmetry between upflows and downflows, an important question arises: can mean structure models be constructed with a net flux (i.e. one component) or should they allow for two streams (one upflow and one downflow component)? Alternately stated: how well does the horizontal averaging capture the high spatial variation in the convective patterns?

Cattaneo *et al.* (1991) examined the difference between energy fluxes in regions of upflow and downflow for both laminar and turbulent regimes (as measured by the Rayleigh number). They found that in the downflows, in the case of turbulent flows, the enthalpy and kinetic energy fluxes nearly balanced giving a net zero flux. This very striking result was not true for laminar flows where the enthalpy flux dominated. Thus, the overall role of intense downdrafts may be less important in the overall heat transport.

2.4. *Improved structure models*

An obvious question which arises from the analysis of numerical simulations is: do the mean properties of the simulations (as presented in Chan & Sofia (1989), for example) allow one to construct a (one dimensional) model of the Sun? This question has recently been addressed in a series of papers by Lydon *et al.* (1992, 1993a, 1993b) by using an expression for the total heat flux, $F_{\mathrm{total}} = F_{\mathrm{ep}} + F_{\mathrm{ke}} + F_{\mathrm{rad}}$, which includes the kinetic energy flux. Furthermore, the formulation does not include the adjustable "α" from the MLT and is thus more attractive for solar variability studies. The distribution of energy fluxes in a solar convection zone structure model using this formulation is shown in Figure 1.

The new formulation makes the resulting models very sensitive to the input physics (Lydon *et al.* 1992) but a solar model can be constructed within the observation bounds (radius, luminosity, p-mode oscillation frequencies, etc.) and furthermore, models have been constructed for the binary system α-Centauri A and B (Lydon *et al.* 1993b). Despite these advances, there is still much work to be done on the formulation of convective energy transport. In particular, since all three models stars are similar to each other, it is necessary to ascertain what needs to be added/modified to models elsewhere in the H–R diagram.

https://doi.org/10.1017/S0252921100024787 Published online by Cambridge University Press

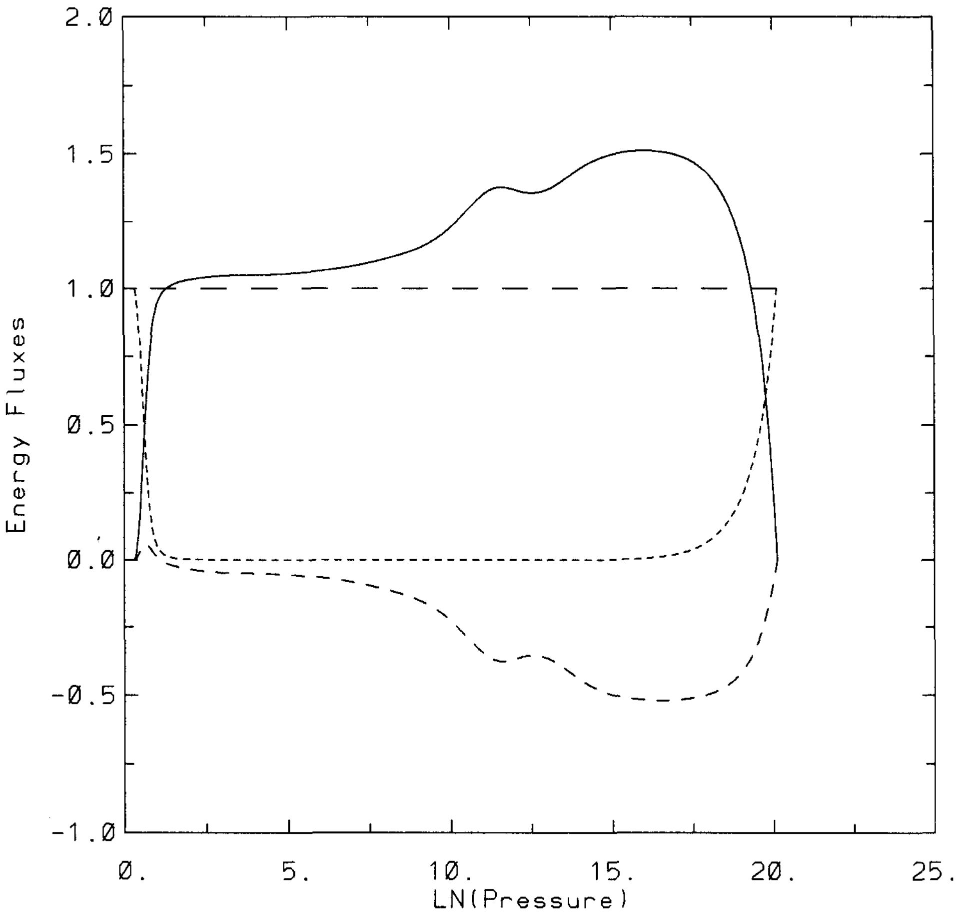

FIGURE 1. Schematic of vertical energy fluxes versus ln(pressure) for a solar model: enthalpy flux (solid), kinetic energy flux (medium dash), radiative flux (short dash), and the total heat flux (long dash).

2.5. *Magnetic fields*

So far in the discussion we have not dealt with the direct influence of magnetic fields on convective energy transport. A primary reason for this is that in the realm of three dimensional numerical simulations, this topic has received little attention until recently.

The general notion that magnetic fields inhibit convection seems to be an oversimplification. A more accurate, but less precise description, is that magnetic fields modify the convective flows depending on the scales and topology of the features and the magnetic field strength. A magnetic flux concentration can store and release heat (through Poynting Flux and radiative exchange; Fox *et al.* 1991) and thus modulates the total heat flux. There is also the possibility of generation of MHD waves which can amount to some fraction of the energy flux (perhaps up to 1%).

Perhaps most importantly for mean structure models, the presence of a magnetic field, either diffuse or concentrated, will alter correlations between flow and thermodynamic quantities, particularly ones like $C[v_z, T']$ which are important for obtaining expressions for the fluxes in eq. (2.1).

The discrete nature of the solar magnetic field also poses the question of how well can

https://doi.org/10.1017/S0252921100024787 Published online by Cambridge University Press

these features be represented in the horizontally averaged sense (i.e. the same question that was posed for concentrated downflows in the unmagnetized case)? Unfortunately this is still an open question.

2.6. *Energy blocking models*

The earliest models of this type were carried out by Spruit (1976, 1977) where time dependence of the problem as well as systematic flows were neglected, and by Foukal *et al.* (1983) and Chiang & Foukal (1984), where time dependence was considered, but still no flows were allowed. The results of these investigations indicated that, because of the much stronger thermal contact between the perturbed region and the deep convection zone than between the perturbed region and the surface, the large majority of the sunspot-blocked energy would be diffused into the entire solar convective region to be released on a thermal timescale of this region (i.e. about 10^5 years). More recently, Nye *et al.* (1988) considered this same problem, but included both energy and mass flow in the *linear* approximation. They found that significant mass flows were generated by the thermal energy blocked by the spot, but that these flows were not accurately in agreement with observations.

With the results mentioned in the previous sections in mind (i.e. importance of kinetic energy fluxes, etc.), we now turn to two simulations which deal with the response of a convective region to a disturbance in the energy flux. These simulations are the only ones available that are solved in the fully *non-linear compressible* regime and include dynamical effects self consistently. The two "experiments" in question are distinctly different and still far from addressing the actual conditions in the solar convection zone, but nevertheless they are both attempts to include detailed convective transport processes in the study of energy blocking.

2.6.1. *Deep seated perturbations*

Kuhn (1991) designed a numerical experiment which consisted of two boxes of convectively unstable gas, side by side in the conventional manner but with a differential heat flux ($1.01 \times F_{\text{total}}$ and $0.99 \times F_{\text{total}}$) imposed on either side. After a short relaxation time, the depth dependence of the average temperature difference between the hot and cold sides of the box shows a peak in the superadiabatic surface region, i.e. at the top of the layer. The temperature difference was about 6 times larger than that induced at the lower boundary.

A conclusion of these results was that a MLT–like representation for the heat transport (i.e. diffusive) is not accurate and that the disturbances were not distributed over the entire convective region.

2.6.2. *Surface layer perturbations*

Fox *et al.* (1991) considered the problem of calculating the flow around a sunspot-like object at various depths in the solar convection zone to study the energy balance in both the immediate area and far from the object, as a function of time. Although magnetic fields were not *explicitly* included, the sunspot-like object was modeled as a region prohibiting convective flow but allowing diffusive heat exchange due to radiation (and conduction). The geometry was two dimensional, in spherical coordinates. The width of the domain was 24.4 Mm and the depth was 2.0 Mm (approximately 6.65 pressure scale heights).

There were a number of results arising from these simulation but only one aspect will be discussed here, namely comparing the modification of the heat flux components due to the sunspot-like object compared to an otherwise identical control case where no object

https://doi.org/10.1017/S0252921100024787 Published online by Cambridge University Press

was present. The pore–sized object (of size 1.2 Mm wide and 0.132 Mm deep) was placed in the top, center of the domain. Further details are contained in Fox *et al.* 1991.

Once the object is in place, there is a short time of dynamic readjustment of the layer surrounding the object to accommodate the altered heat carrying capacity of the object. A closer examination of the region around the object reveals an enhanced horizontal kinetic energy flux which is distributed in both directions, indicating that there is a mix of small scale motions either to the left or right. Thus, once again, kinetic energy flux is an important factor in the heat transport.

To quantify this result, we examine the volume integrated components of the vertical enthalpy (Figure 2) and kinetic energy (Figure 3) fluxes in two regions (close to the object which represents $\approx 10\%$ of the domain;the upper panel of Figs 2 & 3, and far from the object, which is the remainder of the domain; on the lower panel of Figs 2 & 3) as a function of time after the object was introduced. The dash line represents the disturbed case and the solid line represents the undisturbed case.

There are two distinctive effects, the first is the time delay over which the heat flux is modified in response to the object. This is evident by noting that the two cases always begin to differ for the "close" integration (about 10-20 minutes) before they do for the "far" (1-2 hours) integration. The time delay is slightly different for the enthalpy and the kinetic energy fluxes and also for the vertical and horizontal components (not shown here).

The next effect is in the relative changes of the enthalpy flux and kinetic energy flux components and how these can be interpreted as a global indication of modified heat transport.

One very important factor is displayed in Figure 3, which shows that the kinetic energy flux close to the object changes sign compared to the undisturbed case. This is due to the fact that there is a net downward, or near zero, flux close to the object, which is associated with downflows beside and away from the object, as distinct from the broad upflows that occur in the absence of the object. Further from the object both radial and kinetic energy fluxes have larger variations than the undisturbed case: essentially they are responding to the excess heat flux being diverted from the region close to the object.

Despite these horizontal diversions of heat flux, not all of the blocked heat was stored in the convective region. In fact a good fraction of it appeared at the surface (Fox *et al.* 1991). The extent to which horizontal diversion, storage in fluid circulations, or appearance at the surface could occur depends on the size and position of the object, which was limited to a pore–sized object.

Given the importance of the kinetic energy in the redistribution of the heat flux, it is not surprising that previous studies found markedly different behavior. Most of the previous work relied only on a diffusion treatment of the heat flow (e.g. Spruit 1977; Chiang & Foukal 1984), or used linearized equations (Nye *et al.* 1988), and thus excluded the process that is suggested to be important in these calculations. As a result, the timescales of heat redistribution can be markedly different compared to completely diffusive processes.

There are a number of limitations to these calculations: the sub-surface geometry of the sunspot-like objects (their small size and shallow depth extent) and the treatment of radiative losses within the blocking region (diffusive only). For a surface object (the ones that are directly observed) the depth extent may be an important factor. As the depth of the lower boundary of the object increases, so does the local convective efficiency, indicating that convection should deal even more efficiently in redistributing the heat flux and that the conduction of heat into the object would decrease and its timescale for diffusion would increase. The important factor now in the redistribution is the width to

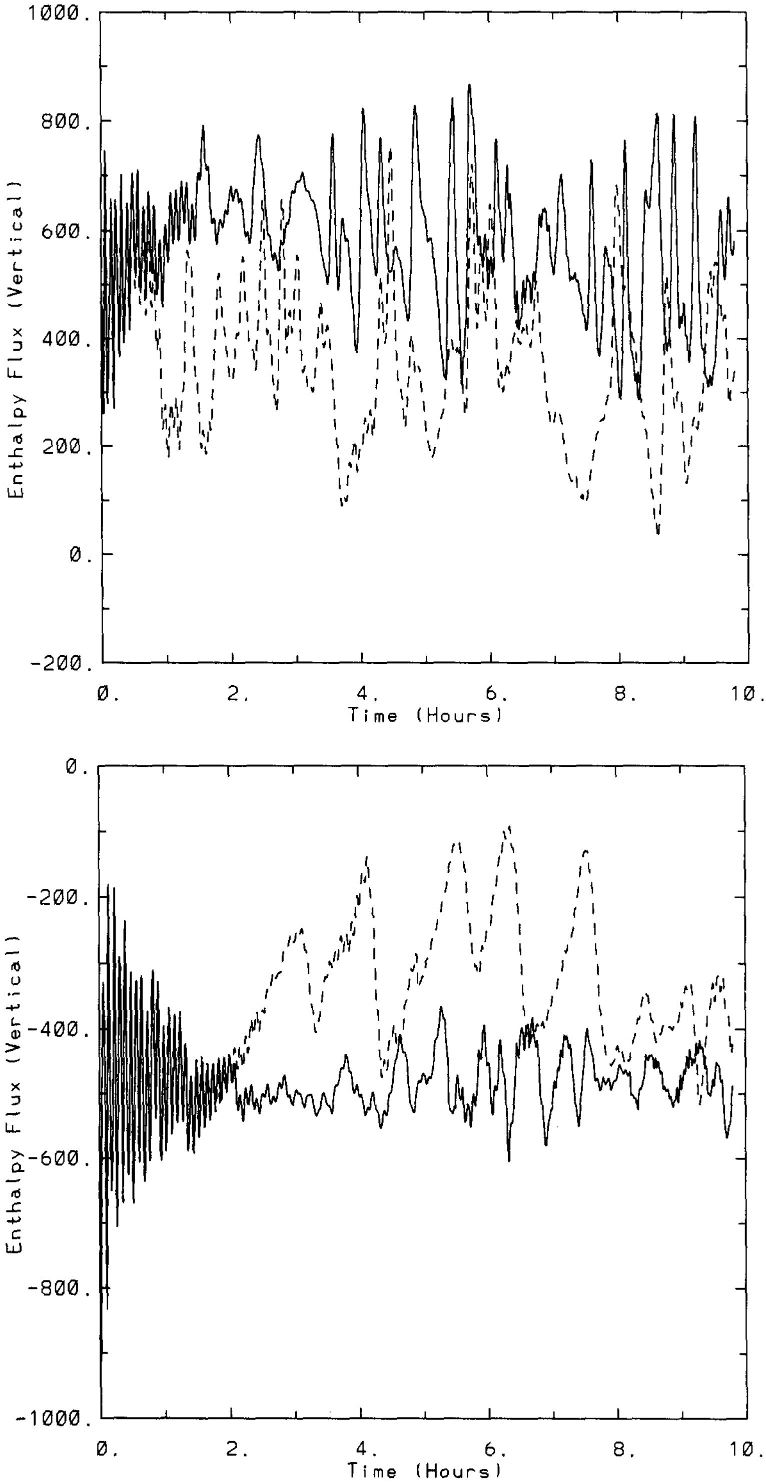

FIGURE 2. Vertical component of the enthalpy flux integrated over the domain close to (upper) and far from (lower) the object versus time after placement of the object. The solid line is the comparison case without the object, the dash line shows the response to the object.

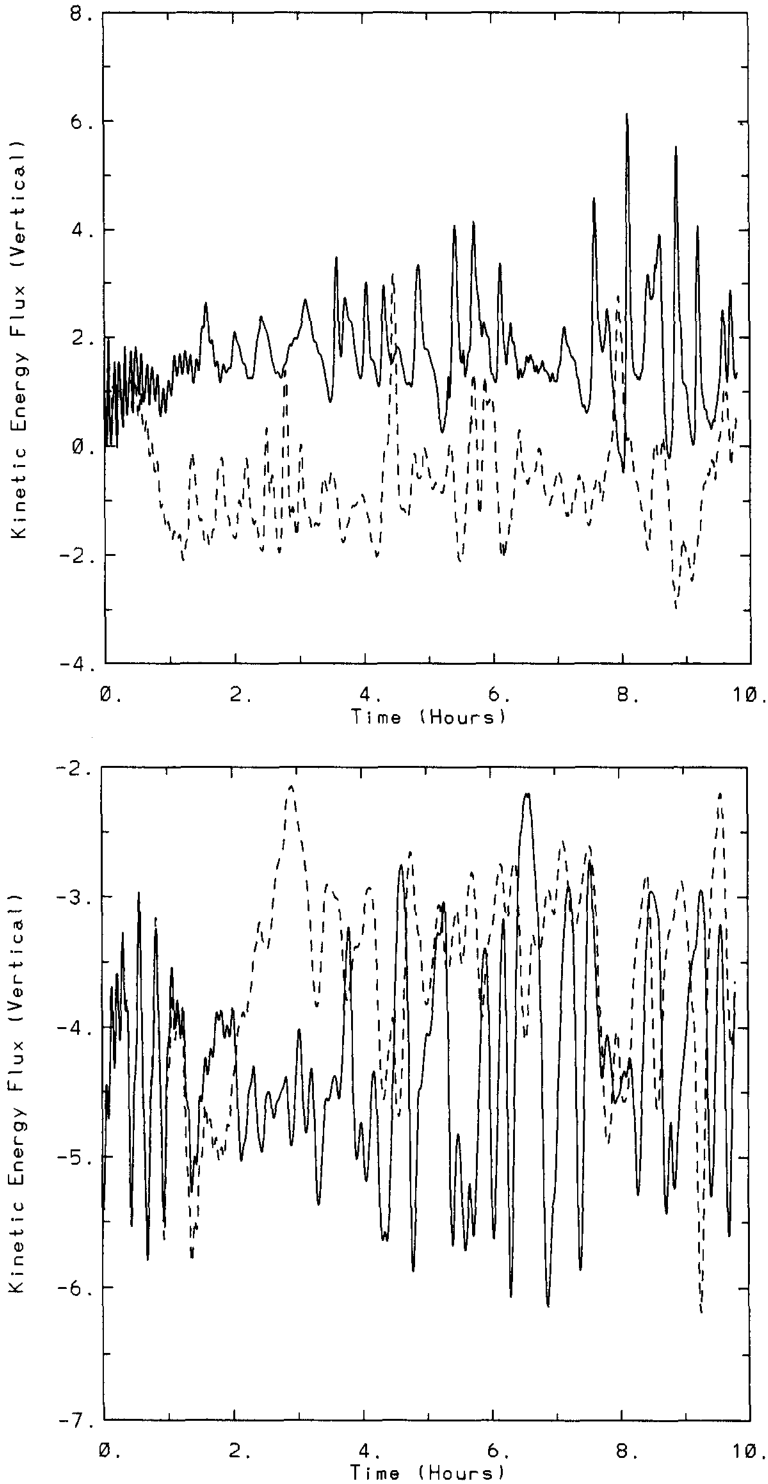

FIGURE 3. Vertical component of the kinetic energy flux integrated over the domain close to (upper) and far from (lower) the object versus time after placement of the object. The solid line is the comparison case without the object, the dash line shows the response to the object.

depth ratio, i.e. how long it takes the flow to go around. Also, because the pressure scale height is also increasing, the object may be "felt" at a larger distance, which would alter the way heat is transported. These considerations could be very important for sunspots.

3. Discussion

All of the preceding discussion highlights an increasing understanding of the physical nature of convective energy transport. The following general conclusions are relevant to solar variability studies:

(*a*) Kinetic energy flux is important in the heat budget in the interior
(*b*) Downflows may not be important in the overall heat transport
(*c*) Localized changes in heat transport can occur quickly
(*d*) Deep thermal perturbations may have a larger amplitude near the surface
(*e*) Heat can be stored in regions of intense magnetic field
(*f*) Diffusive, or mixing length descriptions can be misleading

Clearly, all simulation efforts, whether they deal with general characteristics of the compressible convection, or specifically with energy blocking and redistribution, must include the relevant physical effects. Because active regions have strong magnetic fields, closely surrounded by convective flow, it is likely that there will be some conversion between internal, kinetic and magnetic energy (Fox *et al.* 1991). The current assumption of the passive existence of a heat blocking object is only somewhat valid based on surface observations; however the lack of any knowledge of subsurface fields can be seen as an obvious drawback. For the energy blocking models, it will also be necessary to extend the existing calculations to larger length scales and longer timescales, to address the question of measurable radiance or irradiance variations. Further numerical experiments of the type performed by Kuhn are also essential in understanding how deep seated magnetic fields perturb the layers closer to the surface.

There are also a number of important questions to be addressed, and perhaps the most pressing is: what is the role of the solar activity cycle (on the decadal timescale) in longer term changes in the Sun? Further, can a global change in the Sun be effected in about 11 years? Most correlation studies between solar and terrestrial climate quantities point to timescales longer than a decade (usually 80-100 years), whereas other terrestrial indices apparently correlate with the length of a particular solar cycle (Friis-Christensen & Lassen 1991) and this is far from understood.

Another important area for study is at what scale do localized changes in convective transport alter the solar luminosity? Thus the question of a site for variability, much as solar physicists seek a site for the solar dynamo, becomes prominent.

Numerical simulations of convection and magnetic fields should soon address how the energy flux components are distributed under the influence of interior perturbations (of many varieties) and what their timescale for change is.

Finally, observations must play a crucial role in constraining the theoretical models. Already, helioseismology can probe the mean interior structure and, with improved databases (from global networks and satellites), should start to provide information on flows and latitudinal variations in the solar interior (such as those induced by large scale magnetic fields). The emergence of sunspot seismology also promises some insight into the subsurface structure of active regions, specifically spots, which would be essential in more detailed modeling of energy blocking.

Acknowledgments. The National Center for Atmospheric Research is sponsored by the National Science Foundation. S. Sofia thanks for AFOSR and NASA for support.

REFERENCES

CHAN, K. L. & SOFIA, S. 1986 Turbulent compressible convection in a deep atmosphere III: tests on the validity and limitations of the numerical approach. *Astrophys. J.* **307**, 222–241.

CHAN, K. L. & SOFIA, S. 1989 Turbulent compressible convection in a deep atmosphere IV: results of three-dimensional computations. *Astrophys. J.* **336**, 1022–1040.

CATTANEO, F., BRUMMELL, N. H., TOOMRE, J., MALAGOLI, A. & HURLBURT, N. E. 1991 Turbulent compressible convection. *Astrophys. J.* **370**, 282–294.

CHIANG, W. H. & FOUKAL, P. 1984 The influence of faculae on sunspot heat blocking. *Solar Phys.* **97**, 9–20.

ENDAL, A. S., SOFIA, S. & TWIGG, L. 1985 Changes in solar luminosity and radius following secular perturbations in the convective envelope. *Astrophys. J.* **290**, 748–757.

FOUKAL, P., FOWLER, L. A. & LIVSHITS, M. 1983 A thermal model of sunspot influence on solar luminosity. *Astrophys. J.* **267**, 863–871.

FOWLER, L. A., FOUKAL, P. & DUVALL, T. 1983 Sunspot bright rings and the thermal diffusivity of solar convection. *Solar Phys.* **84**, 33–44.

FOX, P. A., SOFIA, S. & CHAN, K. L. 1991 Convective flows around sunspot-like objects. *Solar Phys.* **135**, 15–42.

FOX, P. A., THEOBALD, M. L. & SOFIA, S. 1991 Compressible magnetic convection: formulation and two-dimensional models. *Astrophys. J.* **383**, 860–881.

FRIIS-CHRISTENEN, E. & LASSEN, K. 1991 Length of the solar cycle: an indicator of solar activity closely associated with climate. *Science* **254**, 698–700.

KUHN, J. R. 1989 Helioseismic observations of the solar cycle. *Astrophys. J.* **339**, L45–L47.

KUHN, J. R. 1991 Inferring solar structure variations from photometric and helioseismic observations., preprint.

LIVINGSTON, W. C. 1990 Sun-as-a-star. its convective signature and the activity cycle.. In *The Sun and Cool Stars: Activity, Magnetism and Dynamos* (ed. I. Tuominen, D. Moss & G. Rüdiger). Lecture Notes in Physics, vol. 380, pp. 246–251. Springer-Verlag.

LYDON, T. J., FOX, P. A. & SOFIA, S. 1992 A formulation of convection for stellar structure and evolution calculations without the MLT approximations I. application to the Sun. *Astrophys. J.* **397**, 701–716.

LYDON, T. J., FOX, P. A. & SOFIA, S. 1993a Improved solar models constructed with a formulation of convection for stellar structure and evolution calculations without the MLT approximations. *Astrophys. J.* **403**, L79–L82.

LYDON, T. J., FOX, P. A. & SOFIA, S. 1993b A formulation of convection for stellar structure and evolution calculations without the MLT approximations II. application to α Centauri A and B. *Astrophys. J.* **413**, 390–400.

MCINTOSH, P. S. 1994, in preparation.

NYE, A., BRUNING, D. & LABONTE, B. J. 1988 Mass and energy flow near sunspots: II. Linear numerical models of moat flow. *Solar Phys.* **115**, 251–268.

SPRUIT, H.-C. 1976 Pressure equilibrium and energy balance of small photospheric flux tubes. *Solar Phys.* **50**, 269–295.

SPRUIT, H.-C. 1977 Heat flow near obstacles in the solar convection zone. *Solar Phys.* **55**, 3–34.

STEIN, R. F. & NORDLUND, Å. 1989 Toplogy of convection beneath the solar surface. *Astrophys. J.* **342**, L95–L98.

WHITE, O. R. 1994 The solar spectral irradiances from X-ray to radio wavelengths. In *The Sun as a Variable Star: Solar and Stellar Irradiance Variations* (ed. J.M. Pap, C. Fröhlich, H.S. Hudson & S.K. Solanki). Cambridge University Press, in press.

VITENSE, E. 1953 Die Wasserstoffkonvektionszone. *Z. F. Astrophys.* **32**, 135–164.